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THE FEASIBILITY OF A LOW-FIELD SUPERCONDUCTING THIN-SEPTUM MAGNET

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Most of the work done in recent years with superconducting magnets has been done with magnets with field strengths greater than 20 kilogauss. This paper discusses the use of superconductors on a thin-septum magnet with a field strength of less than 10 kG.

The magnetic field outside a septum magnet must be zero. In order to achieve this condition a current sheet must be established across the vertical aperture of the magnet. If the septum is used for multiturn extraction, the intensity of the field inside the magnet is severely limited by the thickness of the septum thin conductor.

Superconducting material developed in recent years allows current densities greater than 10^5 A/cm^2 to be achieved, particularly at low magnetic fields.[3,4] If the superconductor is bonded to a copper substrate with cooling tubes, there is no distortion of the current sheet, since current flows through the superconductor only.

The iron core serves as a container for the magnetic field. If the core is not saturated, the iron insures the uniformity of the magnetic field. Saturation should not affect a properly designed septum magnet with field strengths less than 15 kG.

Niobium-zirconium wire operates in the superconducting state at current densities greater than 10^5 A/cm^2. (See Fig. 1.) If a 10-kG septum is wound with niobium-zirconium wire, the thickness of the thin conductor can be less than 1 mm. This is one order of magnitude less than with current water-cooled conductors.[5]

Stability Criteria - The Key to Magnet Conductor Design

The principle of stabilizing a superconductor was first published by Stekly and Zar.[9] The "stable superconductor" is one that returns to the superconducting state following a disturbance that causes the conductor to go normal. Normal zones are not propagated in a stabilized conductor. In general, the stabilized conductor can go normal and then return to the superconducting state without any decrease in the current flowing through the conductor.

A superconductor can be stabilized by mounting the superconductor on a substrate cooled by liquid helium. If the superconductor-substrate combination is stable, there should be no degradation of the current-carrying capacity of the superconductor. It is useful to present the Stekly stability parameter[9]

$$\alpha = \frac{i_{CH}^2 \, \mathrm{Res}\, \ell}{h_c A_c A\, (T_{CH} - T_b)},$$

where

i_{CH} = critical current at the bath temperature,
Res = resistivity of the substrate,
h_c = convective heat transfer to the helium,
A = convective heat transfer area,
A_c = cross-sectional area of the substrate,
T_{CH} = critical temperature at magnetic field that the wire is in
T_b = bath temperature (usually 4.2°K),
ℓ = length of the conductor,
α = stability parameter.

The above equation assumes that all the normal current flows through the substrate and that only the superconductor carries the superconducting current. The stability parameter must be less than unity in order to achieve completely stable operation. When the conductor is stable all the current flows in the superconductor until $i = i_{CH}$. If α is greater than unity the conductor is stable only when $i \le i_{CH}/\sqrt{\alpha}$; when $i_{CH}\sqrt{\alpha} < i < i_{CH}$ the current either flows in the conductor or in the substrate. (The normal region will be propagated throughout the conductor, see Fig. 2.) The stability parameter, in general, is the ratio of the heat generated in the conductor or added from an outside source to the heat removed in the helium bath. The generalized stability parameter is

$$\alpha = \left[\frac{i_{CH}^2 \, \mathrm{Res}\, \ell}{A_c} + Q_c\right] / h_c A\, (T_{CH} - T_b),$$

where

Q_c = the heating rate from an external source.

In a superconducting septum magnet used as an extraction magnet for an accelerator, one may expect outside heating to occur. The sources of this heating would be radiation from other surfaces in the vacuum tank and interaction of the conductor with the accelerated beam.

Since the superconductor has an external source of heat which must be transferred to the liquid helium bath, the conductor should be stabilized ($\alpha \le 1$) at a temperature higher than the bath temperature. This allows the outside heat to be transferred to the helium bath during superconducting operation. If the superconductor is stabilized at a temperature of 7°K, the conductor should be stable if the heat transfer rate to the liquid helium is less than 1 W per cm^2 of convective-heat-transfer area.[2,6] (The above statement assumes that the conductive heat transfer from the superconductor to the bath boundary is good.)

The properties of the substrate affect the operating characteristics of the magnet. A pure copper substrate has the following properties at 4.2°K:[11]

density,	$8.9\ g/gm^3$,
electrical resistivity,	10^{-8} ohm cm,
thermal conductivity,	70 W/cm°K,
specific heat,	1.6×10^{-4} J/g.

The thermal conductivity and electrical resistivity are affected by the purity of the metal; both values given above are for very pure (99.999% pure) annealed specimens. If 0.01% impurity is added to the specimen, the thermal conductivity is reduced by a factor of 10. Cold-worked specimens exhibit lower thermal conductivity and higher electrical resistivity than the annealed specimen. The heat storage of the conductor can be neglected because of the low specific heat at liquid helium temperatures.

The thin septum for slow extraction requires that the conductor interact with the accelerated beam. The wedge-shaped design for the thin conductor shown in Fig. 3 permits maximum heat transfer from the thin conductor to the helium. The density of the current sheet across the aperture must be uniform. Hence, the position of the superconducting layer is along the inner surface of the conductor and this conductor thickness is uniform as it crosses the gap. The wedge-shaped substrate allows the cross-sectional area and convective heat transfer area to be large, to insure stability.

The magnet acts as a septum magnet only when the conductor is fully superconducting. When some of the current flows in the substrate, the flux lines leak out of the conductor. Normalization of the conductor results in an outward motion of the flux lines as the coils' inductance increases. When the superconductor once more becomes superconducting, the inductance decreases as the flux lines are forced inward again.

Basic Magnet Design Criteria for a 5-kG Thin Septum

The design requirements for a thin extraction septum are dependent on the energy of the particle to be extracted and the length allowed for extraction. If the septum field is set at 5 kG, the minimum size of the thin conductor will be about 0.5 mm. The lengths of 5-kG magnet required for various bending angles at various proton energies are given in Table I.

The aperture of the magnet is determined from the beam dynamics of the accelerator and the deflection of the beam in the magnet. Both the machines in the 200 BeV Accelerator Study Report[10] would require extraction septum magnets with a vertical aperture of about 2 cm. The horizontal or radial aperture would be about 6 cm for the injector synchrotron and 4 cm for the large machine. The 2-meter extraction septum for the 200 BeV machine could be replaced by a 50-cm 5-kG superconducting septum.

If the basic magnet iron cross section (see Fig. 4) were 1 cm wide by 14 cm high, the iron pole should not saturate and should allow for cooling with liquid helium. The shape of the B-H curve for iron changes drastically at low temperature.[1] The initial permeability is much lower at 4°K than at room temperature. Experimental magnetization data at these temperatures must be considered before the design of the iron pole is set.

The conductor shown in Fig. 3 should handle the required 8 000 ampere turns provided the external heating is not excessive. The conductor would consist of a layer of niobium-zirconium 0.4 mm thick and 2.0 cm wide bonded to the copper substrate. The conductor could either be a drawn ribbon or a number of wires in parallel that are bonded securely to the substrate. In general, the maximum current density is greater for the wire than for the ribbon. A pure copper bond between the superconductor and the substrate would be desirable for heat-transfer reasons. The magnet shown in Fig. 4 is a two-turn magnet; there is a gap between the two turns. A current of 4 000 A would be carried by each turn. The use of inorganic insulation (such as anodized aluminum) is required for slow extraction.

The vacuum tank that houses the magnet should be helium-cooled to eliminate heat transfer by radiation from the vacuum tank wall to the magnet. The vacuum tank could be housed in a liquid helium Dewar. The vacuum beam tube upstream and downstream from the magnet should be nitrogen-cooled to reduce heat transfer by radiation from these sources.

The helium refrigeration requirement is dependent on several parameters. They include the heat leaks to the magnet from outside sources, joule heating in the conductor during normal operation, and heating due to impingement of the accelerated beam. The refrigeration requirement for the first two heat sources will be less than 25 watts. The last source of heat is discussed in the next section.

The Effect of Beam Impingement on Magnet Performance

Beam impingement on the thin conductor will affect the operation of the thin septum. The first effect of beam collision is the heating of the thin conductor. This heat must be removed by the helium cooling system. The second effect of beam impingement is the change in the properties of the superconductor, substrate, and insulation due to radiation.

The septum magnet would be heated by the beam during slow extraction. This heating is a function of beam intensity, beam energy, and the material the septum is made of. If the energy of an incident proton beam is 200 GeV and its intensity is 3×10^{13} particles per pulse,[10] the amount of energy released on an unshielded septum is about 2 000 joules per pulse during slow extraction.[7]

In order to maintain the septum in the superconducting state, 98 to 99% of the heat load must be deposited on a shield ahead of the magnet. The shield ahead of the magnet should be divided into two parts. The first part, which handles most of the energy, should be made of copper, be 70 cm long and 1 mm wide, and be water-cooled. The second section should also be made of copper. This section is 40 cm long and 1 mm wide, and liquid-nitrogen-cooled. (See Fig. 5.)

These shields should remove at least 95% of the beam interaction energy, but the removal of the remaining 3 to 4% may not occur. The alignment of the shields with the septum magnet is very critical.

Irradiation of the thin conductor will cause changes in its properties. The superconductor, the substrate, and insulation will be changed by irradiation. The change in material properties will affect the operation of the magnet.

Fast-neutron bombardments of niobium-tin and niobium-zirconium by Macevoy and Decell[8] have shown that superconducting properties improve with neutron bombardment. The experiments have shown up to 50% improvement in critical current. The effect of radiation on the annealed sample is similar to the effect of cold-working the metal.

Irradiation of the substrate reduces the thermal conductivity and increases the resistivity of the metal at liquid helium temperatures. These properties are very sensitive to changes in purity and crystalline state.[11]

The effect of radiation on magnet insulation is well known. The use of organic insulation should be avoided. Inorganic insulations such as alumina and anodized aluminum should be investigated.

Conclusion

I feel that the magnet's feasibility will depend on how it is used. If the magnet has no interaction with an accelerated beam, I feel that the magnet can be built. If, however, the magnet is required to interact with the accelerated beam (even when it is shielded), its feasibility is in question.

The engineering problems on this magnet would be formidable. The magnet cost would probably be an order of magnitude higher than present magnets of this type, particularly since cryogenic temperatures must be maintained throughout the system. I feel that further study is important, particularly since new advances are being made in cryogenics and superconductivity.

References

*Work performed under auspices of U. S. Atomic Energy Commission.

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[10]200 BeV Accelerator Design Study, Lawrence Radiation Laboratory, University of California, Berkeley, California, June 1965.

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Table I. The length of 5-kG septum that is required to deflect protons of various energies through various angular deflections.

Proton energy	Angle of proton deflection (milliradians)		
	1	5	20
3 GeV Princeton-Penn AGS	2.55 cm	12.8 cm	51.5 m
8 GeV Injector Synchrotron for 200 BeV Study	5.93 cm	29.6 cm	1.19 m
30 GeV Brookhaven AGS	20.6 cm	1.03 m	4.12 m
200 GeV Advanced Accelerator Study	1.34 m	6.70 m	26.8 m

LIST OF FIGURES

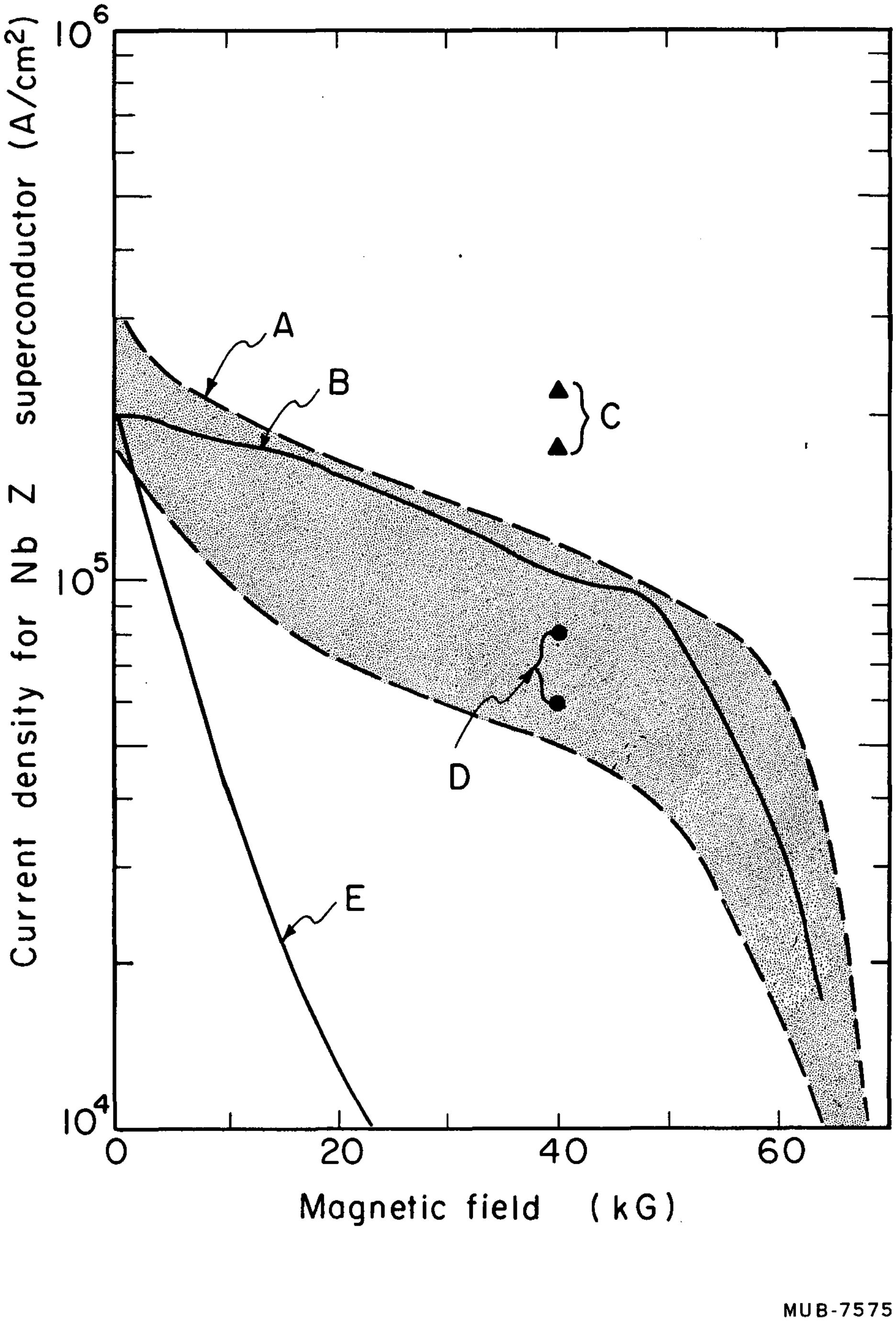
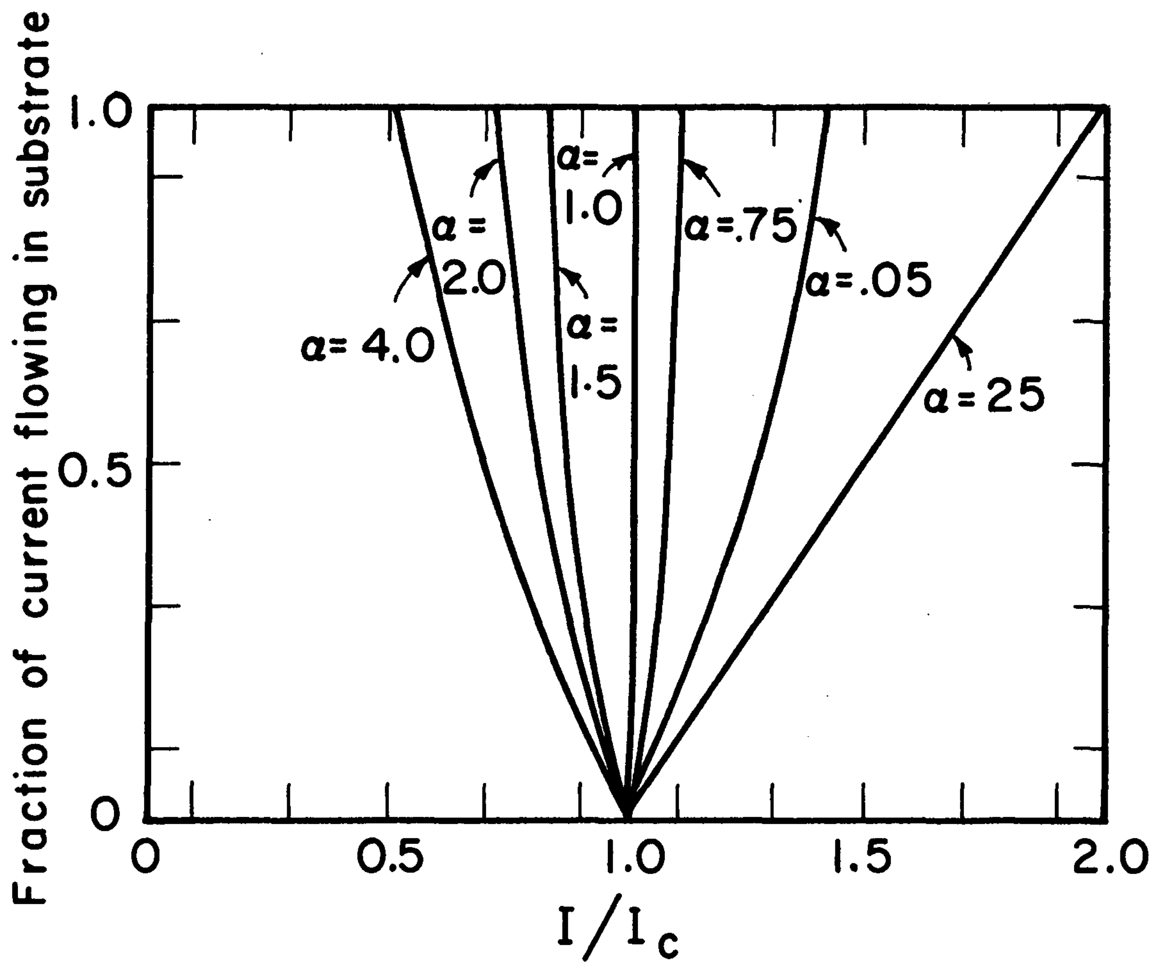

Current density for Nb Z superconductor (A/cm²)
10⁶
10⁵
10⁴
A
B
C
D
E
0
20
40
60
Magnetic field (kG)
MUB-7575

Fig. 1



MUB-7576

Fig. 2

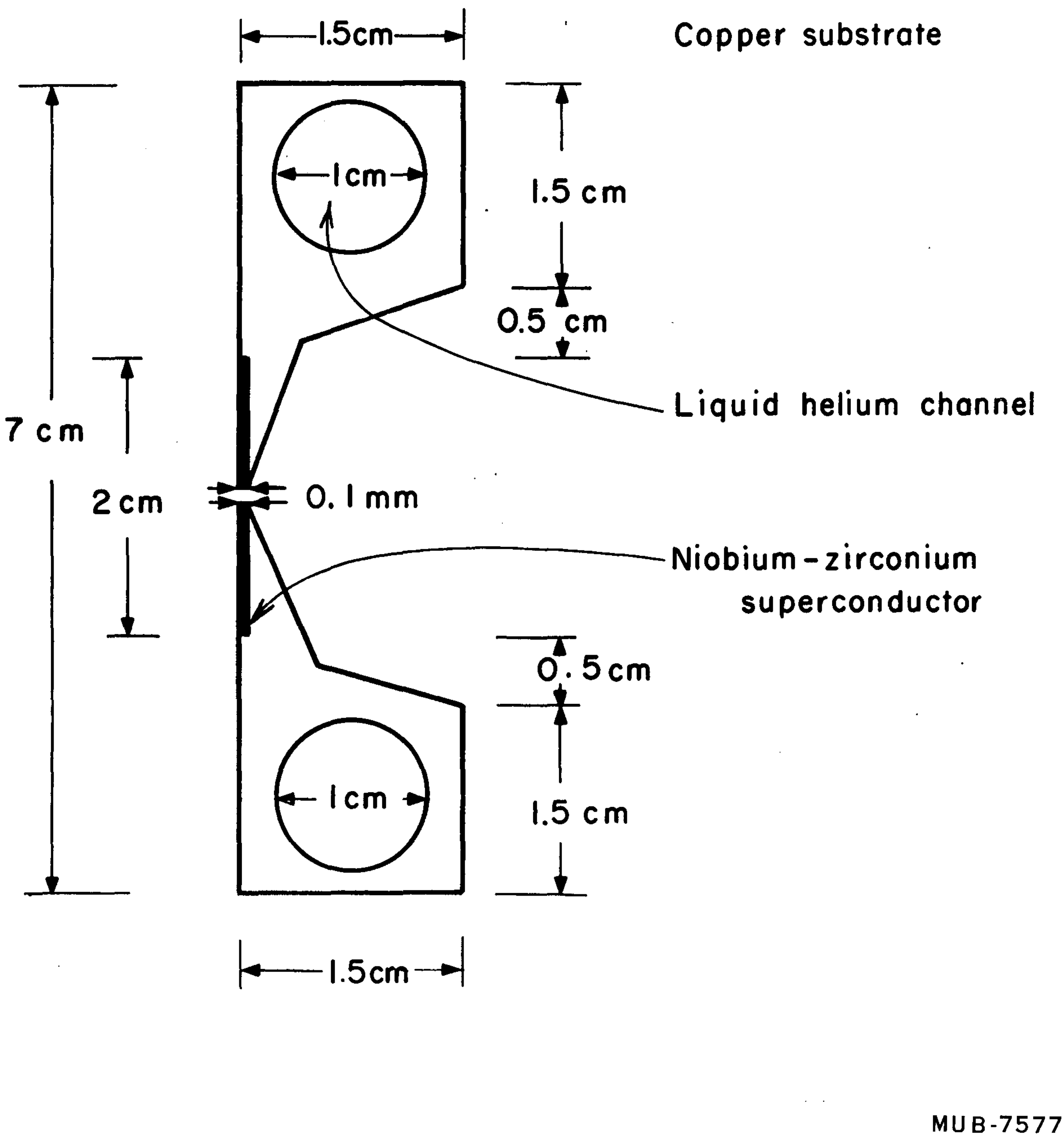

1.5cm
Copper substrate
7 cm
1cm
1.5 cm
0.5 cm
Liquid helium channel
2 cm
0.1 mm
Niobium - zirconium superconductor
0.5 cm
1cm
1.5 cm
1.5cm
MUB-7577

Fig. 3

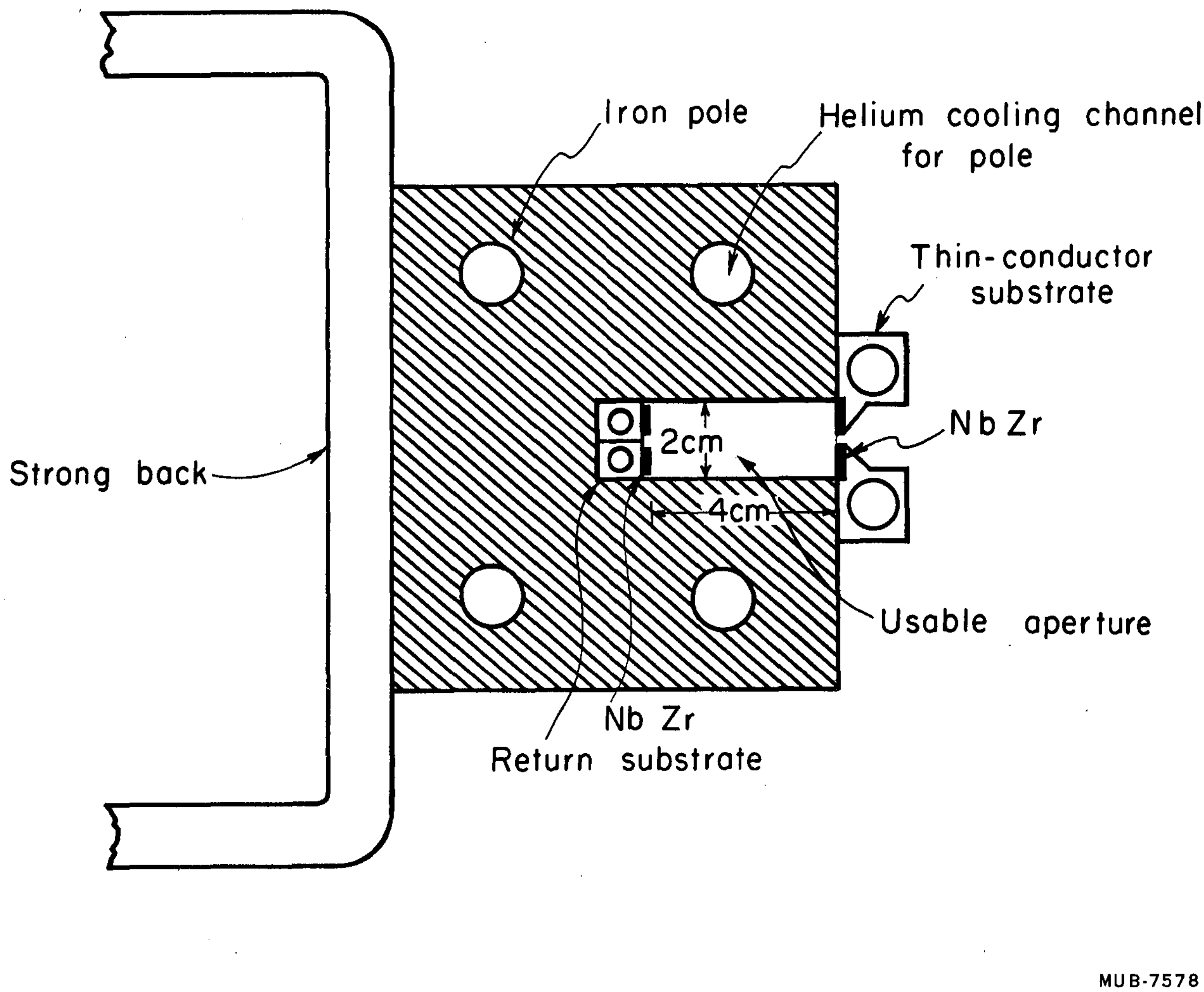

Iron pole
Helium cooling channel for pole
Thin-conductor substrate
Nb Zr
2cm
4cm
Strong back
Usable aperture
Nb Zr
Return substrate
MUB-7578

Fig. 4

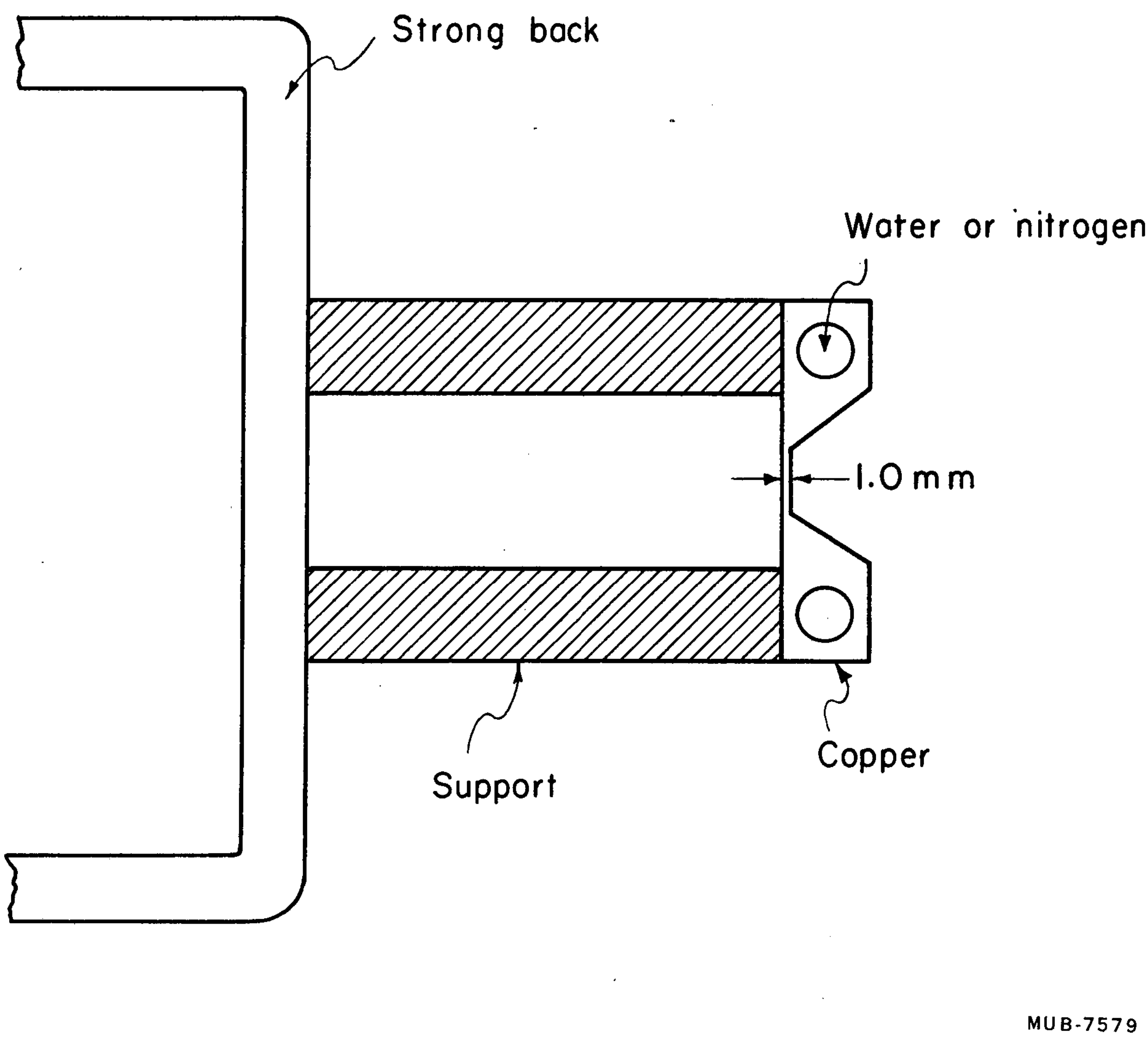


Fig. 5