Magnetic Field Shielding with Superconductors

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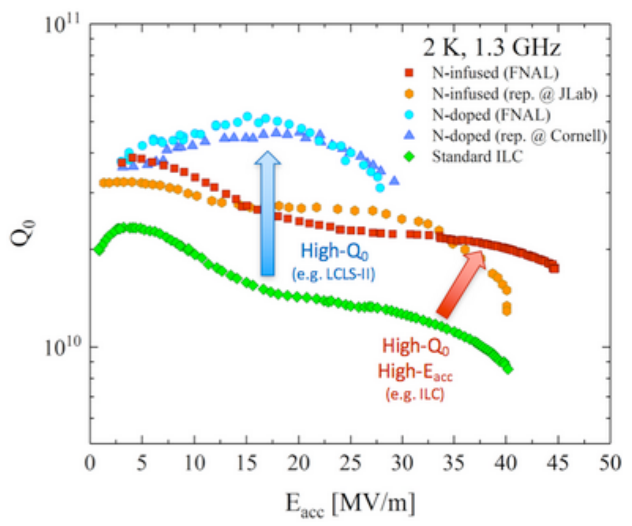
Abstract

Magnetic fields occupy an important position in many physics studies, and control of minute magnetic fields is important for measurement items in many physics experiments. Superconducting accelerating cavities can generate high electric fields with a small amount of high frequency power. However, the material niobium is a type-II superconductor, which traps the environmental magnetic flux in the material during the superconducting transition, resulting in loss during operation. Shielding from a weak magnetic field is essential. However, high magnetic permeability magnetic materials for very low temperatures are expensive, not easy to handle, and increase costs. Therefore, we are proceeding with research focusing on magnetic shields that utilize the diamagnetism of superconducting materials, rather than the magnetic flux absorption phenomenon caused by high magnetic permeability materials.

Background



Cavity's Q is increasing.

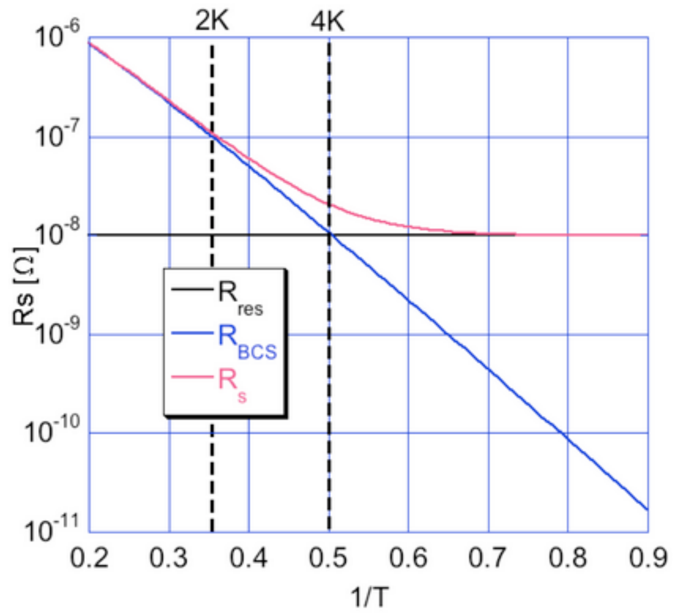
$$Q_0 = \frac{\omega W}{P} \propto \frac{1}{Rs}$$

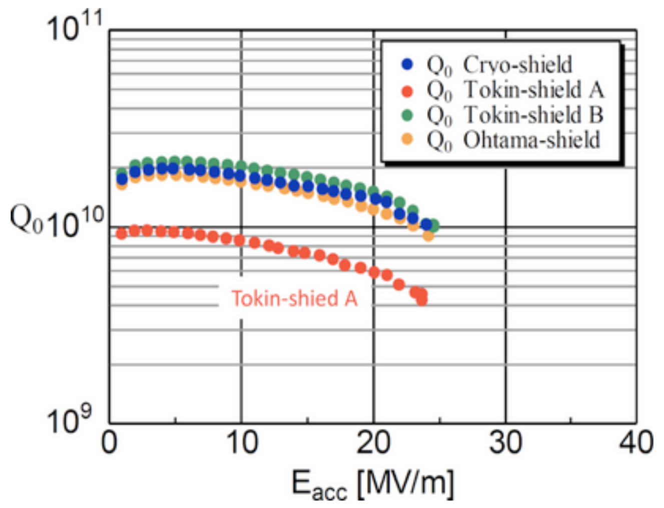
$$R_s = R_{BCS} + R_{res}$$

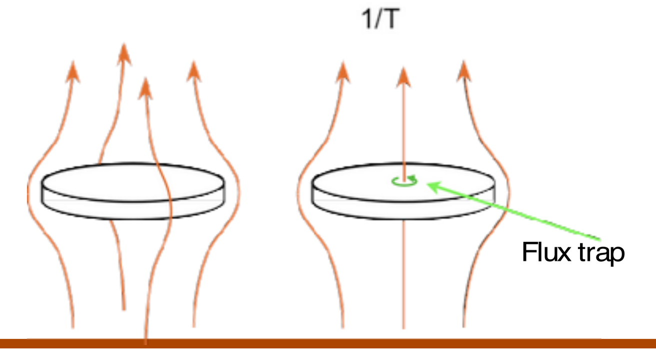
$$R_{BCS} = A\frac{\omega^2}{T}\exp\left(-\frac{\Delta}{k_B T}\right)$$

$$R_{res} = R_{impurity} + R_{defect} + R_{magnetic} + !$$

Rs: Surface resistance

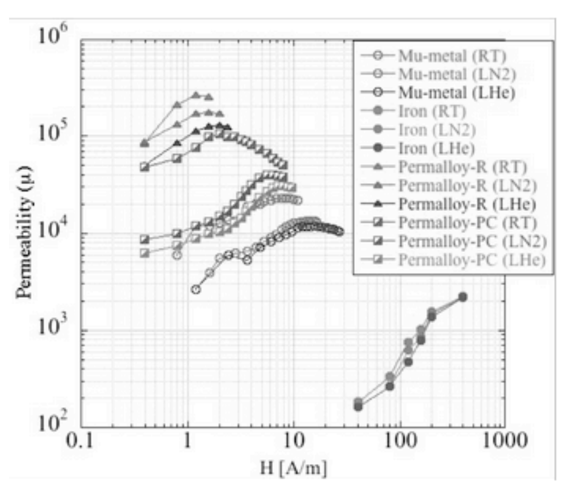


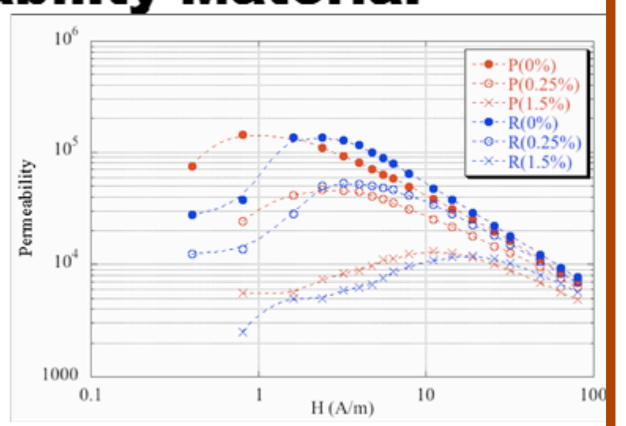


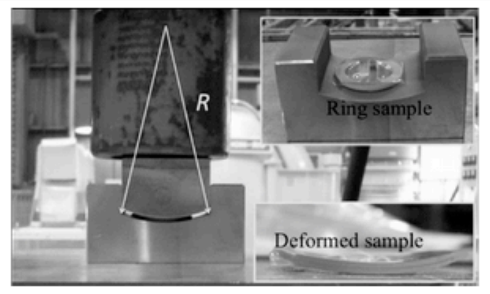


When cavity'Q goes up, residual resistance becomes dominant. $R_{magnetic}$, which comes from the flux trap, should be kept small.

High Permeability Material





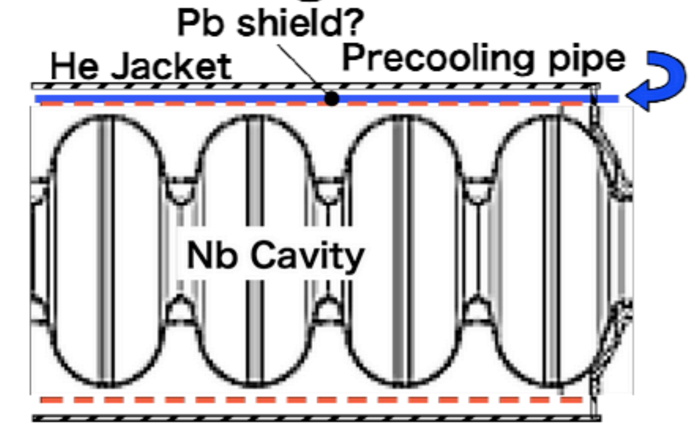


Permeability μ decreases at low temperature.

Permeability μ decreases with stress.

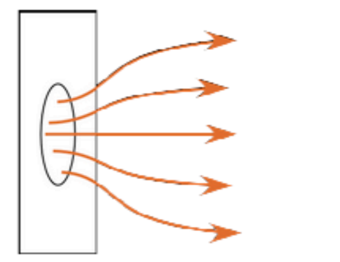
M.Masuzawa, KEK

Faint Magnetic Shield by Sc Mat'l



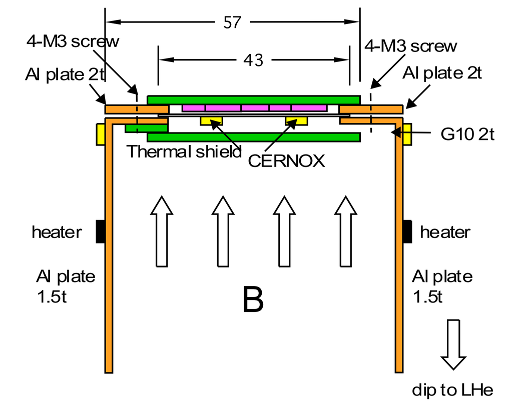
Thin Pb or Nb sheet would be cooled down quicker than thick Nb wall through the precooling pipe.

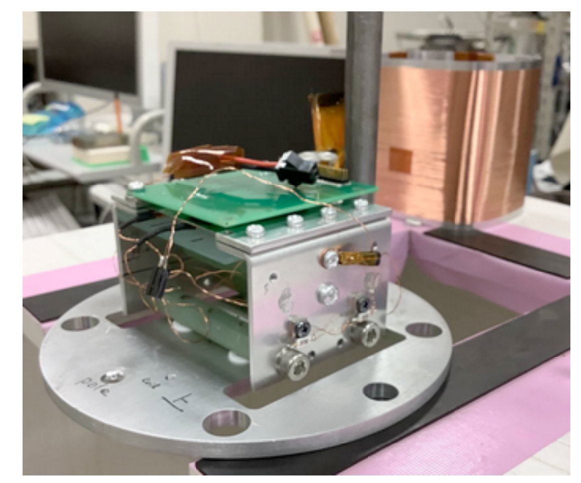
Shield in Jacket



A hole lets flux pass. (We need beam holes at least.)

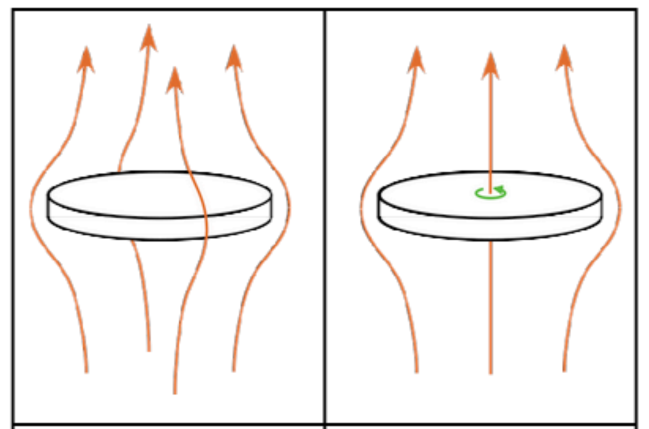
Experiment Planned





Thin Nb sheet is held by two Al clamps from both sides, whose temperatures are controlled for temperature gradient control.
The magnetic field is measured by Fluxgate.

Sc Type I and Type II



Type-I: Perfect diamagnetism (Meissner Effect)

Type-II: Flux penetrates or trapped.

	Tc	Hc[G]@0K	Type
In	3.4	171	I
Sn	3.7	309	?
Hg	4.15	412	I
Ta	4.48	830	I
V	5.3	1020	II
La	5.9	1600	?
Pb	7.2	803	I
Nb	9.2	1950	II

Thin Pb or Nb sheet would be cooled down quicker than thick Nb wall.

Magnetic Resistance

$$\oint_\Gamma H ds = I$$

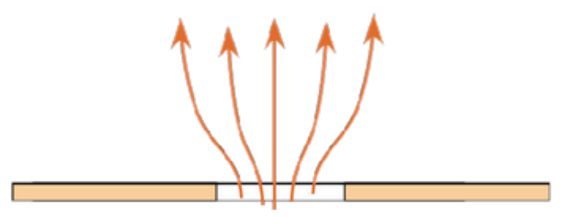
$$\int_A \frac{B_A}{\mu_A} ds + \int_B \frac{B_B}{\mu_B} ds + \cdots = I$$

$$\frac{\Phi_A}{S_A}L_A + \frac{\Phi_B}{S_B}L_B + \cdots = I$$

$$\Phi\left(\frac{L_A}{gap_A} + \frac{L_B}{gap_B} + \cdots\right) = I$$

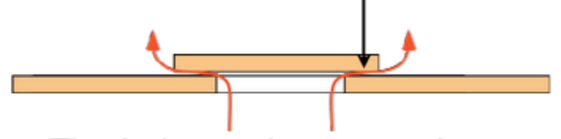
$$\Phi = \frac{I}{\sum_i \frac{L_i}{gap_i}}$$

$\Phi = {}^{gap}/_{L} \cdot I$ for a single gap.



Flux can go through a hole.

Narrow long gap reduces flux.



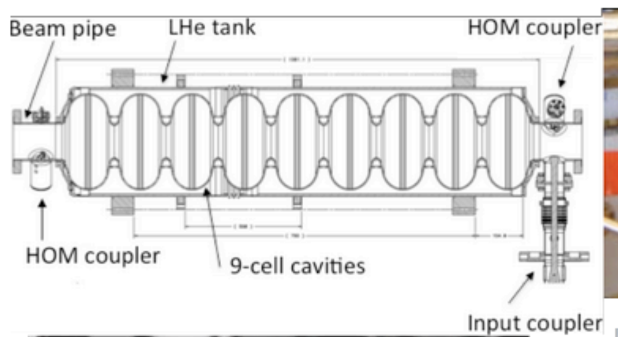
The hole can be covered.

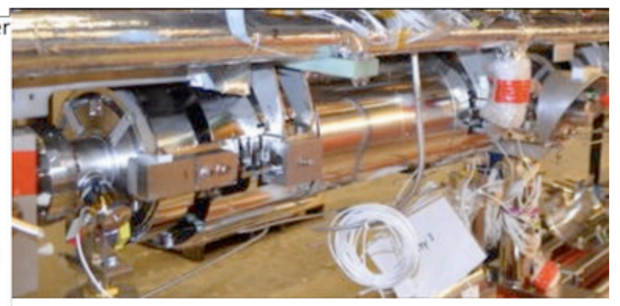
Magnetic resistance is proportional to 1/*gap*.

Experiment Setup

External magnetic field is controlled by the coil.

Mag. Shield w/ High μ Material





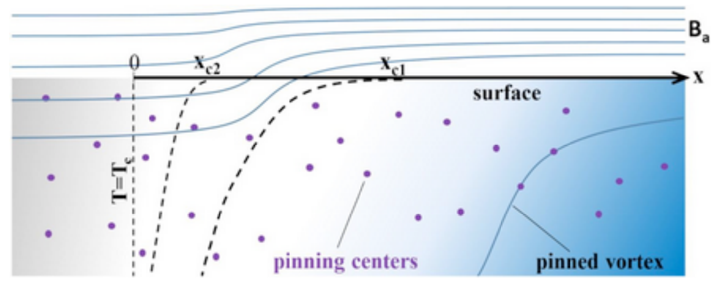
Shield in Jacket

Shield around Jacket

Conventional magnetic shields uses high permeability material.

Flux Explusion of Nb

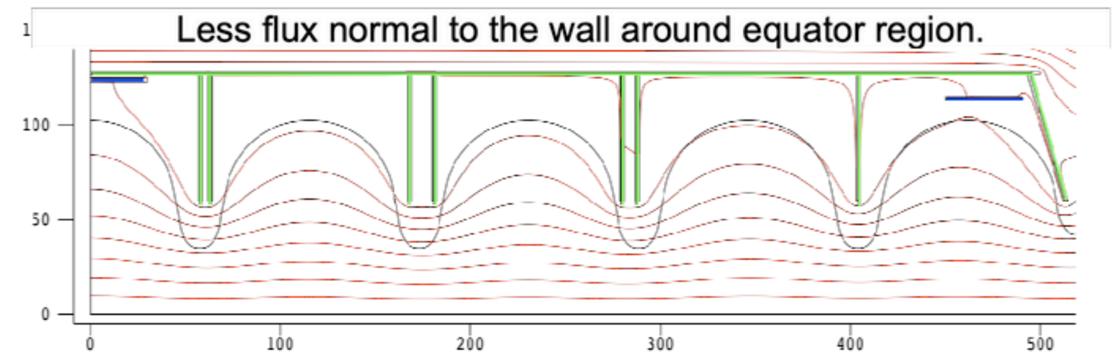
Even type-II superconductor, such as Nb, will expell flux when it is cooled down quickly (see the paper down below).

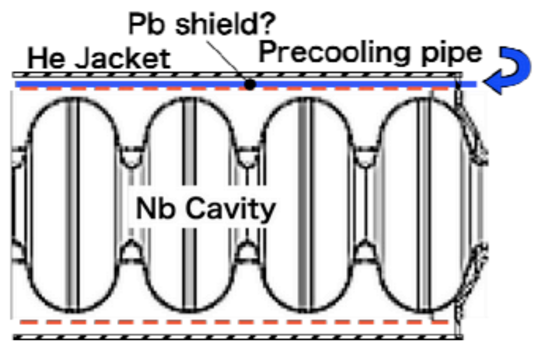


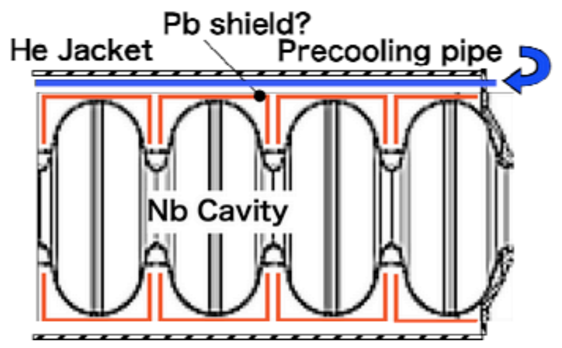
A schematic view of the vicinity of the phase transition fronts with an ambient magnetic field parallel to the surface. The region between the two dashed curves labeled by x_{c2} and x_{c1} corresponds to the vortex state domain. The dots represent pinning centers.

T. Kubo, Flux trapping in superconducting accelerating cavities during cooling down with a spatial temperature gradient
Prog Theor Exp Phys, Volume 2016, Issue 5, May 2016, 053G01, https://doi.org/10.1093/ptep/ptw049

Possible Faint Mag Shield by Pb







Summary

- Nb (Type-II Sc) can trap magnetic flux when cool down.
- Flux trapping degrades Q_0 of Sc cavity.
- Q_0 degradation becomes dominant for Hi-Q.
- Even faint magnetic field has to be shielded.
- Conventional magnetic shield may be: not enough at low temperature, high cost, and delicate.
- Type-I Sc material should exhibit perfect diamagnetism (Meissner effect), which can be a magnetic shielding.
- Even Type-II material can expel flux with fast cooling.
- Thin Sc sheet may be cooled down quicker than thick Nb wall.
- Hybrid magnetic shield may be useful.
- An experiment is planned.