Superconducting Quadrupole Magnets for the LHC Low-Beta Insertions

Tatsushi NAKAMOTO

KEK/CERN

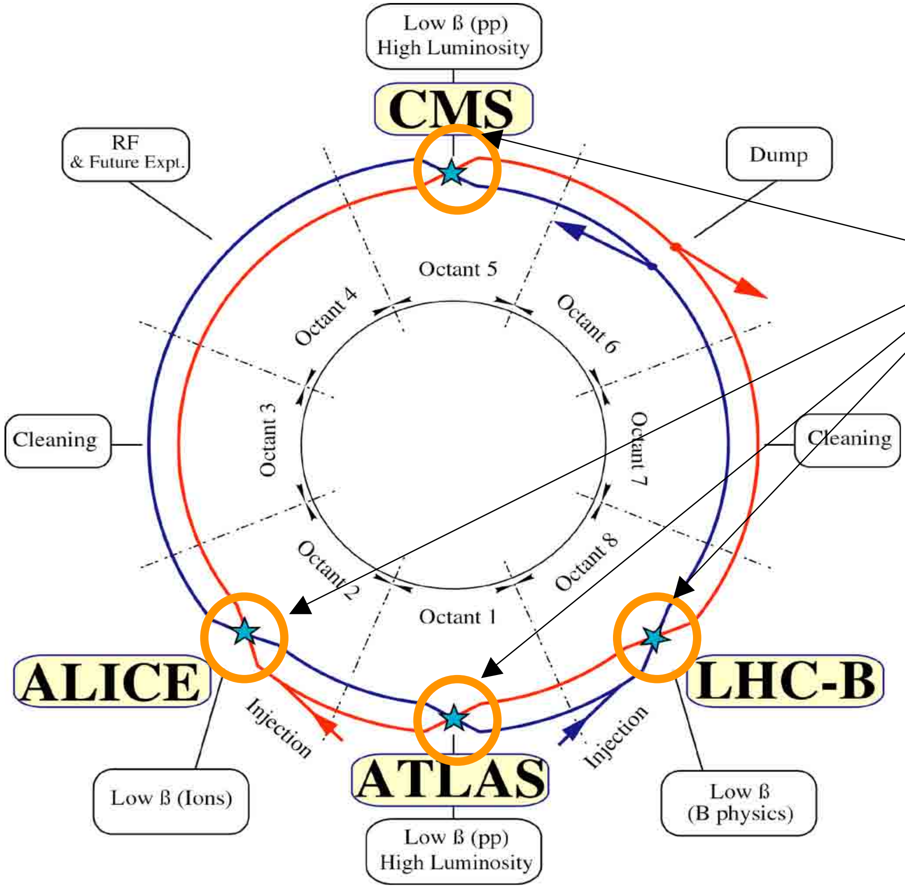
Outline

- LHC Experimental Insertions
- MQXA Development
  - R&D Work
  - Production
  - Measurement
  - Problems and Actions
  - Summary of MQXA
- MQXB Development
- Other Insertion Elements
- Current Status of LHC Insertions

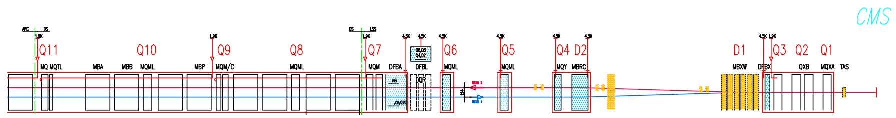
LHC and Experimental Insertions

Circumference: 27 km
Injection Energy: 450 GeV (p)
Collision Energy: 7+7 TeV
Peak Luminosity: 10^{34} cm^2/sec

*** 450 GeV beam commissioning anticipated in Nov. 2007.**



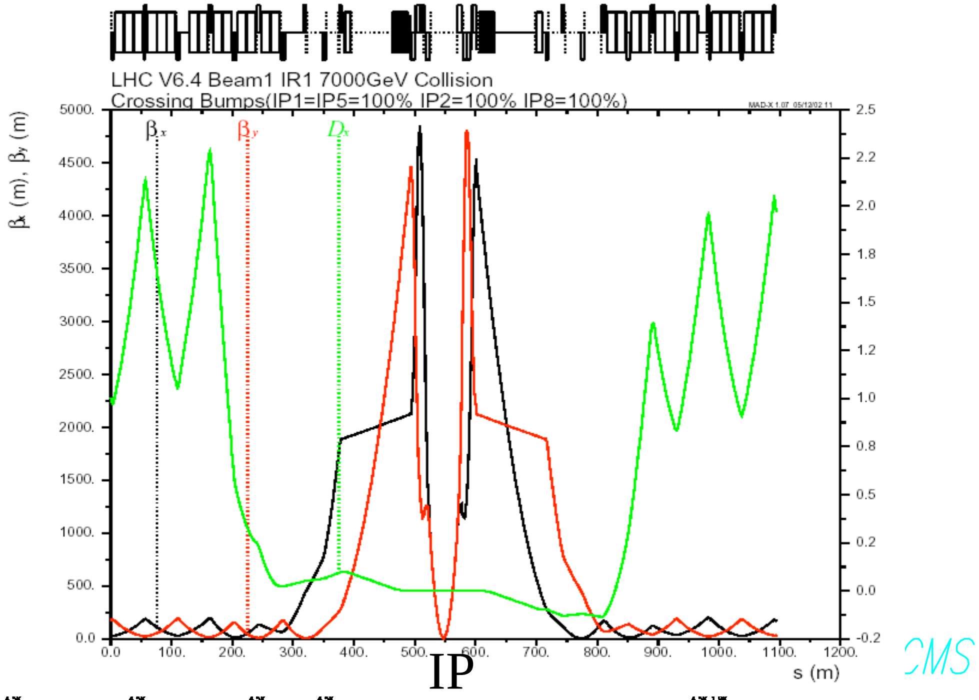
2*4 Experimental Insertions

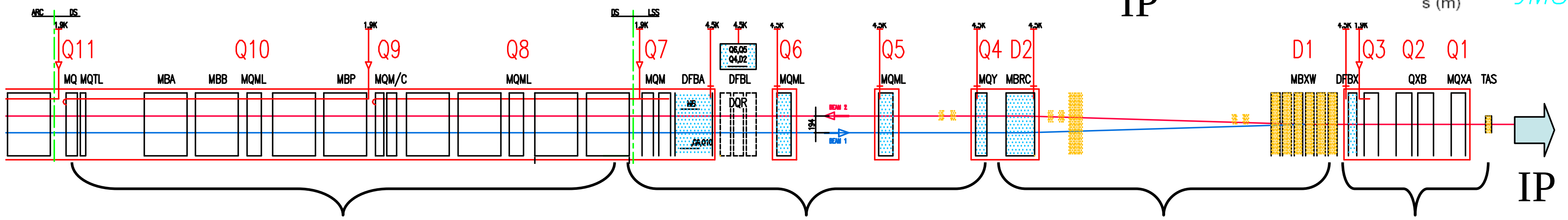


And other insertions for RF, Dump, Cleaning

Layout of Experimental Insertions

Magnet issues:
- **Aperture**
- **Field quality**
- **Alignment**
- **Beam heat load**





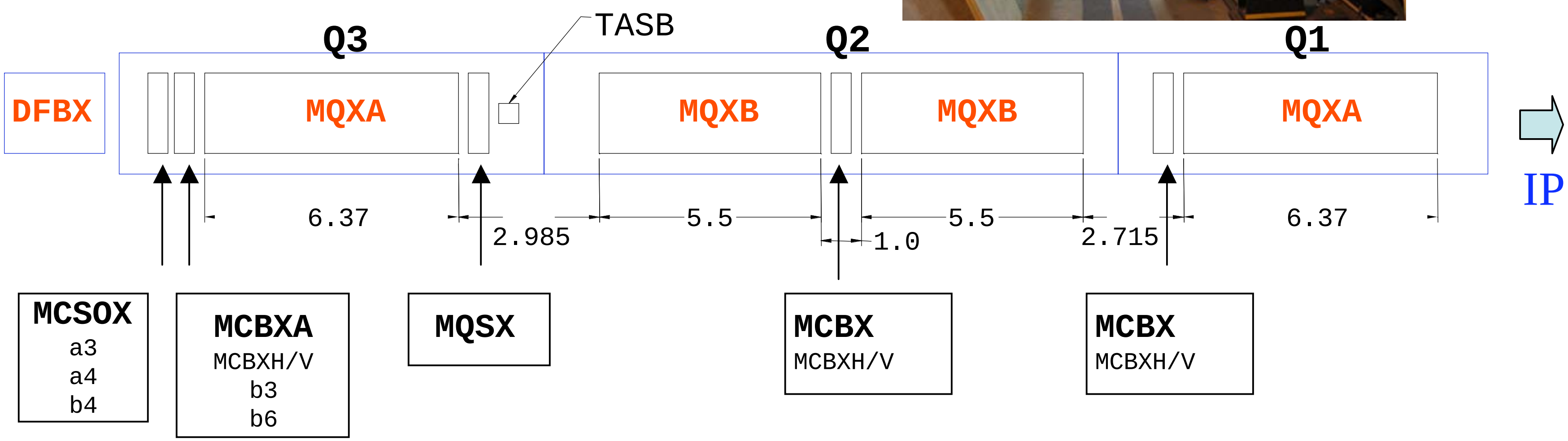
Dispersion suppressor	Matching section	Separation dipoles	Final focus
CERN	CERN	BNL, BINP	KEK, FNAL, LBL, CERN

The Low-Beta Insertion

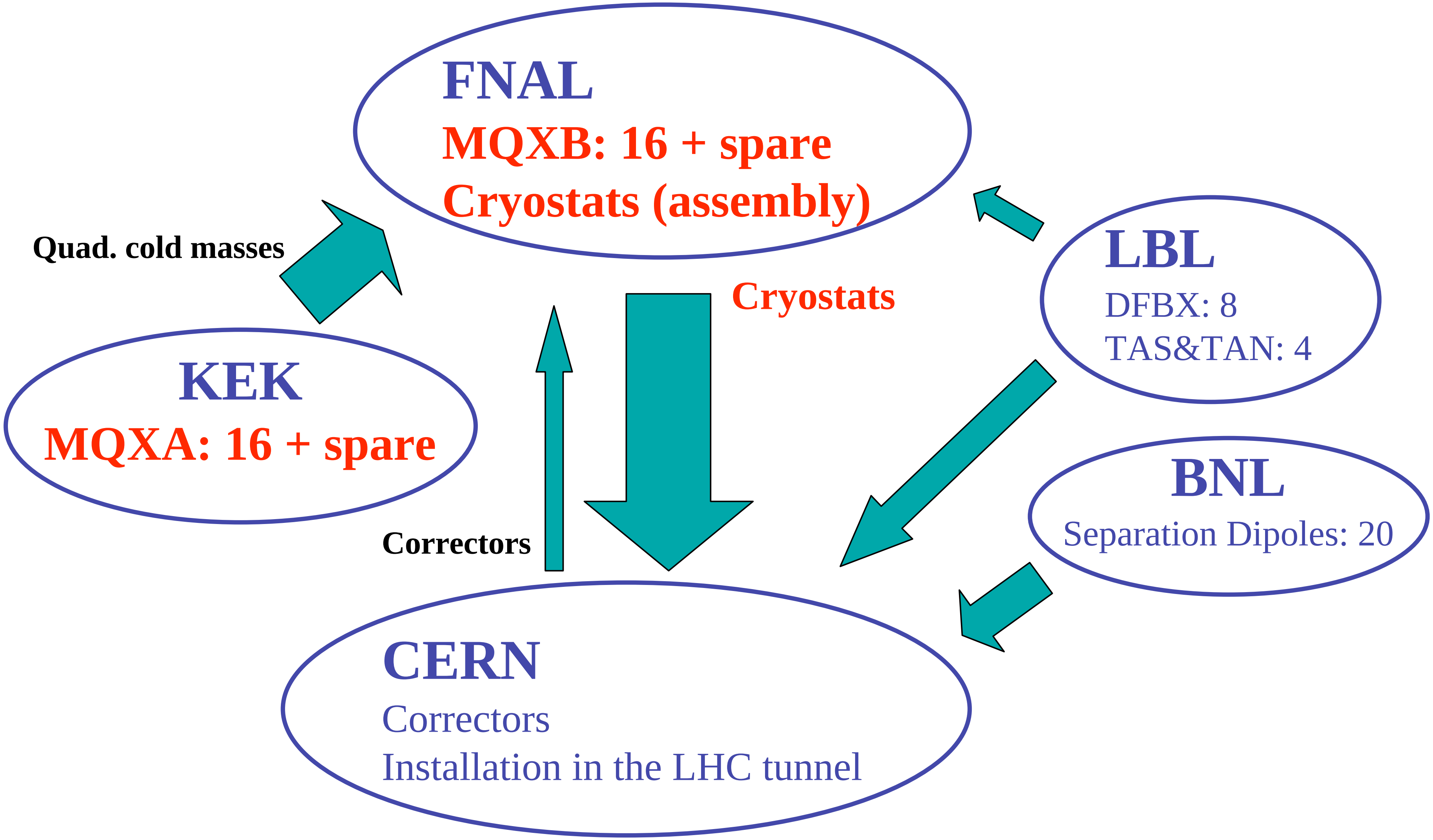
Key Elements to Achieve High Luminosity….

- Quadrupoles: Low-Beta Triplet
  - Q1 & Q3 (MQXA): KEK
  - Q2a & Q2b (MQXB): FNAL
  - Correctors: CERN
- Cryostat Assembly
  - All done by FNAL
- Feed boxes for the inner triplet
  - DFBX: LBNL

G = 215 T/m, Aperture = 70 mm → ~ 9 T
L= 5.5 or 6.37 m
Higher Order Multipoles < 1 unit (10^{-4})
Beam Heating: 5 ~ 10 W/m



CERN-US-KEK Collaboration for the Low-Beta Insertions



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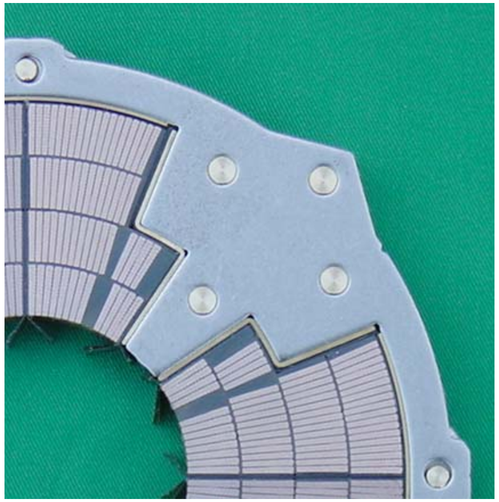
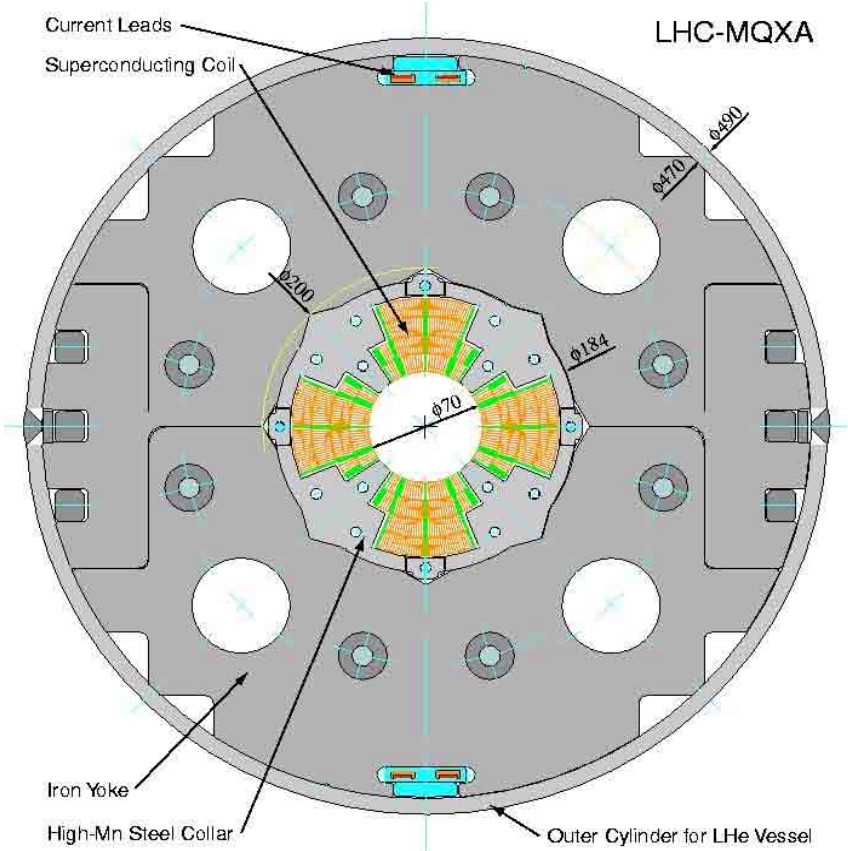
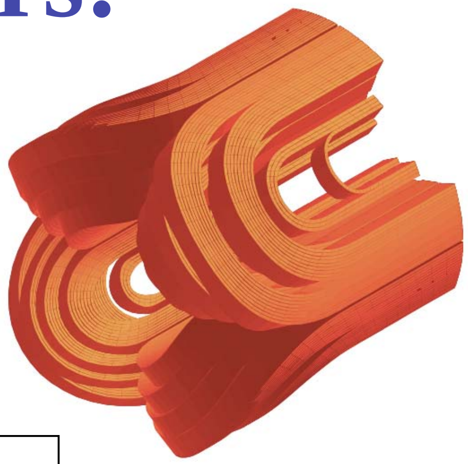
Design Features

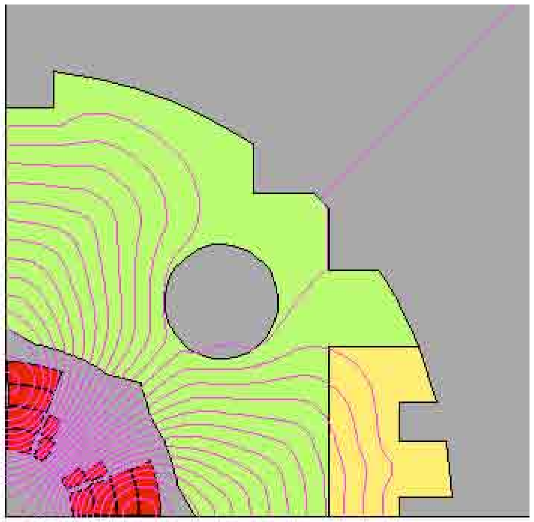
- **Four Layer Coils**
  - **Two 2-layer coils**
  - **with current grading**
    - **Inner & outer SC cables**
    - **Higher J at outer coil**
- **Spacer-Collars**
  - **High-Mn steel**
    - **Low & stable permeability**
- **Flux Return Yoke**
  - **Horizontally split**
  - **Keyed structure**
    - **Pre-stress & mechanical support**
    - **Simple & cost-effective assembly**



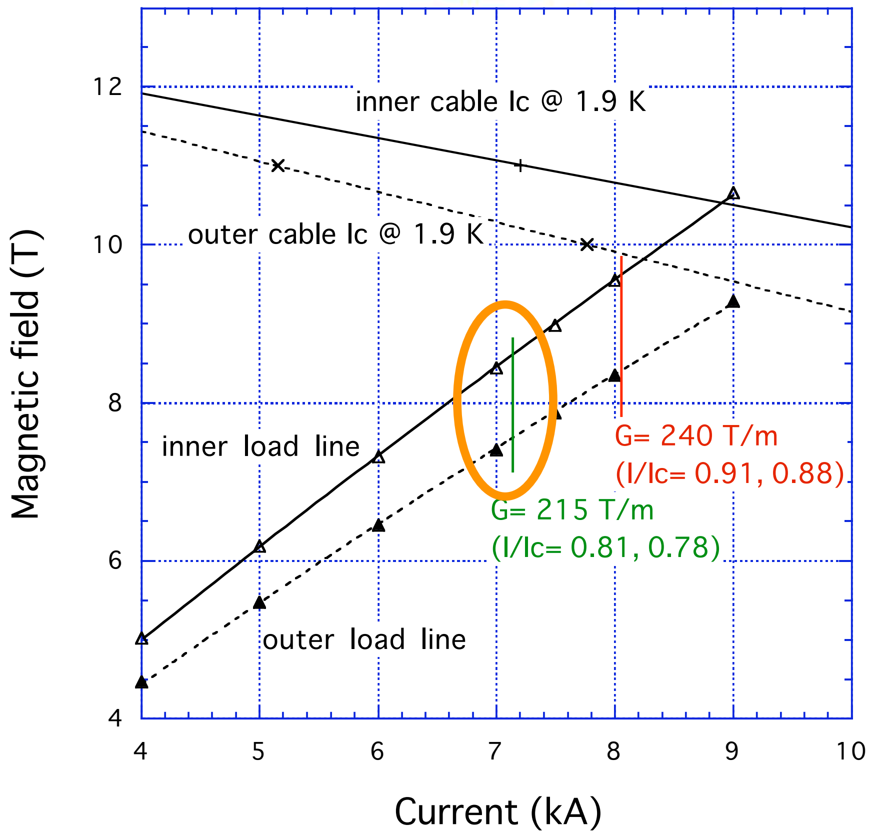


Design Parameters:
Final version

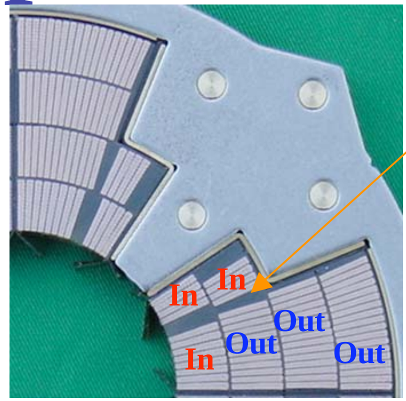




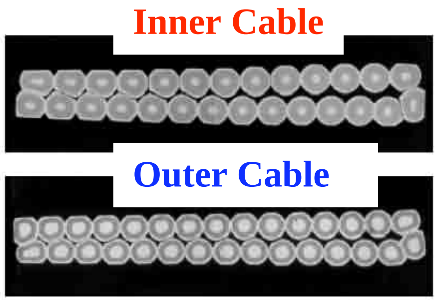
Field gradient	215 T/m
Coil inner radius	35 m
Yoke outer radius	235 mm
Shell outer radius	245 mm
Magnetic length	6.37 m
Peak field in coil	8.63 T
Current	7149 A
Superc. load-line ratio	80 %
Inductance	87.9 mH
Stored energy	2.24 MJ
Magnetic force per pole (octant)	
Fx	1.19 MN/m
Fy	-1.37 MN/m

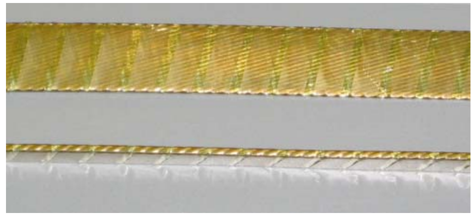


Superconducting Cables: NbTi/Cu



Solder joint in 2nd-Layer

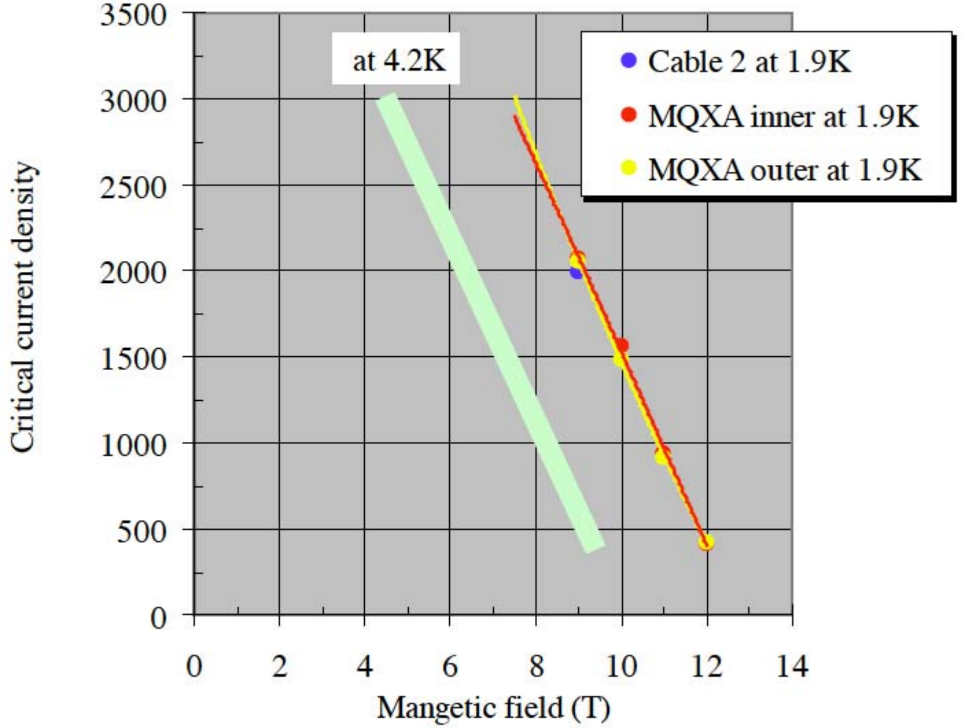




Inner Insulation: UpilexRN (t: 25 μm, w: 15 mm) w/ 50 % overlap.
Outer Insulation: UpilexRN (t: 50 μm, w: 6 mm) w/ 2 mm gap.
10 μm thick B-stage epoxy resin on outer insulation.

Cable	Inner	Outer
Width (mm)	11.00±0.01	11.00±0.01
Thickness:		
Inside edge (mm)	1.264	1.210
Middle (mm)	1.487±0.006	1.340±0.006
Outside edge (mm)	1.697	1.469
Keystone angle (deg.)	2.324±0.05	1.348±0.05
Cable pitch (mm)	90±10	90±10
Number of strands	27	30
Critical current:		
at 9 T, 1.9 K (A)	>13 250	>9000
at 10 T, 1.9 K (A)	>10 000	>6500
at 11 T, 1.9 K (A)	>6000	>4000

Strand	For inner cable	For outer cal
Diameter (mm)	0.815±0.005	0.735±0.005
Cu:SC ratio	1.2±0.1	1.9±0.1
Filament diameter (μm)	<10	<10
RRR of copper	>110	>110
Twist pitch (mm)	15±2	15±2

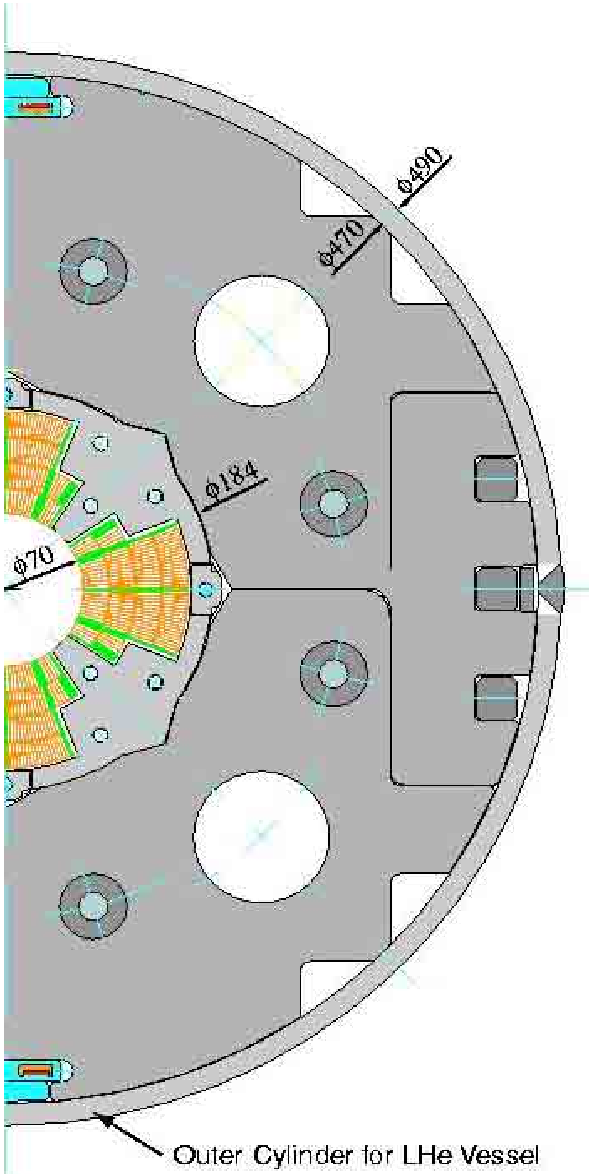


Manufacturer: FURUKAWA

Mechanical Design

Coil position determined by both collar and yoke.

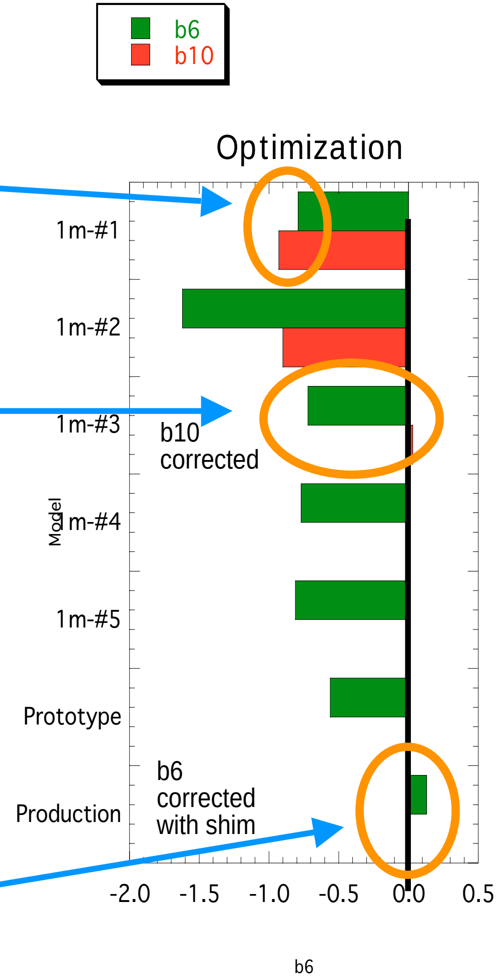
Control of dimensions

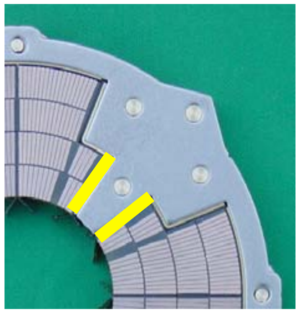


- **Pre-assembly with spacer-collars at low pre-stress. ➡ < 10 MPa**
- **Collaring yoke to provide full pre-stress. ➡ > 50 MPa**
  - **Fine-blanked 6 mm thick low-carbon steel by JFE Steel (formerly Kawasaki Steel.)**
  - **FEM analysis to design keys, slots, median plane shape and stepped cutout.**
- **Redundant radial support by stainless steel shell fitting tightly around yoke.**
- **End plates to restrict longitudinal elongation of coil by Lorentz force.**

R&D Work

	#	Electromagnetic Design	Notes	b6	b10	
1-m Model	1	**Original**	Reach **250 T/m**	**-0.79** (0.32)	**-0.93** (-0.98)	KEK
	2	Repeat		-1.62	-0.90	KEK
	3	**Re-optimize**	**b10** Re-optimized	-0.72 (0.15)	**0.03** (0.00)	KEK (Toshiba)
	4	Reproducibility		-0.77	0.00	KEK
	5	Reproducibility		-0.81	0.01	Toshiba
Full-scale Proto	1			-0.56	0.01	Toshiba
	2	Repeat				Toshiba
Production	**1-19**	**Shim correction**	**b6 Re-tuned**	**0.13**	**0.00**	**Toshiba**



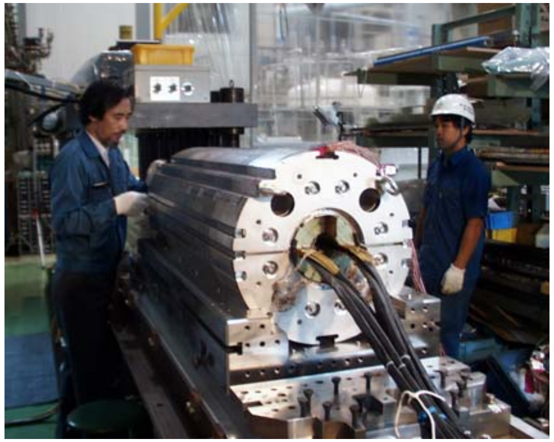


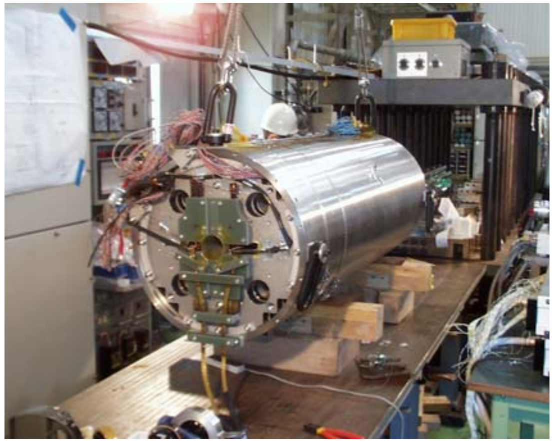
Achievement

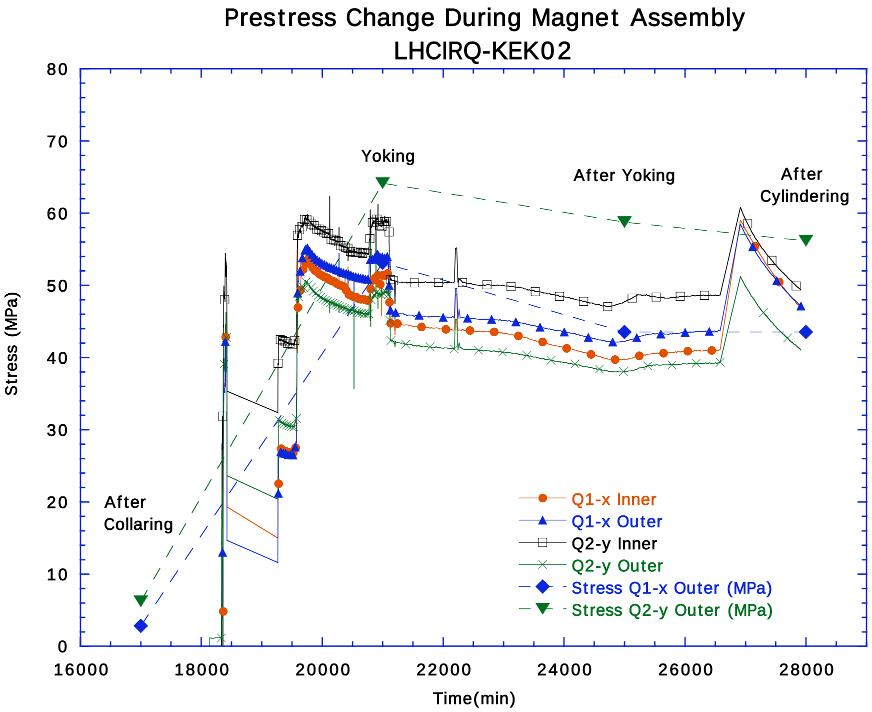
1-m model reached: 250 T/m

Full-scale prototypes: Multiple tuned << 10^{-4}

1-m Model R&D: Fabrication in-house





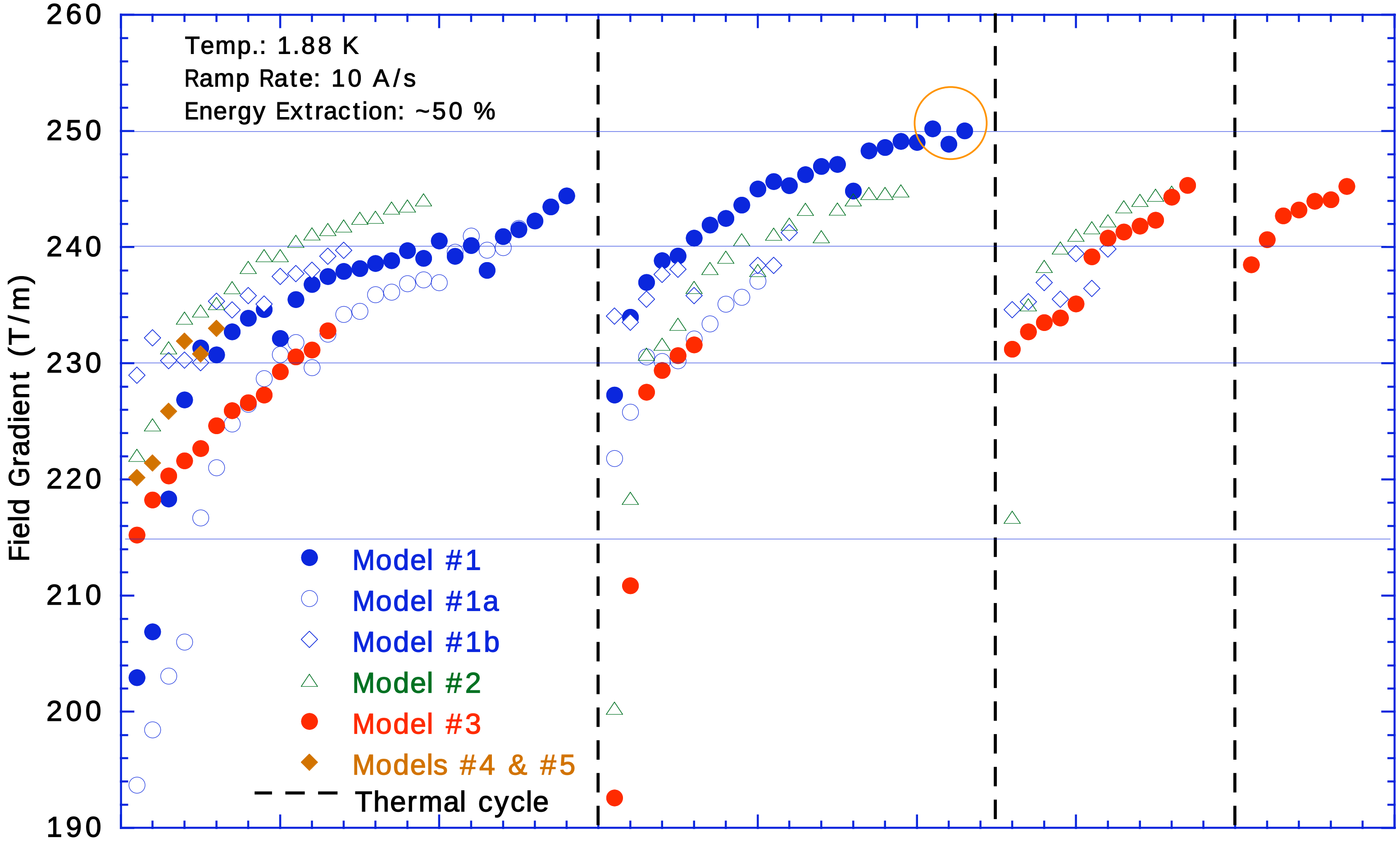


Pre-stress

Collaring: ~ 5 MPa

Yoking: ~ 50 MPa

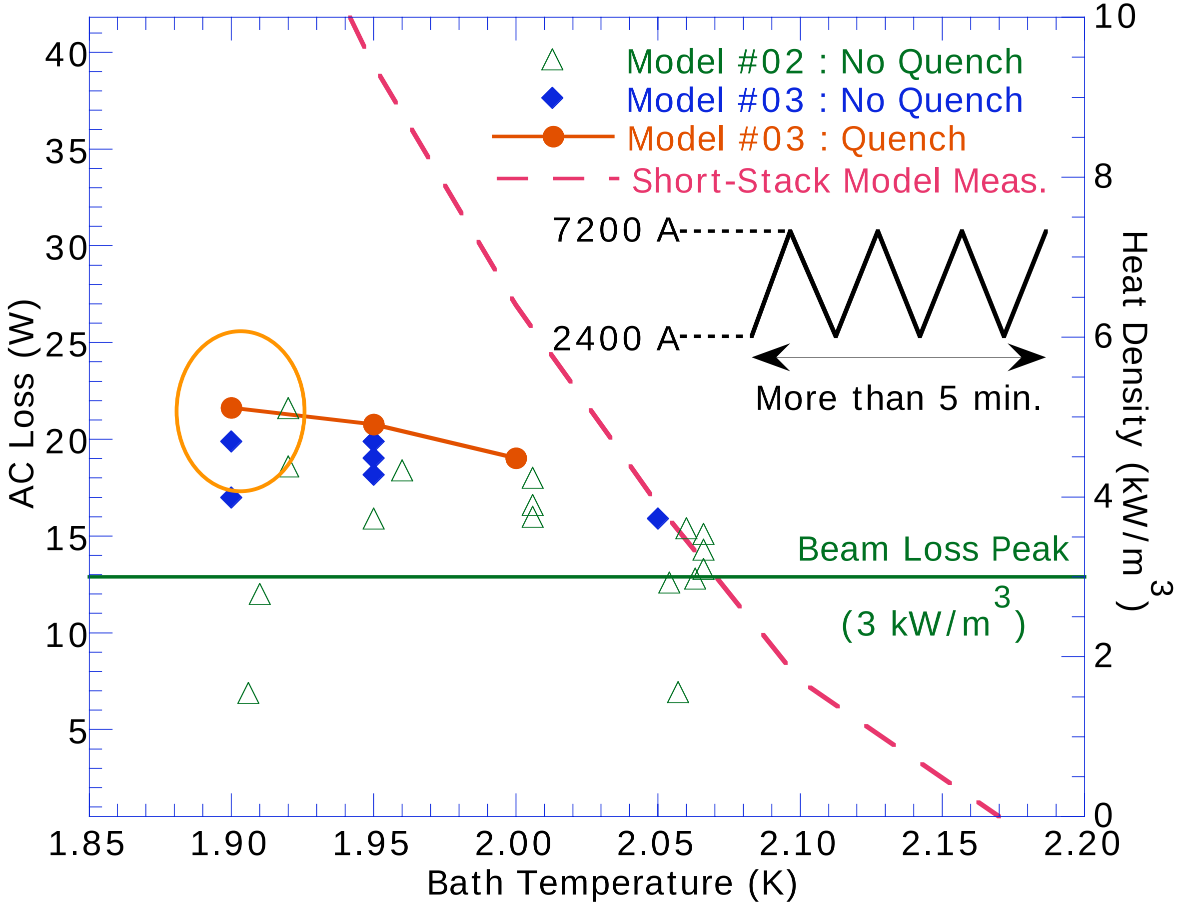
1-m Model R&D: Training Quench



- Reach to 250 T/m for 1st model.
- Exceeding 230 T/m for all models.
- Coil design change for 3rd model and later.
- Training memory after the thermal cycle.

1-m Model R&D: AC Loss Quench

Simulating radiation heat deposition in the coil.



70 % margin to the expected peak heat deposition.

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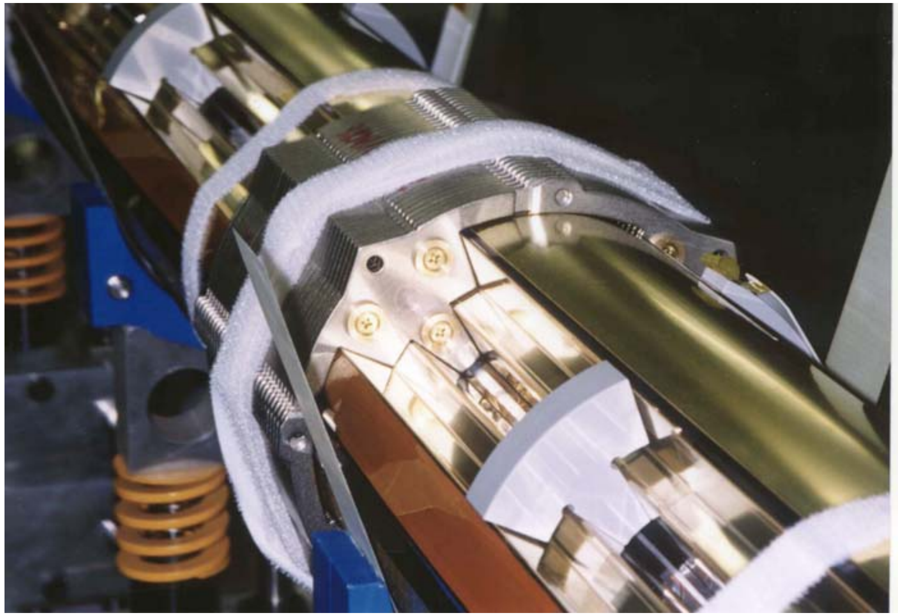
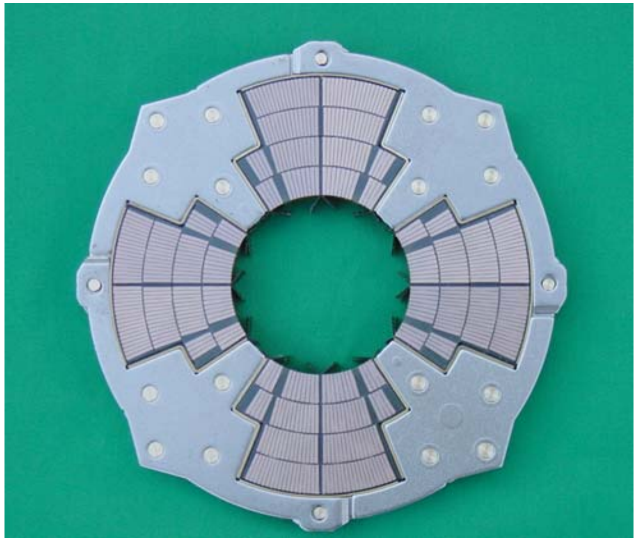
Coil Winding

Courtesy of TOSHIBA

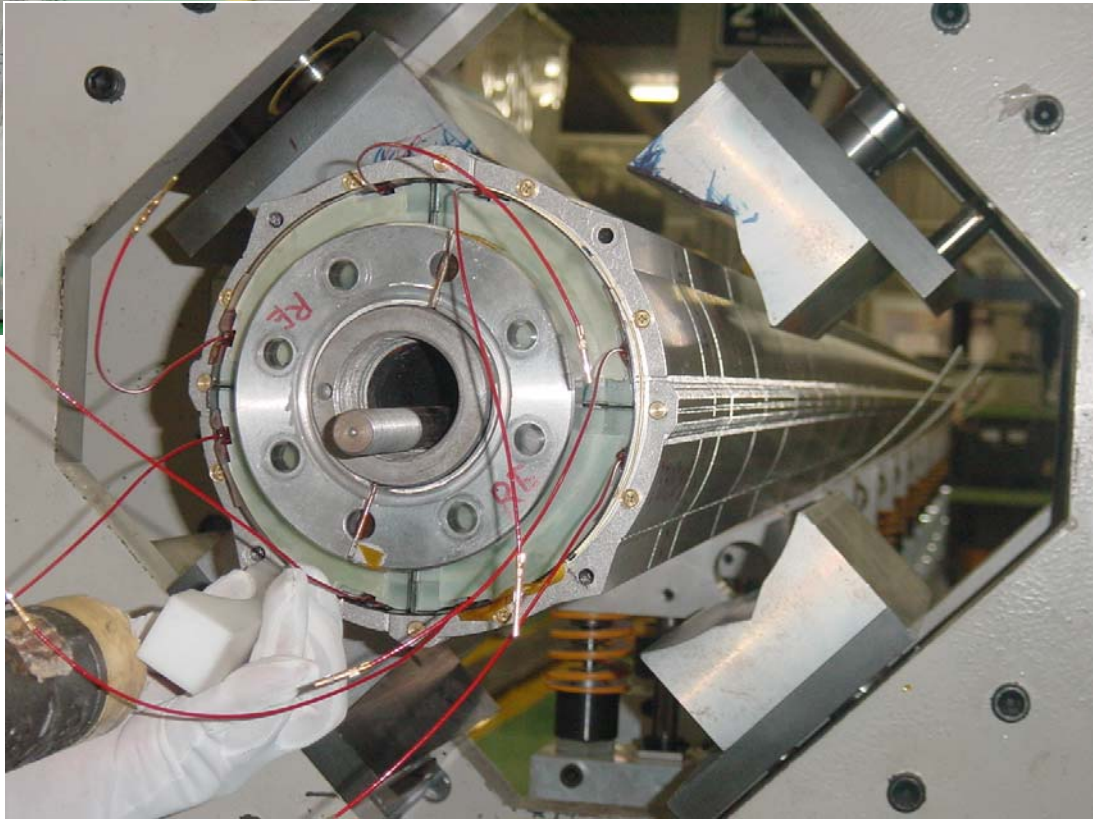
Collaring Preparation





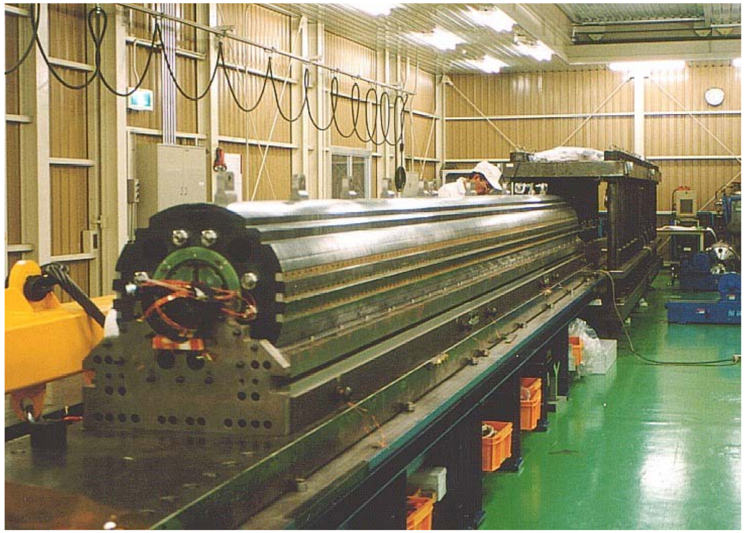
Courtesy of TOSHIBA

Collaring



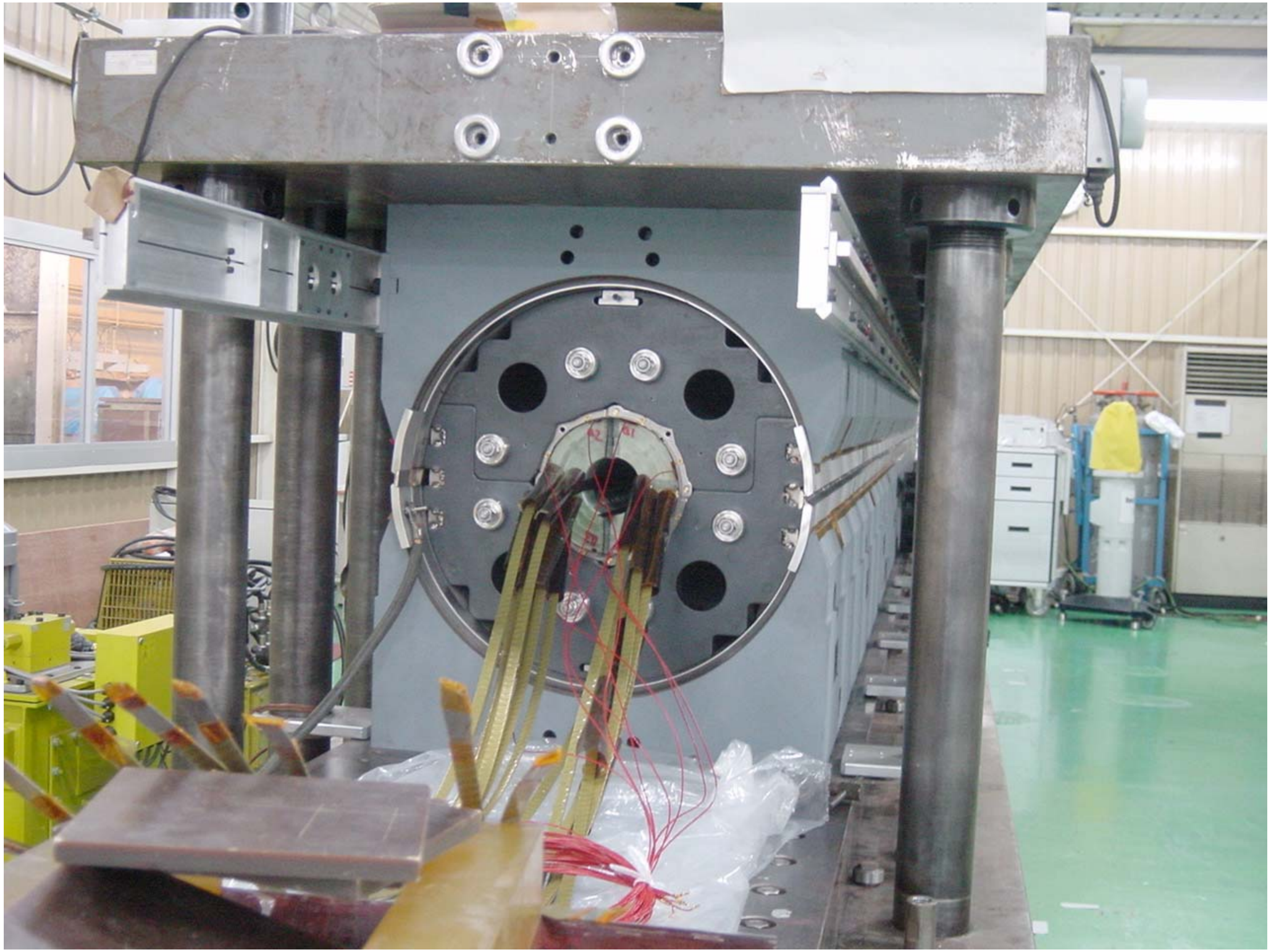
Courtesy of TOSHIBA

Yoking



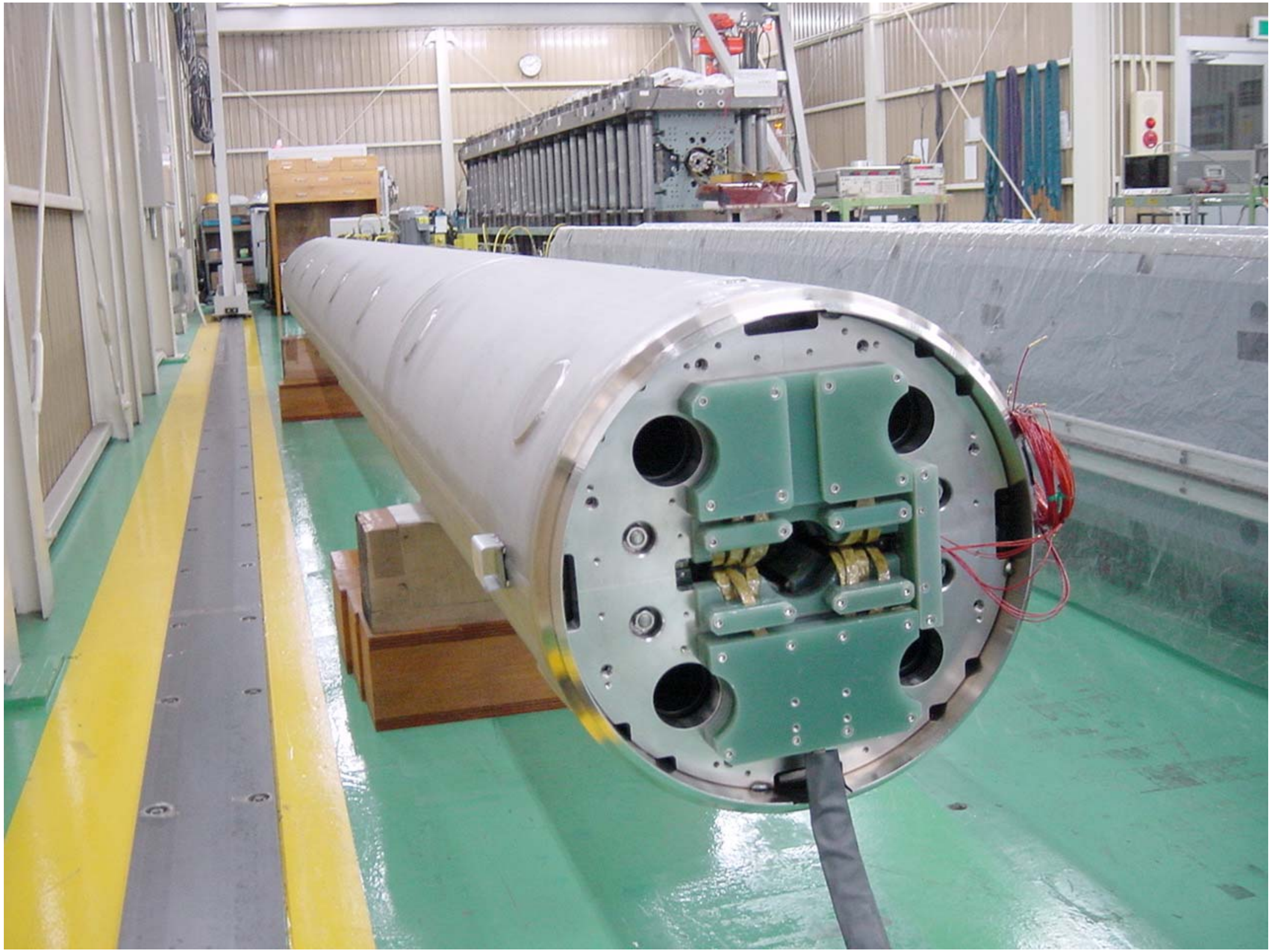
Courtesy of TOSHIBA

Cylindering



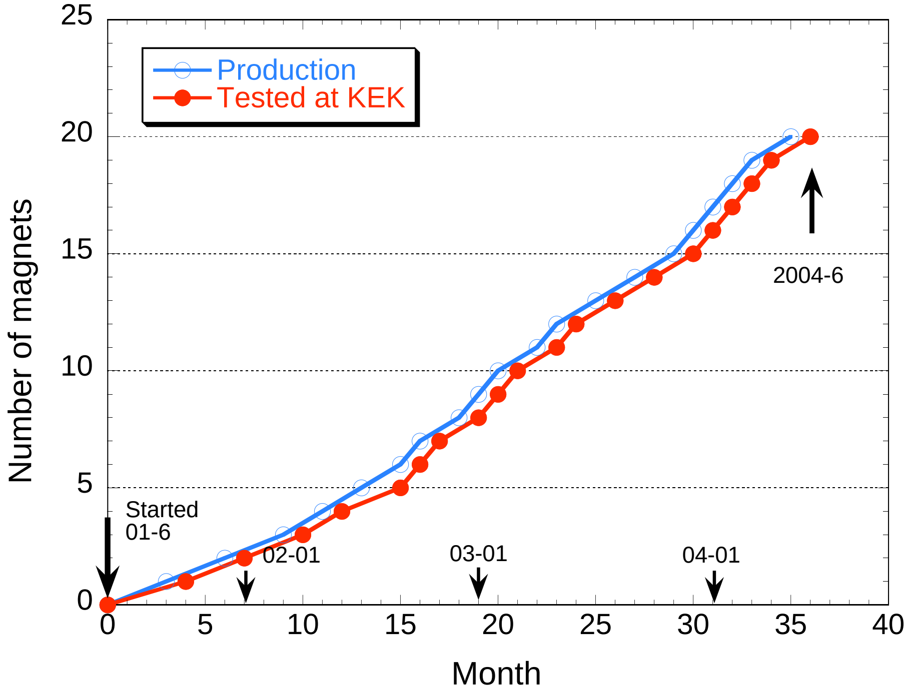
Courtesy of TOSHIBA

Assembly Complete



Courtesy of TOSHIBA

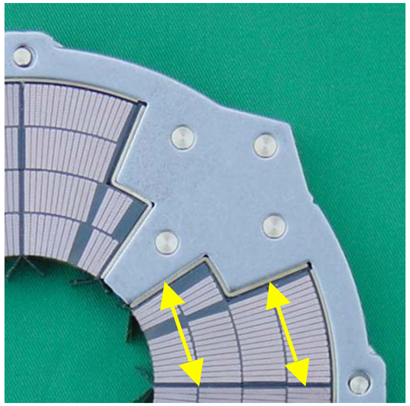
MQXA Production and Tests



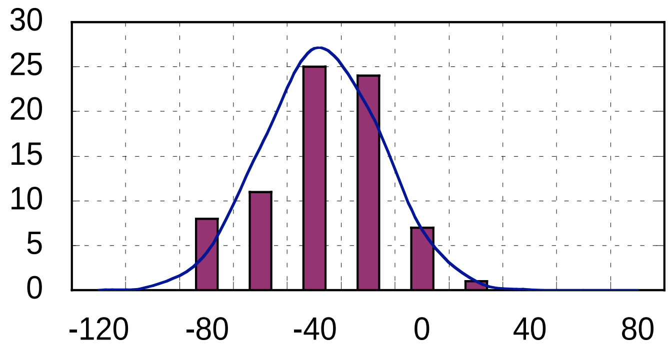
Production has been completed by summer, 2004.

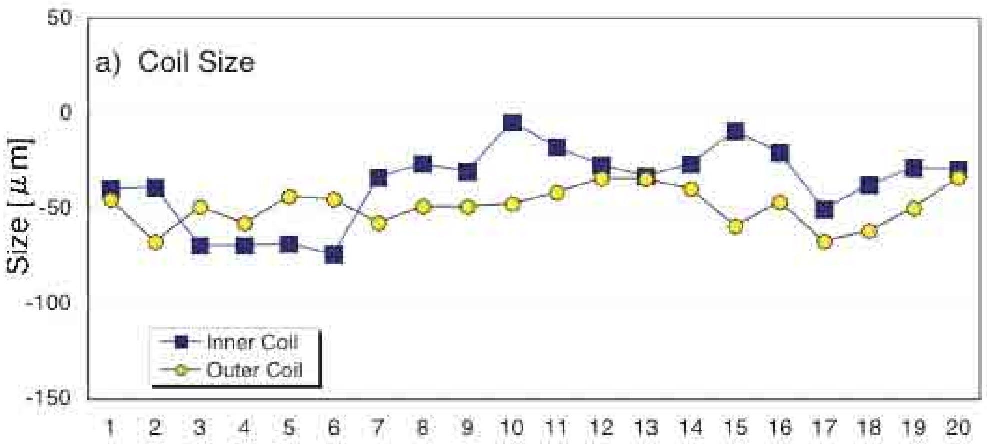
Coil Size @ 50 MPa

Measured at 6 points along each coil.

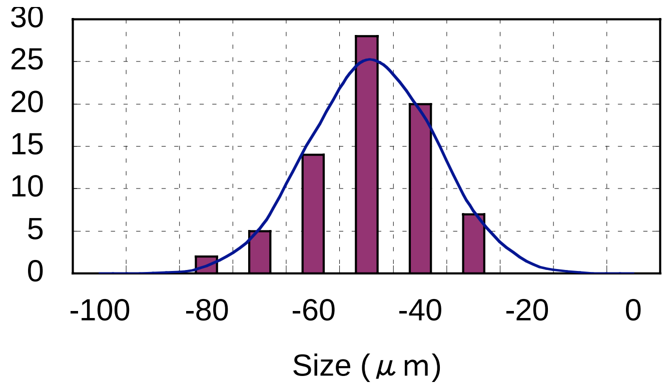


Inner Coil: 1 σ = 22 μm



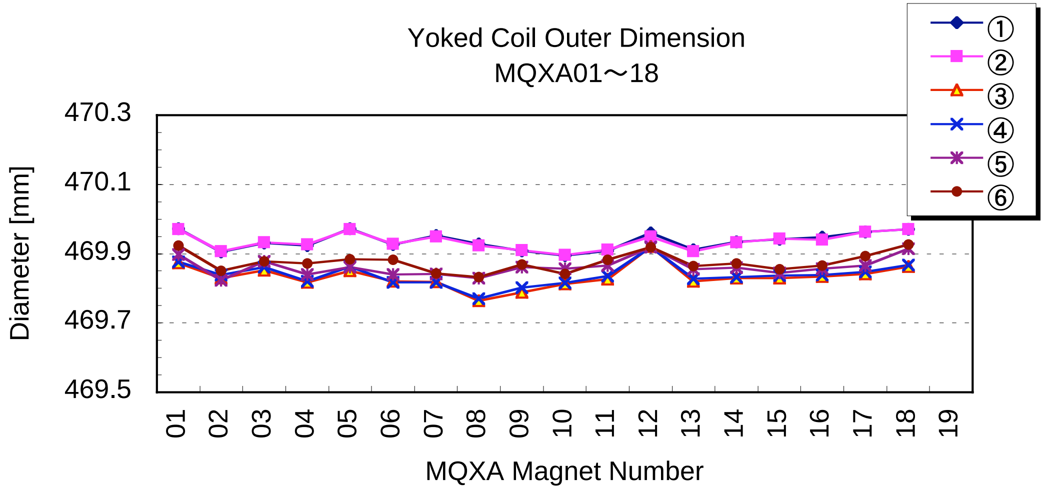


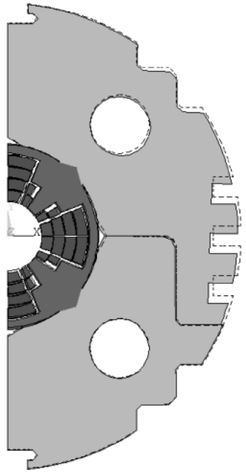
Outer Coil: 1 σ = 12 μm



Relative coil size controlled in a level of 20 μm

Yoke Diameter





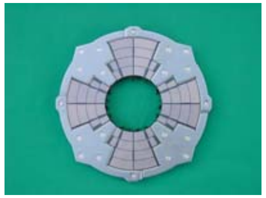
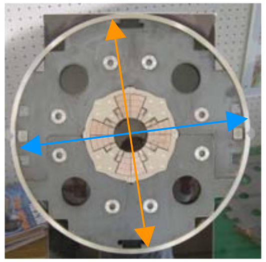
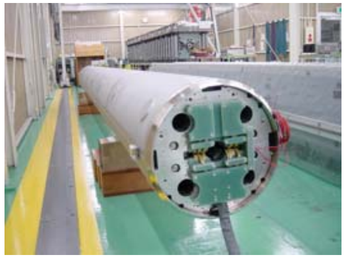
Vertical Diameter: 469.93 mm (1σ = 0.03 mm)
Horizontal diameter: 468.83 mm (1σ = 0.03 mm)
D_Y - D_X = **0.1 mm**
(Ry - Rx = **50 μm**)

Vertical oval deformation of yoke causes field distortion in b4.

Summary of Production Stability

Target of mechanical tolerance is 50 µm to achieve good field quality.

	Design	Av-meas	1 σ	Ratio
Coil Size fm Ref. (in/out)		-37 / -49 µm	22 / 12 µm	5×10^{-4}
Coil Rig. (in/out)		6.0 / 7.2 GPa	0.15 / 0.24 GPa	
Coil L.	6510	6509.7 / 6512.2 mm	0.7 / 0.9 mm	1×10^{-4}
Yoke Size (V/H)		469.83 / 468.84 Δ (V-H) = 0.1 mm	0.03 / 0.03 0.03 mm	6×10^{-5}
Yoke L.	6510	6511.8 mm	1.9 mm	3×10^{-4}
Yoke Weight		6331 kg	6 kg	3×10^{-4}
Yoke Pack. F.		99.25 %	0.07 %	7×10^{-4}
H. Alignment		0.2 mm	0.08 mm	
V. Alignment		0.46 mm	0.17 mm	
Twist		0.54 mrad	0.25 mrad	

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Performance Test at KEK

MQXA from TOSHIBA

KEK

Room Temperature:

- Alignment
- Field Gradient,
- Error field

1.9 K:

- **Training quench → 230 T/m**
- **Full energy dump @215 T/m**
- **Fast Ramp test @150 A/s**
- **Field Measurement**
- **To reach 220 T w/o quench**
- **Electrical Insulation Test**

1.5 kV @ 4.2 K He-gas

Room Temperature:

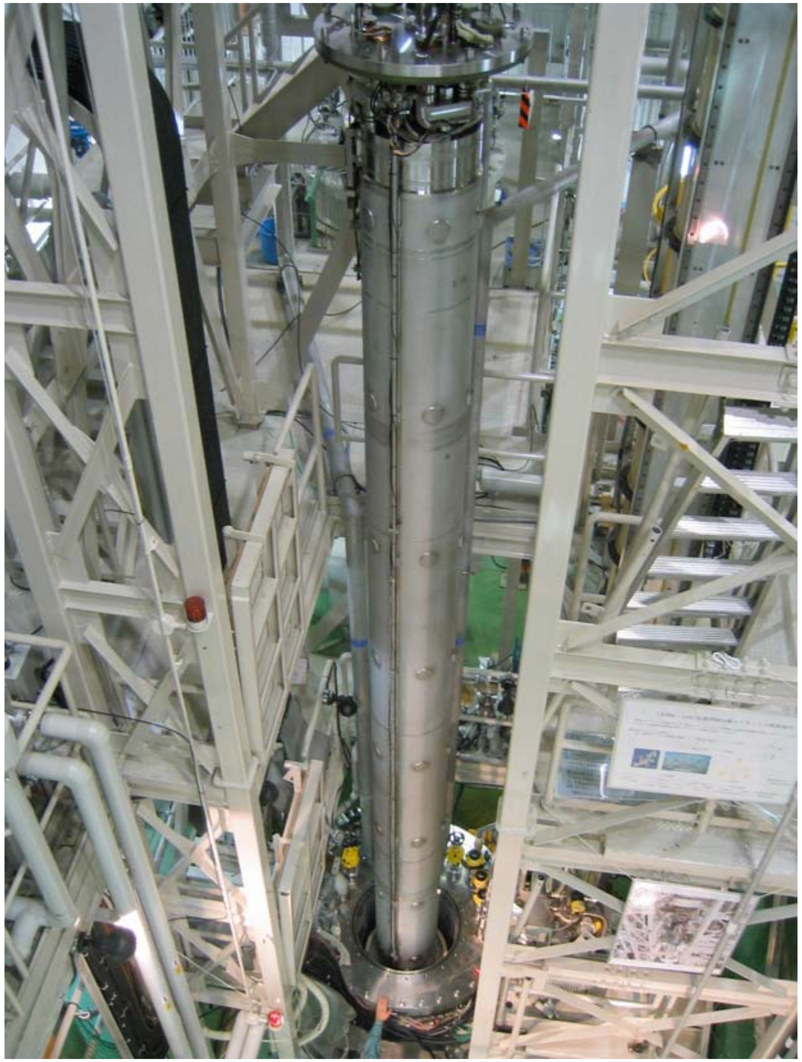
– Alignment check
– Field Gradient,
– Error Field

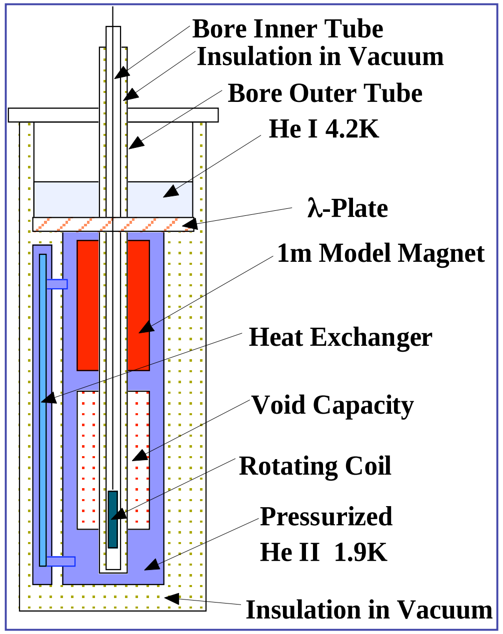
Shipping Preparation @ TOSHIBA

– Pressure Test
– Electrical Test

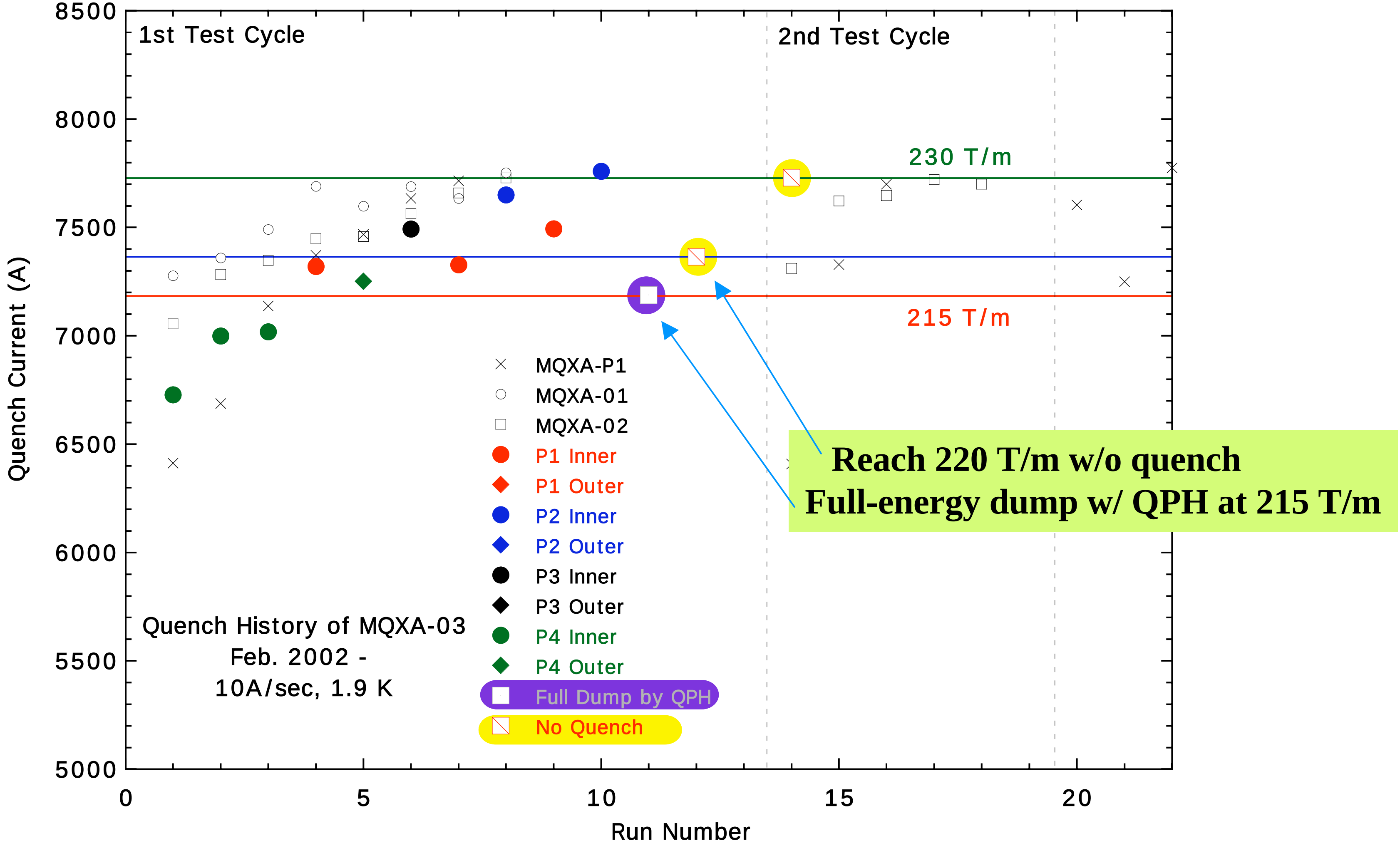
Warm Measurement Setup

Cold Test Station: Vertical Cryostat





Training Characteristics: MQXA-03

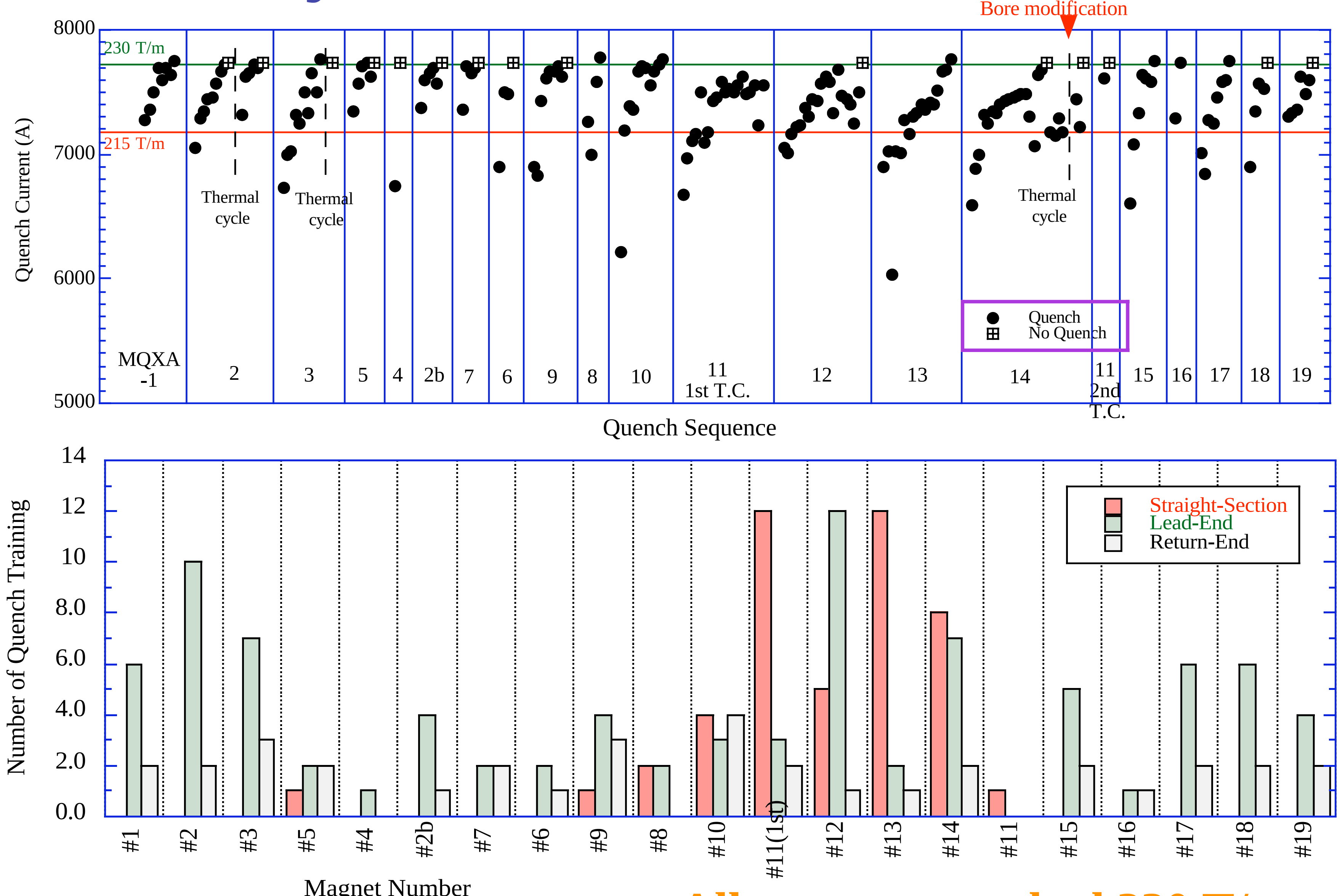


3 quenches to reach 215 T/m

9 quenches to reach 230 T/m

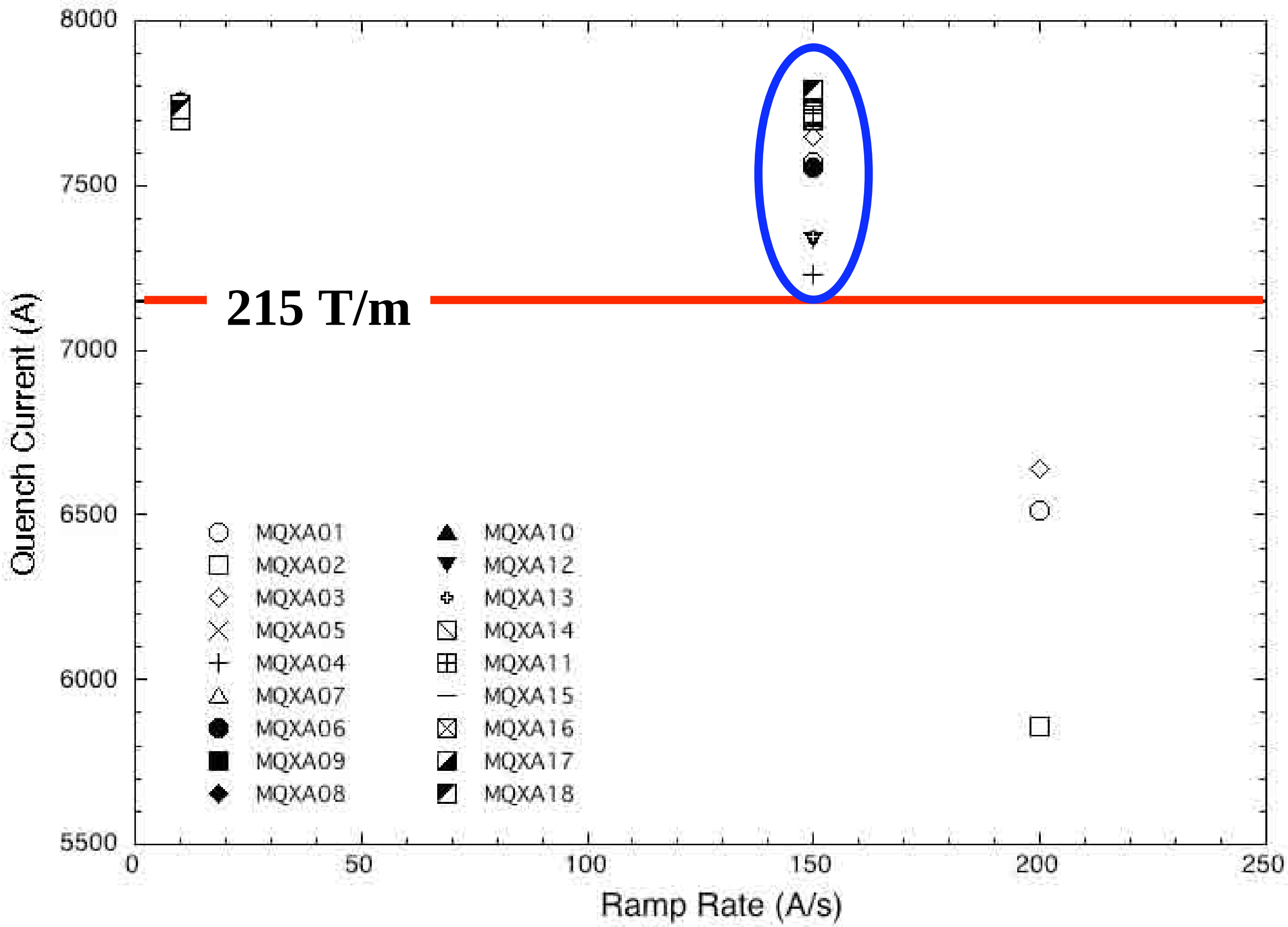
Good training memory after thermal cycle

Summary of Quench Characteristics



All magnets reached 230 T/m.

Fast Ramp Quench



All magnets exceeded 215 T/m @ 150 A/s before quench.

MFM: Field Gradient & Mag. Length

19 units of MQXA

Current (A)	Field Gradient (T/m)		Magnetic Length (m)	
	Average	Standard Deviation	Average	Standard Deviation
392.3	12.445	0.0096	6.3632	0.0048
2011.3	63.475	0.0200	6.3642	0.0010
3207.9	101.01	0.0341	6.3642	0.0009
6134.4	186.53	0.0581	6.3670	0.0009
6677.3	201.73	0.0587	6.3675	0.0010
7227.9	217.07	0.0651	6.3679	0.0012

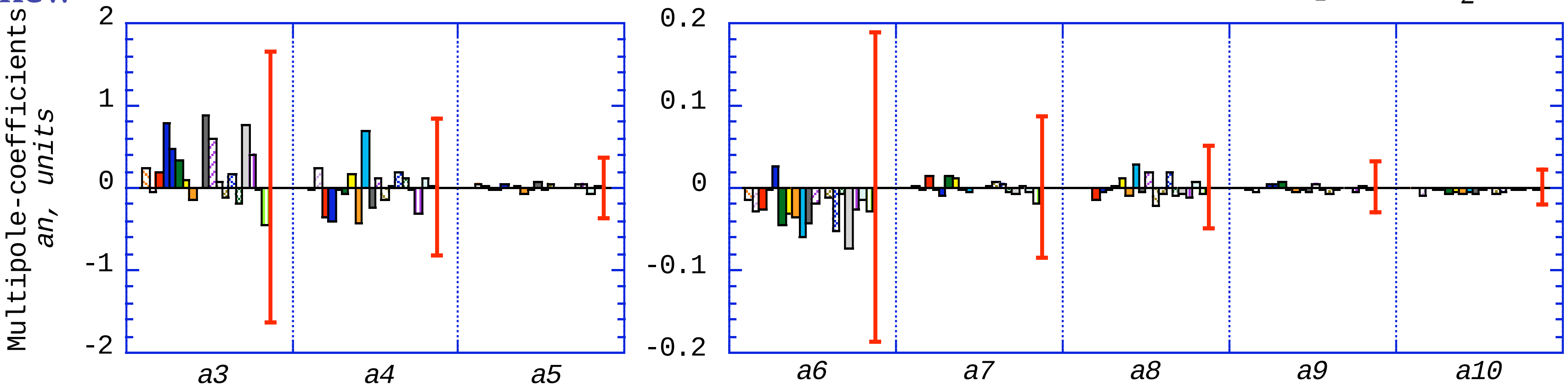
Good reproducibility in the order of 10^{-4}

MFM: Higher Order Multipoles @216T/m

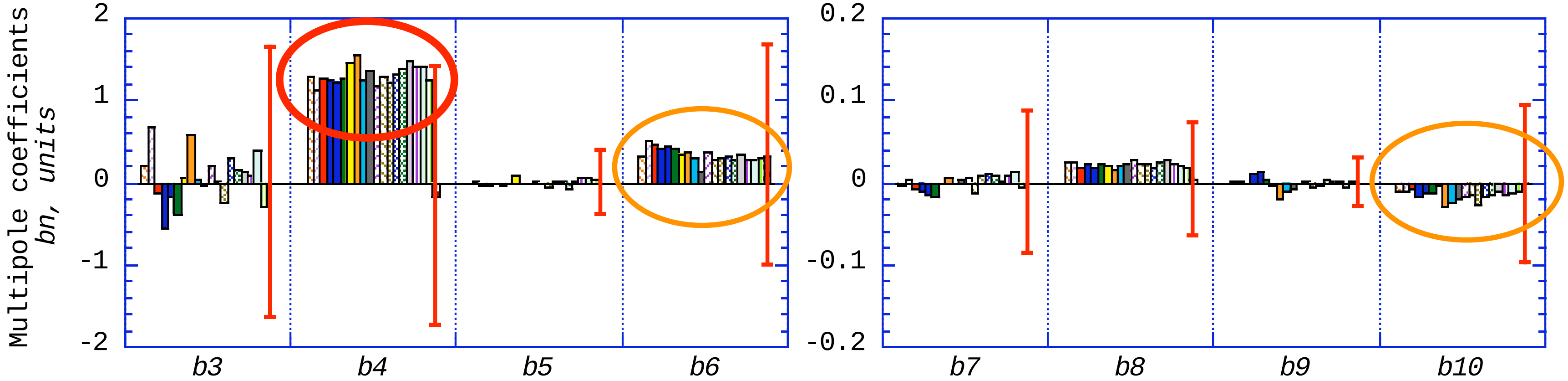
$$B_y + iB_x = 10^{-4} B_2 \sum_{n=1}^{\infty} (b_n + i a_n)\left(\frac{x+iy}{R_{ref}}\right)^{n-1}$$

$$units : 10000 \times \frac{A_n \, , B_n}{\text{Quadrupole } (B_2)}$$

Skew



Normal



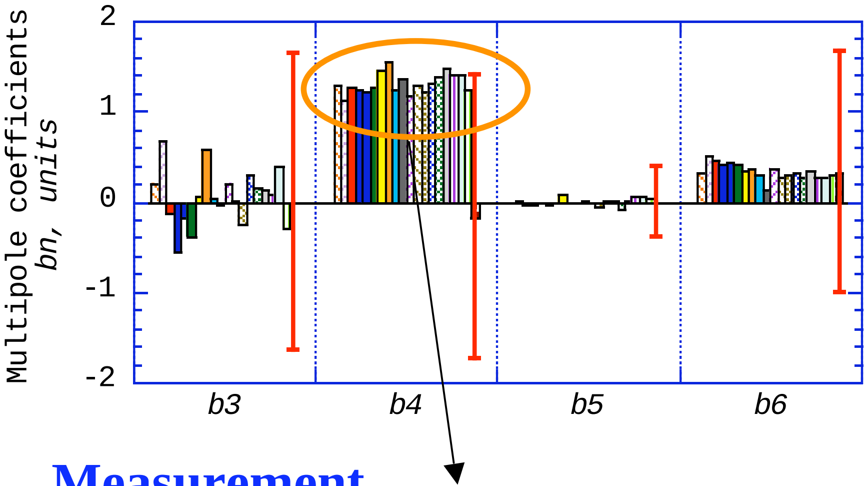
Generally good within reference values.

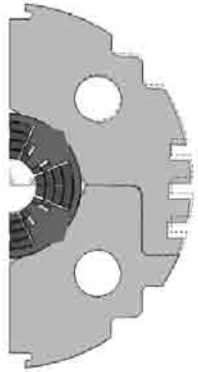
But, large b4…

MFM: Multipole of b_4

Keyed yoke structure ➡ Vertical oval deformation

Model calculation predicts that ΔR of 0.5 mm would induce 0.5 units of b4.





Measurement

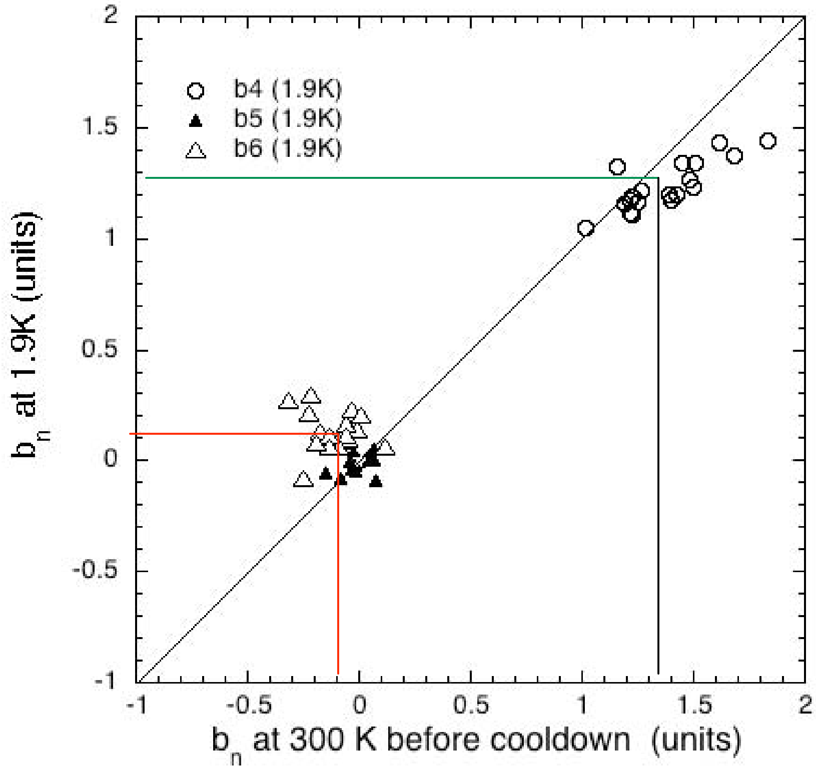
Ave.:	1.314 units
1σ:	0.108 units ➡ ~ 10 μm

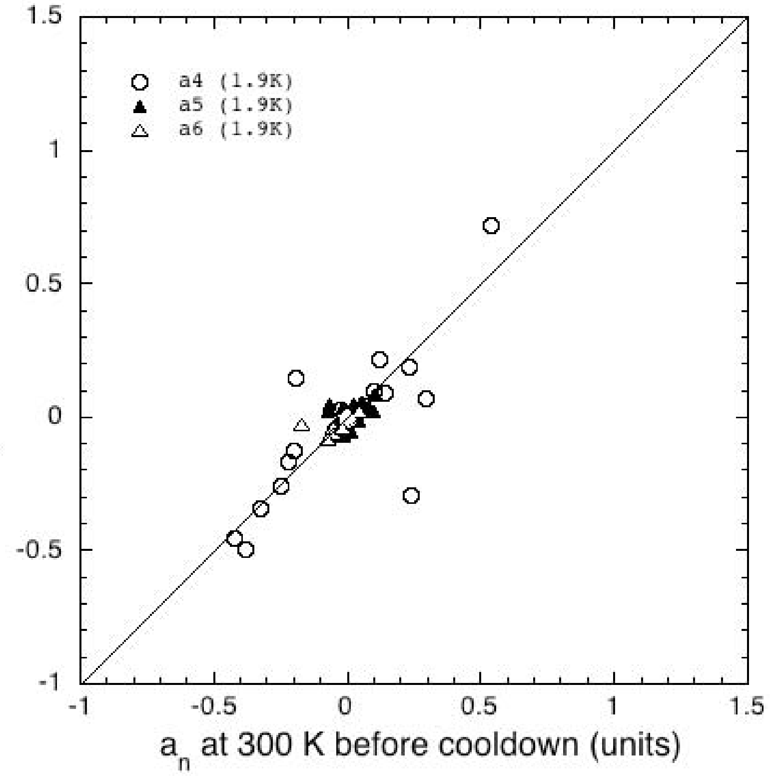
➡ Within reference limit (1.581 units).
Good reproducibility.

Yoke deformation could explain 0.5 units in b4.

But, still another source of 0.8 unit has not been traced.

MFM: Cold & Warm Correlation





- Shift between cold and warm

  b6: ~ 0.3 units, b4: ~ 0.2 units
- Generally good correlation.

Summary of Field Measurement

- **Good reproducibility of field gradient and magnetic length.**

- **Multipole components are controlled at 10^{-4} or smaller.**

- **The reproducibility is very good as its level of 10^{-5}.**

- **Measured results**
  - **fulfill the beam optics requirements,**
  - **are consistent with the mechanical tolerance of 50 μm.**

***exception of b4: twice larger than prediction**

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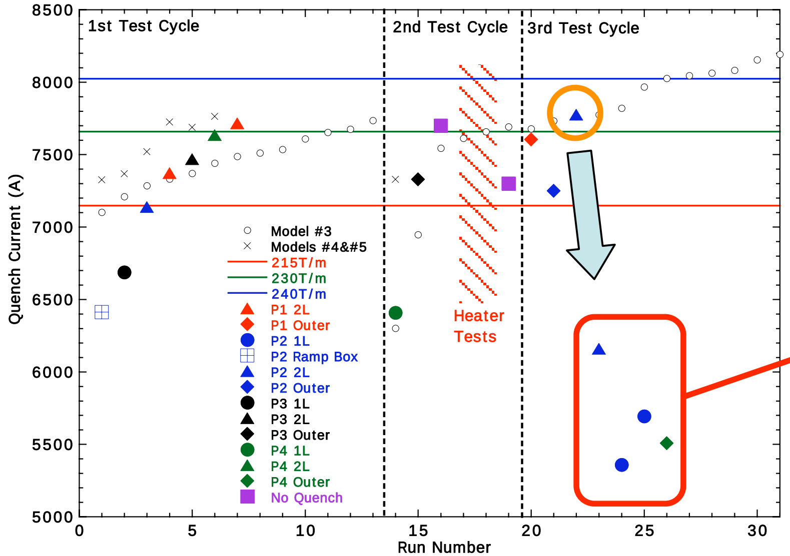
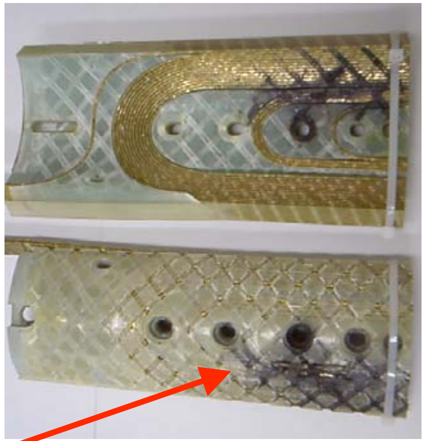
Problem I: Turn Short by Inadequate End Spacer

Quench History of Proto#1





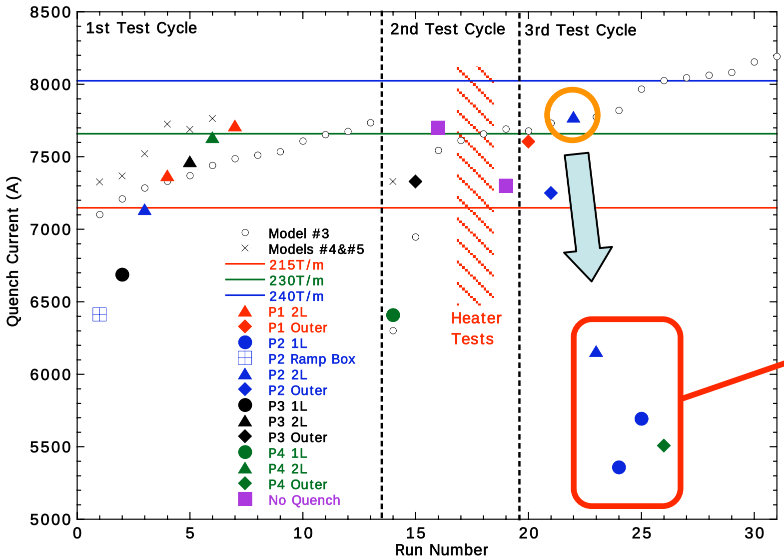
Turn & layer short of Proto #1

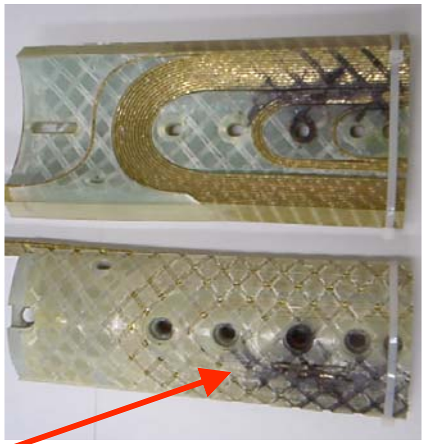
Turn short at 1st turn of 2nd layer: Proto #2

Same problem ??

Problem I: Turn Short by Inadequate End Spacer

Quench History of Proto#1





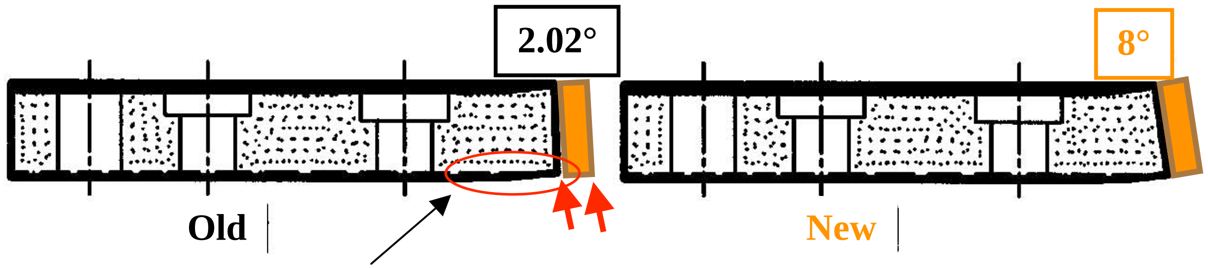
Turn & layer short of Proto #1

Turn short at 1st turn of 2nd layer: Proto #2

Same problem ??

Action!! : Design Change of End Spacer

End spacer for 1st turn, 1st layer



Shorter perimeter at inner edge

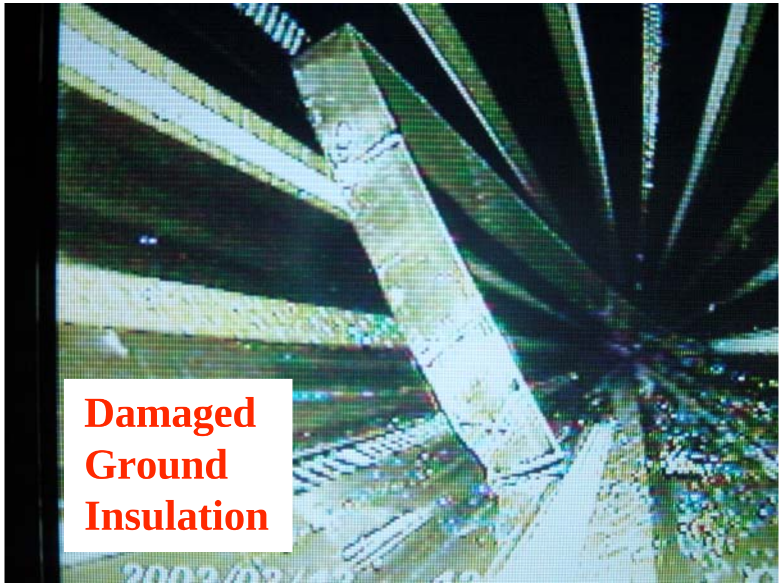
Pop-up of cable

Damage to 2nd layer and adjacent turn

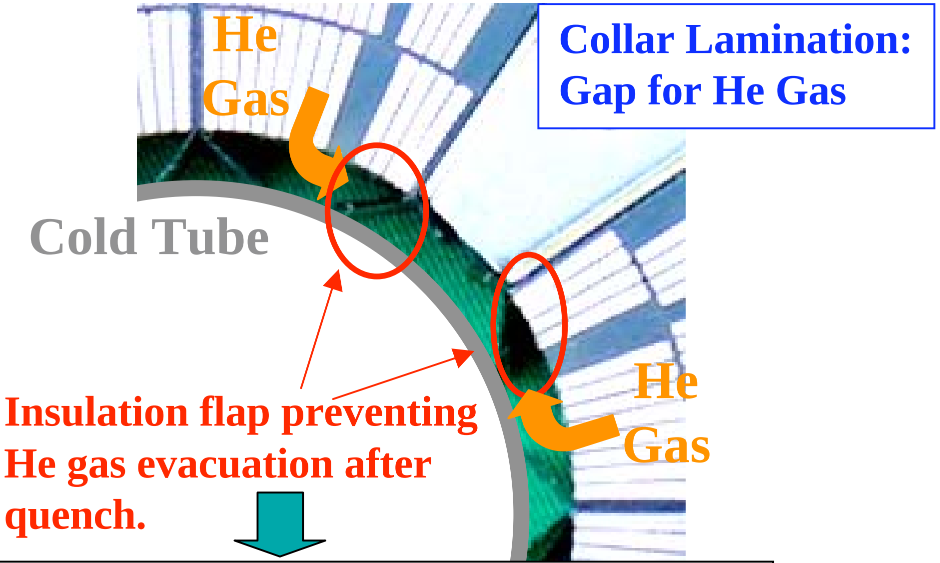
Equidistant perimeters

No problem in production magnets

Problem II : Ground Insulation Peel-off

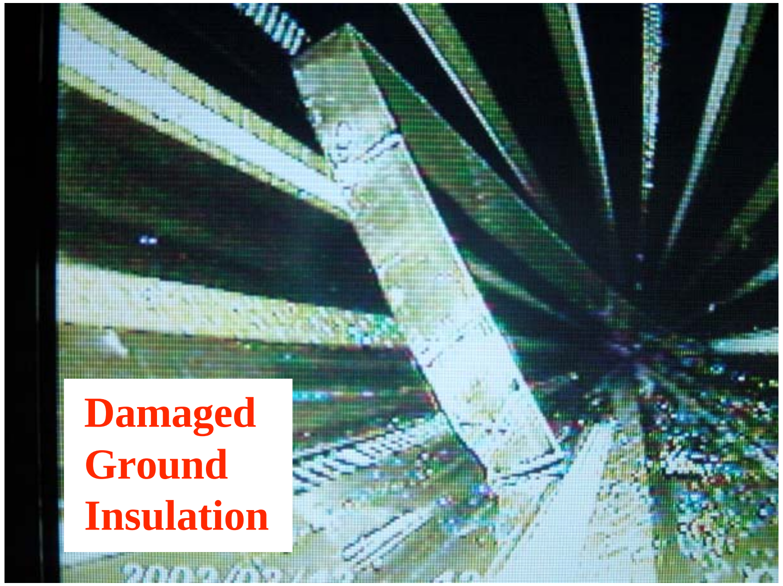


Inside of MQXA02 after cold test

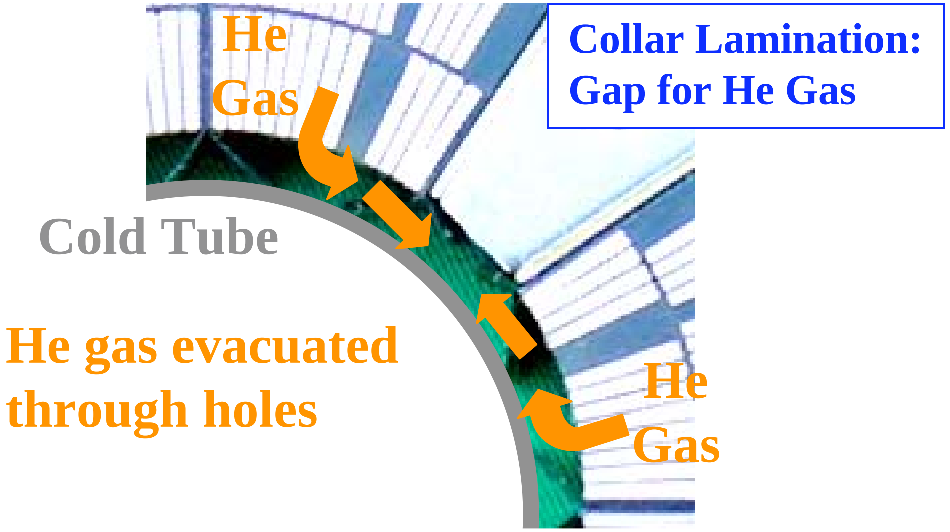


Peel-off or fold in opposite direction

Problem II : Ground Insulation Peel-off

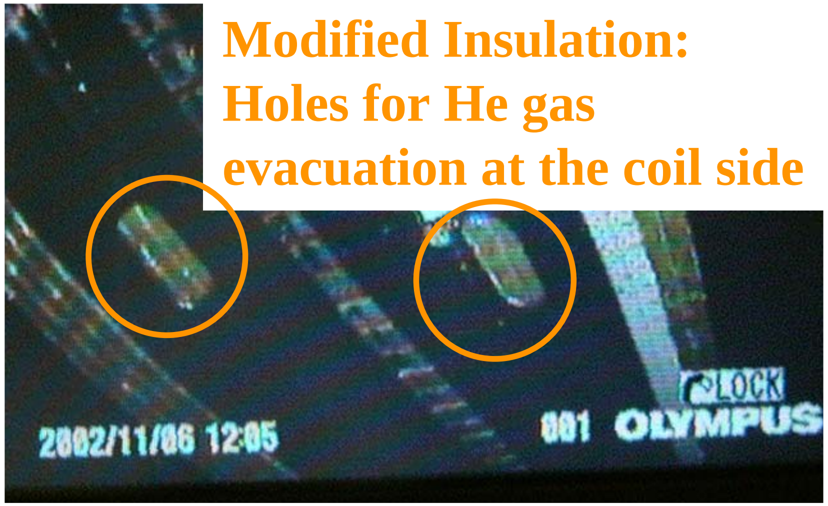


Inside of MQXA02 after cold test



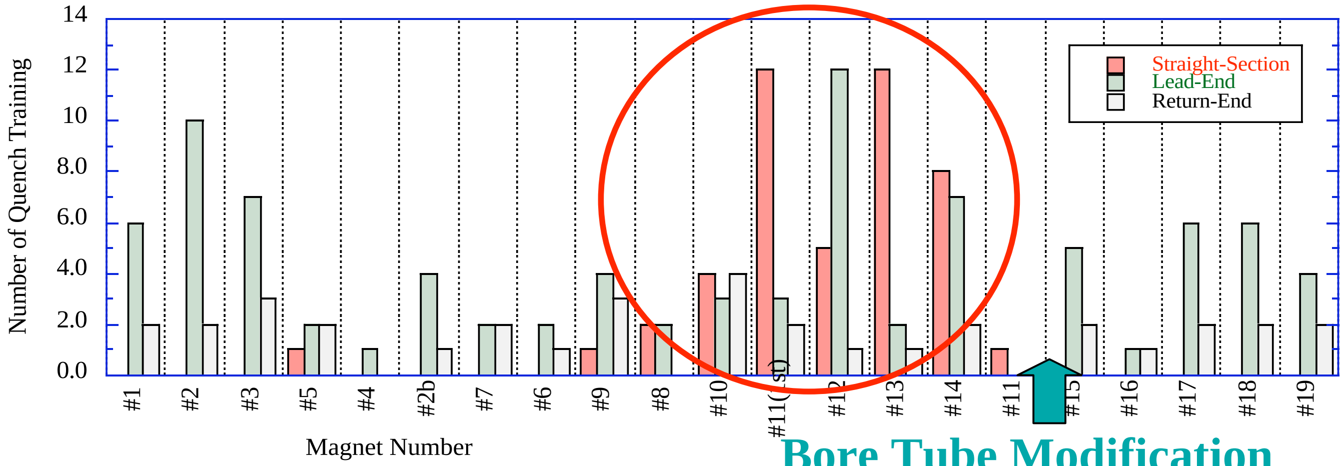
Action!! : Implementation of Holes in Ground Insulation

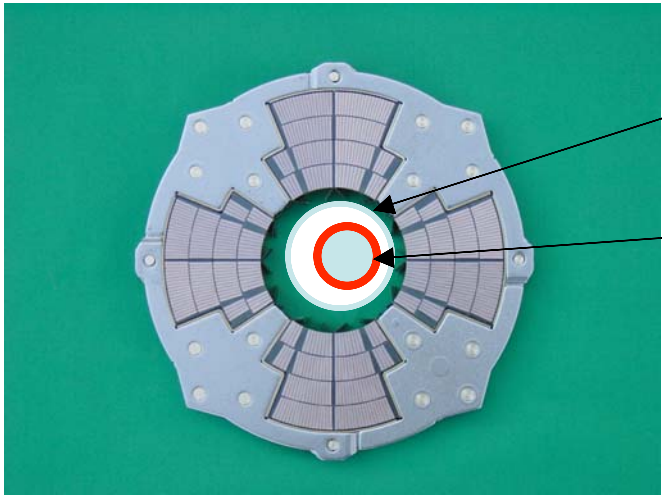
- No further problem after modification.
- New insulation scheme fulfill the electrical insulation specification.
- All magnets passed the electrical insulation tests.



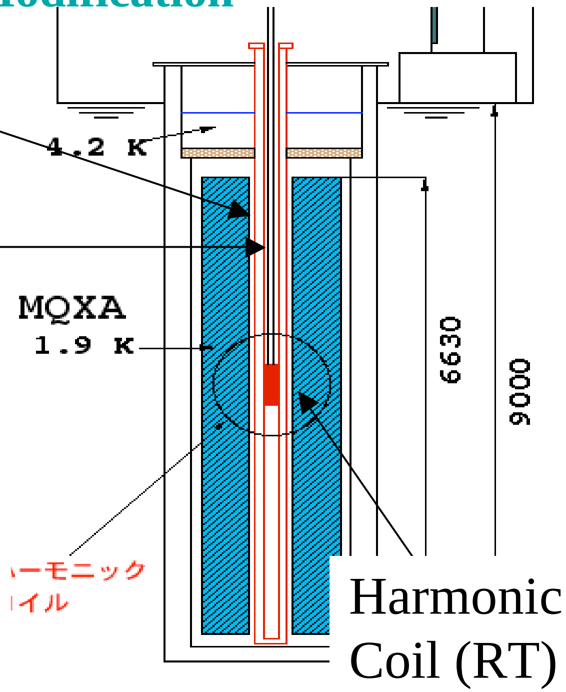
Problem III: Increase of Quenches

Number of quenches increased, and their locations seemed to shift from ends to the straight section.





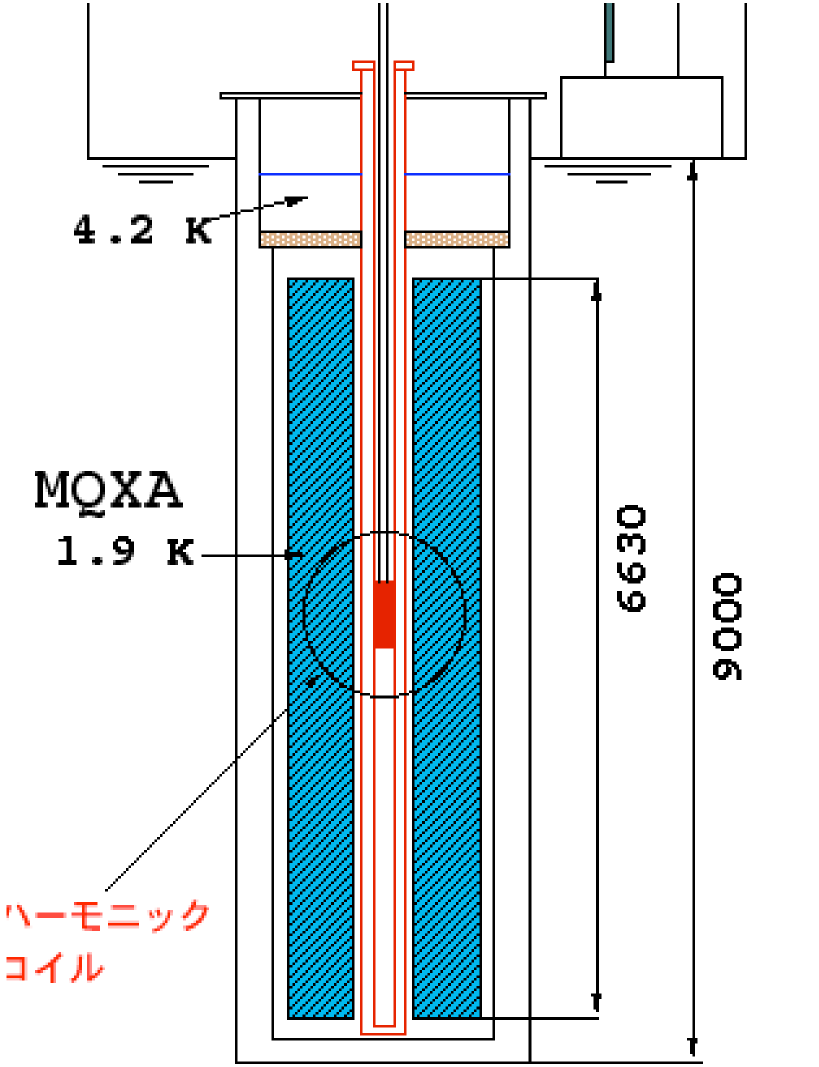
Cold tube (anti-vessel)
&
Warm Tube



Bore tube bent by magnetic force?

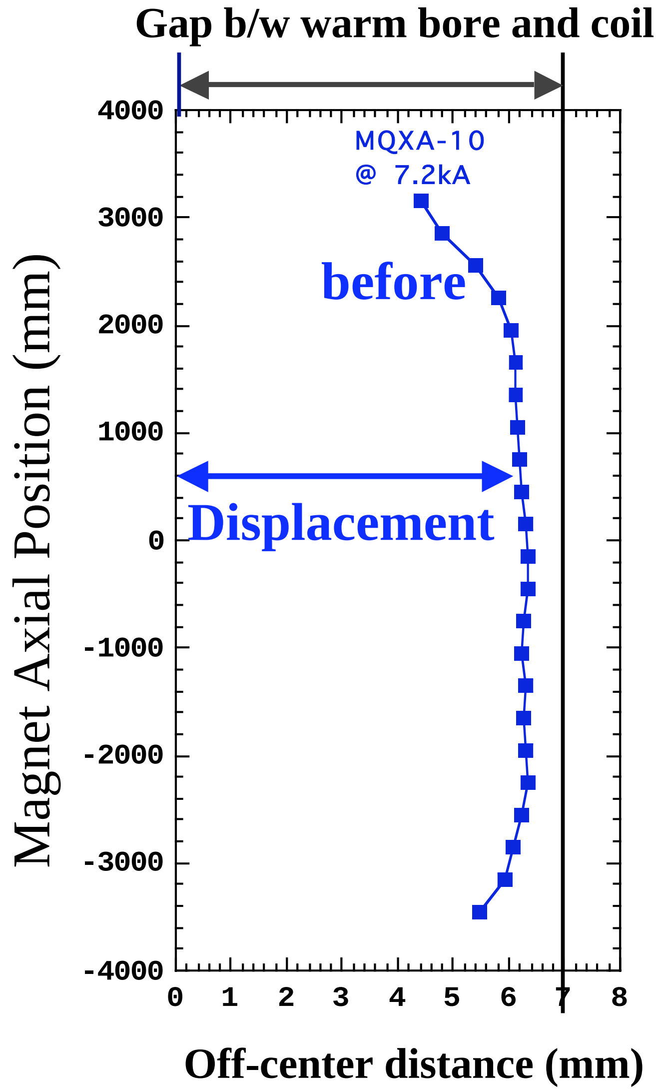
Harmonic-coil Displacement Determined by Field Measurement

Direct heat conduction from warm tube to the coil ⇨ Quench!!



Coaxial tube for warm and cold bore (SUS316L)

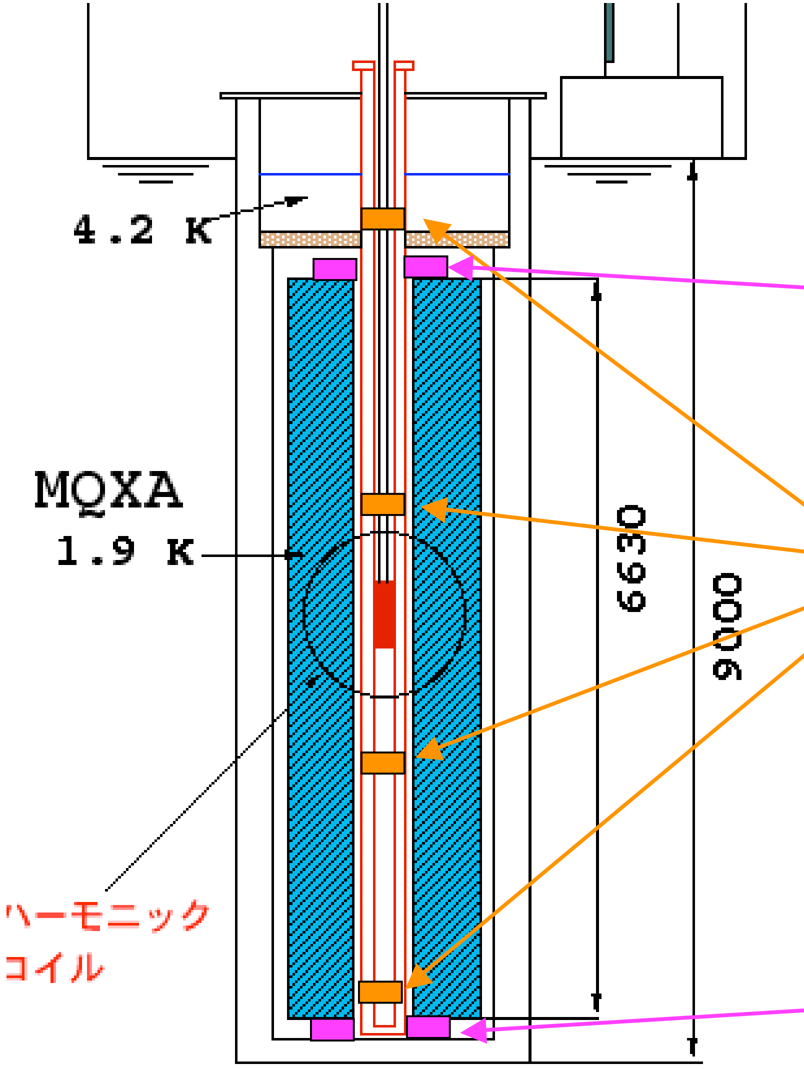
Decentering force:~100N/m。
@ 3 mm deviation at G = 215 T/m

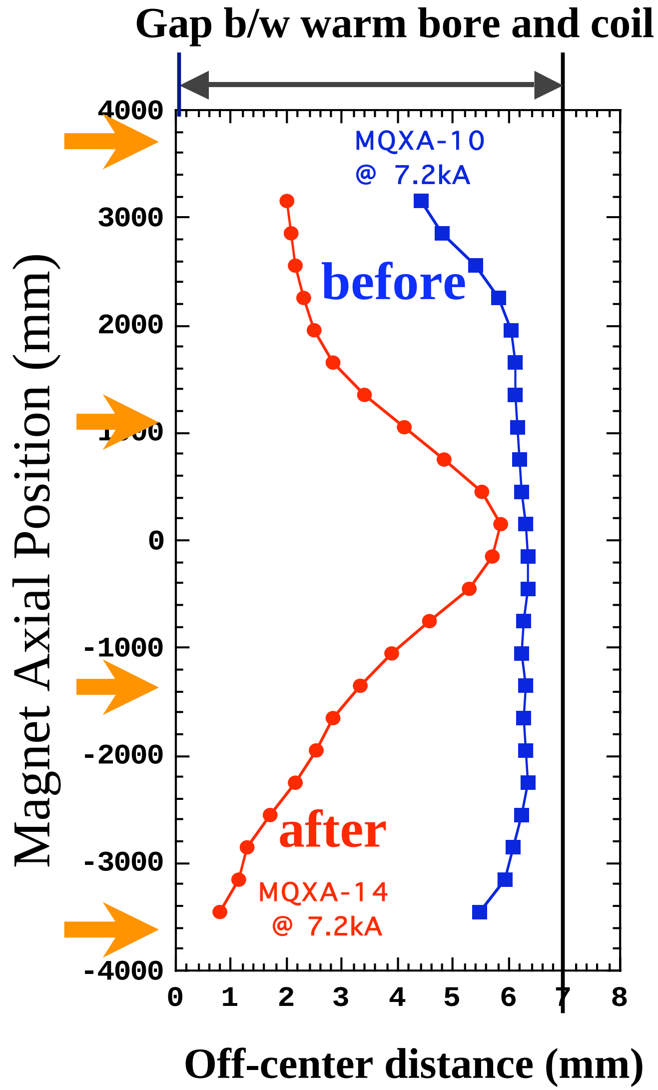


Harmonic-coil Displacement Determined by Field Measurement

Direct heat conduction from warm tube to the coil ⇨ Quench!!

Action!!

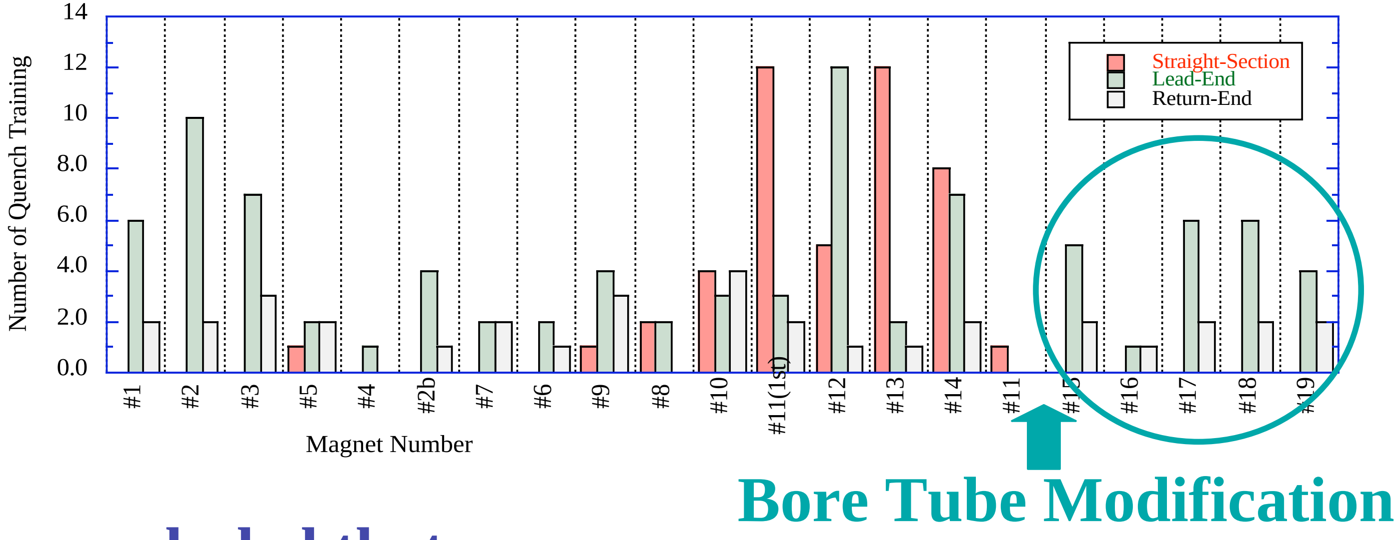




Coaxial tube for warm and cold bore (SUS316L)

Decentering force:~100N/m。
@ 3 mm deviation at G = 215 T/m

Improved Quench Characteristics



We concluded that

- **–Because of magnetic permeability of bore tube made of stainless steel 316L, (~ 1.003 @ 300 K, ~1.01 @ 1.9 K) ,**
- **–Bore tube bent due to electromagnetic fore in strong magnetic field gradient.**
- **–It caused training quench increased.**

Training characteristics were significantly improved after bore tube modification.

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Summary of MQXA

- **The production of 20 MQXA quadrupoles for the LHC low-beta insertions has been completed in 2004.**

- **19 magnets have been cold-tested. All reached 230 T/m after training and showed no re-training up to 220 T/m after full energy dump at 215 T/m.**

- **Field quality fulfilled the requirements for beam optics, and it's uniformity is stable in a level of 10^{-5}.**

- **The tolerance on coil position of 50 μm was attained, and field measurements indicated uniformity of dimensions throughout production in a level of ~ 20 μm (1 σ).**

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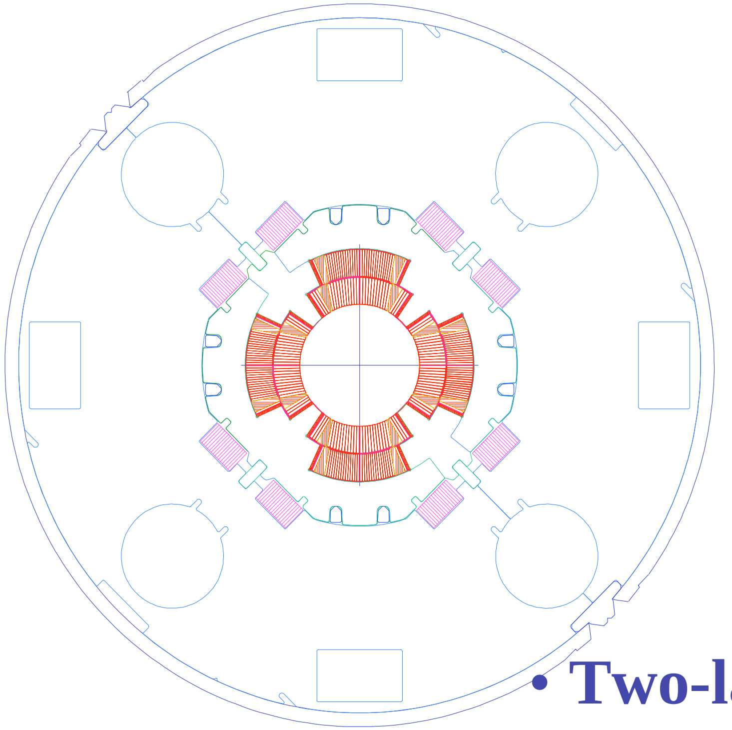
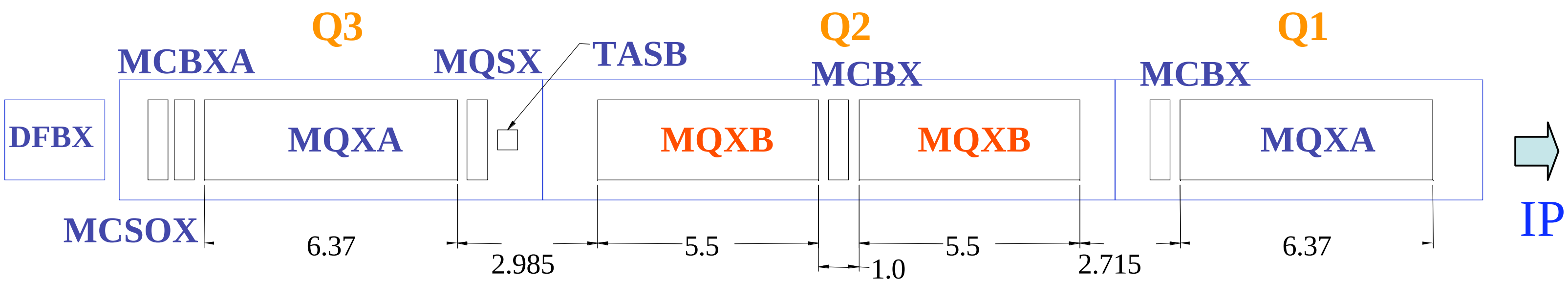
MQXB Low-Beta Quadrupole (FNAL)



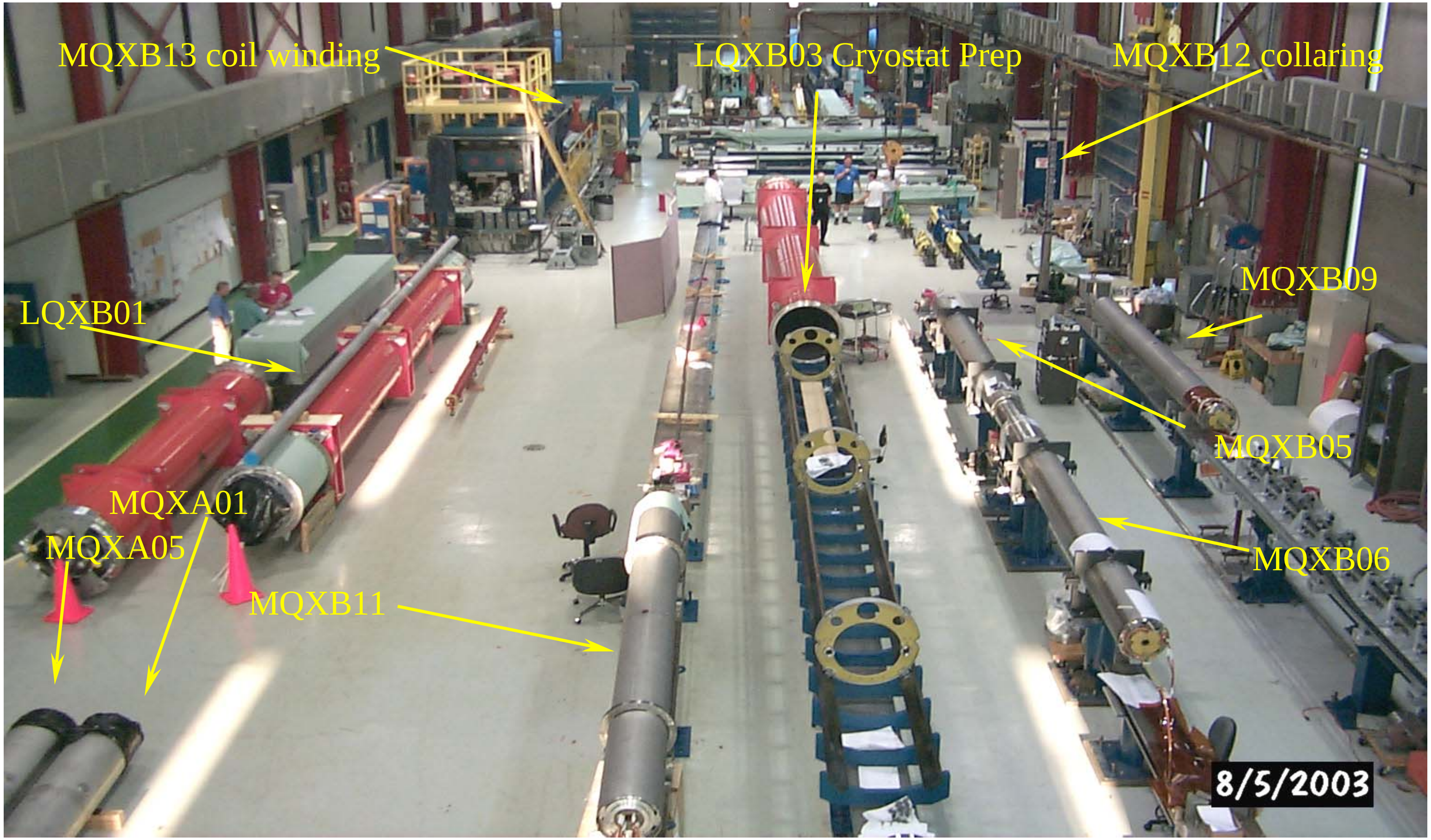
70 mm ID Coil
G = 215 T/m at 1.9 K
I = 11950 A
E = 248 kJ/m
L_{mag} = 5.5 m

2-m Model: 9
Full-scale Proto: 1
Production: 18

- Two-layer, graded coil,
- Free standing collars, fully supporting the forces,
- Keyed iron-yoke. (45° rotated)



Assembly Facility in FNAL



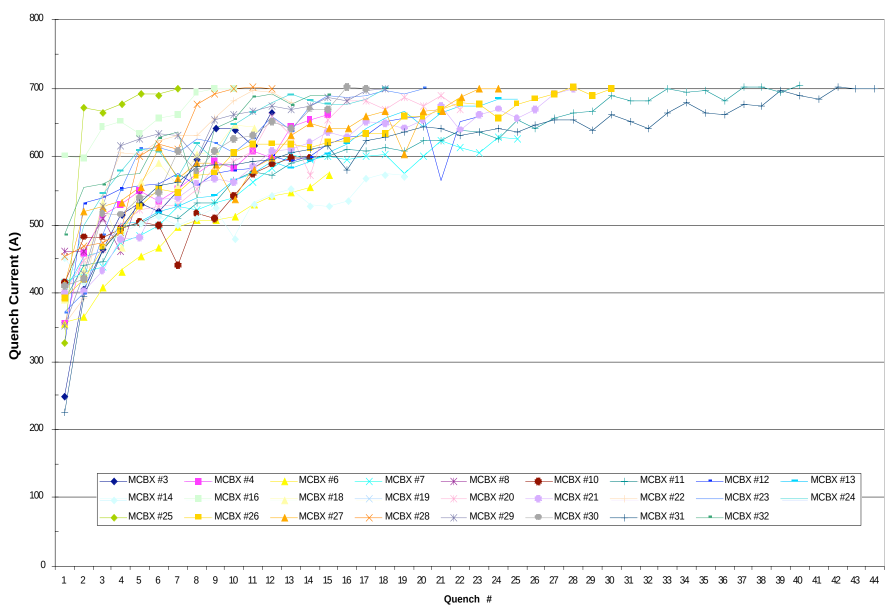
Courtesy of J. Kerby

Low-Beta Correctors: CERN

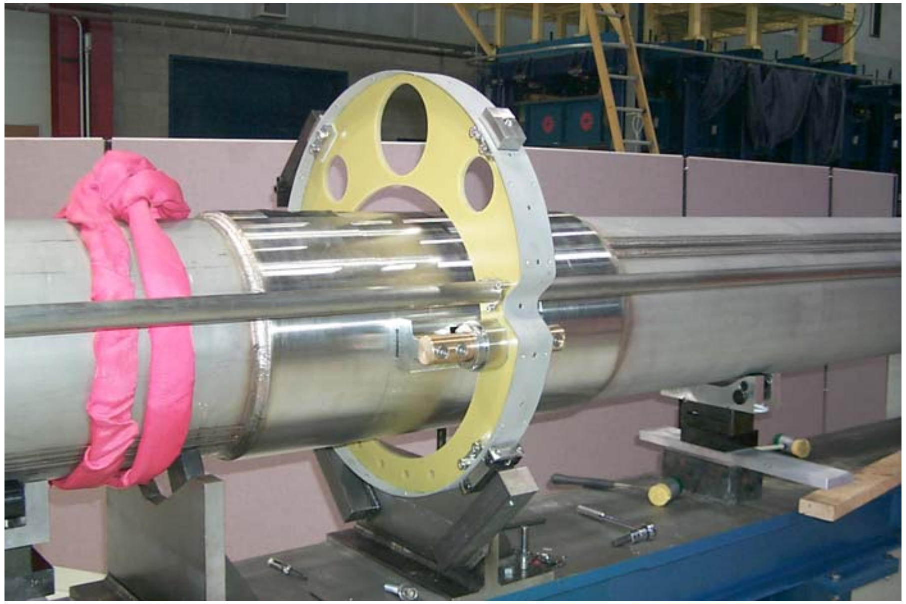
MCBX

MQSX, MCSOX, MCSX and MCTX

MCBXV (Inner Dipole) Training @ 4.3K



Assembly of Q2: MQXB+MCBX+MQXB



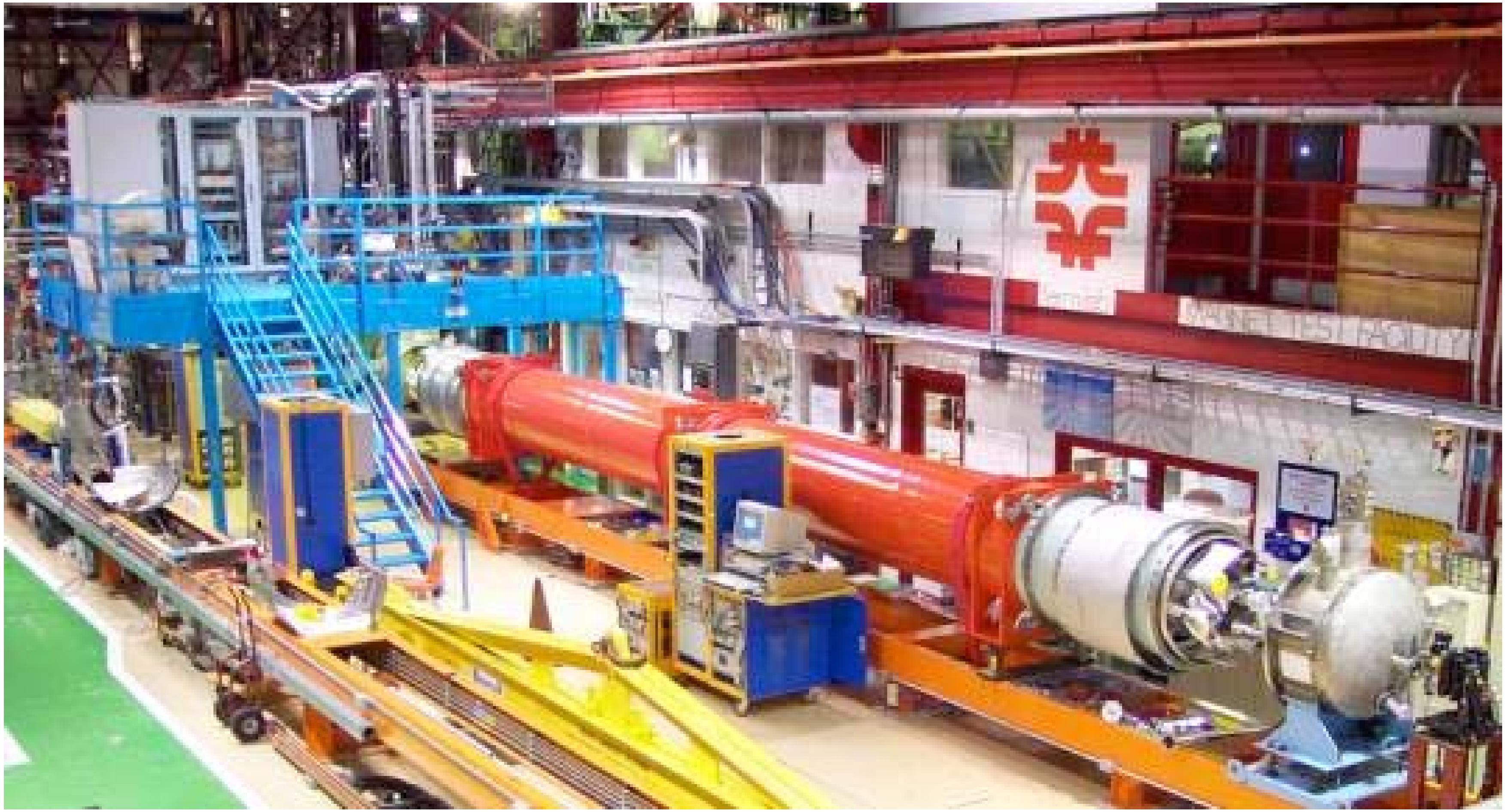
Low-Beta Quadrupole Cryostat

2 MQXB welded end-to-end
with central sleeve; MCBX inside

External Heat Exchanger for
IP1/5 dynamic heat load

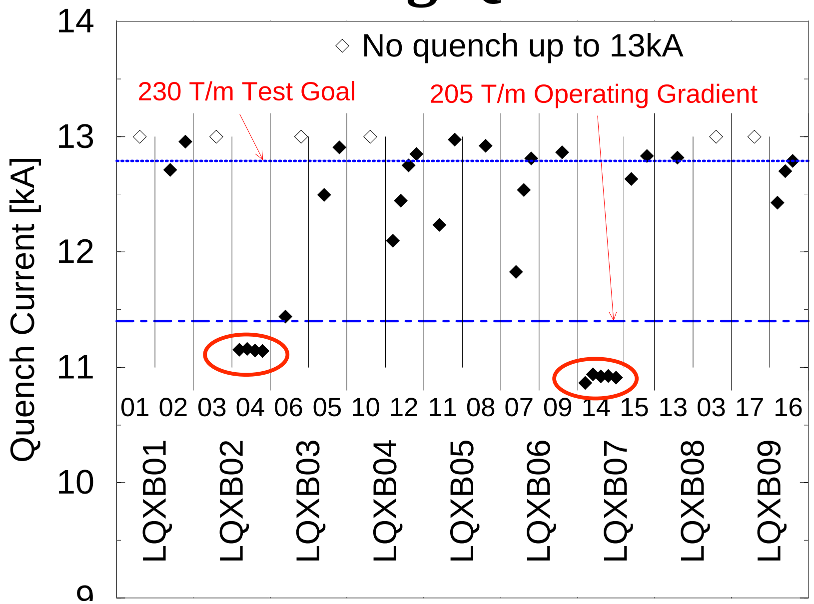
"Spider" support for
alignment rigidity

Q2 on test in FNAL



Test Results of MQXB

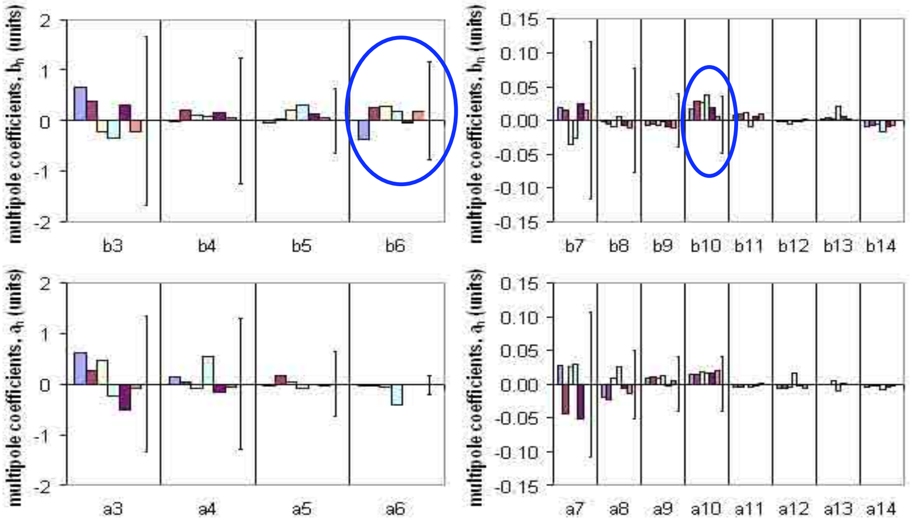
Training Quench



- Most magnets showed excellent quench performance.
- But, 2 magnets trained to a plateau around 200 T/m.

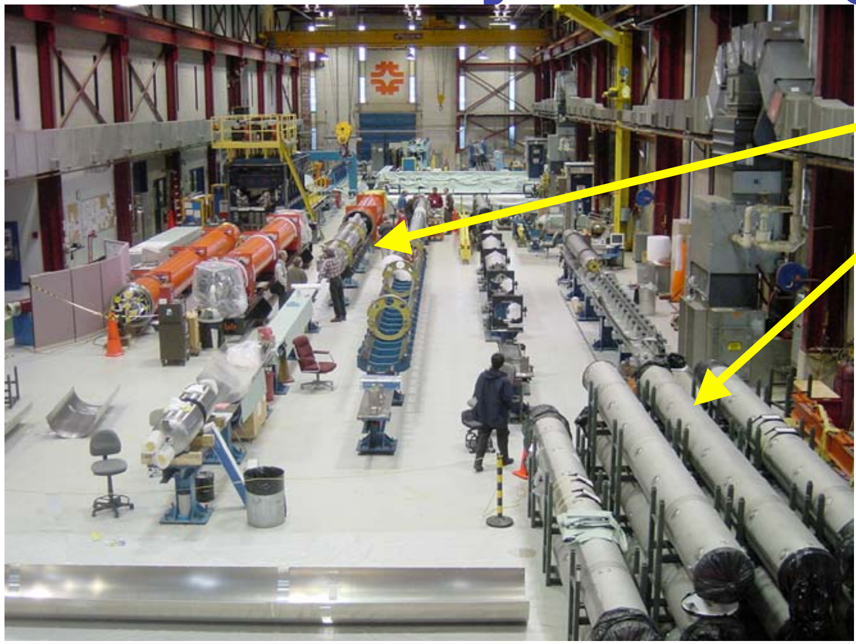
Two magnets were reassembled for repair and reached 230 T/m.

Multipole Components

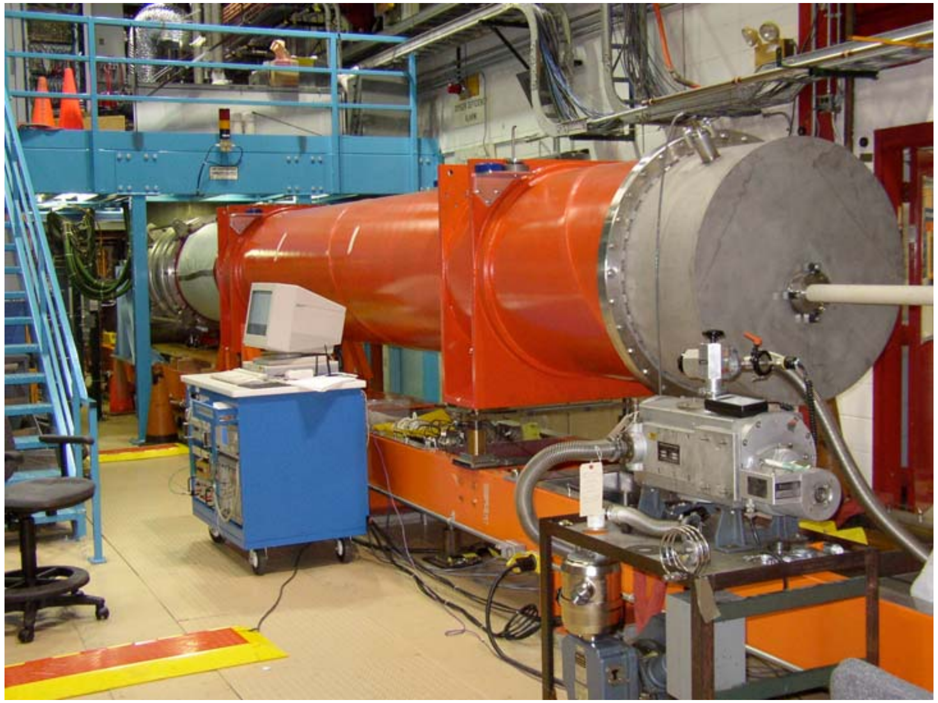


- Multipole components are controlled at 10^{-4} or smaller.
- Generally good within reference values.

MQXA Cryostating & Test at FNAL



MQXA



First Test of MQXA

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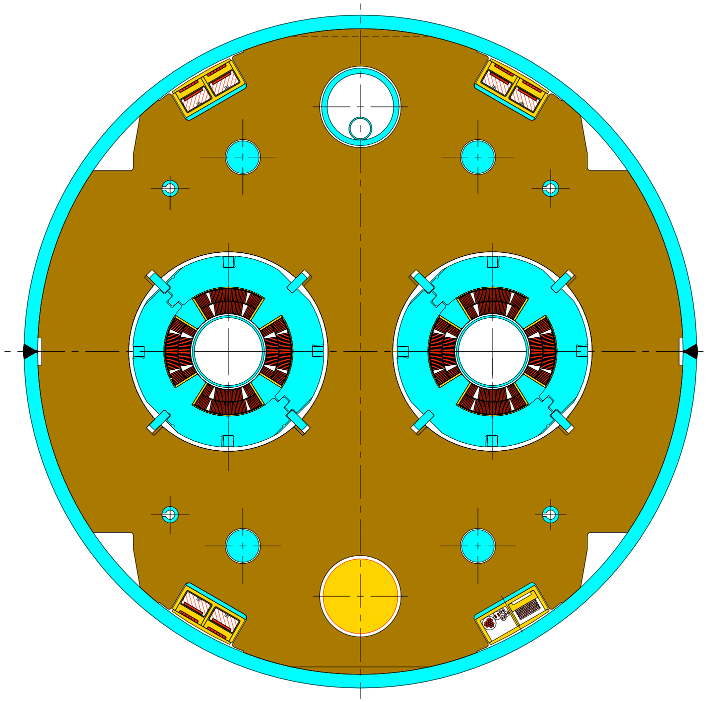
Matching Quadrupoles: MQM

Connecting the beam optics of the arc section to the final focus system.



56 mm ID coil

86 units + spare

G = 200 T/m at 1.9 K

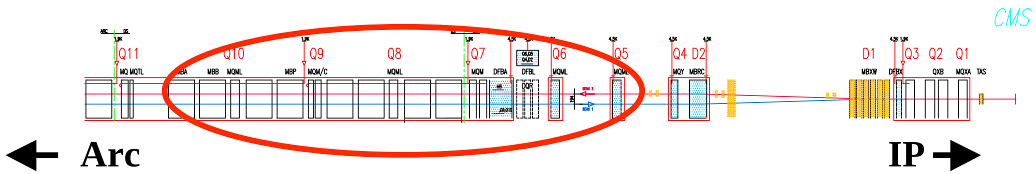
I = 5390 A

E = 64.3 kJ/m/aperture

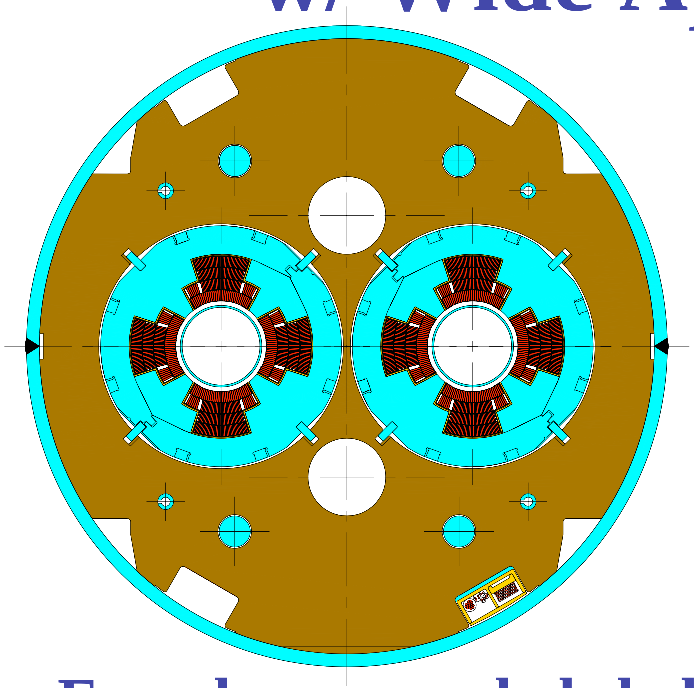
L_{mag} = 2.4/3.4/4.8 m

Manufactured by Tesla

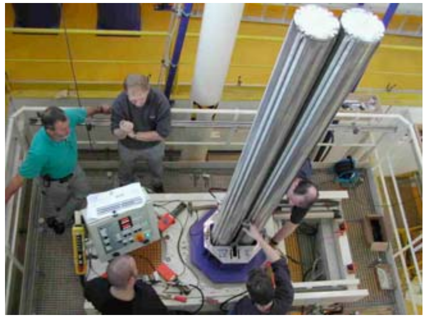
- Two-layer, non-graded coil,
- Free standing collars, fully supporting the forces,
- Two-in-one iron yoke.

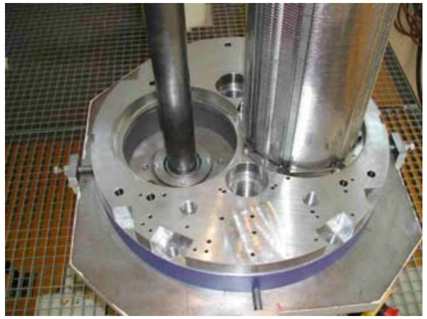


Matching Quadrupoles: MQY w/ Wide Aperture

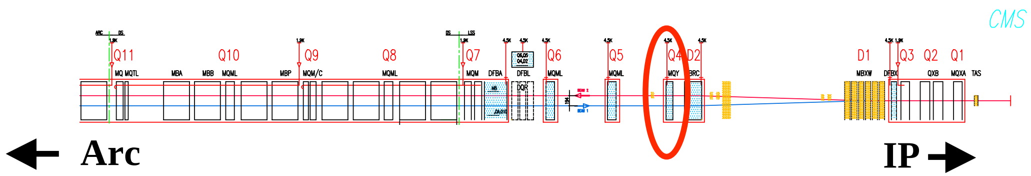


70 mm ID coil
24 units + spare
G = 160 T/m at 4.5 K
I = 3610 A
E = 141 kJ/m/aperture
L_{mag} = 3.4
Manufactured by ACCEL



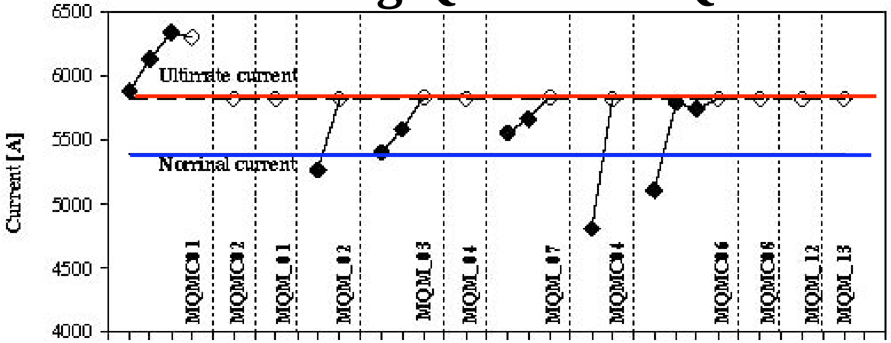


- Four-layer, graded shell coil,
- Free standing collars, fully supporting the forces,
- Two-in-one iron yoke.

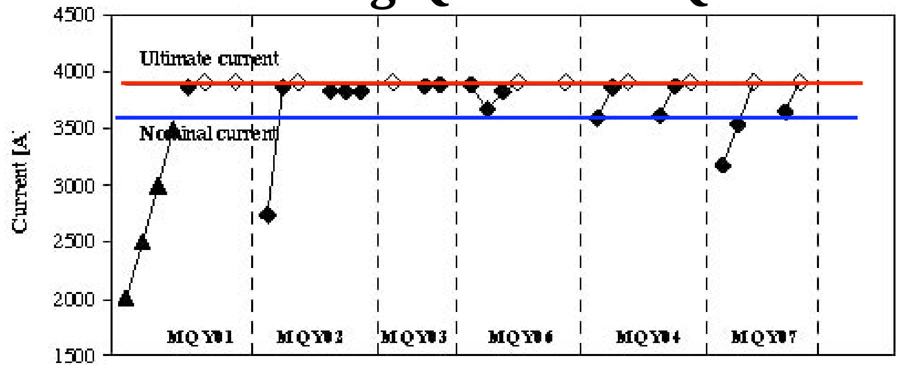


Test Results of MQM & MQY

Training Quench: MQM

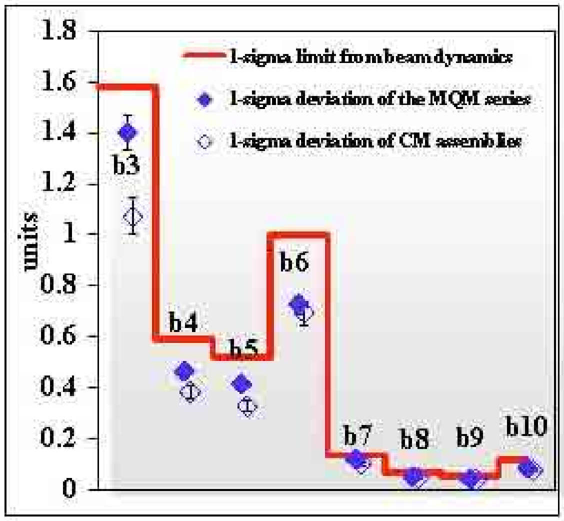


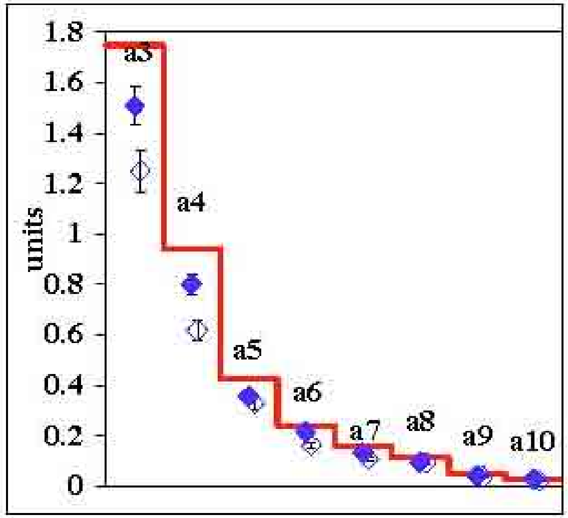
Training Quench: MQY



- Both magnets reached the ultimate current after a few training quenches.

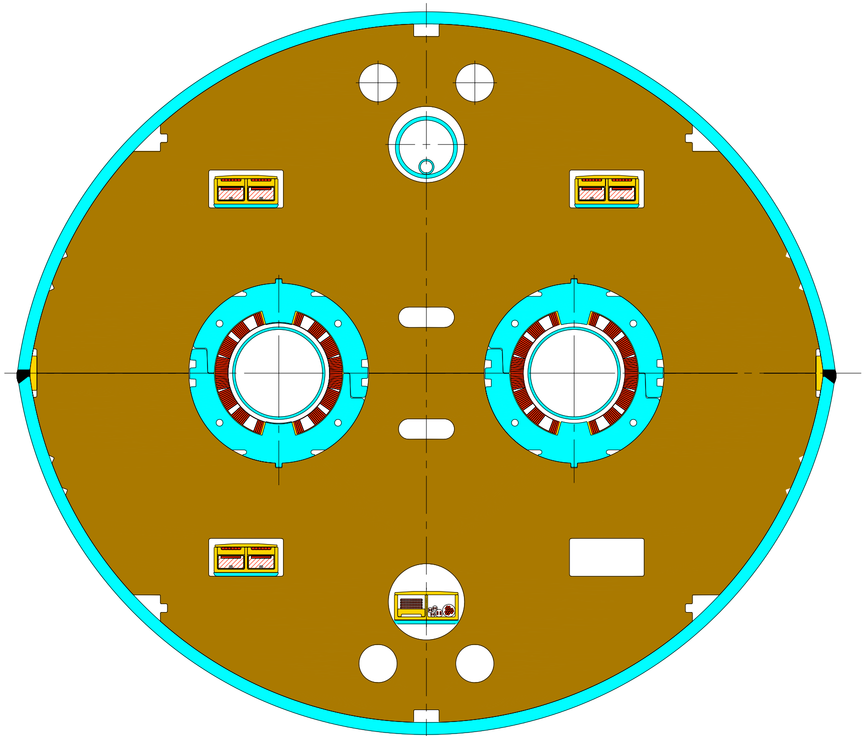
Multipole Components: MQM & its cold mass





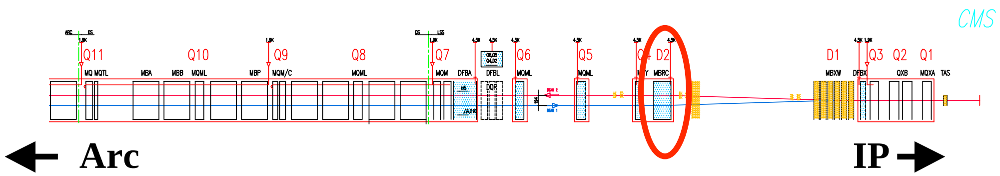
- Multipole components are controlled at 10^{-4} or smaller.
- Matching a set of MQMs effectively reduced the multipole components.
- Generally good within reference values.

Separation Dipoles: BNL



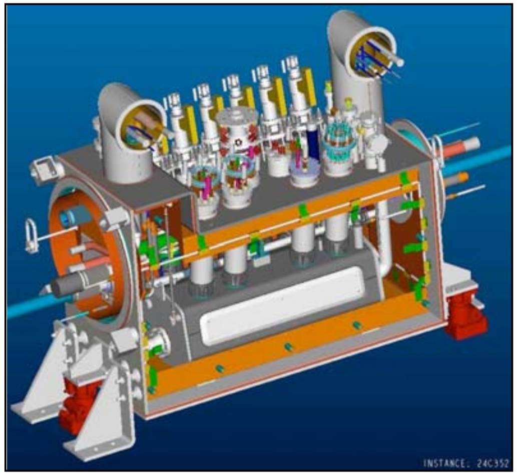
- RHIC main dipole coil,
- Single or twin aperture,
- Free standing collars,
- Horizontal-split iron yoke.

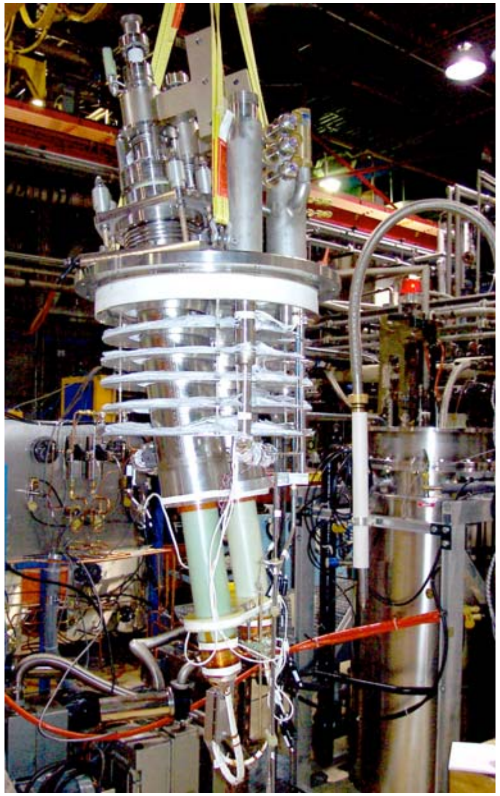
80 mm ID Coil
18 units + spare
B = 3.8 T
I = 6050 A
L_{mag} = 9.45 m



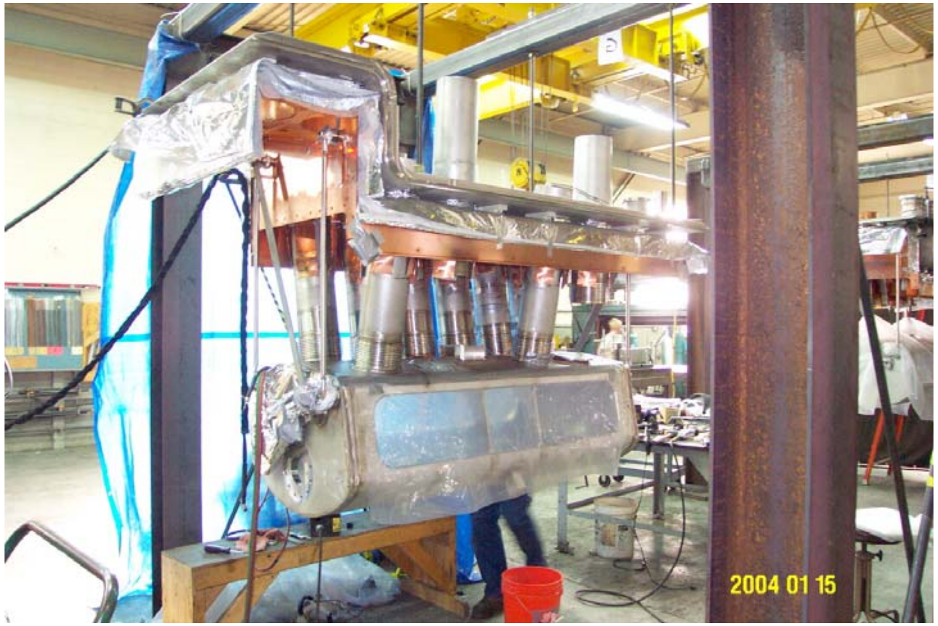
DFBX Production

Feed box for the inner triplets

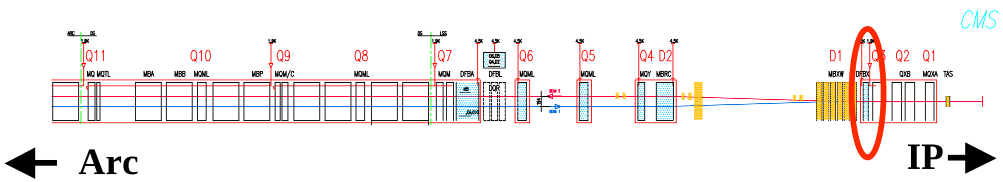




HTS Lead Testing
at Fermilab



Fabrication and Assembly
at Meyer Tool

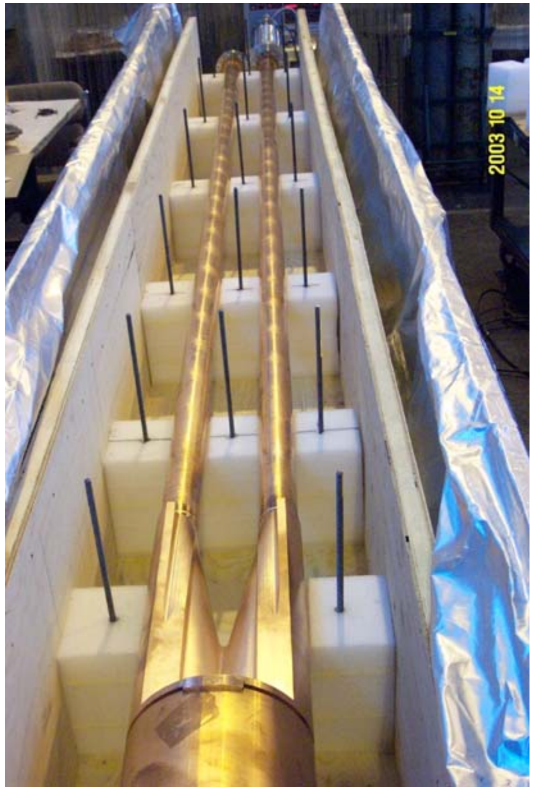


IR Absorber: TAS&TAN

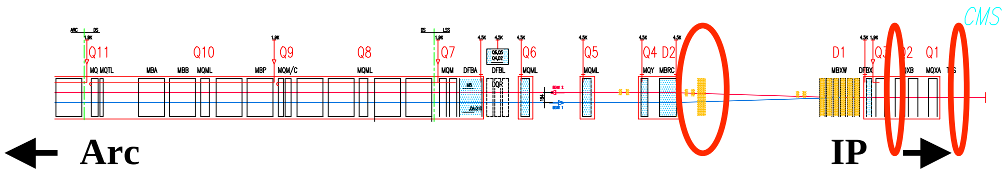
Crucial element to protect the insertion magnets from secondary particles from IP.

Single aperture TAS absorbers.

Twin aperture TAN absorbers.



TAN Beam Tube



*** Copper & Steel**

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Current Status of LHC Insertions

- **Production of the insertion elements was completed.**
- **So far, magnets and relevant apparatuses have been set in 6 out of 8 experimental insertions, and preparation work for the hardware commissioning is underway.**
- **In remaining 2 experimental insertions, magnets will be set by the end of May 2007.**
- **Superfluid helium heat exchangers for the inner triplet with defects are all being replaced to new ones with improvements. Replacement work will be finished soon.**

- **First cooldown of Sector 7-8 in the LHC tunnel is in progress. (3.6 K at March 21) First excitation test will be carried out next week(?). See http://lhc.web.cern.ch/lhc/**
- **Beam commissioning at 450 GeV is anticipated in Nov. 2007.**

Acknowledgment

Many thanks to CERN and Fermilab for their cooperation.