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

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for KEK CCiPM working group

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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
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 multi-purpose kicker (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 multi-pole injection kicker (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) x 5 (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

2019/2/22

TWISS workshop in PSI
Conceptual design of CCiPM based on field req.

Just conceptual design

Overview with insulation

5mm ceramic thickness
Fine ceramics

Cross-sectional view at coil-end part with flange

Implanted Cu (OFHC) coil on ceramic thickness

Contact block for current feeder line

Beam

Vacuum seal by coil

Naturally standing saddle-type end-coils to correct end field

• 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 3μm 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

800A excitation current

Expected performance for 6000A excitation and electron beam

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

Effect of 5mm ceramic thickness

Outer dia.
Dipole field distribution for 60mm diameter

**D60 CCiPM** Optimized field distribution for CCiPM design

- 22.9 mT/1000 A current @ magnet center
- 5.7 x 10^-2% uniformity @ ±4mm
- 0.722 mrad@3000A, D=60mm, ML=0.3m, 8GeV

Ceramic inner surface

Minimum magnetic field

30 degrees
Technical originality of CCiPM structure (1)

- **Slender Metal Brazing Technology (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 < $1 \times 10^{-13}\text{Pa} \cdot \text{m}^3/\text{s}$) and small degassing (< $10^{-8}\text{Pa}$).
  - And, we need another techniques for the construction of the base block connecting to current feeder line: **High Current Base Technology (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)

- **Fine Line coating Process 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

Pair coil for single turn

Ceramic inner surface

Dipole field

Flange sleeve

Feeder-line cap made by DURACON

In first step, connected by conductor epoxy resin

Return-coil

Feeder line to pulsed power supply
Prototype performance test in SP8

- Vacuum pump
- Stud volt
- Pickup coil
- Vacuum flange
- Feeder line (by Litz-line)
- Input terminal
- 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

DC 30A/coil

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

In field strength, difference for calculation and measurement result = 0.02%
This corresponds to the coil arranging precision by ~20 µm

BL = 207 µT · m/30A/coil, Good field region (GFR): 8x10^{-4} @ ±4 mm
1\textsuperscript{st} test of vacuuming and current excitation

1\textsuperscript{st} test of vacuum pumping

- After 1\textsuperscript{st} vacuuming
- Achieved vacuum pressure: $2.3 \times 10^{-6}\text{Pa}$
- Leak rate: $<8.0 \times 10^{-11}\text{Pa} \cdot \text{m}^3/\text{s}$

2 weeks

1\textsuperscript{st} vacuuming W/ pulsed curr.
2\textsuperscript{nd} vacuuming W/o pulsed curr.

1\textsuperscript{st} 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

7140A current excitation test
w/ 130 degree heat cycle test for 70 days

Preliminary type
FLiP (Fine Line coating Process) development

Masking vacuum vapor deposition method

Masked blast method after vapor deposition

Completed FLiP technology

Implementation to dipole type D60-CCiPM
Long time durability test for completed D60-CCiPM

<table>
<thead>
<tr>
<th>Item</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum leak rate</td>
<td>(&lt;1.13 \times 10^{-11} \text{Pa} \cdot \text{m}^3/\text{s})</td>
</tr>
<tr>
<td>Reached vacuum pres.</td>
<td>(&lt;2.6 \times 10^{-6} \text{Pa})</td>
</tr>
<tr>
<td>1Hz current excitation</td>
<td>6240 A @17kV-set</td>
</tr>
<tr>
<td>Supplied HV to CCiPM</td>
<td>9.2kV</td>
</tr>
<tr>
<td>Heat cycle</td>
<td>((120^\circ C \times 4h) \times 3) cycles/day</td>
</tr>
<tr>
<td>Experience days</td>
<td>180 days (continuously)</td>
</tr>
</tbody>
</table>

CCiPM overview

- Blade-type base
- 2mm thickness coils

D60 accelerator implementation model

- ICF152 flange
- Base
- Return coil
- Feeder line to power supply

CCiPM overview

- 2mm thickness coils
- Implanted coil
- Pattern coating
High voltage excitation test

**Rogowski-coil**

**Pick-up signal**

4.9μs

CT110

**CCiPM spec.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>D60 (prototype)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore radius</td>
<td>30mm</td>
</tr>
<tr>
<td>Center field</td>
<td>137mT@6kA</td>
</tr>
<tr>
<td>Magnet length</td>
<td>0.27m (0.3m)</td>
</tr>
<tr>
<td>20.5kV-set</td>
<td>7735A</td>
</tr>
<tr>
<td>Supplied HV to CCiPM</td>
<td><a href="mailto:11.1kV@20.5kV">11.1kV@20.5kV</a></td>
</tr>
<tr>
<td>Pulse width</td>
<td>4.9us</td>
</tr>
<tr>
<td>Kick angle  @8GeV, 20.5kV-set</td>
<td>1.80mrad</td>
</tr>
<tr>
<td>Eddy cur. effect w/, w/o coating by pulsed current</td>
<td>&lt;2% (with reproducibility)</td>
</tr>
</tbody>
</table>
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

22.9 mT/1000 A current @ magnet center

5.7 x 10^{-2} % uniformity @ ±4mm

Ceramic bore

Minimum

D-mode field

Field distribution@1000A

Q-mode field

Parallel Current direction

Injection beam

Stored beam

Qudarupole-like
**CCiPM beam test system in dump line**

- Beam focusing
  - QF1, HD4, QF2
  - Beam direction
  - Q-doublet
  - V-st for vertical beam steering
- Gate valve for vacuum break down
- Beam position monitor
  - To watch the beam position real-time in study
- Dispersion control
- Beam profile monitor 1 using YAG screen
  - To confirm the beam position at CCiPM
- Beam profile monitor 2 using YAG screen
  - To confirm the CCiPM kick angle
- Re-install position of QH1
- Moving mirror system to confirm the coating damage

**Notes:**
- Bending magnet as beam sweeper
  - Operation sweep angle ~1mrad
- On/Off axis injection at CCiPM
- CCiPM install position @QH1
- Beam position monitor
  - To watch the beam position real-time in study
Accelerator implementation setup

Feeder line support

ICF152 flange

Return coil
Feeder line to power supply

CCIPM overview

Test bench setup

Al flame stage

SUS girder

Connection terminal

Beam
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

- Pulsed P.S.
- YAG screen at dump point
- Vacuum pressure: $2 \times 10^{-6}\text{Pa}$
- Front side
- Back side
- Mirror system
- CCiPM inner surface view by mirror

Beam

2019/2/22

TWISS workshop in PSI
We are now developing D30-model!
## CCiPM performance comparison

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