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ABSTRACT

A parametric analysis and a preliminary conceptual design for a 1000 MWe Tandem Mirror Reactor (TMR) are described. The concept is sufficiently attractive to encourage further work, both for a pure fusion TMR and a low technology TMR Fusion-Fission Hybrid.

INTRODUCTION

The concept of tandem mirror confinement due to Dimov et al[1] and Fowler and Logan[2] employs the positive electrostatic potential of an ordinary or standard mirror to plug the end losses from a long solenoid. A proof-of-principle evaluation of the concept will be provided by the Tandem Mirror Experiment (TMX), now under construction at Lawrence Livermore Laboratory. We have recently completed a parametric analysis and a preliminary conceptual design for a 1000 MWe tandem mirror fusion reactor. This report summarizes the results of that work. A more detailed account can be found in Reference 3.

PARAMETRIC ANALYSIS

The analytic model of the Tandem Mirror Reactor (TMR) used in the parametric study begins with a self-consistent description of tandem mirror physics. The physics model relates the densities, energies, and containment times of the ions and electrons in the plugs and central cell. The plugs are assumed to be standard mirror machines with classical end losses sustained by high energy neutral beam injection of deuterium. The central cell is fueled (but not heated) by low energy neutral beams of deuterium and tritium. Electrons heated by the energetic ions

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in the plugs in turn heat the cold ions in the central cell. In the parametric study the equations of the physics model are solved by specifying the plug injection energy, the plug mirror ratio, the mirror ratio between the plugs and central cell, the plasma β in the plugs and in the central cell, and the central cell ion temperature. Encouraged by high beta results in the 2XIIB mirror experiment, we have assumed β values of 1.0 and 0.7 in the plug and central cell, respectively. The physics output consists of the various energies, containment parameters ($n\tau$'s), plug to central cell volume and density ratios, and Q.

Next, the specification of a single magnetic field strength (usually the plug central field) allows calculation of all the plasma densities and the fusion power density in the central cell. Then, specification of the blanket energy multiplication factor M and various efficiencies (thermal conversion, direct conversion, and neutral beam injection) allows calculation of power flows. At this point, the power quantities are only relative because an absolute power level has not been selected.

Finally, specification of a single power quantity (usually the net electric power) allows complete design of the reactor. The dimensions of the cylindrical central cell plasma and the approximately spherical plug plasmas are determined by the central cell to plugs volume ratio, the fusion power density of the central cell, the desired total fusion power, and the requirement for magnetic flux conservation throughout the machine. The plug magnets are designed to provide the specified magnetic field and to be large enough to contain the plug plasma. The central cell design begins at the cylindrical first wall (3 alpha radii away from the plasma) and proceeds outward through the blanket, shield, magnet, support structure, handling and maintenance equipment and finally the reactor building. The plant design is completed by the sizing of the injectors, direct converters, and the thermal conversion system. Cost estimates are made for all elements of the power plant, permitting a final estimate of the cost of power.

There is an optimum set of values for plug injection energy, plug to central cell mirror ratio, and central cell ion temperature which minimizes the cost of power. For a 1000 MWe reactor with a plug central field strength of 16.5 T, plug vacuum mirror ratio of 1.07, we have found the optimum values to be: plug injection energy (deuterium) = 1200 keV, plug to central cell mirror ratio = 7.0, and central cell ion temperature = 30 keV. The blanket energy multiplication factor for this case was 1.2 and the efficiencies for thermal conversion, single stage direct conversion, and injection were 40%, 60%, and 80%, respectively. The total direct capital cost of this reactor is predicted to be $1300/kWe. Characteristics of the optimized Reference Design are listed in Tables 1-6. The cost estimate breakdown is given in Table 7.

MECHANICAL DESIGN

The general mechanical design features of the plant are shown in Figure 1 with some key parameters given in Tables 1-6. The reactor is composed of a power producing central cell, end plug magnets, 1.2 MeV D^0 injectors to sustain the end plug plasma and direct converters at each end to recover the charged particle end leakage. The power producing central cell is 100 m long and cylindrical in shape. The power production in the end plugs is low because it is not supplied with D-T ions but rather only D ions. Thus, an energy recovery blanket is provided only in the central cell. The blanket is helium cooled. A standard HTGR power conversion system is used, and waste heat is dumped to the atmosphere via wet cooling towers.

The central cell, consisting of blanket, shield, vacuum shell, magnet, and coolant supply lines, is divided into 36 modules, each about 2.8 m long (see Fig. 2). Each module is permanently mounted on a crawler transporter. To service the blanket, the main helium coolant manifolds are disconnected and a belt vacuum seal is machined off each end of the module. The module then translates horizontally to a position where it can be approached by two remote maintenance machines. One removes the welds from the internal helium distribution manifolds. The second removes a particular blanket segment and delivers it to a hot parts storage and processing area.

BLANKET

Each central cell module contains 24 identical wedge-shaped blanket/shield segments (see Figure 2). The blanket portion of the segment is 84 cm thick. The blanket structure is Inconel 718, vacuum cast with an egg-crate cross section. Inserted in the egg-crate structure are moderator/tritium breeding "pins," consisting of natural lithium encapsulated in stainless steel cans. Helium coolant flow is inward (toward the first wall) along the periphery of the blanket segment and outward between the "pins." Tritium is removed from the blanket via evacuated tubes of a tritium-permeable alloy which pass through each "pin." The calculated tritium breeding ratio for this blanket is 1.1 and its neutron energy multiplication is 1.2.

MAGNETS

The TMR magnet parameters are given in Table 4. The central cell magnet is a NbTi superconducting solenoid operating at a magnetic field strength of only 2.4 T. The magnetic forces are restrained by an external band of stainless steel.

The central vacuum magnetic field strength of the plug magnet is 16.5 T and its vacuum mirror ratio is 1.07. The plug magnet shown in Figure 3 is a hybrid superconducting and cryogenic magnet. The cryogenic aluminum Yin-Yang magnet is about the size of the MFTF magnet and produces an incremental field of about 1 T over the field of 16 T produced by the pair of Nb_3Sn superconducting solenoids. The resistive heating in the Yin-Yang magnet is 0.25 MW requiring about 12 MW of refrigeration power. Structural integrity of the Yin-Yang magnet requires a layered construction of pure aluminum conductor and aluminum alloy columns and stress plates to transfer the magnetic forces to an external clamping structure (not shown). Restraint of the magnetic forces of the plug solenoidal coils is accomplished by periodic bands of stainless steel.

SHIELDING

Between the blanket and the central cell coils is 90 cm of steel and lead cement sheilding. This shield, along with the blanket, provides adequate protection for the superconducting central cell magnet.

Protecting the cryogenic aluminum Yin-Yang plug magnet is the major shielding challenge in the TMR. The critical area appears to be at the inner mirror of the plug where tritium plasma extending from the central cell reacts with the plug cell deuterium and generates 14 MeV neutrons at a significant rate. Preliminary calculations indicate that a 64 cm thick tungsten-based shield is needed at this inner mirror region if annual room temperature anneals (to restore the initial conductivity) are desired. The present plug magnet design allows for only 15 cm of shielding in this region. Thus, the magnet must be enlarged to provide for more shielding. We do not expect this redesign of the plug magnet to greatly increase the total reactor cost.

NEUTRAL BEAM INJECTORS

In Figure 4 we show a conceptual design of a high current 1.2 MeV D^0 injector. Parameters for the injector design are given in Table 5. All of the components in the proposed beam line are elaborations of physics experiments which have already been reported in the literature. However, major advances in all phases of neutral beam technology are needed to meet the requirements of the TMR. These include a continuous source of negative ions, an efficient electron stripping cell, and the development of associated power conditioning and control equipment.

Figure 4 shows the nested shields which provide voltage isolation in steps of 200 kV. Each shield is subdivided into small areas to limit the energy of any sparkdown to about 10 J. The background pressure along the beam line is kept low by vacuum pumping through the 80% transparent shield structure.

DIRECT ENERGY CONVERTERS

Direct converters are placed at each end of the TMR to recover power from the end-loss plasma. The high ambipolar potential and the low ion temperature result in good efficiency even with a single collector stage. About 60% of the total efflux power (carried by escaping fuel ions, α's, and electrons) can be directly recovered after allowing for losses due to incident electrons, grid interception, secondary and thermionic electrons. The direct converter also serves to control the recycling of cold electrons from the end walls. The preliminary design has addressed the problems associated with space charge, voltage holding, and capacitively stored energy.

The cross section of the direct converter is elliptical with an aspect ratio of about 2 to 1 and with the minor axis vertically oriented. The collector elements are carbon venetian blinds mounted on vertical tensioned wires.

SUGGESTIONS FOR FUTURE WORK

As mentioned previously, the plug magnets must be enlarged to allow for more neutron shielding. A tradeoff to be investigated is to change to H-injected plugs, which would decrease plug confinement but also reduce the plug neutron generation. Another area for further work is the detailed design of the high energy neutral beam injectors for the plug cells. One way to reduce the required plug injection energy and, to a lesser extent, the end plug field strength is to somehow heat the electrons directly. The possibility of doing this with RF heating or e-beams needs to be considered. Finally, the still-developing theory of alpha containment, diffusion, and loss in the TMR needs to be incorporated into the plasma model of the parametric analysis and may result in some changes in the conceptual design.

A LOW TECHNOLOGY TMR FUSION-FISSION HYBRID

A way to dramatically decrease the required plug technology is to add energetic neutral beam injection at the ends of the central cell. A brief look at such a machine (with 125 keV injection into the plugs and central cell, and an 8 T maximum field strength) indicates that, although Q is reduced to 1.8 (vs 4.8 for the 1000 MWe TMR design), it could form the basis for an attractive fusion-fission hybrid. Because the central cell has injection only at its ends, the fissile blanket could be serviced in the same way as the fusion TMR, withoug disturbing the injection system. Preliminary parameters for the TMR hybrid are given in Table 9.

CONCLUSIONS

The TMR is a great improvement over the standard mirror reactor in a number of respects. The higher Q eases the precarious power balance that plagues the standard mirror. The technology of the central cell is low by comparison to most other approaches to fusion in that low field NbTi superconducting coils in a modular, cylindrical geometry are employed. The high technology requitements are concentrated in the end plugs, which are separate from the power producing part of the reactor. In the fusion-fission hybrid version of the TMR, even the end plugs can have low technology. Overall, the TMR concept is sufficiently attractive to encourage further work.

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[1] G. I. Dimov, V. V. Zakaidakov, M. E. Kishinevsky, "Open Trap with Ambipolar Mirrors," 6th Intern. Conf. Plasma Physics and Controlled Nuclear Fusion Research, Berchtesgaden, Federal Republic of Germany, Oct. 6-13, 1976 (IAEA), Paper C4.

[2] T. K. Fowler and B. G. Logan, The Tandem Mirror Reactor, Lawrence Livermore Laboratory, Rept. UCRL-78749 (1976); also Comments on Plasma Physics and Controlled Fusion Vol. II, No. 6 (1977).

[3] R. W. Moir, W. L. Barr, G. A. Carlson, W. L. Dexter, J. N. Doggett, J. H. Fink, G. W. Hamilton, J. D. Lee, B. G. Logan, W. S. Neef, Jr., M. A. Peterson, M. E. Rensink, "Preliminary Design Study of the Tandem Mirror Reactor," LLL report in preparation.

TABLE 1

TMR PERFORMANCE PARAMETERS

P_{net}	1000 MWe
Fusion Power	2500 MW
Plasma Q	4.8
Neutron Wall Loading	2 MW m^{-2}
Plasma Fusion Power Density	5 MW m^{-3}
Recirculating Power Fraction	0.43
Plant Efficiency	34%
Direct Capital Cost	$1.3/We

TABLE 2

TMR PHYSICS PARAMETERS

End Plug	
Injection Energy	1.2 MeV
Mean ion energy	880 keV
Density in plug	8.6×10^{14} cm^{-3}
Trapped current into each plug	220 A
Electron temperature	42 keV
β $\left(\beta=\frac{P_\perp}{B_{vac}/2\mu_o}\right)$	1
Plasma radius	0.48 m
$B_{o,vac}$	16.5 T
$R_{vac,\ plug}$	1.07
Potential at midplane	350 keV
Particle $n\tau$	2.5×10^{14} s cm^{-3}
Central Cell	
Current injected (cold fuel)	1100 A
β	0.7
Length	100 m
Plasma radius	1.2 m
B_{vac}	2.4 T
Electron temperature	42 keV
Ion temperature	30 keV
Density	1.1×10^{14} cm^{-3}
Particle $n\tau$	7.7×10^{14} s cm^{-3}
Potential of Plasma	260 keV

TABLE 3

MECHANICAL DESIGN PARAMETERS FOR THE CENTRAL CELL

First wall radius	1.56 meters
Central Cell length	100 meters
No. of modules	36
No. of parallel heat exchange loops	6
Central Cell Magnetic Field	2.4 T
Blanket Coolant	Helium
Inlet temperature	300°C
Exit temperature	530°C
Inlet Pressure	50 atmospheres
Helium Pressure Drop	2 atmospheres
Blanket Structure	Inconel 718
Average Power Density into Direct Converter	100 W/cm^2

TABLE 4

TMR MAGNET PARAMETERS

Central Cell Solenoid	
B	2.4 T
Material	Nb-Ti
Bore	8.4 m
Length	100 m (36 segments)
End Plug	
B_o	16.5 T
B_{mirror}	17.6 T
R_{vac}	1.07
Solenoidal Pair	
Material	Nb_3Sn
Bore	5.75 m
$B_{conductor}$	17.3 T
Yin Yang	
Material	Aluminum
Length	2.8 m (mirror to mirror)
Resistive power	0.25 MW (each plug)

TABLE 5

TMR NEUTRAL BEAM INJECTOR PARAMETERS

Beam Energy	1.2 MeV
D^{o} Current (per Injector)	120 A
Total Injected Power (4 units)	580 MW
Operating Mode	Continuous
Type of Beam Line	Negative Ions
Source of Negative Ions	Cesium, Double Charge Exchange Cell
Type of Stripping Cell	Cesium Plasma
System Efficiency	80%

TABLE 6

TMR DIRECT ENERGY CONVERTER PARAMETERS

Type	Single Stage
Mean ion energy	470 keV
Mean electron energy	42 keV
Power in ions	950 MW
Power in electrons	85 MW
Power density at collector	100 W/cm^{-2}
Efficiency	60%

TABLE 7

DIRECT CAPITAL COST - TMR REFERENCE DESIGN

	COST	% OF TOTAL
Central Cell		
Blanket	$114 M	8.9%
Shield	62 M	4.9%
Vacuum Vessel	11 M	0.9%
Coil	35 M	2.7%
Coil Structure	21 M	1.6%
Main Structure	51 M	4.0%
Crawler	22 M	1.7%
SUBTOTAL	$316 M	24.7%
Plug Coils	$171 M	13.3%
Reactor Building	44 M	3.4%
Injector System	147 M	11.5%
Direct Conversion System	134 M	10.5%
Thermal Conversion System	199 M	15.5%
Other	270 M	21.1%
TOTAL	$1,281 M	100%

TABLE 8

PARAMETERS OF A TANDEM MIRROR HYBRID REACTOR

Fissile-Fuel-Breeding Central Cell:
- Simple Cylindrical Shape length = 27 m
- outside radius = 3.5
- Axial Modularization
- Magnetic Field Strength = 3 T
- Neutral Beam Injection of D & T = 1070 A @ 125 keV
- First Wall Neutron Loading = 2.8 MW/m^2
- Fusion Power = 260 MW
- Blanket Thermal Power = 1700 MW

End Plugs:
- Spherical Shape outside coil radius = 2.0 m
- Magnetic Field Strength = 8 T
- Neutral Beam Injection of D into each plug = 42 A @ 125 keV

Performance:
- Overall Plasma Q = 1.8
- Recirculating Power Fraction = 0.29
- Net Electrical Output = 500 MWe
- Annual Fissile Production = 1000 kg ^{233}U

TMR REPORT - FIGURE CAPTIONS

Fig. 1	Tandem Mirror Reactor
Fig. 2	Central Cell Module and Blanket/Shield Segment
Fig. 3	Plug Magnet
Fig. 4	Plug Injector

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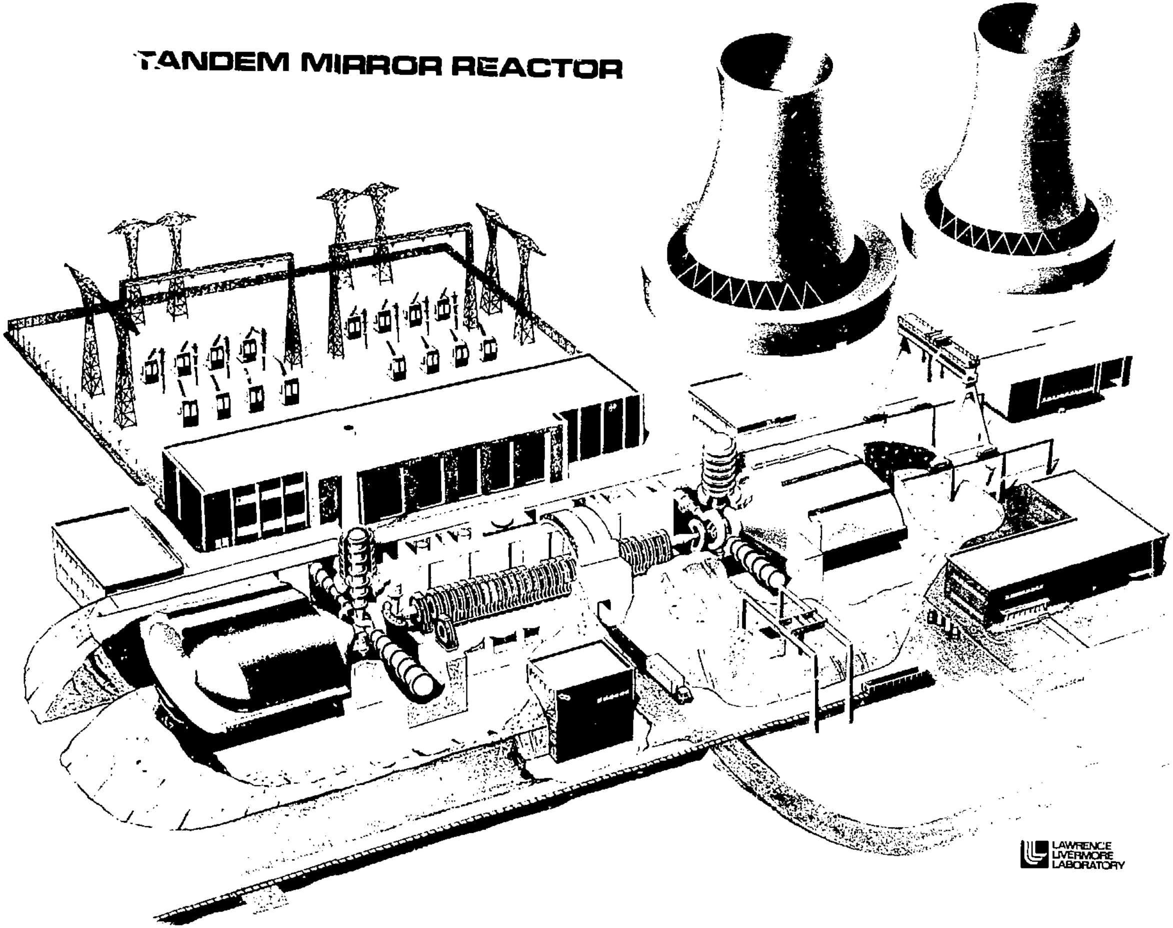


FIGURE 1

TANDEM MIRROR REACTOR

BLANKET / SHIELD SEGMENT

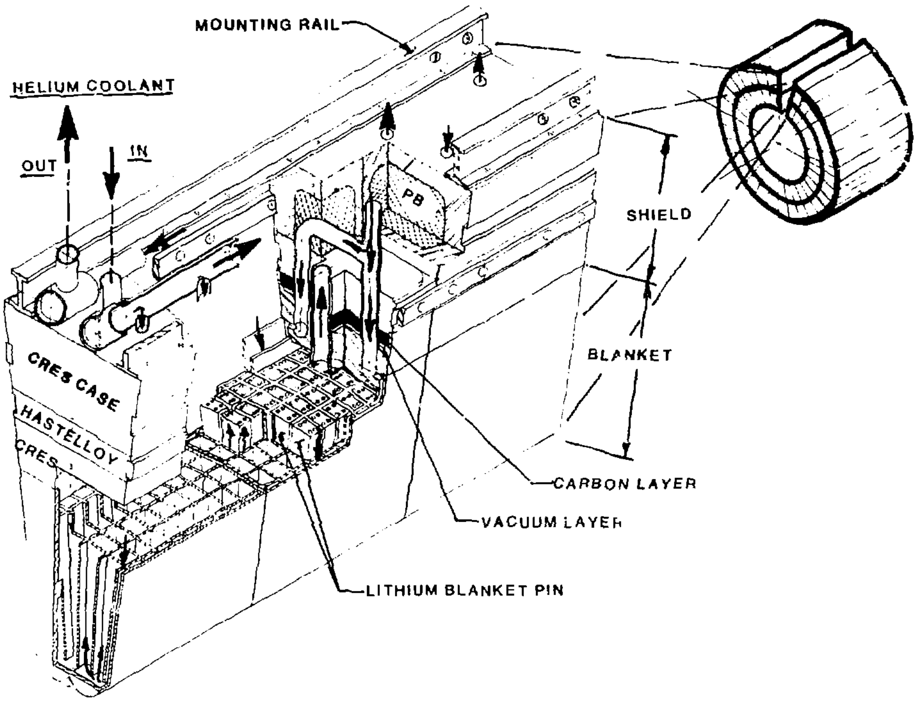
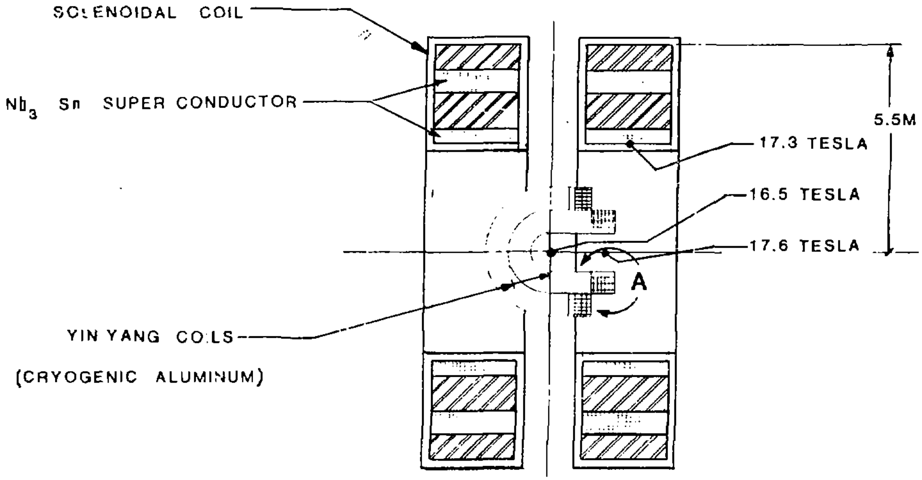
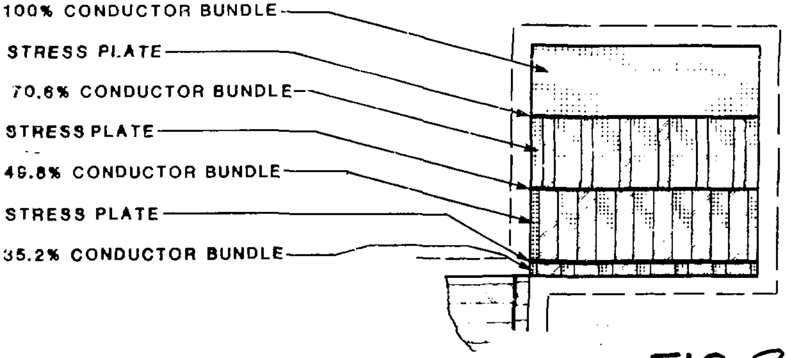


FIGURE 2





DETAIL A

FIG. 3

T-M-R PLUG COIL SET

16.5 TESLA

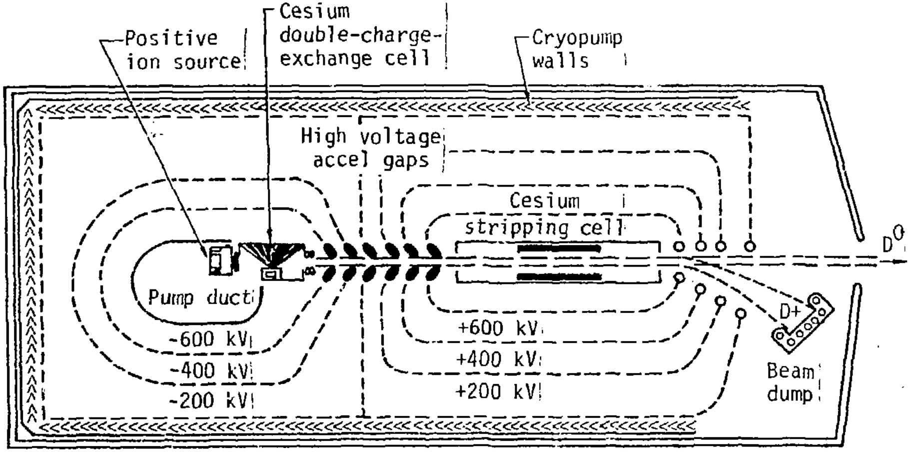


FIG. 4 1.2 MeV NEUTRAL BEAM INJECTOR IN A GROUNDED SHELL