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Mitigation of shielding-current-induced field of a dipole magnet wound with coated conductors during pattern-operation and evaluation of beam orbit

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Outline

1. Background and objective
2. Analysis model for shielding current calculations
3. Analysis results and mitigation of SCIFs
4. Beam orbit evaluation with mitigated magnetic fields
5. Summary

Application of HTS magnets to accelerator systems for carbon cancer therapy

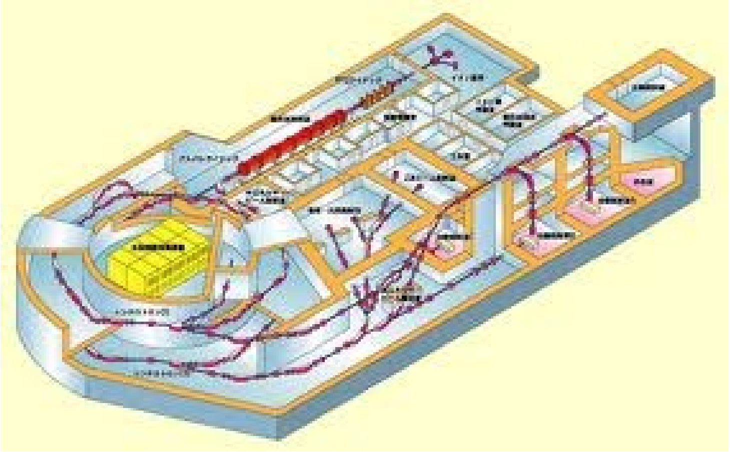
- Carbon cancer therapy

  Irradiation of carbon ion (C^{6+}) to tumor

  Requirement of magnets with high field

- HTS magnets for accelerator systems

  To generate time-changing field with enough field quality



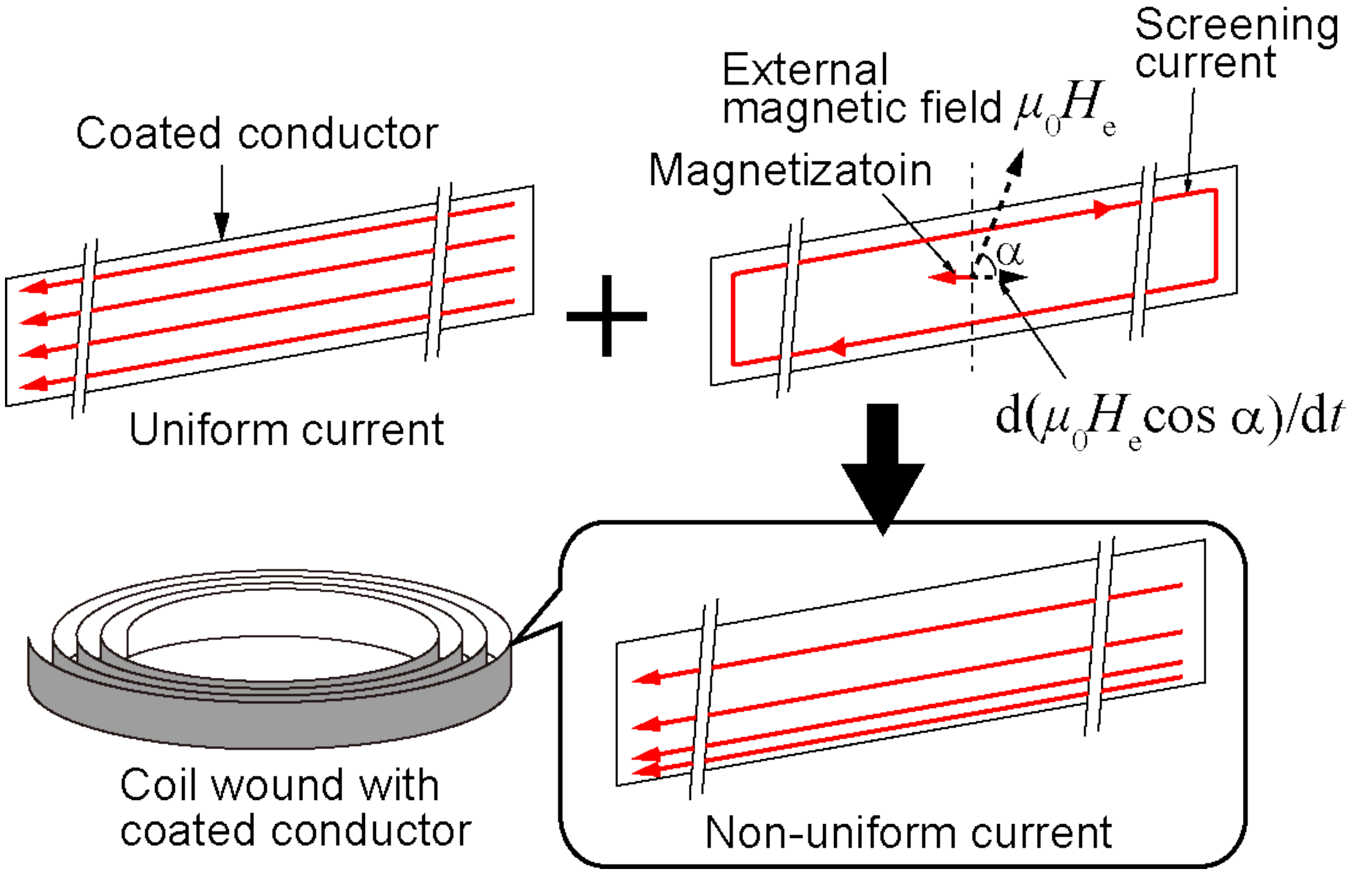
Heavy Ion Medical Accelerator in Chiba (HIMAC, NIRS)

Rotating gantry, HIMAC, NIRS

Shielding-current-induced field (SCIF)

- Persistent eddy currents in coated conductors

- Deterioration of field quality
  - ✓ Error of dipole component
  - ✓ Generation of higher multipole component
  - ✓ Field drift

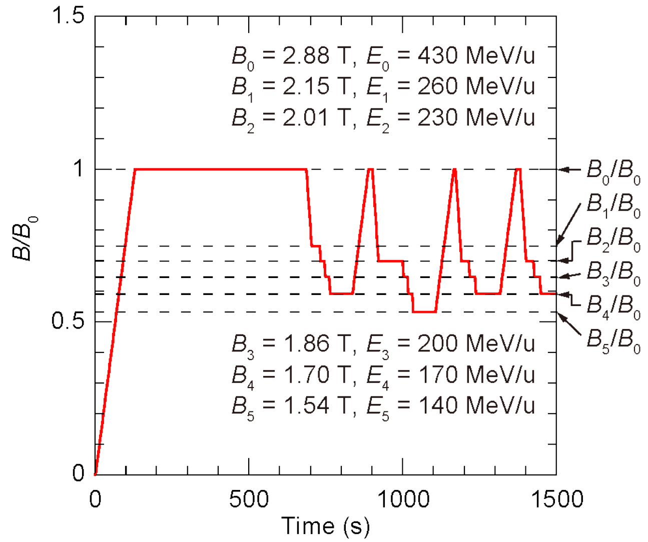


SCIF in HTS magnet for accelerator system

- SCIF depends on current in magnet.
- Magnets in accelerator systems required to generate time-depending magnetic field accurately.

  Striking difference from NMR/MRI magnets which are required to generate stable magnetic field

Influence of SCIF should be mitigated with different current (active shimming required).

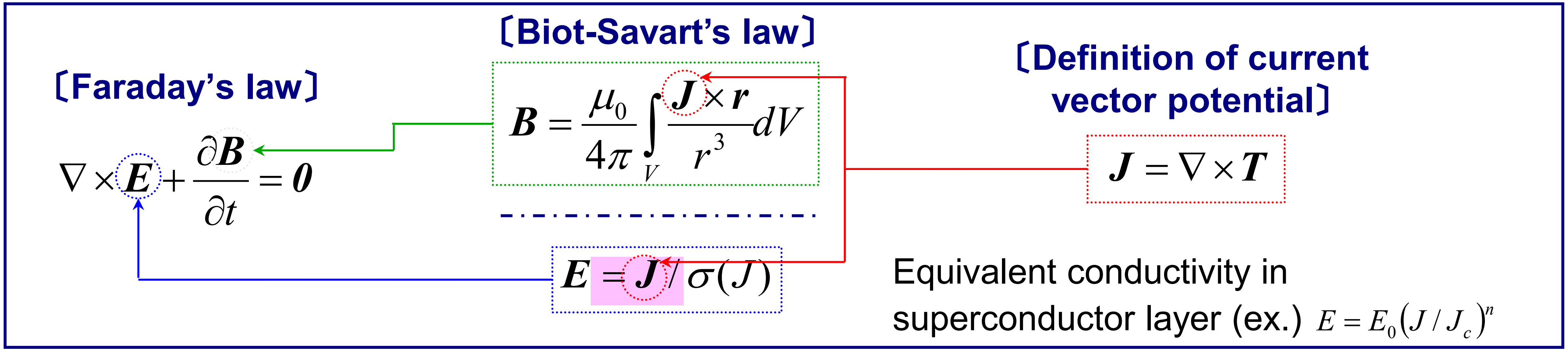


Objective

- Application of large-scale electromagnetic field analysis model to a full-scale HTS magnet wound with coated conductors operated under pattern-operation to calculate SCIF

- Proposal of mitigation method of influence of SCIF on field quality
- Beam orbit evaluation with mitigated magnetic field

Governing equation and thin-strip approximation



〔Faraday's law〕

$$\nabla\times\boldsymbol{E}+\frac{\partial\boldsymbol{B}}{\partial t}=\boldsymbol{0}$$

〔Biot-Savart's law〕

$$\boldsymbol{B}=\frac{\mu_0}{4\pi}\int_V\frac{\boldsymbol{J}\times\boldsymbol{r}}{r^3}dV$$

$$\boldsymbol{E}=\boldsymbol{J}/\sigma(J)$$

〔Definition of current vector potential〕

$$\boldsymbol{J}=\nabla\times\boldsymbol{T}$$

Equivalent conductivity in superconductor layer (ex.) $E=E_0(J/J_c)^n$

$$\nabla\times\left(\frac{1}{\sigma}\nabla\times\boldsymbol{T}_\mathrm{f}\right)+\frac{\mu_0}{4\pi}\frac{\partial}{\partial t}\int_V\frac{(\nabla\times\boldsymbol{T}_\mathrm{s})\times\boldsymbol{r}}{r^3}dV=\boldsymbol{0}$$

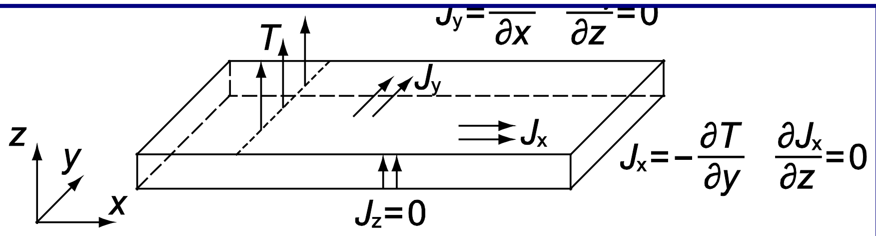
Integrate along thickness of coated-conductor

$$\nabla\times\left(\frac{1}{\sigma}\nabla\times\boldsymbol{T}_\mathrm{f}\right)+\frac{\mu_0 t_\mathrm{s}}{4\pi}\frac{\partial}{\partial t}\int_S\frac{(\nabla\times\boldsymbol{T}_\mathrm{s})\times\boldsymbol{r}}{r^3}dS=\boldsymbol{0}$$

Thin strip approximation

High cross-sectional aspect ratio of coated conductor allows its use.

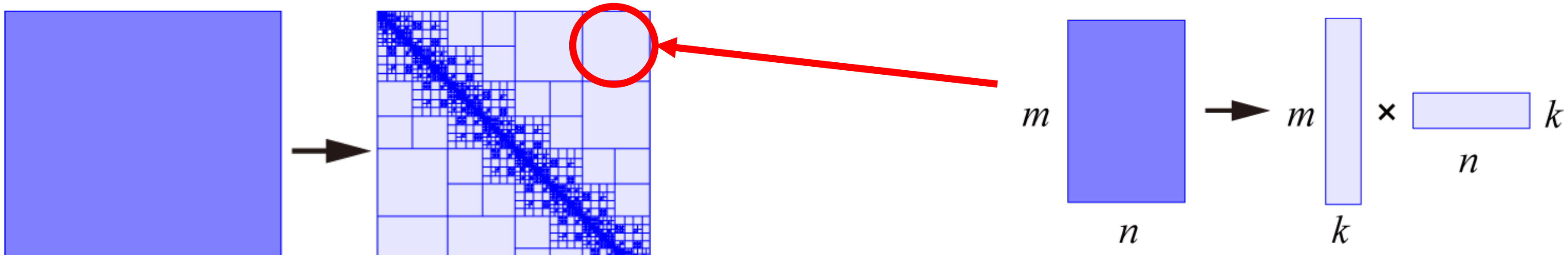
Computational cost reduced drastically from 3D problem to 2D problem.



Hierarchical matrices (H-matrix)

$$\nabla \times \left(\frac{1}{\sigma} \nabla \times \boldsymbol{T}_{\mathrm{f}} \right) + \frac{\mu_0 t_{\mathrm{s}}}{4\pi} \frac{\partial}{\partial t} \boxed{\int_S \frac{(\nabla \times \boldsymbol{T}_{\mathrm{s}}) \times \boldsymbol{r}}{r^3} dS} = \boldsymbol{0}$$

- The equation to be solved in the analyses including integration in analyzed space
  -> Dense matrix in FEM
- To reduce computational costs, H-matrix is applied to our model.



Dense matrix

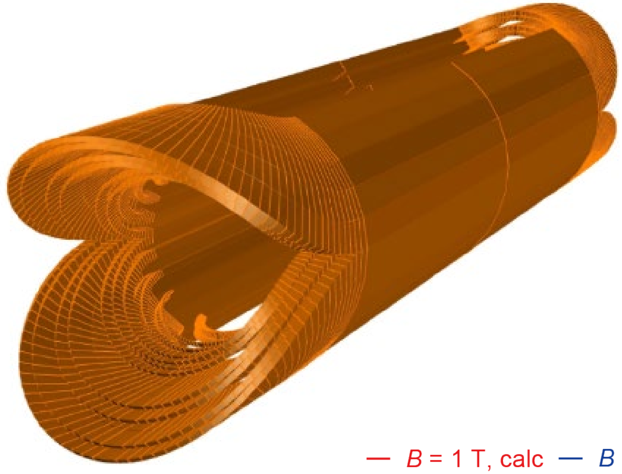
H-matrix

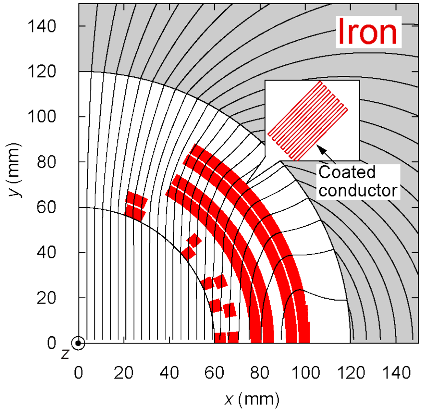
Low rank approximation

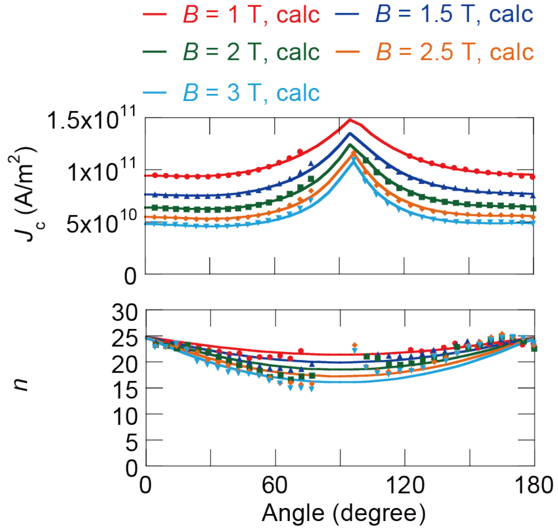
[1] T. Mifune, et. al., SUST, 32, 094002, 2019

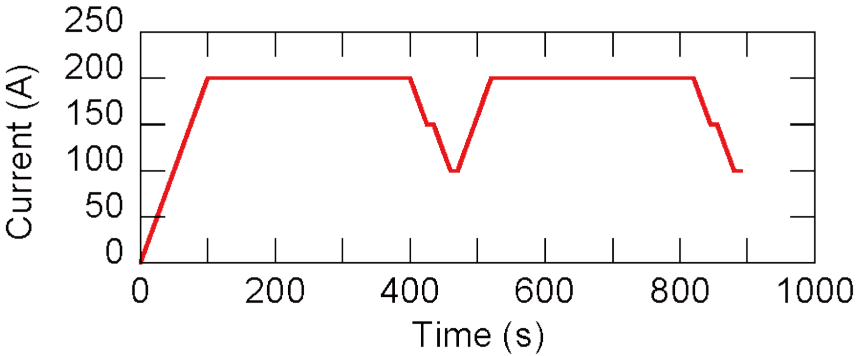
Analyzed magnet

Maximum transport current	200 A
Total number of turns (Total length of used CCs)	2744 (5.48 km)
Length of straight section	700 mm
Length of entire coil	1082 mm
Inner radius of coil	60 mm
Inner radius of iron yoke	120 mm
Designed integrated dipole component of magnetic flux density $BL_{1,d}$	2.64 Tm



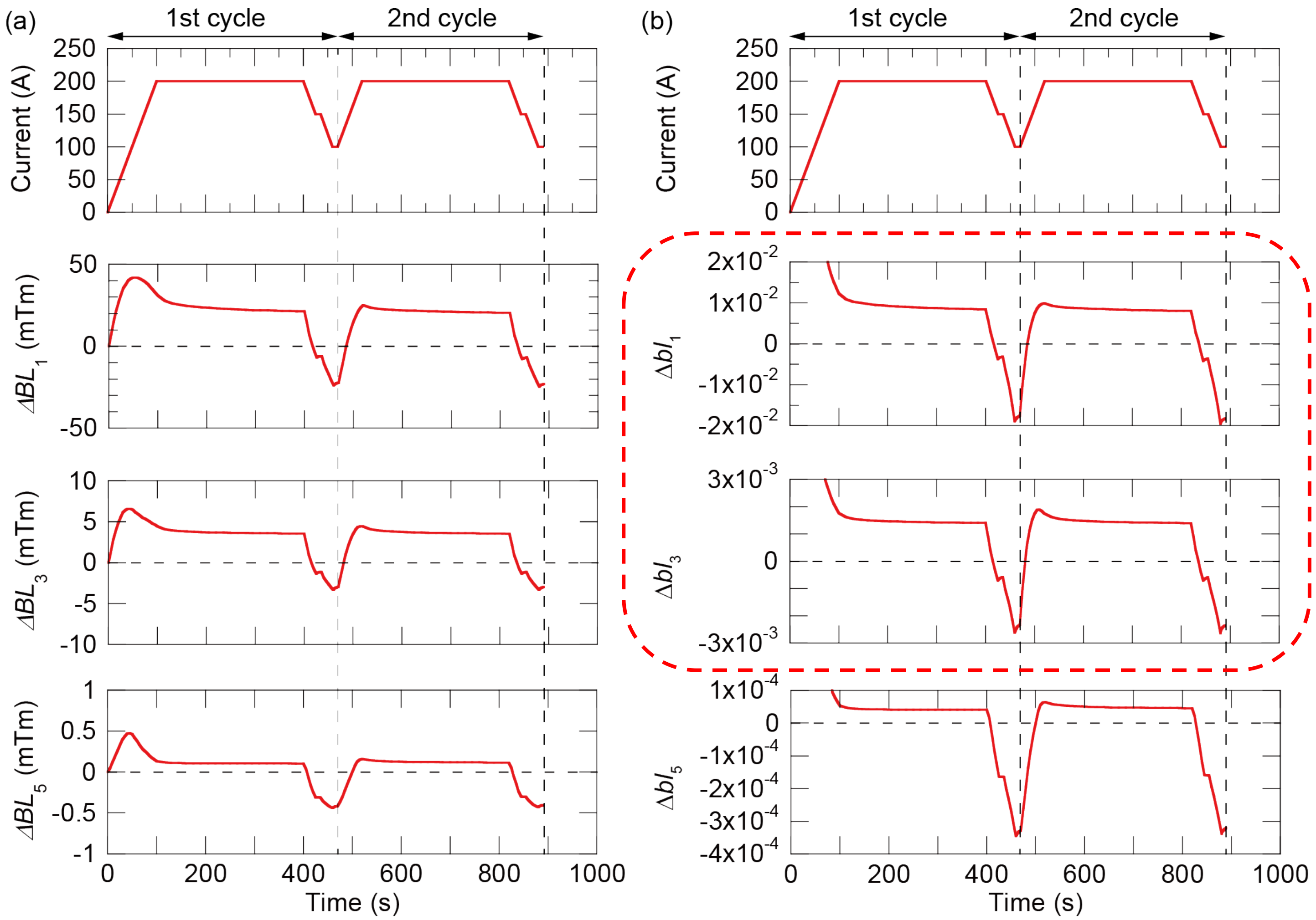






Magnet design and operating condition based on them of magnets in rotating gantry.

Influence of SCIF on multipole components of magnetic field



ΔBL_n: n-th pole component of SCIF
Δbl_n: Normalized ΔBL_n by dipole component of magnetic field

Required field quality for magnets in rotating gantry is $\Delta bl_n < 1\times10^{-3}$ in every time of current profile.

↓

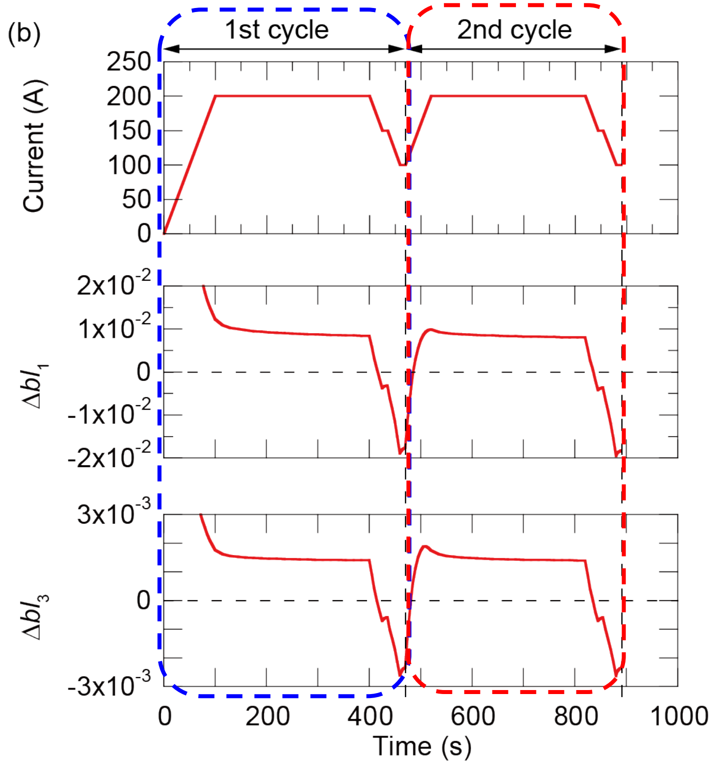
Δbl_1 and $\Delta bl_3 > 1\times10^{-3}$

↓

Mitigation method of Δbl_1 and Δbl_3 is necessary.

Concept of mitigation methods

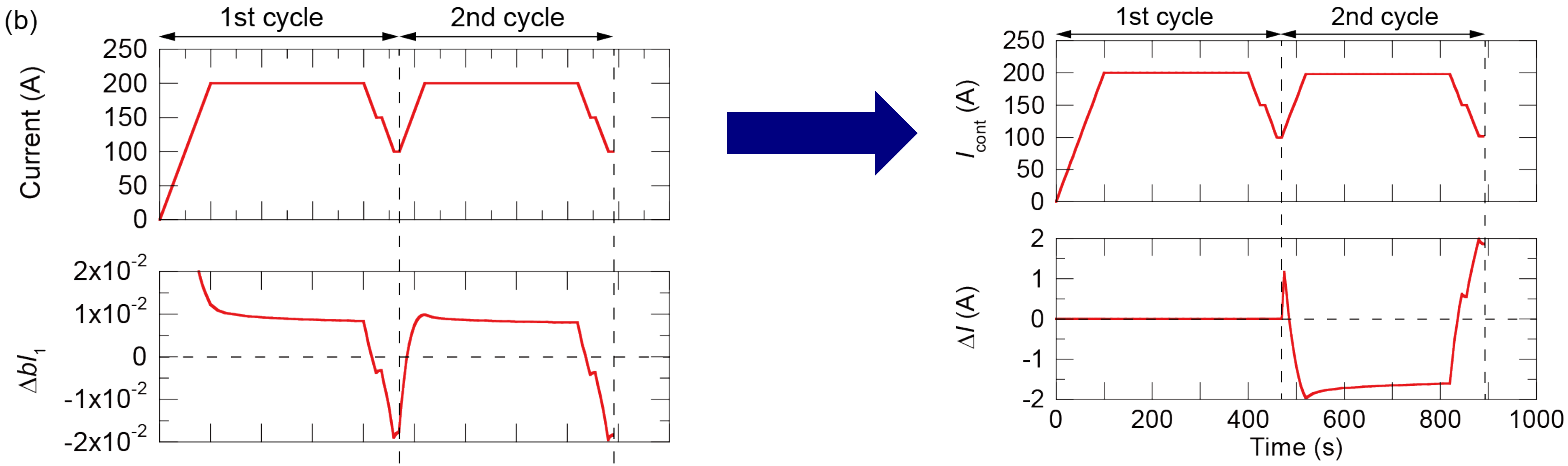
- SCIF in the first cycle is strongly affected by virgin state.
  → SCIF in the first cycle is not mitigated.



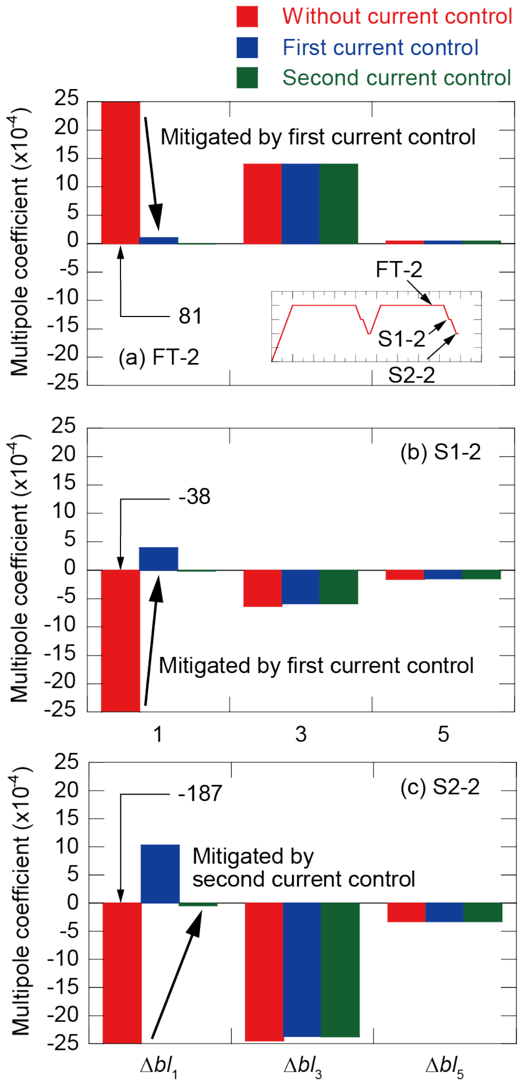
- By the simulations in advance, the operation (current profile) of actual magnets is determined to reduce the influence of SCIF on field quality.
- Here, the influence of SCIF on dipole and sextupole components in the second cycle is mitigated.

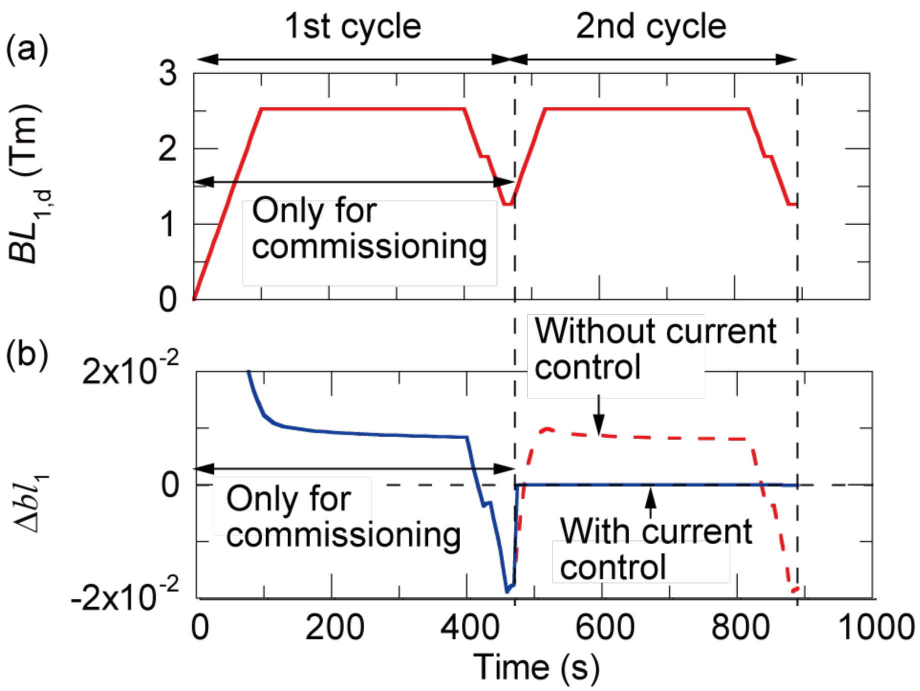
Current adjustment to mitigate Δbl_1

- Magnets for particle accelerator is driven by power supply not but operated in permanent current mode
  By current adjustment, influence of SCIF on dipole component can be mitigated.
  ※ Influence of SCIF on field is not linear to current.



Effect of current adjustment





Current adjustment was applied in the 2nd cycle.

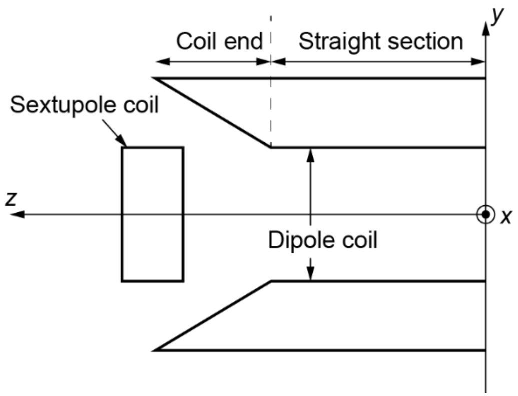
Δbl_1 in the 2nd cycle was less than 1×10^{-3} for every load ratio.

*Twice adjustments of current profile were needed.

Sextupole correction coils for mitigation of Δbl_3

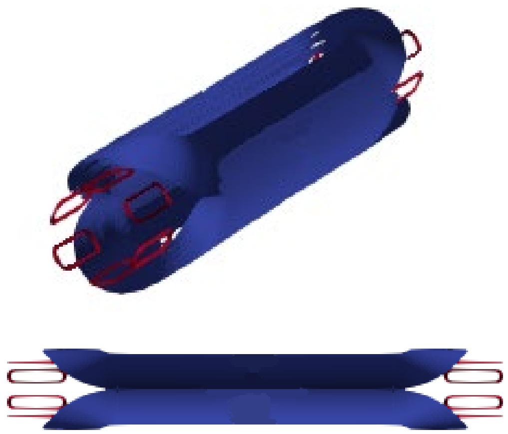
- To mitigate sextupole component of magnetic field, change of magnet design is required.

→ Combination of main dipole coil and HTS sextupole correction coils.



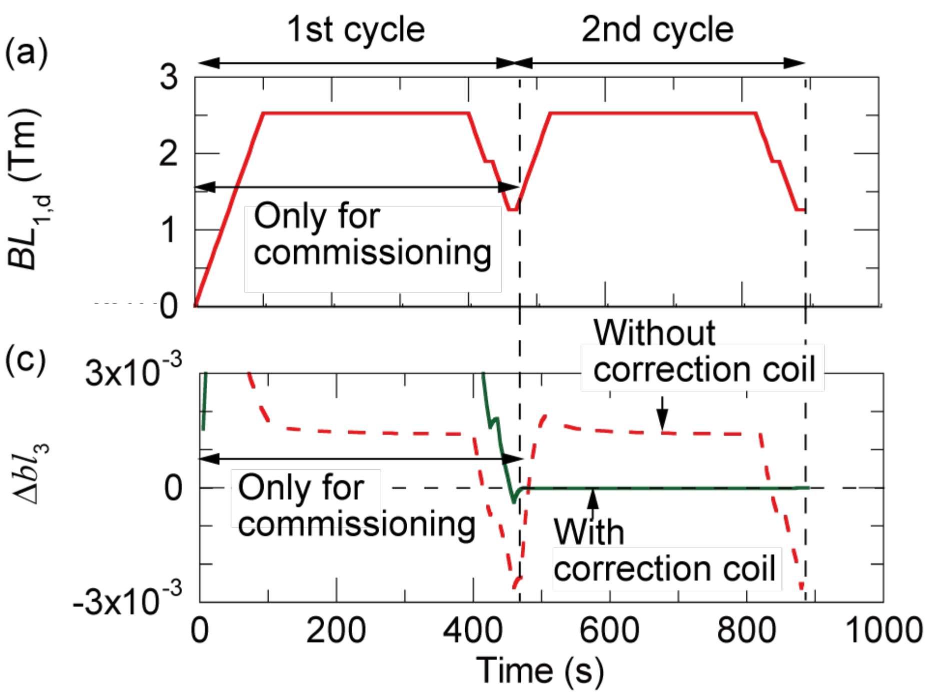
Schematic of sextupole coil arrangement

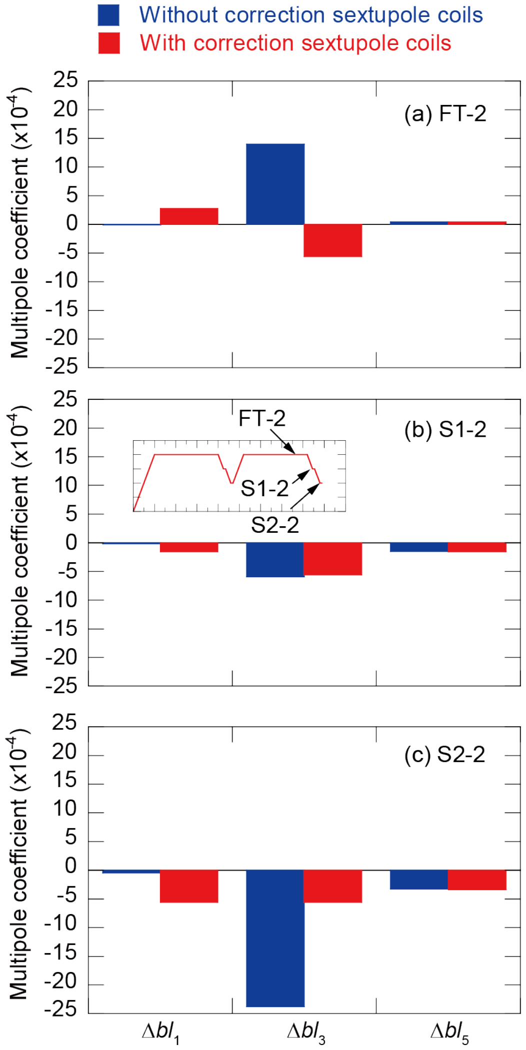
Schematic of HTS Sextupole correction coil

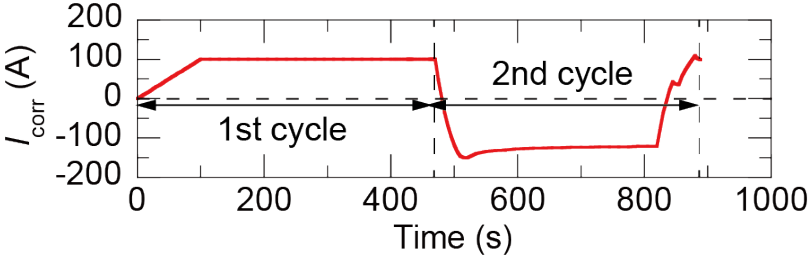


Schematic of combination of dipole coil and sextupole coils

Effect of correction coils



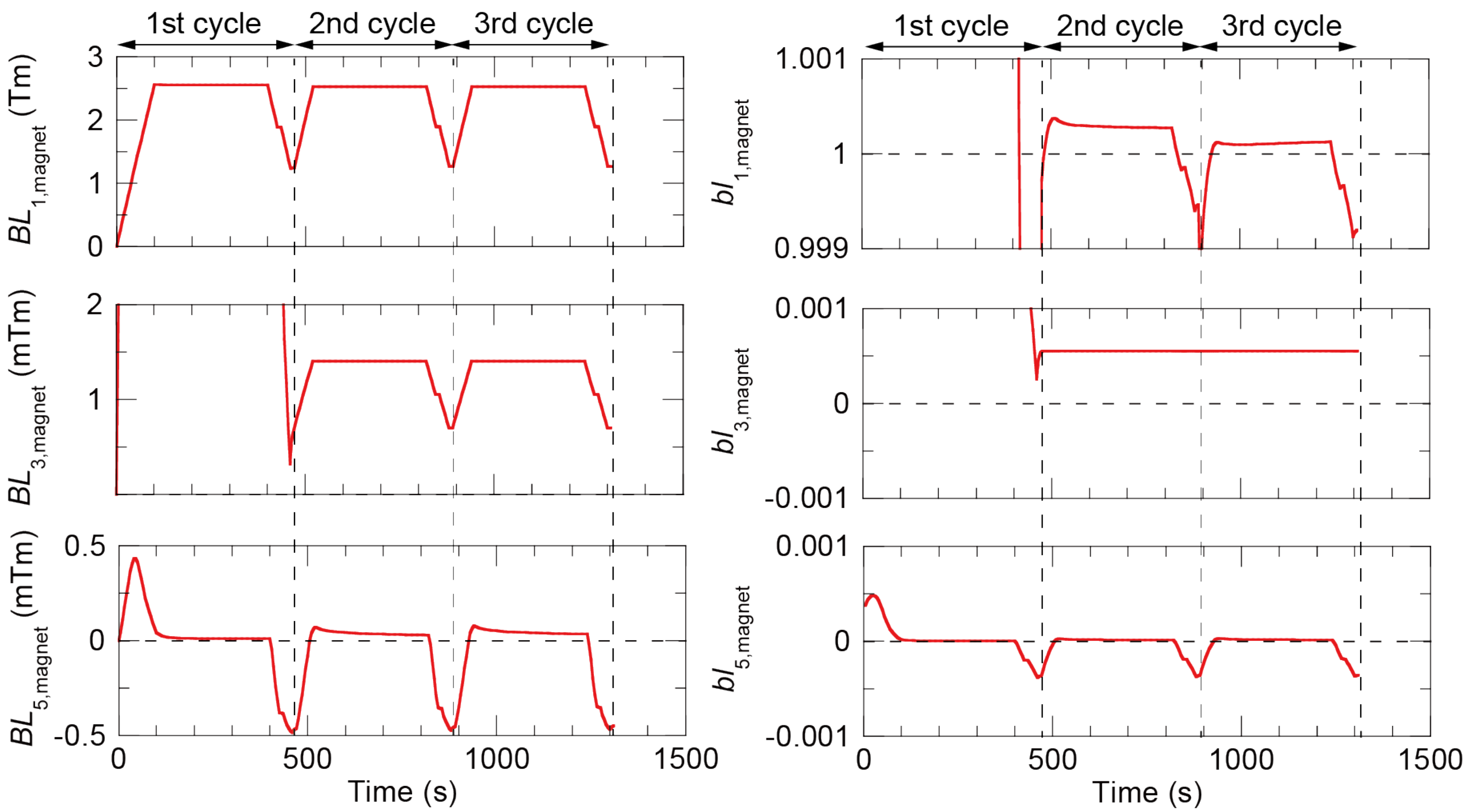




Current profile of sextupole correction coils

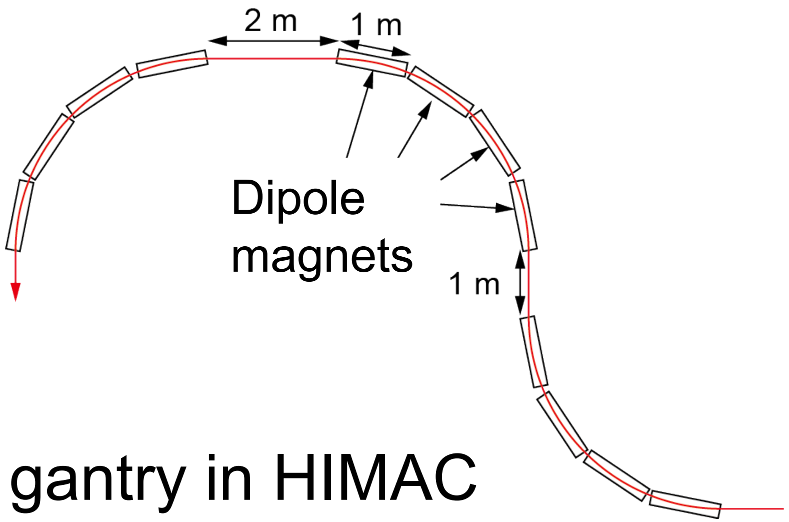
Δbl_3 in the 2nd cycle was less than 1×10^{-3} for every load ratio.

Mitigated magnetic field of the dipole magnet



Error field by SCIF was less than 1×10^{-3} of $BL_{1,d}$.

Beam orbit evaluation by WinAgile



- Aligned dipole magnets whose SCIF was mitigated

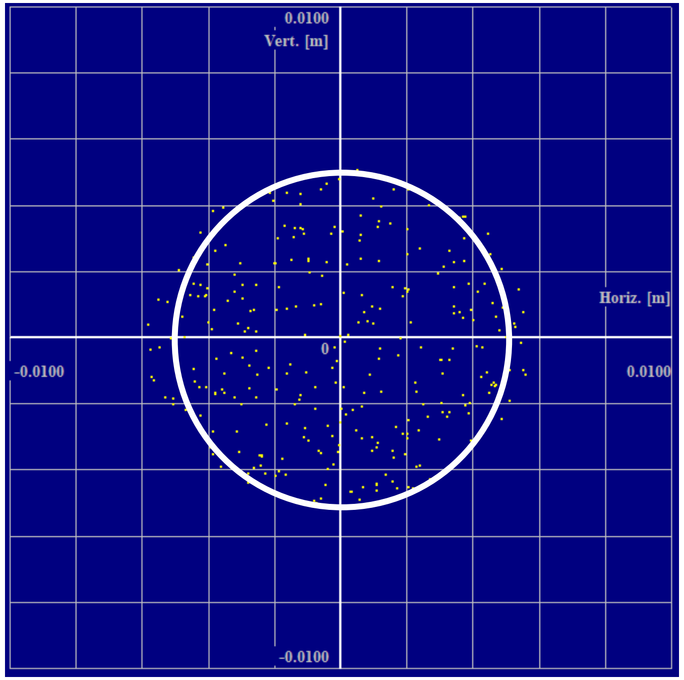
  Alignment based on magnet alignment of rotating gantry in HIMAC

  To simplify, we ignored scanning magnets, and every magnet has same length and magnetic field.

- Simulation result with C^{6+} (430 MeV/u) at irradiation position

  Shift of beam spot did not change,

  and beam deformation ration was less than 20%.



Conclusion

- We conducted large-scale electromagnetic field analyses to evaluate influence of SCIF on field quality.

  Error of dipole and sextupole component should be mitigated.

- Proposal to use current adjustment and sextupole correction coils

  Error field of dipole magnet was mitigated to less than 1×10^{-3} of the dipole component.

- Beam orbit simulation show that the mitigated SCIF did not affect beam spot shape and position.