A_RD_07
Suppression of magnetic flux trapping to achieve high-Q of SRF cavities

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Introduction

Merit of SRF cavity:

High accelerating gradient with significantly small surface loss.

$$P\_loss = \frac{V_{acc}{}^2}{R} = \frac{V_{acc}{}^2}{(R_{sh}/Q)Qo} = \frac{V_{acc}{}^2}{(R_{sh}/Q)(G/RS)} = \frac{V_{acc}{}^2}{(R_{sh}/Q)G} R_S$$

- Rsh/Q: shunt impedance and G:geometrical factor are parameters decided from geometry.

  Ex) L-band, 9-cell cavity: Rsh/Q～1000, G～300
- If Vacc is decided, surface loss is proportional to Rs(surface resistance)

  Ex) Vacc = 10MV/m and Rs ～30nΩ ⇒ P_loss = 10W
- Relation between Q_0 and Rs: $G = Q_0 \times Rs$

  High Q ⇔ low Rs ⇒ small surface loss

Our final goal: Operation of SRF cavity with high-Q

※ 2K He refrigerator need several 100 times of AC power to keep 2K

Surface resistance

$$R_s = R_{BCS}(T, E_{acc}) + R_{res}(T, B_{trap}, E_{acc})$$

$$= R_{BCS}(T, E_{acc}) + R_{flux\_trap}(B_{trap}, E_{acc}) + R_0$$

$$R_{BCS}(T, E_{acc}) = A(E_{acc}) \frac{\omega^2}{T} exp\left\{-\frac{\Delta(E_{acc})}{kTc} \cdot \frac{T_c}{T}\right\}$$

R_{BCS} (BCS resistance):

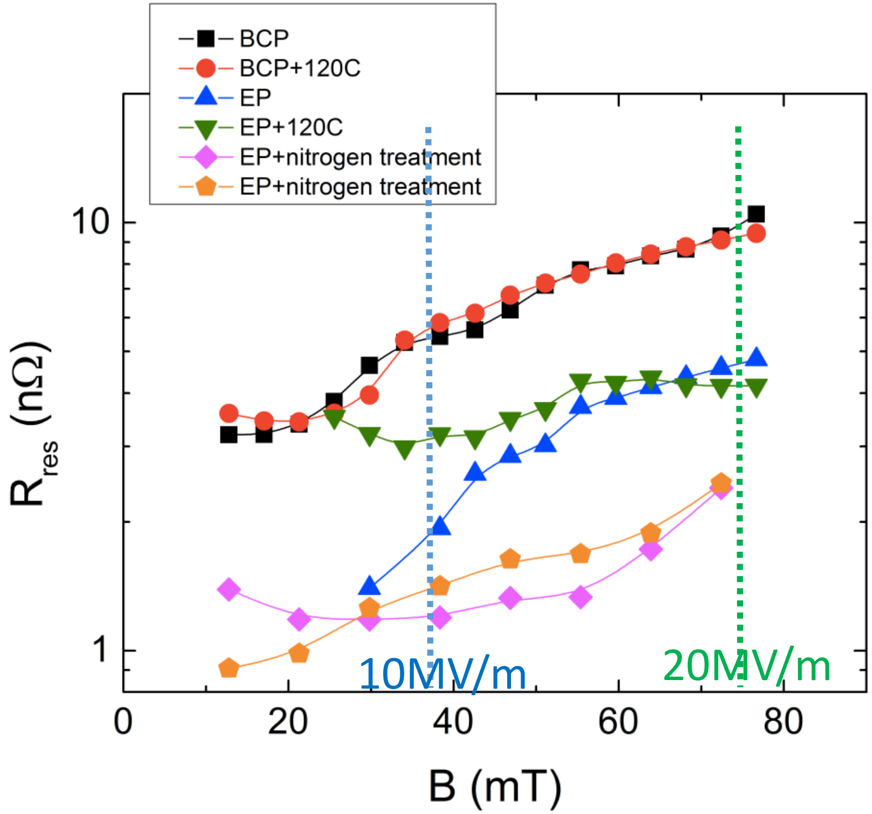
- ✓ Temperature dependent term of surface resistance
- ✓ Nitrogen doping can reduce R_{BCS}

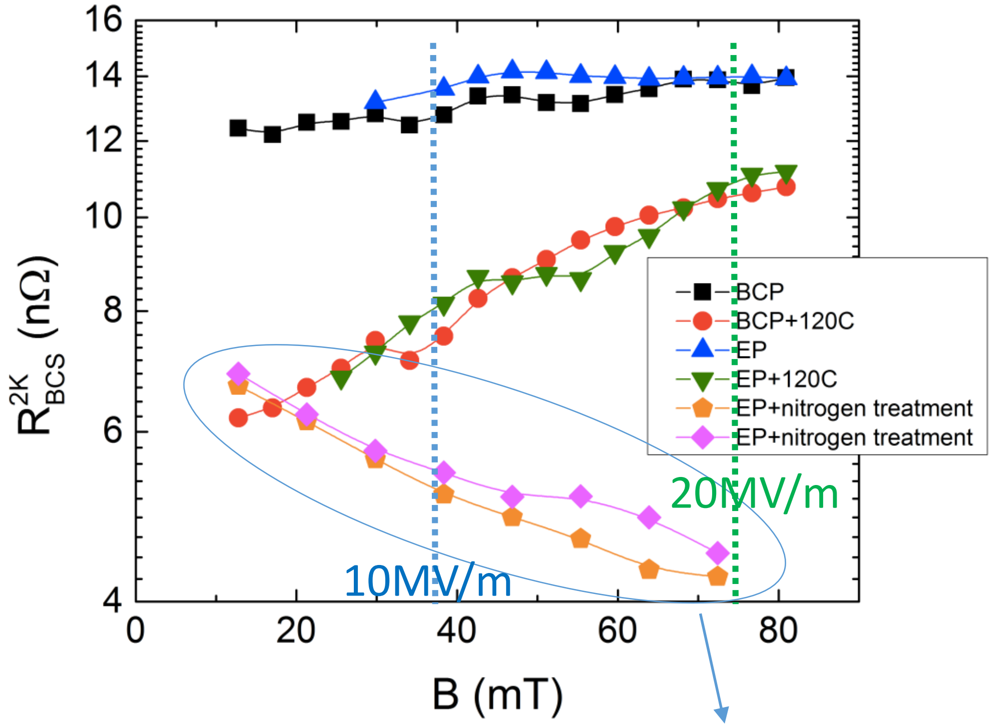
Rres (residual resistance):

- ✓ Only very weakly depend on temperature
- ✓ Summation of contribution from magnetic flux trapping term (R_{flux_trap}) and intrinsic resistance (R_0)
- ✓ Typically $R_{flux\_trap} > R_0$ ⇒ to reduce R_{flux_trap} is important to achieve low Rs

R_{res} and R_{BCS} from FNAL results

$R_s(T) = R_{BCS}(T) + R_{res}$





A. Grassellino et al, 2013 Supercond. Sci. Technol. **26** 102001

Nitrogen doping reduce R_{BCS}

- Nitrogen doping technique reduce R_{BCS} down to several nΩ at 2K.
- Reducing R_{res} became more and more important.
- R_{res} depends on experimental condition

How to reduce R_{flux_trap}?

What is magnetic flux trapping?

- Ambient magnetic field is captured in SRF cavity, when they transient to superconducting state.

How to reduce?

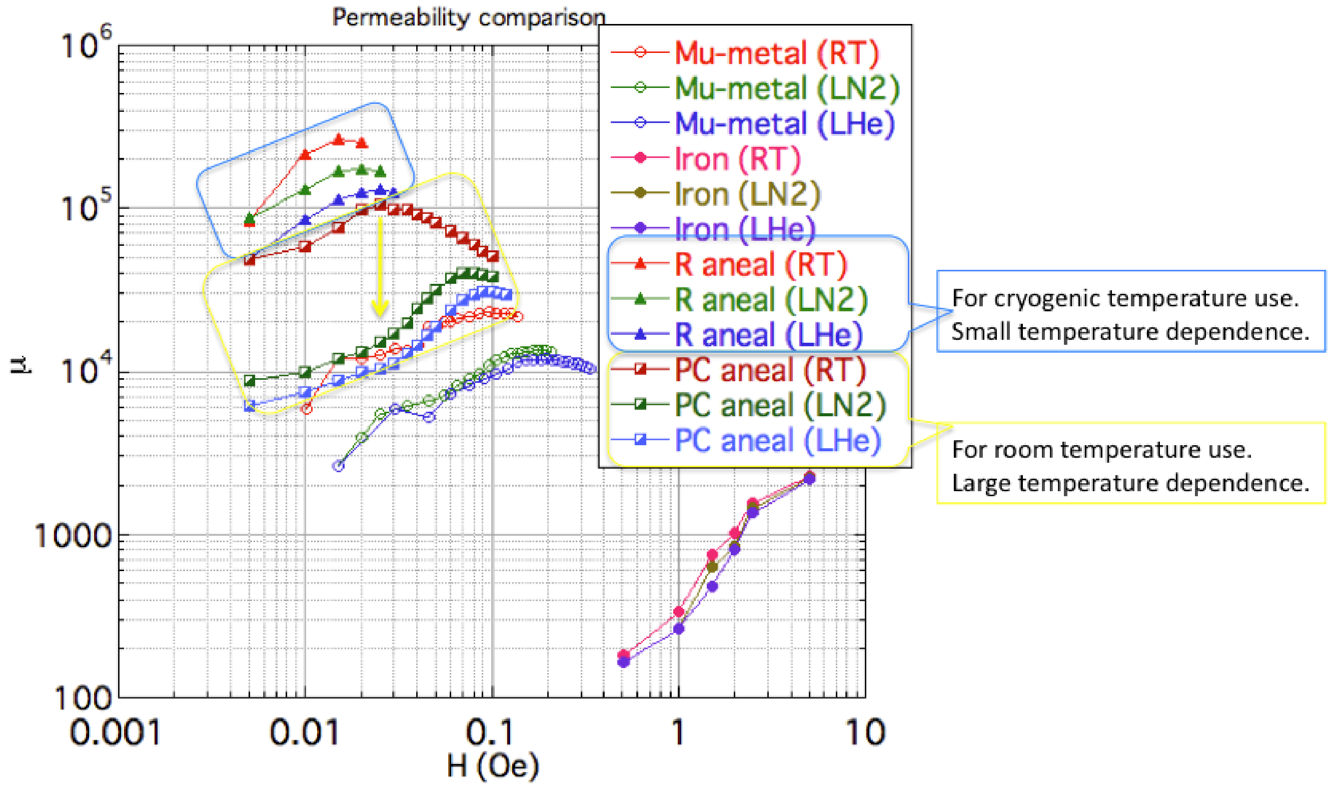
- Reduce ambient magnetic field
  - Magnetic shielding
  - Remove magnetized elements around cavity
  - Cancelling by using coils
- Reduce trapping field and its sensitivity
  - Thermal gradient during transition
  - Surface processing
  - Nb Material

Past and on-going R&D issues in the framework of FJPPL

Study of magnetic shield property

Permeability measurements

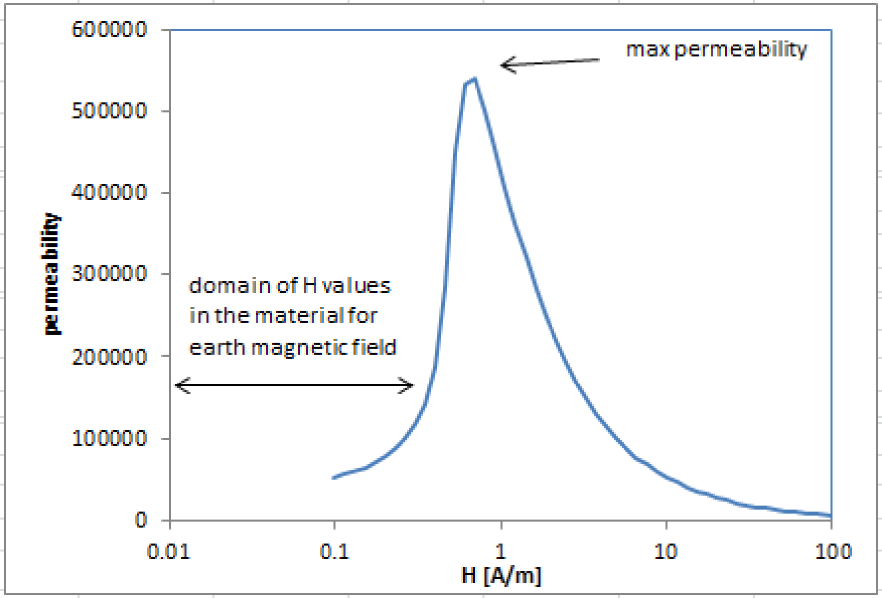
Permeability of various shielding materials
Examples of materials evaluated by KEK



- Property was measured at RT, 80K and 4K, for several materials.
- Magnetic shield is often installed into cryomodule.

⇒Should keep high permeability at cold temperature

Study on magnetic shield & remnant field



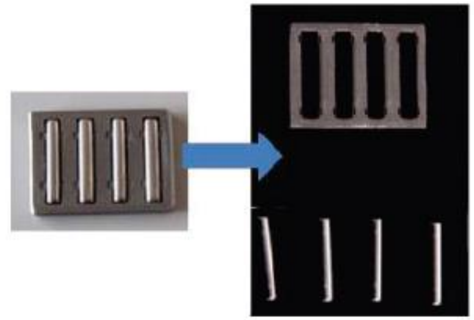


Figure 4: Off the shelf needle bearings.

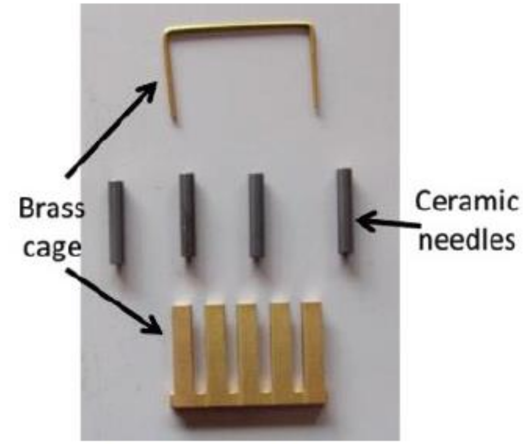


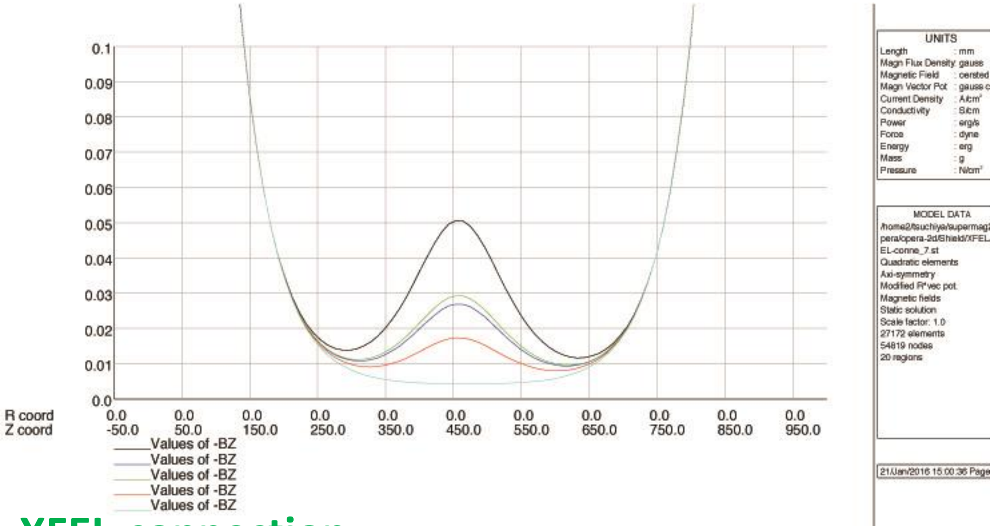
Figure 5: Home-made needle bearing.

J.Plouin et al, SRF2015 TUPB100

- CEA measured property of magnetic shield, which is used for testing IFMIF cavity.
- It is made of mumetal and work at room temperature.
- Evaluated permeability was around 25,000.

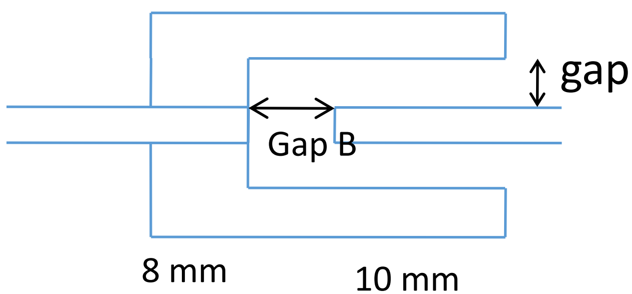
- Remnant magnetization has been studied.
- Invar rods, needle bearing and magnetic shield were investigated.
- Prepare home-made non-magnetized needle bearing.
- Solutions are under development for invar rods.
- Magnetic shield is O.K.

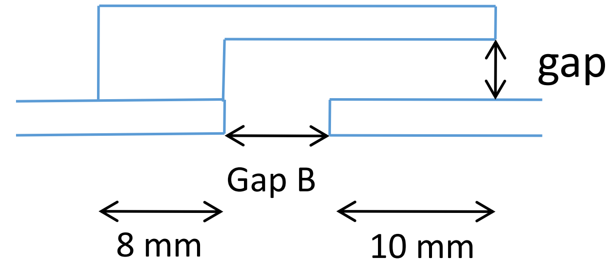
Simulation study on connection of magnetic shield



XFEL-connection

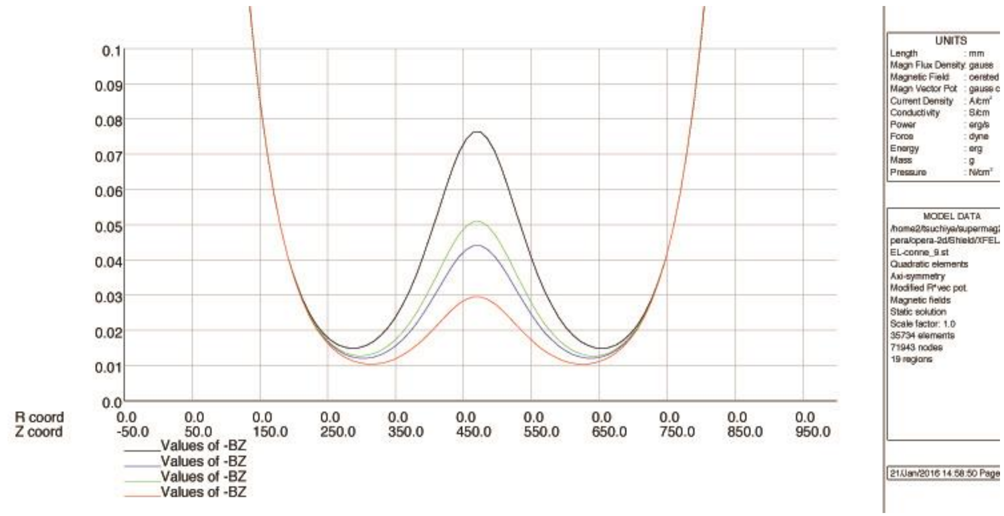
Black: gap=0.5 mm, gapB=0.1 mm
Blue: gap=0.2 mm, gapB=0.1 mm
Green: gap=0.2 mm, gapB=0.5 mm
Red: gap=0.1 mm, gapB=0.5 mm
Sky blue: 0.1 mmL-connection





STF-connection

Black: gap=0.5 mm, gapB=0.1 mm
Blue: gap=0.2 mm, gapB=0.1 mm
Green: gap=0.2 mm, gapB=0.5 mm
Red: gap=0.1 mm, gapB=0.5 mm



- Joint of two parts of shield make leakage of magnetic field.
- Design of connection parts and amount of gap are important to achieve good shielding.

How to reduce R_{flux_trap}?

What is magnetic flux trapping?

- Ambient magnetic field is captured in SRF cavity, when they transient to superconducting state.

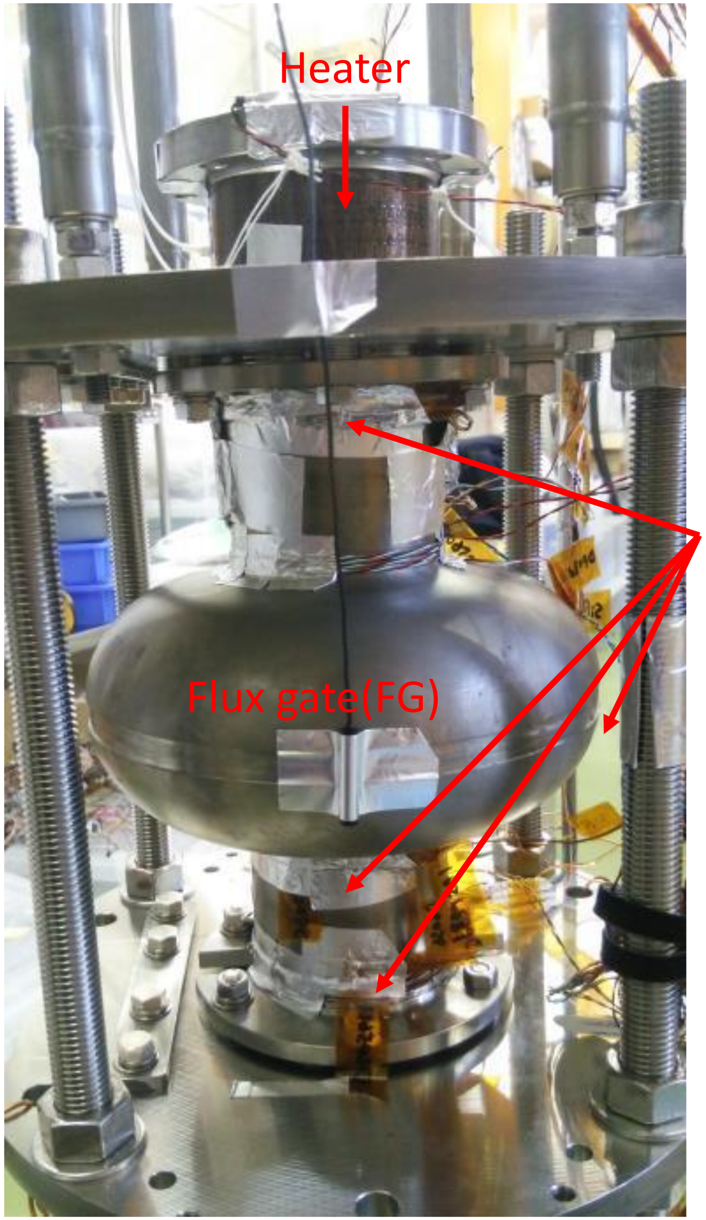
How to reduce?

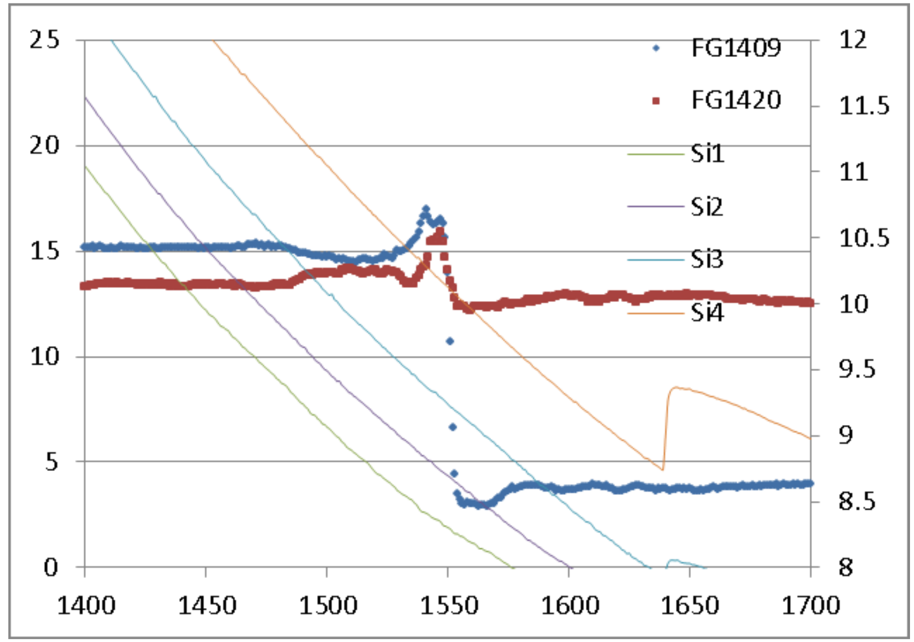
- Reduce ambient magnetic field
  - Magnetic shielding
  - Remove magnetized elements around cavity
  - Cancelling by using coils
- Reduce trapping field and its sensitivity
  - Thermal gradient during transition
  - Surface processing
  - Nb Material

Past and on-going R&D issues in the framework of FJPPL

R&D issues in this proposal

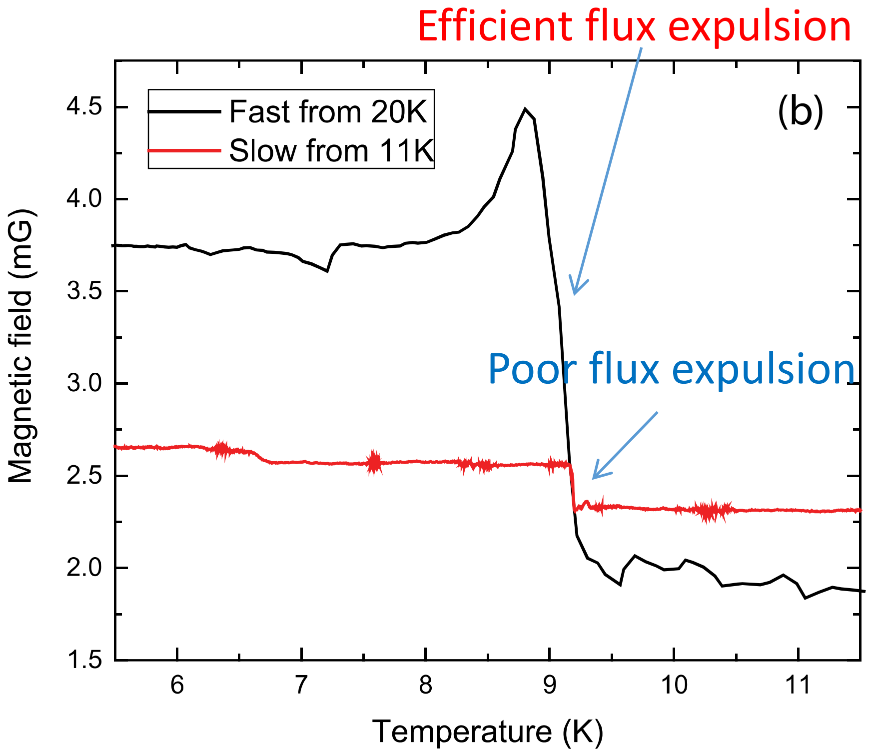
First test of flux trapping at KEK-STF





- Last March, first flux trapping experiment was carried out at KEK-STF.
- CEA people visited KEK and joined to the experiments.
- Some flux expulsion signal could be seen.
- Temperature gradient could be controlled by using a heater.
- We will continue this study.

Flux expulsion



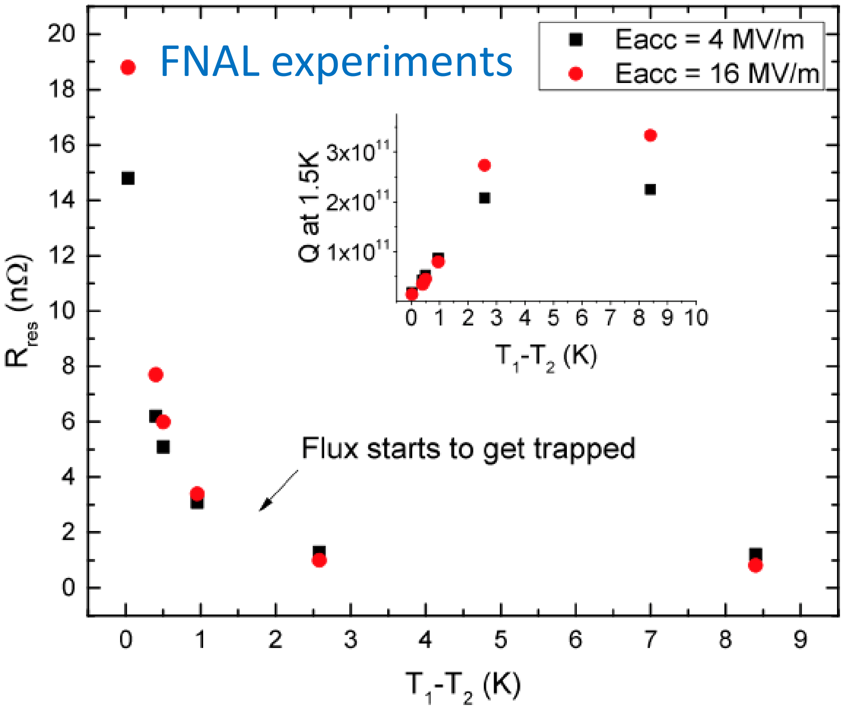
A. Romanenko, A. Grassellino, O. Melnychuk, D. A. Sergatskov, J. Appl. Phys. **115**, 184903 (2014)

- Observe magnetic field outside of cavity.
- Cooling down cavity.
- When cavity temperature goes down to ～9K, Nb transient to superconducting state.
- Magnetic field inside cavity escape to outside. ⇒ This can be seen as flux expulsion.

- Strong flux expulsion is sign of small flux trapping. ⇒ low R_{res}
- Poor flux expulsion means most of flux is trapped inside cavity. ⇒ high R_{res}

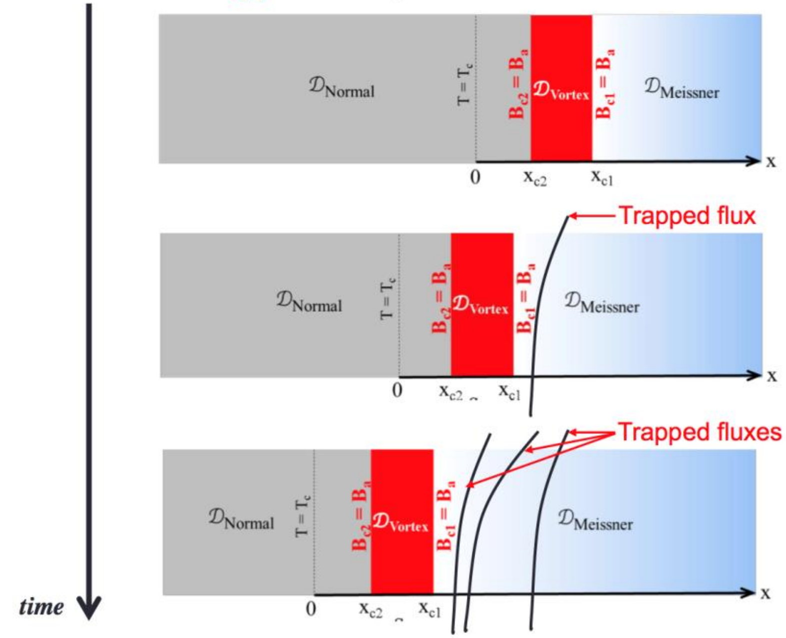
Dependence of thermal gradient on R_{res}

A. Romanenko, A. Grassellino, A. C. Crawford, D. A. Sergatskov, and O. Melnychuk, Appl. Phys. Lett. **105**, 234103 (2014)



Flux trapping model proposed by T. Kubo

As the material is cooled down, the phase transition fronts **sweep** the material, and some fluxes are **trapped** in this process.



T. Kubo, arXiv:1601.02118 [physics.acc-ph] to be published in Progress of Theoretical and Experimental Physics

- Clear behavior was observed between thermal gradient ("T1 – T2" in left figure) and Rres. Large gradient shows small Rs.
- However, physical background is not yet understood well.

Plan of flux trapping experiment

Perform systematic experiments on flux trapping.

- Thermal gradient
  - Control by heater
  - Control by speed of He transfer
- Ambient magnetic field
  - Control by solenoid coil, which was just fabricated
- Surface processing
  - Change condition for EP, CP, annealing etc.
- Nb material
  - Fine grain vs Large grain
  - Nb material from different vendors
  - Single-cell cavities made of different Nb materials alredy exist.
- Cavity shape
  - Elliptical cavity (1.3GHz, single-cell, KEK)
  - Low-beta cavity (ESS, IFMIF)

Both of CEA and KEK can perform flux trapping experiments.

Try to understand physics behind.

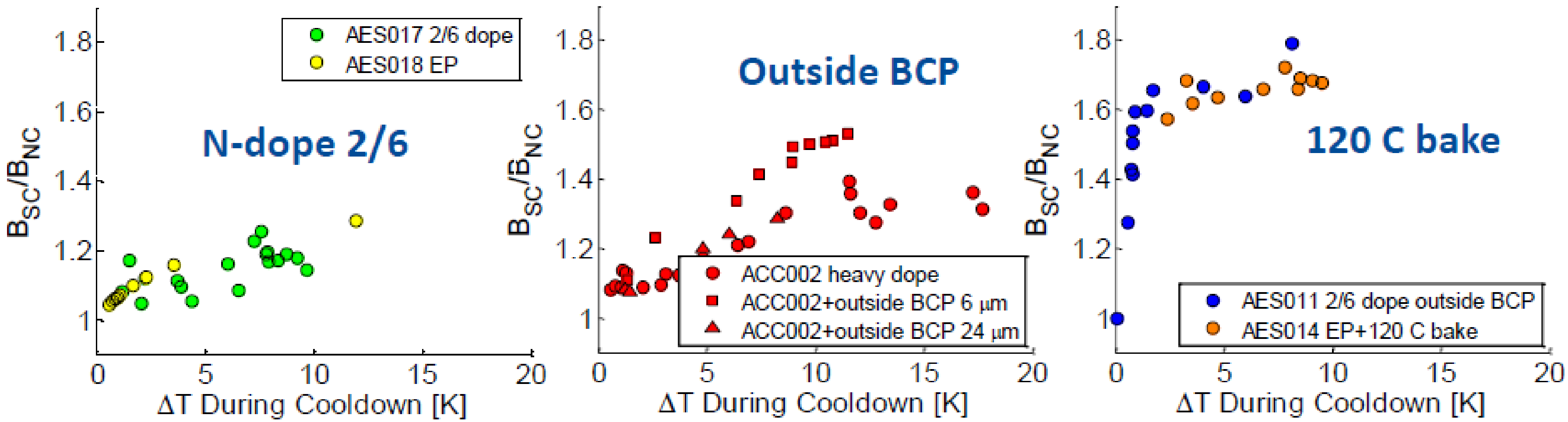
Summary

- For SRF cavities, operation with high-Q is desirable, especially for CW operation machine.
- Magnetic flux trapping at cavity surface is one of cause of surface resistance. Suppression of flux trapping is important.
- We have investigated about magnetic shielding and remnant field in order to suppress ambient magnetic field.
- Another way is to search optimized cooling procedure to realize strong flux expulsion, i.e. small flux trapping.
- Making relatively large temperature gradient is one of candidates.
- We will carry out systematic study on flux trapping by changing several experimental conditions.
- We also try to understand physical background though a series of experiments.

Backup slide

Systematic study of flux expulsion by FNAL

Surface Alteration With No Significant Effect on Expulsion



Different surface conditions in cavities with similar bulk history: similar expulsion