New Design of a Pulse Magnet for the J-PARC RCS Injection Shift Bump Magnet

T. Takayanagi, K. Yamamoto, J.Kamiya, P.K.Saha, T.Ueno, K.Horino, M.Kinsho(JAEA/J-PARC), Y.Irie(KEK)

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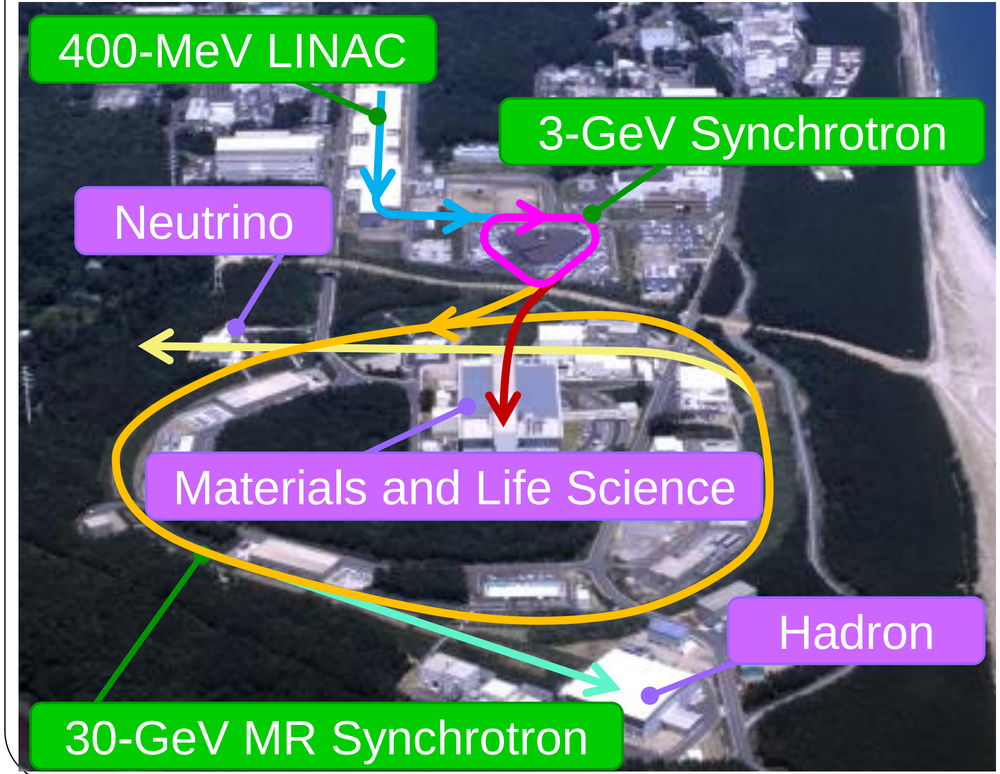
Introduction of J-PARC

J-PARC(Japan Proton Accelerator Research Complex)

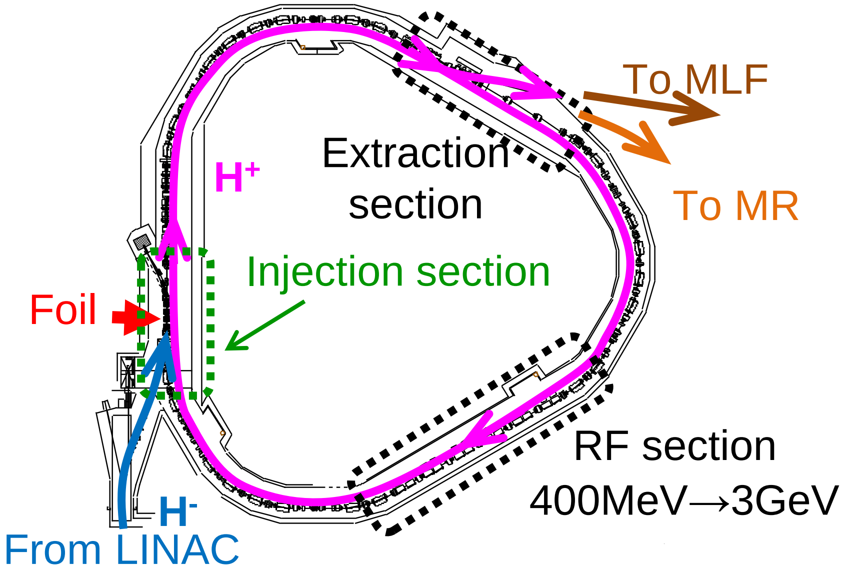


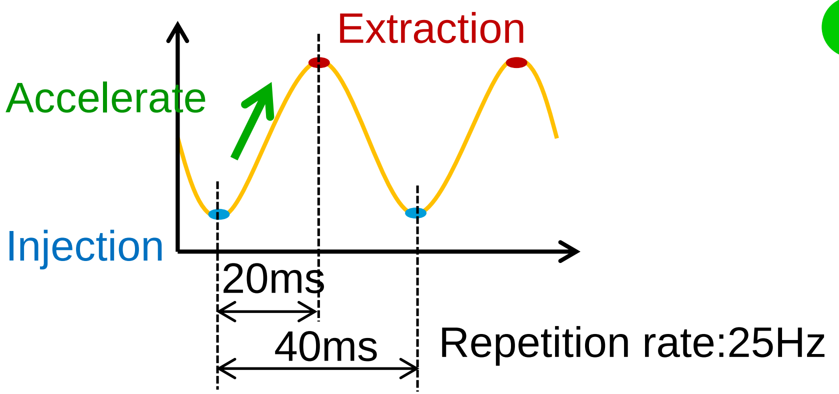
J-PARC consists of a series of world-class proton accelerators and the experimental facilities that make use of the high-intensity proton beams

- Three proton accelerators
  - 400 MeV linear accelerator
  - 3 GeV rapid-cycling synchrotron (RCS)
  - 30 GeV main ring (MR).
- Three experimental facilities
  - Muon and neutron production targets in the Materials and Life Science Experimental Facility (MLF).
  - Nuclear and Particle Physics Program at the Hadron Experimental hall
  - Neutrino Experimental Facility

What is RCS ?

RCS(Rapid-Cycling Synchrotron)





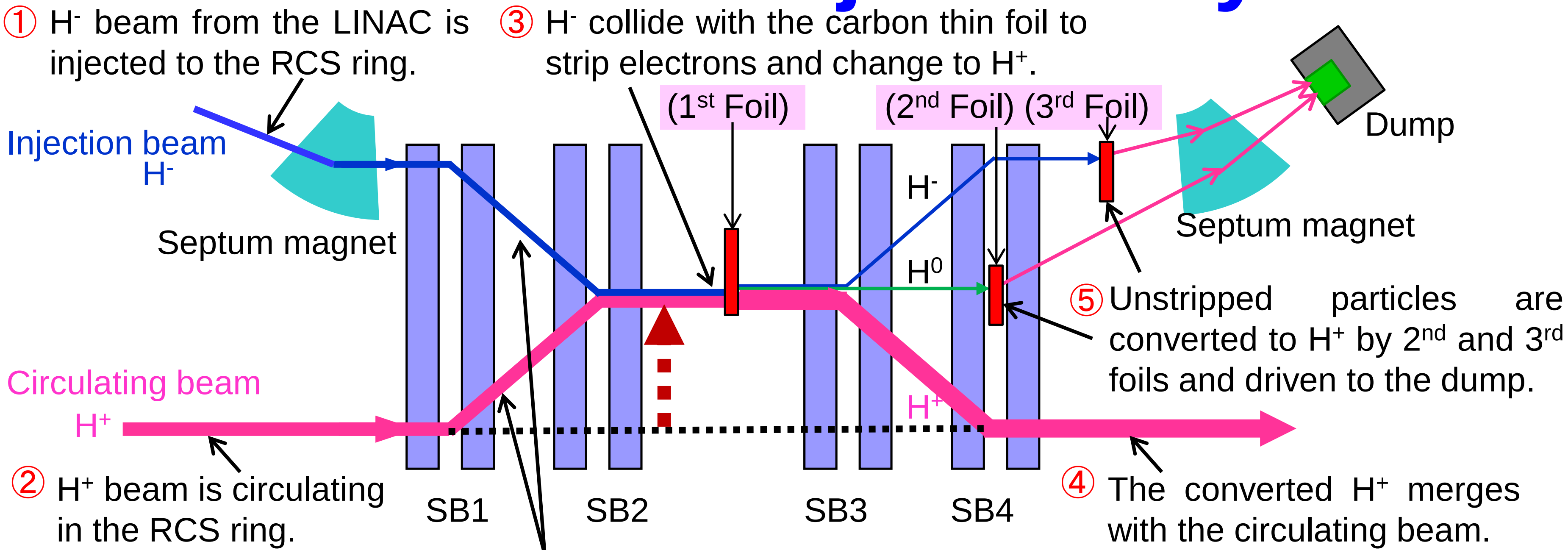
Characteristic

- Circumference : 348 m
- Injection energy : 400 MeV
- Extraction energy : 3 GeV
- Repetition rate : 25 Hz
- Beam power : 1 MW

In January 10, 2015, we successfully achieved the beam acceleration equivalent to 1 MW !

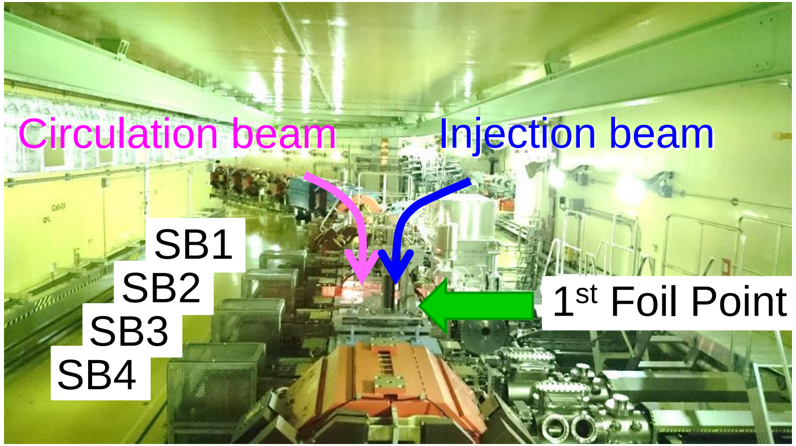
- H^- beam from the Linac passes through the thin foil and is converted to H^+ beam.
- Accelerates the injected H^+ beam up to 3 GeV with 25 Hz repetitive sine waveform.
- RCS has two functions as a proton driver for the MLF and as an injector to the MR.

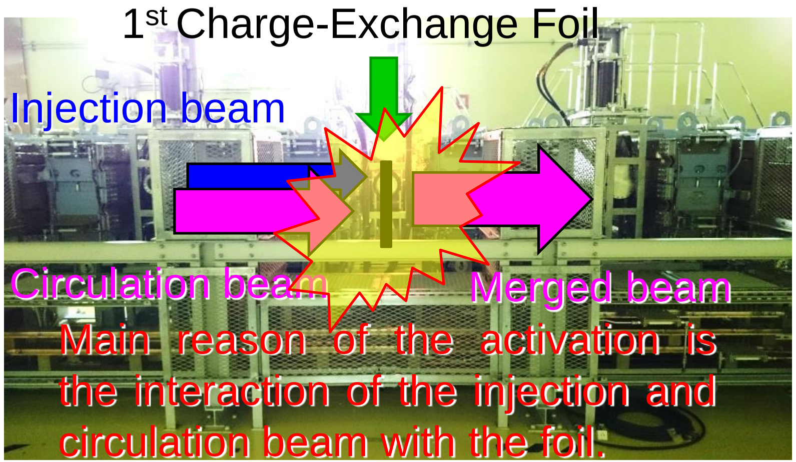
Outline of the Injection System



- This injection orbit is produced by four SB magnets only during the beam injection period.
- H^- beam is multi-turn charge-exchange injected into RCS to generate the high-intensity proton beams. In addition, the position of the 2^{nd} and 3^{rd} foil is important to transport the particles which were not stripped off by the 1^{st} foil to the dump.

Motivation of this Study



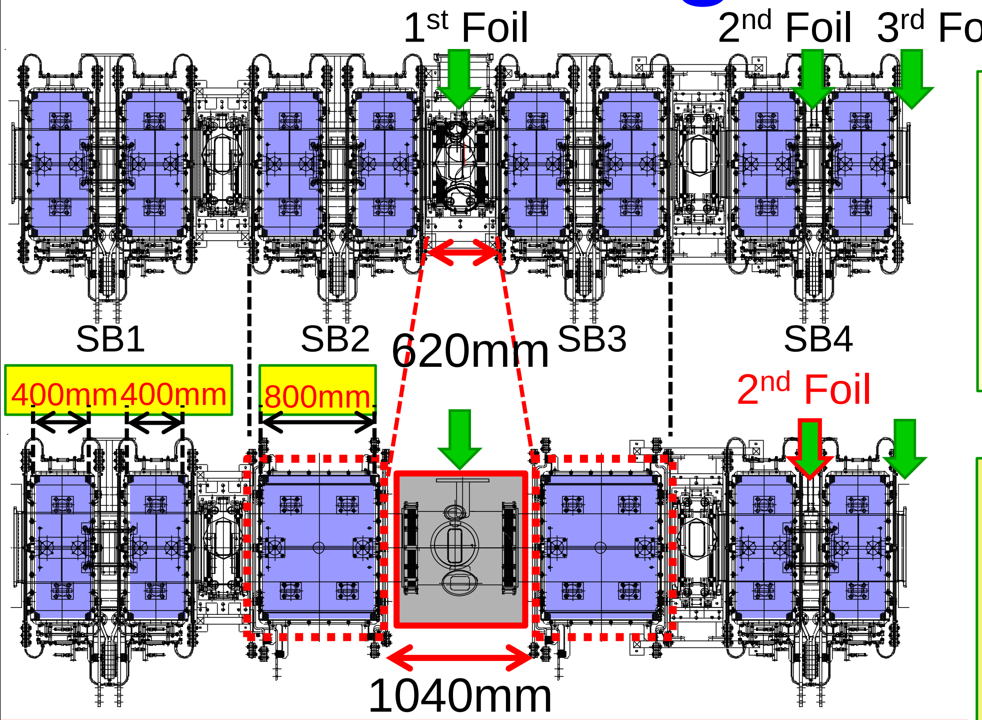


- At the residual dose around the foil after 400 kW beam operation, 15 mSv/h was confirmed.
- The beam loss reduction operation reduced the residual dose to 9 mSv/h.
- But it was not enough to achieve further high power operation.

Design a new injection scheme that can reduce exposure dose during maintenance work in the injection region under the high residual dose environment.

Requirement: Keep the basic scheme of injection, but need more space for shielding.

New Design Concept



Secure enough space for radiation shielding !

Total length of two kinds of the yoke is the same.

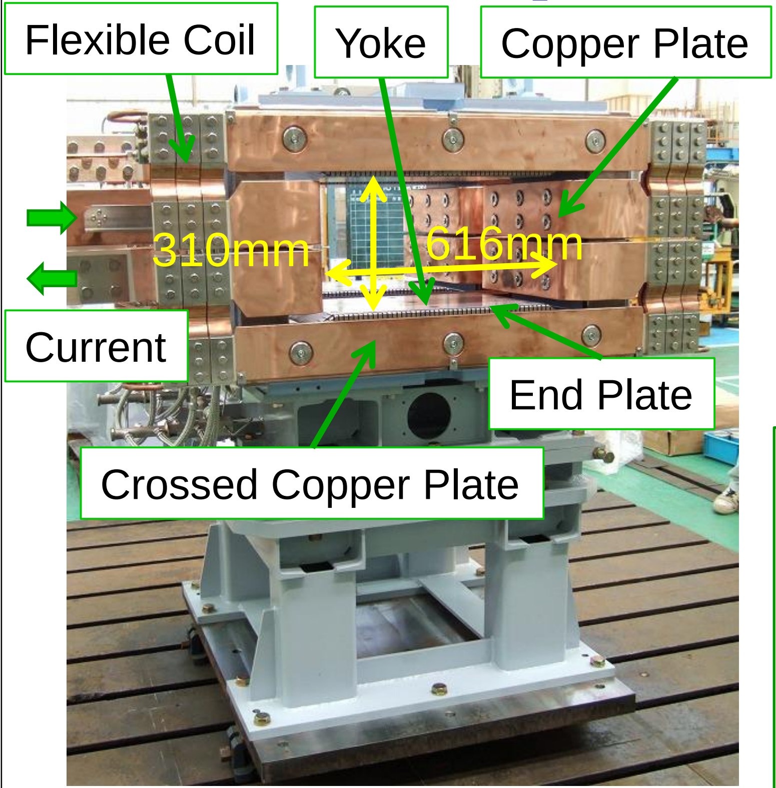
Present design

- The yoke is separated at the center in order to insert a 2nd foil.
- Four SB magnets have the same shape and are connecting in series.
- By exciting with one power supply, a fixed injection orbit will be easily generated.

New design

- The yokes of the SB2 and SB3 are joined.
- The SB1 and SB4 conserve the split yoke to keep the 2nd foil space.
- Two kinds magnets are each connected in series separately and are excited by two independent power supplies made by splitting the present power supply.

Description of SB Magnet



Picture: Present SB magnet

- The divided yokes are configured as one magnetic pole.
- A wide and thin copper plate is used for coil in order to reduce the unused area by the skin effect.
- The number of turns of the coil is 2, and low inductance is realized for high-speed pulse output.
- Coil is exposed to air for cooling efficiency.

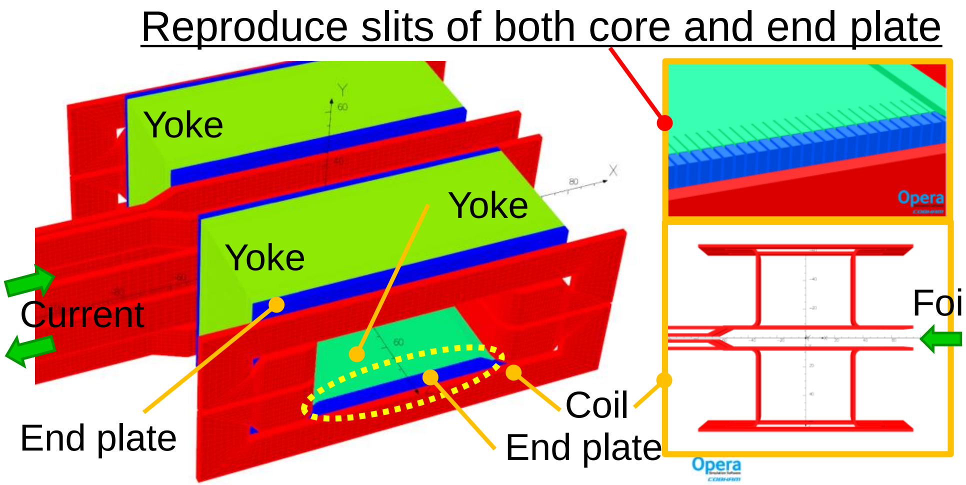
Flow of design of new SB magnet

STEP1: Evaluation of OPERA's analysis model.

- Compare the results of measurement and analyses (TOSCA, ELEKTRA, TEMPO) using the present SB.
- Magnetic field: The present SB designed in the past was analyzed only by TOSCA.
- Temperature: TEMPO is the first evaluation.

STEP2: Design analysis of new SB magnet model.

Evaluation of 3D Analysis ELEKTRA



- ELEKTRA analyses time dependent electromagnetic fields, including the effects of eddy currents.
- Calculate the entire coil by cutting the mesh using the finite element method in this model.

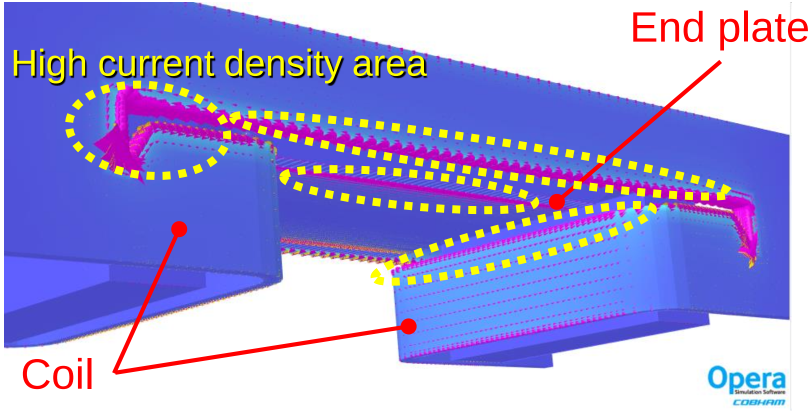


Figure: Distribution of the eddy current density at the end plate and the coil.

The evaluation position at the beam injection start position

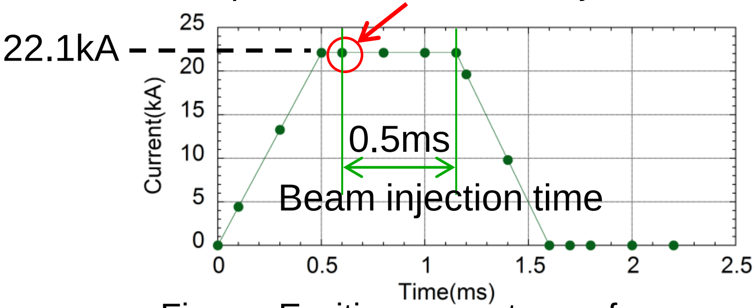
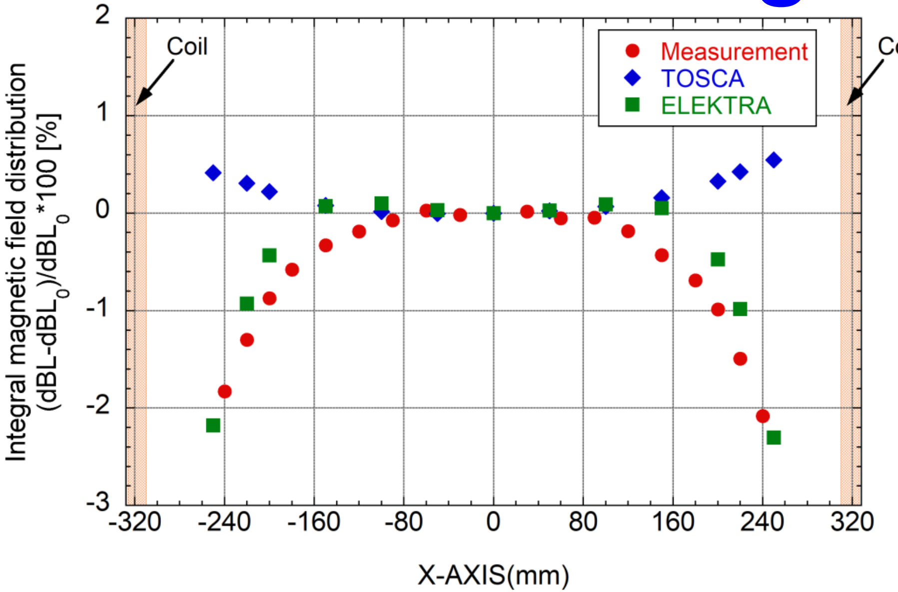
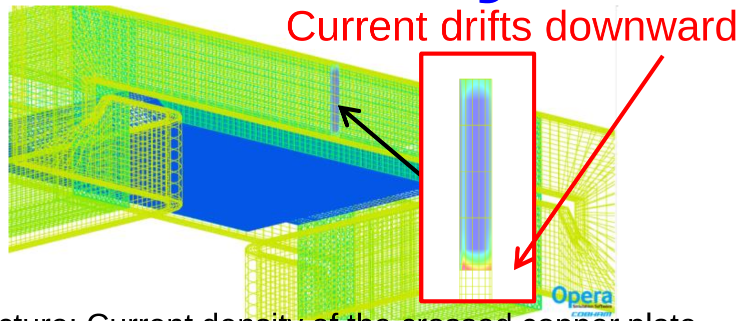


Figure. Exciting current waveform

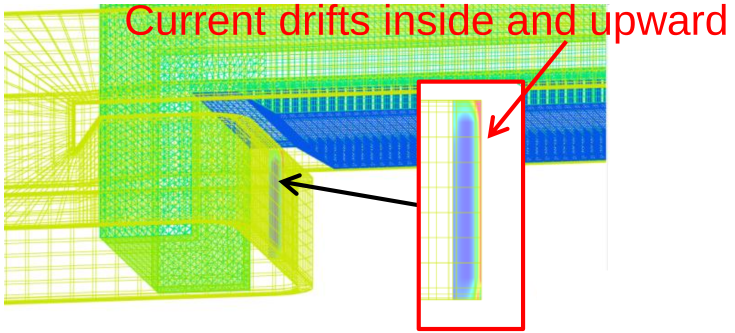
The current flows through the shortest path and concentrates on the edge due to the eddy current effect.

Result of Magnetic Field Analysis





Picture: Current density of the crossed copper plate

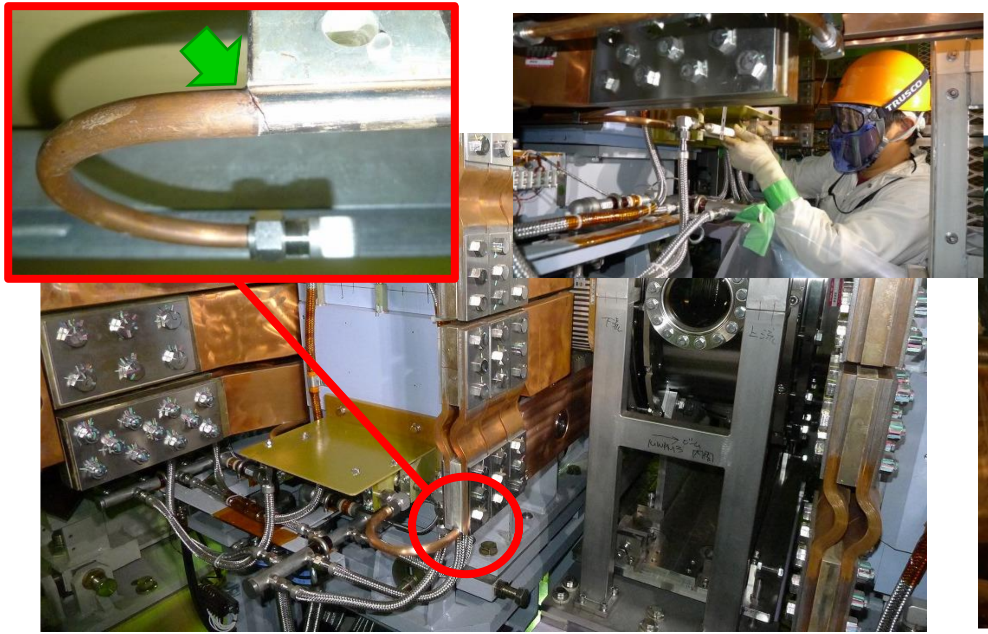


Picture: Current density of the coil inside yoke

- The analysis result by ELEKTRA matched very well with the measured values.
- Analysis result by TOSCA showed a tendency different from the measurement and ELEKTRA.
- The cause is the current drift in the coil due to the eddy current effect

Analysis of the ELEKTRA is effective for the design of pulse magnets !

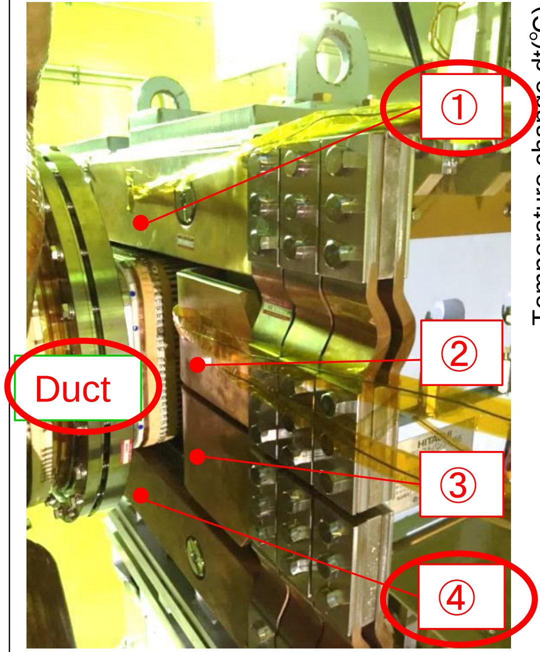
Cooling Water Leak of the SBs

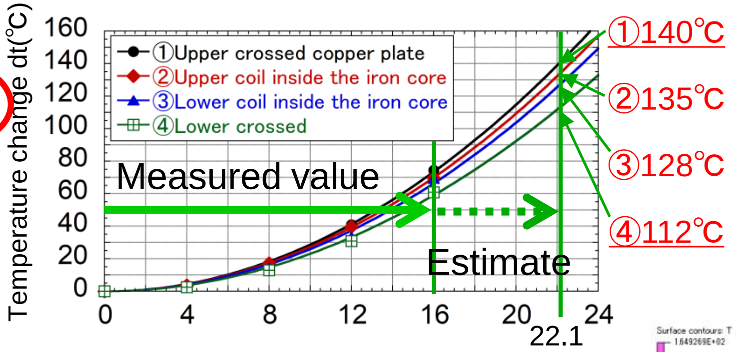


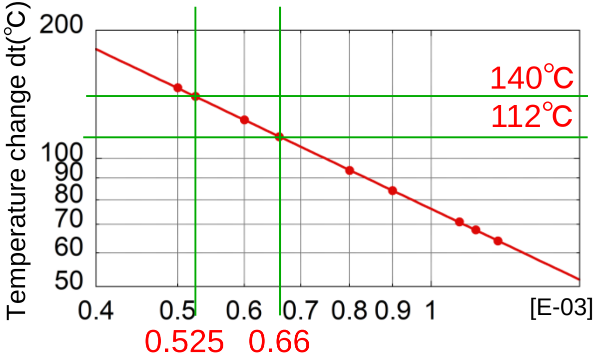
- Leakage failure from cooling water piping occurred several times.
- We will consider changing from water cooling to forced air cooling.

Temperature evaluation

■ Calculation of heat transfer coefficient value corresponding to installation position.

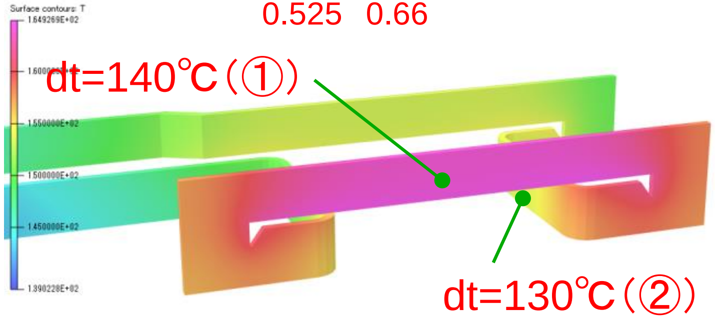






◆The cooling water was stopped and the temperature of the coil was measured.

◆The temperature difference was 30 degrees above and below the duct (140℃ and 112℃).



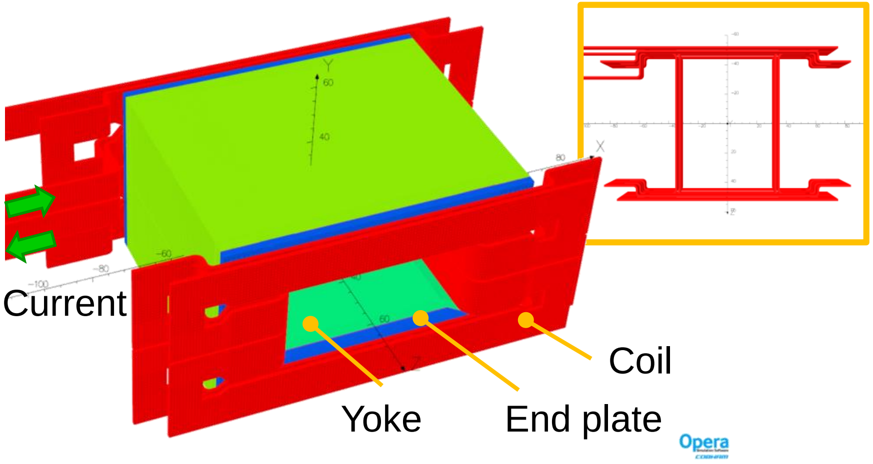
Room temperature 25(℃)

Input pulse current=22.1kA, 0.525e-03(W/cm2･K)

This result shows a good agreement !

◆The temperature difference at the upper and lower position could be attributed to the positional relationship between air flow of the air conditioning and the duct in the middle.

Model analysis of new magnet



- The number of turns of the coil doubles because of the half rating of the power supply.
- The total length of the magnetic poles is maintained at 800 mm.
- The integrated magnetic field is conserved.
- The slit shape of both yoke and end plate is the same as present magnet.

The evaluation position at the beam injection start position.

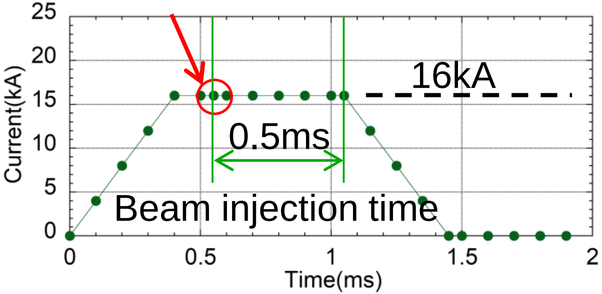


Figure. Exciting current waveform

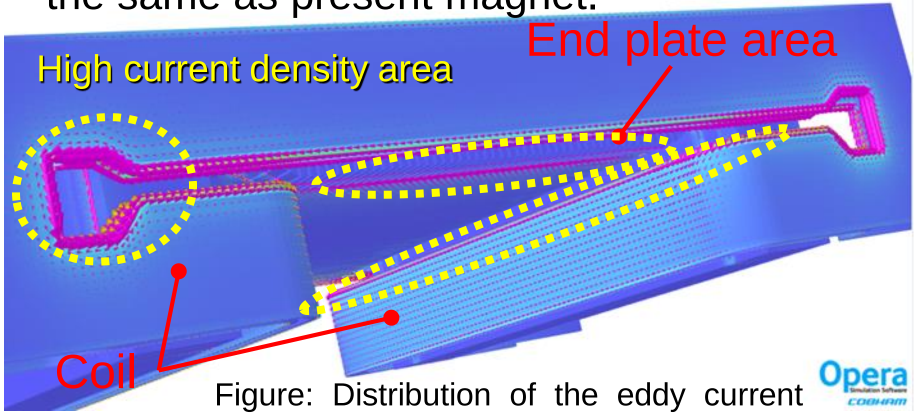
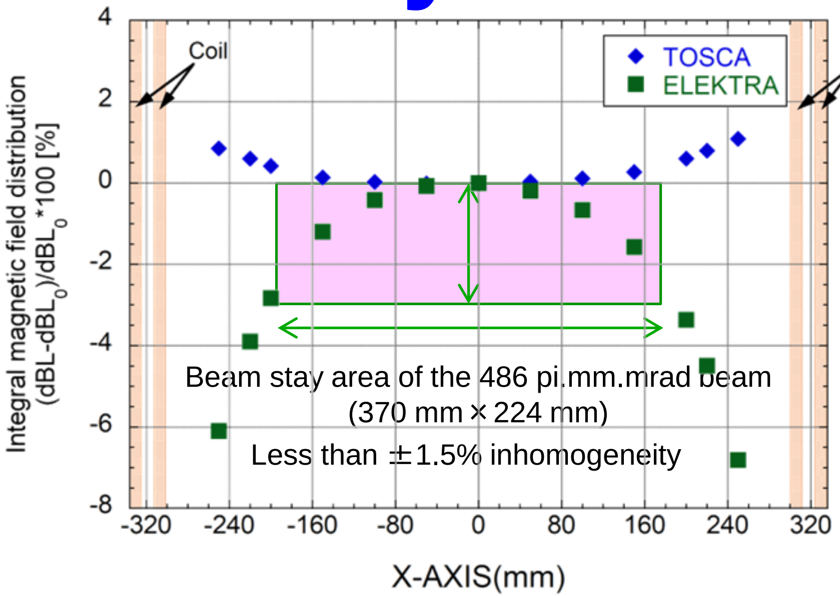
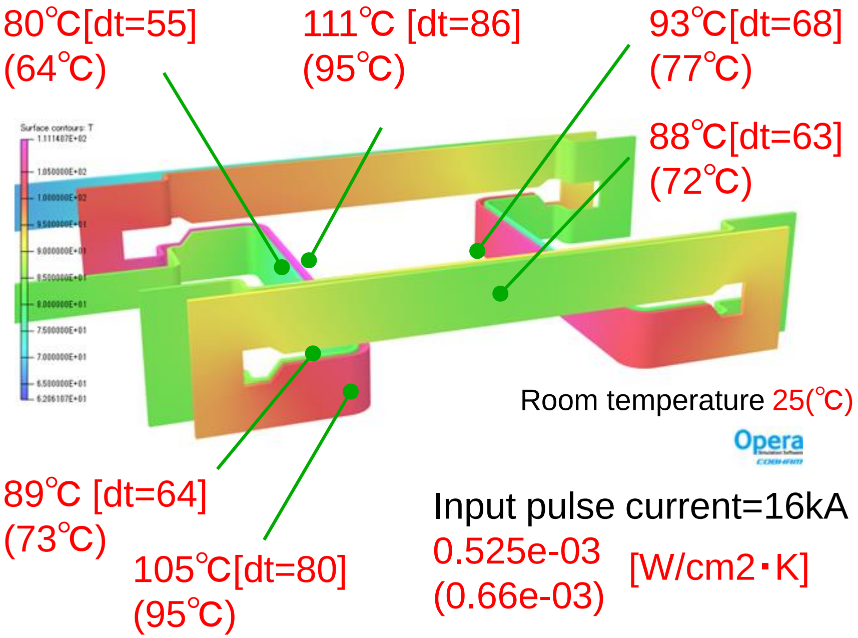


Figure: Distribution of the eddy current density at the end plate and the coil.

Drift of current shows the same trend.

Analysis result

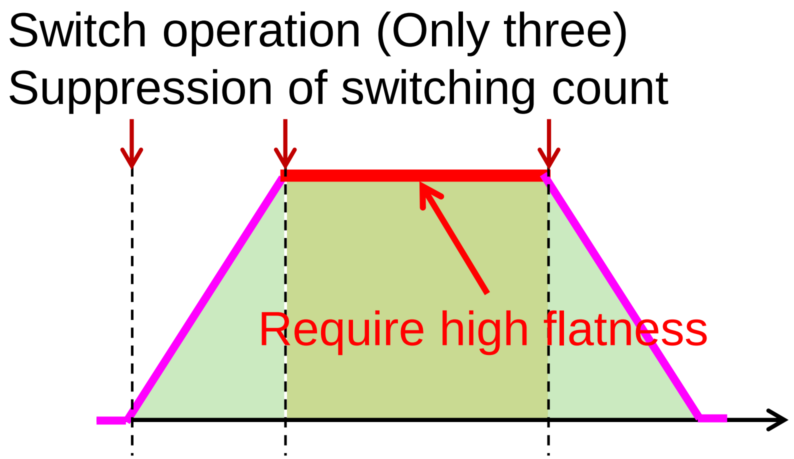




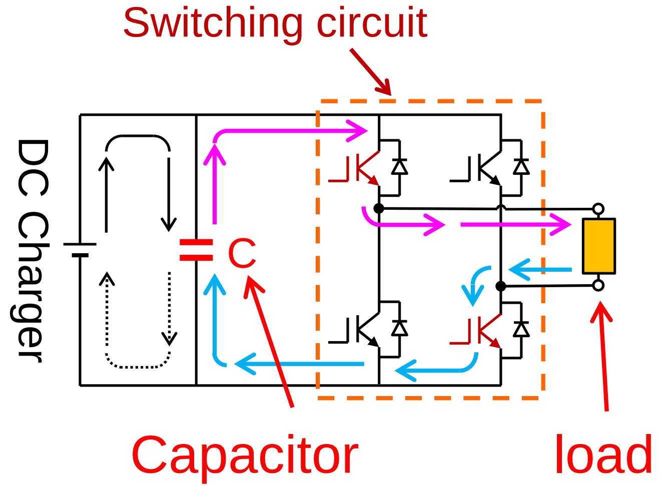
- ◆ The homogeneity of the field distribution is almost the same with expectation.
- ◆ Further improvement of magnetic field distribution is under consideration by optimizing coil shape.

- ◆ Temperature calculated using two heat transfer coefficients is acceptable.
- ◆ In consideration of thermal interference to peripheral equipment, we will also consider air-cooling system using fans.

Description of the Power supply



【Formation of trapezoidal waveform】

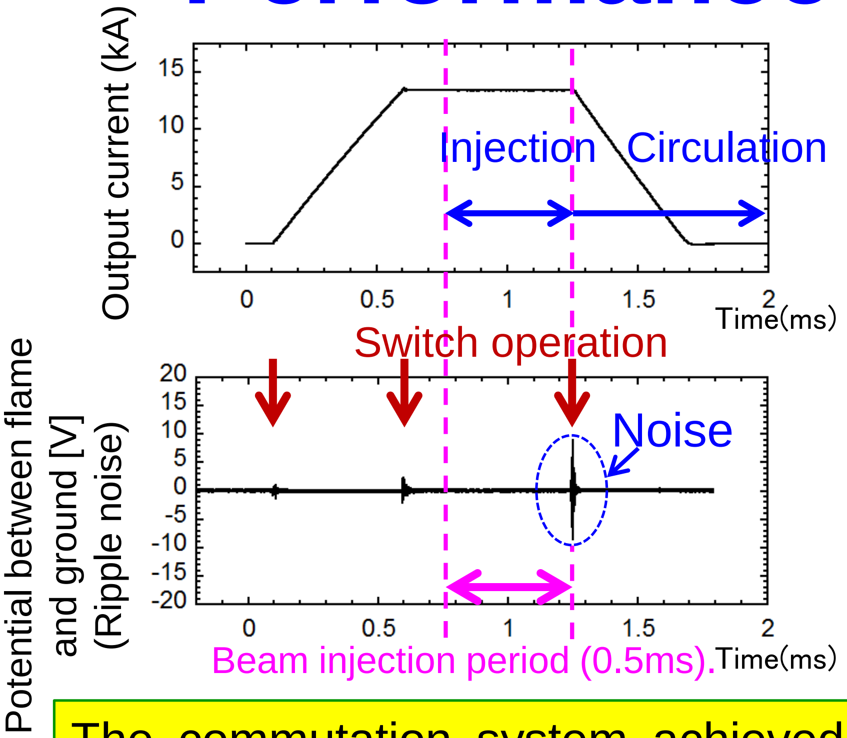


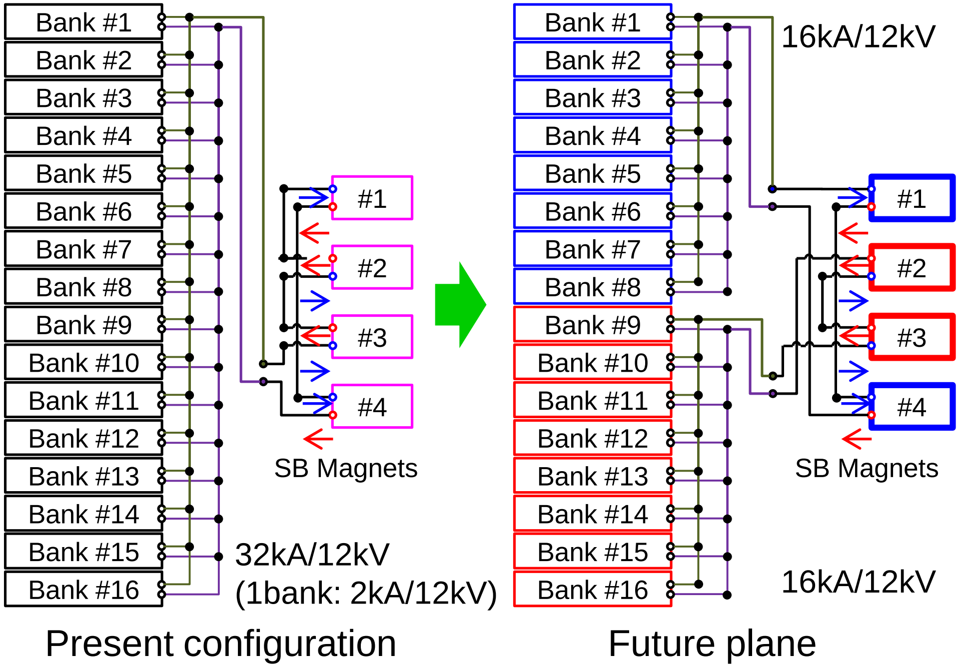
【Basic circuit】

- ■ An injection orbit produced by four SB magnets is fixed by the flat-top of the trapezoidal waveform.
- ■ In order to obtain a stable orbit, high flatness and low noise of the flat-top are required.

- ■ In order to satisfy the requirement, capacitor commutation method was adopted.
- ■ Since the switching is performed only at the timing of waveform switching, occurrence of current ripple can be suppressed.

Performance and Future Plans





The commutation system achieved a zero ripple noise during the beam injection period.

16 banks are connected in parallel to operate as one power supply. In the future, 8 banks will be operate as one power supply.

Summary

- J-PARC RCS has demonstrated a high power beam equivalent to 1 MW.
- In order to reduce the exposure dose and realize further high intensity beam power, a space for installing the shield in the injection straight region is required.

Achievements of the study

- In order to maintain the proven injection system, new design of the pulse magnet and modification of the power supply was verified.
- New design was proposed in which the yoke of the present SB was changed.
- From the measurement results of the magnetic field and temperature of the present SB magnet, we demonstrated that ELEKTRA of OPERA-3D is effective.

Outlook for the future of study

- The number of turns of the present SB coil is also doubled due to the half rating of the power supply.
- I would like to make further improvement of the magnetic field distribution using a OPERA-3D and the upgrade plan of RCS injection system successful.