Development and Operation of a superconducting combined-function magnet system for J-PARC neutrino beam line

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Michael Anerella[2], John Escallier[2], George Ganetis[2], Arup Ghosh[2], Ramesh Gupta[2], Joe Muratore[2], Brett Parker[2], Peter Wanderer[2], BNL

Jean-Paul Charrier[3], Thierry Boussuge[3], CEA Saclay

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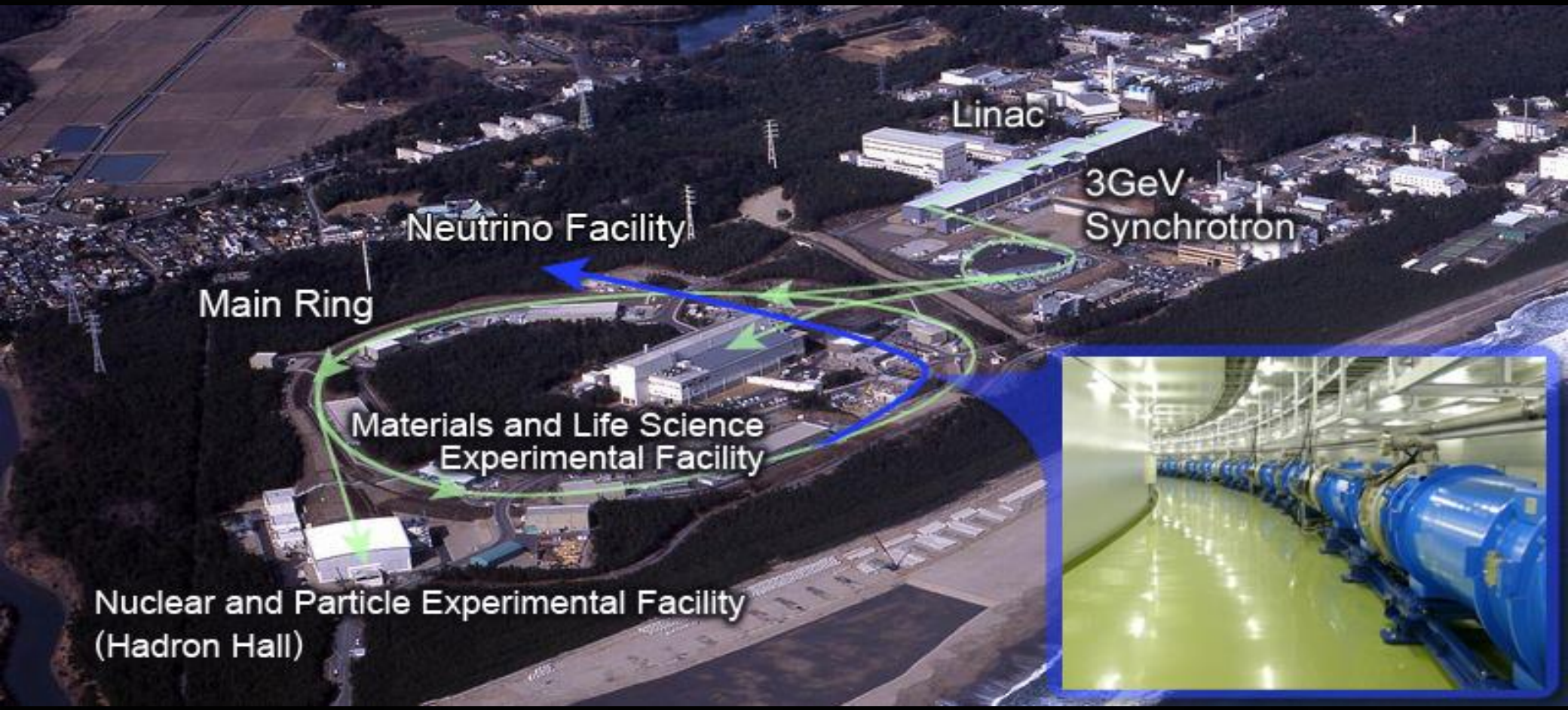
- Operation Statistics (Jan. 2010~ June 2012)
  - Beam induced quench (Nov. 2010)
- The earthquake (Mar.11 2011)
  - damages and recovery (Mar.~ Dec. 2011)
- Corrector Improvement (2011 Summer)
- Cold Diode Bus Consolidation (2014 Summer)
- Radioactive Material Control
- Summary

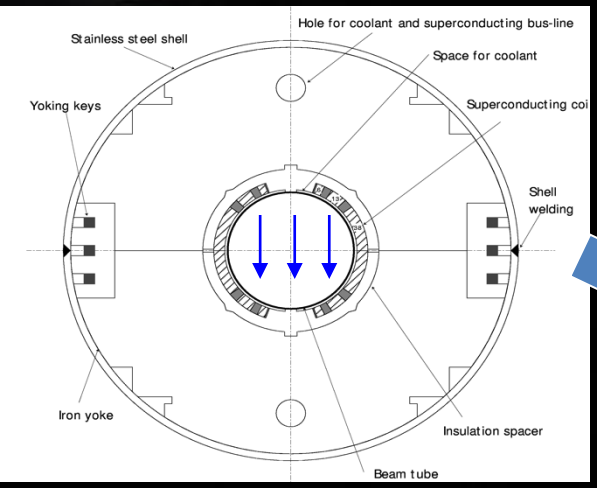
System Overview and Development

System Overview

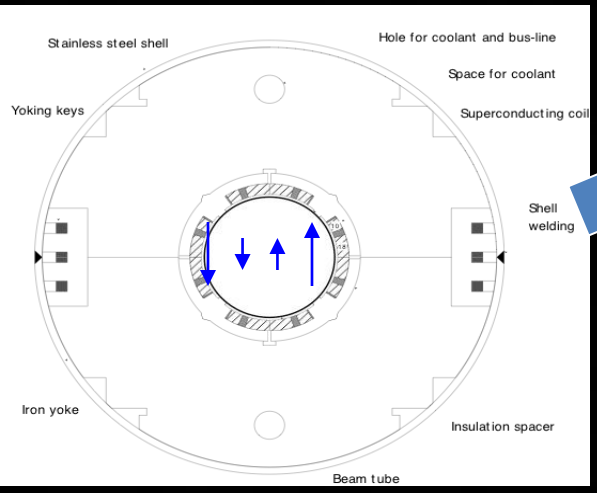
J-PARC Neutrino Beam Line



SC Combined Function Magnet

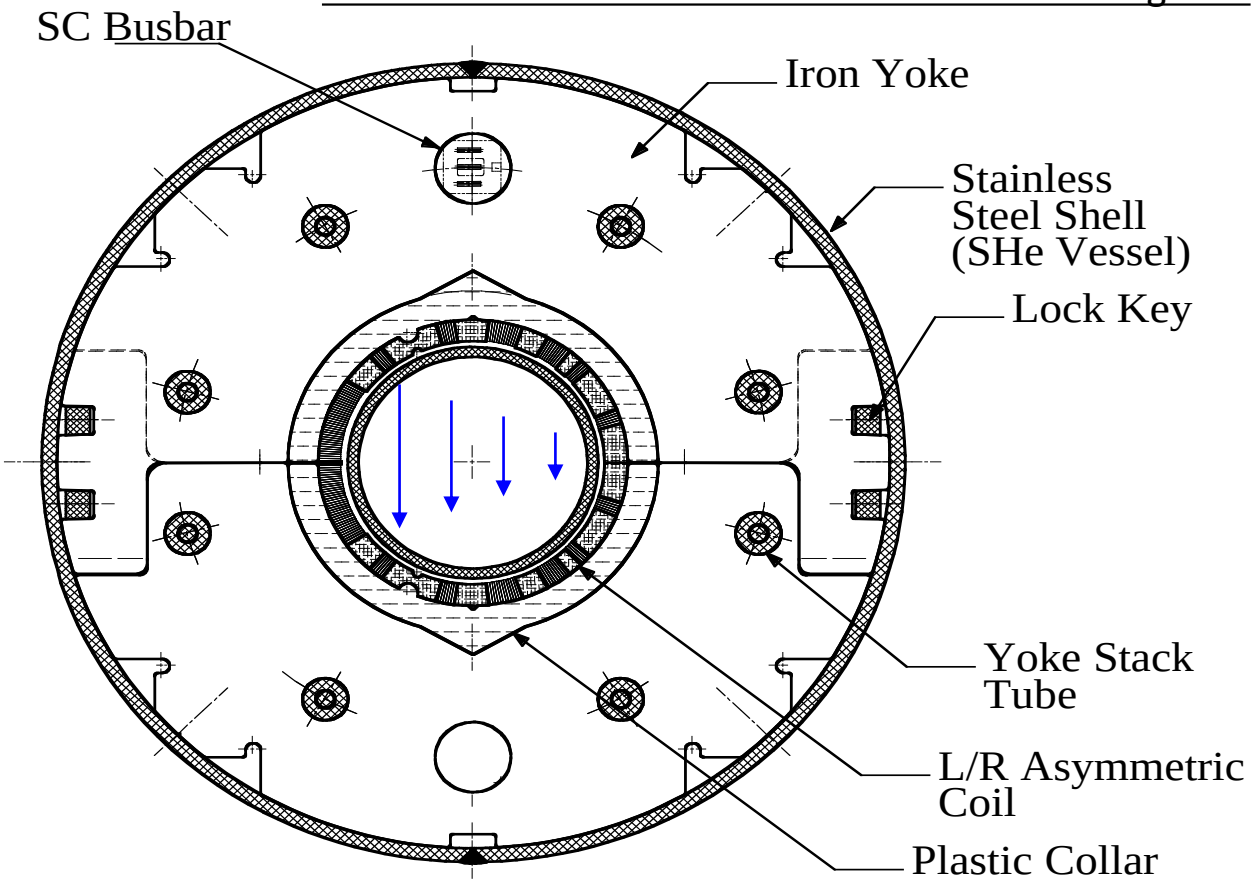


RHIC like Dipole



RHIC like Quadrupole

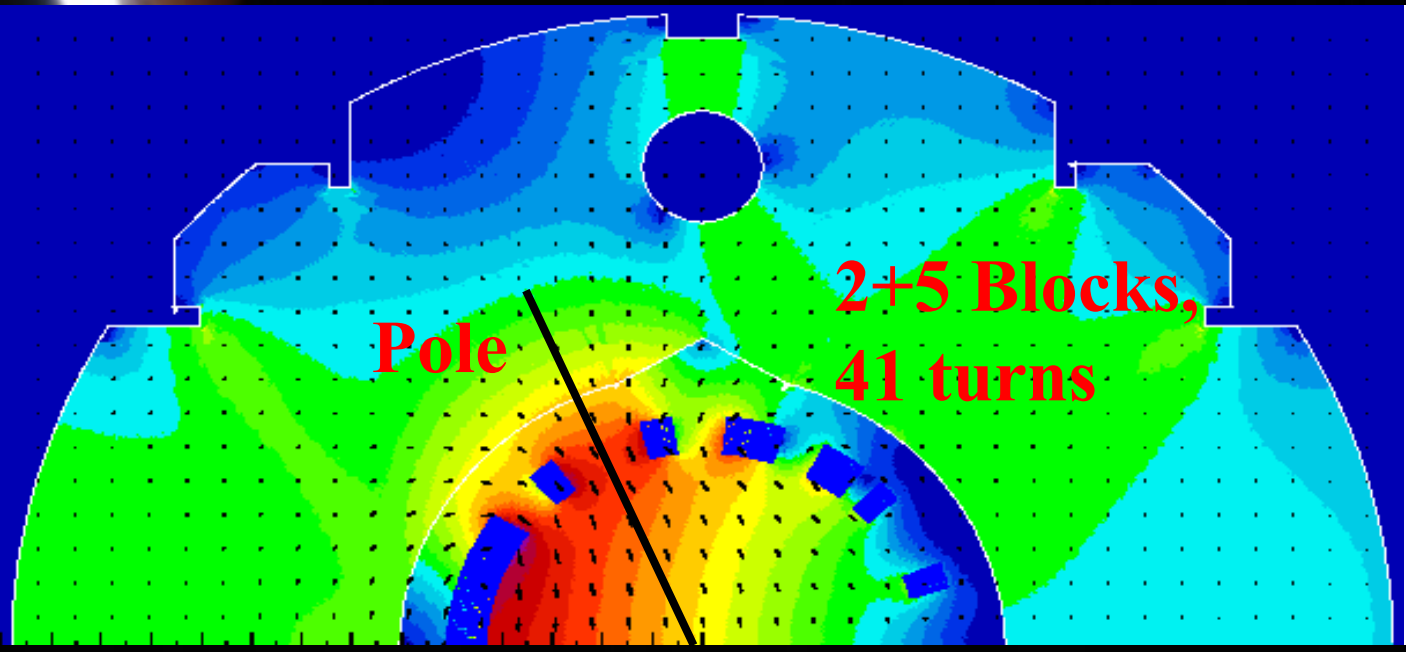
Mechanical Structure learned from RHIC arc magnets



Combined Function Magnet
with Left-Right Asymmetric Coil

Designed for 50 GeV; Dipole: 2.6 T, Quadrupole: 19 T/m
Operation current: 7345 A > Currently 30 GeV: ~4350A

Specification



Coil ID.: 173.4mm
Mag. Length: 3300 mm
Mech. Length: 3630 mm
Tmax: < 5.0K
(Supercritical Helium Cooling)
Dipole Field: 2.59 T
Quad. Field: 18.6 T/m
Field Error: < 10^-3 @ 50mm

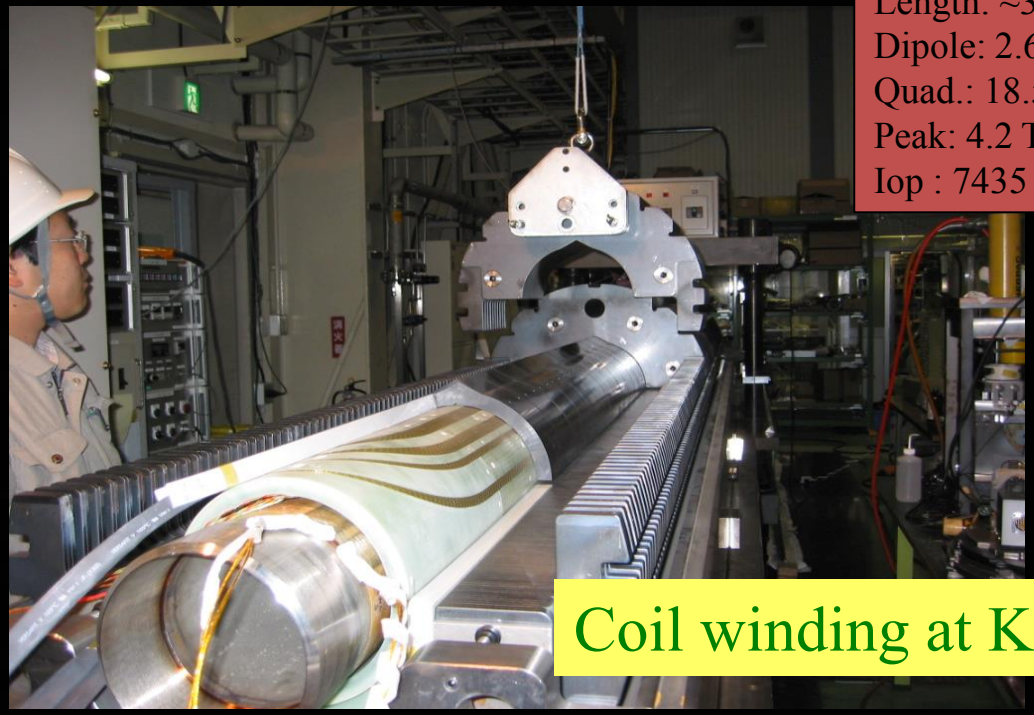
Op. Current: 7345 A
Op. Margin: 72%
Inductance: 14.3 mH
Stored Energy: 386 kJ
# of Magnet: 28
SC Cable: NbTi/Cu
Rutherford Type Cable
for LHC Dipole Outer-L

	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	-58.1	-101.5	-33.7
b4 (unit)	5.01	-11.1	-23.5	-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

- **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.**

Good Not So Good Enough

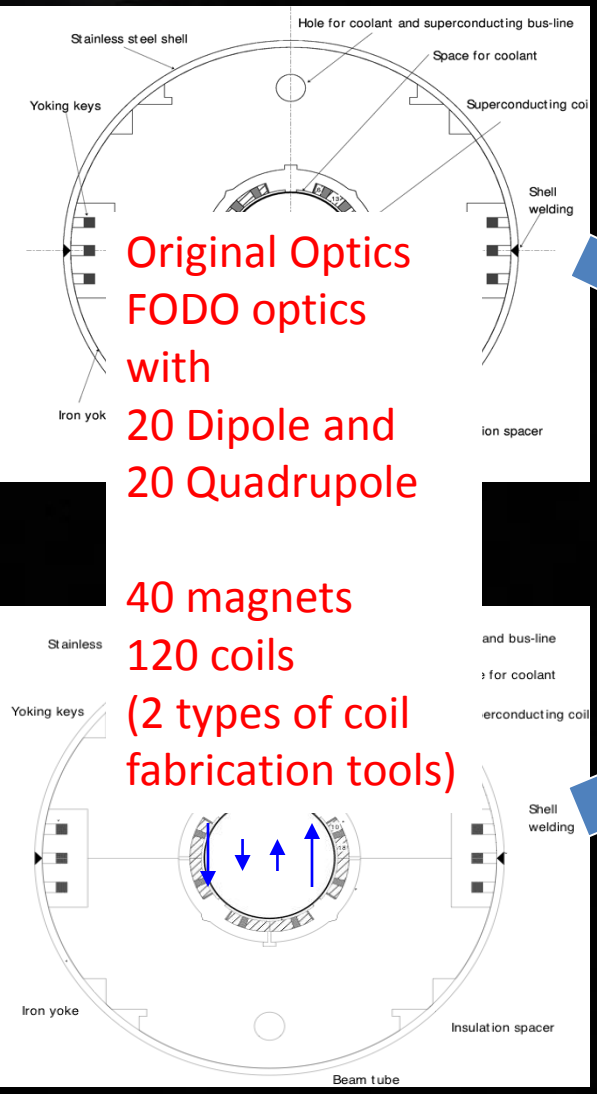
Combined function Magnet
Coil Winding,
Thanks for experience from LHC-MQXA development



Coil ID: 173 mm
Length: ~3.5 m
Dipole: 2.6 T
Quad.: 18.5 T/m
Peak: 4.2 T
Iop : 7435 A

Coil winding at KEK

SC Combined Function Magnet

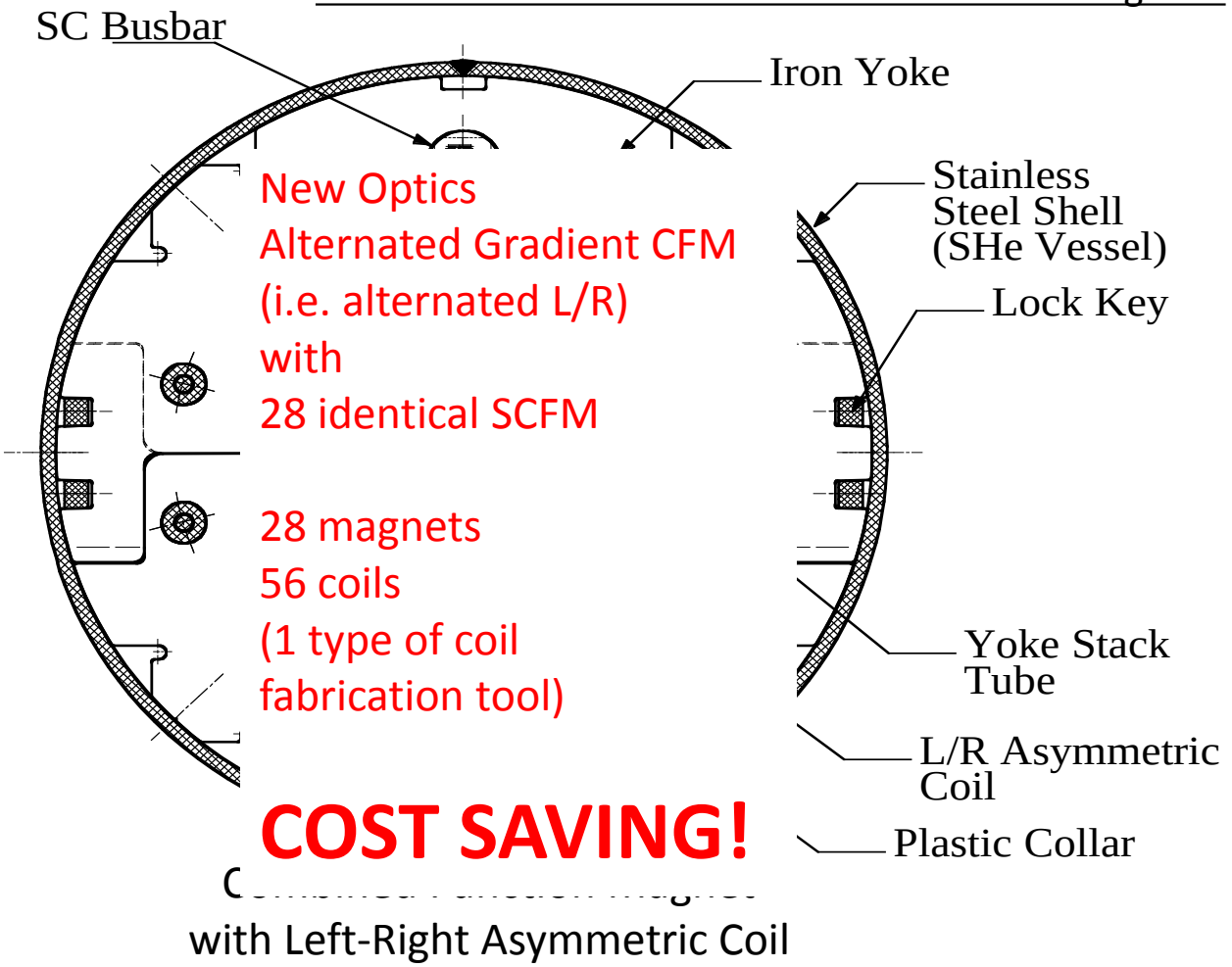


Original Optics
FODO optics
with
20 Dipole and
20 Quadrupole

40 magnets
120 coils
(2 types of coil fabrication tools)

RHIC like Quadrupole

Mechanical Structure learned from RHIC arc magnets



New Optics
Alternated Gradient CFM
(i.e. alternated L/R)
with
28 identical SCFM

28 magnets
56 coils
(1 type of coil fabrication tool)

COST SAVING!

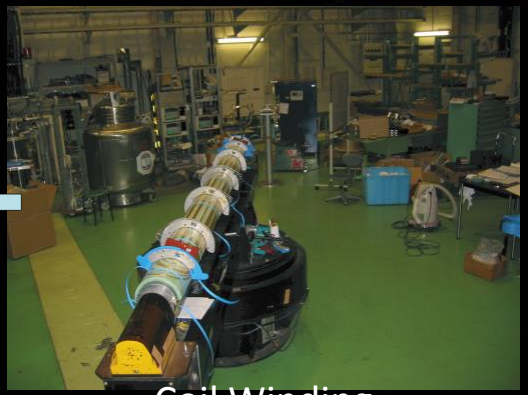
with Left-Right Asymmetric Coil

Designed for 50 GeV; Dipole: 2.6 T, Quadrupole: 19 T/m
Operation current: 7345 A > Currently 30 GeV: ~4350A

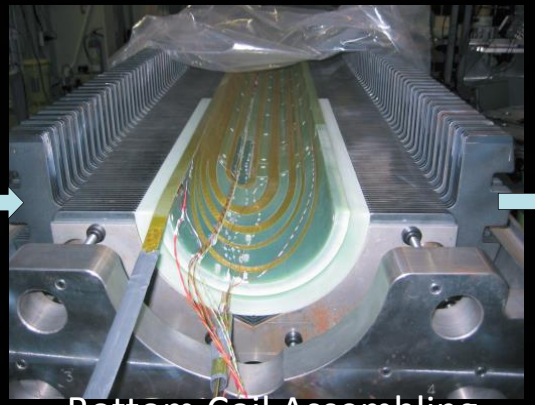
Prototype Fabrication 1


Completed Coil

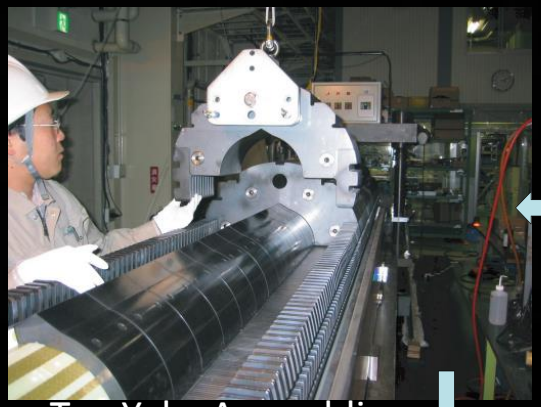

Coil Curing

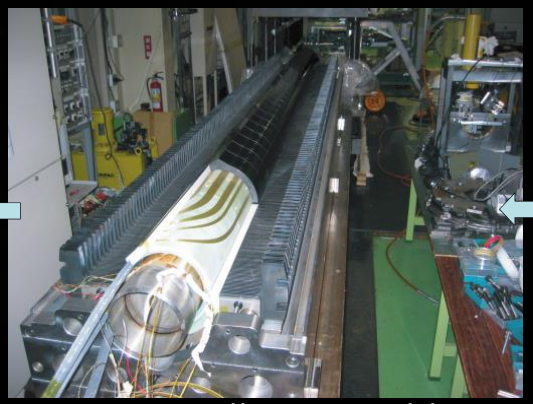

Coil Winding

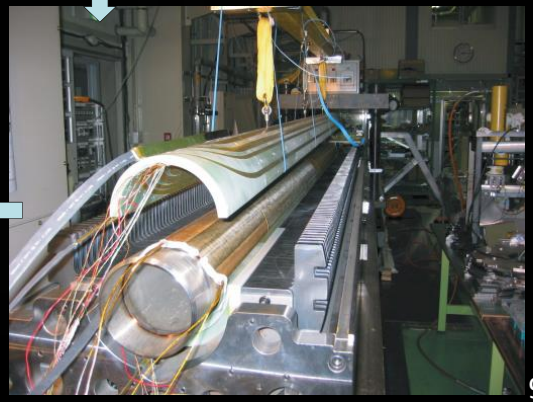

Bottom Yoke and Collar


Bottom Coil Assembling

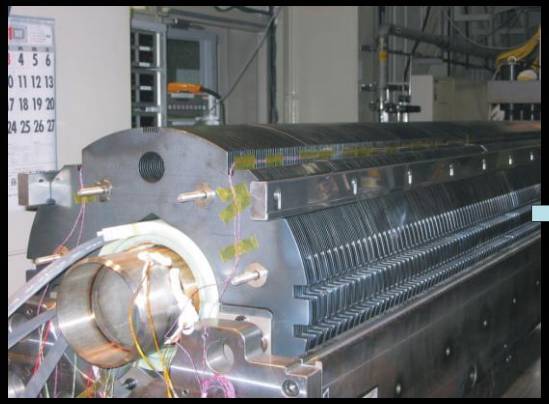

Beam Tube Assembling


Top Yoke Assembling


Top Collar Assembling


Top Coil Assembling

Prototype Fabrication 2



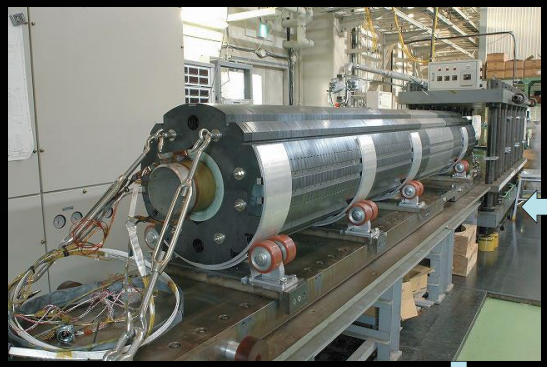
Top Yoke Assembled

Top Press Tool Assembling

Yoke Press

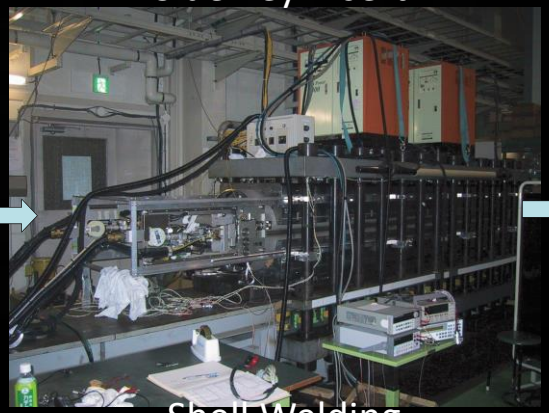
Side Key Insert

Side Key Insert

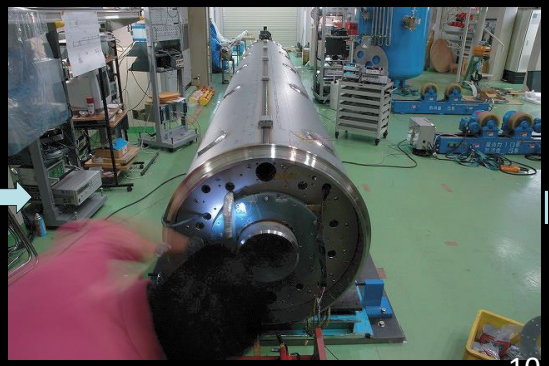


Yoked Coil

Shell Welding Preparation



Shell Welding



End Splice Assembling

Prototype Completion and Testing

Prototype Completed by Jan. 2005

Cold test in vertical Cryostat in March 2005

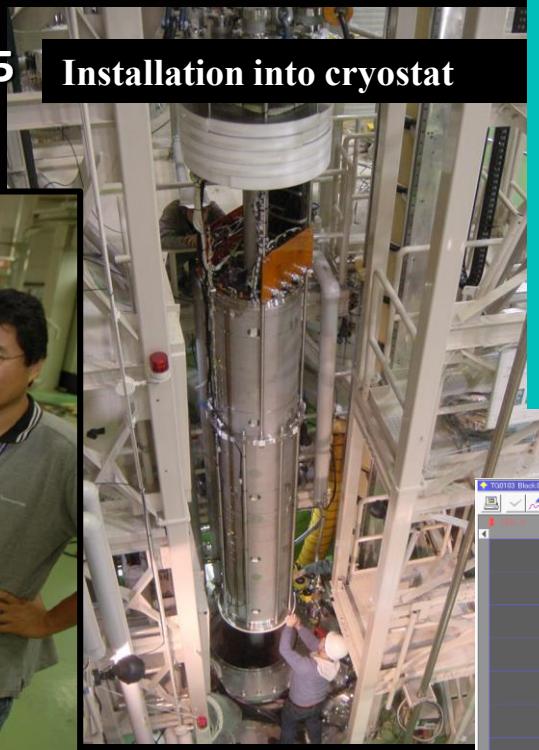
I_{op} = 7345 A @ 50 GeV (and I_{max} = 7,700 A)

reached with no quench, on March 4, 2005

Field Quality Meets
Optics Requirements
No feedback to the design

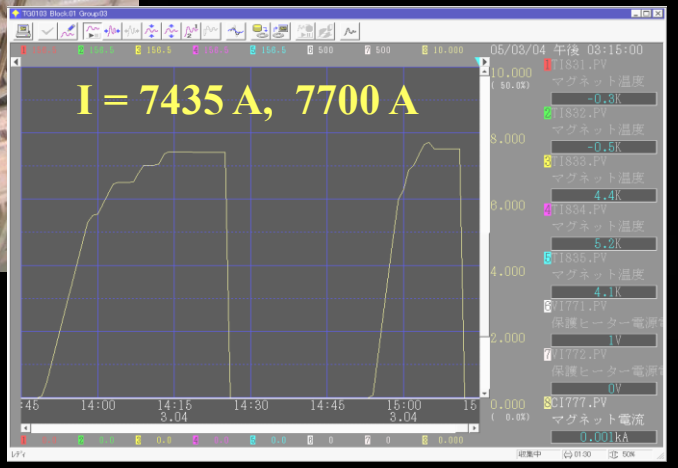
	Measurement	*Computation*
Current (A)	7460	7345
B_1 (T•m)	8.906	8.712
B_2 (T•m)	3.127	3.120
B_3 (T•m)	$-220.6*10^{-4}$	$-293.6*10^{-4}$
B_4 (T•m)	$-5.9*10^{-4}$	$-20.1*10^{-4}$
B_5 (T•m)	$-51.9*10^{-4}$	$-30.6*10^{-4}$
B_6 (T•m)	$-75.2*10^{-4}$	$-62.8*10^{-4}$
B_7 (T•m)	$-44.6*10^{-4}$	$-20.9*10^{-4}$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



Installation into cryostat

Participating member



Record of Excitation current

Production Magnets Field Quality

Mass Production
Started Jan. 2006
All tested in vertical cryo.

Field Measurements
-Meets optics requirements
-Reproducibility:
similar to MQXA

Integral Field Quality

Bn	Unit	Opera 3D			Measured					
		7345 A	5830 A	4400 A	7345A		5830 A		4400 A	
		calculated	calculated	calculated	average	standard deviation	average	standard deviation	average	standard deviation
1	Tm	-8.69	-6.93	-5.20	-8.72	0.023	-6.94	0.020	-5.23	0.016
2	Tm	3.11	2.49	1.87	3.07	0.002	2.46	0.002	1.86	0.002
3	1×10^{-4} Tm	293.45	236.56	179.18	218.99	6.50	181.74	5.38	138.44	3.81
4	1×10^{-4} Tm	-20.33	-64.83	-52.10	-7.55	4.55	-62.67	3.82	-53.71	2.74
5	1×10^{-4} Tm	30.68	41.02	32.12	47.77	3.31	53.79	2.45	40.52	1.74
6	1×10^{-4} Tm	-62.58	-48.25	-36.07	-68.18	1.90	-50.72	1.31	-36.65	0.92
7	1×10^{-4} Tm	20.84	14.77	10.93	33.02	3.80	21.12	2.65	13.50	1.87
8	1×10^{-4} Tm	-31.87	-25.13	-18.84	-59.11	5.14	-42.90	4.02	-29.19	3.22
9	1×10^{-4} Tm	73.20	58.17	43.64	75.50	1.67	59.65	1.17	44.55	0.99
10	1×10^{-4} Tm	-0.33	-0.29	-0.22	-10.57	1.41	-7.40	1.12	-4.69	1.01

Straight Section Field Quality

	Opera 2D			Measured					
	7345 A	5830 A	4400 A	7345A		5830 A		4400 A	
				average	standard deviation	average	standard deviation	average	standard deviation
b3	1.62	1.91	1.21	5.12	0.84	3.86	0.78	3.48	0.76
b4	-9.04	0.26	2.30	-9.19	0.42	-0.64	0.43	-0.77	0.41
b5	2.51	-0.93	-1.47	0.50	0.31	-1.89	0.29	-1.90	0.28
b6	6.28	5.98	5.82	6.72	0.15	6.22	0.12	5.94	0.11
a3	0	0	0	0.12	1.05	0.22	1.05	0.24	1.07
a4	0	0	0	-0.11	0.19	-0.04	0.21	-0.02	0.20
a5	0	0	0	0.08	0.36	0.07	0.34	0.06	0.31
a6	0	0	0	0.04	0.17	0.06	0.13	0.07	0.10

MQXA Straight Section

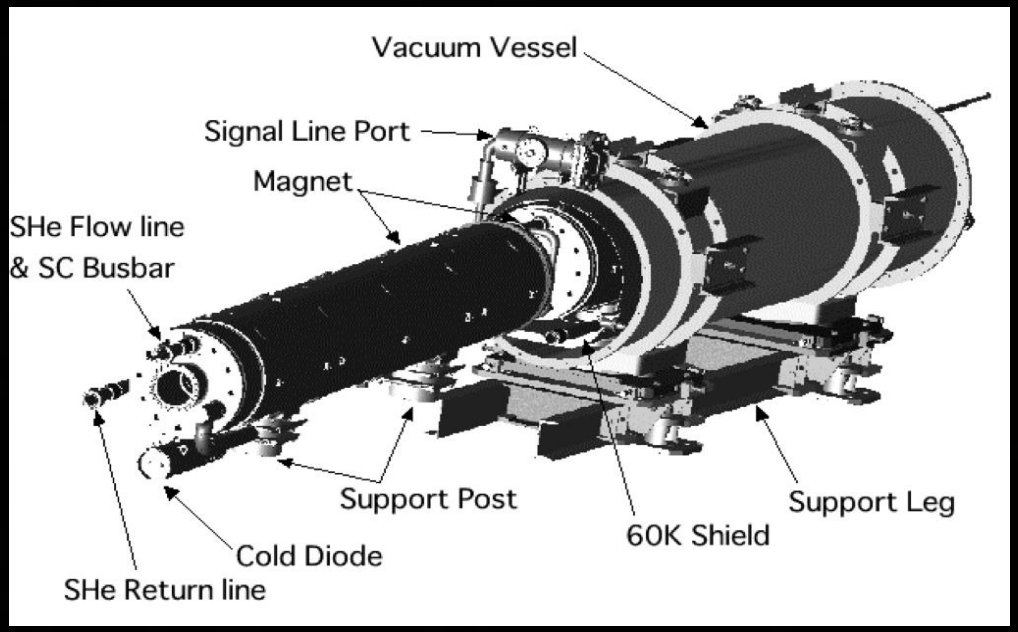
(Reference radius converted to the same ratio)

	Measured	
	average	standard deviation
b3	0.063	0.41
b4	1.94	0.16
b5	0.00	0.07
b6	0.67	0.17
a3	0.27	0.47
a4	-0.02	0.40
a5	0.01	0.07
a6	-0.05	0.04

Doublet Cryostat

Vacuum Vessel

Connecting Sleeve



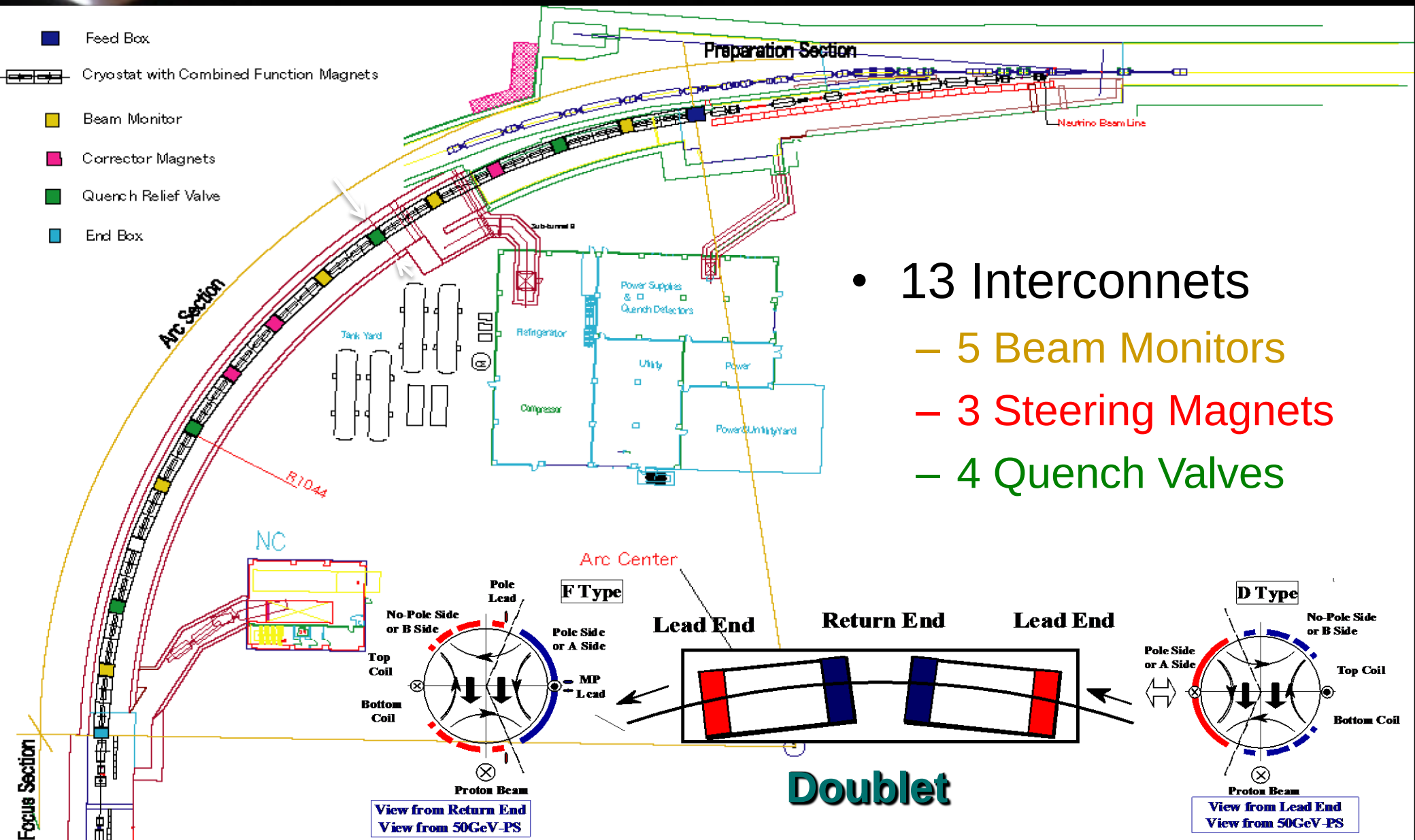
Cold Diode

Support Post

Support Post

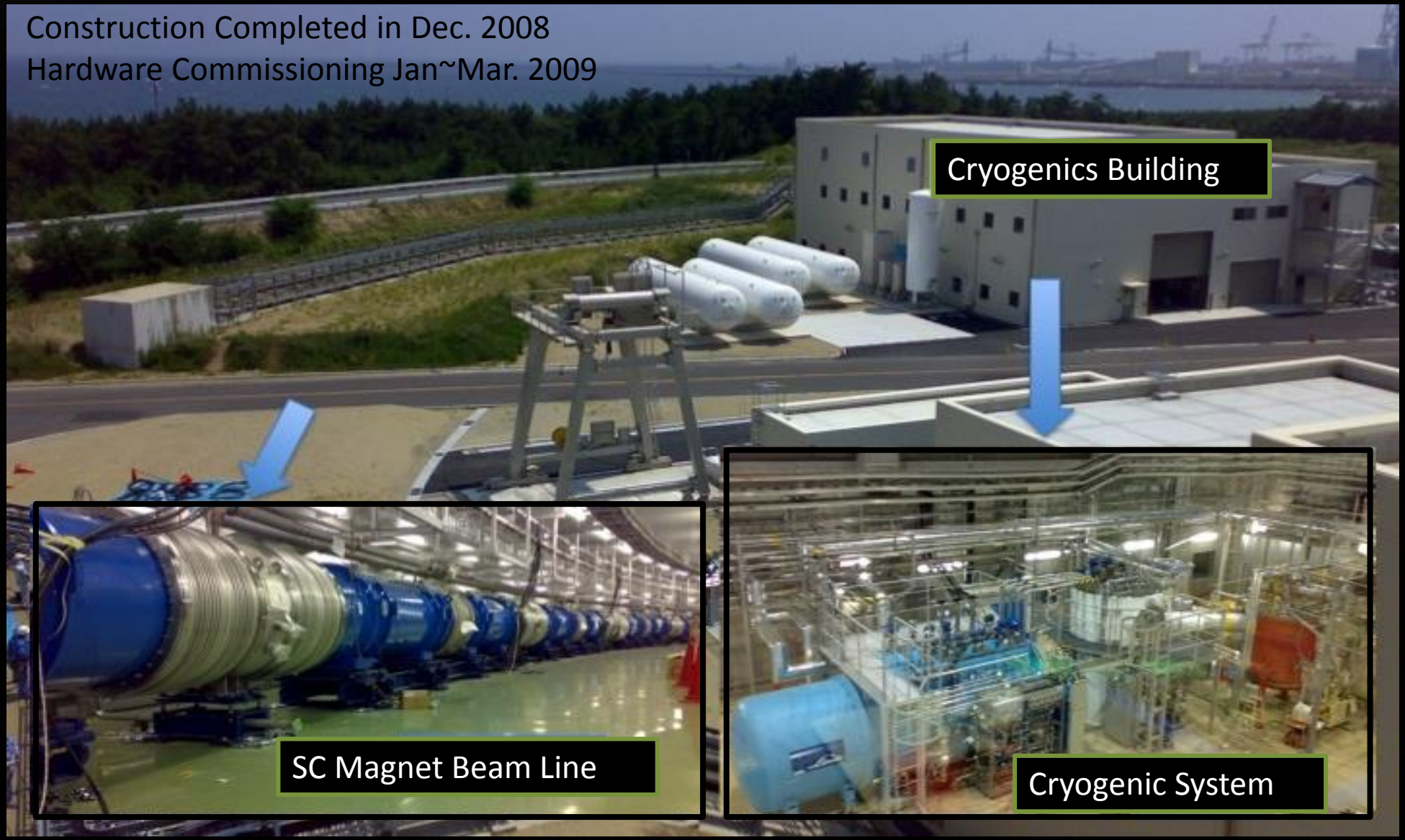
- Cryostat Design
  - Common baseline: LHC cryostat: Reduce Cost and Risk
  - Common Parts ➔advantage of LHC mass production **(also Strong CERN support)**

Beam Line Configuration



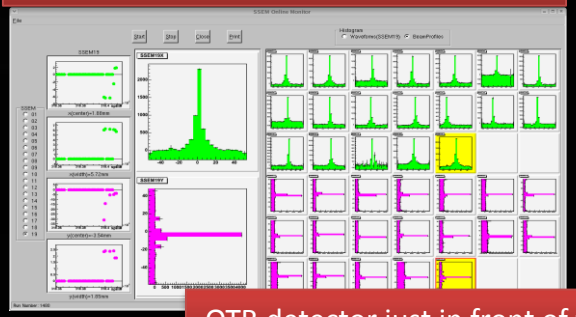
- 13 Interconnets
  - 5 Beam Monitors
  - 3 Steering Magnets
  - 4 Quench Valves

J-PARC Neutrino Beam Line

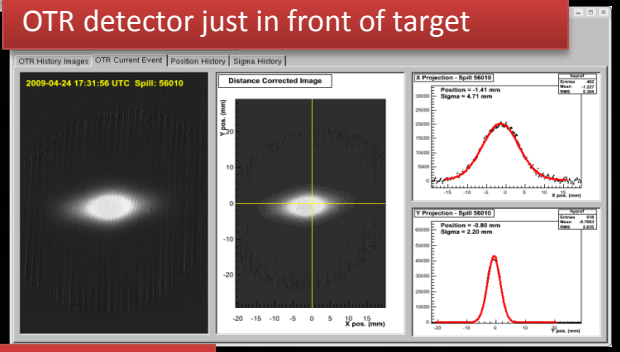


Operation Statistics

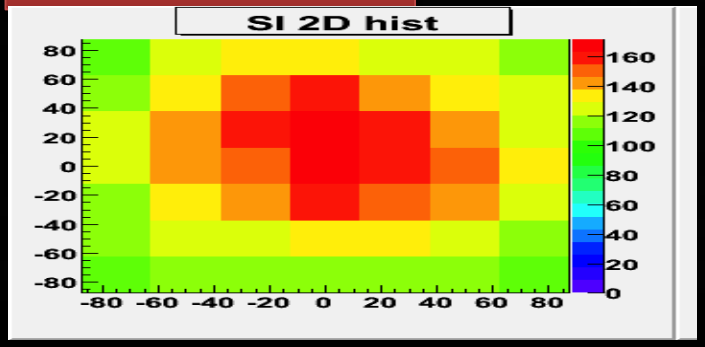
Proton beam profile monitors

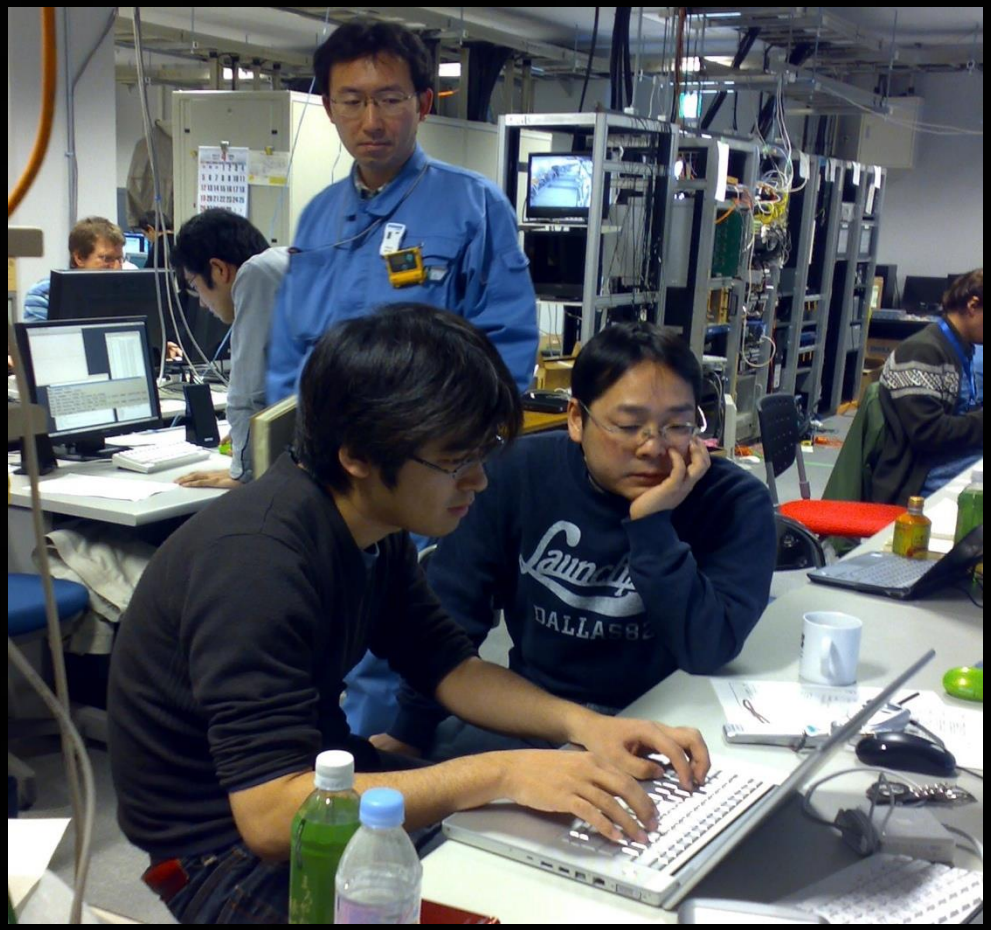


OTR detector just in front of target



Muon monitor profile

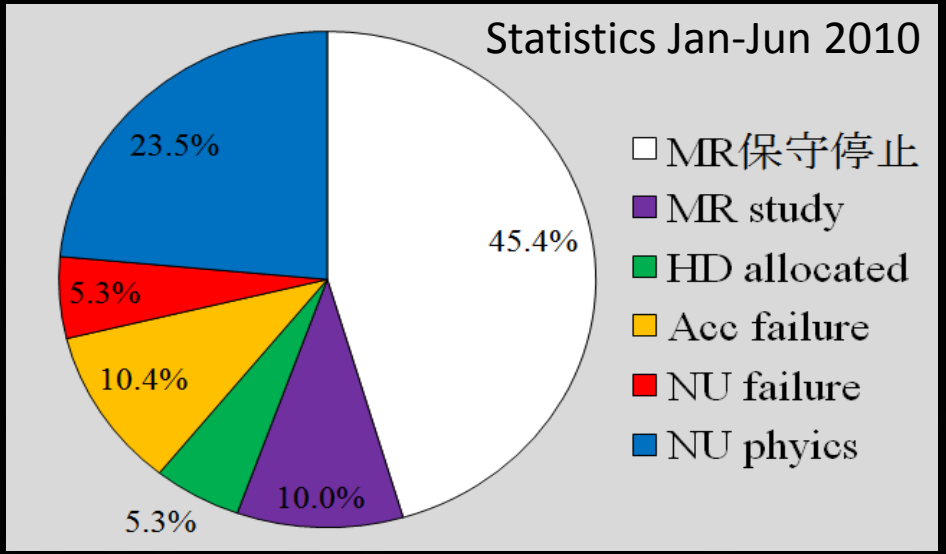




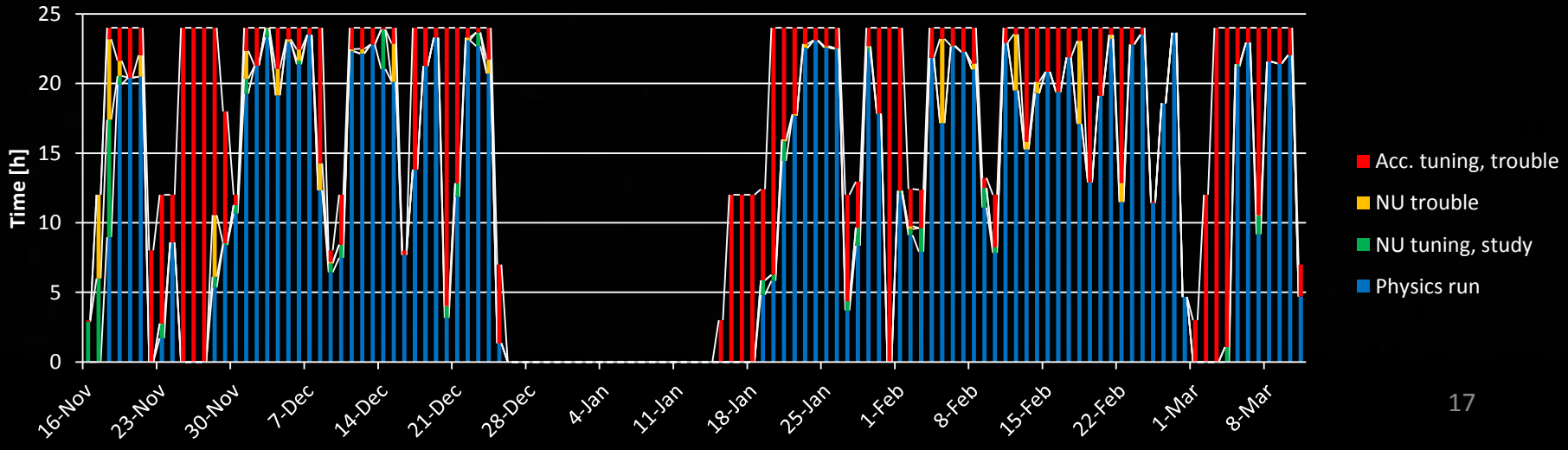
First beam in Apr. 2009
Beam commissioning in 2009
Physics Run starts Jan. 2010

Statistics until the earthquake

- Allocated Time:2430hr
- NU trouble: 107hr (4.4%)
- SC trouble
  - 4 troubles
    - **Beam Induced Quench: 1**
    - Interlock: 3
  - **Total time: 14hr (0.6%)**



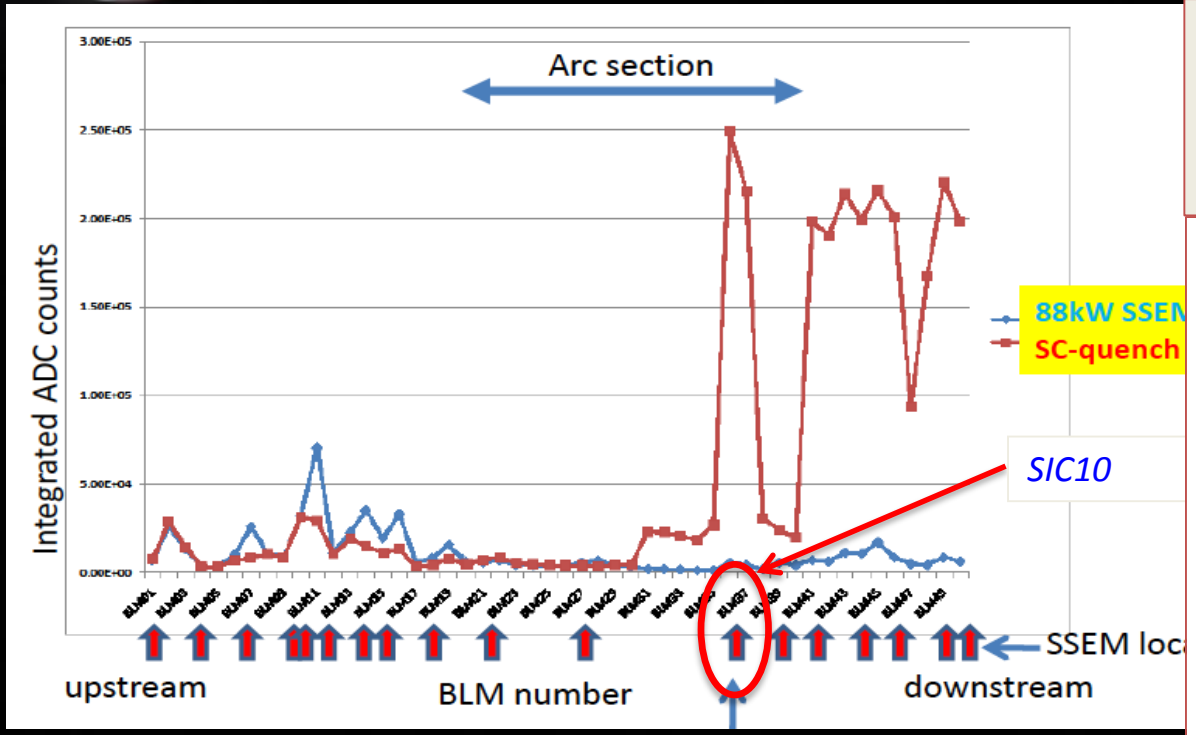
Statistics Nov 2010 ~ Mar 2011



Beam Induced Quench

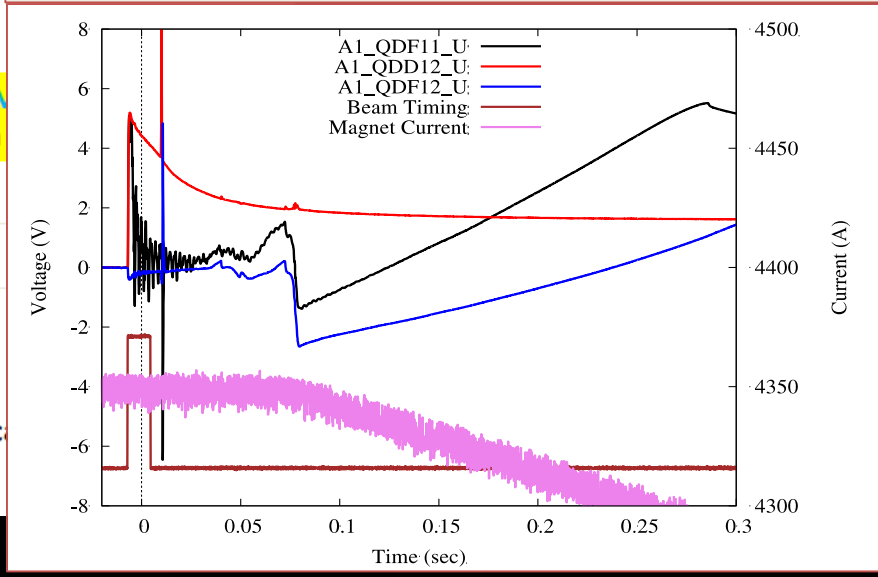
- Nov. 28 2010
- Beam hits beam profile monitor frame

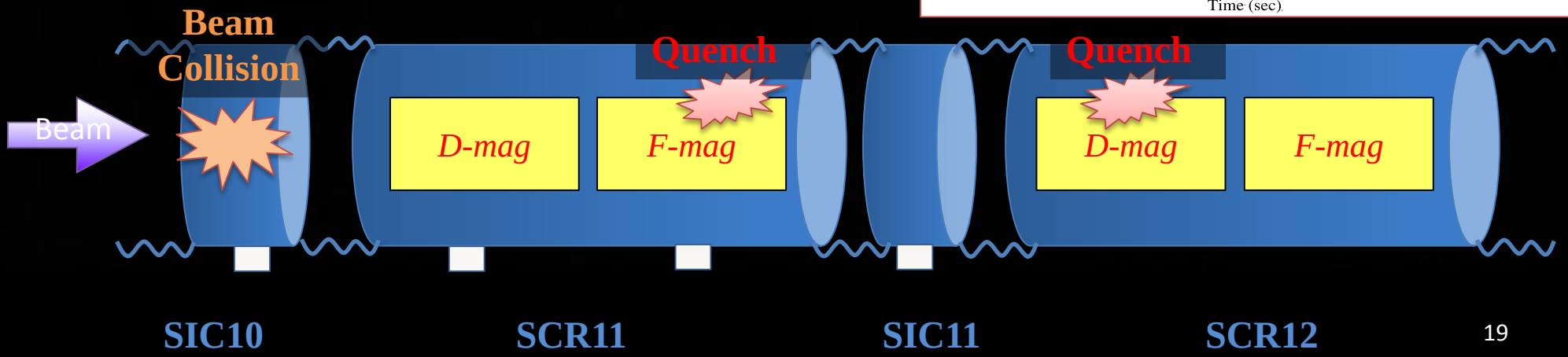
Beam Loss and Quench



Quenched Magnets

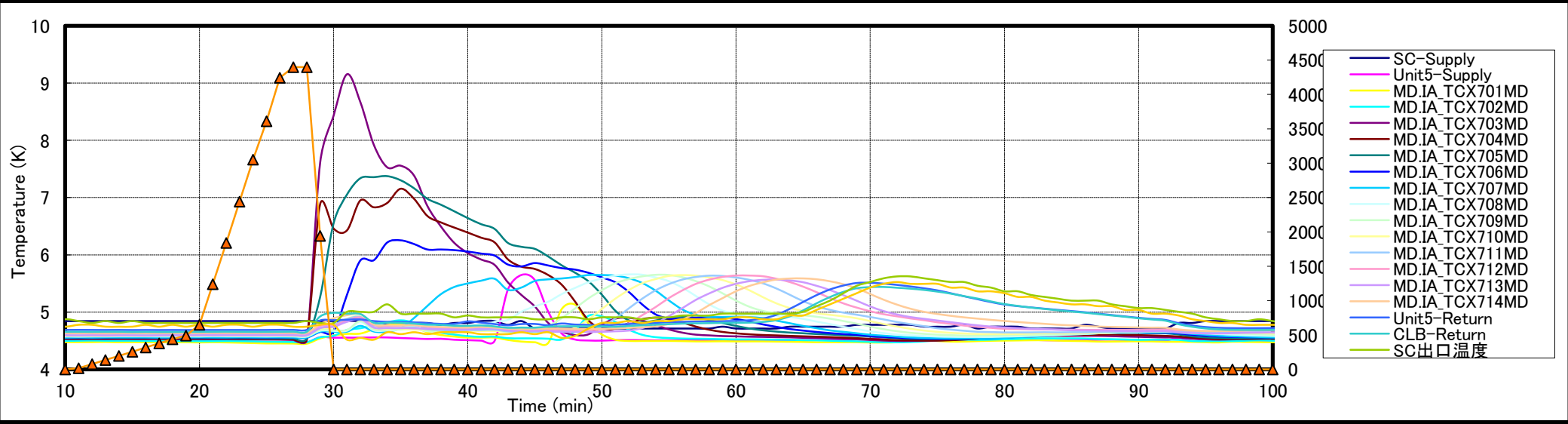
SCR11-F, SCR12-D





Recovery from the quench

- Cooling time ~100 min
- No problem for magnet re-excitation
- Beam operation resumed by about 2 hours



The Great East Japan Earthquake

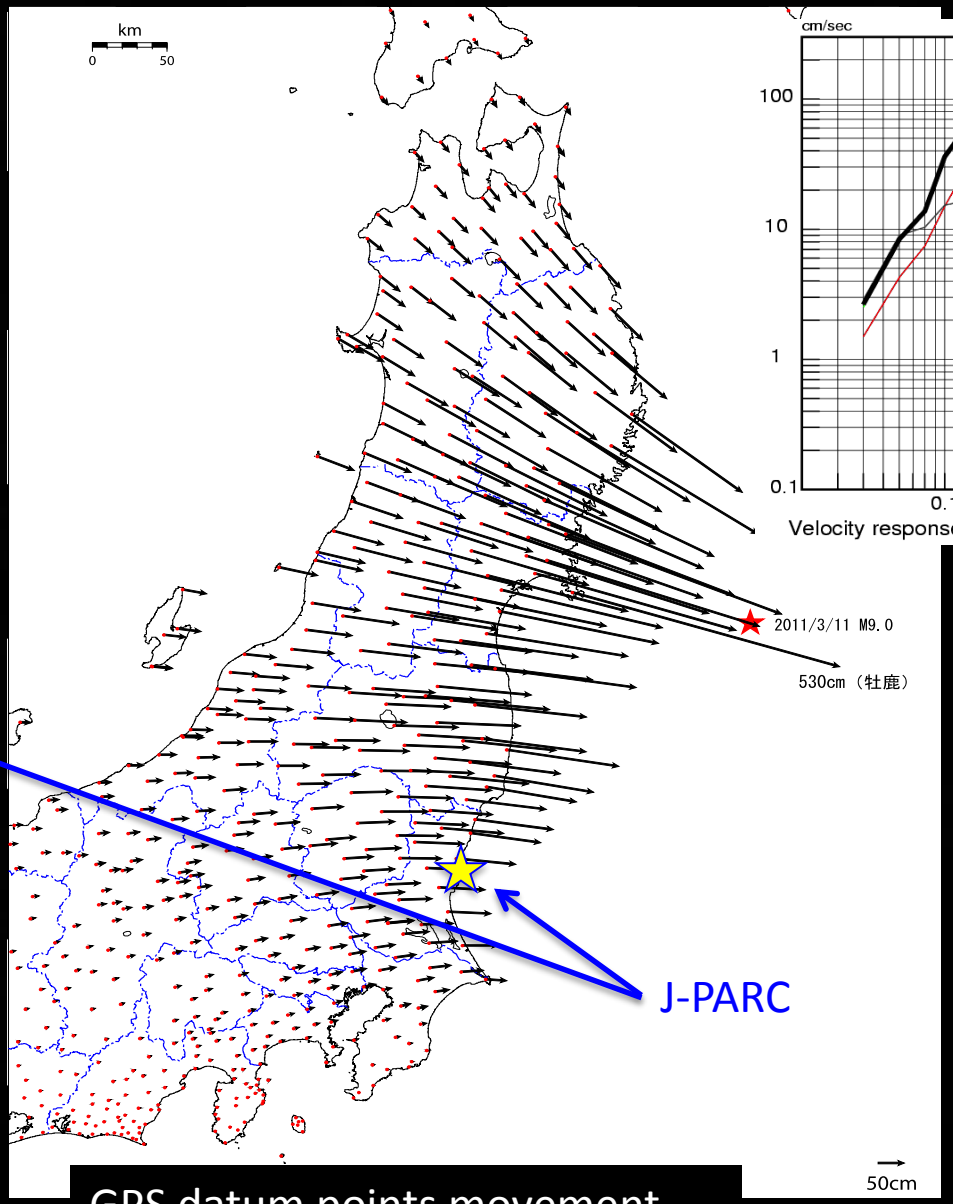
Damages and Recovery

J-PARC LINAC

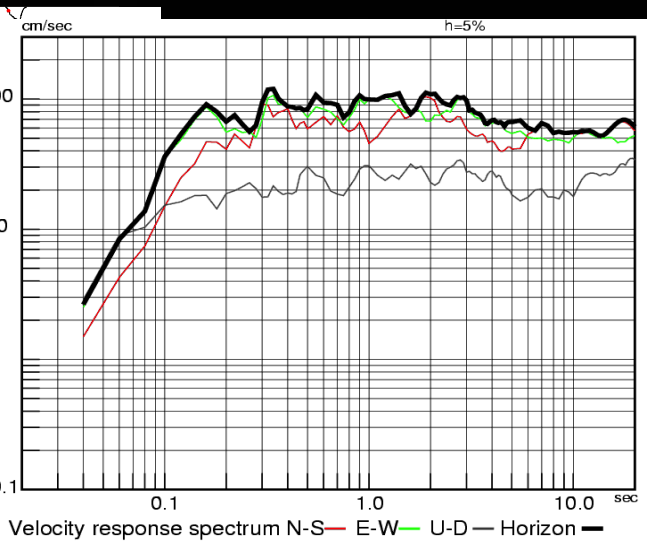
Great East Japan Earthquake

Mar. 11 2011 14.46 M9.0

Tsunami invasion map



GPS datum points movement



Velocity Response Around J-PARC

Peak velocity:
~1m/s
Peak acceleration:
~8.5m/s^2
Integrated Move:
~1m Horizontal
~0.3m Vertical

Impact on J-PARC

LINAC

3GeV RCS

LINAC

River near J-PARC

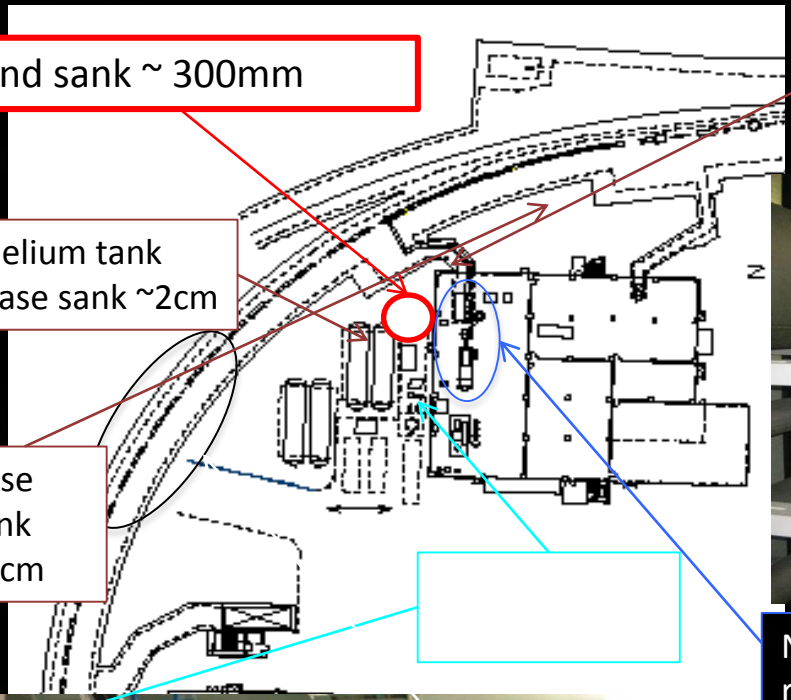
Main Ring

Neutrino Dump

No Tsunami invasion into J-PARC

Damages on Neutrino Beam Line Cryogenics

Cryogenics: in operation
Magnets: not excited



Sub-tunnel sank ~1cm

No damage on refrigeration system

No apparent damages on magnet system

Recovery Procedure

Date	Event	Description
11 Mar	Earthquake	Minimum safety check
13 Mar	Safety Op.	Pressure equalization
17 Mar	Tunnel Check	With handy light and O_2monitor
24 Mar	Low V Recov.	Lights in the tunnel
29 Mar	Water Recov.	
1 Apr.	High V Recov.	High voltage electricity
4 Apr.	Aircon. Recov.	In tunnel
11 Apr.	Refrig. Exam.	Cold box interior
15 Apr.	Mag. Exm.	Mag. Cryo. interior
19 Apr.	Comp. Exam.	Refrig. Main compressor
23 May ~1Jun.	System test	Cooldown and excitation

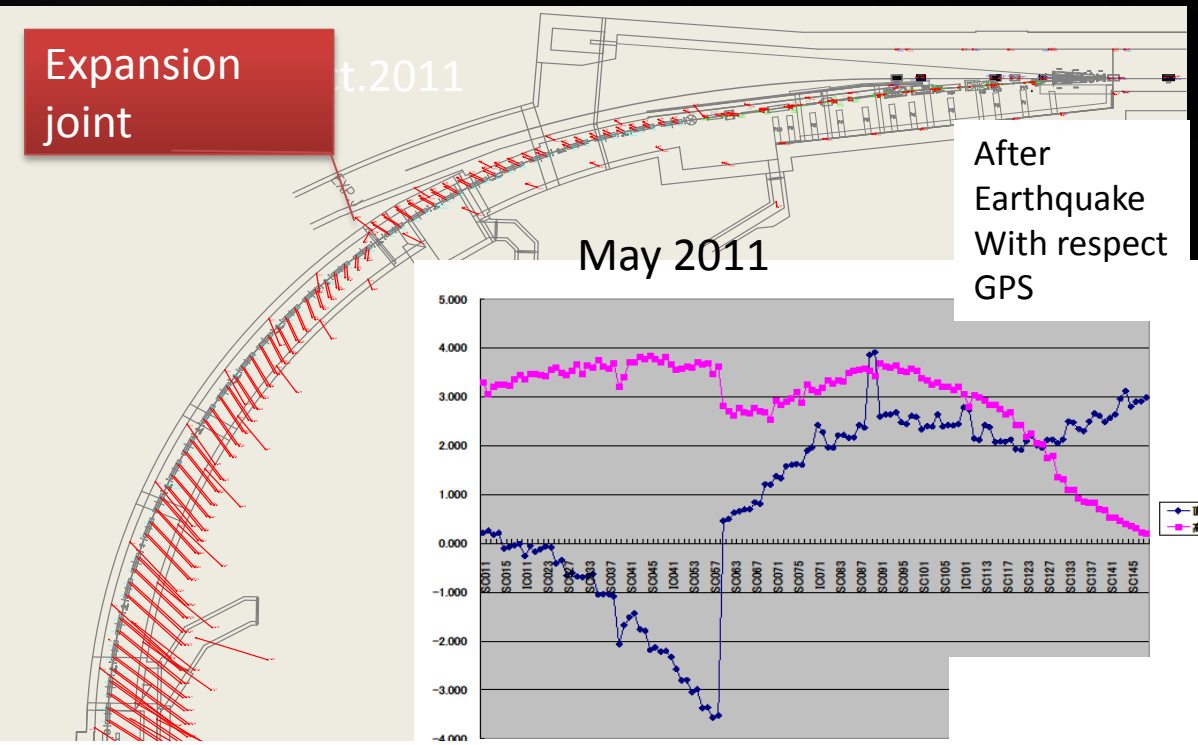
Cold Box Interior

Cryo. Interior

System health confirmed

Displacement and Re-Alignment of Neutrino Beam Line Magnets

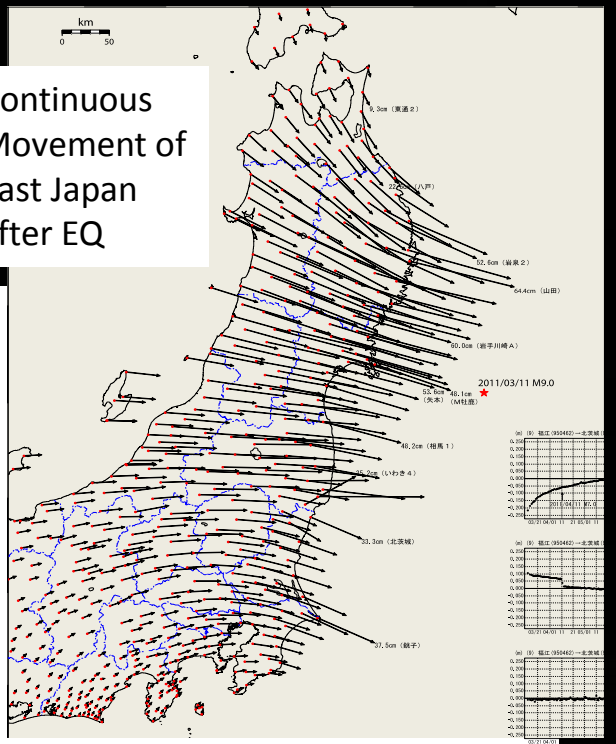
Expansion joint

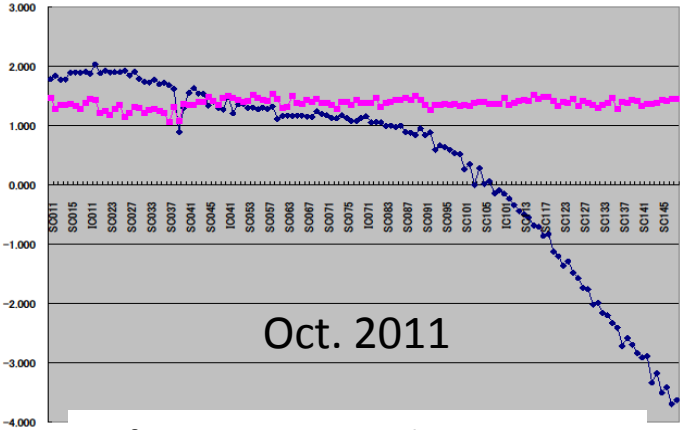


After Earthquake With respect GPS

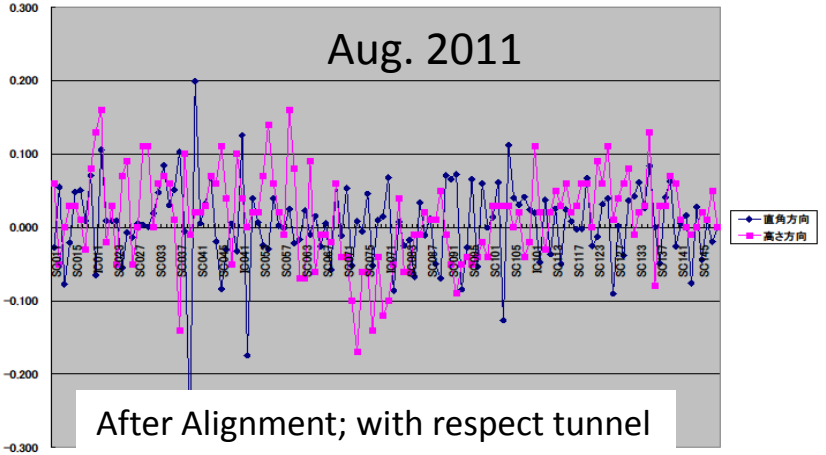
May 2011

Continuous Movement of East Japan after EQ



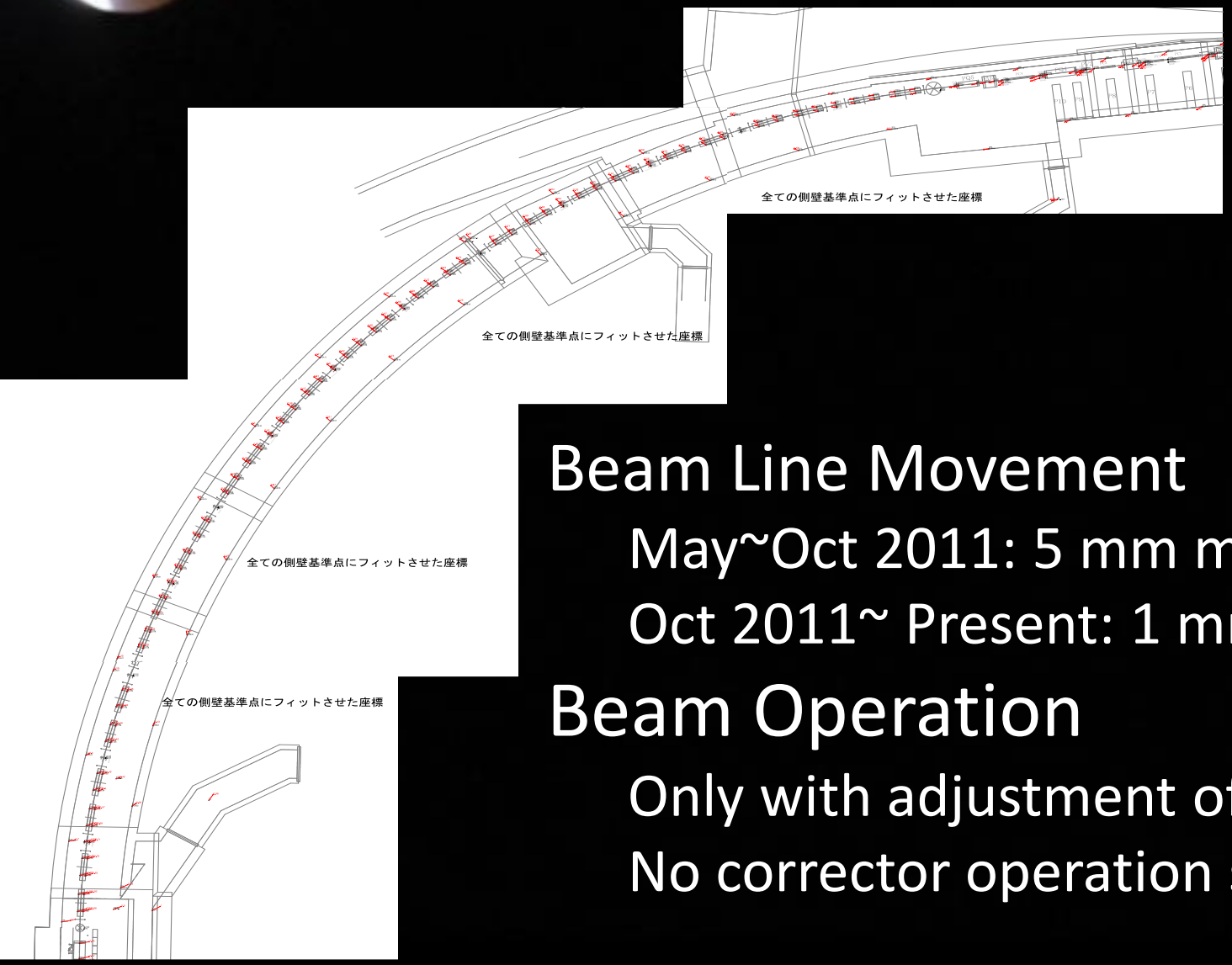


Before operation; with respect GPS



After Alignment; with respect tunnel

Alignment Status



Beam Line Movement

- May~Oct 2011: 5 mm max
- Oct 2011~ Present: 1 mm max

Beam Operation

- Only with adjustment of SCFM current
- No corrector operation so far

Statistics after the earthquake

2012 March-June

Nu trouble 4.2% (77 h)

*Excluding major trouble by the horn

SC trouble 3.5% (46 h)

Mostly false trigger by interlock system

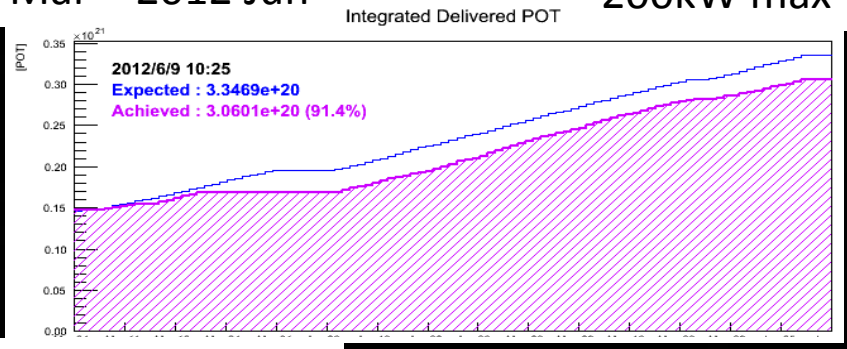
>trouble on the logic boards:

Fixed summer 2012

No beam stop due to SC trouble after summer 2012

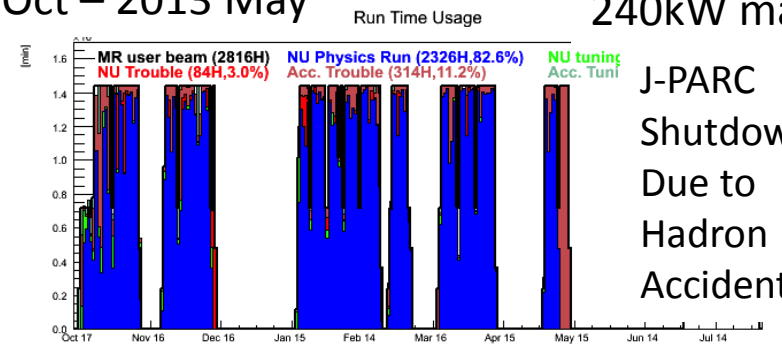
2012 Mar – 2012 Jun

200kW max



2012 Oct – 2013 May

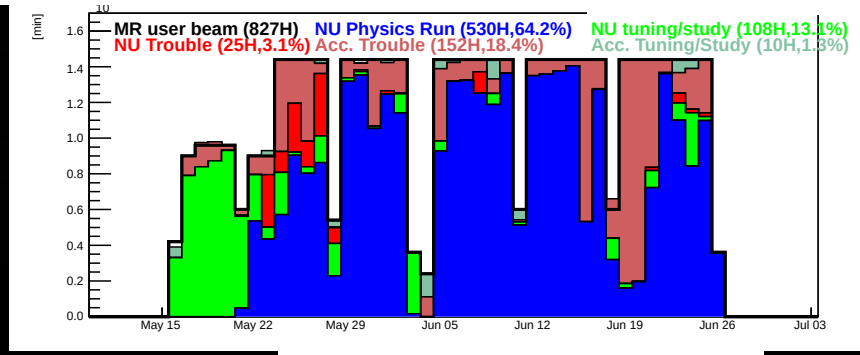
240kW max



J-PARC Shutdown Due to Hadron Accident

2014 May – 2014 Jun

220kW max



Achievements

15th June 2011

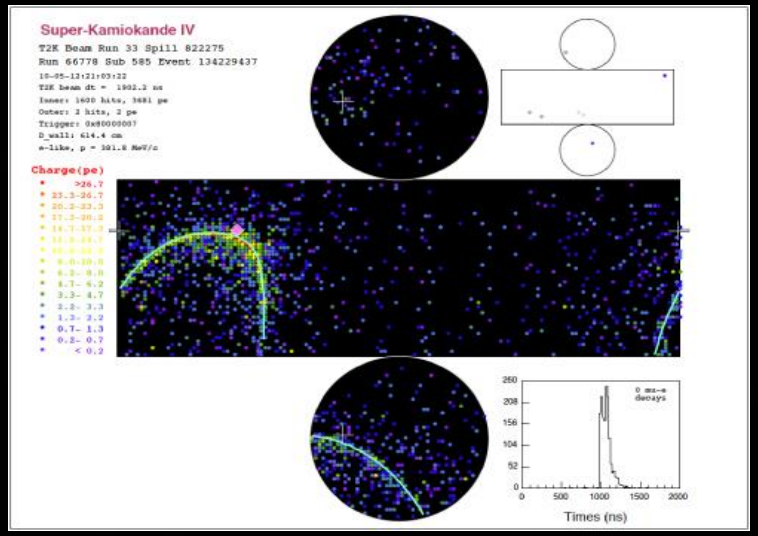
Indication of

Electron Neutrino Appearance

From data collected before March 11, 2011

http://legacy.kek.jp/intra-e/press/2011/J-PARC_T2Kneutrino.html

http://www.j-parc.jp/hypermail/news-l.2011/0005.html



19th July 2013

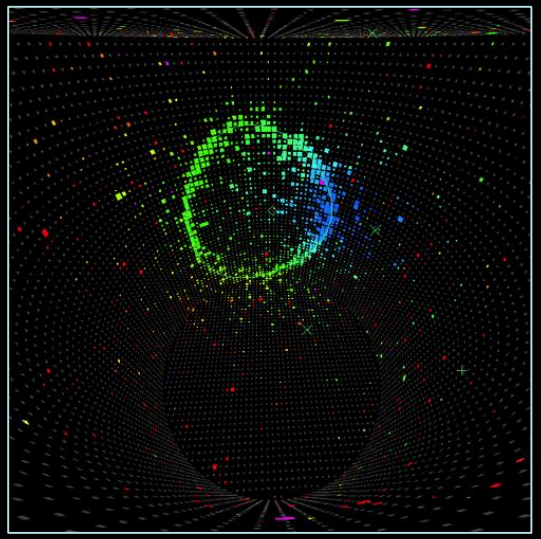
Discovery of

Electron Neutrino Appearance

From data collected before May 23, 2013

http://legacy.kek.jp/intra-e/press/2013/071921/

http://www.j-parc.jp/hypermail/news-l.2013/0004.html



Summary

- Operation Statistics
  - Very good until the earthquake
    - One beam induced quench
  - Worsened due after the earthquake
    - Fixed summer 2012
  - No trouble after Summer 2012
- The Earthquake
  - Damage to the system was minimum
  - Re-alignment was needed
- Corrector Improvement
  - Improve bus cooling and fixed problem
- Bypass Diode Bus Consolidation
  - Same implementation as LHC
- Radioactive Material Control
  - Temporal radiation control area for refrigerator maintenance
- **Ready for stable operation**

Acknowledgments

Also thank to
J-PARC, KEK, CERN staffs
Mitsubishi Electric, Toshiba, Furukawa,
TNSC, MYCOM, etc…