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Lawrence Livermore Laboratory

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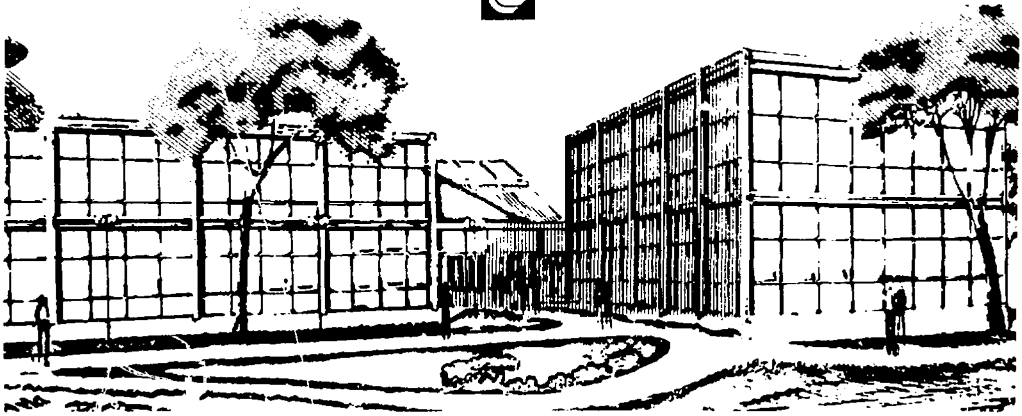

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THE MIRROR FUSION TEST FACILITY*

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ABSTRACT

The MFTF is a large new mirror facility under construction at Livermore for completion in 1981-82. It represents a scaleup, by a factor of 50 in plasma volume, a factor of 5 or more in ion energy, and a factor of 4 in magnetic field intensity over the Livermore 2XIIB experiment. Its magnet, employing superconducting NbTi windings, is of Yin-Yang form and will weigh 200 tons. MFTF will be driven by neutral beams of two levels of current and energy: 1000 amperes of 20 keV (accelerating potential) pulsed beams for plasma startup; 750 amperes of 80 keV beams of 0.5 second duration for temperature buildup and plasma sustainment. Two operating modes for MFTF are envisaged: The first is operation as a conventional mirror cell with $n\tau \approx 10^{12} \text{cm}^{-3}$ sec, $W_i = 50$ keV, where the emphasis will be on studying the physics of mirror cells, particularly the issues of improved techniques of stabilization against ion cyclotron modes and of maximization of the electron temperature. The second possible mode is the further study of the Field Reversed Mirror idea, using high current neutral beams to sustain the field-reversed state. Anticipating success in the coming Livermore Tandem Mirror Experiment (TMX) MFTF has been oriented so that it could comprise one end cell of a scaled up TM experiment. Also, if MFTF were to succeed in achieving a FR state it could serve as an essentially full-sized physics prototype of one cell of a FRM fusion power plant.

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I. INTRODUCTION

Experiments spanning many years and culminating in the successes of the 2XIIB experiment at Livermore have demonstrated the viability of the magnetic mirror approach to the containment of fusion plasmas. The issues now being addressed in mirror research are quantitative in nature - how further to extend present results in the fusion-power-oriented parameters of $n\tau$, ion mean energy and plasma volume. In the pursuit of this goal the Mirror Program at Livermore is investigating two improvements on the conventional mirror - the Tandem Mirror and the Field Reversed Mirror. As a key part of this ongoing program construction has begun on a scaled-up mirror facility - MFTF - budgeted at 94 million dollars and due for completion in 1981-82.

The missions for MFTF include its use in extending the 2XIIB physics results upward in ion and electron temperature and plasma volume, with an eye to the requirements posed by the Tandem Mirror concept, which will be expected to employ mirror cells of roughly MFTF size as end stoppers in a TM fusion power plant. A second mission for MFTF is its employment in the pursuit of the physics of the Field Reversed Mirror, particularly as it relates to the use of high power neutral beams to maintain the field reversed state.

In the sections to follow we will review the technical features of MFTF and discuss some of the physics issues that are being considered in connection with its design and operation.

II. MFTF MAJOR DESIGN PARAMETERS

The MFTF design parameters were arrived at by consideration of the scaling laws for mirror confinement, subject to design constraints imposed by technological and budgetary limitations. The desire to increase the confinement factor, $n\tau$, by at least an order of magnitude beyond that achieved in 2XIIB dictated an increase in plasma ion energy by a factor 5 or more. At the same time the theory of stabilization of the Drift Cyclotron Loss Cone mode pointed to the need for a substantial increase in the parameter R_p/a_i, plasma radius as measured in ion orbit radii. Together with the requirement for higher ion energies this requirement dictated an increase in the confining magnetic field so that the plasma volume would not become excessive.

Increased confinement times and the desire to push the operating conditions in MFTF closer to those that expected to be required in a fusion power plant led to the requirement for neutral beam sources capable of near-steady-state operation (0.5 second or longer). This requirement in turn paced the design of the vacuum pumping system needed to handle the gas input implied.

The mechanical and electrical design of MFTF and the plasma parameters that are expected to be achieved in it have therefore reflected both physics and technology objectives. Table I summarizes the major magnetic field, size and plasma parameters of MFTF. Fig. 1 is a drawing showing a cutaway of the magnet and vacuum tank. Fig. 2 shows the MFTF chamber as it is to be installed in its building (already available). Fig. 3 shows a layout of the peripheral facilities and buildings that are elements of the total MFTF facility.

III. THE REQUIREMENTS OF STABILITY THEORY

The results of the 2XIIB experiment have shown both that an ion cyclotron instability mode with the signature of the DCLC mode can appear and that this mode can be suppressed by the technique of stream stabilization. In this method a low density plasma stream flows in along field lines from outside one mirror. A portion of this plasma penetrates through the mirror and intermixes with the plasma, providing a stabilizing action. In 2XIIB it appears that the fractional density of stream required to stabilize the plasma agrees reasonably well with the theoretical predictions, as illustrated in Fig. 4 - Molvik [1].

However, the fractional density of stream plasma theoretically required to stabilize the confined plasma decreases with increasing R_p/a_i. This trend is illustrated in Fig. 5, taken from the work of Pearlstein, Berk et al. as contained in the report by Simonen et al. [2]. Whereas 2XIIB, with its nominal values of $R_p/a_i \approx 2 - 3$, requires fractional densities of several per cent, an increase in R_p/a_i to 10 - 15 should result in a marked decrease in the fractional amount of stream plasma, n_w/n_h needed to stabilize.

A major motivating reason for decreasing n_w/n_h is the desire to minimize the cooling effects of external plasma on the electrons of the central plasma. It appears that the main reason that the electron temperature is not higher in 2XIIB is the fact that, as it is presently operated, a large external stream plasma density is required to achieve stability, resulting in a substantial cooling effect on the electrons of the central plasma. Recent experiments in 2XIIB, where somewhat larger values of R_p/a_i (to 5 - 6) were achieved by adjustments in the machine parameters, apparently bear out this hypothesis; both T_e and $n\tau$ increased with increasing R_p/a_i, other plasma parameters being held as nearly constant as possible. Fig. 6 shows this trend, as analyzed by Correll [2]. Taking the expected theoretical scaling of T_e with R_p/a_i gives a predicted T_e of order 1 keV for MFTF, assuming the use of the same type of stream stabilization as employed at present in 2XIIB. Note from Fig. 5 that the required ratio of streaming plasma density to hot plasma density has fallen to of order 3×10^{-3} at an R_p/a_i value of 13 as projected for MFTF operation with deuterons. At such a low required value other stabilizing techniques, less likely to cause cooling of the electrons, might be substituted for the present stream stabilization technique. Various alternative stabilization techniques, including the use of low energy ion beams directed into the plasma through one of the mirrors, can be investigated in 2XIIB as alternates to stream stabilization. If successful, these alternate techniques could permit even higher electron temperatures to be achieved in MFTF, with consequent further improvements in $n\tau$. From the standpoint of the Tandem Mirror high electron temperature, leading as it does to higher ambipolar potentials, would be desirable.

IV. NEUTRAL BEAM REQUIREMENTS

The neutral beam requirements of MFTF were based on extrapolations from the experience of 2XIIB and on the results of buildup codes and Fokker-Planck codes developed at Livermore over the last several years.

As presently planned, MFTF will be equipped with two types of neutral beam sources: 24 of the 50 amp, 20 keV accelerating potential-type sources of the type now in use in 2XIIB, and 24 50 amp (nominal), 80 keV accelerating potential sources developed at LBL/LLL for MFTF. Fig. 7 shows a drawing of a 20 keV source module and Fig. 8 shows a drawing of an 80 keV source module. The 20 keV sources are planned for use in plasma startup. Based on 2XIIB experience and on the Livermore BUILDUP code, the 1000 ampere plus beam current available will be able to build up the MFTF plasma from an initial low target plasma density to the 10^{13} - 10^{14} cm^{-3} range where the sustaining beams can take over. As shown by the BUILDUP code (Porter, et al. [3]), after about 150 milliseconds a steady state will be reached at $\beta \approx 0.5$ $n_i \approx 10^{14}$ cm^{-3}, W_i = 50 keV, the design goals for MFTF. Fig. 9, taken from Porter et al. [3] shows the calculated plasma density profile in MFTF following buildup to steady state. The source aiming was here adjusted to achieve a flattened density profile, expected to be advantageous from a plasma stability standpoint. These calculations assumed the availability of 1000 amperes equivalent of startup beams, and 750 amperes equivalent of sustaining beams. The startup beams will have a nominal 10 millisecond pulse length, similar to the 2XIIB system. The sustaining beams will have an initial 0.5 second pulse length capability. The sustaining beam power supplies, however, will have a 30 second pulse length capability, allowing for future source improvements.

By aiming the sources in different ways a considerable range of plasma radii and plasma density profiles will be available. BUILDUP code calculations have been used to estimate the requirements for achieving an approach to field reversal for $\Delta B/B \rightarrow (1.0)$ in MFTF. It appears that this should be possible, at reduced plasma diameter.

The question of providing adequate beam access through openings in the magnet windings has been carefully considered in the design. Fig. 10 shows the results of computer-graphic studies of this question.

V. MAGNET DESIGN

The superconducting magnet coil system for MFTF will be the largest high field magnet ever designed for mirror confinement. As shown in Fig. 1 this magnet is of the Yin-Yang type pioneered at LLL. It will weigh 200 tons, being fabricated on site at Livermore. Fig. 11 shows the large magnet winder machine now installed in the MFTF building.

The superconductor to be used in MFTF, a photograph of which is shown in Fig. 12 was specially designed for this purpose. It consists of an inner bundle of 480 NbTi wires embedded in a copper matrix. This matrix is in turn surrounded by special perforated strips of copper soldered to it. These strips perform the dual function of increasing the heat capacity and the parallel electrical conductivity of the stabilizing copper surrounding the superconductor and also providing channels through which the liquid helium that cools the conductors can circulate.

A special technique was developed to produce, with high reliability, joints in the conductor as needed in the winding. As there will be 50,000 meters of the 10,000 ampere (design current at 7.5 T) conductor used in the MFTF magnet coils, there will be of order 120 joints required in the course of winding the magnets. The technique developed employs hydraulically driven massive clamps to force the butted ends of the conductor together, producing a cold weld of high strength and high conductivity. Following the joining process in the machine the "flash" is cut away from the inner conductor and the strips containing cooling passages are soldered back onto it, resulting in a near-perfect reproduction of the original conductor configuration.

Because of the very large magnetic forces that will be exerted in operation, advantage has been taken in the MFTF magnet design of the fact that in a Yin-Yang coil pair each coil can be made to be a "C-clamp" for the other using the massive coil case of each to help restrain the forces of expansion of the other coil.

Surrounding the magnet is the large (10 meter diameter by 18 meter length) vacuum chamber of MFTF. This chamber performs a multiple function: (1) It provides a cryogenically cooled evacuated environment for the superconducting magnet case, while itself will be cooled to liquid helium temperatures. (2) It provides high speed cryopumping to absorb gas resulting from the operation of the neutral beam sources and (3) It supports the neutral beam modules and other necessary appurtenances. The design operating vacuum in MFTF is 3 X 10^{-6} torr under full beam conditions. To meet this requirement a pumping speed of 7.5 X 10^{7} liters/sec (for deuterium) on interior cryopanels and 40,000 liters per second in external vacuum pumps will be provided.

From a technological standpoint it is significant that the MFTF magnet and vacuum chamber design is being carried out at a scale of size and power handling capability not far below that which will be required in, say, either the end cell of a Tandem Mirror power plant, or in a typical cell of a FRM power plant.

VI. POWER SUPPLIES

The power requirements, and the cost, of MFTF are both dominated by the 80 kV power supplies for the sustaining neutral beams. These power supplies are fed from a 230 keV, 250 megawatt substation, itself fed from dedicated transmission lines coming from a large utility substation located a few miles from LLL.

Each one of the 24 sustaining beam modules is fed from a separate power supply. These power supplies are capable of a maximum pulse width of 30 seconds at full power, with a pulse repetition period of 5 minutes.

Fig. 13 is a block diagram of the power distribution system for the neutral beam sources.

VII. CONTROL AND DIAGNOSTICS

Microprocessors and on-line computer data reduction has been extensively incorporated in the design of MFTF. The experience gained in 2XIIB with computer control of neutral beam sources and on-line computer data analysis has shown the great value of these techniques. A schematic outline of the similar systems planned for MFTF is shown in Fig. 14.

References

[1] MOLVIK, A.W., Bull. Am. Phys. Soc. <u>22</u>, 1144 (1977).

[2] SIMONEN, T.C., et al., paper CN-37-J-1, "2XIIB Plasma Confinement Experiments," submitted to the Seventh IAEA Conf. on Plasma Physics and Controlled Fusion Research, Innsbruck, Austria, Aug. 23-30, 1978.

[3] PORTER, et al., "Review of MFTF Beam Current Requirements", unpublished.

Figure Captions

Fig. 1	Cutaway drawing of MFTF vacuum tank and magnet.
Fig. 2	Drawing showing MFTF in place in building.
Fig. 3	Overall layout of MFTF facility.
Fig. 4	Comparison between theoretically required and experimentally observed stream density needed to stabilize 2XIIB plasma.
Fig. 5	Theoretical curve showing downward trend in stabilizing stream density vs R_p/a_i.
Fig. 6	Experimentally observed increase of T_e and $n\tau$ vs R_p/a_i in 2XIIB.
Fig. 7	Drawing of 20 keV source module.
Fig. 8	Drawing of 80 keV source module.
Fig. 9	Calculated plasma density profile in MFTF from BUILDUP code.
Fig. 10	Computer-graphic study of beam access.
Fig. 11	Photograph of magnet winder.
Fig. 12	NbTi copper-stabilized superconductor to be used in MFTF magnet.
Fig. 13	Schematic of MFTF power distribution system.
Fig. 14	Block diagram of MFTF data analysis system.

Table 1. MFTF Parameters

	Plasma	
	MFTF Goals	2XIIB
$N\tau$ (cm^{-3} sec)	10^{12}	7×10^{10}
$\overline{W}_i$ (keV)	50	13
T_e (keV)	1.0	0.14
R_p/a_i	13	2-4
L/a_i	100	35
β	0.5	$\geqslant 0.5$

	Machine
$B_{central}$ (T)	2.0
$L_{between\ mirrors}$ (m)	3.4
Mirror ratio (R_m)	2.0
Startup	Plasma Stream
Startup beams	1000 A, 20 keV
Sustaining beams	750 A, 80 keV

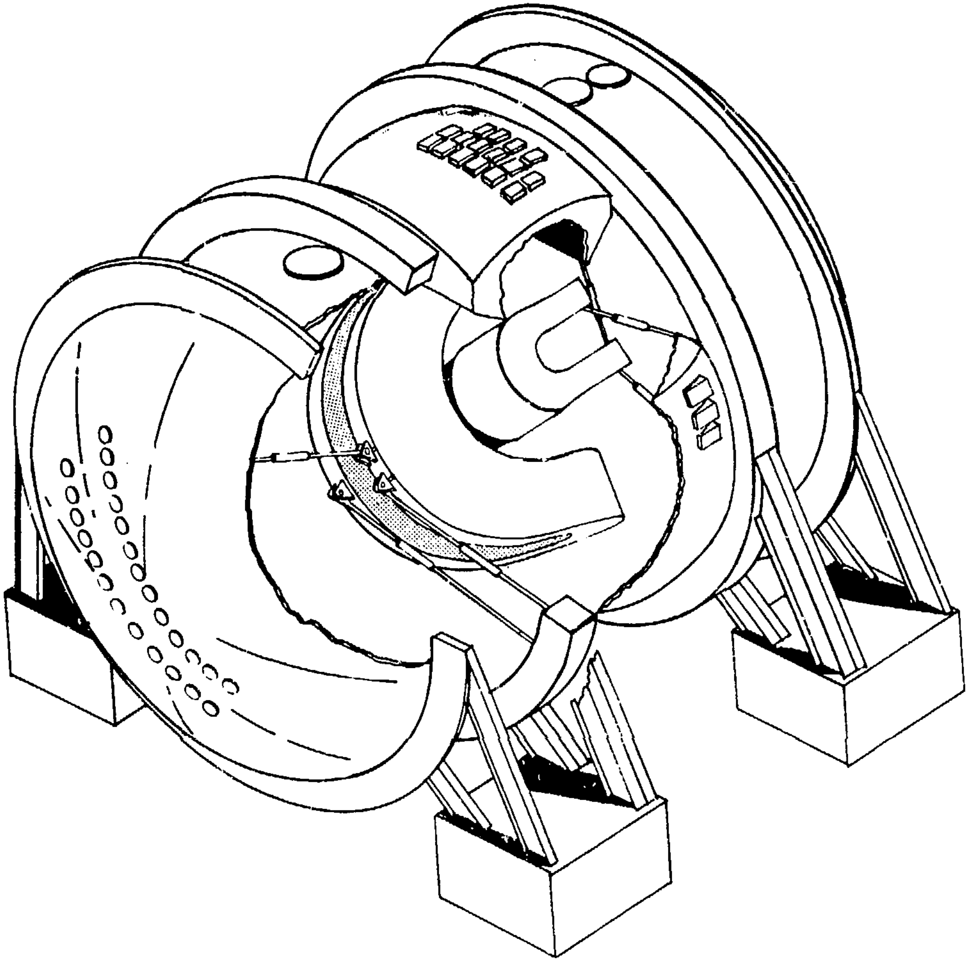


Figure 1: Cutaway drawing of MFTF vacuum tank and magnet.

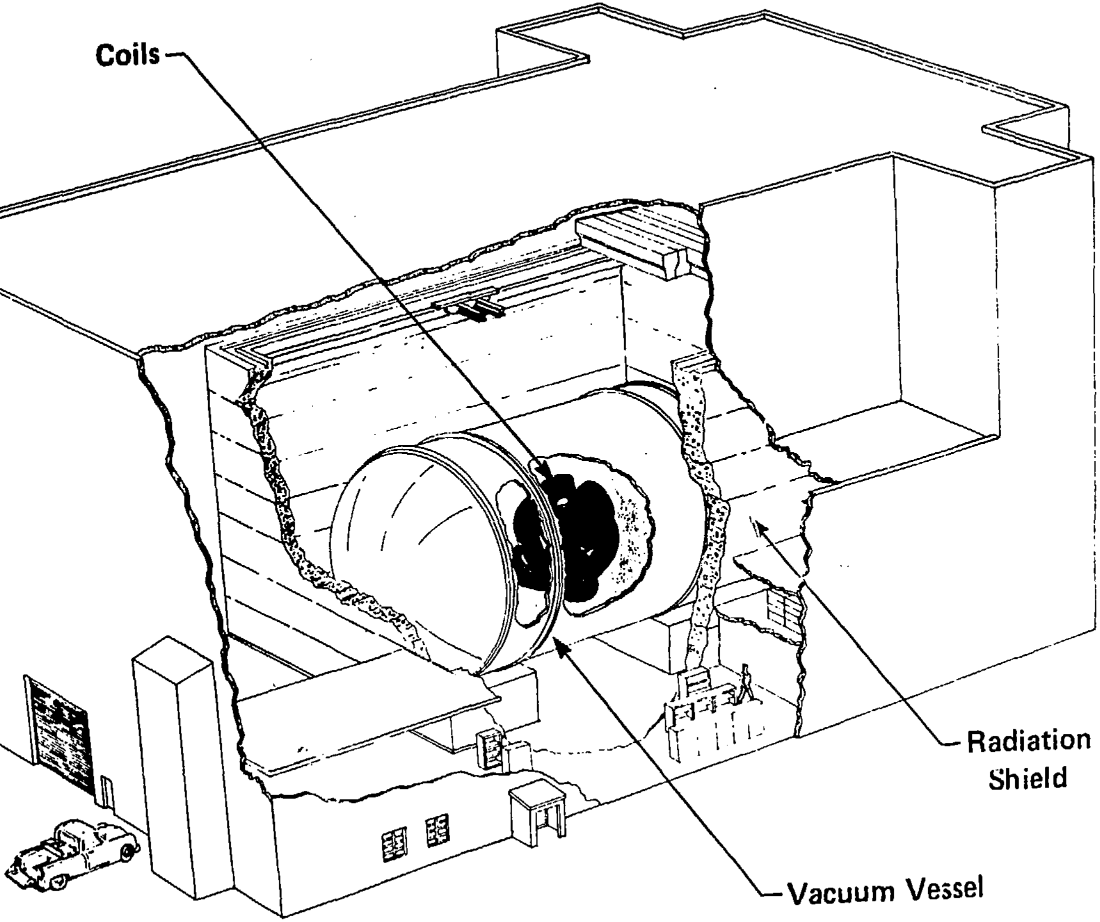


Figure 2: Drawing showing MFTF in place in building.

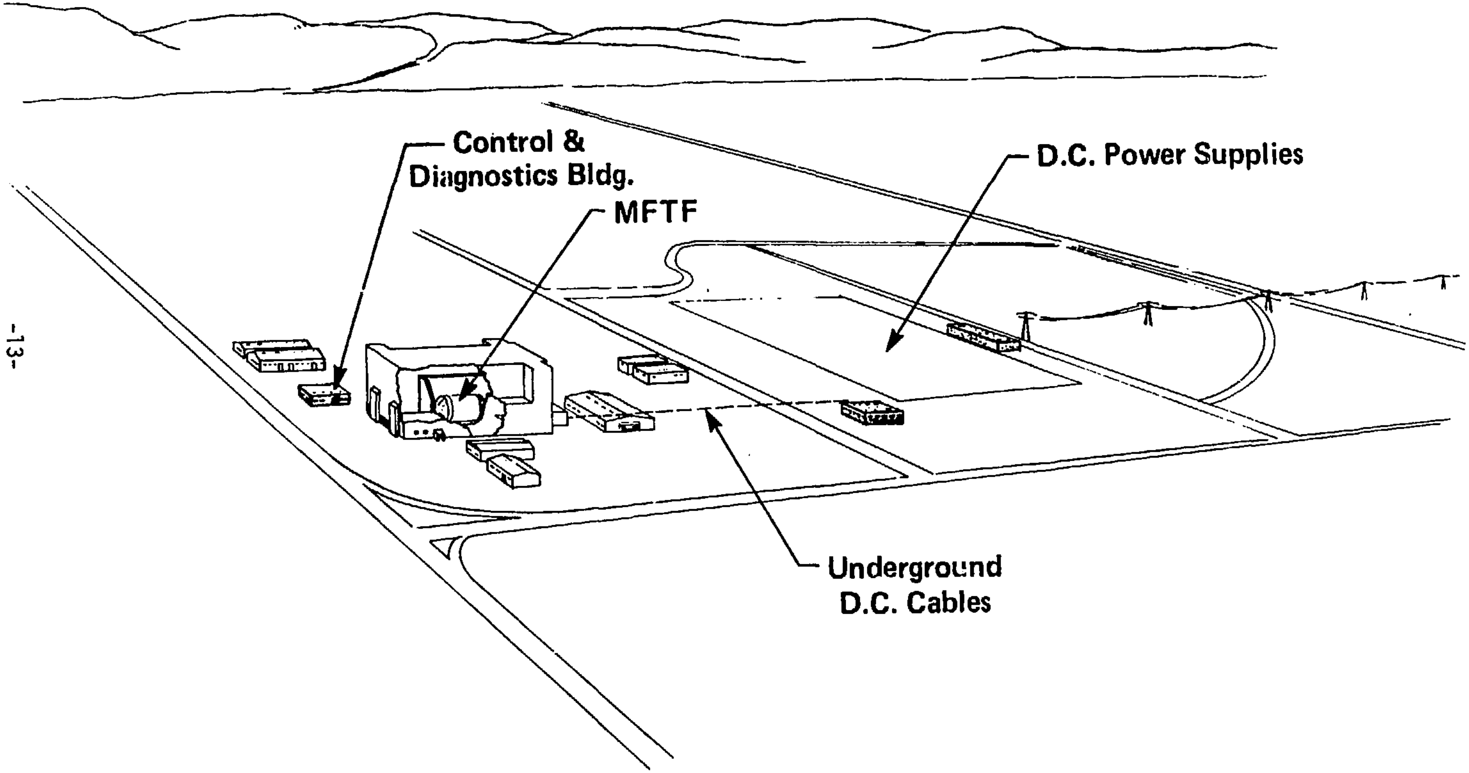


Figure 3: Overall layout of MFTF facility.

MINIMUM MEASURED STREAM SCALES WITH THEORY

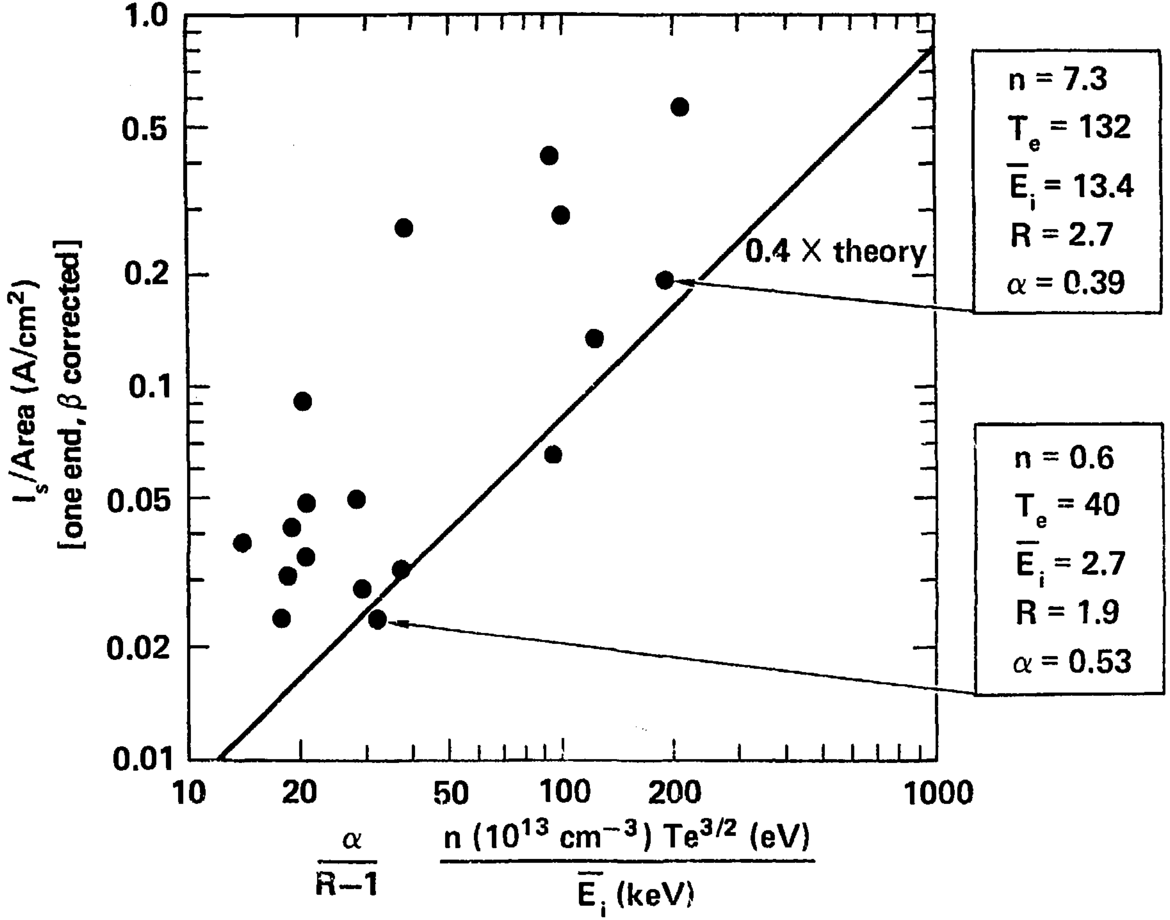


Figure 4: Comparison between theoretically required and experimentally observed stream density needed to stabilize 2XIIB plasma.

THEORETICAL MINIMUM-REQUIRED STABILIZING STREAM DENSITY VERSUS PLASMA RADIUS

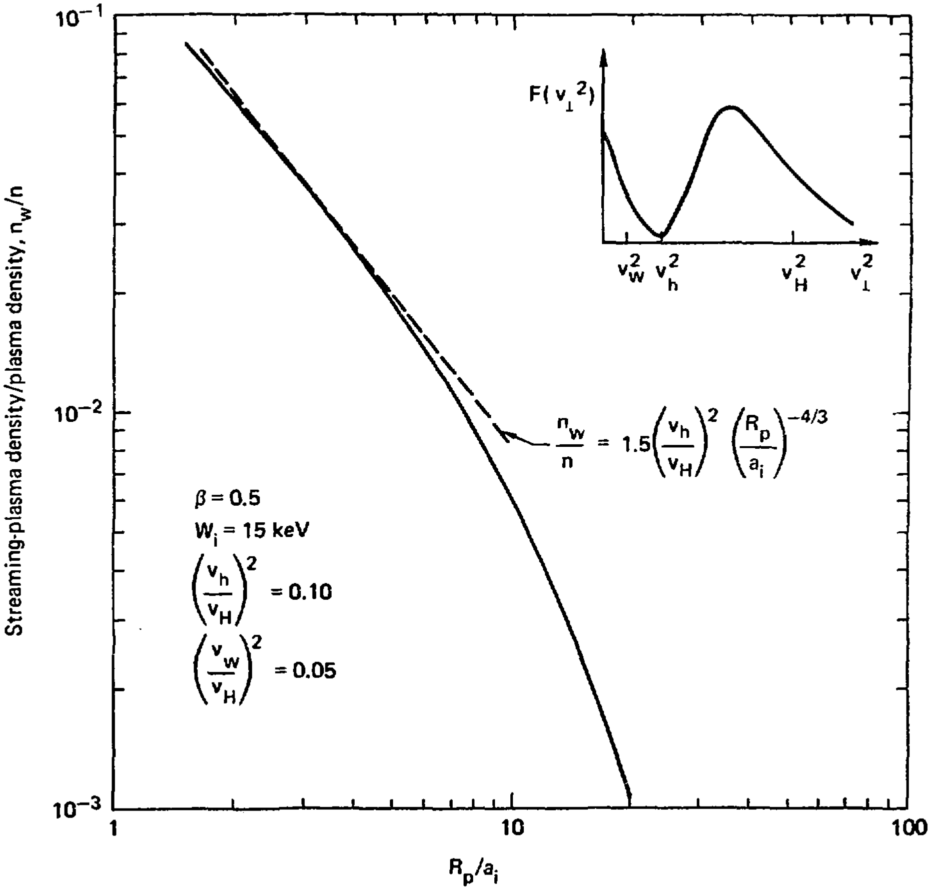


Figure 5: Theoretical curve showing downward trend in stabilizing stream density vs R_p/a_i.

ELECTRON TEMPERATURE AND nτ VERSUS PLASMA RADIUS FOR CONSTANT BETA

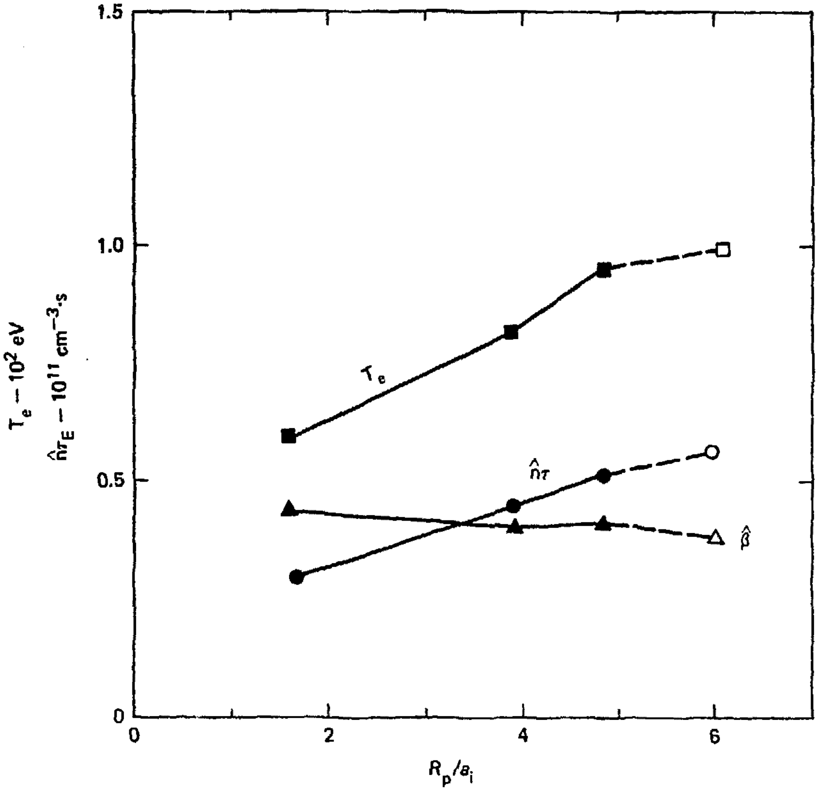


Figure 6: Experimentally observed increase of T_e and $n\tau$ vs R_p/a_i in 2XIIB.

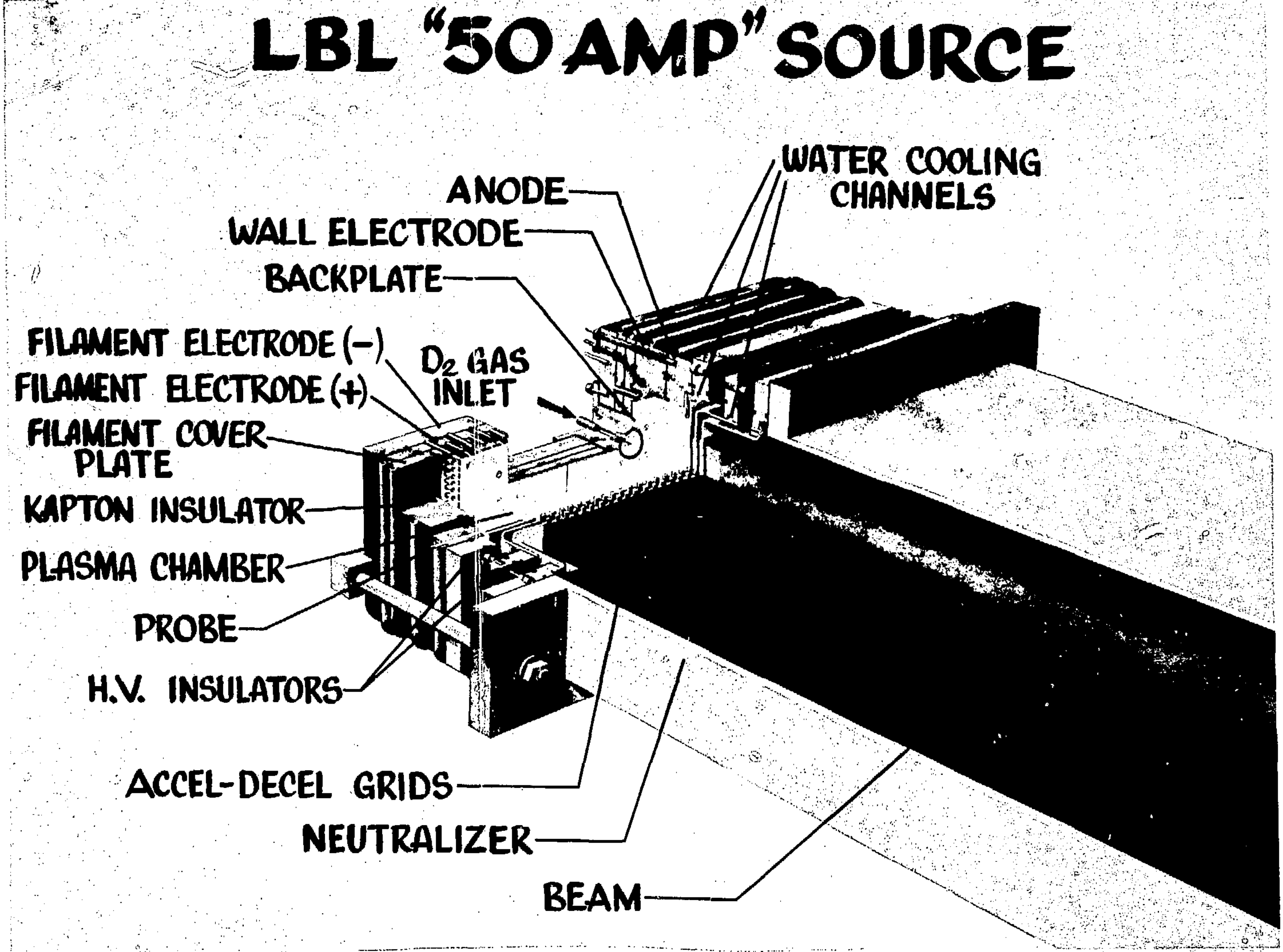


Figure 7: Drawing of 20 keV source module.

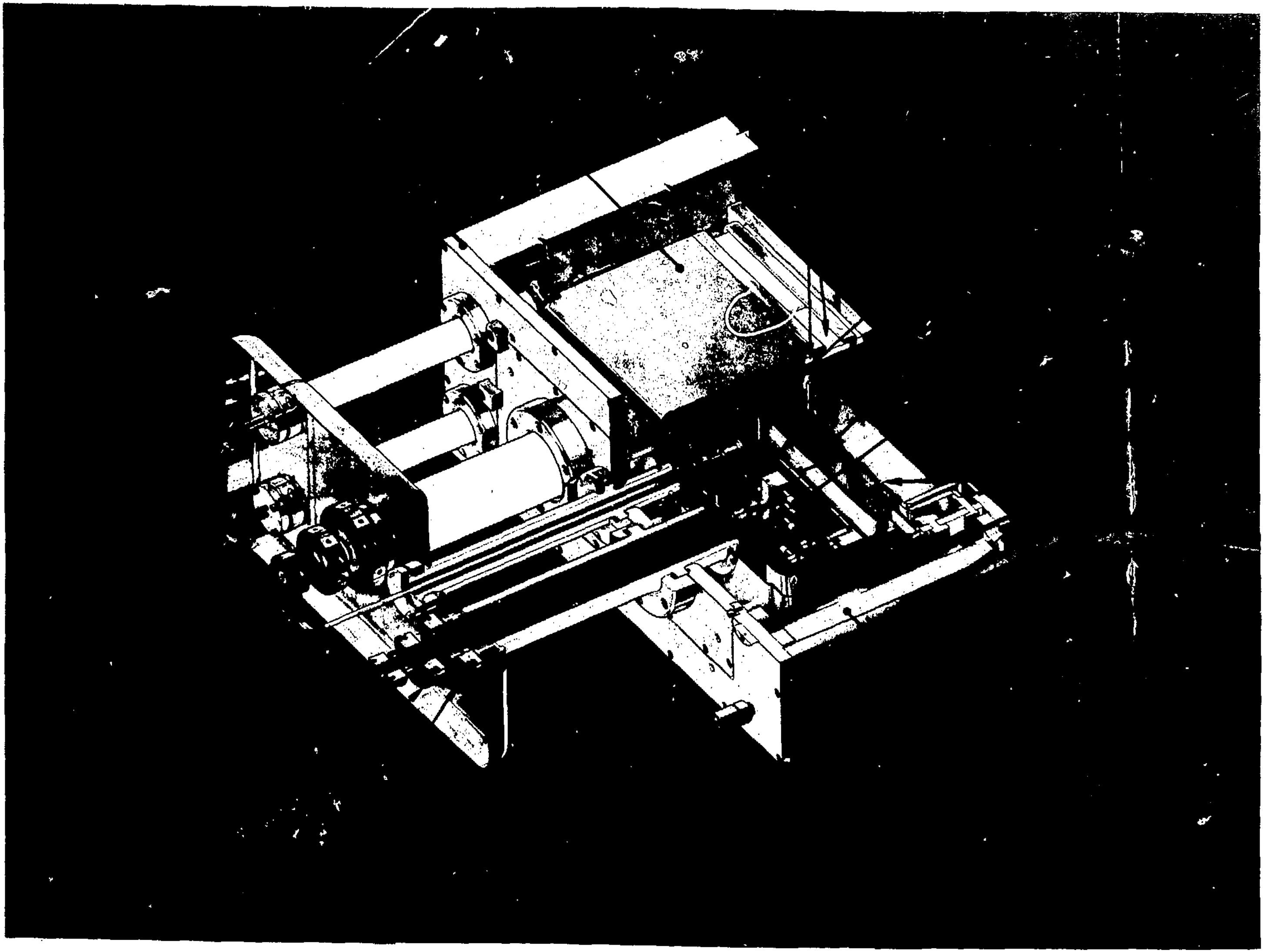


Figure 8: Drawing of 80 keV source module.

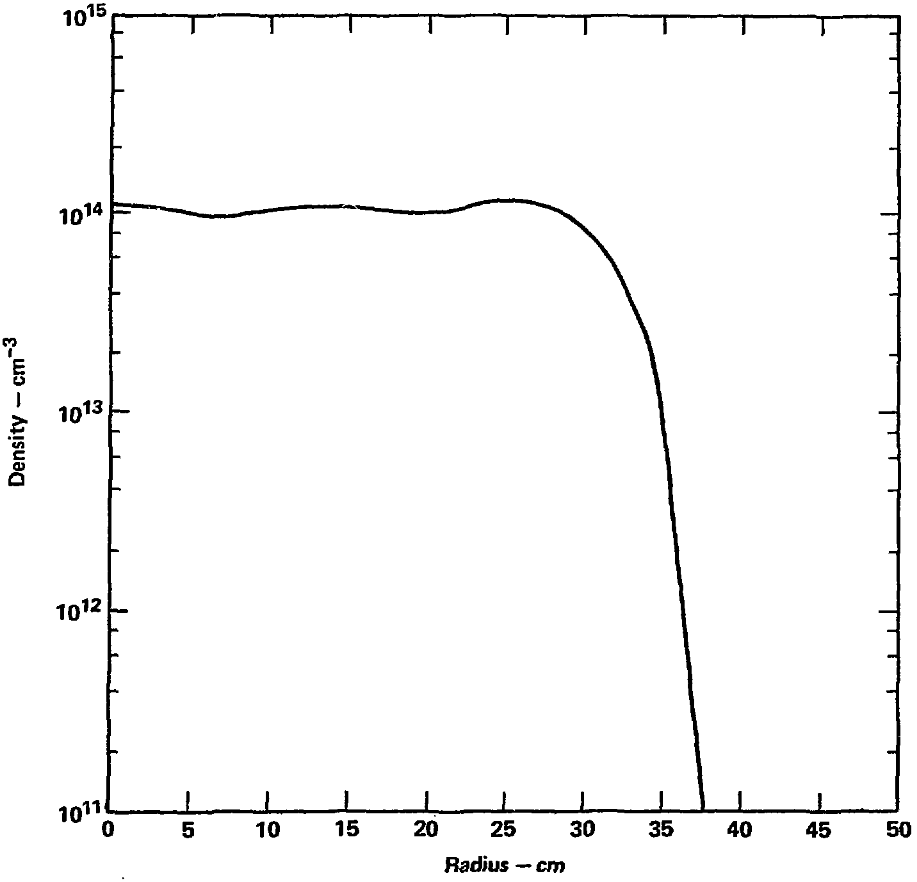


Figure 9: Calculated plasma density profile in MFTF from BUILDUP code.

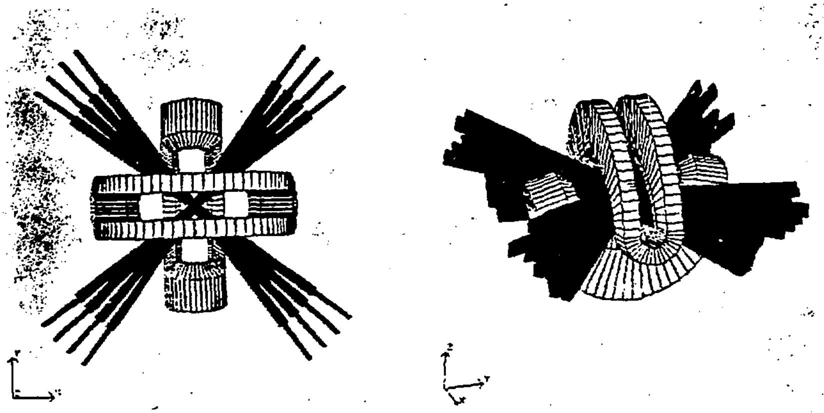


Figure 10: Computer-graphic study of beam access.

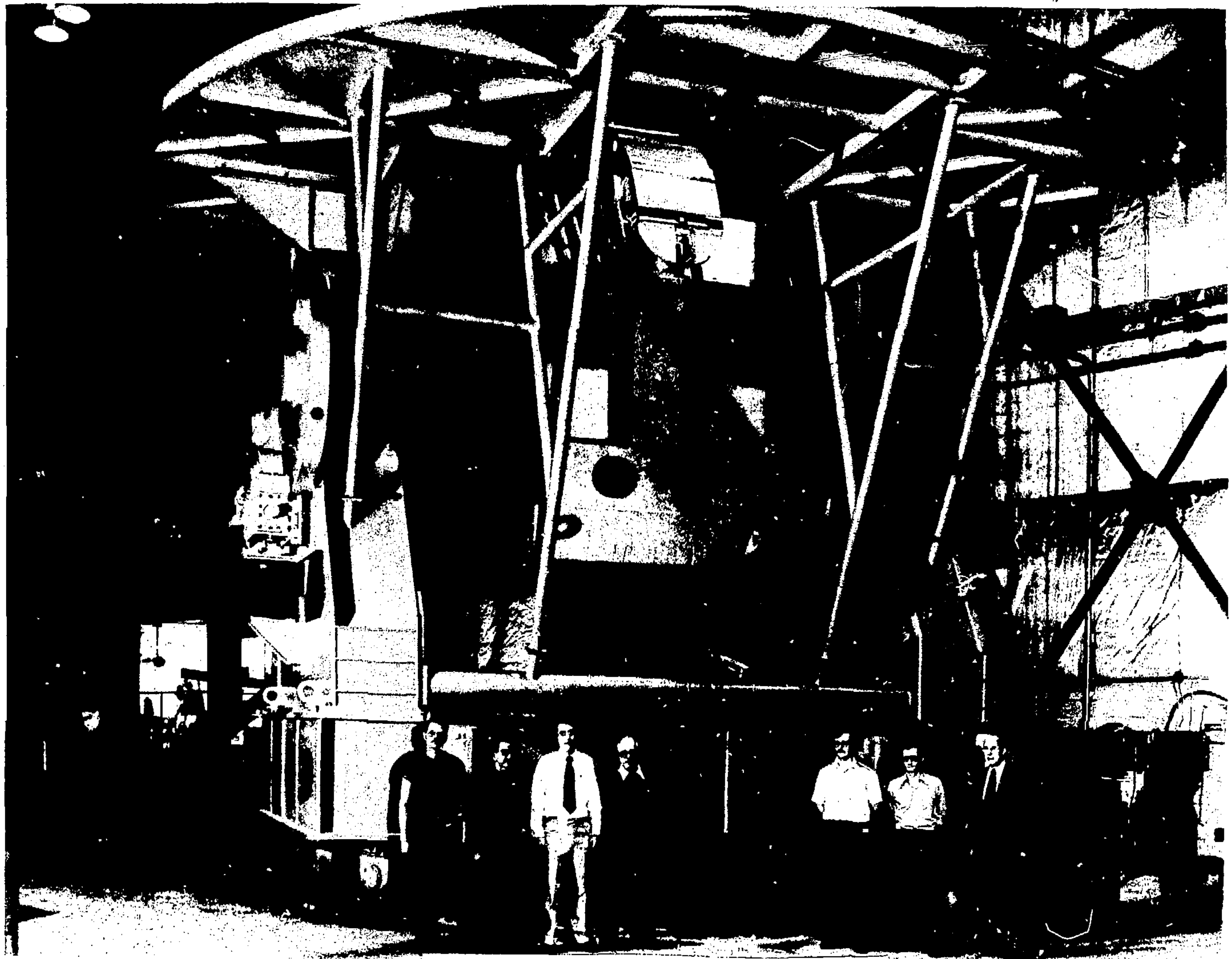


Figure 11: Photograph of magnet winder.

Figure 12: NbTi copper-stabilized superconductor to be used in MFTF magnet.

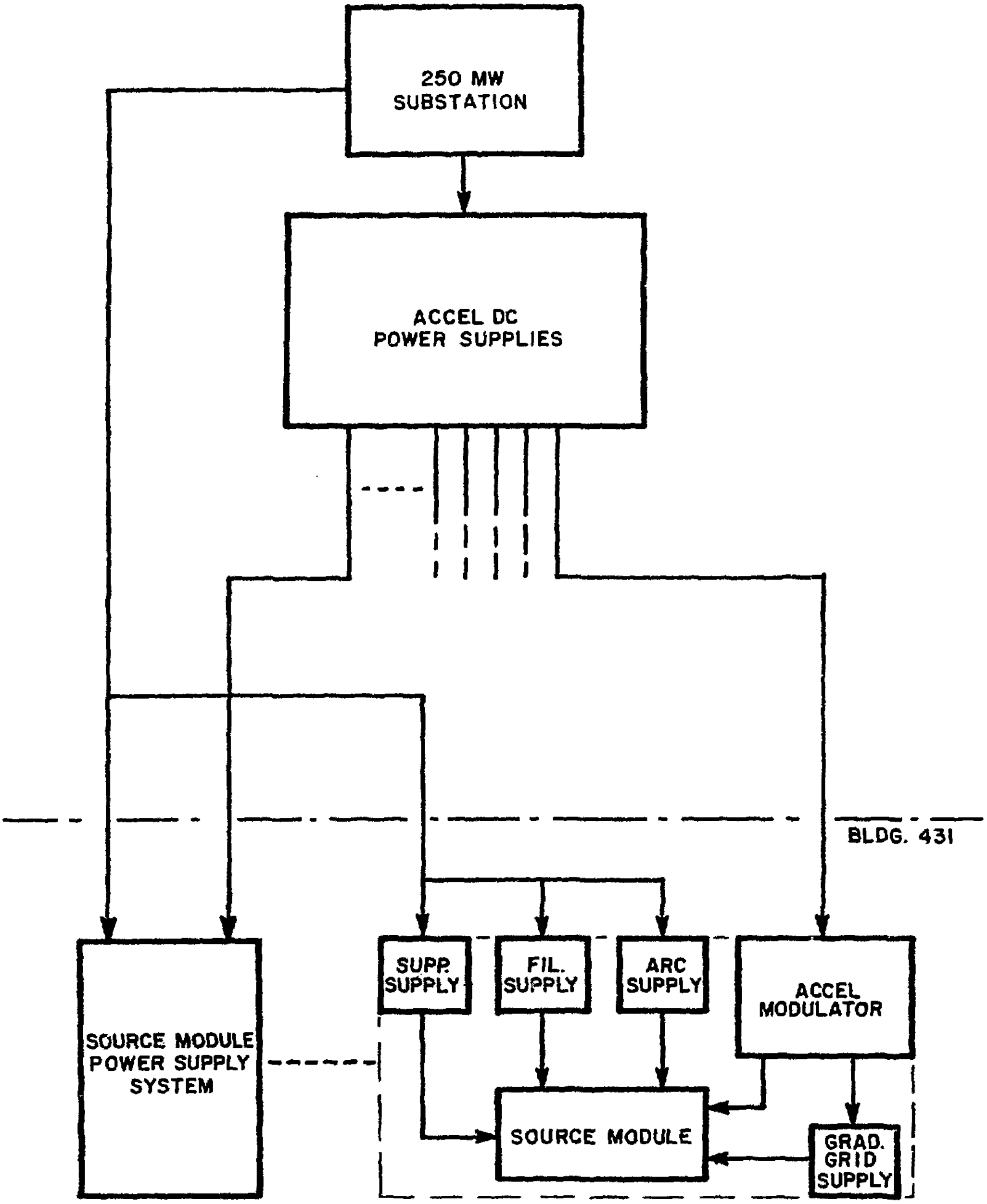
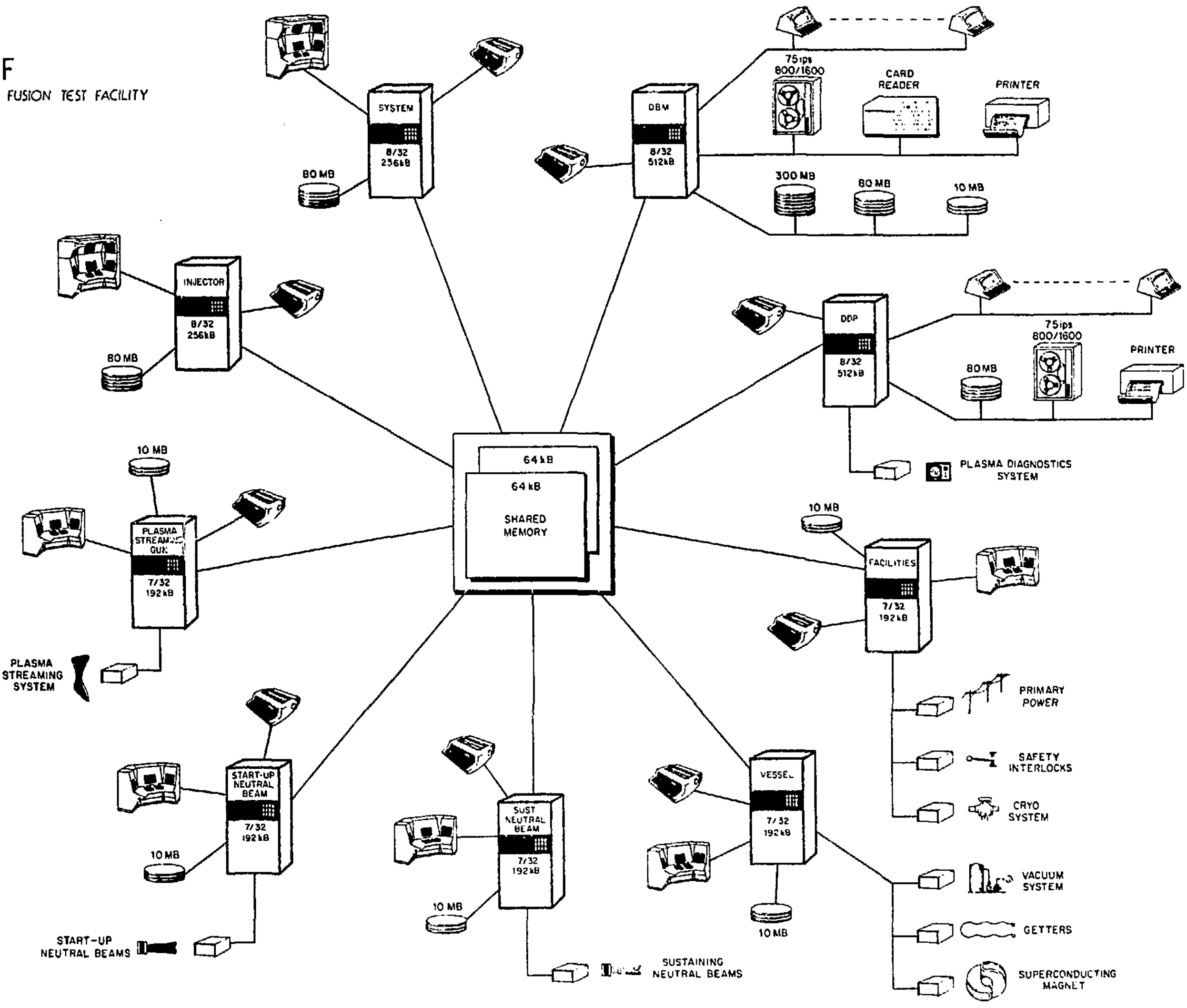


Figure 13: Schematic of MFTF power distribution system.

MFTF
MIRROR FUSION TEST FACILITY



MFTF CONTROL AND DIAGNOSTICS SYSTEM

Figure 14: Block diagram of MFTF data analysis system.