Outstanding Issues of HTS for High Quality Magnets

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NMR Facility

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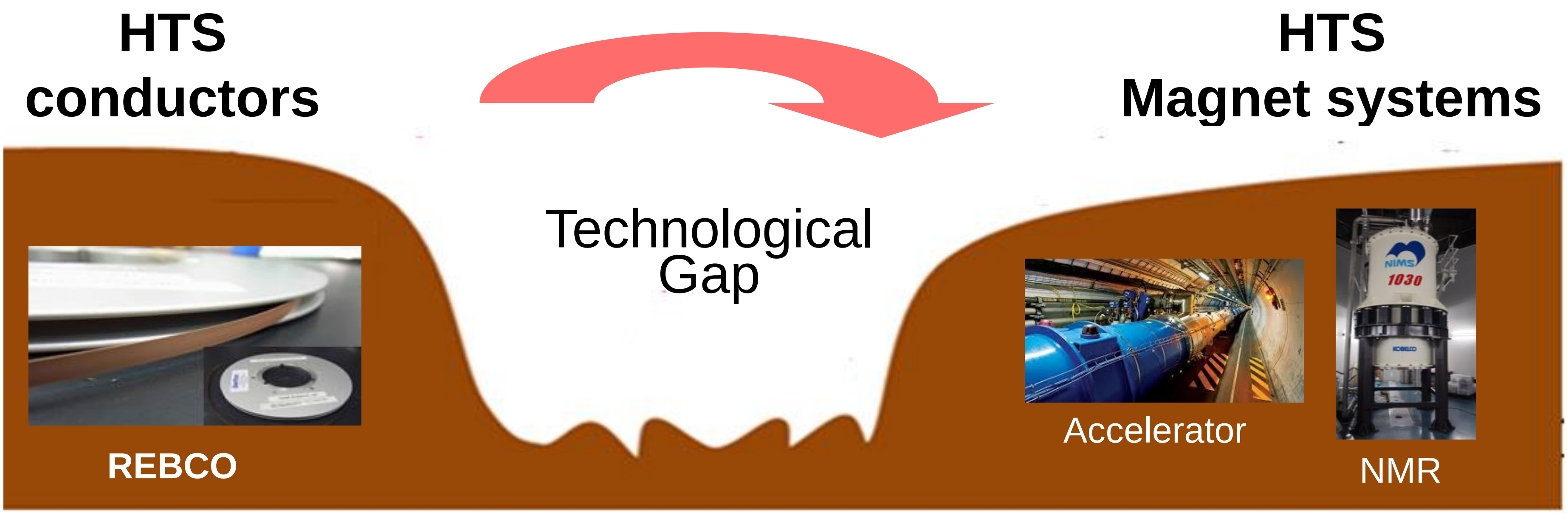
2. Magnetic field distortion and temporal magnetic field drift due to the screening current
3. Effect of screening current on the characteristic of LTS/Bi2223 NMR and LTS/REBCO NMR

Introduction

Gap between HTS conductors and HTS magnets

It is necessary to develop HTS magnet technology



Magnet technology

LTS magnets

- Stability
- AC loss
- Quench protection

- Structure
- Magnetic field
- Cryogenic engineering

HTS magnets

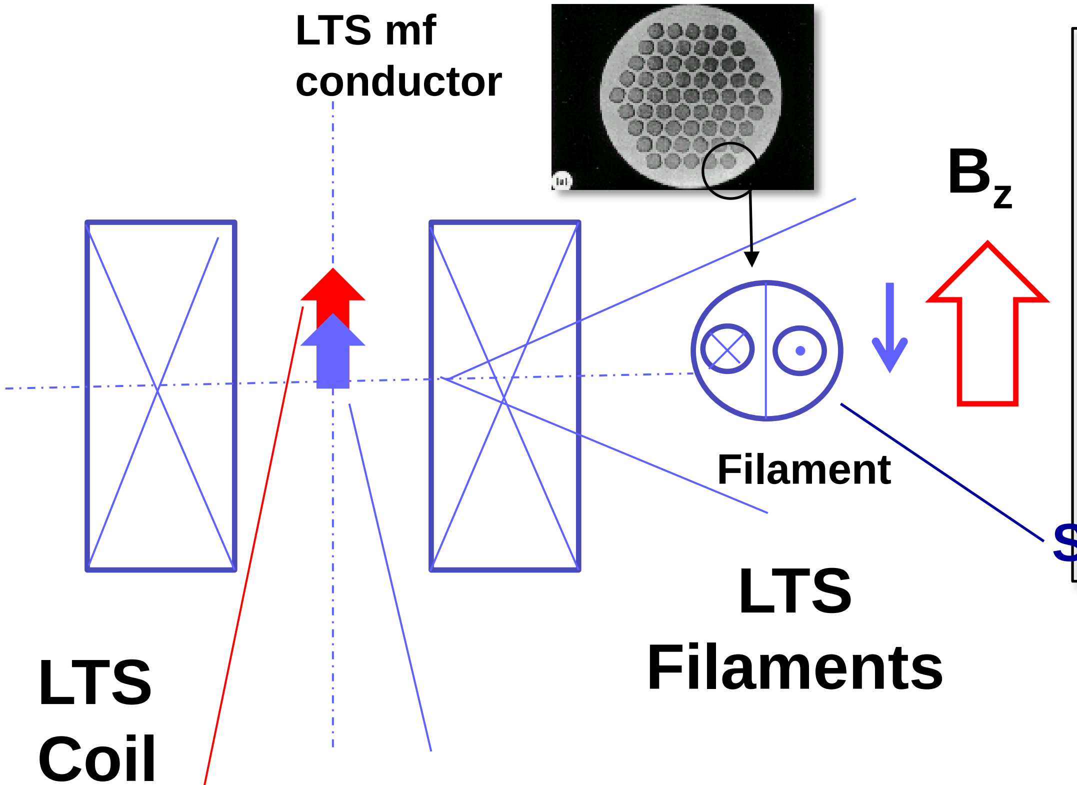
- Degradation in the coil performance due to delamination(REBCO)
- Screening current-induced magnetic field (HTS)
- Protection against thermal runaway(HTS)

- Structure
- Magnetic field
- Cryogenic engineering

Magnetic field distortion and temporal magnetic field drift due to the screening current

a. Basic phenomena of the screening current-induced magnetic field

Screening current-induced magnetic field for LTS magnets



1. For early LTS magnets, the screening current was enormous.
2. However, for modern LTS magnets, effect of screening current becomes negligible as LTS filaments are fine.

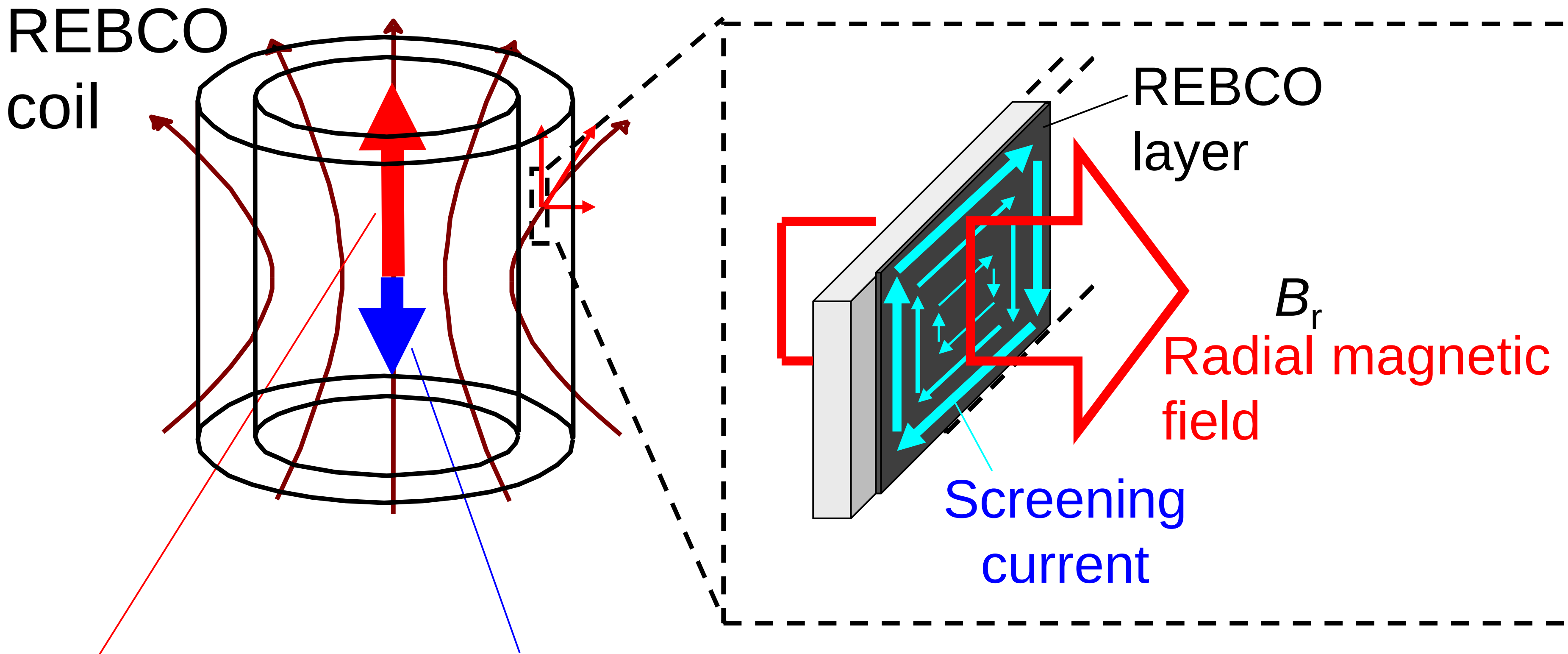
Screening current-induced magnetic field, B_s

Coil current magnetic field, B_c

Net field

$$B_0 = B_c + B_s$$

Screening current-induced magnetic field for HTS magnet



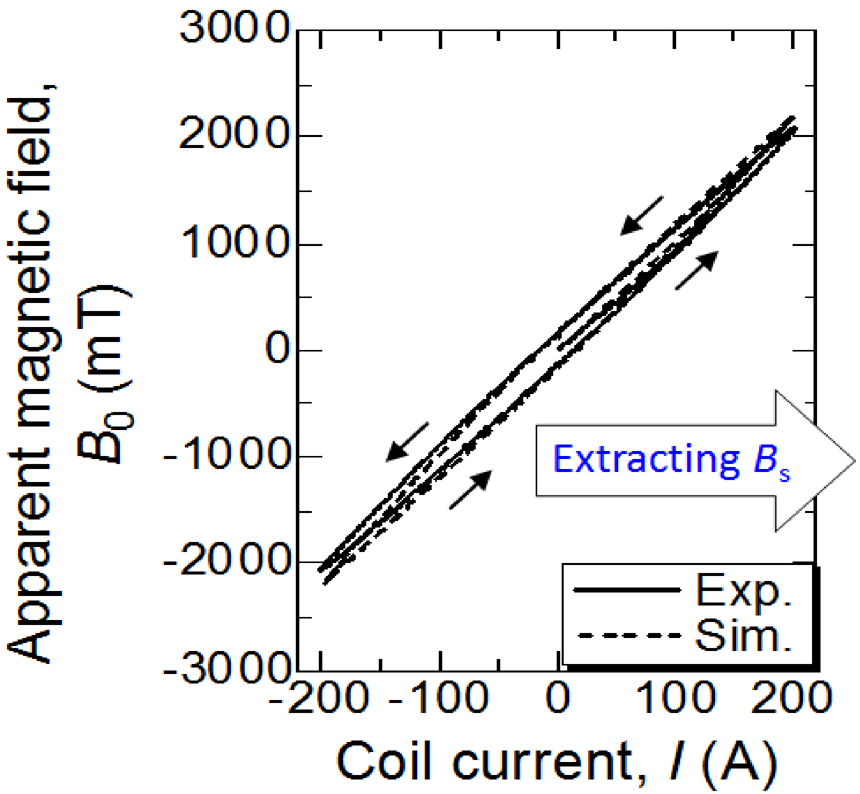
Screening current-induced field, $-B_s$

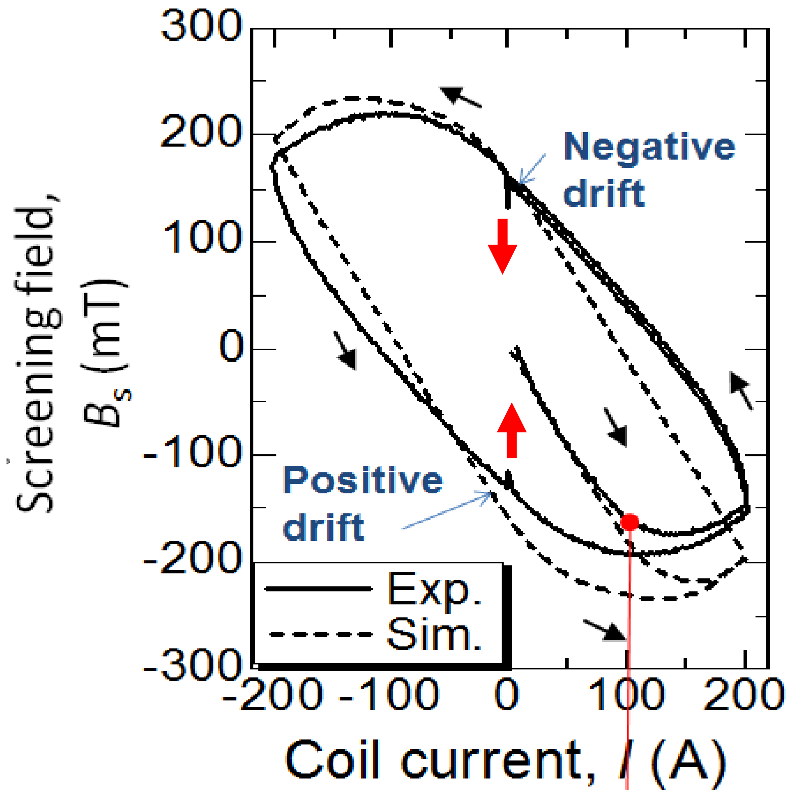
Coil current magnetic field, B_c

Net field

$$B_0 = B_c - B_s$$

Hysteresis effect of the screening current-induced magnetic field for a REBCO magnet





@4.2K

ID 18mm
OD 45mm
L 25mm
Solenoid

B_c = 1100 mT
B_s = -170 mT
$|B_s/B_c|$ = 15%

Major problems:

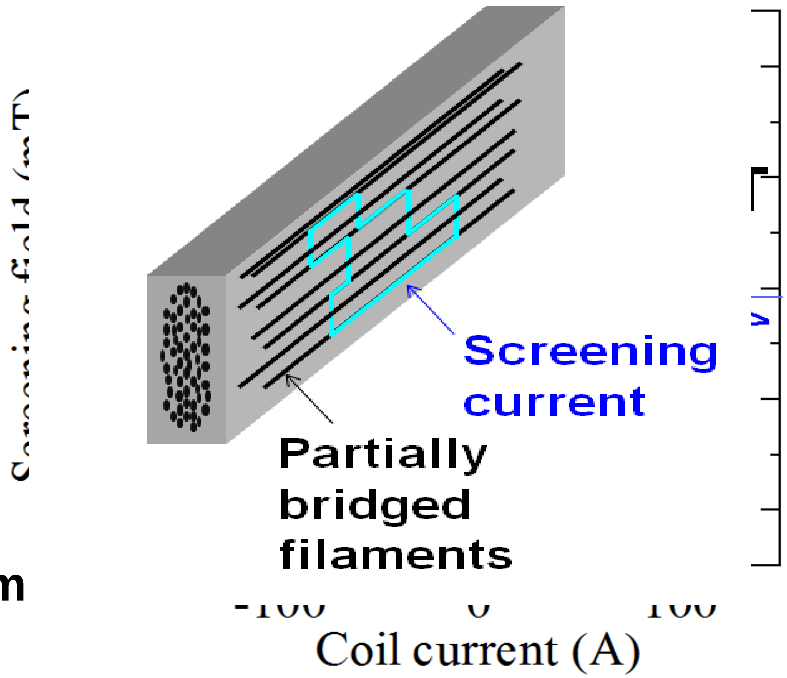
- Hysteresis effect
- Reduction in the central field
- Field drift with time

<u>**Y. Yanagisawa et al.**</u>, IEEE Trans. Appl. Supercond. **20**, 744-747(2013)

Comparison between Bi2223 and REBCO

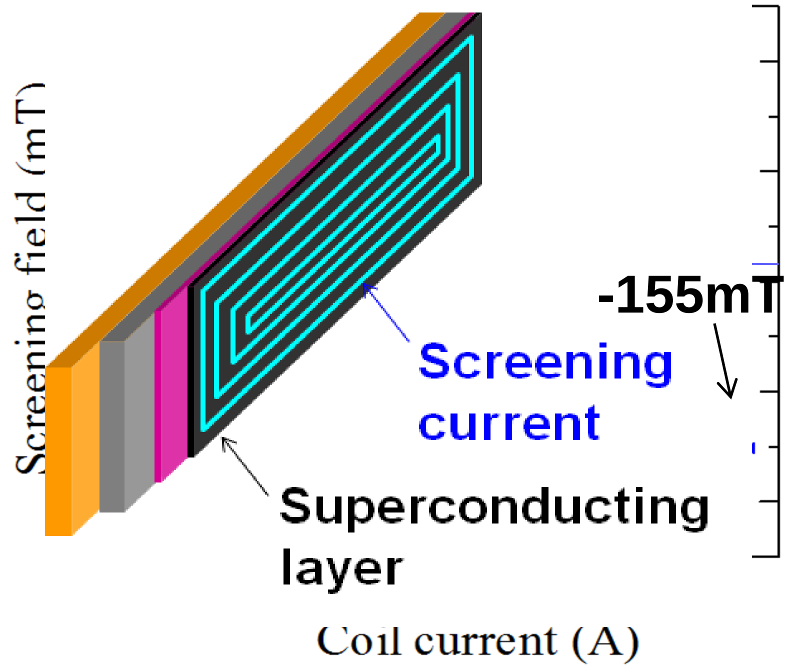
@4.2K

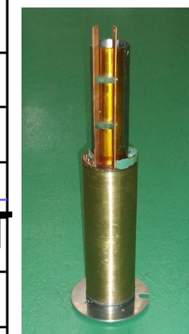
Bi2223 coil



Id 81mm
Od 121mm
L 375mm

REBCO coil





Id 81mm
Od 119mm
L 400mm

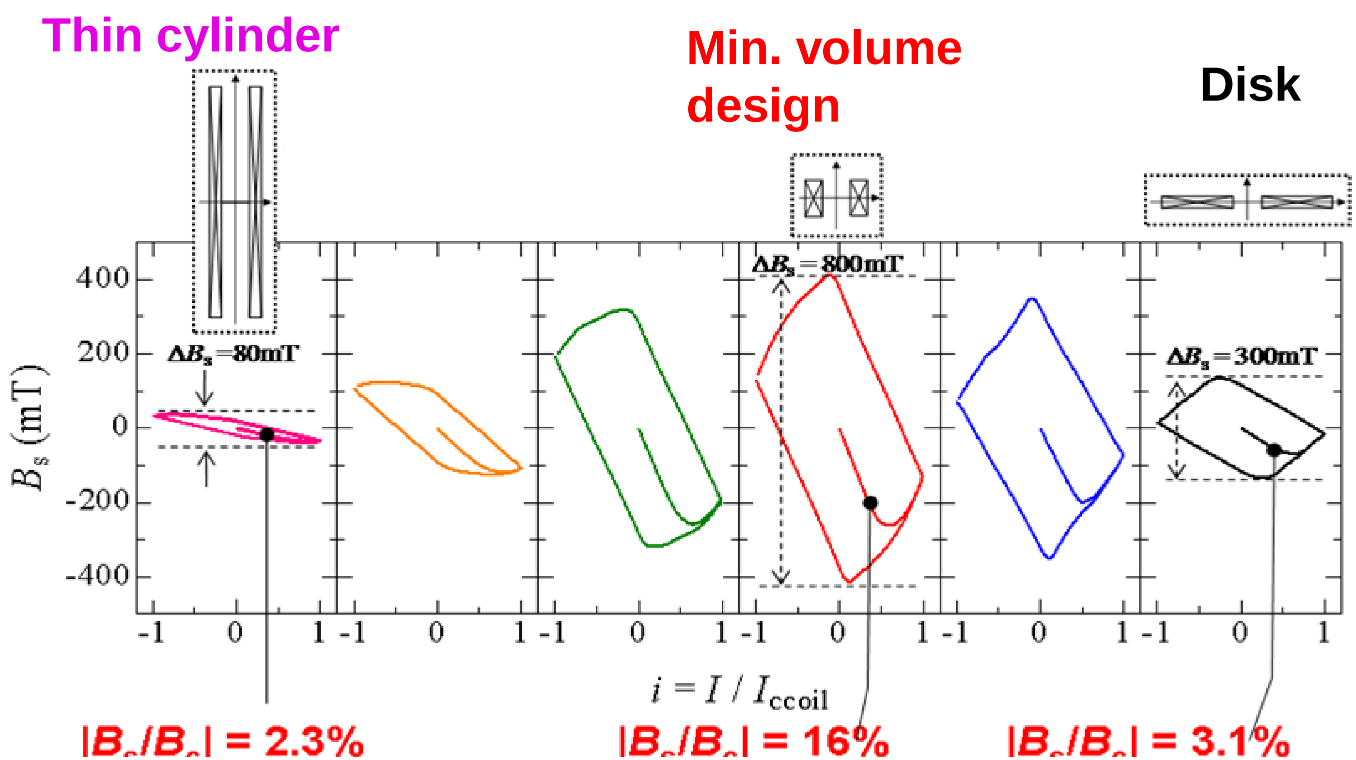
Screening current-induced magnet field for a REBCO coil is 5-fold larger than that for a Bi2223 coil

Dependence of hysteresis on the coil shape

$$B_c = J a_1 F(\alpha, \beta)$$

$$a_1 = 18mm; F = 10.1\times10^{-7}$$: Shape factor of the solenoid

<u>The central magnetic field is the same, while the shape is different</u>

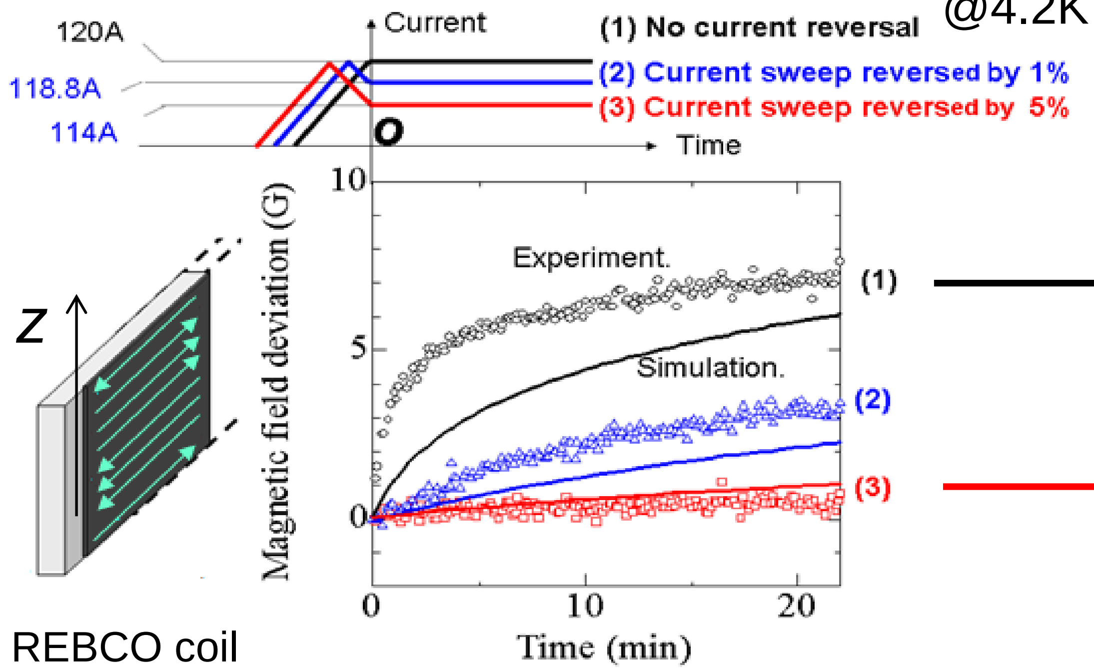


<u>Numerical simulation for REBCO</u>

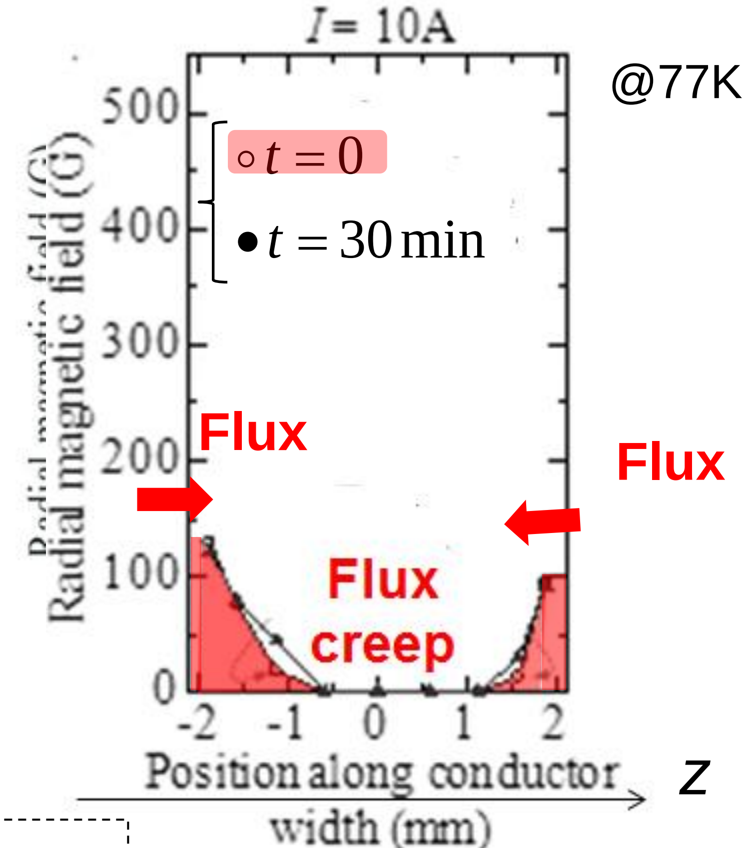
@4.2K

b. Remedies for the screening current-induced magnetic field

Current sweep reversal method



REBCO coil

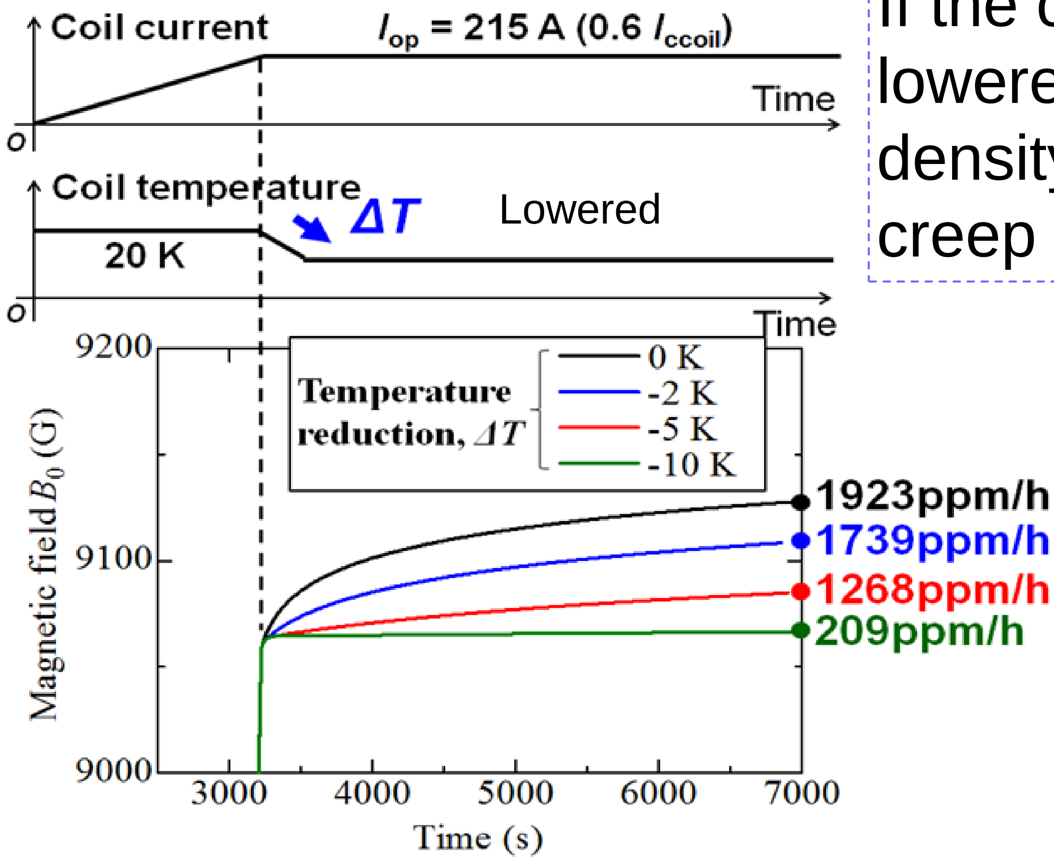


- Several % of current sweep reversal is necessary for HTS magnets, while 0.2-0.5% for LTS magnets.
- The magnet should endure a current of 105% of the operation current

Y. Yanagisawa et al., Physica C 469, 1996-1999(2009)

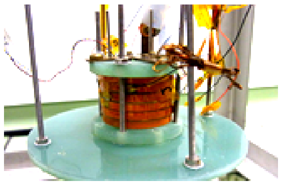
Temperature change

Numerical simulation



If the coil temperature is lowered, the critical current density is enhanced, thus flux creep is suppressed

20K
-2K
-5K
-10K

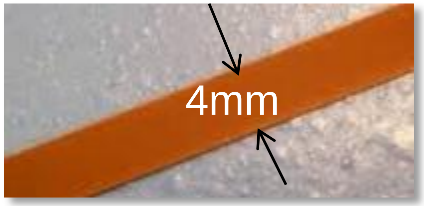


REBCO coil

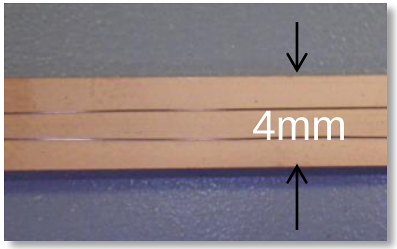
Y. Yanagisawa et al., Adv. Cryo. Eng. 1434, 1373-1380 (2012)

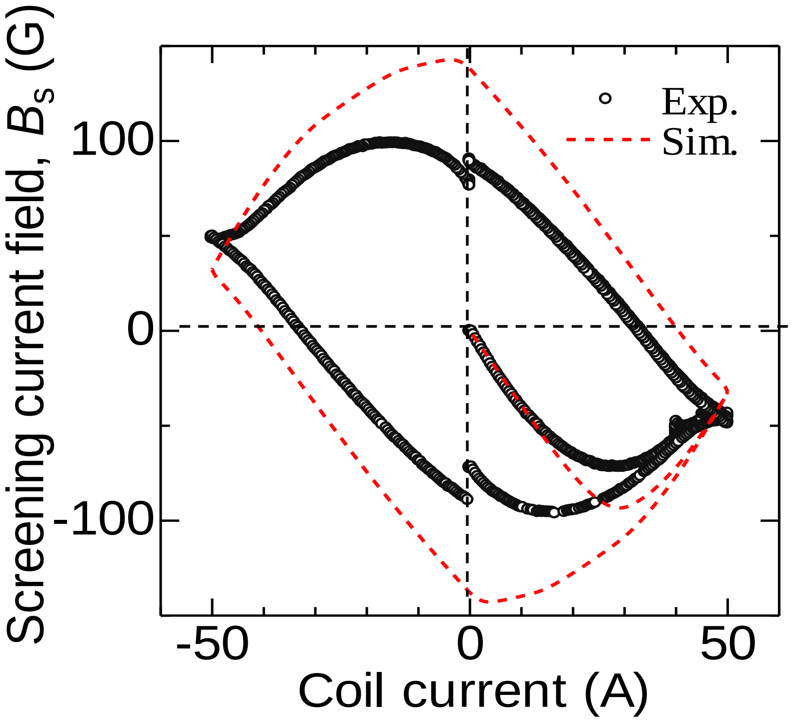
Scribed multi-filamentary REBCO conductor

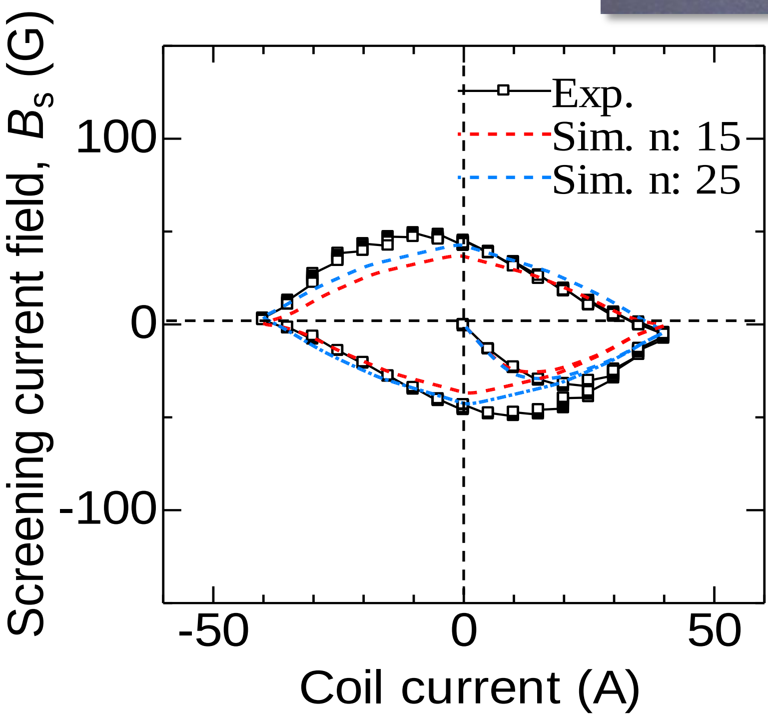
Usual REBCO conductor



Mechanically scribed 3-filasment REBCO conductor





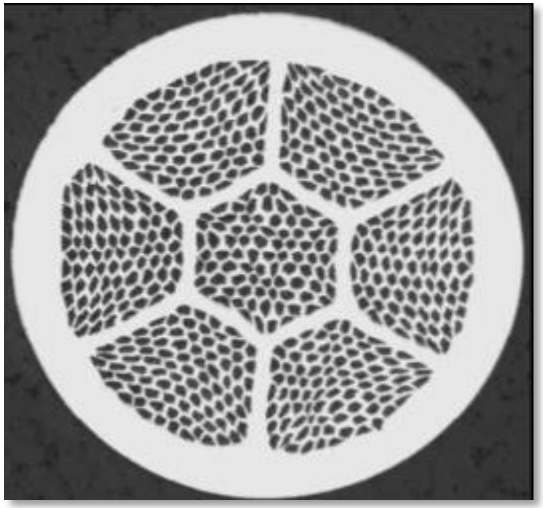


@77K

The screening current-induced field is remarkably reduced, if a scribed REBCO conductor is used

Bi2212 multi-filamentary round conductor

Bi2212 round conductor



33.8T coil, developed in NHMFL

If multi-filamentary/ twisted Bi2212 round conductor is used, the screening current-induced magnetic field will be negligible as for LTS coils.

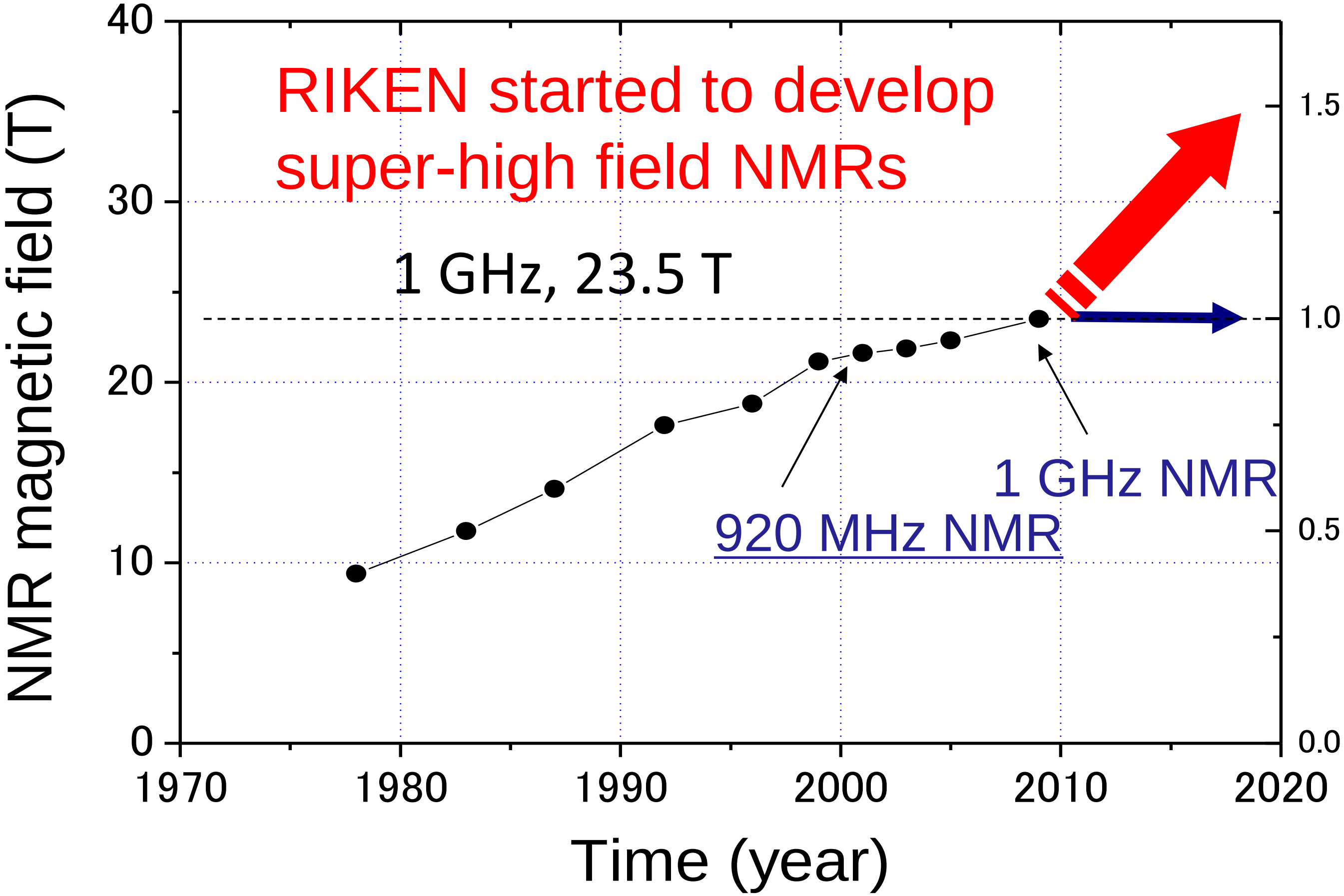
U. P. Trociewitz, et al. *Appl. Phys. Lett.* 99, 202506(2011)

D. C. Larbalestier et al., " A transformative superconducting magnet technology, 2013.

Effect of screening current on the characteristic of LTS/Bi2223 NMR and LTS/REBCO NMR

a. Necessity of the LTS/ HTS NMR magnet

History of the NMR magnetic field



High Temperature Superconducting (HTS) Magnets.

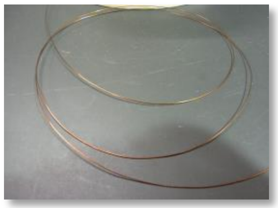
- H_{c2}>50 T

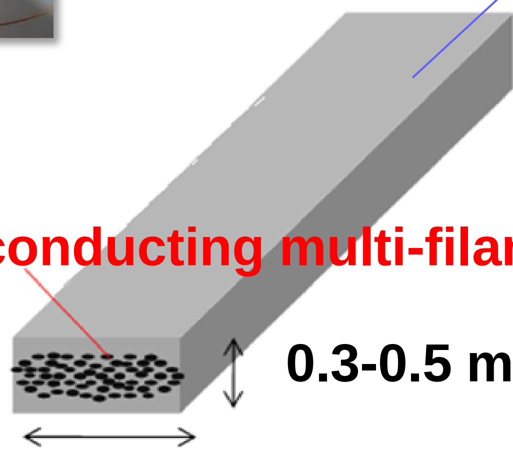
Low Temperature Superconducting (LTS) Magnets.

- H_{c2}< 25 T

Two available HTS conductors

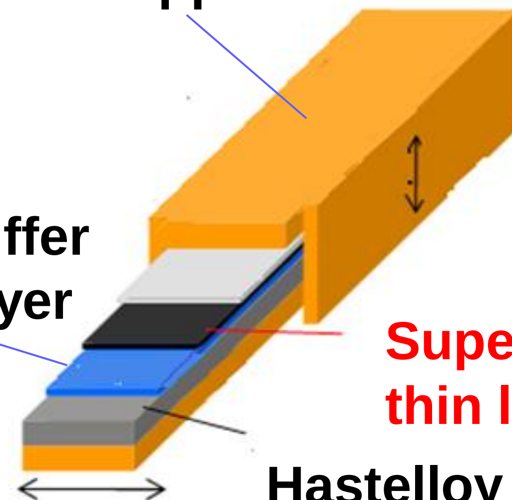
Bi2223 conductors





- A: Long conductor 1 km
- D: Low mechanical strength
  → Lower current density
  → larger magnet

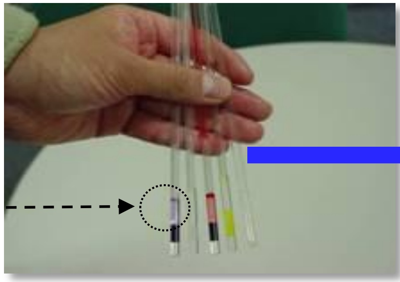
REBCO conductors



- A: High mechanical strength
  →High current density
  → compact size magnet
- D: Shorter length 100-200m

Technical problems for an NMR magnet

- **Strong magnetic field intensity**
- **Spatial field homogeneity**
  1ppb／5mm dia. cylinder
- **Temporal field stability**
  0.1ppb



NMR sample

NMR magnet

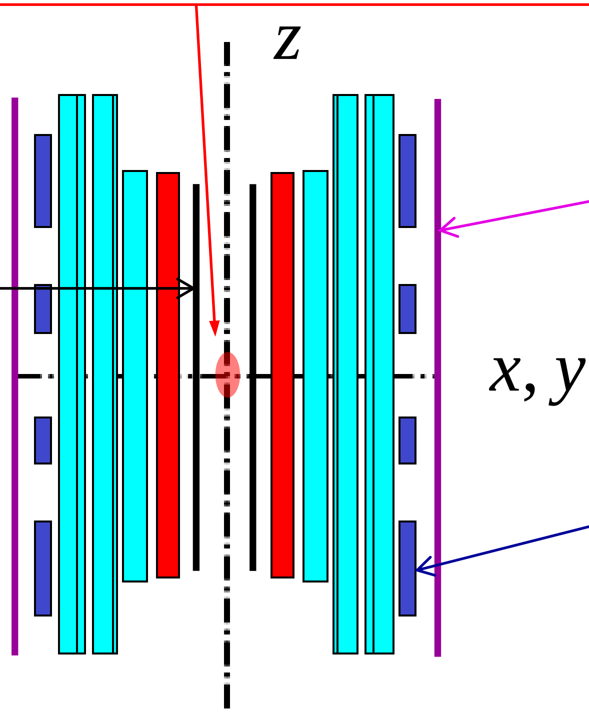
Spatial homogeneity of the magnetic field

Legendre Polynomials

$$B_z = B_0 + a_1 z + a_2 z^2 + a_3 z^3 + a_4 z^4 + - - -$$ Axial error component

$$+ b_1 x + b_2 y + b_3 zx + b_4 zy + b_5 xy + b_6 (x^2 - y^2) + - -$$ Radial error component

Target: 1ppb



Room temperature shim coils & iron shims <1ppb

Superconducting shim coils(z,z^2,x,y, zx, zy, xy,x^2-y^2) < 10 ppm

Field correction coils (z^2 and z^4 are canceled) < 500ppm

b. Comparison between LTS/ Bi2223 NMR magnet and LTS/REBCO NMR magnet

World's first LTS/Bi2223 NMR magnet and LTS/REBCO NMR magnet(400-500MHz)

Bi2223 inner coil

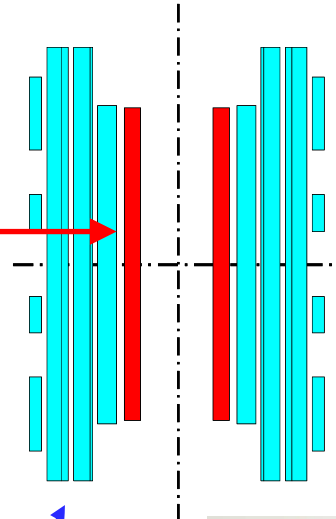
)

(2009)

Id 81mm
Od 121mm
L 375mm

REBCO inner coil

(2013)



NbTi/ Nb_3Sn outer coils

Pulse-tube cryocooler

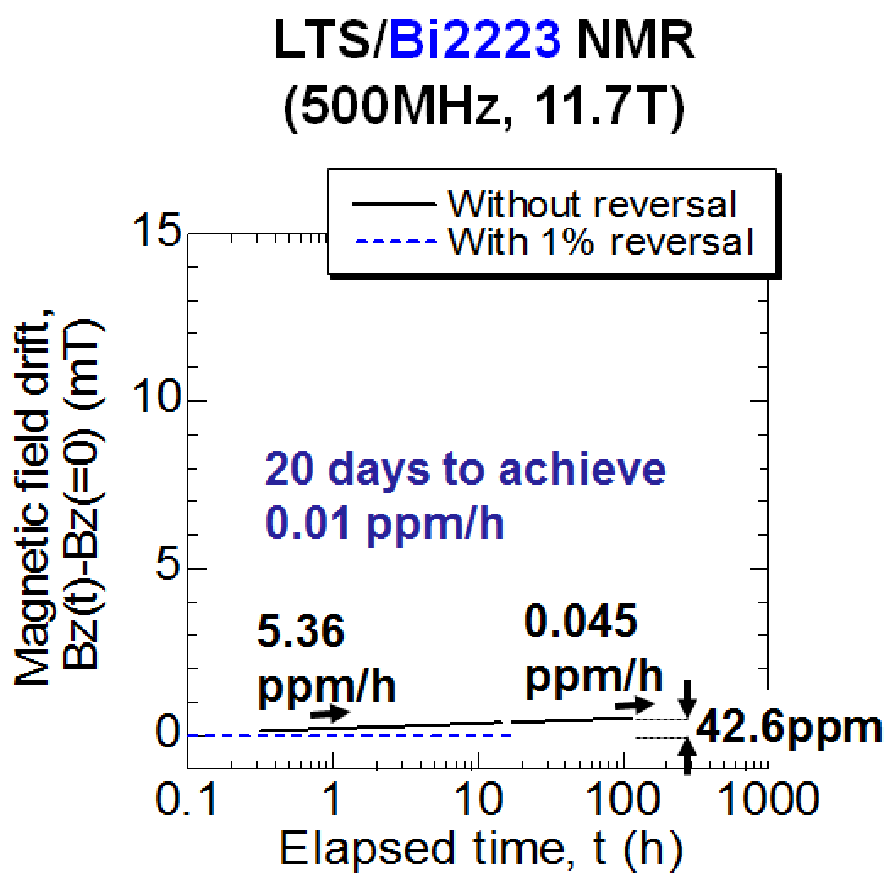
NMR probe

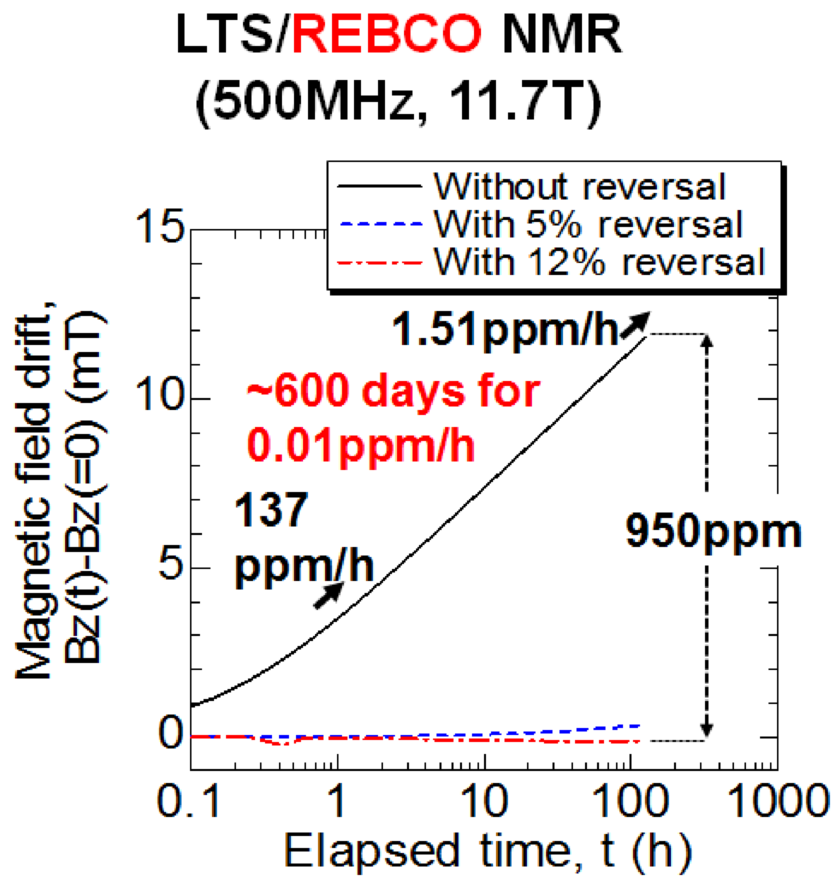
(^{1}H, ^{13}C, ^{15}N)

Ultra-stabilized DC-power supply < 1ppm

- **Yanagisawa et al, *JMR* (2010)**
- **Kiyoshi et al, *IEEE TAS* (2010)**

Temporal field drift after the magnet charge

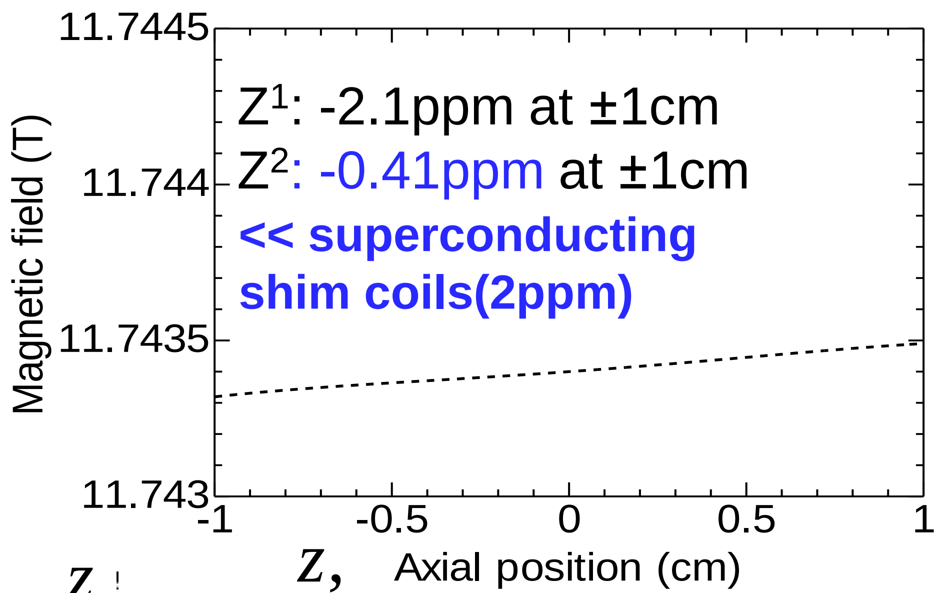




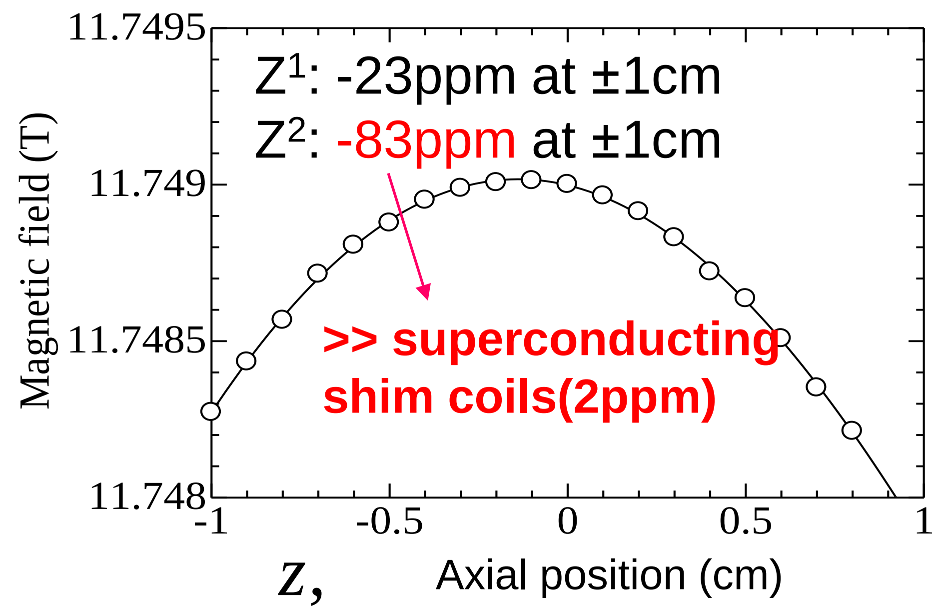
Temporal field drift due to screening current for an LTS/REBCO NMR is >20-times steeper than that for an LTS/Bi2223 NMR

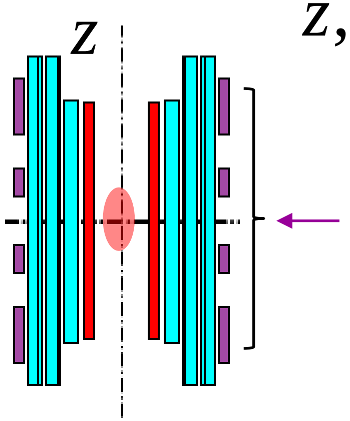
Spatial distribution of the magnetic field

LTS/Bi2223 NMR
(500MHz, 11.7T)



LTS/REBCO NMR
(500MHz, 11.7T)





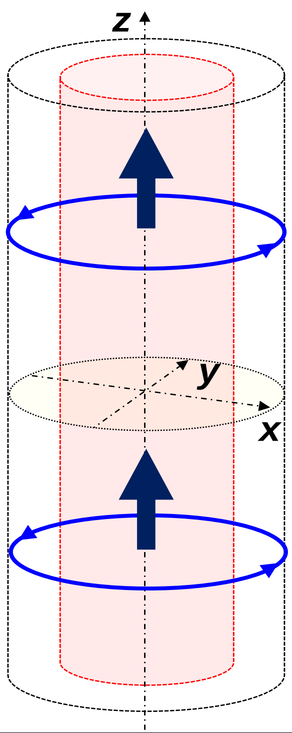
The field generated by the field correction coil is reduced by 27% due to the LTS/REBCO coil, resulting in excessive residual z^2 component. Therefore, <u>additional iron shims were required</u>.

Degradation in the superconducting(SC) shim coil performance

The SC shim coil performance is remarkably degraded due to the screening current induced in the HTS coil, especially for REBCO

Axial SC shim coils

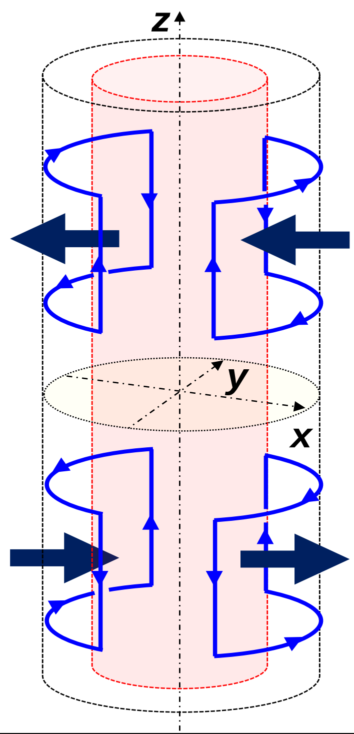
$z \; and \; z^2$



- LTS/Bi2223 → 40% of the design
- LTS/REBCO → 20% of the design

Radial SC shim coils

$x, y, zx, zy, xy, and \; x^2 - y^2$



- LTS/Bi2223 → 20-40% of the design
- LTS/REBCO → < 5% of the design

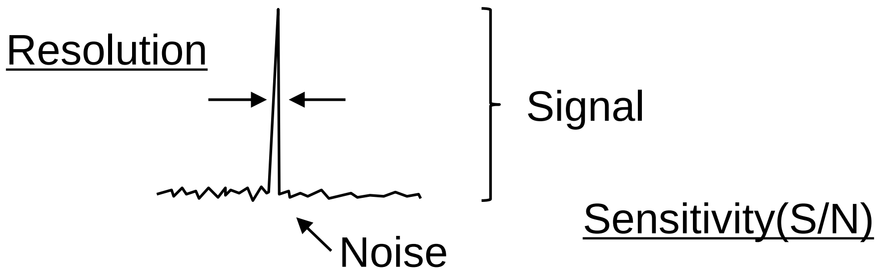
Difficult to make a field correction!

Comparison of NMR resolution and sensitivity

	LTS NMR	LTS/Bi2223 NMR	LTS/REBCO NMR
NMR resolution	<1Hz(2ppb)	0.7Hz(1.4ppb)	15Hz(30ppb)
NMR sensitivity S/N	>600	512	28

The same quality

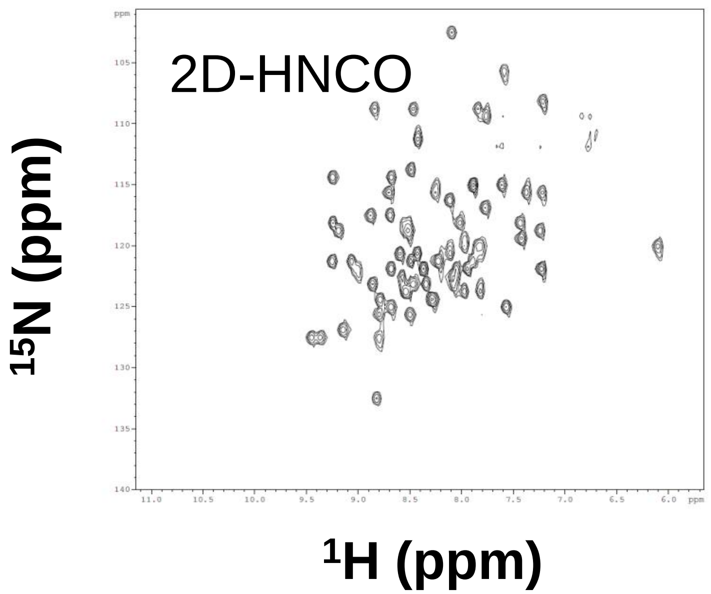
20-fold lower resolution and sensitivity



NMR spectrum

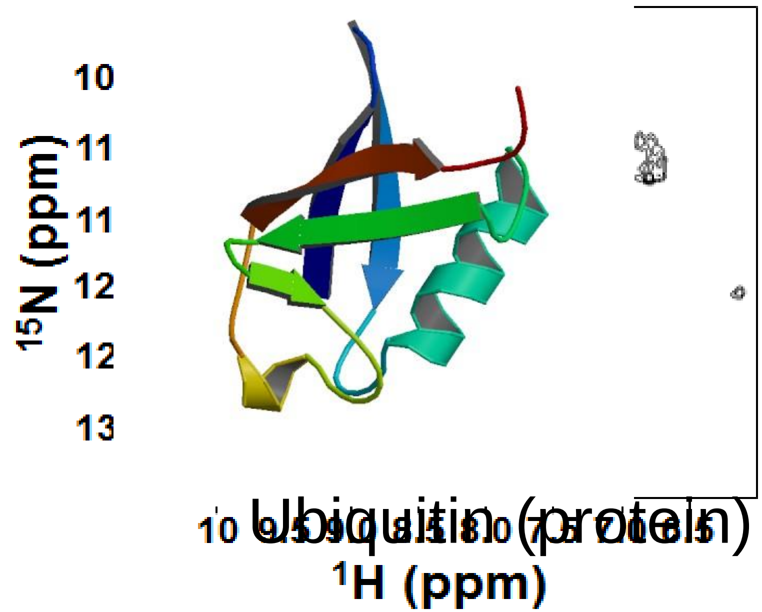
NMR spectra for a protein

LTS/Bi2223 NMR magnet



Nearly the same quality as conventional NMRs

LTS/REBCO NMR magnet



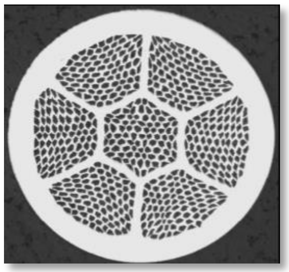
The number of the available NMR measurement is limited

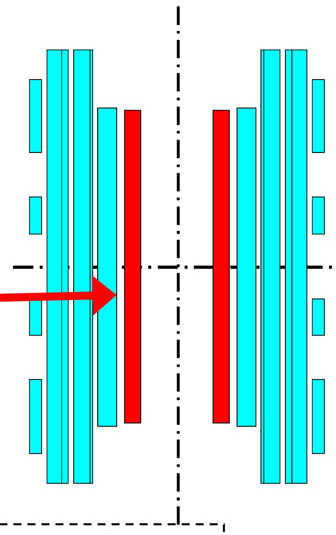
Collaboration between NHMFL and RIKEN on a 400 MHz LTS/Bi2212 NMR magnet

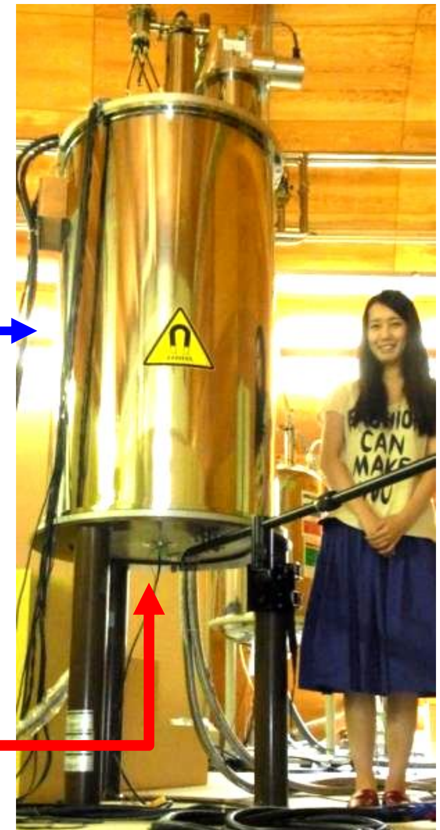
NHMFL

RIKEN

Bi2212 inner coil





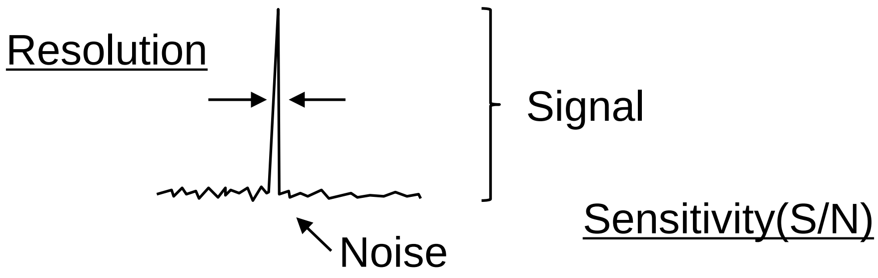


NMR probe

- Develop and evaluate an LTS/Bi2212 NMR magnet in collaboration between NHMFL, coil fabrication, and RIKEN, NMR measurement.
- The experiments in RIKEN is planned to be conducted in 2015.

Comparison of NMR resolution and sensitivity

	LTS NMR	LTS/Bi2223 NMR	LTS/Bi2212 NMR	LTS/REBCO NMR
NMR resolution	<1Hz(2ppb)	0.7Hz(1.4ppb)	XXX	15Hz(30ppb)
NMR sensitivity S/N	>600	512	XXX	28



NMR spectrum

Summary

- Effect of screening current induced magnetic field on the performance of high quality magnet such as NMR, MRI and accelerator is enormous.
- It can be effectively suppressed by current sweep cycling and temperature change cycle, in addition to using adequate conductor.

- The quality of the NMR spectra achieved by LTS/Bi2223 NMR magnet is nearly the same as that by LTS NMR magnet.
- NMR spectra achieved by the LTS/REBCO NMR magnet is 20-fold broader than those by LTS NMR. Therefore, available NMR measurements are rather limited.

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Sophia University
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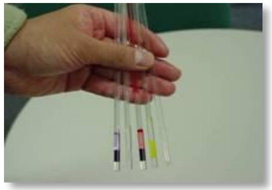
Mr. S. Iguchi

Thank you very much for your attention!

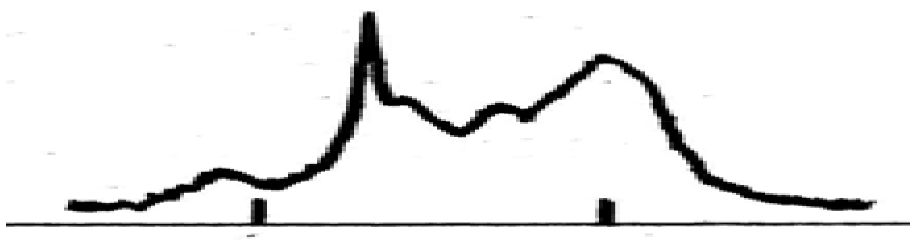
Why higher magnetic field is required in NMR ?

Protein sample

NMR magnet

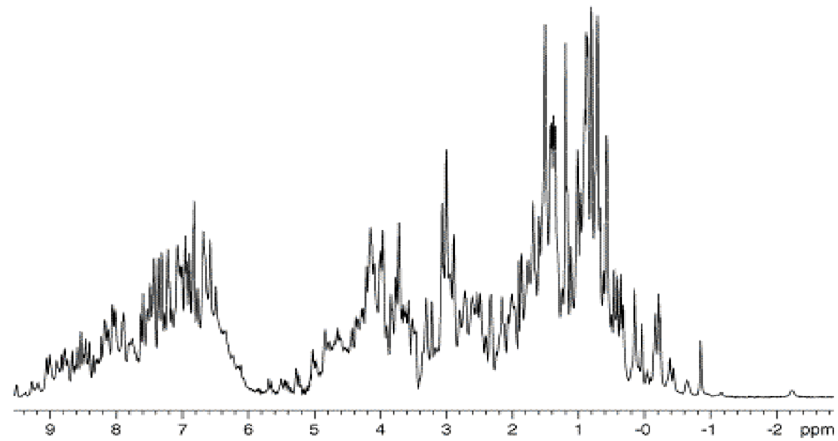


NMR sample



Frequency

0.94T (40MHz)



Frequency

11.75T(500MHz)

NMR resolution and sensitivity (S/N) are remarkably enhanced with the increase of the magnetic field

Numerical simulation of the screening current induced magnetic field

■ Current diffusion equations for each current element

$$J_{m,i}(t+\Delta t) = J_{m,i}(t) + \frac{2\pi\Delta t}{\mu_0 d}\sum_{j}^{N} K_{ij}^{-1}\left[E_{m,j}(t) + \nabla_z \phi_m(t) - y_j \dot{B}_{rm}(t)\right] \quad (m=1,\ldots,M;\, i=1,\ldots,N)$$

■ Relation between transport current and current density

$$I(t) = \frac{2ad}{N}\sum_{i=1}^{N} J_{m,i}(t) \quad (m=1,\ldots,M)$$

■ Power law *E*-*J* characteristics

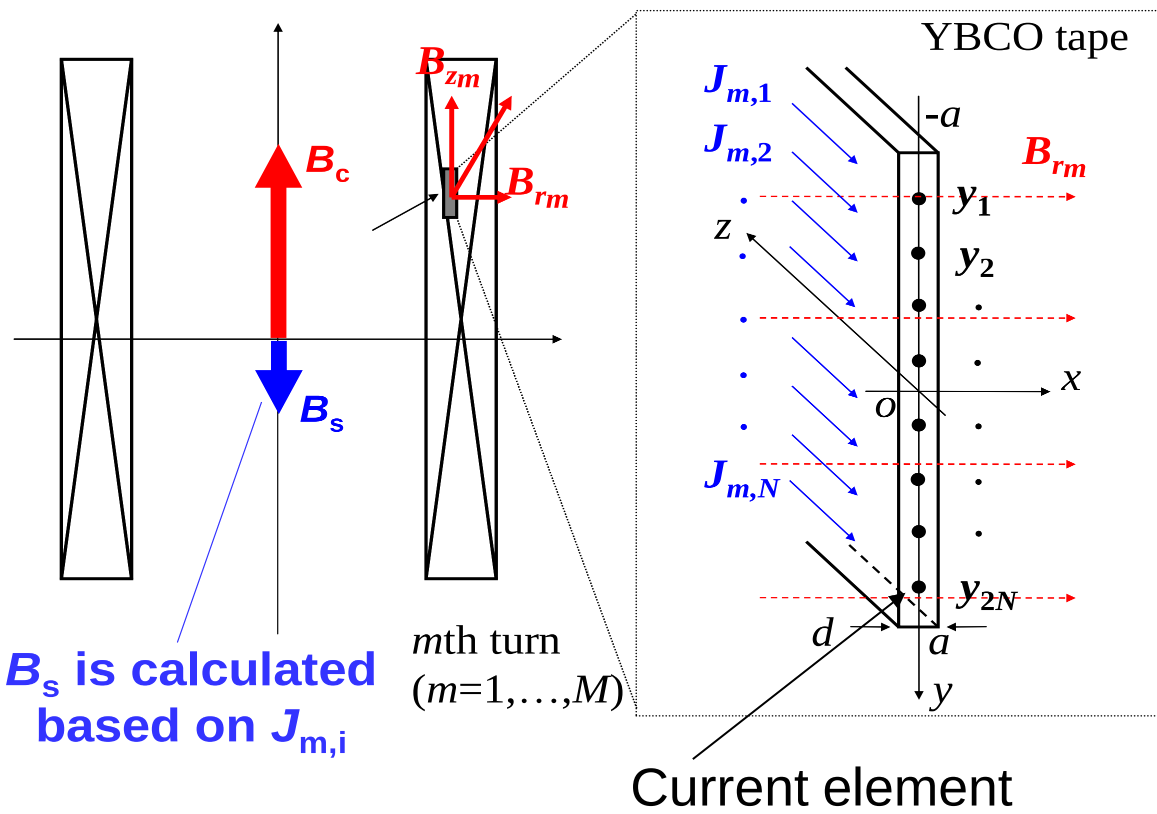
$$E_{m,j} = E_c (J_{m,j} / J_{cm})^n \quad (m=1,\ldots,M)$$

■ J_c-B characteristics

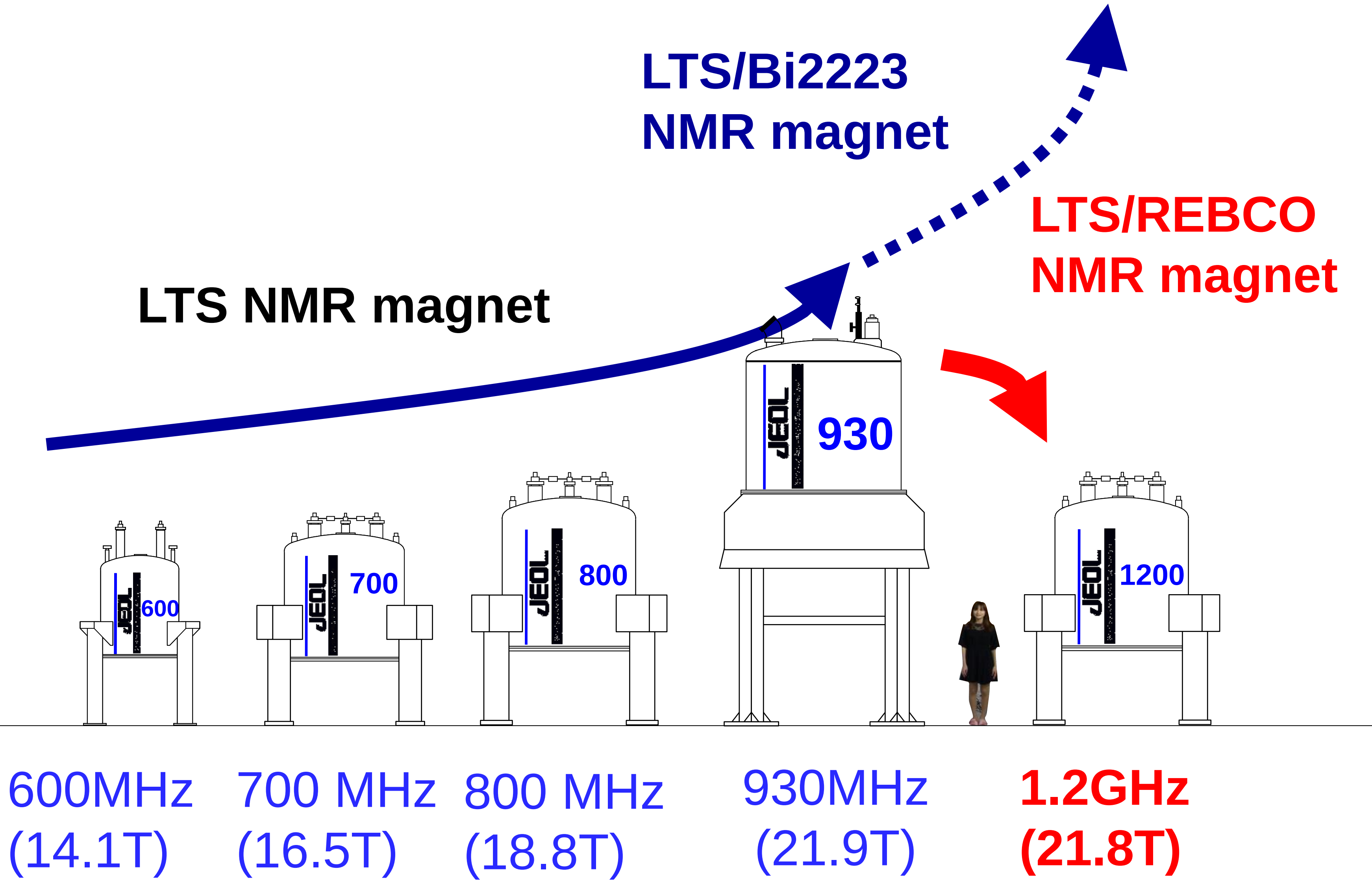
$$J_{cm} = J_{c0}\frac{B_0}{B_m + B_0} \quad (m=1,\ldots,M)$$

Convergence

$$\left|\frac{J_{m,i}^{(k+1)}(t) - J_{m,i}^{(k)}(t)}{J_{m,i}^{(k+1)}(t)}\right| < \varepsilon$$



Bottleneck of high-field NMR magnets

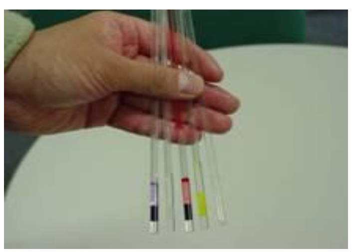


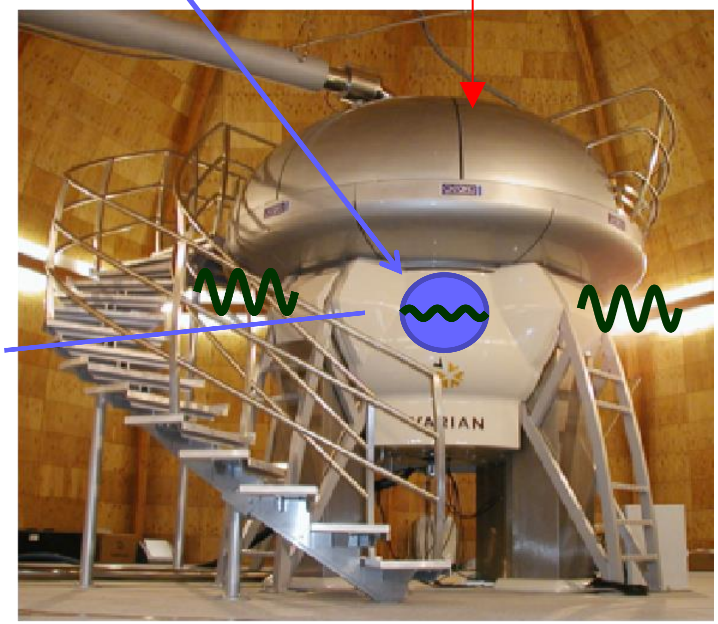
Temporal stabilization of the magnetic field

② High temporal stability of the local magnetic field is achieved by using a ^{2}H field-frequency lock system <1ppb

Target: 0.1ppb

Current





① Ultra-stabilized DC current supply <1ppm