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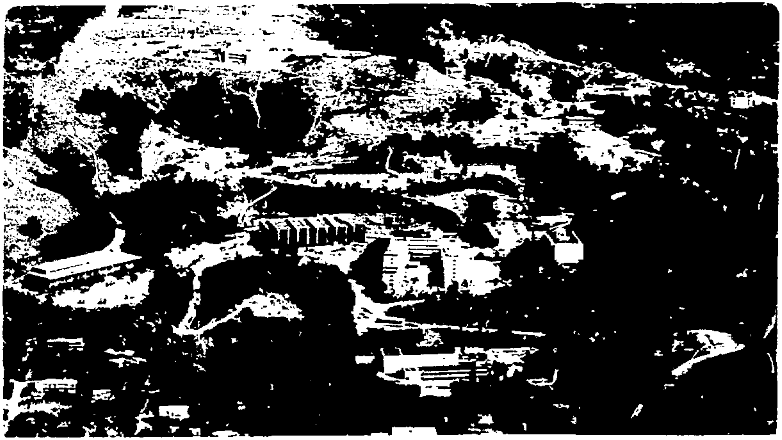
October 1979



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COMBINING MAGNETIC SHIELDING AND CRYOPUMPING FOR A NEUTRAL BEAM SOURCE*

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Summary

Neutral Beam sources similar to the designs executed by LBL for TFTR[1] and for Doublet III[2] require substantial hydrogen pumping speed and careful magnetic shielding in order to optimize neutral beam production.[3] A design which satisfies each requirement separately results in a design where the performance of both the magnetic shield and the cryopump is compromised by the requirement of the other device.

It is suggested that both the magnetic shielding and cryopumping requirements can be satisfied by a design which uses a Type I superconductor cooled to liquid helium temperature. The superconductor will effectively exclude stray magnetic fields generated by the fusion reactor while the cold surface will act as an effective cryopump in the beam neutralizer. The refrigeration load for this design would be reduced since the area of the shield/cryopump could be minimized due to the elimination of aperture restrictions to pumping. The design should result in superior solutions for both requirements.

This paper describes a feasible geometry for the shield/cryopump for a TFTR/Doublet type of neutral beam source, summarizes some of the design parameters, and compares the performance, fabrication, and operating cost of such a system with a more conventional system.

Introduction

It is useful to recall the basic structure of the neutral beam sources to qualitatively review the vacuum and magnet environments required for high neutral beam currents. Fig. 1 is a general schematic of a neutral beam source for plasma heating experiments for the Doublet III and TFTR Fusion Tokamaks. It is, with some variation, representative of neutral beam sources for other fusion research devices. An ion source is followed by a neutralizing duct and subsequently by a deflection magnet. In the case of Doublet III, the deflection magnet reflects the charged beam to a beam dump in the same vacuum space occupied by the neutralizer. TFTR uses a transmission deflection magnet and dumps the charged particles further downstream. Magnetic and vacuum parameters and requirements are reasonably close for the Doublet III and the TFTR sources. The main difference is the need to design remote handling capabilities for the TFTR system. The very different final geometry reflects this additional requirement. Most of the following specific parameters will be related to the Doublet III experience.

The fringe fields from the Doublet III Tokamak vary from approximately .01T at the source to .015T at the neutralizer to .02T in the drift space immediately upstream of the deflection magnet. (Fig. 2) The neutralizer is a charge exchange region and thus requires relatively high gas density. The ambient magnetic field must be reduced to approximately 10^{-4}T in this charge exchange region to prevent significant beam loss. The pressure downstream from the neutralizer must be reduced quickly (a large pressure gradient) to prevent reionization of the neutrals. The magnetic shielding must be continued in this region so that ionized particle orbits can be predictably steered to their beam dumps since the power densities can be significant. The pulsed field must be reduced to 10^{-4}T in the drift space.

The magnetic shielding is accomplished by a series of 4750 nickel-iron fingers surrounding the drift space. These fingers are coupled to the deflecting magnet yokes. The magnetic circuit is completed by the magnet leg slabs which are made sufficiently wide to accomodate the flux collected in the shields, in addition to the main deflecting field.[5]

The shield geometry is influenced by the vacuum requirements. The fingers allow sufficient conductance so that the net pumping speed in this drift space will provide a low pressure in this region in spite of the large gas load emitted from the neutralizer duct. The actual pumping is provided by a large cylindrical cryopanel which surrounds the source, neutralizer, deflecting magnet and beam dump.[6] The finger spacing is, however, sufficiently small so that magnetic shielding looks fairly uniform at the beam centerline.

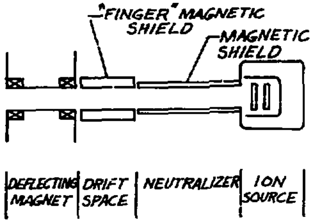

Fig. 1

NEUTRAL BEAM SOURCE SCHEMATIC

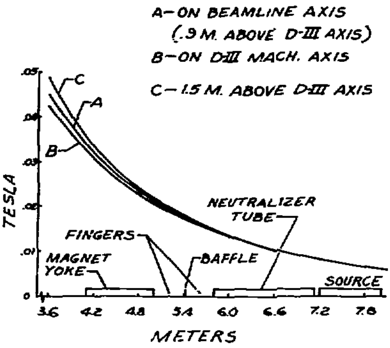

Fig. 2

DOUBLET III FRINGE FIELDS[4]

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Proposed Design

It is proposed that a novel method of addressing both the cryopumping and magnetic shielding requirements is to combine the functions by using a Type I superconductor cooled to $<4.2^{\circ}$K. At this temperature, the superconductor is sufficiently cold to provide hydrogen cryopumping.

Magnetic Shielding

A Type I superconductor (i.e., pure lead or pure niobium) attached to a liquid helium cooled substrate, can be used both as a cryopump and a magnetic shield.[7] A Type I superconductor is, in theory, a perfect diamagnetic material up to its critical field. (At a temperature of 4.2°K, the critical fields of lead and niobium are about 0.05T and 0.2T respectively. Fig. 3 shows the critical field vs temperature for various Type I materials.)[8]

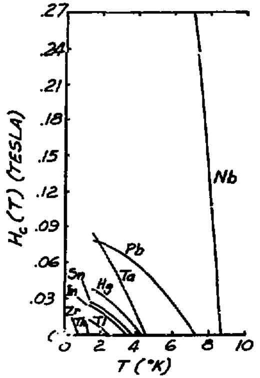


Fig. 3

CRITICAL FIELDS FOR VARIOUS SUPERCONDUCTORS

A cylinder of lead, for example, will exclude up to 0.025T of magnetic field. (The peak field at the surface of a Type I superconducting cylinder can be as high as twice the ambient uniform field. See Fig. 4) The LBL ion sources are rectangular. Magnetostatic calculations using a material with a $\mu = 0$ will have to be performed in order to determine the actual peak field around the rectangular or ellipsoidal magnetic shields. (Circular shields which surround rectangular regions with large width to height ratios will suffer from flux penetration in the third dimension. See Fig. 5)

Pure Type I superconductors do not, in theory, develop any a.c losses as long as the flux remains below its critical field. R.F. cavities built with lead and niobium have developed very high Q's which is evidence of low a.c losses.[9,10] The dynamic magnetic field is expected to be rather mild. For example, the rise time for Doublet III is approximately 40 to 50 msec. Eddy currents produced on the neutral beam source aluminum tank attentuate the field so that the actual field rise time computed for the shield is of the order of 100 to 300 msec.[11]

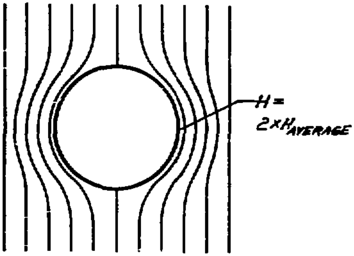


Fig. 4

FIELD DISTRIBUTION AROUND A CYLINDRICAL SHIELD

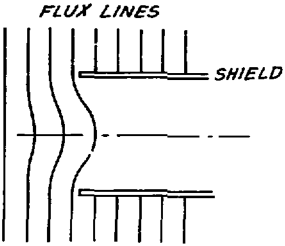


Fig. 5

FLUX PENETRATION INTO THE END OF A CYLINDRICAL SHIELD

The design of the shield requires one to look at the location of normal substrate materials with respect to the superconducting shield material. In general, the superconductor should be outside (on the high field side) of the substrate material (probably liquid helium cooled copper) so that the magnetic flux change seen by the substrate is minimized.

Further research using actual design parameters, geometric constraints, and experimental a.c loss measurements on obtainable superconducting substrate configurations needs to be performed.

Cryopumping

The drift space between the neutralizer exit and the entrance to the deflection magnet is provided to maximize pumping speed in this area where a steep pressure gradient is required. The pressure difference between the neutralizer and the deflection magnet must be maximized to promote charge exchange with the ions in the neutralizer and inhibit reionization of the neutrals downstream. This steep pressure gradient requires a substantial pumping speed at the drift space. The drift space is made sufficently long so that the volume is not conductance limited. The conventional magnetic shield which surrounds this volume inhibits its pumping. A superconducting lead magnetic shield, on the other hand, would significantly enhance the vacuum pumping of this volume.

Consider the four cases shown in Fig. 6. These cases, again are based on the Doublet III experience. For simplicity, only one source is considered.

Take Case A as a datum. The pressure in the drift duct space in Case B is slightly higher than Case A due to the conductance limitations of the shield. Case C is approximately equivalent to Case B. The reflected gas molecules in Case C are directed into the beam space, whereas the reflected molecules in Case A have a less than unity probability of being reflected into this space due to the shape factor of the cylinder to the rectangular space. Case D, on the other hand, could provide up to 4 times the pumping speed of Case A.

Advantages

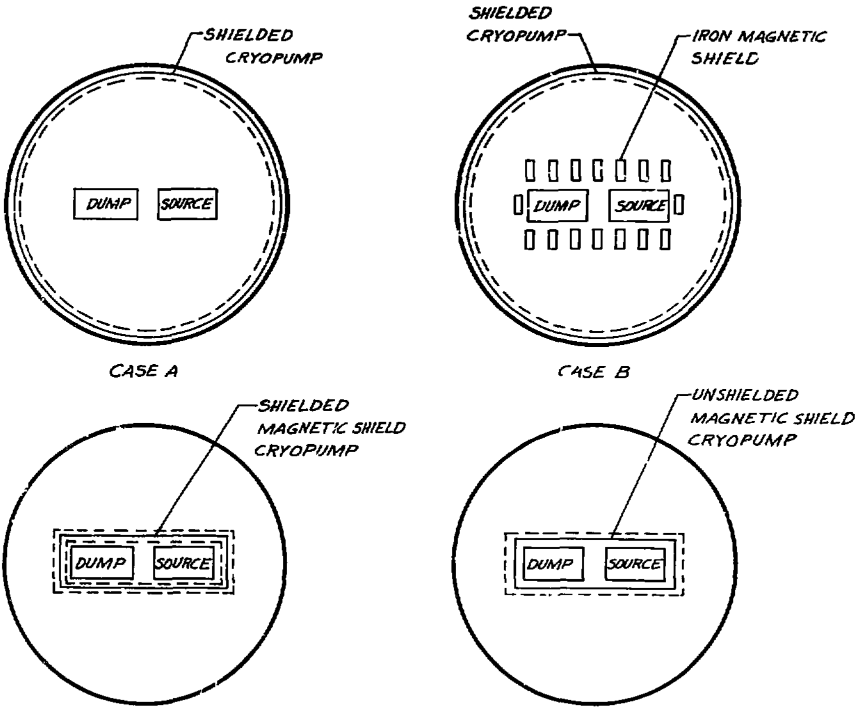
The potential cryogenic advantages of this type of scheme seem quite obvious.

1. The cryogenic load, both liquid nitrogen and helium, can be reduced by a factor roughly proportional to the area reduction. This reduction is axial as well as radial since there is no need to pump in the axial area surrounding the deflection magnet. Savings in initial cost of refrigaration equipment and operating cost due to lower loads can be realized.
2. This reduction in area, and consequently in mass, may allow quick regeneration of the cryoparel thus preventing dangerous buildup of hydrogen.

The design advantages associated with other components in the neutral beam source are less obvious.

1. Presently, the magnet, beam dumps and beam diagnostic and other equipment must be carefully shielded to prevent heat transfer to the cryopanel surfaces which surround them. This precaution must be taken to prevent their water circuits from freezing and damaging these components between operating periods. The smaller cryogenically cooled surfaces proposed here will have a significantly smaller shape factor to these conventional devices and will be more easily shielded.
2. Since the magnetic shielding is accomplished by diamagnetic expulsion, the shielded flux will not have to be carried by the deflection magnet steel. This magnet will shrink.
3. The total radial size of the neutral beam source can be reduced.

Numbers 1, 2, and 3 above will reduce fabrication costs significantly.



CASE A

CASE B

CASE C

CASE D

Fig. 6

NEUTRAL BEAM SOURCE GEOMETRY OPTIONS

Difficulties

The obvious issue which must be addressed is that of gas desorption due to the beam. The three mechanisms of desorption are cited here with not attempt to quantify their probable effects.

Photo desorption due to decay of energetic particles emit ultraviolet radiation. Ambipolar diffusion due to the dynamics of the populations of ions and electrons can cause radial particle motion from the beam center with energies of a few tens of eV's. The third mechanism is direct beam scattering.[12]

Direct beam scattering can be shielded by proper collimation since it is well directed from a known source. The radiation due to decay of energetic particles is similar to the long wavelength radiation from room temperature. Chevron or other similar shielding should shield against this mechanism. Particles accelerated outwards due to amibpolar diffusion may be sufficiently cooled after a few bounces on a liquid nitrogen cooled shield. There seems to be a reasonable probability that the shielded cryopump/magnet shield option (Fig. 6 - Case C) will work. Further experiments will be needed to assess the feasibility of Case D. (No shield)

Closure

The potential problems and difficulties of the proposed magnet shield/cryopanel combination may be fundamental. However, the possibility of having a totally "cold bore" neutral beam source with its size and cost implications on the whole device presents an attractive engineering option which deserves further study.

Acknowledgements

We would like to gratefully acknowledge the guidance and encouragement provided by Dr. Klaus Halbach and Dr. Klaus Berkner.

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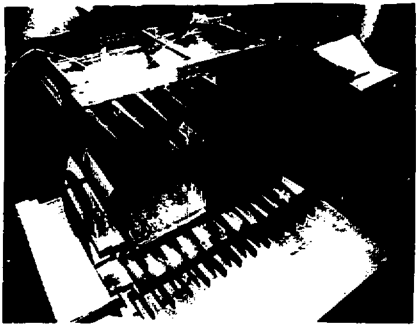

Fig. 7

DOUBLET III DEFLECTION MAGNET AND MAGNETIC SHIELD

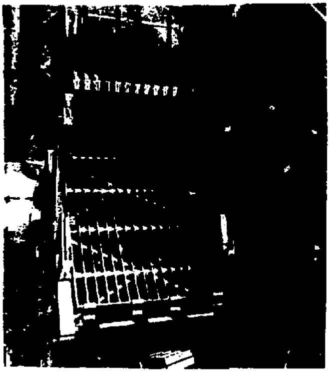

Fig. 8

TFTR MAGNETIC SHIELD

Fig. 9

DOUBLET III CYLINDRICAL CRYOPANEL

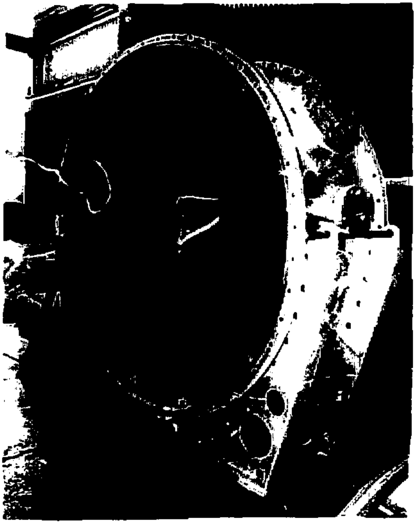

Fig. 10

DOUBLET III FLAT CRYOPANEL

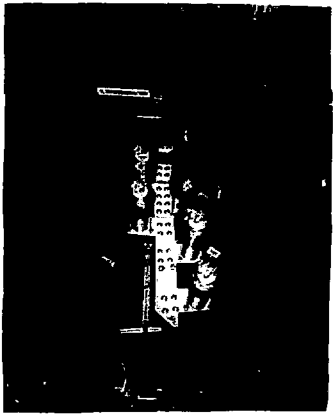

Fig. 11

TFTR DEFLECTION MAGNET AND MAGNETIC SHIELD

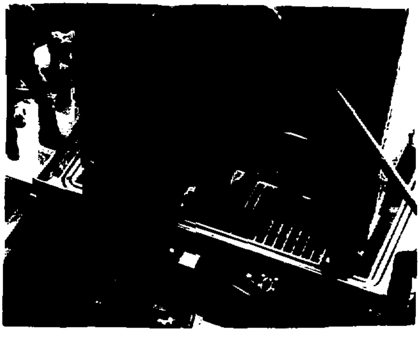

Fig. 12

TFTR MAGNETIC SHIELD AND CRYOPANELS