Workshop "Ultrahigh field NMR and MRI: Science at the cross roads @ NIH
Nov. 12, 2015 8:50-9:10

Toward Super-High Field and Ultra-Compact Size NMR Magnets Operated Beyond 1 GHz (review)

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Outline

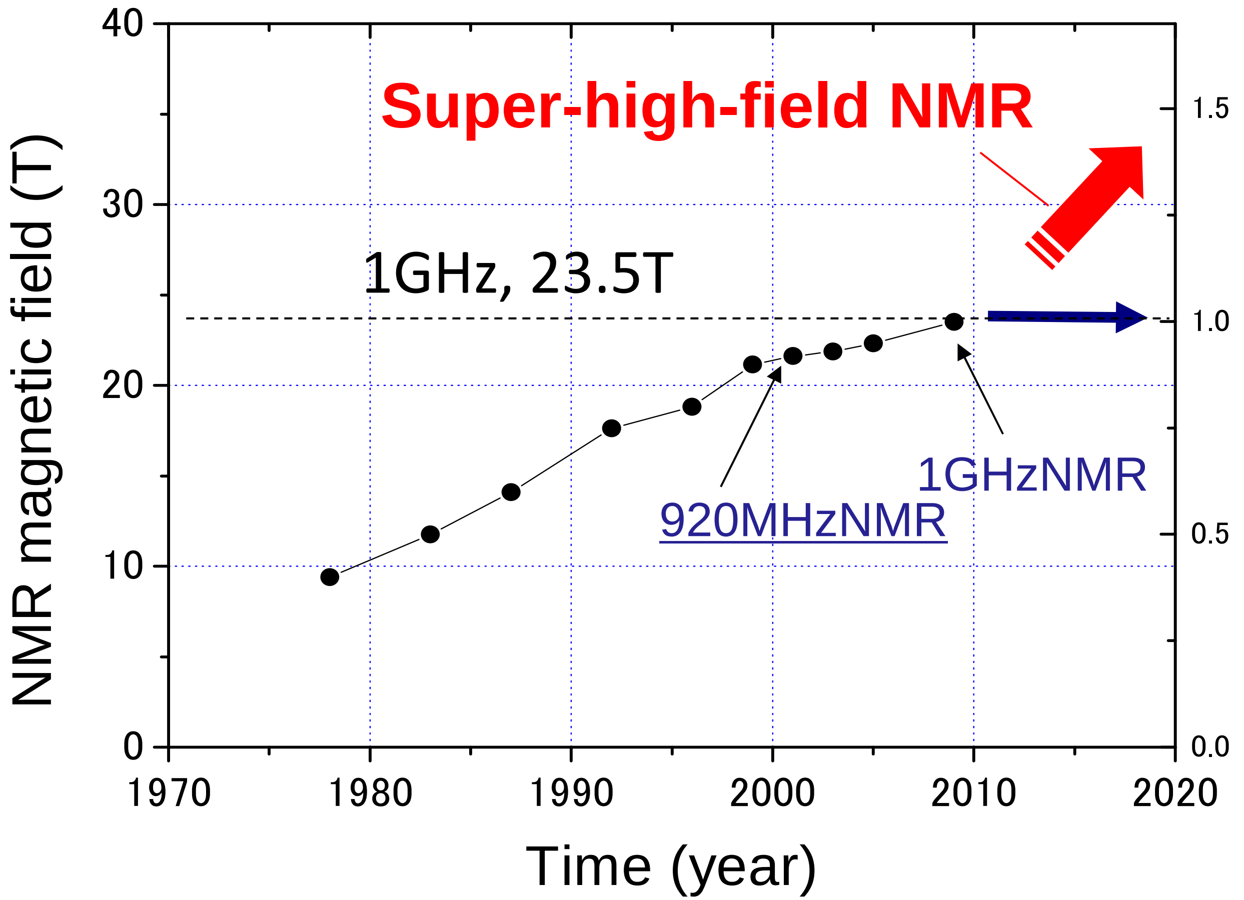
Introduction

1. Real characteristics of medium-field LTS/HTS NMR magnets
2. 1.02 GHz LTS/Bi-2223 NMR magnet
3. New perspective on the super-high-field NMR magnets

Introduction

History of the NMR magnetic field

Our target is to develop super-high field NMRs

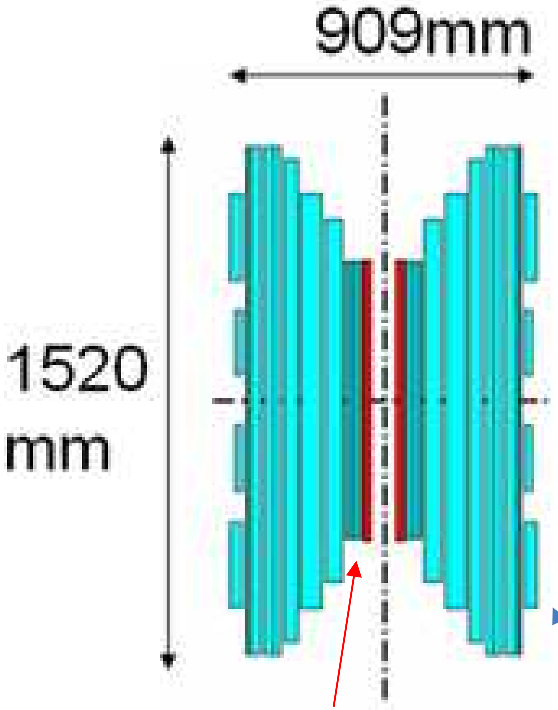


High Temperature Superconducting (HTS) Magnets
- H_{c2}>>30T

Low Temperature Superconducting (LTS) Magnets
- H_{c2}< 25- 30T

Critical magnetic field

Basic configuration of a super-high field NMR



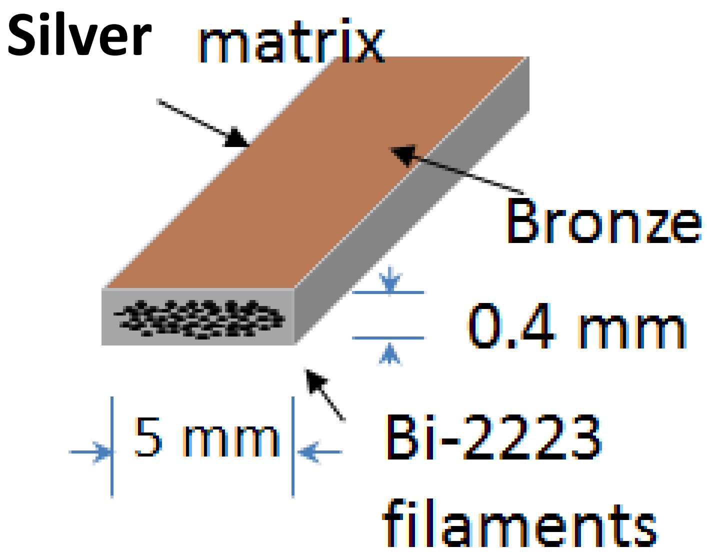
HTS inner coil
(high field)

LTS outer coils
(low field)

<u>LTS/HTS NMR magnet</u>
Cross-sectional view

Two commercialized HTS tape conductors

1st generation HTS

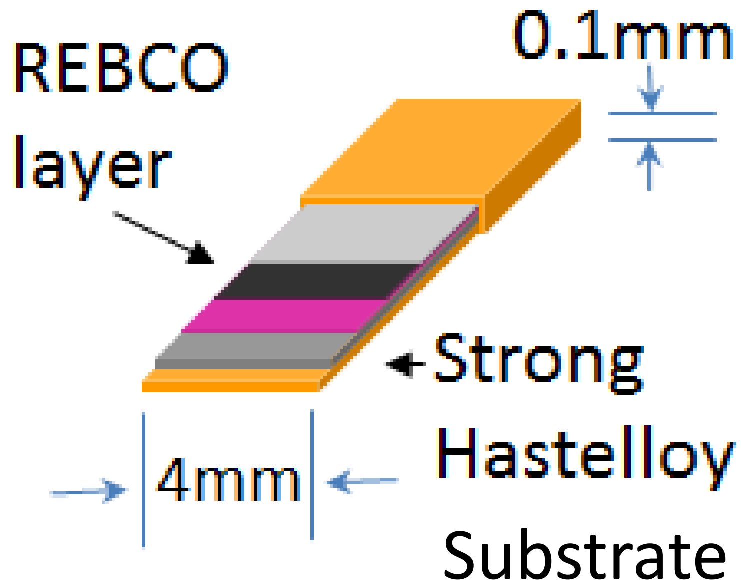


<u>Bi-2223 conductors</u>

$Bi_2Sr_2Ca_2Cu_3O_x$

200MPa (insufficient)

2nd generation HTS



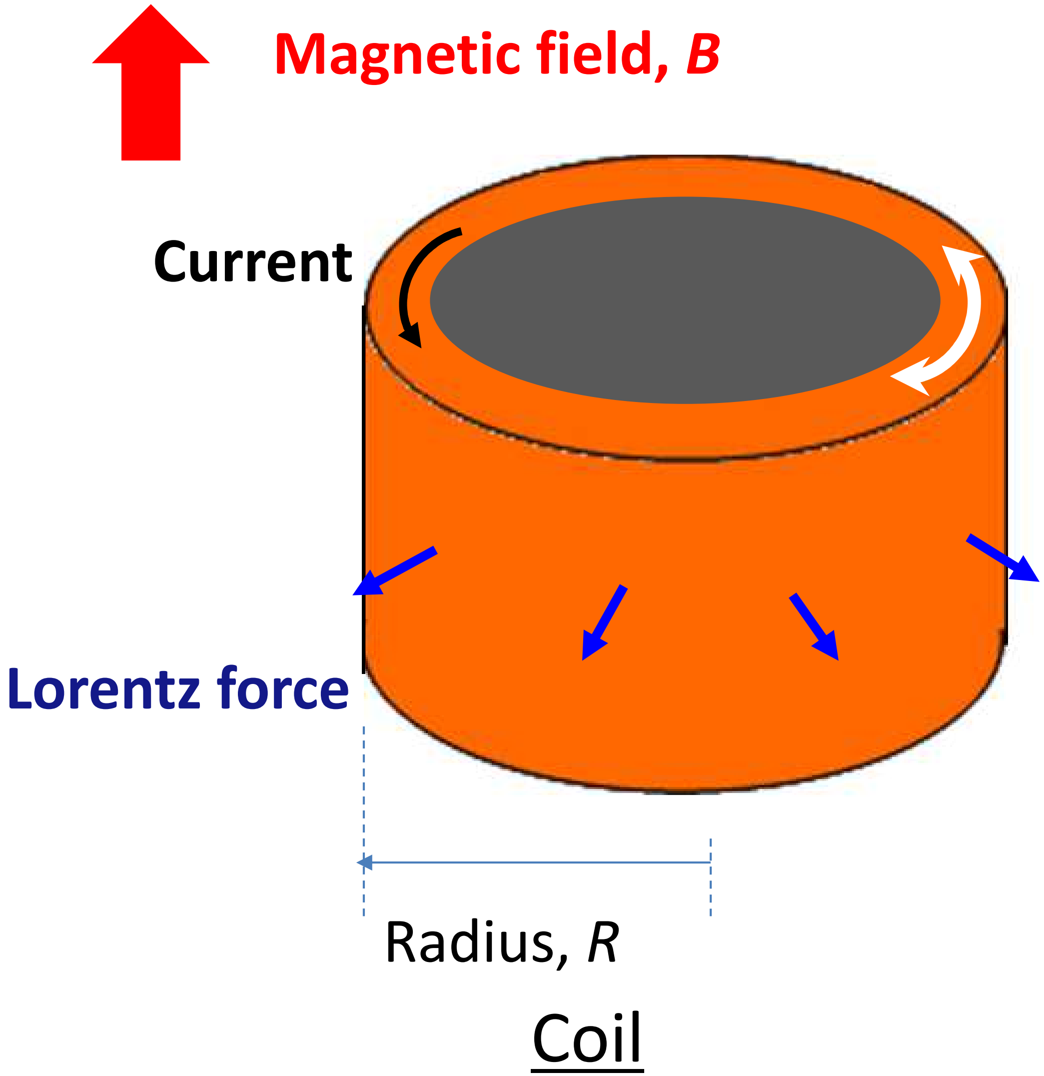
<u>REBCO conductors</u>

$RE_1Ba_2Cu_3O_x$（RE: Y, Gd etc.)

YBCO

700MPa (strong)

High conductor strength reduces the size of the magnet



Tensile stress=*BJR*

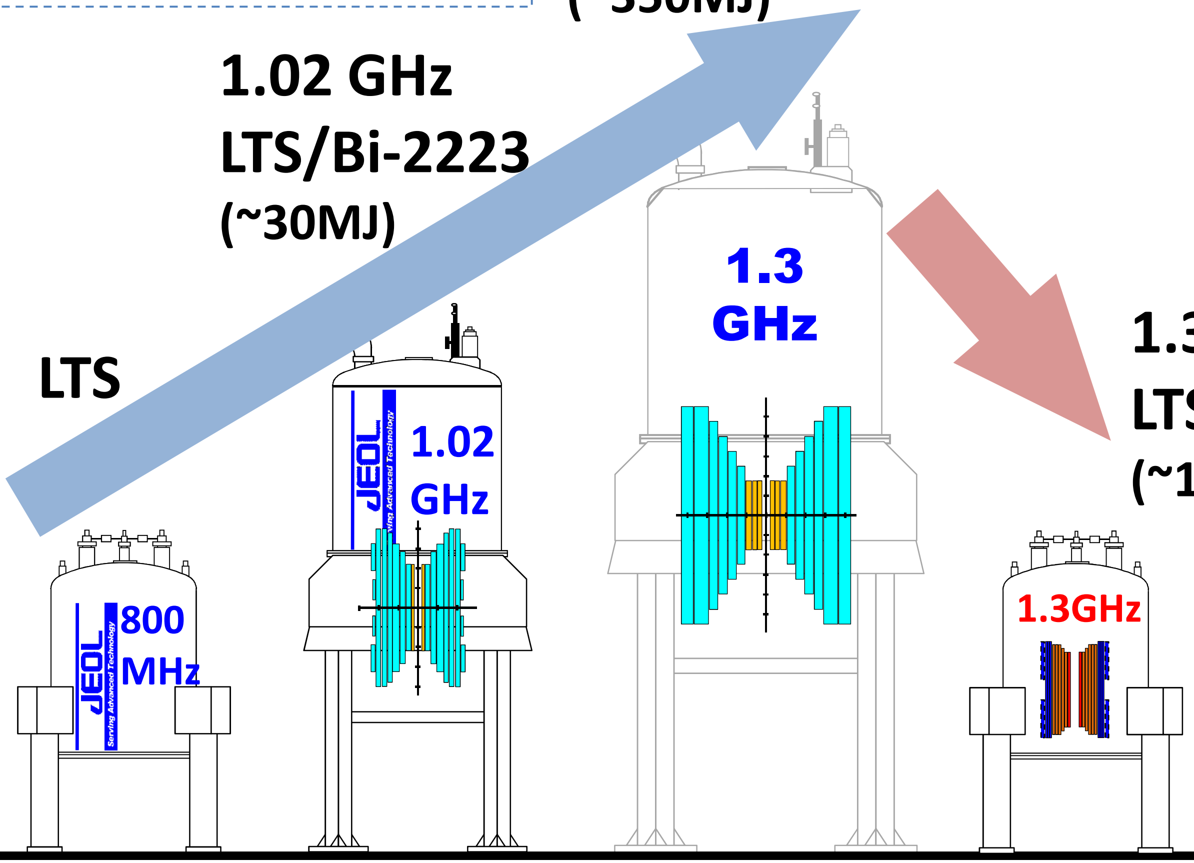
B: Field strength
J: Current density
R: Coil radius

If the HTS conductor is strong, a higher current density is available, resulting in compact size magnet

Current perspective on the super-high-field NMR magnet

LTS/Bi-2223 NMR:
the magnet size rapidly increases with the field intensity

LTS/REBCO NMR:
The magnet size becomes much smaller



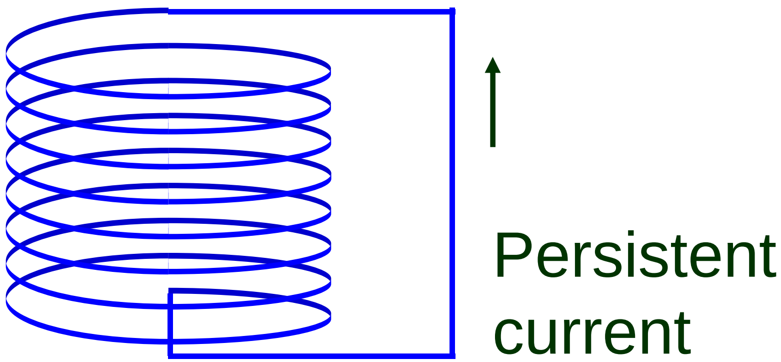
My question:
is this true or is this false?

1. Real characteristics of medium-field LTS/HTS NMR magnets

To check this out, a medium-field LTS/Bi-2223 NMR magnet and an LTS/REBCO NMR magnet were made, tested and compared so that we could achieve the basic knowledge on the performance of LTS/HTS NMRs

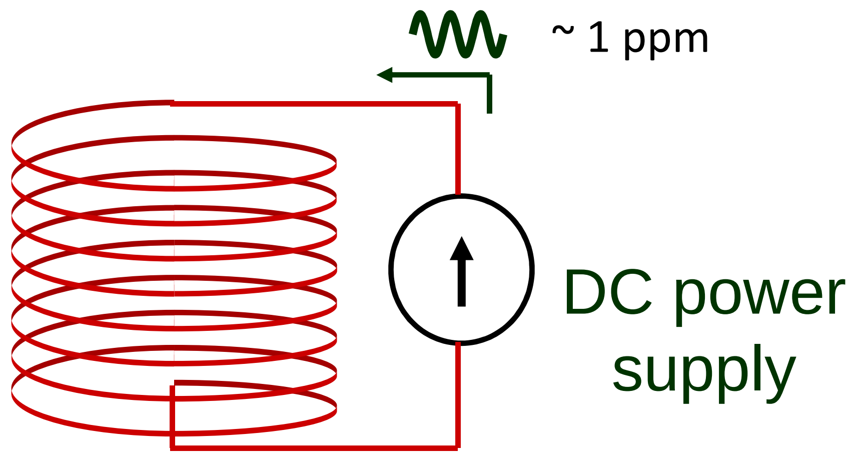
Operation mode of NMR magnets

LTS NMR



Persistent current mode

HTS NMR



~~Superconducting joint~~

Driven mode

Field stabilization is difficult

A 500MHz-class LTS/ HTS NMR magnet operated in driven mode

Bi-2223 inner coil

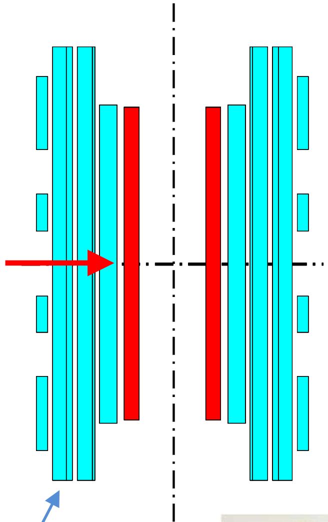
(2009)

Id 81mm
Od 121mm
L 375mm

REBCO inner coil

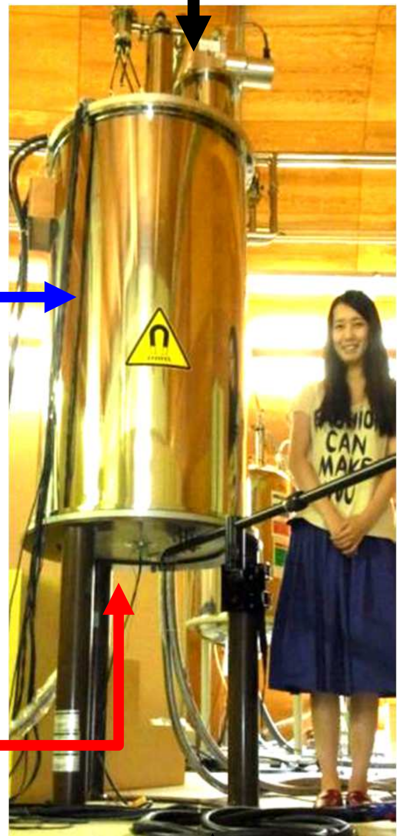
(2013)

Id 81mm
Od 119mm
L 400mm



LTS outer NMR coils

Pulse-tube cryocooler



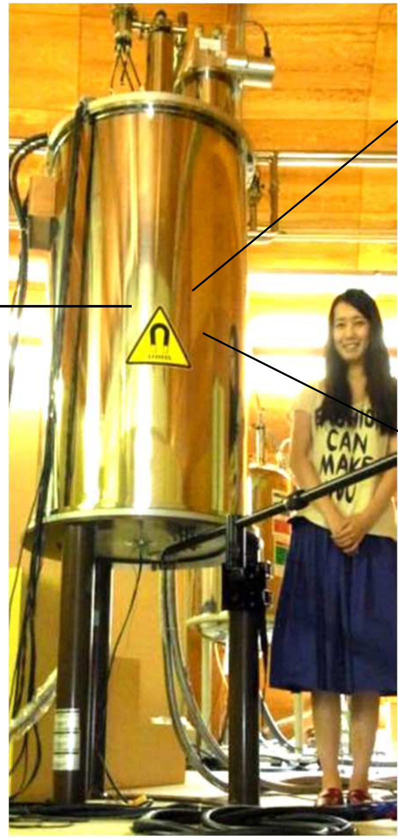
NMR probe

Ultra-stabilized DC-power supply

- Y. Yanagisawa et al, *JMR* 203, 274-282 (2010)
- T. Kiyoshi et al, *IEEE TAS 20, 714-717*(2010)
- Y. Yanagisawa et al., JMR, 249, 38-48(2014)

Problems of the LTS/HTS NMR magnet

(1) Temporal magnetic field stability
: 0.1ppb

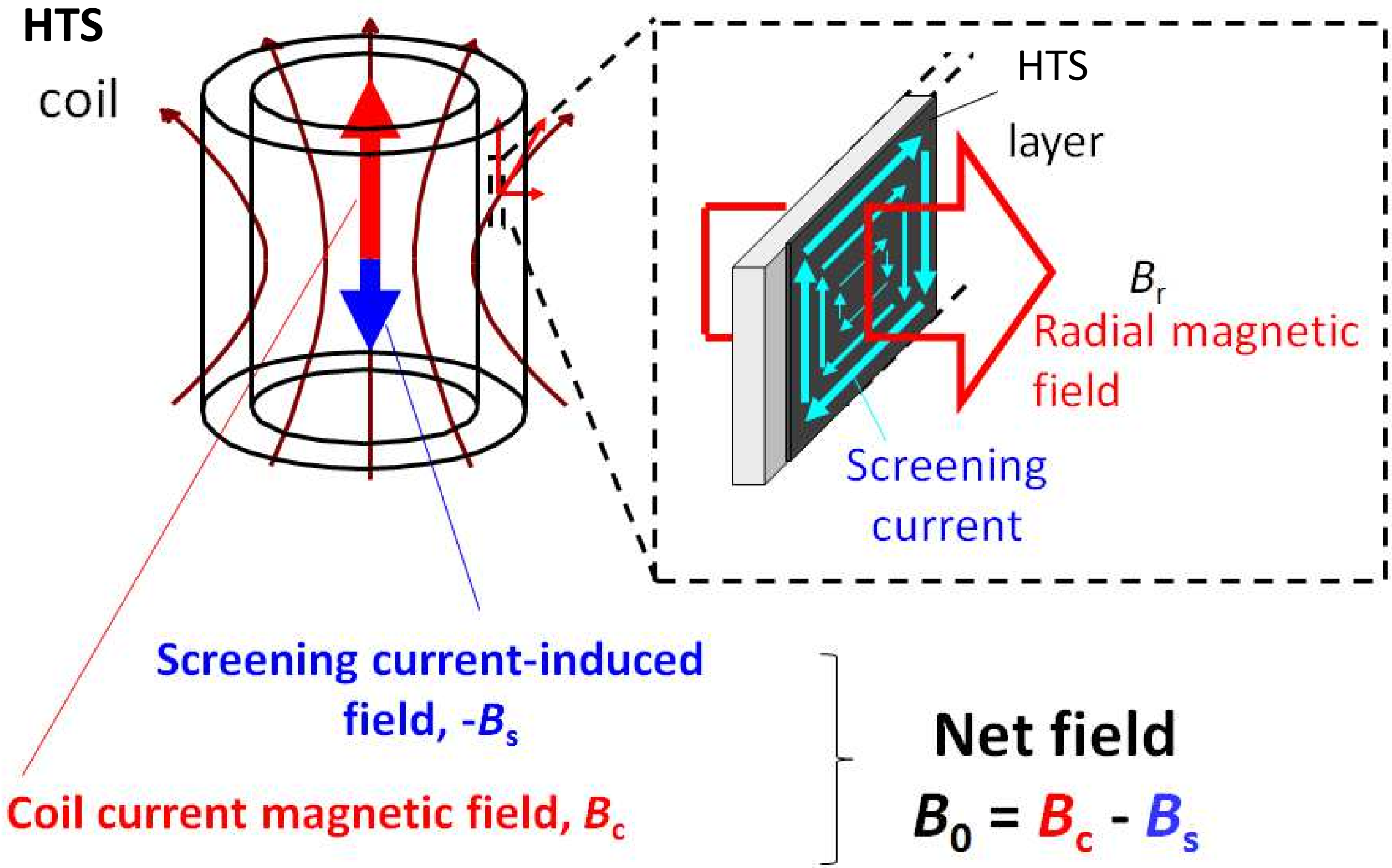


Field intensity

(2) Spatial magnetic field homogeneity
: 1 ppb

(1) Temporal magnetic field stability

Screening current induced magnetic field generated during the magnet charge



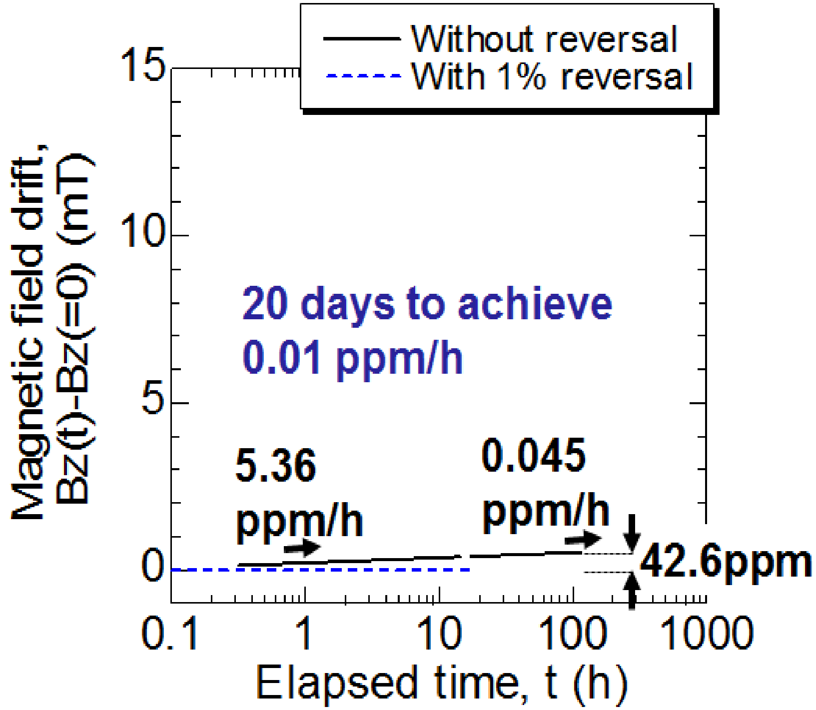
Net field

$$B_0 = B_c - B_s$$

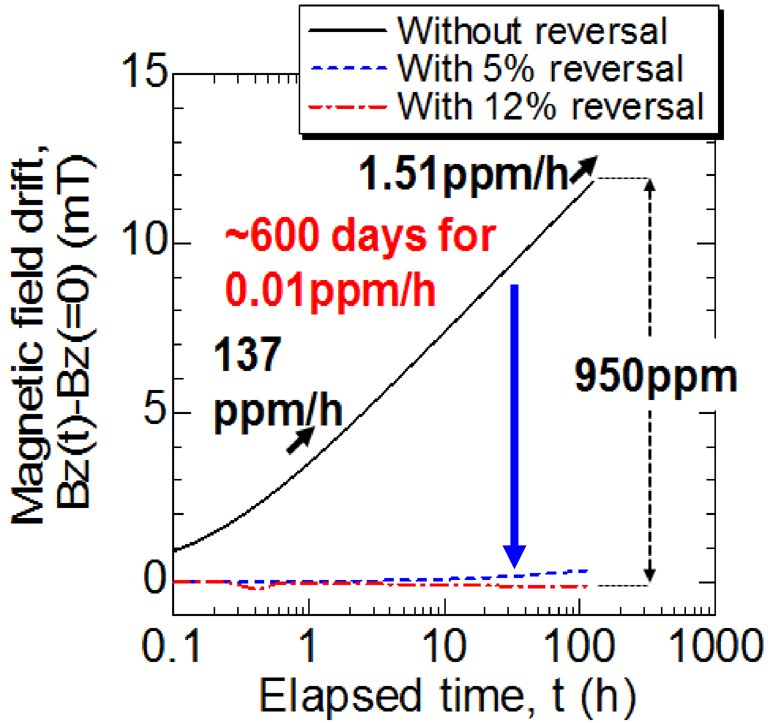
<u>If B_s is relaxed with time, B_0 shows a positive drift (increase)</u>

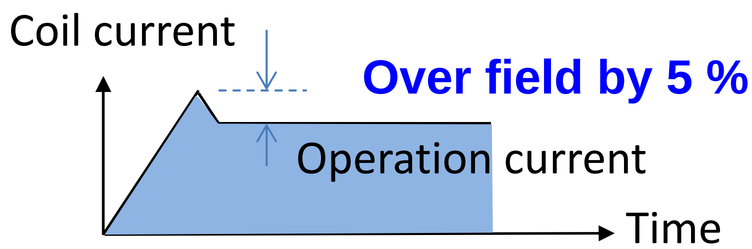
Temporal field drift after the magnet charge, due to the relaxation of the screening-current

LTS/Bi-2223 NMR (500MHz, 11.7T)

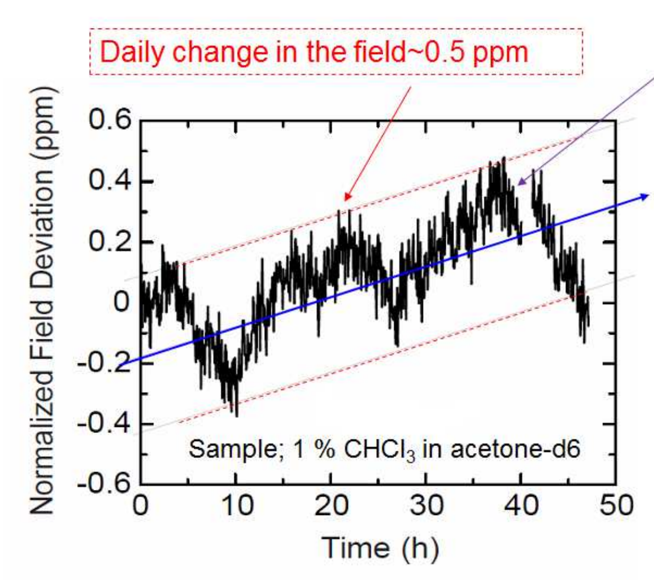


LTS/REBCO NMR (500MHz, 11.7T)

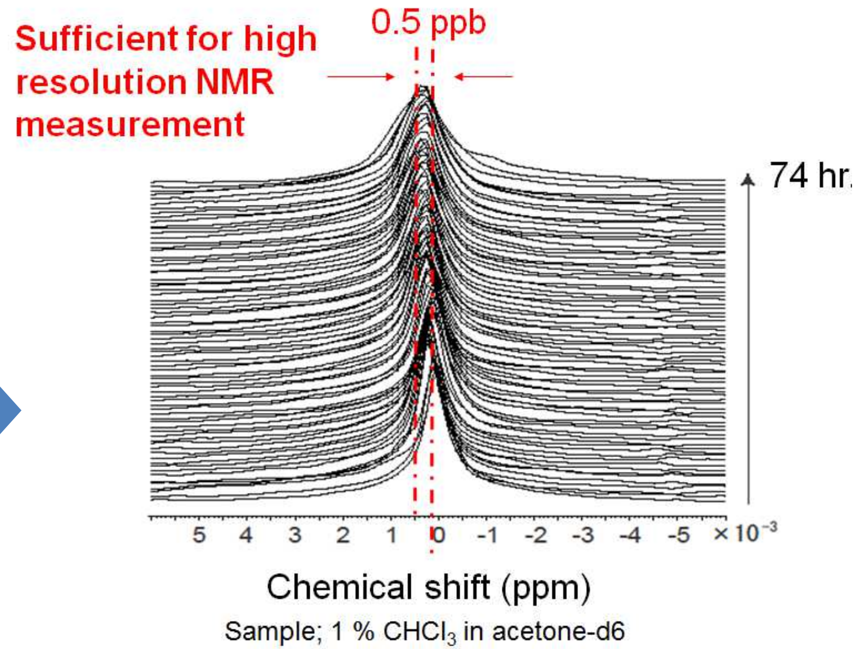




Stabilization of the magnetic field fluctuations(LTS/Bi-2223 NMR)



Temporal field fluctuation in driven mode at the 20th day



Stabilized magnetic field

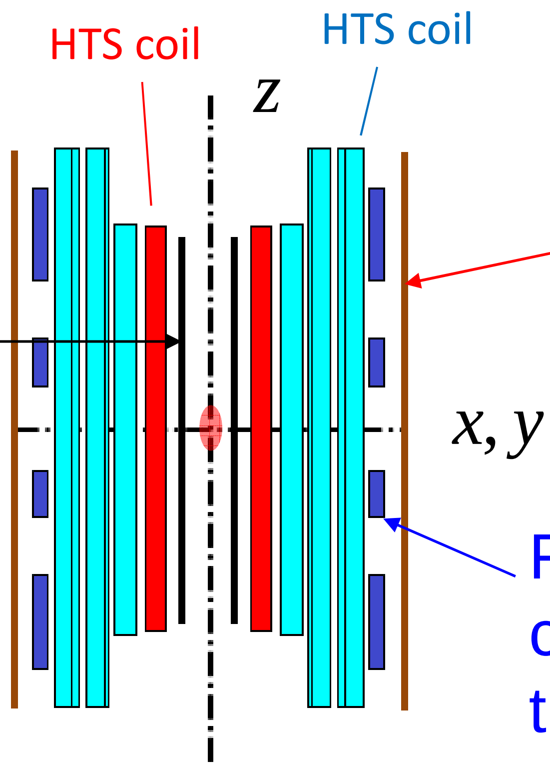
Stabilized by using

- **<u>Internal ^2H lock for solution NMR</u>**
- **External lock for solid state NMR**

(2) Spatial field homogeneity

Magnetic field correction system for the NMR magnet

Room temperature shims <1ppm



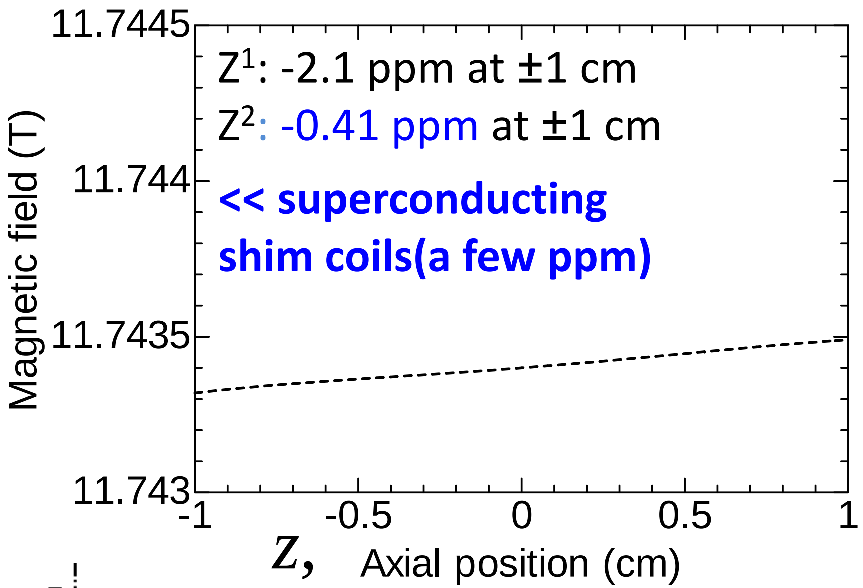
Cryoshims(z,z^2,x,y, zx, zy, xy,x^2-y^2) < 10 ppm

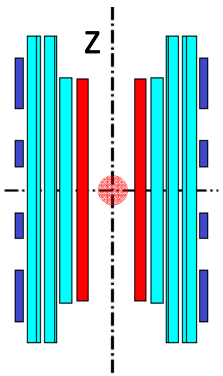
Field correction coils, compensating z^2 and z^4 of the main coil < 500ppm

The magnetic fields generated by the field correction coil and cryoshims are shielded by the screening current induced in the HTS inner coil

(a) Field inhomogeneity

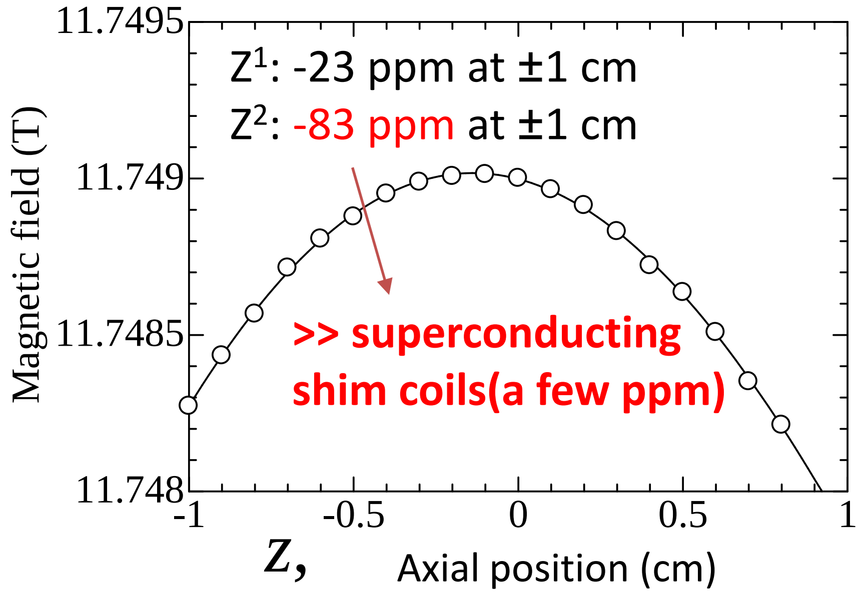
LTS/ Bi-2223 NMR (500 MHz)





Shielding effect is negligible for the Bi-2223 NMR coil

LTS/ REBCO NMR (500 MHz)



Shielding effect on the correction coil is enormous; the z^2 component generated by the main coil is uncompensated and remains >> z^2 cryoshim

(b) Performance reduction of cryoshims

	LTS/Bi-2223 NMR	LTS/REBCO NMR
Axial cryoshims (z and z^2)	→40%	→20%
Radial cryoshims (x, y, zx, zy, xy, x^2-y^2)	→20-40%	→5%

The cryoshim performance is reduced, especially for LTS/REBCO NMRs

(3) NMR spectrum

Spectral resolution and sensitivity for three types of NMR spectrometer

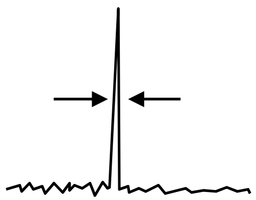
	LTS NMR	LTS/Bi2223 NMR	LTS/REBCO NMR
NMR resolution	<1 Hz(2 ppb)	0.7 Hz(1.4 ppb)	15 Hz(38 ppb)
NMR sensitivity S/N	>600	512	28 (400 MHz)

Nearly the same

10-times worse than the LTS NMR

NMR resolution

Chloroform



NMR sensitivity

Ethyl-benzene

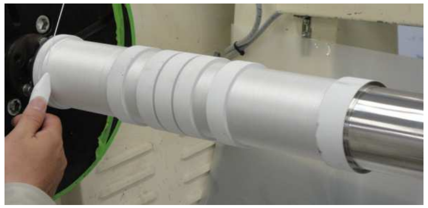
^{1}H solution NMR spectrum

The #2nd LTS/REBCO NMR magnet

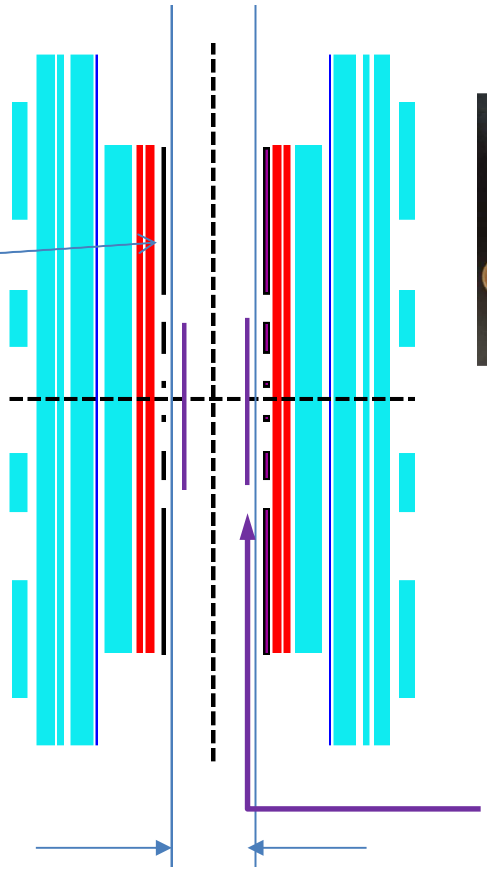
(2) Ferromagnetic-shims against radial error field harmonics

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

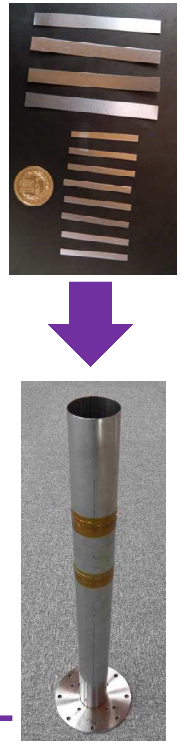
(1) Inner-cryoshims

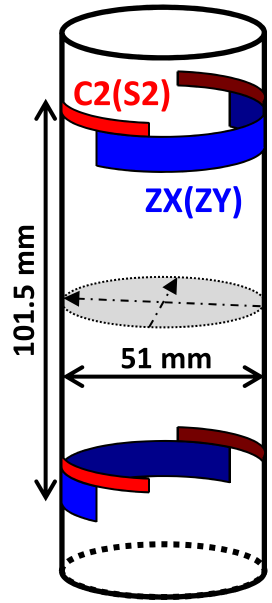


JASTEC



RT bore





2014 (RIKEN)

R. Piao et al., to be published in JMR(2016)

Spectral resolution and sensitivity for three types of NMR spectrometer

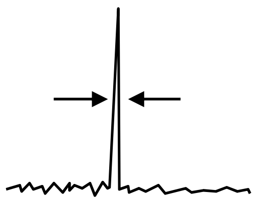
	LTS NMR (persistent)	LTS/Bi-2223 NMR (driven mode)	LTS/REBCO NMR (driven mode)
NMR resolution	<1 Hz(2 ppb)	0.7 Hz(1.4 ppb)	0.5Hz(1.3 ppb)
NMR sensitivity	>600	512	**318**@400MHz (**444**@500MHz)

Nearly the same

The field correction was very difficult and required 2months

<u>NMR resolution</u>

Chloroform

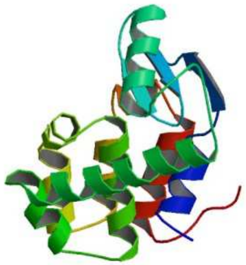


<u>NMR sensitivity</u>

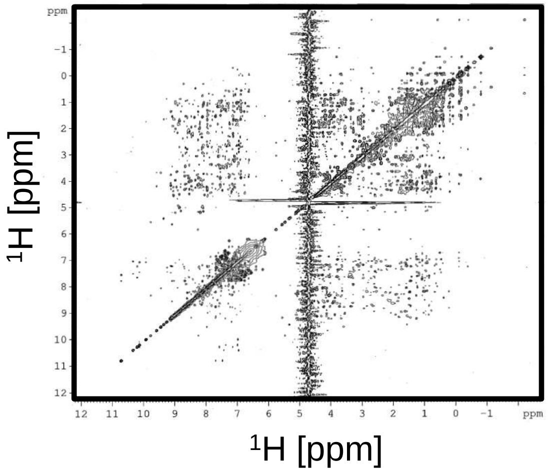
Ethyl-benzene

<u>^{1}H solution NMR spectrum</u>

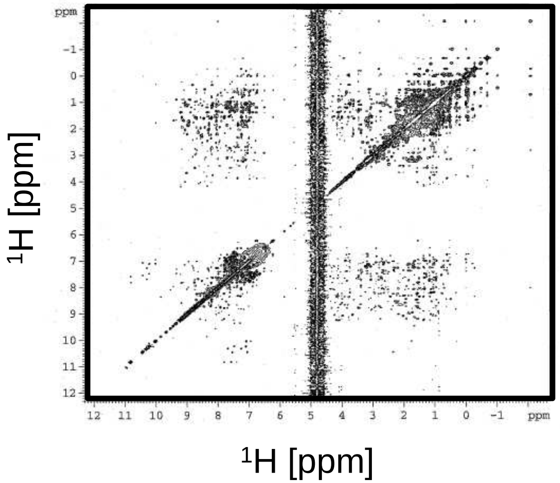
2-D NOESY spectra for Lysozyme



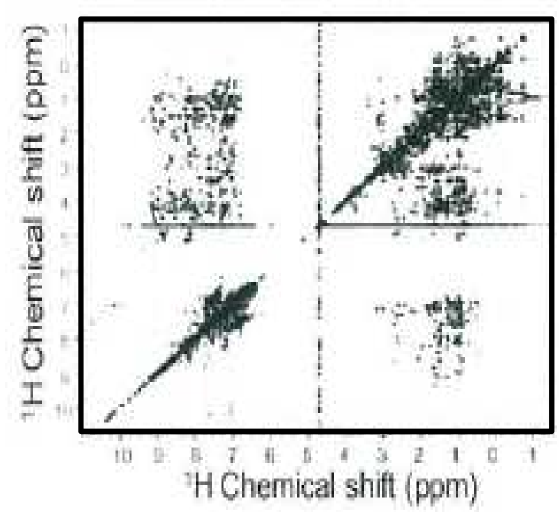
Low T_1 noise, water suppression



(a) 500MHz LTS NMR



(b) 500MHz LTS/ Bi-2223 NMR



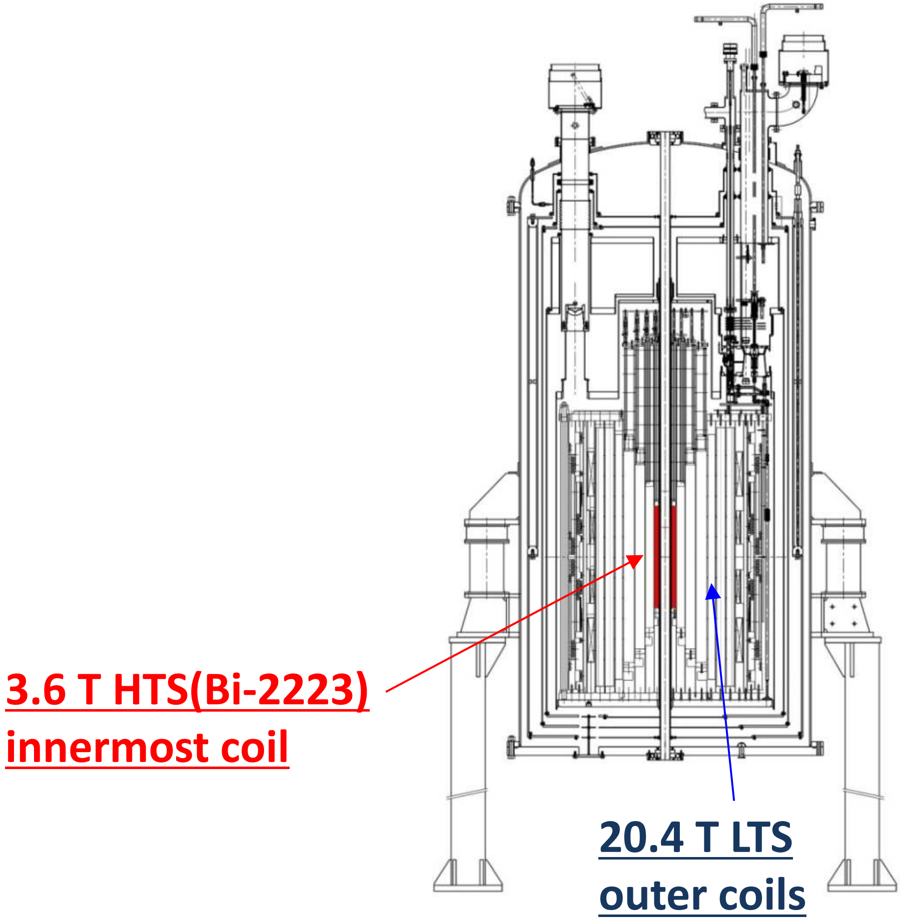
(c) 400MHz LTS/ REBCO NMR

2. 1.02 GHz LTS/Bi-2223 NMR

Based on the method so far developed by using medium-field LTS/HTS NMR magnets, we proceeded to develop an LTS/ HTS NMR operated beyond 1 GHz

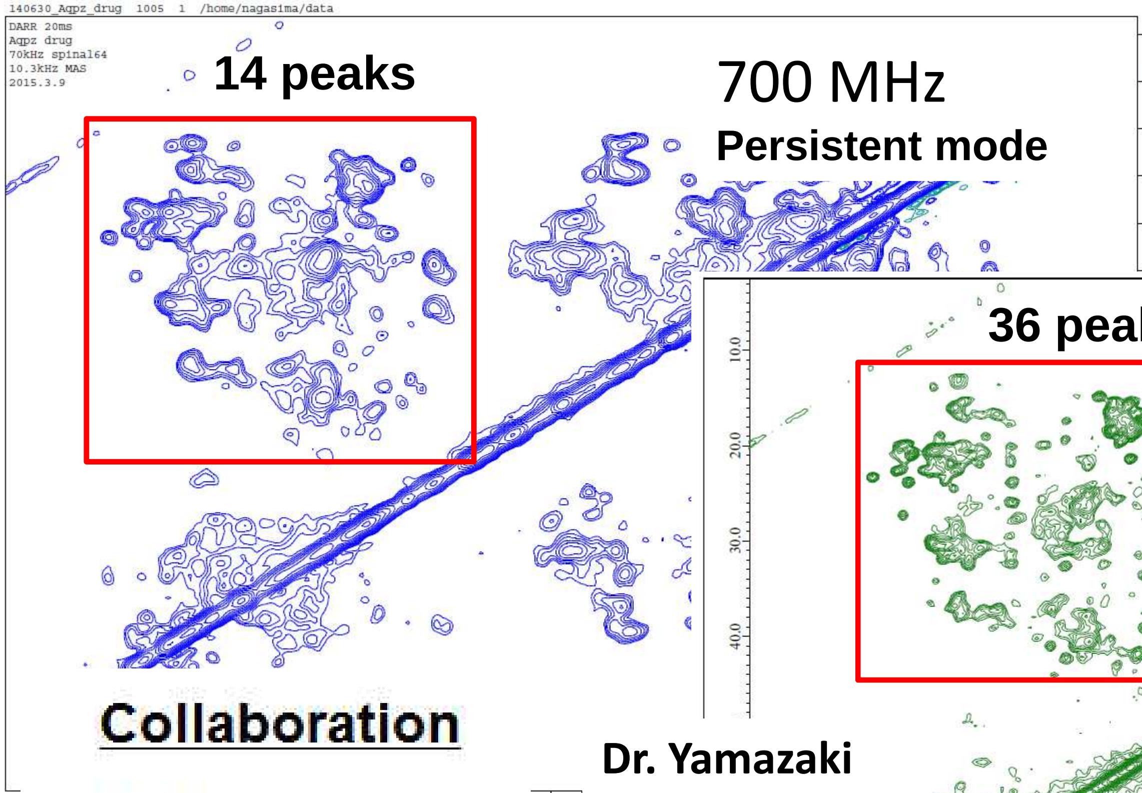
More details will be given by Dr. Hamada in this workshop

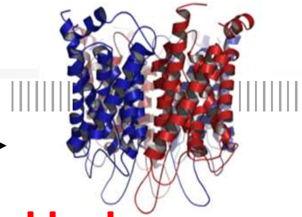
1.02 GHz LTS/ Bi-2223 NMR



K. Hashi, et al., *JMR*, 256, 30-33 (2015)

Solid-state 2D-NMR spectra(DARR) for a membrane protein (Aquaporin Z)

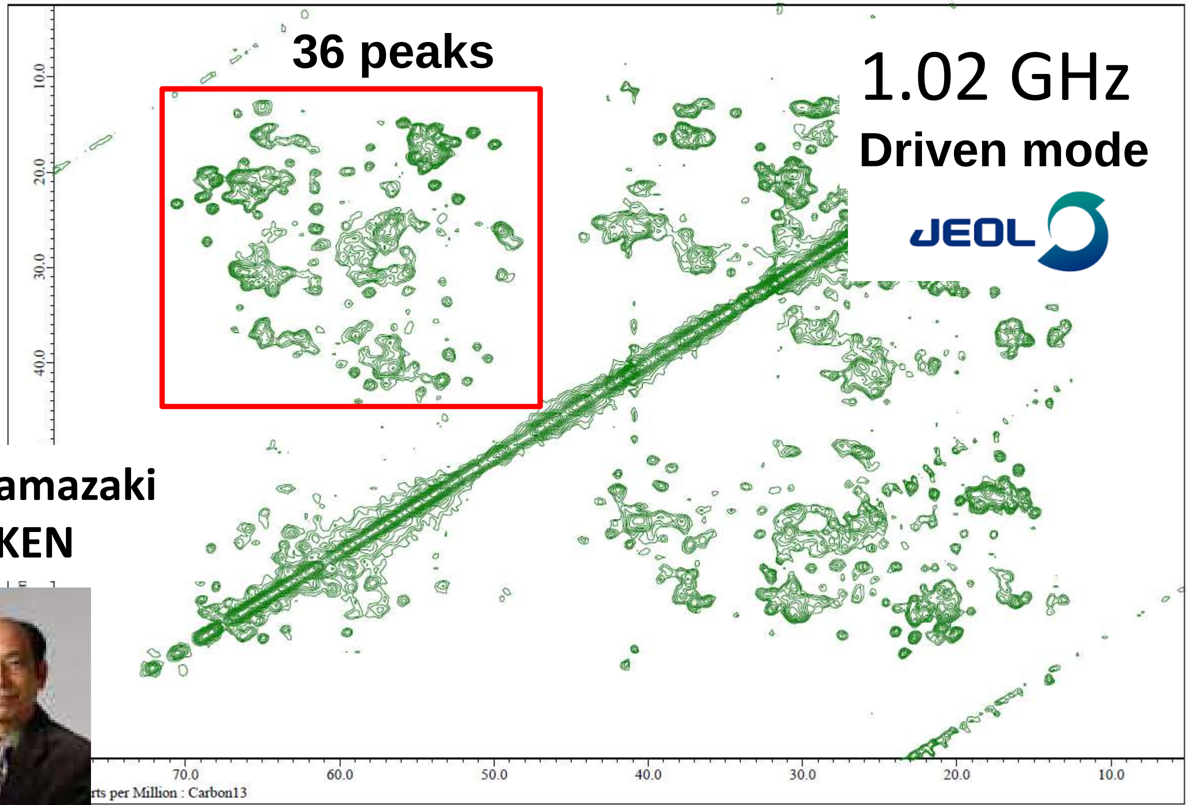




7 Hours with **external lock**

MAS=15 kHz; 2.5 mm rotor

70 kHz; spinal64 decoupling



Collaboration

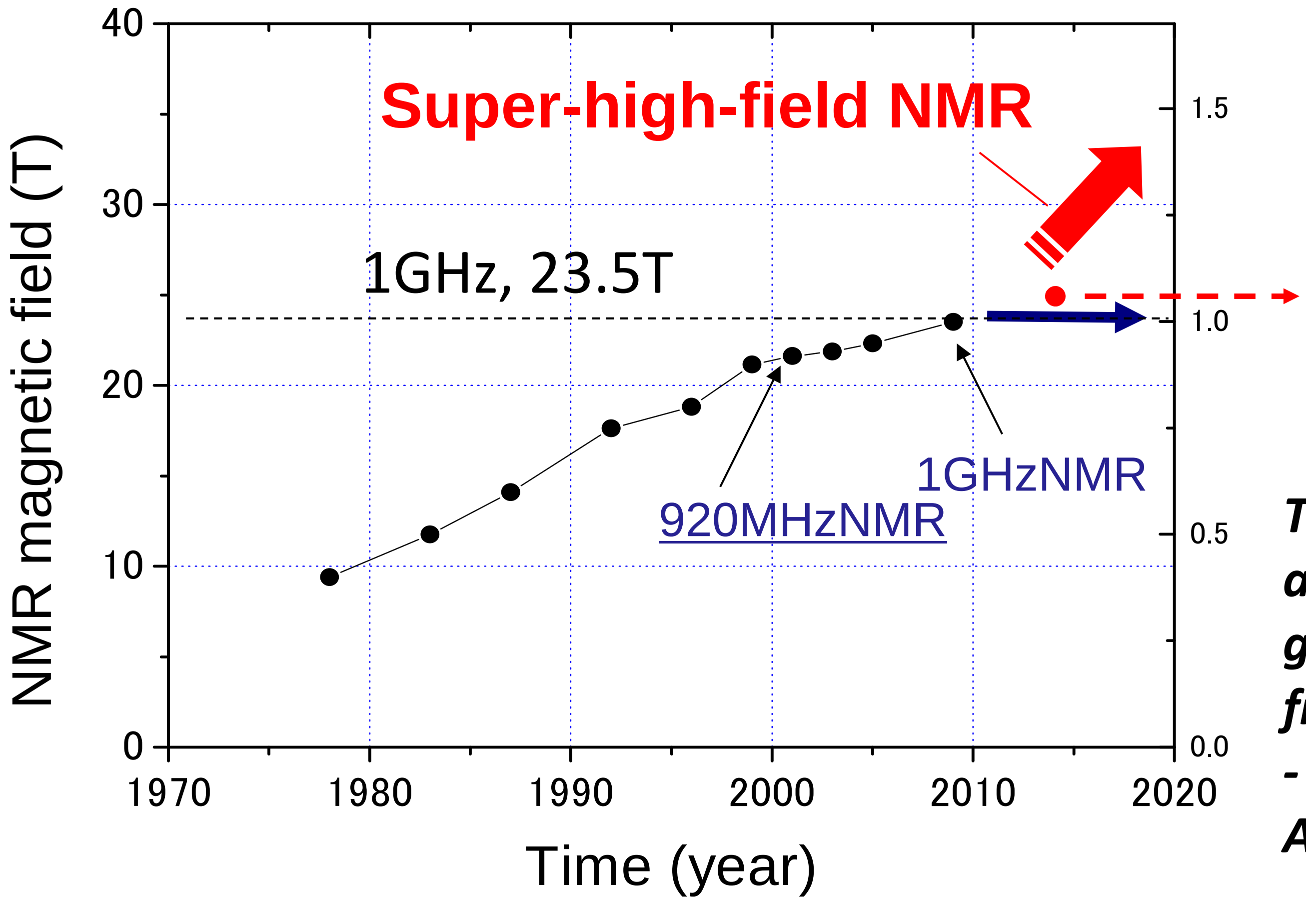
Prof. Pervushin

NANYANG TECHNOLOGICAL UNIVERSITY

Dr. Yamazaki in RIKEN

H. Maeda et al., eMagRes (Wiley) to be published (2016)

One great leap !



This is one small step for an NMR magnet; one giant leap for super high field NMR

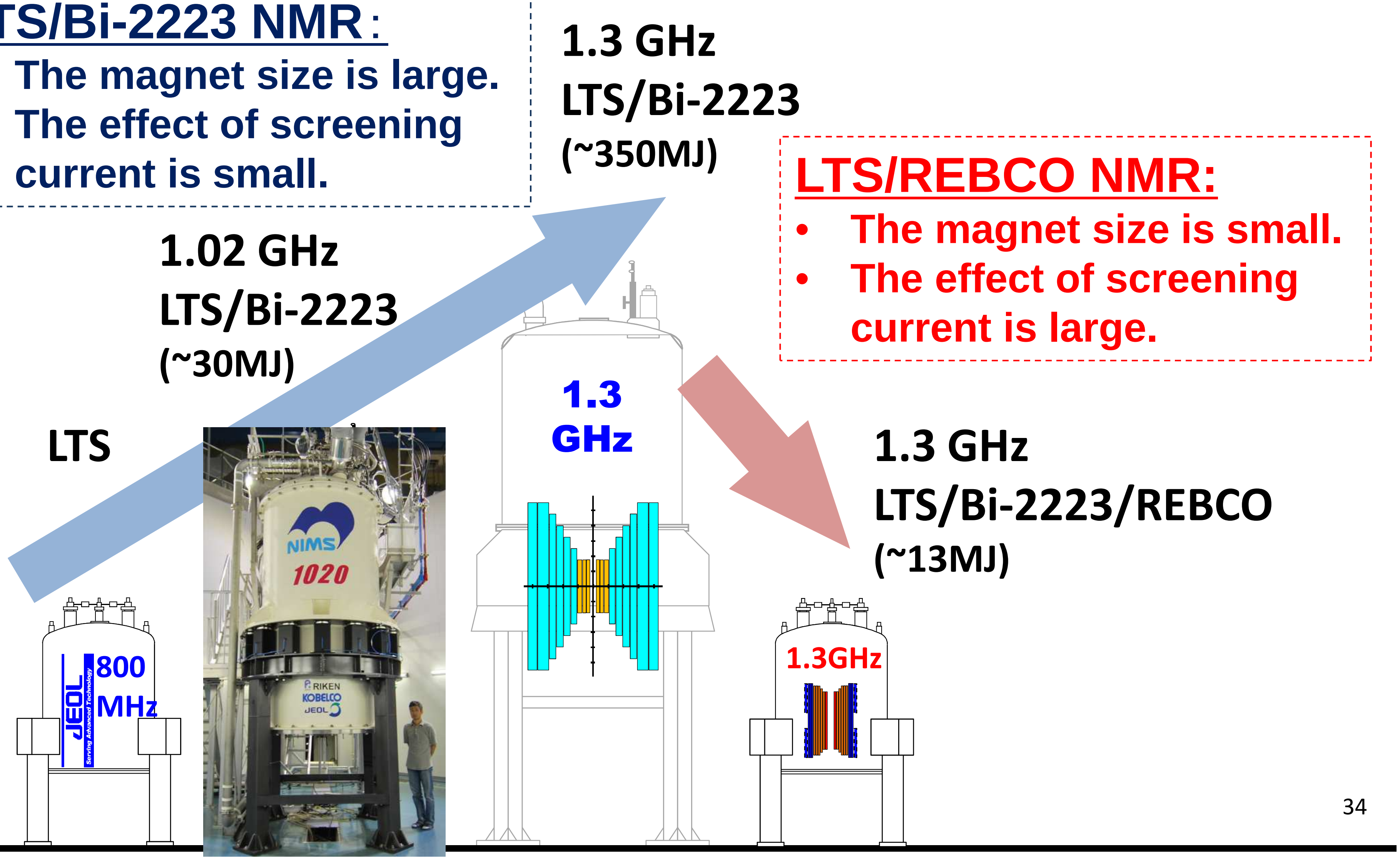
- N. A. Armstrong of Apollo 11 -

3. New perspective of the super-high field NMR

We must reconsider the current perspective based on the screening current effect

LTS/Bi-2223 NMR:
- The magnet size is large.
- The effect of screening current is small.

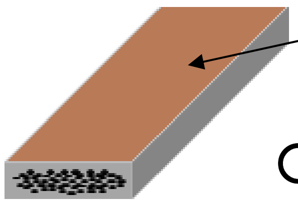
LTS/REBCO NMR:
- The magnet size is small.
- The effect of screening current is large.



(a) New HTS conductors

Bi-2223 conductor

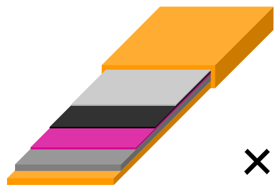
200 MPa



Bronze Reinforcement

○ Screening current
△ Mechanical strength

REBCO conductor



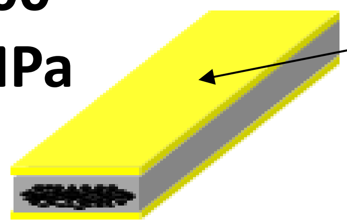
700 MPa

× Screening current
○ Mechanical strength

<u>Both high mechanical strength and low screening current are obtained</u>

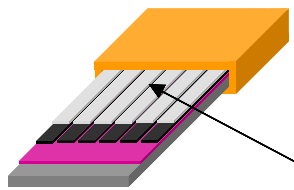
<u>Stronger Bi-2223</u> conductor

400 MPa



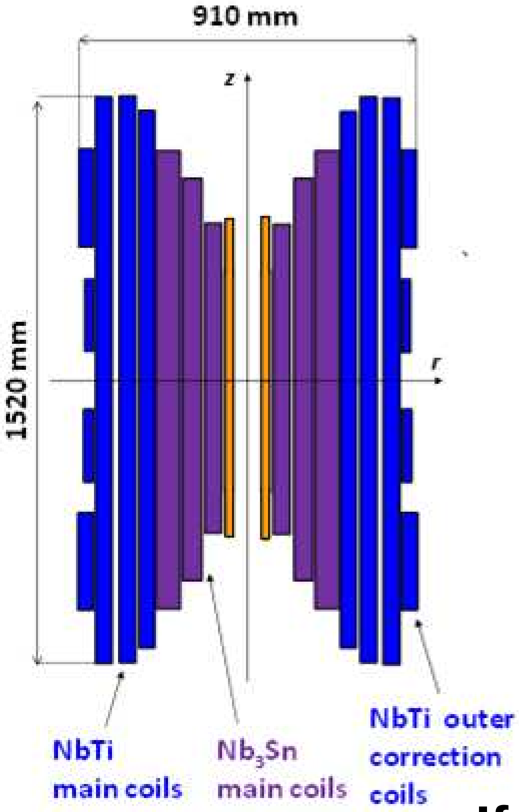
Ni-alloy reinforcement

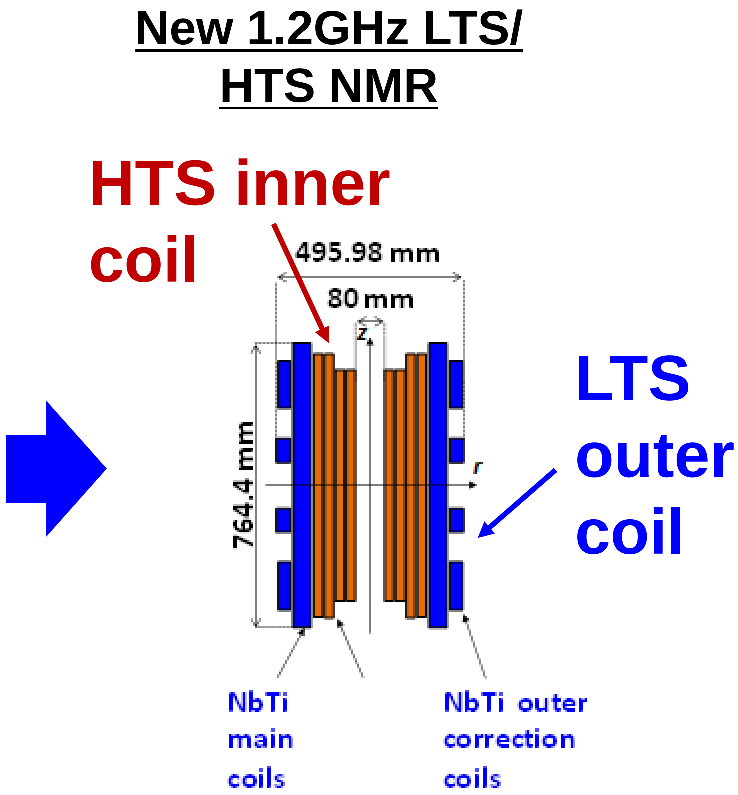
<u>Multi-filamentary REBCO</u> conductor



Separated into filaments (scribed)

(b) Optimal design





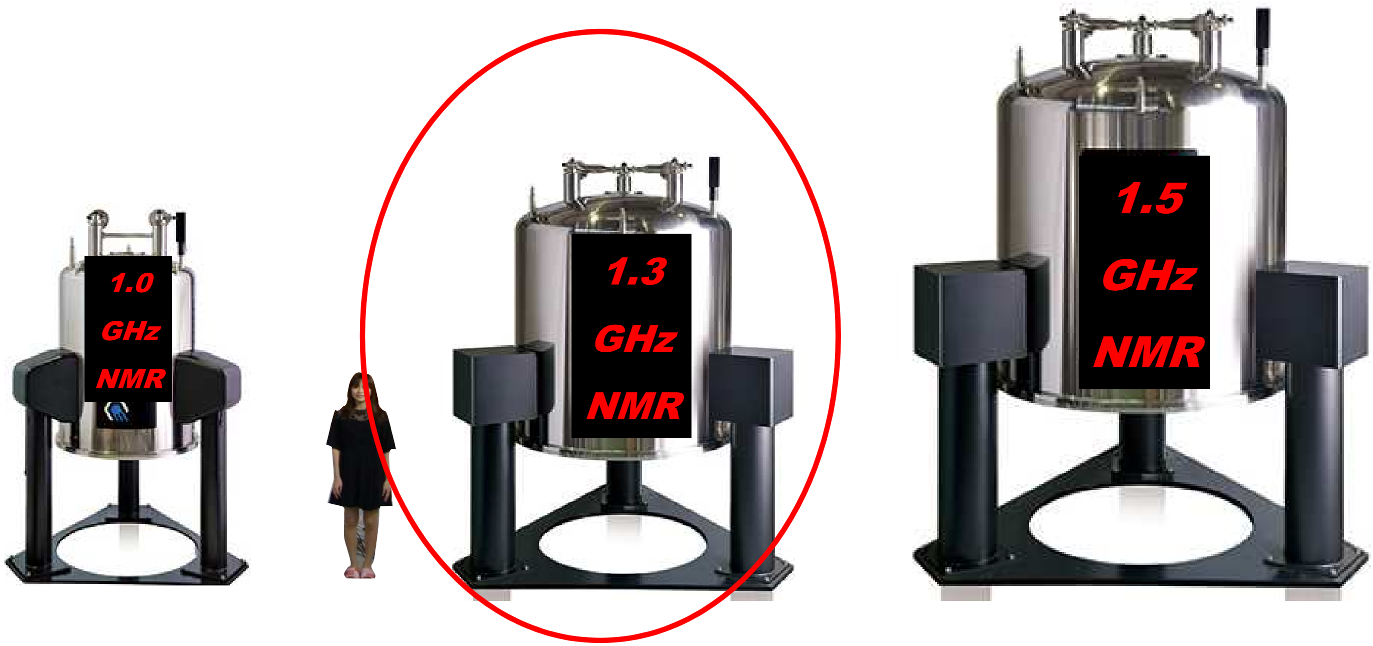
Thin solenoid of the HTS

If we increase HTS coils, we can enhances the current density, reducing the magnet size

Y. Yanagisawa et al., JMR, 249, 38-48(2014)

New perspective on the super-high field NMR

a. New HTS conductors
b. Optimal magnet design
c. Simple cooling system



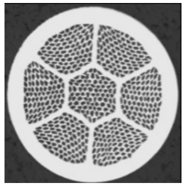
The next target!

Finally --

So far we have limited our discussion to the HTS tape conductor, however we have another choice

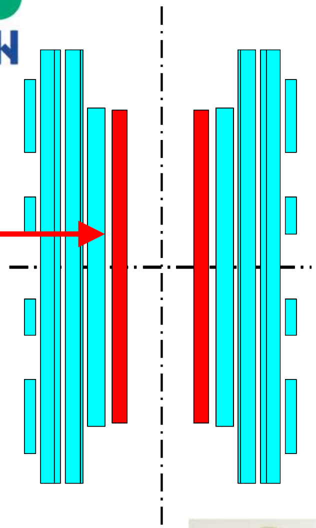
Development of an LTS/ Bi-2212 NMR magnet

NHMFL



1 mm

Id 81 mm
Od 118 mm
L 2795 mm



Bi-2223/ Bi-2212/ REBCO

The screening current effect becomes negligible.

- **D. C. Larbalestier** et al. Nature materials(2014)
- **Y. Yanagisawa** et al, *JMR* (2010)
- **T. Kiyoshi** et al, *IEEE TAS* (2010)

NMR probe

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

Will be installed in RIKEN in 2015


Thank you very much for your attention！
Sakura
桜
Cherry
22
RIKEN NMR Facility
40