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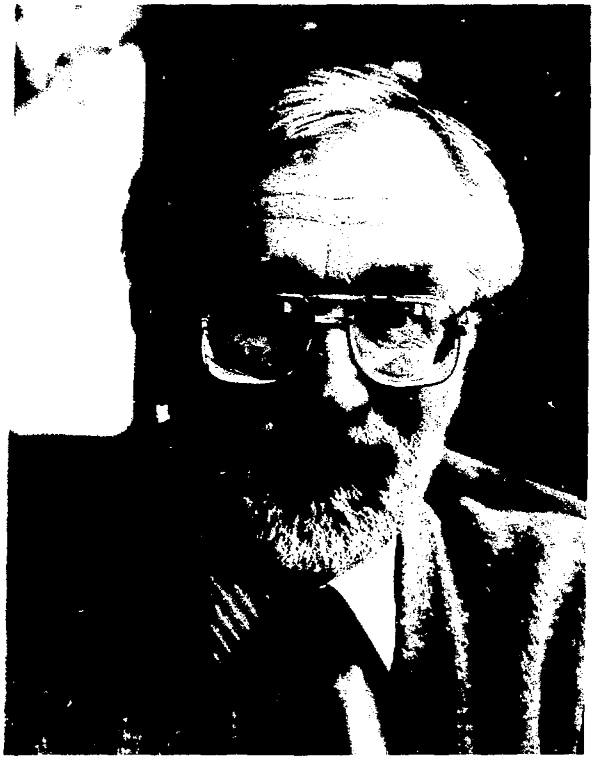
Accelerator Technology Division Annual Report FY 1989

Stanley O. Schriber, Division Leader

Los Alamos
NATIONAL LABORATORY



Stan Schriber became Division Leader of AT Division on November 18, 1987, following two years as Deputy Division Leader. He joined the Laboratory in July 1984 from Chalk River Nuclear Laboratory in Canada, where he was Project Manager for the Accelerator Buncher Project and Group Leader of the Proton Linac Group.

S. O. Schriber
Division Leader

Bob Hardekopf became Deputy Division Leader in February 1988. His previous position in AT Division was Group Leader of AT-3 during completion of the Proton Storage Ring and initiation of the NPB Output Telescope Program. Prior to joining AT Division in 1981, Bob was an associate Group Leader and researcher in the Physics Division for 10 years.

R. A. Hardekopf
Deputy Division Leader

The mission of the Accelerator Technology (AT) Division is to develop accelerator science and technology for application to research, defense, energy, and other problems of national interest.

The Division's technical goals are

to be a world leader in the design, development, and application of high-current, high-brightness, high-efficiency linear accelerator systems;

to develop resources, capabilities, facilities, personnel, and environment to support accelerator technology research and development;

to have the technical capabilities and insight to interact, drive, and react to the accelerator marketplace and to promote technology transfer; and

to commission and operate integrated systems for continuing accelerator experiments.

The Division's program goals are

to emphasize high-risk programs that extend the state of the art in each accelerator technology and position us for future programs;

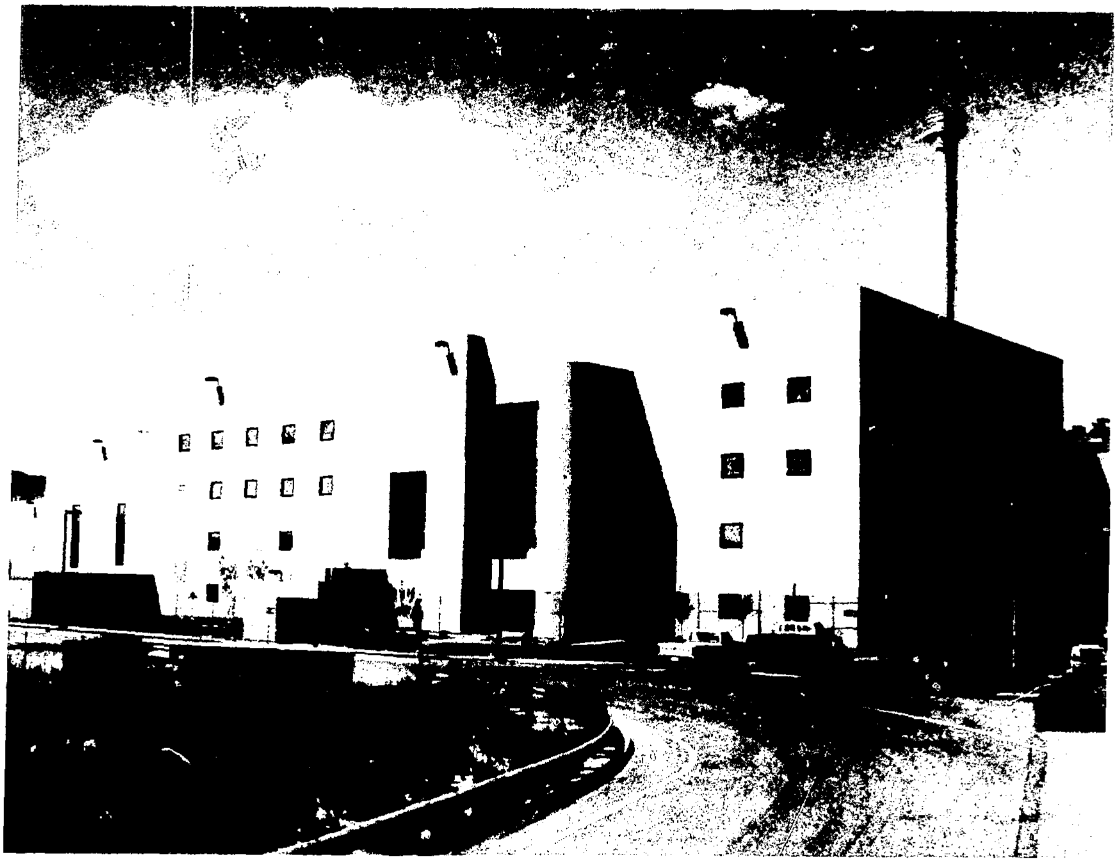
to succeed in current programs to demonstrate our ability to manage, design, build, and integrate significant accelerator systems that establish our national preeminence and reputation; and

to obtain a balanced mix of programs, including defense, energy, research, medical; both large and small programs; and industrial collaborations.

The Accelerator Technology Division continued to make progress in achieving these goals during fiscal year 1989.

Our largest program, the Ground Test Accelerator (GTA) in Strategic Defense Initiative Office's (SDIO) Neutral Particle Beam (NPB) program, saw the completion of the facility (see photo on next page) and the final design and fabrication of many components that will compose the first phase of the GTA accelerator. Crucial experiments that prove the design concepts for GTA were conducted or were in progress on the Accelerator Test Stand (ATS), the Ion Source Discharge Test Stand, and the NPB Telescope installation at Argonne National Laboratory (ANL). In addition, commissioning planning progressed to the stage where an outline could be presented at the annual Strategic Defense Command (SDC) review of GTA in May.

A major milestone in the NPB program was reached in July 1989 when the Beam Experiment Aboard a Rocket (BEAR) was successfully launched from White Sands Missile Range (WSMR). The 2500-pound NPB payload, including the radio-frequency quadrupole (RFQ) linac and radio-frequency (RF) power system, was boosted to



Ground Test Accelerator Facility.

an altitude of approximately 200 km by an ARIES solid-propellant booster. During the 9-minute flight hundreds of beam pulses were propagated into space while on-board instruments measured both beam and spacecraft environmental parameters. This $60M experiment was the first space test of a neutral particle beam and provided critical data for defining future space tests of NPB systems. AT Division is proud of the role we had in the BEAR project, which included the accelerator design as well as about 12 persons who were part of the testing and launch team.

In the Free-Electron Laser (FEL) program, years of hard work paid off when the Boeing Aerospace Corporation–Los Alamos team was awarded the contract to design and build the laser subsystem (LSS) for the Ground Based Free-Electron Laser (GBFEL) to be constructed at WSMR. Winning this competition ensured a major role for the research and development (R&D) being conducted at the Los Alamos FEL facility, renamed High-Brightness Accelerator FEL (HIBAF), with the addition of a photoinjector and upgrade of the electron linac. This upgrade was still in progress at the end of FY 1989, but successful operation of many of the components looks encouraging for meeting the goals.

The Division was successful in obtaining Laboratory Institutional Supported Research and Development (ISRD) funds to initiate or continue research into improved designs for accelerator structures, fabrication of superconducting cavities for high-current ion beams, beam breakup studies in coupled-cavity linacs, neural networks for accelerator control, large-orbit gyrotrons, Lie-Poisson integration techniques, high-brightness electron beams, and short-period magnetic undulators. These activities are being vigorously pursued to keep us in the forefront of high-current accelerator design for application to future programs.

Organizationally, we formed a new group, AT-9, to concentrate our efforts in high-power microwave research, including vulnerability, lethality, and effects (VL&E) programs and microwave source development for the Department of Defense (DoD). The initial base of personnel in this group came from AT-5, the RF Systems Group, which retained responsibility to build and commission RF systems for application to GTA and other accelerator programs. Group AT-9 was strengthened by the addition of several key staff members to consolidate high-power microwave (HPM) development and testing in the Laboratory.

Our staffing level at the end of FY 1989 was approximately 250, about the same as last year. Of the 250, 120 are staff members, 100 are technical support personnel, and 30 are administrative support personnel. Of the staff members, we are balanced between science and engineering disciplines, with the engineers having expertise in mechanical, electrical, and computing science. We remain concerned about the low number of mechanical engineers and took steps during the year to actively recruit new engineers into the accelerator field.

Programmatically, AT Division maintained a stable funding level at approximately $64 M. As the chart on page xv indicates, about 67% was support for the GTA program. We took steps in FY 1989 to diversify our programs.

In order to focus our efforts in promising new directions, the Division formed a Program Development Team during FY 1989. This team meets with the Division management on a weekly basis to brainstorm ideas for new accelerator projects that are appropriate for us to pursue. The minutes of the meetings are distributed to group leaders and program managers in the Division to help us keep a long-range perspective while we are busy meeting the goals of our existing programs. This team is attempting to follow up on our strategic plan by bringing new, exciting programs to the Division that will take advantage of our technical base and help to build a future at the forefront of linear accelerator development.

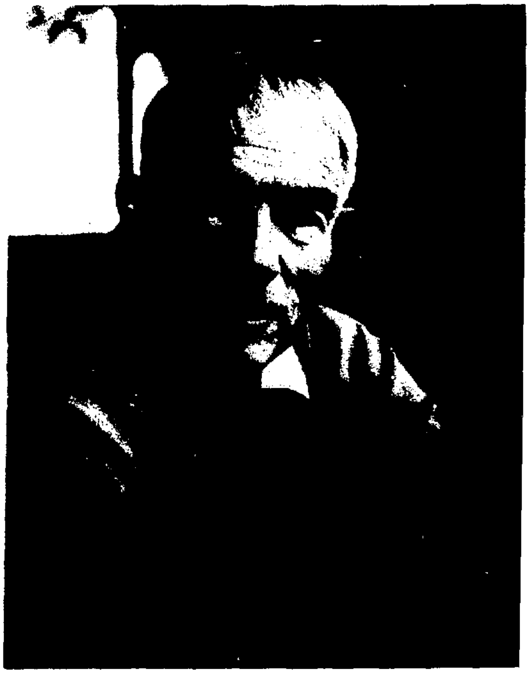
Recent initiatives include collaborations with the SSC Laboratory for design of the SSC linac and consulting in diagnostics and RF systems; designing and building electron linacs for the University of Milan and the University of Twente; and proposals to the Laboratory and Department of Energy (DOE) for very high-current cw proton accelerators for production of tritium and radioactive waste transmutation. We also participated in conceptual design studies for a collaboration with Japan on an International Fusion Materials Irradiation Facility (IFMIF) and have continued discussions on working with the Japanese on their proposal for radioactive waste treatment. We continued to work with Tri Area University Meson Facility (TRIUMF) on testing of ferrite-tuned cavities and other technical issues developed here for the Advanced Hadron Facility (AHF) project. We developed a conceptual design for a high-current, multirod RFQ for neutral beam heating in a tokamak device and presented papers on the design at magnetic fusion workshops.

Division personnel were honored with several awards during the year, and these are listed on page xvi. It is especially noteworthy that these awards were achieved during a period of intense pressure to obtain funding for and deliver on systems with very directed programmatic goals. The strength of a national laboratory is vitally dependent on being able to innovate in the face of such pressures, and we are extremely proud of the achievements represented by these awards.

A listing of publications by AT-Division staff appears in Appendix A. These represent significant contributions to the progress reported at major accelerator conferences and to the vitality of the linear accelerator field.

Our nine groups form the technical backbone of the Division, and on the following pages we describe the FY 1990 progress with a summary of each group's mission, organization, and accomplishments.

Program Managers



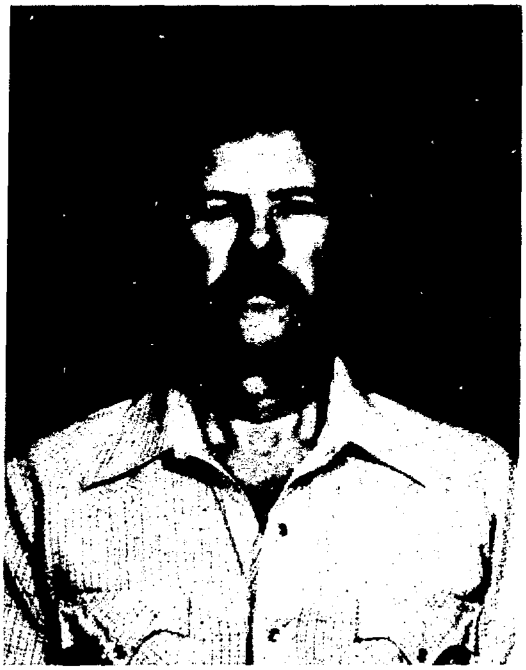
Program Manager—NPB
H. Jansen

Deputy Program Manager—NPB
E. A. Heighway

Program Manager—FEL
L. B. Warner

Division Office Support/Section Leader

Division Safety Officer
E. Kemp



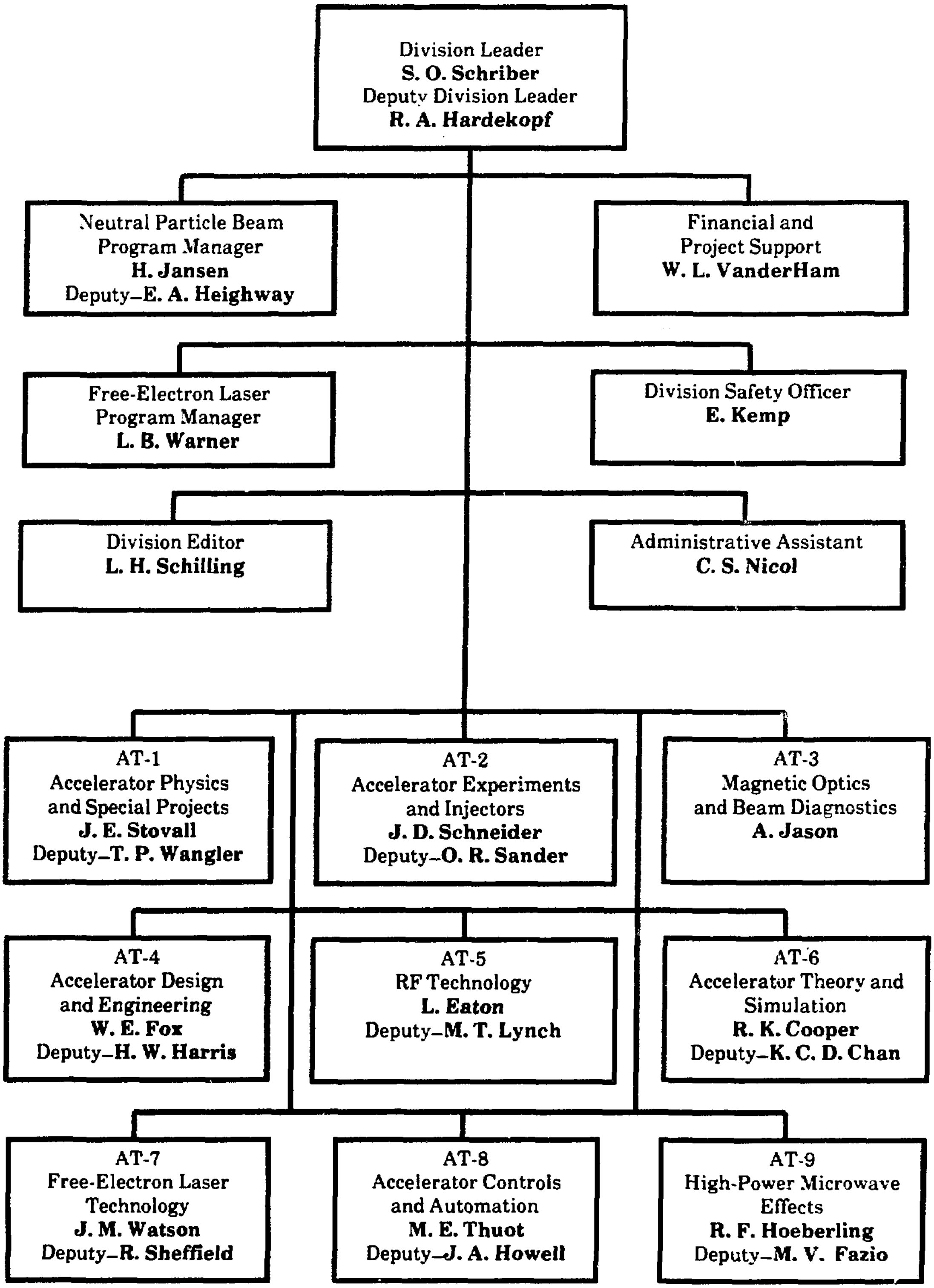
Financial and Project Support
W. L. VanderHam

Administrative Assistant
C. S. Nicol

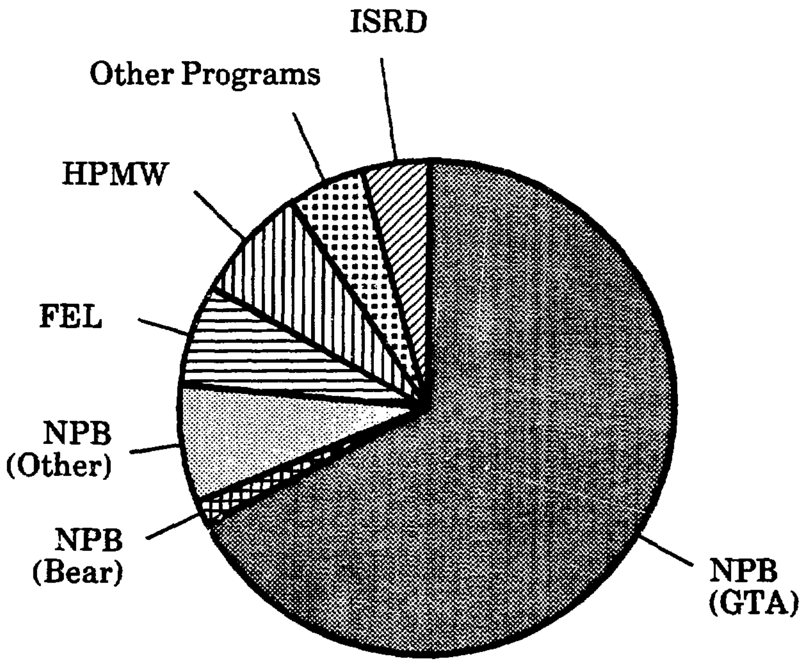
Division Editor
L. H. Schilling

Division Organization

AT Division Organization, October 1989



Division Funding



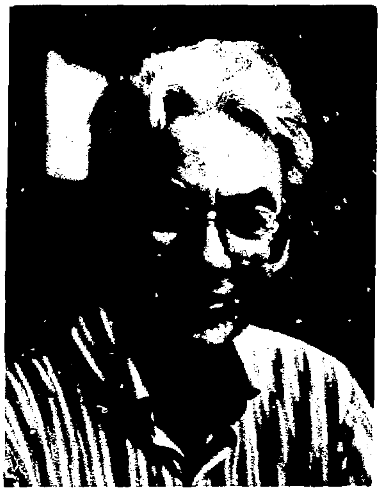
Total $64M

NPB (GTA)	67.2%
NPB (BEAR)	1.7%
NPB (Other)	7.6%
FEL	6.6%
HPMW	7.5%
Other Programs	5.0%
ISRD	4.4%

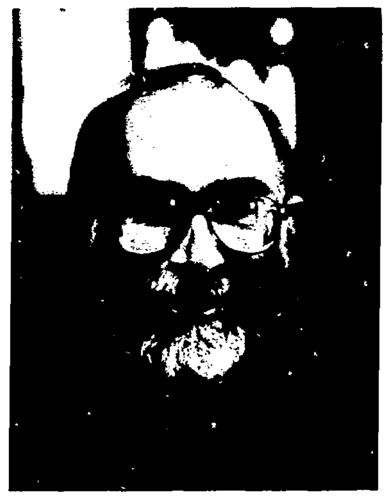
Awards, Honors, and Patents

Several Awards and Honors were bestowed to AT Division during FY 1989.

- The R&D 100 Award was received on the Photoinjector for RF Linear Accelerators.
- The NPB Telescope Control System was nominated for the R&D 100 Award and was honored by the Laboratory at a Director's reception.
- A strategic defense Plaque was received for Strategic Defense Initiative (SDI) Technology Achievement for the Los Alamos NPB Telescope Experiment.
- A strategic defense Plaque was received for the Transfer of SDI Technology to Industry—Strategic Defense Applications Award for Radio-Frequency Quadrupole Linear Accelerator Technology for Medical Industrial Use.
- AT Division received a Distinguished Performance Team Award for The FEL Photoinjector.
- The individual Distinguished Performance Award was given to Group AT-1's S. Watson, J. Allen/T. Cole, and BEAR RFQ Design Team.
- The Distinguished Patent Award was given to R. Sheffield (AT-7) and J. Fraser (retired from AT-7, now a consultant for AT-7) for the Optically Pulsed Electron Accelerator.
- An article for the Laboratory's yearly publication *Research Highlights* was accepted on Photoelectric Injectors for Accelerators.
- R. A. Jameson was elected a fellow of the American Physical Society for original contributions to the development of high-brightness linear accelerators, and in the application of charge-particle beams in medicine, fusion, neutral-beam development, and free-electron lasers.



J.E. Stovall
Group Leader



T.P. Wangler
Deputy Group Leader

Introduction

The Accelerator Physics and Special Projects Group, AT-1, provides accelerator design and physics support for the Division's many projects. Its members also pursue advanced topics in accelerator physics and technology in support of the Division's long-range goals.

Institutional Supporting Research

Longitudinal Emittance Growth in High-Current Linear Ion Accelerators[1]

The control of rms longitudinal emittance growth in linear ion accelerators can be important for two reasons. First, longitudinal emittance growth produces a beam halo in longitudinal phase space that because of longitudinal-transverse coupling, also results in a beam halo in transverse phase space. This can cause undesirable beam spill that may be a serious limitation for linacs with high average current. Second, for some applications, the output beam-optics requirements put limits on longitudinal emittance to minimize chromatic aberration effects.

We use the numerical simulation codes PARMTEQ[2] and PARMILA[3] to study emittance growth phenomena that are induced by both external and space-charge fields under a variety of conditions. We have studied longitudinal emittance growth for two important cases: (1) the bunching section of an RFQ and (2) the drift-tube linac (DTL).

The RFQ forms the bunches from an input dc beam and determines the longitudinal emittance through the bunching process. The bunching is done over many cells (adiabatically) as the accelerating field and synchronous phase are varied. Both nonlinear RF fields and nonlinear space-charge forces act on the beam. We have obtained a scaling formula[4] for transverse rms emittance growth in the RFQ. Similarly, systematic studies of RFQ designs with different beam currents, current limits, injector energies, and RF frequencies to determine a scaling law for rms longitudinal emittance after bunching have been carried out. We find that the rms longitudinal emittance ϵ_ℓ at the end of the bunching section can be approximately expressed as a product,

$$\epsilon_\ell = \epsilon_s \eta \quad . \qquad (1)$$

The quantity ϵ_s is equal to the product of the horizontal and vertical semiaxes of the zero-current separatrix area. The factor η depends on the ratio I/I_{max}, where I is the captured beam current at the end of the bunching section and I_{max} is the longitudinal current limit, which is calculated from the uniform 3-D ellipsoid model. In Fig. 1.1, $\eta = \epsilon_\ell/\epsilon_s$ is shown as a function of I/I_{max} for two different RFQ linacs. The decreasing value of η as I/I_{max} increases is the result of increasing energy transfer to transverse motion. This curve may depend somewhat on the details of the design procedure.

A 200-MHz DTL for acceleration of a proton beam from 2 to 50 MeV to study longitudinal rms emittance growth for low-emittance bunched beams has been generated. Figure 1.2a shows the rms longitudinal emittance versus cell number for the initial Gaussian beam at I = 0 and 100 mA. For I = 0, no longitudinal rms emittance growth is observed, which implies that the nonlinear external field has a negligible effect on the emittance. At 100 mA, a very rapid emittance growth of about a factor of 2 is observed in the first cell, which is followed by beam oscillations and a slow growth throughout the remainder of the DTL. The corresponding transverse emittance plots (Fig. 1.2b) show the presence of the rapid initial growth, but not the slow growth component. We attribute the rapid growth to charge redistribution of the beam as the beam matches itself internally to the accelerator and as field energy is transformed to particle kinetic energy.

We interpret the slow growth as being caused by a slow charge redistribution as the bunch length expands during acceleration. The expansion occurs because of a decrease in the longitudinal focusing force as the beam velocity β increases. This effect can be seen in the longitudinal oscillation frequency $\omega_{\ell 0}^2 = 2\pi q\ E_0T \sin(-\Phi)/\gamma^3 m\beta\lambda$. When E_0T and Φ are constant, $\omega_{\ell 0}$ and the external focusing force decrease with increasing β. We find that the slow, longitudinal emittance growth rate can be significantly reduced by ramping the accelerating field as β increases to keep $\omega_{\ell 0}$ constant. This improvement can be seen in Fig. 1.3, which shows the longitudinal emittance vs cell number for a uniform beam, when $\omega_{\ell 0}$ is kept constant. The result for constant E_0T is also shown for comparison. The practicality of ramping E_0T during acceleration is related to issues of RF electric breakdown and structure cooling.

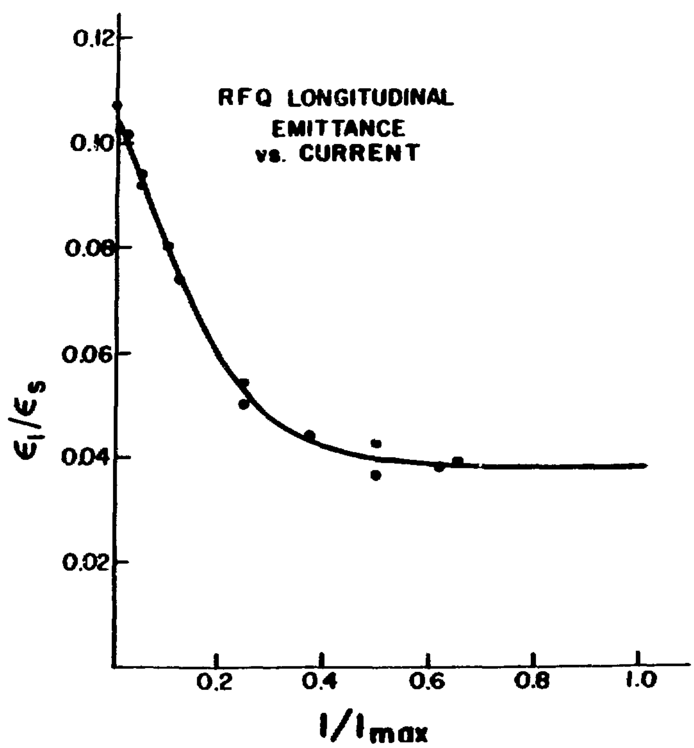


Fig. 1.1 RFQ longitudinal emittance ratio vs normalized current, as described in the text.

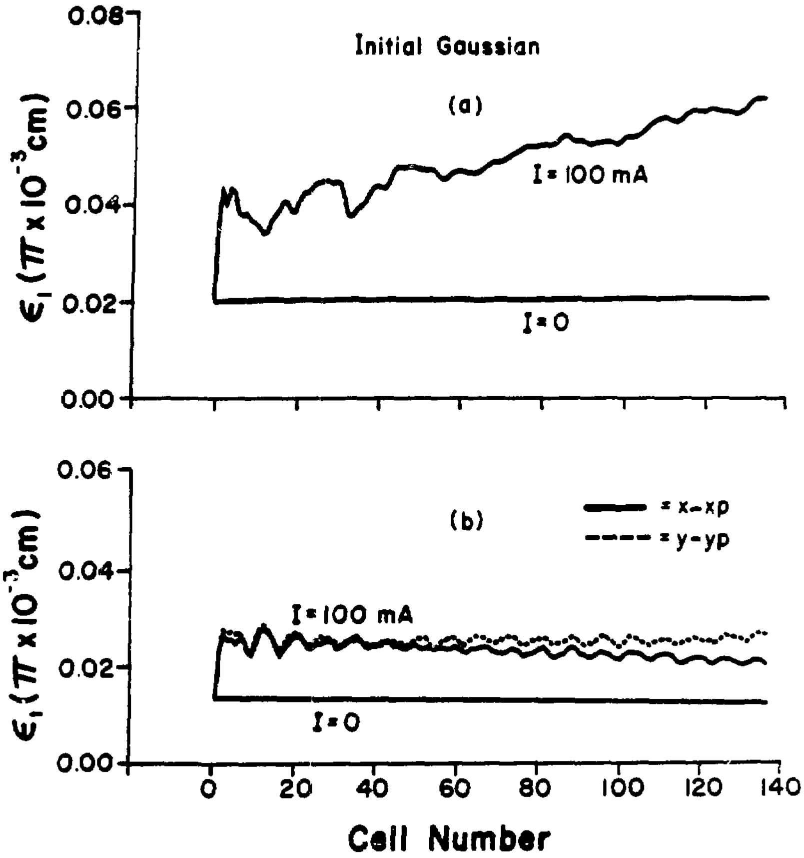


Fig. 1.2a and b DTL rms normalized emittance vs cell number for initial Gaussian beams: (a) longitudinal and (b) transverse.

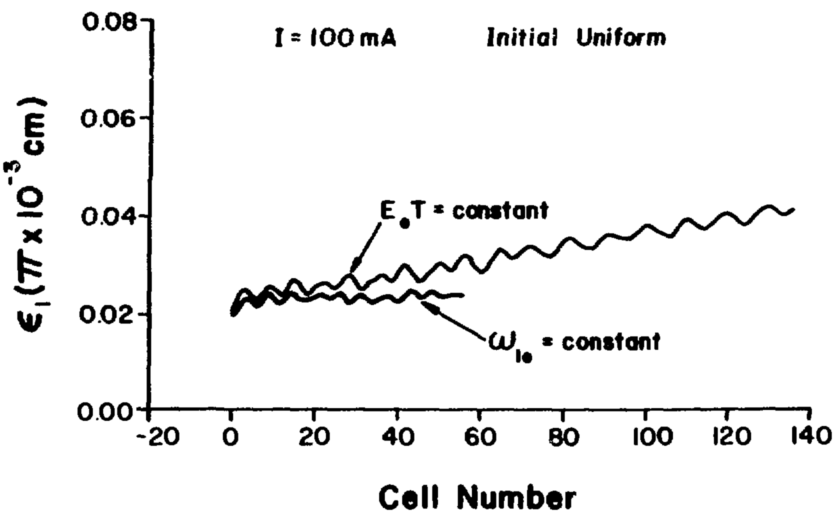


Fig. 1.3 DTL rms normalized longitudinal emittance vs cell number for an initial uniform beam.

Beam-Halo Formation and Implications for the Design of High-Intensity Accelerators[5]

Beam-halo formation in high-intensity accelerators is undesirable because it can lead to particle losses and activation of accelerator components. Although the causes of beam-halo formation in phase space are not completely understood, much has been learned from our numerical simulation studies. In these studies, we observed that nonlinear space-charge forces act to produce halo. Nonlinear focusing forces create filamentation in phase space and increase the rms normalized emittance, but they are not observed in the simulation studies to produce halo. The halo appears to be the result of the nonlinear processes within the beam caused by the time-dependent collective space-charge forces. Particles that populate the halo have acquired larger center-of-mass energies.

Transitions in the accelerator, where parameters change, appear to increase the amount of halo in phase space. Transitions such as changes in the strength of the external focusing force, changes in the periodicity of the focusing lattice, introduction of deflecting elements, or changes in the RF cause a change in the external focusing, and as a result, the beam must adapt. Given a sufficient number of beam-plasma periods after such a transition is introduced, the beam has evolved to a quasi-stationary state. During this evolution process, beam halo appears to be produced. The time scale for halo production is not yet well established but appears to be in the range of a few to a few tens of beam-plasma periods. This time scale may have relevance for the design of emittance filter systems.

The evidence obtained from simulations suggests that strong focusing is an effective strategy for minimizing halo production. This is already known to be the most effective approach for minimizing rms emittance growth, even though it does increase the beam density. It does appear that accelerator transitions should be minimized and introduced only when necessary; ion source extraction, bunching, and (in some cases) funneling are examples of some transitions that are necessary. If these transitions are kept at the low-energy end of the accelerator, the activation effects of the associated local beam losses are minimized, and collimator systems that act as emittance filters to remove the halo will be more effective and easier to implement. Good beam matching across these transitions is very important to minimize the disruption to the beam.

With regard to rms emittance, we believe this is still a quantity whose growth should be controlled. Not only is rms emittance growth often correlated with halo production, but the rms emittance affects the overall spatial size of a given beam distribution; the larger the rms emittance, the larger the beam size and the greater the extension in real space of the halo that already exists. Therefore, an important figure of merit in the design of the high-energy sections of the accelerator is the ratio of the effective aperture (either radial or longitudinal) to the rms beam size, which can be calculated using a uniform 3-D ellipsoid model for the beam.

Comparison of Lens and Lattice Properties for Accelerator Focusing[6]

Because of the importance of maintaining small beam size for control of rms emittance and beam halo, we have derived the relevant properties of various lenses in different lattice configurations in the thin-lens approximation. These formulas are useful for comparing different approaches for accelerator focusing and are shown in Table 1.1. The important quantity is the betatron frequency ω_o, which should be maximized, subject to the constraint for high currents that the zero-current phase advance per focusing period, σ_o, is kept below $\Pi/2$.

Table 1.1. Comparison of Lens and Lattice Properties for Accelerator Focusing

Lens	Lattice	$\frac{1}{f}$	Period	$\cos\sigma_0$ *	σ_0 †	k_0	ω_0
Magnetic Quad	FODO	$\frac{eG\ell}{m\gamma v}$	$2L$	$1-\frac{1}{2}\left(\frac{L}{f}\right)^2$	$\frac{\ell LeG}{m\gamma v}$	$\frac{\sigma_0}{2L}=\frac{\ell}{2}\frac{eG}{m\gamma v}$	$\frac{\sigma_0 v}{2L}=\frac{\ell}{2}\frac{eG}{m\gamma}$
Magnetic Quad	FOFODODO	$\frac{eG\ell}{m\gamma v}$	$4L$	$1-4\left(\frac{L}{f}\right)^2+\frac{1}{2}\left(\frac{L}{f}\right)^4$	$\frac{2\sqrt{2}\ell LeG}{m\gamma v}$	$\frac{\sigma_0}{4L}=\frac{\sqrt{2}\ell}{2}\frac{eG}{m\gamma v}$	$\frac{\sigma_0 v}{4L}=\frac{\sqrt{2}\ell}{2}\frac{eG}{m\gamma}$
Magnetic Solenoid	FO	$\left(\frac{eB_s}{2m\gamma v}\right)^2\ell$	L	$1-\frac{L}{2f}$	$\frac{\sqrt{\ell L}eB_s}{2m\gamma v}$	$\frac{\sigma_0}{L}=\sqrt{\frac{\ell}{L}}\frac{eB_s}{2m\gamma v}$	$\frac{\sigma_0 v}{L}=\sqrt{\frac{\ell}{L}}\frac{eB_s}{2m\gamma}$
Electric Quad‡	FODO	$\frac{eE_0\ell}{m\gamma v^2 a}$	$2L$	$1-\frac{1}{2}\left(\frac{L}{f}\right)^2$	$\frac{\ell LeE_0}{m\gamma v^2 a}$	$\frac{\sigma_0}{2L}=\frac{\ell}{2}\frac{eE_0}{m\gamma v^2 a}$	$\frac{\sigma_0 v}{2L}=\frac{\ell}{2}\frac{eE_0}{2m\gamma va}$
Magnet Quad Doublet	FO	$\frac{eG\ell}{m\gamma v}$	$L+D$	$1-\frac{LD}{f^2}$	$\frac{\sqrt{LD}\,eG\ell}{m\gamma v}$	$\frac{\sigma_0}{L+D}=\frac{\sqrt{LD}}{L+D}\frac{eG}{m\gamma v}$	$\frac{\sigma_0 v}{L+D}=\frac{\sqrt{LD}}{L+D}\frac{eG\ell}{m\gamma}$

Definitions: L=lens spacing, ℓ=lens thickness, G=quad gradient, B_s=solenoid field, B_0=pole-tip magnetic field for quadrupole, E_0=pole-tip electric field for quadrupole, a=quadrupole radical aperture, σ_0=phase advance per period, k_0=phase advance/length, ω_0=phase advance/time.

*Thin lens result for phase advance per period.
†First-order approximation accurate to within about 10% for $\sigma_0 \leq 90°$.
‡Electric quadrupole results can be obtained from quadrupole by making the substitution $G \rightarrow E_0/av$.

Beams with Space Charge in Field-Free Drift Regions[7]

We observe in computer simulations that expanding beams under the influence of space charge alone exhibit a steady emittance growth. When the beam expansion is viewed in phase space, one generally observes some degree of correlation between position and velocity, together with a certain degree of randomness of the particle velocities at each position. One question is whether it is possible and useful to make this distinction more quantitative by identifying two figures of merit of the beam, one for thermal or random motion and a second for correlated motion. It may be convenient to think of this as a conventional fluid model description, except that we will use a more intuitive approach in our basic definitions.

For any degree of freedom, we identify a velocity of thermal motion from which a corresponding effective temperature and thermal kinetic energy are defined.

We express the total space-charge force F as $F = F_u + F_{nl}$, where F_{nl} is associated with the nonlinear space-charge force and F_u is the space-charge force of the equivalent spatially uniform beam, which has the same current and second moments as the actual beam. For a uniform beam, $F_{nl} = 0$ and the space-charge forces are linear.

We have derived an equation for the rate of change of thermal energy, which consists of two forms. The first term depends on F_{nl} and is identified as the contribution from nonlinear space-charge heating. We have been able to show that the second term describes energy transfer between thermal energy and flow energy. For example, when there is no emittance growth from nonlinear space charge, the thermal energy decreases as the beam expands at constant emittance.

The rate of change of flow energy depends on the rate at which work is done by the space-charge force of the equivalent uniform beam. The nonlinear force F_{nl} makes no direct contribution here. In addition, there is energy transfer from thermal energy as the beam cools during expansion, as described by a second term. This cooling term describes an energy transfer that occurs without space-charge forces. This energy exchange is of a different nature than usual because it arises from the kinematics of noninteracting particles, rather than from dynamics. The same effect would occur if an enclosed gas of neutral noninteracting atoms in thermal equilibrium was suddenly released into free space and allowed to expand.

Thus, we observe that if the space-charge force is separated into two components, F_u and F_{nl}, the equivalent uniform beam component F_u affects the flow energy, and the force component F_{nl} affects the thermal energy and emittance. In addition, expansion of the beam with finite emittance results in a continuing transfer of energy from thermal to correlated (flow) motion.

Beam Loss Limits for Niobium Superconducting Cavities[8]

A simple model was developed as a tool for making an initial estimate of the maximum allowable beam loss on niobium cavities in an NPB-relevant superconducting linear accelerator (linac). This model was meant to permit some design-independent conclusions about the impact of beam losses causing the cavities to quench to the normal state and also the liquid helium (LHe) coolant consumption.

Two assumptions are fundamental to our model: (a) the beam is reasonably well tuned in the accelerator, and (b) lost particles deposit all their energy along the surface of the beam pipe. We visualize an elliptical beam grazing a round niobium pipe, as shown in Fig. 1.4, and we assume the beam is somewhat mis-steered so that the beam halo particles enter the niobium along a circumferential zone.

We obtain a quench-limited maximum current loss per unit length given by

$$I_{L,max} = \frac{C_1}{W} \quad ,$$

where $5.2 \leq C_1 \leq 52$ mA·MeV/m and W is the beam energy in megavolts. The quench-limited beam power loss per unit length in niobium is

$$5.2\ kW/m \leq I_{L,max} \leq 52\ kW/m \quad .$$

This would represent an *enormous* amount of power to be removed by the LHe coolant. A typical economically practical power loss per unit length for existing superconducting accelerators is in the range of 40 to 80 W/m (including the RF losses in the niobium). If the above power

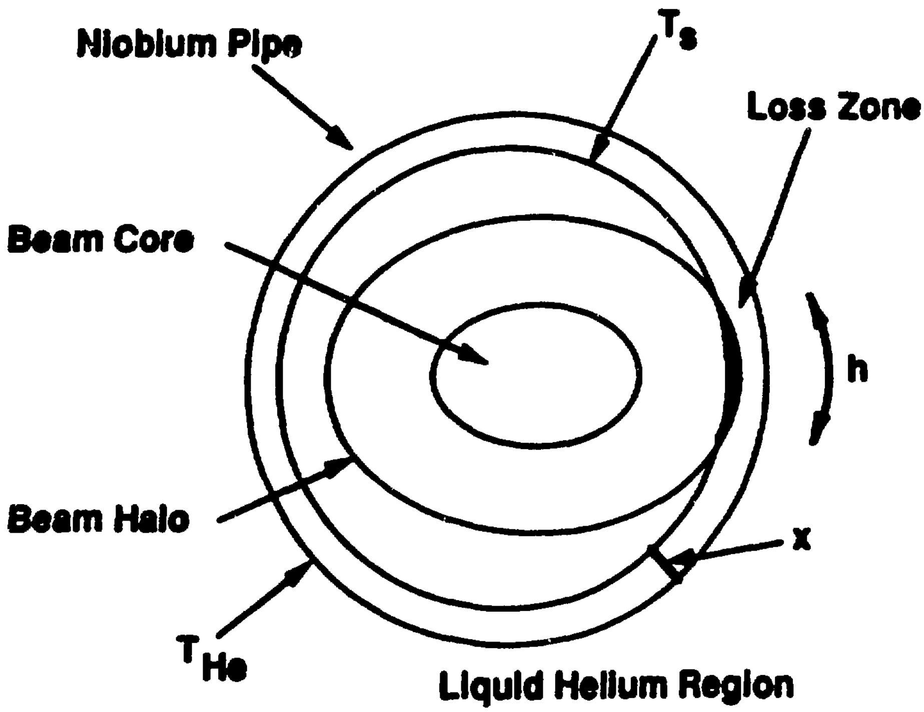


Fig. 1.4 Mis-steered beam in niobium pipe of thickness x with beam halo intersecting pipe surface in zone of height h.

went into vaporization of LHe at a vaporation rate of 1.4 ℓ/h per watt input, the LHe coolant would be vaporized at a rate of 7300 ℓ/h·m at $P_{L,max} = 5.2$ kW/m. For a ground-based research accelerator, the required refrigeration input power would be impractically large; approximately 3 MW/m would be required to remove 5.2 kW/m at 4.2 K and reject it at room temperature. This strongly indicates that the important practical limitation for beam losses on superconducting RF cavities is determined by the LHe consumption, rather than by the requirement for maintaining the cavity surfaces below a certain temperature.

If the maximum beam power loss per meter as determined by LHe consumption were 100 W/m, then the maximum allowed beam current loss per meter would be

$$I_{L,max} = \frac{100\ \mu A \cdot MeV/m}{W} \quad .$$

For a ground-based, long-term application, beam losses to superconducting structures would have to be held to within a factor of 2 to 3 of this value, based on simple economics. However, for a short-term space application (as in an NPB accelerator), the tolerable loss rate could be 10 to 50 times as high without leading to excessive LHe coolant mass requirements on the platform.

Based on the simple model that we have presented, we conclude that beam losses on superconducting niobium cavity surfaces must be limited in a high-current linac and that for most practical geometries, the LHe consumption rate will establish the maximum tolerable loss levels, rather than quenching of the superconducting cavity material. Although we lack a detailed picture of expected beam halos that contribute to the beam losses, we suggest that a system of beam scrapers, thermally isolated from the LHe coolant, should be included in the design of a high-current superconducting accelerator. The practicality of such scrapers remains to be determined by an appropriate engineering design study.

Linac Physics Design for Accelerator Production of Tritium (APT)

The dc injector, the RFQ, the DTL, and the funnel constitute the front end of the accelerator. The primary objective of the front-end design is to produce a high-quality, low-emittance beam that can be injected into the main coupled-cavity linac (CCL) at 20 MeV and subsequently accelerated as a very compact beam to 1600 MeV with minimal beam loss. The emphasis in the front-end design is low emittance growth and low halo production as the beam experiences the major transitions of bunching and funneling with frequency doubling. Minimizing beam loss in the front end is a secondary objective, as long as the activation consequences are acceptable and heating consequences are addressed by providing sufficient cooling. The low emittance growth is achieved by providing a high-frequency linac to reduce the particles per bunch and by providing strong transverse focusing with RF electric quadrupoles, magnetic quadrupoles, and ramped accelerating fields from strong longitudinal focusing in the DTL.

The primary objectives in the CCL are (1) to introduce no major transitions that can lead to further beam halo, (2) to provide large apertures to minimize beam losses that even at relatively low levels can lead to significant activation levels, and (3) to provide sufficient focusing to maintain compact beam dimensions and minimize further emittance growth. An important figure of merit is the ratio of aperture over rms beam size. This quantity can be maximized by choosing a large product of pole-tip magnetic field times effective length for the quadrupoles, using a high density of quadrupole focusing lenses and by providing the largest practical apertures. A high density of focusing elements leads to short accelerator tanks (2 to 10 cells for APT, rather than 30 to 60, as were used for the Clinton P. Anderson Meson Physics Facility [LAMPF]). The CCL is divided into seven different sections so that larger apertures can be used as the particle velocity increases and so that the ratio of aperture over rms size can be maximized for each velocity region. Furthermore, as the velocity increases, the number of accelerating cells per tank can be increased, thereby reducing the number of components.

Conceptual Design of an RFQ Accelerator-Based Neutron Source for Boron Neutron-Capture Therapy (BNCT)[9]

We have produced a conceptual design of a low-energy neutron generator for treatment of brain tumors by BNCT. The concept is based on a 2.5-MeV proton beam from an RFQ linac, and the neutrons are produced by the $^7Li(p,n)^7Be$ reaction. A liquid lithium target and modulator assembly are designed to provide a high flux of epithermal neutrons. The patient is administered a tumor-specific

^{10}B-enriched compound and is irradiated by the neutrons to create a highly localized dose from the reaction $^{10}B(n,\alpha)^{7}Li$. An RFQ accelerator-based neutron source for BNCT is compact, which makes it practical to site the facility within a hospital.

Space-charge effects in the RFQ govern the maximum permissible beam currents. Although we believe that beam currents of 100 mA and higher are practical for 100% duty factor, we have chosen 30 mA for this first example. Figure 1.5 shows a schematic of the overall RFQ linac BNCT treatment facility, including the accelerator system, a vapor-cooled liquid lithium target, the neutron moderator assembly, and a patient undergoing treatment. A block diagram of the accelerator system is shown in Fig. 1.6, consisting of an ion source, the low-energy beam transport (LEBT), the RFQ linac, a high-energy beam transport (HEBT) system, and the RF power system for the RFQ.

We have produced an unoptimized design example for the RFQ and have simulated the performance, including space charge, using the program PARMTEQ. The design and performance parameters are shown in Table 1.2.

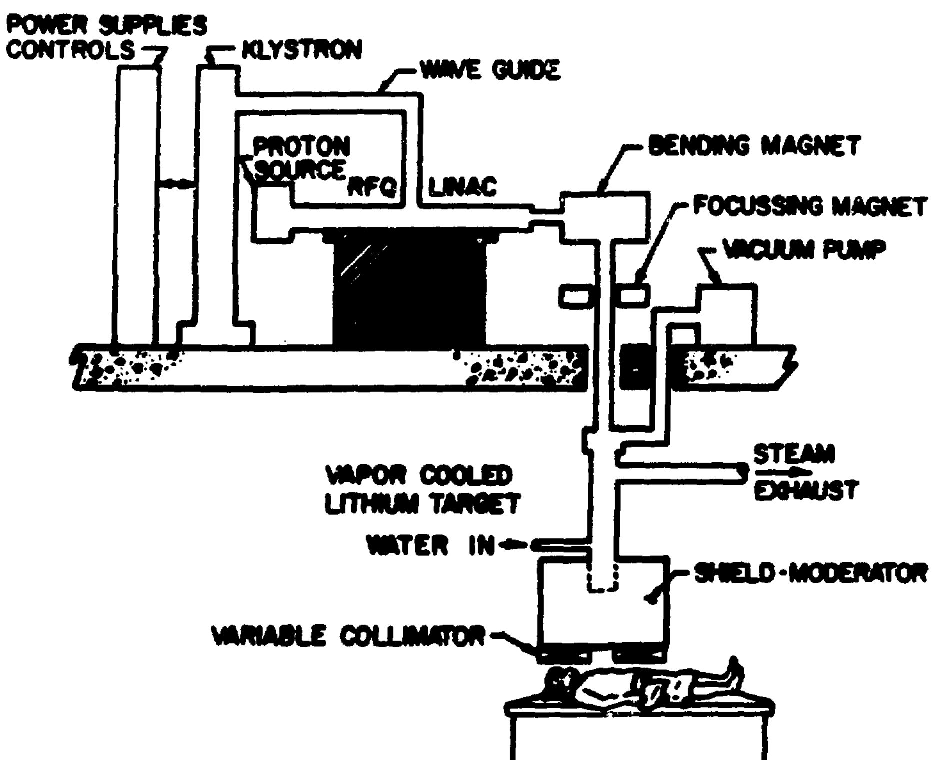


Fig. 1.5 Schematic for RFQ linac BNCT treatment facility.

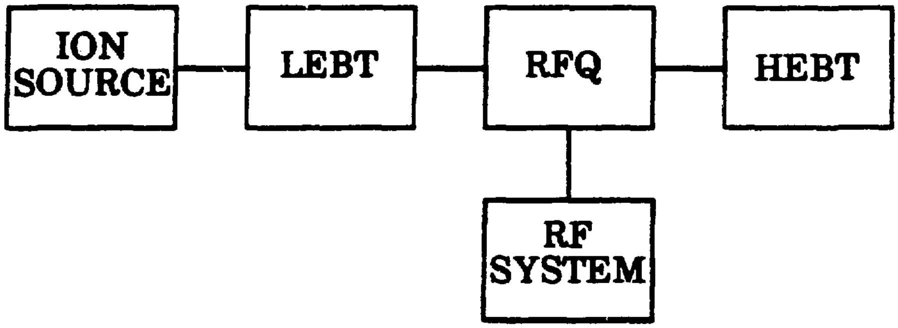


Fig. 1.6 Block diagram of accelerator system.

Table 1.2. Design and Performance Parameters of the RFQ

Frequency	350 MHz
Injection energy	30 keV
Final energy	2.5 MeV
Length	3.0 m
Bore radius, r_0	0.20 to 0.27 cm
Modulation parameter, m	1.00 to 2.58
Intervane voltage	0.050 MV
Input current	33 mA
Output current	30 mA
Input emittance*	0.010 π·cm·mrad
Output emittance*	0.010 π·cm·mrad
Output rms energy spread	15 keV
Structure power	107 kW
Beam power	76 kW
Peak surface electric field	34 MV/m

*The tabulated emittance values are $\epsilon\pi$, where ϵ is the normalized rms value without the factor of 4 that is sometimes used.

Generally speaking, for the neutrons produced by our conceptual neutron irradiation facility, the ratio of the entrance-absorbed dose to the peak-absorbed dose for normal tissue is larger than for an ideal 2-keV reactor neutron beam. The maximum absorbed dose to a tumor is 4.88×10^{-14} cGy/s for a ^{10}B concentration of 30 mg/g tumor. Therefore, for a 30-mA beam and 2.1×10^{13} n/s, the maximum absorbed dose rate is 1.02 cGy/s. For a single-session irradiation of 20 Gy to the tumor, the treatment time is about 33 min. This treatment time is quite reasonable and could be reduced to about 11 min with a 100-mA RFQ.

Simulation of an RFQ Funnel for Heavy-Ion Beams

Use of the magnetic force to focus and deflect heavy-ion beams is marginal at low ion velocities. Low-emittance-growth funnel designs using discrete magnetic elements have not been satisfactory for these beams. A new type of RFQ funnel has been designed that uses RF electric fields for focusing, bending, and merging. Procedures have been developed for computer simulation of this type of device. The simulations use PARMILA or PARMTEQ particle-following techniques and include potential functions similar to those of an RFQ, 3-D space-charge effects, and full-image charge treatment. These simulation procedures have been employed to produce a high-quality funnel design for 20-MeV bismuth (+1) beams, thereby making possible the first and most difficult stage of the three-stage funneling system envisioned for the heavy-ion-fusion HIBALL-II accelerator.[10]

Ground Test Accelerator Program

RF Structure Design of the GTA DTL

We completed the major portion of the RF structure design for the GTA DTL,[11] a high-current, high-brightness DTL operating at 850 MHz. In this machine, a ramped-accelerating gradient minimizes longitudinal emittance growth. Permanent-magnet high-gradient quadrupoles in the drift tubes focus the beam transversely. The modular design includes $2\beta\lambda$ structures at low energy and $1\beta\lambda$ structures at high energy, thus reducing the total number of focusing elements and enhancing the probability of high beam transmission. An innovative postcoupler design provides good longitudinal field stabilization in addition to flexibility in the choice of drift-tube and tank dimensions compatible with a large bore radius. Power densities and peak surface electric fields are within acceptable limits.

Coaxial Postcoupler Design for the GTA DTL

Early in the design work for the GTA DTL, we found that it would be difficult to simultaneously (1) provide a large bore radius, (2) accommodate sufficiently large quadrupole magnets in the drift tubes, and (3) stabilize the structure using postcouplers. The first two requirements led to relatively large drift tubes, which proved to be inconsistent with the usual constraint that the drift-tube-to-wall spacing be approximately a quarter wavelength of the operating mode.[12] This constraint ensures that the postcouplers can be tuned for stabilization.

We proposed a new type of postcoupler that penetrates beyond the tank wall into a short-coaxial line.[11] This design eliminated the usual constraint on the drift-tube-to-wall distance. The drift tubes could be increased in diameter to accommodate large enough quadrupole magnets even with large bore radius, and the tank diameter could be reduced to maintain resonant frequency. The higher capacitance for this design required somewhat higher power. However, in the first few tanks of the GTA DTL, the accelerating fields are low, so sparking, power density, and efficiency are not very important. In later tanks, as the drift tubes increased in length allowing additional space for magnets, we adjusted other cavity dimensions, resulting in more efficient operation.

Low-power model studies on several constant β scale-model configurations verified the ability of coaxial postcouplers to stabilize the fields.[13] In the 10 GTA DTL tanks, the drift-tube-to-wall spacing varies from 59% to 88% of a quarter wavelength. The coaxial design permits proper tuning over this entire range.

Physics Design of GTA Intertank Matching Section (IMS)

At certain points along the beamline of an accelerator system, there may be changes to the focusing and accelerating structure. For a high-current low-emittance beam, matching must be provided at these points to avoid mismatch and consequent emittance growth in the following accelerator section. In GTA, a matching section has been designed for the junction of the RFQ and the first DTL tank. Matching of rms beam parameters from the RFQ to the DTL requires four quadrupoles and two rebunchers, each of which should be adjustable in strength to accommodate variations in the input beam and desired output beams. Two designs were completed for the IMS: a preliminary design assumed ideal maximum field strengths for the adjustable permanent-magnet quadrupoles, and a second design allowed for some degradation of the maximum field strength by extending the length of the IMS slightly. Both designs produce minimal emittance growth in computer simulations and can accommodate up to 30% variation in the input beam Courant-Snyder parameters.

Drift-Tube Linac

The beam dynamics design of the GTA DTL was completed. The DTL consists of 10 RF tanks accelerating the beam from 2.5 to 24.2 MeV. An RF field ramp is used in all 10 tanks to maintain longitudinal focusing strength and minimize longitudinal emittance growth. Simulation studies have shown the most important construction tolerances to be (1) quadrupole transverse position, (2) quadrupole gradients, and (3) quadrupole rotation about the beam axis.

Code Development

Considerable code development work has been undertaken to meet the special needs of the GTA funnel and other GTA- and NPB-related work that requires close attention to emittance growth in intense ion beams.

PARMILA Field Map and Permanent-Magnet Field Calculator

The GTA funnel and other funnels designed in AT Division use a large-aperture defocusing quadrupole through which both beams pass just before entering the RF deflector. This quadrupole helps to deflect the beams onto the final beamline and serves as part of the focusing lattice.

The field of this magnet is essentially all fringe field because the aperture is large compared with the length. The fringe field of a permanent-magnet quadrupole is nonlinear, and it is difficult to analytically assess the effect of this nonlinearity on the trajectory and emittance of a beam that enters at a large angle to the quadrupole axis. Also, the field of the quadrupole overlaps the RF electric field of the deflector, and the effect of the overlap cannot adequately be calculated in the standard PARMILA sequential element-by-element treatment. In addition, the GTA funnel may benefit from using the Halbach double-dipole or double-quadrupole permanent-magnet elements for focusing or deflecting just prior to the large deflecting quadrupole, and there has been no method for accurately calculating these unusual elements. These problems were solved by writing a new PARMILA subroutine that integrates particle motion through a three-dimensional field map that can simulate a generalized element or sequence of overlapping elements. The map includes RF and static electric and magnetic fields. The static electric field map can be generated by CHARGE2D or CHARGE3D; the RF electric field by CHARGE2D, CHARGE3D, or MAFIA; the RF magnetic field by MAFIA; and the static magnetic field by existing magnet codes or by a new permanent-magnet field code. PMELE, which was written to calculate the magnetic field in all space from an arbitrary assemblage of permanent-magnet material regions, can generate the field from Halbach double elements or from any permanent-magnet element that does not include iron. Using the new codes, it was determined that the effect of the large-aperture defocusing quadrupole fringe fields and quadrupole-deflector field overlap in the ATS funnel design was small enough to be ignored for most purposes, a result that previously had to be assumed but now is verified. The new codes also make it possible to use the MAFIA 3-D field calculational results in PARMILA calculations of the RF deflector for more accurate funnel emittance growth calculations.

Capability for Rapid PARMILA Steering and Beam Parameter Calculations

In the ATS funnel experiment, there is need for calculations of steering quadrupole-position adjustment to bring the beam on-axis and to verify or compare experimental beam parameter measurements with calculations. A similar need will exist during GTA commissioning. Controllers and postprocessors for PARMILA have been written to do these calculations rapidly and to present the results in simple graphics. The goal is to minimize the time required and the likelihood of error in the interpretation of experimental results and to guide the setup of the next experimental step. A special problem exists in the ATS experiment since the permanent-magnet bending dipoles were delivered with fields considerably below specifications. This can be compensated for by quadrupole steering, but because of the large error, every quadrupole in the vicinity of a bend had to be offset a considerable amount to guide the beam around the bend. The quadrupole offsets were calculated with the PARMILA controller and the experimental beam followed the bends with 100% transmission without further steering adjustments.

Program Development

RF Deflector-Chopper for Superconducting Supercollider Linac

In one painting scheme for the SSC Low-Energy Booster, a low-emittance 50-MHz bunch structure is required. A 50-MHz RFQ cannot meet the longitudinal emittance requirements. A 150-MHz RFQ can do so but requires that two out of three bunches be chopped out of the beam to produce a 50-MHz-bunch structure. This was accomplished by a conceptual design that uses a "reverse funnel" operated at 200 MHz to separate the

150-MHz beam into three 50-MHz streams, two of which are routed to a beam dump. The remaining beam is matched into a following 450-MHz DTL. Emittance growth is minimal; output beam emittance is a factor of 3 better than required. This is an example of the kind of beam structure modification that can be achieved with this type of design.[14]

RF Deflector-Chopper for the Advanced Hadron Facility

A conceptual injector design for AHF used three 400-MHz RFQs, one producing a polarized ion beam and two producing unpolarized beams. A 50-MHz or 400-MHz final beam structure was desired, selectable on demand. Any one of the RFQ beams could be selected for transport into a 400-MHz DTL. A system was designed (1) with two RF deflectors, electromagnetic bending elements, and appropriate focusing elements that would route the beams properly; (2) to delete seven out of eight bunches with RF deflectors to produce a 50-MHz beam, or alternatively route the beams with electromagnetic or electrostatic dipoles to transmit the 400-MHz beam; and (3) to match the beam to the following DTL with low emittance growth.

Funnel for APT

To achieve the APT beam of 250 mA at the desired low emittance, a funnel must be used in the accelerator system. An APT funnel has been designed to combine beams at 20 MeV from two 350-MHz DTLs for injection into a 700-MHz CCL. The funnel design is consistent with the requirement for low emittance growth and radiation hardness. Electromagnetic quadrupoles are used except at one station, where large-aperture permanent-magnet quadrupoles are necessary because of space limitations.

University of Twente

A preliminary design of a 25-MeV photocathode linac for the University of Twente in Holland was completed.

University of Milan

A preliminary design of a 3-MeV photocathode injector for the University of Milan in Italy has been completed.

Beam Experiment Aboard a Rocket Project

A major highlight of FY 1989 was the successful flight and operation of the BEAR accelerator aboard an Aries rocket at the WSMR during July 1989. This was the first opportunity for testing of an NPB device in space. A 1.0-MeV H^- low-duty-factor accelerator was operated in a suborbital flight. The BEAR accelerator consisted of a 30-mA, 30-KeV H^- injector, an RFQ accelerator, and a gas neutralizer. The output beam from the neutralizer had 12 mA of H^- ions within a diameter of 10 mm (rms) with a divergence of ± 0.95 mrad (rms). The normalized rms brightness of the neutral beam was 1.2×10^{12} A/(m·rad)^2, making the BEAR accelerator the world's brightest neutral beam.

The BEAR Flight Model RFQ was designed and tested by Los Alamos National Laboratory (LANL) with the fabrication being carried out by Grumman Space Systems Division and GAR Electroformers. This device, shown in Fig. 1.7, is a unique design that consists of four identical type 6061-T651 aluminum vane/cavity quadrants joined by four electroformed copper joints. The resonant cavity and vacuum vessel are combined into a single structure weighing less than 55 kg. The resulting monolithic structure, which resembles an octagonal tube, has no RF, vacuum, or structural joints.

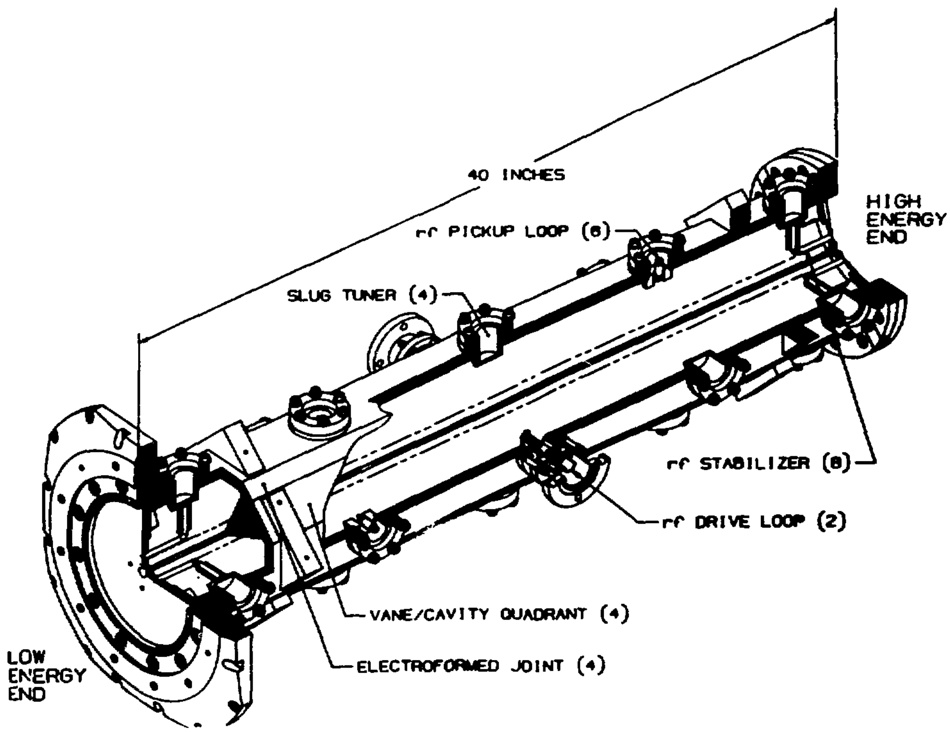


Fig. 1.7 BEAR flight model RFQ.

805-MHz Prototype Linac for the Fermi National Laboratory (Fermilab)

The Fermilab 200-MeV linear accelerator is a proton linac that was commissioned in 1970 as an injector for the circular machine. Since then it has also been utilized as a secondary neutron producer for the Neutron Therapy Facility. The major portion of the injector linac is a 200-MHz Alvarez linac that produces a 200-MeV beam. Fermilab plans to replace the latter portion of this structure with a more efficient accelerator that would provide a 400-MeV beam in the same physical space envelope. AT Division was funded by the Fermilab to design and fabricate a prototype section of a side-coupled linac to accept the 100-MeV proton beam from the remaining Alvarez linac and accelerate it to 400 MeV. The prototype structure (Fig. 1.8) consists of a portion of an accelerator module including a seven-cell tank joined to a three-cell tank with a $2.5\beta\lambda$ bridge coupler. Design work was carried out during FY 1988 with fabrication and testing completed in FY 1989. This unit has been delivered to the Fermilab, where it is currently undergoing high-power testing.

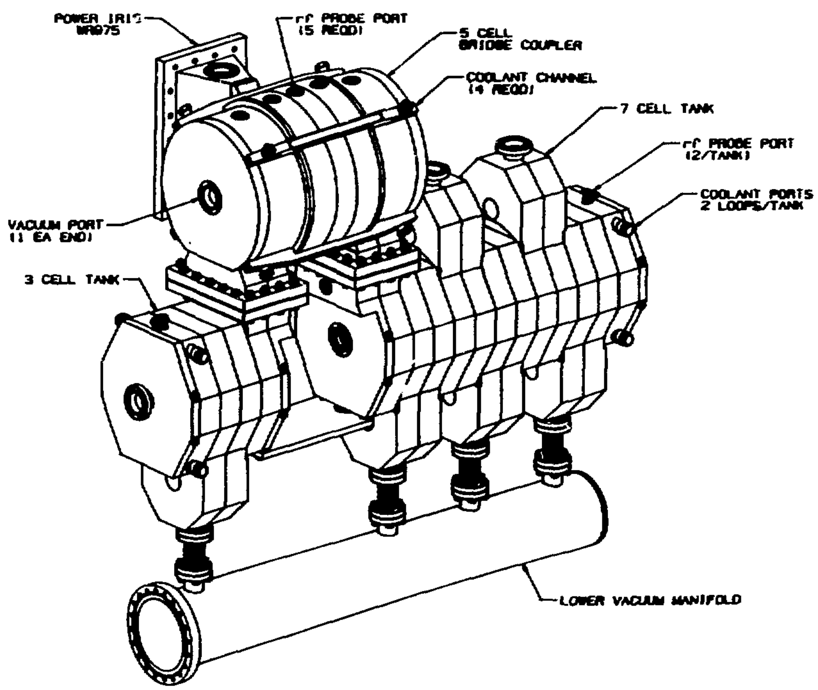


Fig. 1.8 The 805-MHz prototype linac.

6-MeV Photoinjector Linac for the LANL HIBAF Facility

During the past several years the LANL FEL Program has been very successful. As part of a continuing development program, the facility is being upgraded to a HIBAF. The facility will be used for Single Accelerator Master Oscillator Power Amplifier (SAMOPA) experimentation. The upgrade of the facility consisted of replacement of the conventional thermionic electron gun and bunchers with a photocathode RF gun, and a compact 6-MeV photoinjector accelerator along with the installation of a fourth accelerator tank plus a second wiggler.

The compact 1300-MHz photoinjector linac (Fig. 1.9) is a brazed-copper on-axis coupled structure consisting of six accelerating cells mounted inside an annular vacuum jacket. The on-axis coupled structure was selected over the side-coupled structure utilized on the remaining HIBAF accelerator tanks because the on-axis coupled structure provides superior beamline vacuum pumping through pumping slots in the periphery of the cavities. The photocathode lifetime is very dependent upon the absence of water vapor; the requirement is that the pressure not exceed 1×10^{-9} torr.

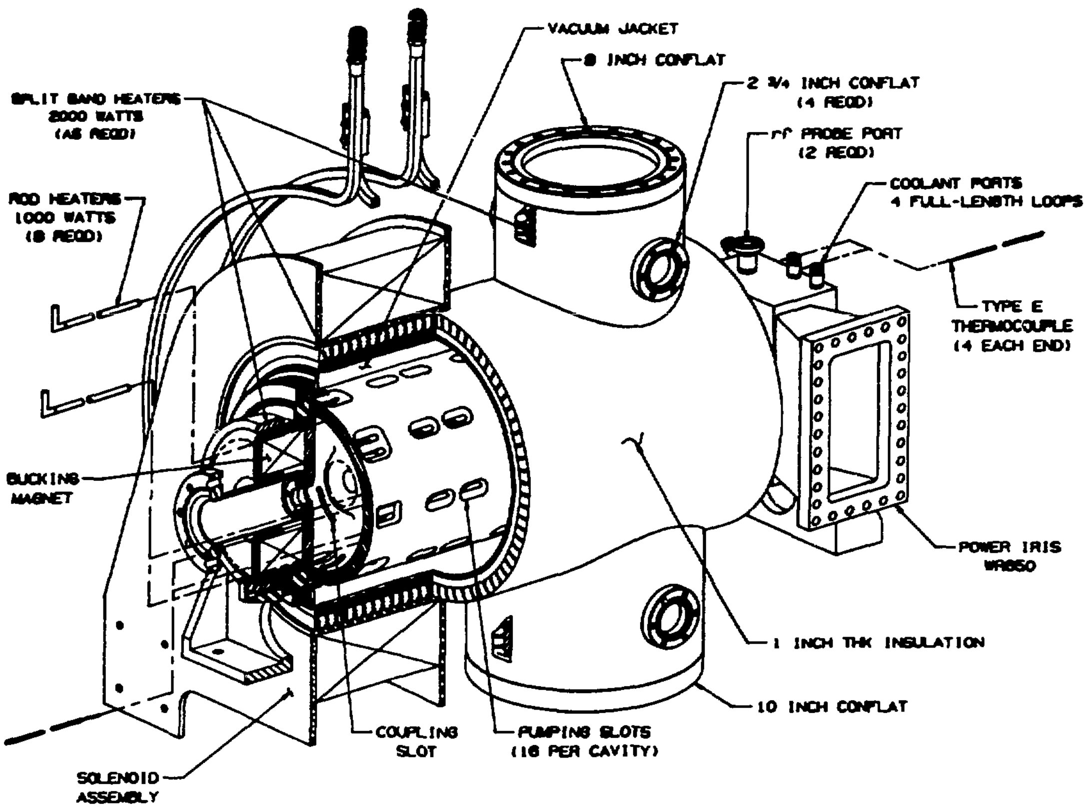


Fig. 1.9 The 1300-MHz photoinjector linac.

The assembly incorporates an integral vacuum bake-out system that consists of non-magnetic resistive rod-type heating elements installed into the accelerator structure controlled by a commercial programmable controller. The design and fabrication of the linac required only four months and it has been in service since the summer of 1989.

Accelerating Structures Development (ASD)

Rotary Tuner Design for DTLs

With AT-4, we designed and tested a paddle-type rotary tuner for dynamic frequency control of the DTL.[15] The tuner consists of a thin flat plate whose frequency effect on the cavity depends strongly on its orientation in the cavity. We also incorporated an analysis of the tuner effects into the frequency-effects computer code discussed earlier. The analysis, which involves calculating the Slater-perturbation shape factors for each component of the electric and magnetic fields, gives estimates of the frequency effects that agree within a few percent with actual measurements. Rotary tuners of this type are now being used in the DTLs for both the GTA and the Continuous-Wave Deuterium Demonstrator (CWDD).

Laser Subsystem

The first half of 1989 was devoted to designing the LSS accelerator for the GBFEL to be build at WSMR. The design is based on simulations of the accelerator with PARMELA. Several improvements in PARMELA were necessary to perform this simulation. In order to establish credibility of the PARMELA simulations of the LSS accelerator design, PARMELA was used to simulate the accelerator used by the Boeing Burst Mode FEL. These improvements were also required for the simulation of this accelerator. In particular, an improvement in the space-charge calculation showed unacceptable emittance growth was occurring in the 180° bend between the accelerator and the FEL wiggler. It also showed that when the beam was focused to a small diameter at the entrance to the bend, the emittance growth was reduced substantially. This was tried experimentally at Boeing and they immediately verified the reduction in emittance predicted by PARMELA. This work contributed to the LANL-Boeing Aerospace Corporation team winning the competition to build the GBFEL.

Continuous-Wave Seal-Test Experiment

Final data were taken of the linear C-seal power test. The intent was to determine if C-seals degraded the cavity Q significantly and if the seals could take a linear current density of 6000 A/m cw. The results indicated there was negligible degradation of the Q and the seals showed no deterioration up to 7000 A/m cw.

RF Materials Processing

Group MST-4 currently has a program to explore the use of microwaves in processing materials, mostly ceramics. Toward this end, they periodically require RF cavities of various colors and flavors. Group AT-1 is working with them on cavity designs and RF physics of driving loaded cavities. To date, work has been done on multimode and single-mode cavities, a cavity for spray drying of material aerosols, and the 500-MHz seal-test cavity as a microwave oven.

RFQ Tuning

The RFQs for CWDD and GTA are long. Long RFQs have many RF modes near the frequency of the desired quadrupole mode. Small imperfections in these RFQs mix the undesired modes with the desired quadrupole mode causing the field strength to be tilted along the RFQ and dipole components in the quadrupole that would deflect the beam off the center line. Tuners placed along the length of the RFQ in each quadrant can be used to make the field flat and dipole-free. In a short RFQ like the BEAR RFQ, it was very straightforward to tune out the undesirable modes. In a long RFQ, this becomes very complicated and tedious if done manually. A computer program was therefore written to model the RFQ and the tuners. The input to the program is the field in each quadrant measured with a bead pull and the frequencies of all the nearby modes. The program can then perform least-squares fit to determine tuner positions to remove mixing of the undesirable modes. With two iterations it is usually possible to have less than 2% variation from the desired field.

Proton Storage Ring (PSR)/Advanced Hadron Facility

A calibration technique was developed for characterization of current monitor response based on the parameters determined by a through short delay (TSD) calibration. Three current monitors and various other devices were characterized for PSR. Various schemes for high-order mode damping for the 50-MHz main ring cavity prototype for AHF were studied and we tested a half-scale model.

Dual-Axis Radiograph Hydro-Test (DARHT)

Modelling and testing was performed to determine the best technique for measuring transverse beam impedance of cavities with very low Qs in preparation for measuring actual DARHT cavities.

Ground Test Accelerator/Accelerator Test Stand

A cold model was designed, built, and tested for the GTA IMS matching section buncher and the ATS deflector cavity was redesigned.

Drift-Tube-Stem and Postcoupler Power Densities in the GTA DTL

To provide data to the engineers designing the cryogenic cooling system for the GTA DTLs, we used SUPERFISH-calculated field distributions to calculate power density distributions on the drift-tube stems and on the postcouplers. We found that the largest power density in a tank occurs at the stem-to-drift-tube joint on the downstream drift tube.[16] We made bead-perturbation measurements of the magnetic field near the postcouplers in a scale model of GTA DTL tanks.[17] These measurements showed that the postcouplers are nominally unexcited if the ramped longitudinal field distribution is preset before the postcouplers are installed. Before the post couplers are installed in a GTA DTL tank, the design end-to-end field ramp will be established by end-cell detuning. In this procedure we raise the cavity frequency by a geometrical perturbation on one end of the tank and compensate by lowering the frequency an equal amount by an adjustment on the other end. The postcouplers stabilize the naturally ramped field, and hence, they show minimum excitation. Using experimental data to project expected postcoupler excitation levels, we were able to calculate the power density on the GTA postcouplers.[18]

Drift-Tube-Stem Proximity Effects

The enhancement of the power density on the drift-tube stems caused by the proximity of nearby stems was investigated.[19] This work resulted in an approximate expression that we applied to existing DTLs running on the ATS and to DTLs being designed for the GTA and the CWDD. The largest enhancement occurs on the low-energy end of a tank where the stems are closest together. In tanks with a ramped accelerating gradient, such as GTA, the fields are lowest on the low-energy end, so the power enhancement there is not usually a problem. An application of the formula to the highest-power cells in the GTA DTL shows an enhancement of only 4% over the power density calculated for an isolated stem.

Frequency Shifts and Frequency Errors in DTLs

In designing DTLs, we distinguish between frequency shifts, which are known effects for the design geometry of different cavity elements, and frequency errors, which result from differences within machining tolerances between the as-built cavity geometry and the design geometry. Both frequency shifts and frequency errors can be estimated using the Slater-perturbation theorem. During the work on the GTA DTL, we developed a computer code to assist in calculating these frequency effects in DTL cavities.[20] The code, which includes the effects of drift-tube stems, postcouplers, dynamic tuners, static tuning bars, and other penetrations and holes in the cavity, should have general applicability to DTL designs other than GTA.

Stem-Produced Longitudinal Field Ramp

Experimental measurements have shown that graded-beta DTL cavities designed using the SUPERFISH cavity code have a naturally ramped longitudinal field distribution. The reason for this is that the drift-tube stem is not included in the 2-D SUPERFISH calculation. For graded-beta DTLs, the stem frequency effect on individual cells is larger on the low-energy end of the tank than on the high-energy end because the stems on the low-energy end displace a larger fraction of the cell stored energy. The continuous detuning of cells along the cavity length is responsible for the ramped longitudinal field distribution.

We have incorporated a calculation of this stem-produced field ramp into the DTL frequency-effects code discussed in the previous section. Stem-produced cell-frequency differences combined with a measurement of the tank's tilt sensitivity give a good estimate of the resulting end-to-end field ramp. The stem-produced ramp may be smaller or larger than the ramp required by the beam-dynamics design. To assist in achieving the design field in a DTL tank, the frequency-effects code also calculates the required amount of end-cell detuning to make up the difference between the design ramp and the stem-produced ramp.

Low-Power RF Modeling of the DTL for the CWDD

Under contract to Grumman Aerospace Corporation, we made measurements on a low-power, constant-β scale model of the CWDD DTL.[21] The work included achieving and stabilizing the design field distribution, measuring the postcoupler magnetic fields, and testing various components in the DTL. We verified that the method of end-cell detuning could be used to minimize the power load on the postcouplers in the 100% duty machine. We provided data and recommended to Grumman critical RF dimensions for the postcoupler, rotary-type tuner, and end-wall surfaces.

Superconducting Laboratory

The mechanical group has completed four 3-GHz and two 806-MHz niobium cavities. Initial tests on these cavities are being run. A 3-GHz cavity has run with fields near 7 MV/m. An 805-MHz cavity has been run up to a level that produced considerable x-rays. Shielding has been installed. More tests are in progress. Clean room facilities are near completion with some painting, cleanup, and electrical work remaining. Equipment for the clean room is on order. The pure water system is complete and is expected to start operation as soon as some sound reduction is implemented for the primary water pump. A high-pressure water-rinse system design is near completion with major components on order.

High T_c work has included measuring a large number of samples. New 18-GHz copper and niobium cavities have been developed. Power tests in the niobium cavities have started. Heat conduction is a serious problem. Current T_i on silver samples have LHe cooling at atmospheric pressure. This provides the best cooling to the sample. Early indications are that the samples are quite power sensitive with the Rs increasing by nearly a factor of 10 for a peak magnetic field in the 20- to 30-G range.

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J.D. Schneider
Group Leader

O.R. Sander
Deputy Group Leader

Introduction

Group AT-2 was the NPB Technology Group from early 1978 until mid 1988. Then it became the Injector and Accelerator Experiments Group; its new name reflects its two primary tasks in support of the Ground Test Accelerator (GTA) project. On November 13, 1989, AT-2 was eliminated and AT-10 was formed. The new group absorbed most of the activities of AT-2 and added several new responsibilities. Group AT-10 is now known as the Installation, Commissioning, and Operations Group for GTA. The injector functions are continuing in this group.

During the past year the group has focused its efforts on three areas. One section has been responsible for the design, construction, and check-out of a 35-keV H^- ion injector for the GTA. Another larger section (mostly a continuation of the accelerator test stand [ATS] team) has been mainly responsible for the staging and testing of one arm of a dual-beam funnel using the ATS 5.0-MeV beam. The third section has worked on a variety of high-power RF projects.

Ion Source and Injector

The Injector Section has the responsibility for design and operation of H^- injectors for accelerator research for the Strategic Defense Initiative (SDI). During the past year, a 100-kV, 100-mA pulsed injector was operated for the ongoing ATS program of research and testing of RFQ and DTL accelerators. During the past year, a compact H^- injector has been designed and built to provide the beams required for the GTA. This injector is based on the developments that have been carried out on the ATS for the past few years and is expected to provide the high-brightness H^- beams needed for this accelerator. Commissioning of this injector has just begun. The ion source for both injectors is a cessiated Penning surface-plasma source. Research and development on this type of source has focused on achieving good quiescence and on extending its duty factor to 2% and beyond for the high-perveance, high-brightness SDI requirements. Different scalings (4× and 8×) of the basic geometry are under investigation. The 4× source has now operated at GTA 2% duty factor with the required emittance. The amount of current was below the GTA requirement. We are still investigating an 8× version to understand the scalings of power efficiency; this understanding is crucial because the power loading of the electrodes is the limiting factor for dc operation. The goal of this work is to build a dc source of H^- or D^- of suitably high quality.

The old Ion-Source Test Stand (ISTS) that had been in use for more than one decade was dismantled. In its place we are expanding the Discharge Test Stand (DTS) to permit us to test ion sources and LEBT diagnostic gear with a configuration very similar to that used on GTA. This upgraded test stand will provide a facility for configuring components for GTA and for executing a reliability enhancement program for the mainline GTA injector.

GTA Injector

The GTA injector was built in a staging area and is now undergoing performance tests in the GTA accelerator hall. A schematic diagram of the injector is shown in Fig. 2.1.

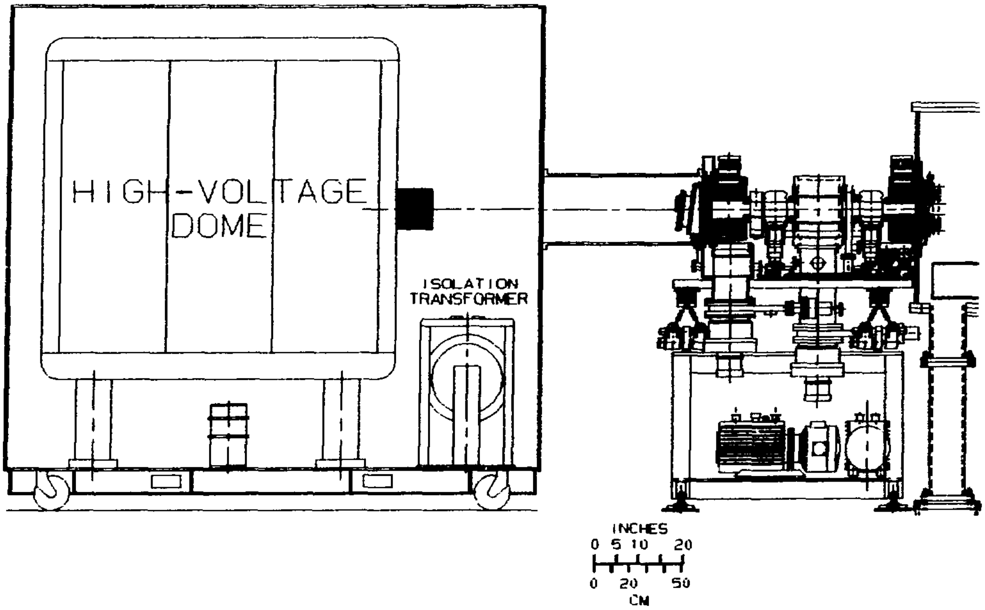


Fig. 2.1 GTA injector and high-voltage dome.

The Penning surface-plasma source employs circular emission and extractor apertures. The plasma generator is a design similar to that used on ATS, and thus much of the equipment required to operate the source is identical to that on the ATS. The extraction system has been modified to produce circularly symmetric, high-brightness beams required for the GTA application. A single-gap, two-electrode accelerator is being employed to minimize the emittance growth during extraction. This design permits gas neutralization to be implemented within 5 mm after extraction and thus facilitates the transport of these beams. The extractor is designed so that the electrons accompanying the ions are trapped near the source, and thus, a relatively pure H^- beam is produced. The GTA ion source was fully tested off line on the high-current test stand (HCTS) and the exact angle of the exiting H^- ions was determined. Changes were made to the ion source wedge to ensure that the output ion trajectories were at the proper angle. The ion source has since been operated on the GTA injector, and beam currents up to 92 mA were extracted at 35 kV in initial tests. The maximum current from this source was 135 mA at 24 keV.

An LEBT system will be employed to transport the beam extracted from this source and to match it to the admittance of the RFQ accelerator on GTA. The LEBT will use two solenoid focusing lenses, together with sufficient beam diagnostics and steering capability, to match these beams to the RFQ accelerator. A relatively long beamline will be used initially, and the capability of introducing neutralizing gases will be provided. We anticipate that proper control of the background gas will be necessary to achieve the desired neutralization without the instabilities from beam-induced plasma in the LEBT. Differential pumping has been incorporated in the LEBT to provide this control. The LEBT is mounted on a remotely positionable surface plate that will allow mechanical alignment of the injector beam into the RFQ accelerator.

The design of the LEBT was initially carried out with the beam envelope code TRACE-2D, and after the basic parameters were established, SCHAR simulations were used to optimize the design for minimum aberration and nonlinear space-charge effects. Once the solenoid magnet parameters were established, the detailed design of the solenoids was done using POISSON and FLUX-2D. Magnet field measurements carried out on both magnets confirmed that the design performance predicted by these codes was achieved and that the manufacturing errors resulted in acceptable variations in the straightness of the magnet field axis. The first magnet has been used to focus the H^- beams produced in the injector; the excitation required to obtain desired beams agreed with the predictions of the beam transport codes. The magnet focusing was observed by viewing the beam on a scintillating plate that was installed in the diagnostic box midway between the solenoids. The operation of both Faraday cups, actuators, and beam toroid was also verified during these beam tests. Installation is well under way on the downstream, auxiliary diagnostics station that will be used to compare with the measurements obtained on the permanent, upstream station during Experiment 1A. The basic design calculations for the first part of the LEBT have been experimentally verified.

The control of the injector is carried out with a VME-based (Versa Module European) computer control system that is interfaced in a commercial interface controller. The control system will permit both manual and automatic operation and a variety of future turn-on and reset algorithms.

The injector has been designed to permit a wide range of beam diagnostic capability and tuning flexibility in order to characterize the various accelerator modules of GTA as they are installed. The injector can be operated with test beam currents of 1, 10, and 55 mA, and the match condition of these beams can be varied in a known manner so that the operating range of the accelerator can easily be mapped. Automatic data logging and reset capabilities are also being planned.

A photograph of the injector in the staging area is shown in Fig. 2.2. Initial operation has already been carried out and it is anticipated that the injector will be ready for GTA experiments in early 1990.

For the first time, the extraction of a negative-ion beam has resulted in a measured beam perveance that agrees with that predicted by a positive-ion code, SNOW (see Fig. 2.3). However, no code has yet been able to predict the emittance area, aberration effects, or detailed distributions.

The beam envelope equation in the absence of focusing or emittance effects is given by $d^2r/dz^2 = K/r$, where K is the generalized beam perveance. For high-perveance beams, that is, $K > 0.001$, space-charge effects expand the beam rapidly. For GTA, $K = 0.005$; in order to neutralize the space-charge effects, we will transport the beam in an Ar^+ plasma channel produced by the H^- beam. Such gas neutralization works well in general, but beam-plasma instabilities can develop and spoil the beam emittance. We have studied the neutralization using xenon with a four-grid analyzer (FGA) (Fig. 2.4) by measuring the energy of ions and electrons ejected from the beam. In the stable propagation regime, the beam potential in Xe^+ was

Fig. 2.2 GTA injector.

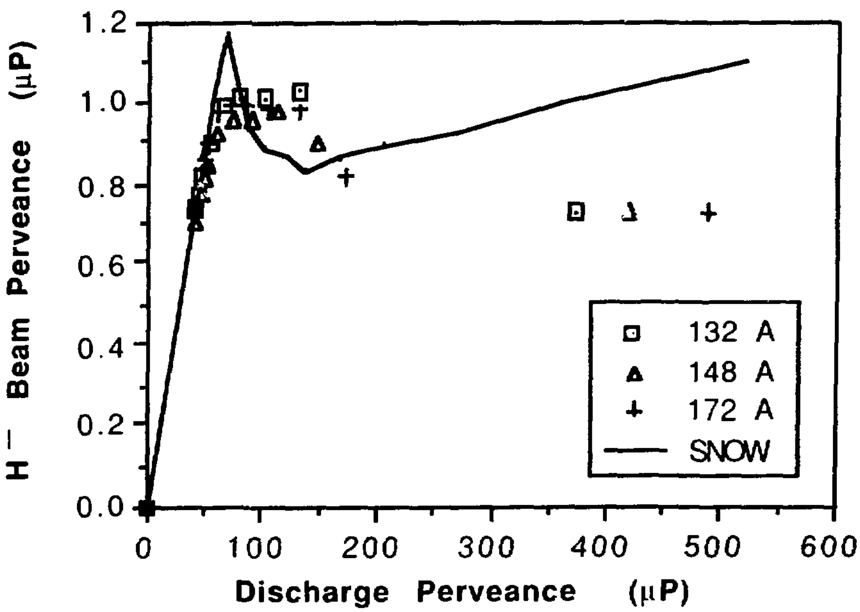


Fig. 2.3 The measured electron-equivalent H^- beam perveance $[(M_{H^-}/m_e)^{1/2}(I_{H^-}/V^{3/2})]$ vs the discharge perveance $(I_d/V^{3/2})$ for the 4× source. The data are for three different discharge currents (inset). Plotted on the same graph is the SNOW simulation of the 4× source target perveance vs the injection perveance.

1 to +10 V (Fig. 2.5), whereas the expected unneutralized potential drop was ~ −400 V. Argon was chosen for GTA because of the possibility that xenon would freeze and condense on the RFQ vanes. Previous experiments indicated that argon and xenon have similar neutralization characteristics. The FGA will be a permanently mounted beam diagnostic in the GTA injector along with Faraday cups, beam current toroids, and emittance scanners; it will be used to repeat the above experiment using argon.

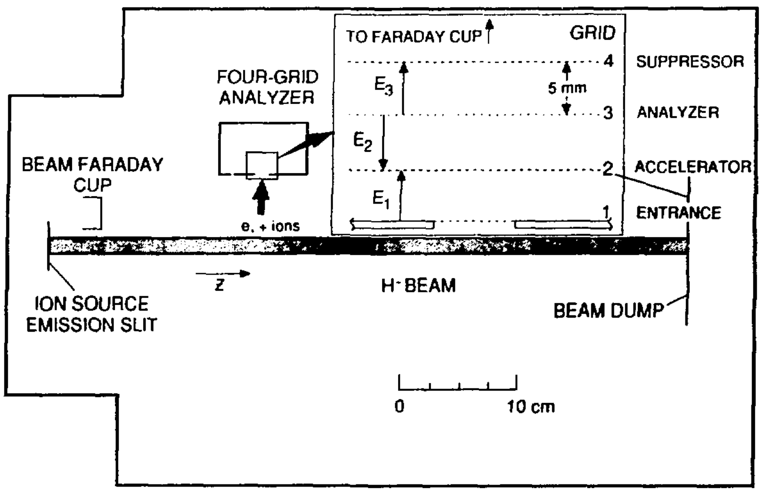


Fig. 2.4 Experimental setup for the beam transport and FGA schematic.

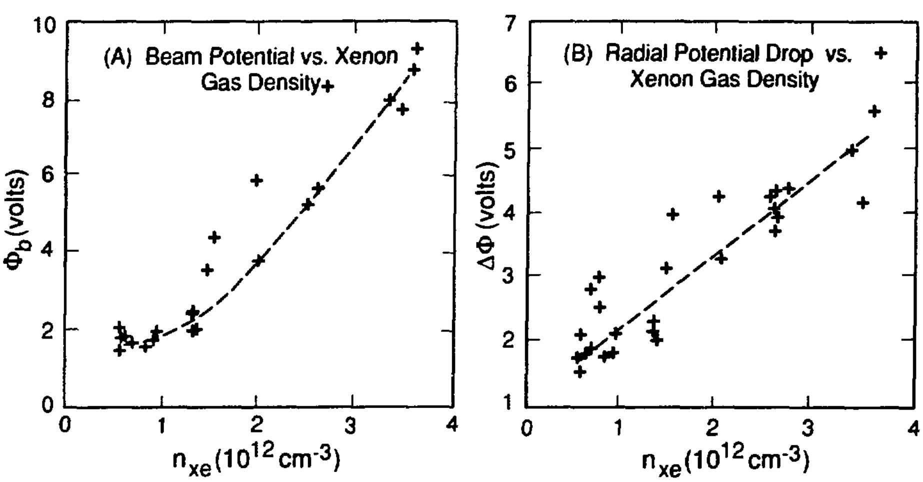


Fig. 2.5 (A) Beam potential Φ_b from the positive-ion current cutoff on the energy distribution for xenon neutralizing gas. (B) Radial beam potential drop $\Delta\Phi$ from the ion distribution width for xenon neutralizing gas. The beam dump is at wall potential in these measurements.

H° Temperature and Density Measurements in a Penning Surface-Plasma H^- Ion Source

The intense source plasma is confined to a small volume, which contains a mixture of hydrogen, cesium, molybdenum, and nitrogen gases in a high magnetic field. These conditions make the use of plasma probes very difficult. We previously studied the optical properties of the light emitted to determine the plasma density and temperature. In a collaborative experiment with Lawrence Berkeley Laboratory (LBL) personnel, we have used vacuum ultraviolet (VUV) laser-absorption spectroscopy to measure the H° density and temperature as a function of the discharge current, H_2 gas flow, and magnetic field in both the plasma column and the drift region between the plasma column and the emitter in the 4× source. The results of these measurements are shown in Fig. 2.6. From other measurements, we know that for the 4× source the H^- beam emittance is lowered when the discharge current I_d is lowered, the H_2 gas flow Q is raised, and/or the magnetic field B_d is lowered. From the figure we see that when I_d is lowered, the atom temperature kT_{H° drops; when Q is raised, the atom density n_{H° increases and kT_{H° drops; and when B_d is lowered, n_{H° increases. Thus, lower H^- beam emittance appears to be associated with increased n_{H° and lowered kT_{H°. For typical 4× source operating parameters, the H° density in the plasma column is 7×10^{14} cm^{-3} and 4×10^{14} cm^{-3} in the drift region; temperature, 1.5 eV in the plasma column and 0.6 eV in the drift region.

H^- Density Measurement Experiment

The purpose of this experiment is to measure the density and temperature of H^-, H, and H_2 in an ion-source plasma via laser absorption spectroscopy. A laser beam whose wavelength corresponds to a Lyman-series transition in atomic hydrogen is passed through the source, and the H° density is inferred from beam attenuation by the plasma. An yttrium aluminum garnet (YAG) laser beam, collinearly aligned with the probe beam, is then used to photoneutralize all H^- ions present in the channel. The probe beam then measures the perturbed H° density, and the difference between the perturbed and equilibrium H° densities gives the H^- density. Temperatures are derived from the Doppler-broadened Gaussian profile of the absorption curves.

Funding for this experiment became available in September 1988. A YAG-pumped dye laser system was purchased from Quantel International and was installed in our laser lab in March 1989. Meanwhile, the tripling cell, grating chamber, and their associated vacuum systems were designed and constructed. Construction of the VUV channeltron detectors and the timing electronics was completed in June 1989.

The UV beam out of the dye laser is frequency-tripled in a pulsed-gas jet of argon to produce a 97-nm VUV beam (corresponding to the Lyman-γ transition). After one month of unsuccessful attempts to detect VUV photons, we removed all optical components in the beam path between the tripling cell and the detector and built a nitric oxide cell for VUV detection. This detector is a static gas cell filled with 1 torr of NO through which the VUV beam passes. These photons ionize the NO resulting ions and the ions are detected by a pair of parallel biased plates. With this setup, frequency tripling was verified.

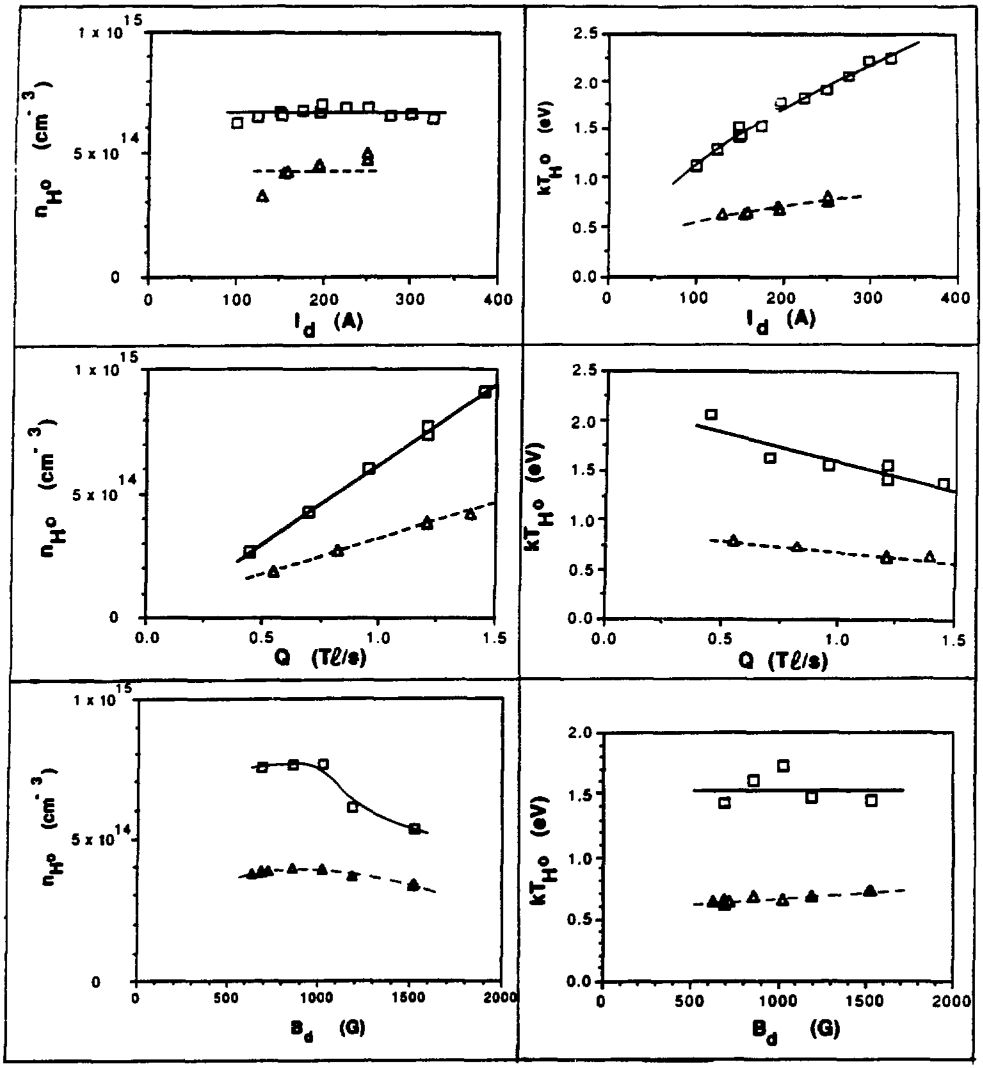


Fig. 2.6 The measured dependence of the H° density, n_{H° (left column), and H° temperature kT_{H° (right column) on the discharge current I_d (upper row), H_2 gas flow Q (middle row), and magnetic field B_d (lower row) for the 4x source. The plasma column measurements are given by the squares and solid lines and the drift region measurements by the triangles and dashed lines. The lines are guides to the eye, except for the kT_{H° vs I_d curves that are least-square fits to the data of the form $kT_{H^\circ}=AI_d^a$, where A is a constant and the exponent a is ~1/2 for both the plasma column and the drift region.

ATS Single-Arm Funnel Experiment

Many group members worked for a large fraction of the year in setting up and conducting an experiment to demonstrate the operation of one arm of a dual-beam funnel. A beam funnel is planned for use on the GTA to permit doubling of the total beam current with little or no increase in beam emittance. Many of the components of this funnel were designed and fabricated by private industry. It was the responsibility of the Los Alamos personnel to assemble these pieces and integrate and run the experiments, which included an extensive series of diagnostic measurements of beam properties. AT Division designed and built the diagnostics, many of which have direct GTA applications. The delivered equipment presented numerous challenges including low-field dipoles; bunchers with unacceptable resonant frequency variation with temperature and power changes; RF drivelines that would not transmit the required power; and a vacuum vessel that did not meet the Los Alamos boiler code. The challenges were met: the quadrupoles were offset to supply additional steering; resonant tuners were designed and built to keep the bunchers on resonant frequency; the drivelines were redesigned; and the funnel vessel was strengthened with internal bracing.

The single-arm beamline (Fig. 2.7) includes 4 RF beam bunchers, 1 RF deflector, 4 permanent-magnet dipoles, and 15 magnetic quadrupoles. Four quadrupoles are mounted on translation stages to provide beam steering. The diagnostics, which are mounted in the funnel line, consist of three wire scanners, three broad-band toroids, and nine microstrip probes. The diagnostics, which are mounted on a movable D-plate and are used to fully characterize the beam as sections of the funnel are added, consist of slit and collector gear for transverse emittance measurements, LINDA (laser-induced neutralization diagnostic approach) for longitudinal emittance measurements, a wide-band toroid and a Faraday cup for current measurements, and three microstrip probes for beam energy, phase centroids, and position centroids.

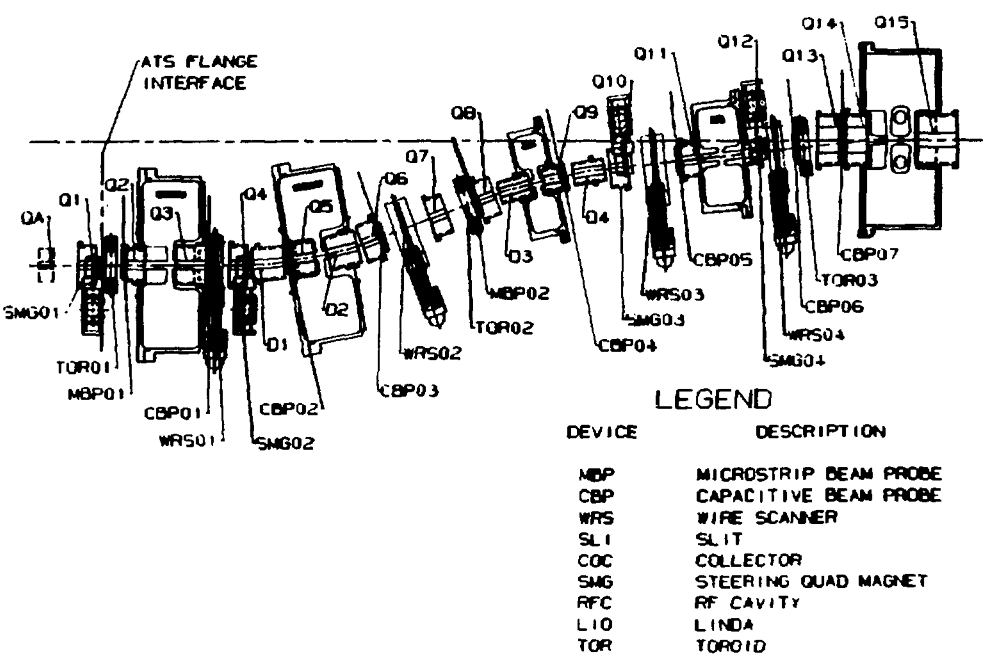


Fig. 2.7 Single-arm funnel plan view showing the beamline components.

The first experiment consisted of characterizing the beam from the DTL in preparation for launching it through the funnel. The beam was first injected into the funnel vessel and into the D-plate diagnostics at the end of April. The beam position and direction were measured, and the funnel coordinated system was moved accordingly. The transverse emittance was also measured and found to be too large to pass through the funnel without scraping. Collimators were designed to mount on the M1 plate, which is the first section of the funnel. The collimators were mounted on translational stages and an additional toroid was added after the last collimator.

The experimental program consisted of measuring the transverse emittance, the beam transmission, and the beam centroids; phase scans of the first buncher (R1); x-ray calibration of the R1 buncher; and measuring longitudinal emittance versus R1 amplitude and phase settings. The resonant control on R1 functioned flawlessly, and the new RF driveline design had no breakdown problems. The transverse emittance was measured and agreed with the predicted value. Current transmission was 58%. The beam was positioned to within 1.0 mm and 2.6 mrad of design for injection into the remaining sections (M2, M3, M4) of the funnel. This beam alignment was determined to be adequate for the remaining funnel experiments. The phase-scan measurements were made on R1, and the inferred phase setting agreed with information from the beam loading observed in the RF amplifier system. X-ray calibration of R1 was completed and used to determine the operating RF amplitude. Confirmation and debugging of the control system and some of the diagnostics are continuing. The plan is to complete the M1 tasks within the first month of FY 1990 and then install and commission the M2 and M3 sections of the funnel. Following this commissioning, the final M4 section with the RF deflector will be installed and commissioned.

High-Power RF Projects

During FY 1989, the section responsible for high-power RF projects performed the following major tasks (work in the first three areas is described):

- completion of the cryogenic DTL experiment,
- support of the funnel experiment,
- performance of *ad hoc* experimental work,
- providing RF power to all operations of ATS, and
- maintaining and modifying the ATS high-power RF system.

The two-cell, cryogenic DTL was operated at 20 K. The experimental program on this cavity demonstrated the successful operation of a cryogenically cooled cavity at GTA operational field levels with beam loading. No RF control problems were observed when the cryogenic DTL was operated either at 2.24 MV/m with 70 to 80% beam loading or at 7.2 MV/m with reduced beam loading. The experiment proved that a high-Q cavity could be operated as part of an accelerator RF system with feedback-stabilized cavity fields.

Support for the funnel experiment included an extensive program of testing and modification to make the buncher cavities accept power and operate on frequency, and the redesign, construction, installation and check-out of the amplitude and phase control in the RF amplifiers for the buncher cavities.

The four buncher cavities were first characterized, and, after an intial determination that the as-built cavities were thermally unstable when subjected to high power, an experimental program was initiated that established the relationship between input power, cooling, heating of the cavity material, and resonant frequency. The simulations of thermal effects on the cavities were in very good agreement with the experimental findings. These studies led to cavity modifications, including the addition of resonant control using paddle tuners and the plating of the drift tube noses for adjustment of the resonant frequency.

The drivelines for the funnel rebuncher cavities were found to be unsuitable for the experiment because they had voltage breakdown problems within 10 h of RF operation. The drivelines were redesigned and tested for suitability. One of the drivelines is now in use for the first stage of the funnel experiment.

In addition to operating the necessary RF power equipment, conditioning the cavities, and developing the amplitude and control of the RF amplifiers, we adapted feedback circuitry to provide cavity resonance control of the buncher cavities. There was significant work on the repair, rebuilding, and modification of the RF amplifiers that were purchased to power the funnel buncher cavities.

An experiment program is under way to evaluate the cryo RF conductivity of a large number of material samples and to determine the relationship of RF surface conductivity to the machining techniques and chemical surface preparation methods used on the copper samples. A copper-plated aluminum sample was used to verify that a plated surface was suitable for the GTA RFQ. A number of solid copper samples have been provided to qualify the surface preparation for the GTA IMS and DTL cavities. The experimental technique is based on the measurement of the Q of a resonant coaxial structure with the various samples being inserted as the cavity center conductor. The actual test process has been automated using an HP 300 series instrument control computer. The samples are evaluated over a temperature range from room temperature to cryogenic temperatures around 20 K. This work is in progress.

A. Jason
Group Leader

Introduction

Group AT-3 was established as the Storage-Ring Technology Group at the founding of the division and was responsible for the construction and commissioning of the PSR. With the advent of the GTA project, the PSR commissioning task was taken over by MP Division. Group AT-3 then became responsible for the magnetic optics and beam diagnostics, a significantly different role, but one involving technologies similar to those exercised in PSR design and construction. The current group charter is to apply beam transport theory, state-of-the-art diagnostic instrumentation, and advanced magnet fabrication techniques to the design, construction, and commissioning of accelerators and magnetic-optics systems.

Group AT-3's main effort during FY 1989 has been in support of the GTA project, specifically to do the following:

- design the output optics for the GTA-24 experiment.
- design and fabricate magnets for the output optics and assist staff in other sectors of the project in magnet design problems. Very large bore magnets are required for the system telescope including a challenging time-dependent steering magnet.
- develop the capability for measurement and qualification of all GTA magnets.
- design and fabricate diagnostics for the GTA accelerator and output optics. This includes design and implementation of experimental setups for characterizing the funnel output, the RFQ output, and the linac output at 5 and 24 MeV as well as design and implementation of the permanent system diagnostics.

Besides the GTA project, the group has been involved in studying wiggler magnets for the Extreme Ultraviolet (XUV) FEL project, special superconducting magnets for the Superconducting Linac project, and magnet construction for the HIBAF project. A novel nonlinear beam expander was developed for the APT project. A successful proposal was made for participation in the LSS project at WSMR. The group also has a continuing interest in developing high-order optics codes that include space-charge effects. Group AT-3 has also participated in PSR development and in the AHF proposal.

NPB Program

Optics Design

The principal task of the optics design effort for the NPB program is the physics specification of a system that transforms the intense H^- pulses from the linac into an ultralow-divergence beam. The important physics issues involved in this process are

- emittance growth control caused by nonlinear space-charge forces,
- minimization and correction of space-charge-induced and geometric aberrations, and
- decreasing system chromatic aberrations to an acceptable value.

Calculation and correction of third-order geometric aberrations are now well understood from experimental work performed on an expanding telescope by AT-3. However, space-charge calculations are less certain. Indeed, the major motivation (supported by the opinion of the National

NPB Optics Panel) for performing Experiment 3 rather than immediately constructing a full-energy device is to assess space-charge effects and determine the applicability of calculational methods to the NPB problem.

The philosophy of chromatic aberration minimization was established during FY 1987. The beam is allowed to expand longitudinally in a section of transport line (known as the matching section), and momentum compaction by an RF cavity is used to reduce the beam momentum spread. This scheme has more recently been elaborated upon to produce a practical system by addition of other cavities for longitudinal focusing and momentum-jitter control.

The matching section has been specifically designed to perform the longitudinal expansion in a manner that precludes emittance growth and nonlinearity formation. The portion of the line just after the linac maintains the tight linac transverse confinement as longitudinal expansion diminishes the space-charge forces. The beam is then matched to a periodic line that contains the momentum compactor cavities and a transverse jitter control system as well as more conventional diagnostics.

As we tried to balance the desire for complete line information against the constraints of space, cost, and time, the line diagnostics underwent several iterations. In particular, construction of a secondary line into which beam would be optionally deflected for emittance and energy measurements (as well as high-duty-factor operation) has been forsaken. Instead, the linac will be characterized in Experiment 2D and its operation during Experiment 3 verified by behavior of the output beam. However, profile, phase, and centroid measurements will be available at canonical points in the line for tuning. An isometric sketch of the matching section is shown in Fig 3.1.

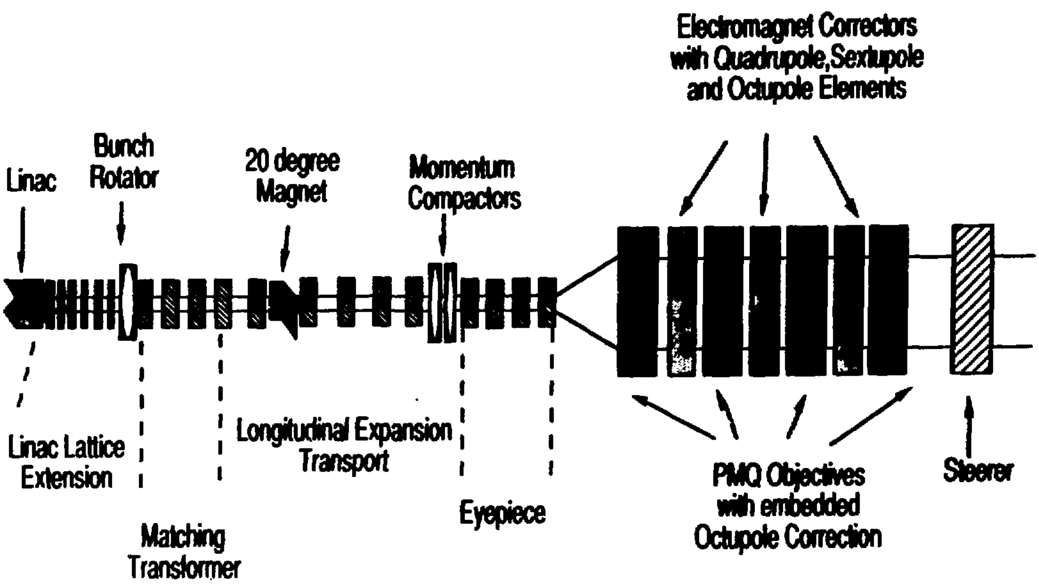


Fig. 3.1 Schematic of the GTA-24 output optics.

The beam-expander portion of the Experiment 3 device by analogy with light optics is known as a telescope. The eyepiece consists of four quadrupole lenses following the matching section and initiates the beam expansion. Most of the telescope length is occupied by the objective—four 1-m-bore quadrupole permanent-magnet lenses, which converge the beam to a parallel focus. The telescope configuration has been optimized with third-order codes to minimize chromatic and geometric aberrations. Octupoles are embedded in the objective quadrupoles to closely correct geometric aberrations. Four sets of electromagnetic corrector magnets, each containing skew and normal octupole, sextupole, and quadrupole windings, reside between the objective magnets for correction of space-charge and magnet-defect effects. In particular, the quadrupole correctors are used to correct the first-order defocus of the steering magnet.

Magnets

The GTA magnet requirements of large aperture and high quality present a challenge to the designer. The (expensive) objective magnets require long lead times and close contact with the fabricator. A prototype has been delivered and qualified. The remainder of these large magnets will be delivered on a schedule ending in April 1991. The corrector magnets are etched panels of copper distributed around a 1-m-diam cylinder and are known as Lambertson magnets. Smaller versions of these magnets have been constructed by printed circuit techniques in house and at low cost. However, the large size and high-positional-accuracy requirements of the Experiment 3 Lambertsons require industrial fabrication. The corrector specification is complete and engineering design is well under way.

The large bore-steerer magnet requires additional consideration of eddy current effects because of its stringent slew and tracking specifications. A physics design has been developed involving a unique conductor pattern and utilizing Litz wire windings. A small prototype is under construction to test the complex design. A laminated iron shield is deemed necessary to avoid interaction with nearby ferromagnetic structures. A conceptual sketch of the steerer design is shown in Fig 3.2.

Diagnostics

One of the principal tasks of the diagnostics sections has been the implementation of diagnostics for the ATS funnel experiment. The funnel portion of this experiment has been assembled by AT-3 and instrumented with wire-scanners, microstrip phase and position probes, and current-monitoring toroids. LINDA, a laser technique for selectively neutralizing time or spatial cuts of the H^- beam pulse, has been implemented for these experiments to be completed in early 1990. Although time consuming, this experiment has been useful in testing the complex concepts involved in the diagnostic instrumentation.

Increasing concentration has been given to construction of the permanent diagnostics for the RFQ and DTL and to the systems that will measure their output. A "D-plate" has been designed for Experiments 1 through 2A; it contains equipment for measuring the necessary beam parameters. This intricate structure, now ready for fabrication, incorporates

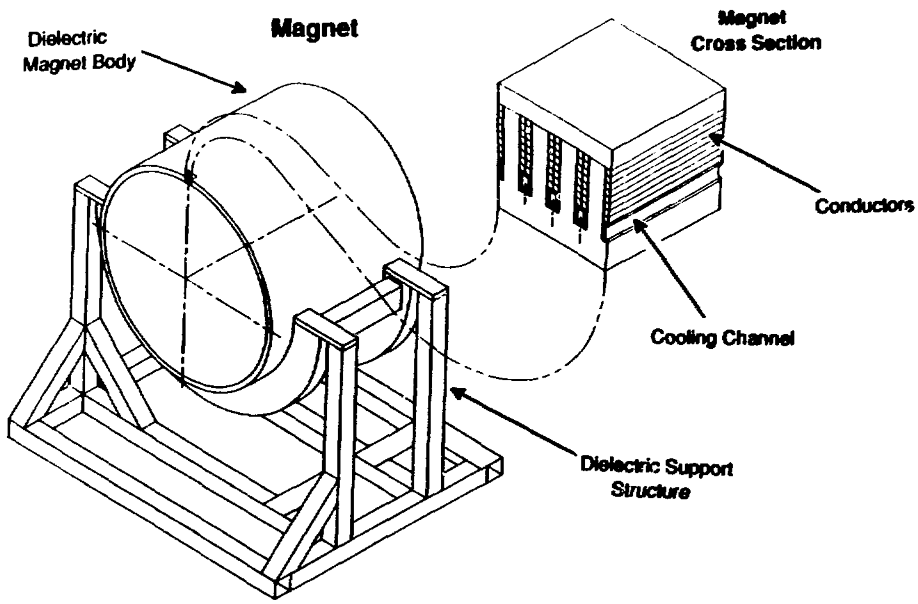


Fig. 3.2 Conceptual design of GTA steerer magnet. The conductors are made of Litz wire, and their distribution around the cylinder determined by field-purity requirements.

slits and deflectors for LINDA measurements as well as microstrip probes, wire-scanners, and toroids.

Experiment 2D, which characterizes the 24-MeV beam, requires a more complex optical arrangement because of the increased energy. The beam from the linac is matched to an offset line and dump to remove the unneutralized beam from LINDA scans. The neutralized portion of the beam is analyzed alternatively by a third-order-corrected spectrometer for longitudinal emittance measurements or by a slit and collector system for determination of transverse characteristics. A mode-locked laser will be needed to meet the stringent LINDA timing specifications.

Progress in the development of Experiment 3 diagnostics also occurred in 1989. In particular, a prototype of a flying-wire scanner has been constructed and tested. A fast scan at uniform speeds up to 20 m/s is needed because of the high beam intensity. Development has also been carried out on the high-resolution measurements of phase and position needed for the momentum and spatial jitter control systems.

Telescope Experiment at Argonne National Laboratory

In 1988 a series of experiments was conducted on a beam-expanding telescope built by AT-3 and installed at ANL. The experiment confirmed the validity of third-order optics codes and demonstrated correction of geometric aberrations as well as developing characterization and diagnostic techniques. A final run was made this spring to determine steerer magnet effects. The facility remains at ANL to be used for NPB-related experiments such as acquisition, tracking, and positioning (ATP) investigations that require a high-quality low-divergence beam.

Magnet Laboratory

The Magnet Laboratory is a division facility possessing highly accurate equipment and expert personnel for the precise measurement and qualification of magnets needed for division projects. Its current emphasis is principally on GTA, but it has been extensively used in other applications. The Magnet Laboratory is nearing the end of a three-year-long facility build-up. This has included construction of suitable working space and establishment of a staff. Lab accomplishments for this reporting period, aside from routine measurements, include the following:

- Refurbishing of the Point Mapper, a precision device used on the PSR for creating point maps of magnets. New concepts of measurement theory and data analysis were developed to limit the complexity of such measurements. A point map of many magnets is needed for the assessment of high-order effects in optics formulations.
- Measurement of prototype DTL magnets at cryogenic temperatures. A drawing of the cryogenic mapper constructed for this purpose is shown in Fig 3.3.
- Design and construction of a fast-cycling cryogenic mapper. This will shorten the cycling time of cryogenic magnets from 24 hours to fewer than 4, an improvement critical to maintaining the schedule for DTL-magnet qualification. This equipment will also be used to assist the Grumman continuous-wave deuterium demonstration (CWDD) program.
- Construction of an improved miniature quadrupole mapping coil made by precision lithography techniques on a quartz substrate to be used for the cryomapper. The coil has a (record) bucking ratio of over 1000. A photograph of this device is shown in Fig. 3.4.
- Construction and implementation of a solenoid mapper used for crucial qualifying measurements on GTA and FEL projects.
- Completion of neutron-damage measurements on permanent-magnet materials. This effort was crucial in determining which materials could be used for the many GTA permanent magnets, particularly since material costs vary greatly.
- Successful implementation of a taut-wire system for establishing the alignment of the quadrupoles in an entire DTL tank at cryogenic temperatures.
- Construction of a drag-test plate for the Naval Underwater Systems Center. The purpose is to reduce hydrodynamic drag in underwater missiles by electromagnetically damping turbulence.

We are engaged in a continuing program to upgrade the Magnet Laboratory's data analysis capabilities by improved algorithms and, with the assistance of AT-8, improved control software. Such optimization is important in the accuracy and speed of measurements.

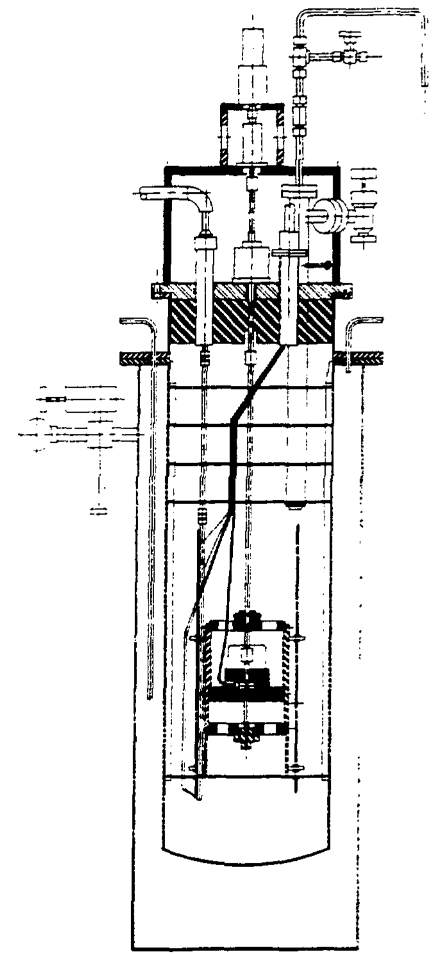


Fig. 3.3 Cross section of the cryogenic mapper. A shaft from the warm apparatus top rotates a measurement coil in the small-magnet bore, seen near the bottom of the dewar.

Code Development

Because of its optics charter, AT-3 has a s rong interest in transport codes useful for design and assessment. A library of advanced codes maintains design capability. In particular, the group, along with AT-6, actively supports the development of MARYLIE and COSY. Although these codes are of increasing practical sophistication in high-order optics, codes with a satisfactory description of space-charge effects do not exist for three-dimensional beams. A low-level effort is maintained for space-charge code development as a design tool. Substantial progress has been made toward this goal. A description of a beam charge distribution as a linear combination of optimal basis functions has been developed. This formalism

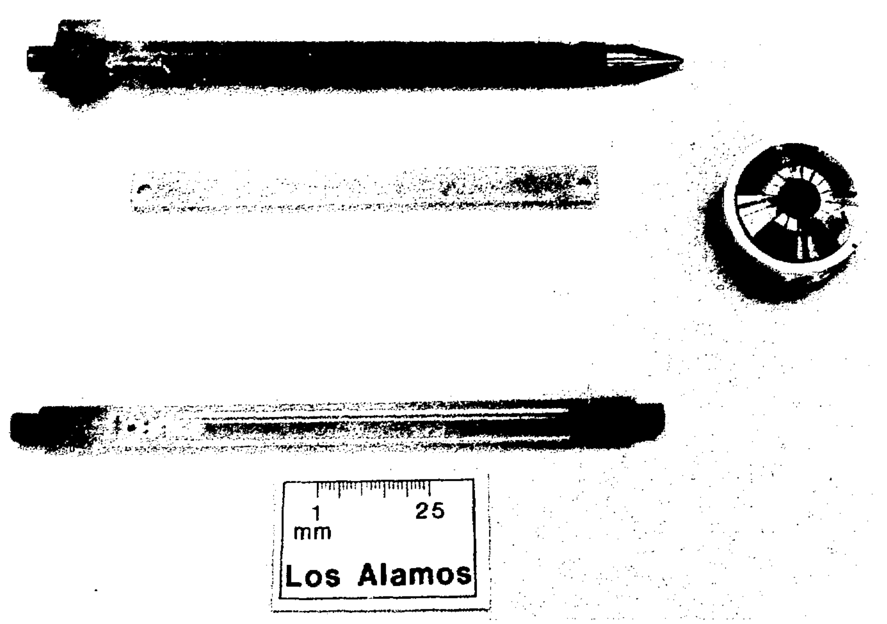


Fig. 3.4 The cryogenic mapping coil. From top to bottom, the assembly with pivot bearing, the coil cover, the multiturn coil (2-μm conductor width located to 0.1 μm) lithographed on a quartz substrate, and the coil mounted on its holder. A DTL magnet is seen on the right.

is being inserted into the framework of a moment code (BEDLAM, developed by AT-6), which uses Lie-Poisson integration techniques for increased speed. The use of moment methods shows great promise for describing and understanding behavior of space-charge-influenced beams; analytical as well as computational work has been pursued in this area.

Free-Electron Laser

A proposal for participation in the ground-based FEL LSS project design was submitted as part of a joint LANL-Boeing Aerospace Corporation package. The proposal was successful and AT-3 will design the beam-dump expander and design and construct the postwiggler achromat for the facility oscillator.

The Los Alamos HIBAF effort was supported by the design and construction of several high-quality dipole and quadrupole magnets.

An extensive study was completed on small-period high-gain wiggler options for the XUV FEL project. Conventional, permanent-magnet, and superconducting options were considered and compared.

Accelerator Production of Tritium

The strong division effort in originating a credible APT proposal was supported by conceptual design of a transport line and diagnostics to convey beam to the production target. In particular, a novel solution to a very intractable beam expansion problem was suggested and developed.

In this scheme, the proton beam is expanded on the target by nonlinear optical elements to produce a very uniform and well-defined illumination. A beamline layout for the scheme is shown in Fig. 3.5. A patent on the technique has been applied for because commercial applications appear evident.

Superconducting Linac

This work augments the division effort in superconducting cavity technology. A superconducting linac requires high-strength focusing quadrupoles that must be small and variable. Group AT-3 has designed a superconducting quadrupole that uses rare-earth materials with 4-T saturation fields as a flux concentrator. Successful coils with high-quench currents have been constructed and a prototype magnet is under construction. Test facilities for the prototype exist in the Magnet Laboratory.

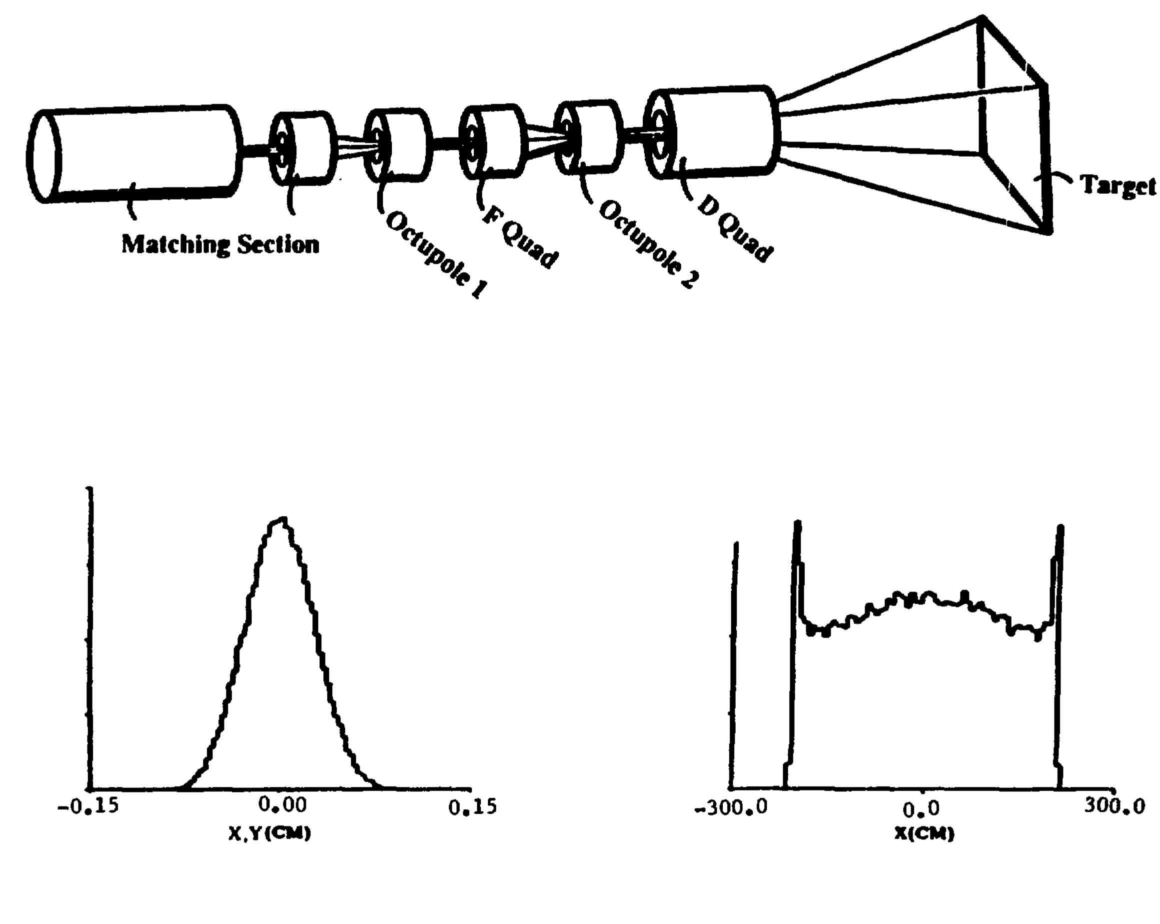


Fig. 3.5 The nonlinear beam expansion scheme. The Gaussian-distributed input distribution is shown on the left, and the distribution on the target is shown on the right.

W.E. Fox
Group Leader

H.W. Harris
Deputy Group Leader

Introduction

Group AT-4 designs, fabricates, and installs accelerator hardware including RFQs, matching sections, and DTLs. The GTA RFQ and DTL are designed to operate at cryogenic temperatures between 20 and 50 K. Supporting tests of prototype hardware used the Cryogenic Component Test-Bed (CCTB) and High-Power Cryogenic Test-Bed (HPCTB).

GTA Radio-Frequency Quadrupole

During FY 1989, the mechanical design of the GTA RFQ accelerator core tank module was completed and fabrication was under way. Figure 4.1 shows a typical example of the precision-machined large accelerator structures produced by AT-4. The first task was to obtain the aluminum 2219-T851 stock for the vanes. Plate stock, 6 in. thick, was chosen and purchased. The plate stock was sectioned into rough machining blanks with a water-jet cutter at the Pan-Am shop and then machined square at Shop 6 in MEC Division. Several pieces of the excess material were then shipped to Carlson Tool Manufacturing Corporation in Cedarburg, Wisconsin, for qualification of the deep-hole drilling process for the cooling passages. It was originally hoped to drill 3/8-in.-diam passages, but the test holes drilled were showing that to maintain the minimum desired wall thickness, the hole diameter would have to be reduced to 1/4 in. The drill drift was roughly 0.040 in. in 29 in. of drill depth. With the smaller 1/4-in.-diam hole, it was possible to stay within the original theoretical hole region even with the drift. Each bore was inspected along its entire length with a transit and movable target sliding in the hole. The squared blanks were then rough-machined at Shop 6, MEC Division, to within 1/8 in. of their finished size and shipped to Carlson.

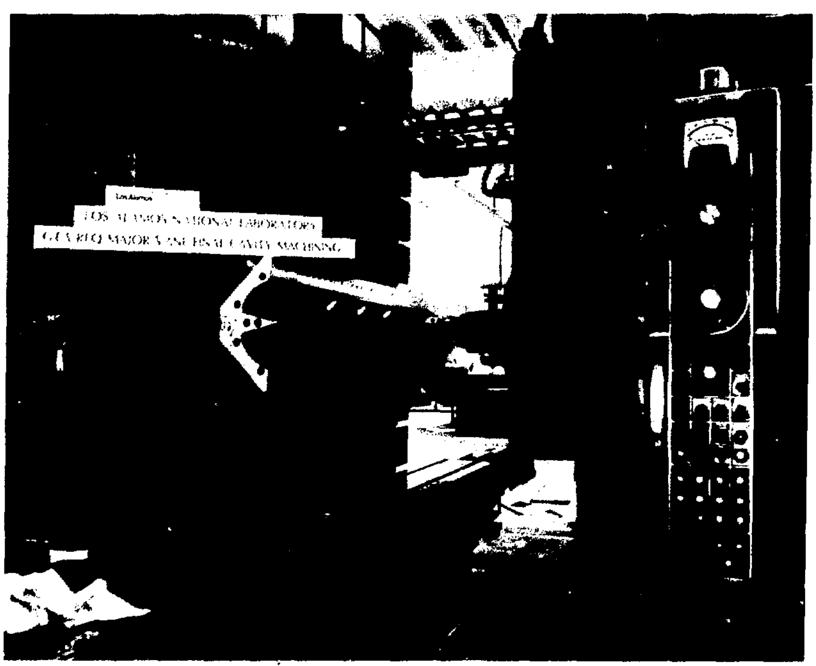


Fig. 4.1 GTA RFQ major vane final cavity machining.

After the drilling was complete, the rough vane blanks were returned to Los Alamos where they were prepared at Shop 6, MEC Division, for the electron beam welding process. Counterbores were machined in the ends for welding closure plugs to cap off the passages. On the back sides of the blanks, connecting passages were drilled and a counterbore was machined to receive the trision fittings. The trision fittings (proprietary process licensed to Applied Fusion Incorporated, San Leandro, California) allowed transition from the aluminum coretank to the stainless tubing of the cryogenic coolant manifolds. Extensive thermal cycling tests under pressure were done on the trision fittings to qualify them for cryogenic service.

The welding blanks, as they were now called, were thoroughly cleaned in an ultrasonic alcohol bath and shipped to EB-Tech West in Los Angeles, California, for welding. EB-Tech was the closest facility that had a chamber large enough to weld the end plugs into the 56-in.-long blanks. The blanks were welded and returned to Los Alamos. As the vanes were received, Shop 6 began to machine the vanes to finished size except for the vane-tip profile waveform.

In parallel with the vane blank fabrication, Shop 6 was machine-testing the vane waveform samples and interfacing the MEC-4 inspection to develop a method of inspecting the waveform in an automated process. Group MEC-4 was able to take the same data used in the vane machining files and write a program to inspect the test samples and final vanes. In early October 1989, vane-tip machining was just beginning.

GTA Drift-Tube Linac

In November, a conceptual design review took place for the GTA DTL, which then moved quickly into the preliminary stage. Low-power tests in the structures lab showed that extremely steep face angles for the drift tubes were feasible up to 55°. Using these angles allowed the cell designers greater freedom in determining cell frequency and in controlling RF field intensities. A means of adjusting the coupling coefficient at the iris was incorporated into the design. This adjustment involves cutting the iris for critical coupling with full beam loading and then installing removable cutoff limiters in the E-plane taper of the waveguide to accommodate RF conditioning without beam. Standard WR975 waveguide and elbows were adopted for GTA that set the two-channel configuration spacing at 46 cm, up from 35 cm. The beamline center height was also reduced from 203 to 147 cm. Preliminary designs of the steering quadrupole positioner and rotary tuner were completed and prototypes were built to test cryogenically in the Cryogenic Component Test Vessel. A low-power mockup of the GTA waveguide drivelines was designed for use in an experiment to determine these coupling coefficients and to locate the appropriate position for the RF window in GTA.

Other prototypes designed and fabricated were the coaxial resonant postcoupler and the RF monitor loop. Modifications were added to the DTL modules. Among these were stripline probes between each DTL module, wakefield shields between modules, and attenuation tubes in the vacuum pump-out ports to provide at least −150 dB of RF attenuation to protect sensitive pickups.

A preliminary design review of the first five DTL tanks was held in April 1989. An all-electron beam-welded approach for the drift tubes greatly simplifies their fabrication. Final design drawings for the drift tubes were prepared and completed for tanks 1 through 5 by early July following a final design review of the drift-tube concept in June. The final quadrupole designs to fit into these oddly shaped drift tubes were also completed and released. The cryogenic alignment tests on the prototype drift tubes and prototype adjusters were completed in June, and the magnetic centers were found to remain essentially aligned from room temperature down to 20 K over six thermal cycles. The cryogenic test, coupled with earlier cryogenic qualification of the quadrupoles, prompted the placing of an order for the first five DTL module quadrupoles with the successful vendor in the qualification completion, Field Effects, Inc. An order was also released for the drift tubes for the first five tanks. This order went to Westinghouse Hanford.

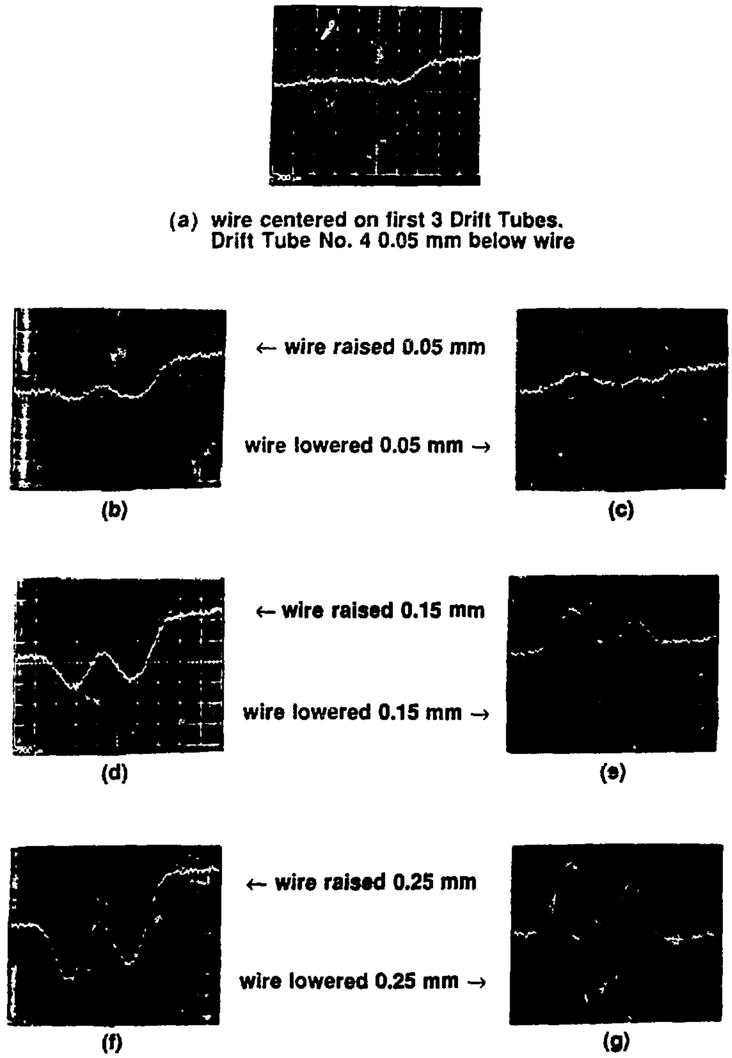
Difficulties were encountered in the testing of the first articulated prototype rotary tuner at 20 K. Design modifications followed, and tests are continuing. The RF monitor loops were cryogenically qualified. Some minor improvements were made to the prototype drift-tube adjusters before final testing preparation for qualification on GTA.

An experiment for testing copper surface treatment (that is, annealing temperatures, chemical/electro-polishing, and machining procedures) to qualify the treatment is under way for drift-tube fabrication. In addition, a contract was completed with a second source of cryogenic quadrupoles, Permag Corporation, to build two prototypes of the design used in the $2\beta\lambda$ section of the GTA DTL.

Cryogenic Test-Bed Experiments

Two important tests were completed in the CCTB. One was the final development and qualification of the fast-pulsed, taut-wire alignment technique started in the last quarter of FY 1988. The other was the successful testing of the adjusters for the four prototype drift tubes that had also been completed; the installed development quadrupoles were also tested in these prototype drift tubes. Following reference runs at room temperature, the drift-tube array was taken down to 20 K and the alignment rechecked. After six such cycles were completed, two facts emerged: the fast-pulsed taut wire is the most appropriate tool to check cryogenic alignment of magnetic centers, and the drift-tube adjusters designed for the GTA prototypes are able to prevent excessive displacements of the magnetic centers upon cryogenic cooldown. The alignments stayed well within the inside diameter (IO) 0.13 mm stipulated for GTA. Test results are shown in Fig. 4.2.

Other CCTB experiments involved tests on the two articulated devices required for GTA, the rotary tuner and the steering quadrupole positioner. The rotary tuner seized before reaching 20 K because of motor-bearing problems, which are being rectified. The $x - y$ positioner was successfully tested to about 50 K, and tests are continuing at lower temperatures.



TAUT-WIRE RESPONSE IN VERTICAL PLANE

Fig. 4.2 Alignment results for four-prototype drift-tube assembly.

High-Power Cryogenic Test-Bed

The HPCTB vessel is large enough to hold the GTA RFQ for high-power conditioning as well as the DTL modules. Designs were implemented on a bead-pull apparatus to test the DTL modules in CCTB and to test power feed and rail supports for high-power conditioning in HPCTB.

Cryogenic Quadrupoles

The DTL premier achievement for the year was the cryogenic qualification of the GTA DTL prototype quadrupoles. Until this point, no complete permanent-magnet quadrupole had ever been tested at 20 K. It was reported in FY 1988 that a cryogenic test dewar had been designed and fabricated and that the first prototype quadrupoles were received late in FY 1988. Subsequently, the dewar, search coil, drive hardware, and computer software were fully developed and the eight prototype quadrupoles from two manufacturers were tested down to 20 K. Field intensity was found to rise with decreasing temperature and then flatten out, as shown in Fig. 4.3. Furthermore, the field harmonic distortions remained within allowable limits. Also, a limited number of thermal cycles were imposed on the quadrupole assemblies, one as low as 4.2 K, followed by heat gun rapid warmup. No apparent mechanical damage resulted. Following cryogenic tests, a selected few of the prototype quadrupoles were irradiated in the Omega-West reactor at doses up to 10^{16} n/cm^2. These units are yet to be tested cryogenically, but testing will be at the final stage of the cryogenic quadrupole developmental program.

Further Ramped-Gradient (RG) DTL Development

The highly successful ramped-gradient DTL (RGDTL) program has continued into FY 1989. As of late FY 1988, the physics experiments on the ATS were completed successfully, and the RGDTL was removed.

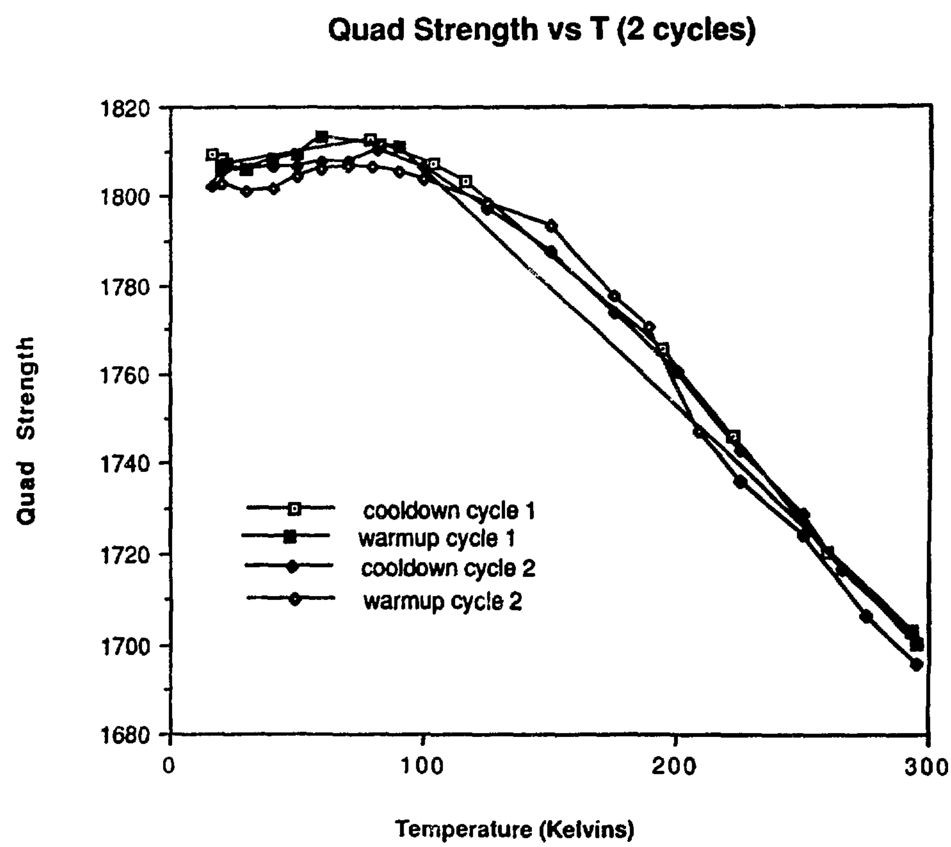


Fig. 4.3 Relative change in quadrupole field gradient with temperature.

In early FY 1988, a continuation to the test program was approved to test the engineering capacity for the RGDTL design, that is, higher-duty-factor operation. The RGDTL had been designed nominally for 5% duty factor, but RF tests would now be carried out to as high as 8% duty factor. The RGDTL was modified to include a rotary tuner, an instrumented drift tube was installed at 6.5 MeV, flow meters and thermocouples were attached to selected cooling circuits, and a water supply control panel was developed and installed. The RGDTL was thus brought up to a turn-key state preparatory to giving the system over to AT-5 as a developmental load for their 425-MHz klystron program. In July, the RGDTL was used in another test of the fast-pulsed, taut-wire alignment technique at room temperature on a long string of 29 permanent-magnet drift tubes. These tests were also successful and show that alignment precision of better than ±0.05 mm can be measured (and adjusted) on a long drift-tube string. Test results are shown in Fig. 4.4.

Summary of Hardware Accomplishments

Significant hardware developments during FY 1989 were the cryogenic test dewar for the DTL quadrupole development program, completion of the CCTB, application of the fast-pulse taut wire to the four-prototype drift-tube array, and the further application to the RGDTL. GTA-related developments include the prototype postcoupler, rotary tuner, steering quadrupole $x - y$ positioner, and high-gradient miniature quadrupoles for cryogenic testing.

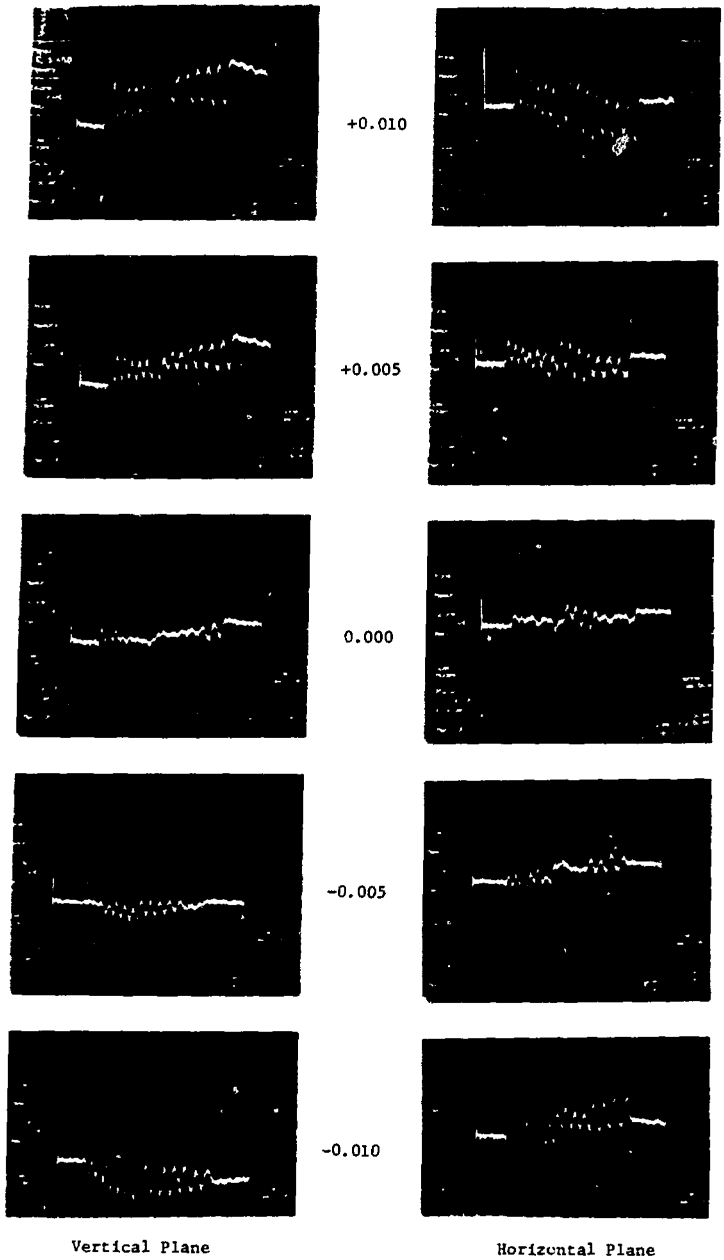


Fig. 4.4 Alignment precision of 29 drift tubes in the RGDTL using the fast-pulsed, taut-wire technique.

L. Eaton
Group Leader

M.T. Lynch
Deputy Group Leader

Introduction

Group AT-5's charter is to design, develop, and build RF systems for accelerators. This effort is for a total RF system capability, which consists of high-power amplifiers, low-level RF controls, and computer interface controls. These RF systems are for both linear accelerators and circular machines. Our present effort is predominantly for the GTA system now being built in AT-Division. We are responsible for the entire RF power system for this linear accelerator.

Group AT-5 has also been involved in the BEAR flight project, for which we also designed the RF power system. We are working on circular machine concepts such as the ferrite-tuned cavities for SSC and the TRIUMF Kaon Factory. We are delivering a low-level RF system for Boeing's Modular Concept Test Development (MCTD) Project and we have been involved in system studies for APT. We are also doing some work and have collaborated and given advice to Continuous Electron Beam Accelerator Facility (CEBAF) for beam positioning technology where it involves RF electronics.

In summary, AT-5 has developed an expertise and capability for RF system design for accelerators.

Ground Test Accelerator

Overview and Goal

The GTA is a proton linear accelerator being developed in AT-Division for SDI. The accelerator is powered by RF sources, and AT-5 is responsible for delivering the total RF system for this accelerator. The goal of AT-5 is to build turn-key packages that are delivered to the GTA installation group.

Our emphasis is broken into four areas: high-power RF, medium-power RF, low-level RF, and computer interface for RF.

High-Power RF

The high-power RF for GTA is presently configured for 850 MHz. Group AT-5 is designing, developing, and building a two-socket modulator to house 850-MHz, 1-MW, 2%, 10-Hz klystrons. We will build these systems here in AT-5 and integrate off-the-shelf klystrons with the modulators. Figure 5.1 shows the modulators being assembled. Five of these systems will power the ten 850-MHz DTL cavities for GTA. A sixth modulator will be a spare and used for cavity conditioning. The klystrons are Thompson tubes rated at 1.25 MW.

850-MHz Klystron Development

A contract was let to industry to develop a prototype 1.25-MW peak-power klystron at 850 MHz for GTA. The prototype klystron was first assembled in April 1989, but a series of quality control problems prevented RF testing until September. By the end FY 1989, it was clear that the klystron could not pass its acceptance tests and it had to be rebuilt several more times before high-power RF tests were started again. The prototype now is operating well at the factory and acceptance tests are scheduled next fiscal year. The contract for 12 production klystrons was let in FY 1990.

Fig. 5.1 Modulators being assembled.

In FY 1989, AT-5 used similar modulators to drive high-power 425-MHz klystrons. One of these klystrons were used to deliver power to a cryogenically cooled DTL cavity on ATS.

These high-power systems being developed for GTA are applicable to other efforts such as SSC.

Medium-Power RF System

GTA requires up to 250 kW at 425 MHz. We call this development medium power and we are using gridded tube tetrodes for this application. Mr. Carl Friedrichs is responsible for this design.

The tetrode is capable of delivering 50 kW to 250 kW of RF power in a linear mode and is easily configured with the rest of our system. The tetrode is controlled by an Allen-Bradley industrial controller that is interfaced to the GTA control system. The tetrode package is a three-rack configuration that is easily moved and can be operated in a stand-alone mode. The tetrode has shown robustness and reliability and is now being interfaced to the low-level RF system. GTA requires four such systems initially. Group AT-5 has built one and will build three more in FY 1990. Figure 5.2 shows this tetrode amplifier package.

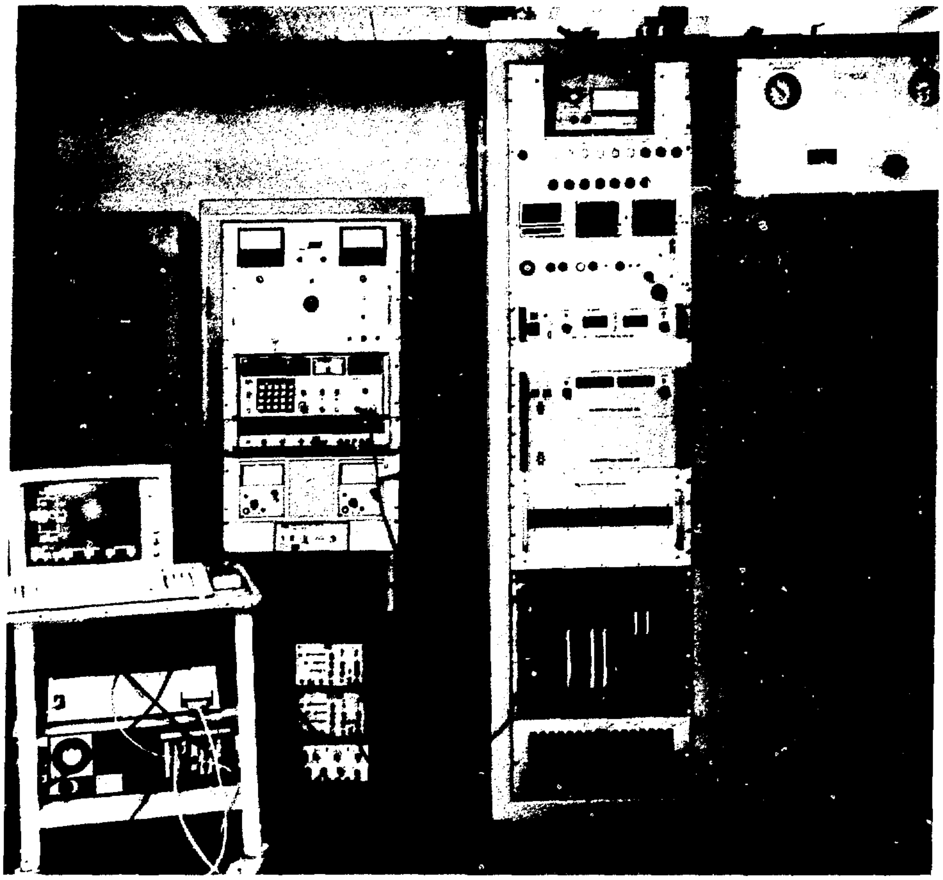


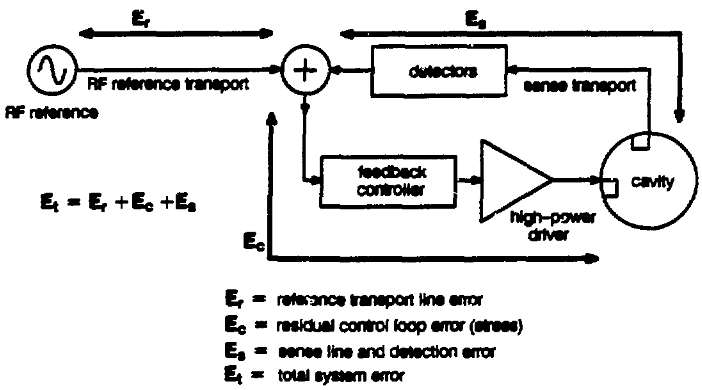
Fig. 5.2 Tetrode amplifier package.

Low-Level RF

The GTA requirement for low-level RF is that the cavity field be held to ±1/2% in amplitude and ±1/2 degree in phase. This stringent requirement means that the error budget for field control is very tight and thus requires a low-level RF system of high performance. Figure 5.3 shows the block diagram of this system with appropriate error budget information on the control system. In FY 1989 AT-5 provided the prototype design for this system on the cryogenic DTL cavity. During FY 1989 we have taken the prototype design and are configuring it to a production-ready PC board/VXI configuration. Mr. Stephen Jachim is the Section Leader responsible for this design.

The low-level RF design is frequency- and power-independent, is modular, and thus can be applied to other areas such as SSC, ferrite-tuned cavities, or Boeing's MCTD Program. The system is also interfaced to the GTA control system to allow automatic operation.

Group AT-5 also has done extensive analytical modeling of the accelerator/RF design. This has included the cavities, controls, and high-power amplifiers. We have also modeled multidrive loop systems. Figure 5.4 shows the model for the GTA DTL.



PERFORMANCE OBJECTIVES

PEAK AMPLITUDE ERROR: ≤ 0.5%

PEAK PHASE ERROR: ≤ 0.5°

TOLERANCE BUDGET

	AMPLITUDE (%)	PHASE (deg)
E_r	N/A	+/- 0.15
E_s	+/- 0.2	+/- 0.2
E_c	+/- 0.3	+/- 0.15

Fig. 5.3 Low-level RF system with error budget information.

An innovative diagnostic for controlling the resonance of the GTA cavities is the six-port reflectometer. Group AT-5 developed this system that measures reflected and forward power from the RF drivelines and lets the computer calculate the cavity frequency. Figure 5.5 shows an Operator Interface (OPI) plot of the information available to the operator to display the resonance of the cavity on the Smith chart.

Computer Interface for RF

The GTA has a major requirement that the system show the capability of being automated. This means that all RF systems need to be controlled by the overall computer system, and AT-5 has made a concentrated effort to design automated control into all of the RF designs. Mr. Chris Ziomek is the Section Leader.

For most GTA systems the interface of choice is an Allen-Bradley industrial controller. This choice means the Allen-Bradley controller has local control and that the GTA control system can communicate with it easily. The low-level RF is configured in a VXI format, which is a VME-based system for high-bandwidth video. All packaging has been done so that this system is compatible with the GTA control system. Figure 5.6 shows a VXI card developed by AT-5.

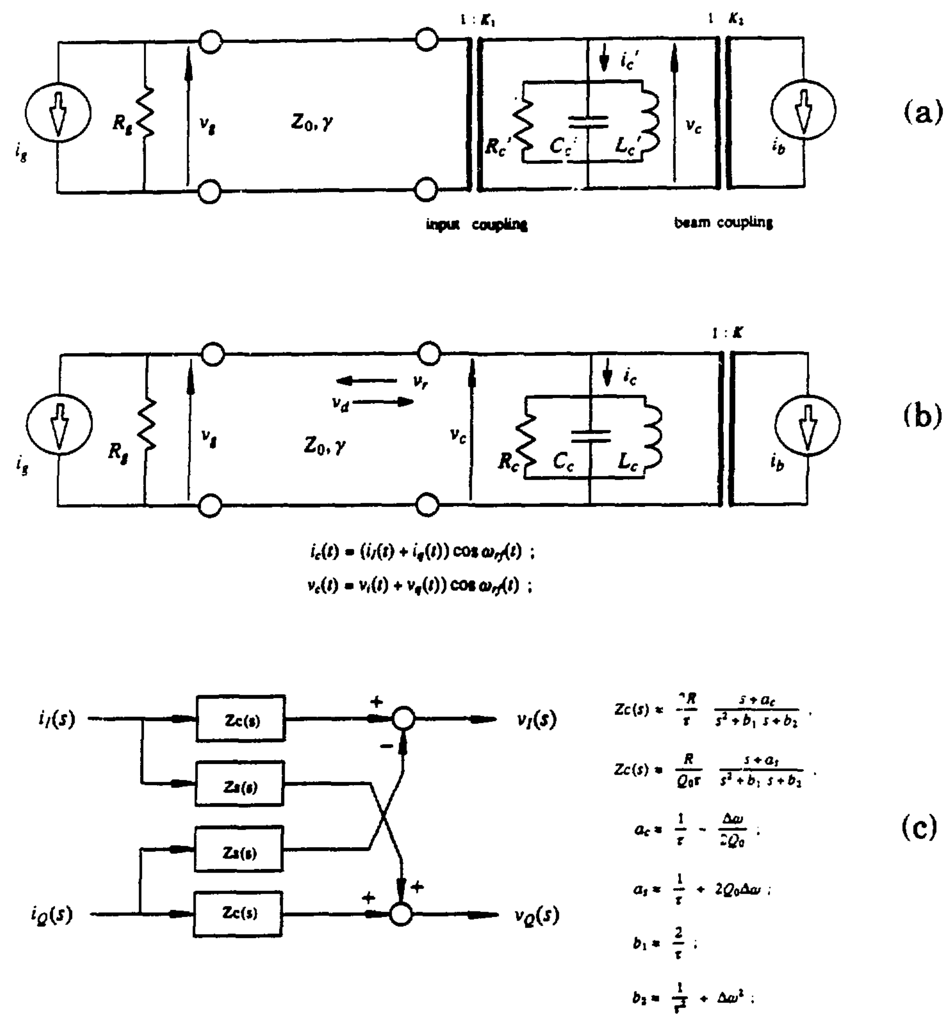


Fig. 5.4 Model for the GTA DTL shows (a) resonant cavity, (b) simplified resonant cavity, and (c) LRC resonance in IQ representation.

In FY 1989 the interface was tested and shown to be operational when the cryogenic experiment was done and controlled by the GTA control system. Again this application is easily compatible with other systems.

Beam Position Support for CEBAF

Beam position information on accelerators is highly dependent on RF electronics. Because AT-5 has this expertise in-house, we have been assisting areas where beam position signal processing is required. In this regard we have been on committees for CEBAF and have given advice to these committees on their beam position system. We have also collaborated with AT-3 in work for the ANL Telescope for the beam position electronics there.

With this expertise in AT-5, we continue to support any areas that may need signal processing for beam position electronics.

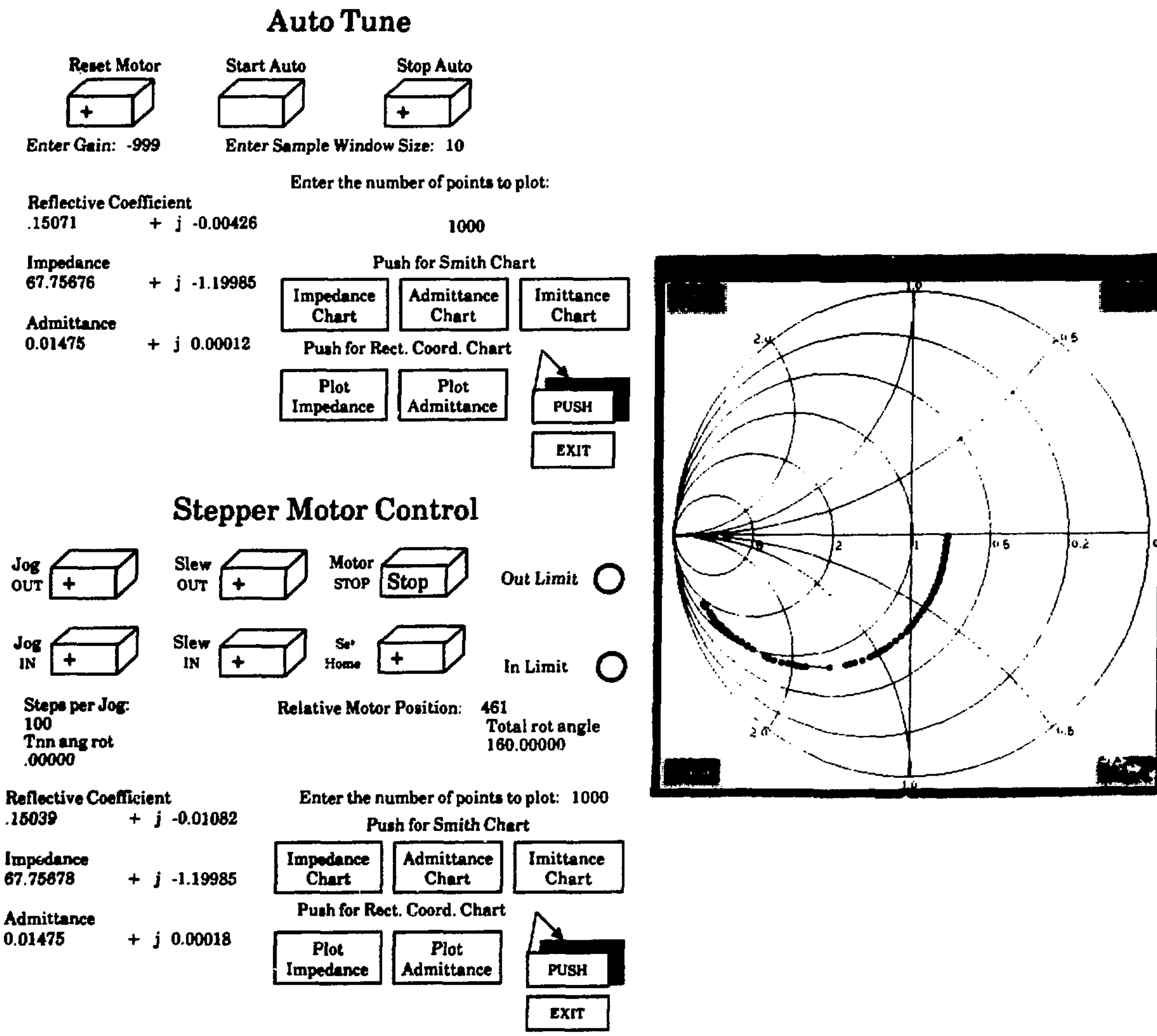
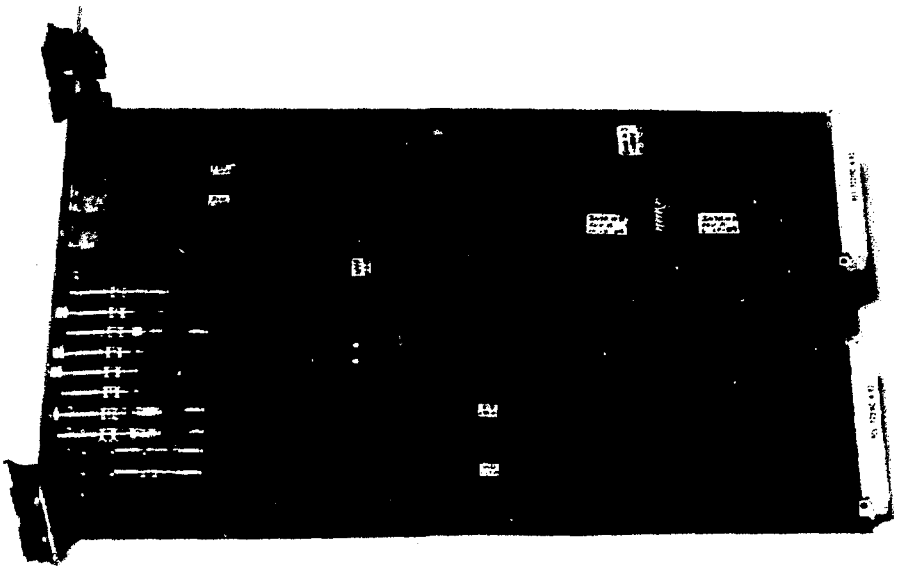


Fig. 5.5 OPI plot.

RF System for BEAR

During the early portion of 1989, all flight components for the BEAR RF system were completed by AT-5 personnel assigned to the BEAR Project Office. The RF system was the first major accelerator component ready for flight.

The RF system for the BEAR flight consisted of two 70-kW, solid-state amplifiers, an RF controller, and a 40-V regulator. The amplifiers (Fig. 5.7) were designed and built by Westinghouse Electric Corporation Defense and Electronics Center in Baltimore, Maryland, under a contract with LANL. The RF controller and 40-V regulator were designed and built by LANL. A block diagram of the RF system is shown in Fig. 5.8.



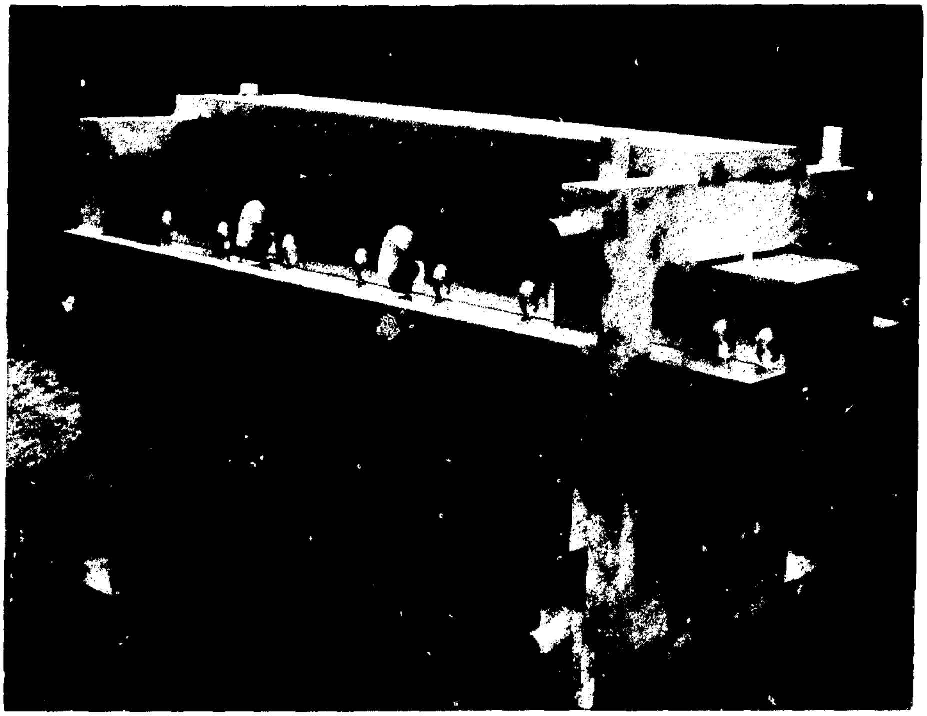


Fig. 5.7 Solid-state amplifiers.

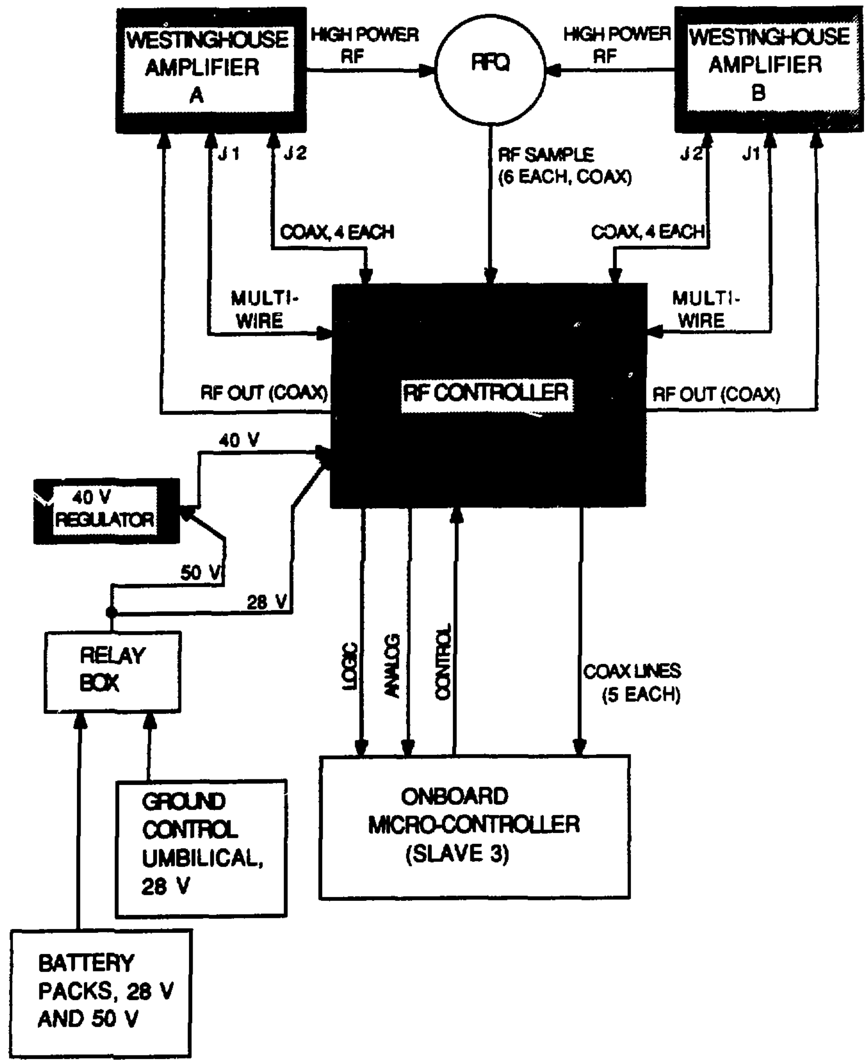


Fig. 5.8 RF system block diagram.

The primary function of the RF system was to provide the necessary power to the RFQ to accelerate the 30-kV beam from the injector to 1 MeV. In addition, the RF system had to interface with the on-board controller and telemetry system for timing and control signals and diagnostics.

The RFQ was not frequency-stabilized. Therefore, the RF system had to follow the resonant frequency of the RFQ as it changed with temperature. In addition, the RF controller had to maintain the RFQ field levels with variations in beam loading.

A block diagram of the RF control system is given in Fig. 5.9. The RF controller consisted of three subsections (power supply, RF, and control) in a box 10 in. x 14 in. x 6 in. high and had 10 circuit boards and hundreds of interconnecting wires. The 40-V regulator had four individual regulator circuits in a box 8.5 in. square by 1 in. high. All flight assemblies had to undergo thorough environmental and electrical testing before being declared "flight-ready."

Integration of the payload was completed in early 1989 in Los Alamos, and the integration for the flight was completed at the WSMR by June 1989.

The RF system operations during the flight, which occurred on July 13, 1989, were normal. The RF system came on at the scheduled time into the flight, found the resonance frequency for the RFQ, and established the proper fields within one or two pulses. A summary of the operation of the RF system during the flight is given in Table 5.1. One important characteristic about the flight operation is that the fields in the RFQ were held to the correct level to within 0.3% despite beam-loading variation from 0 to 40%. In addition, there were only 17 arcs in the RFQ out of 1444 total pulses.

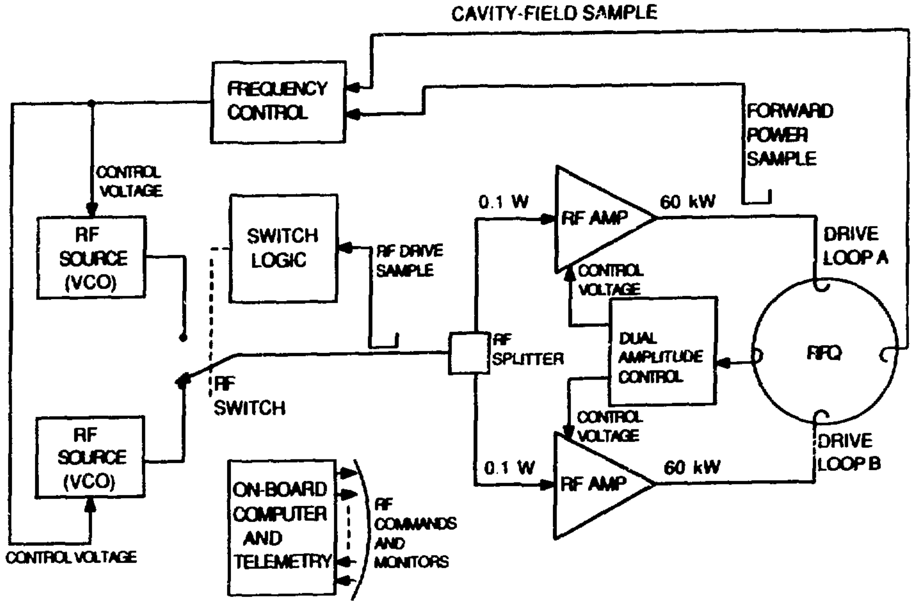


Fig. 5.9 RF control system.

Table 5.1. Summary of the Flight RF System Operation

Total RF Pulses	1444
Number of RFQ Arcs	17 (1.2%)
Number of Arcs (when beam was being injected)	1 (<12 mA)
RFQ Field Level (ignoring arcs)	95 ± 0.3%
Beam Loading	0 to 40%
RFQ Resonance Frequency	425.05 MHz

The RFQ field level used for the flight was 95% of the nominal design level determined by initial measurements. The RFQ was shown to be able to transport beam to 1 MeV at fields above 80%. Reduced output current is obtained when the fields drop below about 85%. The selection of 95% was based on a desire to be well above the 95% level, but low enough to minimize the chances of arcing in the RFQ.

The payload was returned to Los Alamos after the flight and continues to function properly. The draft final report of the RF system was completed in late 1989, and the complete final report will be published in early FY 1990.

RF System and Ferrite-Tuned Cavity Development

FY 1989 was the last year of funding of this work by ISRD funds and internal MP Division funds. The LAMPF upgrade and the AHF lost endorsement by the physics community to the joint United States/Canadian Kaon Factory at TRIUMF in Vancouver, British Columbia. However, advances were made in the ferrite-tuned cavity development that will be of interest to the TRIUMF Kaon Factory and to the SSC.

The ferrite-tuned cavity development has been focused around the use of a perpendicularly biased ferrite. The perpendicular biasing leads to lower losses in the ferrite and higher gap voltages so that fewer cavities are needed in any particular application. Initial work was pointed toward booster cavity development. The booster cavity developed here demonstrated 150 kV in the gap and a tuning range of 20%. During the past year, this cavity was loaned to TRIUMF for further work while the effort at LANL shifted to main ring cavity development. Figure 5.10 shows the cavity setup here at LANL.

The main ring cavity was designed and built for full-power testing and ac biasing. The biasing implies the ability to sweep the frequency of the cavity over the pulse width of interest (50 ms). This cavity was completed in 1989 and initial experiments were performed. The cavity Q was measured with respect to frequency, and a peak gap voltage of 151 kV was obtained.

In working group meetings that took place near the end of 1989 (June 26–27 in Los Alamos; October 4–5 in Duncanville, Texas; and November 29 in Vancouver), further work was outlined that would be useful to both the Kaon Factory and to SSC. Funding for 1990 has been obtained that will allow a portion of this work to take place.

Modular Concept Test Development

Group AT-5 received funding from Boeing Aerospace Corporation in Seattle, Washington, to provide frequency and field controllers for its MCTD work. These controllers use the same design as those being developed for the GTA project. This work was started in late FY 1989 and will be completed in early FY 1990. It will be the first opportunity to operate the GTA type controls on an accelerator.

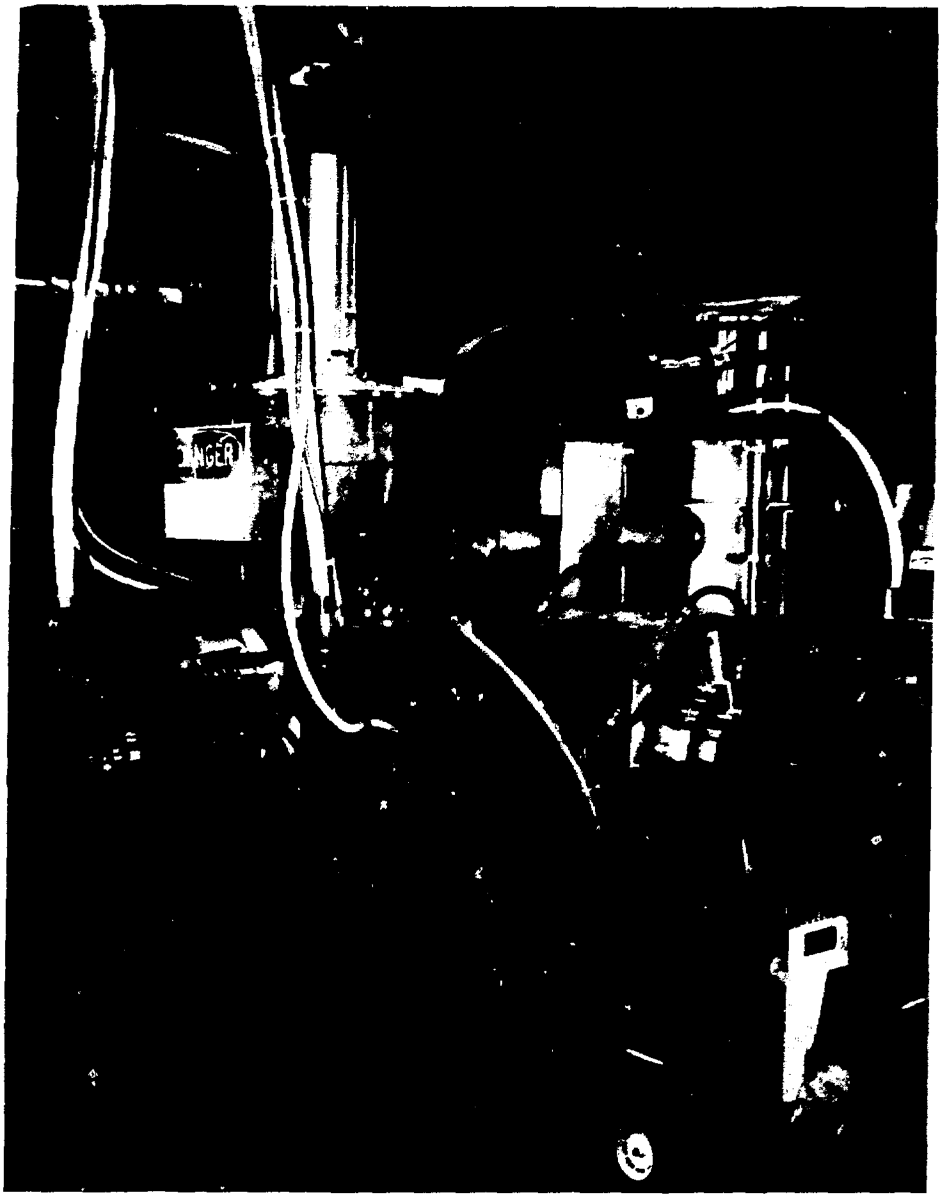


Fig. 5.10 Cavity setup.

Accelerator Production of Tritium

The proposed RF system for the APT project is shown in Fig. 5.11. The system was designed with state-of-the-art components, which require minimal development for the project. The RF systems would use 11-MW power supplies to drive groups of six klystrons from each power supply. Each power supply would have its own crowbar and capacitor bank. Each klystron has its own low-level RF controls, solenoid, circulator, and oil tank.

The group of klystrons on each power supply would be cooled by a common water system. The total of 482 klystrons, each capable to 1.25 MW, would be required to produce the goal amount of tritium each year. The power line to beam efficiency is over 49%. Significant cost reductions are possible with larger klystrons, but more development would be required to produce more powerful klystrons. The APT system could also be optimized for lesser amounts of tritium production.

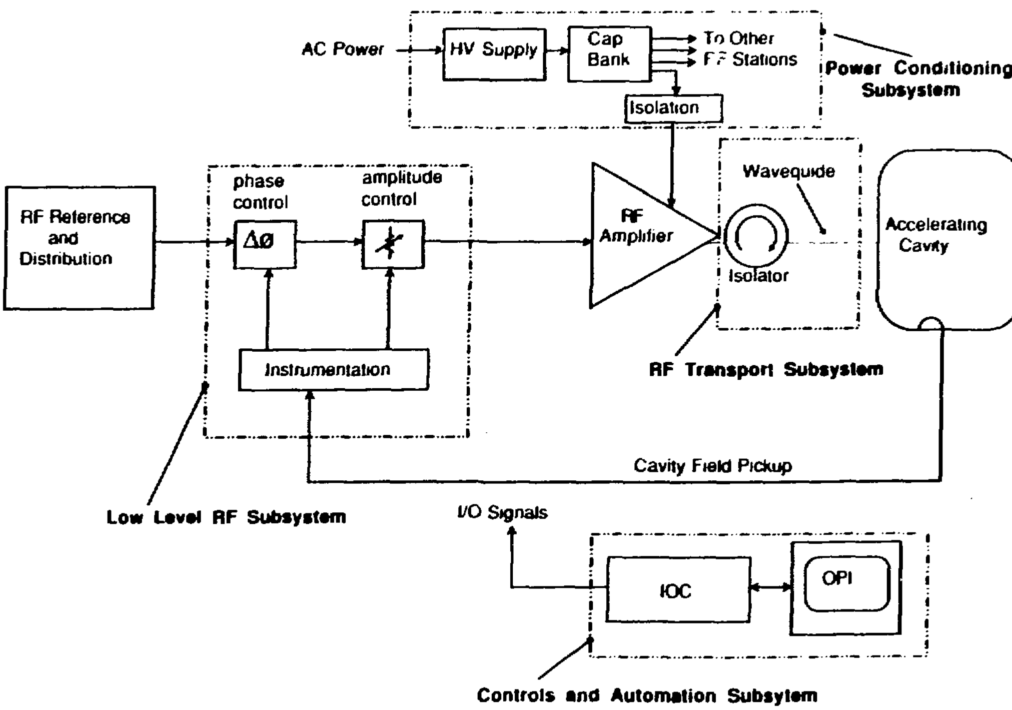


Fig. 5.11 Proposed RF system for the APT.

RF System for the University of Twente FEL Accelerator

Group AT-5 began a proposal in late FY 1989 to provide the RF system for the University of Twente FEL accelerator. A large portion of the RF system will be provided by the University of Twente with the remaining components and the system integration provided by LANL. Figure 5.12 shows the RF system, which indicates who is responsible for each component, and the feedback control system using RF feedback, which is the preferable feedback scheme.

The primary areas/components to be provided by LANL include the low-level RF system including feedback controls, solid-state drive for the klystron, accelerator resonance controller, high-power RF transport system including a wave-guide isolator for the klystron output, timing and computer control system, system interlock controls, and RF system integration. The University of Twente will provide the klystron and magnet and all associated power supplies, high-voltage supply and pulse-forming network (PFN) system, klystron water manifold, RF source, injector electronics, and some of the interlocks and timing hardware.

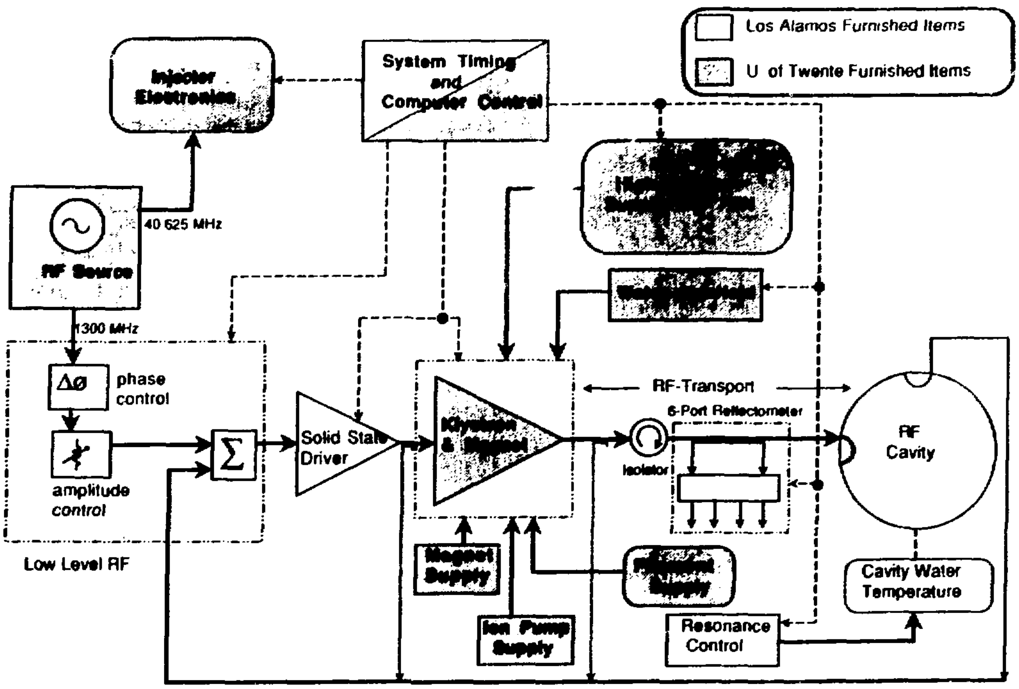


Fig. 5.12 RF system.

In late FY 1989, the University of Twente gave AT Division a small amount of money to develop a proposal to build an accelerator for an FEL facility at the university. Initial design and cost studies were begun that include a complete RF system. The University of Twente would provide the klystron and the PFN for the klystron, but all other components and the system integration would come from LANL. A decision about final funding should come in early FY 1990.

The Lasertron Development Program

The RF-driven lasertron was assembled and tested during the year. Mr. Paul Tallerico was the chief investigator. Data were taken for three sets of experimental conditions, and output powers of up to 1.1 MW were measured with beam to output power efficiencies measured between 35% and 60% as the beam current and output power were varied. Although the experimental uncertainties of the efficiency data are about 15%, both the output power and efficiency are much better than ever measured on other lasertron projects. The photocathode lifetimes were short, but as we gained experience, the lifetimes increased to 12 h. With a better beam-dump and differential pumping system, one can expect to see cathode lifetimes of several weeks. The project met its goal of producing over 1 MW of output power at 1300 MHz with a lasertron that operated at over 50% beam to microwave power efficiency. The major results of the experiments are shown in Table 5.2. The data were taken with three different accelerator energies and currents. The output power was reproducible, but there is a ±20% experimental uncertainty on the beam to RF conversion efficiency. The cathode life was shorter than desired but still long enough for careful measurements. A report summarizing the experiments is being prepared.

Table 5.2. Major experiment results.

Beam Energy (kV)	Peak Current (A)	RF Output Power (kW)	Efficiency from Power Flow
420	0.56	107	36
610	1.34	386	60
1210	1.12	1092	48

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Introduction

The Accelerator Theory and Simulation Group, AT-6, provides analytical and computational support for the many activities of the Accelerator Technology Division. The group's theorists are responsible for proposing new accelerator schemes and developing a physical understanding of phenomena observed in operating accelerator systems. In addition to developing and maintaining a large number of accelerator design and analysis codes, the staff assists other members of the Division in using these codes, and AT-6 staff members are often called upon to analyze physical devices, some of them proposed and some as built. Group AT-6 has supported the AHF, ATS, FEL, GTA, PSR, and SSC projects. Additionally, the Los Alamos Accelerator Code Group (LAACG), resident within AT-6, maintains, distributes, and documents a number of codes (most of them in the POISSON/SUPERFISH group of codes) and provides assistance to users outside AT Division and outside the Laboratory. The group also maintains and documents not only the POISSON/SUPERFISH codes on the computers of the National Magnetic Fusion Energy Computer Center (NMFECG) but also the MAFIA three-dimensional electromagnetic design codes. Thus, AT-6 provides national access to these valuable design tools.

Neutral Particle Beam Physics

While not involved in a major way with the NPB program, AT-6 personnel responded in a timely manner to requests for studies in areas as indicated below:

- The copper power and power density distributions for the GTA DTL tanks were computed and documented.
- An input sensitivity study of the GTA RFQ was executed and documented.
- Output beam parameters of the ATS RFQ RGDTL as a function of input beam phase and accelerating field amplitude were documented.
- Work on the two-stream instability as a possible source of the reported anomalous longitudinal emittance growth was accomplished and documented. In particular, a possibility for experimentally testing whether the two-stream instability is responsible by inserting an alternating array of dipoles in the drift region was proposed.
- Three-dimensional calculations were performed for purposes of designing a cavity for testing RF windows. Further 3-D calculations were performed to determine the current densities in the mounting recesses of GTA DTL support stems.

All these areas of study and the results obtained are documented in Accelerator Theory Notes (ATNs) or in AT-6 Technical Memos (TMs).

Free-Electron Laser

The Los Alamos National Laboratory was teamed with the Boeing Aerospace Corporation during the report period for the purpose of competing for the privilege of building an LSS at the WSMR.

The competition was won by the LANL/Boeing team against the TRW/Lawrence Livermore National Laboratory (LLNL) team.

In support of both ground-based and space-based FEL systems, work done in AT-6 included the following:

- The PARMELA code was modified to include three-dimensional wakefield and cavity asymmetry effects.
- Studies to determine the effect of a large coupling hole into an RF cavity and to determine how to compensate for the effect were conducted.
- A study of increasing the efficiency of an FEL by adding a prebuncher wiggler indicated that the efficiency of the Boeing experiment could be enhanced by 22% by using a four-period prebuncher.
- We discovered how to make a beampipe size transition with little or no longitudinal wakefield. The principle involves preserving the static energy of the beam throughout the transition.
- The effects of resistive walls on beam dynamics including emittance growth were determined.
- Work on an assessment code for the space-based FEL included beam-breakup effects, wakefield effects, and resistive wall effects. The code will be used for initial design of FEL systems and scaling law studies.

Synchrotron and Storage Ring Studies

The personnel of AT-6 have been involved for a number of years in studies relating to the SSC, the AHF, and the PSR. During the report period Tai-Sen Wang of AT-6 spent a Professional Research and Teaching (PR&T) Leave at the European Center for Nuclear Research (CERN) helping commission the large electron-positron (LEP) collider machine and studying beam-cavity interaction effects in storage rings. The following items indicate some of the range of studies performed in the circular machine subject area:

- Work continued on the novel chromatic correction scheme. We believe that the use of this scheme in a machine such as SSC will result in significant cost savings.
- Extensive analytical and numerical studies of the electron-proton (e-p) instability were carried out for PSR, with an extension being made to include the AHF parameters. The results indicate an e-p instability could exist in PSR but would be no problem in AHF.
- Wire-scanner data from the PSR were used to calculate the emittances of the circulating beam, and from these emittances, the space-charge-induced tune shifts were calculated to be near 0.25, the limiting value to avoid machine resonances.
- A reinvestigation of the Robinson instability including the coupling of the longitudinal dipole and quadrupole modes was made. The results indicate that for small-cavity detuning and short bunch length, the maximum stable beam current can be higher than that described by the usual Robinson stability condition.

- The stability of counter-rotating beams was the subject of another study involving the extension and reformulation of previous work.

Accelerator Production of Tritium

- Preliminary cavity designs for the high-energy sections of the APT projects were made. This information was incorporated in the present design. The beam-breakup aspect of the accelerator was also examined. We concluded that the present design should be free from regenerative beam breakup. If care is taken, it should be free from cumulative beam breakup as well.
- Two issues related to beam instability in APT were addressed—cavity-energy depletion by beam bunches and beam breakup. The conclusions are summarized in Ref. 1.

Code Development

Computer codes are developed concurrently with theoretical studies of accelerator dynamics. We have supported in part the further development of MARYLIE for application to beam transport and accelerator problems. The beam dynamics code BEDLAM was significantly improved during the report period, and the CERN code HERSIM was also improved during this period. These improvements include the following:

- We developed and installed in MARYLIE the ability to compute (using GENMAP) the transfer maps for any number of combined-function rare-earth cobalt (REC) quadrupoles with overlapping fringe fields. This capability is important because the GTA telescope has four REC quadrupoles with overlapping fringe fields. These quadrupoles also have built-in sextupole and octupole components.
- A procedure for minimizing octupole corrector strengths when more than three correctors are used in a telescope has been developed. This has been written up and will appear as an AT-6 TN. This procedure has been incorporated into MARYLIE as a user-written constraint routine.
- The items above were used to show that it is feasible (within the constraints imposed by the contractor) to use combined-function REC quadrupoles in the GTA telescope. That is, the octupole components that can be built into REC quadrupoles will be sufficient for aberration correction.
- A new MARYLIE format for fitting procedures was developed and standardized, in collaboration with University of Maryland workers and AT-3 personnel. This new format will make it possible to fit for essentially every quantity that MARYLIE is able to compute. This feature will be of importance to the GTA in fitting beam moments.
- We developed an analogous format for optimization procedures and established an appropriate structure for related MARYLIE commands.
- We determined what is needed to compute PSR dipole transfer maps from measured PSR dipole magnetic field data.

These transfer maps, when computed, can be used in MARYLIE to simulate as closely as possible actual PSR orbits. In particular, it will be possible to compute expected nonlinear effects.

- A technique for numerically integrating Lie-Poisson dynamical systems while exactly preserving the Lie brackets was developed with great success. Lie-Poisson systems include the Vlasov-Poisson equations, which describe nonrelativistic charged particle beams. The second example investigated (after the rigid body) was a system derived from the Vlasov-Poisson equations that included second and fourth moments, the effects of an external nonlinearity, and a mockup of the effects of space charge.
- BEDLAM now includes full 3-D space-charge and arbitrary external forces. External force coefficients are read in from an external file at each time step so that the interface with other descriptions of the accelerator should be relatively straightforward. Initial tests indicate that the scaling with the time step is correct and that the energy stability is very good because of the use of an integrator that is exactly Lie-Poisson. A new Lie-Poisson integrator was installed in BEDLAM with a resulting increase in speed of a factor of 1000.
- Optimization: The algorithm previously developed for finding optimum configurations of nominally identical elements with errors has been extended to the problem of finding the optimum configuration when elements of more than one type can have errors. The extended algorithm has been applied to a "real" problem; i.e., a periodic focusing-defocusing (FD) transport channel for 24-MeV protons with identity transfer matrix was designed using MARYLIE and consisted of six F-quadrupoles and six D-quadrupoles each 10 cm in length. Two merit functions, the rms mismatch and the deviation from initial rms radius, were evaluated using tracking of 1000 particles through the channel. The channel with no errors had the same final radius to 1 part in 10 000 but had a 15% mismatch due to the nonlinearities in the magnet fringe fields. With a set of errors of less than 1% in both the F- and D-quadrupoles, the algorithm produced configurations with a least radius of 85% of the original and a greatest radius of 115%, in complete agreement with the MARYLIE runs used to confirm the results. The algorithm also yielded configurations with a minimum mismatch of 13% and a maximum mismatch of 200% when the configurations were checked with MARYLIE. The performance of this optimization algorithm is thus excellent.
- Benchmarks: In developing 3-D codes such as BEDLAM, it is difficult to develop confidence in the results because of the lack of significant benchmarks in 3-D. As a partial remedy for this, we have developed spherically symmetric time-dependent analytic solutions of the Vlasov-Poisson equations with analytically prescribed external forces and significant space-charge effects. Although these do not test all elements of a 3-D code, they do test some elements not otherwise accessible to benchmarking.

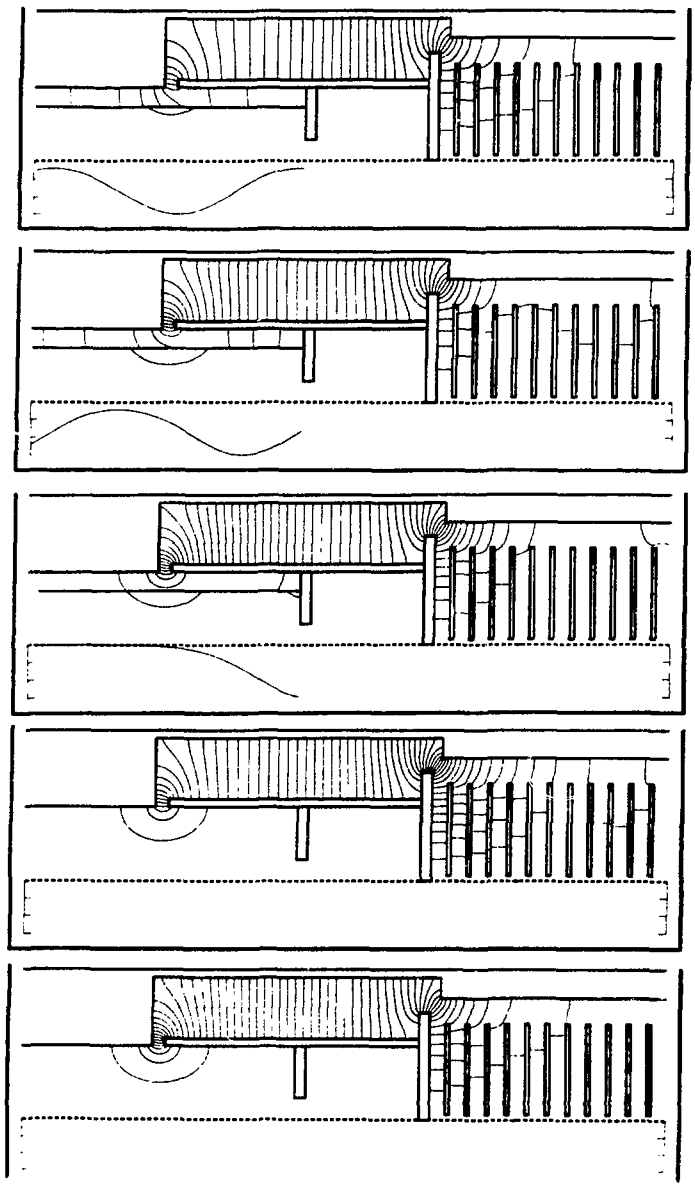

Fig. 6.1 Time sequence showing the excitation of a structure with relativistic beam bunches used in a wakefield accelerator experiment at the NRL.

- MAFIA—To support the development of a high-power microwave source, we have made a movie to simulate the relativistic klystron being studied at the Naval Research Laboratory (NRL). A time sequence of pictures showing the propagation of the electromagnetic fields in such a device is shown in Fig. 6.1. Simulation like this allows the researchers a better understanding of the complicated coupling mechanism involved. MAFIA codes were used to study the effect of recessing the stems on the wall currents at the RF seals of a drift-tube linac (see Fig. 6.2).

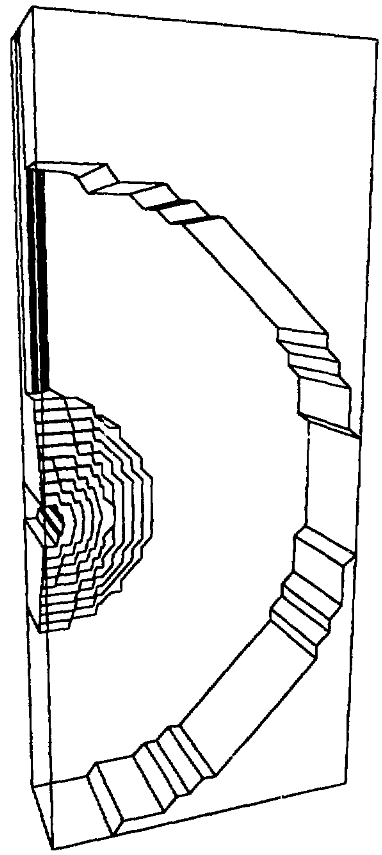

Fig. 6.2 MAFIA model of the DTL.

- The program ARCHSIM (developed for the VAX/VMS system) has been installed on the CRAY. The graphics have been improved and the program runs 10 times faster on the CRAY than it does on the VAX/VMS system. This program is being used in PSR studies.
- Computer Simulation Program HERSIM: HERSIM is a CERN computer simulation program built for studying the longitudinal and transverse wakefield effects due to the beam-cavity interaction. The program considers fast-decaying wakefields in the cavity and uses smooth approximations for particle orbits together with a table-searching technique for wakefield calculation to reduce the computation time. The original version of HERSIM allows only one cavity in the ring as an input to the program, and the effects due to the nonlinear elements were not included. An upgrading of HERSIM to incorporate the effects of dispersion, sextupoles, multiple cavities, and chromaticity has been accomplished recently by Tai-Sen Wang on his PR&T leave at CERN.

Code Group Activities

We have continued to distribute the POISSON/SUPERFISH group of codes, as well as the codes PARMILA, PARMELA, PARGRAF, LTRACK, and TRACE 3-D. As part of our distribution work, we have also continued to field questions regarding these codes.

The AT-6 Conference Room has 12 Ethernet ports installed and can be used as an AT Division computer classroom.

A computer network mailing address was set up at the node "LAMPF" on the network "BITNET" for the LAACG. This address should be easier for our users to remember and it is not dependent on the presence of any particular individual's account. Mail coming to this address can be forwarded easily to any desired account.

Documentation

We were invited to submit the first edition of "Computer Codes Used in Particle Accelerator Design," (LA-UR-86-3320) for inclusion in the published proceedings of the 1987 Accelerator Summer School.

It was decided that the second edition of "Computer Codes Used in Particle Accelerator Design" will be called "A Compendium: Computer Codes Used in Particle Accelerator Design and Analysis." We sent 1200 copies of a letter soliciting new entries for the second edition and accompanying forms to the organizers of the Particle Accelerator Conference held in Chicago on March 19-23, 1989, for inclusion in the registration packets. Two staff members attended the conference. They prepared a poster outlining the project; the response to this solicitation was enthusiastic.

A manual for the PARMILA code, a 25-year-old continuously evolving code for the calculation of phase and radial motion in ion linear accelerators, was essentially completed during the report period. We plan to distribute it at the Conference on Codes and the Linear Accelerator Community to be held in Los Alamos in January 1990.

Code Access, Verification, and Distribution

- Version 2.003 of the POISSON/SUPERFISH group is installed in `/at6/poicodes/cray` and `/at6/poicodes/vax` here at Los Alamos and in `/lacc/poicodes/cray` and `/lacc/poicodes/vax` at the NMFECC at LLNL.
- A set of six test examples, DEC command language (DCL) command files to run them, and an appropriate README are stored on the Central File System (CFS). These examples will be routinely distributed with version 2.003 of the POISSON/SUPERFISH group.
- A version of E31, the 3-D resonant frequency solver for the MAFIA group, has been implemented on the LANL CRAY XMPs with fully dynamic memory allocation and use of absolute files for the scratch files. This change resulted in a 100-s CRAY time-sharing system (CTSS) time saving for a 23 000-point problem formerly requiring about 350.0 s.

- We are testing the VAX-VMS-DISSPLA (PDN.FOR) for the MAFIA codes on the AT-6 VAX.
- Million-point versions of the MAFIA codes were installed at NMFECC for the CRAY2s, Machines B and F. In the course of the report period, it was necessary to recompile them to compensate for an operating system change. We are running a version of the side-coupled-cavity problem with MAFIA at NMFECC with over half a million points.
- Updated versions of URMEL, URMELT, TBCI, and E31 (all version 2.0+) were implemented on the CRAY-XMPs.
- The use of CHTEXT to change the text label in a MAFIA direct access file was documented.[2] A simple program, referred to as AREA, to calculate the MAFIA cross-sectional area of a specified material number was documented.[3] The new MAFIA power loss routines were tested and the results documented in an ATN.
- Work continued on "Programmer's Guide for the MAFIA Power Loss Routines." Two new DYN routines and one new MAF routine for MAFIA were written, debugged, and sent to West Germany. Two existing DYN routines were also modified and sent to West Germany. Version 3.00 of the Interface for MAFIA codes is being tested.
- The particle-in-cell code TBCI-SF was brought to operating condition so that it can be used for simulation of relativistic klystrons. TBCI-SF is now operational with an additional postprocessor that can plot different dynamical variables of the beam to help the understanding of beam dynamics. The postprocessor also calculates transverse emittances.
- Work is continuing on correcting the stored energy calculation in POISSON/PANDIRA/MIRT.
- The UNIX project has progressed to include the following: The complete POISSON/SUPERFISH group is up and running on the Sun workstations and a subset of POISSON/SUPERFISH is up and running on UNICOS and on the Florida State University ETA-10. The Weiland code URMEL-T is also up and running on UNICOS. We are in the process of getting URMEL-T up and running on the ETA-10. We also submitted a request for time on the ETA-10 as follows: 500 Computer Resource Units (CRUs) for accelerator code studies with the ETA-10 and Virtual Memory UNIX. We made the first UNIX tape of the POISSON/SUPERFISH group, and it will be installed at the Center for Research on Electrical Optics and Lasers (CREOL) in Orlando, Florida, on the Center's Sun workstation. The first tape of the experimental MAFIA interface was distributed to CREOL.
- We submitted three requests for time on the NMFECC CRAYs as follows: 500 CRUs for maintenance of the MAFIA and POISSON/SUPERFISH code groups, 9600 CRUs for fine-mesh studies using MAFIA 3-D codes, 2000 CRUs for time-domain wakefield studies for a very short bunch. The requests for 9600 and 2000 CRUs at NMFECC qualified for Grand Challenge

projects. We submitted summary sheets and proposals for Grand Challenges for both of these projects.

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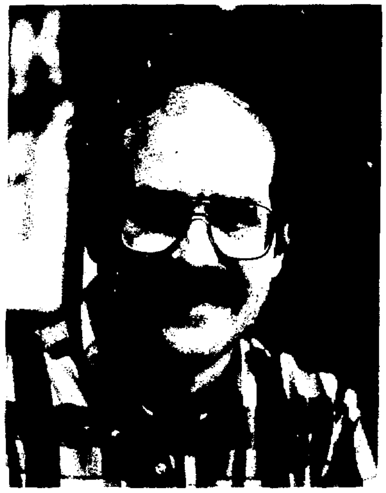
2. M. J. Browman and T. C. Barts, "Program to Change the Text Label on a MAFIA Direct Access File," Los Alamos National Laboratory technical memo AT-6:89-34, July 26, 1989.
3. M. J. Browman, "A Simple Program to Calculate the MAFIA Cross-Sectional Area of a Specified Material Number," Los Alamos National Laboratory technical memo AT-6:TM-89-30, June 13, 1989.

J.M. Watson
Group Leader



R. Sheffield
Deputy Group Leader

Introduction

With primary responsibility for FEL Program activities within AT Division, AT-7 manages accelerator-based experiments, coordinates the work of other contributing groups, and provides technical guidance to the FEL Program Office for proposals, program direction, and external collaborative arrangements.

The Los Alamos FEL program began in the late 1970s to investigate the practicality of FELs. Since then, AT-7 has operated both FEL amplifiers and oscillators. An energy-recovery experiment was performed that demonstrated a technique for improving the overall efficiency of an FEL. A new electron source, the photoinjector, was developed. The source produces an extremely bright high-current electron beam, necessary for successful operation of high- and low-power FELS. The success of these programs eventually resulted in our involvement in the design of very powerful FELs for the SDI Program, funded through the U.S. Army Strategic Defense Command at Huntsville, Alabama, and White Sands Missile Range, New Mexico. Our SDI mission has been to develop the potential of FELs for ground-based, directed-energy weapons. Group AT-7's development of a photoinjector for improved FEL operation also led to a program aimed at making FELs more compact and simple to operate. Group AT-7 is also investigating an extension of the FEL wavelength range into the ultraviolet region, where there are many potential chemical and solid-state applications, as well as semiconductor processing applications.

Group AT-7 addresses many important technical issues: FEL power, efficiency, optical quality, bandwidth, reliability, optics, and high-current, high-brightness accelerators. Important advances have been made in nearly all of these areas—we have learned much about the physics and operation of FEL systems.

Advanced FEL Technology Development

Group AT-7 is responsible for the operation of two FEL facilities—the FEL at TA-46 and the photoinjector test stand at TA-53. Although AT-7 is responsible for the project management of these experimental facilities, many groups from other Laboratory divisions contribute to the experiments and assist in management as well as in facilities oversight.

The photoinjector test stand at TA-53 was used in FY 1989 to further develop the utility of laser-driven photocathode-based injectors for electron accelerators and lasertrons. The program included the demonstration of adequate photocathode lifetime and efficiency, exceptional beam quality, and drive-laser stabilization. A lasertron RF power source proof-of-principle experiment was also performed using the photoinjector beam. In FY 1991, this test stand will be expanded with a 15- to 20-MeV accelerator to demonstrate matching to an accelerator with maintenance of beam quality. An optical resonator will also be added to demonstrate a compact FEL suitable for medical applications.

Very High Brightness Electron Beams

Extremely high beam brightness, or equivalently, a very low transverse beam emittance, is possible through the use of a photoelectric injector in an accelerator structure. This possibility is partly due to the rapid acceleration to relativistic energies in which the beam is relatively stiff and no mixing of the electrons can occur. An associated benefit also needed for high brightness is that little axial expansion can occur, providing high instantaneous currents.

Simulations using the particle-pushing code PARMELA were made to study the physics of high-brightness beams, leading to a conceptual accelerator design for a compact FEL.[1] A single, on-axis coupled accelerator tank was studied, using a single external solenoid for focusing and emittance compensation. The selected accelerator frequency was 1.3 GHz, and the beam transport included an isochronous dogleg (two 10-degree bends) that displaces the beam. A quadrupole doublet focuses the beam into the wiggler. The resulting pulse length is about 14 ps, the beam current exceeds 350 A, the energy spread is about 0.5%, and the 90% emittances range from 9 to 10 πmm · mrad over most of the pulse.

Wigglers

A workshop was held at LANL on April 13, 1989, on small-period wiggler and undulator designs. Wiggler designs based on the following mechanisms were studied: microwave fields, electromagnetic coils, miniature permanent magnets, current sheets, superconductive coils, and iron-free pulsed wires.[2] The technical issues involved in each of these approaches were considered; we chose to study experimentally iron-free electromagnet drive by high pulsed currents. Such a construction allows for the high fields necessary to achieve high gains.

A series of wigglers was fabricated and experimentally measured to determine limitations on fabrication tolerances, field quality, and end effects. The results of many of these features were reported in Ref. 3. We discovered a technique of terminating the bifilar helix construction to minimize end effects on electron beam motion (see Fig. 7.1). Novel construction techniques were studied and remain part of future studies (see Fig. 7.2). These model wigglers were based on calculations performed by a summer student, who developed our ability to use 3-D magnet codes in this area. Students also performed simulations, using a circuit analysis code, on pulsed-power supplies used to drive such wigglers.

Analytical studies of the effects of construction limitations on the electron-beam motion were carried out in conjunction with this experimental program. References 4 to 6 provide details of these analytical studies.

High-Brightness-Accelerator FEL

In FY 1988, experiments on the FEL at TA-46 at 10 μm demonstrated sideband-suppression techniques, high-efficiency operation, harmonic content, and simulation comparison of mode-media effects. In FY 1989, an upgrade of the FEL facility was started with the addition of a photoinjector (see Fig. 7.3). In FY 1990, two more accelerator tanks and another wiggler will be added, so that master-oscillator power-amplifier experiments can be performed at wavelengths as short as 3 μm. The completed upgrade allows HIBAF to produce a beam that is significantly brighter and of higher quality throughout the entire laser spectrum,

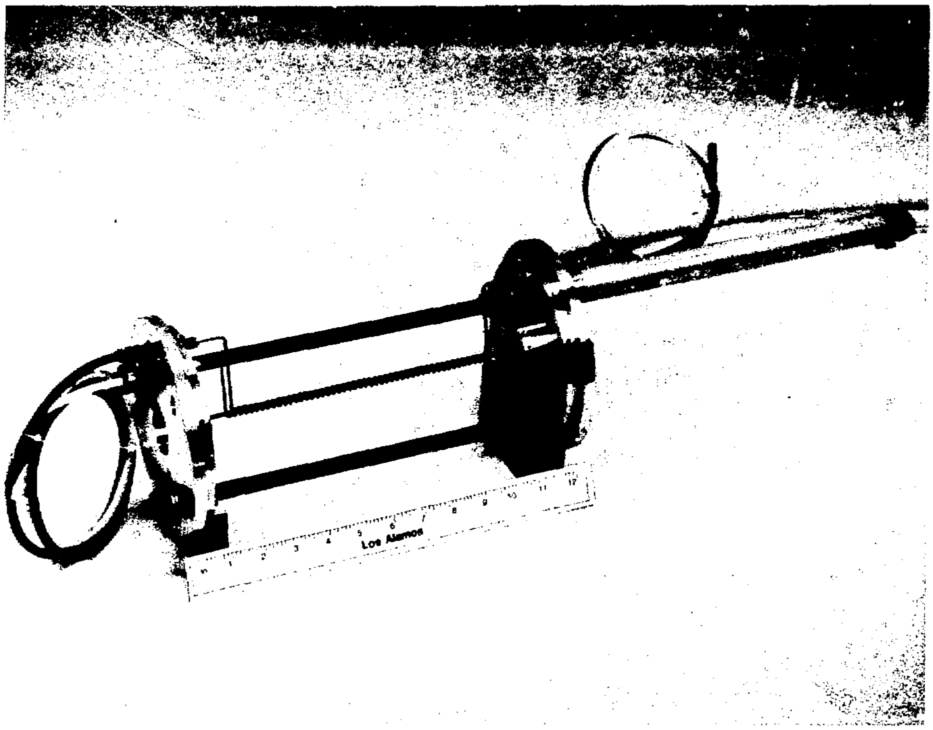


Fig. 7.1 Double-crossed helix microwiggler.

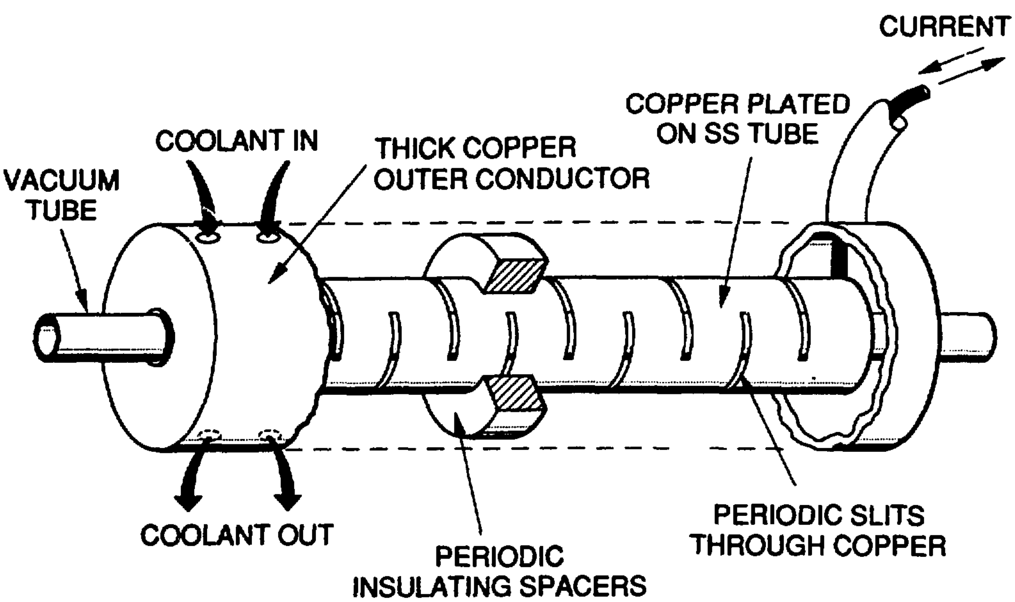


Fig. 7.2 Cross-helix microwiggler.

thus bringing us closer to meeting the needs of SDI for high-power, GBFELs.

The integrated numerical experiment (INEX) group of codes provided much of the theoretical information we used to redesign the HIBAF. Using INEX as a design tool for the facility upgrade also gave us an opportunity to validate INEX predictions once the facility upgrade was complete.

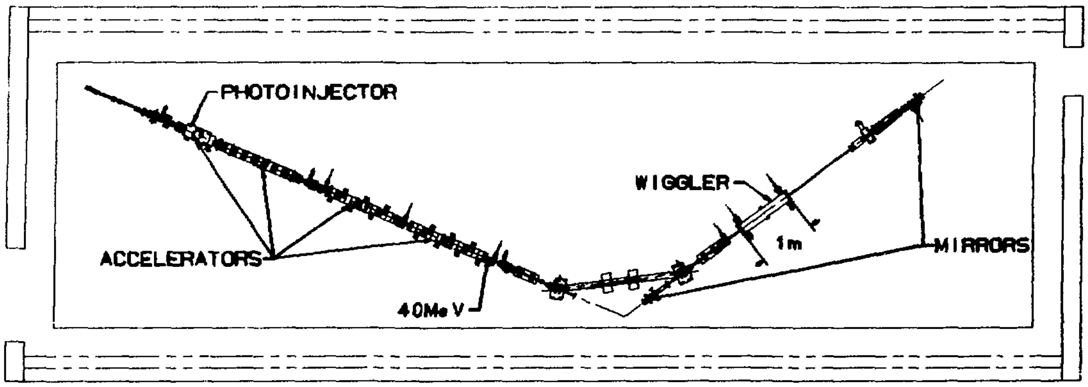


Fig. 7.3 *Los Alamos* HIBAF Facility.

Group AT-7 dismantled the FEL in December 1988 and implemented a schedule for accelerator commissioning to begin in the first half of 1989. Because temporally and spatially uniform density pulses are required for optimal beam quality from a photoinjector, we performed preliminary tests of the photoinjector drive laser. These tests produced temporally square, 15-ps pulses.

Removal of old equipment at the TA-46 laser laboratory was completed in February, and renovation of the laboratory began. The photoinjector was installed and aligned in April, and installation of the drive-laser transport line began. The laser oscillator was operated in the new facility at full power (into a calorimeter) in mid April.

The upgraded facility produced its first electron beam in June. We produced and transported approximately 0.25 nC per pulse of electron beam to the beam stop, a beam current one-twentieth of the design current of HIBAF. Although failure of a solenoid magnet power supply prevented a full-power demonstration, the test verified preliminary system operation.

In July, the HIBAF attained a micropulse electron charge of 5 nC, meeting its design specification, with acceleration to 17 MeV in the first two accelerating sections.

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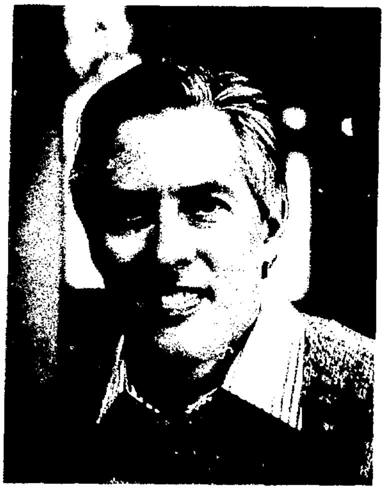

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Introduction

The Accelerator Controls and Automation Group provides control systems for AT Division projects like GTA and for other large projects that need computer controls systems like the Free-Electron Laser with Boeing and the Advanced Photon Source at Argonne National Laboratory. The AT-8 control-system design uses advanced software tool concepts to greatly reduce the amount of programming required to implement a control system. We also employ VME- and VXI-based computers and interfaces with the VxWorks real-time operating system to provide high-performance controllers to run our software tools. The result is a control system that is powerful enough to support full automation and easy to implement with lower costs than any accelerator control previously available.

Experiment 1 Controls

GTA Source

The source presently installed on the GTA injector is under regular operation with the GTA control system (Figure 8.1 shows a GTA injector control screen). Beam was extracted into a Faraday cup under computer control system.

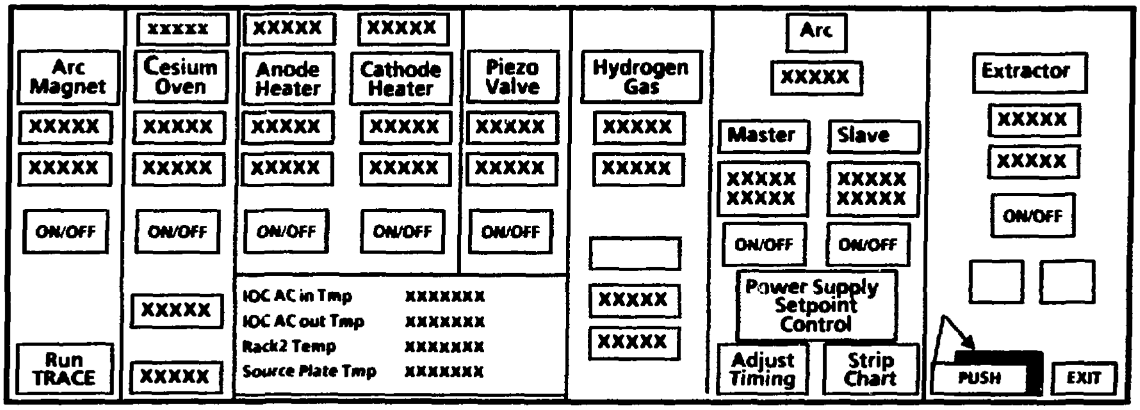

Fig. 8.1 GTA injector control screen.

The injector system ran very well (35-KeV beams at 0.5% duty factor with beam current up to 80 mA) for the SDIO overview open house. A video-image display was set up to observe the beam image in the LEBT as reflected on a fluor screen. Operators were able to focus the beam with changes to the solenoid magnet current and observe the beam on a viewing screen. The extractor is also under computer control. From the operator interface, one can control the extractor pulse width and delay, the slope of the ramp, and the amplitude.

ATS Support

Progress on a control algorithm for the ATS ion source continued. Although the identification of tune conditions seemed somewhat erratic, the algorithm appeared to be working with just minor problems. We continued to monitor waveforms from the ATS injector on a daily basis to understand the problems in the instrumentation.

Studies of the Van der Pol (VdP) equation as it applies to ion-source modeling continue to demonstrate progress. We can generate anomalous waveform behavior seen from the ion source numerically by manipulating the parameters of the Van der Pol equation.

Several engineering changes were made to the instrumentation on ATS to improve the controllability. We provided new fiber optic drivers and receivers, new calibration signals, and recalibrated transient digitizers for arc voltage and current; we replaced a bad digitizer on the high-speed link from the Faraday cup; and we continued to encourage use of the grounded snubber.

Injector Vacuum Controls

The LEBT vacuum equipment, Allen-Bradley chassis, and junction box were installed in Building 18 at TA-53. All racks and input/output controllers (IOCs) were positioned as they are planned for MPF-365. Vacuum control screens (see Fig. 8.2) are complete. It appears vacuum controls can be implemented without additional applications codes, although sequences will be required to implement interlocks. An Allen-Bradley Redi-panel will be used for manual control of certain valves and actuators and has been tested with the software.

GTA Cooling System Controls

The design of the cooling control system was completed. A test setup was established for checking the temperature ranges of the Scientific Instruments diodes to be used in the cryogenic cooling system. Once the temperature ranges are verified, the diodes will be connected to check their accuracy through the control system. CVI's plan to install the cooling controls uses Allen-Bradley Programmable Logic Controllers (PLCs). The procedure for PLC to IOC communication is under study. We have specified that CVI program the ladder logic control software for the cryogenic cooling system in the adapter mode so it is compatable with GTA controls.

RF Controls

We successfully demonstrated the integrated GTA control system running GTA RF hardware powering the Cryo-DTL installed on the ATS. The 1-MW klystron was remotely controlled and the software closed the control loop to keep the cavity on resonance. The Q of the cavity was measured at high power with the control system using the Smith chart display of reflection coefficient. This is the first time that Q measurements have been taken under software control. The cavity was 80% beam-loaded—the GTA specification. The field controller—phase and amplitude—was

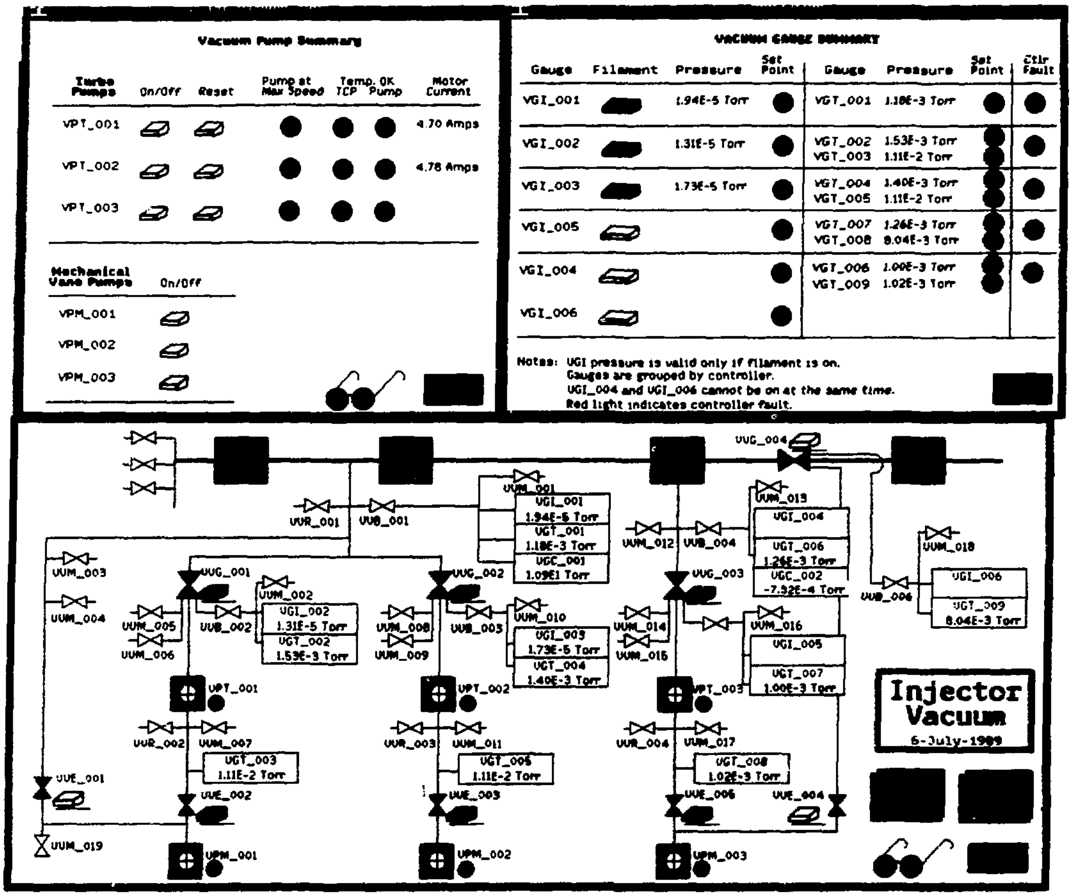

Fig. 8.2 Injector vacuum control screens.

under supervisory control. Phase was controlled within one degree and the amplitude was kept to within 1%.

Magnet Mapper Controls

Quadrupole Mapper

A users guide for the quadrupole mapper was written. An evaluation of the large-bore GTA quadrupole mapper requirements revealed that the same motor driver software can be utilized with minor changes for position limits as is used for a small-bore quadrupole mapper. We completed the required software and motor drive electronics for the large-bore GTA quadrupole mapper mockup.

Solenoid Mapper

A senior engineer from ANL joined the Controls and Automations Group for several months in support of a software exchange program arranged between ANL and LANL. Within one month he generated and validated the database for the solenoid mapper using the GTA control system.

Integrated tests of the mapper software with the motor validated required operational performance and data retrieval. Top-level documentation of the software was provided.

ATS Funnel Diagnostics Controls

D-plate

We completed the phase-scan window software coding and testing associated with the microstrip measurements. The microstrip system was validated. The considerable benefit of the phase-scan process was demonstrated; it reduced the test and analysis from half a day to 5 min. Toroid and Faraday cup diagnostic devices were integrated and made available to funnel operation.

M-plate

The sample-and-hold electronics for all M-plates were assembled and tested. We completed integrated functional tests of all microstrip electronics with the corresponding software. The collimator and steering magnet position control software was tested with a multiple-prototype motor set and the stepper motor database.

IOC Development

GTA Timing System

Good progress was made on the IOC timing hardware subsystem. Computer-aided design packages were completed and printed circuit boards were delivered for several devices, including the VME oscillator/trigger/clock interface, the VME coaxial transition module, the VME fiber-optic timing transmitter, the fiber-optic timing receiver module, an ac line synchronization module, a line synchronization counter, an optical clock fan-out module, an optical clock trigger/receiver, and a dual coaxial four-channel fan-out module. Production versions of several modules types were completed and are in use on the ATS funnel IOCs and the GTA injector IOC.

Injector IOC

The remote Allen-Bradley hardware for the first rack in the high-voltage dome was installed and is fully operational. The first rack includes controls for the arc magnet power supply, the cesium oven power supply, the anode heater power supply, the cathode heater power supply, the piezovalve power supply, the hydrogen flow controller, and the nitrogen flow controller.

Allen-Bradley controls were installed and tested for the third equipment rack in the injector high-voltage dome. Included are the interface for the 40-kV extractor power supply and thermocouples for the anode, cathode, source plate, cesium oven, cesium valve, and cesium feed tube.

Fast Analog Fiber-Optic Link

Group AT-8 evaluated commercial devices for GTA subsystem applications requiring isolated high-bandwidth analog signals. The production version of a transmitter with built-in calibration was tested and installed on ATS for field evaluation. A prototype production version was successfully demonstrated in the laboratory environment.

LEBT IOC

Fabrication on the vacuum controls for the LEBT was started. We decided to place the LEBT controls on a separate IOC during commissioning. When the LEBT/injector is operational, the two IOCs will be combined.

RFQ IOC

A preliminary RFQ IOC hardware design was completed. The RFQ IOC will be the first GTA IOC to incorporate cryogenic temperature measurement using silicon diode temperature sensors. A series of tests was planned to determine if the existing IOC voltage monitoring (analog input) hardware provides the accuracy necessary for the specified cryogenic temperature range.

IOC Enclosure Security Upgrade

The design of the standard RFI-shielded enclosure for the IOC was modified to meet the requirements of OS Division in preparation for secure operation of the GTA injector. Two IOCs were upgraded and inspected by OS Division and are operating on the secure network.

GTA Stepper Motor Standardization

We have developed a project standard for motion control components for use on GTA. We are evaluating a multichannel VME-bus motor indexer and phase driver hardware for use with the standard motors.

System Software Development

Several enhancements to the system software were made during the year. Enhancements included addition of trigonometric functions to database calculation records; modification of the Database Configuration Task to handle new devices; addition of a proportional, integral, differential (PID) record for closed-loop feedback control; more effective software release control; implementation of multibit binary input/output (I/O) through the Allen-Bradley hardware; error reporting through the database for most drivers; and multiplexing of stepper motor drivers. Performance was also improved through database improvement, driver changes, and an improved hashing algorithm.

Other improvements to the system software include improved error reporting, performance enhancements, and additional automation of software configuration control.

Computer Network

The AT Division "Q" network was installed and is now functional. The "L" network was extended from MPF-31 to MPF-18, -19, and -409 and is in the process of being extended to the new building MPF-365. The open portion of the network in MPF-365 is already functional.

Free-Electron Laser Project

The GTA control system was selected for use on the Ground-Based FEL project. Funding for this project was awarded to the LANL/Boeing team after a competition with a team from LLNL/TRW. The control system is an important part of the FEL LSS, for check-out of subsystems during installation, commissioning of the laser facility, and automatic startup and tuning during operation. Boeing chose to use the expertise and technology developed by AT-8 as the cornerstone for the LSS control system. The Los Alamos Accelerator Control System uses standard hardware and software components that are highly modular and flexible and will easily adapt to the LSS. For instance, a software "Toolkit" facilitates early prototyping, standard development practices, and rapid response to changing requirements during system integration. A few color graphic computer display consoles in the control room of the LSS replace numerous control panels usually required for an installation in this complex. Display screens can be created or modified in minutes without rewiring the facility. Accelerator automation studies performed at LANL in conjunction with the University of New Mexico will help reduce the time to get the LSS operational. By specifying the Los Alamos Accelerator Control System, Boeing is able to use proven technology, thus minimizing risk and cost to the project, which is under a tight schedule. A model of the computer hardware and preliminary copy of the control software were shipped to Boeing for early testing.

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Introduction

Group AT-9, High-Power Microwave Sources and Effects Group, was formed in August 1988 to perform research, development, and testing of very-high-power microwave systems. These systems include microwave generators that have peak output powers in the 0.2- to 10-GW regime and that extend linear accelerator technology beyond the current state of the art. The primary goal of AT-9 is to develop the microwave sources and systems required to meet Department of Energy (DOE) and Department of Defense (DoD) requirements. The DOE requires innovative microwave sources to power advanced accelerators such as the tera-electron-volt (TeV) electron-positron collider, which is the next generation accelerator beyond the SSC that is presently beginning its construction phase. Many thousands of gigawatts of microwave power will be required by these accelerators to produce the particle beam that will probe the fundamental forces of the universe.

The DoD is concerned with the presence of microwave weaponry on the tactical battlefield of the future. The issues to be considered here are the effects of high-power microwaves (HPMs) on strategically important electronic systems. In this age of microelectronics, conventional weapons have become much smarter and more accurate because of the ability to place progressively more computing power on the weapons platforms. However, the electronics in these weapons are much more sensitive to upset and burnout when irradiated with microwave energy, thereby causing the system to fail in its mission. Group AT-9 is chartered with building the HPM systems and is working on advanced microwave weapon concepts.

Group AT-9 is developing several different types of HPM sources for various applications. These include the large-orbit gyrotron, both the virtual cathode oscillator and virtual cathode amplifier, and the relativistic klystron amplifier. Work is also in progress that is advancing the state of the art in pulsed power modulator technology.

Development of a High-Intensity Single-Pulse Microwave Source

This effort is directed toward doing the research and development necessary for building a portable microwave source in the gigawatt class. The microwave source uses a virtual cathode surrounded by a resonant cavity to produce an intense, very narrow band, microwave output.

Two major accomplishments have been achieved with this microwave source. The virtual cathode oscillator, typically a wide-bandwidth oscillator with very poor frequency stability, has been made to operate as a frequency-stabilized source. Second, the virtual cathode source has been demonstrated for the first time to operate as an amplifier. The significance of amplifier operation is the potential for a parallel array of virtual cathode amplifiers that are frequency- and phase-locked for higher output power than could be obtained in a single device.

A cylindrical cavity resonator is used; the microwave power is extracted radially through circumferential slot apertures into the waveguide. The interaction of the electron beam and the cavity produces strong feedback between the induced cavity field and the oscillating virtual cathode, forcing it to lock to the resonant frequency of a cavity mode over a 70% variation in electron beam current. This configuration (virtual cathode/resonant cavity) results in a 3-dB bandwidth of less than 1%, a dramatic reduction compared with that of a free-running virtual cathode microwave source. The bandwidth appears to be limited by the finite temporal width of the microwave pulse that is about 100 ns. As the electron beam pulse is lengthened, the bandwidth of the microwave pulse should correspondingly narrow.

The virtual cathode source has been demonstrated to operate as a microwave amplifier when the virtual cathode is surrounded by a resonant structure that is driven by a low-power signal. The output frequency from the device is locked to the input signal frequency. Although the observed gain is relatively low for a practical microwave device, there has been no attempt to optimize the gain and the output power. The measured microwave output power was 24 MW, with a gain of 4.5 dB.

LANL-Supported Program Development in the Microwave Source Area

Group AT-9 supported the Laboratory's Microwave Source Program Development initiative with work on the Large-Area Resonant-Cavity Vircator and on the relativistic klystron oscillator and amplifier (RKO/A). Both projects are interdivisional efforts.

Large-Area Resonant-Cavity Vircator

The basic idea behind the large-area vircator is to use a large-diameter cathode in order to reduce the current density to a level low enough that electron beam diode closure is eliminated in a microsecond-long pulse. Diode closure, or shorting, is produced when plasma is formed on the anode because of electron beam bombardment and then flows toward the cathode, eventually shorting the anode/cathode gap.

A 3-ft-diam cylindrical cavity operating in the TM_{011} mode at 800 MHz was built. Output power was extracted through four WR-975 waveguide ports. Because a high-voltage pulser with a microsecond output was not currently available at LANL, the experiment was performed on the Long Pulse Experiment (LPX) pulser at Sandia National Laboratories.

Although the data are still being analyzed, several important results emerged: the electron beam diode functioned on the microsecond time scale, and the virtual cathode source demonstrated single-frequency operation during the pulse. Because of the short time available to do the experiment, we were not able to optimize the output power by adjusting the output loading.

Relativistic Klystron Oscillator and Amplifier

This effort has concentrated on the design and fabrication of the RKO structure as well as on fielding the device on the BANSHEE pulser at AT-9. This effort has been conducted in collaboration with the Shock Wave Physics Group (M-6) and the Pulsed Energy Applications Group (X-10).

The RKO consists of three main components: (1) the input cavity where the beam begins to bunch (in the amplifier version of the RKO [the RKA], this cavity is driven by a low-power microwave source); (2) one idler cavity that serves to enhance the bunching or depth of current density modulation on the beam; and (3) an output coupler for extracting the microwave power from the fully modulated electron beam. Also some type of electron gun must be provided, which in the first experiments is a foil-less diode. The RKO has been conservatively designed with the philosophy that we would stay close to the design parameters reported in recent experiments by Moshe Friedman of NRL. These experiments were very successful, but his technique for microwave power extraction was unsuitable for most practical applications. Consequently, we have concentrated our design effort on developing a better method for coupling power out of the structure.

Group AT-9 has responsibility for the overall microwave design of the RKO/A device. The input and idler cavities have been designed using the cavity electromagnetic design code SUPERFISH. With this code we could look at the effects of beampipe diameter and cavity gap spacing on the ratio of gap field to field on axis, cavity shunt impedance, and frequency. Also carefully examined were techniques for tuning the cavities, one of which has been incorporated into the design. The microwave design of these two cavities was completed and turned over to Group M-6 for mechanical design and fabrication.

Group AT-9 assumed the responsibility for both the microwave and mechanical design and the fabrication of the output coupler, the component that is used to extract the microwave power from the bunched electron beam. An informal design team comprising two staff members from AT-7 and AT-5 who have extensive experience in the design of microwave power tubes and AT-9 personnel resolved the design issues associated with the output coupler. The design that evolved uses a nonresonant output coupler consisting of a reduced-height rectangular waveguide placed broadside across the beamline. The reduced height provides for a better impedance match to the bunched electron beam and a correspondingly higher extraction efficiency. This waveguide will then taper up to a full-height waveguide enabling us to use all of our conventional waveguide diagnostics. The advantage of this approach is twofold: (1) the power is produced in the waveguide in the dominant mode that can very easily drive an antenna with a good radiation pattern or an accelerator, and (2) power measurements are not ambiguous because of the dominant mode operation and the availability of well-established diagnostics and measurement techniques. The design and construction of the output coupler are complete.

The RKO has been installed on the BANSHEE, our 1-ms high-voltage pulser, and experimental development of this high-power microwave source has just begun.

Large-Orbit Gyrotron Development

Work continued to develop a large-orbit gyrotron RF source for the Navy's HPM 8-GHz testing program. Experiments demonstrated 30 to 50 MW of RF power at 2 GHz (see Fig. 9.1). The conversion efficiency of 7% to 10% is comparable to that achieved by other laboratories. Further increases in power can best be achieved by increasing the current that is injected into the gyrotron.

To this end, we have invoked sophisticated theoretical modeling of the device to guide an advanced, higher-power design. To bring the RF to the radiating antenna, we have explored three schemes to couple the RF into the rectangular waveguide. The pulsed power modulator being built by Texas Tech University was delivered uncompleted in August 1989 and requires additional effort by LANL personnel to become operational.

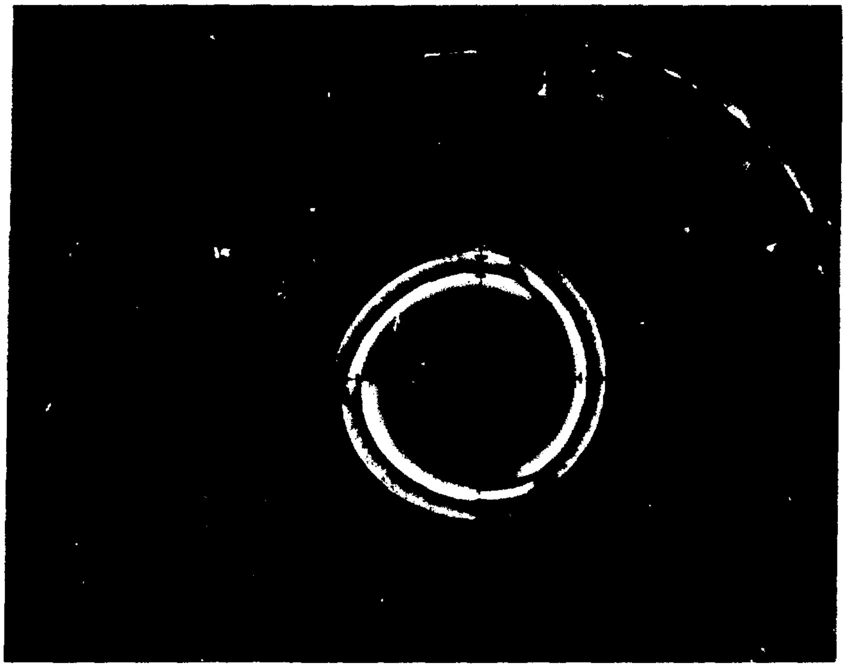

Fig. 9.1 Rotating electron ring in a large-orbit gyrotron HPM generator.

Work at a higher frequency, nominally 8 GHz, was begun in August. This work at the higher frequency is in the early stage of development. Issues we will address next in developing a source for implementation include (1) implementing an electron beam diode that will optimize the beam trajectory within the gyrotron resonator to provide high efficiency in the conversion of electron beam power to microwave power and (2) developing a technique to extract RF power from the source into waveguide for subsequent transmission to an antenna or accelerator load.

Field Emission Diode

We have made major progress in diode development by computationally finding an optimum design. During the second quarter of this year, we undertook an effort in collaboration with Rick Faehl (X-10) and Bruce Carlsten (AT-7) to perform a calculational design for such an advanced vacuum diode. They utilized particle-in-cell computer modeling to track the trajectories of electrons emitted from cathodes having arbitrarily complex shapes. The computer codes allow us to consider unusual vacuum diode designs for future experiments. Such design capacity allows us great control over the accurate positioning of the electron beam in the gyrotron. This optimization can allow a maximum conversion efficiency of electron beam energy into microwaves.

The approach first entailed a technique developed by the Soviets called synthetic design. This technique involves defining a desired trajectory in the gyrotron structure, and, by working backwards in time, marking the trajectory an electron beam will follow back to the cathode. This technique has indicated the cathode position needed to launch the electron beam along the desired trajectory. Once this position is identified by synthetic design, conventional modeling of the trajectories of the electrons launched from the cathode (with time advancing in the forward direction) was used to explore alternative cathode shapes surrounding the emitting region. This electrode shaping is a method of fine control of the paths the electrons follow in accelerating toward the anode.

A cathode shaped as a concave cup is shown to best guide the electron beam into the gyrotron, where the beam skirts the inner wall of the resonant structure for the entire length of the gyrotron. This computational design effort essentially is completed, and we are preparing to field hardware based upon the design.

Microwave Output Extraction Structure

Three techniques have been investigated for power extraction from the 2-GHz gyrotron. The simplest has been to allow the RF to radiate from the end of the resonator. Although this approach has yielded the largest extracted power levels, 30 to 50 MW, the radiation pattern is very complex and not suited to coupling to waveguide or a high-gain antenna. The second approach has been to couple RF from the wall of the resonator into the sidewall of rectangular waveguide through an iris. This approach has not coupled much power to date, and a more careful study of the modes in the structure is needed to understand the reason. The third approach has been to cap the downstream end of the resonator with a copper plate in which three radial irises have been cut. Each iris crosses the resonator slot in the radial direction and couples RF into rectangular waveguide running axially. This approach coupled slightly more RF than the side wall design but still requires improvement to approach the RF output that we can produce by axially extracting into free space with no output structure or waveguide.

Pulsed Power

A more fundamental component of the RF system is the electrical pulsed power modulator that drives the RF source. The pulsed power for the microwave sources we are developing extends existing modulator technology into the kiloampere, megavolt regime.

We have started a program for a portable pulser with 650-kV, 3-kA, 150-ns, 10-Hz pulses. This modulator was built for us by a group at Texas Tech University through a subcontract. We hope that we can make the modulator suitable for our effort within the next three to six months and can then integrate the unit into the microwave source development effort. This integration will help us in two ways. First, it will give us a much faster data acquisition rate for RF source development and optimization, speeding our progress. Second, it will provide us with the proper electrical pulse waveform for best operation of the gyrotron. This better pulse shape should enable us to improve the performance of the source, compared with the waveform we have available using our existing test-bed.

BANSHEE Modulator

BANSHEE is a pulsed power modulator designed to deliver 1-MV, 10-kA, 1-μs pulses at a 5-Hz repetition rate to drive electron beam diodes on high-power microwave sources (see Fig. 9.2).

Fig. 9.2 The BANSHEE pulsed power modulator showing pulse-forming networks and switching thyratron producing 10-GW electrical pulses.

BANSHEE is presently operating in a single-shot mode. The peak output has been ~7 kA at ~700 kV with a flat pulse section of 890 ns into a resistive load. This system incorporates four lumped constant Blumleins switched by a pressurized spark gap. The Blumleins' output drives a 10:1 step-up pulse transformer that provides up to a megavolt output. The unit, using only two Blumleins, had previously produced output at 315 kV, ~2 kA at a repetition rate of 1 Hz using a large thyratron tube as the switch. In the repetitive pulse mode, the Blumleins are command-charged resonantly using another thyratron. Technical problems with the thyratron switches, which are still under development by English Electric Valve (EEV) for SDIO, have necessitated using the spark gap switch temporarily. As soon as new tubes arrive from EEV, we will resume repetitively pulsed operation.

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Glossary

AHF	— Advanced Hadron Facility
ANL	— Argonne National Laboratory
APT	— accelerator production of tritium
ASD	— Accelerating Structure Development
AT	— Accelerator Technology
ATN	— accelerator technical note
ATP	— acquisition, tracking, and positioning
ATS	— accelerator test stand
BEAR	— Beam Experiment Aboard a Rocket
BNCT	— boron neutron-capture therapy
CCL	— coupled-cavity linac
CCTB	— cryogenic component test-bed
CEBAF	— Continuous Electron Beam Accelerator Facility
CERN	— European Center for Nuclear Research
CFS	— Central File System
CREOL	— Center for Research on Electrical Optics and Lasers
CRU	— computer resource unit
CTSS	— CRAY time-sharing system
CWDD	— continuous-wave deuterium demonstrator
cw	— continuous-wave
DARHT	— Dual-Axis Radiograph Hydro-Test
DCL	— Digital Equipment Corporation (DEC) command language
DoD	— Department of Defense
DOE	— Department of Energy
DTL	— drift-tube linac
DTS	— discharge test stand
e-p	— electron-proton
EEV	— English Electric Valve
ERAB	— Energy Research Advisory Board
FD	— focusing-defocusing
FEL	— free-electron laser
Fermilab	— Fermi National Laboratory
FGA	— four-grid analyzer
GBFEL	— Ground Based Free-Electron Laser
GTA	— Ground Test Accelerator
HCTS	— high-current test stand
HEBT	— high-energy beam transport
HIBAF	— High-Brightness Accelerator FEL
HPM	— high-power microwave
HPCTB	— High-Power Cryogenic Test Bed
IFMIF	— International Fusion Materials Irradiation Facility
IMS	— intertank matching section
INEX	— integraded numerical experiment
I/O	— input/output
ID	— inside diameter
IOC	— input/output controller
ISRD	— Institutional Supported Research and Development
ISTS	— ion-source test stand
LAACG	— Los Alamos Accelerator Code Group
LAMPF	— Clinton P. Anderson Meson Physics Facility
LANL	— Los Alamos National Laboratory

LBL — Lawrence Berkeley Laboratory
LEBT — low-energy beam transport
LEP — large electron-positron
LHe — liquid helium
LINAC — linear accelerator
LINDA — laser-induced neutralization diagnostic approach
LLNL — Lawrence Livermore National Laboratory
LPX — Long Pulse Experiment
LSS — laser subsystem
LVDT — linear variable differential transformer
MCTD — Modular Concept Test Development
MPF — Meson Physics Facility
NMFECC — National Magnetic Fusion Energy Computer Center
NO — nitric oxide
NPB — neutral particle beam
NRL — Naval Research Laboratory
OPI — operator interface
OS — Operations Security & Safeguards
PFN — pulse-forming network
PID — proportional, integral, differential
PLC — programmable logic controller
PMQ — permanent-magnet quadrupole
PR&T — professional research and teaching
PSR — proton storage ring
R&D — research and development
REC — rare-earth cobalt
RF — radio frequency
RFI — radio-frequency interference
RFQ — radio-frequency quadrupole
RG — ramped-gradient
RGDTL — ramped-gradient DTL
RKO/A — relativistic klystron oscillator and amplifier
SAMOPA — Single Accelerator Master Oscillator Power Amplifier
SDC — Strategic Defense Command
SDI — Strategic Defense Initiative
SDIO — Strategic Defense Initiative Organization
SSC — Superconducting Supercollider
TeV — tera-electron-volt
TRIUMF — Tri Area University Meson Facility
TSD — through short delay
TM — technical memo
UFT — ultrafast track
VdP — Van der Pol
VL&E — vulnerability, lethality, and effects
VME — Versa Module European
VUV — vacuum ultraviolet
WSMR — White Sands Missile Range
YAG — yttrium aluminum garnet
XUV — extreme ultraviolet

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