Status and Plan for Superconducting Magnet Development at KEK

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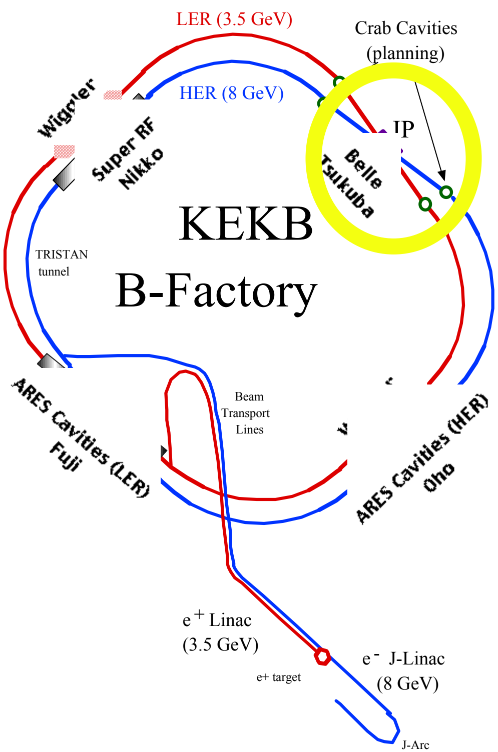
KEK

March 22, 2004

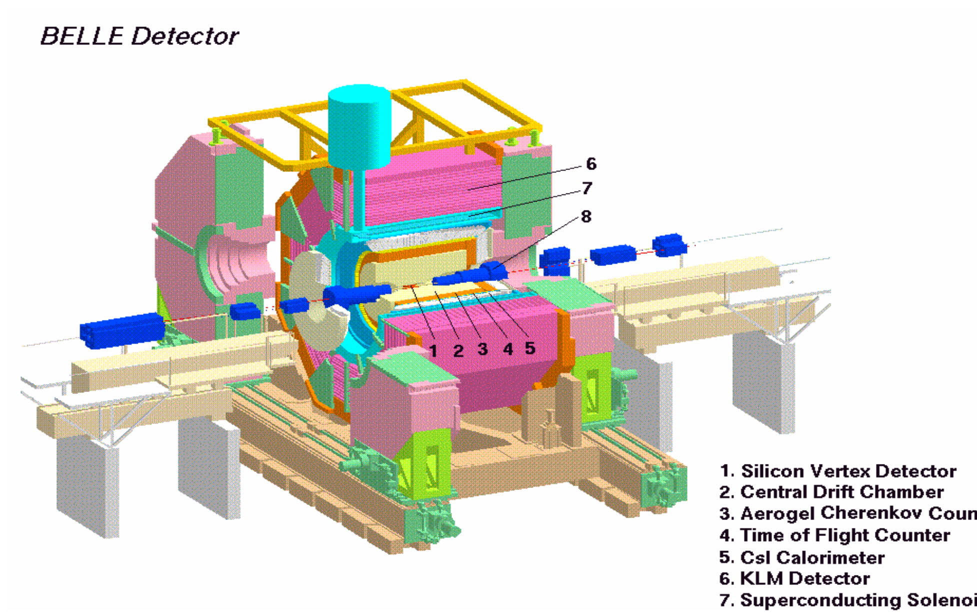
Outline

- **Current Status**
  - KEK-B: IR Quadrupoles, Detector Solenoid (BELLE)
  - LHC: IR Quadrupoles, Detector Solenoid (ATLAS)
- **J-PARC Neutrino**
  - Neutrino: 50 GeV Proton Beam
- **Basic R&D for Future Plans**
  - PRISM: Pion capture for intense muon beam
  - Neutron Optics with Nb3Sn Sextupole
  - High Field Magnet with Nb_3Al, Nb_3Sn

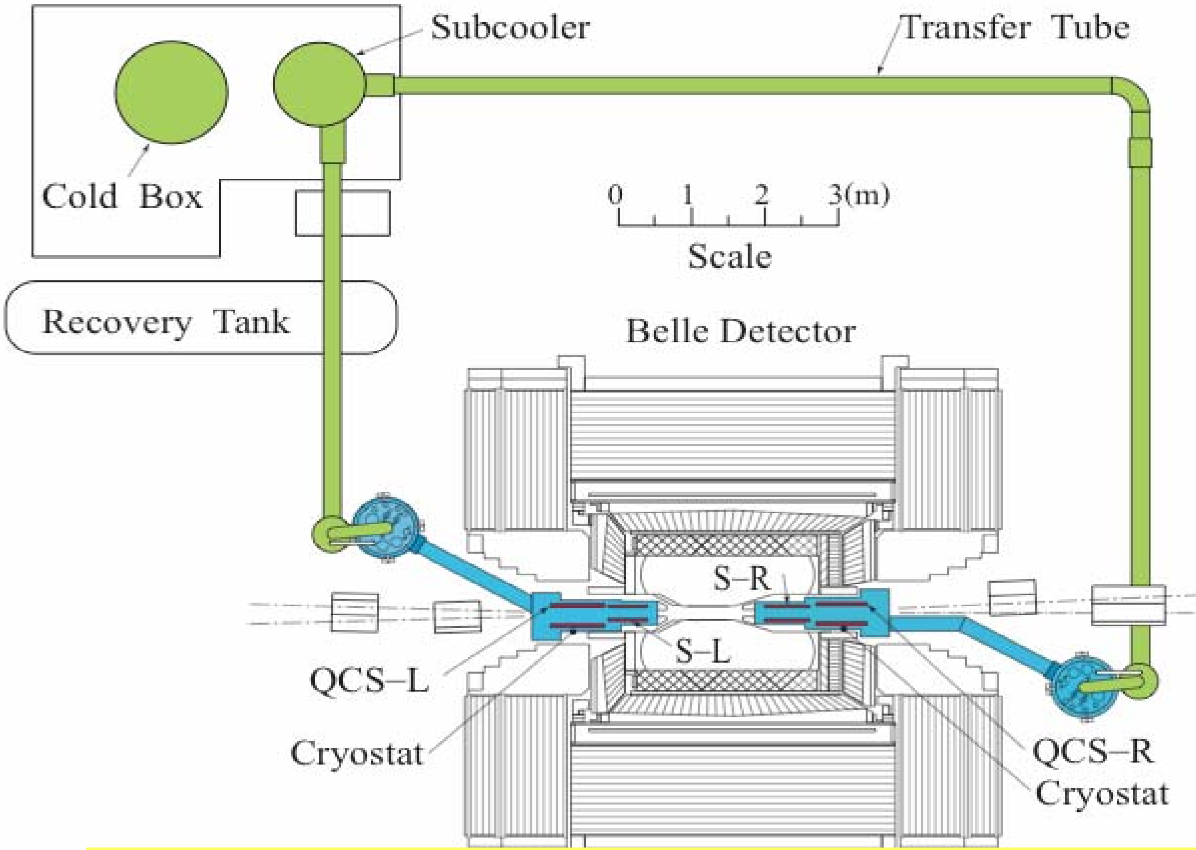
KEK B-Factory



KEK Site

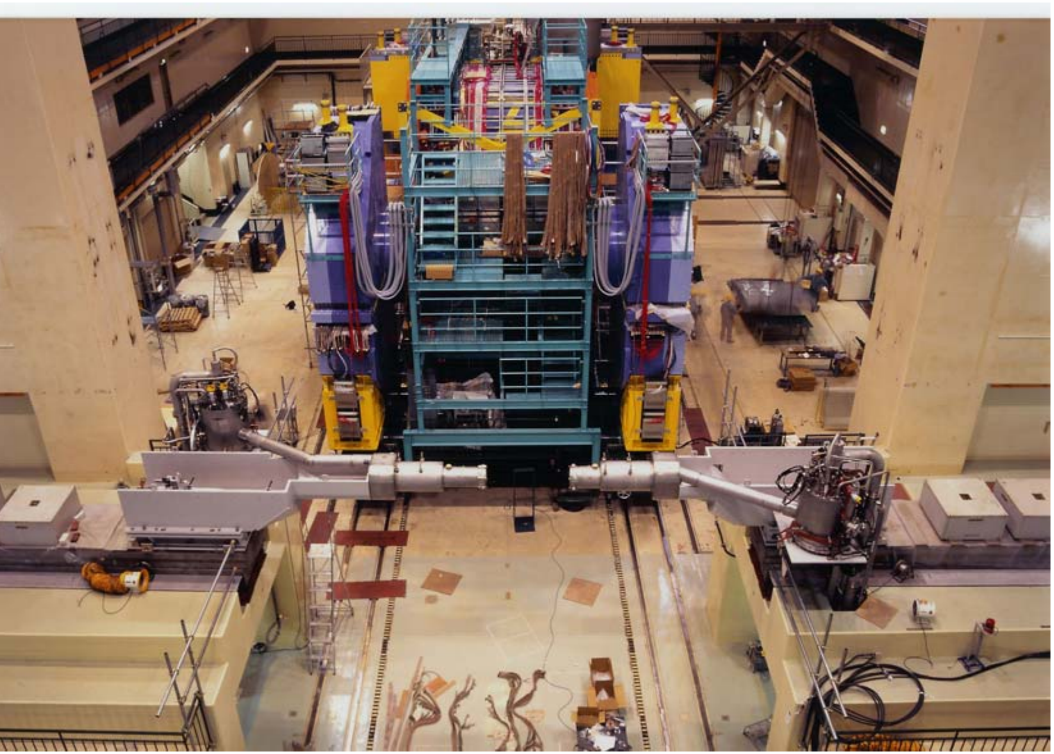


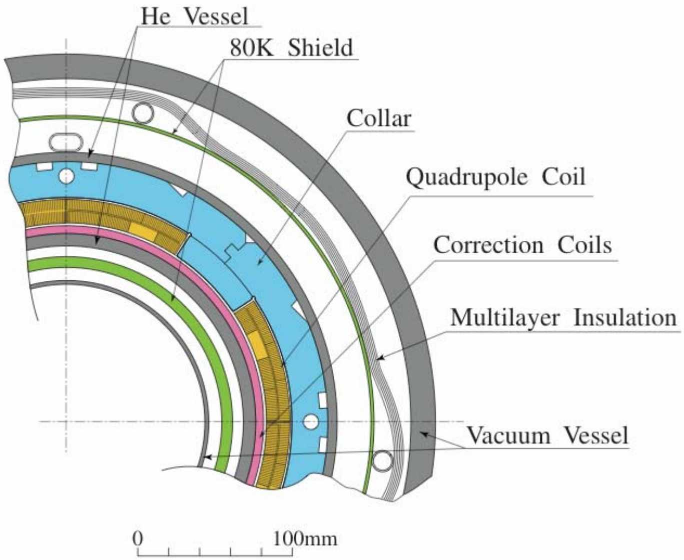
Layout of superconducting magnet system for KEK-B IR

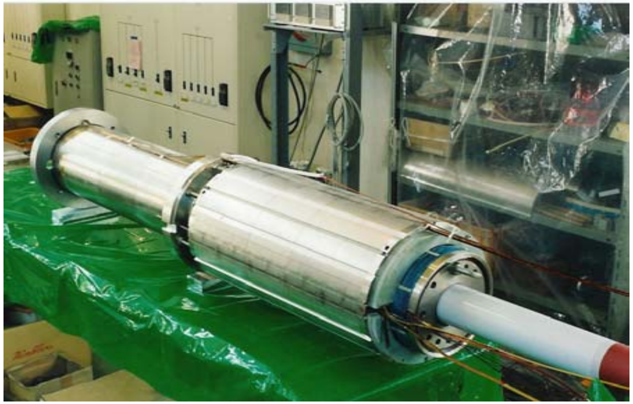


- IRQ G = 22 T/m @ IR = 13 cm
- Comp. Solenoid B = 4.5/5.8 T @ IR = 13 cm
- Belle Solenoid: B = 1.5 T @ R = 4 m

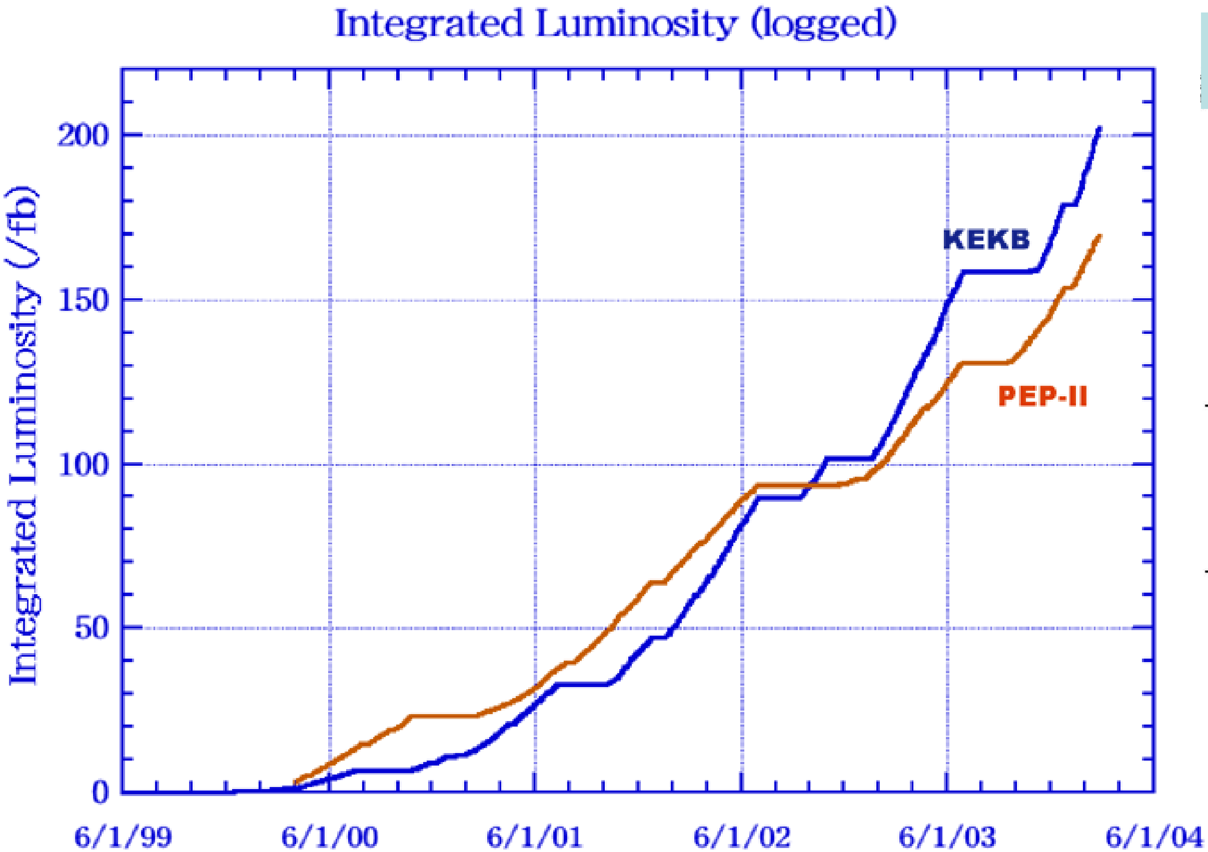
IR Quadrupoles and Correctors at KEK-B

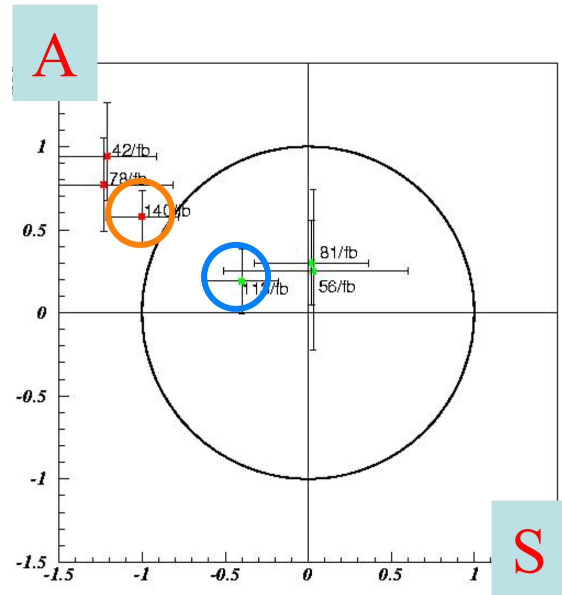






KEK-B Integrated Luminosity

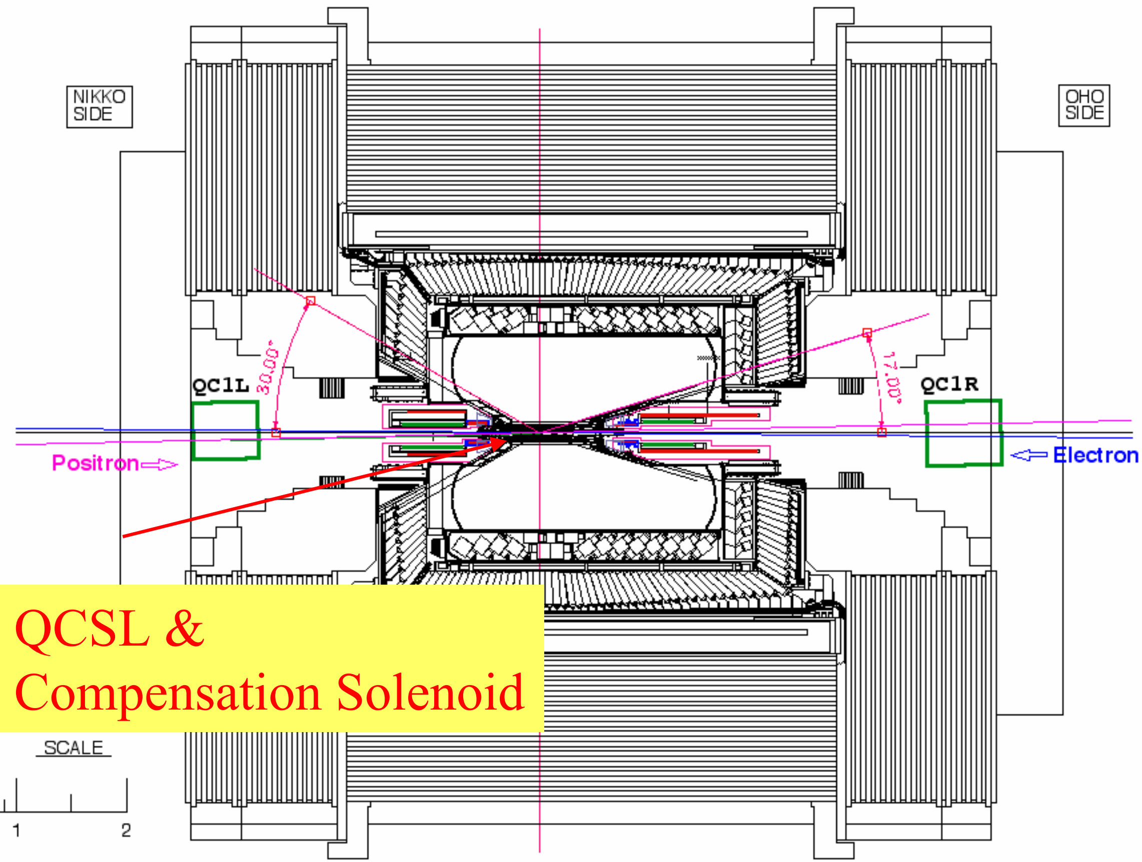




- Integrated Luminosity at KEK-B: > 200 /fb
- Peak Luminosity : > 10^{34}

B- pi-pi decay, CP violation confirmed by **Belle** and **Babar at > 5 σ**

Study of Future Upgrade for Super-KEKB



QCSL &
Compensation Solenoid

6 layer coils

I.R. : **90 mm**

G =**36 T/m** @1134A

B-max = **3.74 T**

Effect. L. = 0.333 (0.398) m

R 239

9.2

Corrector Coils

Compensation Solenoid

R 69

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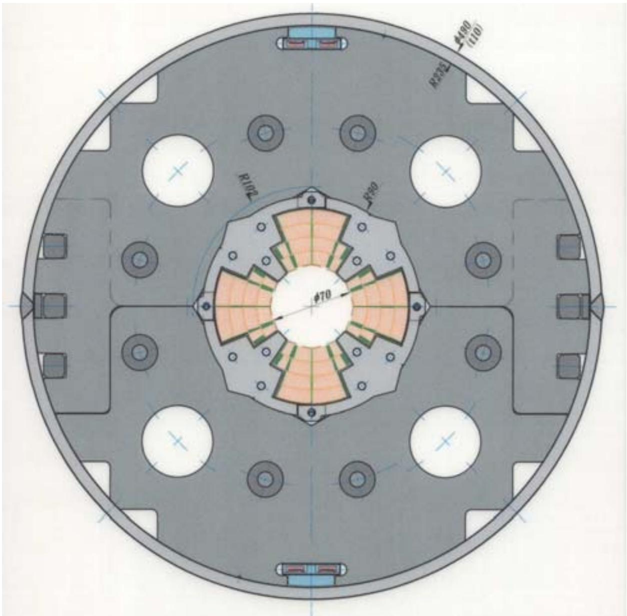
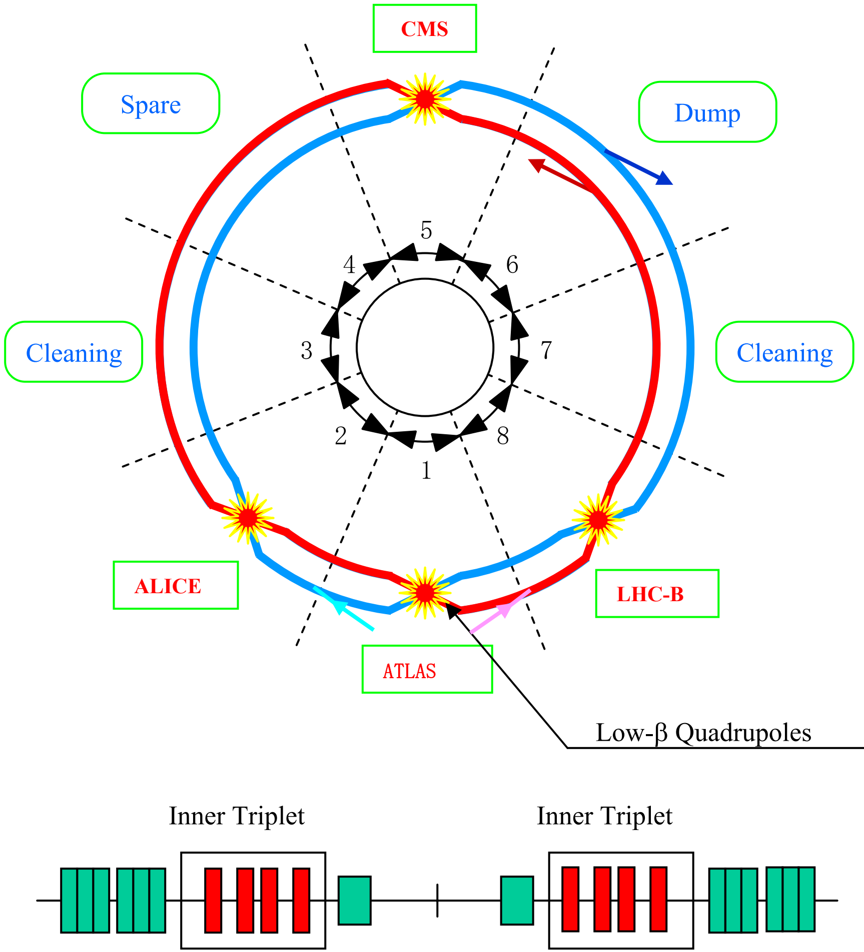
LHC
Low-beta Insertion Quadrupoles

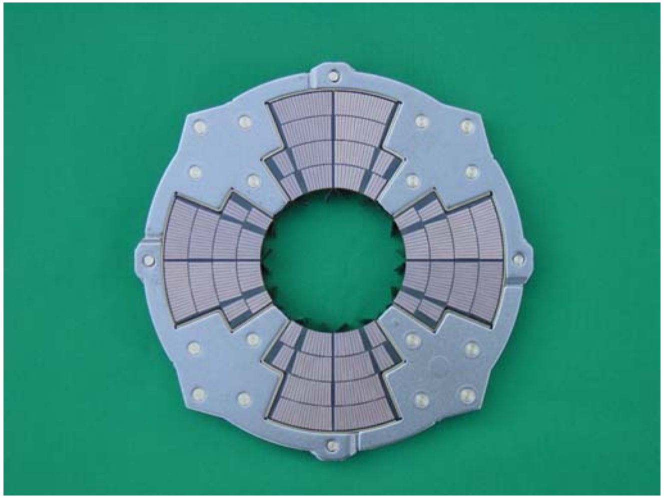
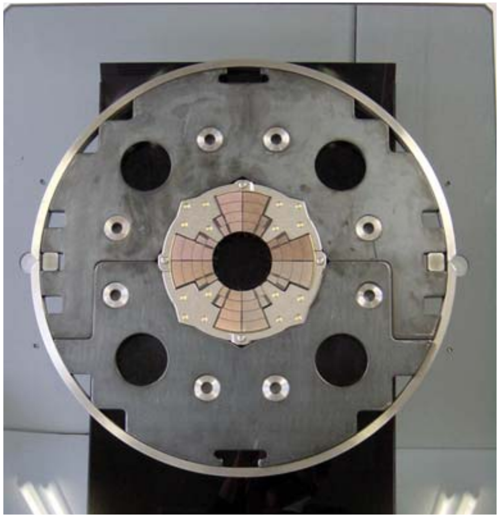
- **G = 215 T/m,   (B-peak = 8.4 T)**
- **Aperture = 70 mm**
- **Multipoles (b_6, b_{10}): < 1 unit (10^{-4})**
- **Beam Heating: 5 ~ 10 W/m**



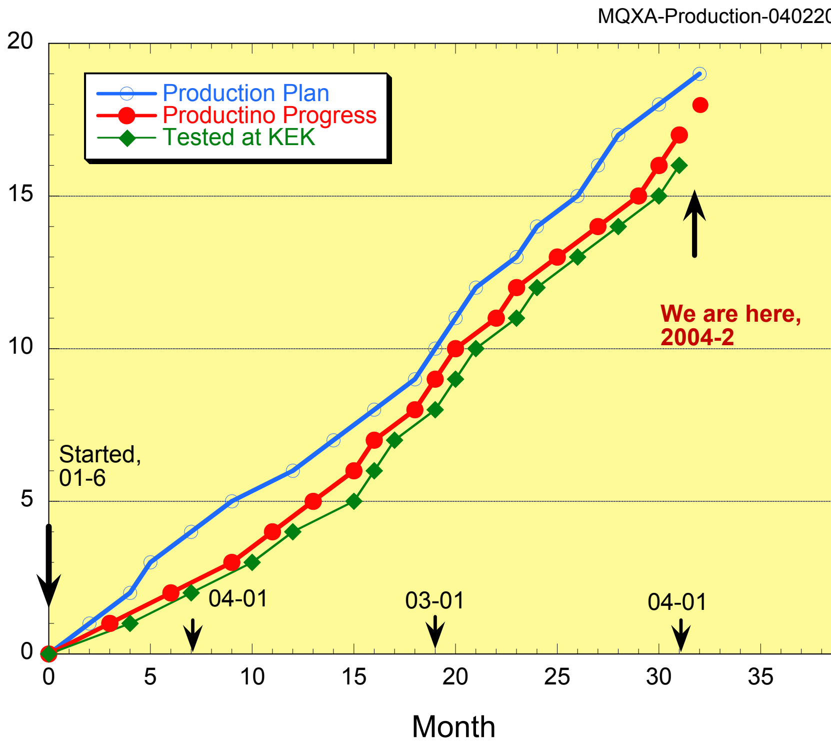


MQXA Production



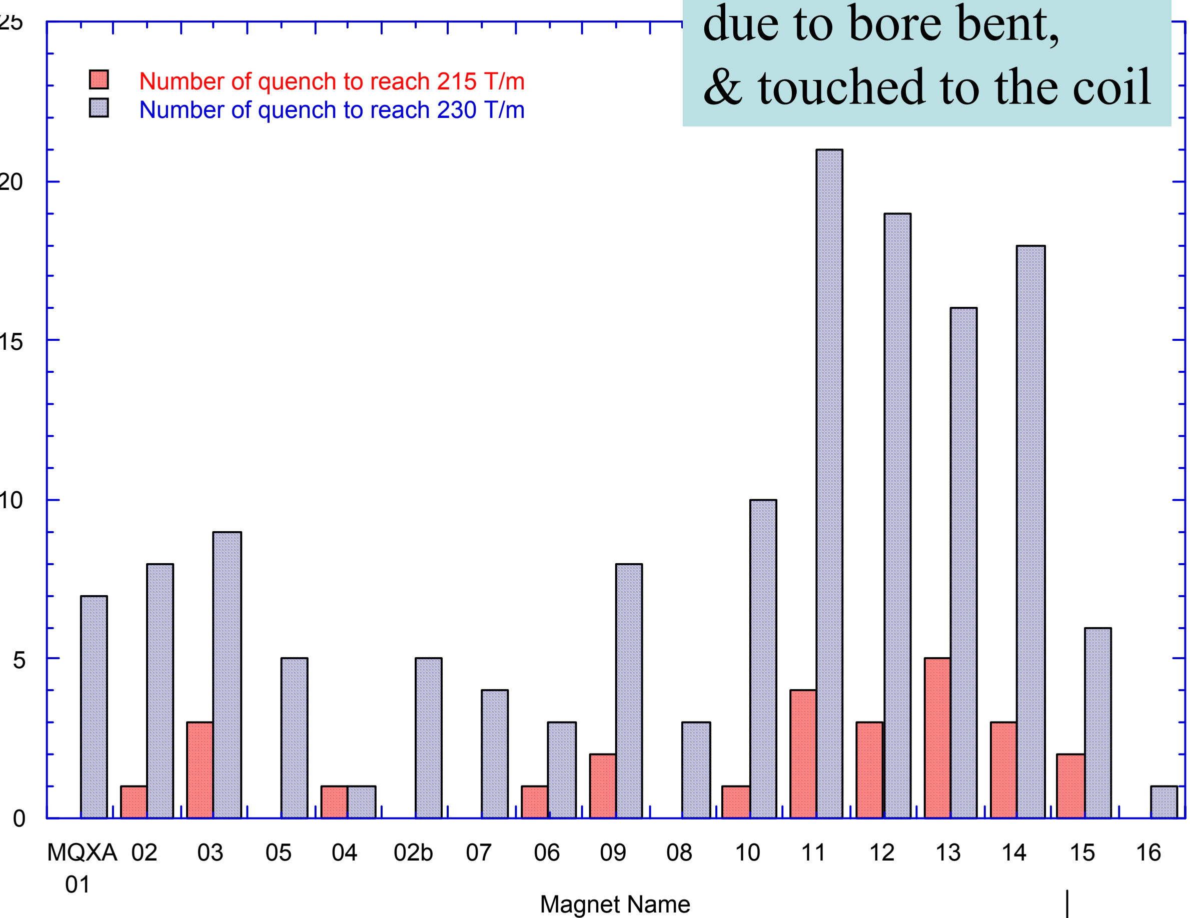
MQXA Magnet



MQXA-Production-04022
Production Plan
Productino Progress
Tested at KEK
We are here,
2004-2
Started,
01-6
04-01
03-01
04-01
Month
0
5
10
15
20
0
5
10
15
20
25
30
35

Number of Quenches to 230 T/m

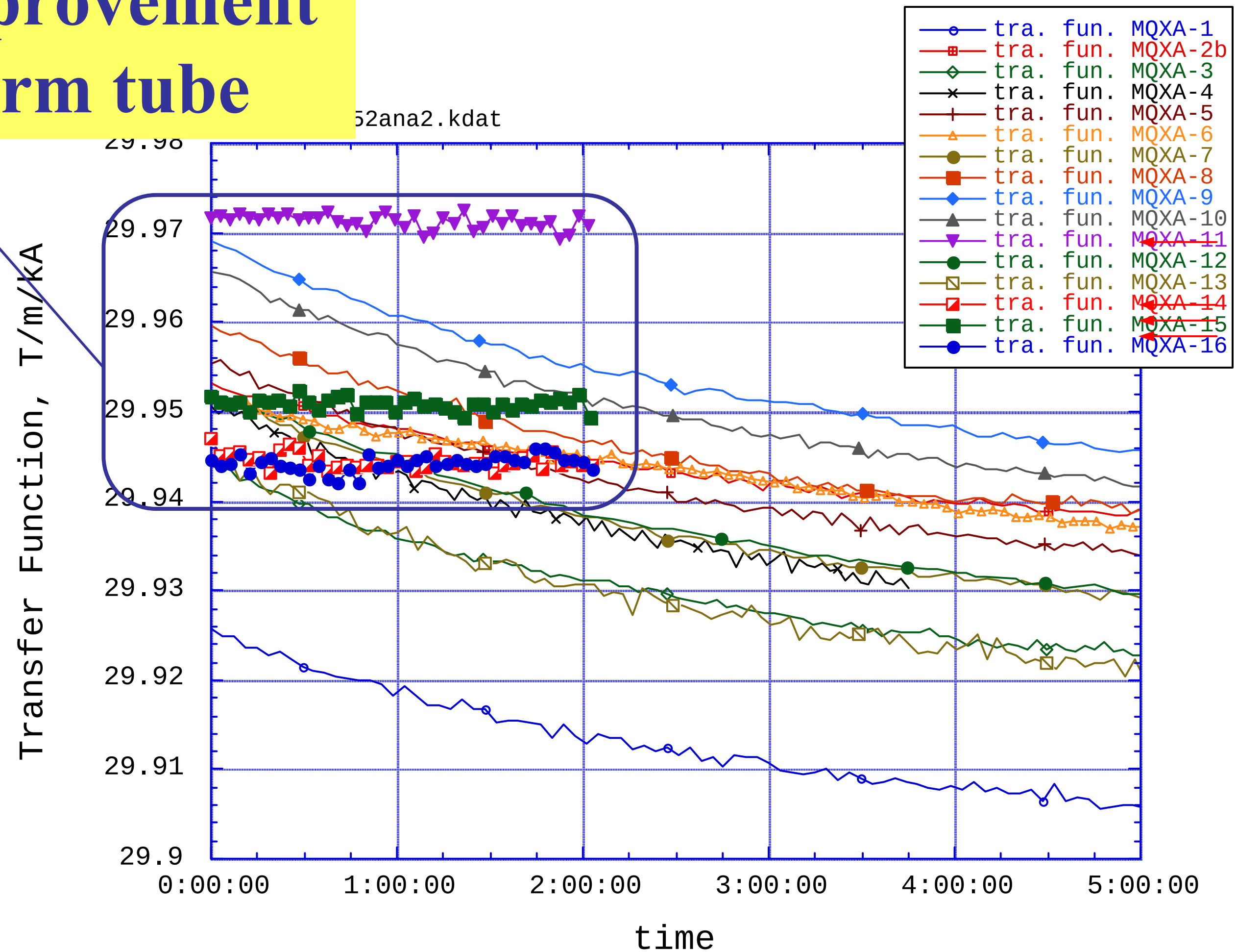
Training increased due to bore bent, & touched to the coil



Before Spacer installed → After

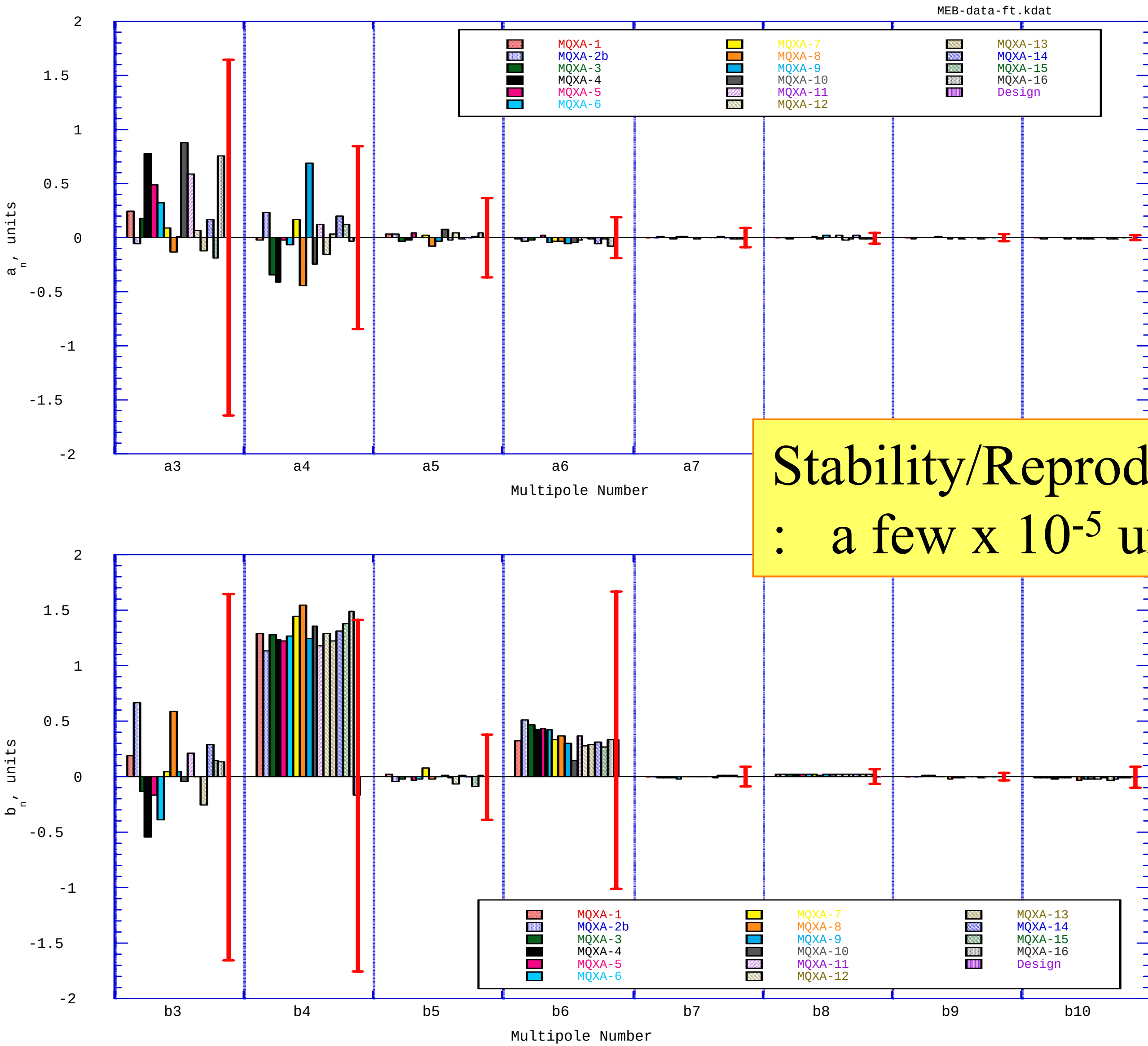
MQXA-1~16 transfer function as a function of time @216 T/m

After improvement of the warm tube



Harmonic components of MQXA-1~16

a_n



b_n

Stability/Reproducibility : a few x 10^{-5} units

+/- 1unit

Status and Plan

- All production and test to be completed in 2004.
  - 19 magnets completed at Toshiba,
  - 17 magnets tested at KEK,
  - 13 magnets delivered to Fermilab,
- Field Quality well under control.
- 18 production magnets to be delivered to Fermilab.

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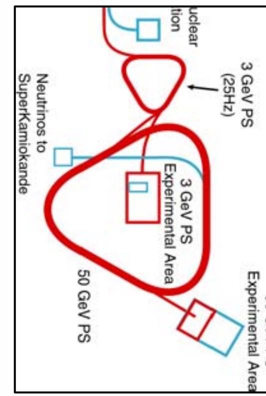
J-PARC Neutorino Beam Line with Superconducting Magnets

LOI: http://neutrino.kek.jp/jhfnu

ν_μ beam of ~1GeV



JAERI
(Tokai-mura)

Super-K: 50 kton
Water Cherenkov

~Mt "Hyper
Kamiokande"

0.75 MW 50 GeV PS

4MW 50GeV PS

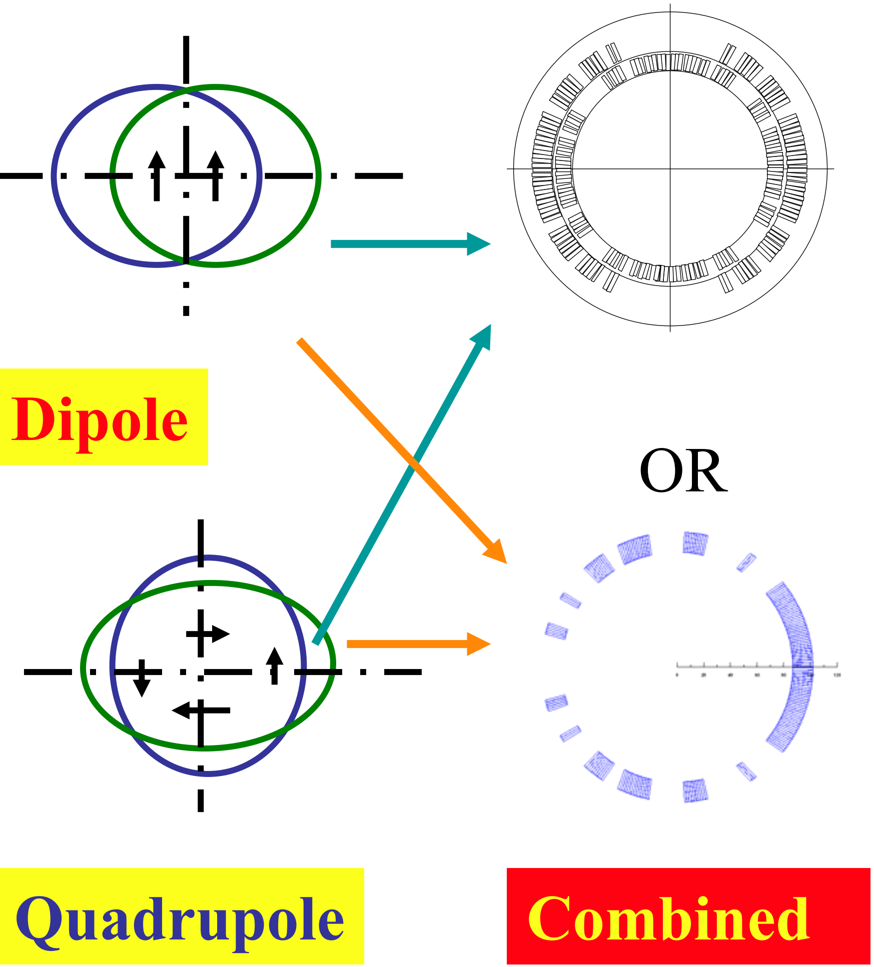
Approved exp ($\times 10^2$ of K2K)

A Challenge for SC beam line

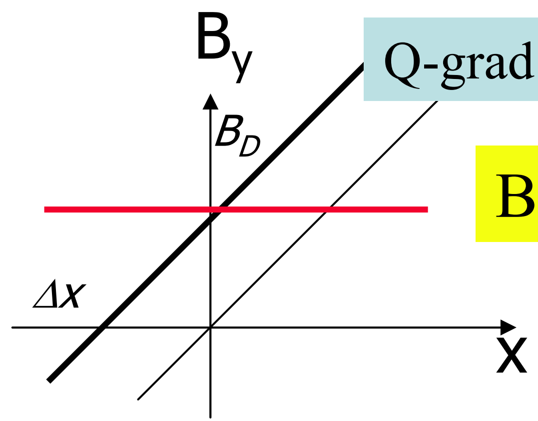
- Single component design with combined function magnet of dipole and quadrupole field,
- Single layer coil with left-right asymmetric current distribution, and plastic collar,
  - Learn BNL experience
- Use of experience at LHC Low-beta quadrupoles,

- Save construction cost to be equivalent to the conventional magnet option.

Concept of Combined Dipole Field with Quadrupole



$$B_y = B_D + Q_{\text{grad}} \times x$$
$$= Q_{\text{grad}}(x - \Delta x)$$
$$\Delta x = -\frac{B_D}{Q_{\text{grad}}}$$

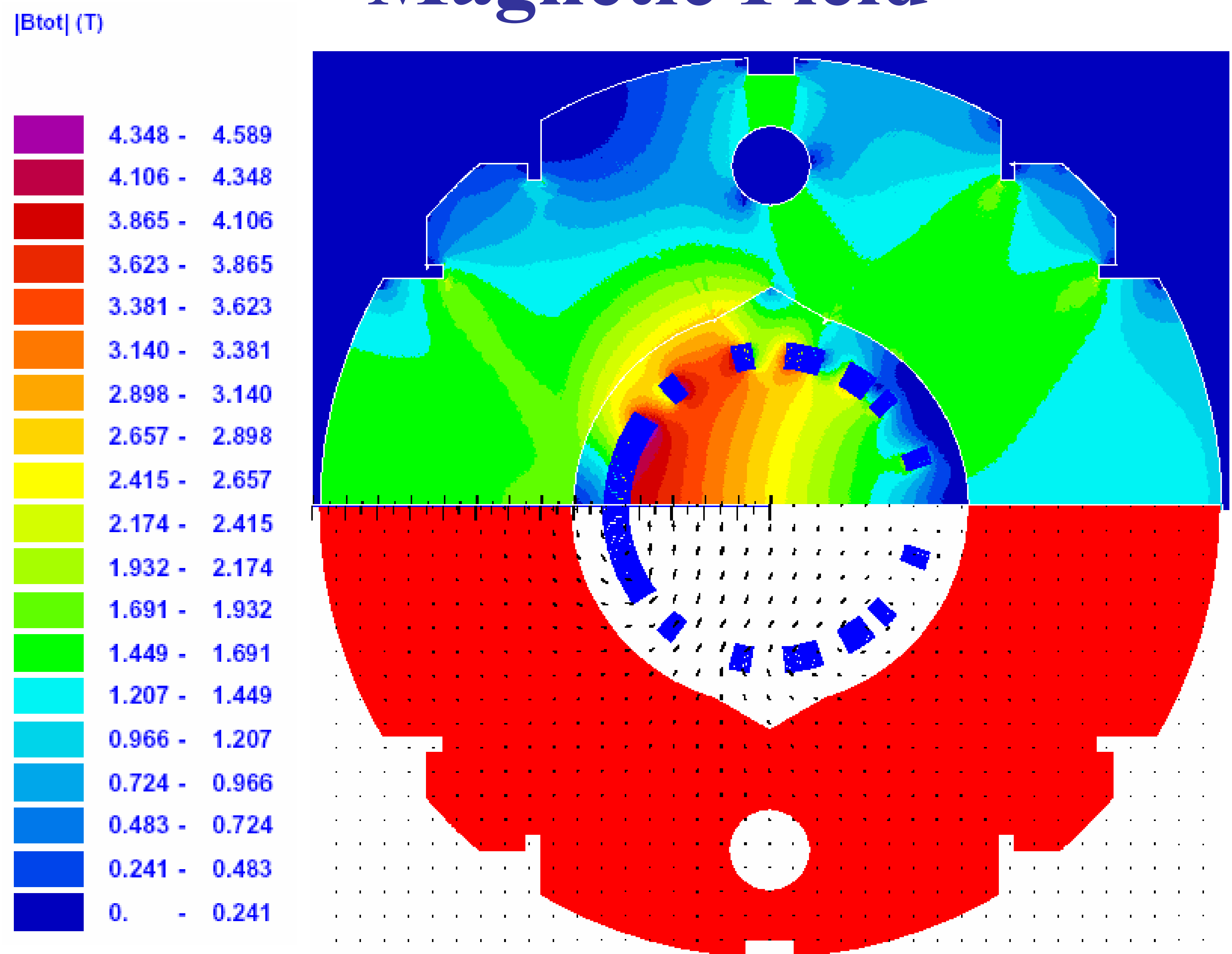


Q-grad = 19 T/m

B = 2.6 T

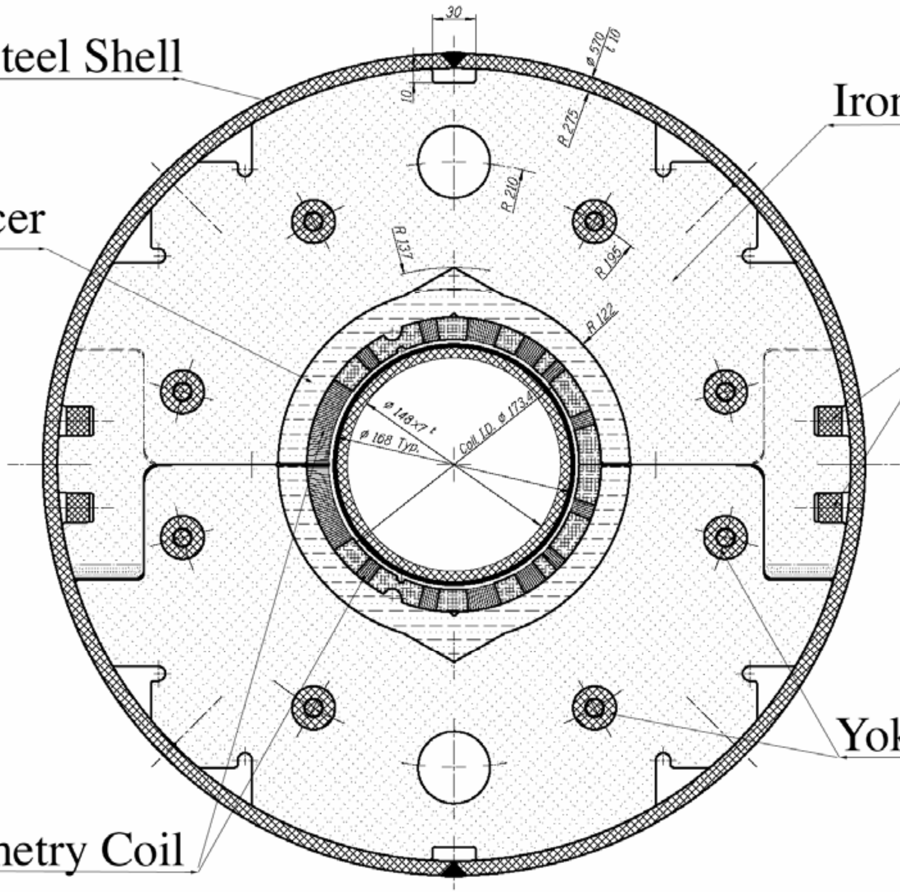
Peak Field: 4.2 T

Magnetic Field

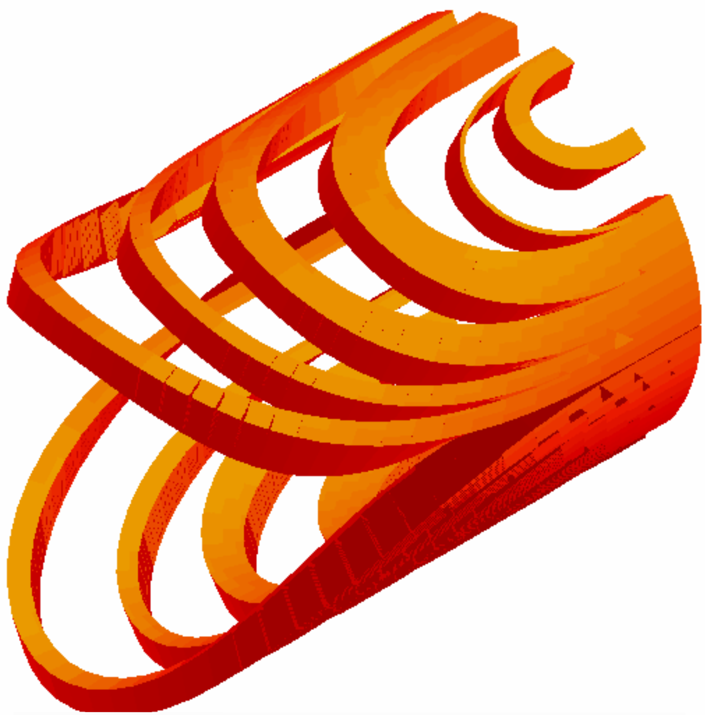


2D Design

- Dipole Field
  - 2.587 T
- Quad. Field
  - 18.62 T/m
- Inductance
  - 14mH
- Magnetic L
  - 3.3m
- Current
  - 7345A
- Stored E
  - 0.38MJ



End Design



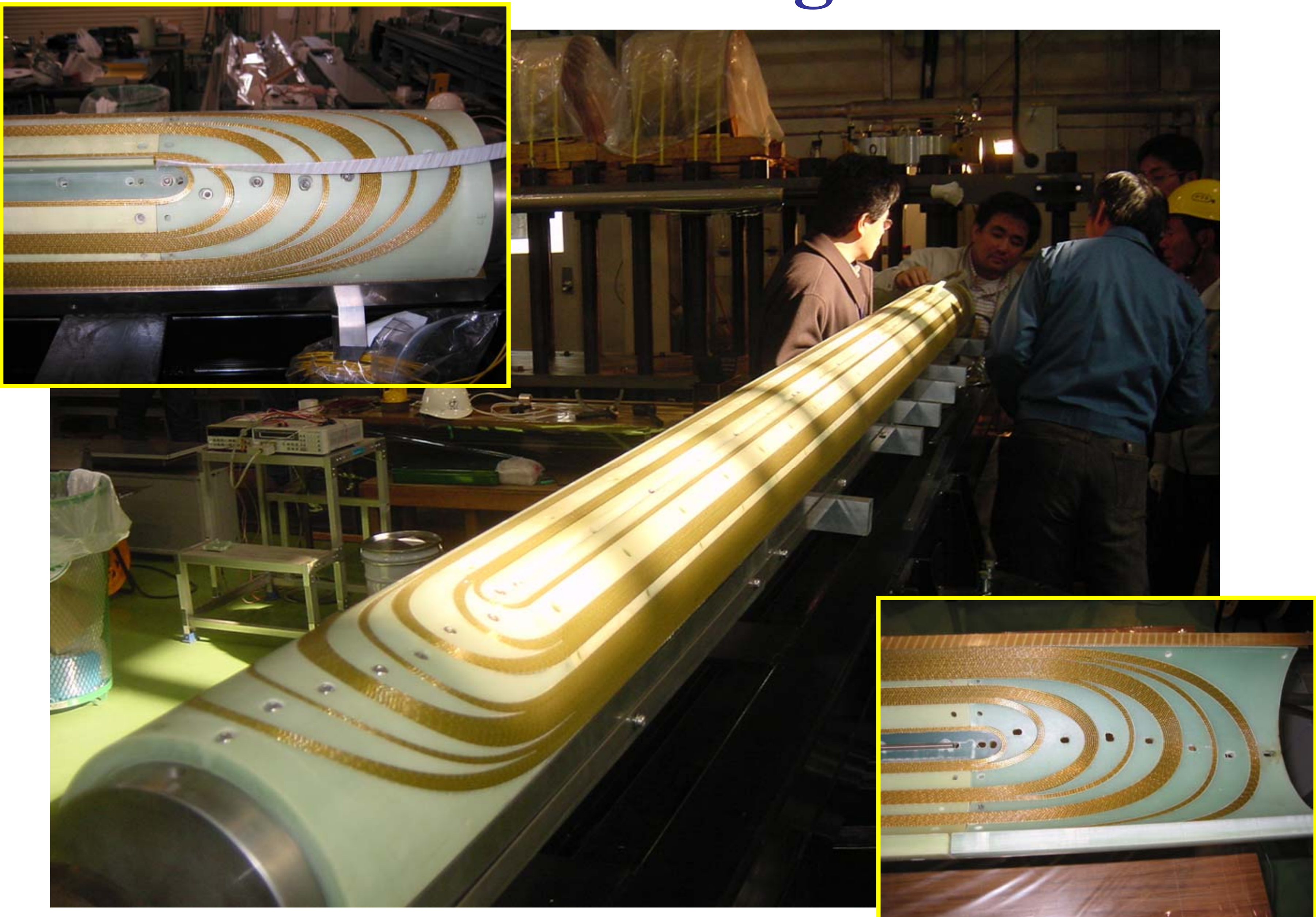
Left/Right Asymmetric
Coil End
⬆
Lead End & Return End
are same complexity

Thanks for ROXIE!

Trial Winding

QuickTimeý Ç²
DV/DVCPRO - NTSC êLí£ÉvÉçÉOÉâÉÄ
Ç™Ç±ÇÃÉsÉNÉ`ÉÉÇ¾å©ÇÈÇžÇ½Ç…ÇÕïKóvÇ-Ç□ÅB

Trial Winding Coil

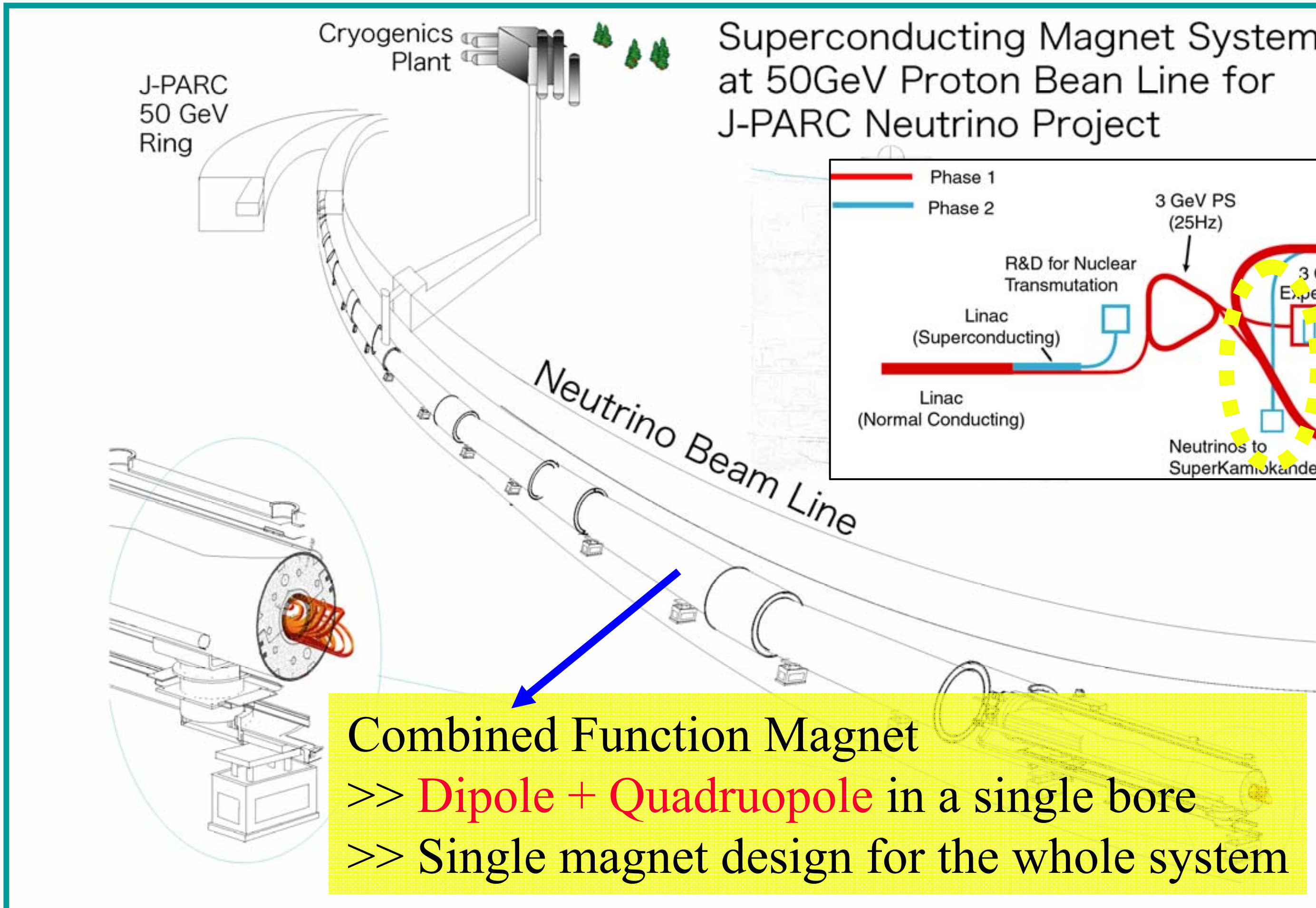


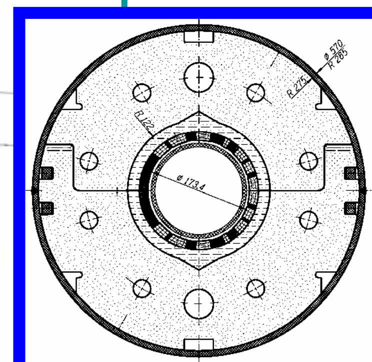
Trial Plastic Collar & Yoke

QuickTimeý Ç²
TIFFÅiLZWÅj êLí£ÉvÉçÉOÉâÉÄ
Ç™Ç±ÇÃÉsÉNÉ`ÉÉÇ¾å©ÇÈÇžÇ½Ç…ÇÕïKóvÇ-Ç□ÅB

Superconducting Magnet System for

50 GeV Primary Proton Beam





Combined Function Magnet
>> Dipole + Quadruopole in a single bore
>> Single magnet design for the whole system

B = 4.2 T, L= 3.3 m, 28 Magnets in String

Construction Schedule

FY	2004	2005	2006	2007	2008
Magnet	1	6	12	12	2
Cryostat		3	6	6	2
Mag. Install				8	6
Cryogenics			Purchase	Install	
PS etc			Purchase	Install	
Commission				with half magnets	with full magnets

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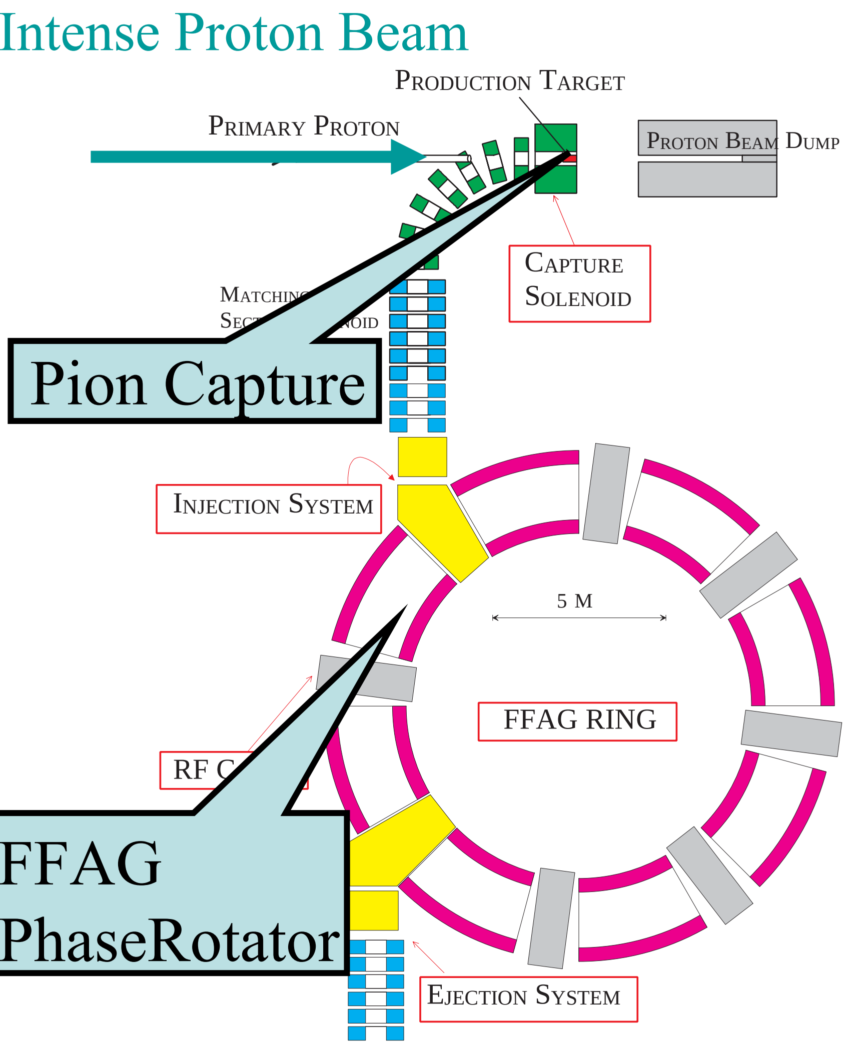
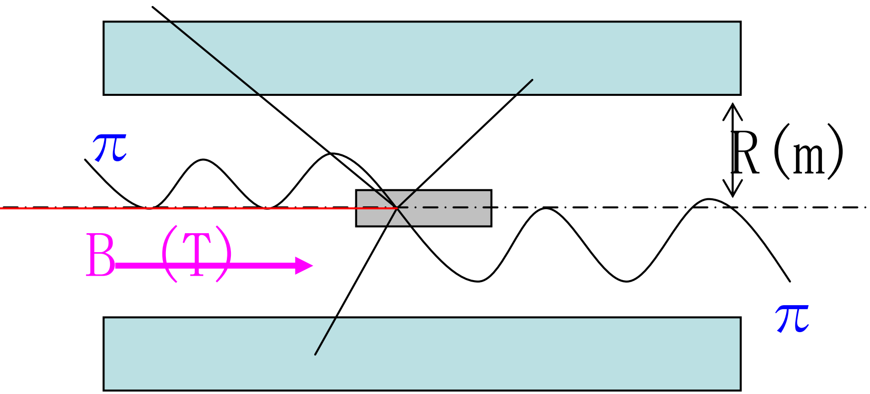
What’s PRISM



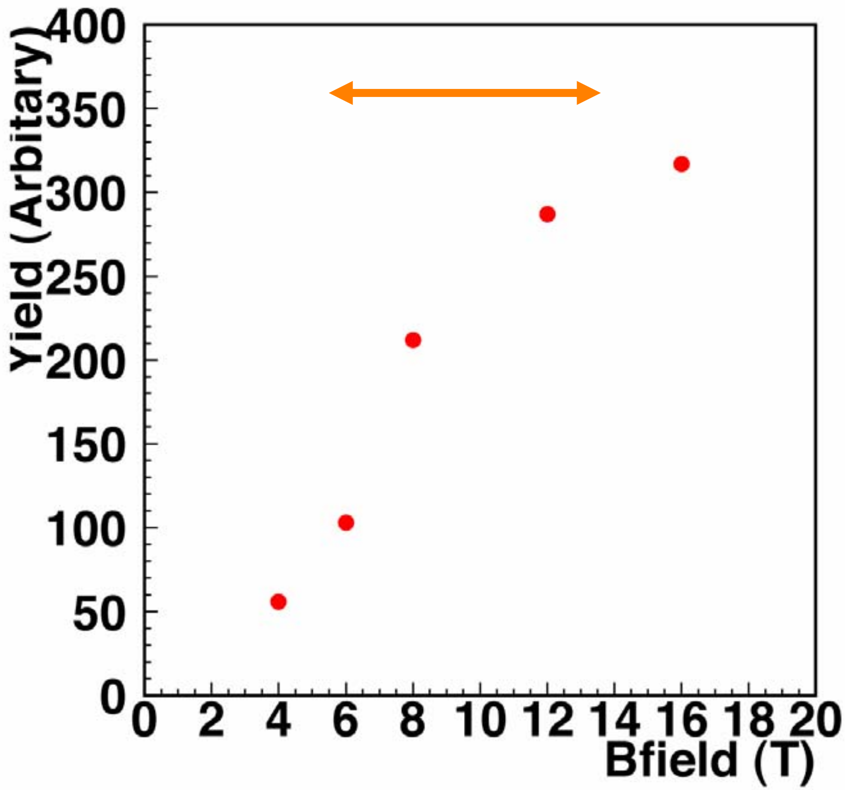
- PRISM
  (Phase Rotation Intense Slow Muon source)
- A dedicated secondary muon beam channel
  - high intensity (10^{11}~10^{12} μ/s)and
  - narrow energy spread(a few%)
    for stopped muon experiments
- Search for Lepton Flavor Violation

High Field Pion Capture

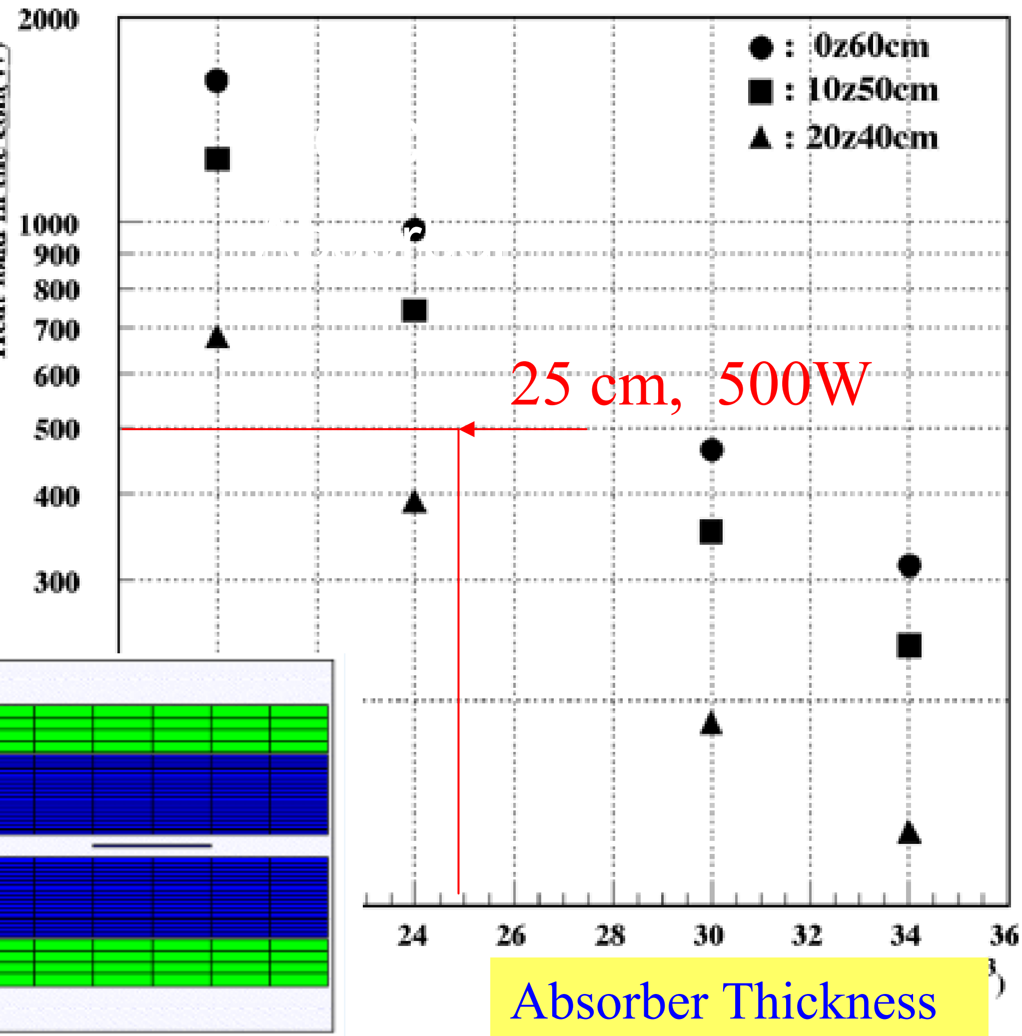
- Pion Momentum
  - ~100 MeV/c
  - **backwards** capture scheme available!
  - **(6) ~12 Tesla** field to confine within □ Φ 10cm bore



$$Pt < 0.3BR$$

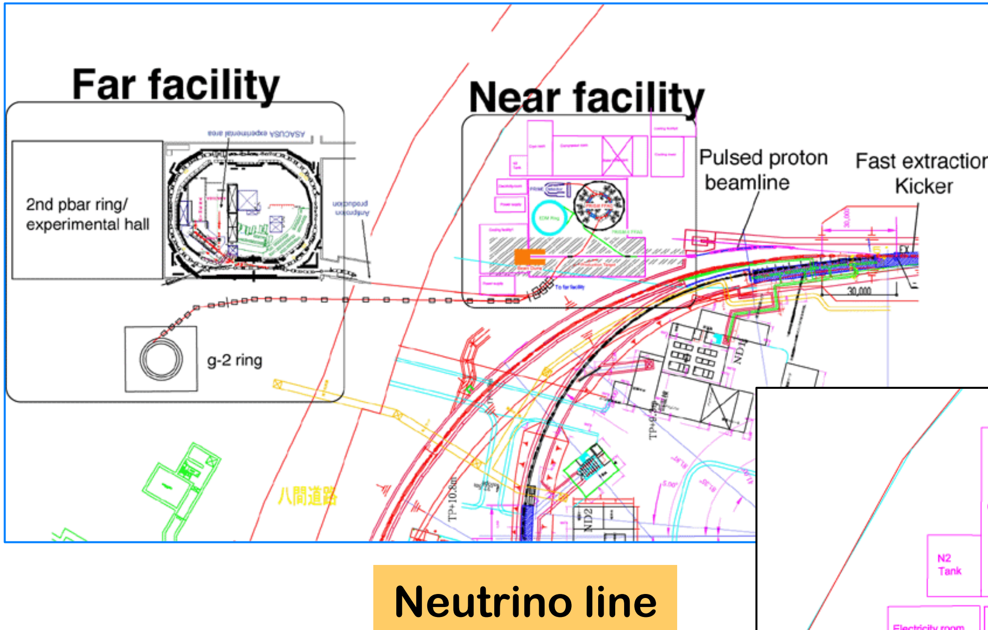


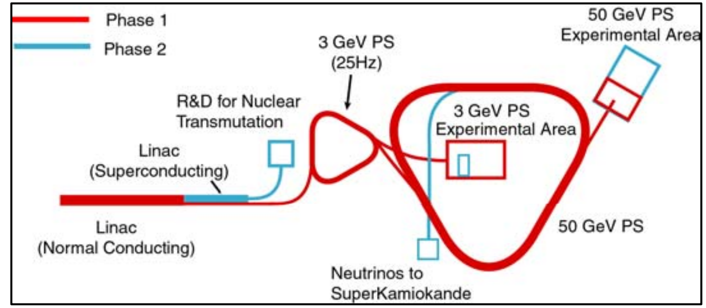
SC Solenoid in High Rad. Env

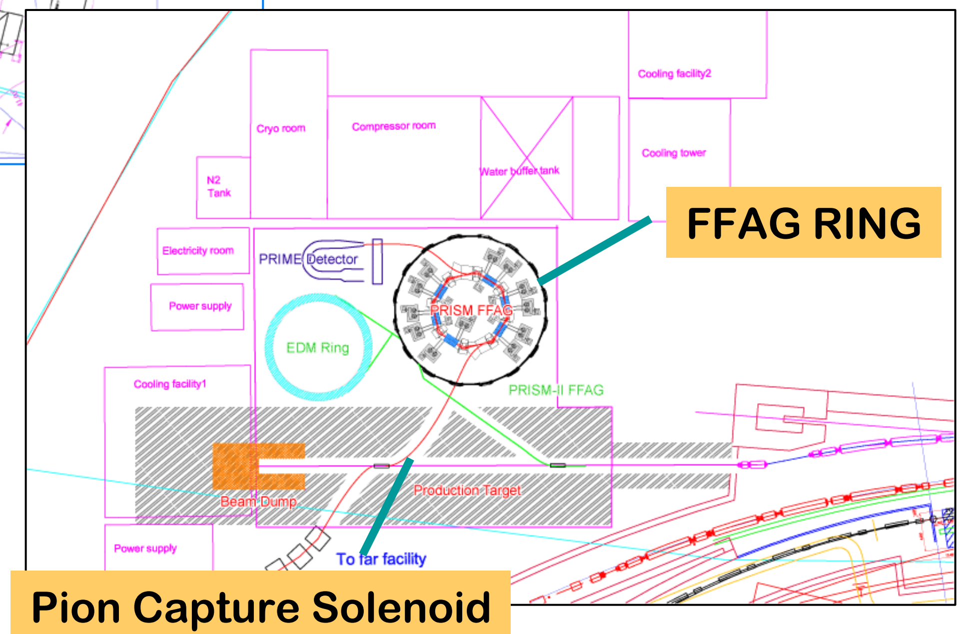


- Thick absorber required
  - Thickness ~ > **25 cm**
  - Still, **~500 W**
- Large coil-bore
  - R coil = **~ 0.5 m**
  - Stored Energy = **10 $^{7\sim8}$ J**
- Coil design to be optimizee
  - **Simulations need to be experimentally evaluated!**

J-PARC PRISM Pulsed Beam Facility







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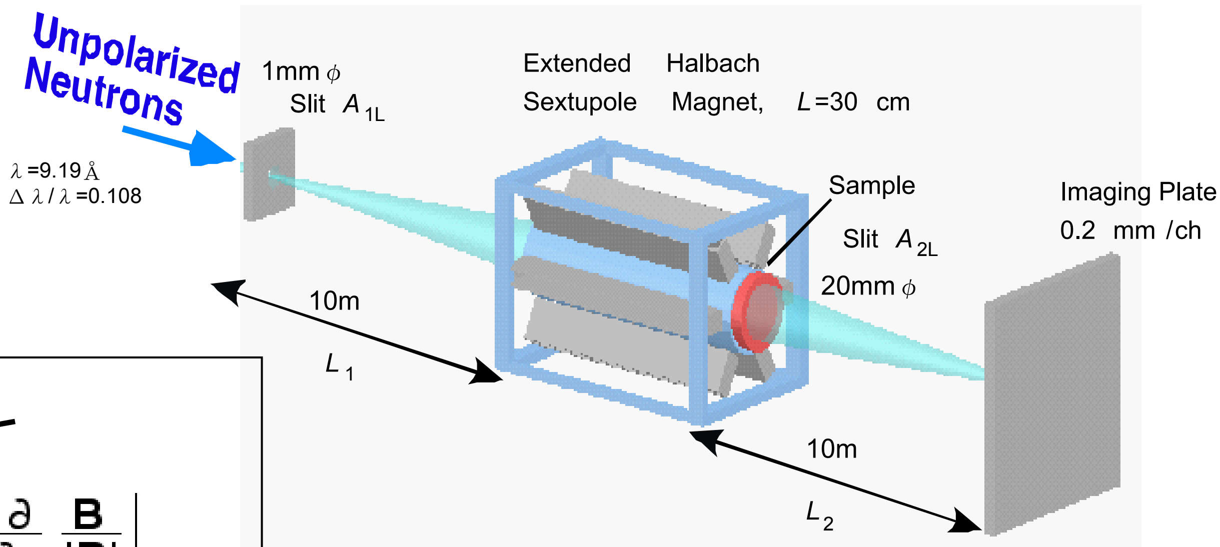
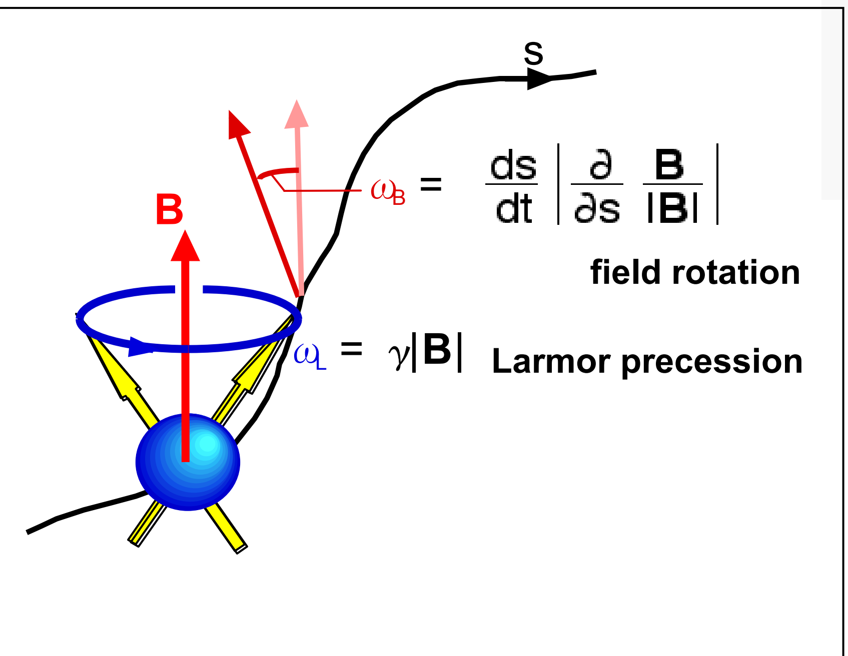
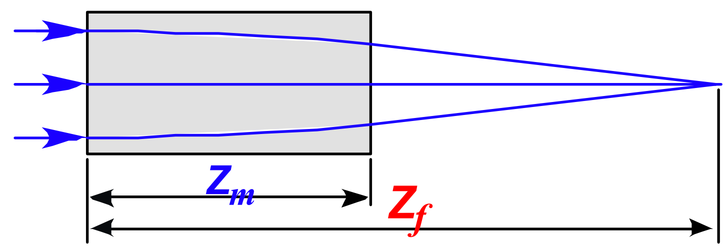
Neutron-beam Focusing by using Sextupole Field





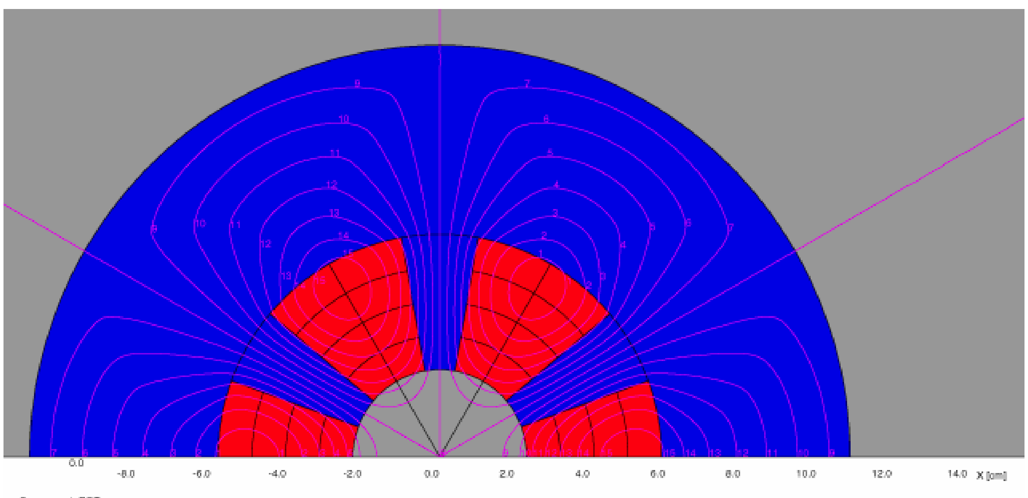


$$Z_f = Z_m + \frac{h}{\sqrt{G\alpha m_n}\,\lambda}\cot\left(\frac{\sqrt{G\alpha m_n}\,\lambda}{h} Z_m\right)$$

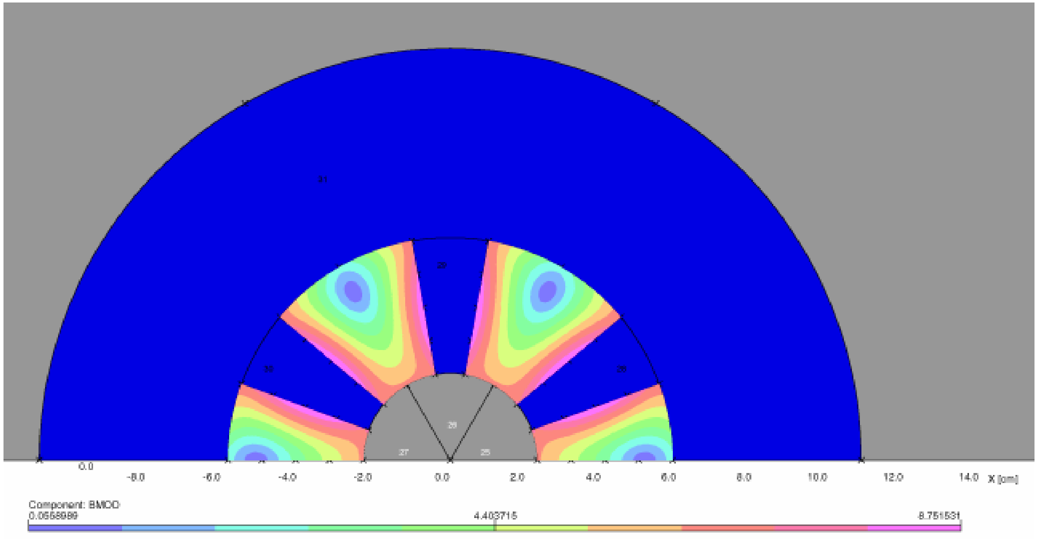
R&D of Nb_3Sn Sextupole Magnet

Main parameters

Sextupole field	**12,780 T/m^2**
Max. field in winding	**8.75 T**
Current	1000 A
Av. Current density in winding	**580 A/mm^2**
Coil IR	23.0 mm
OR	58.8 mm
Length	500 mm
Stored energy	98 kJ

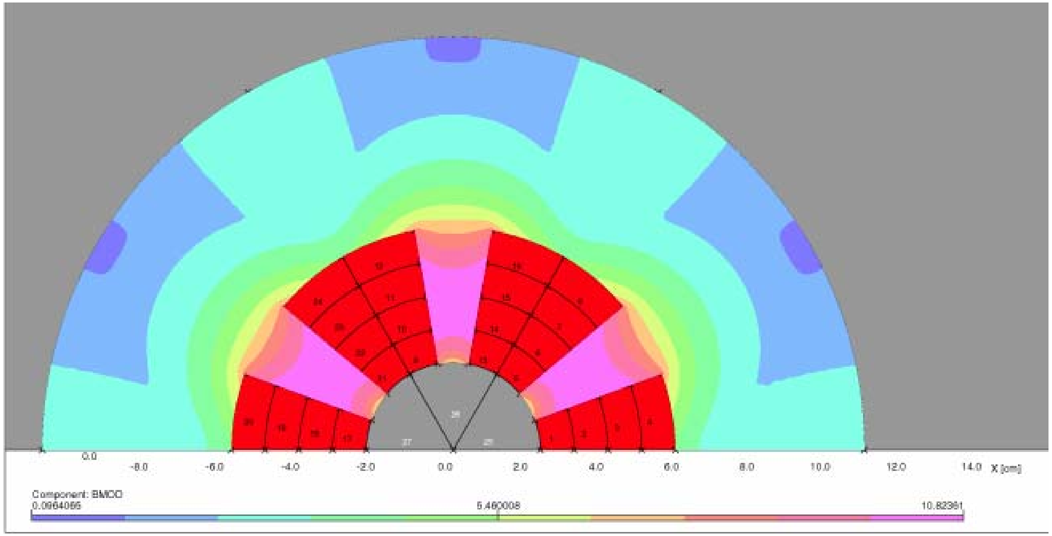


Field strength



Max. field in the coil

8.75 T



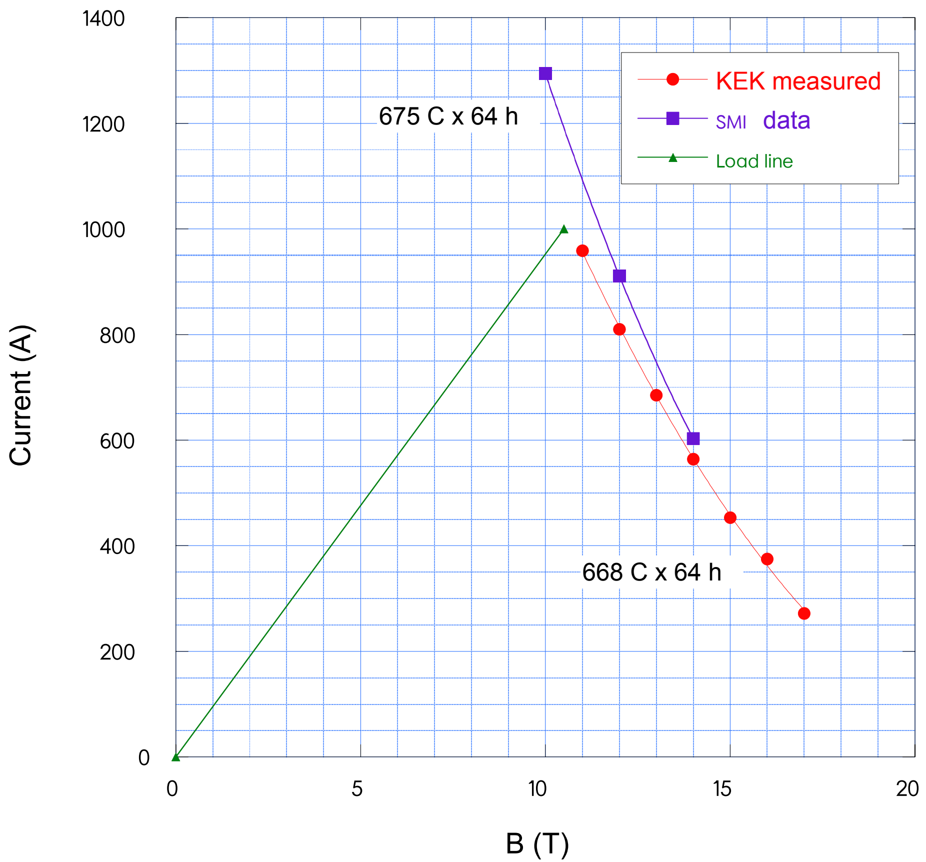
Max. field in the iron

10.8 T

Nb_3Sn conductor (SMI)

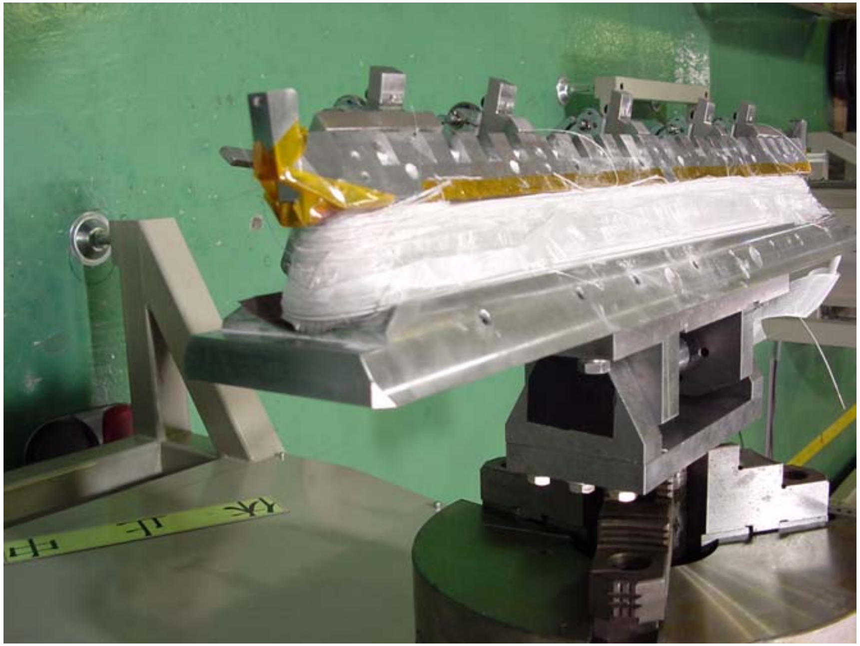
Wire dia. **1.00 mm**
Copper ratio **45.3 %**
No. Filaments **192**
Filament pitch **25 mm**

Insulation **T-glass**
75 μm x 2



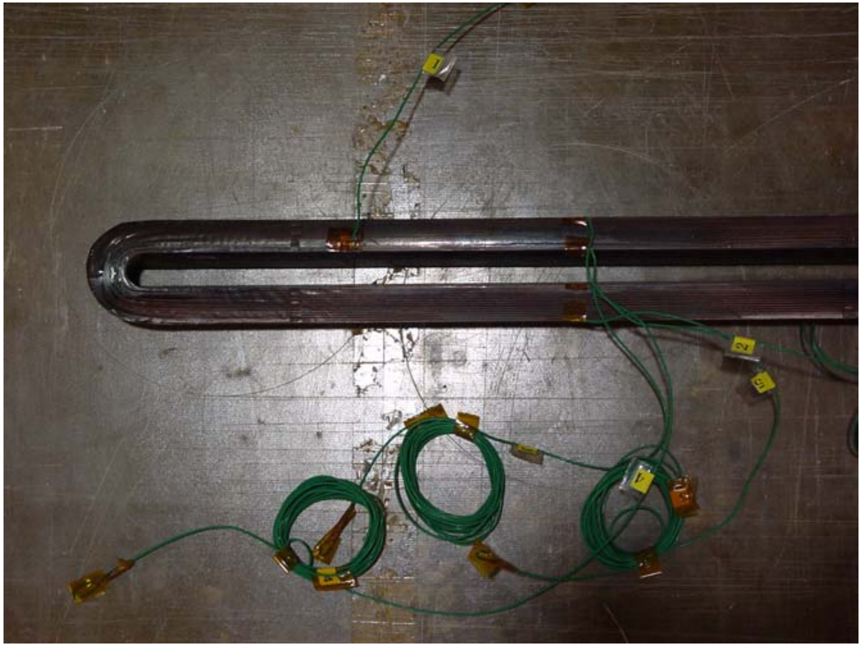
R&D of the Nb_3Sn coil

Winding
Insulation: T-glass

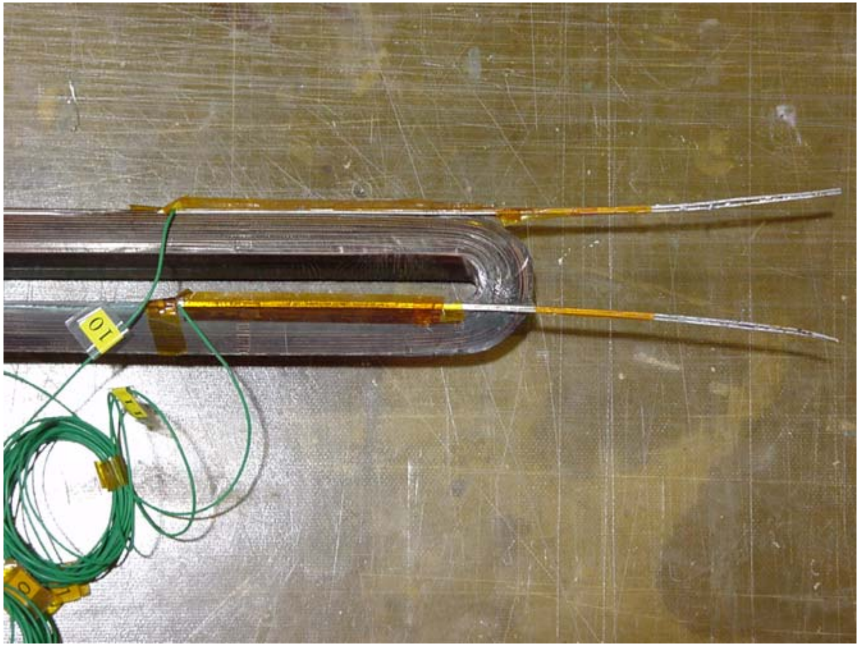


After the HT

R&D of the Nb_3Sn Coil



Return end



Lead end

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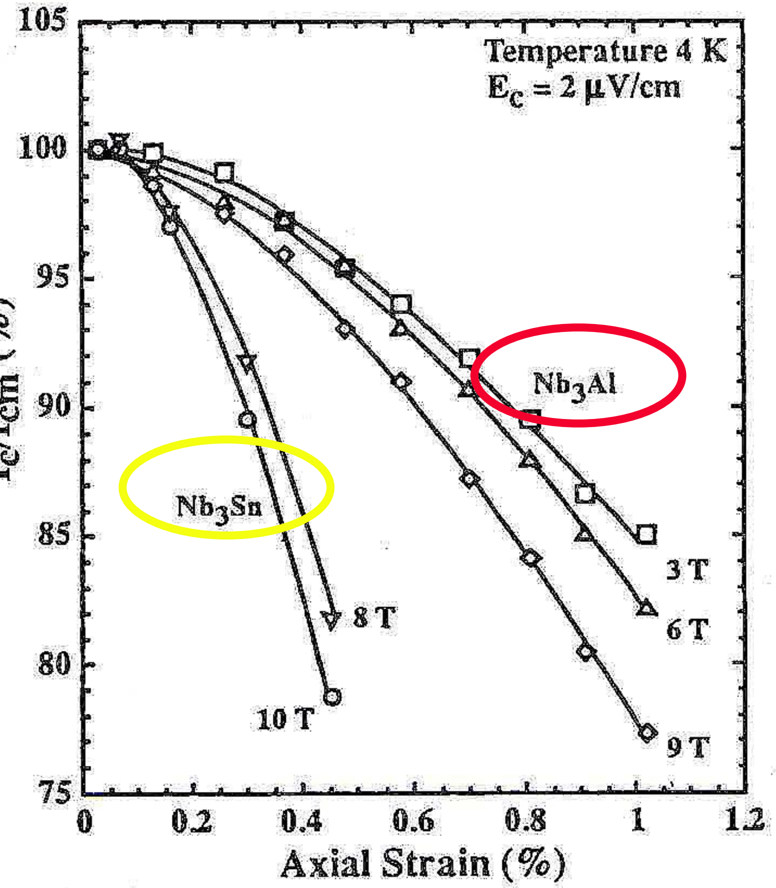
Nb3Al for Future High Field Conductor

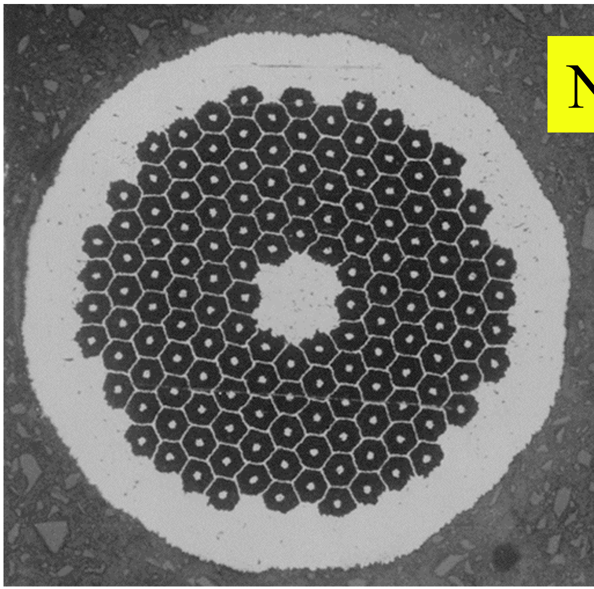


- Mechanically more stable than Nb3Sn
- Technical progress with a novel Rapid Quenching process developed at NIMS (Acknowledged!!)
- **Jc** @ ~ 12 T to be improved,
- **Stabilizer** required with a cost-effective method

Development of Nb_3Al in Cooperation with NIMS

- **Motivation**
  - Nb_3Al conductor for acceleratos
    - High field dipoles,
    - Pion capture solenoid,
- **Target**
  - J_c = 2,000 A/mm^2 @ 10 T
  - Subject to be solved
    - Stabilizer (to be discussed by Dr. Takeuchi)
- **Cooperation** with NIMS
  - Nb3Al being developed for high field NMR magnet

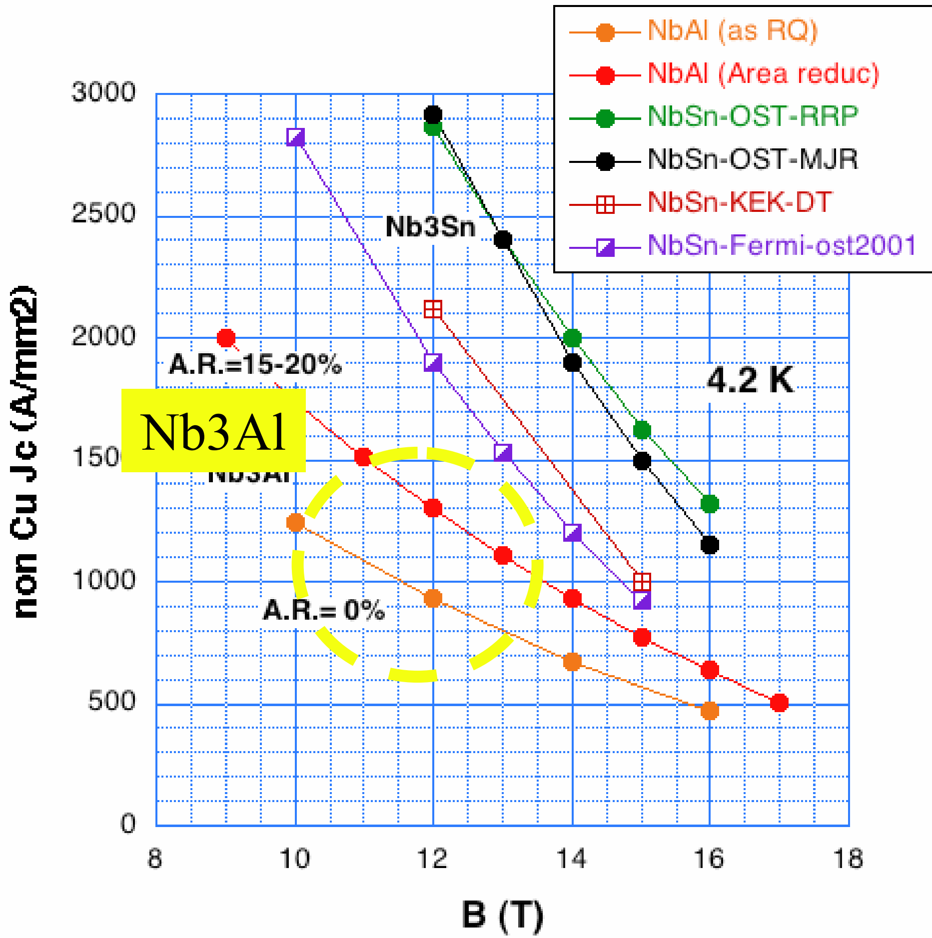
Nb3Al and NB3Sn Conductor Progress



Nb3Al

K. Tsuchiya et al., presented at MT-18.

White: Nb
Black: Nb3Al
(no Cu)



Large Superconducting Magnet System at TML

innermost coils

(cold bore: 13 mm$^{\varnothing}$)

Nb_3Al (RHQ)

22.5 T

Bi-2212 double-pancakes

23.4 T

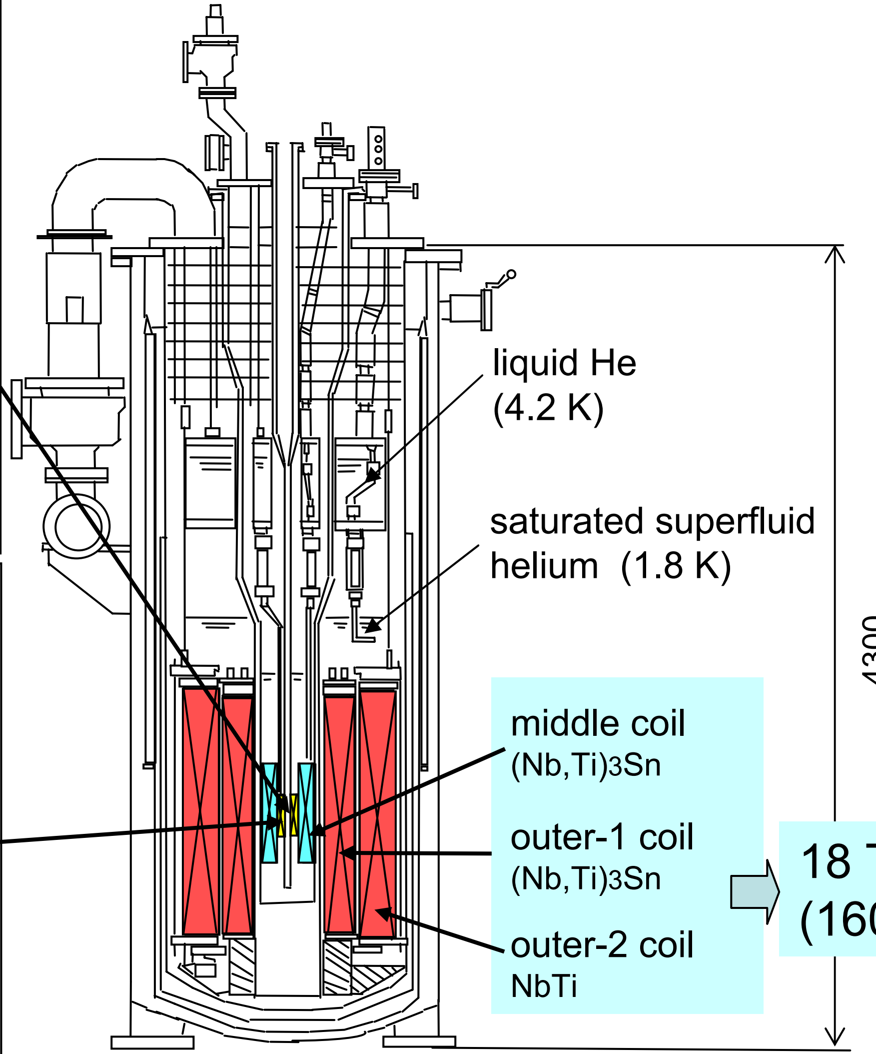
inner coils (cold bore: 61 mm$^{\varnothing}$)

$(Nb,Ti)_3Sn$ (bronze-route)

21.7 T

Bi-2212 double-pancakes

21.4 T



18 T
(160mm$^{\varnothing}$)

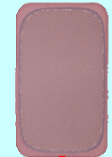
High-Field NMR Magnets at TML

Superconductors Developed by TML

Large-Current Nb3Sn A
(15 wt%Sn in bronze)

High-Strength Nb3Sn (Ta reinforced)

Large-Current Nb3Sn B
(16 wt%Sn in bronze)
***Jc*: 23 % higher than A**



Operated at the World's Highest Field of High-Resolution NMR magnets
21.6 T (920 MHz)
with
Extraordinary Field Stability
(0.31 Hz/h without lock system)

2nd Spectrometer

Solution NMR
for Structural Biology
in Collaboration with
RIKEN and JEOL

Protein Data Bank
registered: 3
analyzing: 5

Solid-State NMR
Catalyst
Steel Making Process
Fuel Cell

Further Plans for Nb_3Al

- Near Term Efforts to reach **higher Jc**:
  - **Nb/Nb_3Al** Ratio: 1 --->> 0.6
  - No. of **Filaments**: 144 --->> 200~250
  - Filament size: 50~60--->> 40 micron
- Long Term Efforts (Optimization @ **B = 10 ~ 20 T**)
  - **Nb/Al** ratio: ~3:1 --->> ~ 4:1
  - **Less hardening**: Advantage in low field
  - **Grain size**: smaller
- Possible candidate for applications:
  - PRISM pion capture solenoid,
  - Dipoles and/or solenoid magnet ~ 5 years,

Summary

- **LHC/IRQ** development program at KEK being complete,
- **J-PARC** neutrino beam line project launched.
  - The primary proton beam line to be constructed by using combined function magnets in coming 5 years.
- **Basic R&D** and/design studies of high field magnets being carried out for the high field superconducting magnet, such as pion capture solenoids and neutron optics sextupole,
- **Nb_3Al** development still to be progressed for future applications.

Magnetic Optics

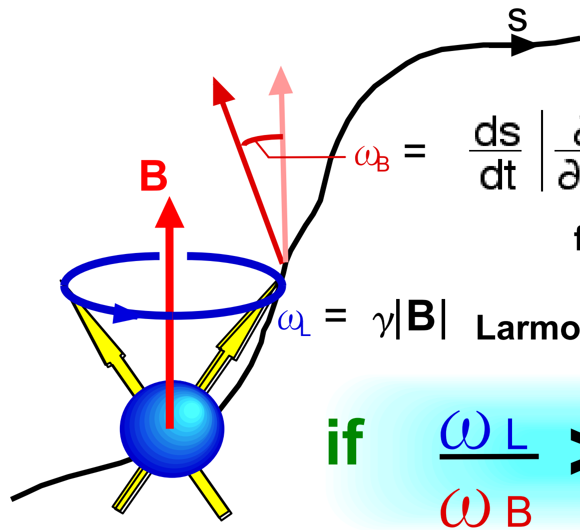
Neutron motion in B field

$$\frac{d\mu}{dt} = \gamma\, \mu \times B \quad \text{Larmor precession}$$

$$m\frac{d^2r}{dt^2} = \nabla(\mu \cdot B)$$

neutron spin "polarity"

positive	negative
parallel	antiparallel
B spin	B spin



$$\omega_B = \frac{ds}{dt}\left|\frac{\partial}{\partial s}\frac{B}{|B|}\right|$$

field rotation

$$\omega_L = \gamma|B| \quad \text{Larmor precession}$$

$$\text{if} \quad \frac{\omega_L}{\omega_B} >> 1$$

spin "polarity" conserved

positive polarity

$$\frac{d^2r}{dt^2} \pm \left|\frac{\mu}{m}\right| \nabla|B| = 0$$

negative polarity

sextupole field case

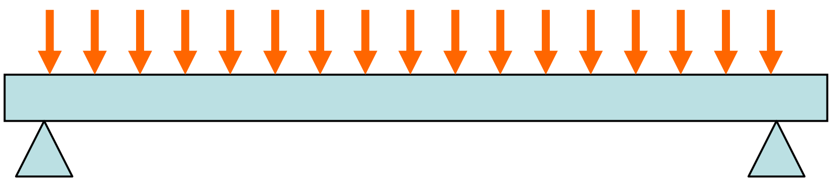
$$|B| = C(x^2+y^2)/2$$

$$\frac{d^2x}{dt^2} = \mp\omega^2 x$$

$$\frac{d^2y}{dt^2} = \mp\omega^2 y$$

$$\omega^2 = |C\mu/m|$$

Magnetic Force to Bore Tubes



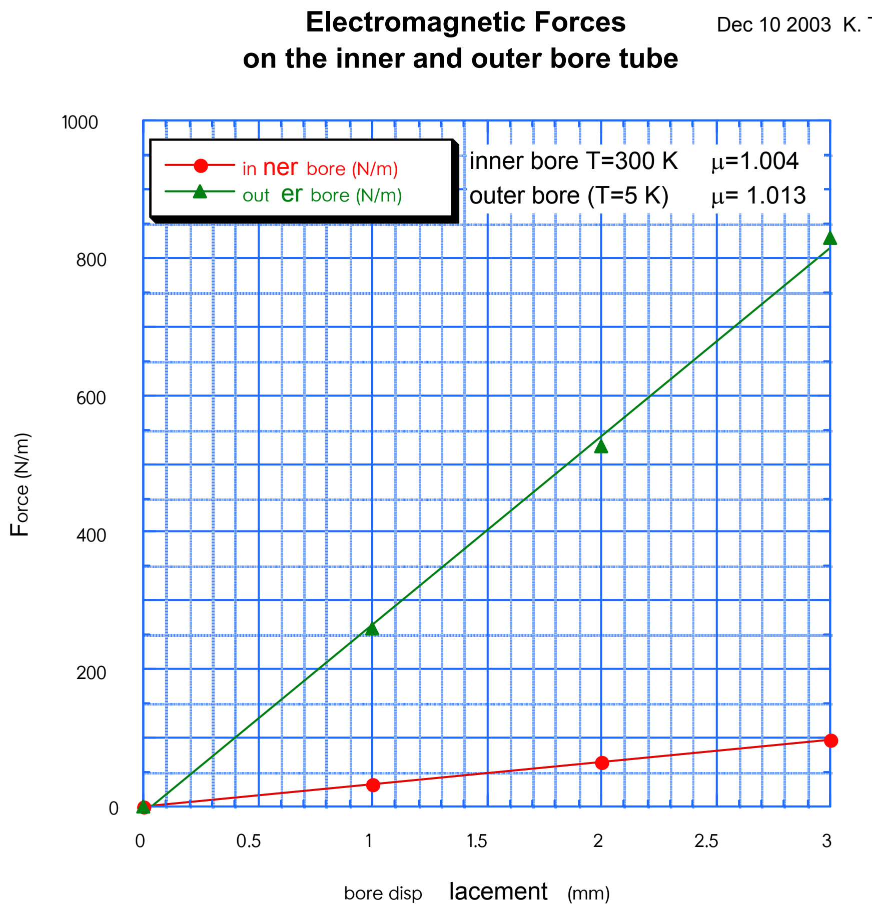
V＝5・w・L＾4／（384・E・I）

w：force (kgf/mm)

V：displacement (mm)

E：Young's modulus (kgf/mm^2)

I ＝π＊(OD^4－ID^4)／64 (mm^4)



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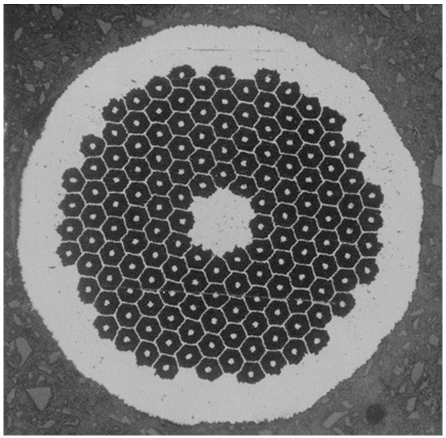
KEK

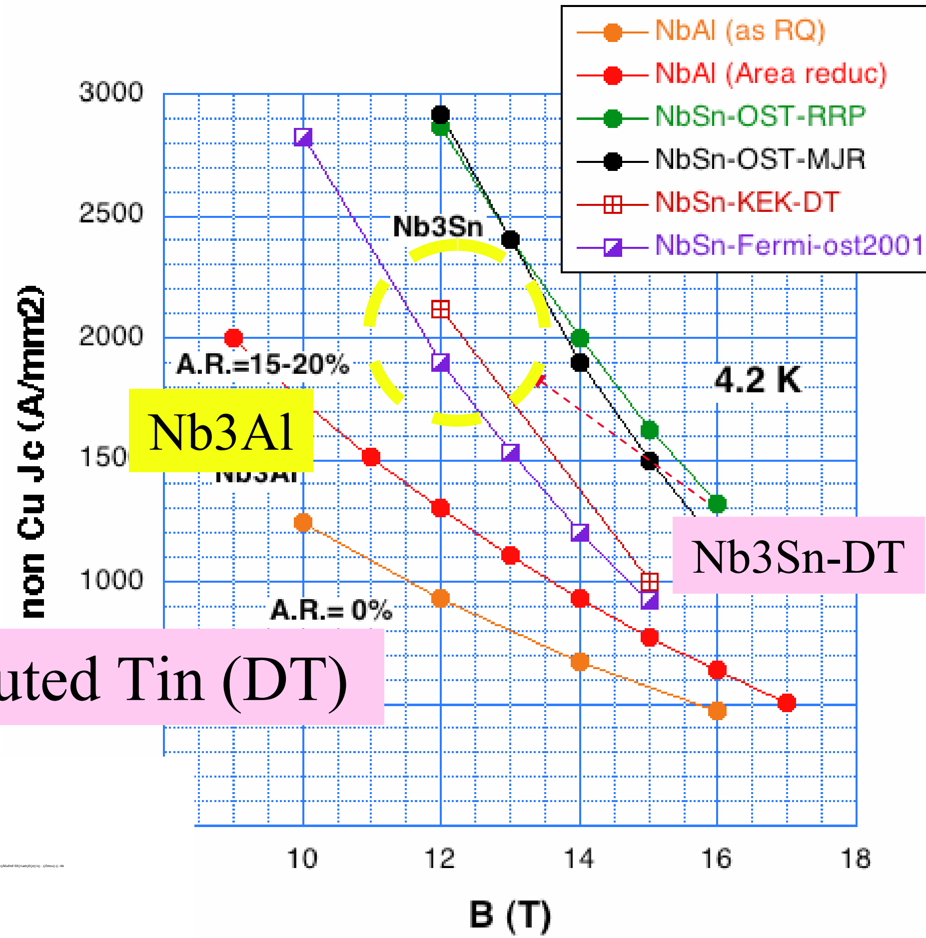
Nb3Al and NB3Sn (DT) Conductor Progress



Nb3Al

White: Nb
Black: Nb3Al
(no Cu)

K. Tsuchiya et al., presented at MT-18.



Nb3Al

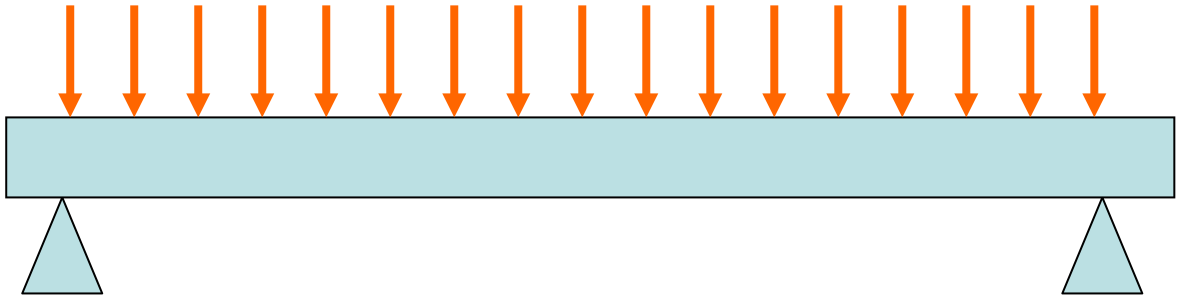
Nb3Sn-DT

Distributed Tin (DT)

QuickTimeý Ç² TIFFÅìà□èkÇ»ÇµÅj êLí£ÉvÉçÉOÉâÉÄ Ç™Ç±ÇÃÉsÉNÉ`ÉÉÇ¾â©ÇÈÇžÇ½Ç...ÇÕìKóvÇ-Ç□ÅB

M. Wake et al., ICMC-2003

Bore Tube Bending Due to Magnetic Force



Ｖ＝５・w・Ｌ^４／（３８４・Ｅ・Ｉ）

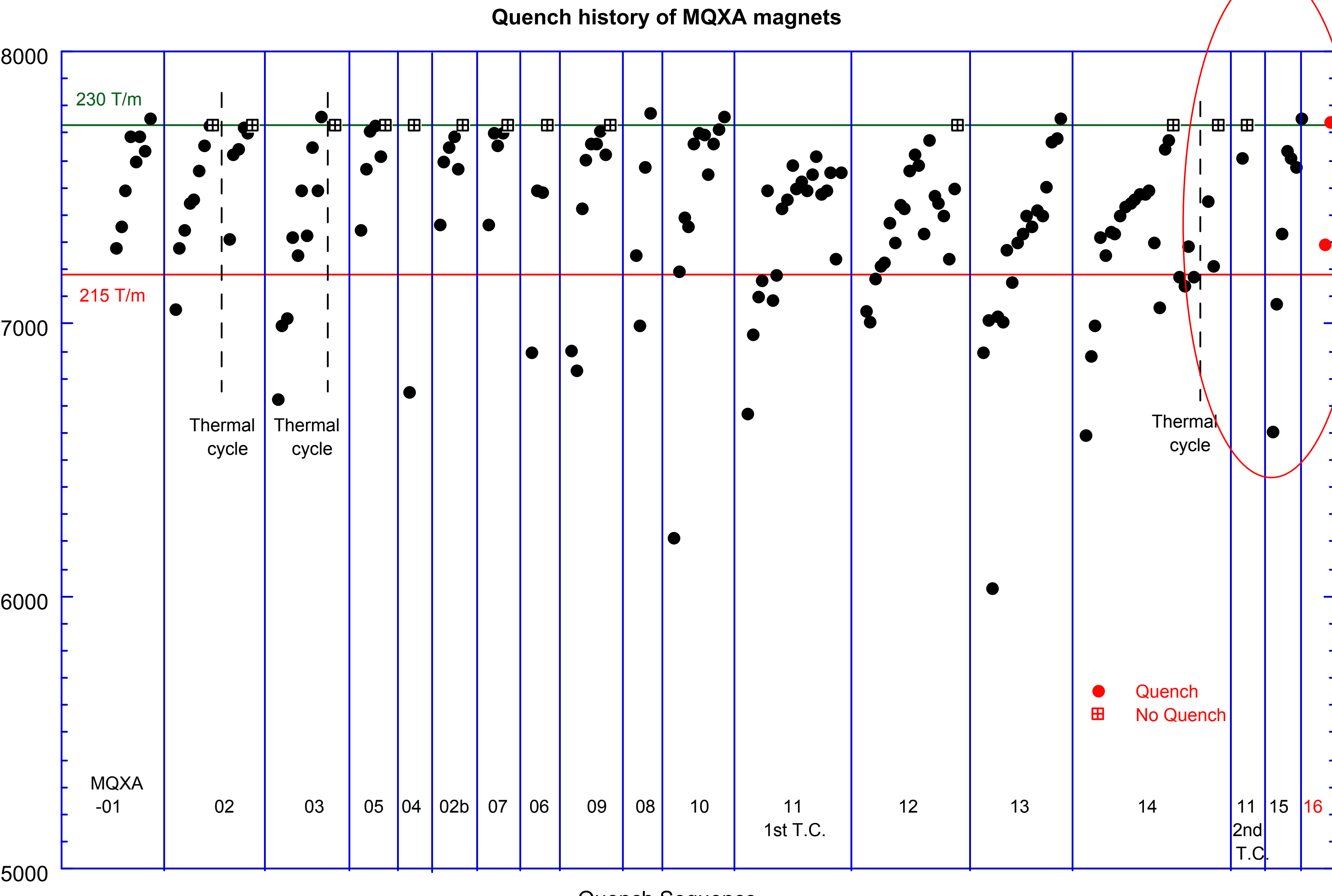
w：force (kgf/mm)

V：displacement (mm)

E：Young's modulus (kgf/mm^2)

Ｉ＝π＊(OD^4－ID^4)／64 (mm^4)

Training History of MQXA



Cross Section of Magnet Cryostat

R 239

9.2

Corrector Coils

Compensation Solenoid

R 69

6 layer coils

(3-double pan cakes)

Inner radius : **90 mm**

Field gradient =**36 T/m** @1134A

Max. field in the coil = **3.74 T**

Effective magnetic length

QCSR(L) = 0.333 (0.398) m

I_{op}/I_c = 68 % @ 4.7 K

Field quality (@ r=55mm)

b_2=10000, $\boldsymbol{b_6}$**=0.16**, $\boldsymbol{b_{10}}$**=0.61**