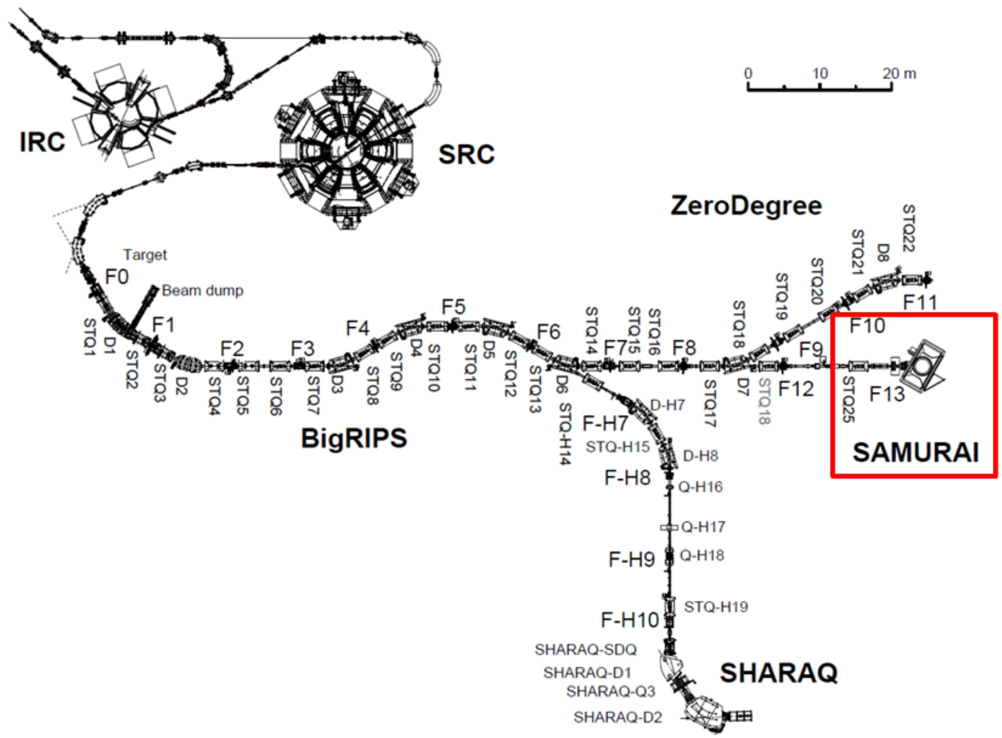
SAMURAI

Superconducting Analyzer for Multi-particles from Radioisotope beams



Overview

The SAMURAI spectrometer is designed for kinematically complete reaction measurements by detecting multiple particles in coincidence.

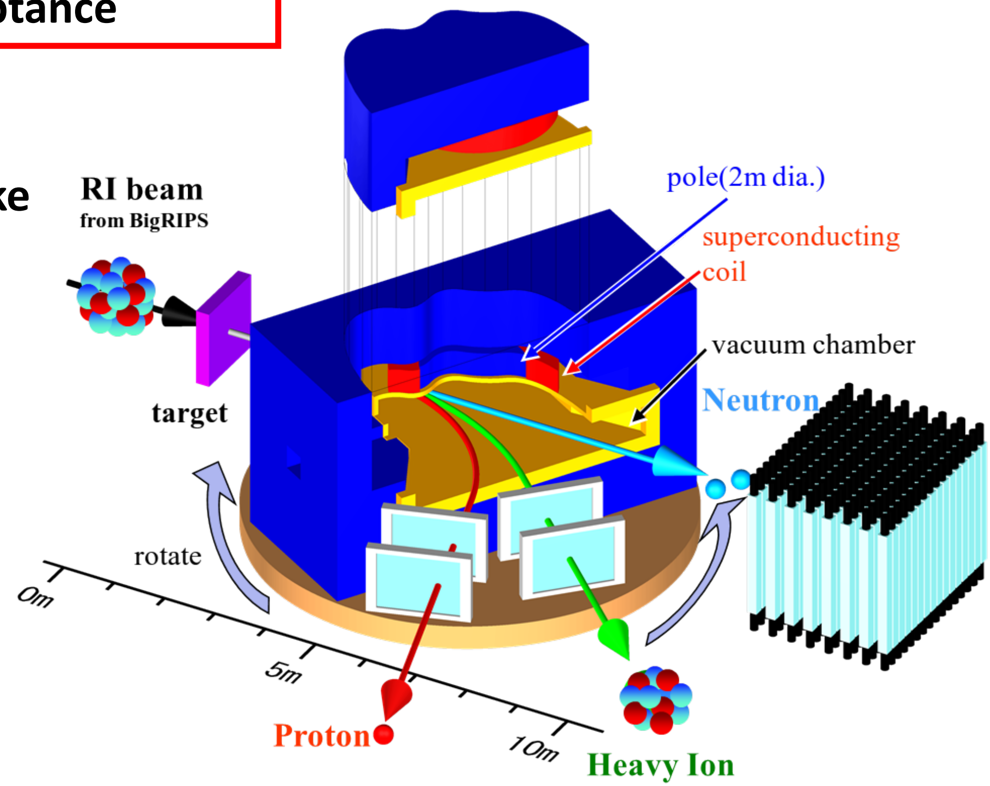
Large angular- and momentum-acceptance

Large pole gap

Wide horizontal opening of a yoke

SAMURAI consists of …

- ✓**Superconducting dipole magnet**
- ✓**Heavy Ion detectors**
- ✓**Proton detectors**
- ✓**Neutron detectors**
- ✓**Large vacuum chamber**
- ✓**Rotatable base**



The construction of the SAMURAI was completed in Feb. 2012.

Requirements for Magnet

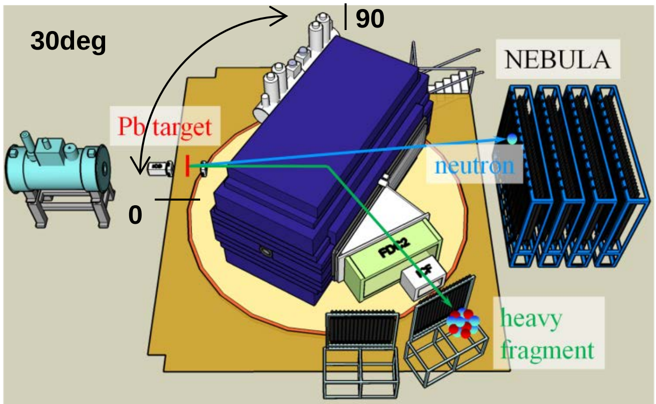
- **Requirements**
  - **Large field integral --> for high precision momentum analysis**
  - **Large pole gap --> for large vertical acceptance for neutrons**
  - **No coil link --> for large acceptance in the horizontal direction**
  - **Small fringing field --> for detectors around the target region and tracking detectors**
  - **Flexibility --> for various experimental conditions**
  - **Large momentum acceptance --> for heavy fragments and protons in coincidence**
  - **High momentum resolution --> for deuteron-induced reactions**

- ✓ **Field Integral 7 Tm (dR/R ~ 1/700 @ 2.3 GeV/c for A/Z=3)**
  --> mass separation σ_A=0.2 for A=100
- ✓ **Large Gap (0.8 m --> vertical ±5 degrees)**
- ✓ **Large opening (3.4 m --> holizontal ±10 degrees)**
- ✓ **Small Fringing Field (< 50 gauss @ 50cm from magnet)**
- ✓ **H-type magnet with cylinder poles (2m in diameter)**
- ✓ **Magnetic field … about 3T at center by ~1.9MAT**
- ✓ **Field clamp**
- ✓ **Build-in vacuum chamber**
- ✓ **Rotatable base (from -5 to 95 deg, 0.1deg/sec)**

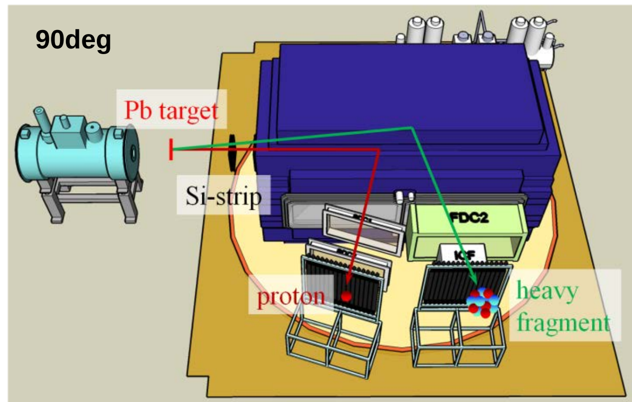
Versatile usage

Magnet can rotate around it's center.

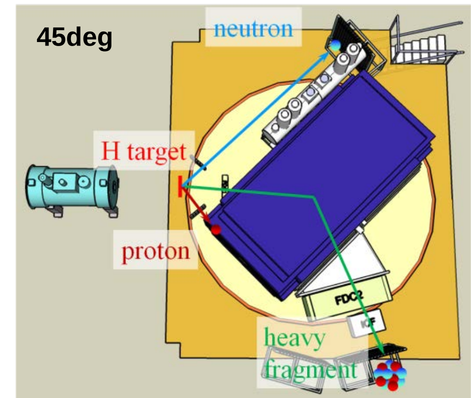
(γ, *n*) reaction: neutron-rich side



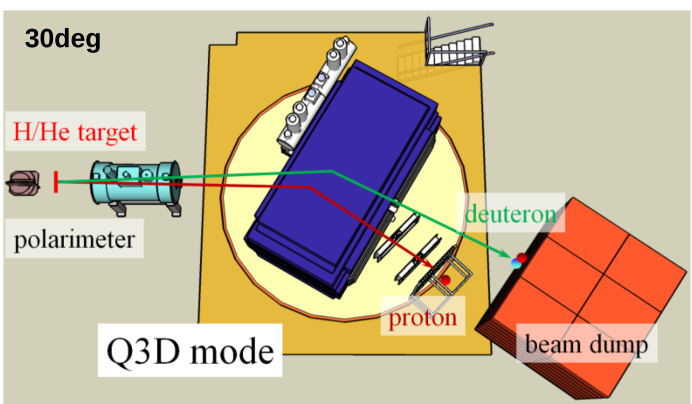
(γ, *p*) reaction: proton-rich side



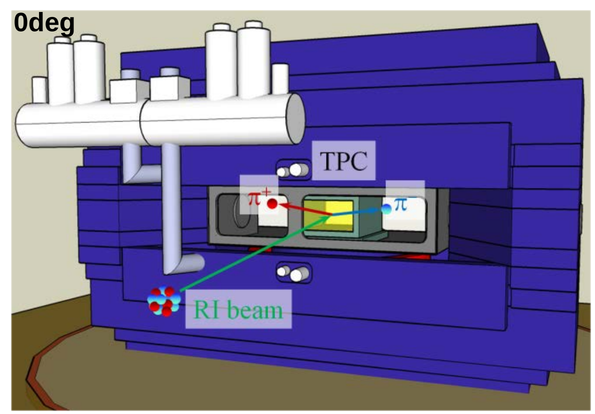
(*p*,*p*'), (*p*,2*p*), (*p*,*pn*), …



pol. *d*-induced reaction



EOS measurement



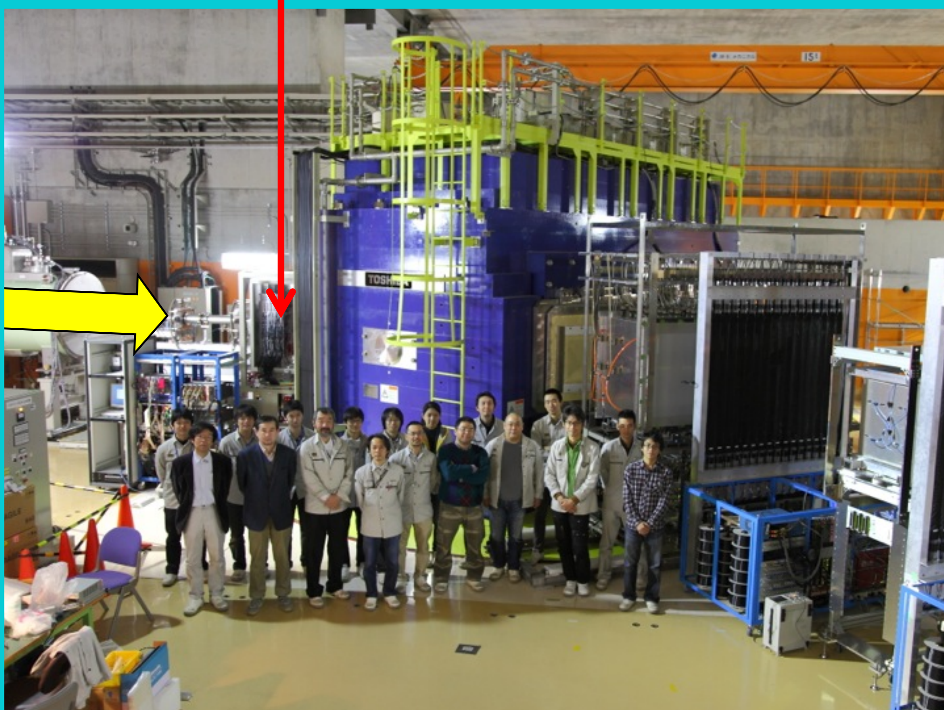
Flexibility of settings is one of the good properties of SAMURAI.

Photo

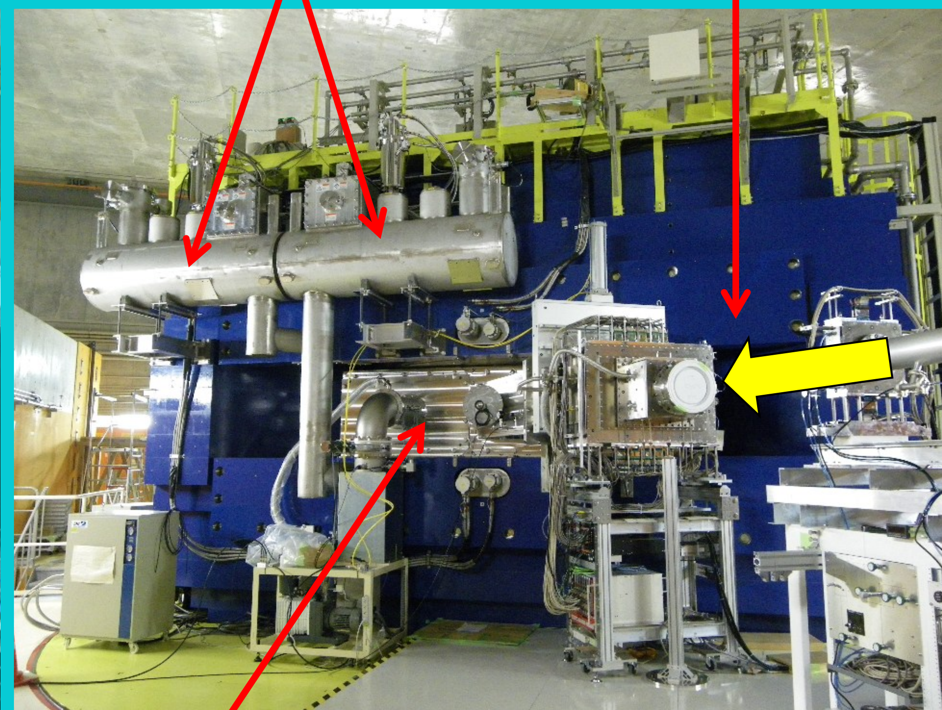
target

LHe reservoir vessels

Field cramp



side view



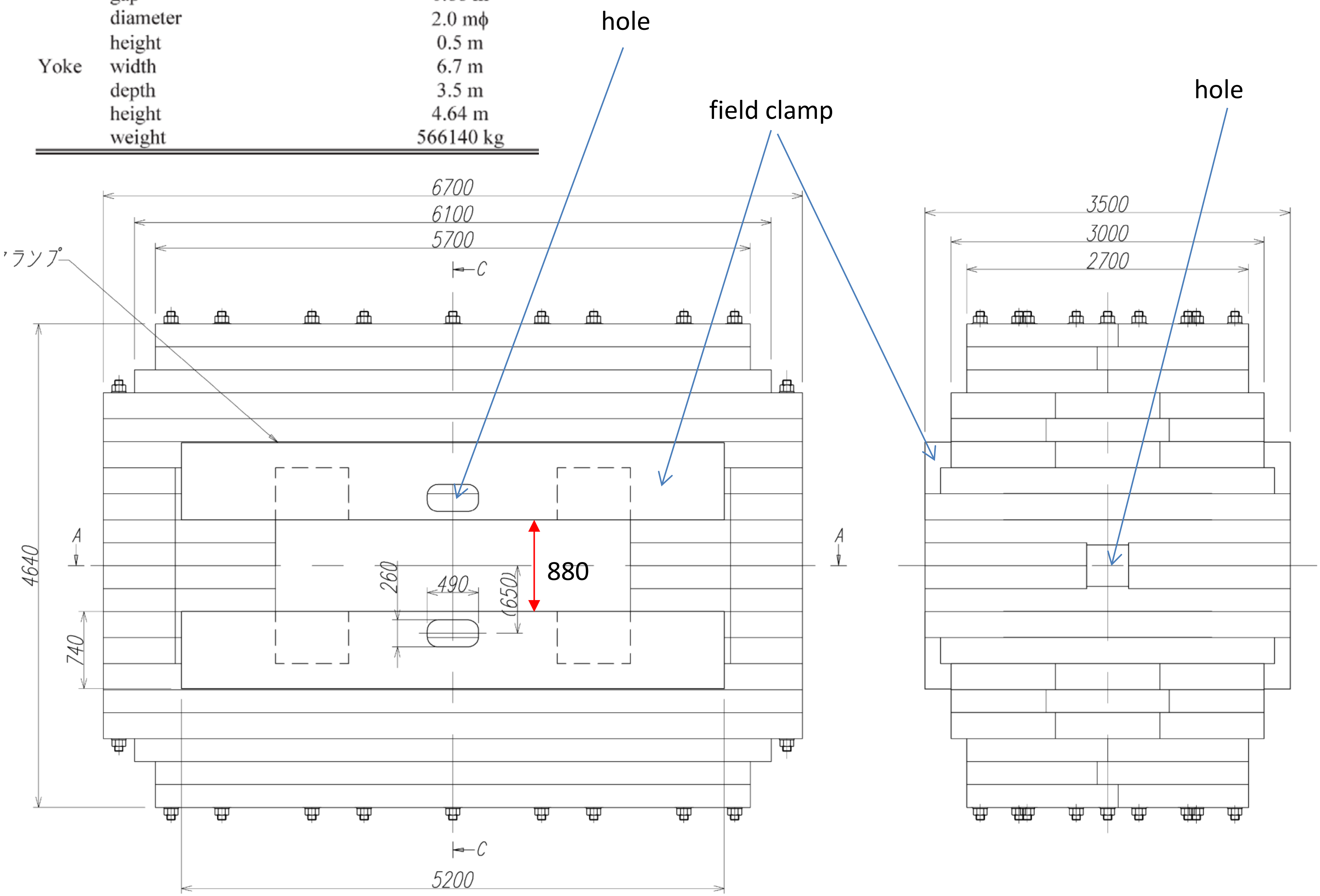
upstream

Vacuum chamber

* The magnet was rotated at an angle of 30^o.

Yoke

Pole	shape	circular type
	gap	0.88 m
	diameter	2.0 mϕ
	height	0.5 m
Yoke	width	6.7 m
	depth	3.5 m
	height	4.64 m
	weight	566140 kg

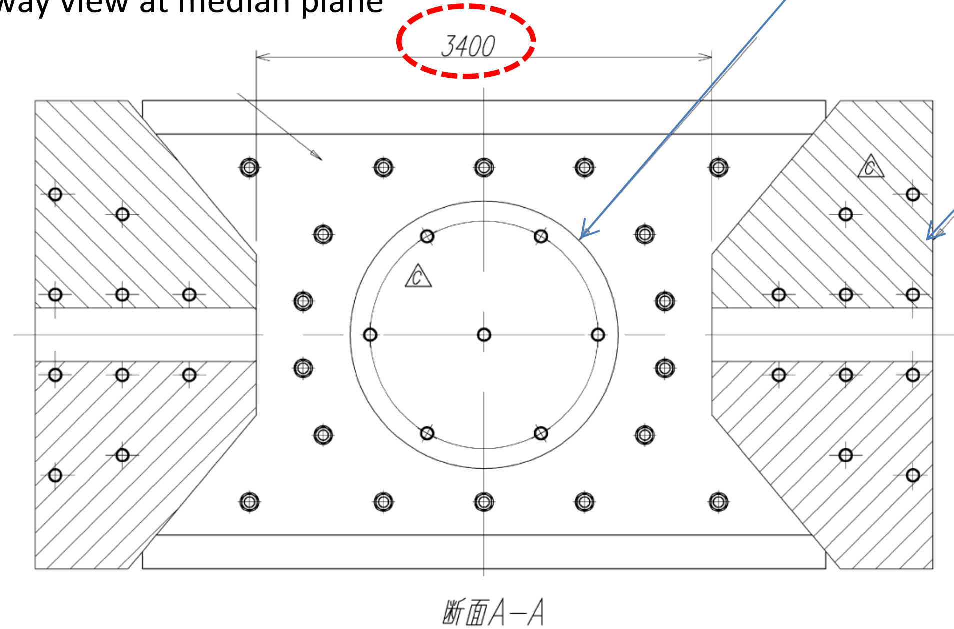


Yoke

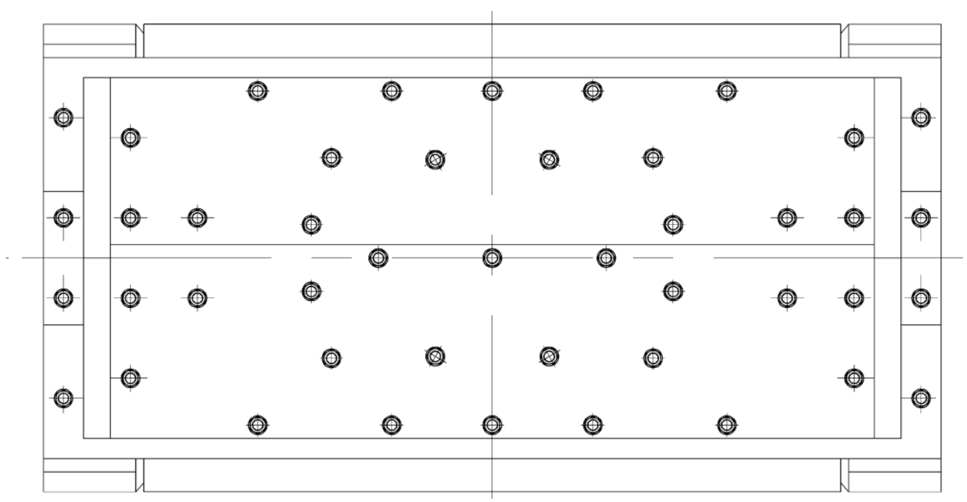
cutaway view at median plane

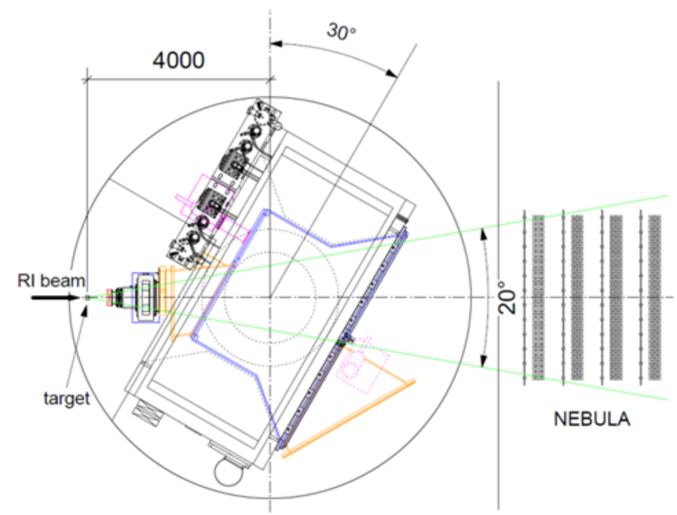
pole (2m dia.)

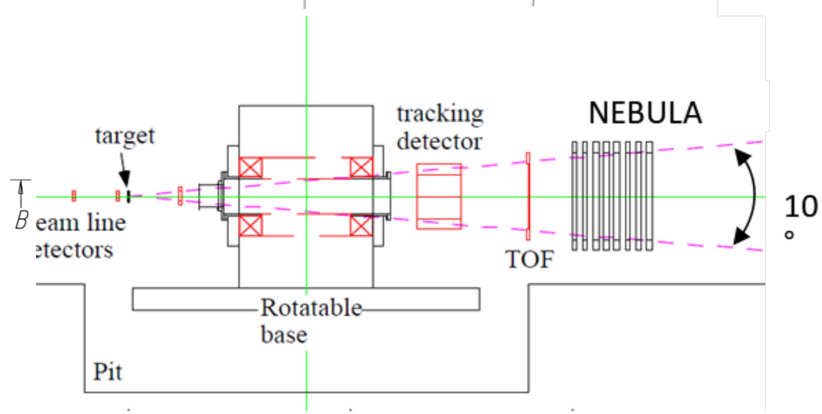
side yoke



top view

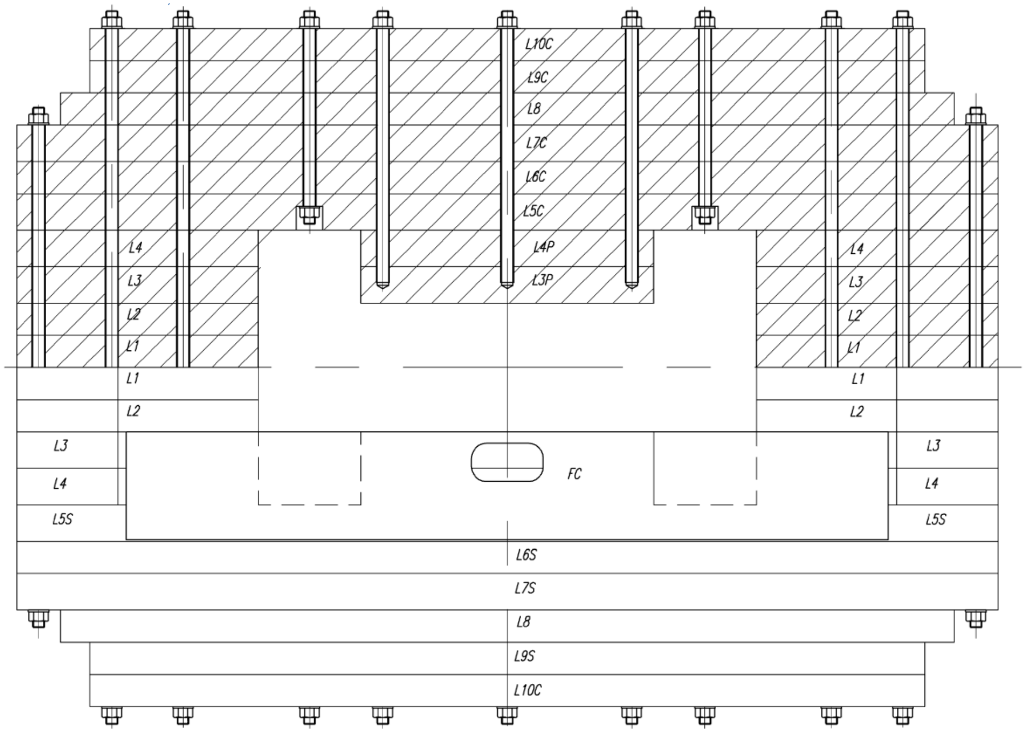


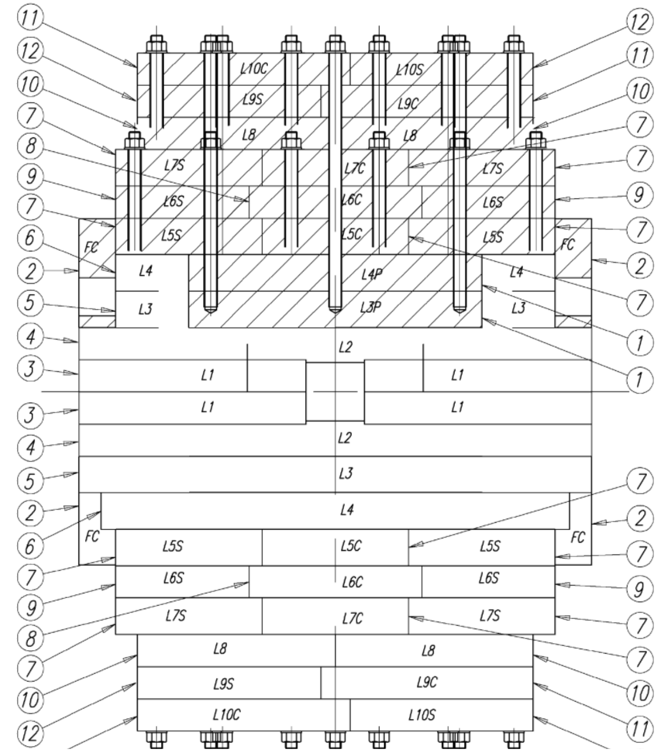




Yoke

70 stud bolts
M90, S45C





yoke = 58 slabs

The slabs weigh less than 15 tons due to the load limit of the crane.

鉄心構成鉄板

1）材質：電磁軟鉄（SUY−2相当）

PNo.	名称	厚さ	幅（または直径）	長さ	質量（kg）	数量
1	磁極鉄板L3P/L4P	250	ϕ2000	−	6120	4
2	フィールドクランプFC	250	740	5200	7410	4
3	サイドヨーク鉄板L1	220	1650	1550	3340	8
4	サイドヨーク鉄板L2	220（一部240）	1650	3500	7900	4
5	サイドヨーク鉄板L3	250	1650	3500	8770	4
6	サイドヨーク鉄板L4	250	1650	3200	8370	4
7	天板鉄板L5C/L5S/L7C/L7S△	250	1000	6700	12880	12
8	天板鉄板L6C	220	1180	6700	13630	2
9	天板鉄板L6S	220	910	6700	10330	4
10	天板鉄板L8	220	1350	6100	14200	4
11	天板鉄板L9C/L10C	220	1450	5700	14200	4
12	天板鉄板L9S/L10S	220	1250	5700	12100	4
				総合計	566140	58

注1）寸法は製品仕上がり寸法

Specifications of the soft steel

- ✓ Company: JFE Steel Corporation
- ✓ Product name: Hot Rolled Steel Plate
- ✓ Model: JFE-EFE 2003
- ✓ SPEC: SUY-2 (defined in JISC2504)

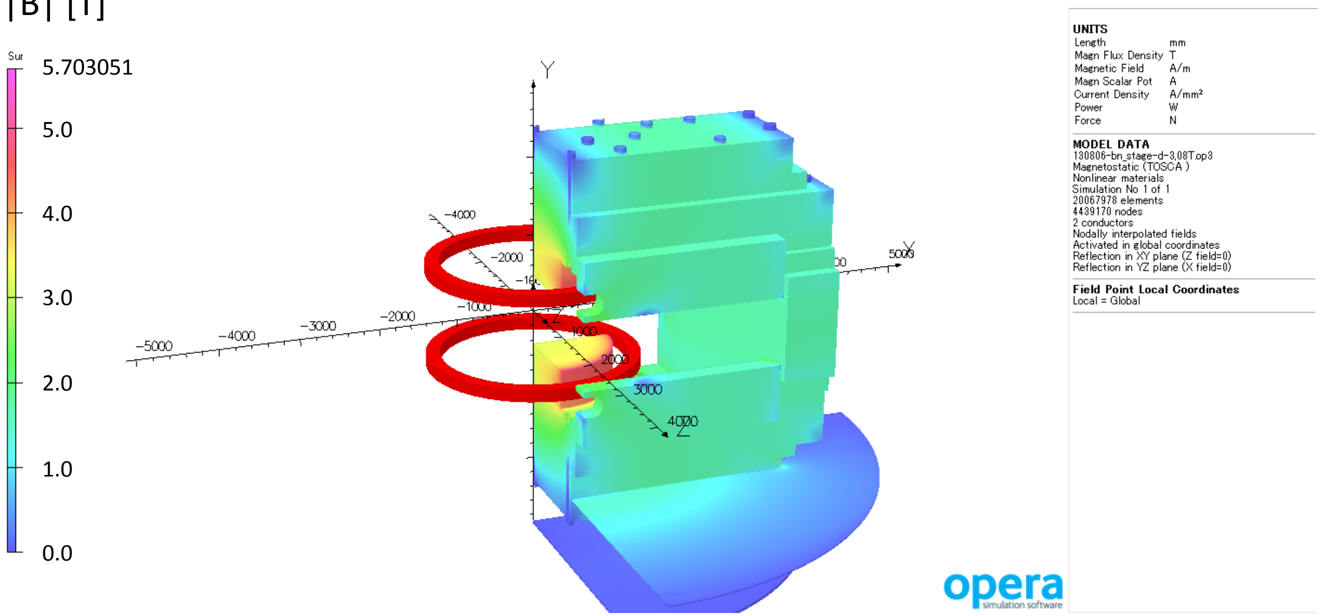
Chemical components										
	C	Si	Mn	P	S	Cu	Cr	Mo	Al	N
[%](mass)	< 0.03	< 0.20	< 0.50	< 0.03	< 0.03	(0.15)	(0.05)	(0.02)	(0.06)	(0.01)

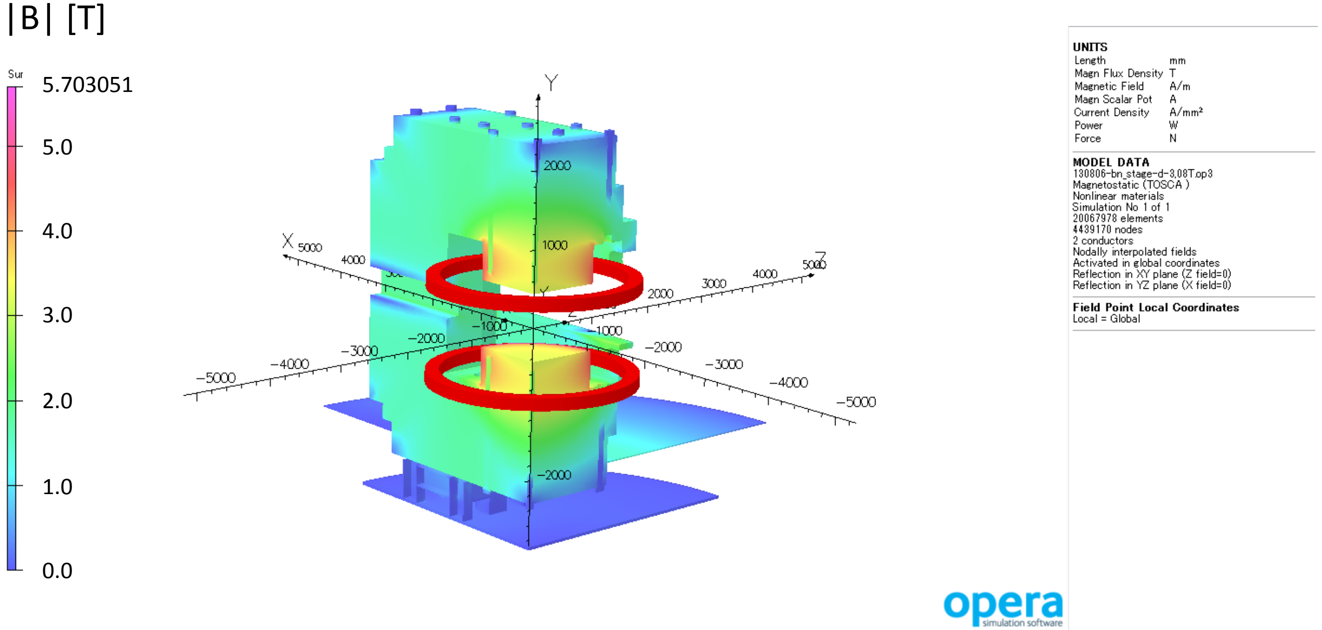
Mechanical properties	
0.2% proof stress	> 120 MPa
tensile strength	> 220 MPa
Elongation	> 20%

DC magnetic properties				
H [A/m]	300	500	1000	4000
B [T]	> 1.15	> 1.30	> 1.45	> 1.60
coercive field strength	< 100 A/m @1.5 T			

Saturation of the Yoke

B(0)=3.08 T

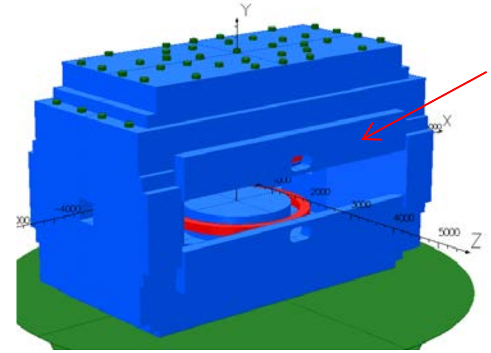




Field clamp

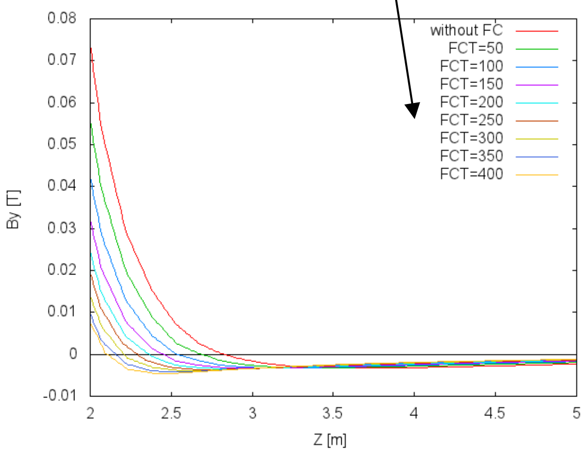
B=3.08T

Field clamp (W5400 x H740 x D250) was designed so as to obtain smaller fringe field.



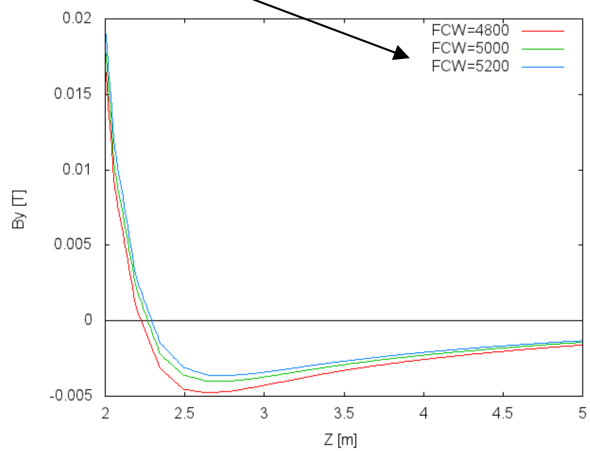
Thickness dependence

W5400 x H740 x D***



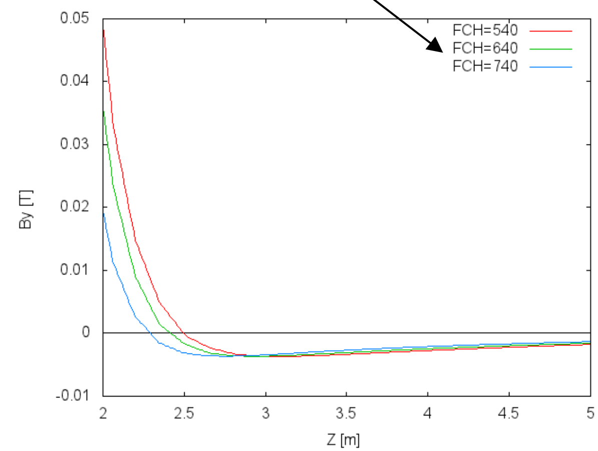
Width dependence

W**** x H740 x D250

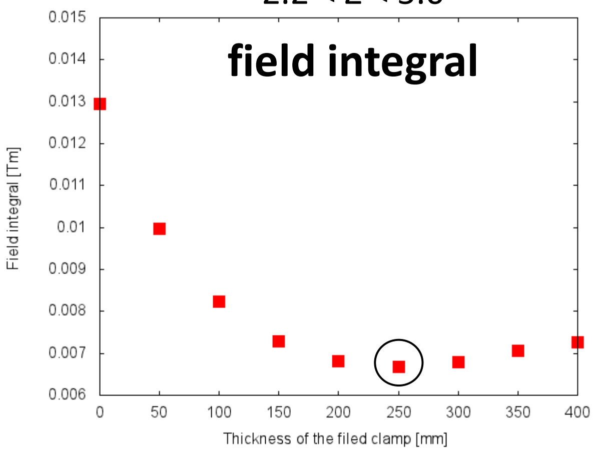


Height dependence

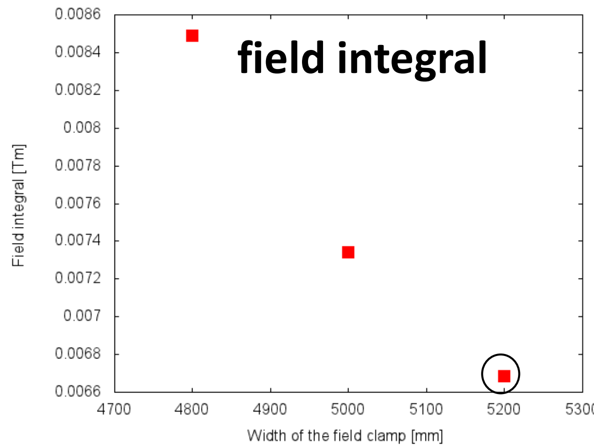
W5200 x H*** x D250



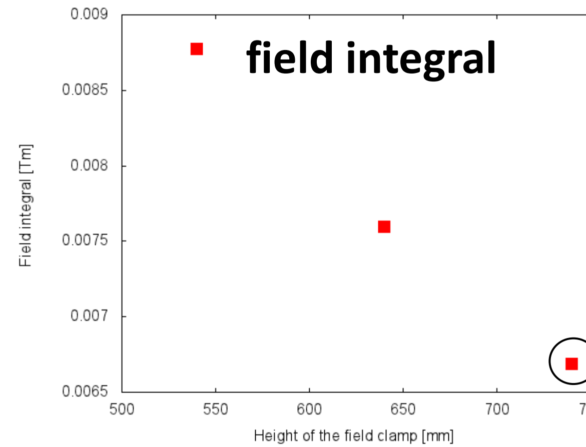
2.2 < Z < 5.0



2.2 < Z < 5.0



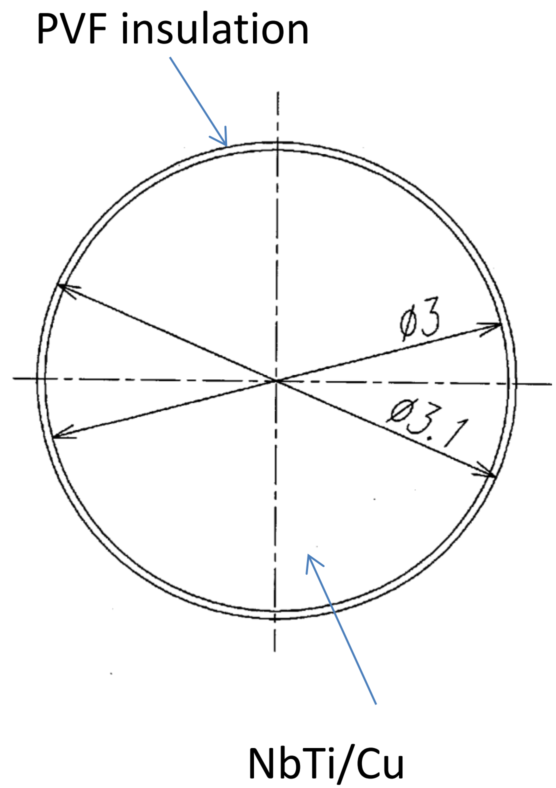
2.2 < Z < 5.0



Super conducting wire

TABLE II
MAIN PARAMETERS OF THE SUPERCONDUCTING WIRE

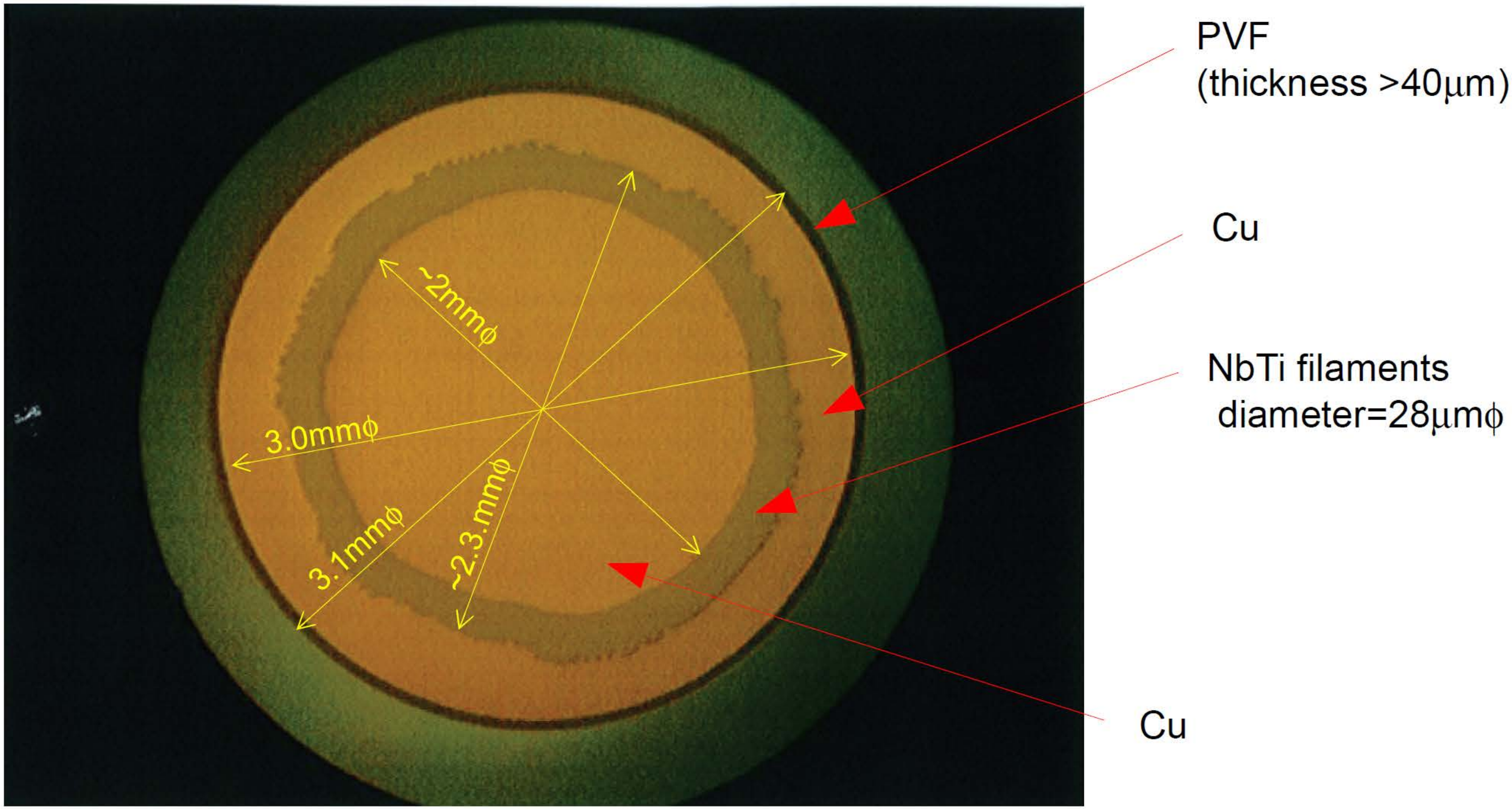
	Value
Material	NbTi/Cu
Diameter (bare)	3.0 mmϕ
Diameter (insulated)	3.1 mmϕ
Cu/SC ratio	5.0 – 6.0
Insulation	PVF coating (> 40 μm)
Filament diameter	around 28 μm
Number of filaments	around 1760
Twist pitch	around 88 mm
RRR	> 100
Critical current at 4.2 K	> 4000 A at 3 T
	> 3290 A at 4 T
	> 2690 A at 5 T
	> 2150 A at 6 T



FURUKAWA ELECTRIC CO., LTD.

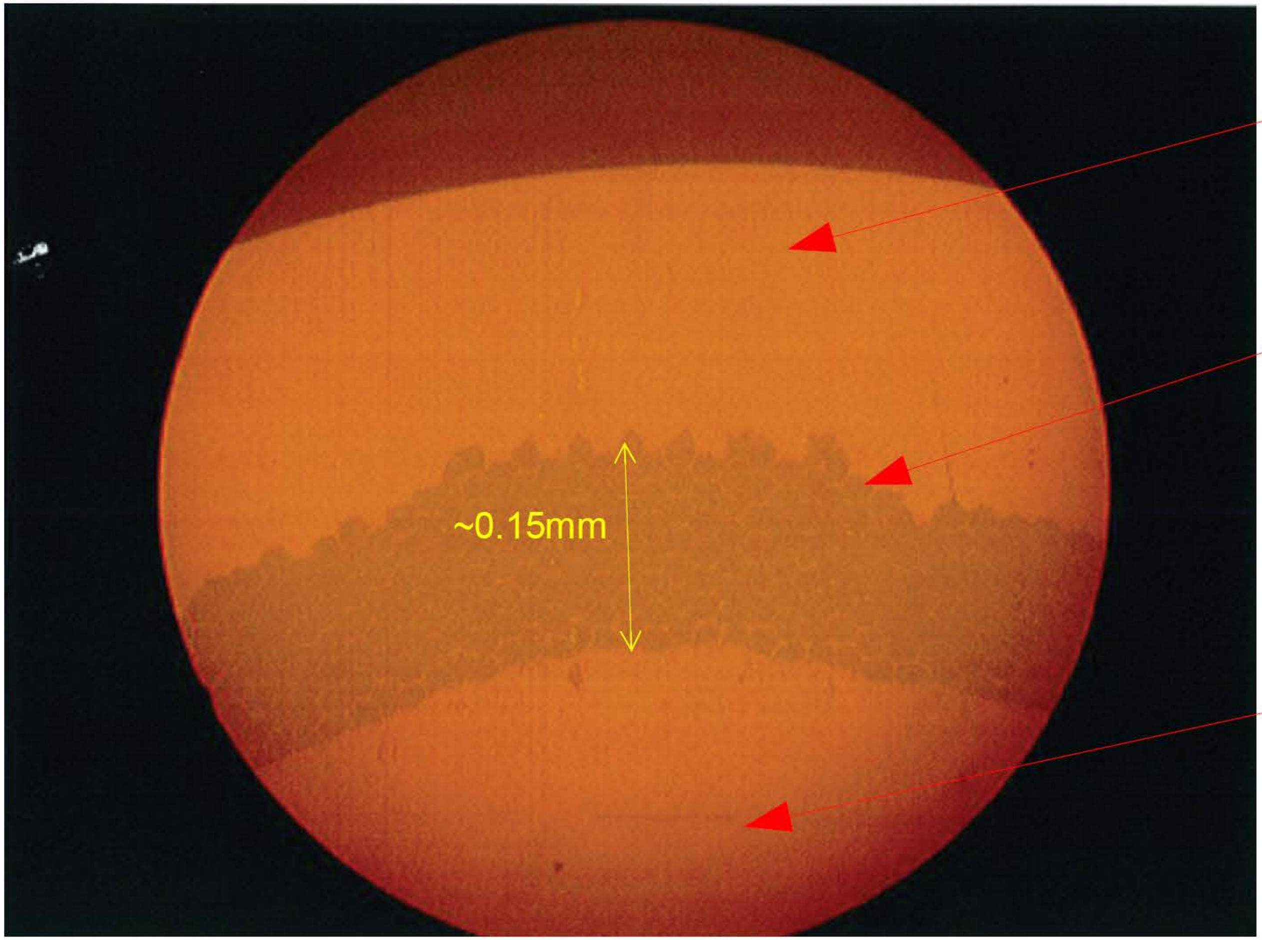
SC wire

Crosssection of the superconducting wire of the SAMURAI magnet

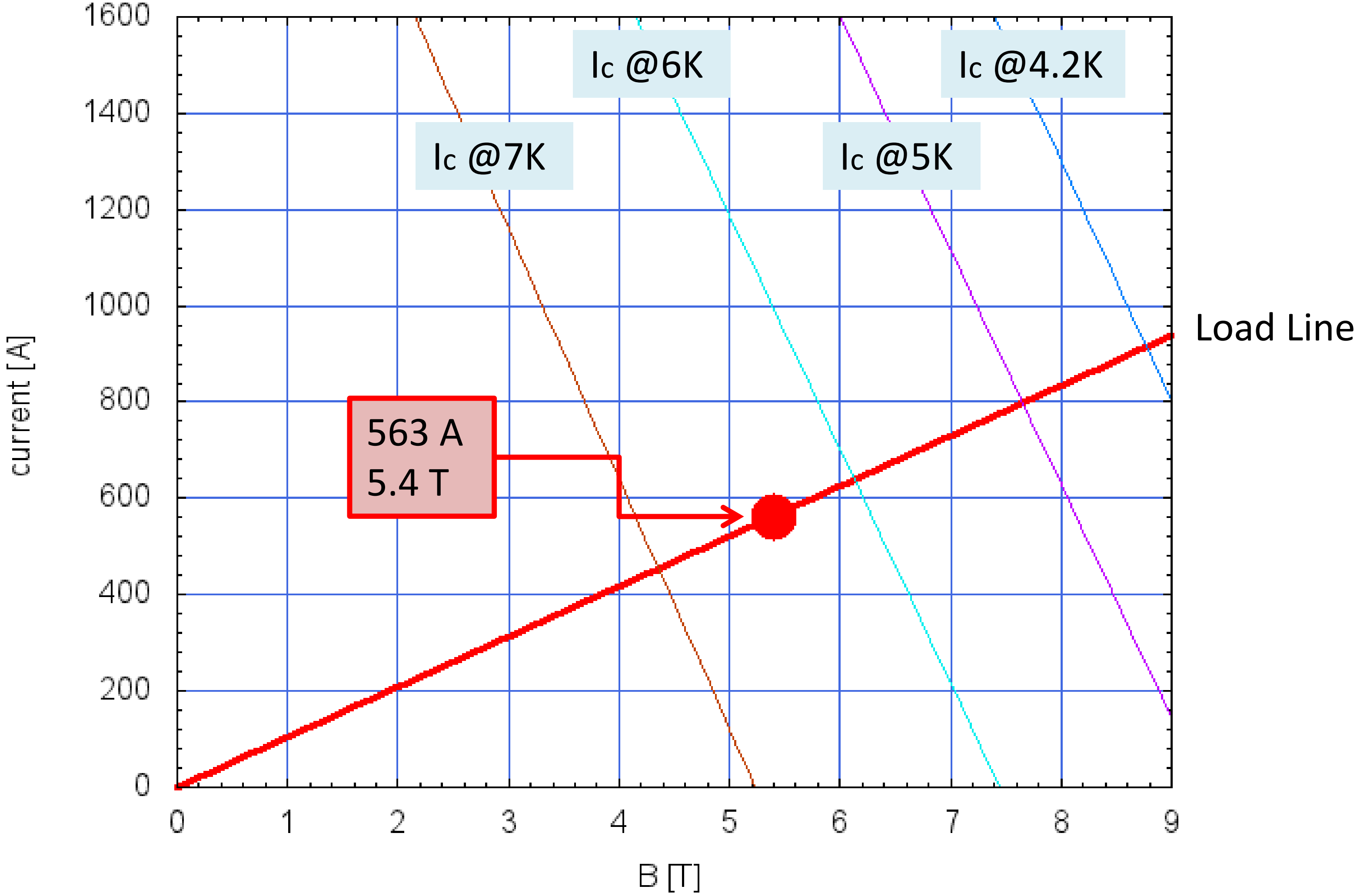


SC wire

Magnified view at the layer of the NbTi filaments



SC wire



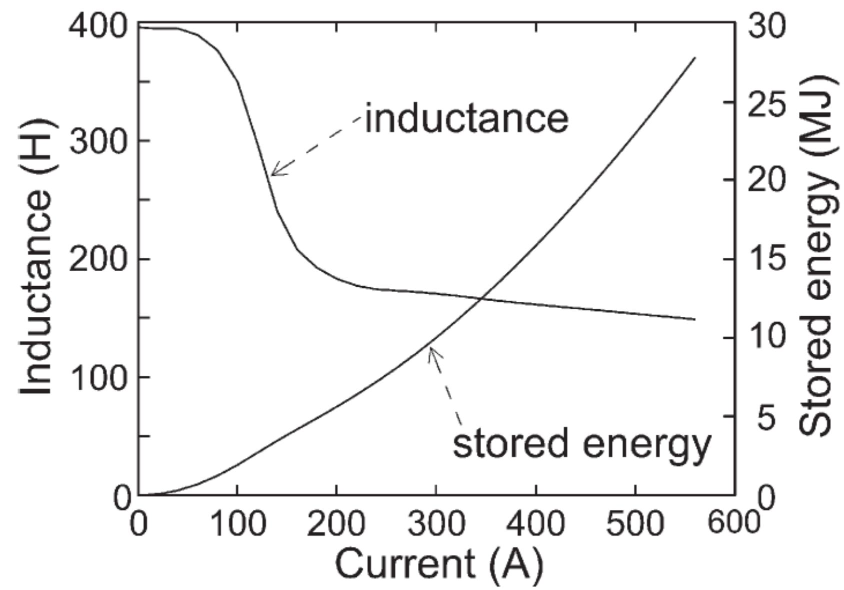
Load factor : 60% @4.2K

Specifications of the coil

TABLE I
MAIN PARAMETERS OF THE SUPERCONDUCTING DIPOLE MAGNET

		Value
Type		H-type, superconducting magnet
Number of turns		3414 turns/coil (51 turns × 64 layers+50 turns × 3 layers)
Windings of coil		impregnated close coiling, orderly winding
Maximum current		563 A
Magnetomotive force		1.922 MA turns/coil
Current density		66.74 A/mm^2 (for coil cross-section)
Central field		3.08 T
Field integral at 3.08 T		7.05 Tm
Maximum field at coil		5.4 T
Inductance		396 – 150 H
Stored energy		27.4 MJ
Coil	inner diameter	2.35 m (at 4 K)
	outer diameter	2.71 m (at 4 K)
	cross section	180 mm × 160 mm (at 4 K)
	weight	1783 kg/coil

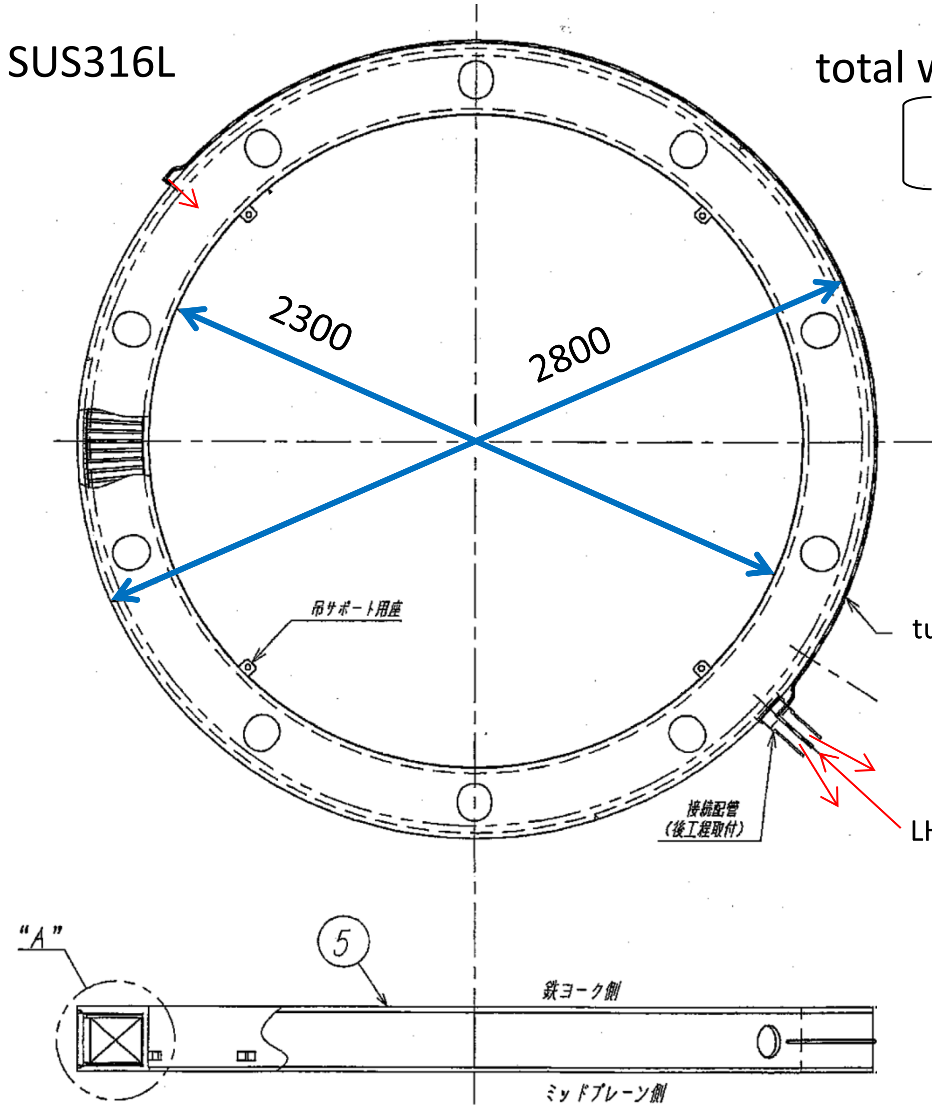
- NOT stabilized
- Wet winding using the special epoxy resin



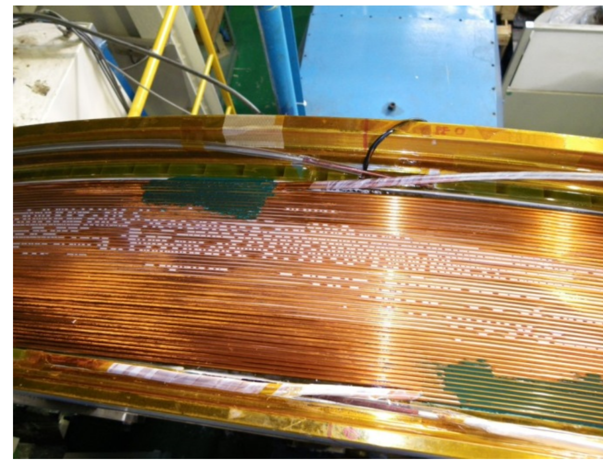
Coil vessel

SUS316L

total weight: 3 ton
- coil: 1.8 ton
- vessel: 1.2 ton



LHe: 57.4 L



Coil

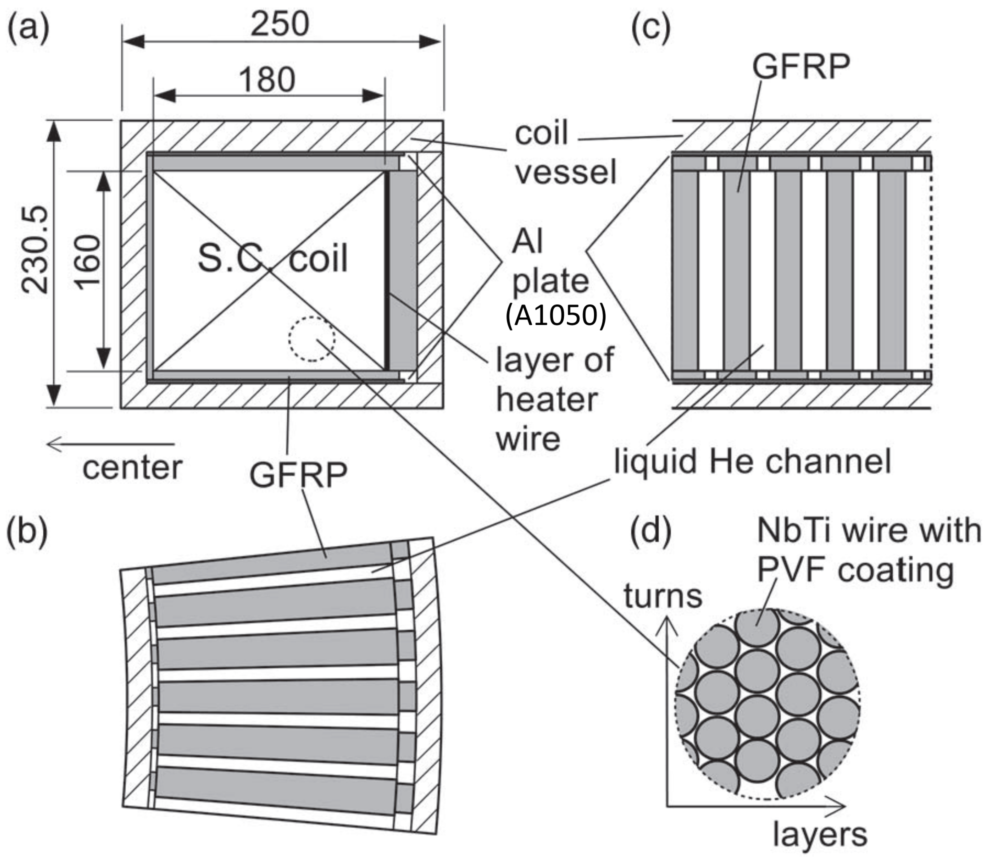


Fig. 7. Schematic view of the superconducting coil and the coil vessel. The coil vessel is made of SUS 316L. (a) Cross-sectional view. The copper heater wire is wound on the outermost layer of the coil. (b) Top (bottom) view of the inside of vessel. (c) Side view of the inside of vessel. (d) A detailed view of the wires in the coil. The epoxy resin is applied layer by layer.

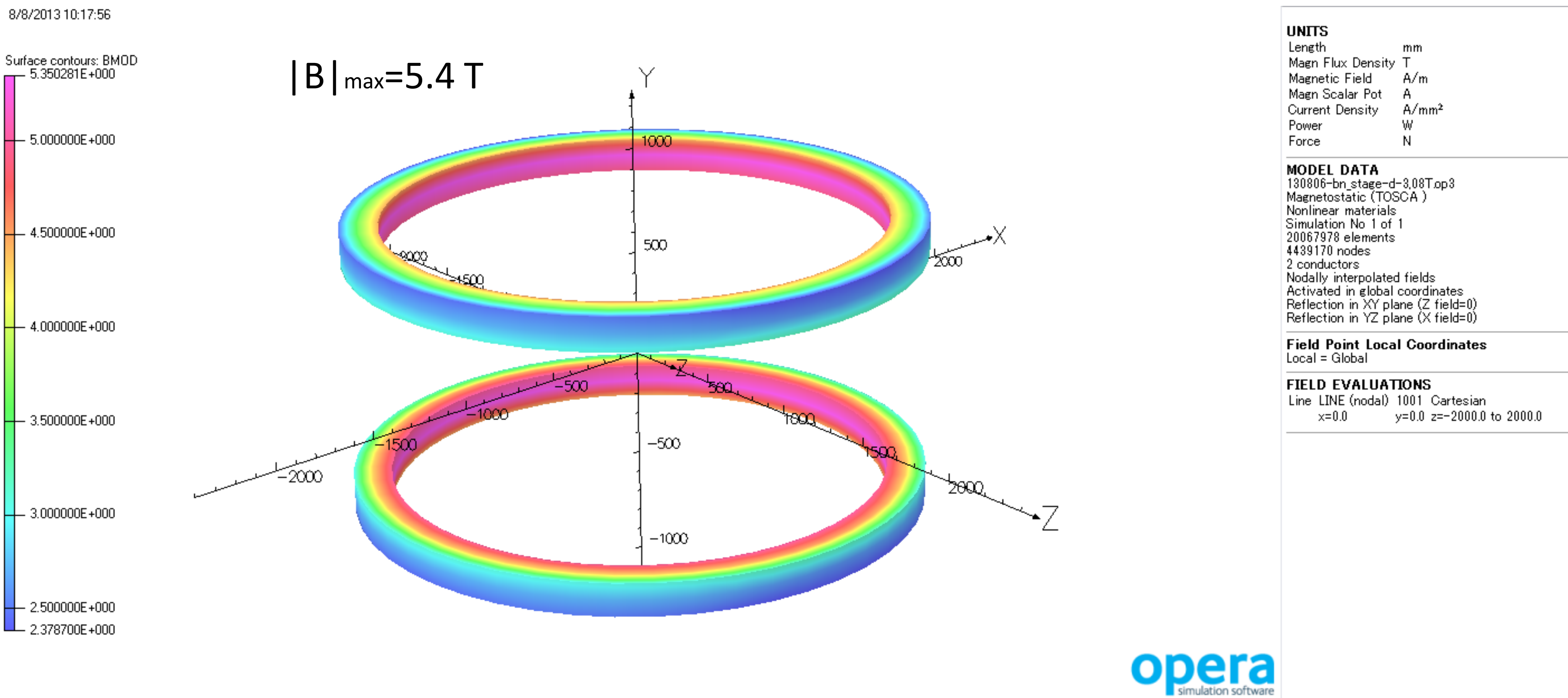
Coil

Fields at the coil surface

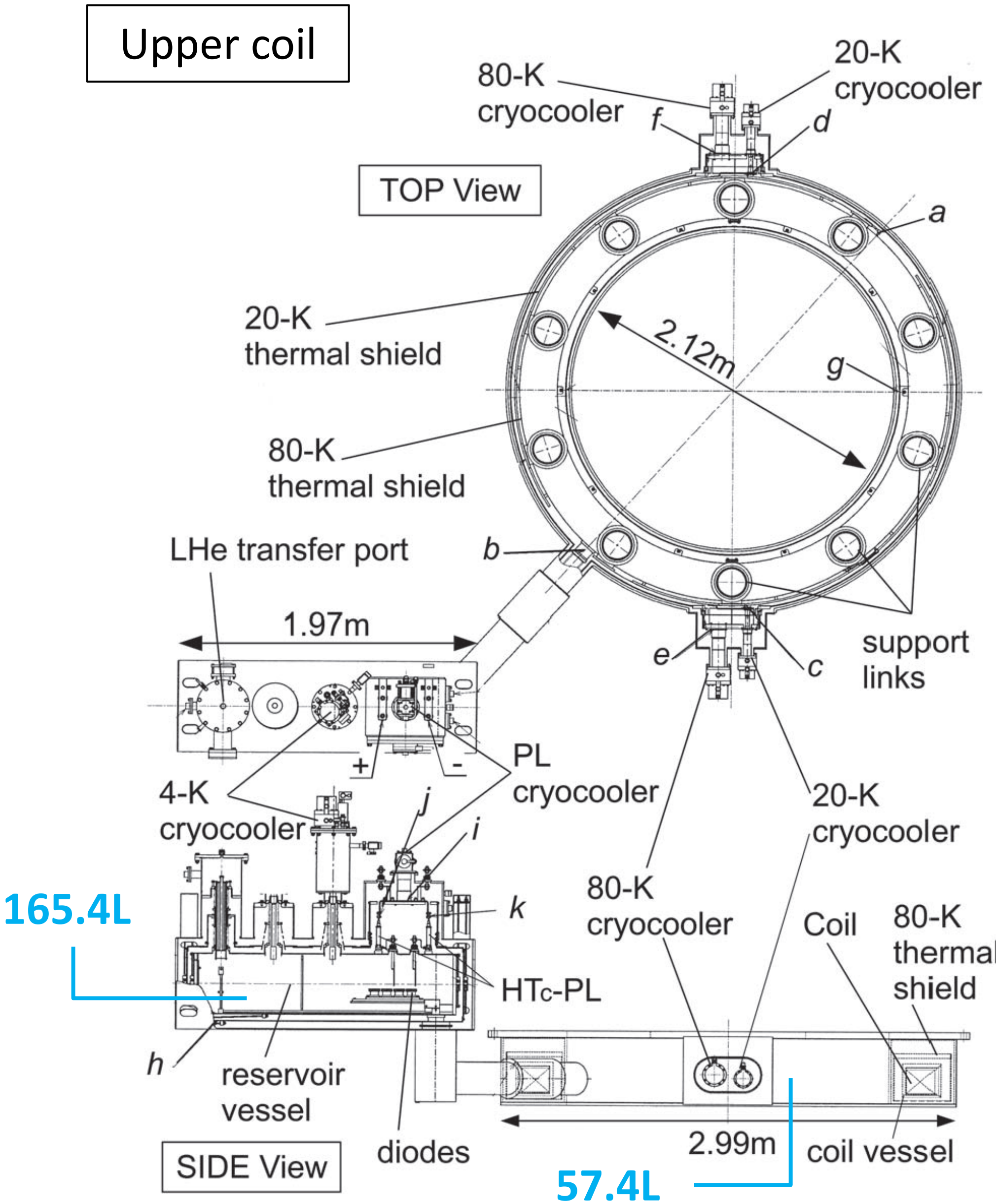
I=563 A, B=3.08 T

|B| [T]

$|B|_{max}$=5.4 T



Cryostat



Cold mass (@4.2K)

- coil: 1.8 ton
- coil vessel: 1.2 ton
- reservoir vessel+pipe: 0.5 ton

→ 3.5 ton / coil

From RT to 4.2K …

LN_2: 3000L/coil
LHe: 1500L/coil

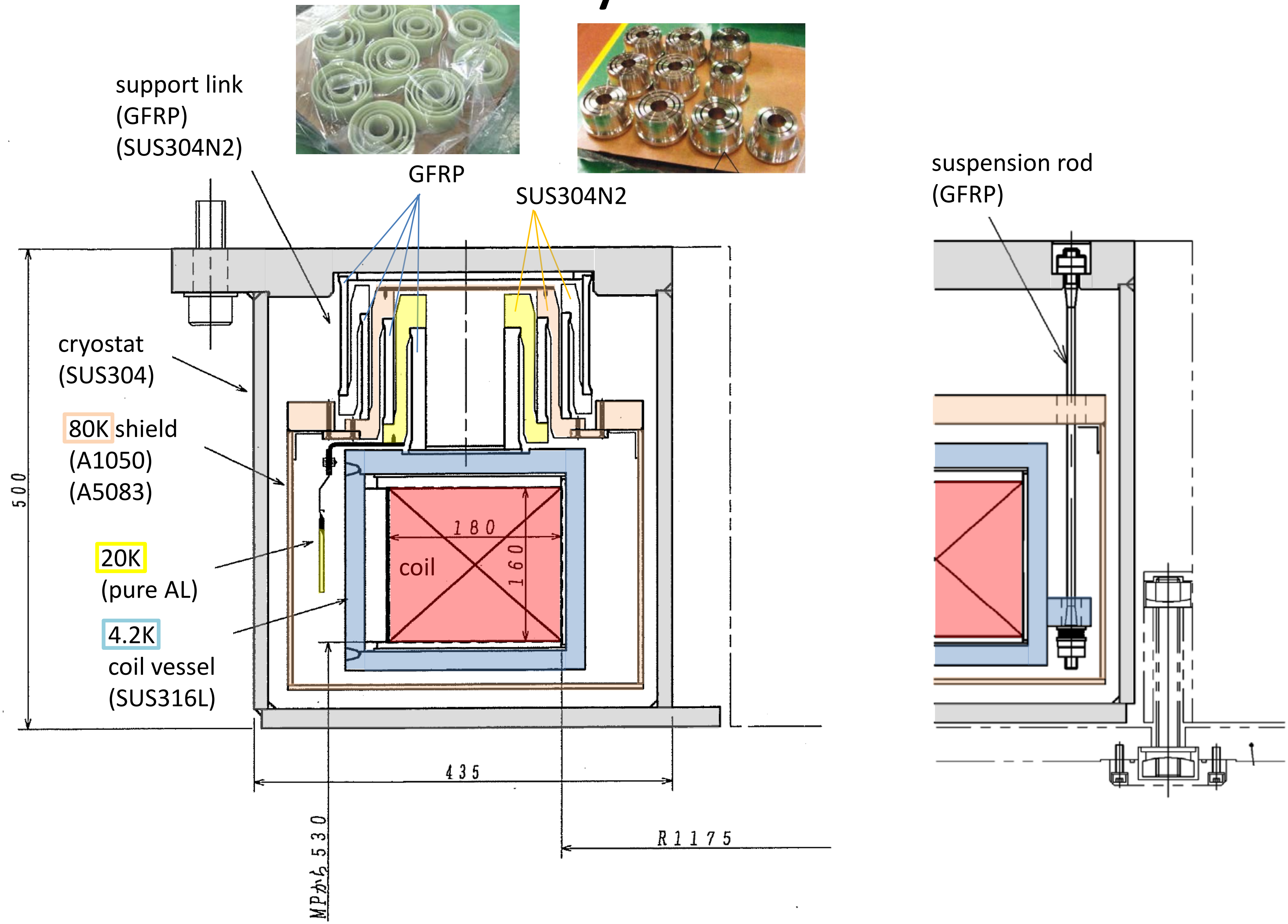
3 weeks / 2coils

Amount of LHe

- coil vessel: 57.4 L
- reservoir vessel: 165.4 L
- pipe: 10.9 L for upper coil
  16.7 L for lower coil

→ ~240 L/coil

Cryostat


support link
(GFRP)
(SUS304N2)
GFRP
SUS304N2
suspension rod
(GFRP)
cryostat
(SUS304)
80K shield
(A1050)
(A5083)
20K
(pure AL)
4.2K
coil vessel
(SUS316L)
coil
180
160
500
435
R1175
MPから530

Estimated Heat load/coil

(calculated for the lower coil)

4K part

Place	Parts	Heat load	@ramping	@I=560 A	@I=0 A
In the cryostat + Chimney pipe	Thermal shield	Radiation	0.40	0.40	0.40
	Support	Conduction	1.35	1.35	1.35
	Coil	AC loss	0.50	0.00	0.00
In the reservoir vessel (port)	Thermal shield	Radiation	0.52	0.52	0.52
	Support	Conduction	0.04	0.04	0.04
	Power leads	Conduction + Joule loss	0.54	0.54	0.30
	He gas	Conduction	0.57	0.57	0.57
	Bellows		0.07	0.07	0.07
	Signal leads		0.12	0.12	0.12
Sum			4.11	3.61	3.37

GM/JT 2.5W@4.3K x2

20K part

Place	Parts	Heat load	@ramping	@I=560 A	@I=0 A
In the cryostat	Thermal Shield	Radiation	0.08	0.08	0.08
	Support	Conduction	4.88	4.88	4.88
Sum			4.96	4.96	4.96

GM 4.2W@12K x2

Estimated Heat load/coil

80K thermal shield

Place	Parts	Heat load	@ramping	@I=560 A	@I=0 A
In the cryostat + Chimney pipe	Thermal shield	Radiation	23.79	23.79	23.79
		Residual gas	0.60	0.60	0.60
	Support	Conduction	53.83	53.83	53.83
Sum			78.22	78.22	78.22

GM 100W@80K x2

Power lead

Place	Parts	Heat load	@ramping	@I=560 A	@I=0 A
In the reservoir vessel (port)	Vacuum chamber	Radiation	10.99	10.99	10.99
		Residual gas	0.28	0.28	0.28
	Support	Conduction	0.47	0.47	0.47
	Power lead	Conduction + Joule loss	40.496	40.496	22.344
	Bellows	Conduction	1.708	1.708	1.708
Sum			53.94	53.94	35.78

GM 54W@40K x1

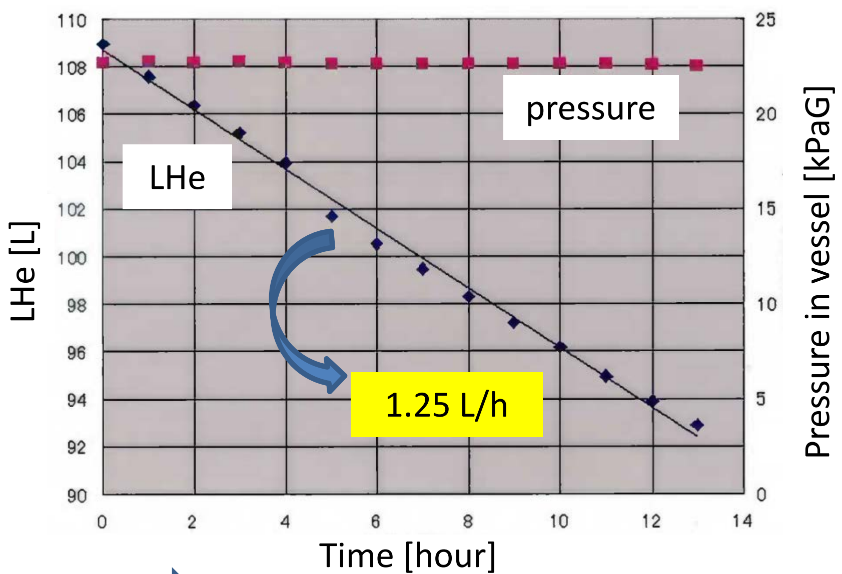
Heat load @4K

Heat load @4K /coil (estimation)

	@Ramping [W]	@I=560 A [W]	@I=0 A [W]
4 K part	4.11	3.61	3.37

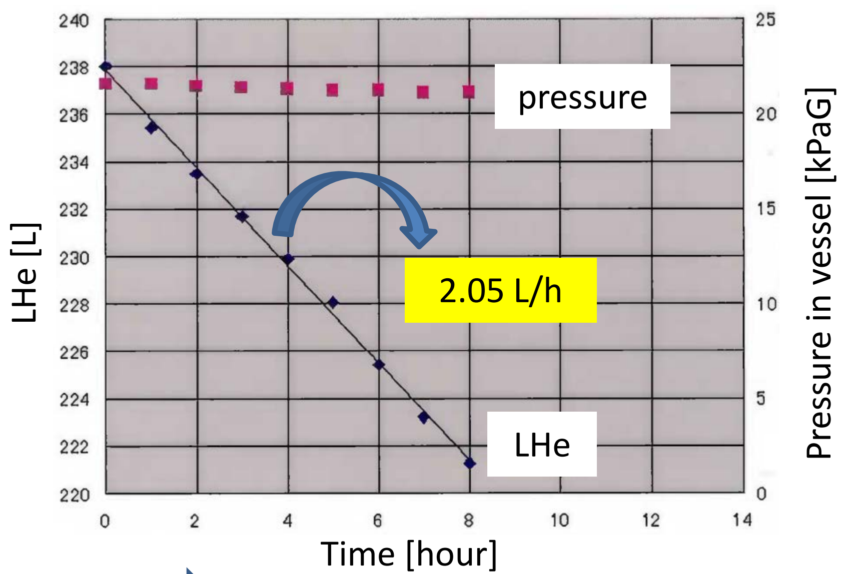
Evaporation rate of LHe (measurement @I=0 A)

Upper cryostat



0.9 W

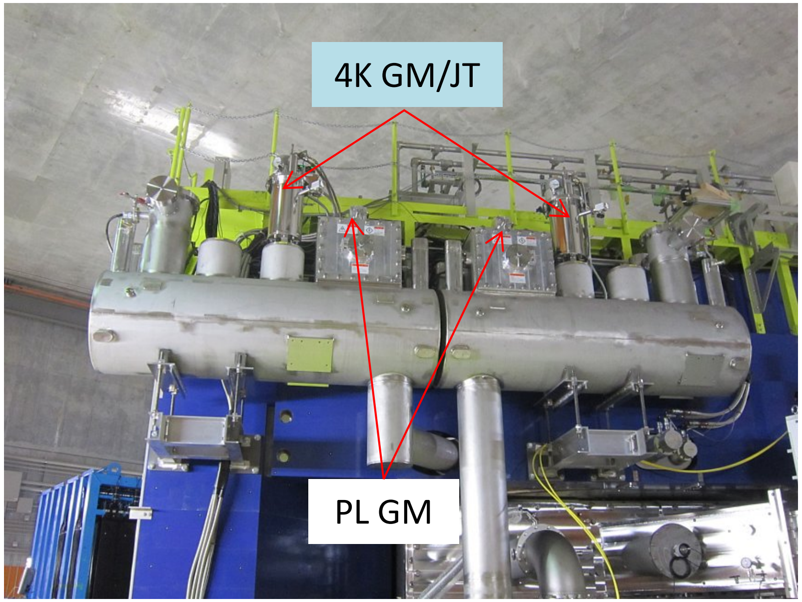
Lower cryostat

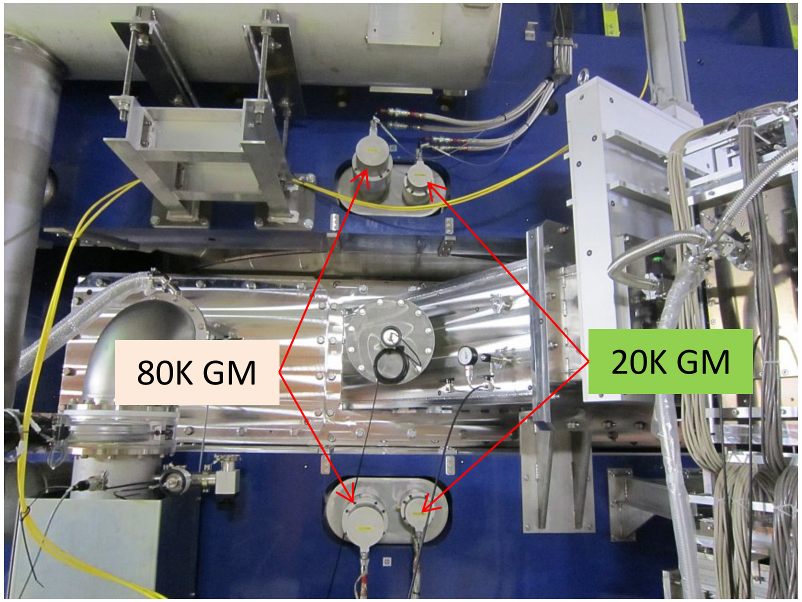


1.5 W

Two GM/JTs were prepared, but the measured heat load is smaller than the estimated value. Thus, just one GM/JT is used now.

Cryocoolers





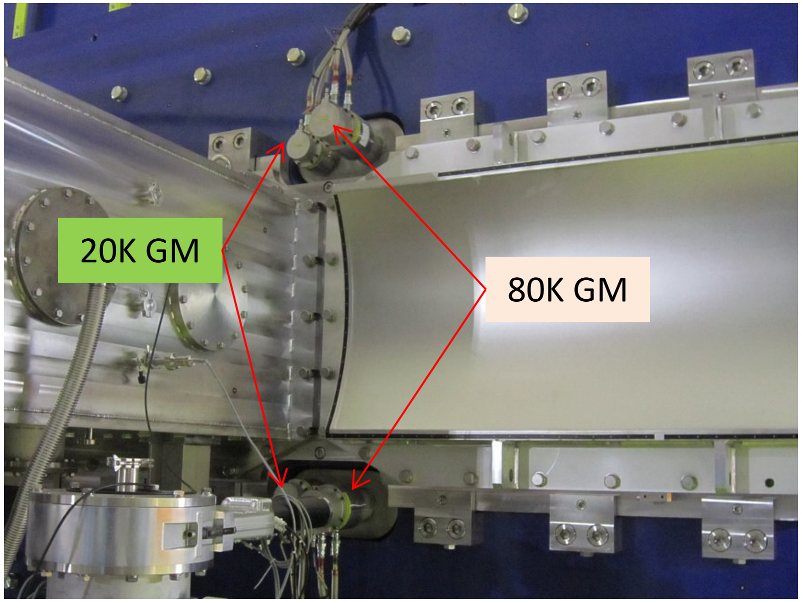


TABLE III

LIST OF THE CRYOCOOLERS FOR ONE CRYOSTAT

	He reservoir vessel	Thermal Shield 20 K	Thermal Shield 80 K	Power lead
Type	GM/JT	GM	GM	GM
No. of pcs	1	2	2	1
Model[a]	V308SLCR	V204SCP	V110CLR	RDK-400B
Cooling capacity	2.5 W @4.3 K	4.2 W @12 K	100 W @80 K	54 W @40 K

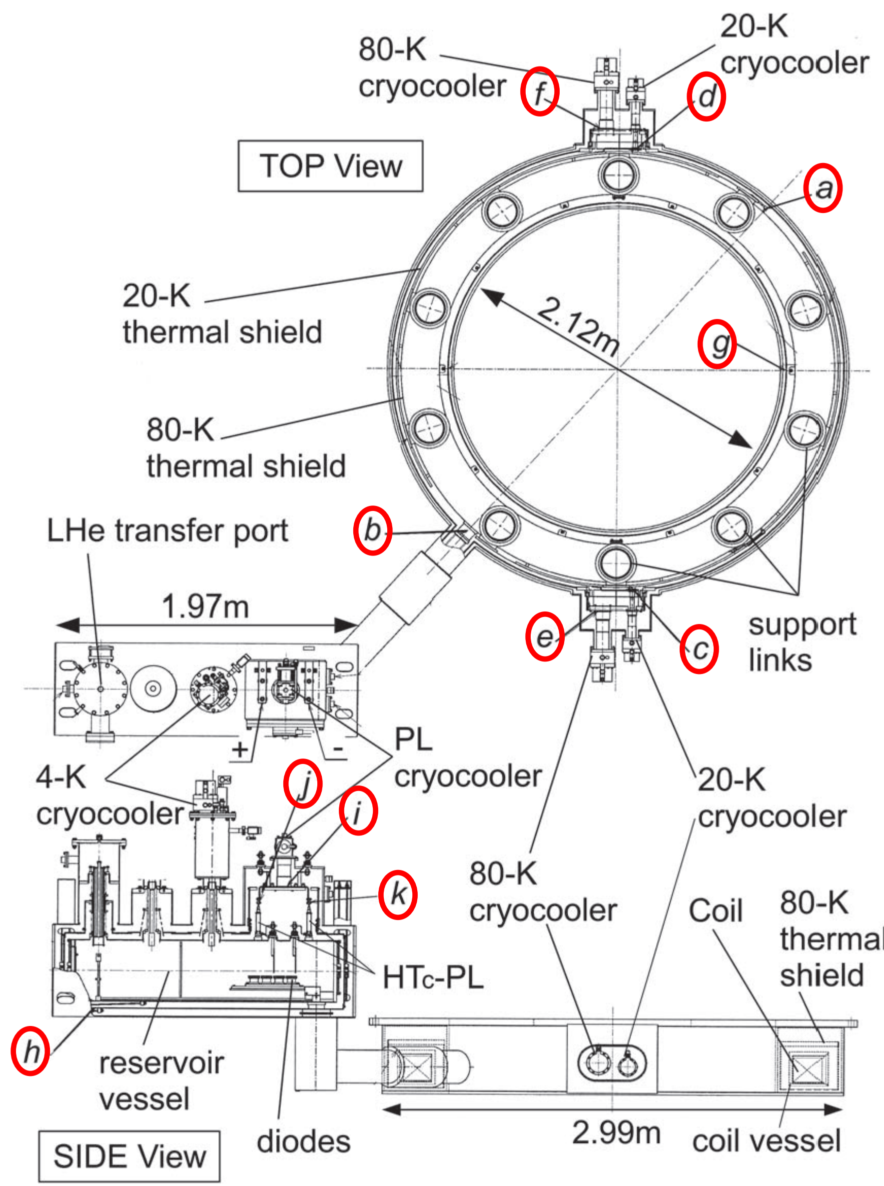
[a]Sumitomo Heavy Industries, Ltd.

12 cryocoolers are equipped.

Temperature

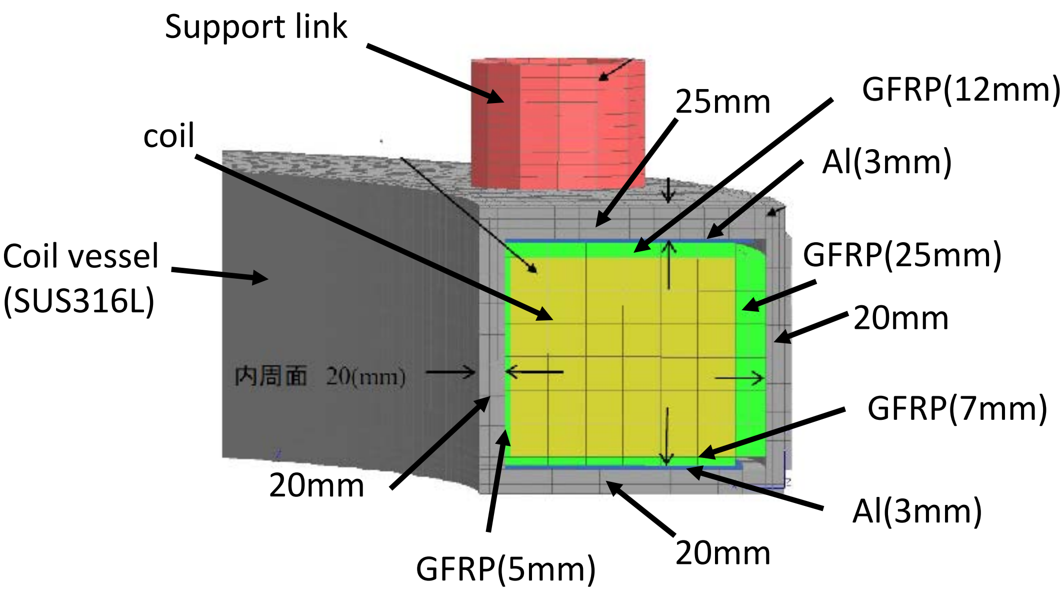
monitor screen of the controller
(6 Sept. 2013)

	Place	Upper coil [K]	Lower coil [K]
a	He vessel (outside of the wall)	4.2	4.3
b	He vessel (port)	7.1	7.1
c	20K GM A	11.8	11.9
d	20K GM B	11.6	11.2
e	80K GM A	40.9	43.3
f	80K GM B	41.6	40.6
g	80K thermal shield	45.1	47.5
h	80K thermal shield (reservoir vessel)	45.3	43.8
i	PL GM	42.6	41.5
j	PL (+)	42.9	41.6
k	PL (–)	42.8	41.6

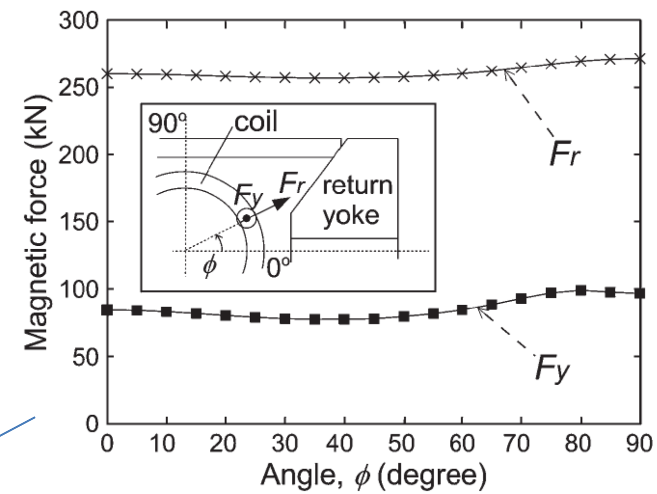


Structural Analysis

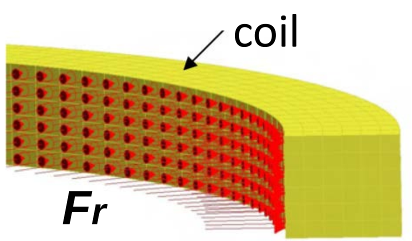
FEM analysis: coil + coil vessel + support link

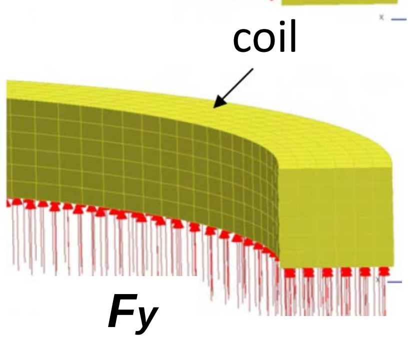


Magnetic forces as a function of the azimuthal angle



integrate





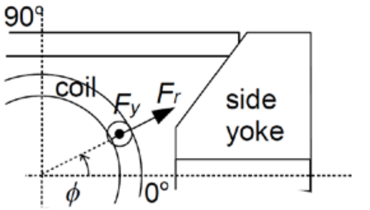
***Fr*=5x10^3 kN**
(2000ton/coil)

***Fy*=1.5x10^3 kN**
(600ton/coil)

TABLE V
MATERIAL PARAMETERS OF THE COIL AND THE VESSEL

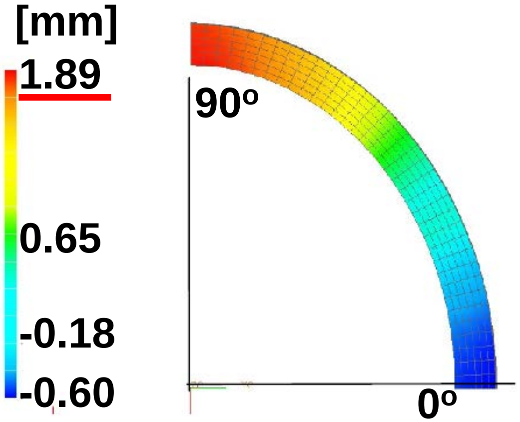
Material		Young's modulus	Poisson's ratio	Transverse elasticity modulus
	r direction	30 GPa	0.3	17 GPa
Coil	ϕ direction	97 GPa	0.3	19 GPa
	y direction	30 GPa	0.3	17 GPa
GFRP		32 GPa	0.3	-
SUS316L		200 GPa	0.3	-
Aluminum		80 GPa	0.3	-

Structural Analysis



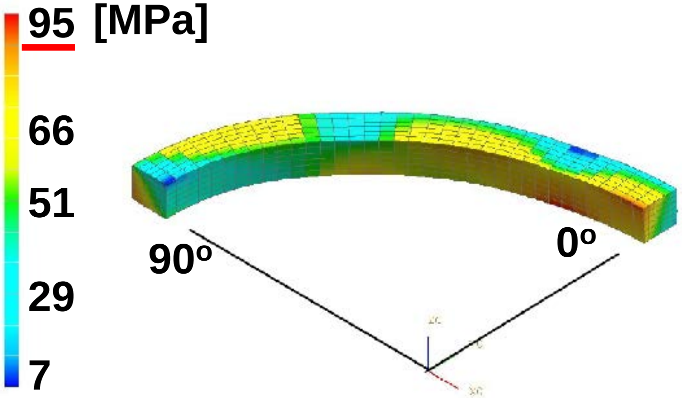
R-direction

Displacement of the coil



Y-direction:0.22 mm

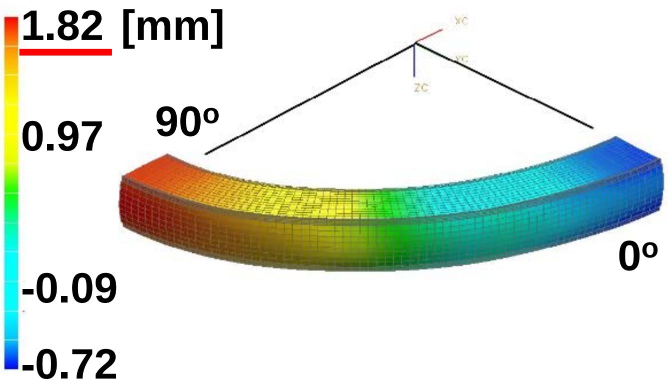
Principal stress in the coil



Allowable stress=180MPa@RT

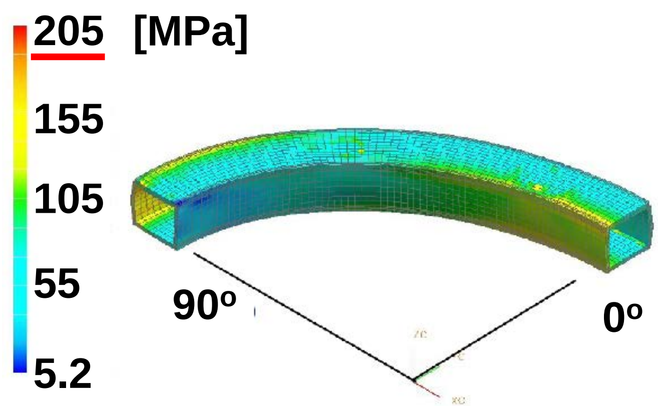
R-direction

Displacement of the vessel



Y-direction:0.19 mm

Von Mises stress in the vessel



Allowable stress=600MPa@4K

Safety interlock

	Interlock	Condition	Action: CUT OFF (DCCB open)	Quench back heater ON	Power supply OFF	Alarm
1	Failure of power supply	Over voltage, Over current, Water leakage, Door open			○	○
		Fuse break Cryo-controler down	○	○		○
2	Water flow (PS) down	< 40 L/min			○	○
3	Quench	V_{diff} > 1 V Duration time > 0.5 s	○	○		○
4	Power failure	Power failure	○	○		○
5	Failure of the PL cryocooler	Stop			○	○
6	Voltage of HT_c-PL	V_{PL} > 10 mV, V_{PL} < -10 mV	○	○		○
7	Temperature of HT_c-PL 1	T > 70 K			○	○
8	Temperature of HT_c-PL 2	T > 75 K	○	○		○
9	Lack of LHe	Level < 80%			○	○
10	Pressure of the vessel 1	P > 19 kPaG (120.3 kPa)				○
11	Pressure of the vessel 2	P > 40 kPaG (141.3 kPa)			○	○
12	Emergency stop	Push emergency button	○	○		○

cryostat

DCCB

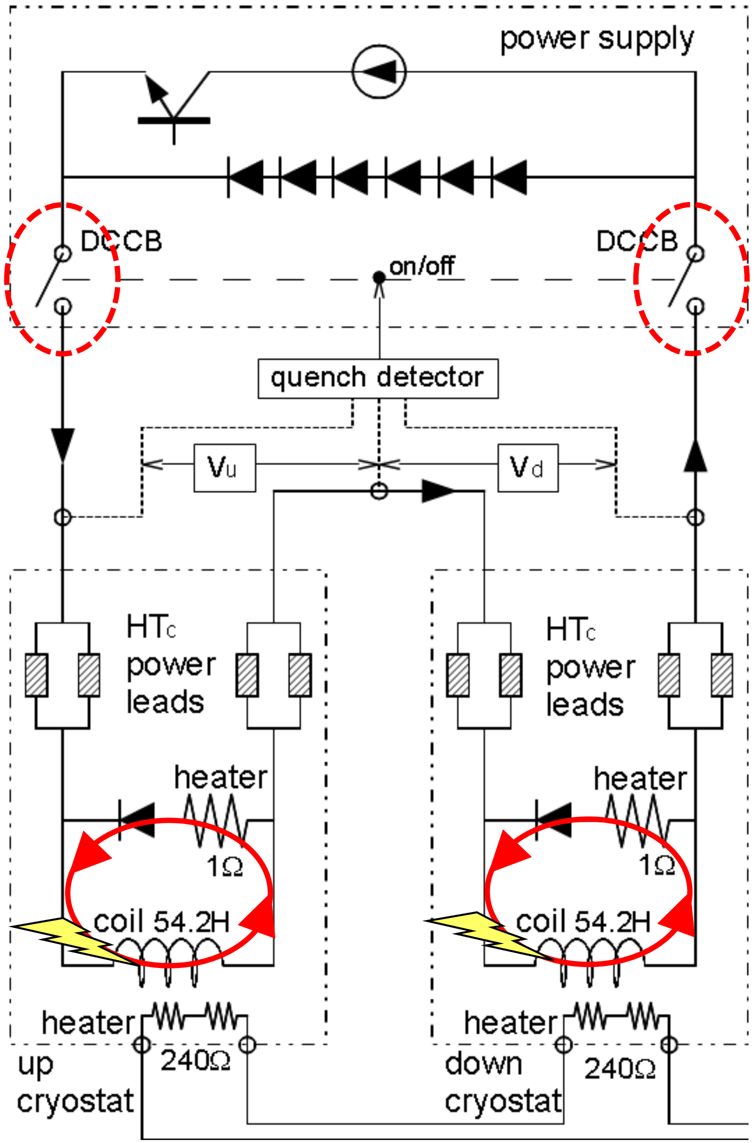
PS OFF

The coils are forced to quench. The current is discharged through the diodes in the cryostat and the coils.

The current is discharged through the diodes mounted in the power supply.

power supply

Quench protection



Quench

1. **The detector recognizes the quench. (1V, 0.5s)**
2. **DCCB open (Coils are cut off.)**
3. **Current flows to the heater layer on the outermost of the coil.**
4. **Backup heaters switch on within 50 ms.**
5. **Coils are forced to quench from the outer to inner layer.**
6. **Stored energy is dumped by the superconducting coils.**

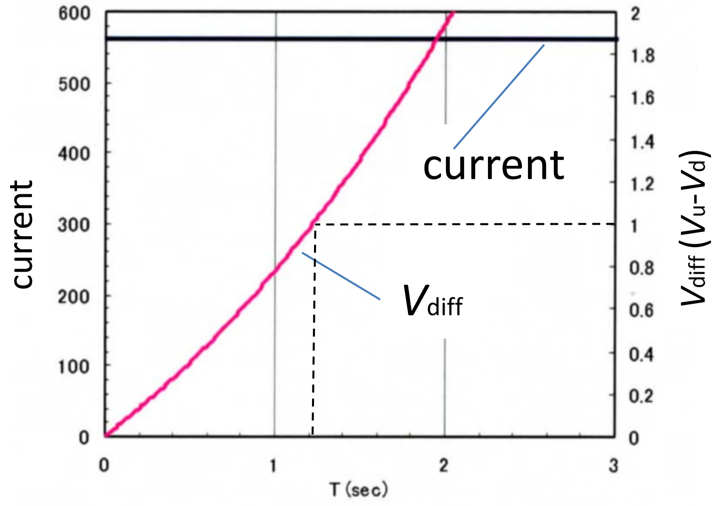
In the case …

- cryo-conroler down
- power failure
- $|V_{PL}| > 10$ mV
- $T_{PL} > 75$ K
- emergency stop

Same procedure as the quench case will be done.

Quench analysis

change of V_{diff} after quench



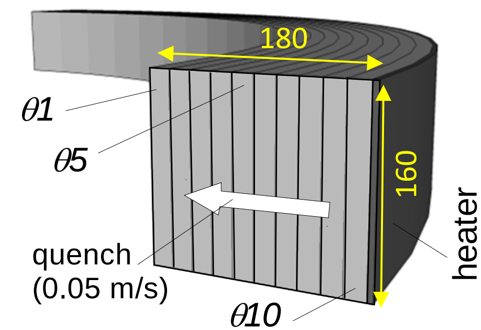
quench propagates longitudinal direction

$v_{q\,//}$=10 m/s

V_{diff} > 1V at 1.2 sec.

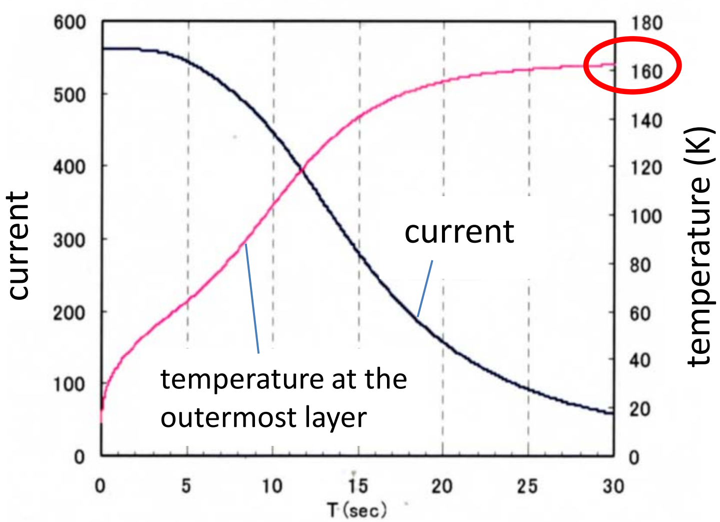
0.5 sec. before cut off
+
0.3 sec. delay before heater on

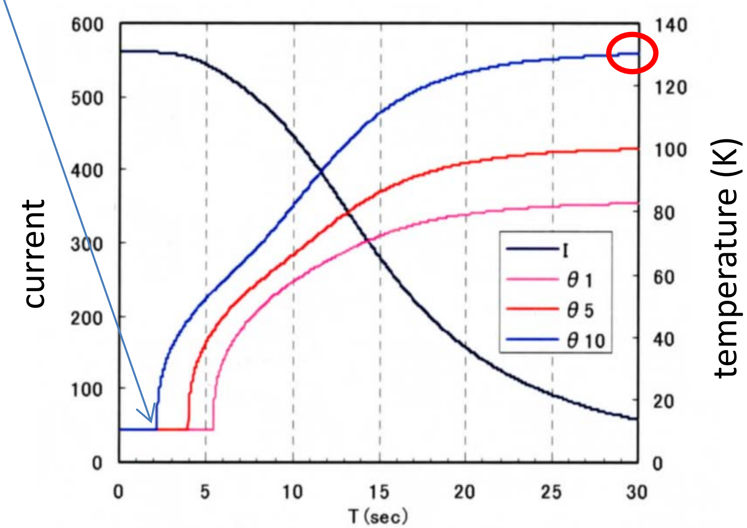
Total: 2 sec.



quench propagates transverse (radial) direction

$v_{q\,\perp}$=0.05 m/s (estimated from the value of KEK-SKS)





Temperature rise is moderate and acceptable

Quench analysis

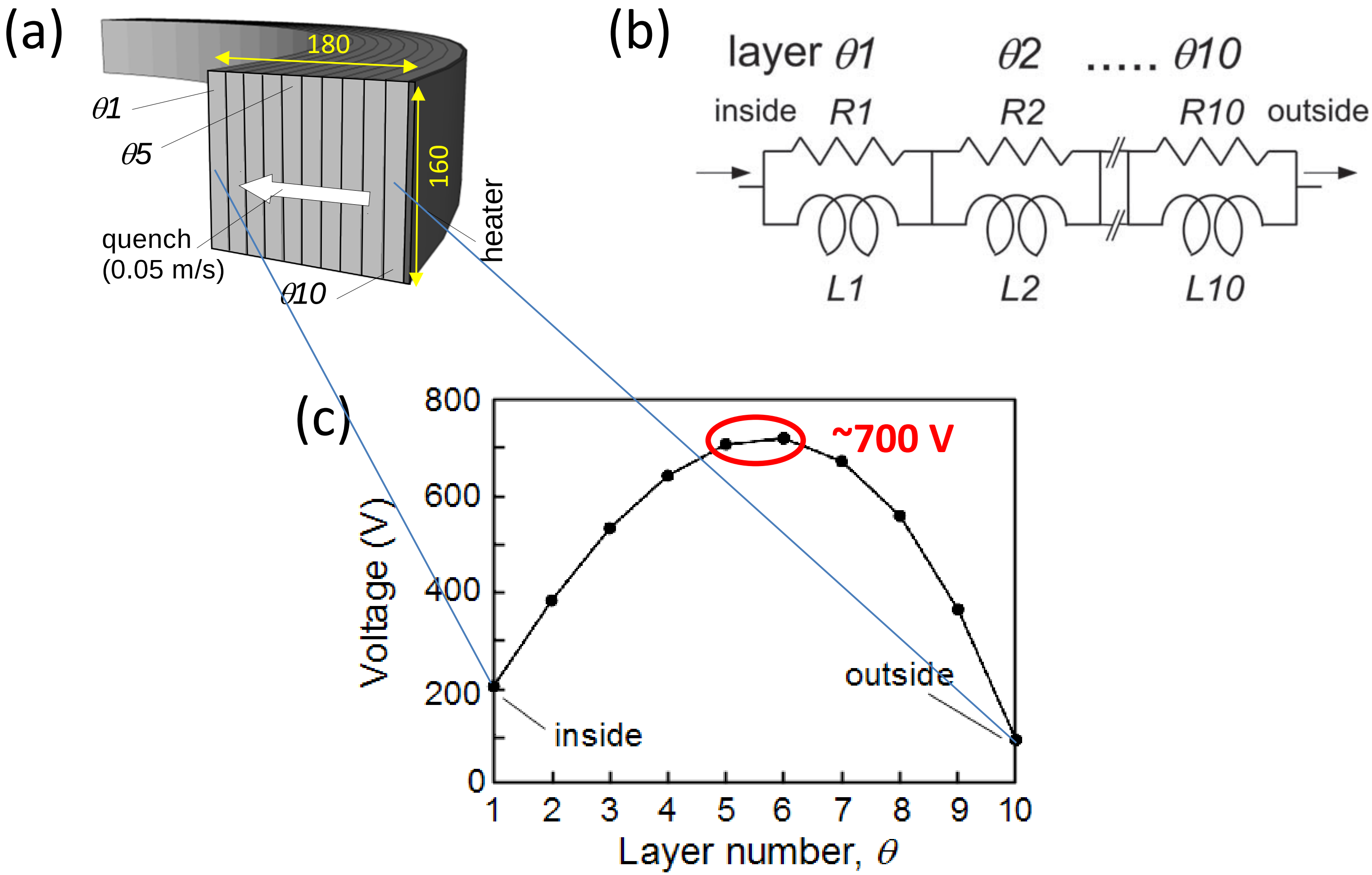
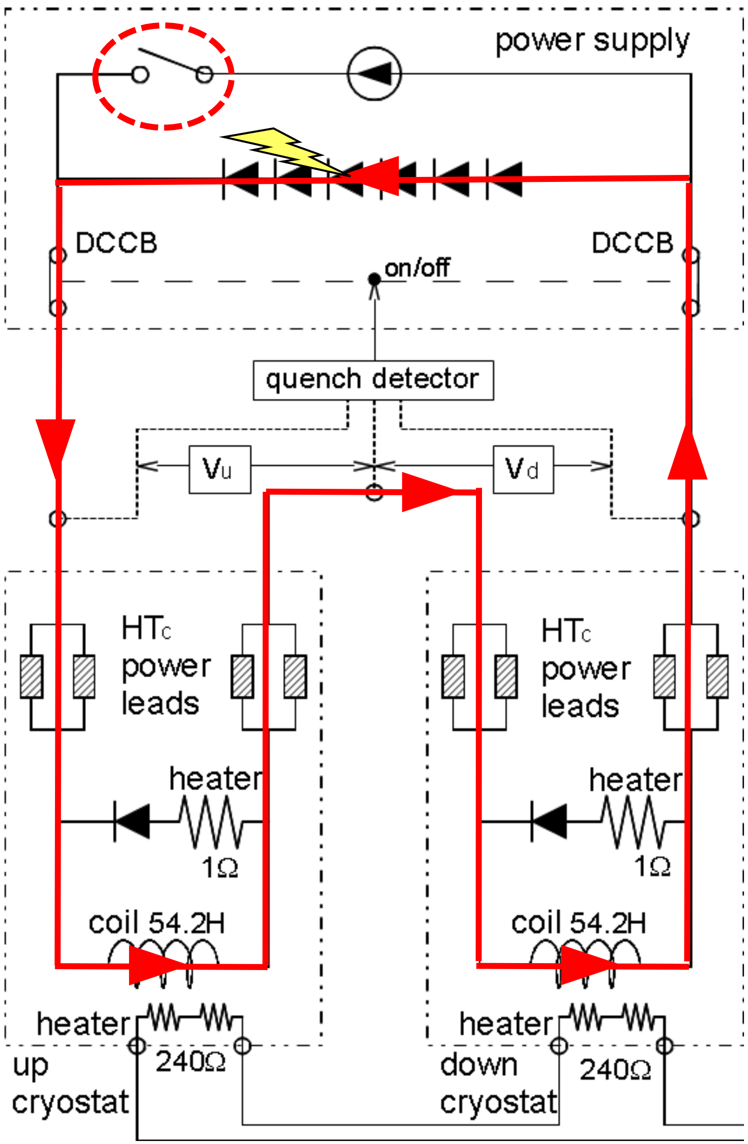


Fig. 13. Simulated quench characteristics for the induced voltage. (a) Definition of the layer segmentation. (b) Equivalent circuit of the coil assumed in the simulation. Each layer θ has a resistance R and an inductance L. (c) Maximum induced voltage at each layer.

Induced voltage is moderate and acceptable

Coil protection



In the case …

- over voltage
- over current
- door open
- water leakage
- water flow down
- PL cryocooler failure
- $T_{PL} > 70$ K
- LHe level < 80%
- $p_{He} > 40$ kPaG

1. Power supply is cut off

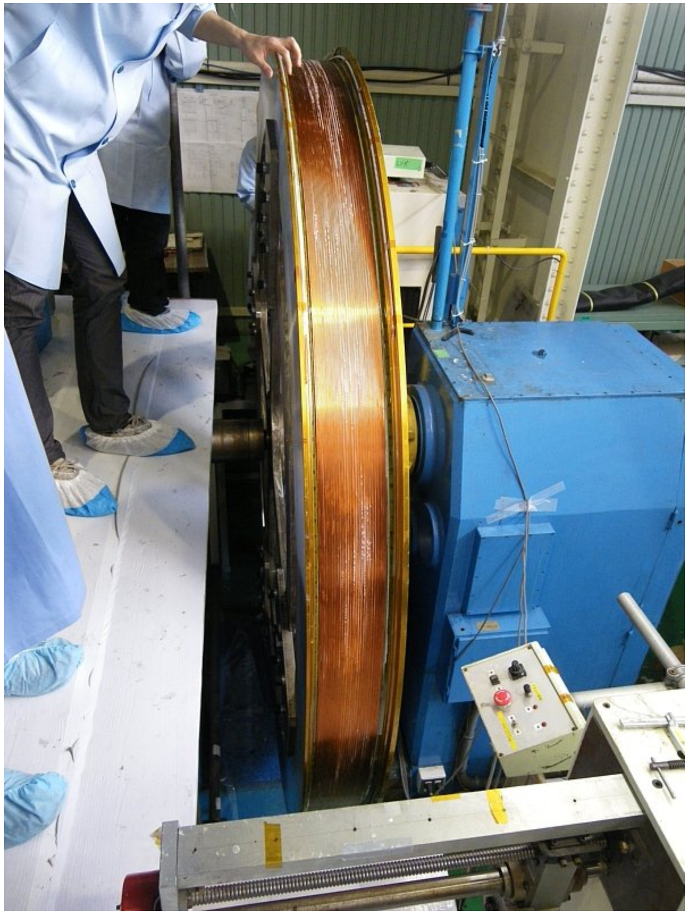
2. Stored energy is dumped by diodes in the power supply

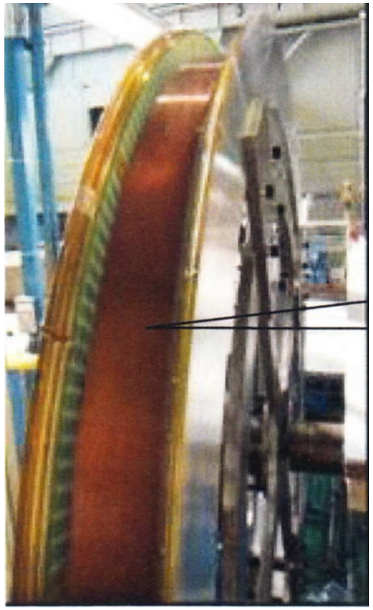
3. Diodes are cooled by heat-sink and fan

from 560A to 0A : ~1 hour

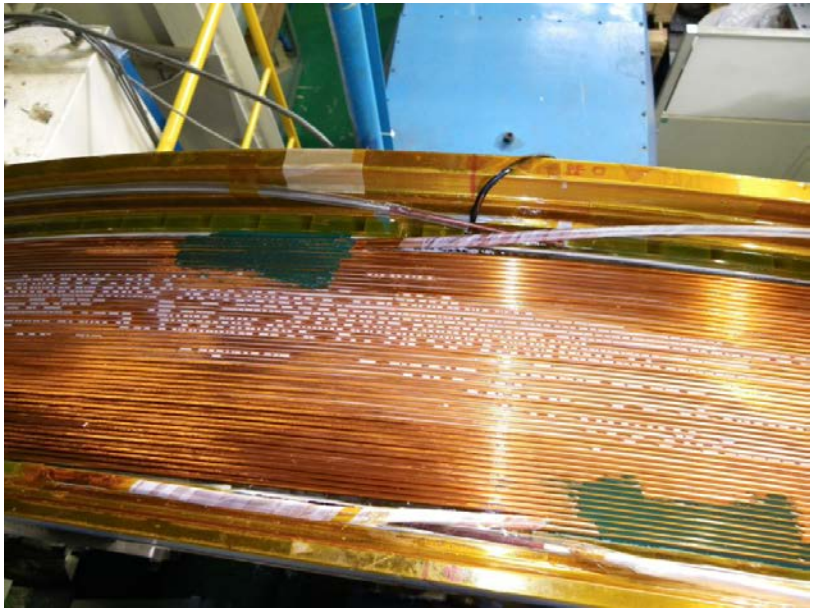
decay const. : 0.25A/sec

Cryostat assembling





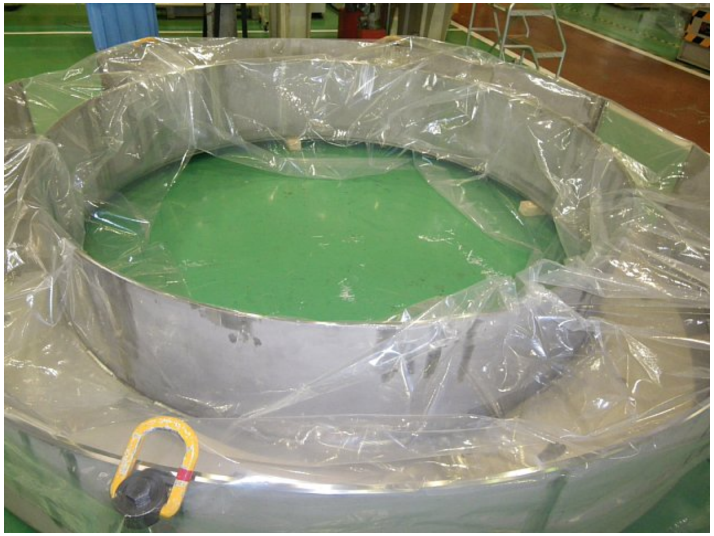
coil winding



Cryostat assembling

reservoir vessel

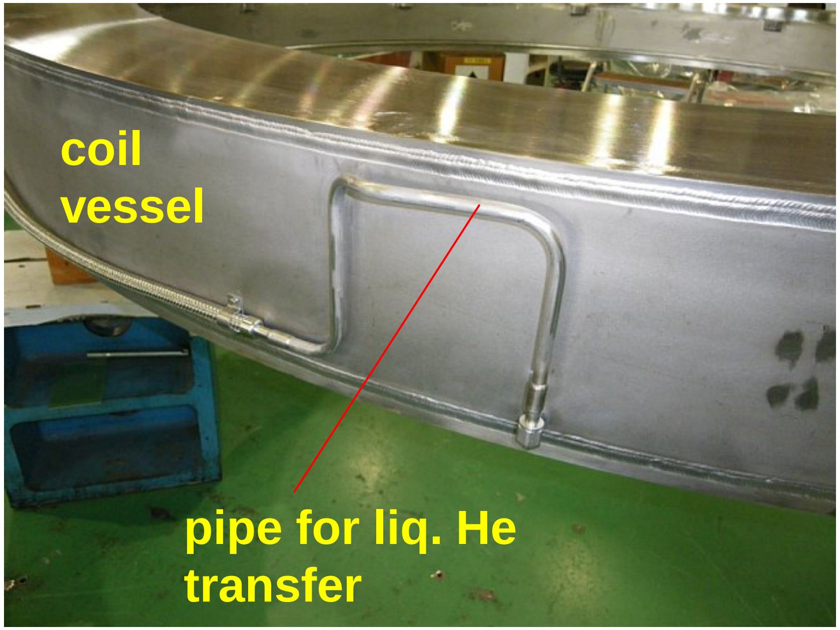
cryostat chamber

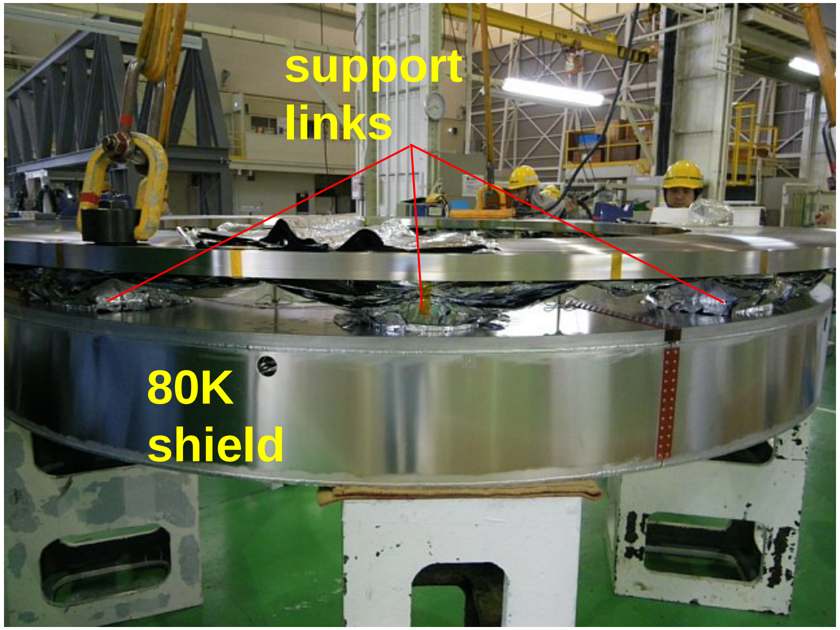


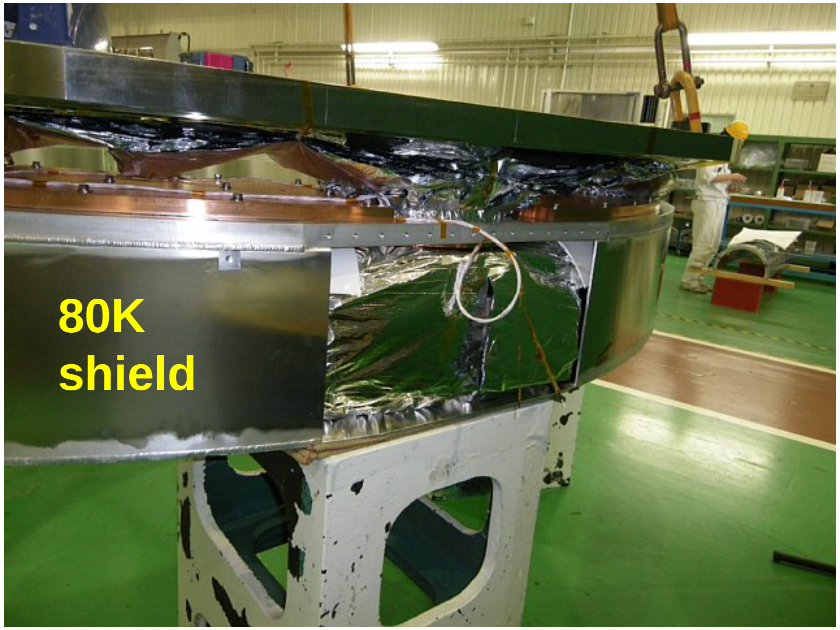
Cryostat assembling

Lower cryostat assembling

Cryostat assembling

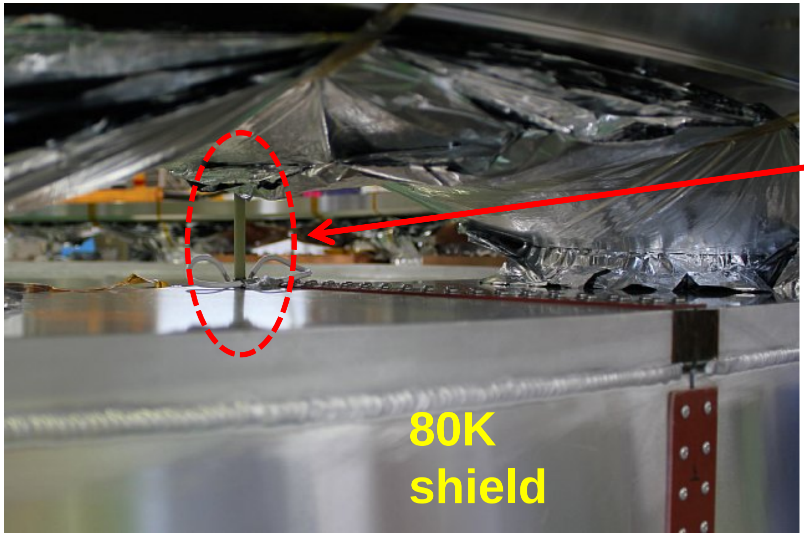






Cryostat assembling

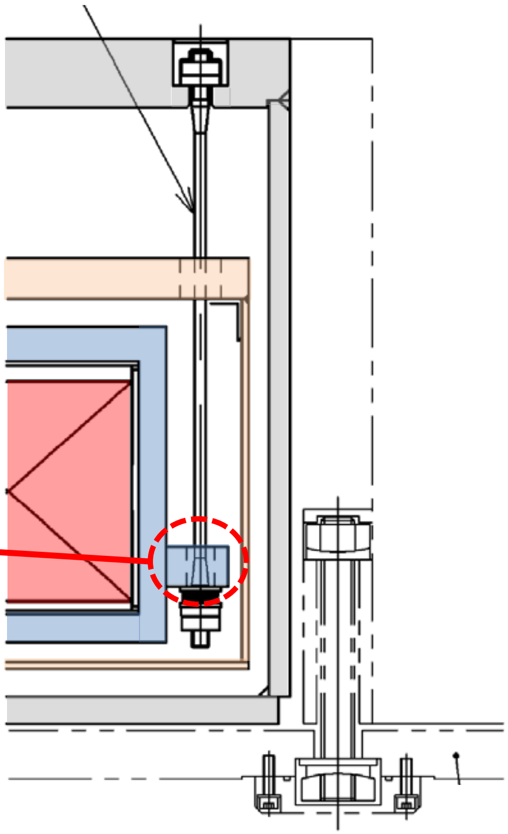
Upper cryostat



Lower coil

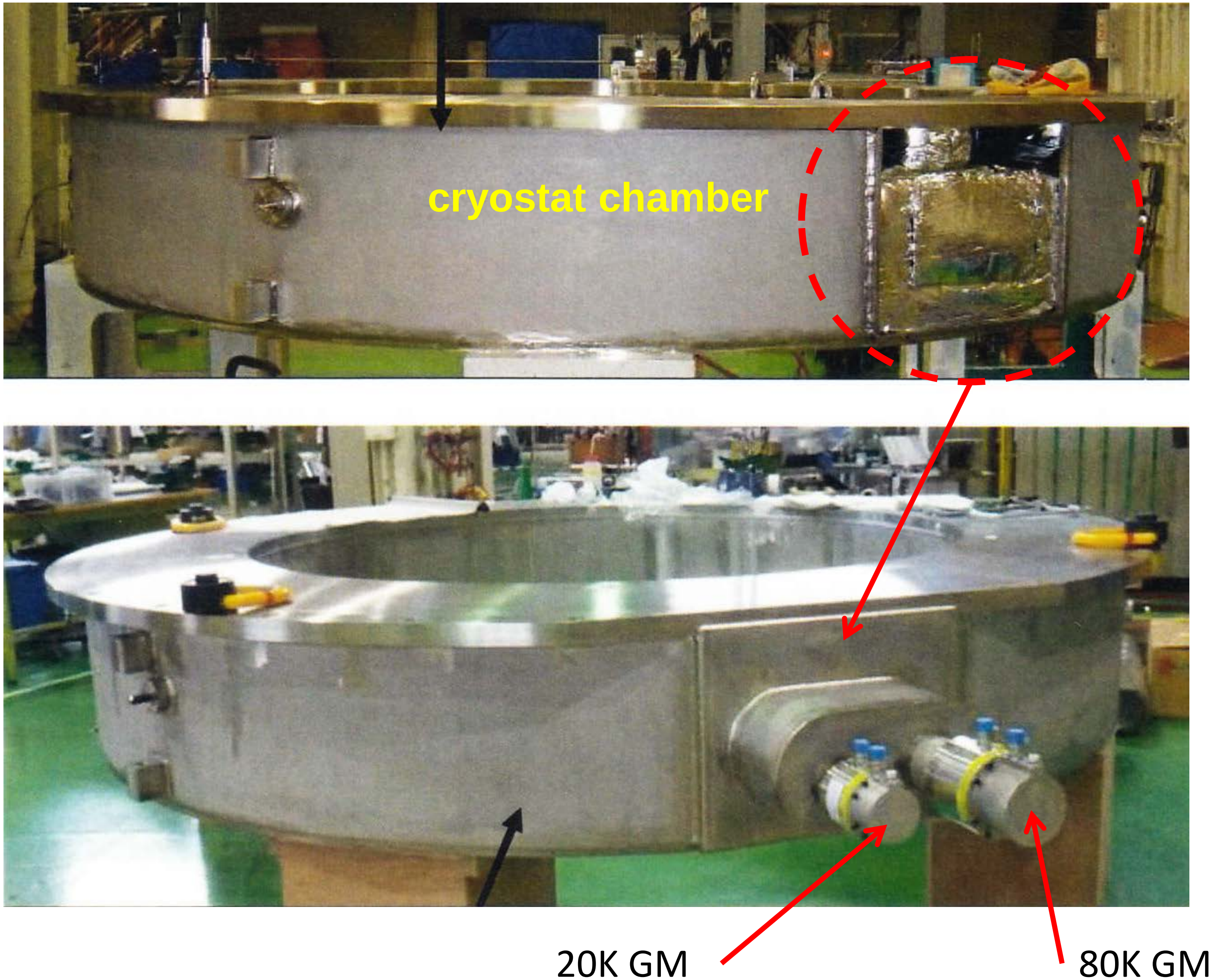
Upper cryostat

suspension rod
(GFRP)

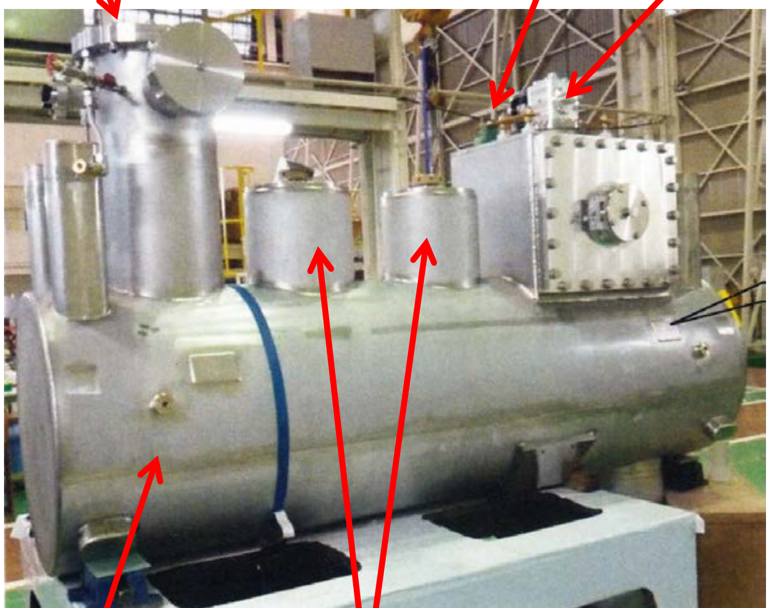


Cryostat assembling

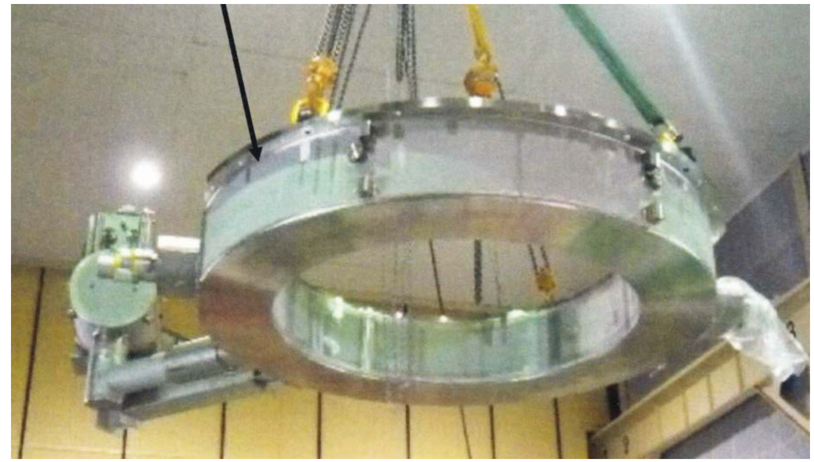
Upper cryostat



Cryostat assembling

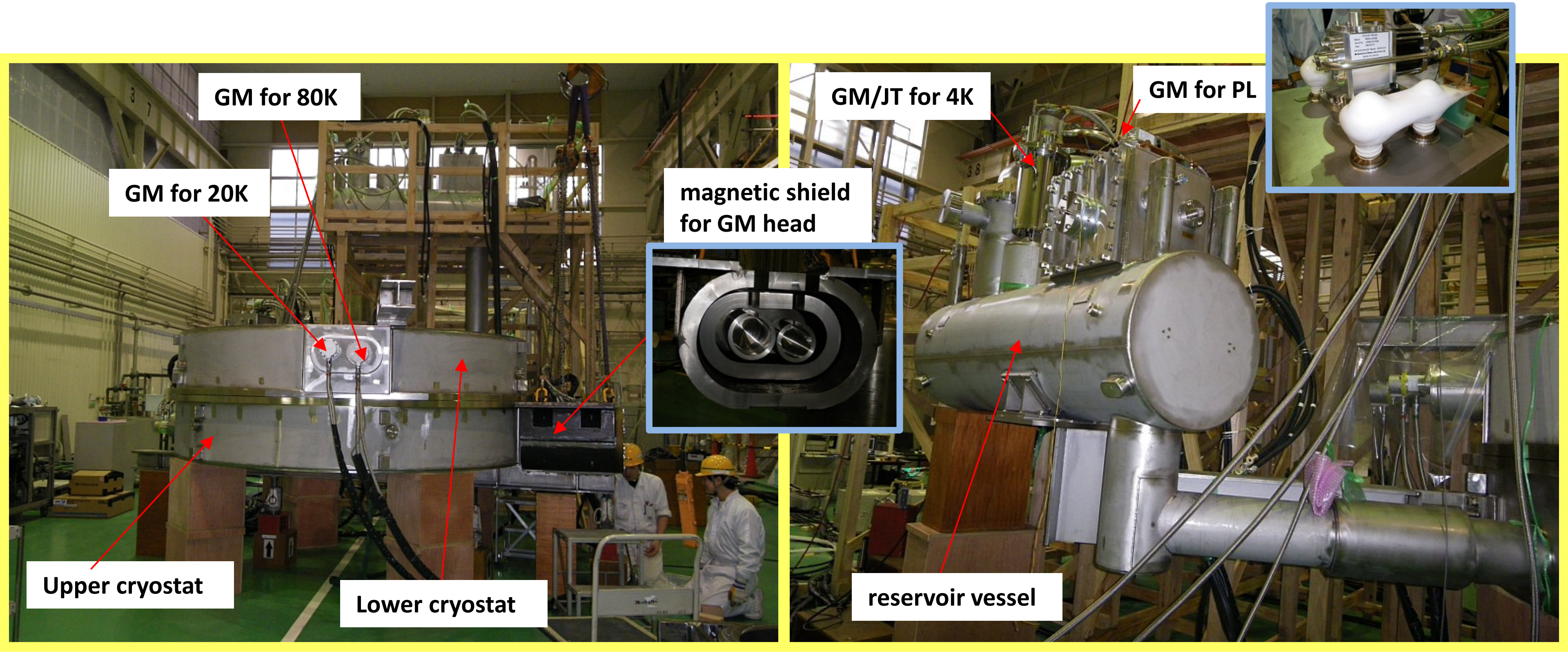


Upper cryostat



Lower cryostat

Test in Toshiba factory



Excitation test (1st time)

1. polarity check by applying 1 A
2. apply 10A -> cut off to check the protection sequence
3. excite to 518.4 A -> training quench happened @450 A

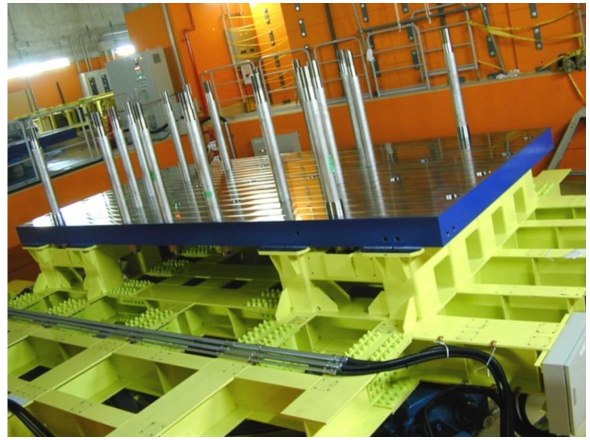
Excitation test (2nd time)

1. excite to 530 A -> success without quench

- ~4 T in the coil region
- ~624 ton

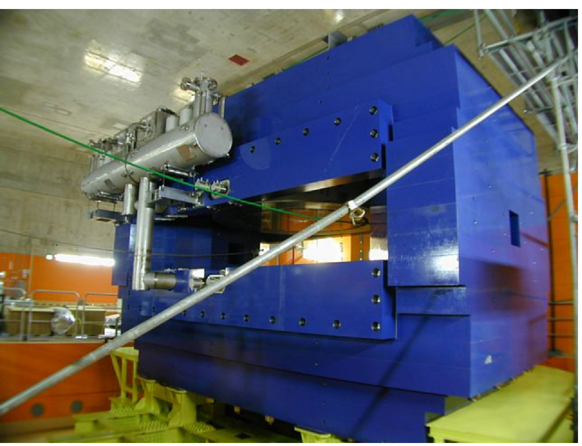
On site assembling

Rails for rotatable base (11/13/2010)

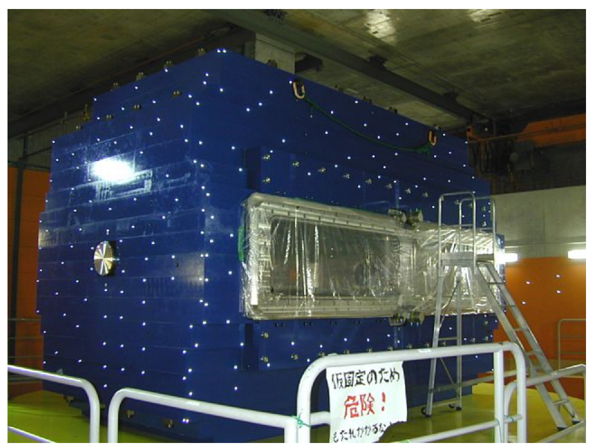


Rotatable base with the first layer of the yoke

Magnet yoke with poles



Coils with cryostats, LHe reservoir vessels

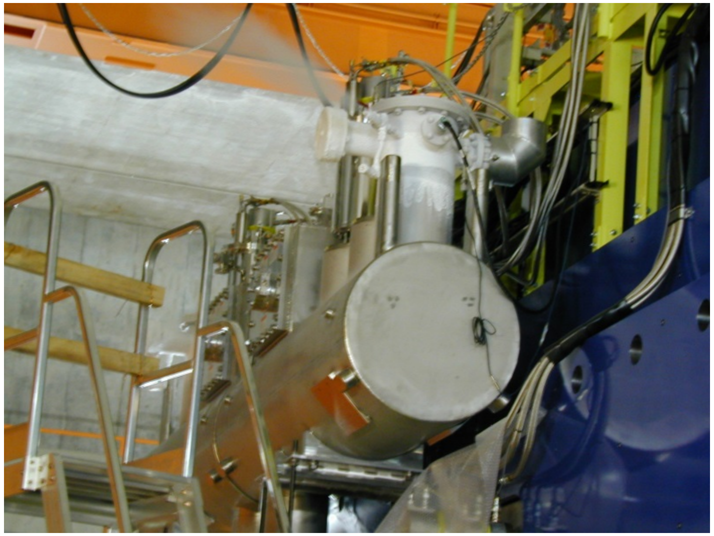


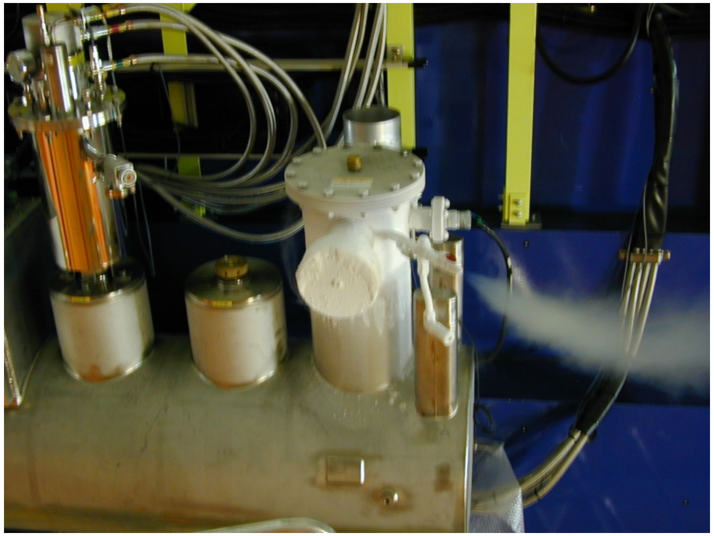
Vacuum chamber

After day-one experiments (9/19/2012)

Excitation test

May 2011, excitation test was performed.

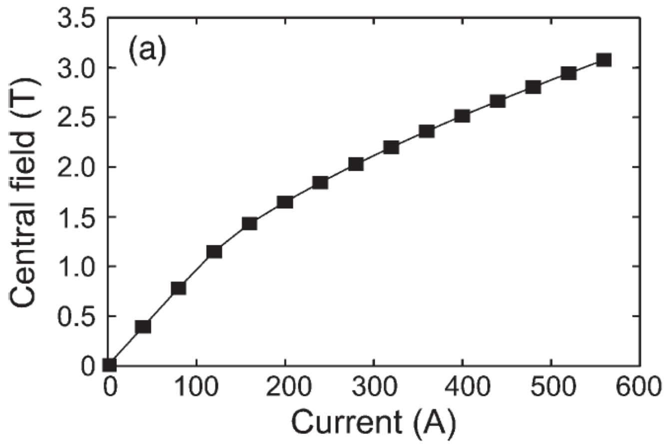




A training quench happened in the lower coil at 561 A (3.07 T), which corresponds to 99.6% of the maximum operation current, 563 A (3.08 T).

During subsequent excitation testing after refilling of LHe, the current reached 563 A without quenching and the test was continued up to 573 A (3.10 T) successfully.

Magnetic Field



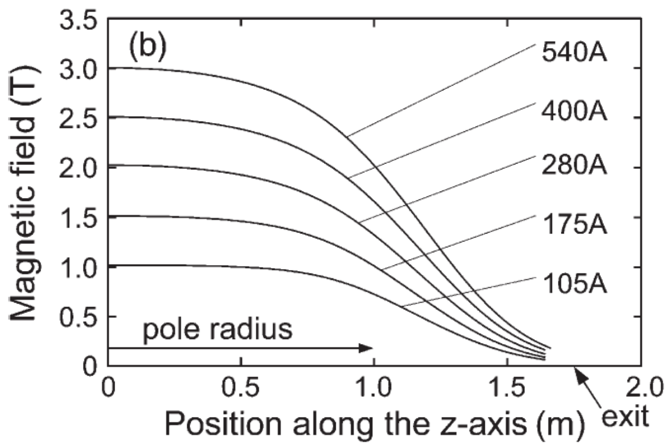


Fig. 14. (a) Measured excitation curve of the SAMURAI dipole magnet. (b) Measured magnetic field distributions along the z-axis. The z position labeled as "exit" corresponds to the edge of the iron yoke which is located at $z = 1.75$ m.

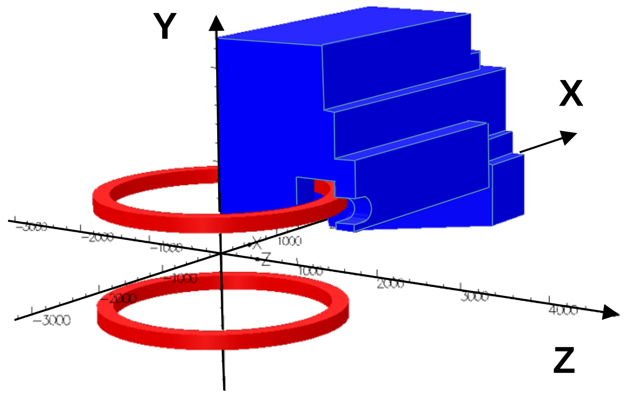
TABLE VI
RAMPING SPEED OF THE CURRENT

Current (A)	Magnetic Field (T)	Ramp Speed (A/s)
0 – 100	0 – 0.97	0.04
100 – 120	0.97 – 1.14	0.05
120 – 140	1.14 – 1.29	0.06
140 – 160	1.29 – 1.42	0.07
160 – 180	1.42 – 1.54	0.08
180 – 563	1.54 – 3.08	0.09

They are determined in response to changes is the inductance of the coil so as to keep the induced voltage below 20 V, which is the maximum voltage of the power supply.

Magnetic Field

model 1



The value of the central field is compared between measurements and calculations (TOSCA).

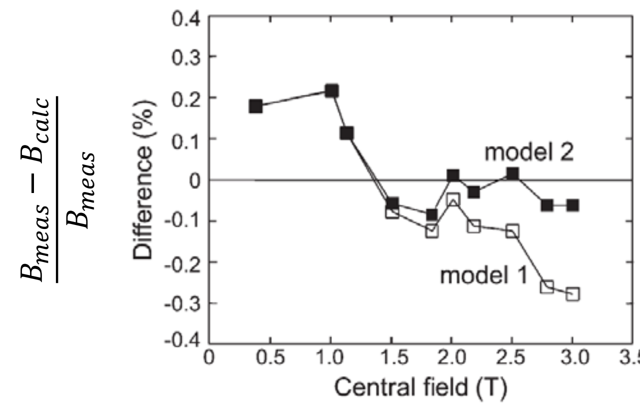
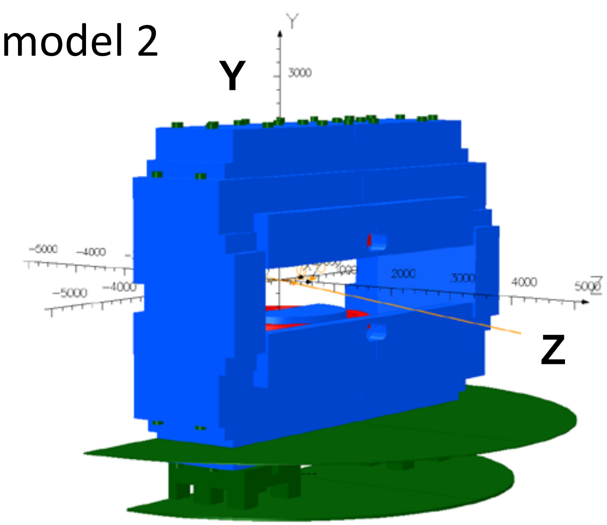
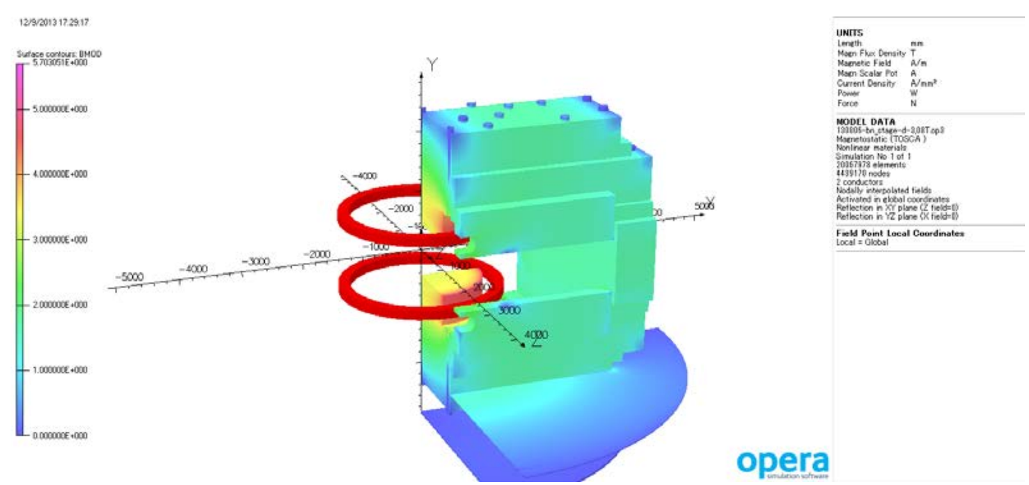


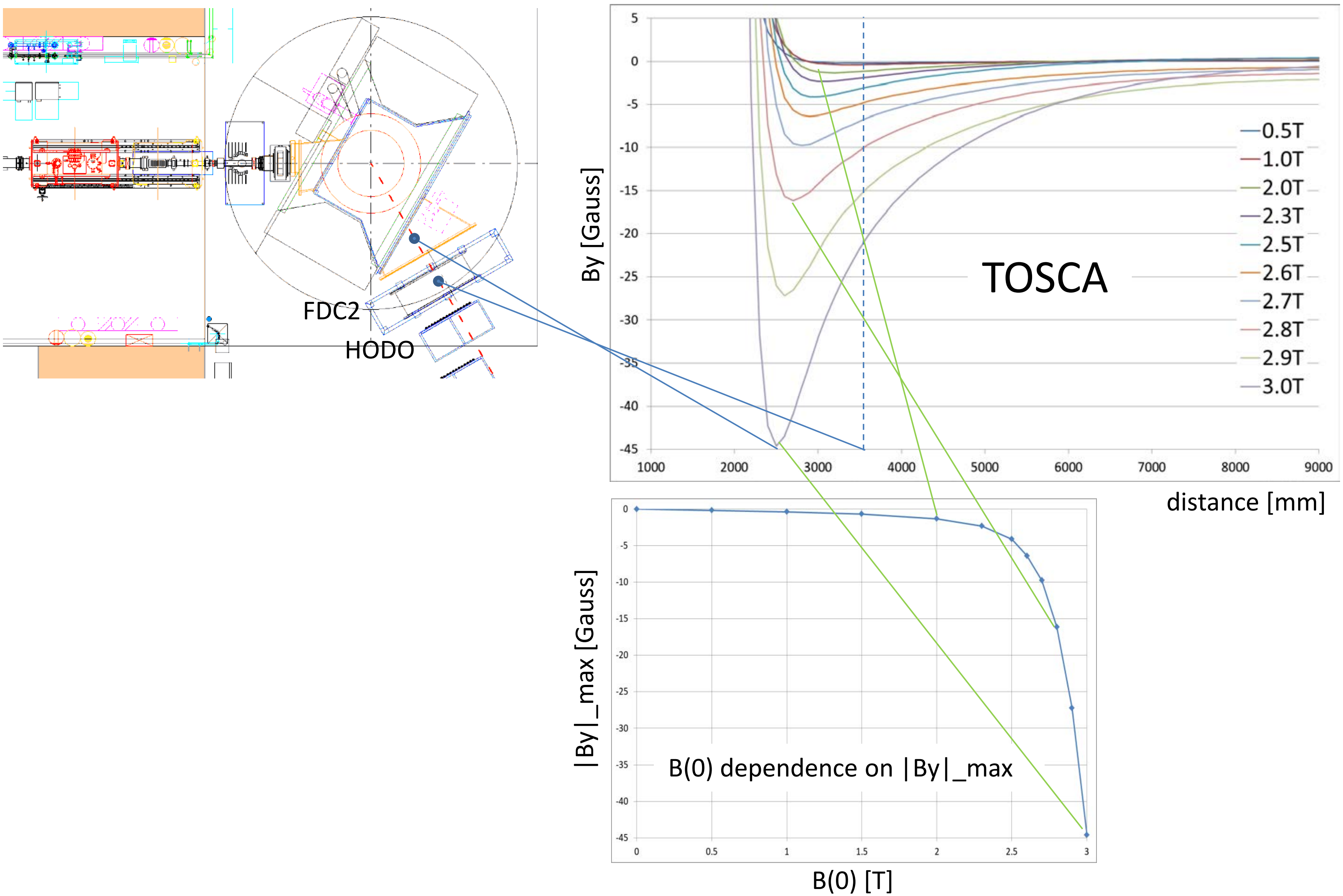
Fig. 15. Difference of the calculated central field from the measured value shown as a function of the central field. The open squares indicate the results with model 1 (TOSCA calculation with the iron yoke only) and the closed squares those with model 2 (TOSCA calculation with the iron yoke, the rotatable base, and the stud bolts).

model 2

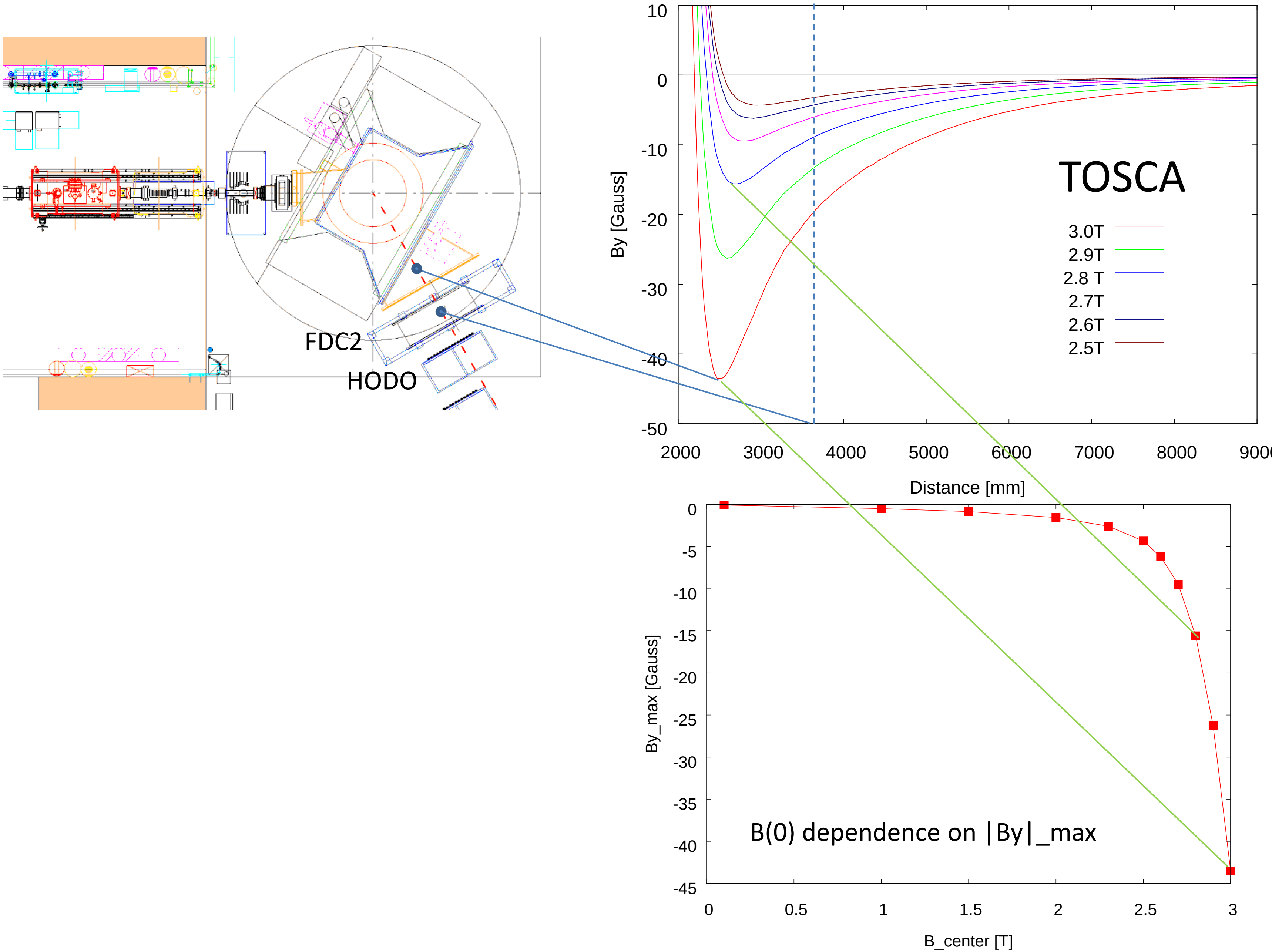




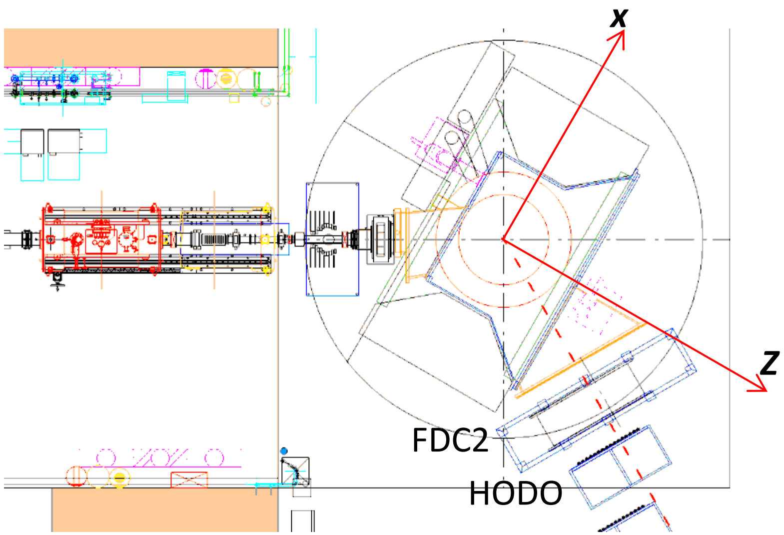
Fringe Field



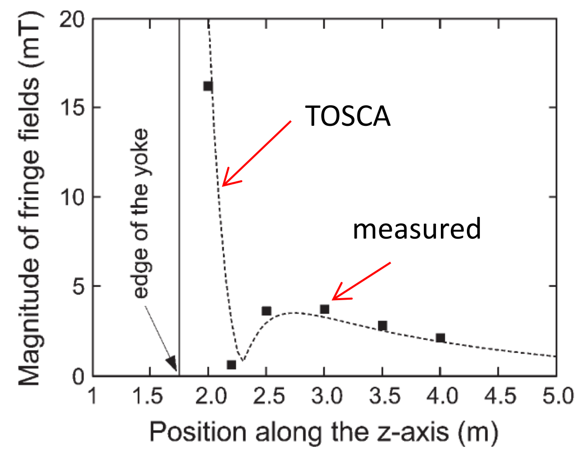
Fringe Field



Fringe Field

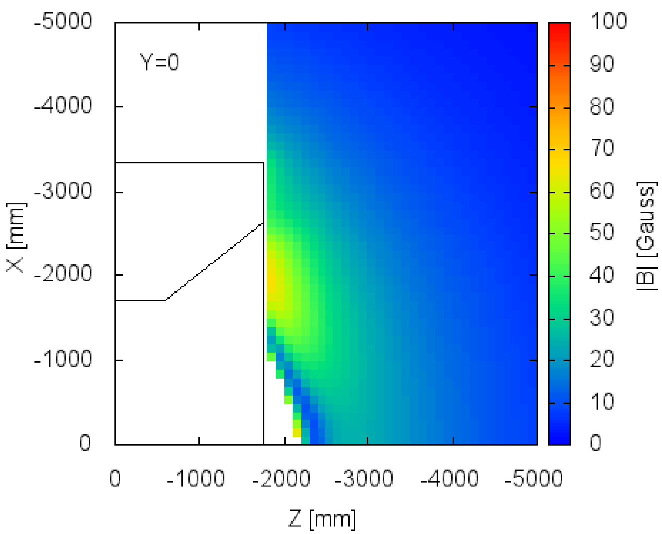


By(center)=3.08T



18. Magnitude of fringe fields on the z-axis at the central field of T. The closed squares indicate the measured values, while the dotted corresponds to the TOSCA calculation. Model 2 is used in the TOSCA ulation.

TOSCA B(0)=3.0T



The calculated values and measured values agree well with each other. The fringe fields are smaller than 50 Gauss in the region more than 0.5 m distant from the edge of iron yoke, satisfying our experimental requirements.

Summary

✓Large-acceptance spectrometer “SAMURAI” has been constructed at RIKEN RIBF.

✓The construction of the H-type superconducting dipole magnet was finished in June 2011.

✓Large pole gap (800mm effectively)

✓Wide horizontal opening (3400mm)

✓Central field =3.08T, BL=7.05Tm, I=563A, E=27.4MJ

✓The coils are cooled by liquid He.

✓Twelve cryocoolers are used to keep the temperature.

✓The first reaction experiments using SAMURAI were carried out in May 2012, and the second experiments were carried out in April 2013.