Superconducting Combined Function Magnet System for J-PARC Neutrino Beam Line

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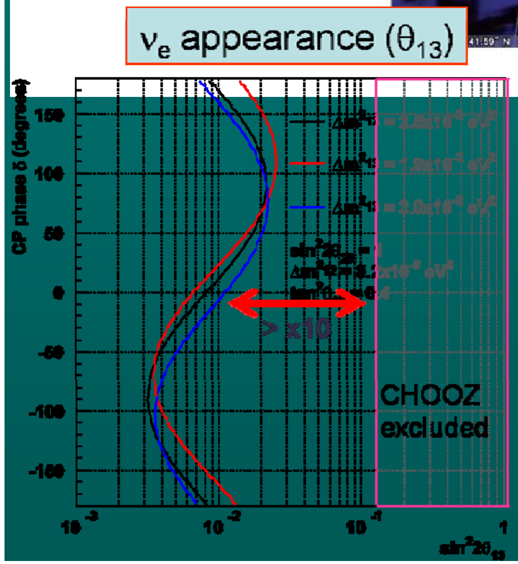
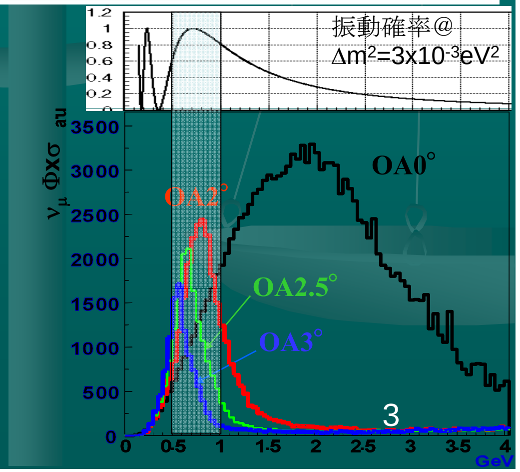
Contents

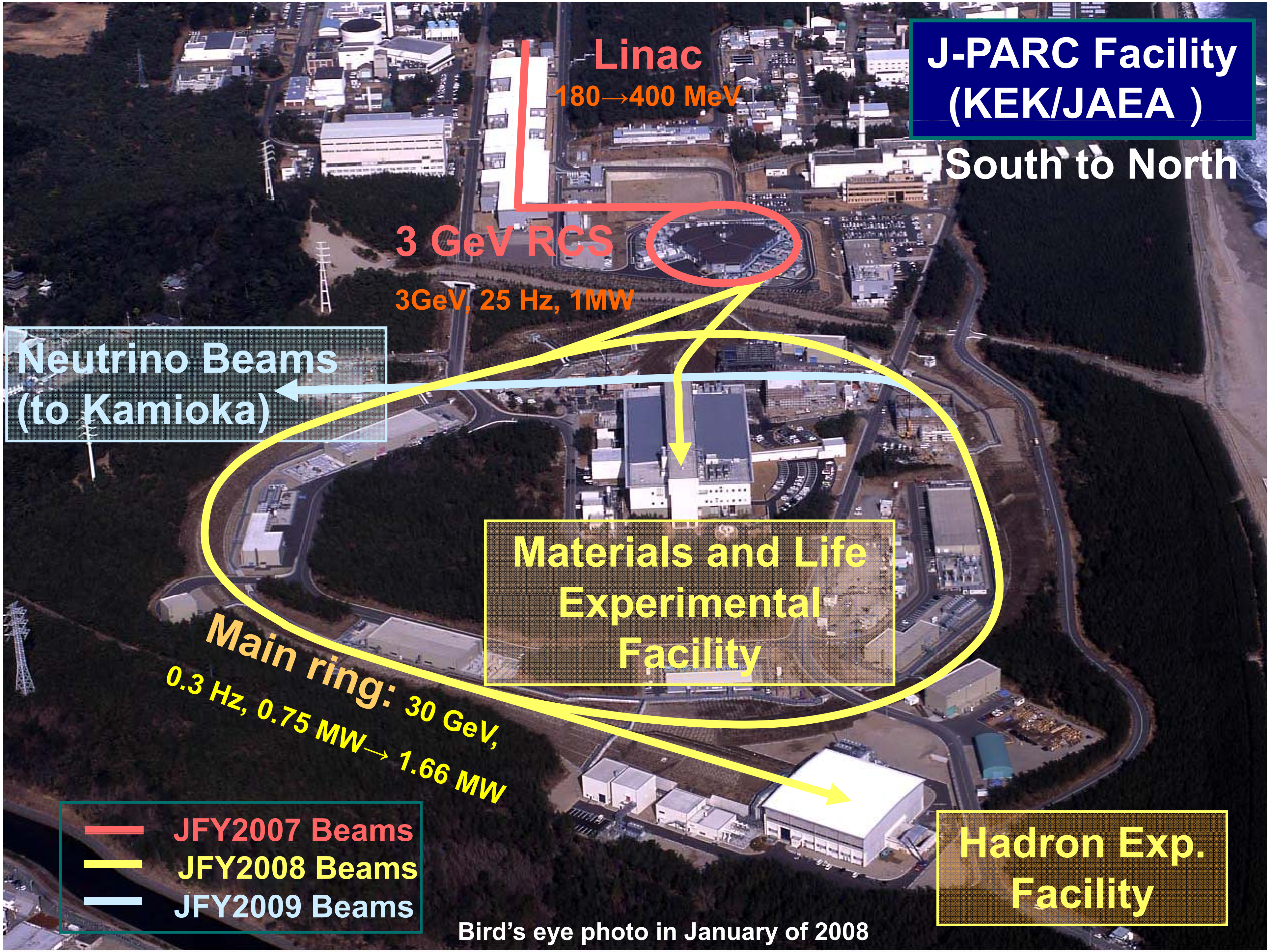
- **Introduction**
- Superconducting Combined Function Magnet
  - Prototype Development
  - Mass Production
- System Overview and Cryogenics
- Commissioning
  - Hardware Commissioning
  - Beam Commissioning
- Conclusion

Tokai-to-Kamioka (T2K) long baseline neutrino oscillation experiment

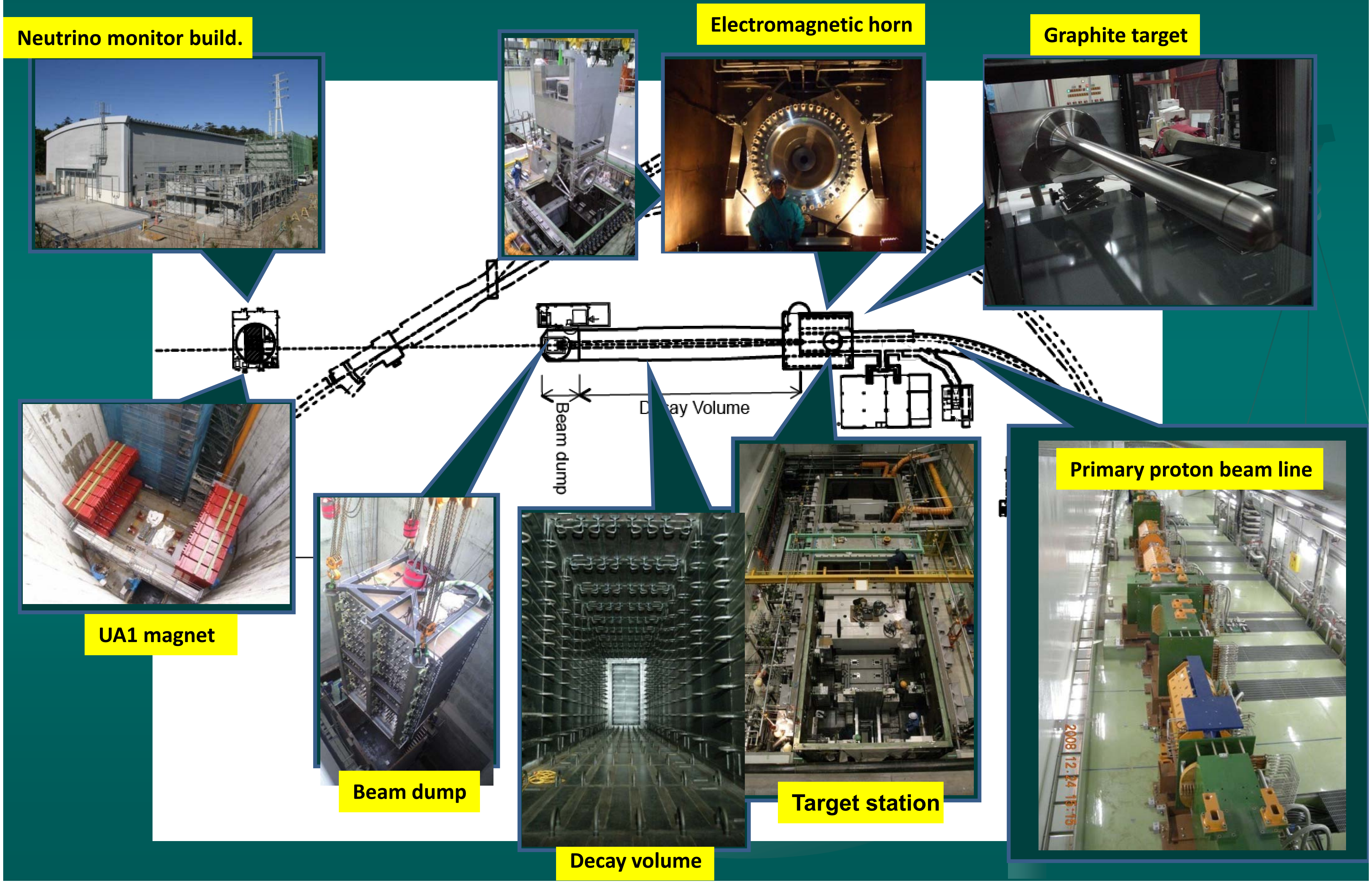


- Goal
  - **Discover νe app.**
  - νμ disapp. meas.
- Intense narrow spectrum νμ beam from J-PARC MR
  - Off-axis w/ 2~2.5deg
  - Tuned at osci. max.
- SK: largest, high PID performance



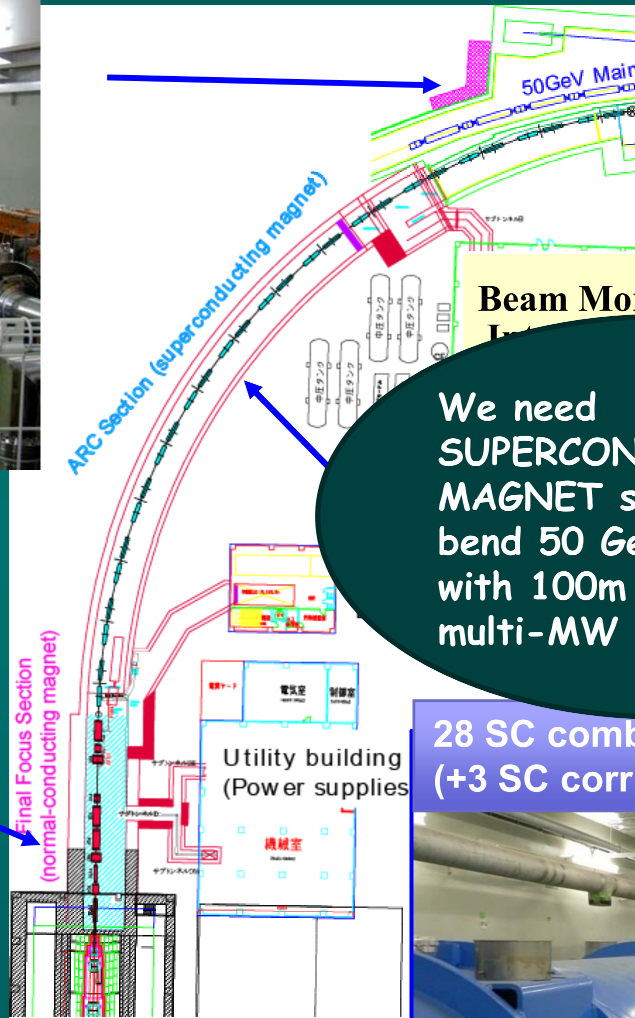

J-PARC Facility
(KEK/JAEA)
South to North
Linac
180→400 MeV
3 GeV RCS
3GeV, 25 Hz, 1MW
Neutrino Beams
(to Kamioka)
Materials and Life
Experimental
Facility
Main ring: 30 GeV,
0.3 Hz, 0.75 MW→ 1.66 MW
Hadron Exp.
Facility
JFY2007 Beams
JFY2008 Beams
JFY2009 Beams
Bird's eye photo in January of 2008

Neutrino beamline



Primary Beam-line

Assumed Beam Loss
750W@Prep.
250W@FF.
(1W/m @ ARC)



But they are expensive and also takes time… I don't like it…

We need SUPERCONDUCTING MAGNET system to bend 50 GeV proton with 100m R for future multi-MW option.

20D+20Q > 28 SCFM
Optimize Cost & Schedule

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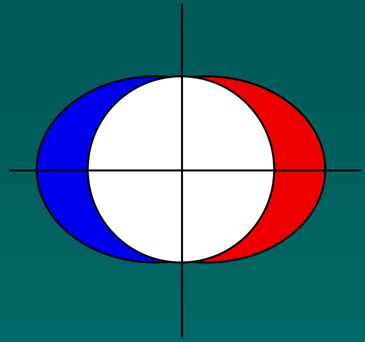
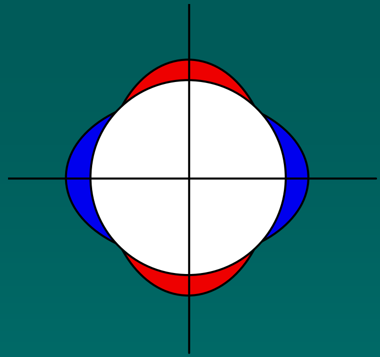
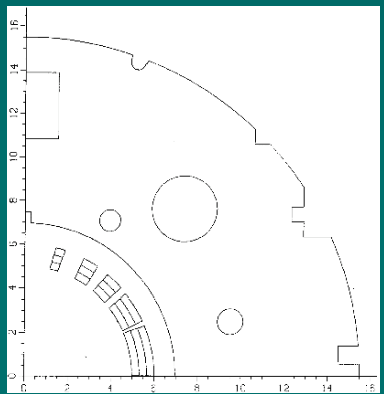
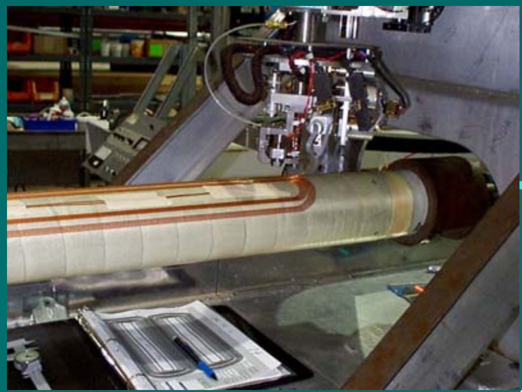
Combined Function Magnet Concept

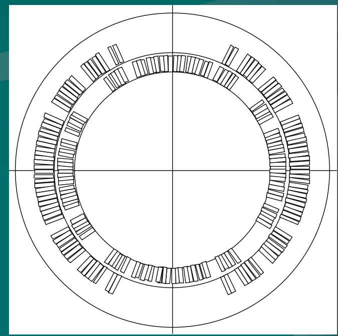






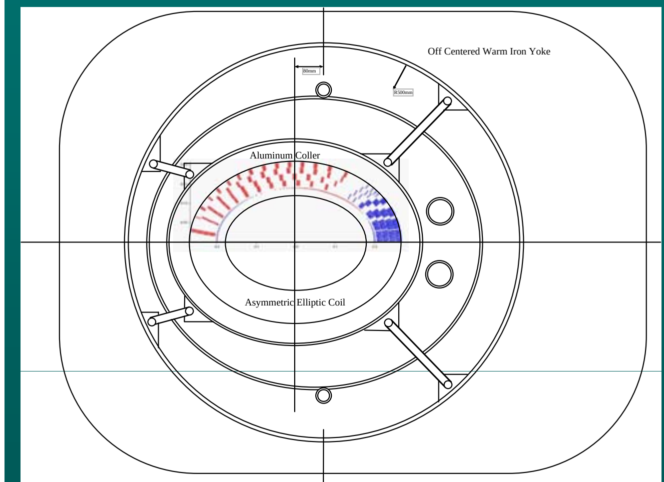


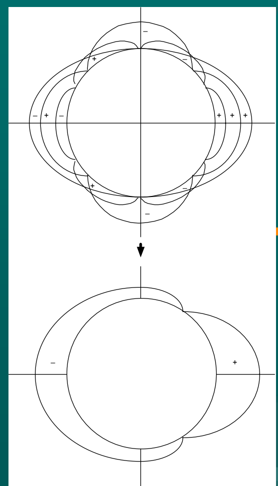
Current Distribution

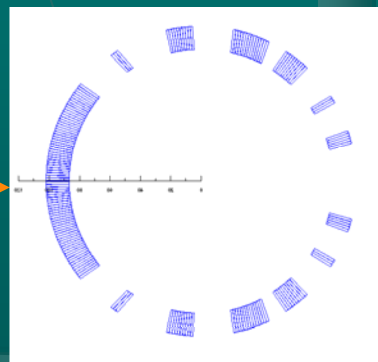


2002 Spring
Proposed by BNL
RHIC DX +
Direct winding coil

OR





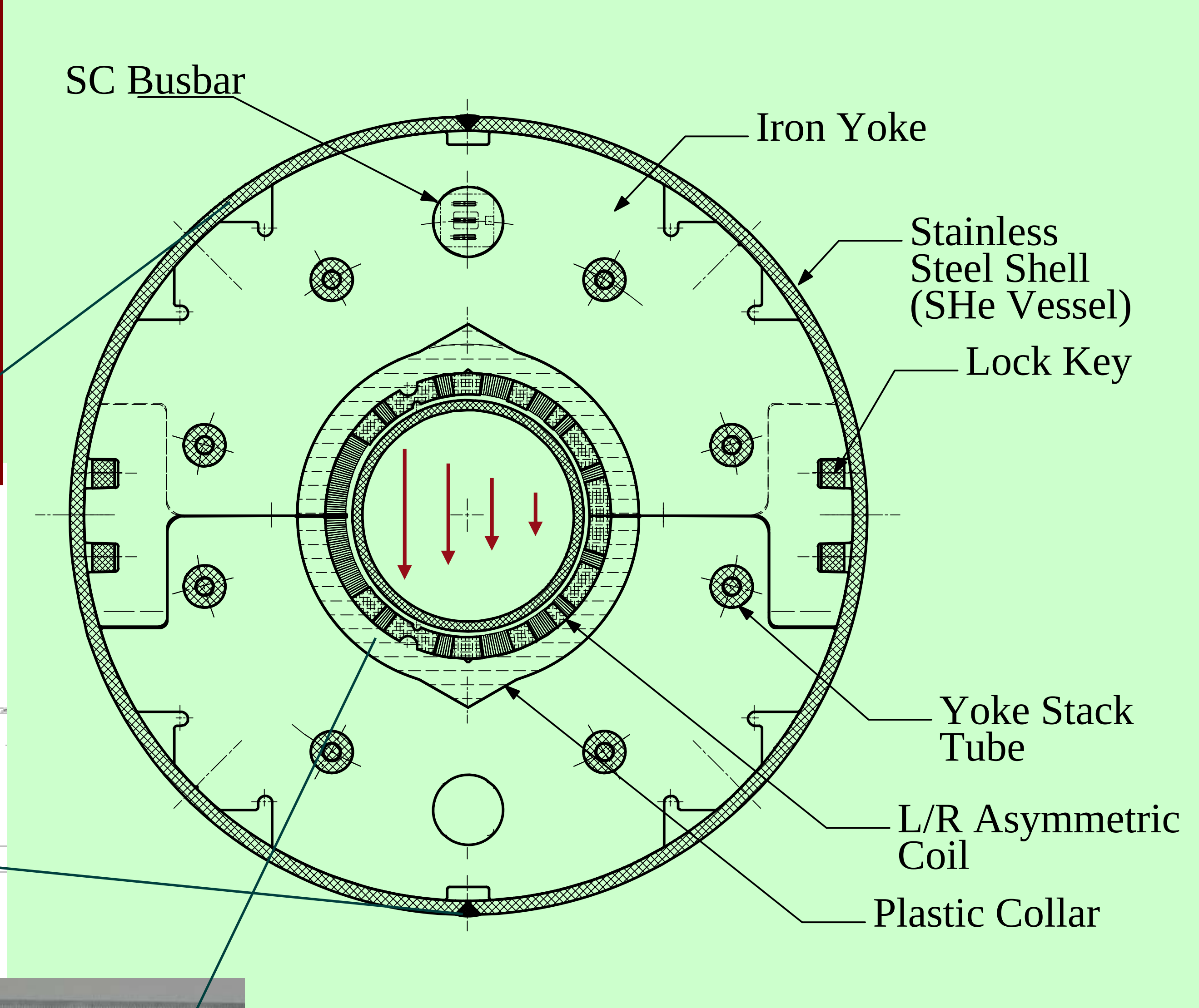


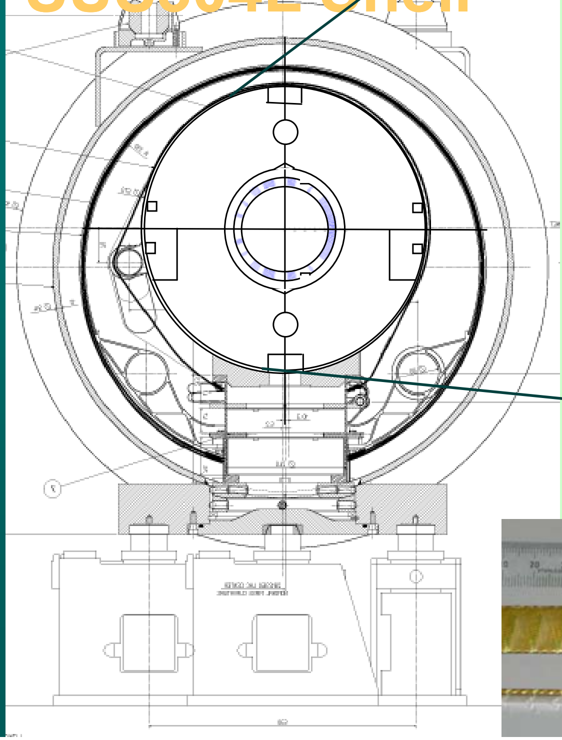
2002 Summer
Proposed by T.O.
L-R Asymmetry Coil
Based on FFAG SCM

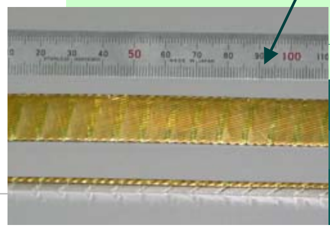
SC Combined Function Magnet

E.M. Design:
Single layer CFM

Mech. Design:
Plastic Spacer, Keyed Yoke, SUS304L Shell

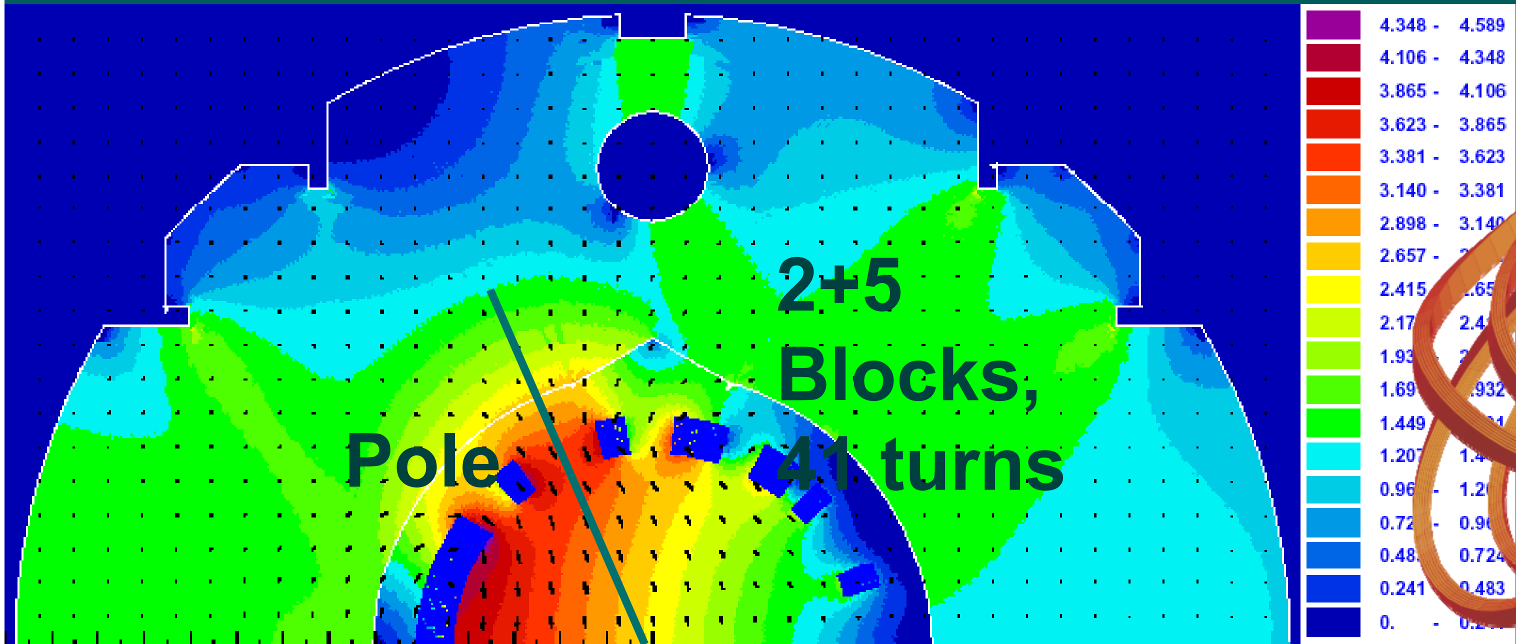


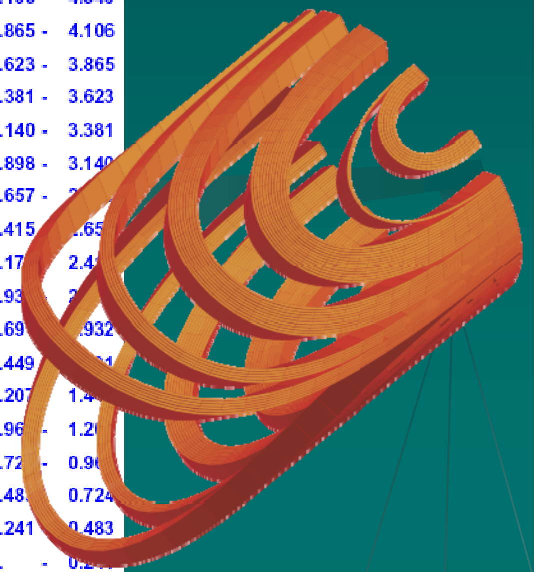




S.C. Cable for LHC-Dipole-Outer (strand: LHC leftov
w/ MQXA Insulation

Specification





Coil ID.:	173.4mm	Op. Current:	7345 A
Mag. Length:	3300 mm	Op. Margin:	72%
Mech. Length:	3630 mm	Inductance:	14
Tmax:	< 5.0K	Stored Energy:	386 kJ
(Supercritical Helium Cooling)		# of Magnet:	28
Dipole Field:	2.59 T	SC Cable:	NbTi/Cu
Quad. Field:	18.6 T/m		Rutherford Type Cable
Field Error:	< 10^-3 @ 50mm		for LHC Dipole Outer-L

	3D-SS	3D-LE	3D-RE	3D-Integral
Lmag(m)	1.94	0.78	0.58	3.3
B1 (T)	2.591	2.602	2.603	2.601
b2(unit)	3628	3567	3517	3581
b3(unit)	-0.93	-5.81	-10.15	-3.37
b4(unit)	5.01	-1.11	-2.35	-2.3
b5(unit)	2.07	-8.9	-16.0	-3.5
b6(unit)	-6.36	-7.9	-9.8	-7.2
b7(unit)	-1.16	-3.5	-5.3	-2.4
b8(unit)	-3.95	-2.9	-3.6	-3.7
b9(unit)	-8.86	-7.7	-7.9	-8.4
b10(unit)	-0.25	0.3	0.3	-0.0
b11(unit)	-3.10	-2.7	-2.6	-2.9
b12(unit)	2.07	1.7	1.6	1.9

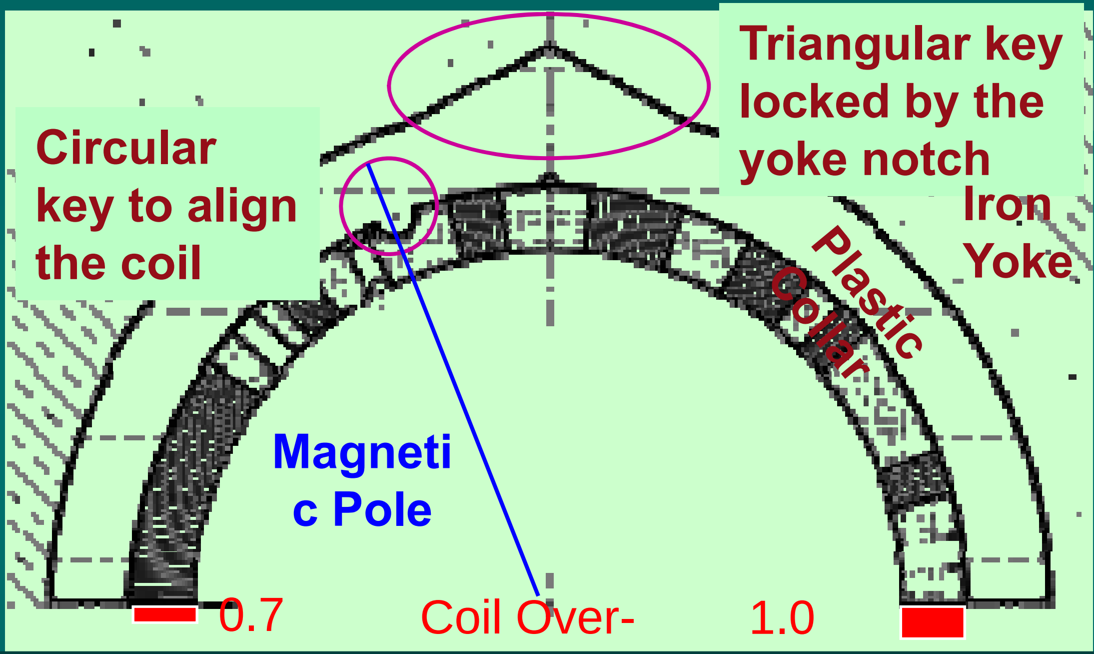
Good | Not So | Good Enough

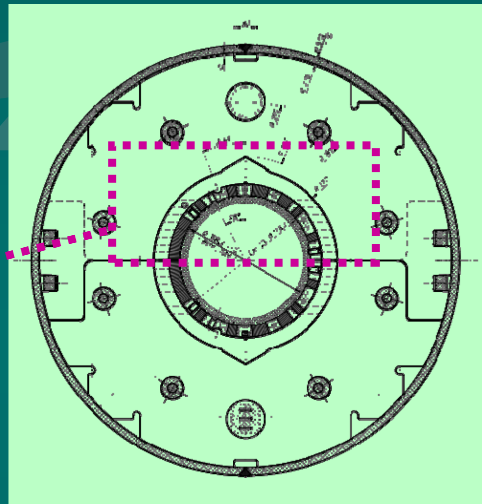
- Peak field at conductor in straight section is 4.6 T at 50 GeV.
- Load line ratios at 5 K for 40 & 50 GeV are 58 % & 72 %, respectively.
- Field quality within a tolerance of 10^{-3} is acceptable.

Contents

Coil & Collar

- Off-center magnetic pole ⇨ Left-right asymmetry
- Different thickness of wedges for both sides
  ⇨ Asymmetric mech. property
- Cured with wedges and the pole spacer
  ⇨ No collar insertion

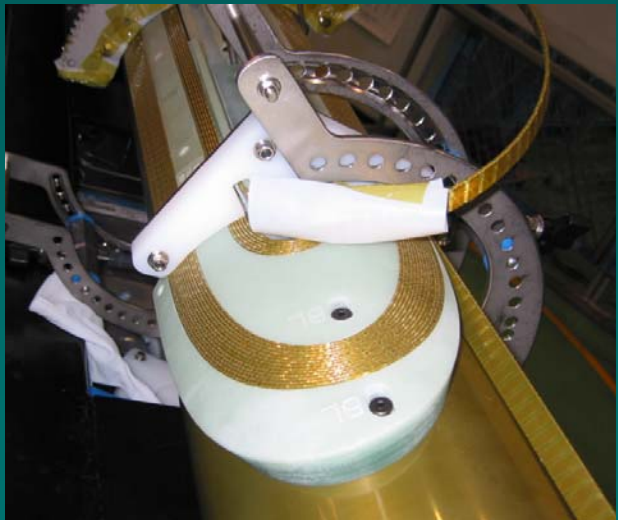




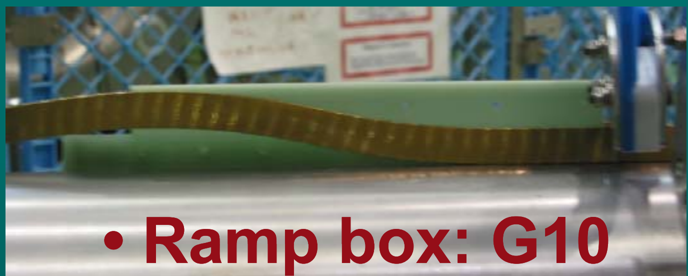
For excitation : ~30 MPa
For cool down : ~20 MPa → 50 MPa required
⇨ **Pre-stress of 80 MPa given by Yoking**

Process ⇨ **Coil over-size of 0.7 mm & 1.0 mm**

GFRP Wedges and Spacers



• End spacers: G10 (CNC file)



• Ramp box: G10

• Wedges: G11

Size Tolerance

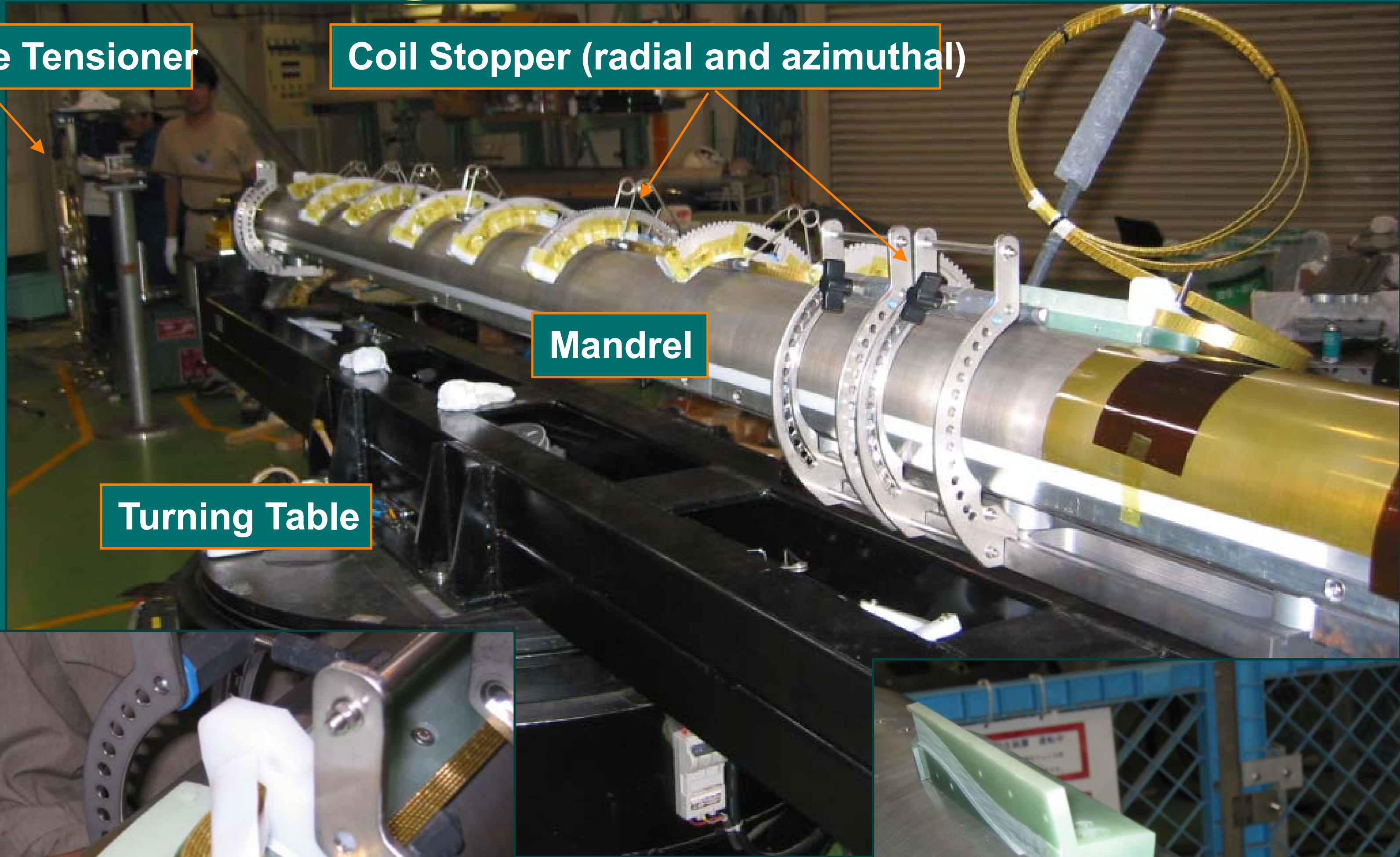
Target: < 0.05 mm

Actual: 0.1 mm

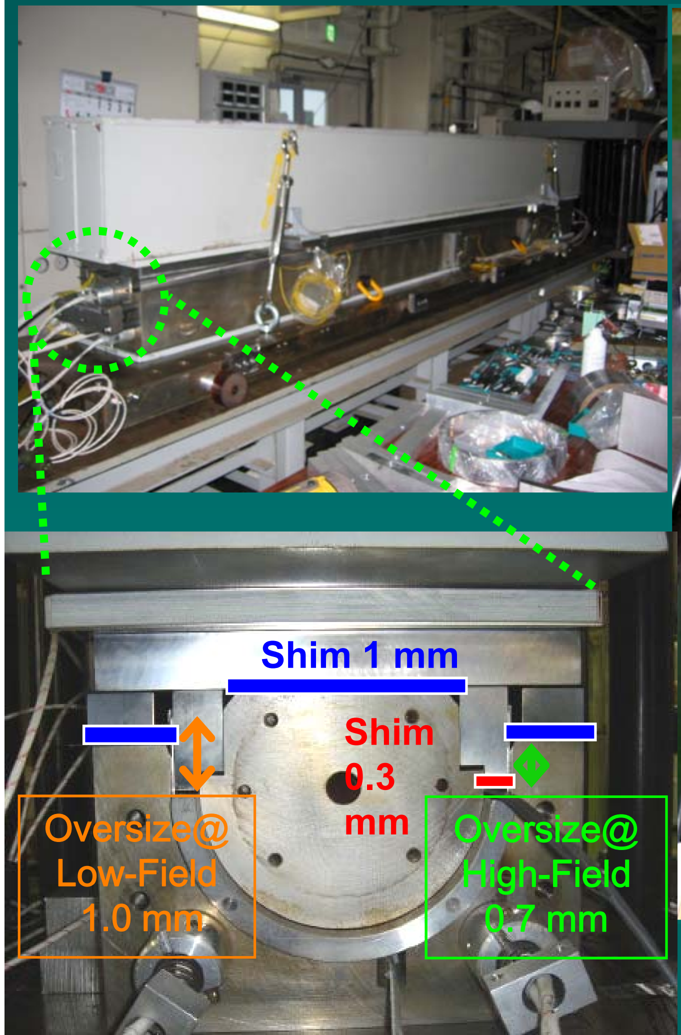
*Coil Pre-stress tolerance after yoking:

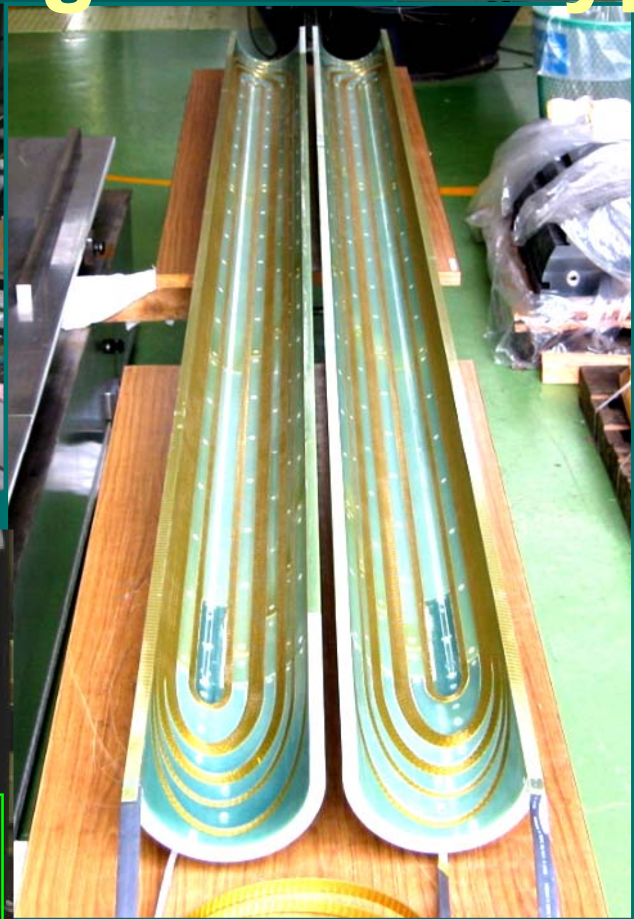
Verified by practice coil winding and mechanical short model study

Coil Winding Tool

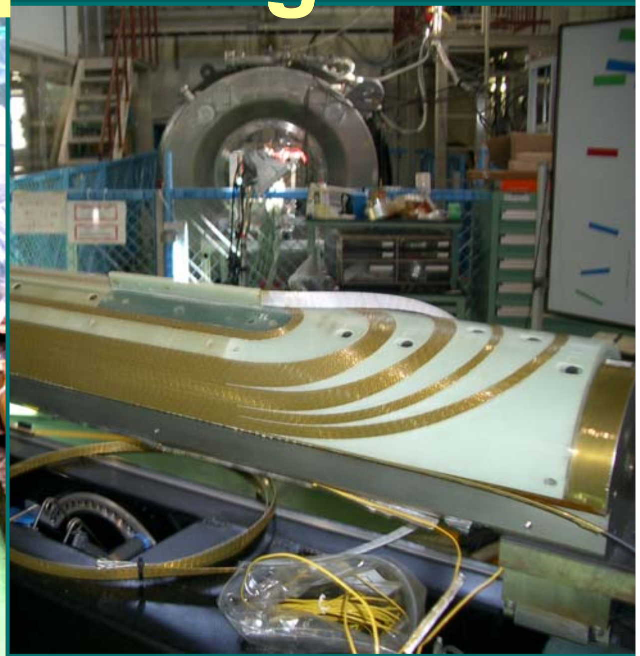


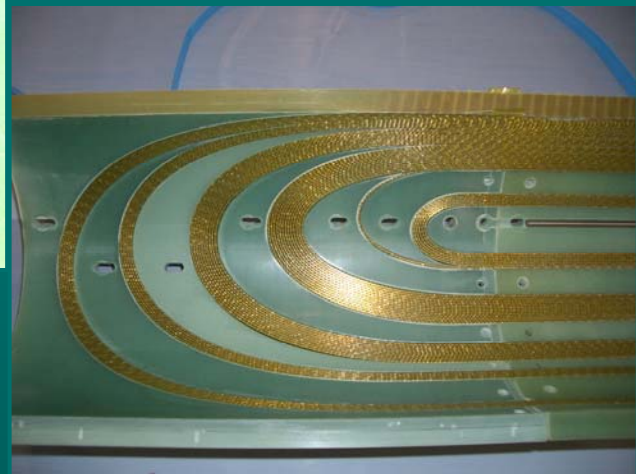
Coil Winding for Prototype Magnet





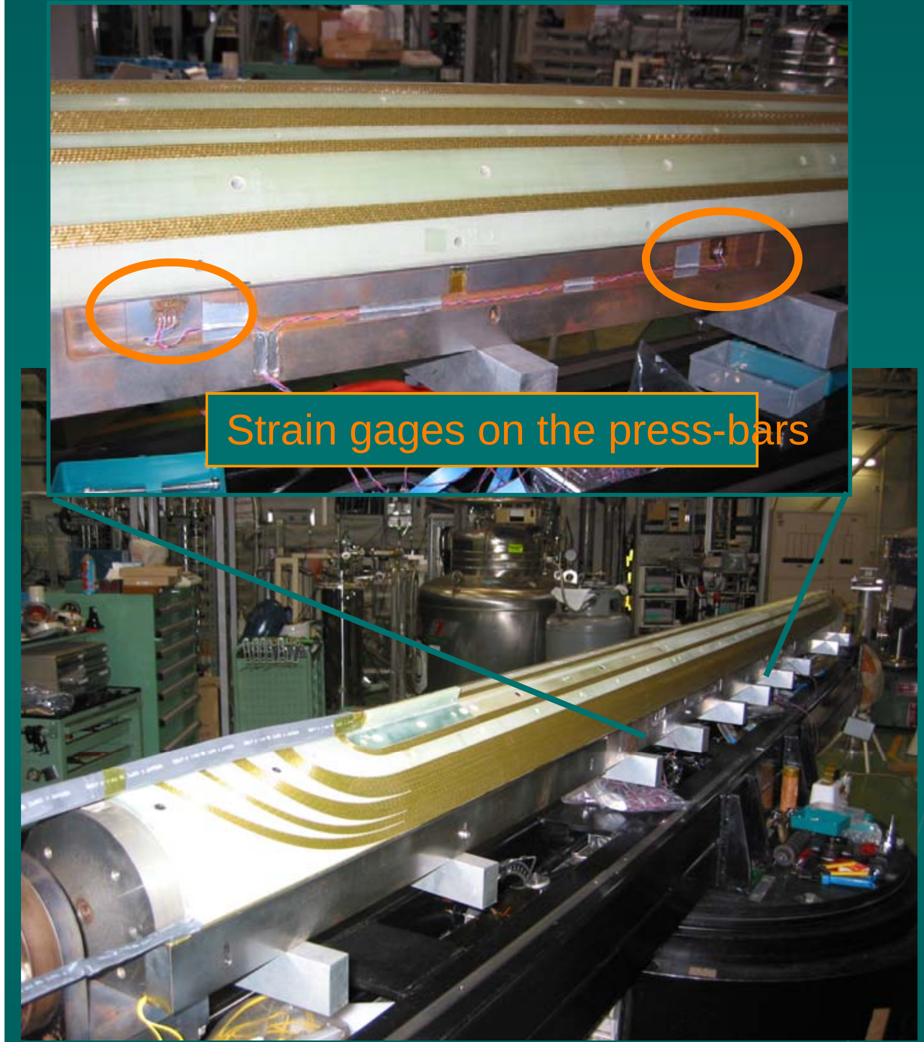
Mirror-symmetry Top & Bottom coils of the prototype

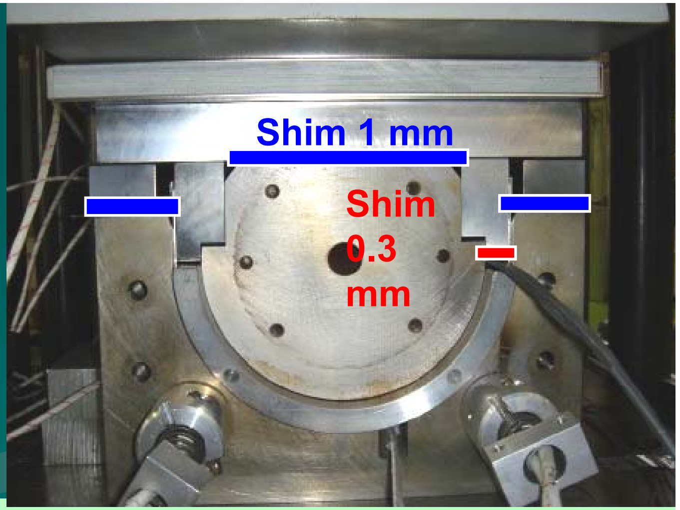


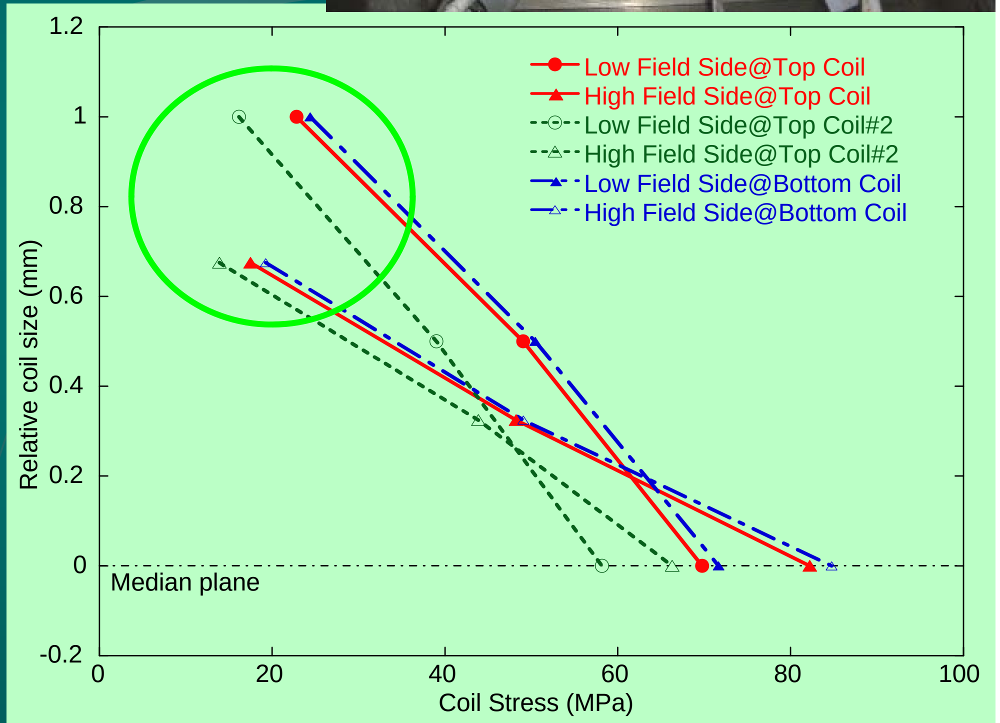


- Coil with pre-pregnant Epoxy resin cured at 400K for 5 hours.
- Asymmetric coil oversize determined by 2 sets of shims.

Coil Size Measurement

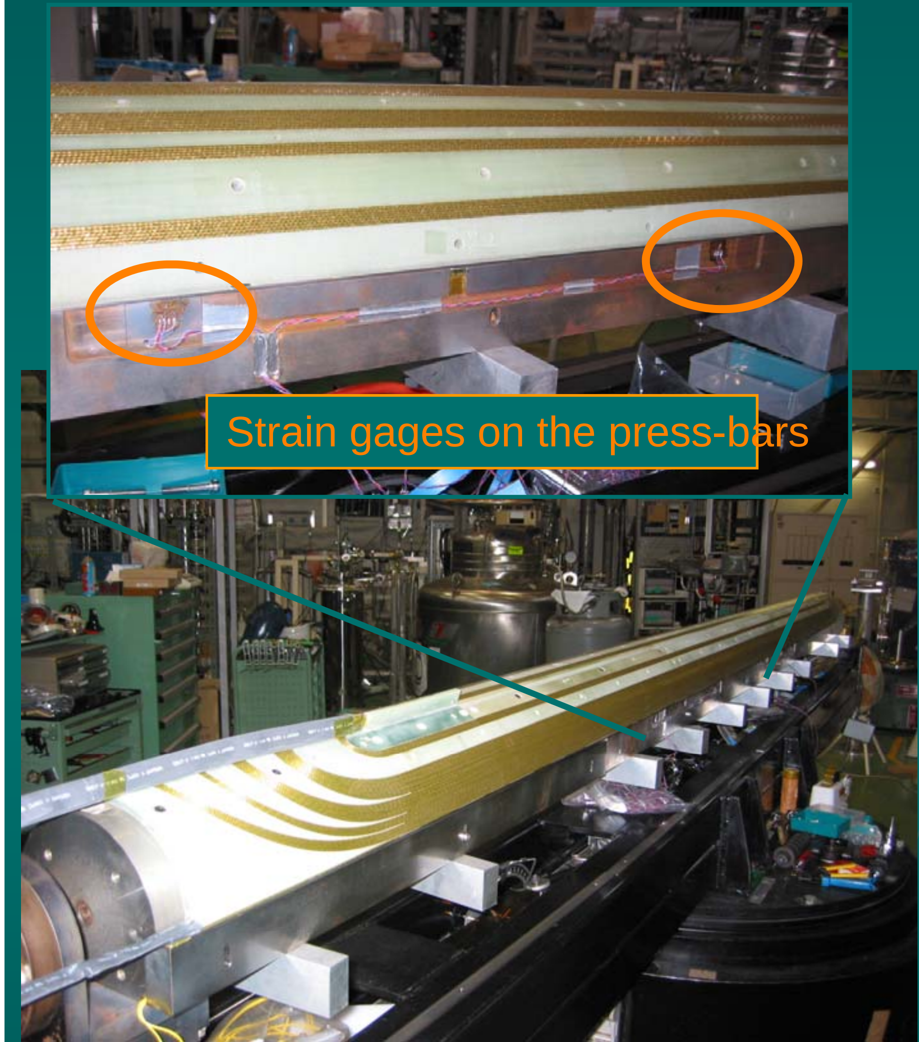


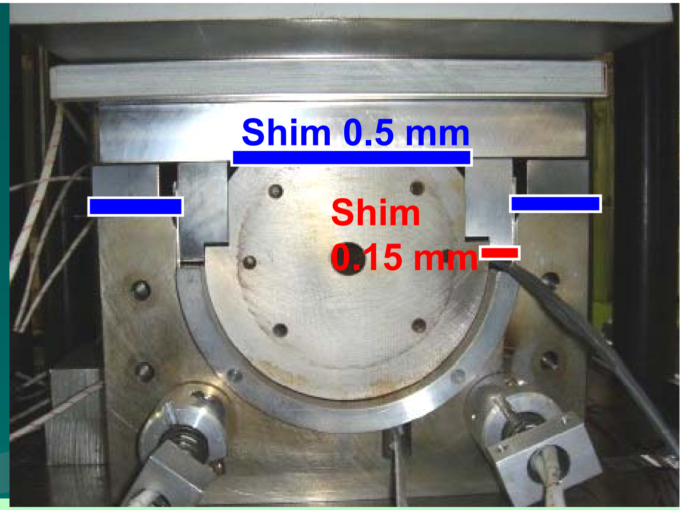


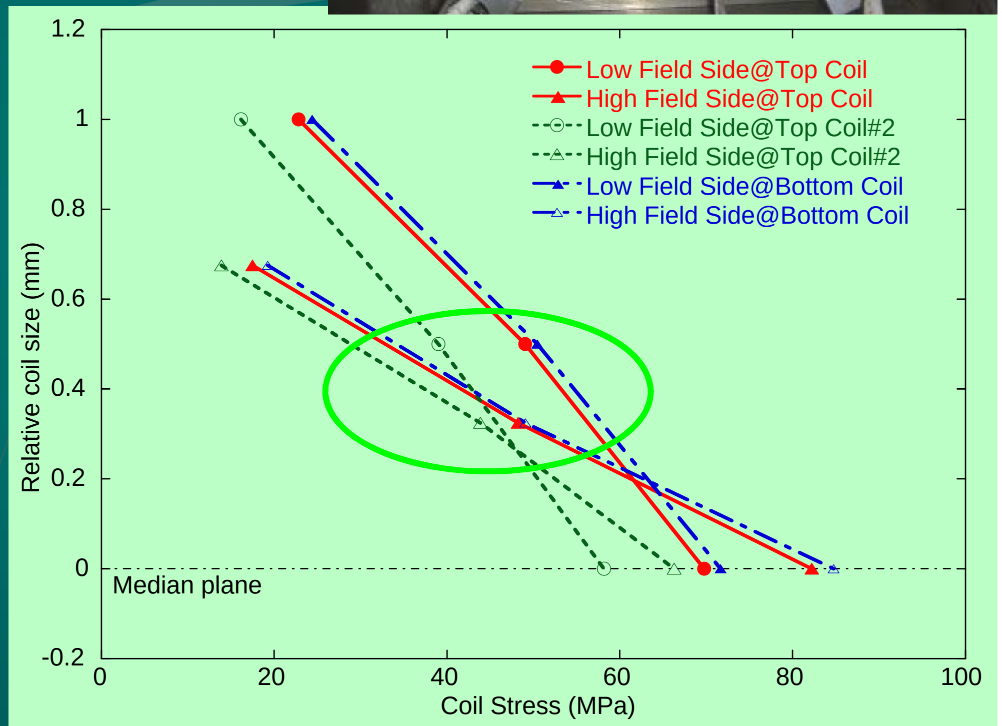


Cured bottom coil on the mandrel. Several sets of strain gauges are installed on the press-bars in both sides to measure coil stress during the coil size measurement.

Coil Size Measurement







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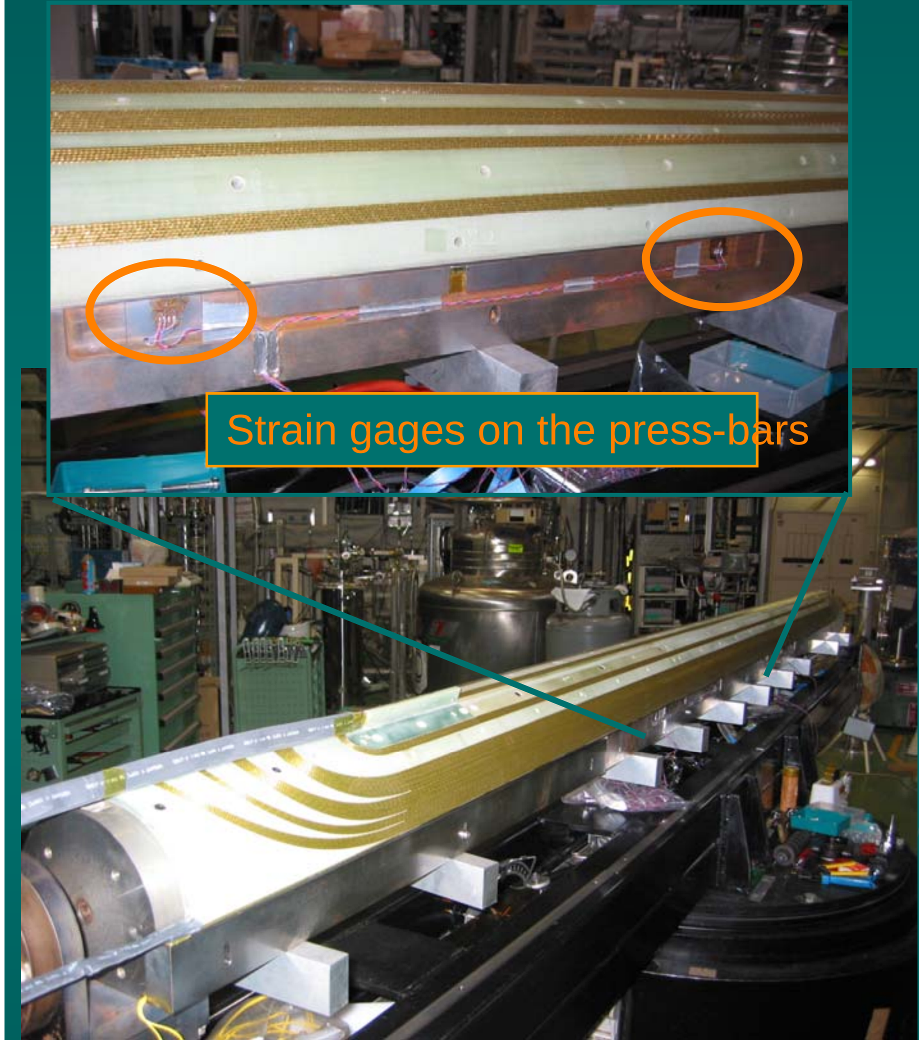
Coil Size Measurement



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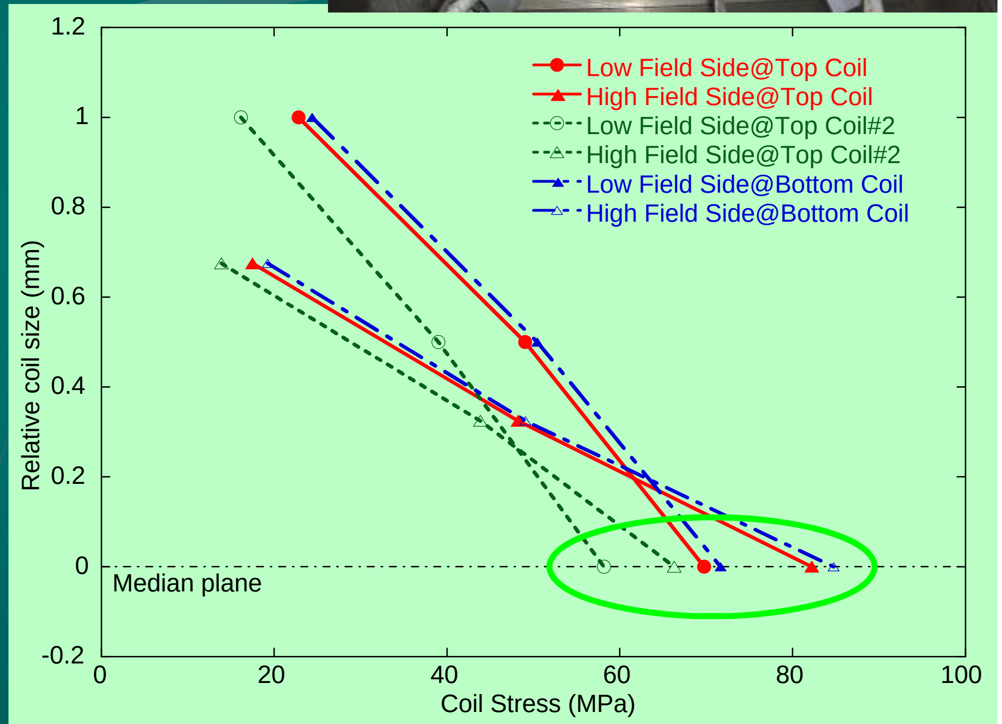
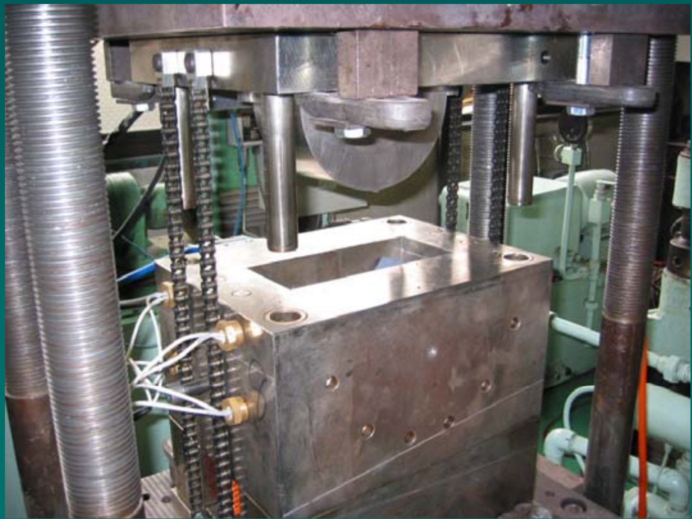


Expected pre-stress of 60-80 MPa after magnet assembly is similar to the design value of 80 MPa.

Plastic Collar



Compression Molding

@430 K, 10 min.

&

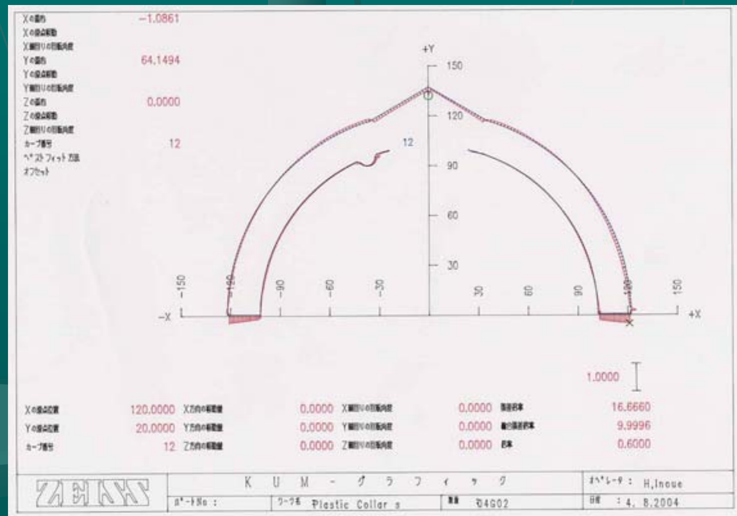
Post-curing w/ Forming Jig

@ 450K, 10hrs

Glass-reinforced Phenolic Thermosets
Rin=102 mm, t=20 mm, L= 100 mm
***PM9640 supplied by Sumitomo Bakelite, and fabricated by Arisawa**

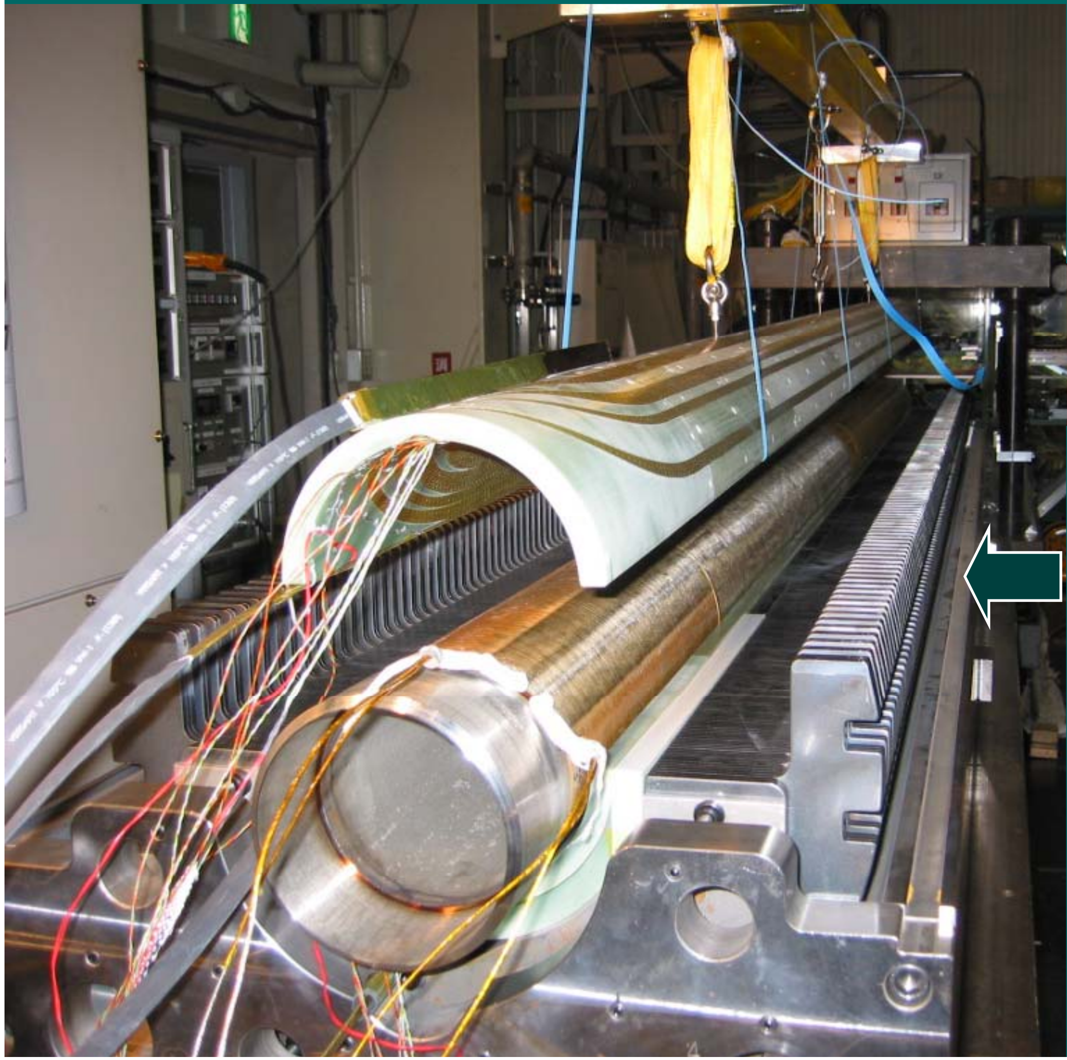
Size control is very important!!

- **R&D to search the most appropriate condition needs 18 months.**
- **Molding jig was designed with taking into account the consistent deformation.**



- ***Maximum Deformation: 0.1-***

Yoking
-Coil Installation-

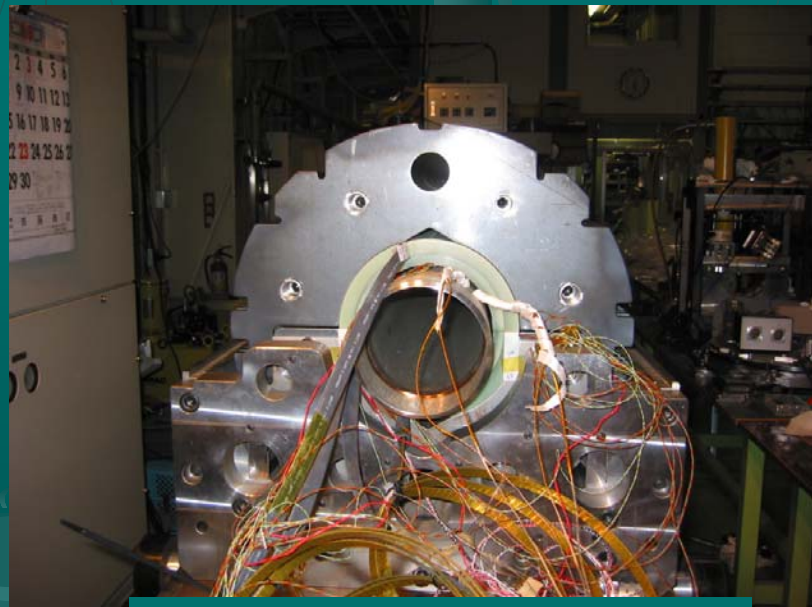


Yoking -Top Assembly Installation-

Top Collar Installation

Top Yoke Installation

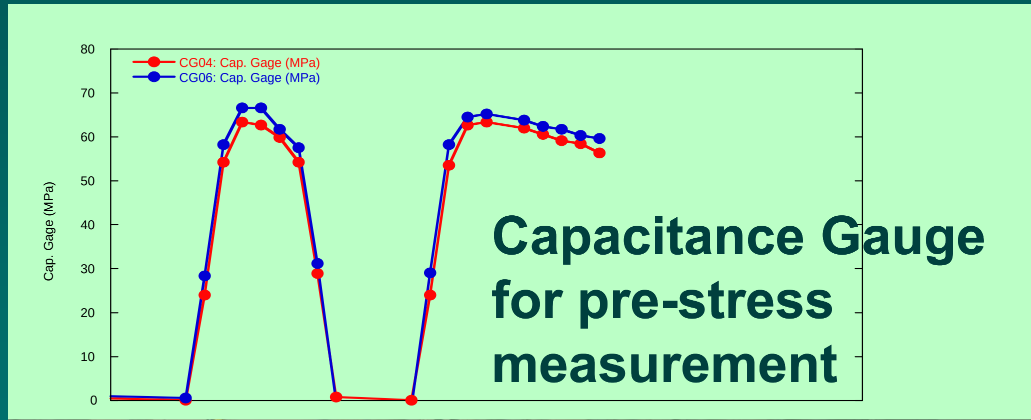
Top lead Collar Installation



Top Yoke Installation Complete

Yoking **-Press-**

Press Bar Installation



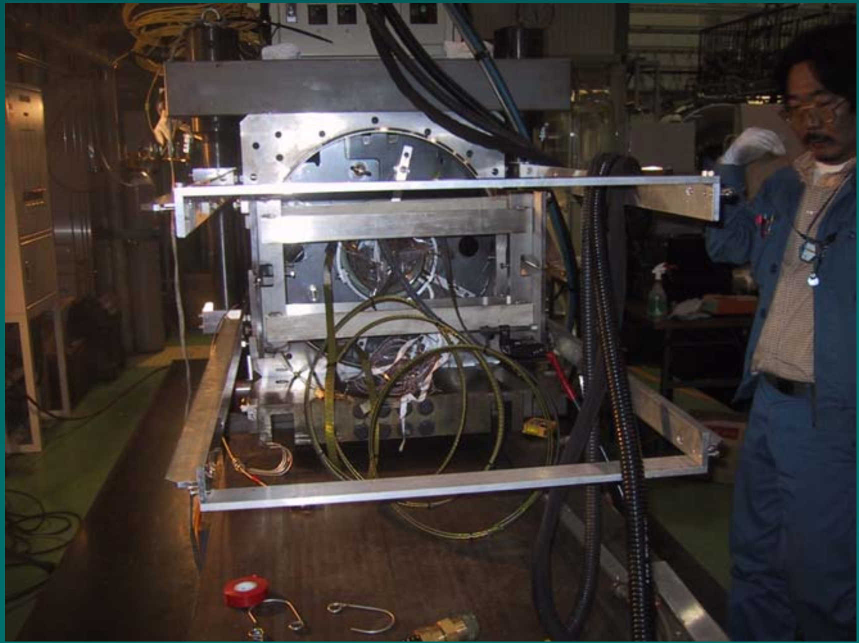
Capacitance Gauge for pre-stress measurement

Top Hat Installation

Yoking **-Keying-**

Shell Welding

Longitudinal shell welding by a set of two automated welding machines.



Final Assembly

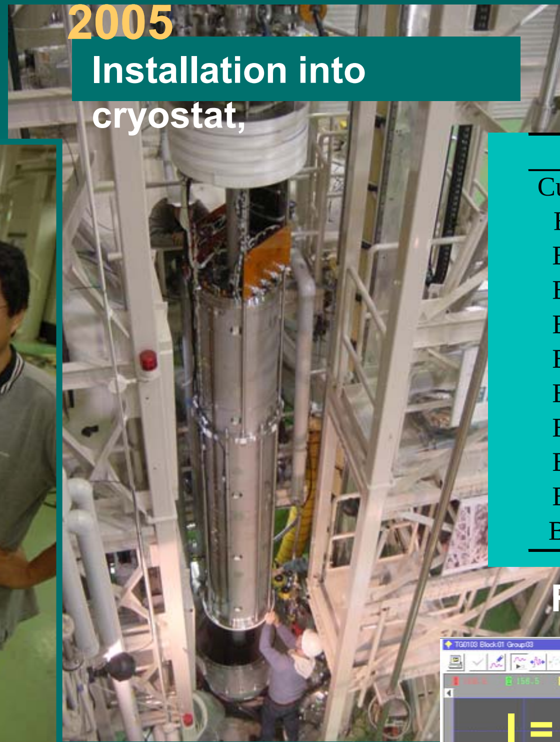
End-ring welding

Installation of the alignment target

Leads connection by soldering.

Excitation Test of the 1st Prototype

I_{op} = 7345 A @ 50 GeV (and I_{max} = 7,700 A) reached with no quench, on March 4, 2005



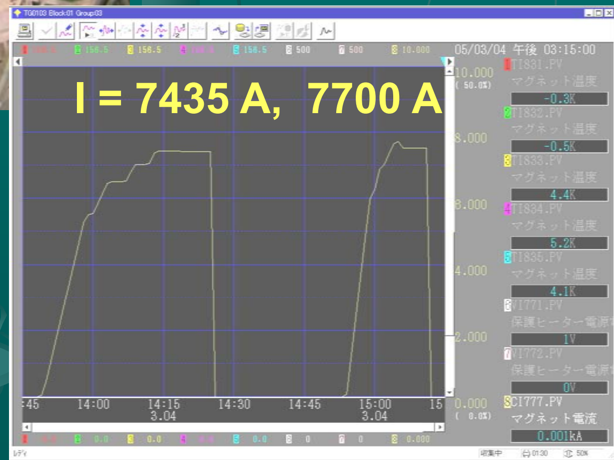
Installation into cryostat,

	Measurement	*Computation*
Current (A)	7460	7345
B_1 (T•m)	8.906	8.712
B_2 (T•m)	3.127	3.120
B_3 (T•m)	$-220.6*10^{-4}$	$-293.6*10^{-4}$
B_4 (T•m)	$-5.9*10^{-4}$	$-20.1*10^{-4}$
B_5 (T•m)	$-51.9*10^{-4}$	$-30.6*10^{-4}$
B_6 (T•m)	$-75.2*10^{-4}$	$-62.8*10^{-4}$
B_7 (T•m)	$-44.6*10^{-4}$	$-20.9*10^{-4}$
B_8 (T•m)	$-74.5*10^{-4}$	$-32.0*10^{-4}$
B_9 (T•m)	$-79.9*10^{-4}$	$-73.4*10^{-4}$
B_{10} (T•m)	$-13.8*10^{-4}$	$-0.3*10^{-4}$

Field Measurement Result

Participating member

Participating members



Record of Excitation current

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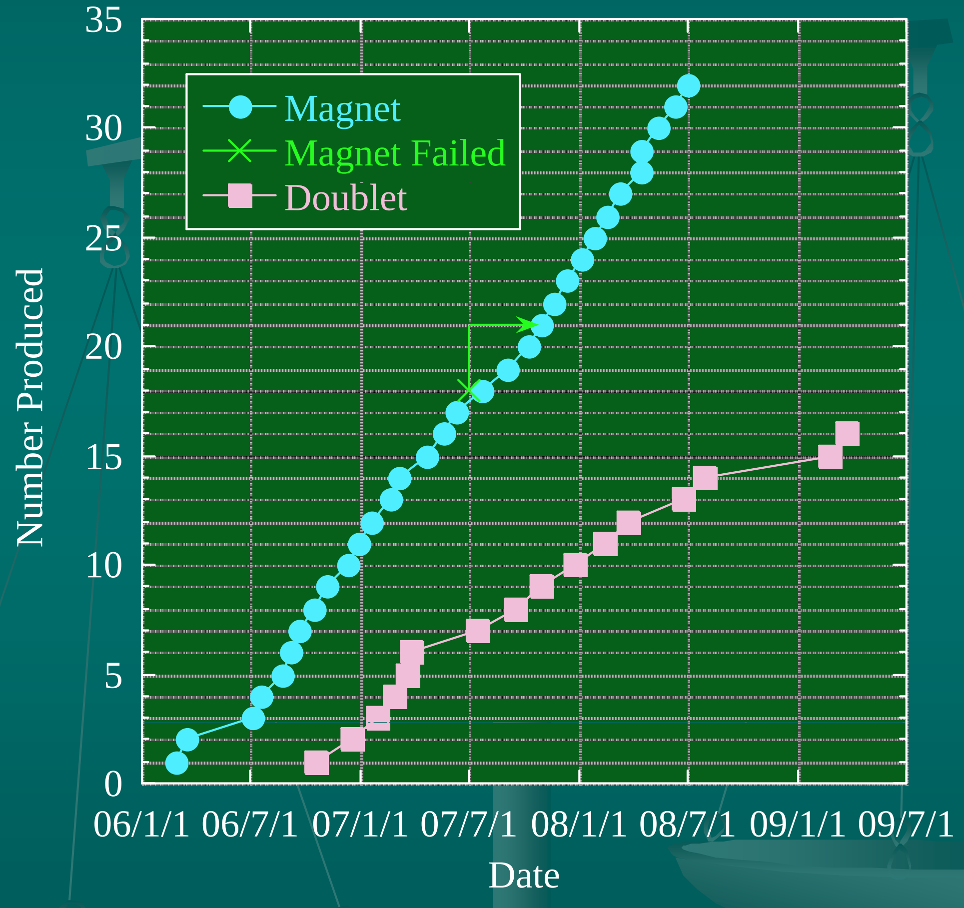
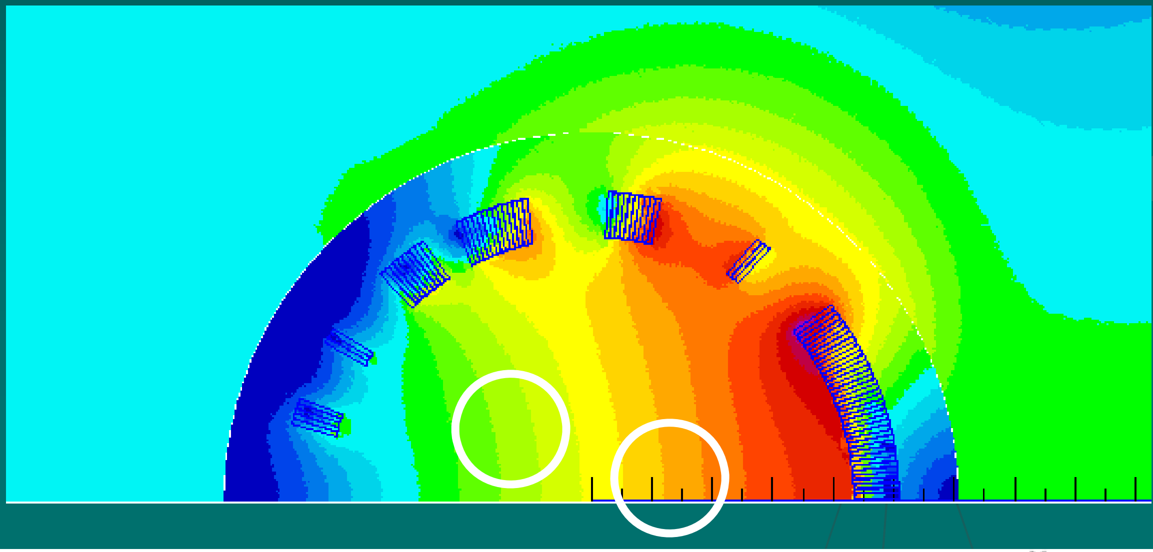
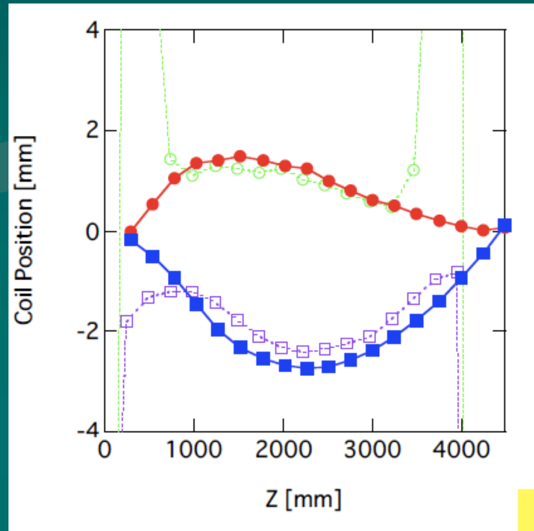
Manget Mass Production

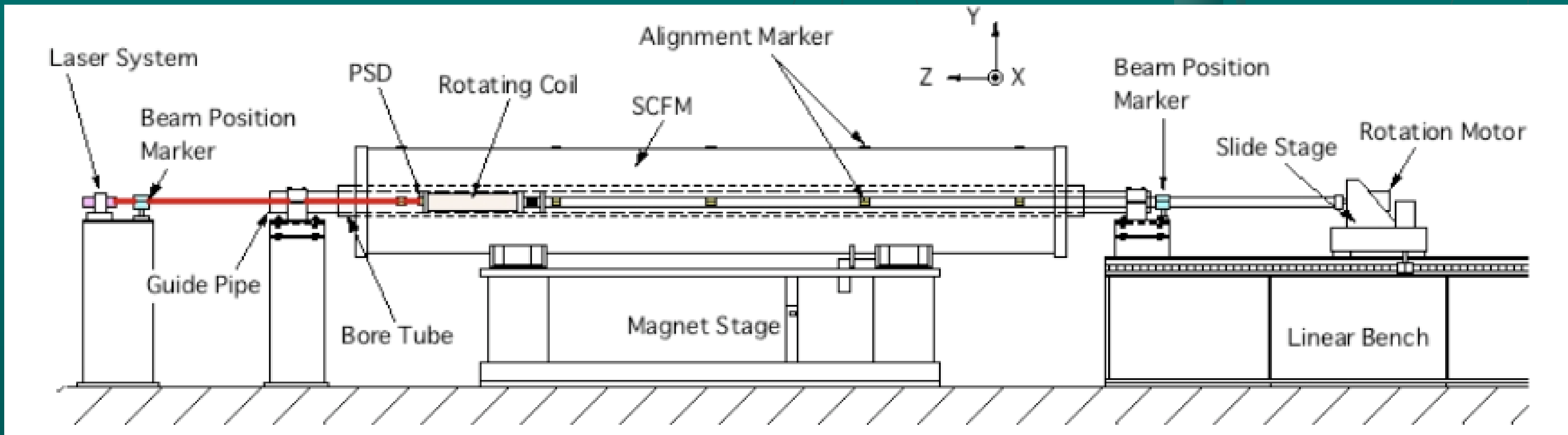
- Mass production
  - bidding won by Mitsubishi Electric
  - Built to Print Contract
- Major Monitoring Data
  - Coil Length, Prestress
  - Yoke size
  - Shell size
  - Warm Field Quality
- Cold Test at KEK
  - Presented by Okamura (Wednesday Poster)



Warm Field Measurement







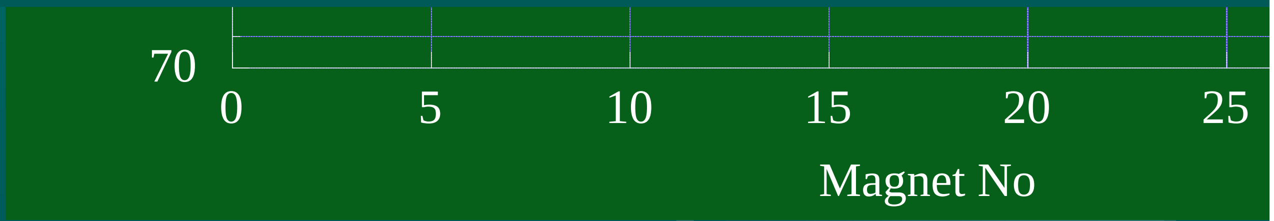
R_{ref} = 50 mm

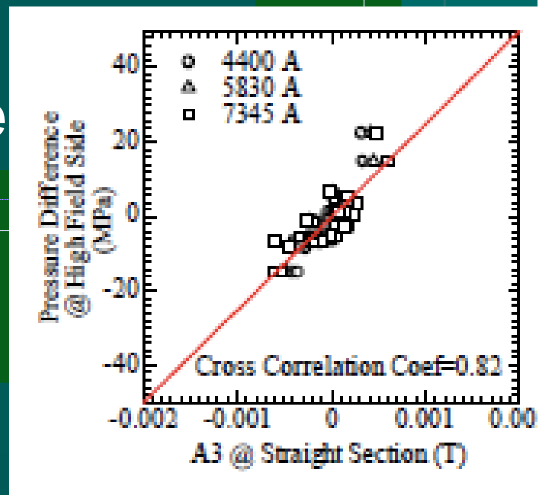
Coil Prestress Measurement Results

Average: ~90 Mpa
Standard Deviation: ~7 Mpa
Equivalent Coil Size Deviation
- High Field Side: 0.07 mm (0.13 mrad)
- Low Field Side: 0.14 mm (0.26 mrad)

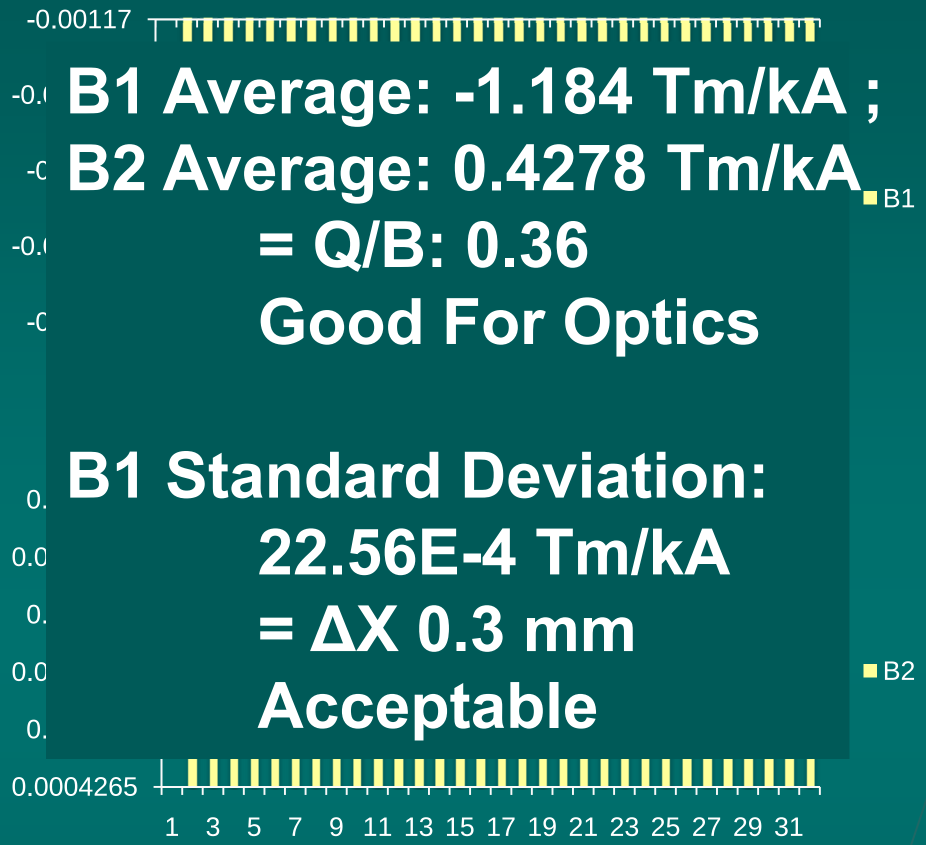
MQXA (LHC IRQ)
- Inner Coil Size Deviation: 0.022 mm (0.1 mrad)

Influence to Field Quality by Coil Prestre





B1



B1 Average: -1.184 Tm/kA ;
B2 Average: 0.4278 Tm/kA
= Q/B: 0.36
Good For Optics

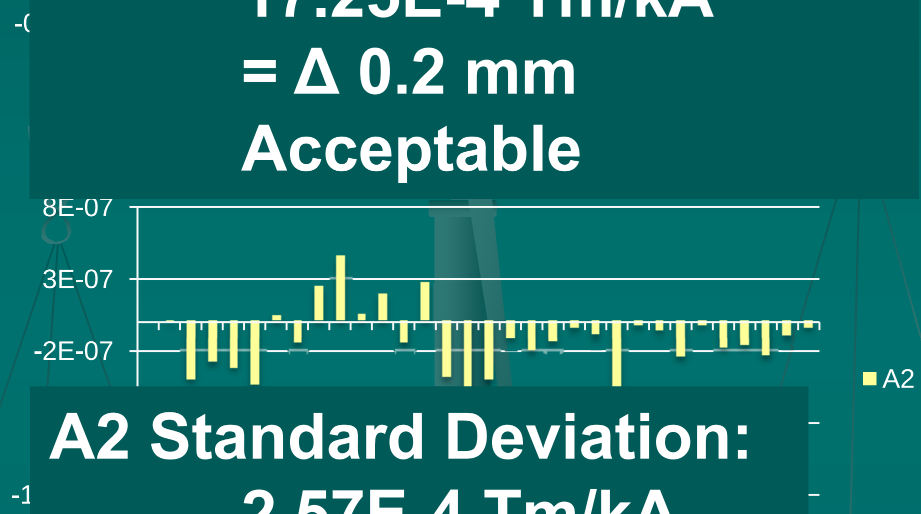
B1 Standard Deviation:
22.56E-4 Tm/kA
= ΔX 0.3 mm
Acceptable

WMFM Results

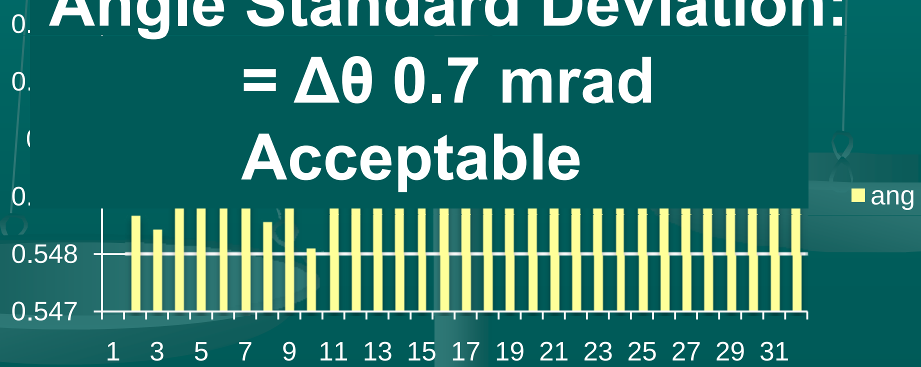
R_{ref} = 50 mm

A1

A1 Average: -42.22e-4 Tm/kA
= ΔY 0.5 mm
A1 Standard Deviation:
17.25E-4 Tm/kA
= Δ 0.2 mm
Acceptable



A2 Standard Deviation:
2.57E-4 Tm/kA
= Δθ 0.5 mrad
Angle Standard Deviation:
= Δθ 0.7 mrad
Acceptable



Higher Harmonics

		Opera 3D			Measured					
B_n		7345 A	5830 A	4400 A	7345A		5830 A		4400 A	
n	Unit	calculated	calculated	calculated	average	standard deviation	average	standard deviation	average	standard deviation
B3int	1×10^{-4} T· m	293.45	236.56	179.18	218.99	6.50	181.74	5.38	138.44	3.81
B4int	1×10^{-4} T· m	-20.33	-64.83	-52.10	-7.55	4.55	-62.67	3.82	-53.71	2.74
B5int	1×10^{-4} T· m	30.68	41.02	32.12	47.77	3.31	53.79	2.45	40.52	1.74
B3	UNIT	1.62	1.91	1.21	5.12	0.84	3.86	0.78	3.48	0.76
B4	UNIT	-9.04	0.26	2.30	-9.19	0.42	-0.64	0.43	-0.77	0.41
B5	UNIT	2.51	-0.93	-1.47	0.50	0.31	-1.89	0.29	-1.90	0.28
B6	UNIT	6.28	5.98	5.82	6.72	0.15	6.22	0.12	5.94	0.11
A3	UNIT	0	0	0	0.12	1.05	0.22	1.05	0.24	1.07
A4	UNIT	0	0	0	-0.11	0.19	-0.04	0.21	-0.02	0.20
A5	UNIT	0	0	0	0.08	0.36	0.07	0.34	0.06	0.31

R_{ref} = 50 mm

Higher Order Mutipoles: Acceptabl

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- Introduction
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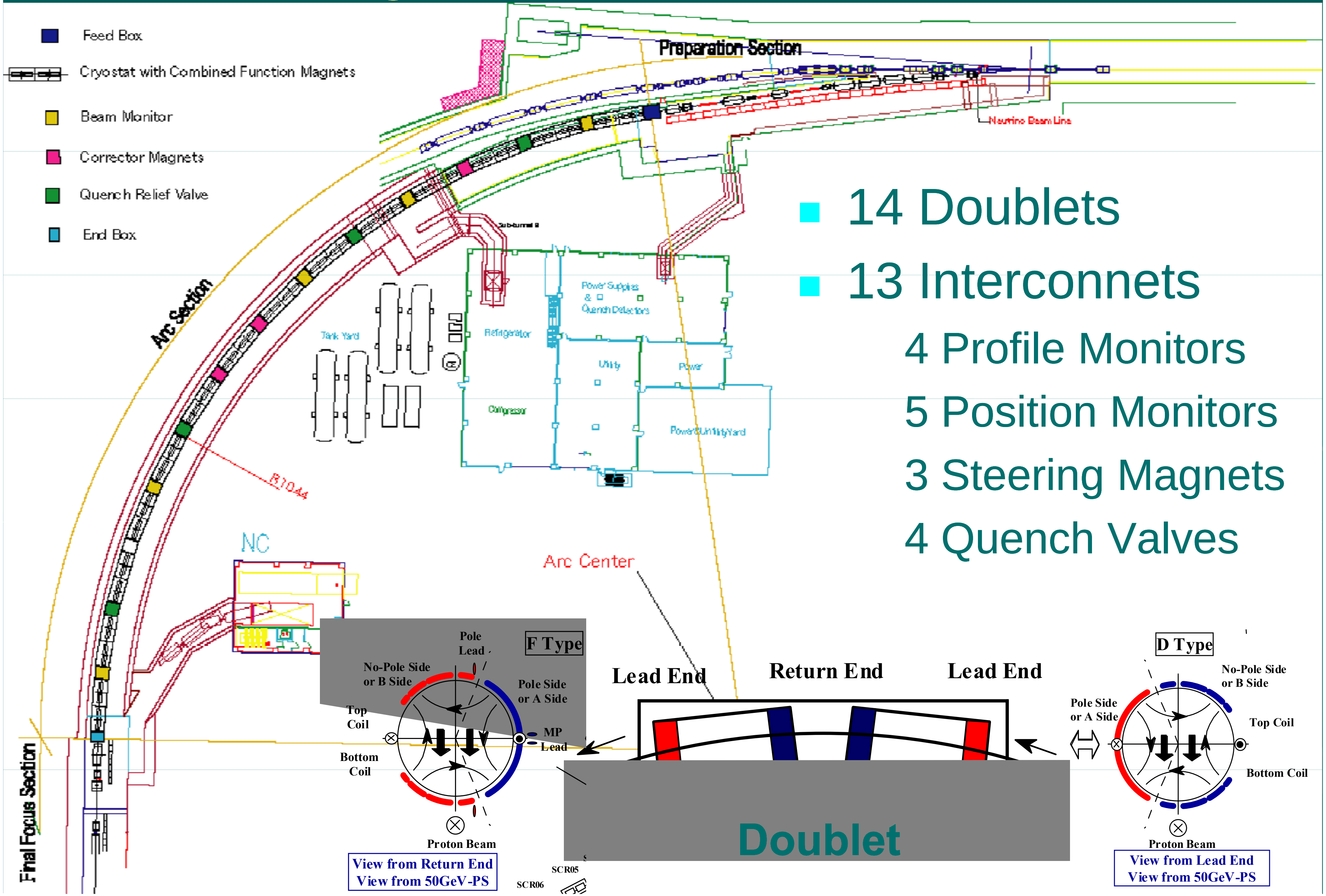
  - Beam Commissioning
- Conclusion

System Overview

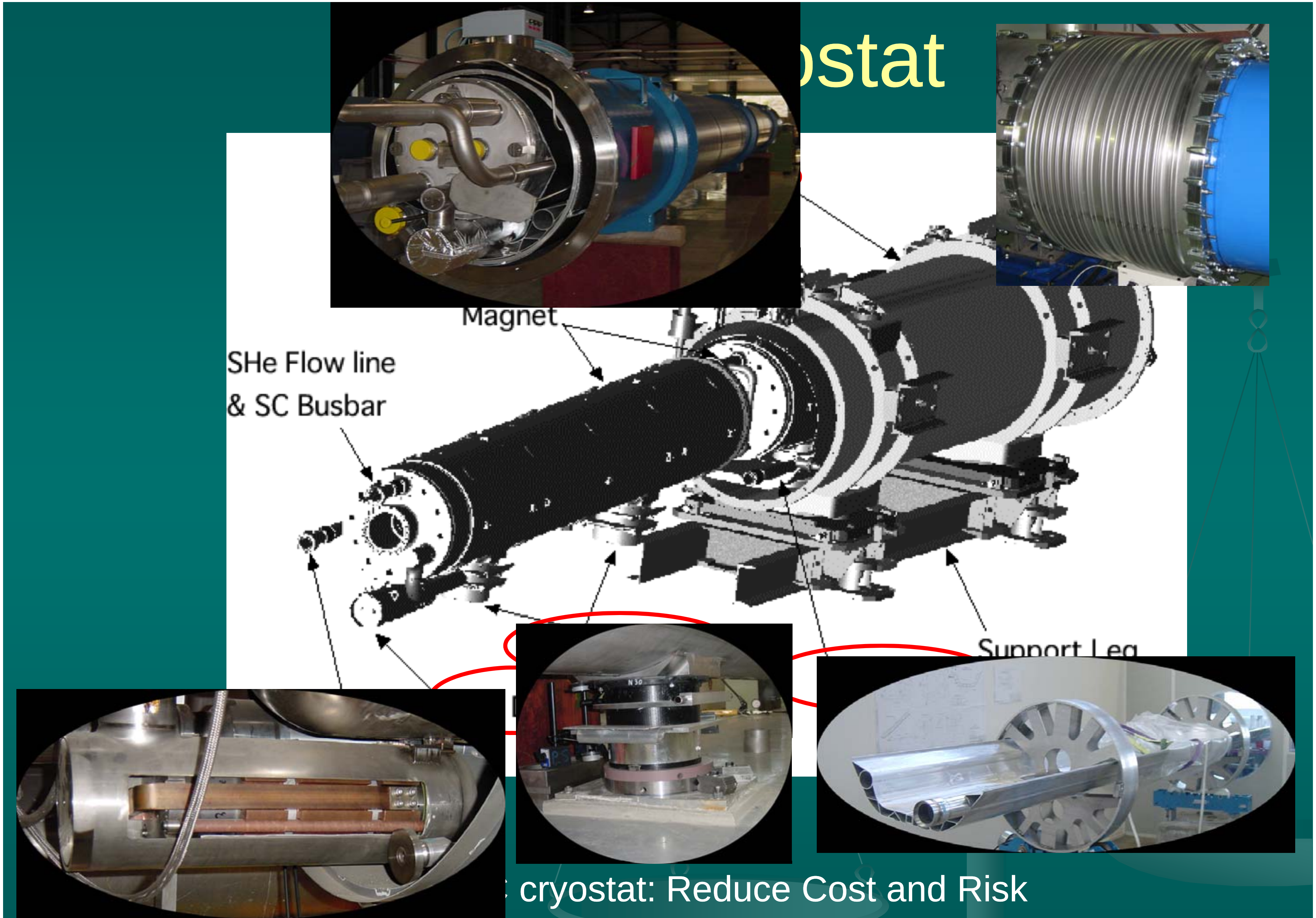
- 14 Doublets
- 13 Interconnets
  - 4 Profile Monitors
  - 5 Position Monitors
  - 3 Steering Magnets
  - 4 Quench Valves



LHC&J-PARC Neutrino SC System

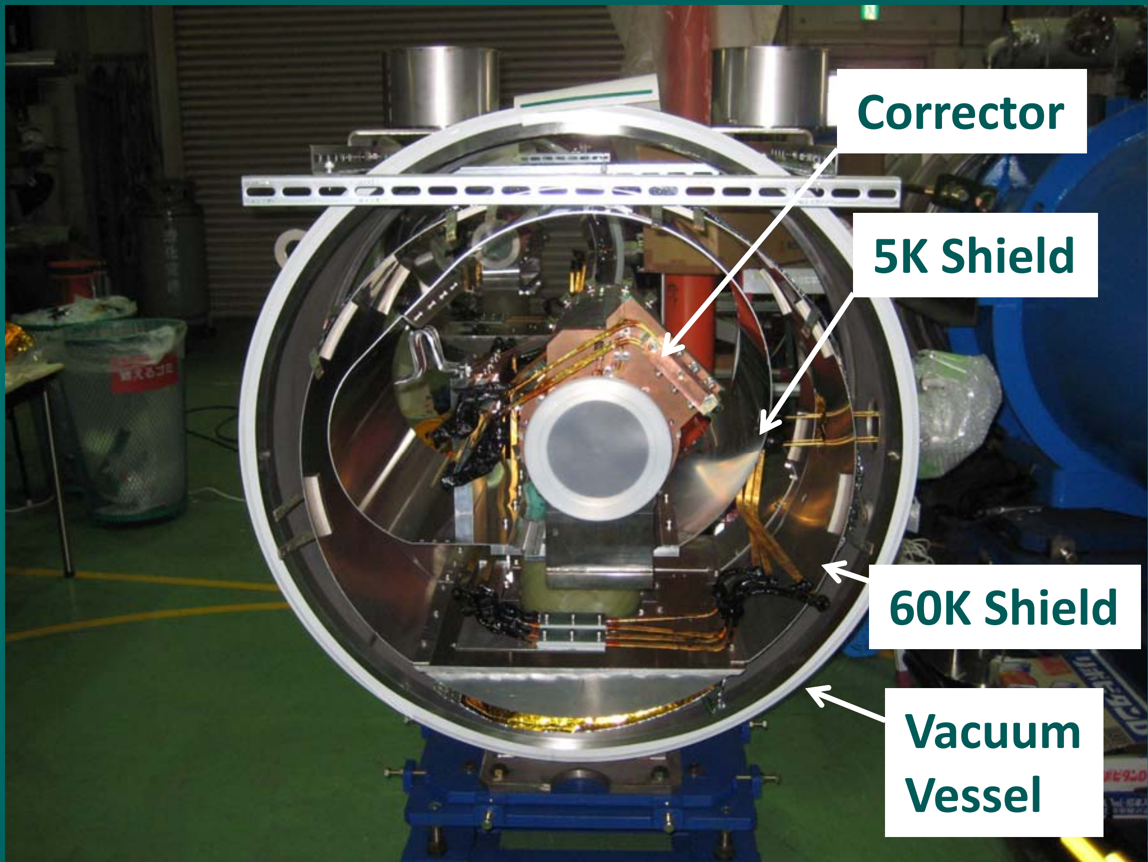
- **Comparison**
  - Size 27km vs 150m
  - Number of Magnets ~5000? Vs 28
  - Inductance and Stored Energy
    - LHC（ 1 sector）: 15.1H, 1.2GJ
    - J-PARC: 0.4H, 10MJ(50GeV), 5MJ(30GeV)
  - Helium Inventory
    - LHC(overall）: 56万Nm^3
    - J-PARC: 4000Nm^3

ostat

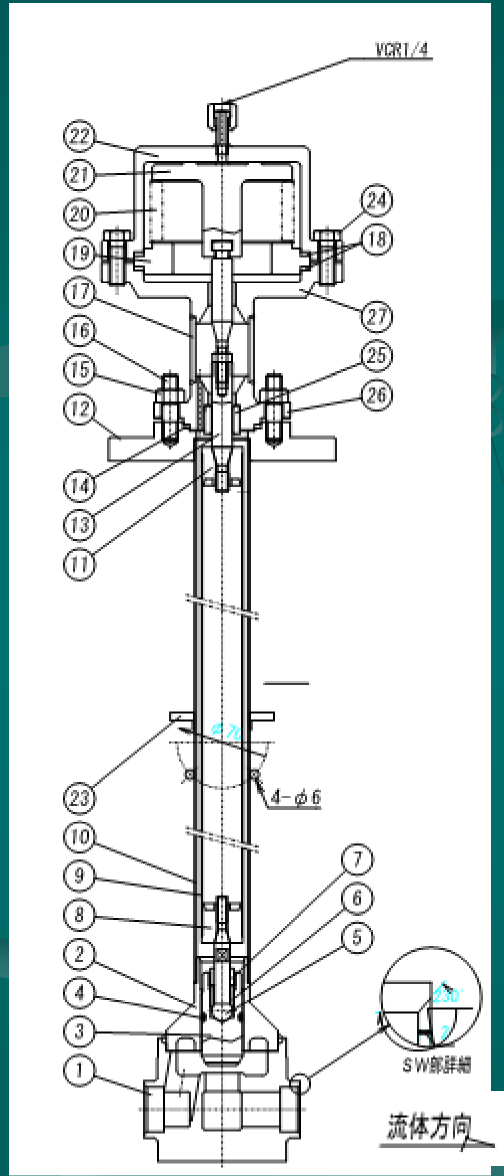


- c cryostat: Reduce Cost and Risk
- Common Parts → advantage of LHC mass production

Interconnects



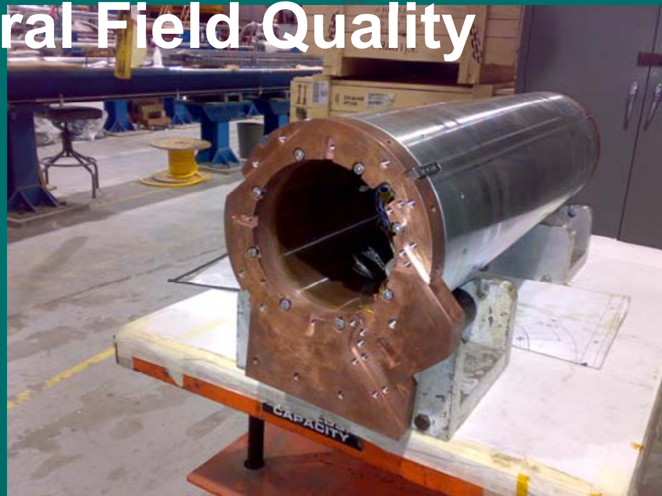
Corrector Interconnect



Quench Relief Valve

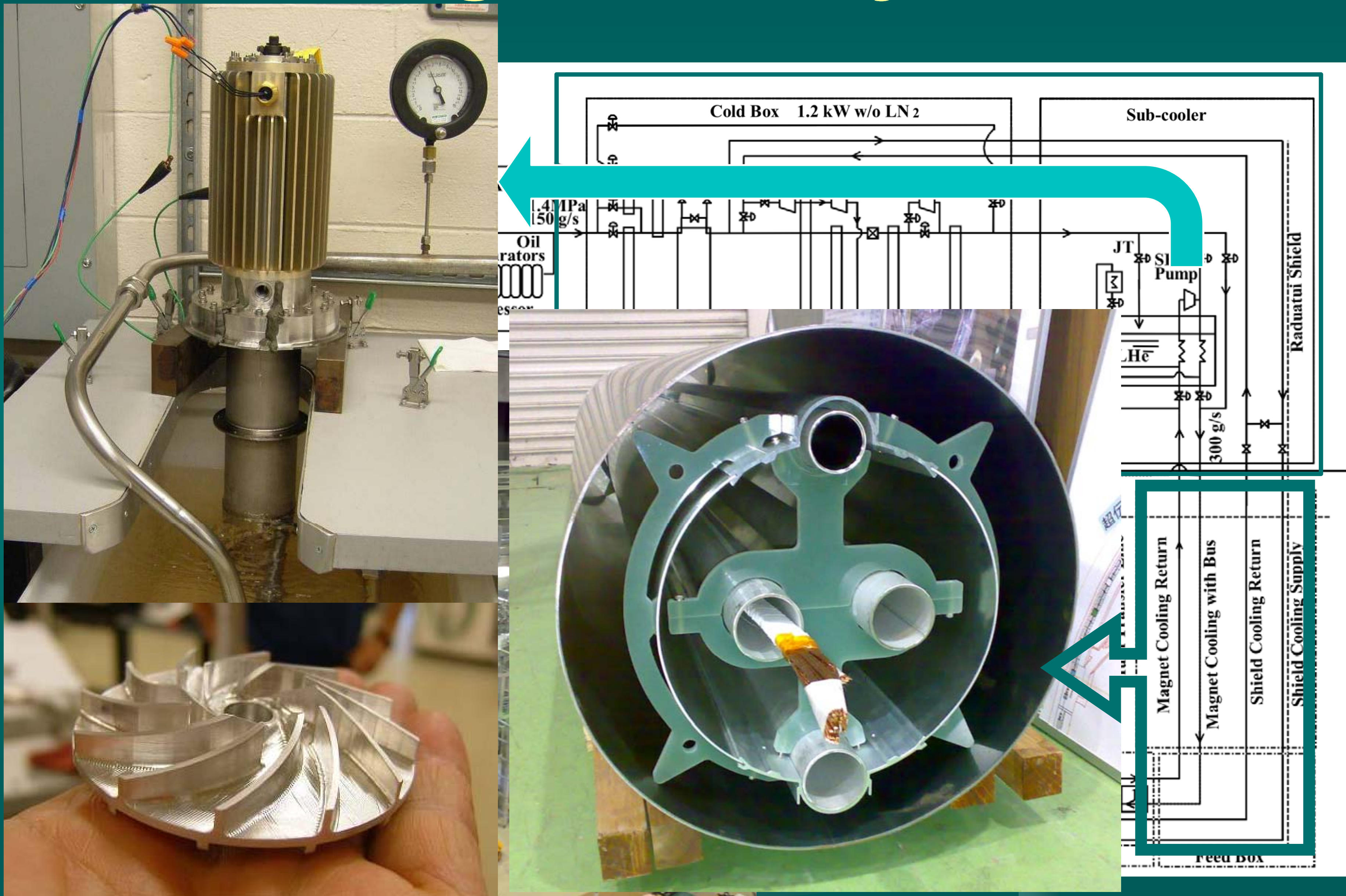
Corrector Production

Manufactured and Tested at BNL
Direct Winding on Copper Bobbinn
Cold test for Quench Performance
ral Field Quality



Parameter	Average Value	Std. Dev.
B1 Integral	2.34 Tm/kA	$22.4 \cdot 10^{-4}$ Tm/kA
A1 Integral	2.32 Tm/kA	$32.3 \cdot 10^{-4}$ Tm/kA
B1-A1 angle	-1.4 mrad	2.2 mrad

Refrigeration System

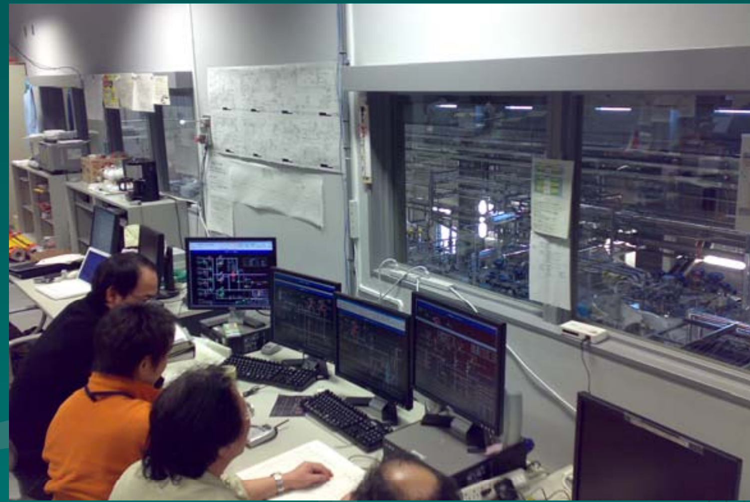




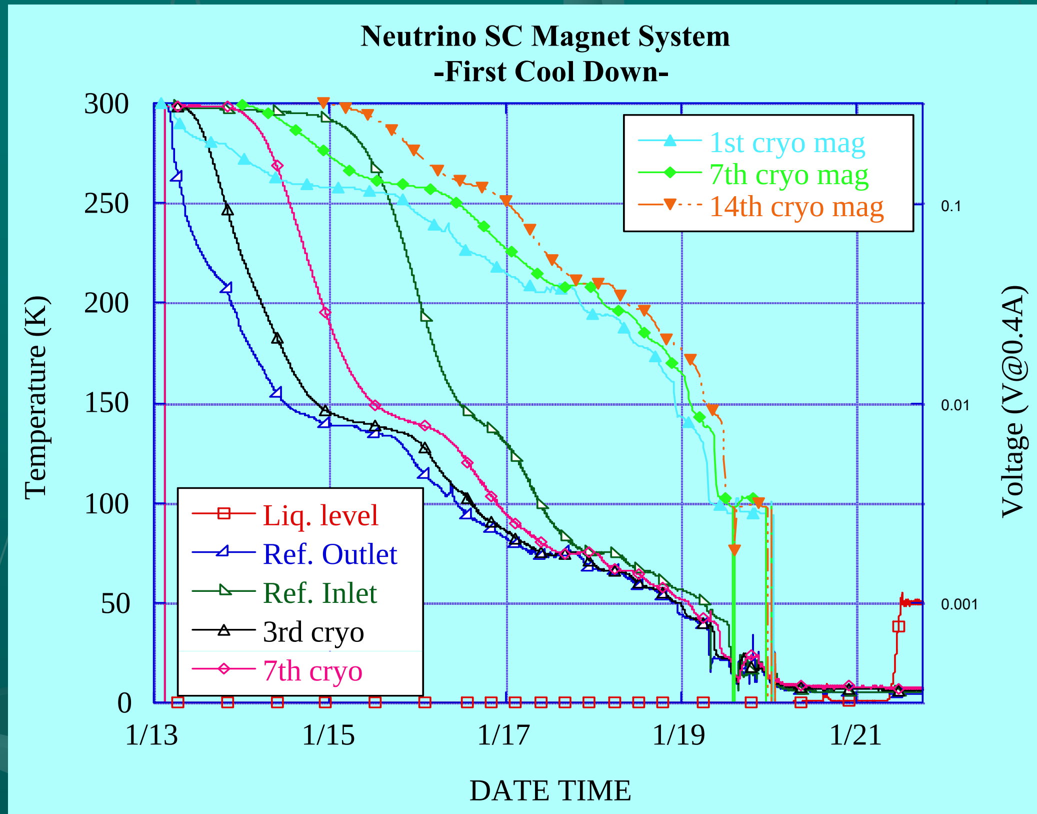
Installation Completed by Dec. 2008


Contents

Refrigerator Test & Magnet Cool Down

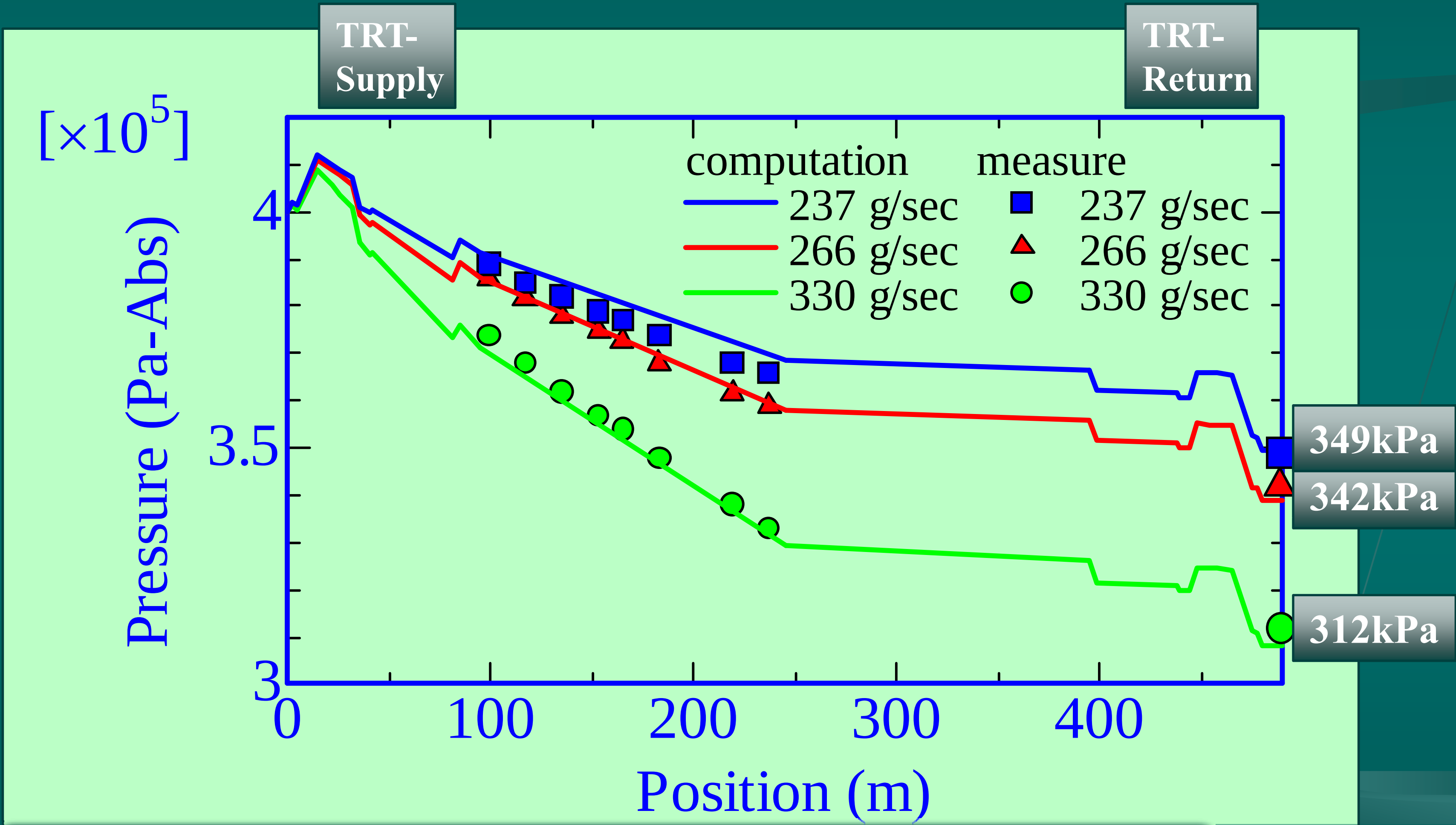


- Refrigerator Test in Dec.
  - Refrigeration Power ~ 1.5kW
- Cool Down Magnet By about 10 days



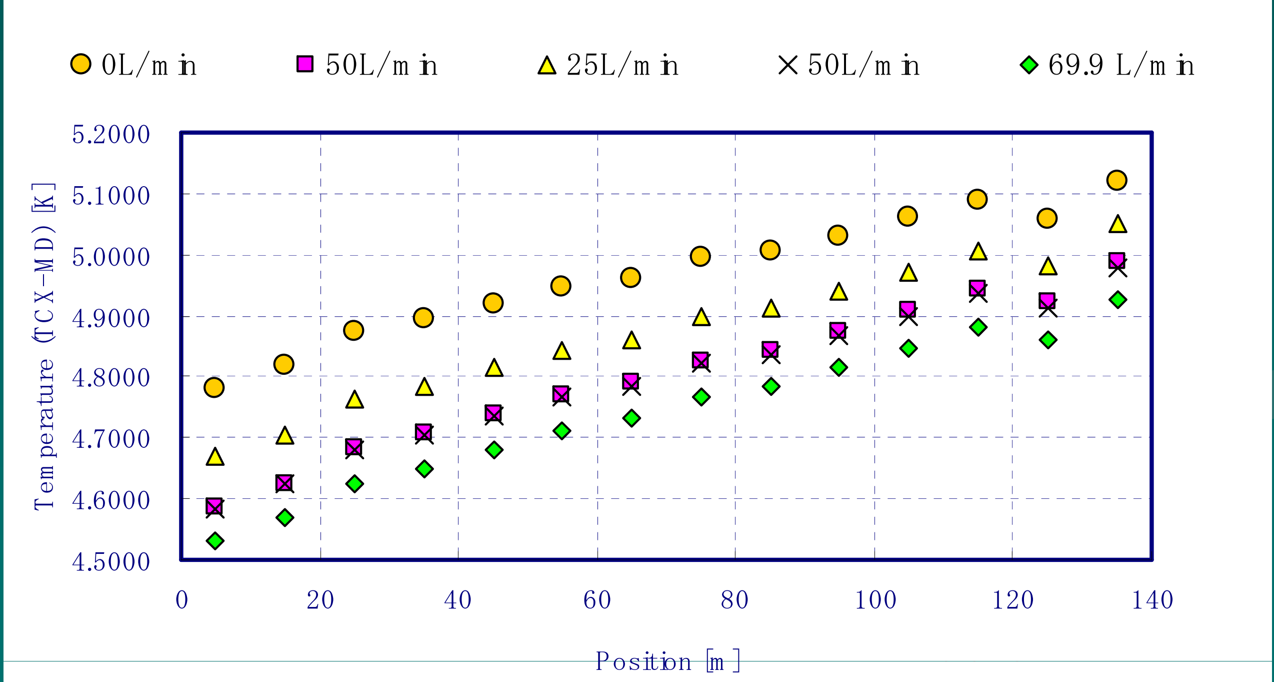
Pressure Drop

--steady state mode (230 g/sec ~ 330 g/sec)--

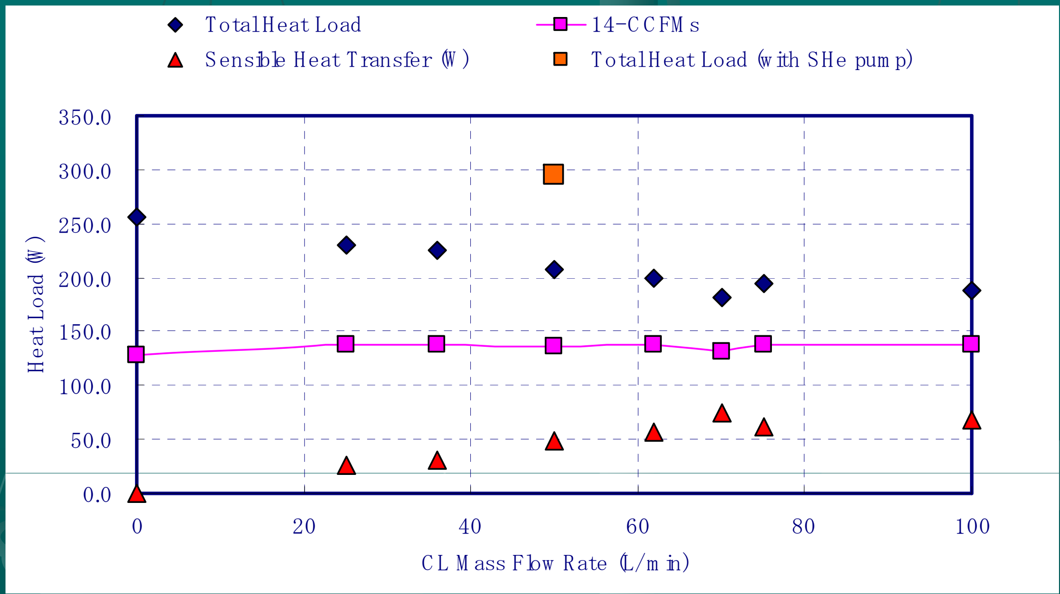


- Pressures at Cernox sensors can be obtained from above figure.
- Wall Friction Coefficient, λ, is treated as adjustable parameter.

Heat Load

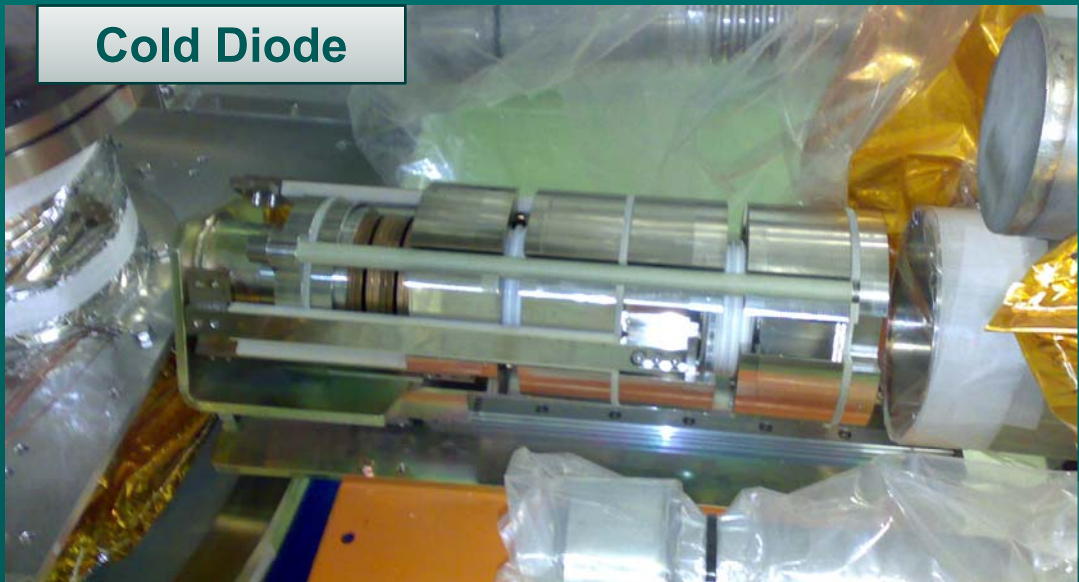


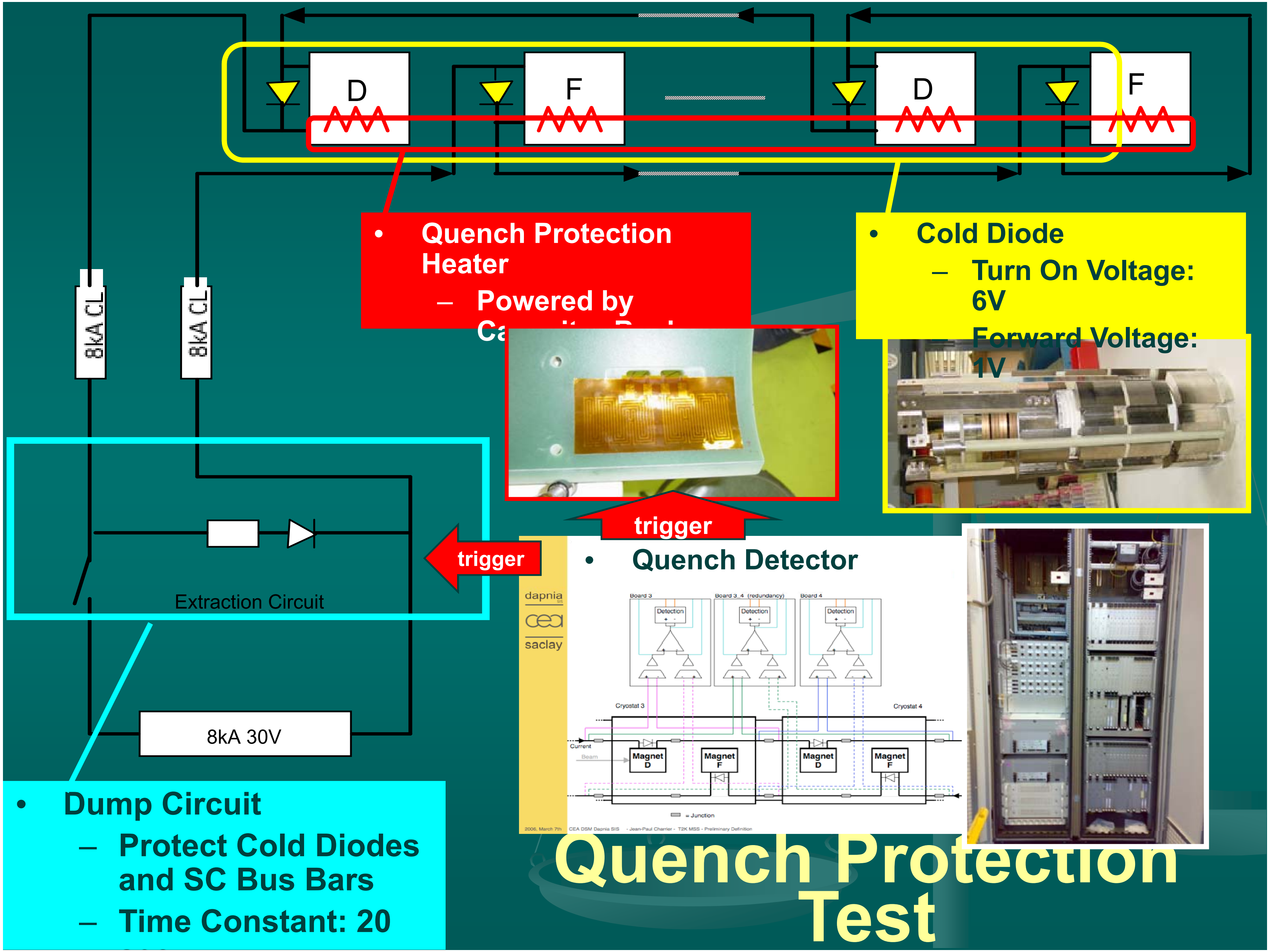
- Magnet String
  - 140 W
- Transfer Line
  - 50 W
- Current Lead
  - 60 W @ 0 flow
  - 0 W @ 70 L/min
  - 100 L/min @ 4kA



Quench Protection Test

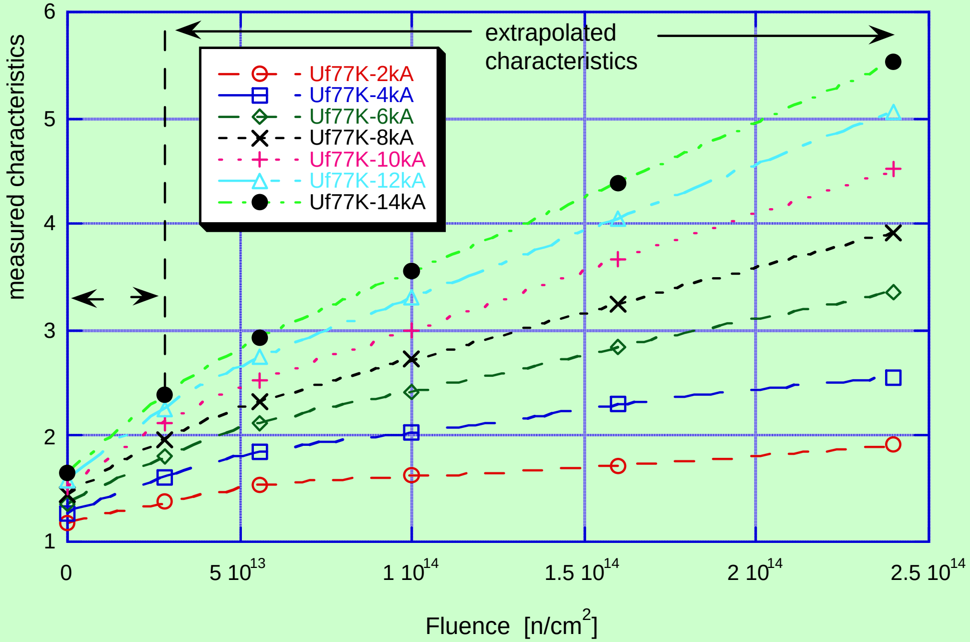
- Performance test of quench protection system
  - Heater Induced Quench
  - Quench Recovery

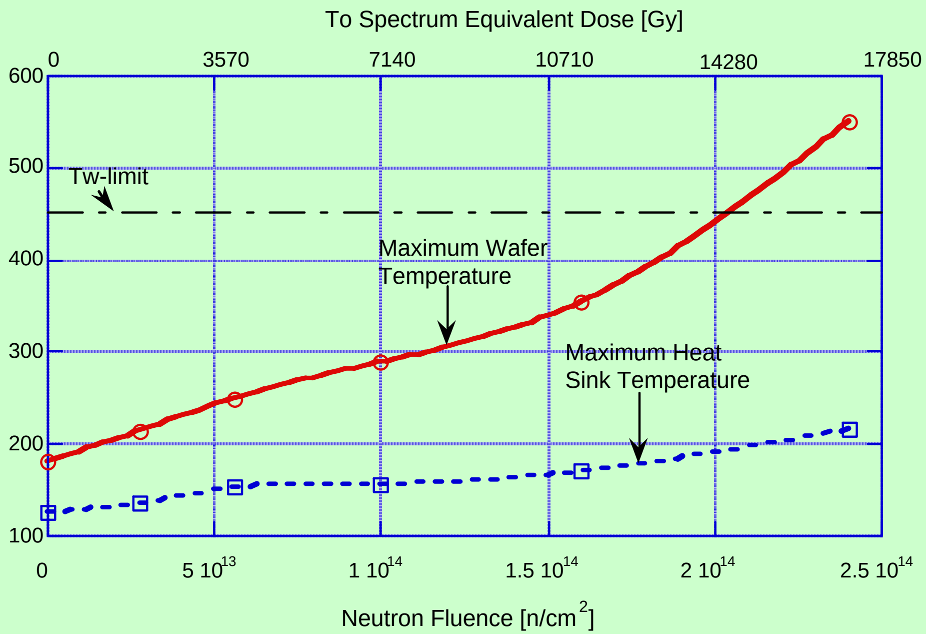



D
F
D
F
8kA CL
8kA CL
Quench Protection Heater
Powered by
Cold Diode
Turn On Voltage: 6V
Forward Voltage: 1V
trigger
trigger
Quench Detector
Extraction Circuit
8kA 30V
dapnia
saclay
Dump Circuit
Protect Cold Diodes and SC Bus Bars
Time Constant: 20
Quench Protection Test

Cold Diode

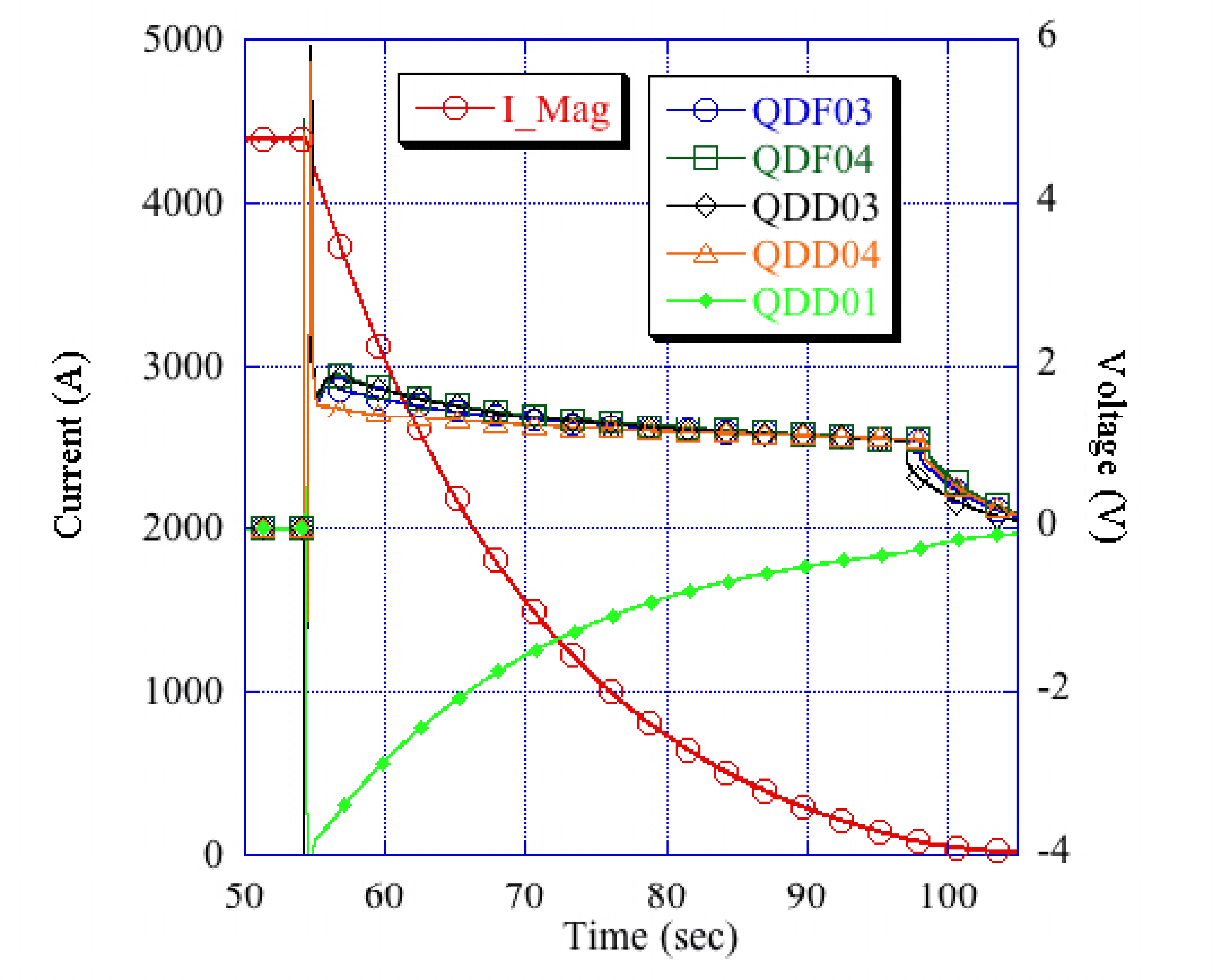
- Influence of Neutron to Cold Diode
  - Intensively studied at CERN by D. Hagedorn
    - Change Forward Voltage
  - Using LHC Arc Quad Assembly
    - 7.5kA Operation
    - Limit; 2• 10^{14} n/cm^2





Courtesy D.Hagdo

Bypass Diode Test



Cool Down after Quench

- Quench Test at 4400A (30GeV nominal)
  - Normal case (4 magnets) : ~2 hour to recover

Good noise reduction by MSS

↓

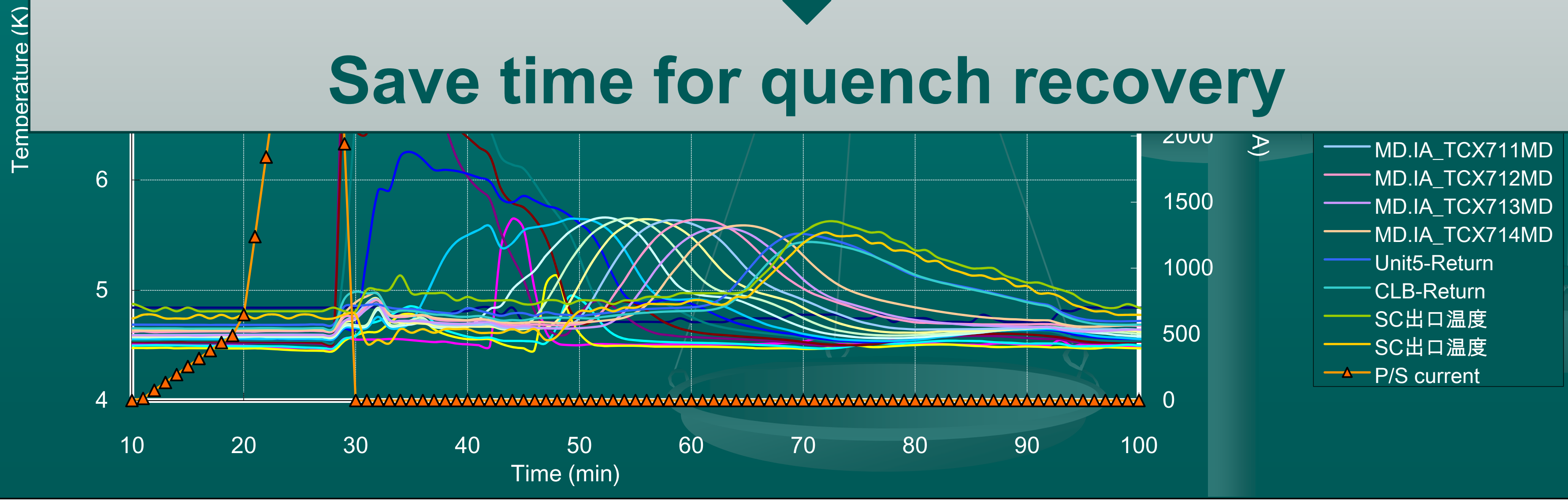
No false quench detection by system shut down

↓

Avoid extra magnet to quench

↓

Save time for quench recovery



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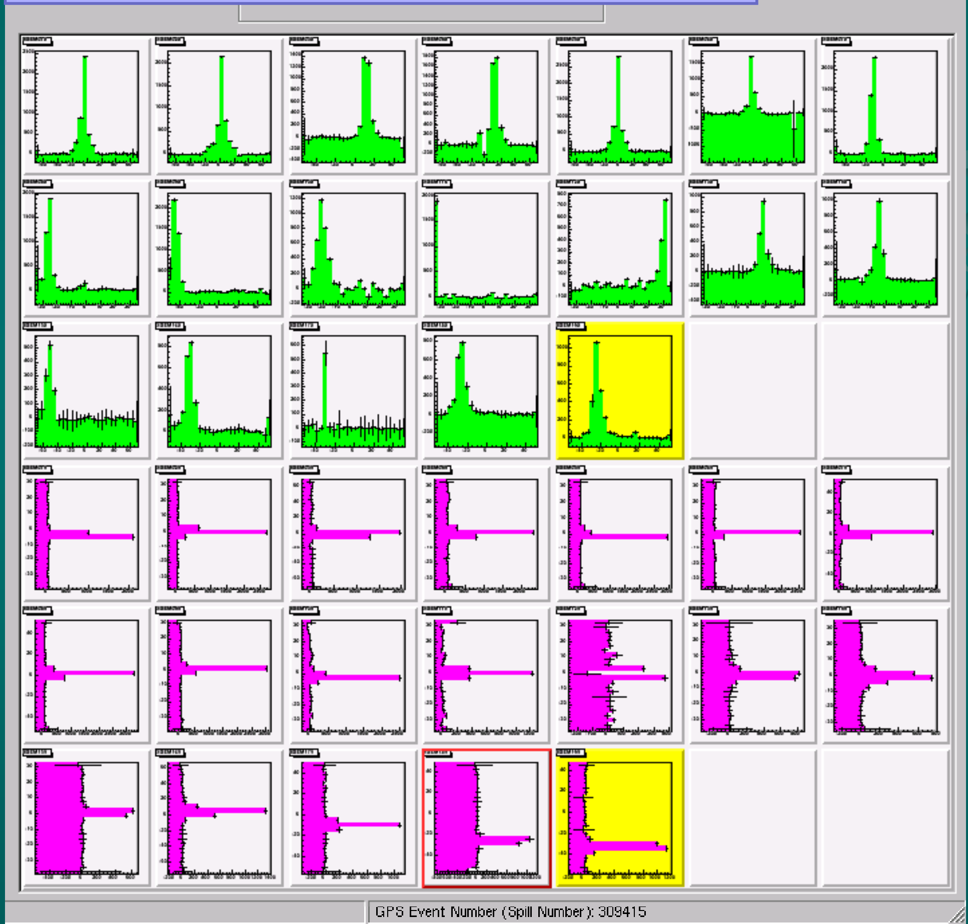
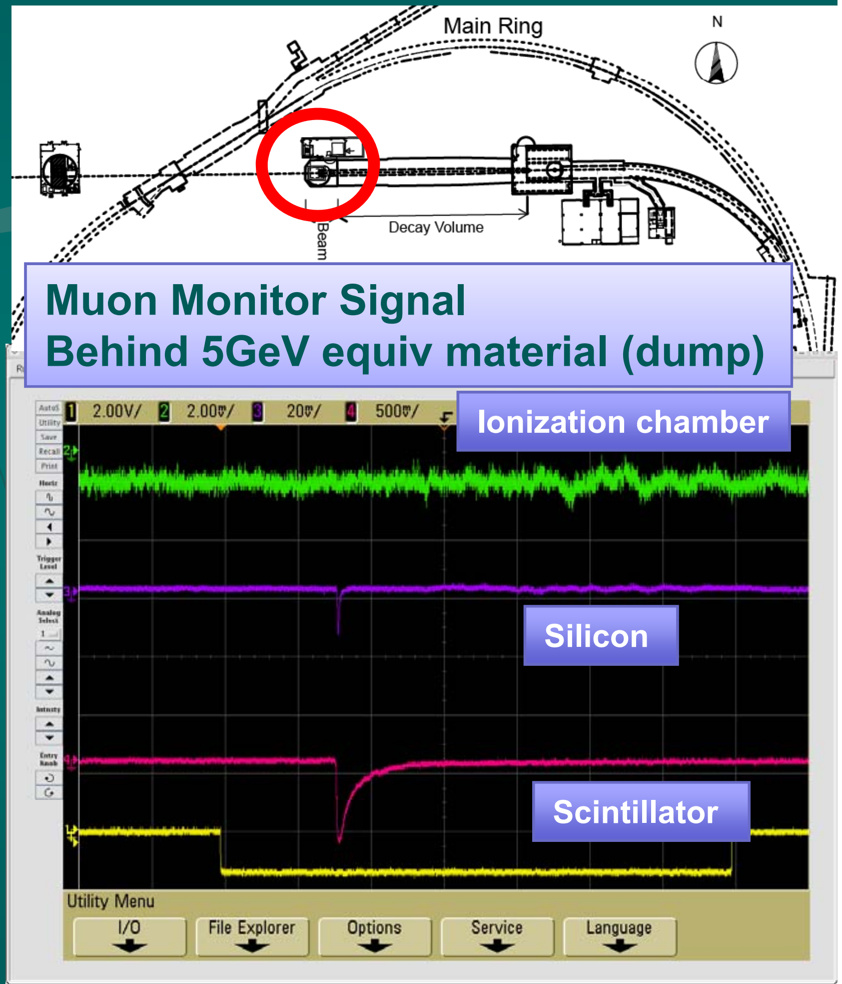
T2K beamline started operation!

FIRST SHOT after turning on SC magnets at 19:09, Apr.23, 2009

Beam profile monitor signal



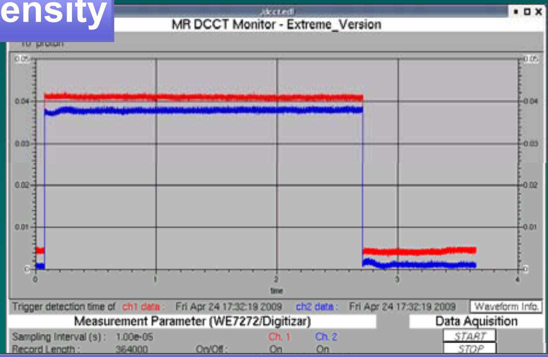
Muon Monitor Signal
Behind 5GeV equiv material (dump)



First observation of muons produced in neutrino beamline

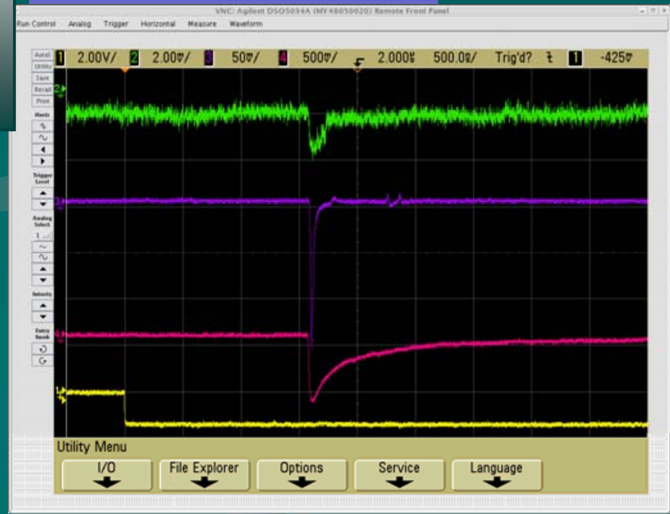
T2K beamline started operation!

MR intensity

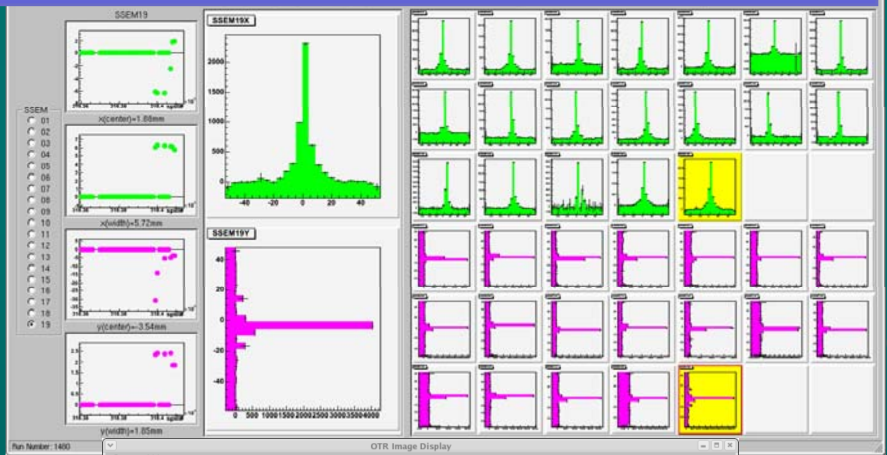


After ~10 shots for tuning, proton beam hit around target center

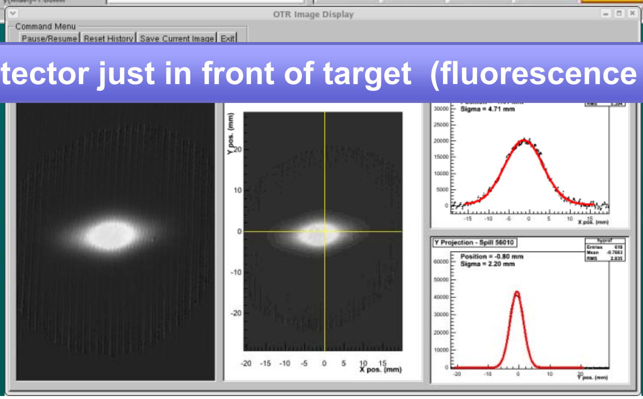
Muon monitor signal



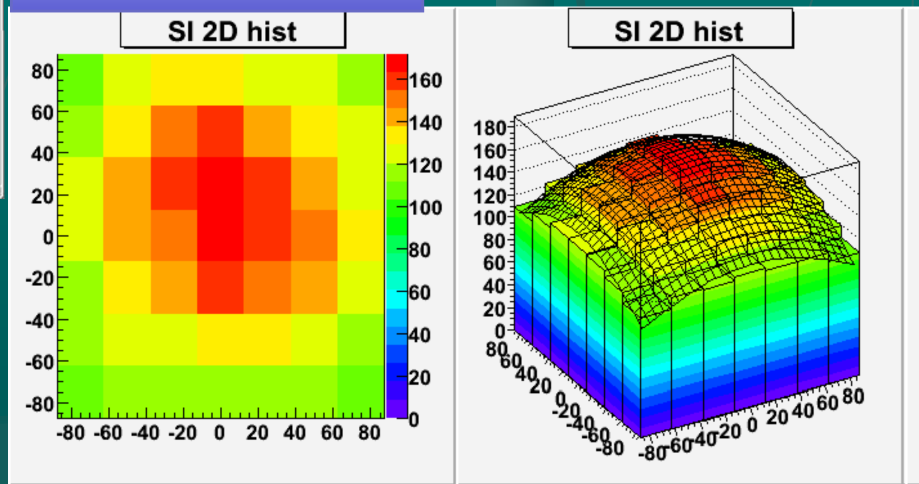
Proton beam profile monitor along nu beamline



OTR detector just in front of target (fluorescence plate)



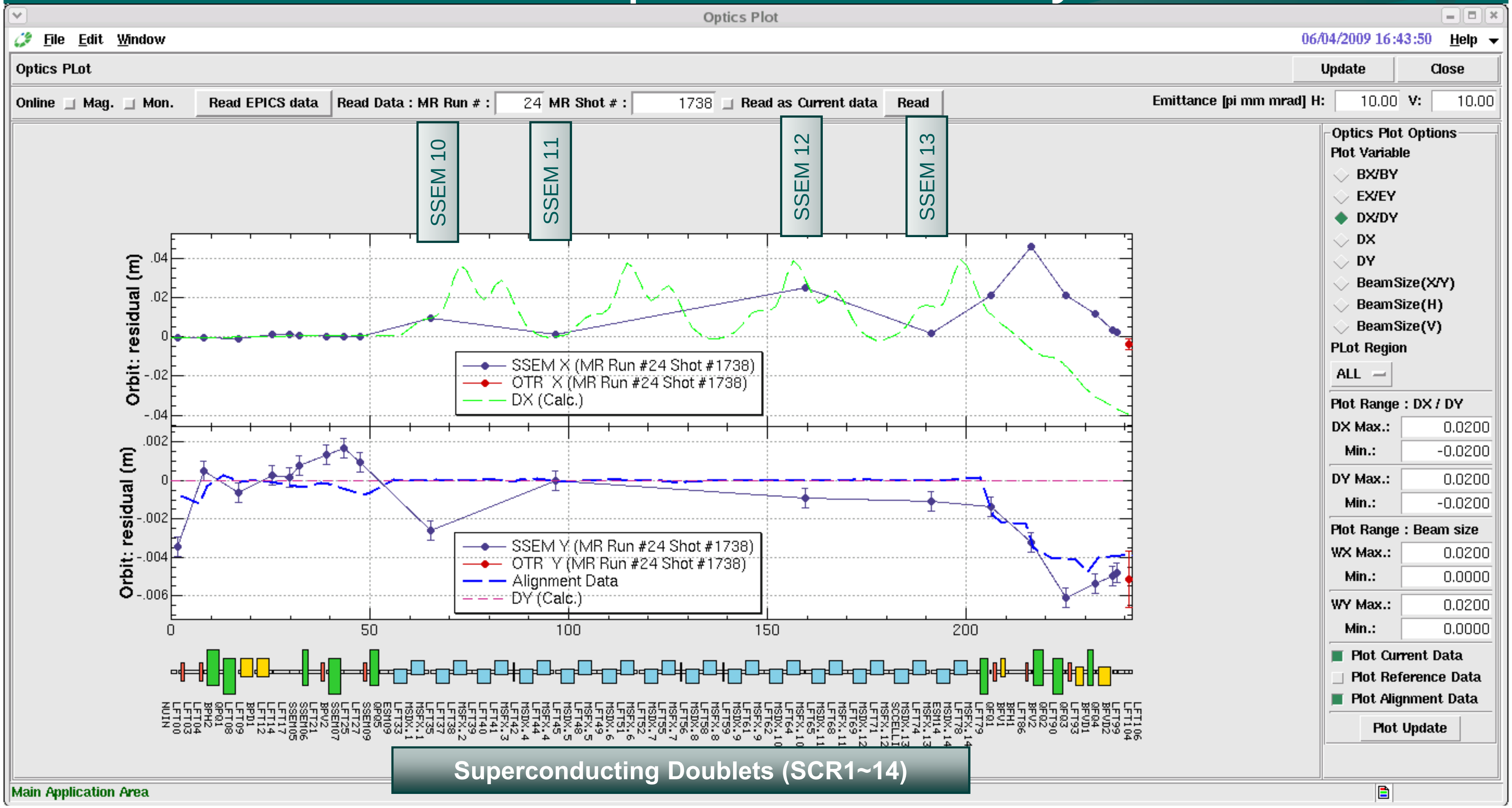
Muon monitor profile

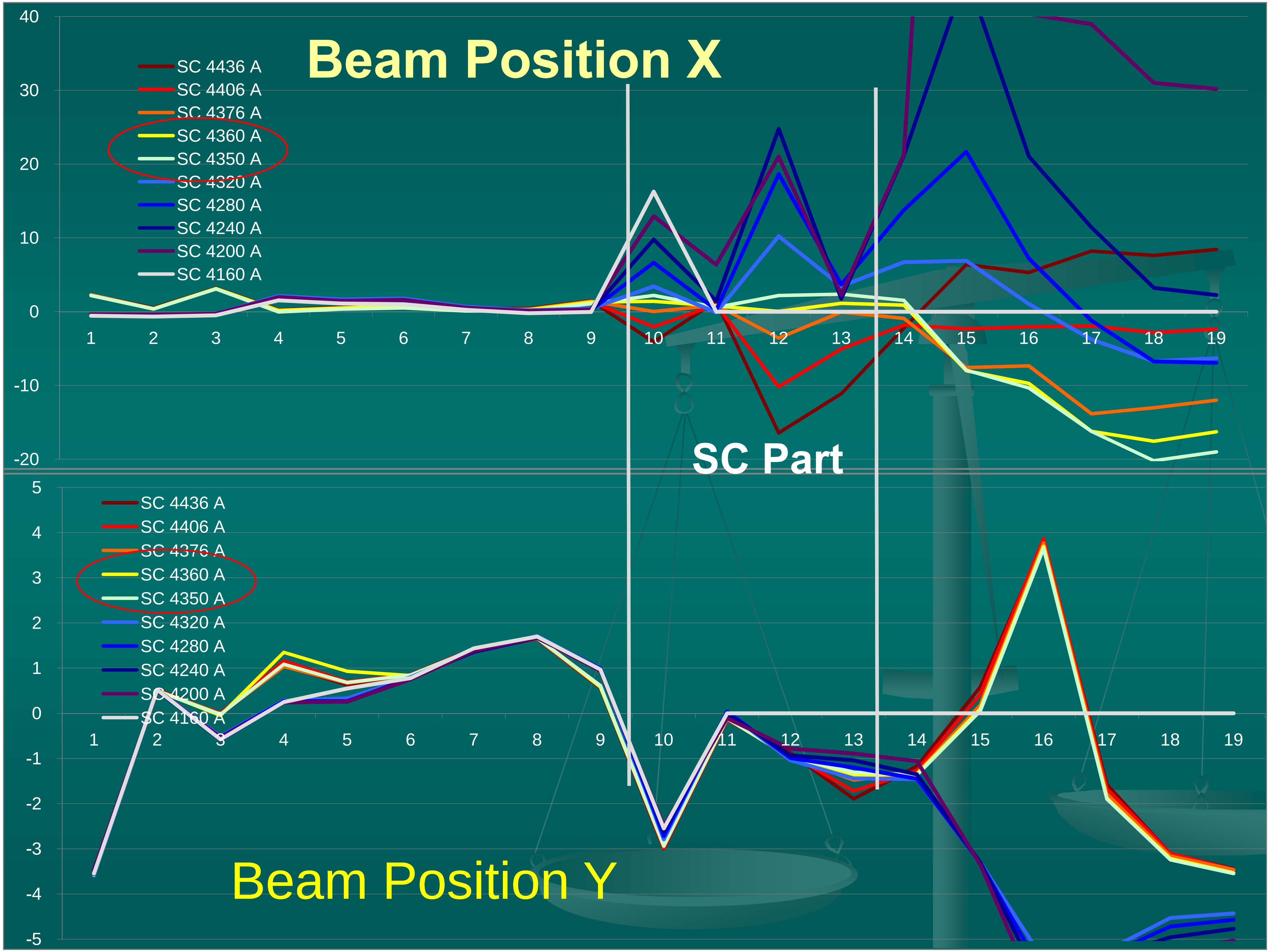


Horn

Optics Study

- SC Magnet current dependence
  - Beam induced quench eventually





Beam Position X
SC Part
Beam Position Y
SC 4436 A
SC 4406 A
SC 4376 A
SC 4360 A
SC 4350 A
SC 4320 A
SC 4280 A
SC 4240 A
SC 4200 A
SC 4160 A
40
30
20
10
0
-10
-20
5
4
3
2
1
0
-1
-2
-3
-4
-5
1
2
3
4
5
6
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13
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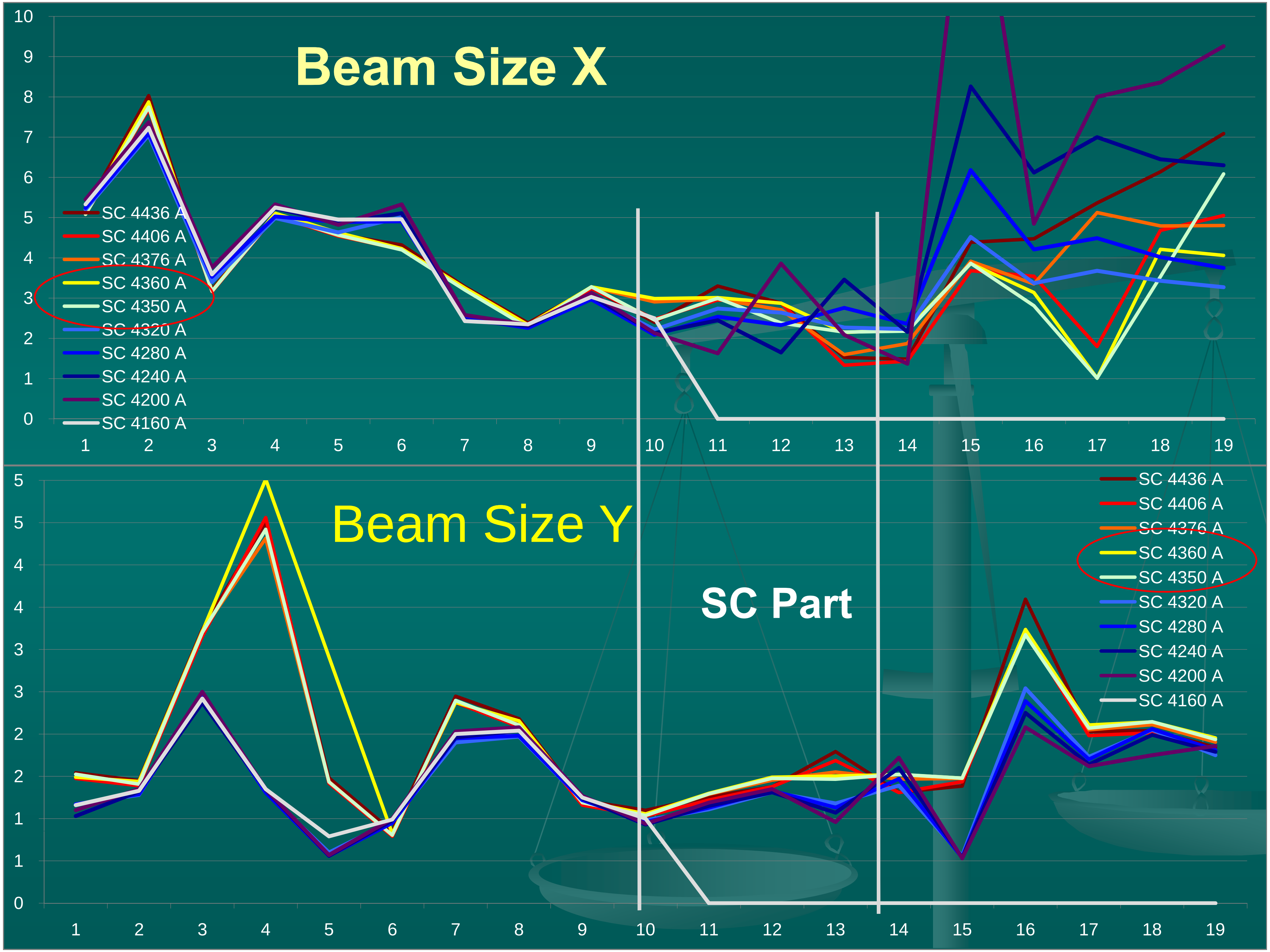
15
16
17
18
19


Beam Size X
Beam Size Y
SC Part
SC 4436 A
SC 4406 A
SC 4376 A
SC 4360 A
SC 4350 A
SC 4320 A
SC 4280 A
SC 4240 A
SC 4200 A
SC 4160 A

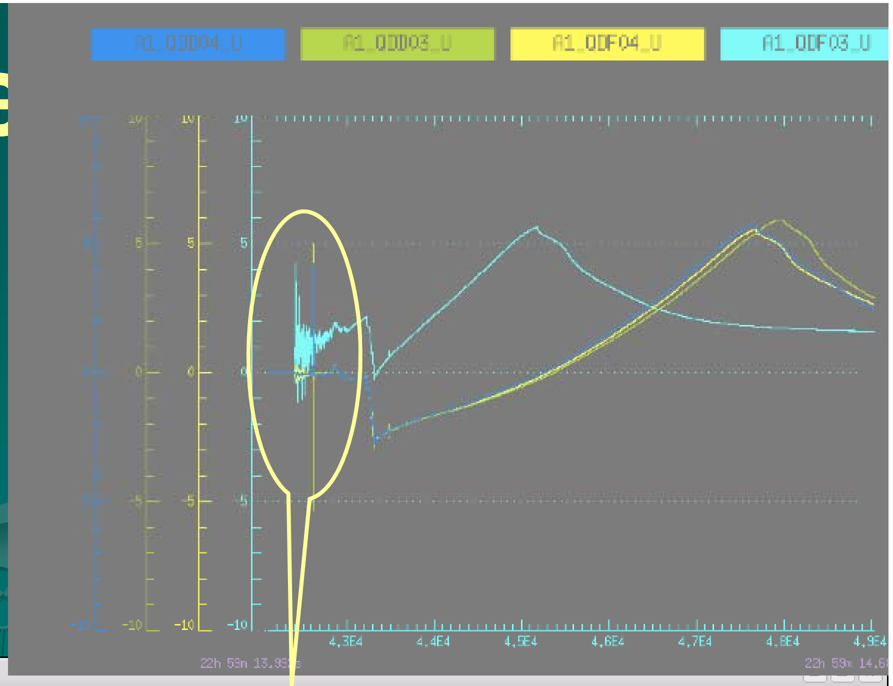
Beam Induce

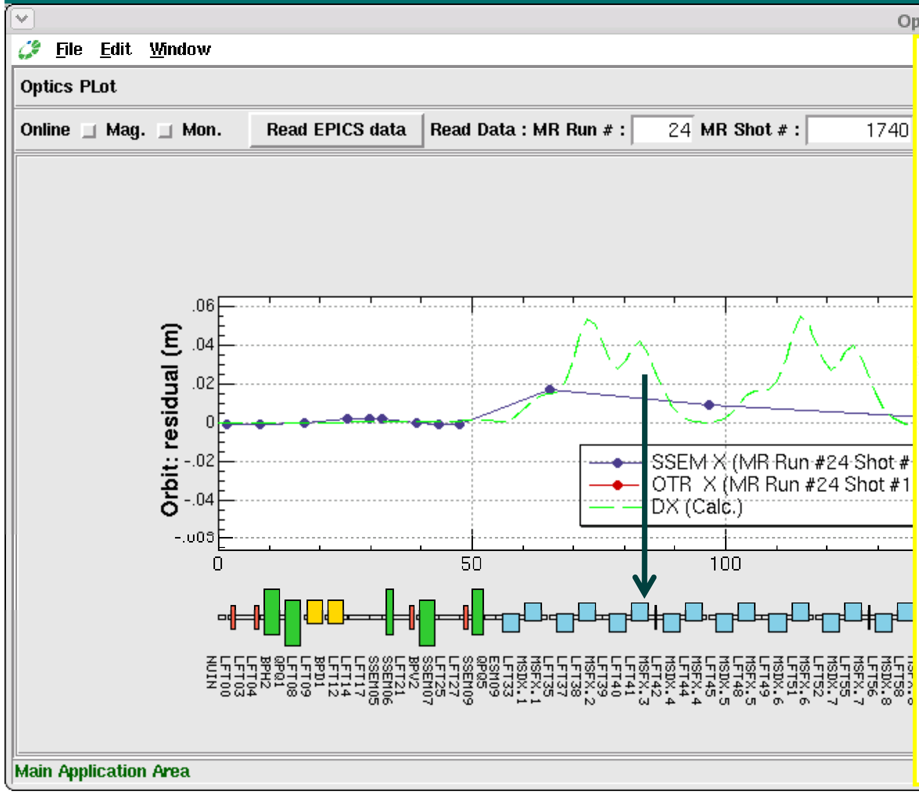
Partial beam loss observed at 4200

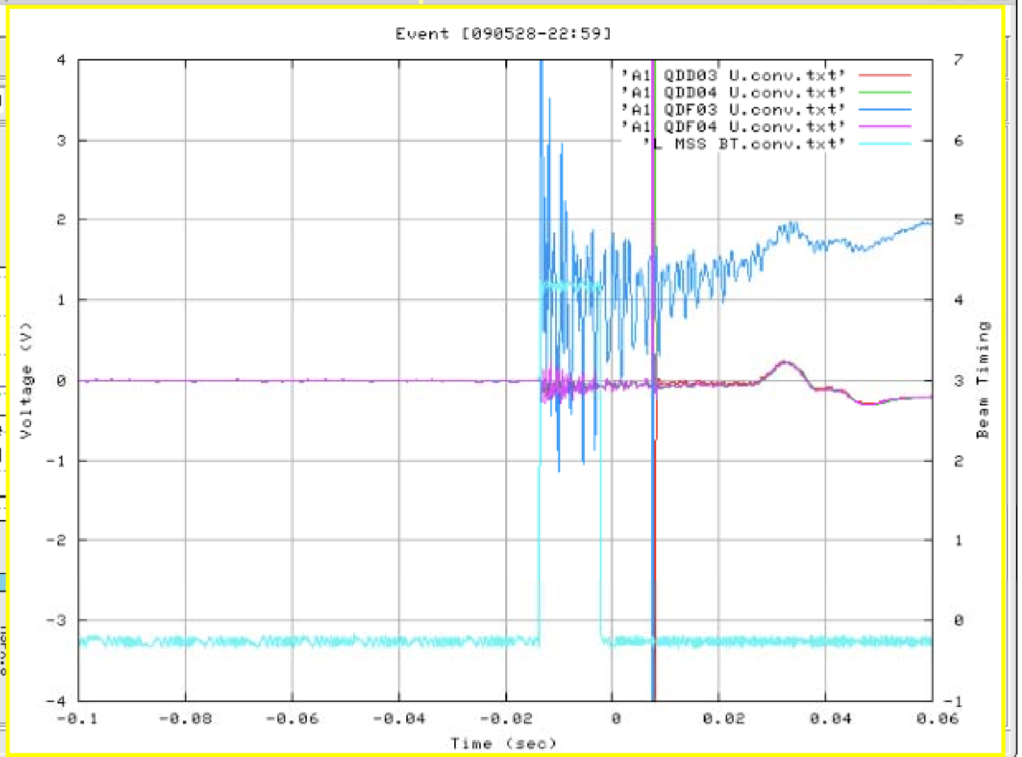
- At around SCR2~SCR4

Full beam loss observed at 4160 A

- Beam loss in between SCR2 ~ SCR4
- Quench at SCR3F
- No damage observed







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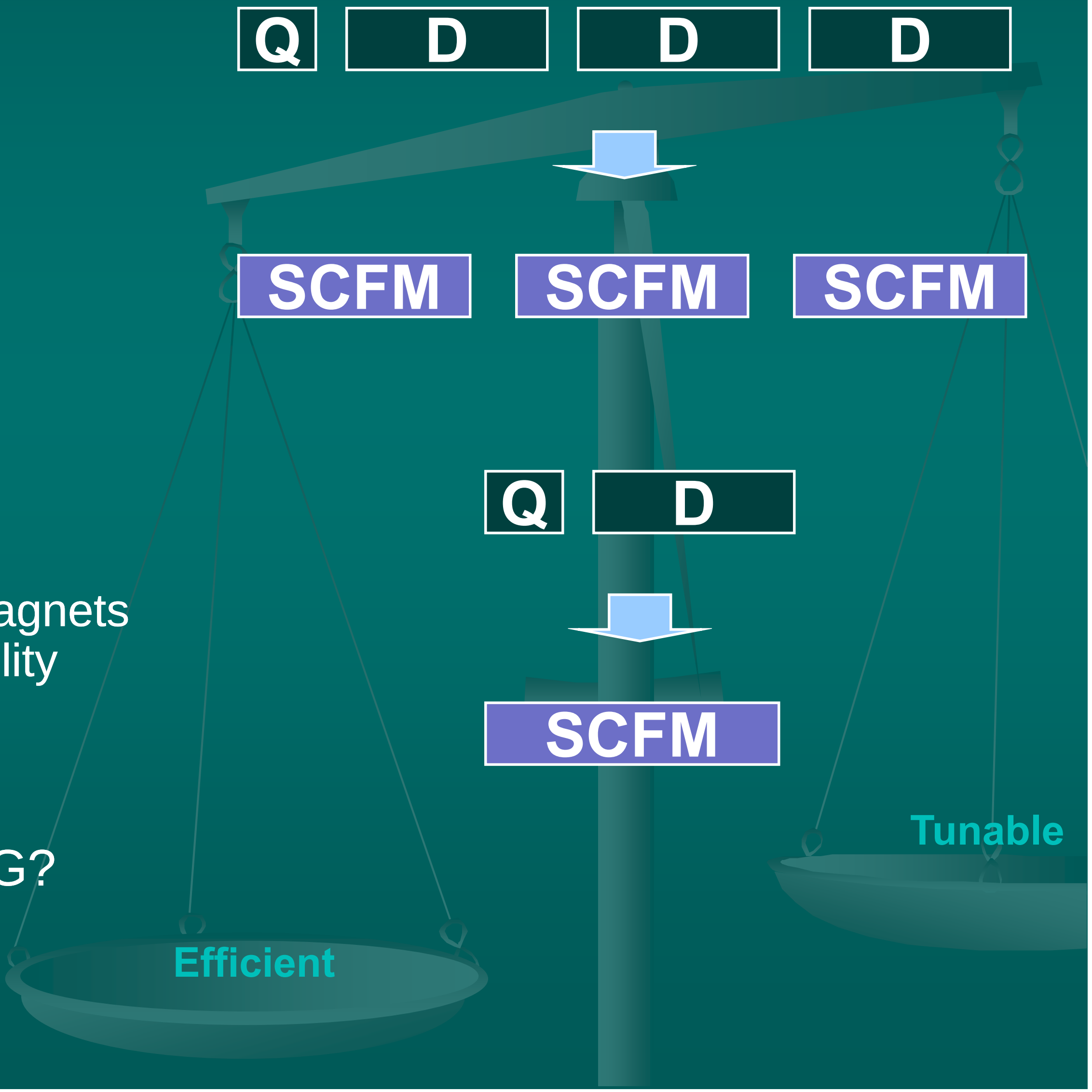
Conclusion

- **A SCFM with Single Layer Coil Winding is Developed**
- **Good Cost & Time Saving with Optimum Condition**
  - Half Cell = one SCFM; Dipole > Quadrupole
- Draw back
  - D/Q ratio fixed ➔ **It appears to be OK**
- International Collaboration
  - BNL, Saclay, CERN
- Construction Completed on Schedule
- Commissioning
  - No major problem with hardware commissioning
    - Minor problem associate with corrector current lead
      - scheduled to be fixed in this summer
  - Beam Commissioning went smoothly
    - Beam went through SC arc with the first attempt
    - Beam behaved as expected (almost)
    - Beam induced quench > quench protection works OK

Application of SCFM 1

- **Good Cost & Time Saving with Optimum Condition**
  - **Half Cell = one SCFM**
  - Dipole > Quadrupole
- For Beam Line
  - Already good enough?
    - So far so good.
- For Accelerator Ring
  - Needs more study on field quality
    - Neutrino production magnets show good reproducibility

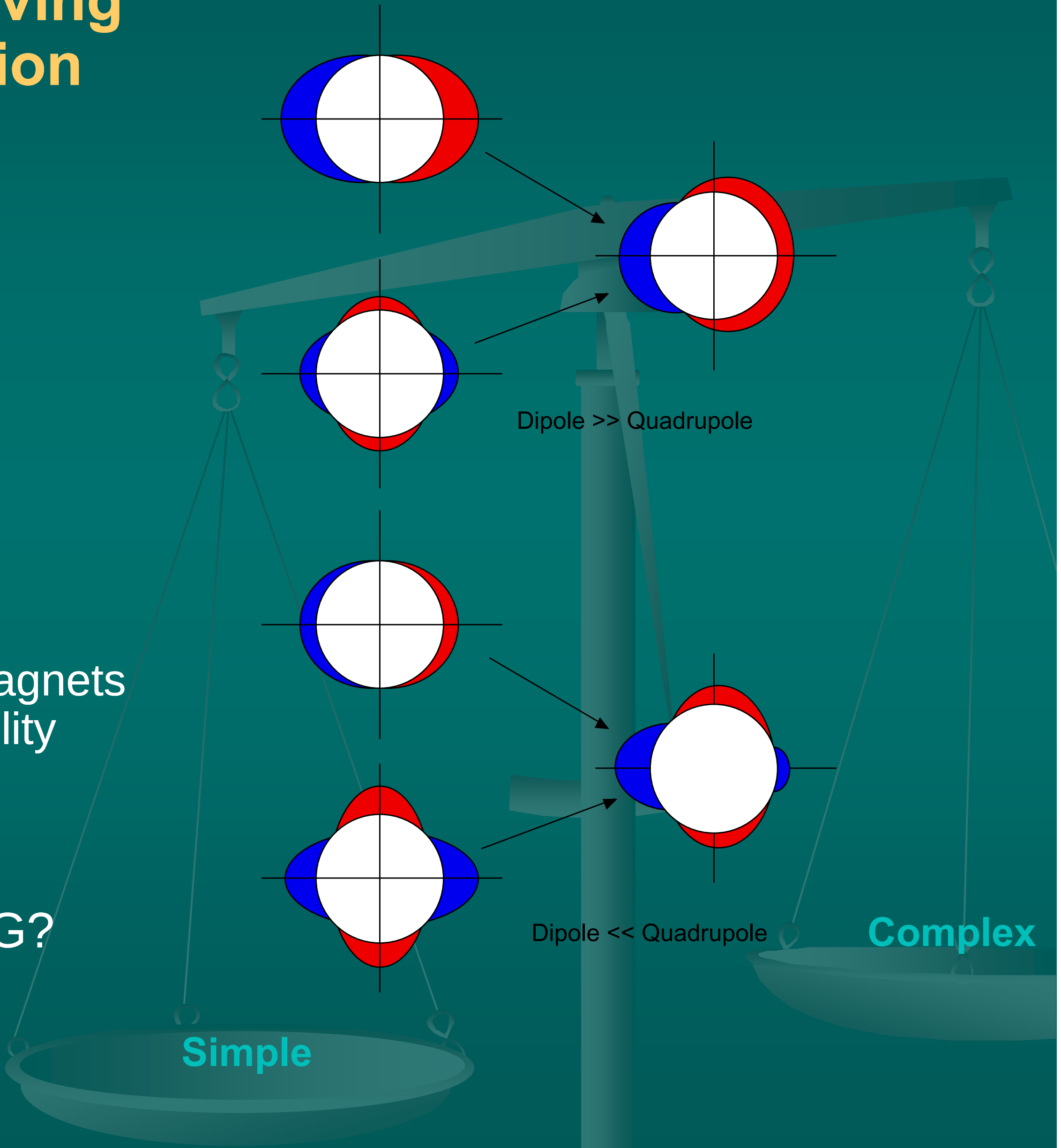
    = there are some hope
- Special Accelerator
  - Muon Acceleration FFAG?



Application of SCFM 2

- **Good Cost & Time Saving with Optimum Condition**
  - Half Cell = one SCFM
  - **Dipole > Quadrupole**
- For Beam Line
  - Already good enough?
    - So far so good
- For Accelerator Ring
  - Needs more study on field quality
    - Neutrino production magnets show good reproducibility

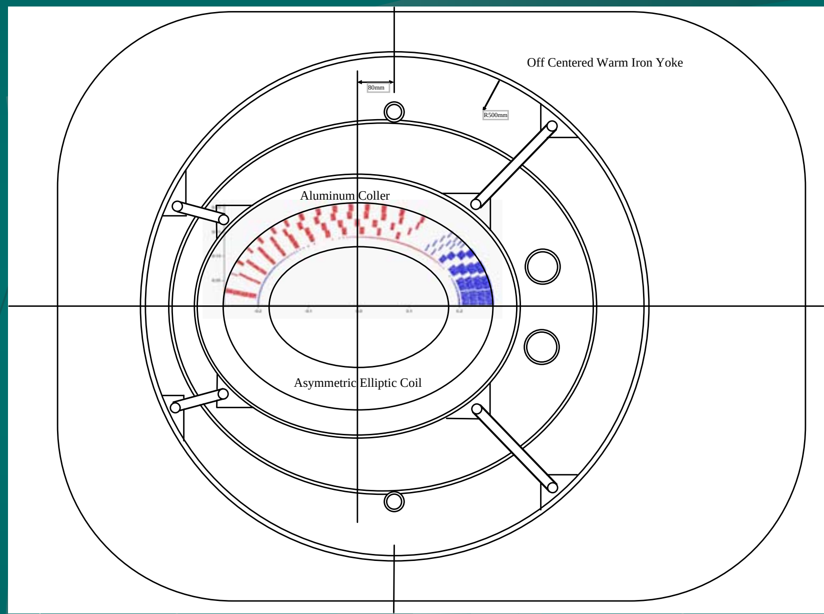
    = there are some hope
- Special Accelerator
  - Muon Acceleration FFAG?



Application of SCFM 3

- A SCFM with Single Layer Coil Winding is Developed
- Good Cost & Time Saving with Optimum Condition
  - Half Cell = one SCFM
  - Dipole > Quadrupole
- **For Beam Line**
  - **Already good enough?**
    - **So far so good**
- **For Accelerator Ring**
  - **Needs more study on field quality**
    - **Neutrino production magnets show good reproducibility**

    = there are some hope
- **Special Accelerator**
  - **Muon Acceleration FFAG?**



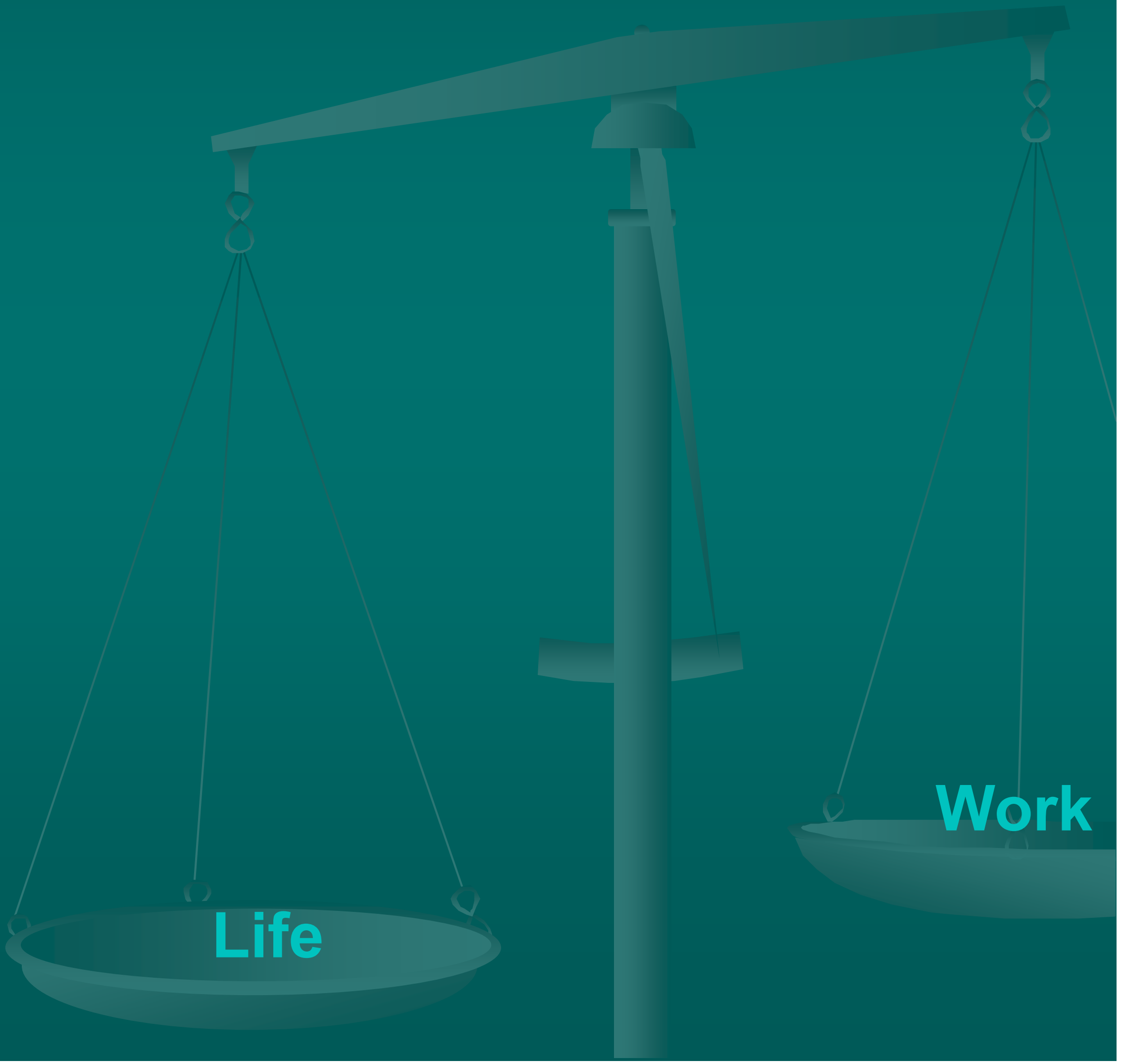
New Idea

Risk

Acknowledgment

Thank you very much

for your listening

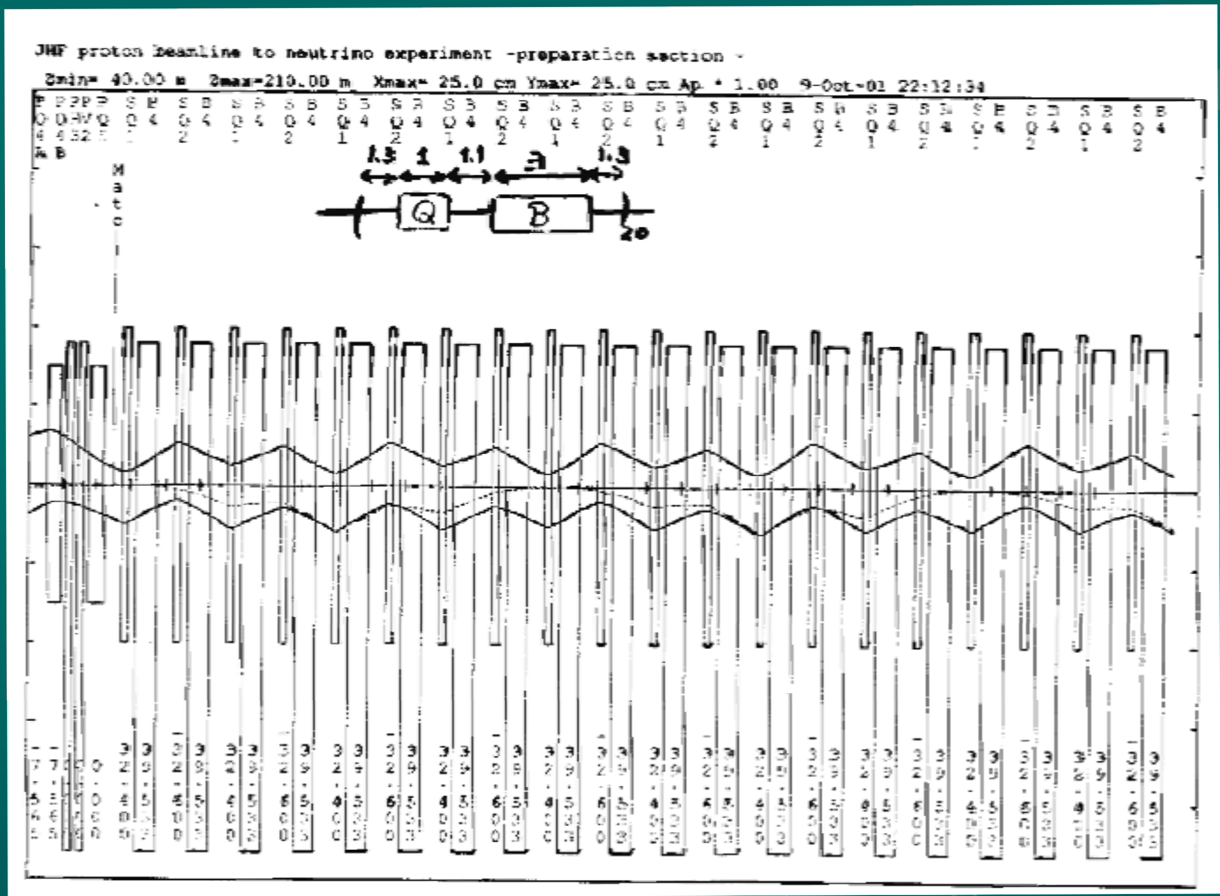


Acknowledgment

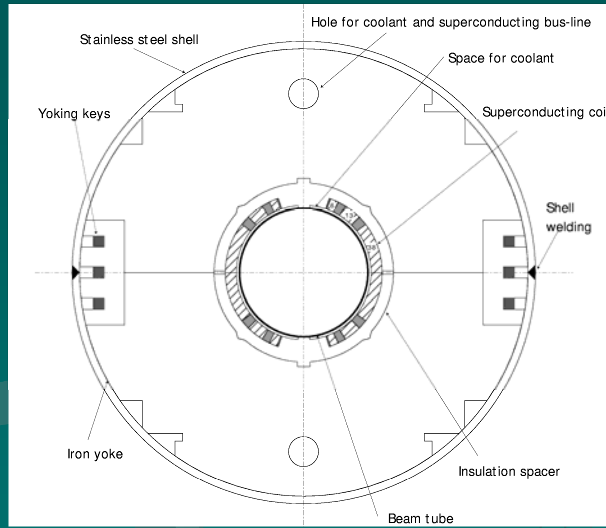
Acknowledgment

JFY 2001 : 10 Cell FODO

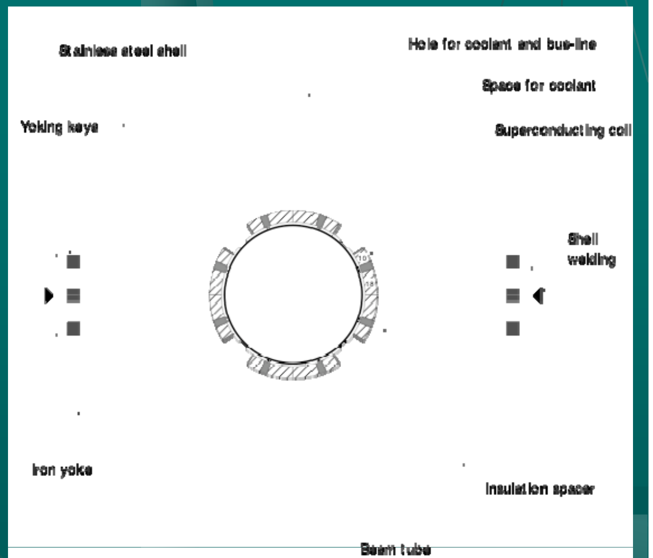
20 Dipole + 20 Quads = 40 Magnets



Ichikawa w/ help Doornbos

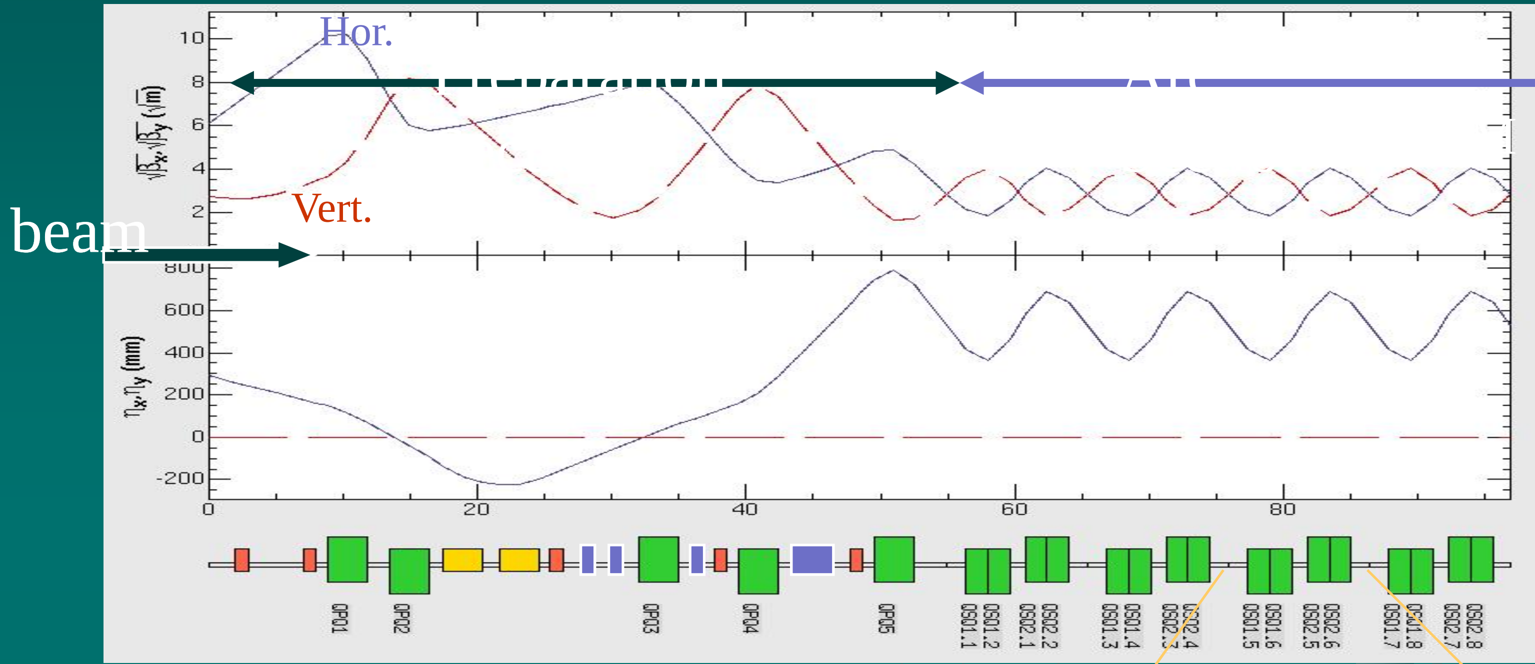


Dipole: 4T*3m

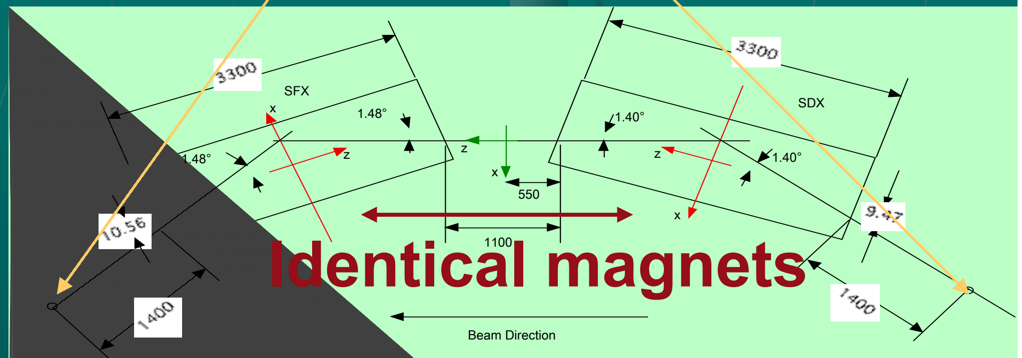


Quadrupole: 36T/m*0.9m

Optics with 14 Doublets



コリメータ



- Arc Section Optics
  - 14 doublets; 28 SCFM
- Optimized Collimator in Prep. Sec.
  - Minimize risk to Arc Section

Ichikawa, Iwamoto, Tanabe
w/ help Doornbos, Noumi, Oide