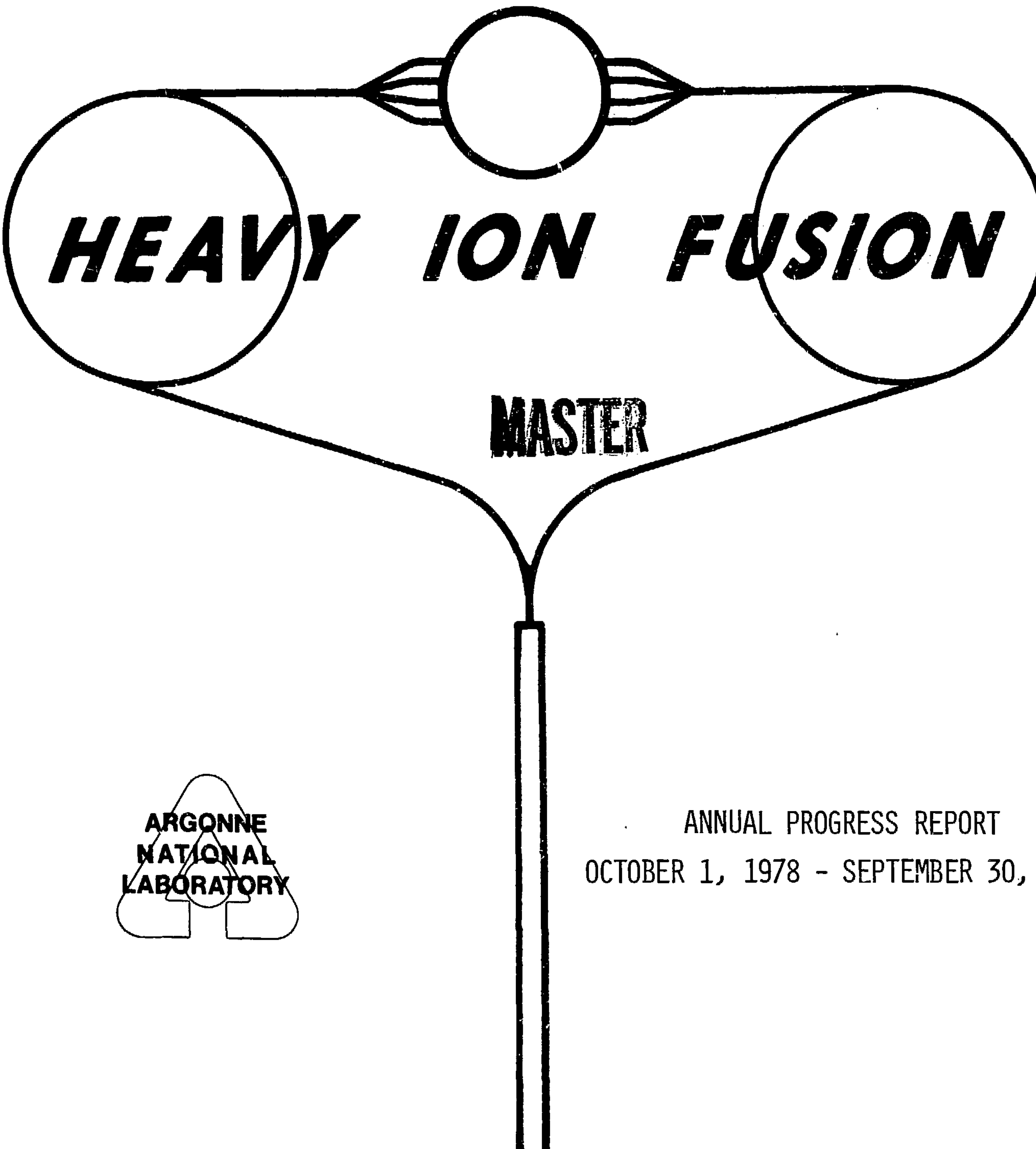
ANL-HIF-80-1

HEARTHFIRE



ARGONNE NATIONAL LABORATORY

ANNUAL PROGRESS REPORT

OCTOBER 1, 1978 - SEPTEMBER 30, 1979

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HEAVY ION FUSION PROGRAM

ARGONNE NATIONAL LABORATORY
ACCELERATOR RESEARCH FACILITIES DIVISION

TABLE OF CONTENTS

I. Introduction

At the end of FY 1978, the HIF community had reached a consensus on the status of adapting HEP accelerator technology to drivers for ICF. This consensus was expressed in the overview section of the 1978 HIF Workshop at ANL.

The four conceptual accelerator designs presented to the workshop participants were: a 10 MJ, 200 TW linac-accumulator system with U^{+2} (BNL); a 1 MJ, 160 TW linac-accumulator system with Hg^{+8} (ANL); a 1 MJ, 160 TW synchrotron-accumulator system with Xe^{+8} (ANL); and a 1 MJ, 160 TW induction linac system with U^{+4} (LBL).

Specific comments were made on each of the conceptual designs and are contained in the report of the Reference Design Committee. General conclusions were as follows:

1. High confidence was expressed in the feasibility of the linac-accumulator system.

2. Considerably lower confidence was accorded to synchrotron-accumulator systems. This rating is based on the seemingly more complex beam manipulations required, the greater technical difficulty (i.e., the vacuum system), and the possibility of unfavorable charge changing cross-sections. The cost advantage of synchrotron acceleration over linear acceleration for this application has also proven to be less than originally anticipated.

3. Induction linacs are attractive because of the simplicity of the required beam manipulations. The acceleration of ions, however, has yet to be demonstrated; and more R&D is required to prove their practicality for this application.

The immediate task for the community at that time was to prepare a coherent, affordable technology development program for the next few years, preparatory to a later HIDE.

ANL's response was the proposal of our Phase I, a 10 kJ Accelerator Demonstration Facility, which was powerful enough for initial physics experiments, as pictured in Figure I.1. The concept was presented to D.O.E./ASDP in December 1978, and to D.O.E./OLF in January 1979. A conceptual design report was prepared in May 1979 and presented (at a review of ANL's program on May 14) to D.O.E./OIF. Excerpts from that report are reproduced here in Section IV.

A second less detailed program step, to a (HIDE) facility of $\gtrsim 100$ kJ for significant-burn target experiments, was also proposed and labeled Phase II, as shown in Figure I.2.

The 1979 Foster panel review of ICF recommended a vigorous program in HIF, beginning with smaller scale ($25 M) accelerator demonstration facilities at ANL and LBL. To meet that criterion, we developed our "Phase Zero" plan, also described in the Phase I design report excerpt; it was called "minimal RFL R&D" there.

Considerable effort took place in FY 1979 to involve industrial firms in the early HIF Program steps such as Phase I.

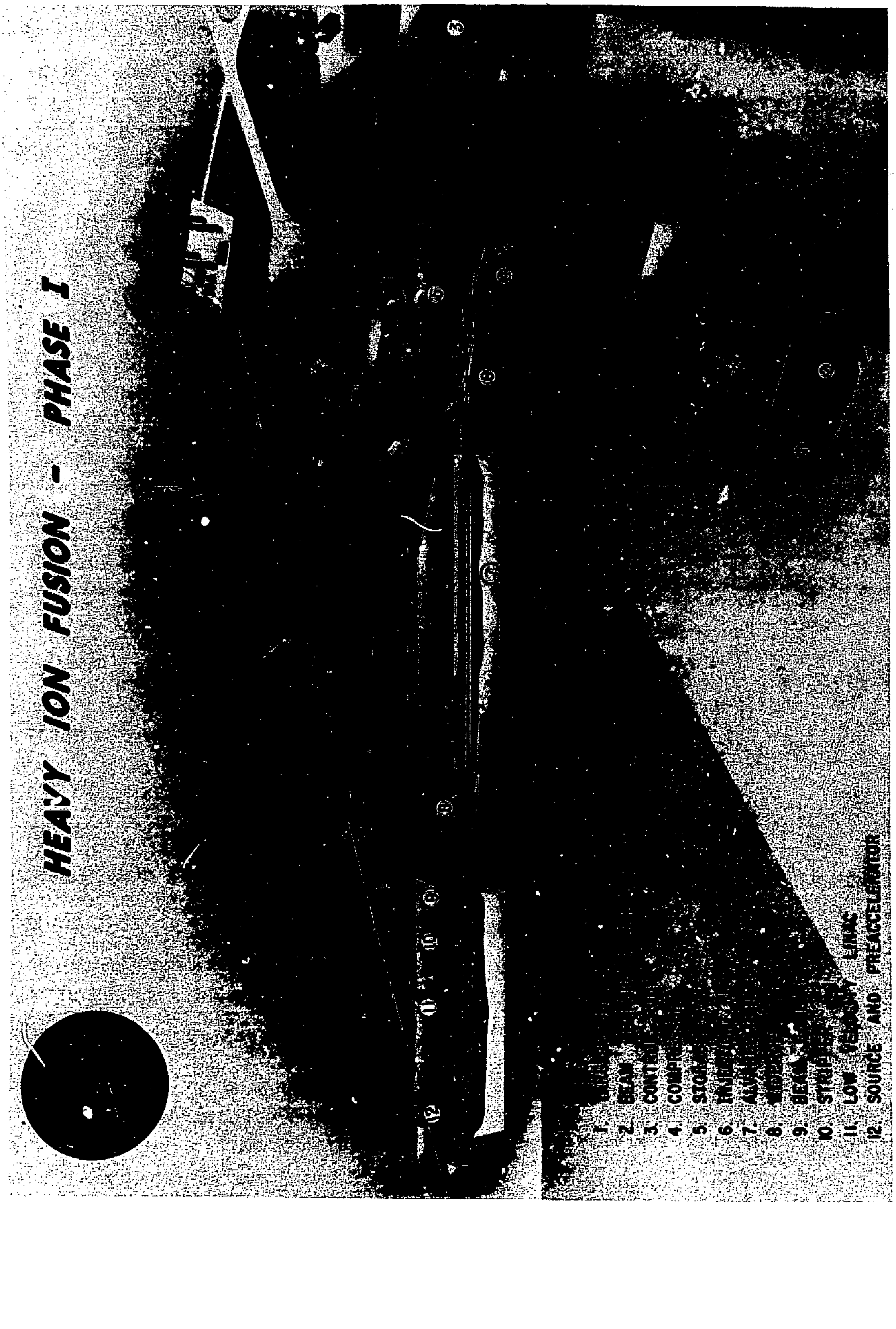

FIGURE I.1

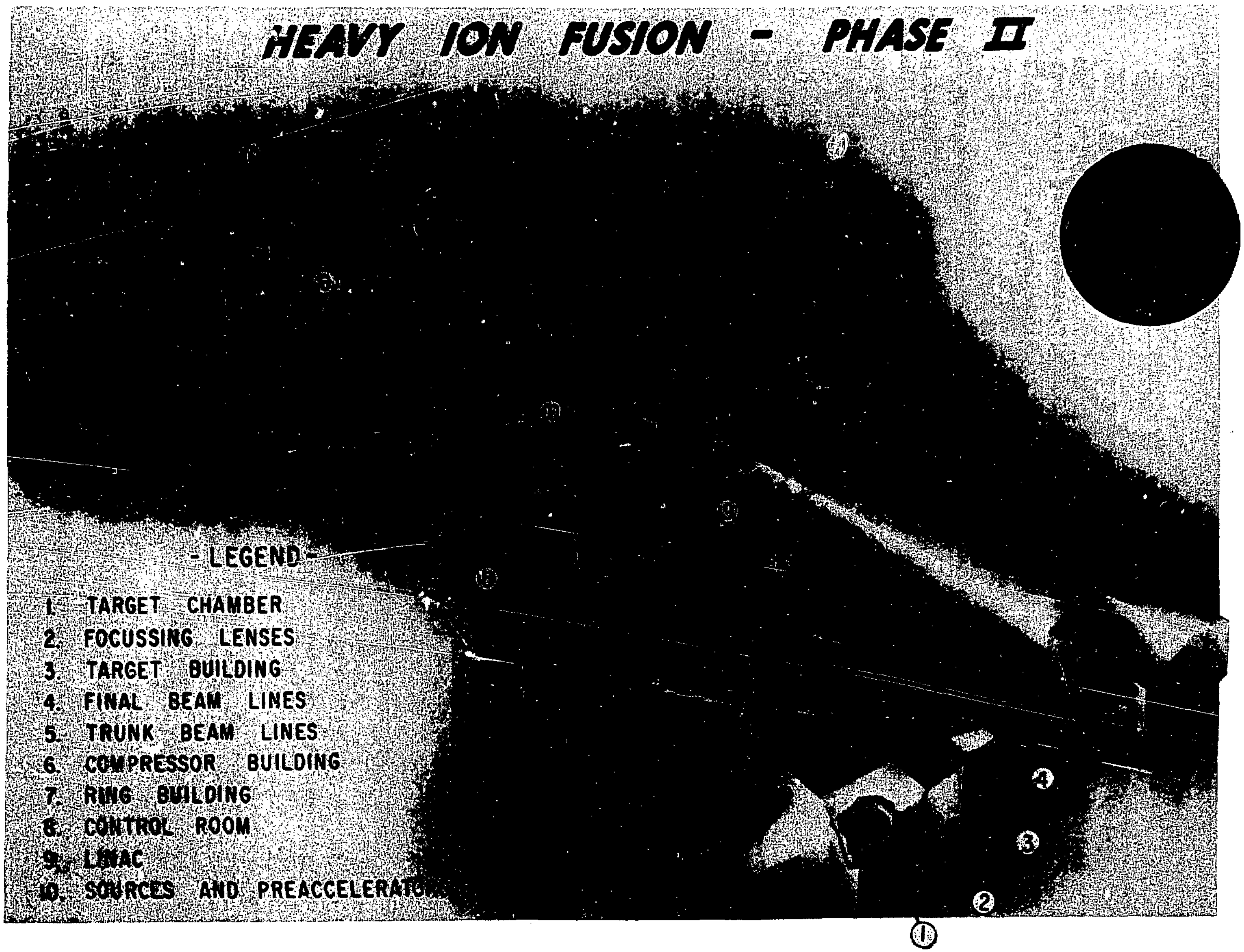
HEAVY ION FUSION - PHASE II
- LEGEND -
1. TARGET CHAMBER
2. FOCUSSING LENSES
3. TARGET BUILDING
4. FINAL BEAM LINES
5. TRUNK BEAM LINES
6. COMPRESSOR BUILDING
7. RING BUILDING
8. CONTROL ROOM
9. LINAC
10. SOURCES AND PREACCELERATO
1
2
3
4

FIGURE I.2

II. Conceptual Design and Program Planning

On October 2, 1979, ANL held an open briefing for industries concerning our planned HIF program, inviting their participation. A dozen firms responded, and several of these followed up with specific initiatives for future collaborative effort, including Hughes Aircraft, McDonnell-Douglas, Maxwell Laboratories, Rocketdyne, Westinghouse, KMS Fusion, and Burns and Roe.

On October 16, ANL representatives visited D.O.E.'s Office of Laser Fusion to describe informally our new initiatives toward a heavy-ion demonstration facility smaller than HIDE but capable of some significant target interaction experiments. We received warm encouragement to continue the design of this facility.

During November the preliminary specifications were developed for Phase I, and in December a short briefing was given to D.O.E./ASDP on our proposed program initiative. In January a more detailed presentation was given to D.O.E./OLF.

Our conceptual design work during FY 1979 shifted emphasis in response to the abandonment by D.O.E. of the HIDE plan. The clearest feature of the new guidelines was that the goal should involve a machine costing in the $50 M range, in contrast to the $100 M range previously discussed for HIDE. With less investment, the strength of the beam that could be produced was expected to be much lower. A large drop in beam strength would be the reverse effect of the attractive scaling of HIF driver capability with <u>increasing</u> investment. Also contributing to the likelihood of a sharp loss of beam capability were the "fixed" costs, including the components of the low energy end of the accelerator and buildings. As a result, the idea grew that the program would now emphasize demonstrations of accelerator technology and de-emphasize experiments with intense beams.

An issue that compounded this problem was the sentiment against synchrotrons expressed at the ANL workshop in September 1978. This was especially important for lower-cost projects because the cost-effectiveness of synchrotrons for achieving high ion energies would be most relevant where even this kinetic energy would be limited by the scale of the project. The combined effect of the reduced attractiveness of synchrotrons for reactor drivers and the trend toward making the primary program goal the demonstration of that accelerator technology that would be relevant for the development of ICF beyond scientific feasibility, which was to be demonstrated by NOVA, was the premature but often-stated opinion that synchrotrons were no longer interesting.

The three main issues we faced in our planning were, then, 1) the decrease in the cost ceiling, 2) sentiment that synchrotrons were irrelevant, and 3) a trend to restrict the next half-decade of HIF to accelerator demonstrations. Responding to the new prospects, our plan had two components. The main objective was demonstration of the accelerator technology for rf linac/storage ring systems. This would entail completing the front-end (source, pre-accelerator, and low velocity linac) and constructing additional linac, an injection-ring, a storage ring, compression system, a transport line, and a final focusing system. Although the maximum beam possible with a system that could be built under the new funding guidelines was clearly far too weak to consider breakeven (which has been conceivable for a 100 kJ HIDE), it did appear possible to produce kilojoule beams. Thus, the second objective of the new plan was to achieve enough intensity of beam on target to make possible experimental investigation of the interaction of intense heavy ion beams with dense matter at temperatures around 100 eV. In addition, the intense beams would also allow experimental

The Phase I design study incorporated the ongoing investigations of important issues. The most overlap was in the low velocity linac, which was continuing to be the focus of our experimental program. Other theoretical work that dovetailed with the Phase I study included injection schemes, transport, and final focusing systems corrected for geometric and chromatic aberrations. In addition, looking forward to fabrication, industrial concerns were involved in studies of some components. McDonnel Douglas Astronautics developed a plan for the procurement of a 10^{-11} Torr vacuum system, which developed into a preliminary engineering and costing study late in the year as the program was modified to the Phase Zero plan. Maxwell Laboratories studied an induction buncher concept using a simple, low cost circuit, and later considered the design of bumper magnets for the Phase Zero storage ring. It was proposed that these have a risetime ~ 1 μsec to minimize emittance dilution during stacking. The Hughes Aircraft Company and Research Laboratories made an effort to characterize the control problems relative to an HIF accelerator system. This effort, and others concerning industry, have been motivated by a concern for the limited expertise in industry concerning accelerator design. The control problem is both esoteric and crucial to HIF, where rapid achievement of design intensity will be needed.

In parallel with the Phase I design, but at a much lower level, was the development of the concept for a multi-hundred kilojoule device that could also make substantial use of existing ANL facilities. This machine (Phase II) would use a linac to accelerate to full energy and multiple storage rings. The rings would still fit in the ZGS tunnel, and about half of the linac would also fit into existing buildings.

An artist's conception of Phase II is shown in Figure I.2.

Needing to be compact as well as cost-effective, Phase II would use beam splitting (like Phase I) and also telescoping beams. In telescoping, various ion species are individually accelerated over a sequence of rf linac pulses and injected into different storage rings. The condition for telescoping is that the different bunches have different velocities but a common magnetic stiffness. This is met by appropriate choices of the mass, charge state, and velocity of the different species. Thus, after extraction from different storage rings, the bunches may be sequentially switched into a common beamline, where they overtake one-another to arrive simultaneously at the target. The advantages of telescoping include expanded usable volume in six dimensional phase space, (allowing more emittance dilution), reduced space charge problems during beam transport (since the peak power in each beam only arises during the final portion of the transport distance) and additional possibilities for shaping the beam pulse to achieve higher pellet implosion efficiency. Of most obvious importance to Phase II, however, is that telescoping allows the number of final beams to be less than the total number of bunches. This meant, for example, that Phase II could use six storage rings and 4 x 4 splitting. By using three charge states (e.g., Hg^{+5} at 3.9 GeV, Hg^{+6} at 6 GeV and Hg^{+7} at 7.6 GeV), the total number of final beams would be 32 (two 4 x 4 clusters) instead of 96. In addition, Phase II would utilize the concept of integrated quadrupole clusters to minimize the overall area occupied by the beams and to minimize costs. Rough cost estimates (using the data in the 1977 BNL workshop report) indicated that the additional construction costs (using Phase I apparatus as well as previously existing facilities) could be less than $200 M, without EDIA, etc.

The Phase I plan was displaced in May by another halving of the budget guidelines for the near-term program. In the new plan, called Phase Zero, demonstration of accelerator technology for rf linac/storage ring systems would investigation of the propagation of relevant beams through various, potential HIF reactor atmospheres. The apparatus that would be built would, therefore, use ion parameters and design concepts that would maximize the targetable beam intensity. This plan was called Phase I.

In visits to LLL and LASL during the middle of fiscal 1979, we discussed the experimental potential of Phase I, and possibilities for a collaborative target experimental program.

An important consideration in the Phase I design was to make maximum use of the facilities that would become available when the ZGS was shut down. In particular, the storage and injection rings would use the ring tunnel and the linac and final beam lines could be housed in other existing buildings. The cost savings would tend to decrease the "fixed costs" and maximize the application of the anticipated funding to the apparatus. The building available for the linac was long enough for 200 MV, and Xe^{+8} at 1.6 GeV could be comfortably contained in the ZGS ring tunnel ($B\rho$ = 8.2 T-m, R = 25 m). Because the higher charge state involved higher kinetic energy, the space charge limited energy storage in the ring was unchanged. Achieving a short pulse on the target was aided, however, because the higher velocity at injection into the ring resulted in fewer linac bunches in the ring circumference, hence less longitudinal emittance in the accumulated beam and less momentum spread when the beam was compressed to a few nanoseconds. This is additional to the lessened compression required with the shorter ion revolution period of the faster Xe^{+8} ions.

Beam splitting was incorporated to increase the space charge limit in the storage ring. The emittance of the stored beam would be twice the value that could be focused on the planned 1 mm radius spot, about 5 cm-mrad. To target this beam, it would be split in half in the horizontal phase plane and each of those beams would be split in half in the vertical plane. Each of the four beams would be focussed on a common 1 mm spot. This made it possible to store about 1 kJ, which could be put on target in about 10 nsec. Calculations of the deposition of this beam in foils indicated that a temperature of 35 eV could be reached.

An important increase in total targeted energy and power would be achieved if the storage ring were, instead, a synchrotron which could be incorporated with modest additional cost because a power supply to ramp the magnets would become available after the ZGS shutdown. The beam energy would be increased by boosting the kinetic energy of the ions and also by increasing the allowable emittance at injection, and, thus the space charge limit. The kinetic energy would be raised a factor of four, requiring a factor of two increase in the magnetic field strength. The resulting ion magnetic rigidity (16 T-m) would still be easily accommodated in the ring. The emittance damping produced by acceleration allows the injected emittance to be doubled, with no increase in the targeted emittance. Quadrupling the output energy (to 6.4 GeV) and doubling in initial emittance (to 20 cm-mrad), raised the total beam energy to 8 kJ. For the single synchrotron pulse, momentum spread in a 10 nsec pulse was much less of a problem than it had been in the design study of the rapid cycling synchrotron system (Hearthfire Reference Design #3), and the larger total energy produced by the synchrotron would raise the temperature achievable in a 1 mm radius spot on a foil to 100 eV.

An artist's conception of the Phase I concept is shown in Figure I.1. A conceptual design report was written for Phase I; excerpts are reproduced in Section IV of this progress report.

be stressed. The largest item of cost savings would be by reducing the length of the linac. This and the neglect of synchrotrons accompanying the nearly-exclusive interest in the concept of an accelerator demonstration facility (ADF) for rf linac systems eliminated further consideration of achieving intense beams. The bright side of the shift to Phase Zero, as advocated by the 1979 Foster panel recommendations, was that the program would now move forward with minimal delay, starting with a five-fold increase in budget in FY 1980. The plan could foresee completion of the apparatus in three years, with significant demonstrations en route. In addition, indications of smooth-sailing in the demonstrations could lead to an early upgrade of the system back to Phase I with minimal time lost.

The Phase Zero machine would accomplish the following:

- Full scale front end
- rf capture and acceleration
  - space charge limits
  - efficiency
  - emittance growth
  - stripping
  - beam combination
  - frequency transitions
  - debunching
- Accumulation
  - injection
  - beam loss, vacuum effects
  - ion lifetime
  - extraction
  - transfer
- Transport, Focusing (relatively low current), Compression

The Alvarez section of the Phase I linac would not be built and only one front end would be used. Beam combination would, therefore, be simulated by appropriate deflections during the transition from the 12.5 MHz to the 25 MHz structures. Other demonstrations of the linac would be unchanged, although debunching would be by a smaller factor.

The pace of the program was increased to take advantage of the imminent start. Following encouragement that linac structures could be plated at the G.S.I. in Darmstadt (West Germany) if necessary, the decision was made to base linac construction on electroplated steel and the effort to find a U.S. plater was stepped up. The specification for the Wideroe's rf amplifier system was revised and bids were requested. Our funding was increased in August by $250 K B/A to accelerate procurement of the rf, which was expected to require the longest lead time. Emphasizing the procurement efficiency, the Hughes Aircraft Company (Laser Systems Division) carried out a preliminary study of the engineering, costing, and procurement of the linac drift tubes using electroplating, a simplified plan for cooling the quadrupole magnets, and our simplified scheme for mounting and alignment.

A strong move toward speeding up the program was acquisition of the bending magnets of the former Princeton-Pennsylvania Accelerator, to serve as the bending magnets for the first (injection) ring of the Phaze Zero plan. These were brought to ANL in late June using $100 K of additional OIF money supplied for the purpose. Figure II.1 shows these magnets in storage at ANL. They will be installed in the ZGS ring building, shown in Figure II.2. Design of this ring started from an aborted earlier plan of the High Energy Physics program to use

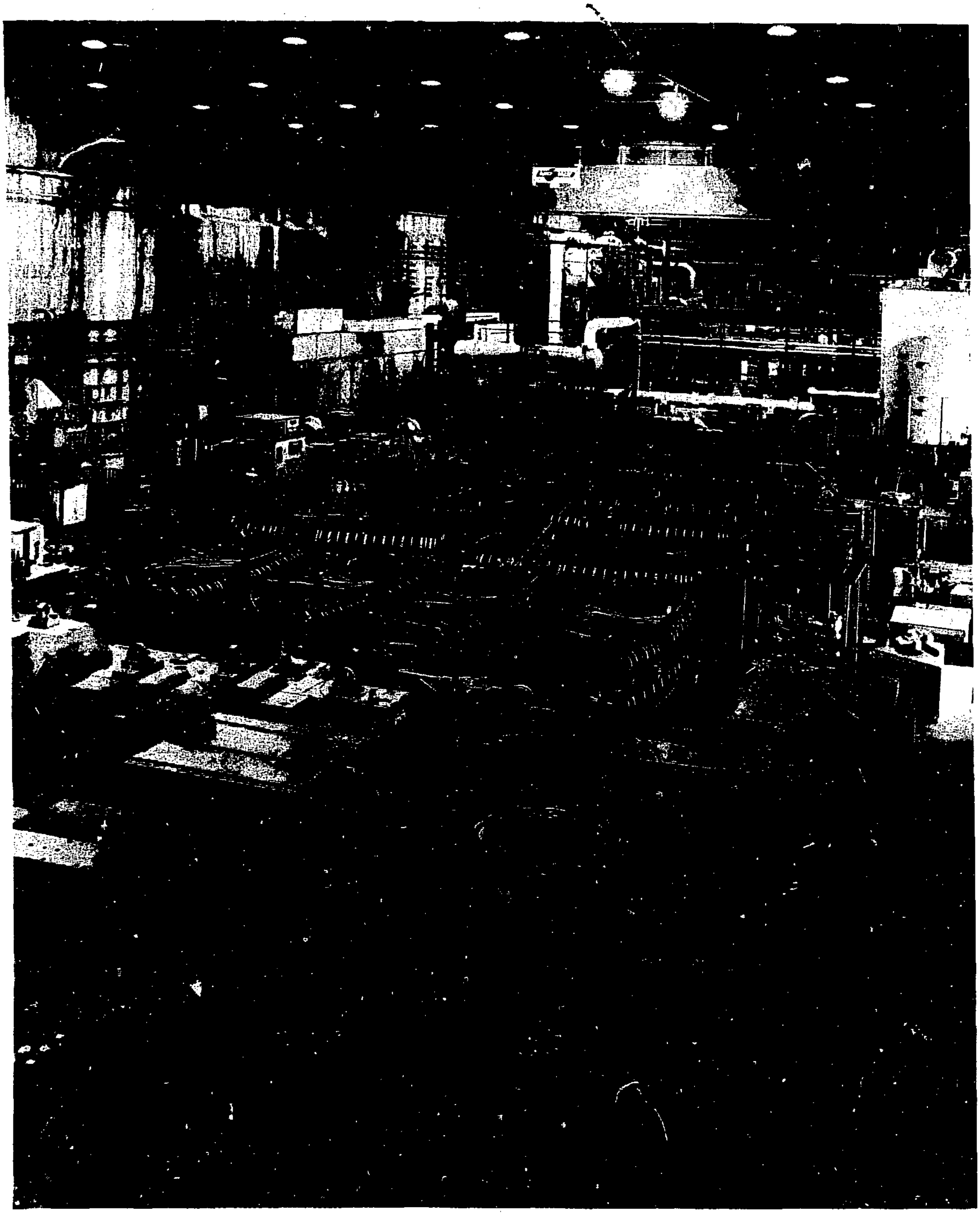

FIGURE II.1

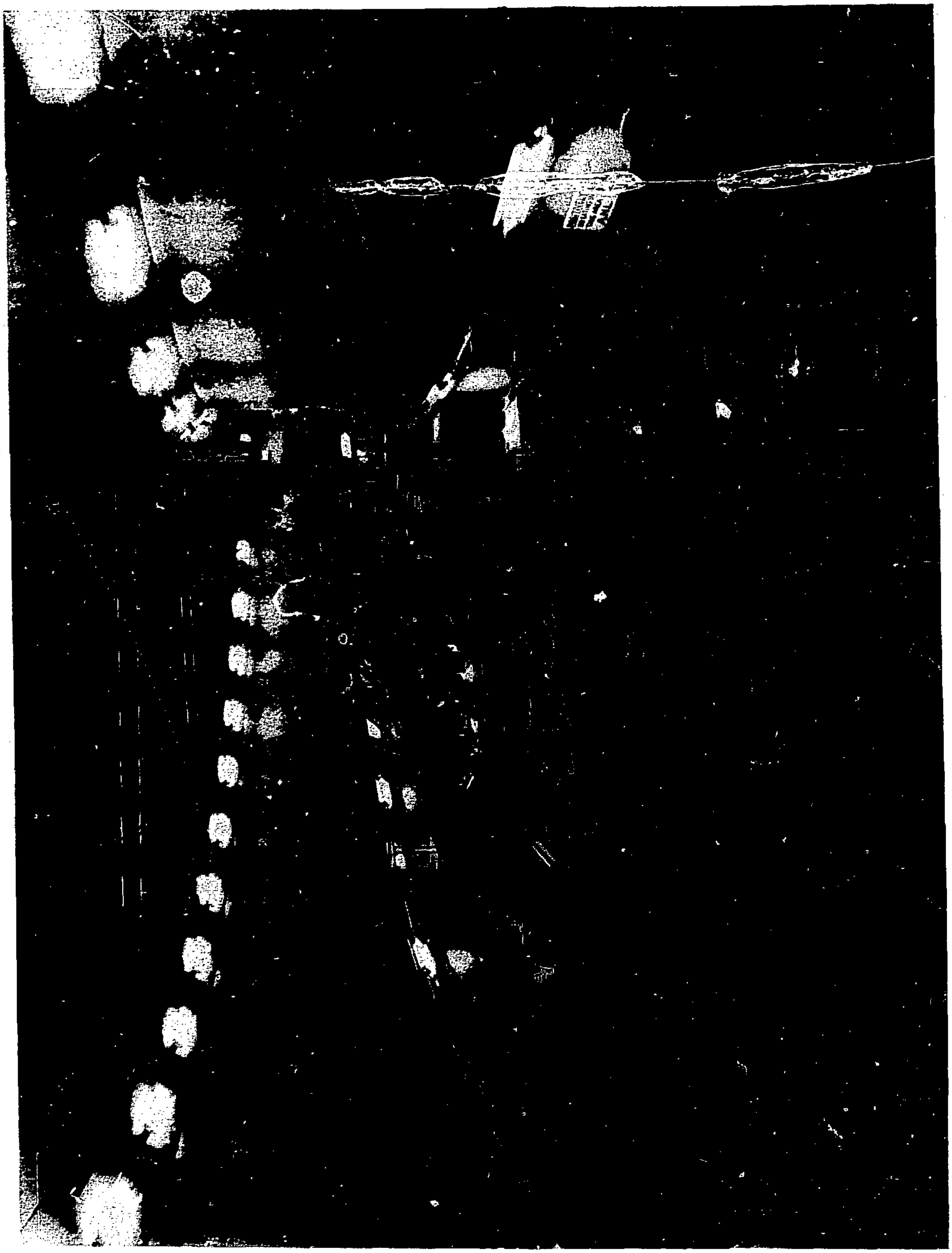

FIGURE II.2

these magnets for accelerator R&D with polarized protons. Changes from the former plan included maximizing the acceptance of the ring, going to doublet focusing, and pushing the base pressure down from 10^{-10} Torr to 10^{-11} Torr or better. The quad requirements became large in numbers (40), but it was discovered that more than this number of one kind of beam line quadrupole (10 inch bore, 36 inch length) would become available from ZGS surplus. A request for these magnets was submitted, and was ultimately granted. The large overall transverse size of the quads posed a difficulty in injecting and extracting the beam, and they used up more length than necessary; but on balance their use was felt an advisable, cost-saving step. A study of the bump magnets for injection (involving Maxwell Laboratories) considered the space and bending requirements. Planning for procurement of the 10^{-11} Torr vacuum chamber involved McDonnel Douglas Astronautics, who completed a thorough preliminary engineering study, with component itemization, procurement planning and costing, by the end of FY 1979. The results of that study has provided encouraging insight into the potential for efficient contribution to our program from industrial sources.

As this progress was being made, however, the program was hit by major funding and management changes. By the end of the fiscal year, it was clear that the FY 1980 funding would be much lower than OIF had been planning; and the program would further be held in abeyance as technical direction of the program was being transferred to the Los Alamos Scientific Laboratory. Since that lab had not been significantly involved up to that time in HIF, it would take some time for LASL to review the program and formulate a plan.

III. Experimental Program

Introduction

Most of the experimental activity in FY 1979 was committed to completion and performance of the preaccelerator and design and construction of the independently-phased low beta rf linac cavities. The design goal is to operate the preaccelerator near 1.5 MV with Xe^{+1} currents near 40 mA. The independently-phased cavities (IPC's) will capture and accelerate 25 mA up to 3.1 MeV for injection into the first Wideröe linac tank. The output energy of the first 12.5 MHz tank will be 8.8 MeV.

The heavy ion source, its power supplies, and controls were installed in the high voltage terminal and the high gradient accelerating column was mounted on the redefined output end of the Dynamitron. During the initial performance tests, the beam was transported to a biased Faraday Cup near the linac buncher.

The accelerating column voltage conditioned easily to 1.0 MV and with difficulty to 1.4 MV. In doing this, moderate damage occurred along the inner surfaces of the outer shell. Cleaning and modifications to the column were accomplished during the last two months of FY 1979, which should improve the voltage standoff capability of the column and reduce damage from the spark-downs which occur during conditioning.

The source performance was excellent and closely matched the test results from Hughes Research Laboratories (HRL). Beam currents up to 50 mA of Xe^{+1} were accelerated to 1.3 MeV with the majority of the testing at 1.0 MeV.

The construction of the two independently-phased linac cavities was completed and both were installed. They were tested successfully to rf power levels in excess of their design goals. The next two IPC's were designed and construction was terminated at approximately 50 percent completion because of lack of funds until FY 1980. The design of the first Wideröe linac tank is nearing completion.

Preaccelerator

High Voltage Power Supply

The modified Radiation Dynamics Incorporated 4 MeV Dynamitron has been a reliable power supply and well suited to our application. With the present oscillator it is capable of 30 mA of dc current at 1.5 MV, and experiences a 0.25 percent drop over 100 microseconds with a 42 mA current. After a few weak diodes were eliminated, the power supply has been remarkably reliable considering the adverse sparking conditions involved in conditioning high-gradient accelerating columns.

A program of upgrading the controls is continuing which will allow full feed-back operation and extensive monitoring by our local computer.

A gas handling system for the insulating gas was assembled using a surplus high capacity compressor and a used 15,000 cu. ft. pressure vessel. This allows the preaccelerator to be opened within 2 hours of shutdown without any loss of the SF_6 gas. To evacuate the preaccelerator and refill with gas to 70 psig requires another 2 hours. The turnaround time using liquefiers was previously over 8 hours.

Until our program demonstrates that higher currents are needed, the plans for adding energy storage to the oscillator or buying a larger oscillator have been deferred.

Heavy Ion Source

The development of the low-emittance heavy ion source was contracted to Hughes Research Laboratories. It utilizes a low-voltage Penning discharge coupled with a single-aperture Pierce extraction electrode configuration. Early in FY 1979 two 100 mA sources had been tested and delivered to ANL. One was assembled with a piezoelectric gas valve for room temperature gases; the other has a porous-Tungsten vaporizer and a solenoid-actuated piston to pulse neutral mercury vapor. Mercury or other vaporized elements may be more suitable heavy ions in later phases of our program.

The source performance with xenon has been excellent with the perveance matching the HRL projections. Multiple exposures of 40 mA Xe^{+1} at 1.0 MeV into the biased Faraday Cup are shown in Fig. III.1. The gas valve is pulsed for approximately 1 msec. After 50 msec the gas has uniformly filled the source to approximately 20 mTorr at which time the anode is pulsed. In order to turn on the source quickly, the anode pulse has two components; a brief 150 volt spike for ignition, followed by a 50 volt pedestal which controls the pulse duration. The source turns on in 10 microseconds and off in 50 microseconds.

It was anticipated that the slow turnoff of the source could cause arc downs in the column so a split anode was built which could be biased transversely to sweep the plasma quickly. No operational problems have been experienced because of the turnoff period, so the split anode has not yet been used.

The only difficulty experienced with the source has been with the operation of the piezoelectric gas valve. The response of the crystal is very temperature dependent. It is necessary to select crystals and carefully test and adjust the mounting tension to get uniform operation over the 20 degree temperature variation experienced within the preaccelerator. Once a valve is properly adjusted, it is reliable for many months.

When adequate funding and manpower are available, a test stand for the mercury source will be assembled and its performance evaluated. The stand will also be used to evaluate the design problems associated with using mercury in an accelerating column.

Accelerating Column

The development of the high-gradient accelerating column was the dominant activity of the preaccelerator group this year. In bringing the column into operation much has been learned about design and component contraints for high-gradient columns above 1 MV.

The column as initially voltage conditioned to 1.0 MV without great difficulty. At that point it was clear that the voltage dividing resistors would not be adequate because of an excessively large voltage coefficient. These were ceramic resistors with resistances near 5 megohms. New carbon black formulations forced on manufacturers by OSHA the previous year had rendered these resistors unacceptable for high voltage applications. Rather than install a water resistor with its usual unreliability, stacks of two watt resistors in groups of 50 each were constructed into modules which exactly replaced the ceramic resistors physically. These exhibit only a 10 percent

10 mA/cm

1 MeV Xe^{+1}
40 mA
200 μs Pulse

50 μs/cm

FIGURE III.1. ANL Preaccelerator Beam Pulse drop in resistance over 1 MV and have been essentially trouble-free. The current drain of the divider is kept high at 6 mA to prevent substantial voltage redistribution within the column during the beam pulse because of the different currents experienced by the internal electrodes.

With difficulty the column did voltage condition to 1.4 MV. Beams of 50 mA of Xe^{+1} were extracted at 1.3 MV successfully. To keep the spark rate low, it is customary to voltage condition 100 kV above the operating voltage.

After no progress could be made above 1.4 MV, the column was opened for inspection. The interlaced rings on the inside of the outer shell were badly pitted and plated from electrical arcs. It was clear that their gap spacing was not adequate. The ceramic rings in the sections near the terminal were badly chipped by the overvoltage transients. The column was dismantled, ceramics cleaned by aluminum oxide blasting, half of the titanium rings polished, and the others replaced with simpler rings to open up the gaps. A third internal electrode was installed to reduce the magnitude of the transients. The column is now being conditioned to 1.1 MV with less difficulty than before, even though three ceramics have been short-circuited as a precaution because of full-width cracks.

The present configuration of the column is shown in Fig. III.2. The source is re-entrant on the right and the focusing magnets re-entrant within the ground electrode on the left. The new electrode is closest to ground and merely halves the total voltage of the final gap. Not only is the magnitude of a spark across that gap halved, but its transient is distributed over twice as many ceramics. The new simpler rings on the outer shell are also shown alternating with the original rings.

The base vacuum in the column is maintained by cyropumps at approximately 1×10^{-8} Torr. During operation at 1 Hz, the vacuum rises to 2×10^{-6} Torr because of the source gas. In many applications intentionally spoiling the vacuum improves the voltage standoff; the experience with this column has been that the standoff improves with vacuum. This may be related to the background gas involved here being xenon. Figure III.4 shows the preaccelerator.

Low-Beta Linac

The layout of the first sections of the rf linac is shown in Fig. III.3. The front end has great flexibility through the use of independently-phased cavities with only a few drift tubes per cavity. These can accommodate at least 250 keV variation of the injection energy from the preaccelerator and still satisfy the 3.1 MeV needed at the first Wideröe tank. The necessity of IPC 5 will depend on the performance of the preceeding cavities.

Independently-Phased Cavities

The first two cavities, IPC-1 and IPC-1′, were completed this year and have been installed and rf tested. Both have been tuned to 12.5 MHz and excited with more than 25 kW with no breakdown or multipactoring problems. The lumped-inductance cavity, IPC-1′, is now installed in the buncher location 3.5 meters upstream of IPC-1 for beam testing.

The design of the two drum-loaded four-gap cavities, IPC-2 and IPC-3, was completed and their fabrication is approximately half complete. Because of lack of funds their fabrication was halted until FY 1980 - a delay of at least four months.

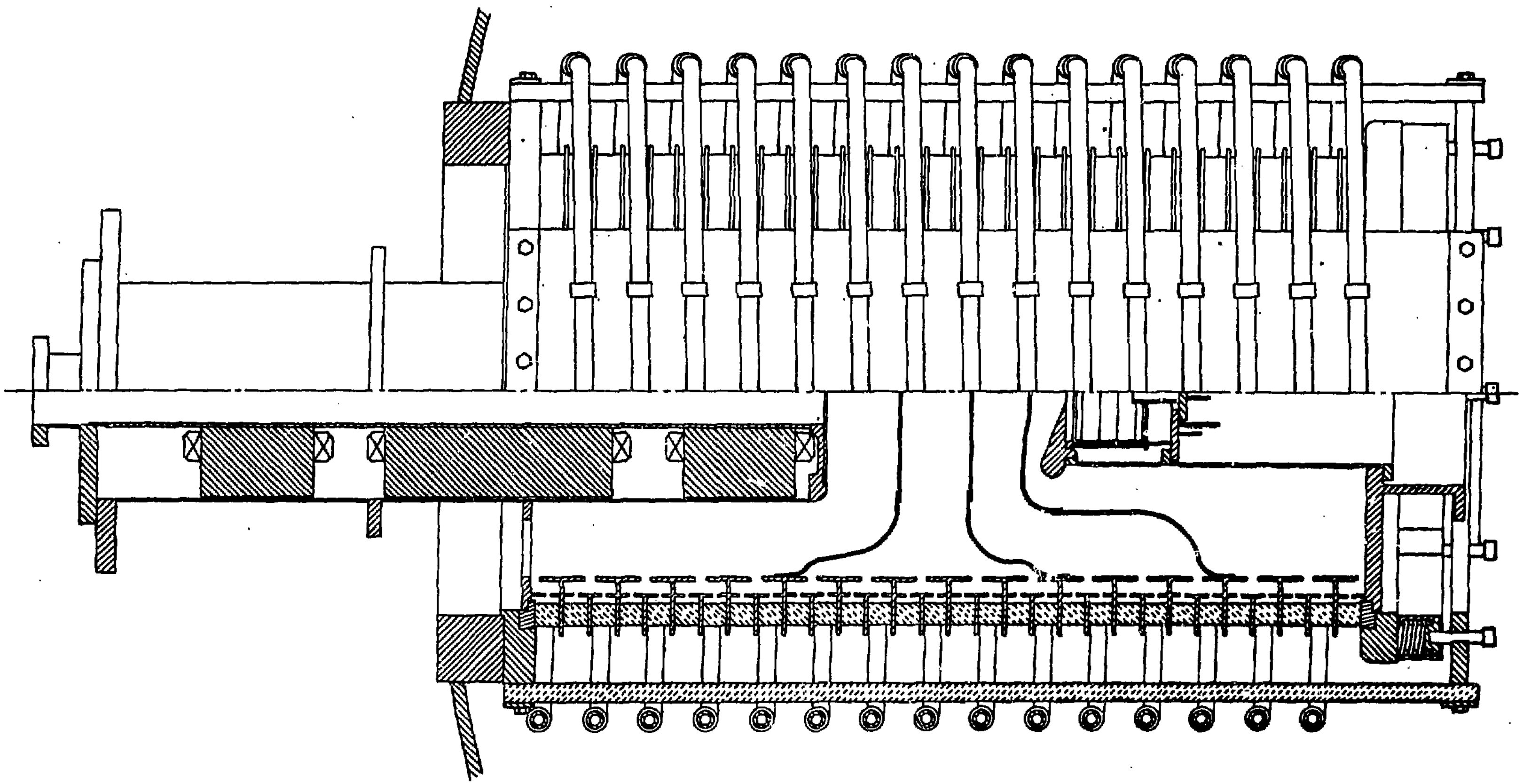

FIGURE III. 2. HIF High Gradient Accelerating Column

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12.5 MHz LOW - BETA LINAC

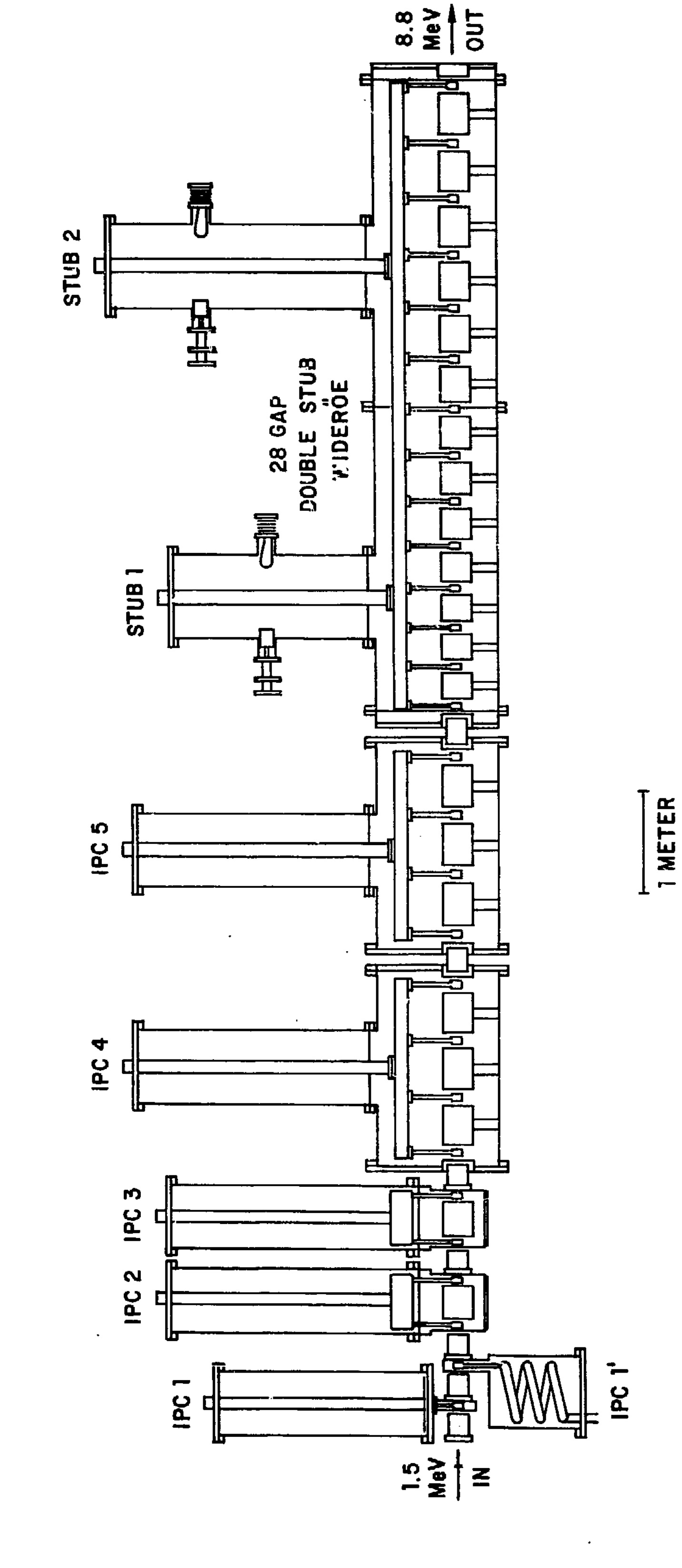


FIGURE III.3

FIGURE III.4. ANL Heavy-Ion Preaccelerator (clockwise, starting at upper left)

1. High gradient accelerating column
2. Pressure enclosure
3. 1.5 million volt power supply
4. Ion source

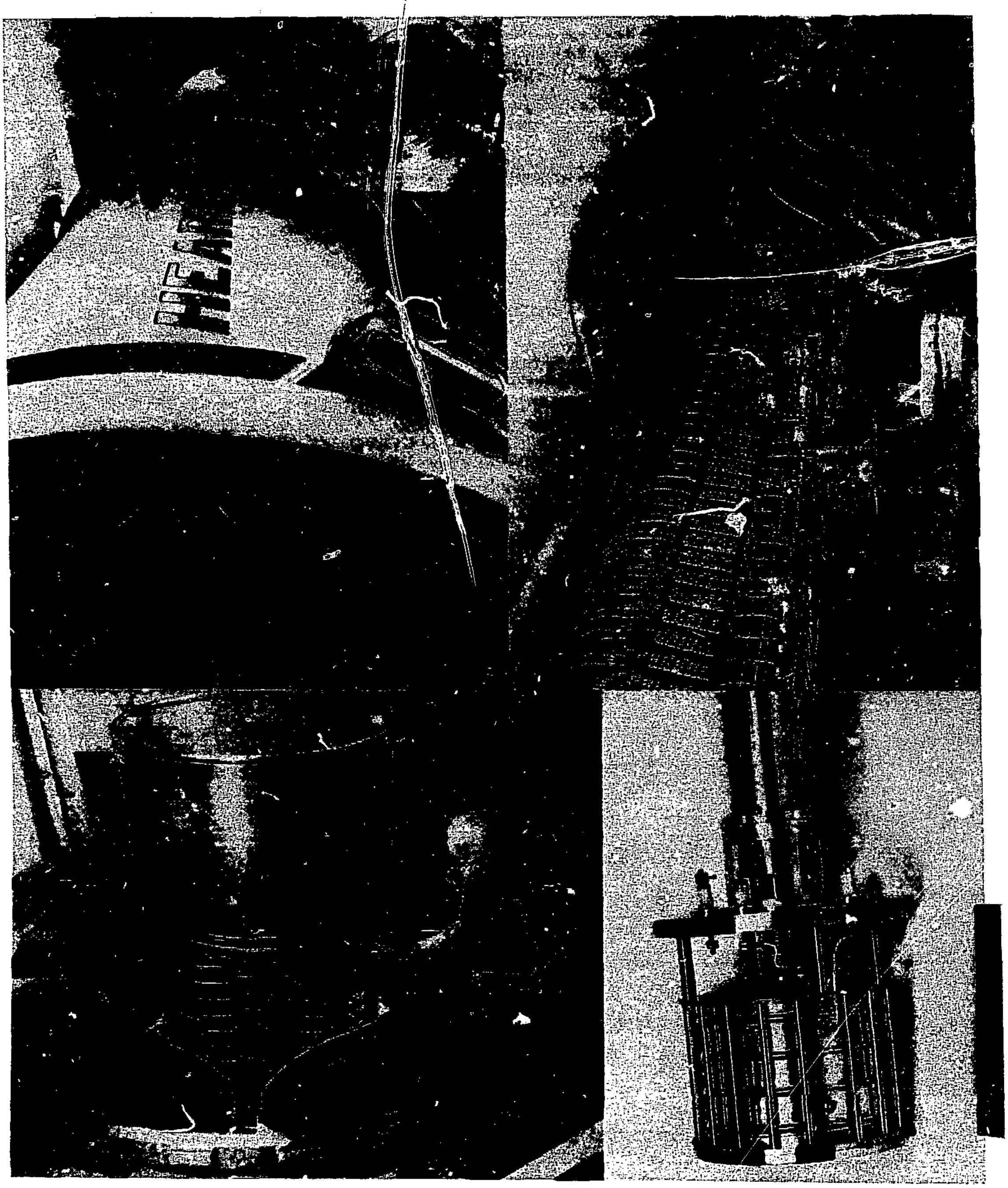


FIGURE III.4

Wideröe Cavities

Much of the linac design effort this year was devoted to detailing the first Wideröe cavity which will accelerate 25 mA of Xe^{+1} from 3.1 to 8.8 MeV. A two-stub structure with 20 gaps in a $\pi/3\pi$ configuration was chosen as most suitable. The long drift tubes will contain pulsed quadrupole magnets. To reduce construction costs, most of the cavity will be of mild steel and electroplated with copper. Experimental plating tests and vendor acceptance tests are in progress.

The first three Wideröe cavities will each require a 450 kW, 12.5 MHz amplifier. Bids for these have been received; however, their purchase will await increased funding in FY 1980.

80 keV Xe^{+1} Test Beam

Before dismantling the test beam line for upgrading to a high vacuum transport, a series of measurements were made under clean transport conditions of the time required to establish neutralization by residual gas ionization. This was done by pulsing clearing electrodes within the beam pipe and measuring the final focus as a function of time. This is indirectly a measurement of the ionization cross-section. The results as a function of energy and gas composition are shown in Table 1. The cross-sections are consistent with expectations and the neutralization times are therefore long compared to the pulse lengths which will be needed in HIF reactors. This means that if neutralization is to be used, external sources of electrons will be required.

Table I

Energies KeV	Gas Pressure x 10^{-6} Torr	Gas Composition P_{Xe}/P_{N_2}	Neutralization Time (μ sec)	Ionization Cross Sec. x $10^{-16}cm^2$
43	2.5	.93	700 ± 100	4.1 ± .72
54	2.5	.93	480 ± 50	5.2 ± .80
65	2.8	1.1	380 ± 50	6.7 ± 1.3
75	2.9	1.2	280 ± 50	6.9 ± 1.4
86	3.2	1.5	230 ± 30	7.8 ± 1.2
97	3.2	1.5	230 ± 30	7.2 ± 1.2
107	3.4	1.6	180 ± 30	8.4 ± 1.6

The test beam was being modified in FY 1979 to a transport line with a vacuum of 10^{-8} Torr, and a second intersecting line was being installed in preparation for Xe^{+1} - Xe^{+1} charge-exchange cross-section measurements. The second beam line will use a collimated duoplasmatron source set up by an ANL - University of Chicago collaboration. This was planned to be ready for operation by mid-FY 1980.

IV. Excerpts from Phase I Conceptual Design Report, May 1979

PHASE I CONCEPTUAL DESIGN REPORT
Argonne National Laboratory
Heavy Ion Fusion Accelerator Demonstration Facility

Contents

Contributors to the Design Report include:

R. Arnold	R. Martin
J. Bogaty	M. Mazarakis
R. Burke	K. Menefee
E. Colton	J. Moenich
S. Fenster	A. Moretti
M. Foss	D. Nikfarjam
S. Grammel	E. Parker
T. Khoe	L. Ratner
Y. Kim	N. Sesol
R. Kustom	B. Snyder
A. Langsdorf	R. Stockley
R. Lari	H. Takeda
G. Magelssen	J. Watson

ii. SUMMARY OF THE REPORT

Commercial power from inertial confinement fusion requires development of a high power driver with good energy deposition, focussable beams, high efficiency, high repetition rate, and acceptable cost. Heavy ion conventional accelerator technology promises to fulfill these requirements. An accelerator facility (Phase I) based on a conventional rf linear accelerator which will demonstrate convincing levels of high beam power, focussing, and energy deposition (at the 1-10 kJ level) in targets as described in this report. This facility will supply the necessary technology base for a multi-megajoule rf linac HIF driver. An addition to the facility, denoted by Phase II, is possible and could provide at least 200 kJ of beam energy, to demonstrate substantial fusion gain with heavy ion beam bombardment of pellets at the earliest possible time.

Two options for power levels (and cost) are discussed for Phase I. The higher level, designated by "Phase I upgrade," contains two 40 mA Xe^{+1} ion sources, 1.5 MV preaccelerators, 12.5 MHz low velocity rf linacs to 15 MV, and two strippers to produce Xe^{+8}; these are combined in one 25 MHz Wideroe linac, leading into one 100 MHz Alvarez linac, yielding a beam of 1.6 GeV Xe^{+8}. Using an intermediate stacking ring, this beam is accumulated to a current of 2.2 A in two storage rings. After filling is complete, the circulating beams may be further accelerated in the rings to 6.4 GeV. Longitudinal bunching by a factor of five is performed; the bunches are then extracted and passed into beam lines through a linear induction buncher. The pulse is further compressed thereby a factor of 40 when it reaches the target end of the beam transport line.

Beam splitting (2 x 2 in each of two beam lines) and aberration correction elements in the final segments of the beam lines would allow focussing 1-10 kJ of ion beam energy in 2-10 nsec pulses on a target 1 mm in radius, with eight beams. Energy deposition physics for ions in a target plasma of order 100 eV temperature could be verified by foil target experiments.

The lower capacity option, denoted by "basic Phase I," would inject 0.9 GeV Xe^{+8} (also using a stacking ring) into one storage ring, accumulating 1 A of circulating current. Acceleration in the ring to 6.4 GeV remains an option; this could produce a single beam of 2 kJ energy. Target deposition experiments would not be significant with this option.

Beam plasma interaction experiments can be carried out with the Phase I facility (either option) to explore filamentation, two stream, and hose instabilities which might be encountered while propagating ion beams in a reactor vessel environment.

Expanding the facility for 200-500 kJ experiments (Phase II) can be accomplished using a linac four times longer, 4-8 more storage rings, sophisticated beam handling techniques involving several charge states (telescoping), and an additional experimental area with suitable beam lines.

If construction of Phase I begins in October 1980, 1 kJ beam experiments can be carried out in 1983. The program could also be paced to provide early data on rf linac performance for a design decision on a larger ($\geq$ 1 MJ) driver by 1982, if desired. Phase II construction could be completed by 1985.

Construction costs of the basic Phase I option could be held to $50 M (including EDIA, escalation, and contingency) by using existing buildings and other facilities at ANL which will be available when the ZGS is closed down in October 1979. (ANL has submitted to DOE a Schedule 44 for such a facility.) Additional costs for the Phase I upgrade would be $10-20 M. Phase II costs would be of order $150 M additional.

This conceptual design report primarily discussed the full (Phase I upgrade) program with the basic option treated where appropriate. The functions of the facility for driver R&D, as well as experimental programs for beam propagation and target experiments, and a management plan for construction, are given in detail.

An artist's conception of the Phase I facility is shown in Fig. 2.

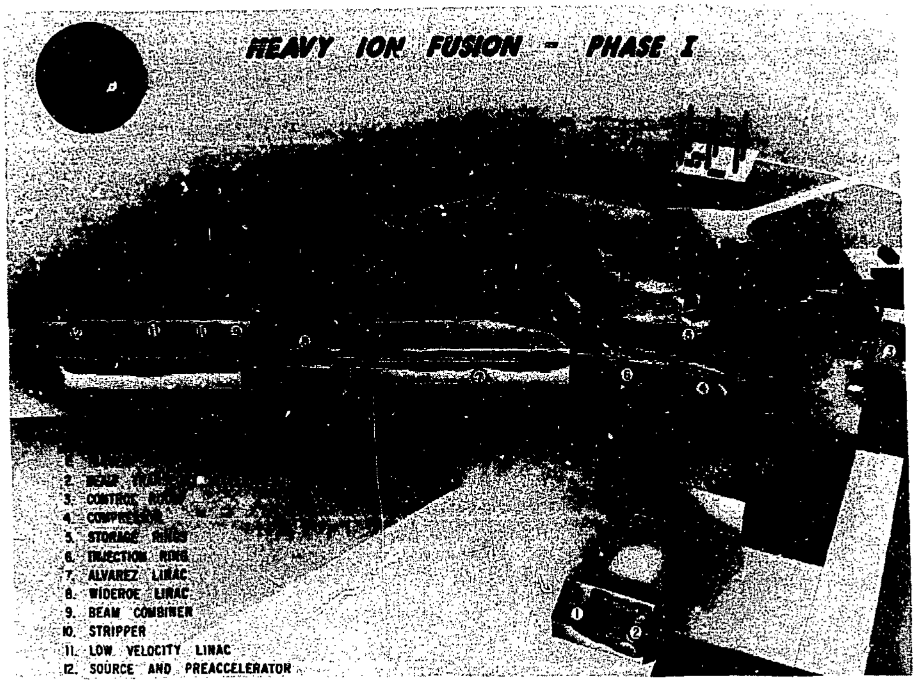


Figure 2

I. INTRODUCTION

A. Fusion Power through HIF

The outstanding potential of thermonuclear fusion for supplying a major fraction of the world's future energy needs is well known. Although much progress has been made on diverse aspects of the controlled fusion problem, a satisfactory design does not yet exist for a practical fusion reactor. The major difficulties opposing realization of such a design are fundamentally different for the two main approaches to controlled fusion.

For magnetic confinement, experiments on fuel heating and confinement now allow predictions that the conditions needed for a positive energy balance can be reached with the next generation of experiments; but, as noted in the DOE "Policy for Fusion Energy" (DOE/ER-0018, September 1978, p. 18), tokamaks, on which these experiments are based, "appear to possess disadvantages as reactors." The underlying problems, due to their coincident number, suggest that the fusion program not only try to overcome them by improving tokamak design but also "vigorously seek new schemes which, by their conceptual nature, avoid the problems altogether." (DOE/ER-0018, p. 19)

For inertial confinement, the situation is reversed. Inertial confinement reactors are expected to be practical because, as noted in the "Final Report of the AD Hoc Experts Group on Fusion" (DOE/ER-0008, June 1978, p. 7), "the physical separation of the complicated and expensive driver mechanism from the target area is an attractive feature for reactor design," but an instrument has not been demonstrated for quickly driving small quantities of fusion fuel to the densities and temperatures needed for substantial fuel reaction. Moreover, little progress has been made toward the further goal of demonstrating the instrument that will drive the fuel to the conditions needed for high energy gain and also possess the additional characteristics needed to give a power plant an adequately exothermic energy cycle, adequate power output, reliability, and reasonable cost.

The justification for the Phase I Heavy Ion Fusion Project is, therefore, that the heavy ion driver approach to inertial fusion seems to make it possible to design a practical fusion reactor system. This prognosis is due to the conjunction of the demonstrated capabilities of high energy accelerator systems, which allow the prediction that beams can be generated with the characteristics needed to produce fusion energy by inertial confinement on a commercial scale, and the aforementioned, basic reason for expecting the engineering of the inertial fusion reactor itself to be straightforward.

From the point of view of the fundamentals of igniting thermonuclear burn in pellets of fusion fuel, focussing particle beams to spots the size of fusion fuel pellets and storage of megajoules of beam energy are critical capabilities that are routinely demonstrated with conventional accelerators; using standard procedures, designs have been worked out for delivering the beam energy in the required short pulses; and the vacuum required for storing heavy ions for times of a second or less has been developed for the circular machines used to hold proton beams for hours. The prospect of such high total energy, high power, tightly focussed beams with the favorable deposition properties characteristic of ions gives high confidence in achieving high energy multiplication for imploded fusion pellets. This confidence is a result of making the basic physics highly similar to that of proven thermonuclear devices.

From the point of view of a complete reactor system, the use of conventional accelerators complements the engineerability of the reactor vessel itself with the feature of focussing the beams from a distance by magnetic lenses that are durable and may be shielded from the fusion reaction products. The other necessities for a practical reactor system are also provided as conventional accelerators can efficiently convert line electrical power to ignitor beam power, as will be needed to give the fusion plant a good overall power balance; pulse rapidly, as will be needed to give the plant an adequate power output; and operate reliably, as is needed of all power plant subsystems.

The potential for ultimate success and the maturity of the technology that justify the scale of the Phase I Heavy Ion Fusion

Project also create pressure to arrange the program to move a efficiently and quickly as possible through the rest of the steps that will precede significant contribution by fusion to the energy supply; that is, demonstrations of technological, engineering, and economic feasibility. The capabilities of accelerator systems make it possible to meet and possibly shorten the current schedule (DOE/ER-0018, p. 14) for realization of these sequential steps. The principal reason for this is that the requirements for each of the facilities needed for these sequential steps (Engineering Test Facility, Engineering Prototype Reactor, and Commercial Demonstration Reactor) could be supported by a single accelerator system that is progressively developed. For instance, the progression from ETF to EPR might entail addition of components to increase the total beam energy; and the progression through the EPR stage could be facilitated by adding beam lines to simultaneously power multiple facilities, including alternative reactor concepts, much as high energy accelerators routinely supply beam simultaneously to a number of experiments. (See Fig. I.A.1.)

Capitalization on these possibilities will require a strong effort to involve industry, as well as multiple national laboratories, in the earliest stages of the HIF program.

As envisioned today, the path to commercialization of HIF must take place within the framework of the DOE reference scenario shown in Fig. I.A.2. The elements of this scenario call for evaluation of competing magnetic and inertial confinement concepts, ultimate selection of a victorious concept(s) around the year 1997, and construction of major facilities utilizing this concept in order to demonstrate that electricity can be produced in a manner attractive to industrial investors.

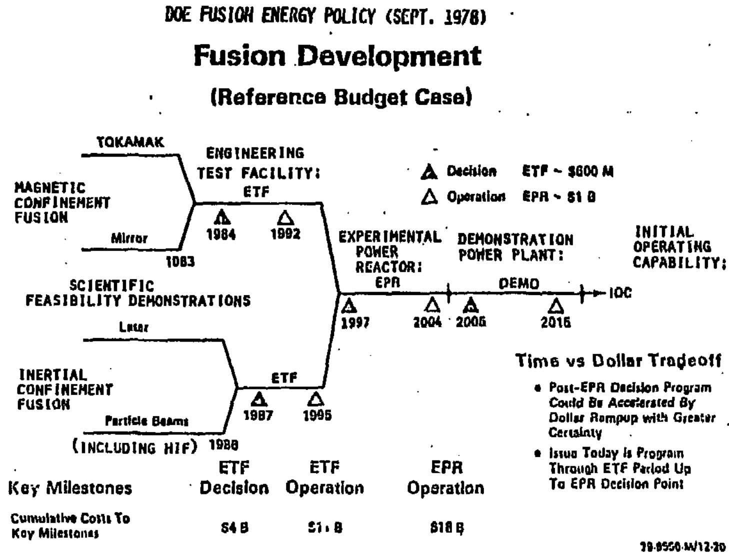


Figure I.A.2

In order to place the heavy ion concept in perspective, it will be useful to look more closely at the requirements for a Demonstration Power Reactor. This analysis will not only provide a basis for evaluating competing inertial and magnetic confinement concepts, but will also define the prerequisite technologies that preceding inertial confinement fusion facilities must demonstrate.

Requirements for a Demonstration Power Reactor (Demo)

The Demonstration Power Reactor represents the proving ground for commercial acceptance of fusion power. It will be compared to other sources of energy such as a well developed nuclear fission power generation industry and, thus, must achieve a relatively high degree of maturity during its precommercial development stage. Specific issues of cost, reliability, safety, environmental impact, and public acceptance will have to be satisfactorily demonstrated to the electric utilities before they would be willing to introduce this new power system at a time when fission power technology is projected to be operating and fully proven. To achieve the overall goal of fusion power commercialization, the following conditions must be met:

- The fusion reactor must project economic viability for the utility industry when compared to other base load power generators available in the same period.
- The reliability of the fusion power system must be clearly established through successful operation of the demonstration plant under practical utility conditions.
- The basic supply of critical materials must be assured. This need includes not only the basic ingredients of the fusion reaction, deuterium and tritium, but also other exotic materials which may be required for first walls, blankets, cooling, vacuum pumping, etc.
- Adequate safety and reliability standards must be defined along with criteria for design, fabrication, and construction to assure attainment of and continued adherence to these standards. This is especially important because of mechanical forces generated by the repeated micro-explosions, proximity of very hot (800°K) to very cold (4°K) materials, and, of course, the existence of radioactive materials as fuel or activated by-products.
- Industrial design competence, manufacturing capability, and construction expertise must exist to fabricate the reactor components and to construct the plant reliably, predictably, and economically.
- An infra-structure of government regulators, materials and component suppliers, utilities, etc., must be developed and established.
- The licensability and environmental compatibility of a fusion reactor must be established with regulatory agencies and communicated to the public.
- A nucleus of trained operators and management personnel must be available with specific programs for training additional personnel to serve the growth of the industry.

Operation of the DEMO as a central station power plant requires that the fusion reactor be capable of feeding a continuous supply of electricity into existing utility grids. Inertial confinement fusion reactors will be operated in a pulsed fashion so an energy storage system will have to be an integral part of the blanket or it will have to be inserted between the reactor and turbine in order to remove discontinuities in reactor heat output resulting from the pulsed operation. In addition, pellets will have to be injected at a rate of ~ 10^5/day, the driver beam aimed and focussed accurately at that rate, and the appropriate atmosphere in the reaction chamber reestablished before each shot. The consequences of these requirements will impact the design of vacuum pumping systems, first wall and heat management systems, tritium handling and processing systems, aiming, tracking and focussing systems, etc. The output of the micro-explosions may cause severe mechanical and neutronic damage to a solid first wall; thus, first wall designs must be developed which will absorb the mechanical and neutron impact and also breed tritium. The practical attractiveness of these designs will have to be demonstrated first in test beds and then in actual facilities.

The DEMO and its components should be prototypical or reliably scalable to commercial size. This feature can be demonstrated when all systems, components and materials in the DEMO operate as expected for reasonable lengths of time while producing a reasonable amount of net electrical power, say 100-200 MWe. This approach will not only check out the DEMO itself, but will also check out the interfacing systems between the DEMO and a stream turbine system.

Based on the preceding considerations, therefore, the DEMO is expected to include the following technical features:

- Operation at favorable power balance; i.e., with $\eta Q \geq 10$.
  High plant availability for long periods of time.
- Breeding and reprocessing of tritium; reprocessing of other gases and liquids; closed cycle production of pellets.
- Production of 100-200 MWe.
- Completely designed and tested materials and systems which provide solutions to major technological problems.

The scenario for reaching the DEMO must provide for a sequence of facilities and development efforts which will confront and solve the problems associated with making the various systems, components and materials compatible with reactor requirements. In addition, the scenario must provide for impact on early stages of development and design of requirements for commercial acceptability of the power plant. The goals of favorable power balance, long life potential, high plant availability, convenient maintainability, etc., must be specified early and used as a basis for defining R&D programs to meet those goals as well as for deciding which driver concepts cannot meet them and which, therefore, should be no longer considered.

From this point of view, HIF appears attractive, since it uses technologies which have been developed over many years to make the driver easily maintained, operable at high efficiency and for extended periods. In addition, the high efficiency with which ion beam energy can be deposited in the target indicates that low Q and cheaper targets can be used. The technologies and techniques proposed for heavy ion fusion are extrapolations from systems that accelerate electrons or protons now in operation in various parts of the world. It will be important to demonstrate that these approaches will work under the conditions required for a fusion driver.

Technical problem areas which must be addressed and solved by the time of the DEMO are: driver design, pellet fabrication and injection, first wall and structure, tritium removal and processing, shielding and blanket, maintenance and remote handling, coupling to turbines, and isolation of the system from mechanical, radioactive and thermal transients. Time, money, and ancillary facilities will have to be made available to properly develop successful solutions. For example: to develop a structural material with service life of 40 MW-years/m^2 for the MFE program, the cost is estimated to be ~ \$600 M over a period of 20 years; development of pumps, valves, and joints to handle lithium is expected to take 20-30 years; heat transport systems development will be paced by the availability of test reactors so it is likely to be completed sometime after 2010 at an estimated cost of \$100 M; and so on. The very long lead times associated with development of commercially feasible solutions to these kinds of problems indicate that work would start on them now (1979-1980) in order that they be available by the year 2000.

The ultimate application of inertial confinement fusion to commercial power generation will impose conditions and requirements on the system which will demand that industrial engineering expertise be incorporated sufficiently early for the concepts and final designs to be ready when facilities are ready to go. This is accomplished by involving industrial engineers at early stages of the design and promoting interaction with the scientists and engineers at the national labs in identifying and solving problems. These interactions usually reveal that constraints exist which require iteration of both the scientific and engineering considerations in the development of final concepts. The choice of successful subsystem and system concepts will, of course, be determined by actual demonstration in a facility. It is clear that heavy industry and utility involvement will be needed in design, construction, and operation of the facilities which precede the DEMO which, according to Fig. I.A.2, are in the EPR phase of the Fusion Development Program. However, these facilities will have to be used to qualify materials and system concepts and designs for the DEMO which must have been developed previously, during the ETF phase of the development program. Thus, significant industry and utility involvement should exist by the time scientific feasibility is established, sometime around 1985.

Several alternative scenarios for engineering development through DEMO are shown in Fig. I.A.3. The other facilities described are abbreviated as follows:

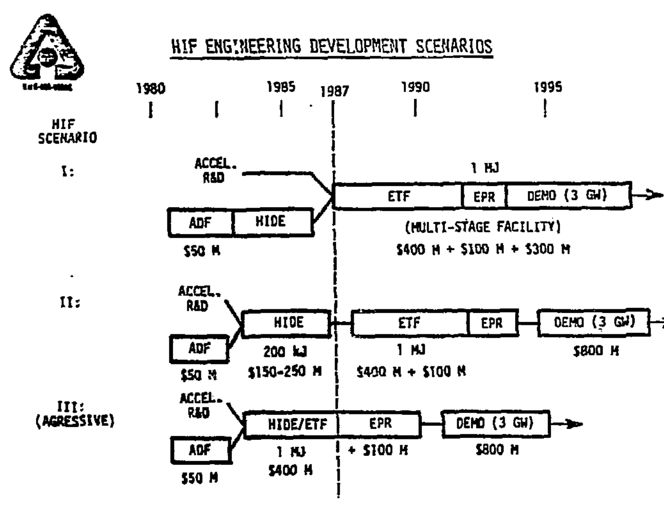
ADF - Accelerator (technology) Demonstration Facility, without significant thermonuclear experiments (e.g., the Phase I facility).

HIDE - Heavy Ion Demonstration Experiment, with 200-500 kJ beam energy, appropriate for significant thermonuclear burn experiments, possibly with pellet gain $G \geq 1$.

ETF - Engineering Test Facility, with approximately 1 MJ beam energy, appropriate for full-scale reactor environment testing, with high gain pellets.

EPR - Engineering Prototype Reactor, a facility producing electrical power, but not necessarily at a commercially economic rate; its purpose is to provide the technology proving ground for DEMO.

The Phase I conceptual design report is appropriate to any of the first three scenarios, or one which is a modification of Scenario III, allowing a HIDE (Phase II, upgrade of ADF) to be completed by 1985, while ETF is being constructed, as described in the next section.



COSTS: \$ FY79, w.o. EDIA & CONT.; DRIVERS ONLY.

Figure I.A.3

Summary

1. Goal of commercialization must define R&D effort and choice of driver. The heavy ion driver appears attractive because it uses well developed technologies and promises high efficiency operation.
2. Industry and utility involvement must be heavy by the time scientific feasibility is demonstrated around 1985. In addition, a total infra-structure must be developed by the time of the DEMO.
3. Development of systems, components, and materials compatible with commercial requirements will require ongoing efforts over at least a 20 year period.

B. HIF Driver Development Plan

1. Minimal Accelerator R&D Prior to ETF Decision

Construction of an ETF will require that a choice be made between conventional rf linac technology, as proposed for Phase I, and the linear induction accelerator technology being developed at LBL. We see the accelerator issues confronting heavy ion fusion as outlined in Table I.B.1. Both systems must demonstrate adequate and reliable front ends, through R&D programs. We will outline later what we see as the specific requirements of the front end of the rf linac.

The feasibility of the induction linac for acceleration of ions at high energies must also be demonstrated in order to allow a clear choice between these two linac systems which we assume could be done before the ETF design is chosen, at the end of FY 1982. [In our view, the main issue in determining the feasibility of the induction linac for the heavy ion fusion application is the required precision of pulse shape in order to deal adequately with the longitudinal emittance, the practicality (and cost) of providing this shape, and the reliability of control of 1000 units in timing, amplitude, and shape. One cannot make realistic cost estimates without understanding these requirements.]

The feasibility of the rf linac, on the other hand (beyond the difficult front end), is a question which most accelerator people would accept as answered by existing experience; and this was reflected in the analyses at the 1978 HIF workshop at ANL. However, there are many beam manipulations that are specific to the rf linac systems. The efficiency, emittance growth, and effect of beam loss (on vacuum and components) during these beam manipulations are much more important with heavy ion beams for pellet fusion reactors than with the proton beams for research applications with which we are familiar. A minimum program to demonstrate the practicality of rf linac systems would involve demonstration of some critical issues involving accumulator rings (injection, accumulation, extraction, emittance growth, beam lifetime, internal compression, etc.). Other goals of the accelerator R&D programs are:

a. To improve the design and test new designs (mostly for reliability, improved efficiency, and cost savings).
b. To reduce the risk (better understanding of efficiencies, emittance growth, effect of beam losses); i.e., to avoid as many surprises as possible when we do things beyond what has been done before.
c. To demonstrate that costs and reliability questions are well in hand.

The layout of suitable minimal R&D equipment, with operating parameters, is shown in Fig. I.B.1 with an ANL site sketch shown in Fig. I.B.2.

We estimate the cost of such a minimal program could be held under $25 M for the first three years (FY 1980, 1981, 1982).

It would include:

a. Xe source, preaccelerator, buncher, first stage low beta (2 MV) (existing equipment).
b. Additional diagnostics, beam dump, matching, etc.
c. 15 MV - 12.5 MHz linac
d. Stripper system, charge selection, diagnostics, matching, combination system.
e. Long transport line to ZGS tunnel
f. 25 MV - 25 MHz linac
g. Two accumulator rings with 20 - 40 cm mrad acceptance, including:
   Injection system
   Debuncher, rebuncher rf
   Intermediate extraction system
   Phase space rotator
   Second injection system
   Internal compressor
   Second extraction system
h. External compressor
i. External transport line
j. Beam dump (from rings)
k. Splitting septums (with matching system)
l. Charge recombination section

This minimal R&D program would answer questions about the following rf linac accelerator design issues:

a. Front End
   - Source and column characteristics, reliability
   - RF capture, low beta acceleration, current limitations
   - Stripping efficiency, charge selection, rematching, recapture (longitudinal emittance control)
   - Beam combination, frequency transition (longitudinal emittance control)
   - Six-dimensional emittance growth
   - Transport limits of high space charge beams
b. Storage Rings
   - Debunching (but not significant, unless linac gets to 100 MHz)
   - Injection (efficiency, emittance growth, effect of beam loss)
   - Beam lifetime - charge changing cross sections
   - Filling both transverse phase planes (transferring from one ring to another with phase rotation)
   - Internal beam rf compression (beam handling above space charge limit)
   - Extraction efficiency, reliability (effects of beam loss)
   - Demonstrate adequate vacuum technology under operational conditions
   - Feasibility of single pulse synchrotron acceleration (optional; see below)
   - Reliability of superconducting magnets in ring under operating conditions (optional)
c. Extracted Beam
   - External Compression
     - Demonstrate acceptable dilution of longitudinal emittance
     - Provide short pulse duration for transport, propagation, focussing, and deposition demonstrations
     - Demonstrate compression of successive pulses with ringing compressor for charge state telescoping
   - Transport
     - Check instability theory (transport power limits)
     - Inject beams into common beam line for telescoping (essential for Phase II upgrade)
   - Splitting
     - Demonstrate acceptable emittance dilution
     - Demonstrate survivability of splitter
     - Demonstrate multiple splittings (two or more in each plane)
   - Focussing on target spot
     - Demonstrate ultimate achievement of expected emittance
     - Aberration corrections; chromatic and geometric in the presence of space charges

Important additions, not covered in our minimum plan, would include:

Mercury option (dedicated effort to establish reliability) preaccelerator and special column	$1.5 M
Isotope telescoping, ganged column	0.5
High frequency transition, 10 MV 100 MHz Alvarez	1.0
Synchrotron option, vacuum and rf	1.5
Ganged focussing system, clustered quadrupoles	0.5
	$5.0 M

TABLE I.B.1. HIF ACCELERATOR ISSUES

	LIA	RFL
"Source" Qualification	Front end (drift tube linac)	Front end (low velocity linac)
Accelerator Demonstration	Established for electrons; needs demonstration for ions: - feasibility (longitudinal phase space) - cost - reliability	Established for protons; needs demonstration for heavy ions with q/A << 1: - beam manipulation (n,ε) - beam loss effects (vacuum, reliability (How cost effective and reliable are systems which solve these?)
Pellet, Reactor Related Questions that Affect Accelerator Design for Drivers:	Transport; Focussing; Plasma Instabilities; Target Coupling (Common to either system; need be demonstrated on one only.)	

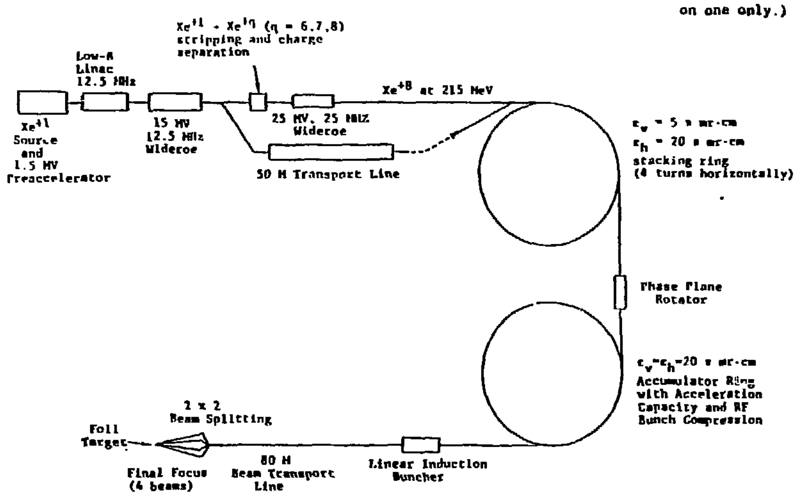
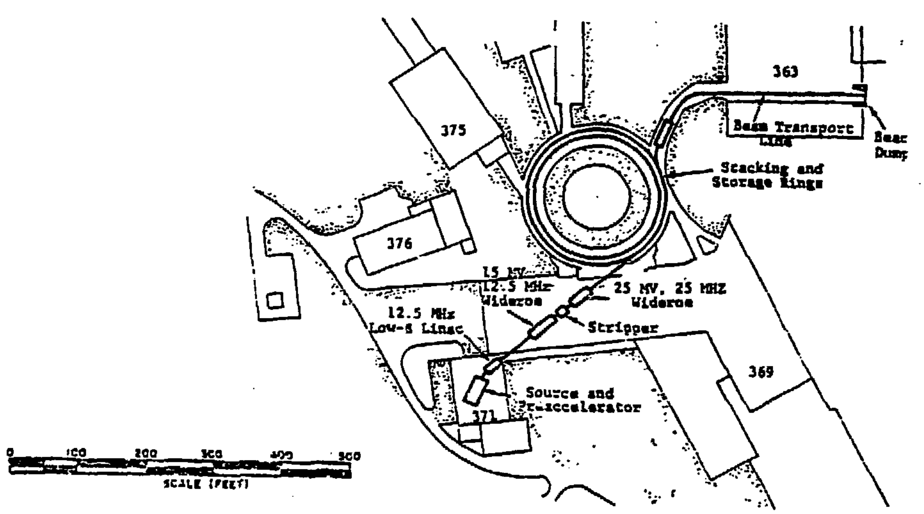


FIGURE I.B.1
Minimal (1980-1982) RF Linac R&D

FIGURE I.B.2
Site Layout for Minimal RF Linac R&D



2. Full Driver R&D: The ADF (Phase I)

Questions of final transport and focussing, questions of plasma instabilities in a gas, and the target coupling of heavy ions are common to both systems and need be investigated by only one system. Transport of space charge dominated beams to verify the theoretical calculations (and computer simulation) of instabilities and emittance growth should he carried out at each ion energy in which it is feasible to do so. The credibility of the application of the results to the heavy ion fusion application, however, increases as the current gets higher. Consequently, it is important to do such experiments at as high an energy and beam current as practicable in the accelerator demonstration phase.

Likewise, the questions of final focus--focussing to small spot sizes in order to see effects of chromatic and geometric aberrations--requires small beam emittance. To have sufficiently intense beams to involve space charge forces at the same time again requires as high an ion energy as practical, although focussing experiments may be carried out at any available energy. Such experiments, in fact, are one of the better ways of measuring the emittance of the beam.

Verification of the theories of plasma instabilities and their effect on the beam are very important. The results impact very strongly on the design of reactors for heavy ion fusion and, hence, are useful to the overall program before the ETF is operational. If the pressure window through which final transport can take place without difficulty does exist, then the reactor design can be significantly simplified. In order to verify these theories, one must be able to adjust conditions appropriate to excite and study filamentation, two-stream, hose, and reverse current instabilities. This criteria places certain minimum limits on beam current and, hence, ion energy because of current limitations due to space charge forces. Argonne's Phase I accelerator demonstration program is designed with the above goals in mind. It requires a total expenditure of around $60 M (including EDIA, escalation, contingency, and parallel R&D).

The ADF can, however, be considered as an extension of the basic (minimal) rf linac R&D program and can utilize the equipment constructed for that purpose so the additional costs are reduced to about $40 M. Basically, a higher energy linac (≈100 MV) is required to allow much more circulating ring current and stored energy. The facility layout is shown in Fig. I.B.3; an artist's conception was shown in the summary of this report. The operational goals are given in Table I.B.2, and the next two tables give experimental parameters.

A prototype I MJ ETF (based on rf linac design similar to HEARTHFIRE Reference Concept No. 2 as described in the 1978 HIF Workshop Proceedings) is sketched in Fig. I.B.4.

In Table I.B.5 we compare beam handling parameters for the following three cases:

Minimal RFL R&D equipment
ADF (Phase I): realistic currents
ETF (1 MJ RFL driver)

Note that the stored currents in the ADF are much closer to those of the ETF compared to those attained in the minimal R&D program. Thus, higher confidence in beam handling techniques can be achieved in the ADF.

3. Upgrade of the ADF to HIDE (An Option for Rapid Progress toward HIF Pellet Experiments)

One very exciting possibility is the practicality of proving the viability of achieving pellet ignition and pellet gain with heavy ions at a very early date with the help of existing facilities at the ZGS site. It now appears possible to achieve 200-500 kJ, at a deposition of 20 MJ/g, by utilizing the concept of telescoping beams of different charge states, accumulating large emittance beams, and splitting them to several beamlets in the final transport line, and possibly single pulse acceleration in the accumulator rings.

The feasibility and cost (initial estimates are $150 M, without EDIA, contingency, and escalation) of such a facility is presently being studied. If feasible, such a program could greatly accelerate the inertial confinement fusion program, without biasing a choice between the two types of linacs for further development or construction of an engineering test facility at a location at which the development could expand into the demonstration plant.

We show in Fig. I.B.5 the logic of the program which includes such a facility.

The decision as to whether one might proceed in this manner or shift to a new location for an ETF which has the capability of evolving to the 10 MJ capability and demonstration power plants does not have to be made at this time. Nevertheless, it seems highly desirable to provide the flexibility to go to Phase II if that option should appear advantageous in the future.

4. Overall HIF Program Scenario

In this plan (Fig. I.B.6) we indicate the Phase II HIDE option in the context of the "agressive" ETF schedule and some of the parallel ICF reactor issues.

TABLE I.B.2

PHASE I & II GOALS

Driver Technology	Beam Properties	Target Interactions	Beam Propagation
	Phase I (ADF)		
Acceleration	Beam Energy	Deposition	Neutralization
0.1 A Linac	5-10 kJ	1 MJ/g	Charge
10 A Ring	Beam Power	> 50 eV	Current
Accumulation	2-4 TW	Slab Hydro	Instability
Fast Extraction	Particle Energy		Filamentation
Pulse Compression	1-6 GeV		Two Stream
Transport	Beam Quality		Reverse Current
Focus	5 mrad cm		Hose
1 mm Radius			
	Phase II (HIDE)		
	Beam Energy	Deposition	
	200 kJ - 500 kJ	20 MJ/G	
	Beam Power	Compression	
	50 TW	Significant Neutron Yield; G ≥ 1	

PHASE I

ENERGY DEPOSITION EXPERIMENTS:

XE^{+8} BEAM, 10 NS PULSE,

PB FOIL THICKNESS ≈ RANGE

TEMPERATURE ACHIEVED IN DEPOSITION VOLUME:

BEAM ENERGY

SPOT DIAMETER	1.6 GeV/1 KJ (.05 MM. FOIL)	6.4 GeV/8 KJ (.5 MM. FOIL)
2 MM.	35 eV.	100 eV.
1 MM.	75 eV.	(200) eV.

[CALCULATIONS BY KMSF]

Table I.B.4

INSTABILITIES	TO STUDY, WHAT DO WE NEED?	CAN WE STUDY?	DIAGNOSTICS
FILAMENTATION	1) Focused beam 2) Large [illegible] ratio 3) Variable background pressure and gas. 4) Small port radius and long chamber. 5) Neutral and preionized gas conditions.	N_e = 6.5 Doubles the emittance	1) Schlieren technique using lasers and proton beams. Laser will measure density fluctuations. Proton beam will measure electric & magnetic field fluctuations.
TWO STREAM	1) Focused beam 2) Variable background pressure and gas. 3) [illegible]	N_e = 21	1) Schlieren technique using laser and proton beams. 2) Laser scattering
REVERSE CURRENT	1) Focused beam	Depends critically on the ratio [illegible] giving greater growth as this ratio increases.	1) Schlieren technique using laser and proton beams. 2) Laser scattering
HOSE	1) Focused beam 2) Variable background pressure 3) Small emittance	N_e = 8	1) Schlieren technique using laser and proton beams. 2) Laser scattering 3) Segmented activation & thin metal foils.
OTHER			
CURRENT NEUTRALIZATION	1) Focused beam 2) Neutral and preionized gas conditions. 3) Variable background pressure and gas.	Current neutralization can be studied by varying the type of chamber gas & by varying the gases ionization state.	1) Faraday cups 2) Rogowski coils
MULTIPLE SCATTERING	1) Variable background pressure and gas	Multiple scattering can easily be studied by varying the chamber pressure	1) Segmented activation foils 2) Lucite plates

Table I.B.3

Beam Propagation Experiments

TABLE I.B.5. COMPARISON OF PARAMETERS

	RF Linac: Minimal R&D	RF Linac ADF	1 MJ RF Linac Driver
Ion	Xe	Xe	Hg
No. Sources	1	2	2
Source Current	40 mA	40 mA	60 mA
Preaccelerator Voltage	1.5 MV	1.5 MV	1.5 MV
Stripping Energy	~ 15 MV ($Xe^{+1} \rightarrow Xe^{+8}$)	~ 15 MV ($Xe^{+1} \rightarrow Xe^{+8}$)	~ 20 MV ($Hg^{+1} \rightarrow Hg^{+8}$)
Linac Current	I_L = 40 mA (maximum)	I_L = 100 mA (electrical)	I_L = 128 mA (electrical)
Normalized Emittance at Linac Output	ϵ_n = 0.10	ϵ_n = 0.10	ϵ_n = 0.10
Ion Kinetic Energy	0.21 GeV	1.6 GeV	20 GeV
No. Turns, Transverse Stacking	16 (2 steps)	25 (2 steps)	256 (4 steps)
Circulating Stored Current	0.2 A	2.2 A (electrical)	24 A (electrical)
RF Bunch Compression	x 5	x 5	x 5
Linear Induction Bunching	x 20	x 40	x 15
Peak Current in Transport Lines	20 A	440 A	3500 A
Focussed Emittance	ε = 10π mr·cm	ε = 5π mr·cm	ε = 4.4π mr·cm
Spot Size	r = 2 mm	r = 1 mm	r = 1 mm

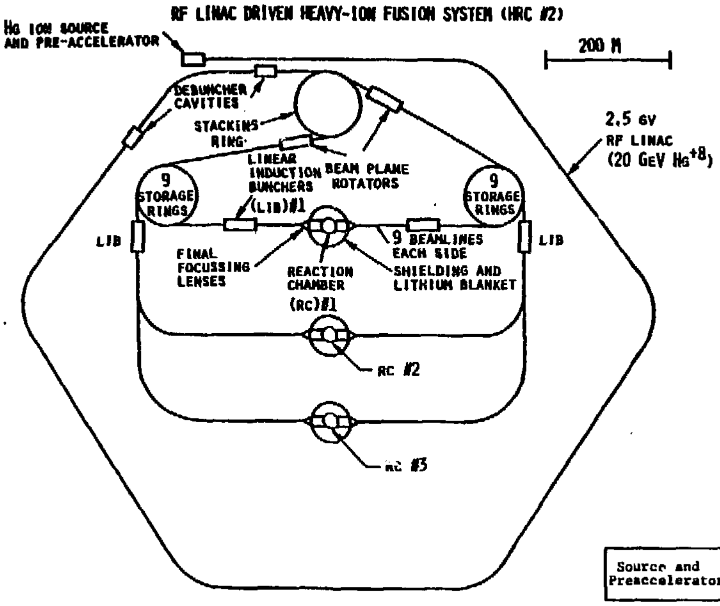


Figure I.B.4

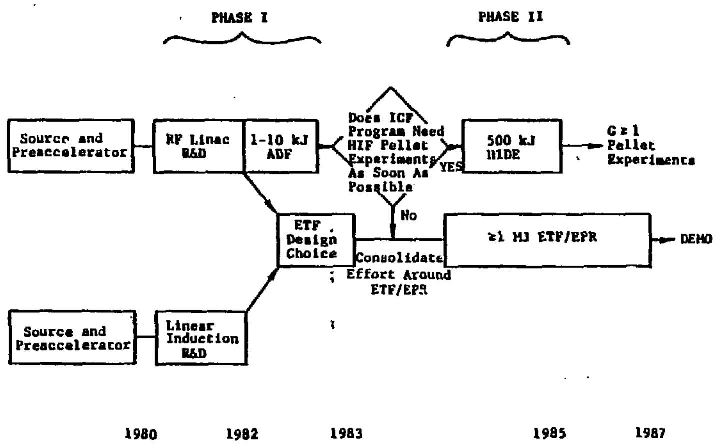


FIGURE I.B.5
Development Logic for Aggressive HIF Program Scenario

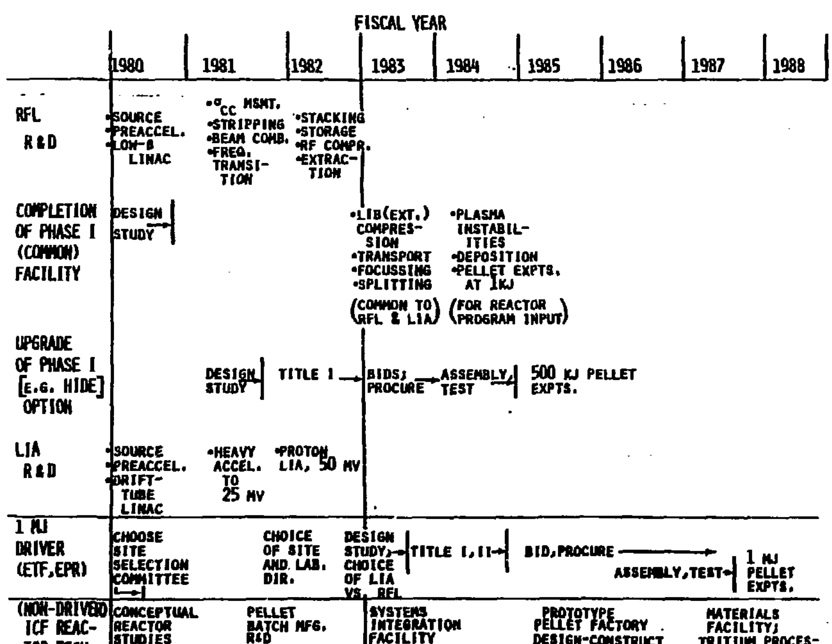


Figure I.B.6

V. Abstracts of Publications, FY 1979

Heavy Ion Beam Inertial-Confinement Fusion
Review Article - Nature, Vol. 276 (11/2/78), Page 19
by: R. Arnold

This is a survey article covering the current status of inertial-confinement fusion driven by heavy ion acclerator systems. Although developed only since 1975, system designs of this type appear to provide a convincing basis for developing commercial power from inertial-confinement fusion.

Abstracts of Papers Presented at the 3rd International Conference on High Power Electron and Ion Beam Research and Technology, July 3-6, 1979 at Novosibirsk, U.S.S.R.

Status of the Argonne National Laboratory Heavy Ion Fusion Program
by: R. Martin and R. Burke

Abstract

We have recently been successful with accelerating 50 mA of Xe^{+1} to 1.1 MeV in our modified Dynamitron in a pulse 100 μsec long. We anticipate conditioning the column to 1.5 MeV and bunching and accelerating the beam to 2 MeV in the first stages of the low velocity linac within the next few months. On the basis of the recommendations by a national committee (Foster II) reviewing inertial confinement fusion drivers, support for the heavy ion fusion program will be significantly increased in the next fiscal year with a view toward a choice between the two competing systems, rf linac with accumulator rings and induction linacs, in 1982 or 1983. Argonne has proposed a development program which will demonstrate by this time (at a relatively low current level) all the accelerator technology involved in the ignition source for a fusion power plant. The plan includes an interesting new concept of telescoping beams of different charge states with the same magnetic rigidity into the same beam line to reduce the number of beam lines otherwise required. The status and plans of the Argonne program will be reported.

The Use of Multiple Ion Species in Accelerator Systems for Heavy Ion Fusion
by: R. Burke

The concept of telescoping beams simultaneously utilizes a number of heavy ion species to improve the performance of accelerator systems for heavy ion beam induced inertial fusion. In the concept, the various species are individually accelerated over a sequence of rf linac pulses, injected into storage rings, and prepared into bunches with the characteristic short duration needed for inertial fusion. The condition for telescoping, that the different bunches have different velocities but a common magnetic stiffness, are met by a consistent adjustment of the mass, charge state, and velocity of the different species. Thus, after extraction from different storage rings, the bunches may be sequentially switched into a common beamline. They then overtake one-another to arrive simultaneously at the fuel pellet. Some of the advantages of telescoping are as follows. Increasing the number of beam bunches that may be used with a given number of beam lines expands the total usable volume in six dimensional phase space, since each bunch may occupy the maximum volume permitted by the focusing requirements. The expanded usable volume in phase space allows the various operations from source to target to involve more emittance dilution. Space charge problems during beam transport are alleviated since the peak power in each beam only arises during the final portion of the transport distance, with substantial power multiplication during the flight through the reactor chamber. The beam pulse may be power shaped to achieve higher pellet imposion efficiency, and the efficiency may be further improved by capitalizing on the changing range of the sequentially-arriving species. An accelerator system will be described that shows that telescoping also decreases the size and cost of the accelerator system by permitting designs using shorter linacs, fewer storage rings, shorter and fewer beam compressor sections, and a small number of long drift lines for bunch collapse.

Abstracts of Papers Presented at the 1979 Particle Accelerator Conference
at San Francisco, California
March 12-14, 1979

Published in the IEEE Transactions on Nuclear Science, Vol. NS-26, No.3, June 1979

A Minus-I Quadrupole System for Containing Aberration-Correction Octupoles
by: S. Fenster (p. 3034)

Abstract

Octupoles may be used to correct the third order spherical aberration of quadrupole transport systems. Crosstalk in the coupling of an octupole placed at a given point causes it to add a term with the wrong sign in the y-channel if it has the right sign in the x-channel, thus severely reducing efficiency. It is often convenient to utilize a special correcting section insertion which is seen as a +I transfer matrix by the first order focusing. Within point-to-point thin lens optics we give two-parameter systems with 16 magnets having locations with large S_x where $S_y = 0$ and vice versa for octupole placement.

Transport Experiments with Neutralized and Space Charge Dominated Deneutralized 2 mA 80 keV Xe^{+1} Beams (p. 3042)
by: M. Mazarakis, R. Burke, E. Colton, S. Fenster, J. Moenich,
D. Nikfarjam, D. Price, N. Sesol, and J. Watson

Abstract

The Argonne National Laboratory Ion Beam Fusion Group is presently studying the transport and charge neutralization of beams of heavy ions using a small PDPE (Penning Discharge Pierce Extraction) ion source. This source is a scaled down version of the high current high brightness source of the 1.5 MeV Heavy Ion Preaccelerator. Both sources were developed by Hughes Research Laboratories.

This report gives results obtained with a low vacuum system (up to 5 x 10^{-7} Torr static vacuum) and an 80 keV dc Xe^{+1} beam. The emphasis of these measurements was on neutralization times and space charge blow up of the beam.

A 12.5 MHz Heavy Ion Linac for Ion Beam Fusion (p. 3045)
by: A. Moretti, J. Watson, J. Moenich, M. Foss, T. Khoe, E. Colton, and R. Burke

Introduction

Argonne National Laboratory (ANL) is currently developing the injector of a heavy ion beam driver for the inertial confinement fusion program. The first phase of the program is to accelerate about 20 mA of Xe^{+1} from a 1.5 MV preaccelerator to 11.4 MeV in a low-beta rf linac. The first section of the linac utilizes a single harmonic buncher and independently-phased short linac resonators with a FODO magnetic quadrupole focusing lattice. These are followed by two double-stub Wideröe linacs. A layout of the linac up to 6.4 MeV is shown in Fig. 1. The operating parameters of the low-beta linac are given in Table I. This paper gives details of the low-beta linac design and results of low power measurements on the first accelerating cavity.

Telescoping Beams for Heavy Ion Fusion (p. 3092)
by: R. Burke

Abstract

In addition to the strong longitudinal compression and multiple beams now used in all designs for heavy ion fusion drivers, attaining the required beam power could be helped by telescoping bunches of different ion species. Telescoping is here defined as the overtaking and interpenetration of bunches consisting of ions of different species but whose velocity, mass, and charge state have been selected so that the typical ions in the various bunches have the same ratio of momentum to charge, or magnetic rigidity, and, therefore, the same single particle dynamics in transport and focusing lines. With velocities differing by 10% or more, the highest powers would only arise close to the end of the transport lines. Telescoping also increases the total available phase space of the different species. This can be translated to a smaller final momentum spread or a means to accommodate greater phase space dilution.

A High Intensity 1.5 Megavolt Heavy Ion Preaccelerator for Ion Beam Fusion (p. 3098)
by: J. Watson, J. Bogaty, R. Burke, R. Martin, M. Mazarakis, K. Menefee, E. Parker, and R. Stockley

Abstract

A preaccelerator is being developed at Argonne National Laboratory (ANL) in a program to demonstrate the accelerator technology which will be needed for power plants utilizing inertial-confinement fusion (ICF). The preaccelerator has been constructed and is now undergoing performance tests with the initial objective of achieving pulsed 30 mA beams of 1.5 MeV Xe^{+1}. The design, construction, and initial performance of the preaccelerator are described.

Buncher Cavity Resonant at the First and Second Harmonic (p. 3104)
by: M. Foss

Abstract

A buncher is an rf accelerator followed by a drift space. Its purpose is to bunch the dc ion source beam into suitable bunches for acceleration in a linac. The voltage in a simple buncher is a sine wave at the linac frequency. A more elaborate wave form can result in increased capture of ion source beam. The cavities discussed here are resonant at 12.5 and 25 MHz, the first and second harmonic of the Argonne National Laboratory (ANL) low beta linac. They will support a wave form which should give improved bunching. Three designs are given to compare their relative merits.

A Noninteractive Beam Position and Size Monitor for Heavy Ions (p. 3349)
by: J. Bogaty

Abstract

The Ion Beam Fusion Development Program at Argonne National Laboratory requires noninteractive size measurements of a pulsed, 30 mA, Xe^{+1} particle beam. Pulses of 100 μs duration will be produced by the 1.5 MV preaccelerator; therefore, fast response diagnostics are required. Techniques of utilizing residual gas ionization to profile particle beams have been reported before. This paper discusses the development of vertical and horizontal beam profile monitors that are synchronously clocked to interface with oscilloscopes and computers. Modern integrated circuitry is utilized which boosts performance to a point where pulses are short as 20 μs can be analyzed. A small, simple ionization chamber is shown which provides sixteen channels of position resolution over 12 cm of aperture.

A Rapid Cycling Synchrotron Magnet with Separate AC and DC Circuits (p. 4201)
by: R. Burke and M. Foss

Abstract

In present rapid cycling synchrotron magnets, ac and dc currents flow in the same coil to give the desired field. The circuit reactance is made zero at dc and the operating frequency by running the magnet in series with an external parallel resonant LC current. We propose to return the ac flux in a gap next to the synchrotron. The dc coil encloses the ac magnetic circuit and thus links no ac flux. A shortened turn between the dc coil and ac flux enhances the separation of the two circuits. Several interesting developments are possible. The dc coil could be a stable superconductor to save power. The ac flux return gap could be identical with the synchrotron gap and contain a second synchrotron. This would double the output of the system. If the return flux gap were used for a booster, the ac coil power could be greatly reduced or radiation hardening of the ac coil could be simplified.

VI. ANL Ion Beam Fusion Notes Written During FY 1979*

Beam Splitting, Telescoping Beams, Chromatic Corrections, and Synchrotrons (IBF Note #83, 10/23/78)
by: R. Burke

It may be possible to make a practical synchrotron system by taking several steps that maximize the space charge limit. Compared to the synchrotrons in HRC #3, the steps to maximize the space charge limit would be to increase the transverse emittance and the bunching factor.

Some Thoughts on How to Hit the Pellet (IBF Note #87, 11/2/78)
by: E. Colton

An aiming scheme is needed to track the pellet and hit it with a number of beams simultaneously at the center of the reaction chamber. It should be possible to adjust the beam intersection point by correcting dipoles so as to be "on target" when the pellet reaches the distance of closest approach to the reaction chamber center.

Electrostatic vs Magnetic Quadrupoles (IBF Note #88, 11/2/78)
by: E. Colton

Multiturn Resonance Injection (IBF Note #89, 11/8/78)
by: H. Takeda

Multiturn resonance injection suggested by T. Khoe, et al., is pursued further for Xe^{+8}, 20 GeV beam injected into 30 m, effective radius R storage ring. By introducing perturbative dipole and sextupole field, the phase space admittance ellipse of the storage ring is distorted to have two equilibrium orbits.

Conceptual Design of the Wideroe Linac (IBF Note #90, 11/29/78)
by: T. Khoe

* This list is included to provide a survey of the topics investigated at ANL during FY 1979. The reports themselves are informal and not generally circulated.

Charge States of Projectile and Background Gas Ions (IBF Note #91, 12/20/78)
by: Y. Kim

Earlier studies have indicated possibilities of damping plasma instabilities inside a fusion reactor by introducing a background gas of $\sim$ 1 Torr pressure. Atomic data (e.g., charge states of the beam, average kinetic energy of ejected electrons, ionization cross-sections) are used in estimating plasma parameters (conductivity, plasma temperature, etc.) that govern beam-plasma interaction. In this note, we discuss (A) expected charge states of the beam, (B) selection of the background gas, and (C) identification of the projectile and gas ion charge states by optical and mass spectrometry.

Target Experiments: Suggestions from the University of Rochester (IBF Note #92, 12/20/78)
by: G. Magelssen

Target Experiments (IBF Note #93, 12/20/78)
by: G. Magelssen

Introduction

One of the target experimental goals is to determine the ion deposition of 1.6 GeV Xe in a hot (100 eV) plasma. A possible approach, and the one considered here, is to heat a target of solid material with the ion beam to temperatures on the order of 100 eV. The experiments would be performed with constraints on the total energy and power. The total energy of the 1.6 GeV Xe beams would be about 1 kJ. This energy would be delivered in roughly 10 nsec to a spot size greater than or equal to 0.5 mm radius. To achieve temperatures of 100 eV, a number of energy losses must be overcome.

Transport of 1.6 GeV Xe^{+8} Beam Through a Background Gas (IBF Note #94, 12/20/78)
by: G. Magelssen and M. Mazarakis

The plasma instabilities which can occur during beam propagation depend on the background density, temperature and charge state, the plasma electrical conductivity, and beam charge state. A knowledge of the beam density structure (i.e., its structure transverse to the direction of propagation) before entering the gas chamber will also be important to the understanding of the experimental results. A description of the diagnostics which are needed for the beam propagation experiments are given below.

What Influence Does the Beam Propagation in a Gaseous Chamber Have on a Heavy Ion Beam Reactor? (IBF Note #95, 1/31/79)
by: G. Magelssen

Final Report on ANL-IBF Preaccelerator Power Supply (IBF Note #96, 1/25/79)
by: J. Bogaty

Preliminary Design Parameters of the Wideroe Linac (IBF Note #97, 2/15/79)
by: T. Khoe

Argonne Beam Propagation and Target Experimental Program for Proposed Heavy Ion Facility (IBF Note #98, 4/18/80)
by: G. Magelssen

To insure a complete understanding of the target physics, we belive it is important to begin to develop experiments which test existing classical theories of ion coupling of hot dense plasmas and to have theoretical support for interpretation of the experiments. Also, because of a possible imcomplete understanding of transport processes within targets irradiated by ion beams, we believe it is important to do experiments as early as possible to study transport phenomena.

Of at least equal consequence will be experiments which test theories of beam propagation and focusing. Besides testing the design of compensated focusing elements (i.e., correcting geometric and chromatic aberrations), it is important to check existing theories of beam propagation in a reactor chamber environment.

Quadrupole Line Segment for 1.6 GeV Xe^{+8} Bunches Undergoing 8X Compression (IBF Note #99, 3/15/79)
by: S. Fenster

This note describes the design of a particular segment of the Phase I quadrupole line located downstream from a battery of bunchers at the storage ring exit and upstream of an aberration correction section for final focusing.

Four Dimensional Phase Space Consideration (IBF Note #100, 4/4/79)
by: H. Takeda

When we consider two dimensional injection (x plane and y plane) in configuration space (x-y phase space) where x and y are horizontal and vertical displacement of beam, we need to know how we should handle a four dimensional phase space point.

Bunching and Acceleration of a 20 mA Xe^{1+} Beam in an RF Quadrupole Structure (IBF Note #101, 4/13/79)
by: T. Khoe

Space Charge Effects on the 80 KeV, 1 mA Xe Beam at Argonne (IBF Note #102, 5/18/79)
by: G. Magelssen

Argonne is currently doing charge neutralization and deneutralization experiments with a 80 KeV, 1 mA Xe beam. In this note we explain the observed beam blowup which occurs after beam deneutralization.

Heavy Ion Deposition in Hot Dense Plasma (IBF Note #103, 5/3/79)
by: G. Magelssen

Argonne has proposed to study experimentally the energy transfer from heavy ions to hot dense plasmas. The purpose of this note is to motivate both experimental and theoretical work in this area.

Notes on the Design of an Acceleration Tube (IBF Note #104, 10/5/79)
by: A. Langsdorf

This note sets forth a set of concepts on how to design a practically buildable acceleration tube incorporating many of the features now believed to be important to achieve the best possible performance under realistic conditions.

Dilution and Efficiency Calculation in Four Dimensional Phase Space
(IBF Note #105, 5/9/79)
by: H. Takeda

Beam Transport of 1.6 GeV Xe^{+8} Using 10Q36 and 5Q14 Quadrupoles
(IBF Note #106, 5/18/79)
by: E. Colton

Using the parameters listed in ANL/IBF Note #99 I have set up a 140.5 m long transport time to carry bunched 1.6 GeV Xe^{+8} ions; the line is basically FODO with a zero current phase advance per cell of $\mu_0 = 60^\circ$. The tune depression is never pressed below $\mu = 24^\circ$. Actually the system is changed with each element in order to conform to the increasing current, i.e., quadrupole spacing decreases and gradients increase with distance down the transport line. The results confirm the method of findings of IBF Note #99.

Brightness of Combined Beams (IBF Note #107, 5/21/79)
by: M. Foss

We all recognize that thinking of phase space as a uniformly illuminated ellipse is naive. S. Fenster has pointed out to me that such simple assumptions may lead to a tremendous overestimation of the brightness after beams are combined. T. Khoe points out that some phase space distributions may be unstable.

A Method of Two Dimensional (x-y) Injection (Tune Stacking)
(IBF Note #108, 5/29/79)
by: H. Takeda

We want to perform a high efficiency and low dilution multiturn injection in both x and y plane. In order to achieve this, we need to know what requirements are imposed. Since we are considering stacking of beam ellipse next to each other (allowing overlap), we have to move instantaneous equilibrium orbit IEO (defined as the origin of coordinates of transverse motion).

Heavy Ion Beam Propagation in a Background Gas (Knockon Electrons, Current Nonneutralization, and Beam Profile Effects)
(IBF Note #109, 7/11/79)
by: G. Magelssen

The purpose of this note is to relate some new thoughts regarding heavy ion beam propagation through a background gas. In a previous note we pointed out that the hose, two stream, return current and filamentation instabilities would need to be studied to determine the focusability of a heavy ion beam through a background gas. We also mentioned, but did not elaborate, that beam current nonneutralization could cause focusing problems. Here we examine the nonneutralization problem more carefully. We discuss propagation through a low pressure ($< 10^{-4}$ Torr) chamber. Lastly, some thoughts concerning the generation of knockon electrons by heavy ions are given.

Design Parameters of the Wideroe Linac Quadrupoles
(IBF Note #111, 7/13/79)
by: T. Khoe

Design Parameters for Post Stripper and Elevation Changing System
(IBF Note #112, 7/18/79
by: E. Colton

In Hearthfire Phase Zero we must raise the beam by $\sim$ 54 inches (1.3716 m) in Building 370. The charge selection can also be performed simultaneously. The basic scheme was proposed in Fig. III. A. 12 of the Hearthfire Phase I design report.

Space Charge Tune Change in the Hot Dog Packing Scheme of Multiturn Injection
(IBF Note #113, 7/19/79)
by: G. Bart

It is sometimes thought that the tune change for the radial and the horizontal directions, $|\delta \nu_x|$ and $|\delta \nu_y|$ respectively, both always increase with turns of injection. This is not so in general because $|\delta \nu_x|$ and $|\delta \nu_y|$ are correlated.

Measurements of Neutralization Times of Xe^{+1} Beams in the Energy Region of 40 to 100 keV. Estimation of Ionization Cross-Sections (IBF Note #114, 11/29/79)
by: M. Mazarakis, D. Nikfarjam, and J. Watson

Abstract

This note gives results on the average beam-residual gas ionization cross-sections obtained with the low vacuum transport system (up to 5×10^{-7} Torr static vacuum) by measuring the beam neutralization times. The measurements scanned the beam energy region from 40 to 100 keV.

Phase I Periodic Transport Line to Hearthfire Storage Ring
(IBF Note #115, 7/24/79)
by: E. Colton

We develop a scenario for transport of low energy heavy ions using 20 or more surplus ZGS 10Q36 quadrupoles. The line starts downstream of the elevation changing system (see IBF Note #112) and transverses 40-45 m of distance after which the beam will be injected into the Hearthfire storage ring.

RF Requirements for the Accumulator Ring (IBF Note #116, 8/15/79)
by: T. Khoe

On Multiturn Injection Strategies (IBF Note #117, 8/17/79)
by: G. Bart

Introduction

Documented herein are several schemes for multiturn injection into storage rings to achieve beam stacking in four dimensional phase space. Some of the schemes have been proposed previously, while others are new. Both one-plane and two-plane schemes are considered. Some of the schemes have been studied by computer simulation. Here we provide a theoretical analysis to provide a foundation for understanding the schemes. This we hope will be useful by giving accurate values of dilution factors, for proper interpretation of computer simulations, and for critical comparative evaluations of different schemes.

Quadrupole Requirements for the Revised Gap Voltages
(IBF Note #118, 8/31/79)
by: T. Khoe

Design of the Wideroe Linac Quadrupole Magnets
(IBF Note #119, 9/4/79)
by: R. Lari