Development of a Ceramics Chamber with integrated Pulsed Magnet (CCiPM) for KEK PF-Ring and SPring-8 (Ceramics integrated Kicker, CiK)

2019.4.2

KEK, Accelerator laboratory, 7th division, PF/PF-AR

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CCiPM development history

- **In 2010 FY**, S. Sasaki suggested the idea at JASRI/SPring-8.
  - "**Closing the pulsed magnet pole to the beam as much as possible w/o disturbing the beam impedance**."
- **In 2011 FY**, C. Mitsuda proposed, "Ceramics Chamber Integrated Pulsed Magnet (CCiPM)" and start giving shape with fine ceramics maker, KYOCERA Co.
- **From 2012 to 2014 FY**,
  - Started the development of chamber diameter of 60 mm (D60 type)
  - Technology of copper metal brazing on the cylindrical ceramics was developed
- **From 2015 FY**,
  - Started the D30 type development whose chamber diameter is 30 mm. Now, continue.
- **From 2018 FY**,
  - Started the beam test in KEK

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DEVELOPMENT OF THE CERAMIC CHAMBER INTEGRATED PULSED MAGNET FITTING FOR A NARROW GAP

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Abstract

We are pushing forward the development of a pulsed magnet that has a combined structure of magnet coils with a ceramic vacuum chamber, aiming to realize a small gap. The structure we are developing is that single turn air-coils are implanted along the longitudinal axis in the cylindrical ceramic chamber wall with thickness of 5 mm. The ceramic wall works for separating the vacuum from the atmosphere, as well as holding the coil structures mechanically and the electrical insulation of coils. We achieved the continuous operation over 200 days, without any failure, of current-excitation with 20 kV/7.7 kA pulse with 4 μsec width and repetition of 1Hz, using the dipole type prototype with the bore radius of 30 mm and the magnetic length of 0.3 m in 2013, while maintaining the vacuum pressure less than 10^{-6} Pa.

CERAMIC CHAMBER INTEGRATION DESIGN AND THE ADVANTAGE

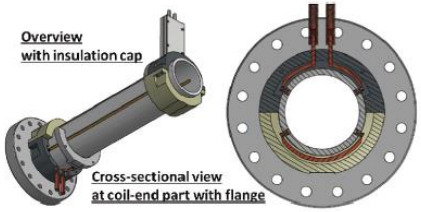


Figure 1: Design of dipole type CCIPM for the fabrication.

First report for CCiPM development in IPAC2015, Richmond

Development motivation

- Needing pulsed magnet with “fast current rising and strong magnetic field” by short magnet length
  - Only power supply development is not sufficient
  - Some developments for magnet is necessary
- Needing compact (;slim) pulsed magnet with high power so as to install any narrow space as an additional requirement
- For **m**ulti-**p**urpose **k**icker (**MPK**)
  - Realizing both low cost and flexible magnetic field generation
  - Matching between power supply and magnet to get good similarity for some magnets simply
  - Installing kicker to any space easily
  - Achieving the strong structural strength for high repetition stress etc
- For **m**ulti-**p**ole injection **k**icker (**MPK**)
  - Generating the complex and corrected multi-pole field shrinking a pole gap
  - Fitting to narrow bore and narrow space in future ultra low emittance ring
  - Fitting to narrow dynamic aperture and multi-pole injection scheme

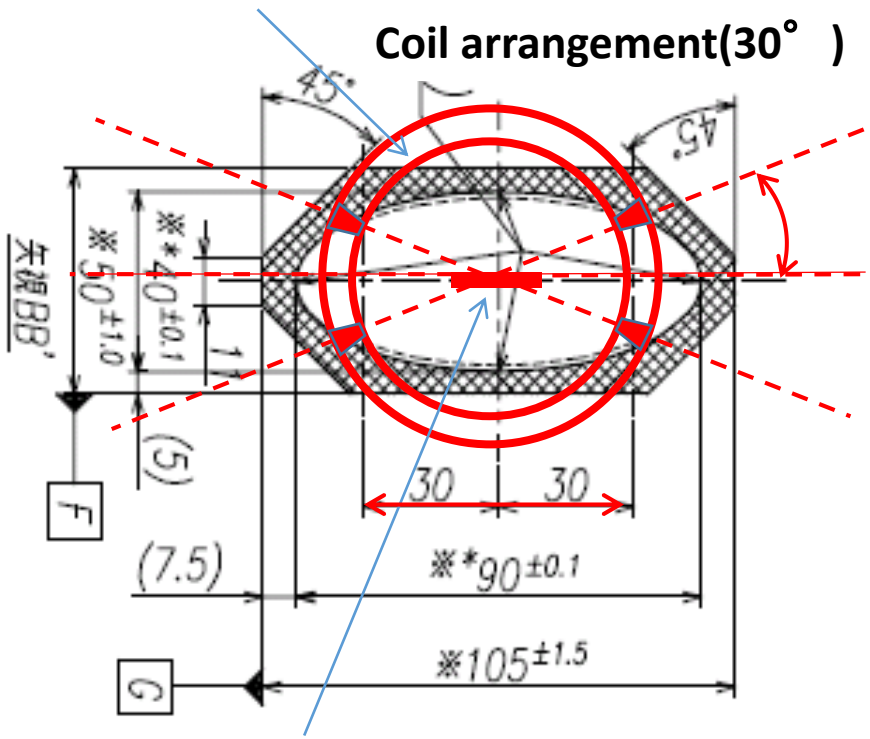
Idea of ceramics with Integrated Kicker

Design based on current ceramics duct

Chamber inner diameter: 60mm

Ceramics thickness :5mm

Coil arrangement(30°)



Beam stay clear: 2（H）x5（W）mm

CCiPM advantage and the knock-on effect

Closing poles to beam by chamber inner surface w/o disturbing the beam impedance

- Pole gap is chamber inner diameter
- Field strength and pulse speed is increased

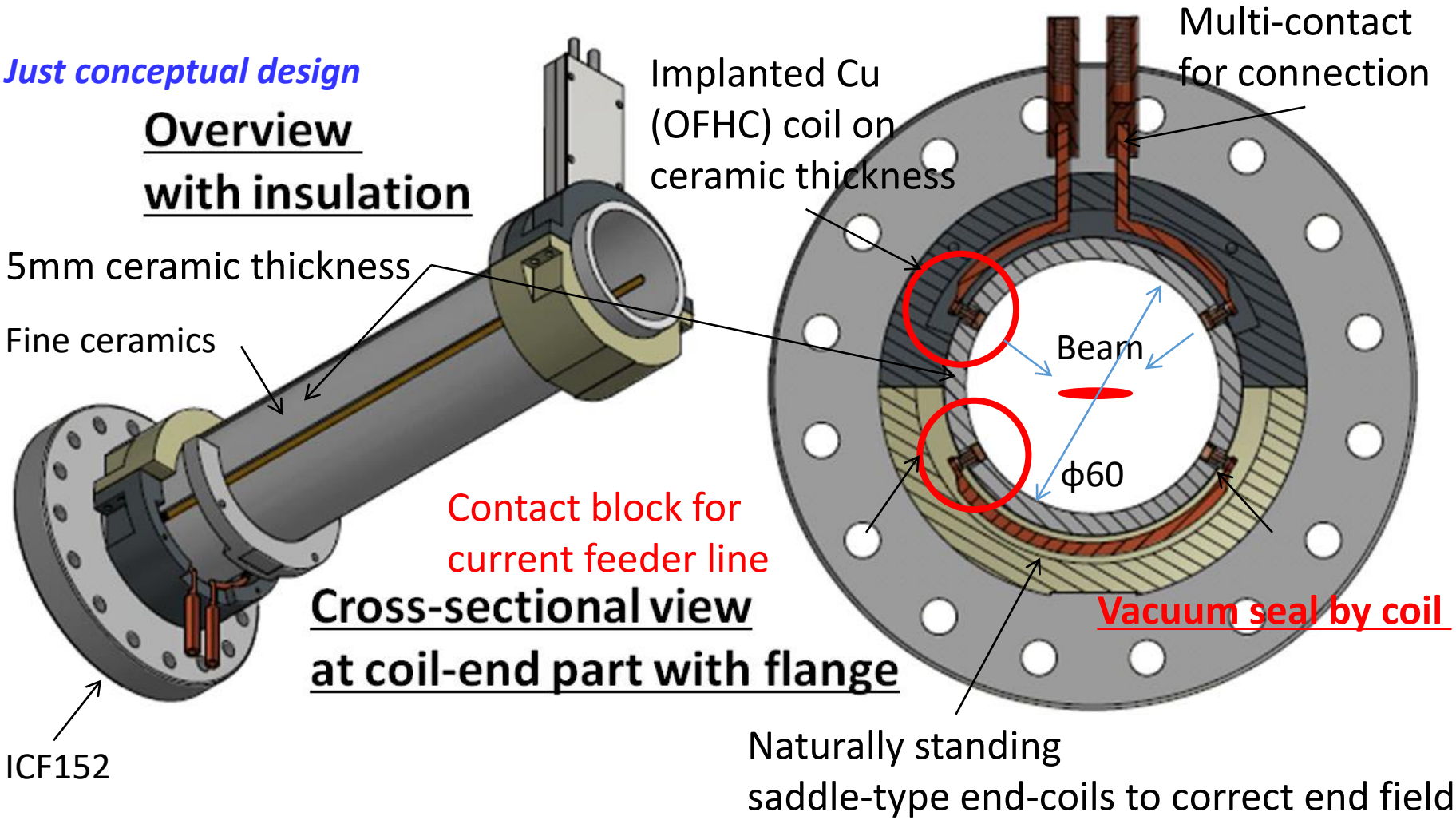
Slimming down the pulsed magnet body

- Any chamber size and narrow space are fitted
- Structural strength and coil arranging flexibility w/o taking care of aperture are achieved

Multiplexing ceramics role

- Coil insulation increasing the high voltage resistance
- Solid coil support structure
- Precise coil arrangement
- Enhancement of deformation stress resistance about magnetic and vacuum force

Conceptual design of CCiPM based on field req.



- **Building coil support and coil insulation structure by ceramics**
- **No limitation to close the magnetic pole to beam**

Inner coating for accelerator implementation

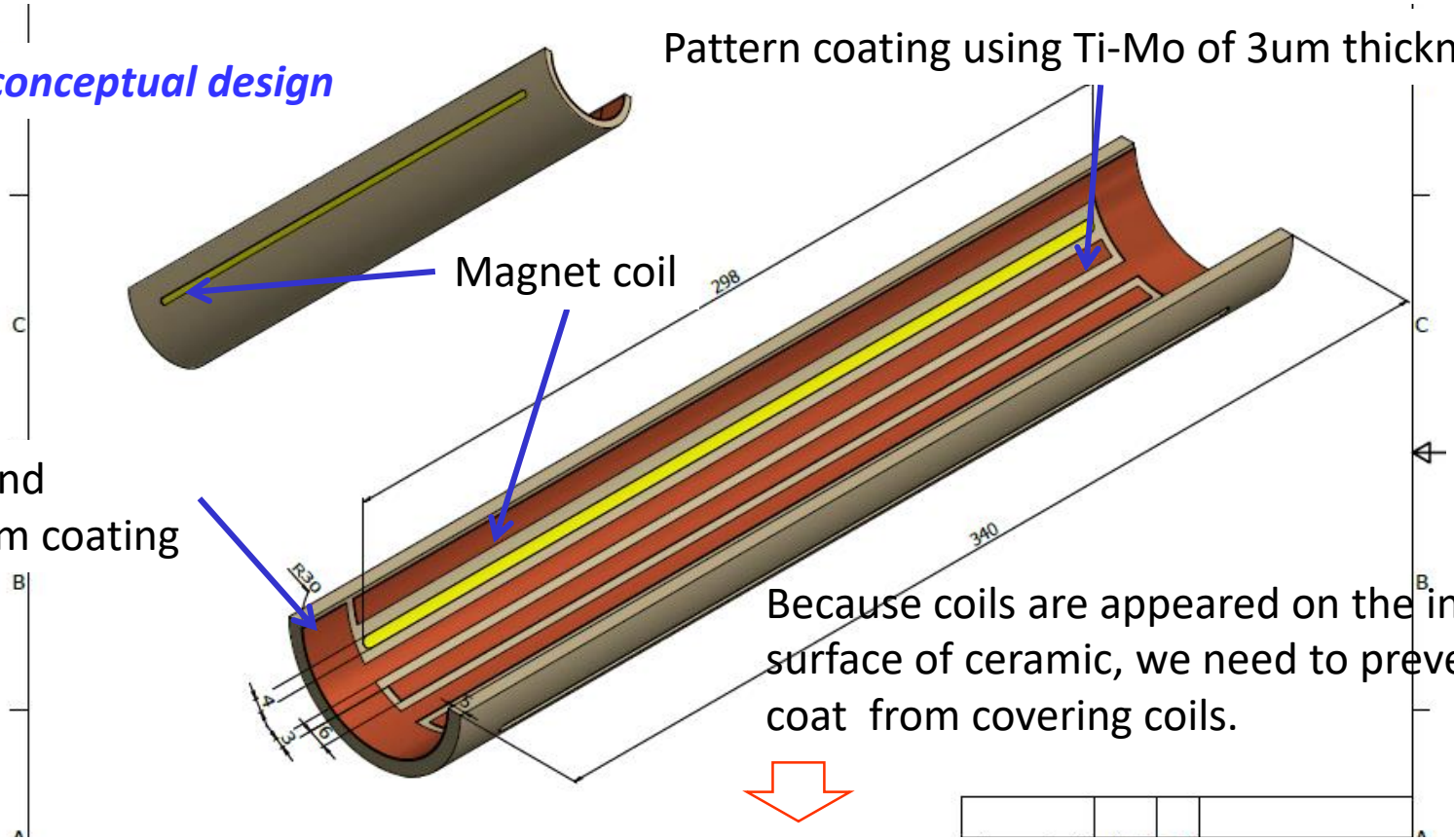
Implementing Functional Precise (or Pattern) Coating (FPC) to CCiPM inner surface to reduce the eddy current and pass the beam wall current

Just conceptual design

Pattern coating using Ti-Mo of 3um thickness

Magnet coil

Side-end uniform coating

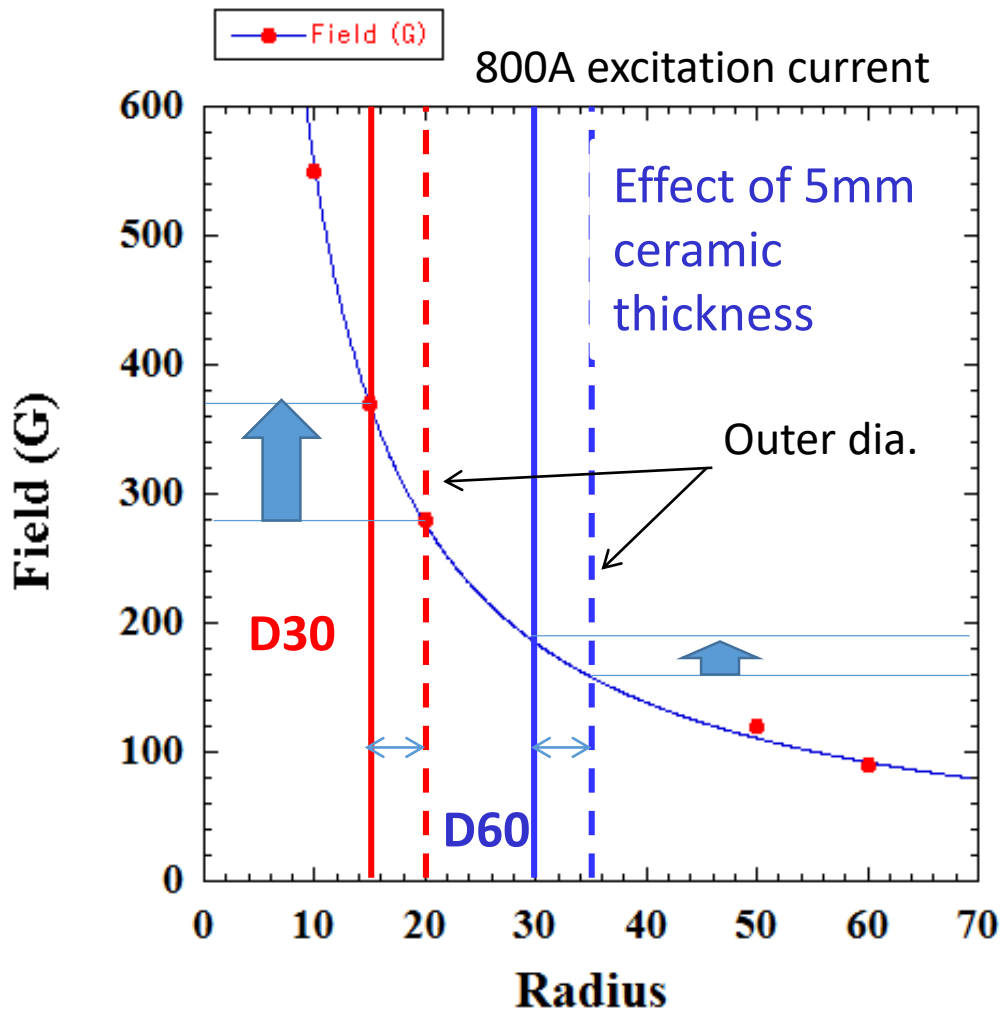


Because coils are appeared on the inner surface of ceramic, we need to prevent the coat from covering coils.

Metal coating for beam wall current＋pattern coating to reduce the eddy current ＝ **Comb-type coating**

Expected performance of dipole-type CCiPM

Magnetic field strength for bore radius

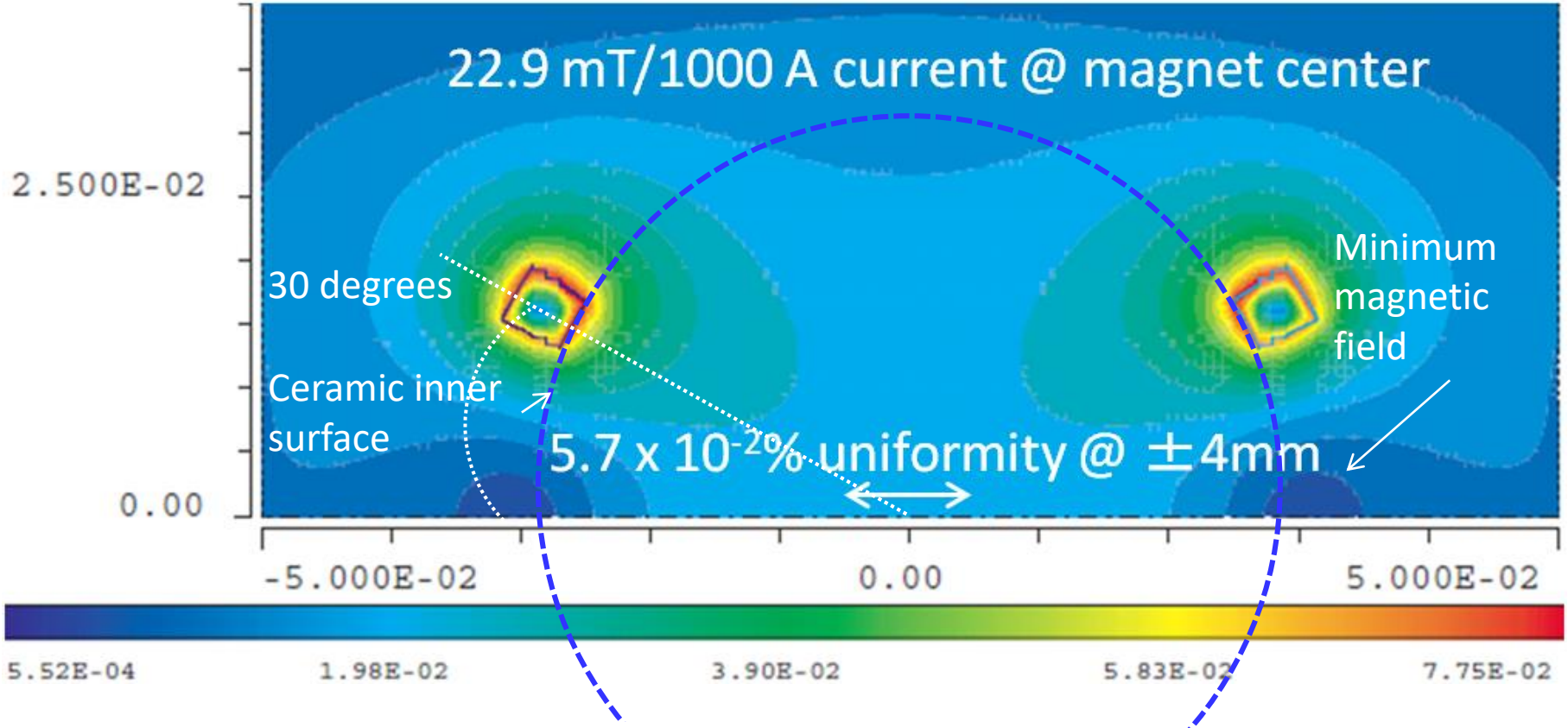


Expected performance for 6000A excitation and electron beam

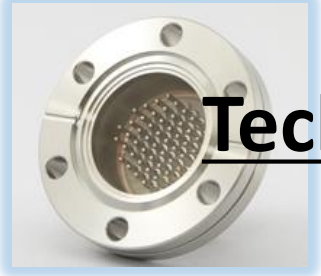
6000A	D30	D60
Bore radius	15mm	30mm
Centre field	277mT	137mT
ML	0.3m	0.3m
Kick angle @ 8GeV	**3.11mrad**	**1.54mrad**
@ 6GeV	4.15mrad	2.05mrad
@ 3GeV	8.31mrad	4.11mrad
SP8 bump @8GeV Iron-core	**3.5mrad ML=0.32m,gap 56mm**	

Dipole field distribution for 60mm diameter

D60 CCiPM Optimized field distribution for CCIPM design



0.722 mrad@3000A , D=60mm,ML=0.3m, 8GeV

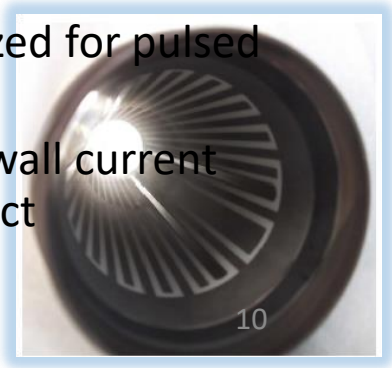


Technical originality of CCiPM structure (1)

- **S**lender **M**etal **B**razing **T**echnology (**SMBT**) for CCiPM structure
  - Usually, metal brazing techniques in vertical direction is established and used with vacuum seal components like a feed-through etc.
  - But, metal brazing techniques in longitudinal direction is not achieved because there is large different thermal expansion between ceramics and copper
  - Additionally, because ceramics is vacuum chamber for beam and magnet core, magnet coil has to be responsible for vacuum seal
  - Technical hurdle exists in keeping high vacuum quality like a vacuum pressure (leak rate < 1×10^{-13} Pa・m^3/s) and small degassing (< 10^{-8} Pa).
  - And, we need another techniques for the construction of the base block connecting to current feeder line : **H**igh **C**urrent **B**ase **T**echnology (**HCBT**)
- Merits in CCiPM structure
  - Stress of vacuum, magnetic force, and thermal expansion generated in CCiPM operation is distributed by bonding surface between coils and ceramics
  - The temperature increasing up to 200 degrees is allowed by bonding temperature boundary

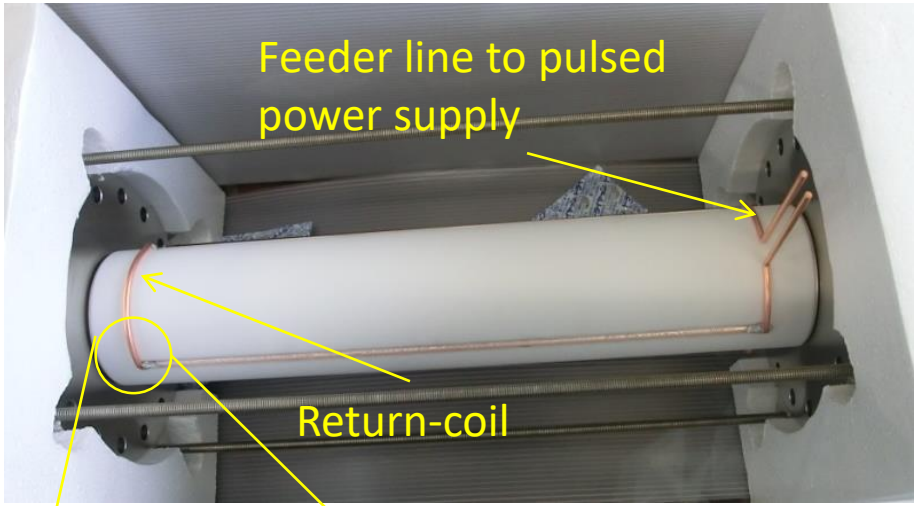
Technical originality of CCiPM structure (2)

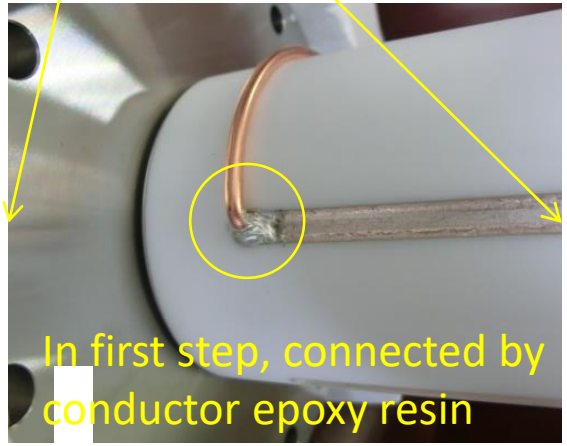
- **F**ine **Li**ne coating **P**rocess technology (**FLiP**) for functional pattern coating
  - Ceramic is not conductor and dielectric material. So, the metal coating is necessary in order to pass the beam wall current.
  - Uniform and micro-thin coating is most popular way to pass the wall current and reduce the eddy current generation
  - In order to prevent the eddy current generation, though the strip-line type coating is most suitable, the conducting area is reduced for beam wall current. Comb-line type is responsible for dividing the eddy current area and providing the capacitance structure to beam wall current
  - Technical hurdle exists in giving the precise pattern shape in narrow cylindrical inner surface and insulating the coil surface
- Merits of FPC
  - If pattern shape is coated precisely, the coating can be optimized for pulsed frequency and beam impedance in the ring
  - The coating thickness can be increased to increase the beam wall current passage performance without taking care of eddy current effect
  - So, we can give various roles to the coating

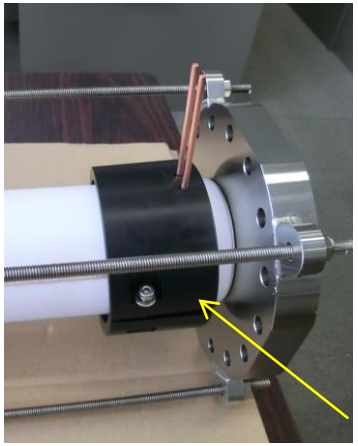


Prototype of D60 dipole CCiPM

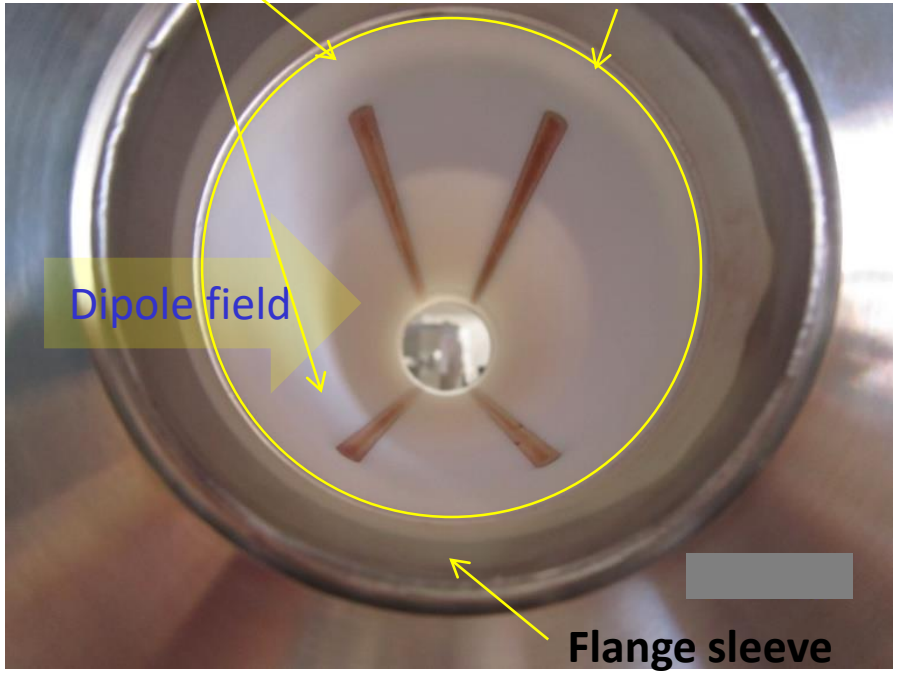
"DEVELOPMENT OF THE CERAMIC CHAMBER INTEGRATED PULSED MAGNET FITTING FOR A NARROW GAP" *C. Mitsuda, IPAC15, p2879, 2015*





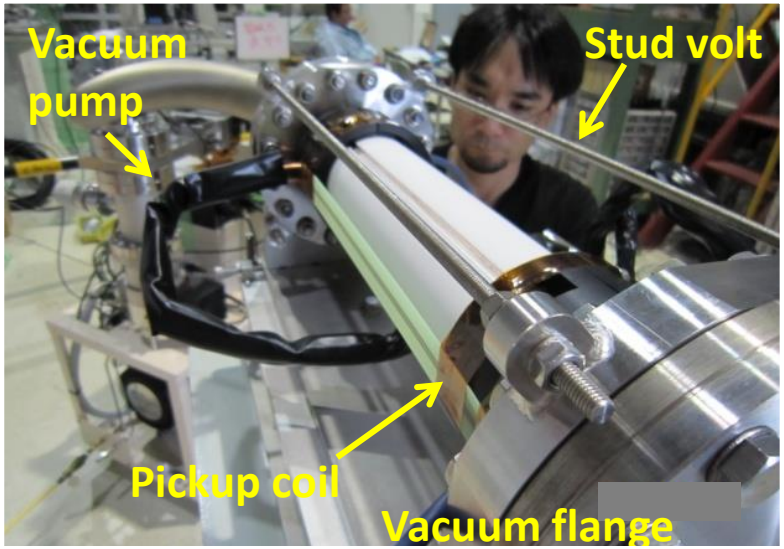


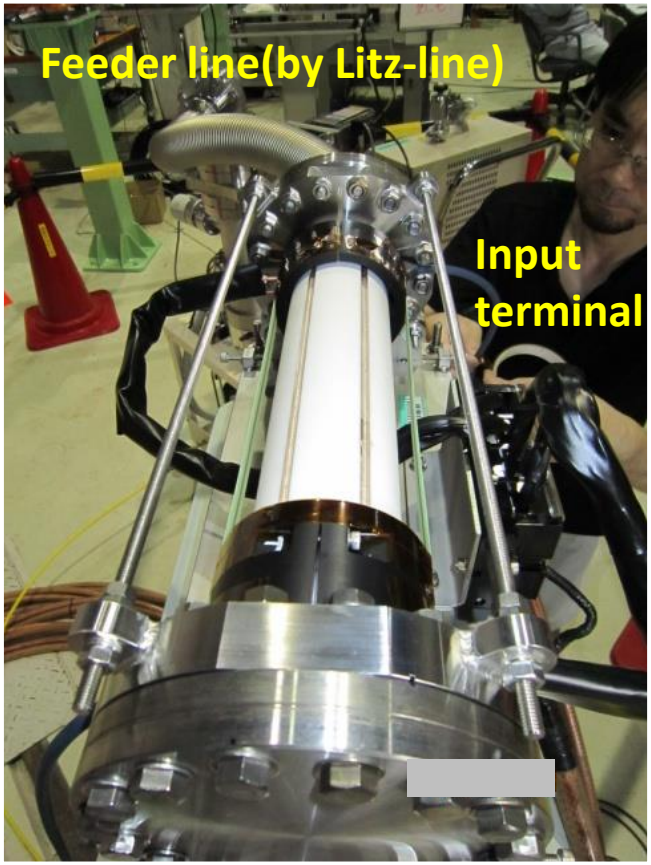
Before HCBT and FCLiP establishment

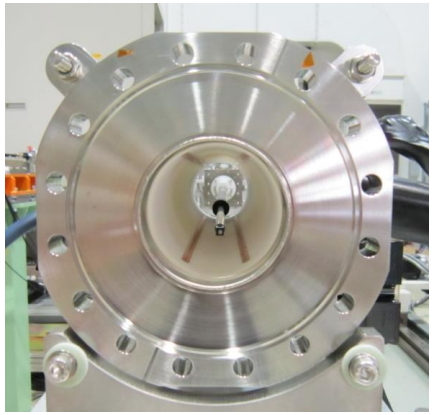


Feeder-line cap made by DURACON

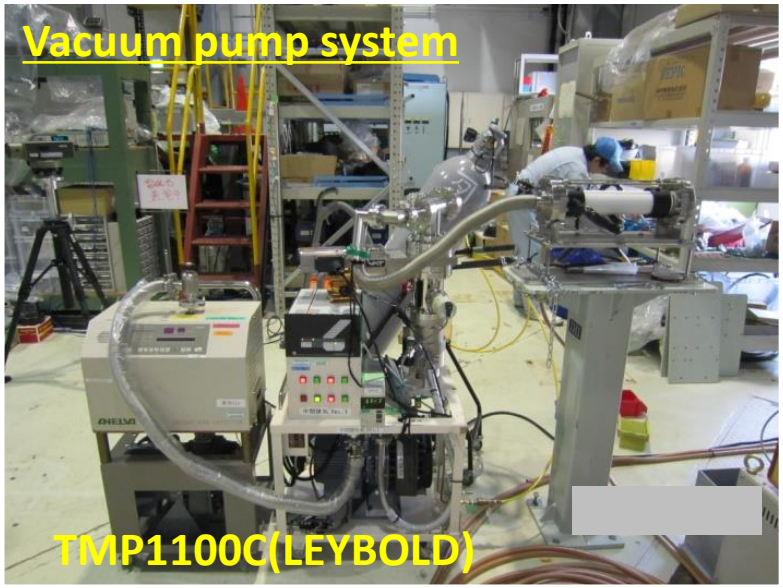
Prototype performance test in SP8



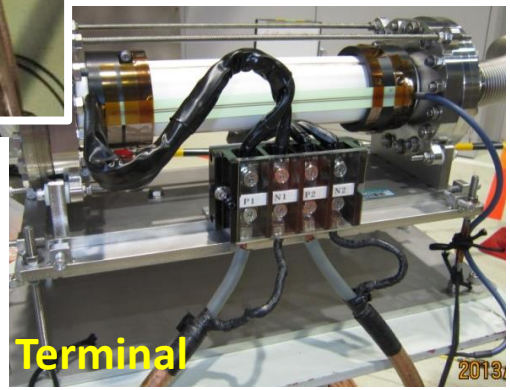




Field measurement
Using 3D hole probe system with 1um step resolution



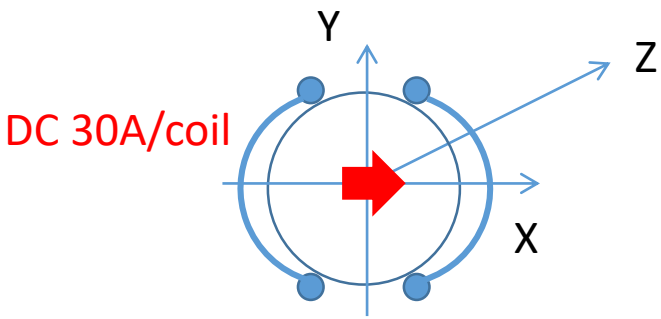
Pulsed power supply system
Rated current and voltage: 6400A/22kV @ 8.0us Half-Sine



DC magnetic field measurement

0.8%reproducibility

Main dipole field

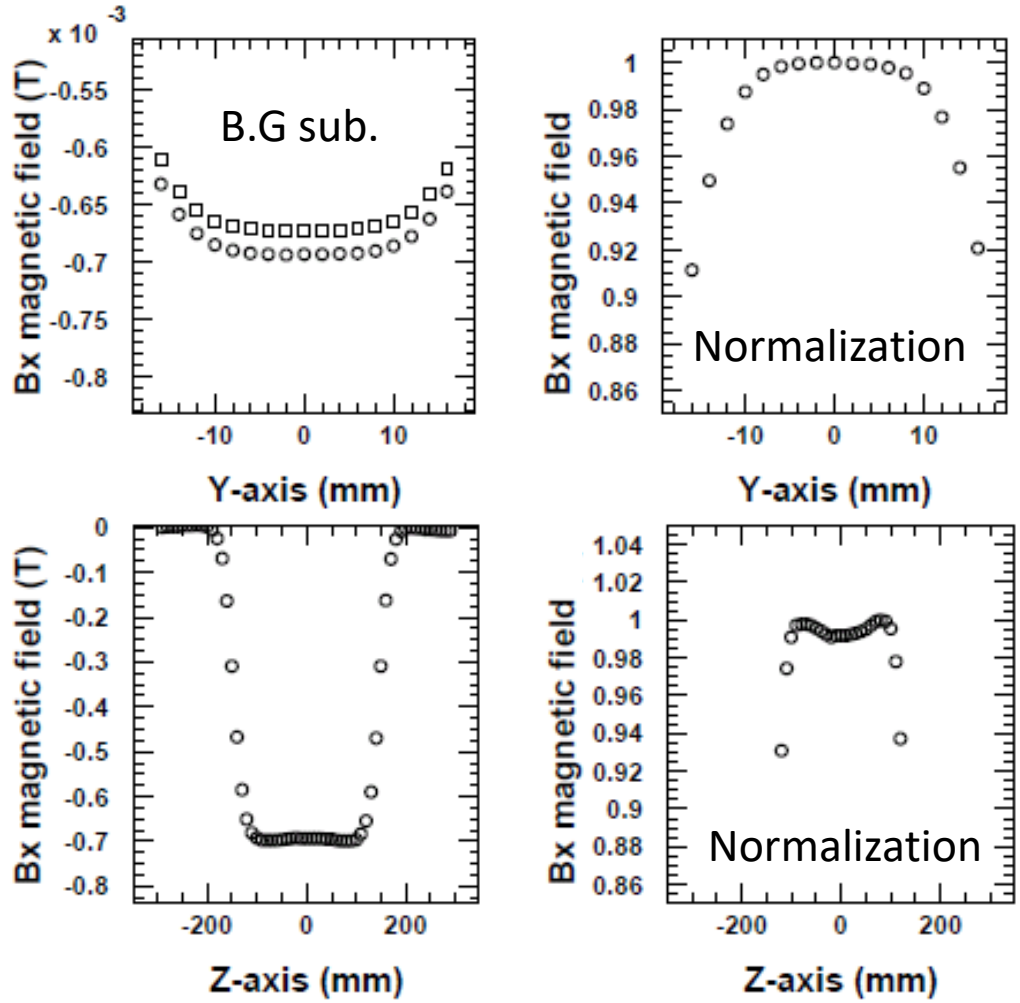


Field mesh survey
Y=-16~16mm/2mm step.
X=-10~10mm/5mm step.
Z=-290~290mm/10mm step.

In field strength, difference for calculation and measurement result = 0.02%

This corresponds to the coil arranging precision by ~20μm

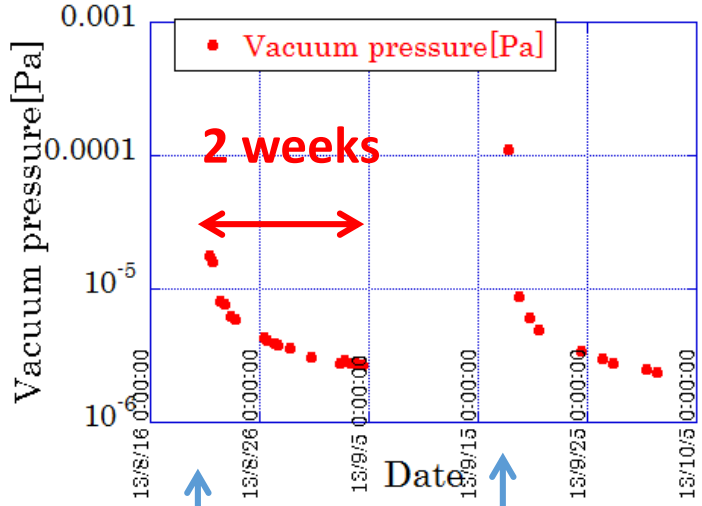
X=0, Y=-16~16, Z=0 @ centre field



BL=207μT・m/30A/coil, Good field region (GFR): 8x10^{-4}@±4mm

1st test of vacuuming and current excitation

1st test of vacuum pumping

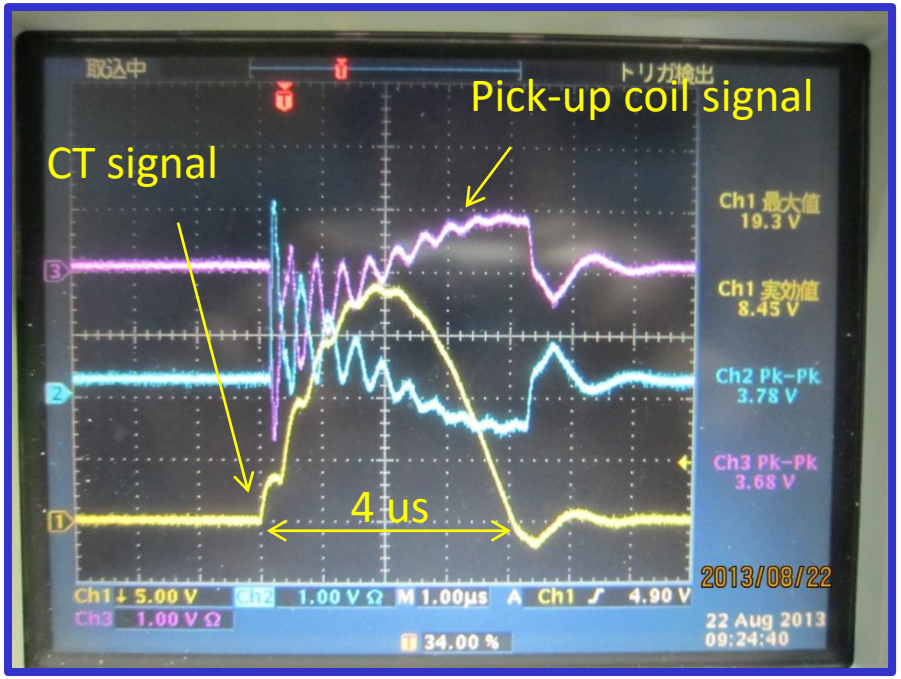


1st vacuuming
W/ pulsed curr.

2nd vacuuming
W/o pulsed curr.

- After 1st vacuuming
- Achieved vacuum pressure : 2.3×10^{-6}Pa
- Leak rate : <8.0×10^{-11}Pa・m^3/s

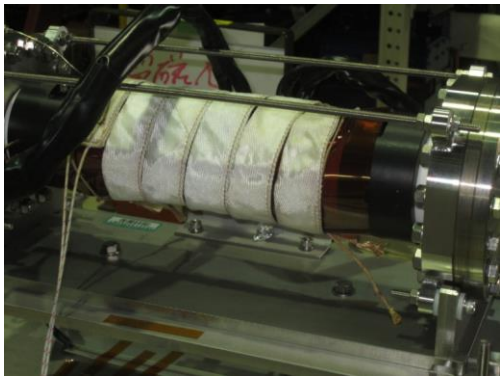
1st test of current excitation



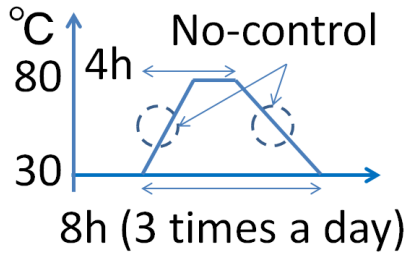
- Parallel connection to 2 coils
- Output current : 1930A/2.7kV supplied to load/10kV-set
- Pulse width : 4.0 us
- Inductance: 803nH/coil

Long time durability test

80 degrees heat cycle supplying by heater

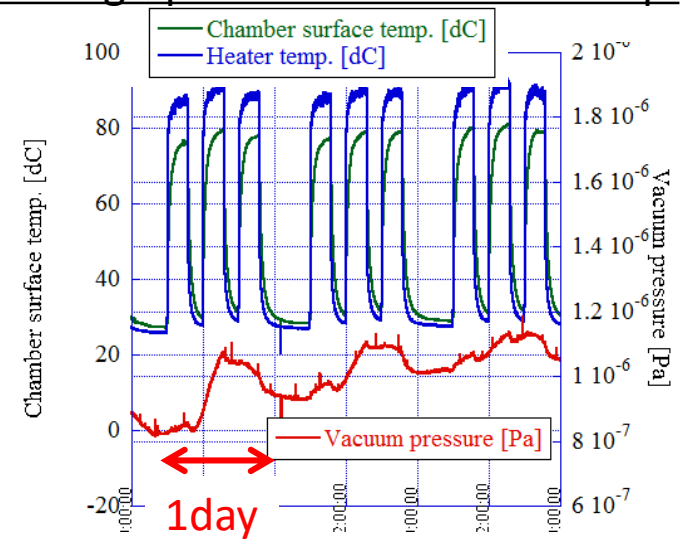


Thermal cycle pattern



Date (red: w/ heat cycle)	P.S. HV[kV] (to load)	Elapsed Days
8/26	7.9 (4.3)	1
8/27-9/4	10.0 (5.4)	9
10/18-11/11	15.0 (8.1)	24
11/26-12/27	15.0 (8.1)	32
1/6-2/7, 2/12-3/2	15.0 (8.1)	51
3/3-7/16	20.0 (10.8)	135
Total	218(thermal)/**252**	

Trend graph of VP and CCiPM temp.



All stress were given to CCiPM

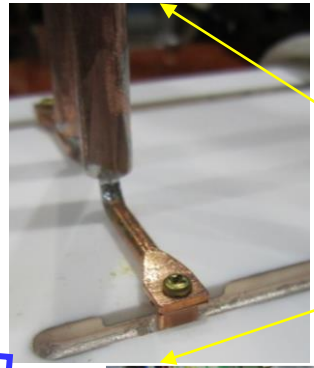
+ Heat cycle (80 degrees)
+ Vacuuming (10^{-6} Pa)
+ Pulsed excitation(1Hz, 4.9us, >7kA)

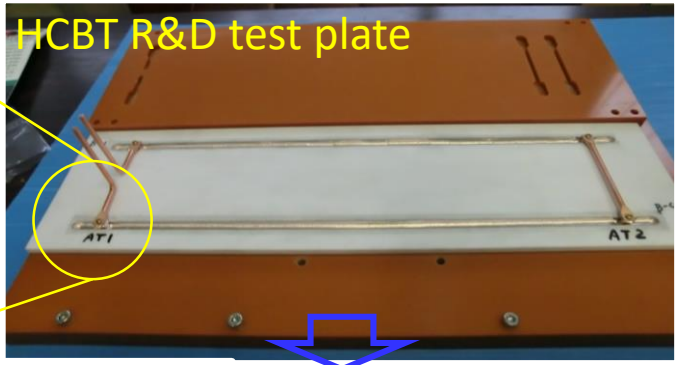
- Supplied voltage to load
  = 0.54 x set P.S. High Voltage
- Output current: 5505A@15kV-set
  7340A@20kV-set

Long endurance performance was achieved

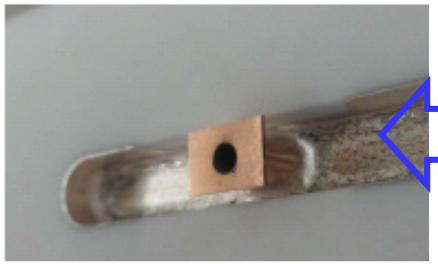
HCBT development and implementation

Critical issue was happened in epoxy resin connecting point

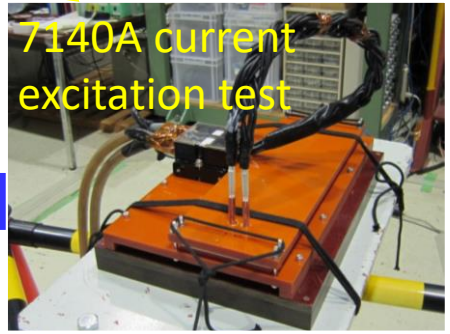


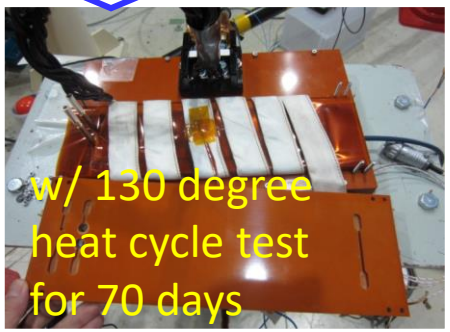


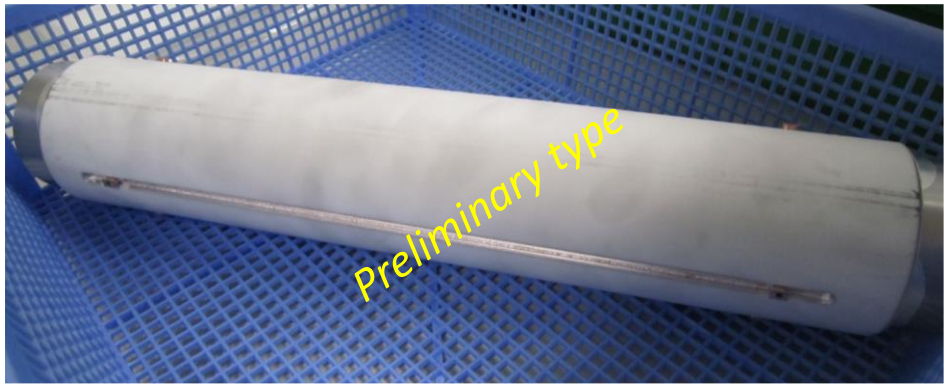
Mechanical connection was required

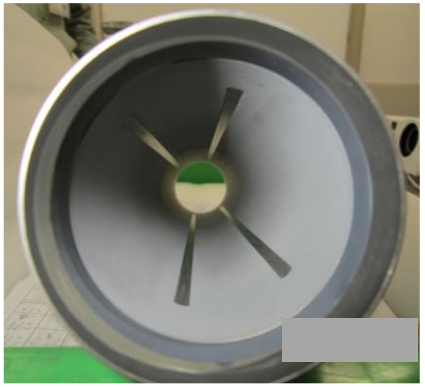


Optimizing the high current base shape and metal brazing recipe





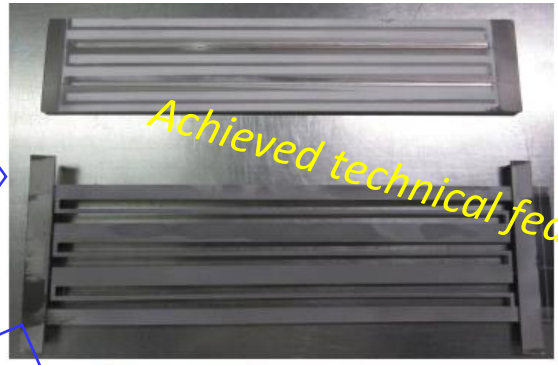


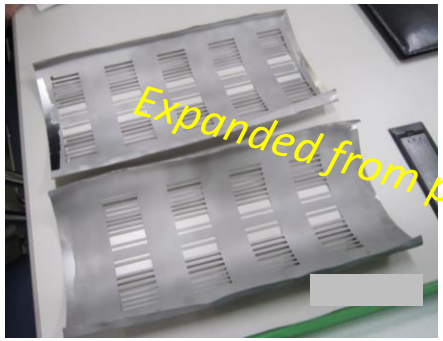


FLiP（Fine Line coating Process）development

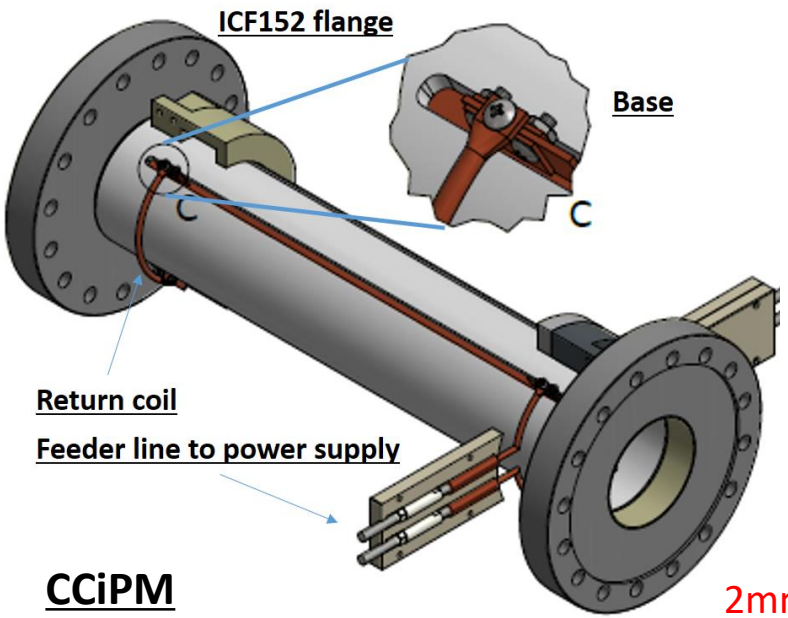
Masking vacuum vapor deposition method

Masked blast method after vapor deposition





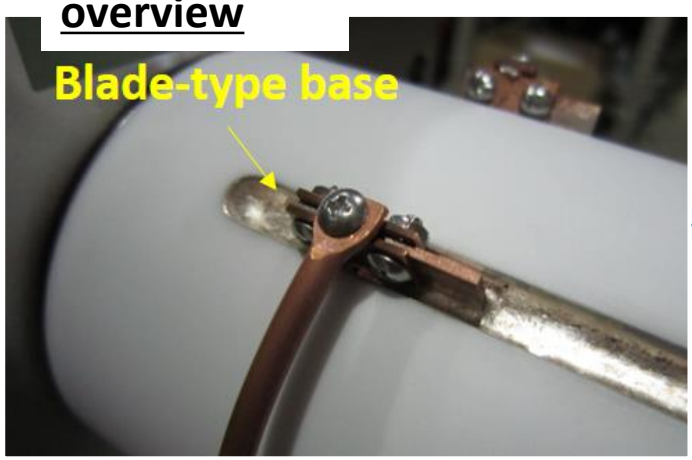
D60 accelerator implementation model

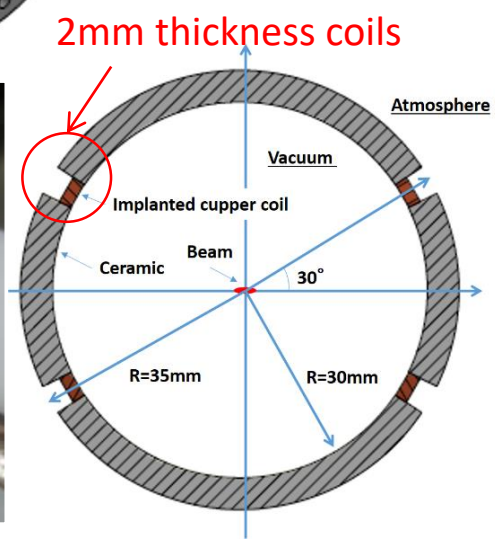


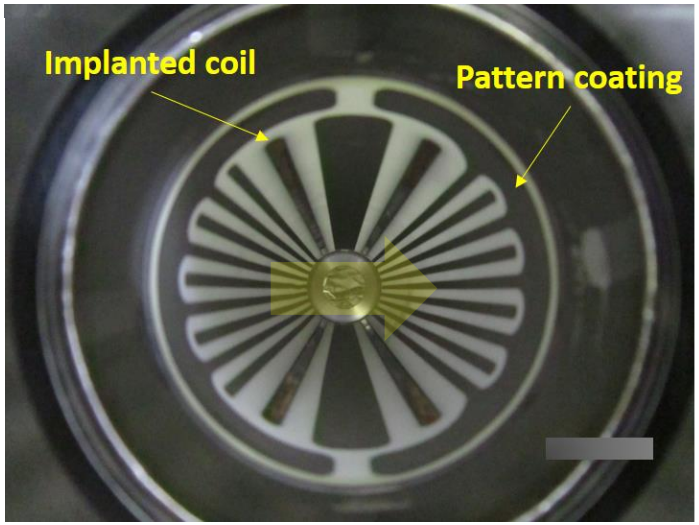
Long time durability test for completed D60-CCiPM

Item	Condition
Vacuum leak rate	$<1.13 \times 10^{-11}$ Pa・m^3/s
Reached vacuum pres.	$<2.6 \times 10^{-6}$ Pa
1Hz current excitation	6240 A @17kV-set
Supplied HV to CCiPM	9.2kV
Heat cycle	(120℃x4h) × 3 cycles/day
Experience days	180 days (continuously)

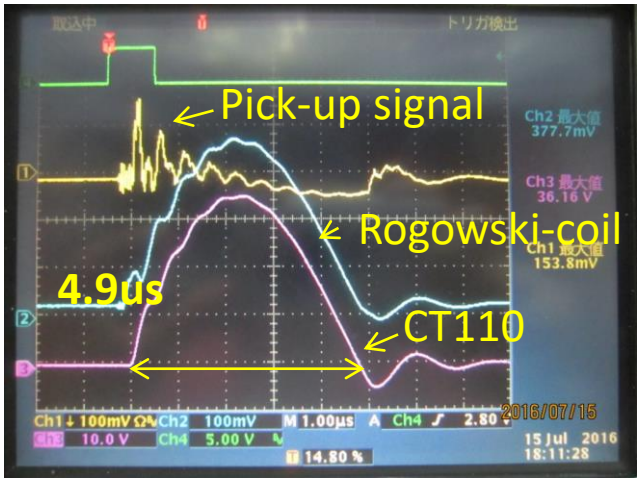
CCiPM overview

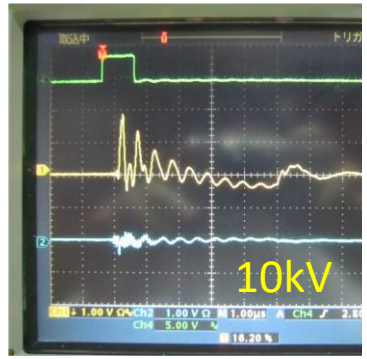


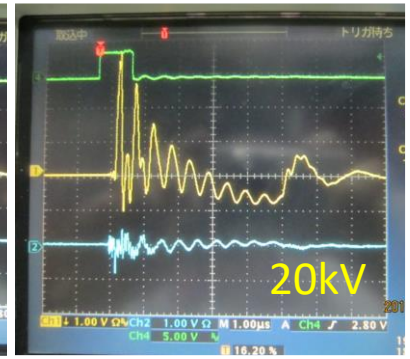


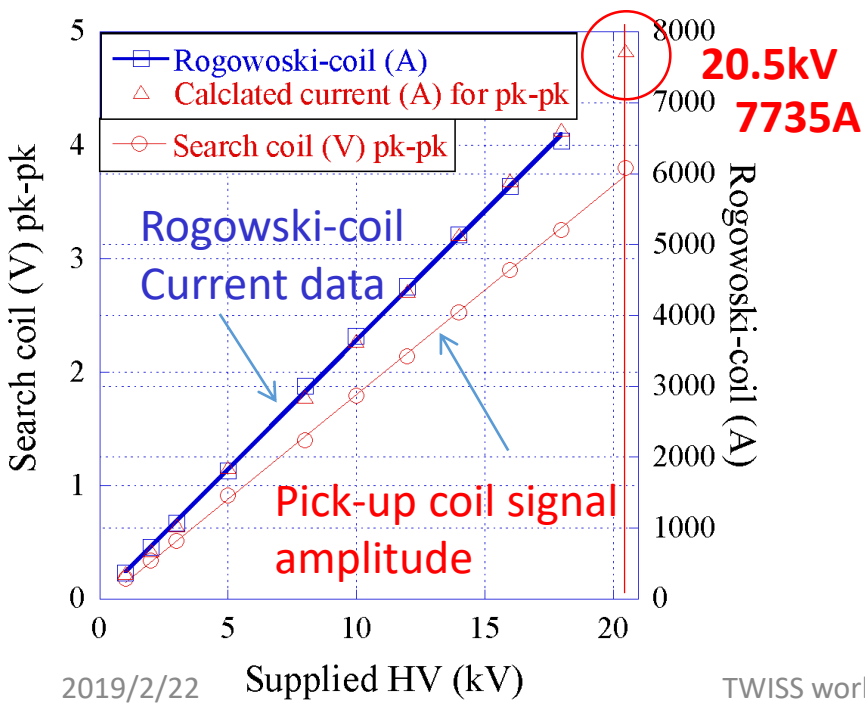


High voltage excitation test









CCiPM spec.	D60 (prototype)
Bore radius	30mm
Center field	137mT@6kA
Magnet length	0.27m (0.3m)
20.5kV-set	7735A
Supplied HV to CCiPM	11.1kV@20.5kV
Pulse width	4.9us
Kick angle @8GeV, 20.5kV-set	1.80mrad
Eddy cur. effect w/, w/o coating by pulsed current	<2% (with reproducibility)

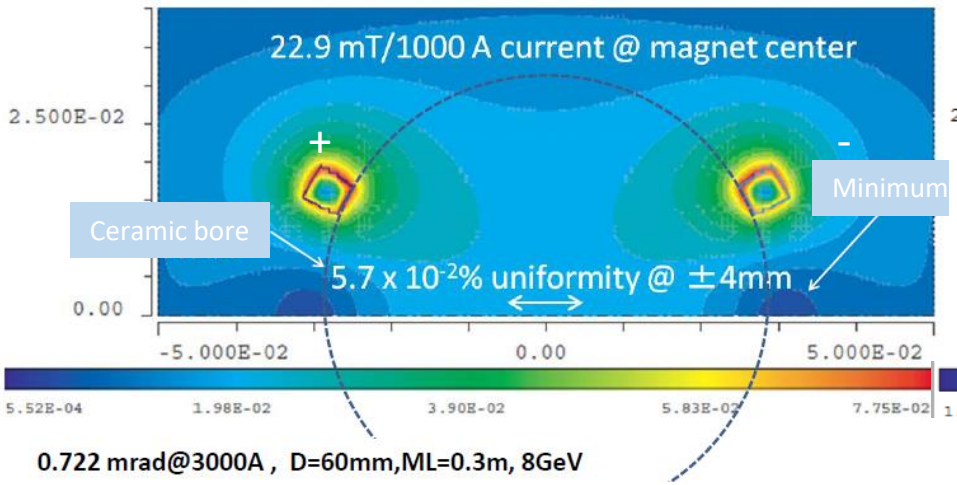
Installation plan to PF-BT dump line

- We started preparing CCiPM installation to PF-BT dump line in order to evaluate the kick performance from Apr. 2018
  - Evaluating performance as **dipole kicker** and **quadrupole kicker** precisely
  - Proving the durability by exposing to electron beam
- We were afraid of the following risks because we don't have any experiences for beam test
  - Vacuum breakdown
  - Electrical discharge between coating and coils or between flange and coils
- PF-BT-dump line is low risk line from a point of view of above risks unlike PF-ring which is user operation machine
- We improved the dump line in this winter
  - Installing beam position monitor to watch the beam position (energy jitter) and charge without destructive and in real-time
  - Installing the beam profile monitor in just upstream of CCiPM and dump point to observe the beam position and profile before and after kicking
  - Installing the mirror system to confirm the damage of the inner surface coating in CCiPM real-timely

Dipole mode and Q-mode test study

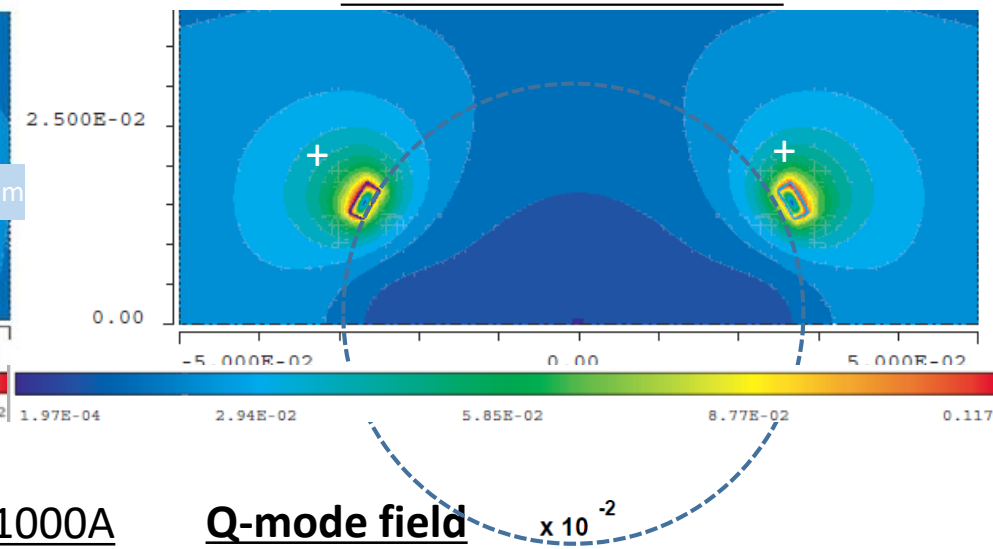
Proposing the Quadrupole-like field test by changing the current direction

Optimized field distribution for CCIPM design

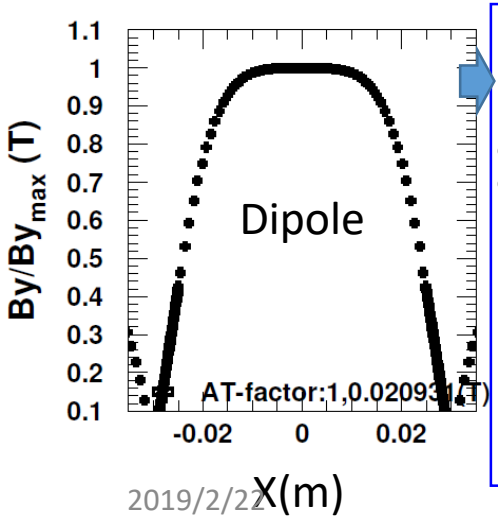


0.722 mrad@3000A , D=60mm,ML=0.3m, 8GeV

Parallel Current direction

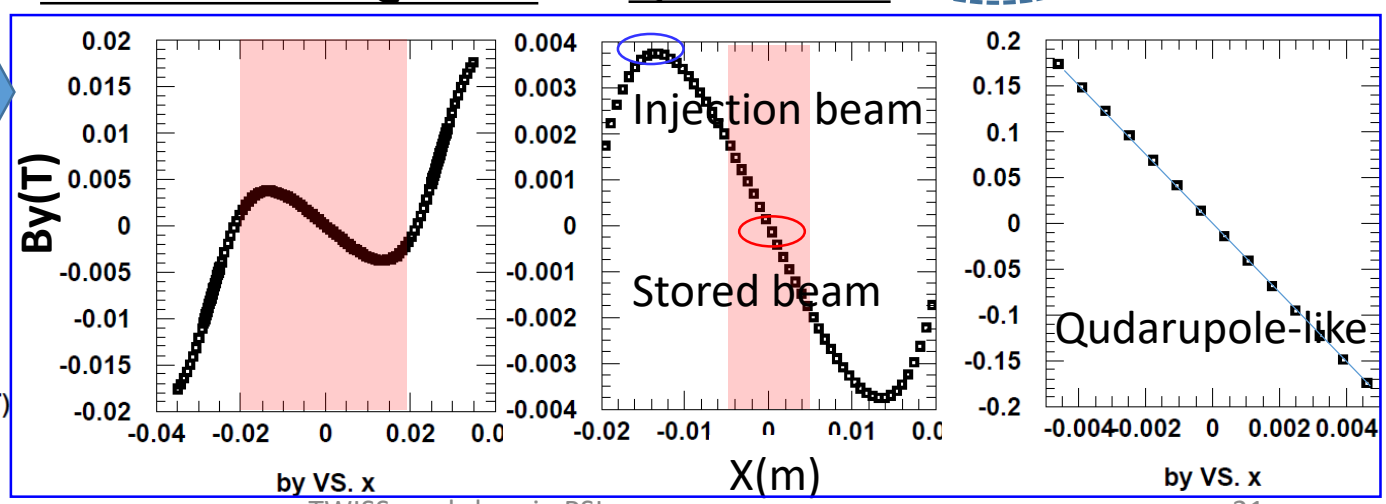


D-mode field



Field distribution@1000A

Q-mode field



CCiPM beam test system in dump line

Bending magnet as beam sweeper
Operation sweep angle ~1mrad
On/Off axis injection at CCiPM

Beam profile monitor 1 using YAG screen
To confirm the beam position at CCiPM

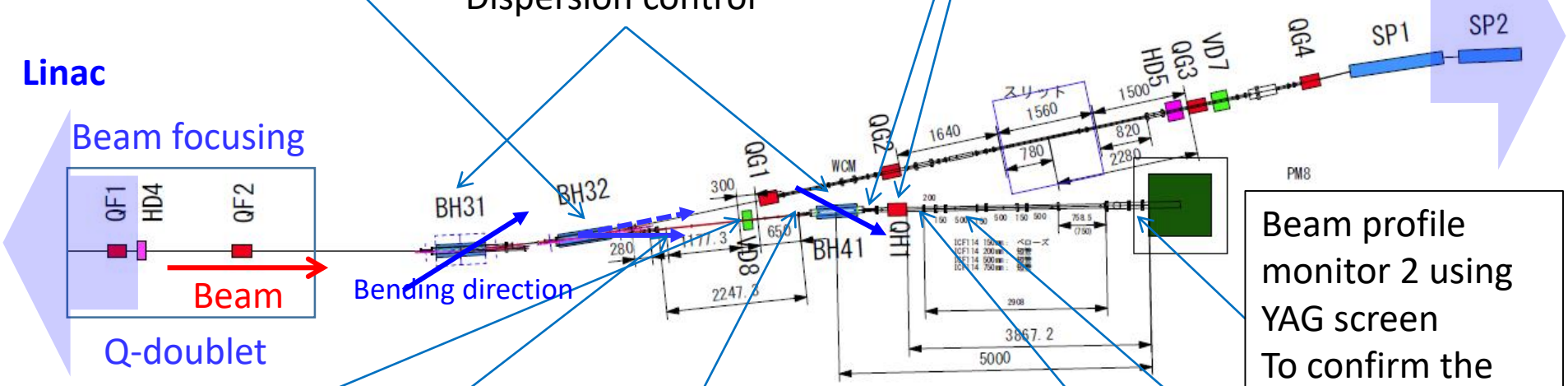
PF Ring

CCiPM install position @QH1

Dispersion control

Linac

Beam focusing



Q-doublet

V-st for vertical beam steering

Beam profile monitor 2 using YAG screen
To confirm the CCiPM kick angle

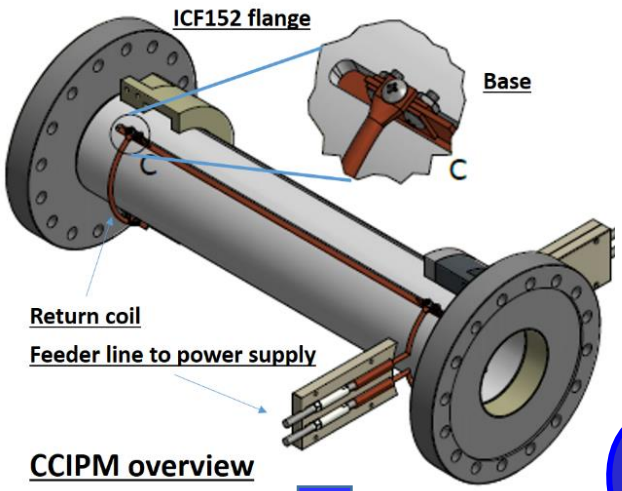
Re-install position of QH1

Beam position monitor
To watch the beam position real-timely in study

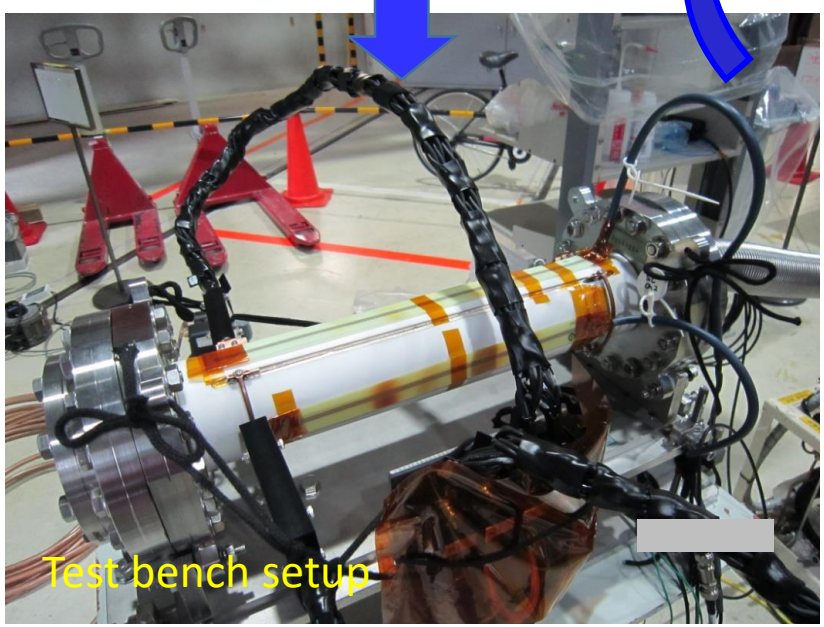
Moving mirror system
to confirm the coating damage

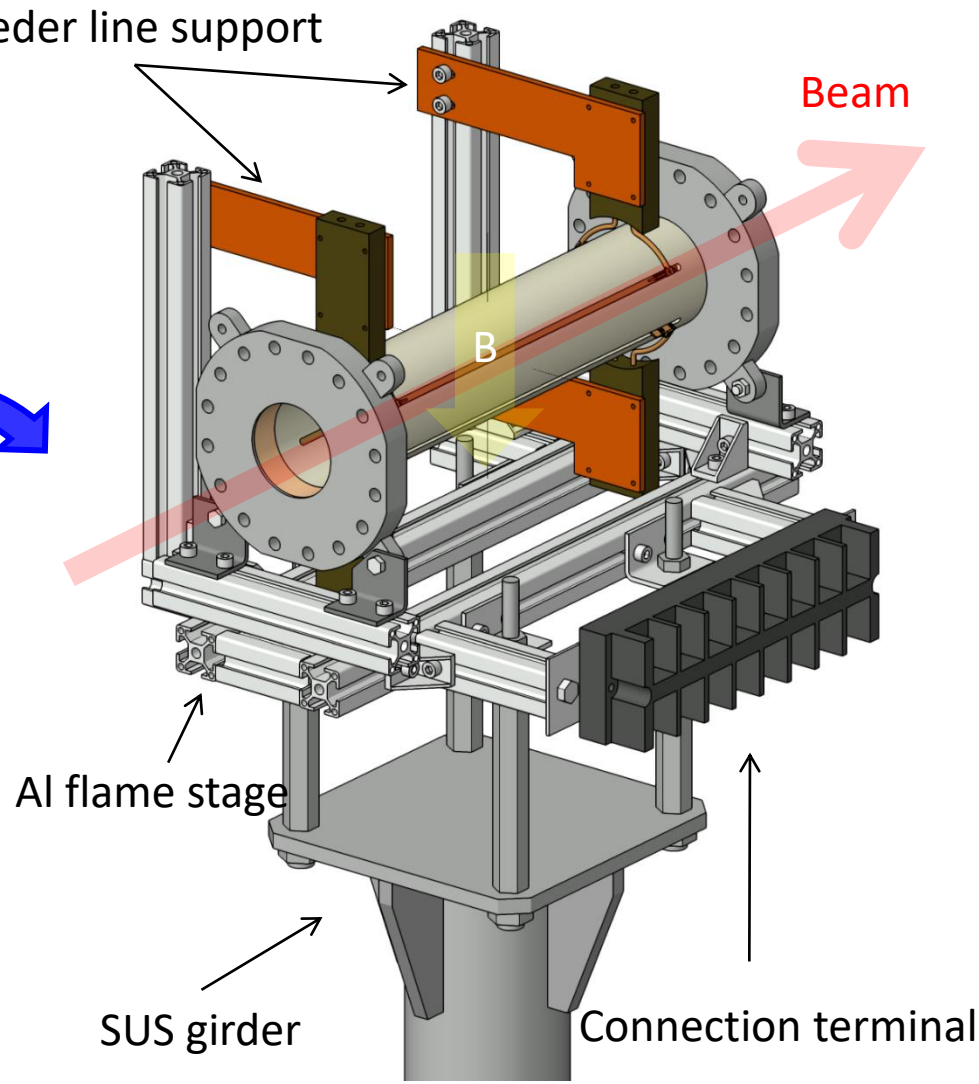
Gate valve
for vacuum break down

Accelerator implementation setup

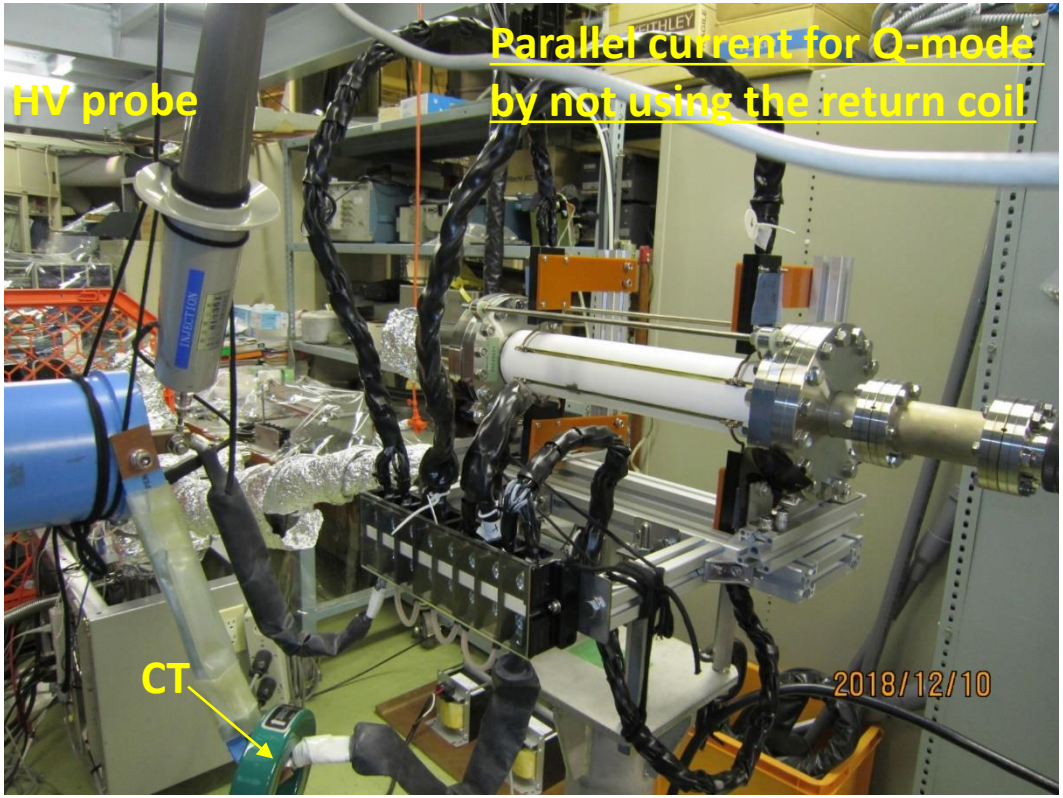


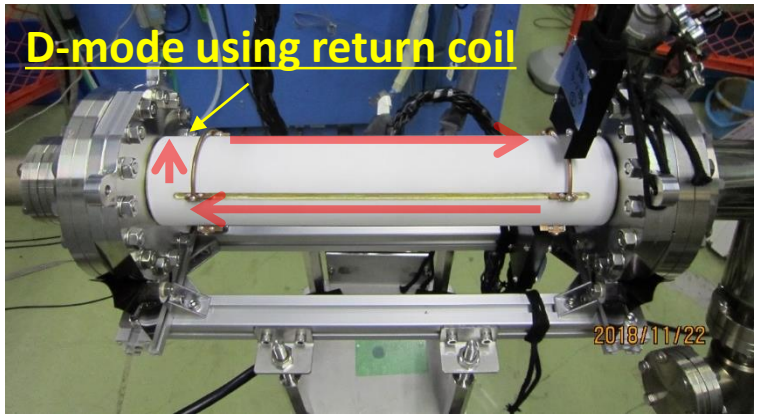
CCIPM overview

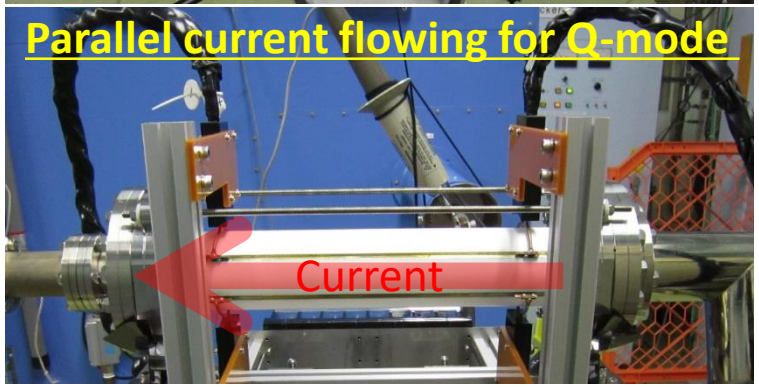




Connection change in D/Q-mode change

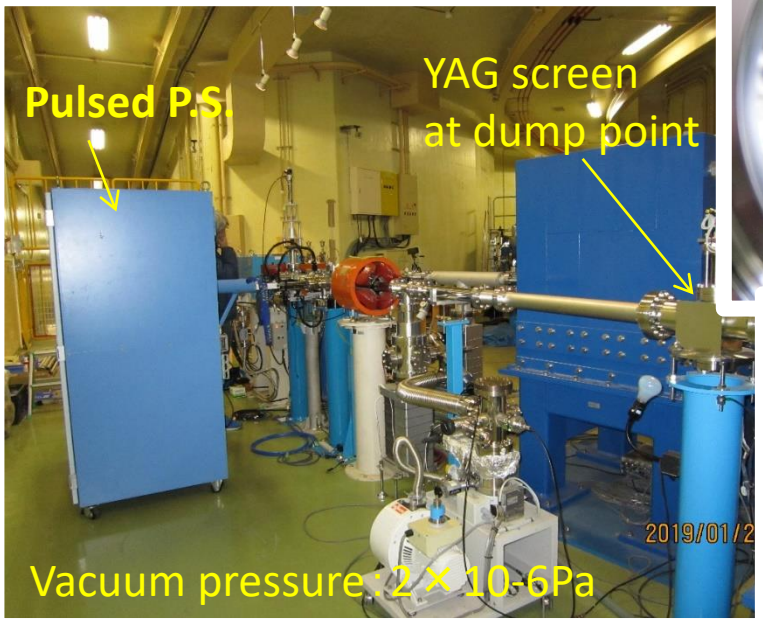


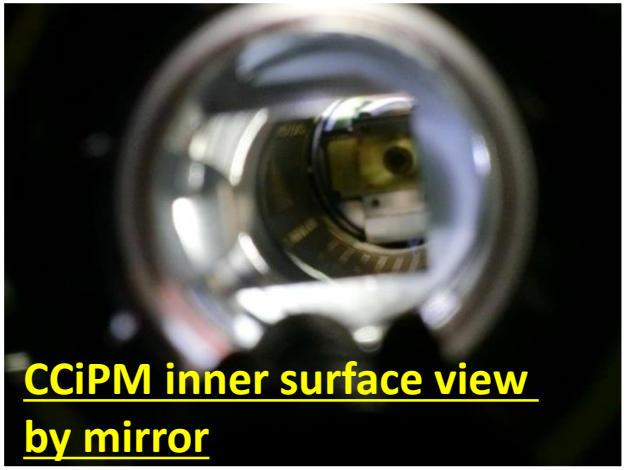


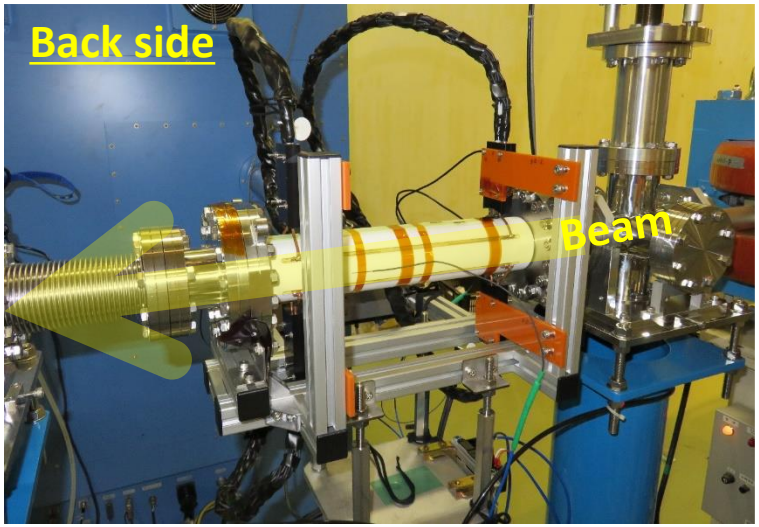


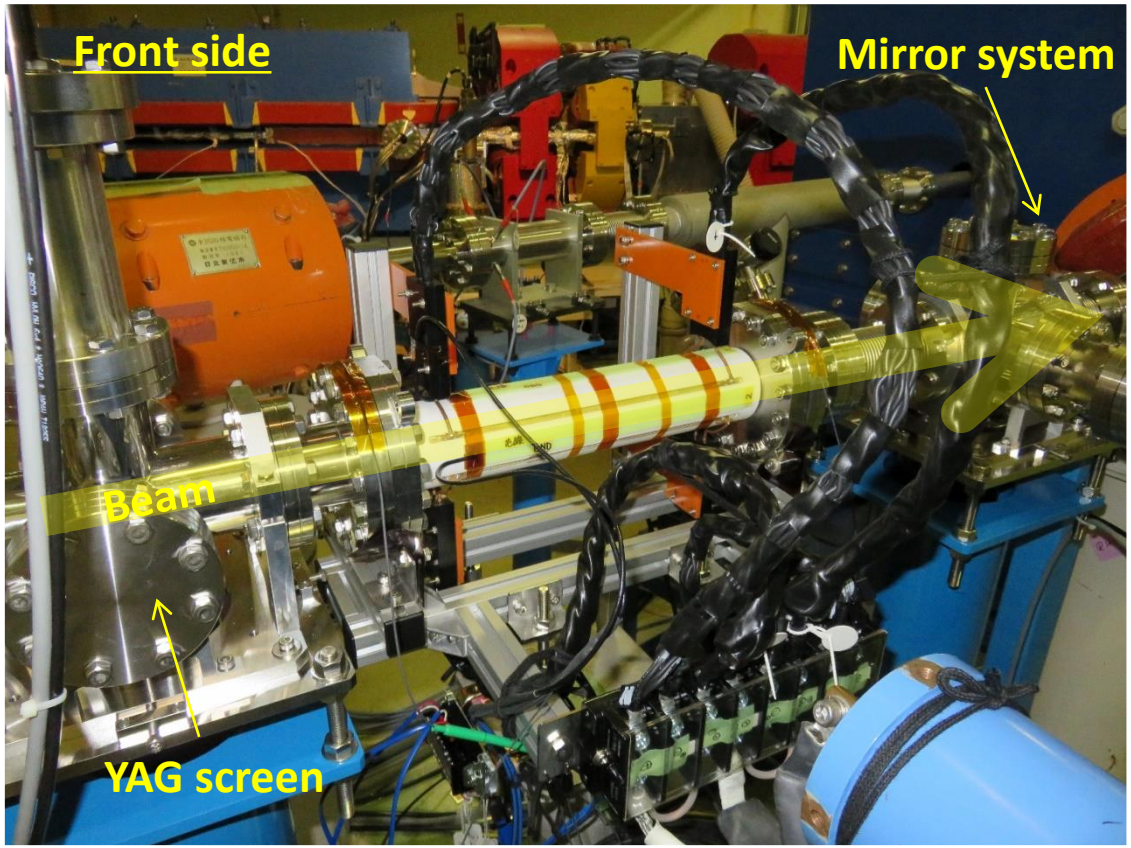
We can easily
change B/Q-field mode by using
bridge cable in terminal table

Constructed the beam test line



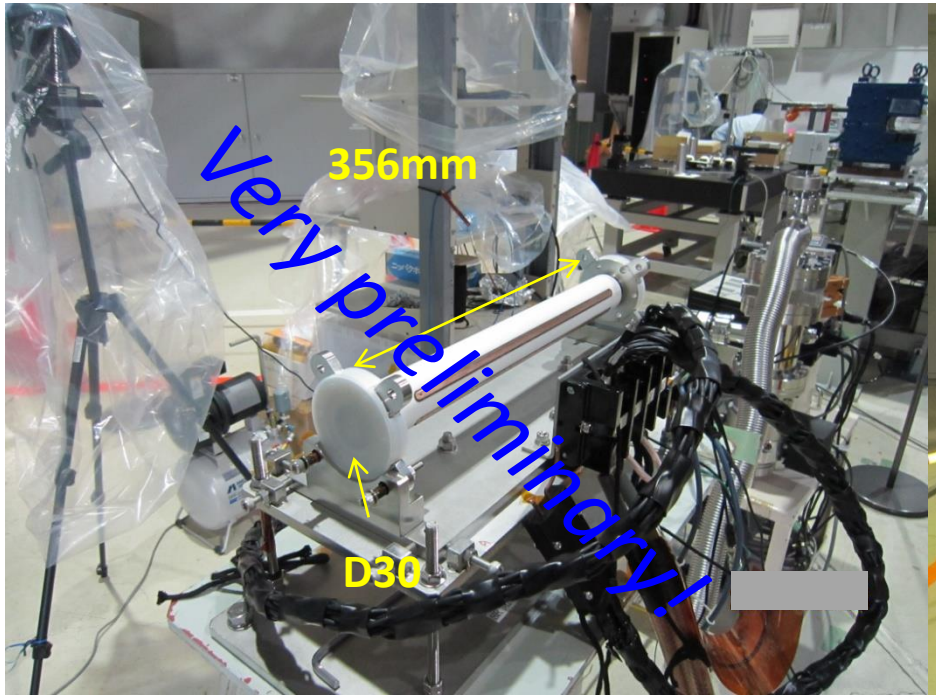




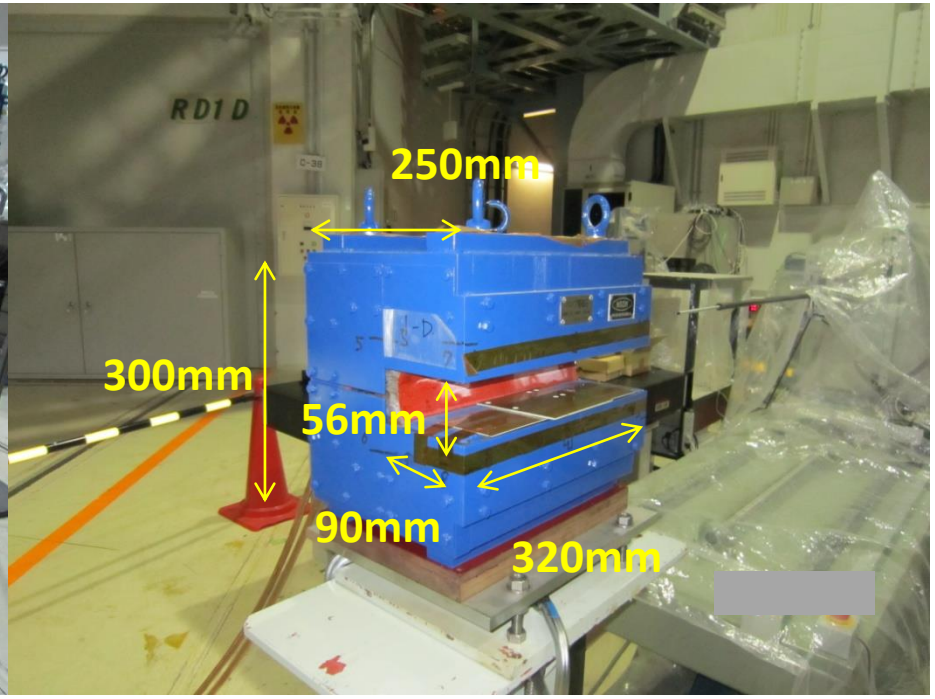


D30 CCiPM model for iron-core type

D30 CCiPM
air core kicker with ceramic chamber



Bump magnet
Iron core (thin plate laminating) kicker



We are now developing D30-model !

CCiPM performance comparison

Parameter	D30 type w/o coating	D60 type w/ coating	Iron-core Bump magnet
Load side, Rogowski@1kV	**357A**	367A	**258A**
PS side, Rogowski@1kV	368A	380A	-
Load side, CT-110@1kV	361A	362A	-
Output current @20kV	**7140A**	7340A	**5160A**
Z(Ω)@4us	**1.19Ω(1.01@4.6us)**	1.43Ω(1.14@4.9us)	**3.46Ω (2.25@6.5us)**
Kick angle@8GeV,20kV	**3.4mrad**	1.71mrad	**3.2mrad**
L(uH)@4us	**1.52(1.51@4.6us)**	1.81(1.78@4.9us)	**4.37(4.65@6.5us)**
Pulse width (us)	**4.6**	4.9	**6.5**
ML(mm)	300	268	320
Coil dis. (mm)	7.5	15.0	56.0
Weight	**1.7kg (w/ flange)**	5.5kg(w/ flange)	**206kg(w/o chamber)**

Very preliminary!

Summary

- We developed and established the original technology to realize the CCiPM structure
  - Slender Metal Brazing Technology SMBT
  - High Current Base Technology HCBT
  - Fine Line coating Process FLiP
- Though we think that CCiPM has many advantages, its technology should be verified carefully, because no one has tried yet
- The endurance and performance of CCiPM structure was proved clearly to satisfy practicability for the accelerator implementation
- Now, we are testing the beam performance of CCiPM on dump line in the PF beam transport line. 1st beam test was done in this February. The results are being verified deeply. It is going very well
- In near future, we will install the CCiPM in the same position as PSM which is installed in PF-ring to prove the practicability as an injection kicker

Future plan

- We are now planning the following developments for future low emittance ring
  - Establishing the CCiPM technology in narrow bore model such as D30
  - Expanding CCiPM structure from dipole-type to higher order multi-pole type like 8-order and 12-order
  - Developing the additional structure to make more corrected and complex field
- We are now aiming at applying the CCiPM to future low emittance ring, KEK-LS in PF upgrade plan.

Thank you so much for your time and attention