Correction of focusing force with pole surface coils for FFAG accelerator

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FFAG'17 Workshop September 10, 2017

Outline

- Introduction
- Design of additional pole (patch)
- Purpose
- Index for focusing force
- Evaluating conditions of 3D magnetic field calculation
- Design of pole surface coils
- Measurement of magnetic field distribution
- Summary

Introduction

For an operation of an accelerator,

an appropriate operation point needs to

be selected.

In general, Scaling FFAGs has combined function magnets.

Therefore, the conventional method of changing an operation point during its operation was only changing FD ratio.

Equipment which corrects focusing effects is needed to select operation point more flexibly.

Tune variation control

Approximation formulas for radial sector type FFAG[*1]

$$\nu_H \approx \sqrt{1+k} \qquad \nu_V \approx \sqrt{-k+F^2(1+2\tan^2\varepsilon)}$$

(k : field index) (F : flutter factor, ε: spiral angle)

Tune	**Factor**	**Correcting equipment**
Vertical	flutter factor	Additional pole[*2] (Patch)
Horizontal	field index	Pole surface coils

Developed

Proposed

*1 K.R.Symon, et al. :"Fixed-Field Alternating-Gradient Particle Accelerators", Physical Review, Vol.103, No.6, pp.1837-1859 (1956).
*2 N.Motohashi , FFAG'15 workshop

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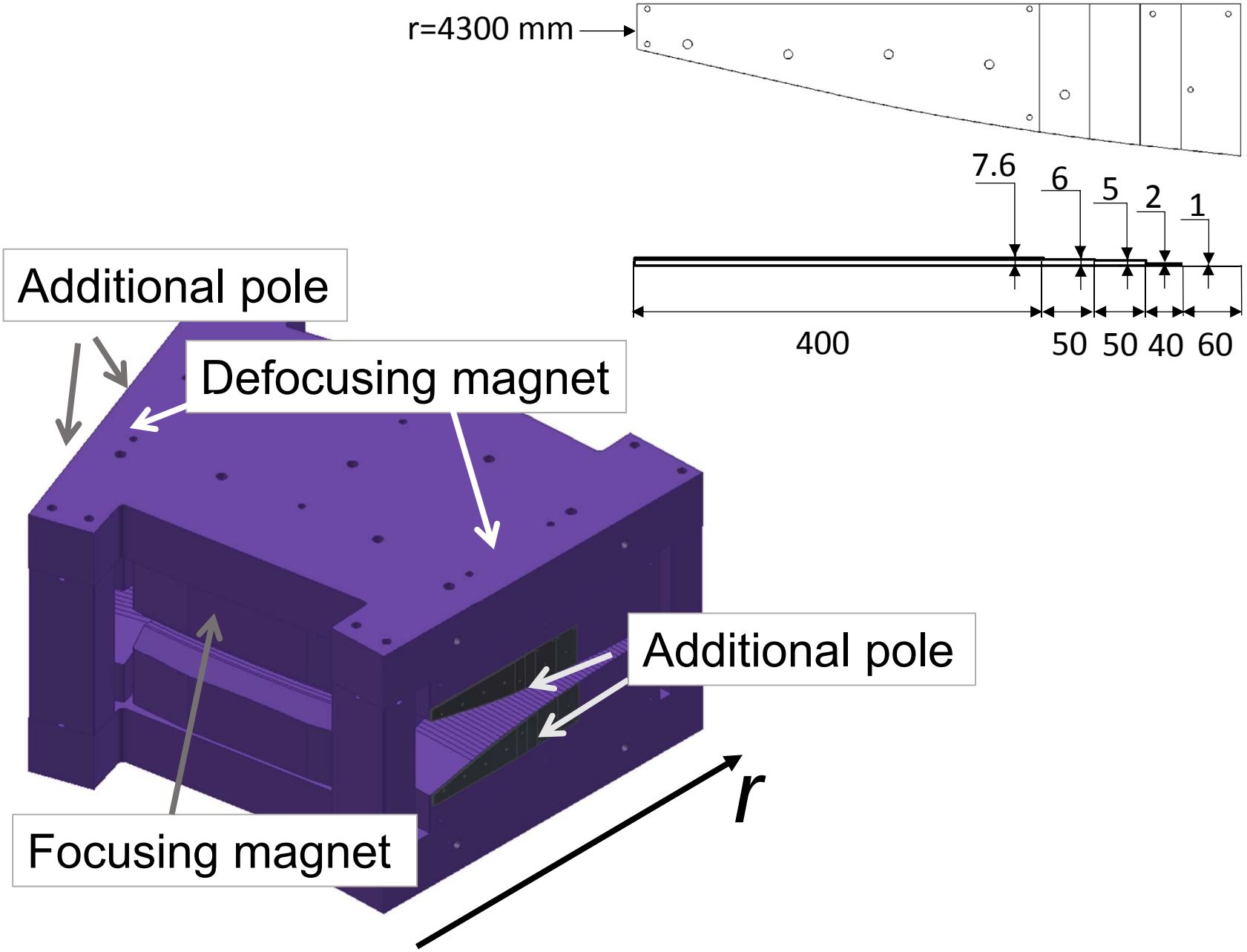
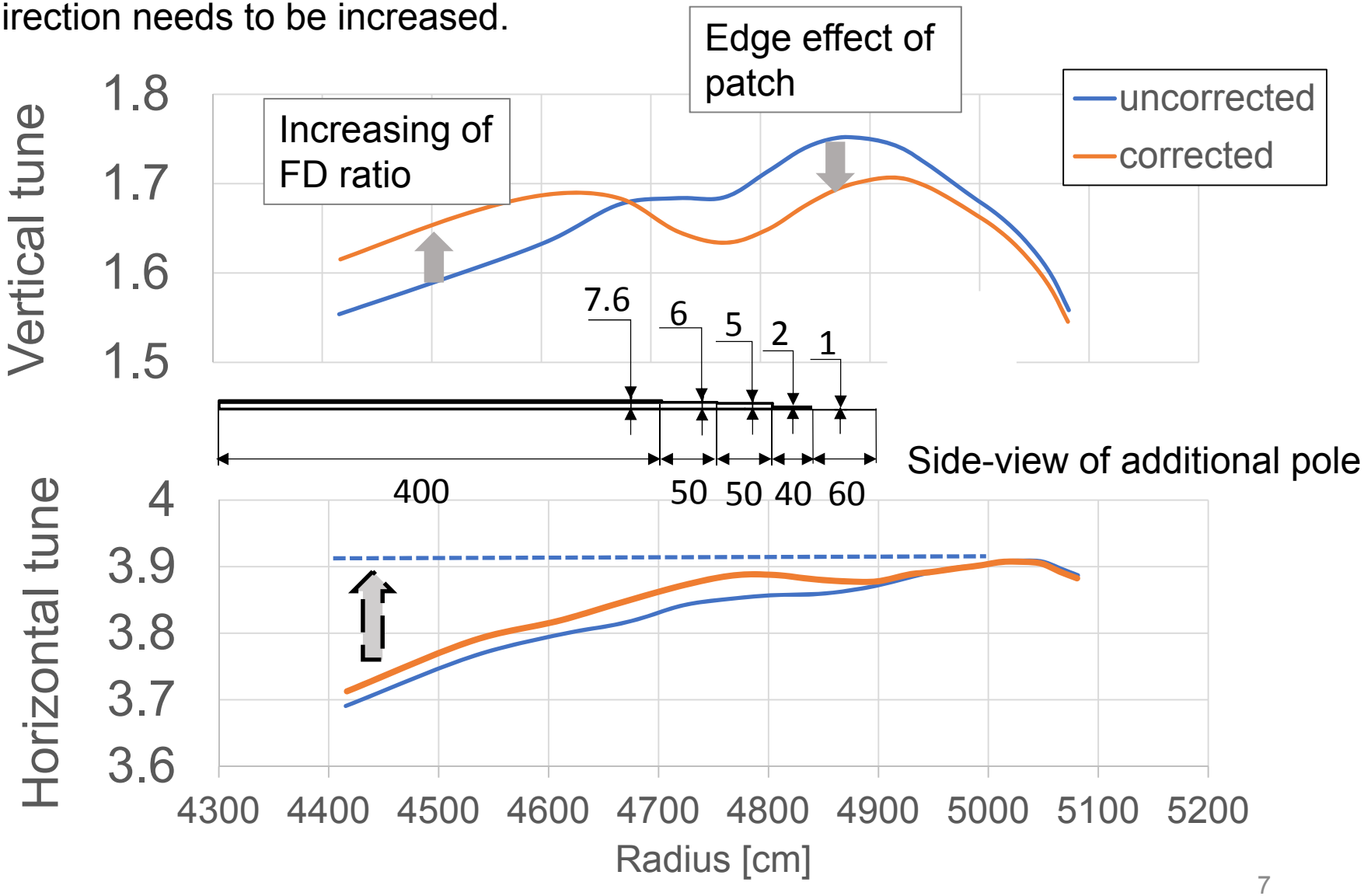
Design of additional pole



Result of tracking simulation

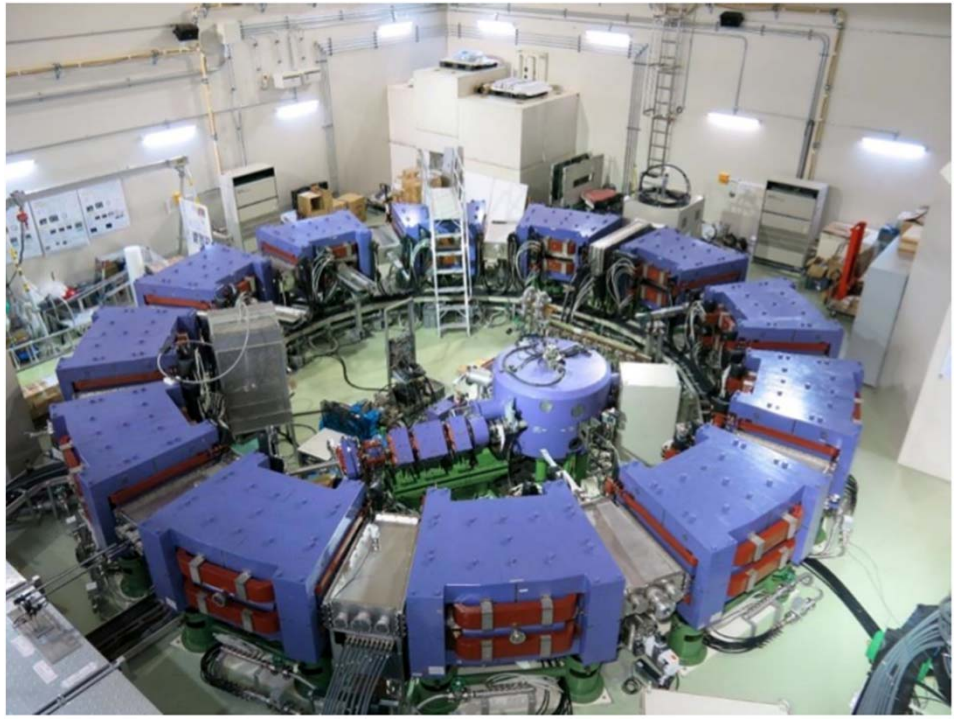
Vertical tune variation was decreased by patches.
For decreasing of horizontal tune variation , the tune inside in a radial direction needs to be increased.



Purpose

Development of pole surface coils to control horizontal betatron tune.

We developed prototypes of pole surface coils for 150 MeV FFAG in Kyushu University.



Overview of 150 MeV FFAG

Pole surface coils

Magnetic field distribution of radial sector type scalling FFAG:

$$B_z(r) = B_0\left(\frac{r}{r_0}\right)^k$$

Series expansion

$$B(r) = B_0[1 + \frac{k}{r_0}(r - r_0) + \frac{k(k+1)}{2r_0^2}(r - r_0)^2 + \cdots]$$

quadrupole sextupole

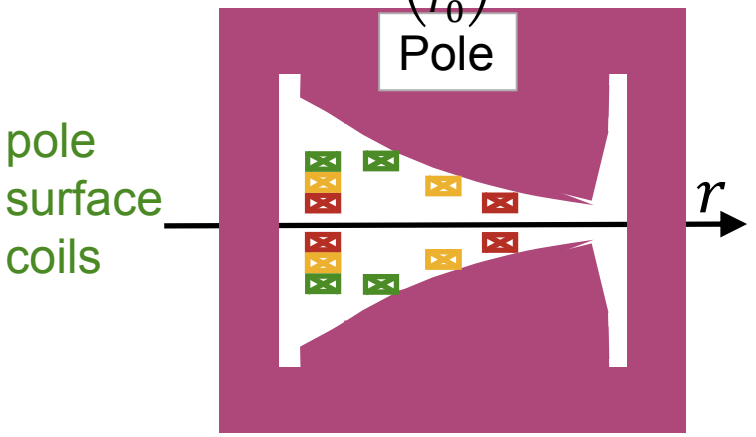
Focusing force elements can be changed by changing field index.

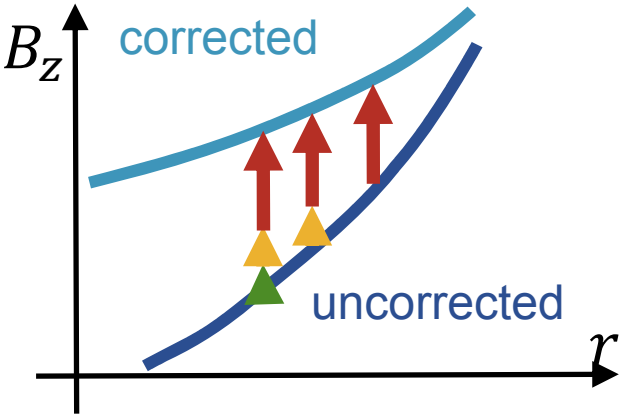
For correction of magnetic field, multiple air-core coils which have different electric currents are arranged in a stepwise shape.

The coils can change focusing force without a change of pole shape during an accelerator operation.

Pole shape(half gap)

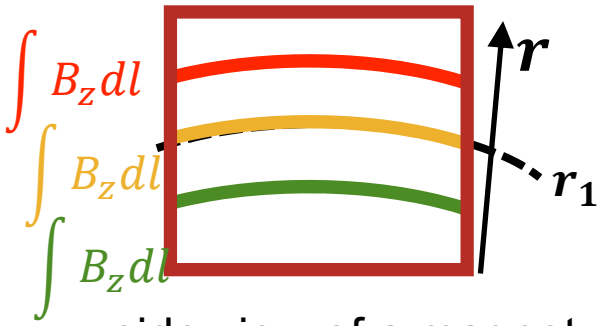
$$g = g_0\left(\frac{r}{r_0}\right)^{-k}$$





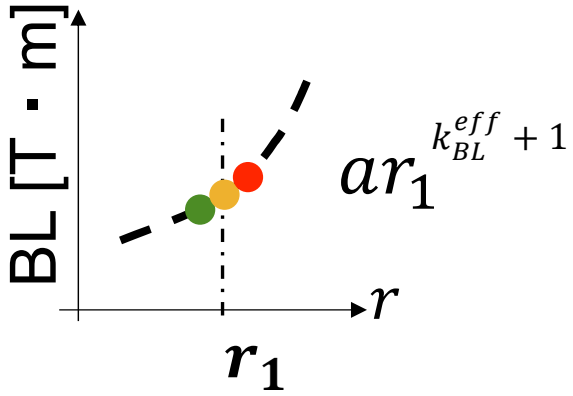
Index for focusing force

BL integral
Integration value
of B_z along circular arc inside
of an electromagnet.



side view of a magnet

Plot and
exponential function fitting

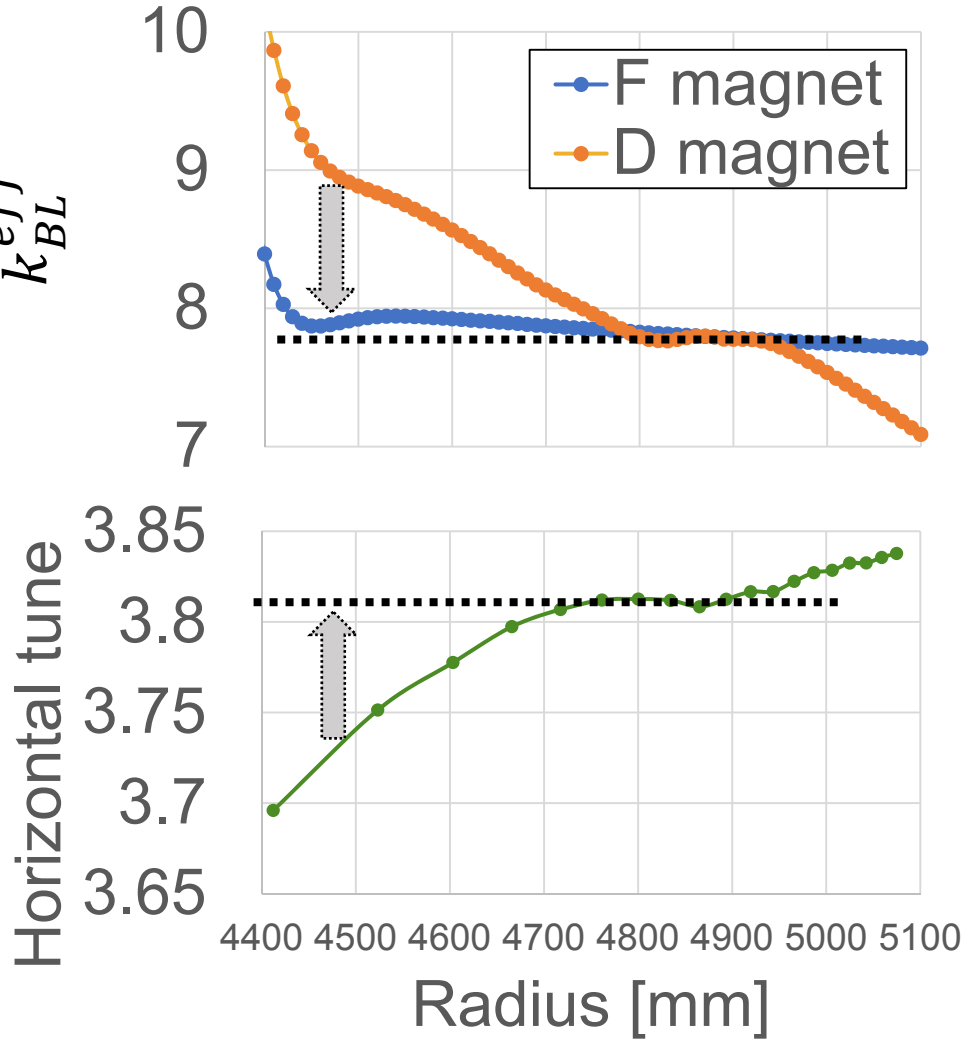


k_{BL}^{eff} is derived as a index of
effective focusing force of
each radius

Design of pole surface coils

v_H changes
in k_{BL}^{eff} of D magnet change area

In order to decrease
horizontal tune variation,
we will correct the k_{BL}^{eff} variation of
defocusing magnets.



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- Evaluation of conditions of 3D magnetic field calculation

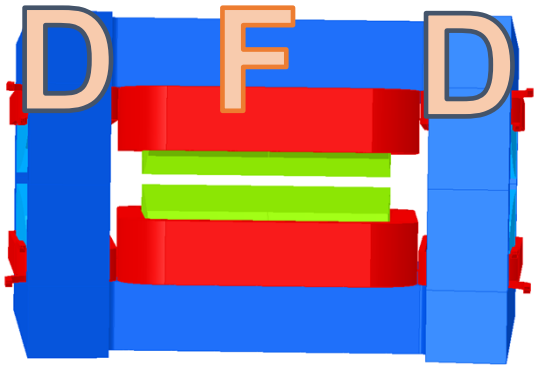
  There are differences of magnetic field between 3D model of 150 MeV FFAG in TOSCA and actual machine. Before design of the coils, how much of effects made by change of calculation condition were evaluated.

- Design of pole surface coils
- Measurement of magnetic field distribution

Evaluation of shapes of main coils

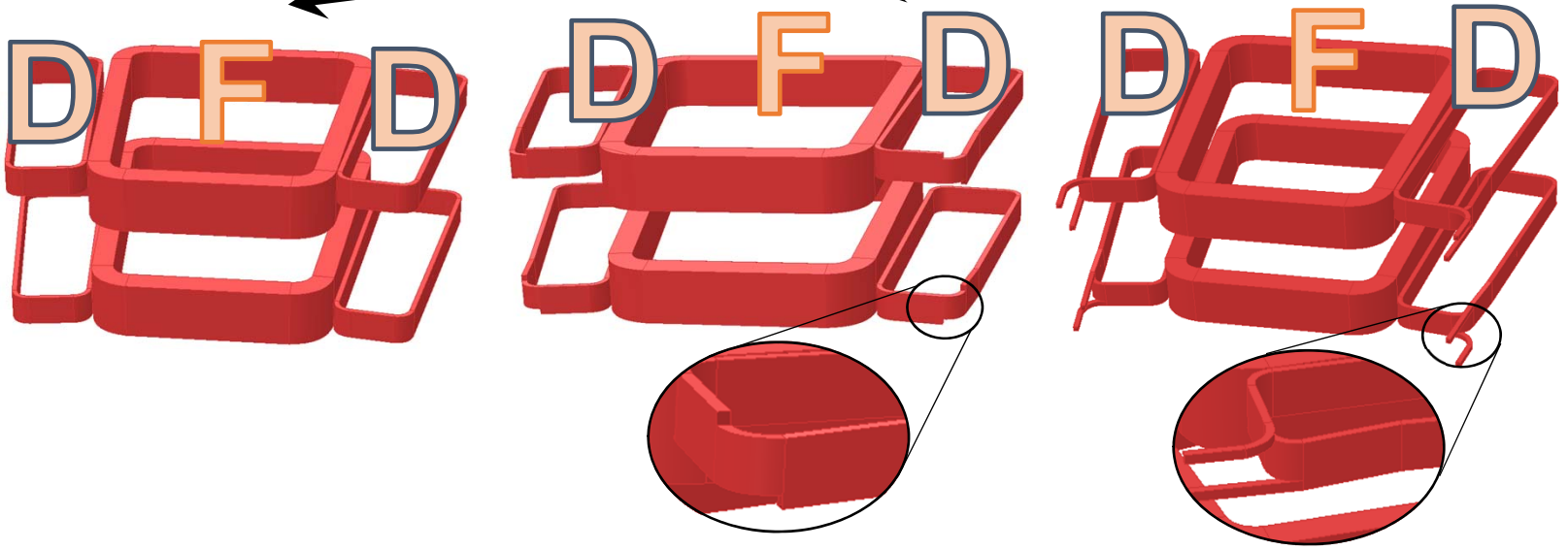
Effect of shapes of main coils on B_z and k_{BL}^{eff} was evaluated.

Three patterns of the shapes were compared.



Front view of DFD triple

Shapes of main coils were changed



Simple race track

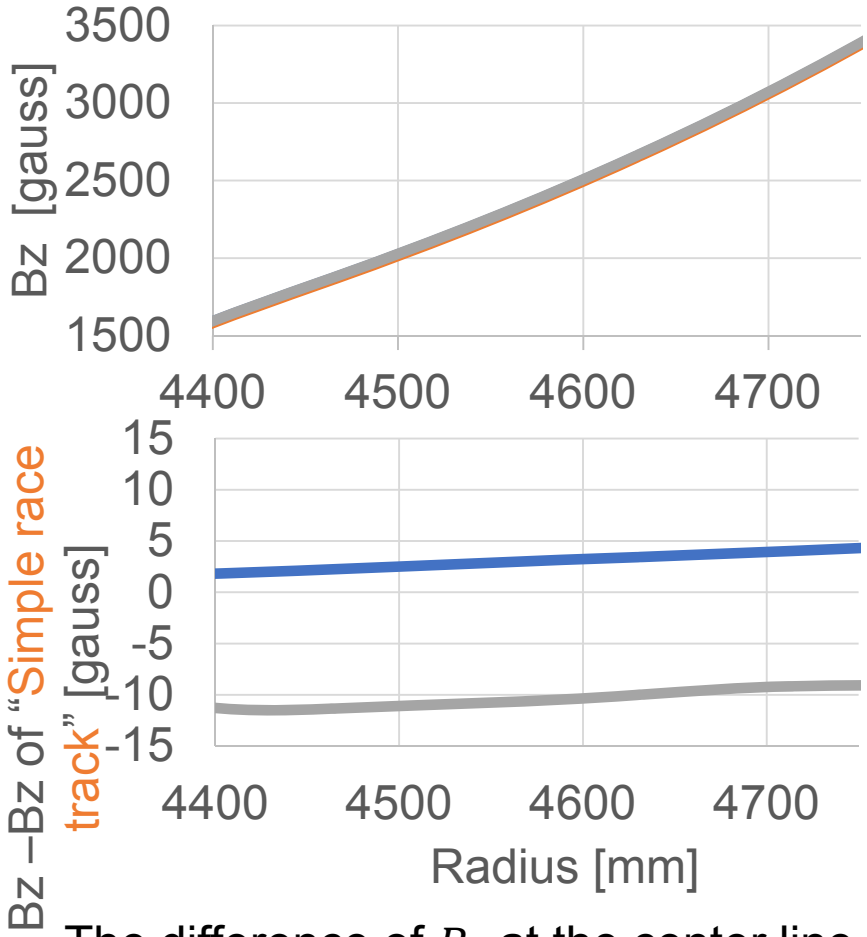
With more real shape

With more real shape and feeder

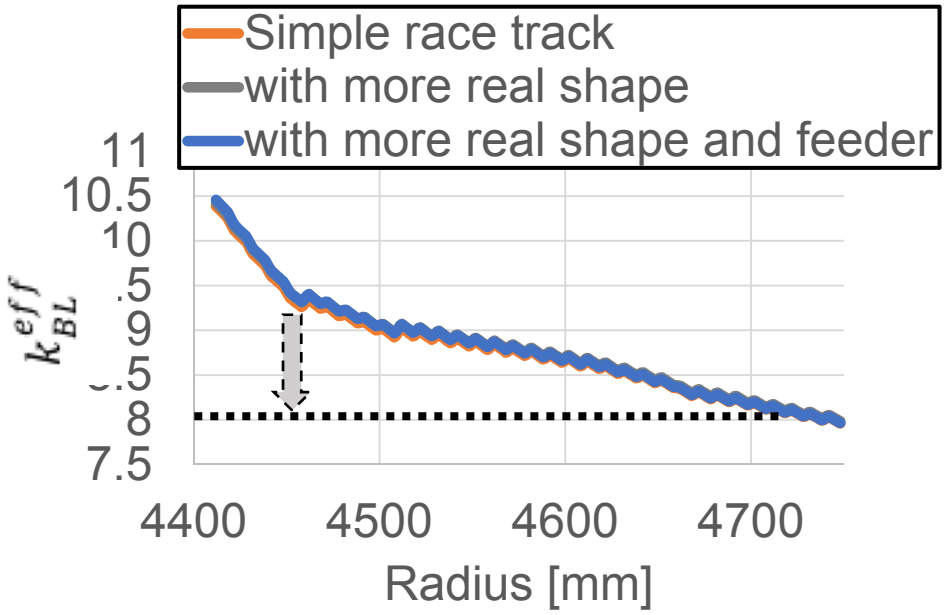
Calculation results of comparison of B_z and k_{BL}^{eff}

B_z and k_{BL}^{eff} about each coil shape were compared respectively.

Shown range of radius is an area where D magnets needs correction of k_{BL}^{eff} .



The difference of B_z at the center line of D magnet between the shapes was less than **15 [gauss]**.



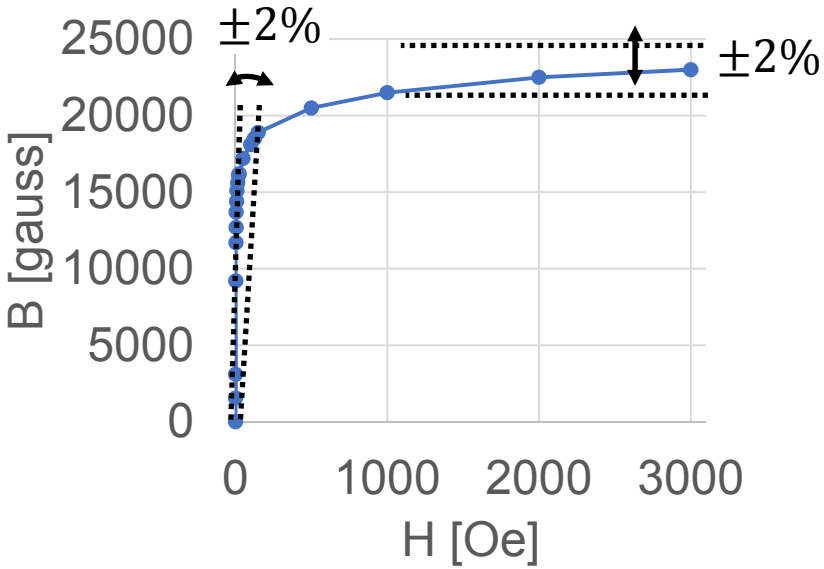
The difference of k_{BL}^{eff} was less than **0.06**.

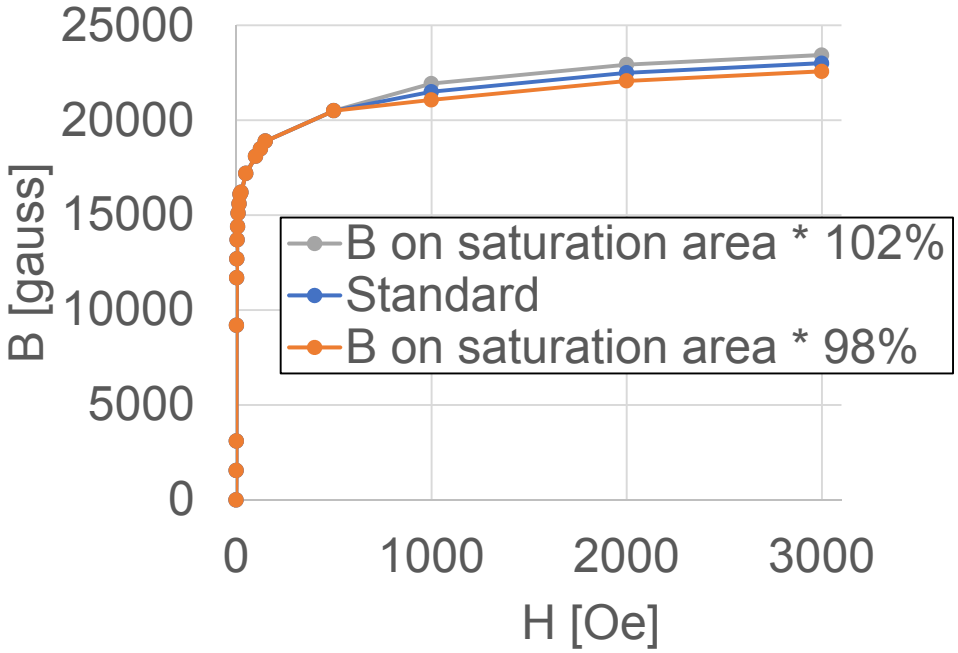
(The amount of k_{BL}^{eff} correction required in D magnets was about **1.0**)

Evaluation of BH curve

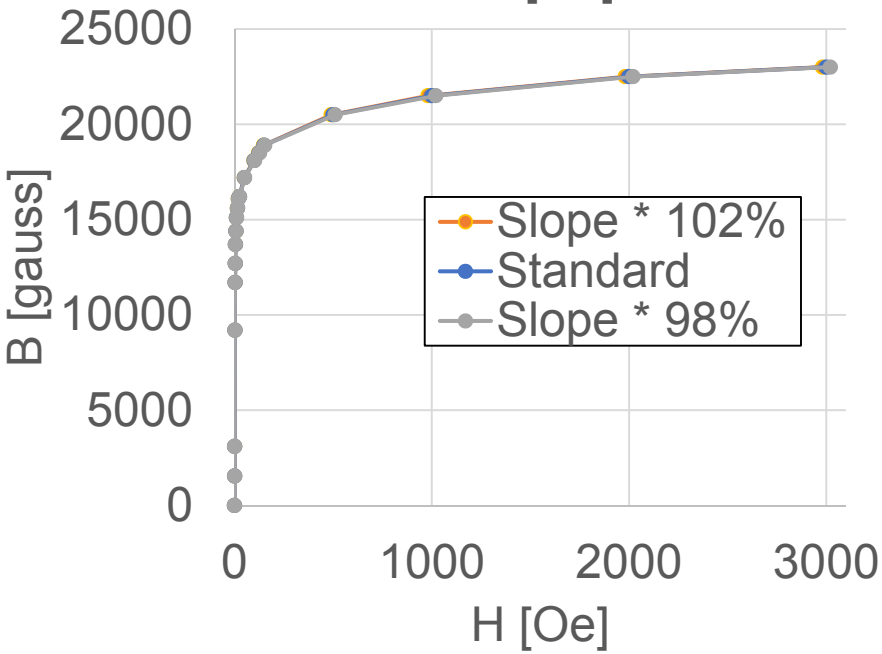
Effect of shapes of main coils on B_z and k_{BL}^{eff} was evaluated.

Slope of BH curve on a linear area (magnetic permeability) and value of B on a saturation area were changed respectively by $\pm 2\%$.



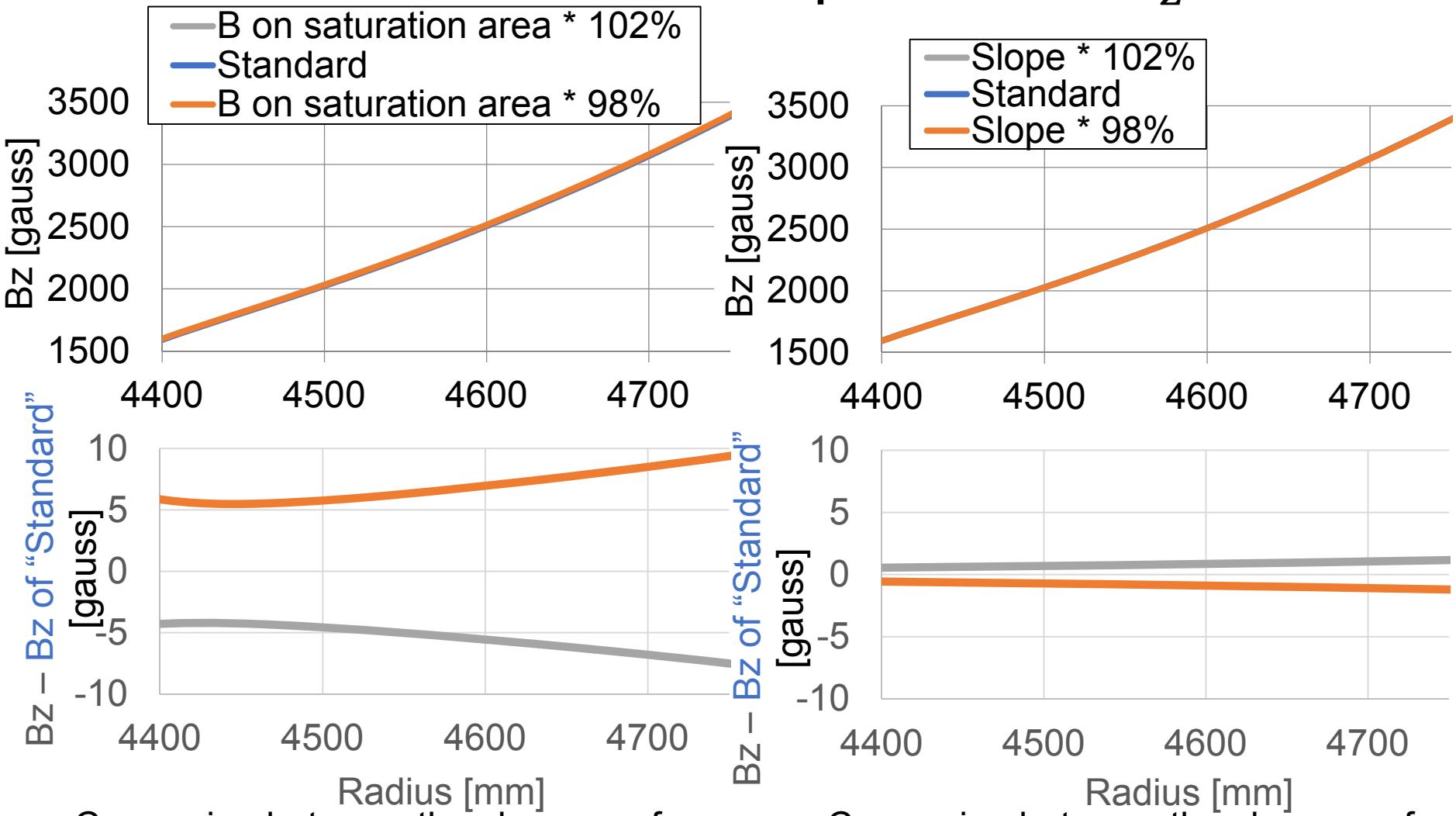


Change of B on saturation area



Change of B slope on linear area

Calculation results of comparison of B_z

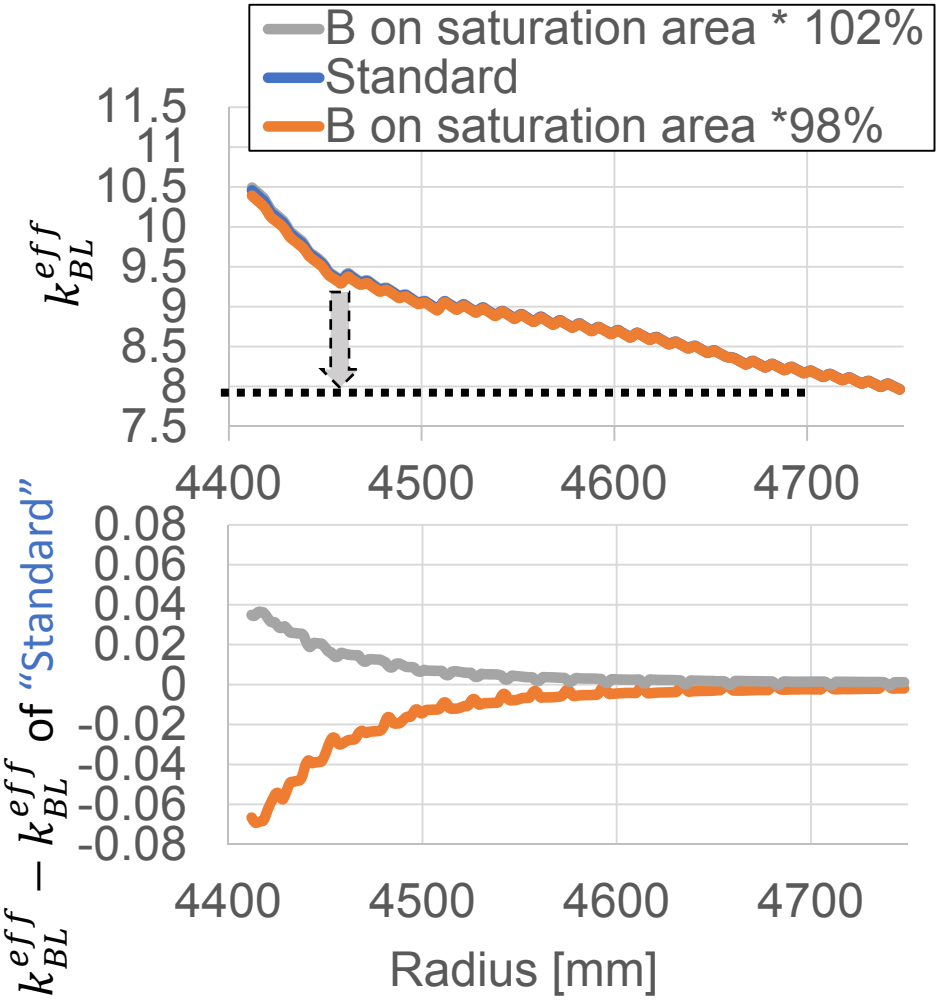


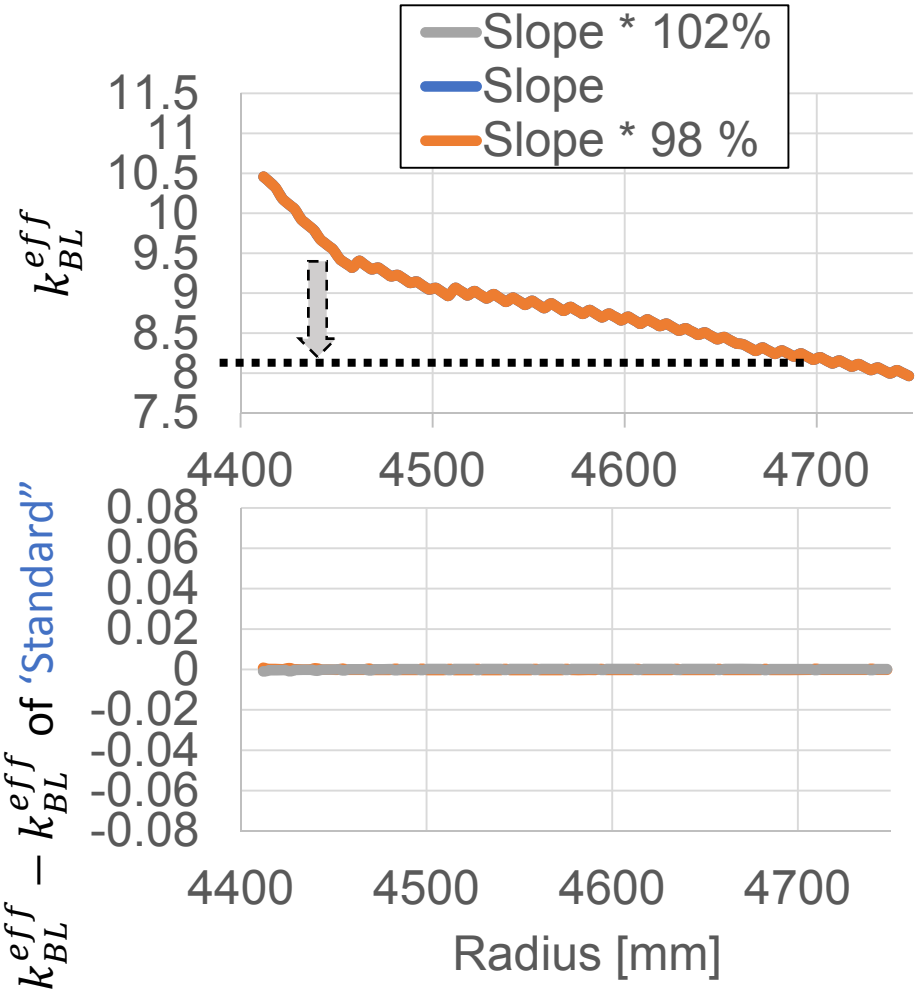
Comparing between the changes of **saturation**

Comparing between the changes of **slope**

The change of saturation was more dominant than slope.
The change of Bz at the center line of D magnet was less than **10 [gauss].**

Calculation results of comparison of k_{BL}^{eff}





Comparing between the changes of **saturation**

Comparing between the changes of **slope**

The difference of k_{BL}^{eff} was less than **0.08**.

(The amount of k_{BL}^{eff} correction required in D magnets about **1.0**)

Evaluation of BH curve

Although B_z was changed by changes of shapes of main coils and BH curve were small, the change of k_{BL}^{eff} were small with respect to the amount of k_{BL}^{eff} correction required in D magnet.

It is seemed k_{BL}^{eff} calculated from the result of TOSCA show partly actual k_{BL}^{eff} and a design of pole surface coils with k_{BL}^{eff} and TOSCA will be achieved.

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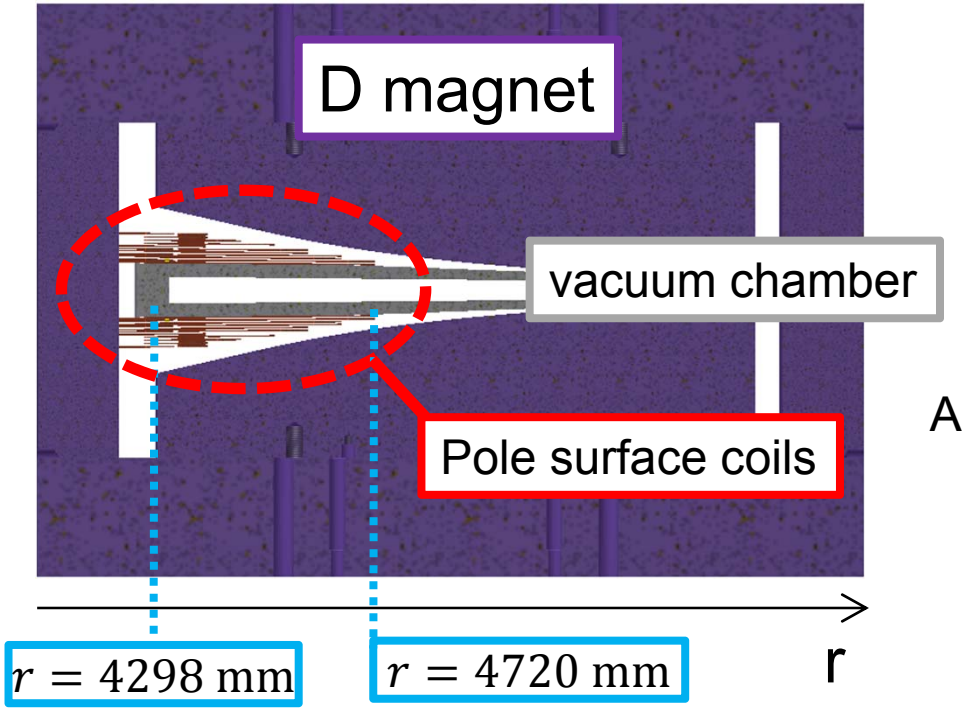
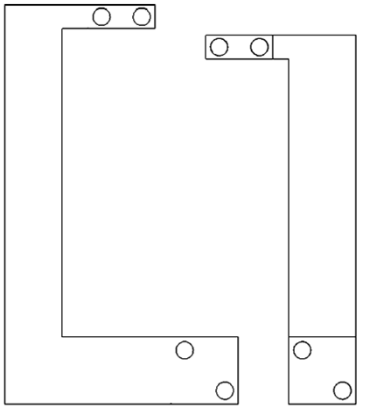
Design of pole surface coils





Material:
Oxygen-free copper

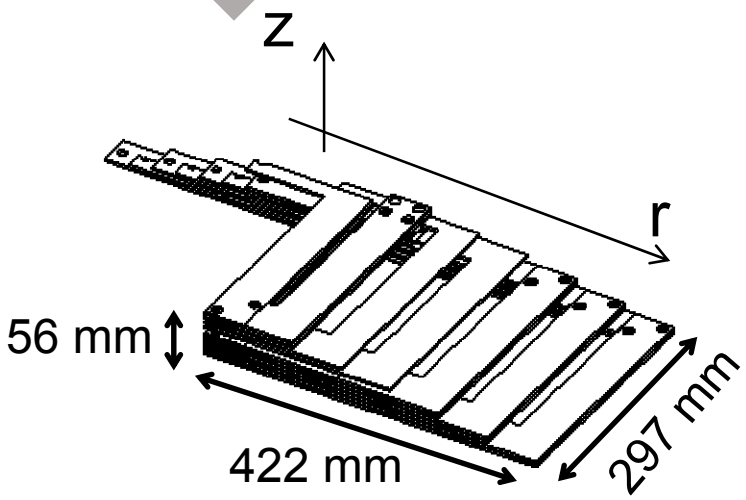
3 mm

50 mm

Cross section

A set of 1 turn air-core coil

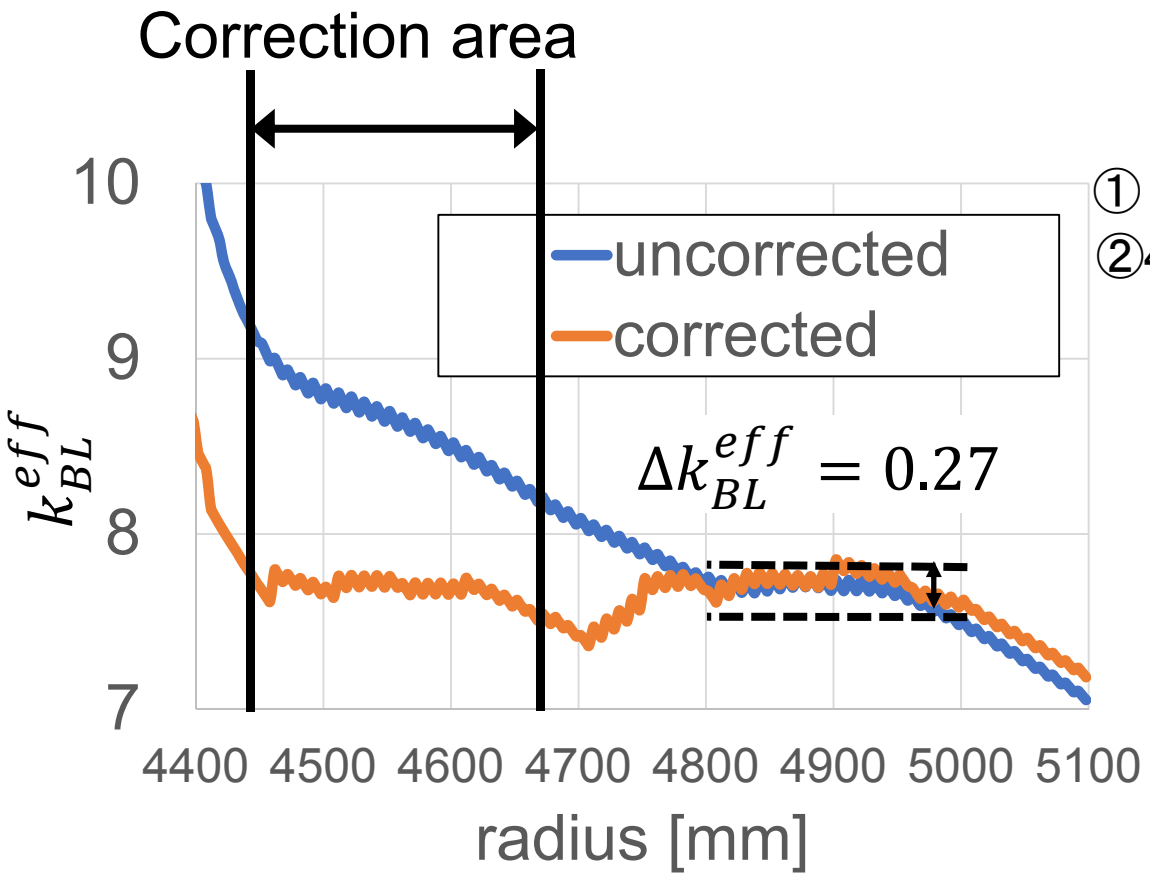
Installed and assembled

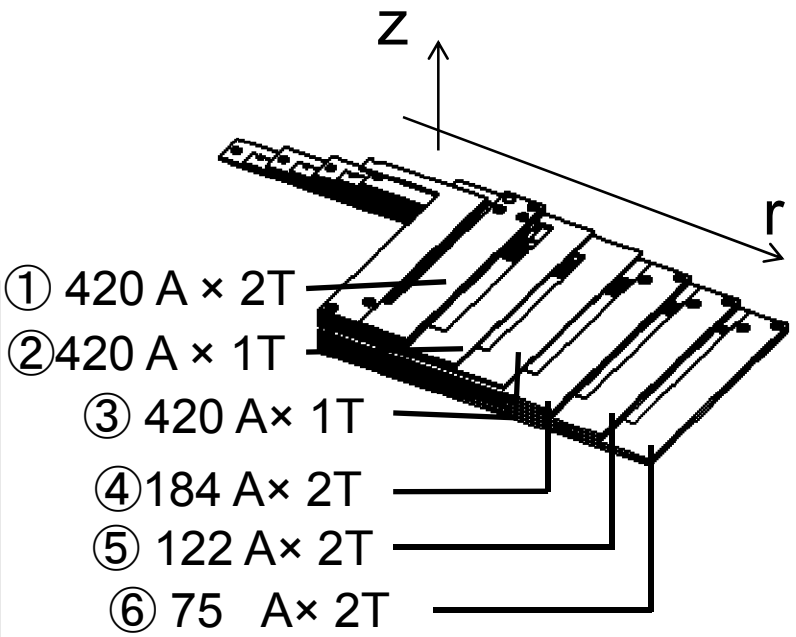


Pole surface coils

6 steps pole surface coils are installed to gaps between defocusing magnets and vacuum chambers.

Calculation result of k_{BL}^{eff}

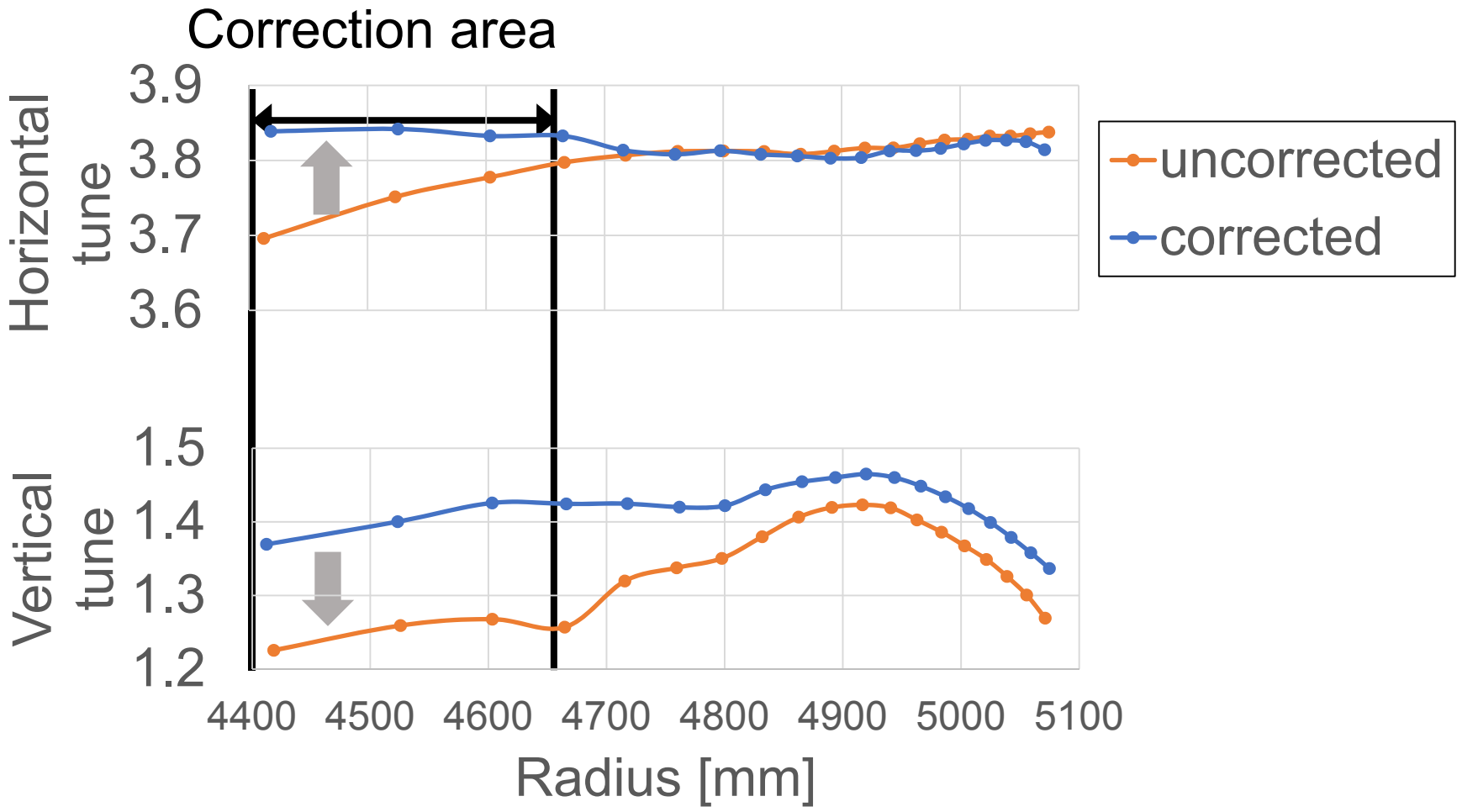




We optimized respective currents of coils
to make Δk_{BL}^{eff} of correction area less than 0.27

uncorrected : $\Delta k_{BL}^{eff} = 1.00 \rightarrow$corrected : $\Delta k_{BL}^{eff} = 0.25$

Result of tracking simulation



Horizontal tune was increased by coils.
Vertical tune was decreased by coils.

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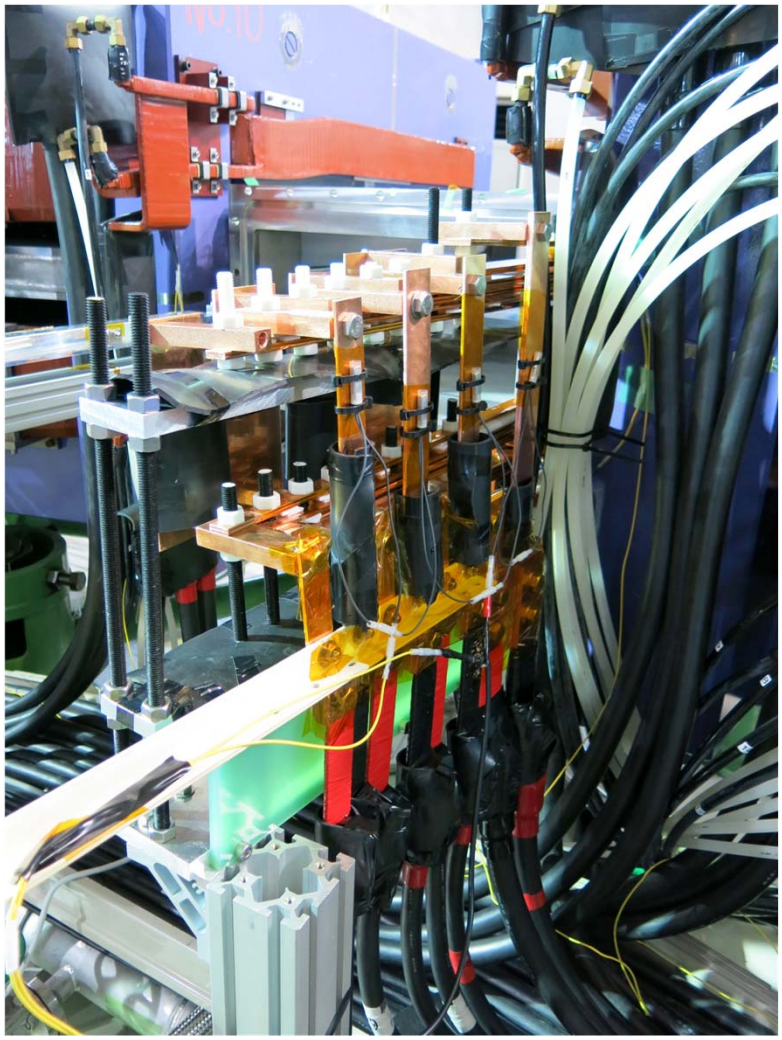
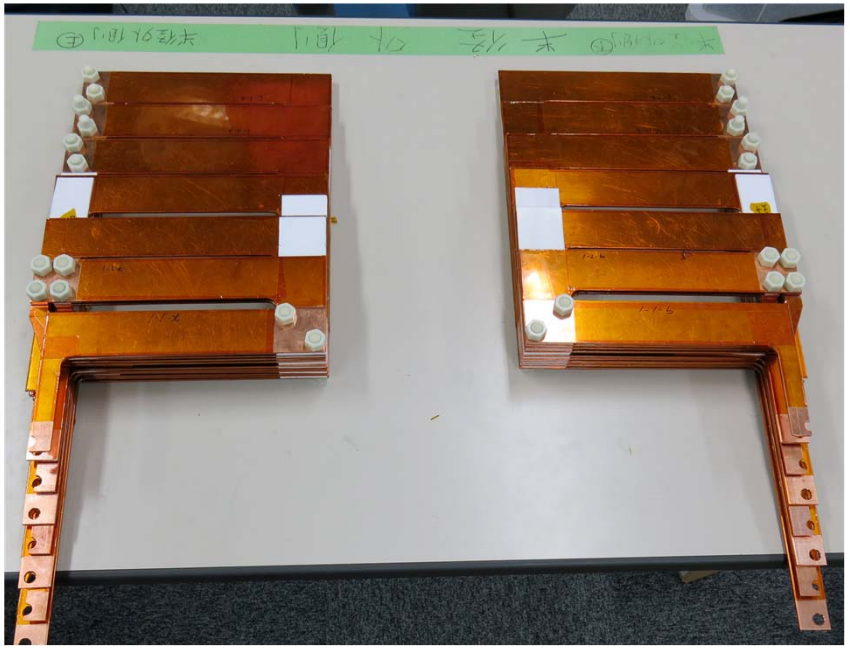
Developed pole surface coils



Feeders of pole surface coils

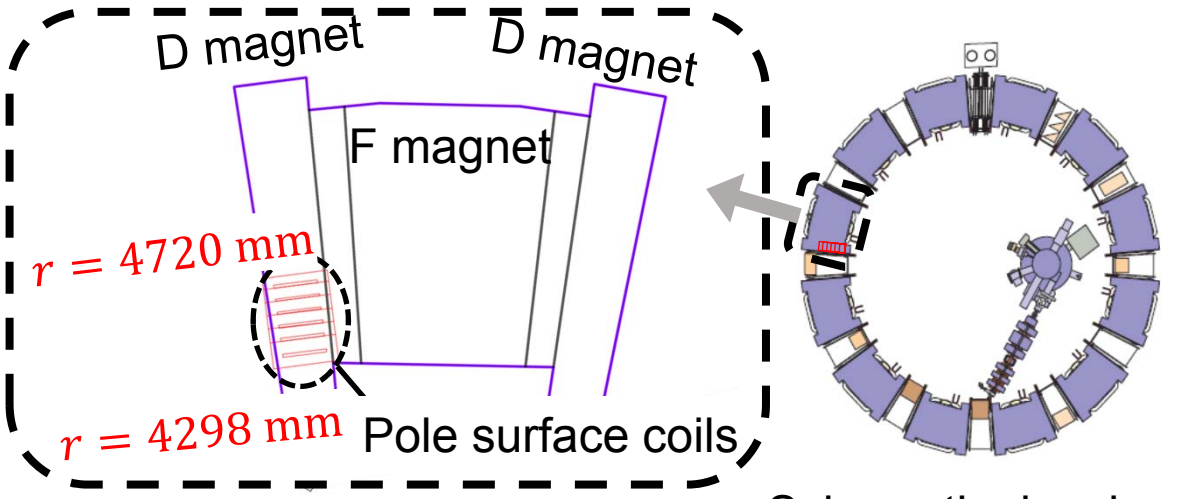


Pole surface coils

Three power supply devices connected to pole surface coils.

The coils are cooled by natural air cooling.

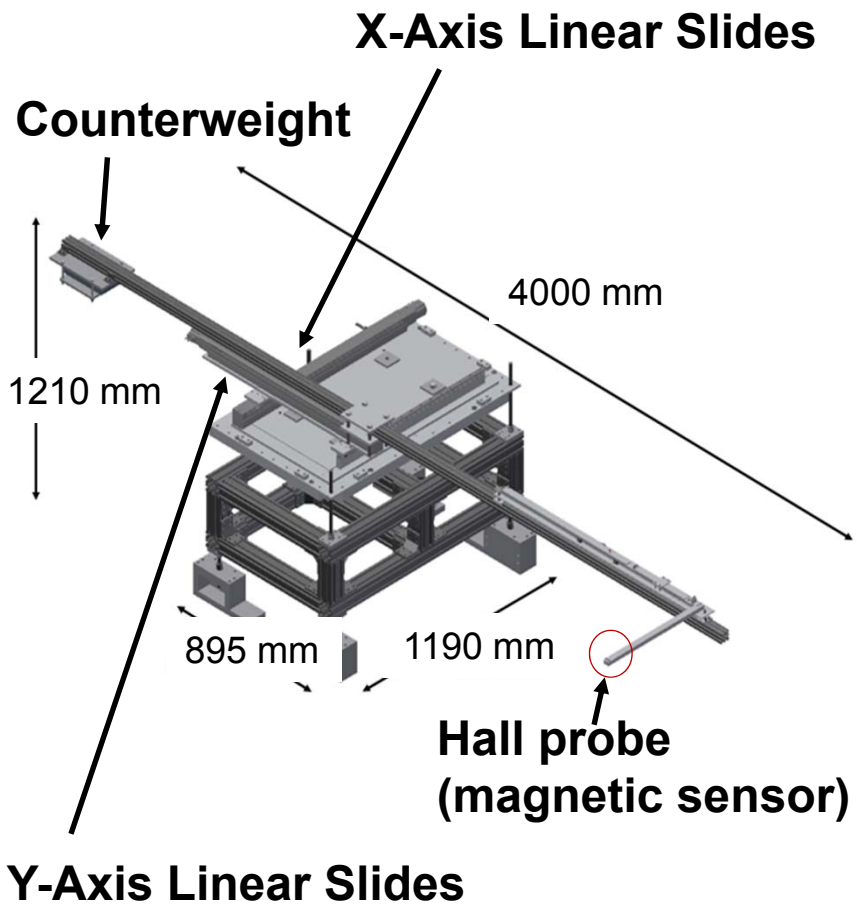
Experimental verification of the principle of the correction method

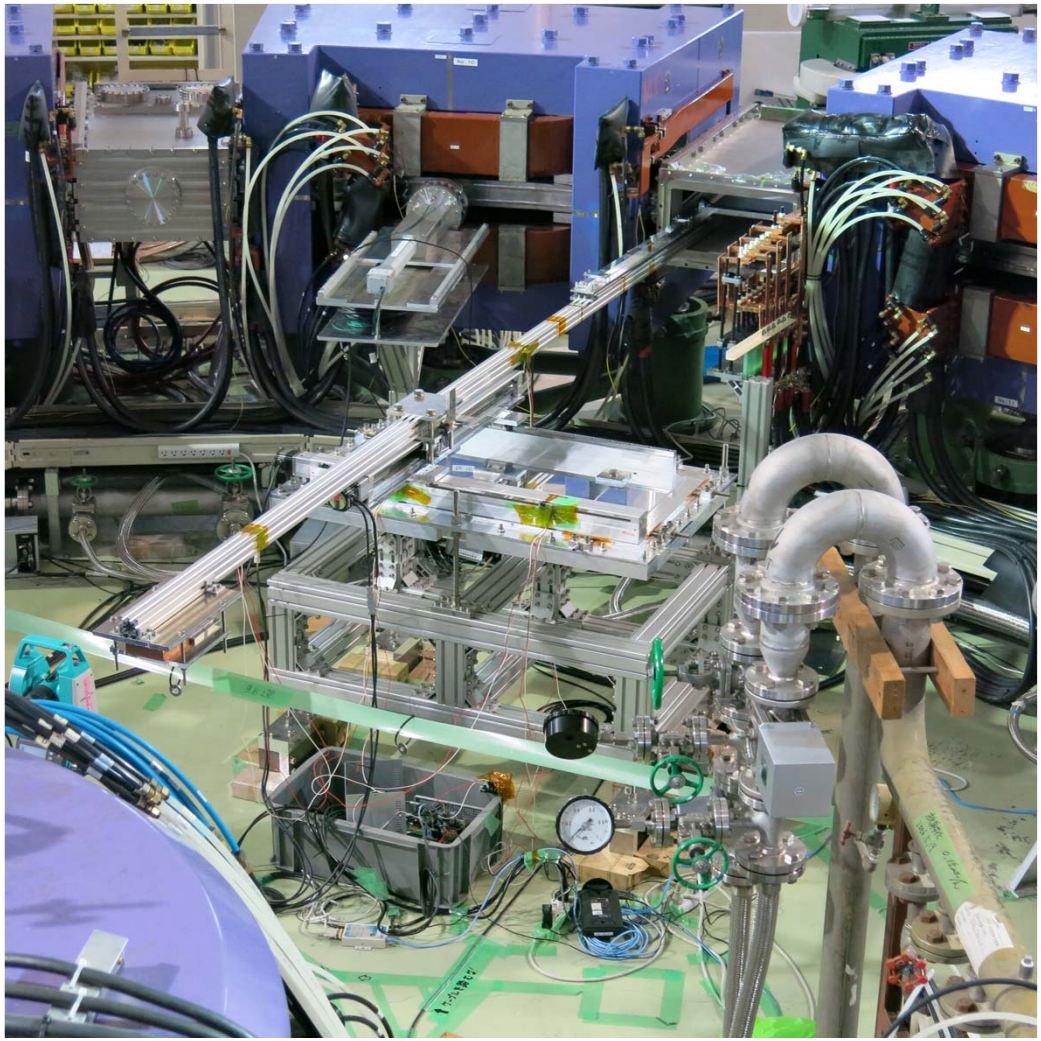


Schematic drawing of 150 MeV FFAG

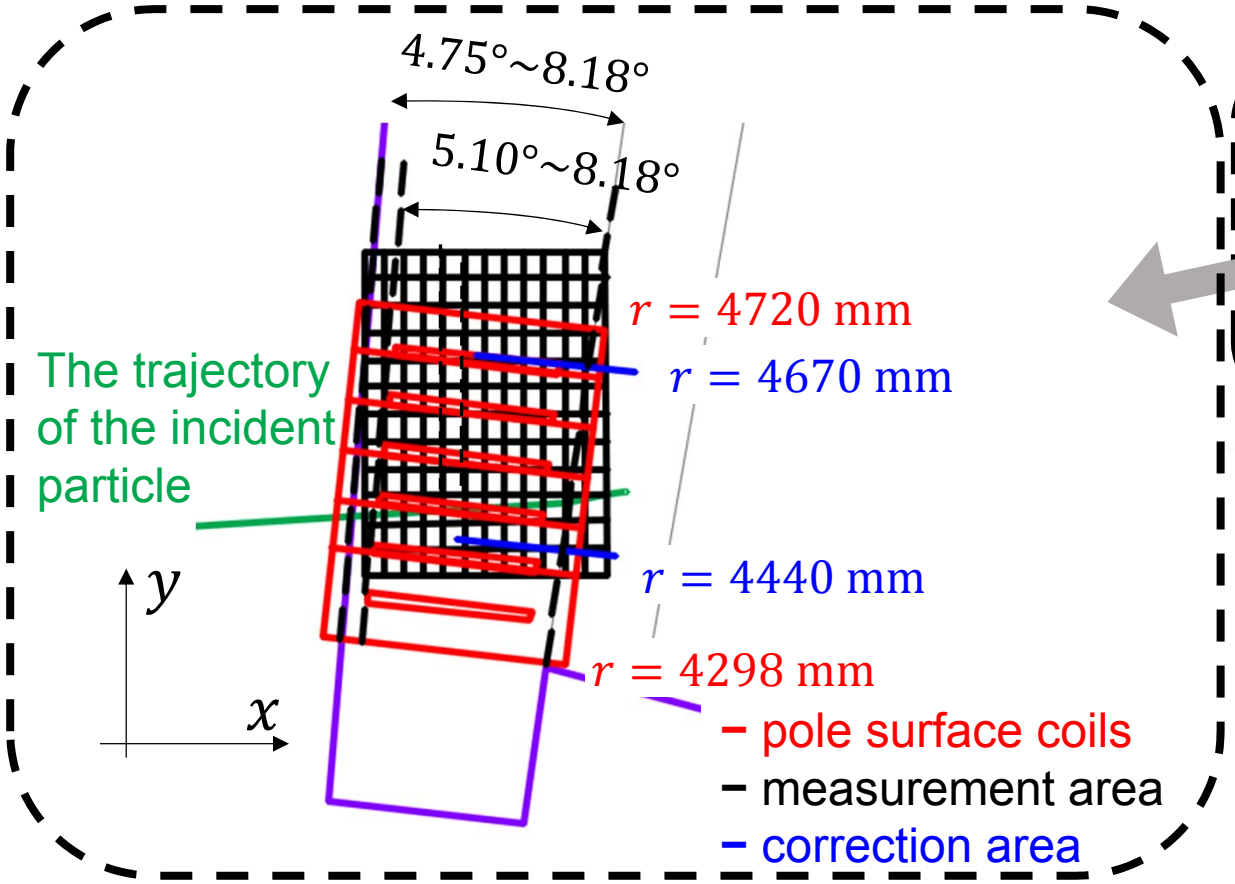
We made one set of pole surface coils and put it to a D magnet of 150 MeV FFAG.
And then, we measured magnetic field.

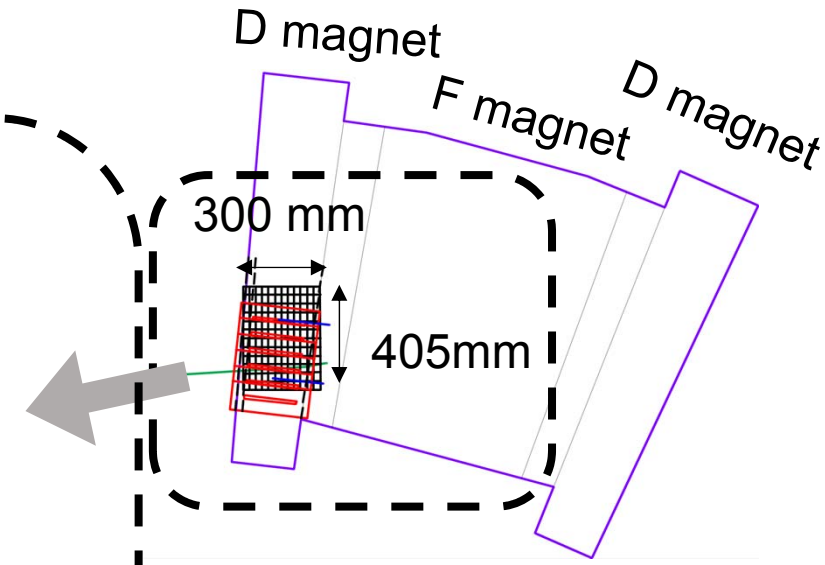
Development of magnetic fields measurement device





Measurement area





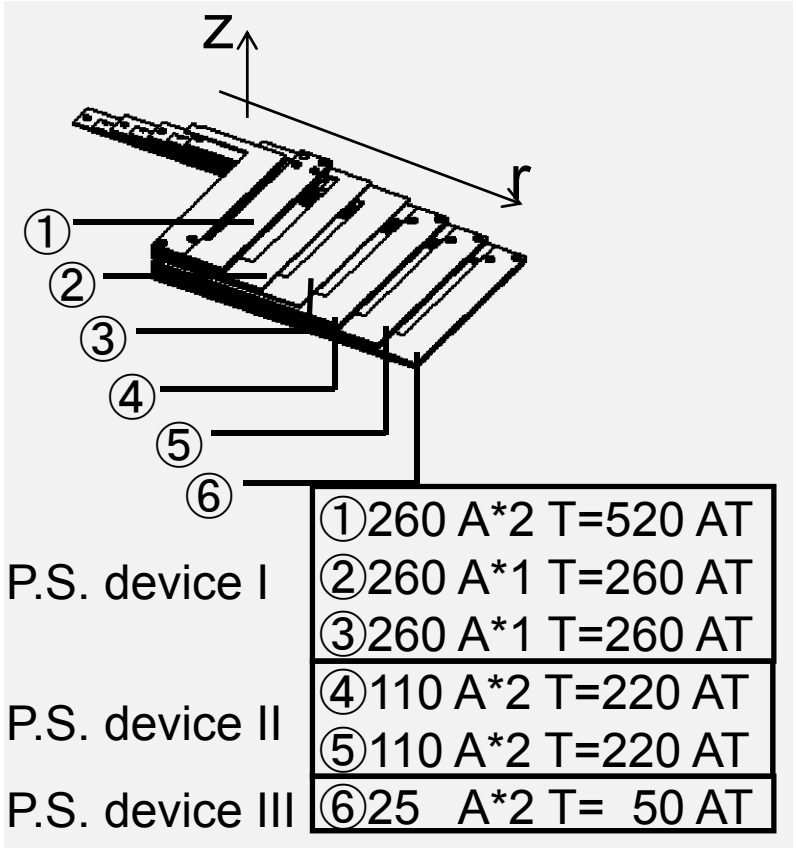
Angle of view [degree]
D magnet : 4.75~8.18
Measurement area : 5.10~8.18

BL was calculated with integration of B_z within measurement area.

Measurement point
13 points × 13 points

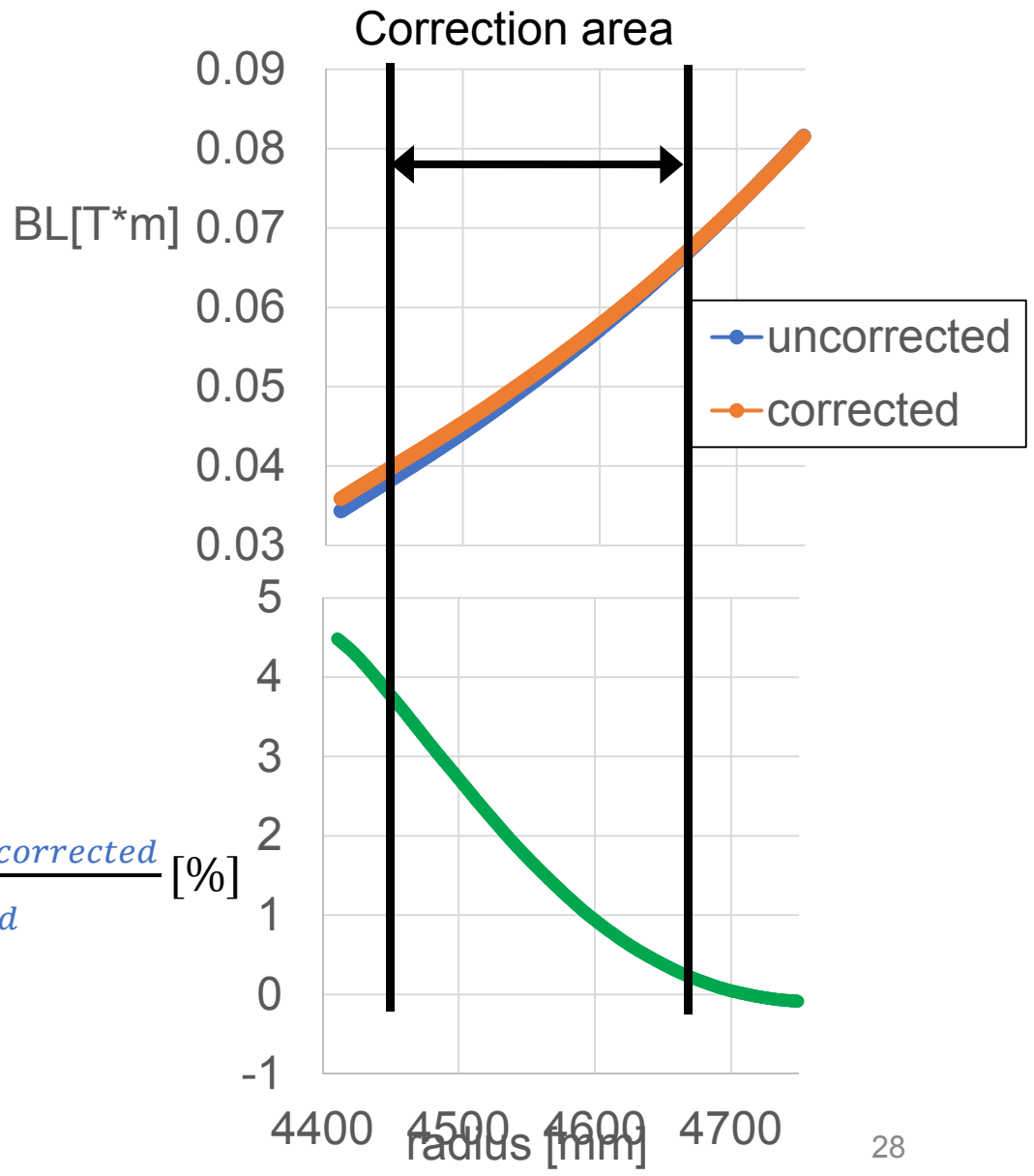
Measurement mesh size
X: 25 mm Y:33.75 mm

The result of measured BL integral



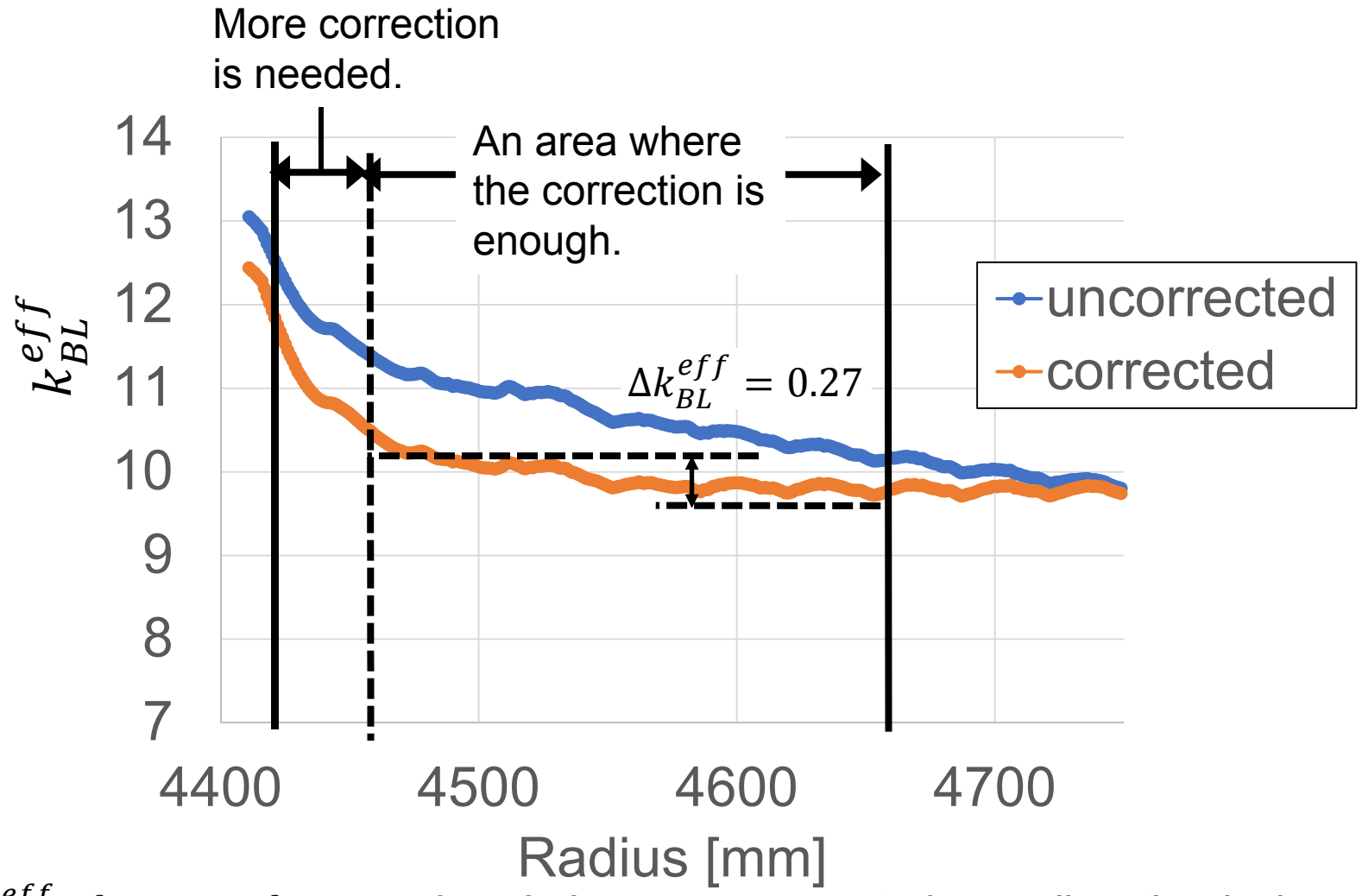
P.S. device I	①260 A*2 T=520 AT
	②260 A*1 T=260 AT
	③260 A*1 T=260 AT
P.S. device II	④110 A*2 T=220 AT
	⑤110 A*2 T=220 AT
P.S. device III	⑥25 A*2 T= 50 AT

$$\frac{BL_{corrected} - BL_{uncorrected}}{BL_{uncorrected}} [\%]$$



The result of measured k_{BL}^{eff}

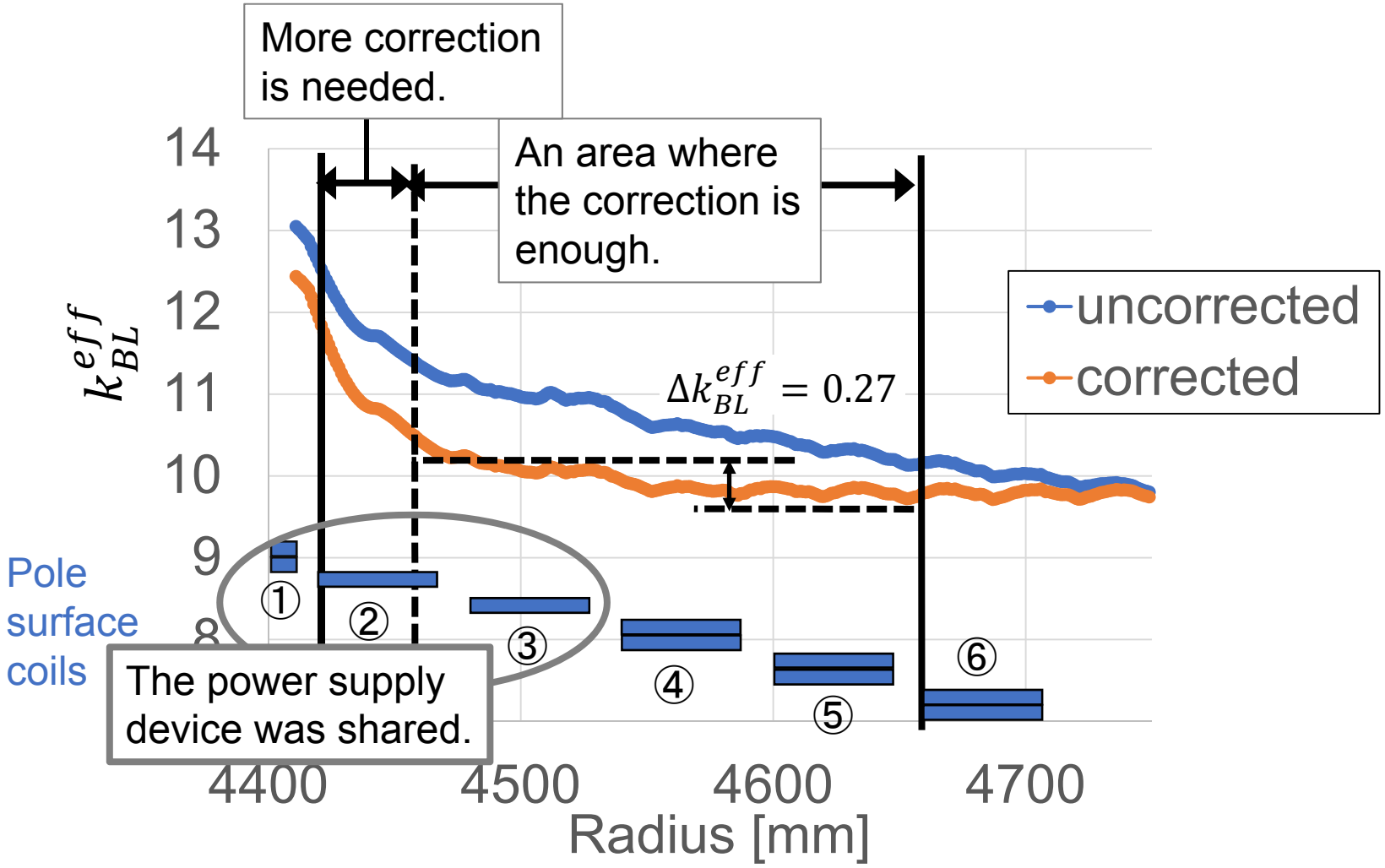
k_{BL}^{eff} was calculated with exponential fitting to 3 points of calculated BL integral.



k_{BL}^{eff} of an area from 4470～4670 mm was corrected as well as the design, $\Delta k_{BL}^{eff} = 0.27$.

The result of measured k_{BL}^{eff}

k_{BL}^{eff} was calculated with exponential fitting to 3 points of calculated BL.



If variation of currents of coil①, ②, and ③ are prepared or if the number of turn of those three coils are optimized, all of the correction area will be actually corrected.

Summary

- In this research, k_{BL}^{eff} was introduced as in an index of effective focusing force, and correction of focusing force considering the index with air-core coils were proposed.
- Design goal was achieved by experiment at large radius area in the correction area.
- Utility of the method of correction of focusing force with pole surface coils was confirmed.

Work plan

- In order to achieve design goal all of the area where the coils are installed, I will optimize the number of power supply device and turn of each coil and improve the design of the coils.
- I will install 12 sets of improved pole surface coils to 150 MeV, and then will confirm its effect on beams by experiment.