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A Brief History of High Power RF Proton Linear Accelerators

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Introduction

The first mention of linear acceleration was in a paper by G. Ising in 1924 (Ref 1) in which he postulated the acceleration of positive ions induced by spark discharges which produced electric fields in gaps between a series of "drift tubes". Ising apparently was not able to demonstrate his concept, most likely due to the limited state of electronic devices. Ising's work was followed by a seminal paper by R. Wideroe (Ref 2) in 1928 in which he demonstrated the first linear accelerator. Wideroe was able to accelerate sodium or potassium ions to 50 keV of energy using drift tubes connected alternately to high frequency waves and to ground. Nuclear physics during this period was interested in accelerating protons, deuterons, electrons and alpha particles and not heavy ions like sodium or potassium. To accelerate the light ions required much higher frequencies than available at that time. So linear accelerators were not pursued heavily at that time.

Research continued during the 1930s but the development of high frequency RF tubes for radar applications in World War 2 opened the potential for RF linear accelerators after the war. The Berkeley laboratory of E. O. Lawrence under the leadership of Luis Alvarez developed a new linear proton accelerator concept that utilized drift tubes that required a full RF period to pass through as compared to the earlier concepts. This development resulted in the historic Berkeley 32 MeV proton linear accelerator which incorporated the "Alvarez drift tube" as the basic acceleration scheme using surplus 200 MHz radar components. This development was key to the future directions for proton linacs (Ref 3).

The first attempt at a very high power linac was made at a branch of the Berkeley laboratory at a former Navy base in Livermore, California. This Livermore RF accelerator was designed in 1948 to produce a continuous wave (CW) beam of protons or deuterons with the goal of producing plutonium by bombarding uranium. This was a challenging project since only 12 MHz RF tubes were available that operated CW. The result was a vacuum tank to hold the drift tubes that was 60 ft in diameter and 60 ft. long as shown in Figure 1. Overcoming some major difficulties they were able to achieve CW currents of 50 mA up to 10 MeV and pulsed currents as high as 225 mA. Later generation accelerators at Livermore, such as the A-48, were able to use smaller cavities as tube development improved; the A-48 achieved 75 mA of protons at 3.75 MeV and 30 MeV of deuterons at 7.5 MeV. This project was abandoned in 1958.

These developments set the stage for the significant advances that were made starting in the mid-1960s until the present time. The remainder of this paper will discuss those advances and how they have lead to the present situation in which routine acceleration (production plants) of proton beams up to 100s of milliamperes can be realistically considered.

The Los Alamos Meson Physics Facility (LAMPF)

In the 1960s there was considerable interest in developing very high intensity beam of pions for nuclear physics studies. These pion "factories" were proposed using both linacs and cyclotrons. In 1967, the U.S. chose to build at Los Alamos National Laboratory an 800 MeV pulsed proton linac with an average current of 1 milliampere for pion and muon research. This accelerator facility, called LAMPF for Los Alamos Meson Physics Facility,

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utilized the earlier work of Alvarez for the design of the "drift tube" linac (DTL) up to 100 MeV (see Fig 2 for a photo of the LAMPF DTL) but required a major advance for energies above 100 MeV.

When drift tube structures are extended to higher energies, the shunt impedance drops and power losses in the cavity become too high to sustain any reasonable efficiency. To overcome this , the LAMPF designers (Ref 4) utilized a clever adaptation of resonant or standing wave structures made up of chains of resonant cavities. Fig. 3 shows a side coupled cavity (SCC) design utilized in LAMPF. This SCC allows one to take advantage of the fact that the even numbered cavities are the only excited cavities in the $\pi/2$ mode and thus are largely free from problems of cavity mistuning. The Los Alamos SCC design cleverly places the odd numbered ("unexcited") cavities out of the beamline and thus allows the on-line cavity to be designed for maximum efficiency.

This SCC design has been in use at LAMPF for the past 25 years in the energy region of 100 to 800 MeV. It has been highly successfully in extending linacs up to the 1000 MeV region. The LAMPF accelerator has been the highest power proton linac in this range operating with a current of 1 mA for the past 15 years.

The Radio-Frequency Quadrupole (RFQ)

An important concept that allowed the consideration of moving beyond average currents of 1 mA to much higher currents in the 100 mA region was the radiofrequency quadrupole (RFQ) first proposed by Kapchinskii and Teplyakov (Ref 5). The RFQ, shown in Fig 4, is a low energy ion accelerator in which both acceleration and transverse, azimuthally-symetric focusing are performed by RF fields.

Traditionally low energy acceleration of ion beams prior to injection into linear accelerators was accomplished by Cockroft Walton accelerators which consists of a ion beam injector floating at high voltage and an electrostatic acceleration column. Space charge forces are strong for low-velocity beams and long transport sections are needed to provide bunching of the beams for injection into the linac. Magnetic lenses are ineffective for focusing low-energy ions so the beam intensity is limited in this type of front end system.

The RFQ, in contrast, uses strong electrostatic focusing a narrow channel. The geometry of the electrodes varies in the RFQ which results in a variation of the transverse and longitudinal electric fields throughout the device. The net effect is to take a DC steady state beam entering the RFQ and to accelerate it and bunch it at the same time while keeping it confined with electrostatic focusing.

The first successful demonstration of the RFQ was described by Stokes et al. (Ref 6)

The RFQ designs have advanced over the past 15 years to the point that they have progressed from a 1 MeV design to 7 MeV designs for the APT system. The Strategic Defense Initiative, that was funded by the Department of Defense, in the time period of 1984 - 1991 was instrumental in advancing this technology rapidly through the Neutral Particle Beam (NPB) program.

A 40 mA, 1 MeV RFQ was designed and built by a team from Los Alamos, Grumman Corp., McDonnell Douglas, and Westinghouse as part of the Beam Experiment Aboard a Rocket (BEAR) project. BEAR was flown in an Aries rocket out of White Sands in July 1989. The RFQ performed excellently in this test above 100 km altitude. The RFQ system was recovered after the flight without significant damage and continued to operate well on the ground. A picture of BEAR payload is shown in Fig 5.

The next major NPB test was the Ground Test Accelerator (GTA) whose goal was to produce a 100 MeV, 100 mA, neutral hydrogen beam, at a duty factor of 6%. The GTA contained a negative H- ion source coupled to a 2 MeV RFQ followed by a 12 MeV cryogenically cooled drift tube linac (DTL). The combination was operated successfully at I12 MeV but the GTA was canceled before it was extended to higher energies.

Other Advances

Drift tube linac technology also advanced during the SDI period through the NPB program. In particular, the development of permanent magnet technology allowed the scaling of the DTL to smaller sizes while maintaining performance. The smaller size allowed reduced weight and size which was critical to rocket- or space-based NPB concepts.

Fig 6 shows the progression in technology from the 1980 period when a DTL was designed with electromagnets for a fusion materials irradiation facility (FMIT) to the NPB advances from a x MHz to y MHz DTL that utilizes different magnetic materials.

This advance was key for SDI but is not crucial for all future high power designs which are not so constrained on size and weight.

Superconducting Radio-Frequency (SCRF) Linac technology

Superconducting cavities have been investigated for use in accelerators for over 30 years. Although both proton and electron superconducting linacs have been built, the electron linacs have received the most development. Superconducting electron linacs differ from proton linacs in that the electrons are relativistic ($\beta = 1$) throughout the entire accelerating structure while protons are much less than the speed of light in the energy range of interest to the applications addressed by the APT technology.

Superconducting technology has been most extensively developed in this country at Cornell University and a the Continuous Electron Beam Accelerator Facility (CEBAF), now called the Thomas Jefferson National Accelerator Laboratory. CEBAF accelerates beams of electrons up to the 4 GeV range at currents in the 500 mA region. CEBAF has developed the engineering capability to produce high accelerating gradients in their superconducting cavities with high reliability. Gradients above 10 MV/meter have been achieved although the average gradient in use at CEBAF is less.

Superconducting technology holds great promise for CW proton linacs because the electricity costs are significantly reduced due to cavity wall losses in the room temperature designs. In the APT program, it has been estimated that superconducting technology could save 20-30% in the electricity bill which is a significant savings - perhaps $20-30M/year for APT. Similarly for ATW SCRF designs, the higher efficiency would translate into an overall reduced cost for implementing these systems to process nuclear waste.

SCRF designs have some advantages for high power proton linacs. The aperture in the SC cavities is much larger than room temperature designs so that concerns over beam halo loss should be significantly reduced. The operation of a SCRF linac should be more flexible in achieving stable operation since the cavities are not subject to tuning shifts from temperature variations as are room temperature designs.

Gradients in the cavities as high as 30 MV/meter have been demonstrated. However, the actual "real estate" gradient is much less due to issues associated with the requirements to get the RF power into the cavities, to maintain low temperatures and to provide for beam focusing elements. Nonetheless, SCRF technology is an important consideration for future high power accelerators

The Future

While it is always difficult to predict scientific advances, there are some developments that are on the horizon that their implementation for high power accelerators in the next 15-20 years seems likely.

As mentioned above SCRF technology is likely to become the technology of choice for many high power applications due to reduced operating costs and more reliable operation. The present RF power sources (klystrons) operate at efficiencies of 58%. Other concepts (e.g., klystrodes) project efficiencies above 70%. This would add another efficiency factor to reduce operation costs which increase the attractiveness of high power accelerator technology for applications discussed in this Symposium.

Other advances involve more efficient designs for the DTLs which allow better beam control in the early stages of acceleration. Theoretical advances in predicting and controlling the beam halo size should allow higher power beams to be produced and allow maintenance of the accelerator without remote handling devices. Such hands-on maintenance reduces down-time and hence increases overall availability of the machine for its application.

References:

1. G. Ising, Arkiv for Matekatik, Astronomi och Fysik, **18**, 1 (25)
2. R. Wideröe, Archiv für Elektrotechnik, **21**,387 (28)
3. L. Alvarez, H. Bradner, J. Franck, H. Gordon, J. Gow, L. Marshall, F. Oppenheimer, W. Panofsky, C. Richman, and J. Woodyard, Rev.Sci. Instr. **26**,111 (55)
4. B. Knapp, E. Knapp, G. Lucas, and J. Potter, IEEE Trans. Nucl. Sci. **NS-12**,159(65)
5. I. Kapchinskii and V. Teplyakov, Pribory I Teknika Eksperimenta **2**,19 (70)
6. R. Stokes, K. Crandall, J. Stovall, and D. Swenson, IEEE Trans. Nucl. Sci. NS-**26**, 3469 (1979)

Figures:

1. Photo of LLNL linac
2. LAMPF DTL
3. SCC diagram
4. RFQ picture
5. BEAR payload
6. DTL progression

Figure 1

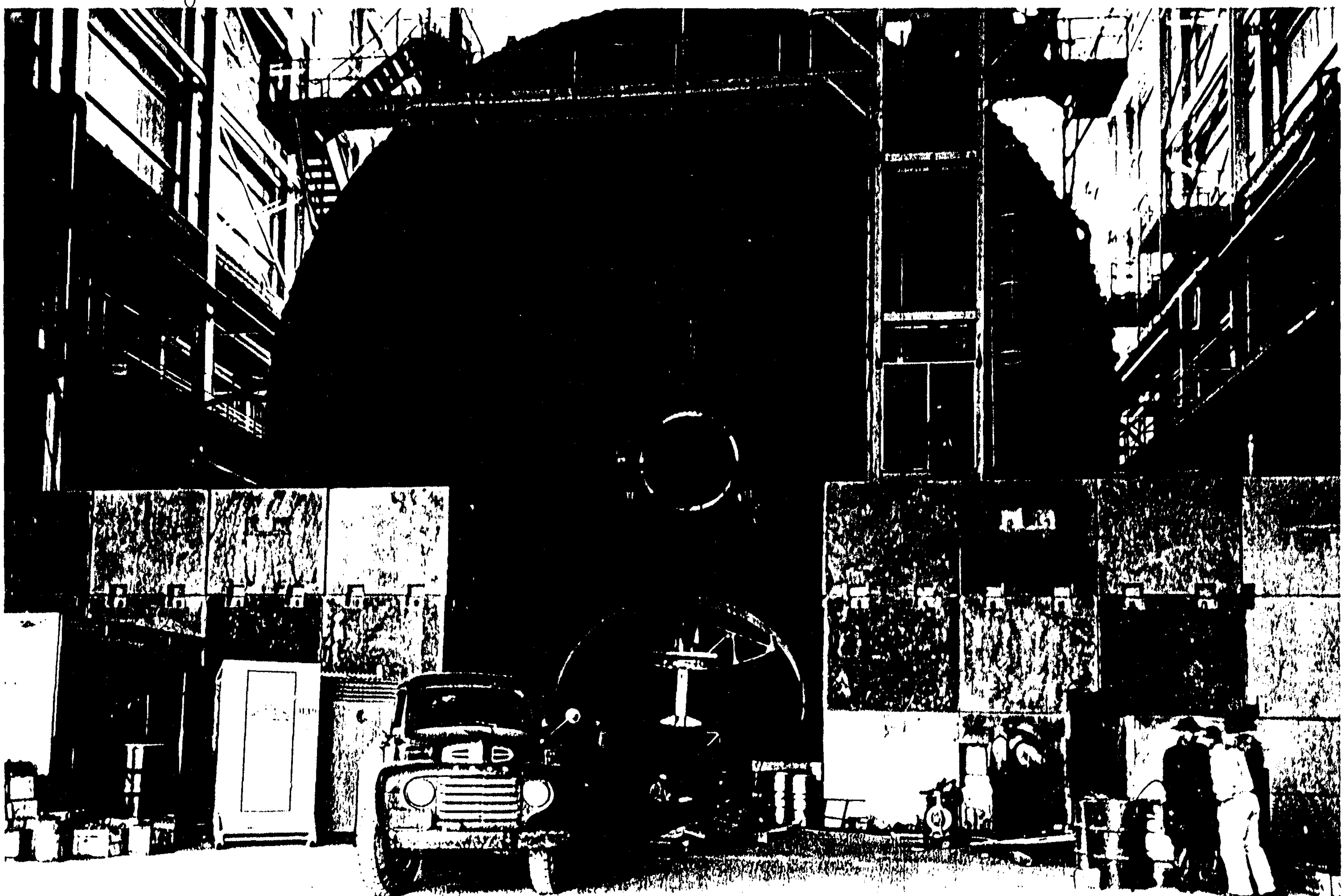


Figure 1

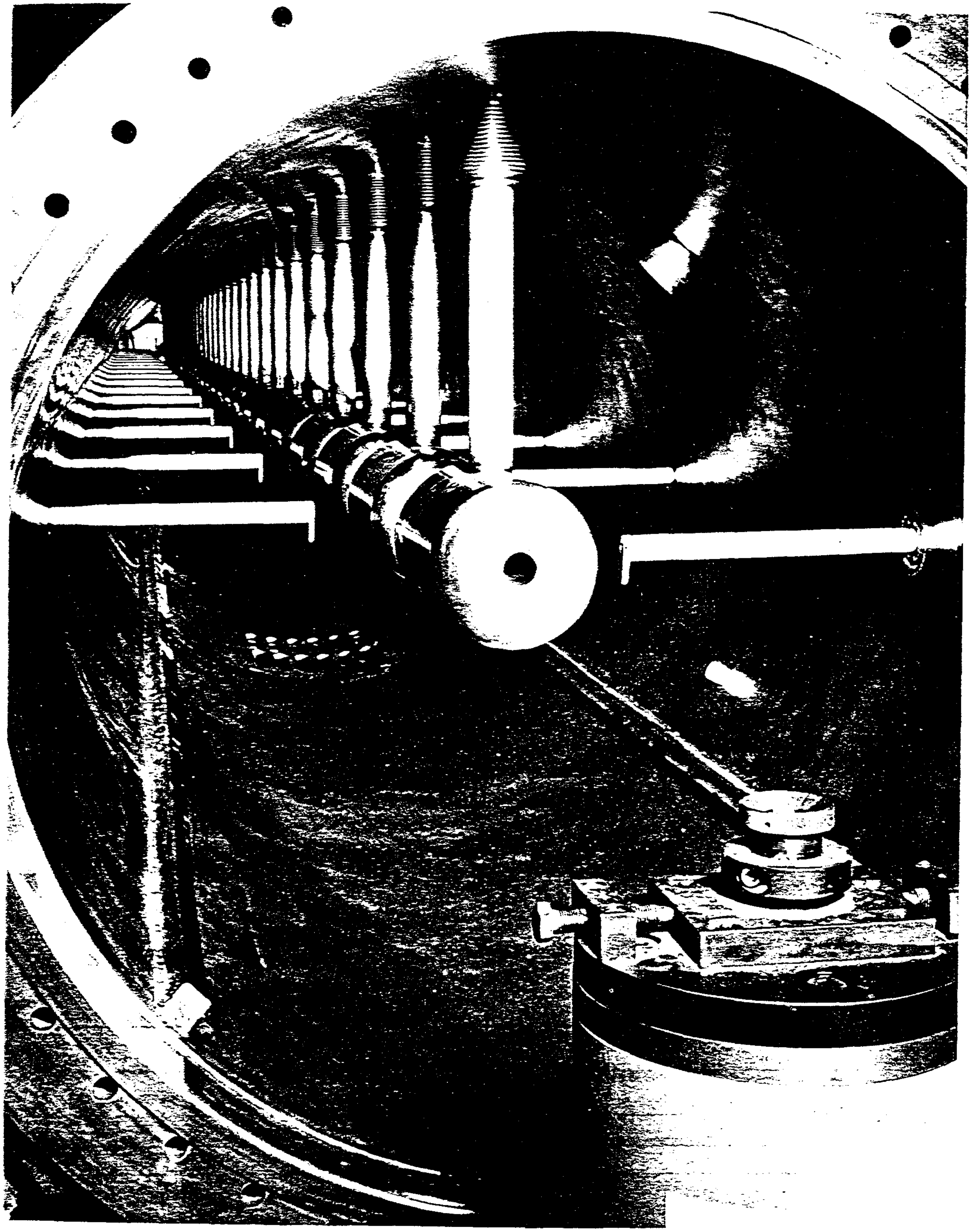


Fig. 2
— *Drift-tube linac, interior view of electrodes.*

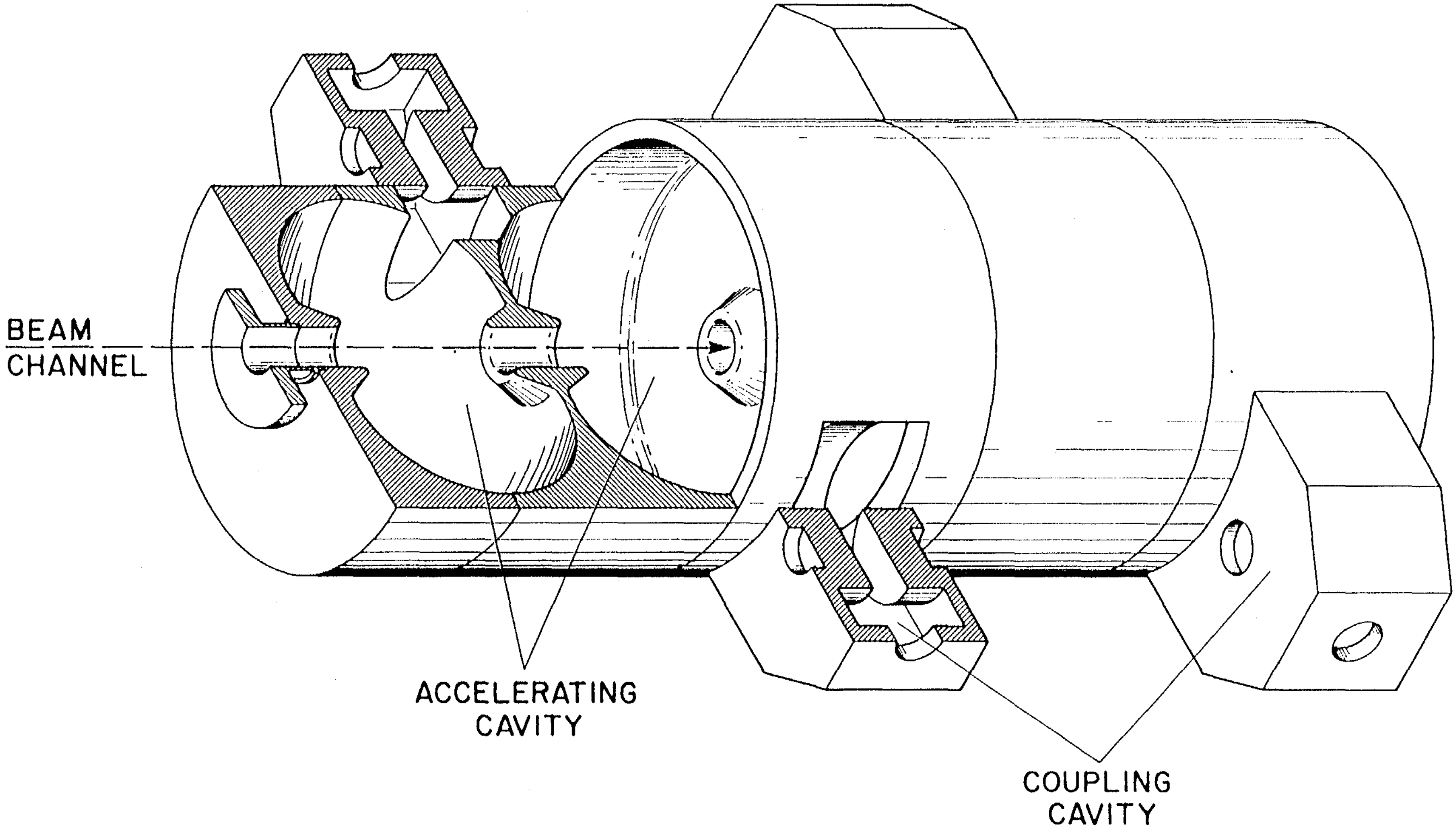
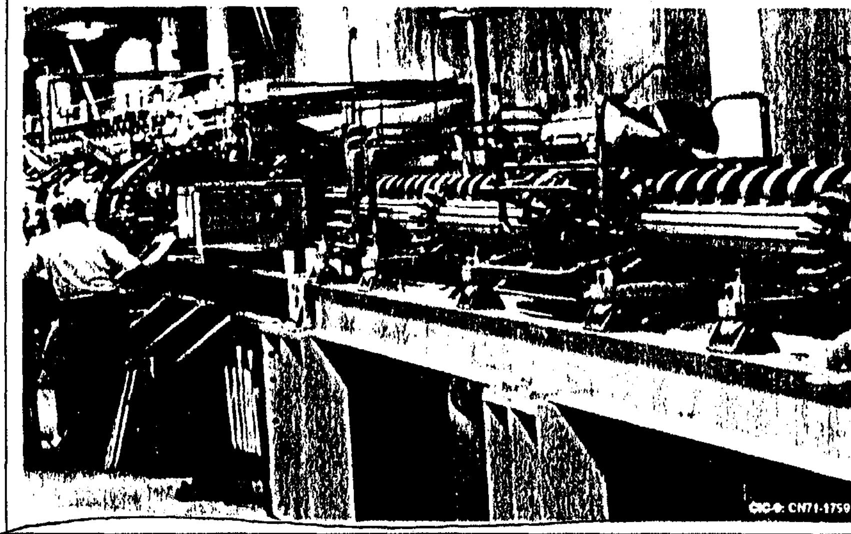
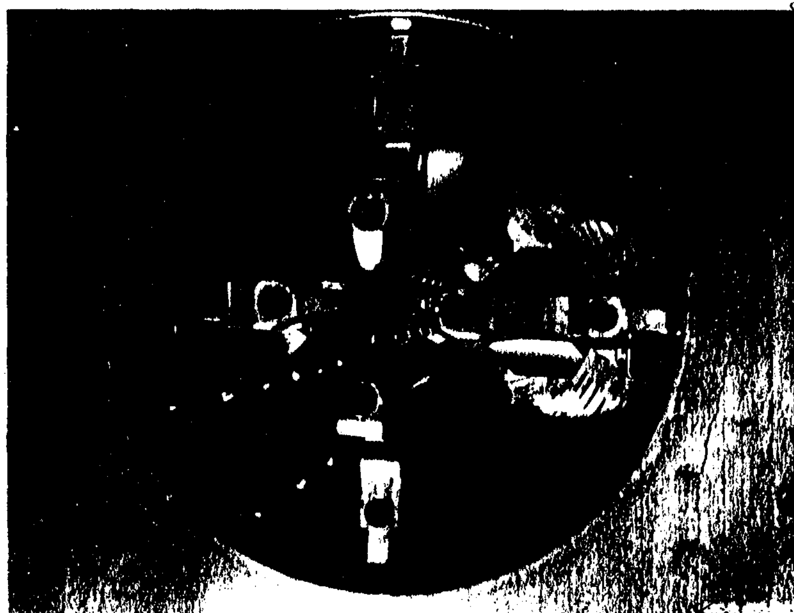
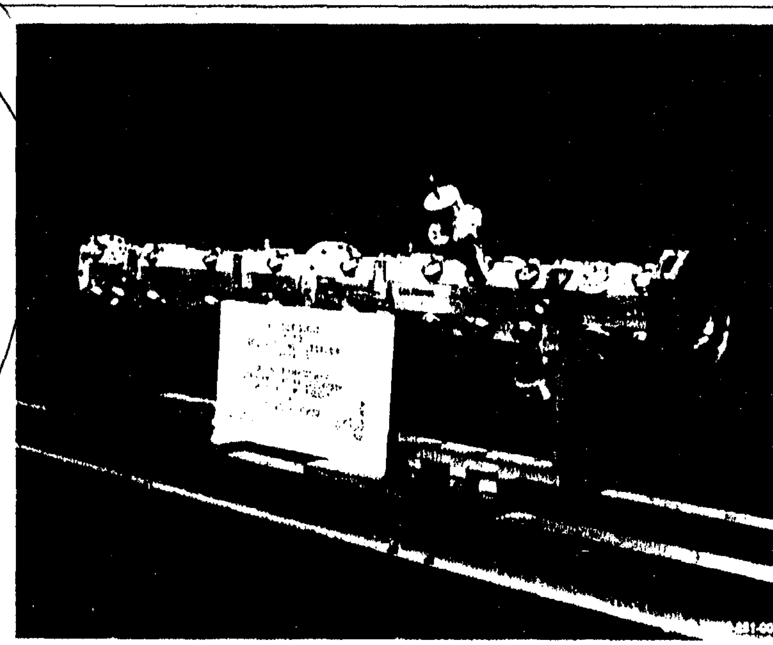


Fig. B
Side-coupled-cavity linac, cutaway section.

LINAC Developments at Los Alamos







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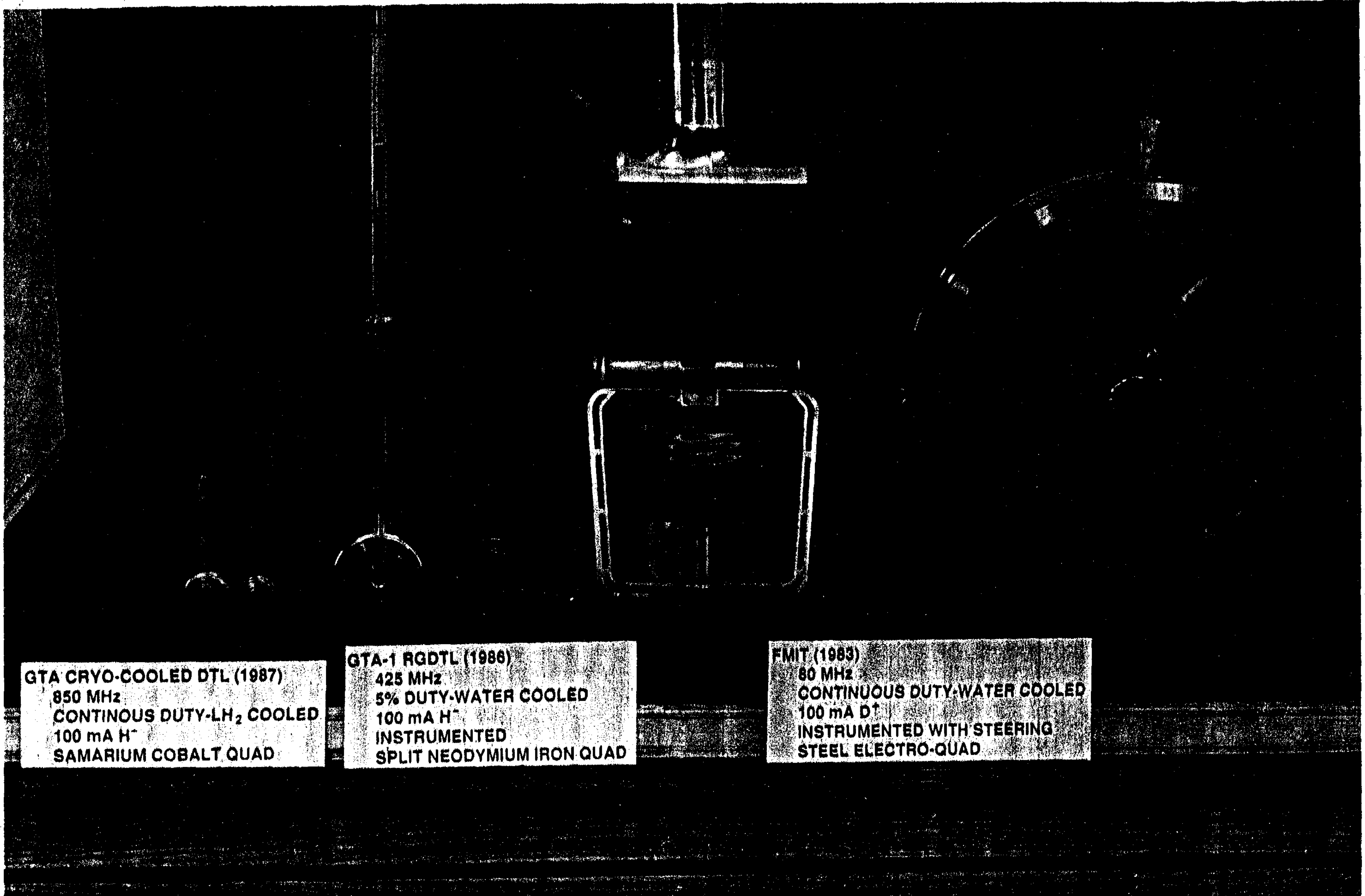
GTA CRYO-COOLED DTL (1987)
850 MHz
CONTINOUS DUTY-LH_2 COOLED
100 mA H^-
SAMARIUM COBALT QUAD
GTA-1 RGDTL (1986)
425 MHz
5% DUTY-WATER COOLED
100 mA H^-
INSTRUMENTED
SPLIT NEODYMIUM IRON QUAD
FMIT (1983)
80 MHz
CONTINUOUS DUTY-WATER COOLED
100 mA D^+
INSTRUMENTED WITH STEERING
STEEL ELECTRO-QUAD

Figure 6