Study of a control method for vertical focusing force by using stair-like additional magnetic poles in the FFA

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Outline

- Introduction
- Purpose
- Principle of focusing force control device
- Evaluation of the parameters on focusing force
- Determination of the shape of the focusing force control device and Beam Experiment Results
- An attempt to radically improve the problem of magnets in the current 150 MeV FFA
- Summary

Focusing force for radial sector type FFA

Approximation formulae for radial sector type FFA[*1]

$$\nu_H \approx \sqrt{1 + k}$$

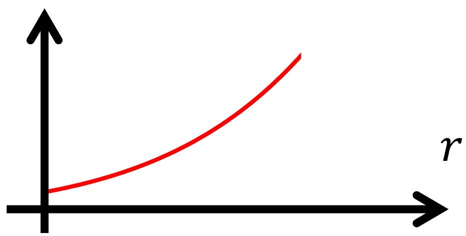
(k : field index)

$$\nu_V \approx \sqrt{-k + F^2}$$

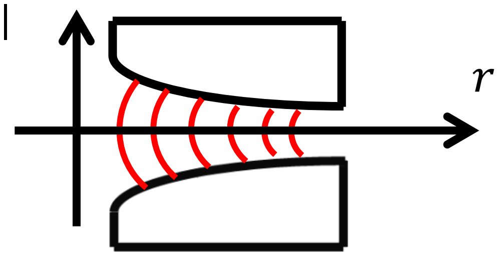
(F : flutter factor)

k : field index

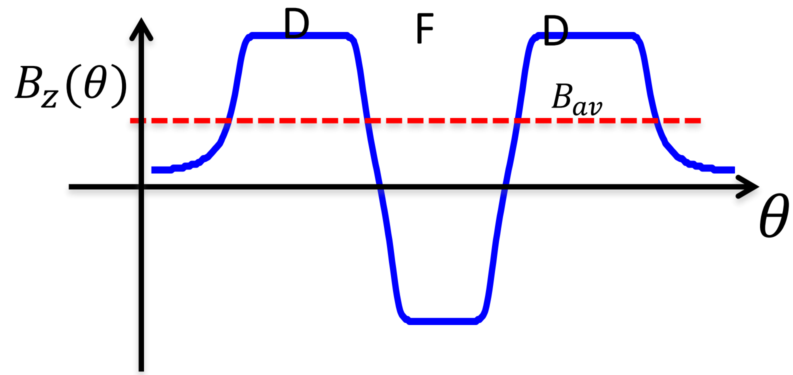
$$B = B_0 \left(\frac{r}{r_0}\right)^k$$



Cross-sectional view of magnet



F : flutter factor

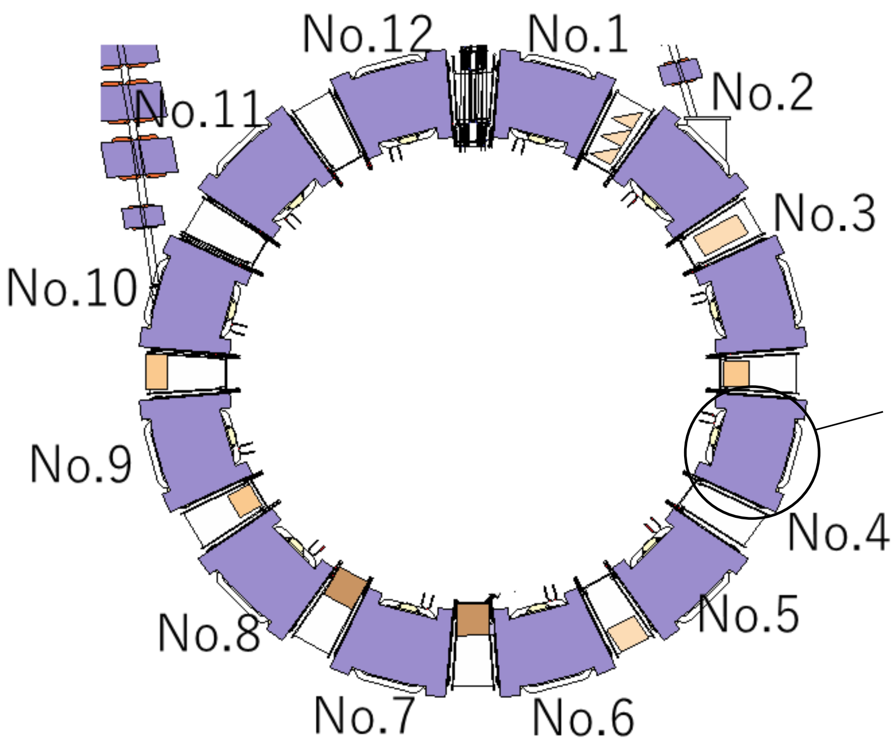


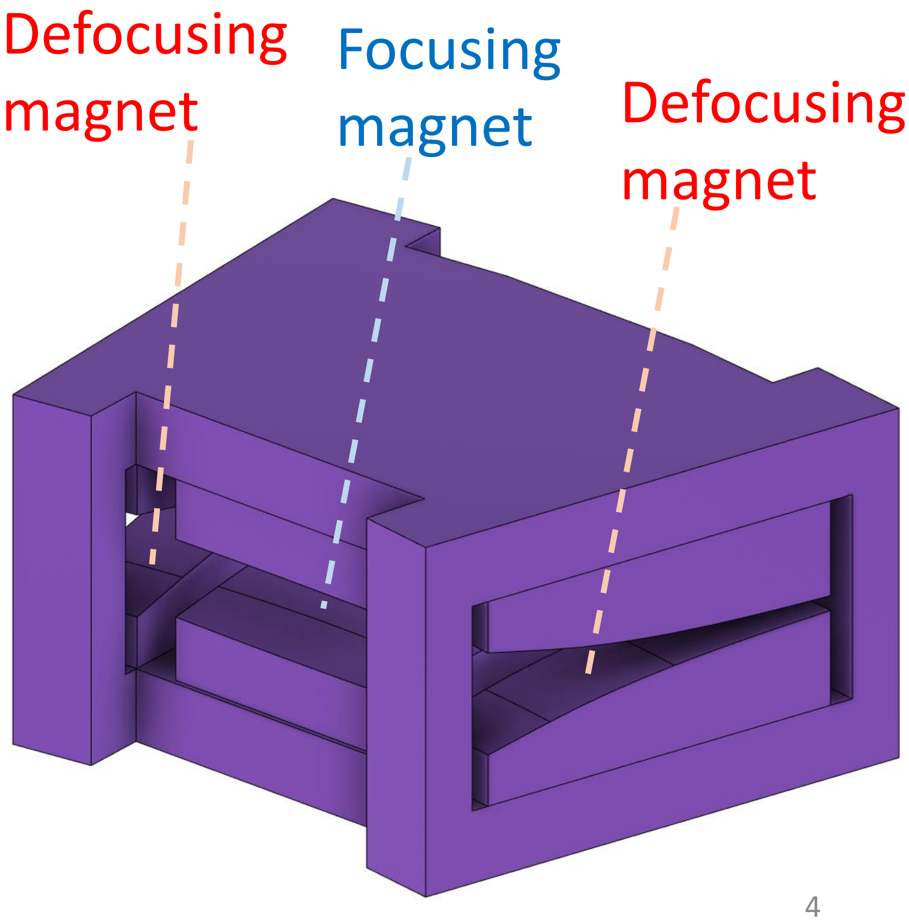
$$F^2 = \left\langle (B - B_{av})^2 \right\rangle / B_{av}^2 \qquad B_{av} = \left\langle B_{(\theta)} \right\rangle$$

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

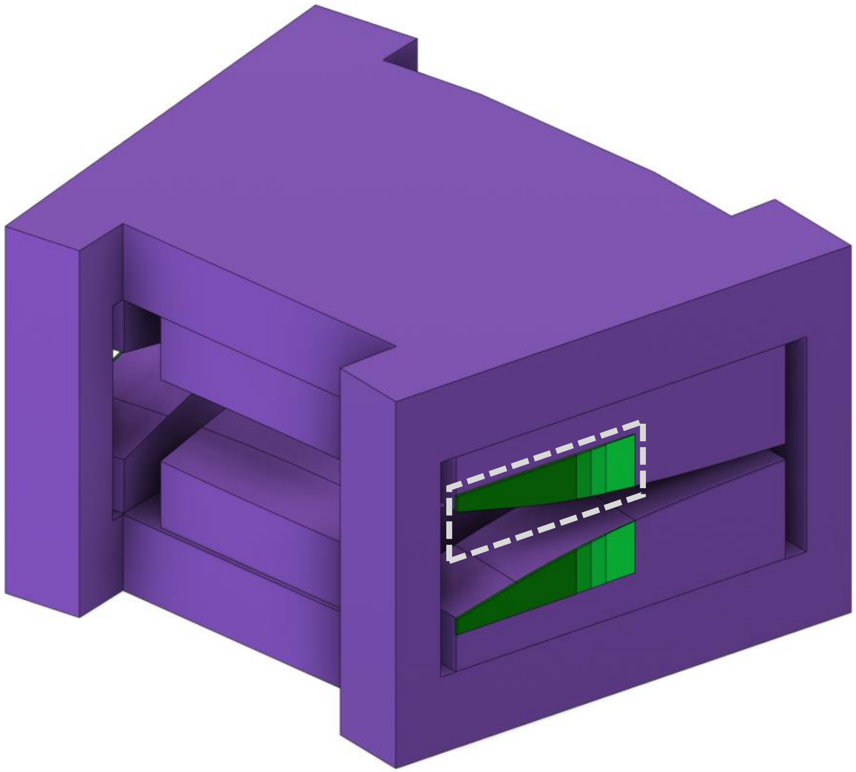
Optics of 150 MeV FFA

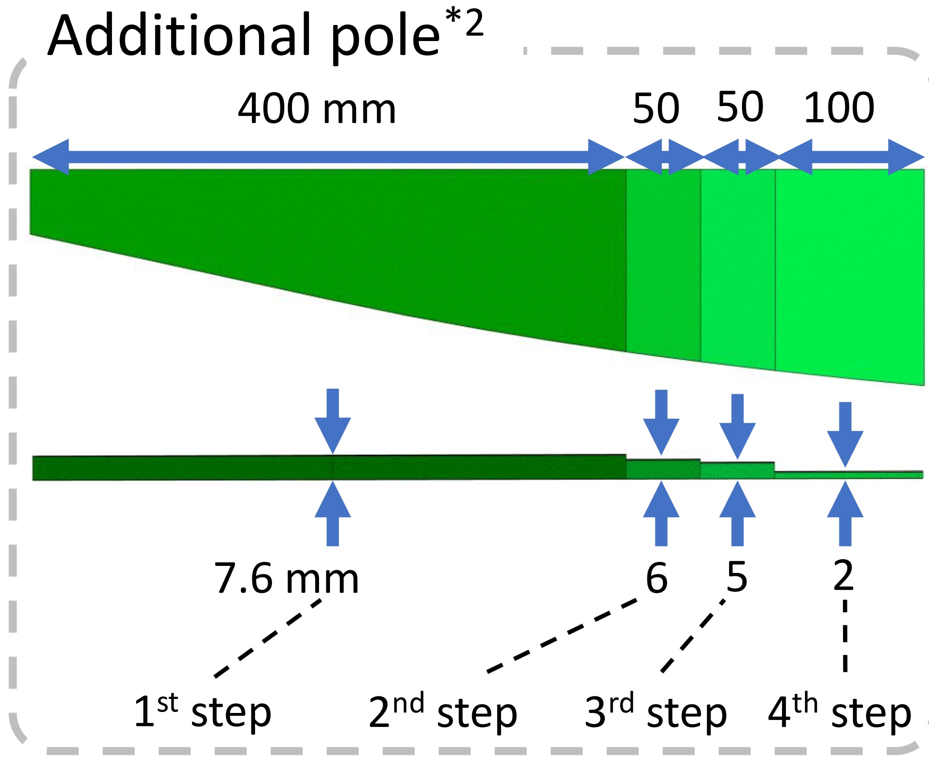
Number of cells	12
Focusing system	DFD triplet magnet
Sector type	Radial sector



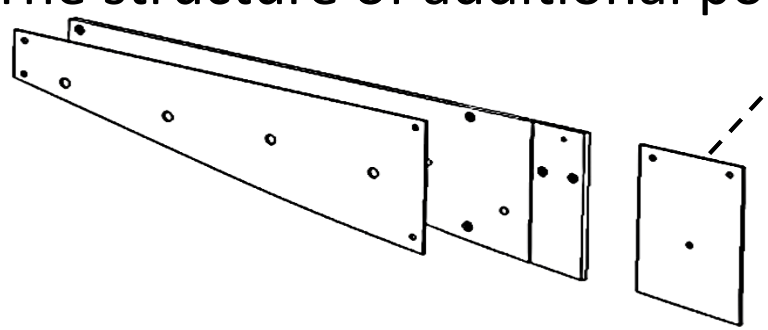


Device for vertical focusing force control





The structure of additional poles



4th step additional pole can be replaced with ones of different thickness

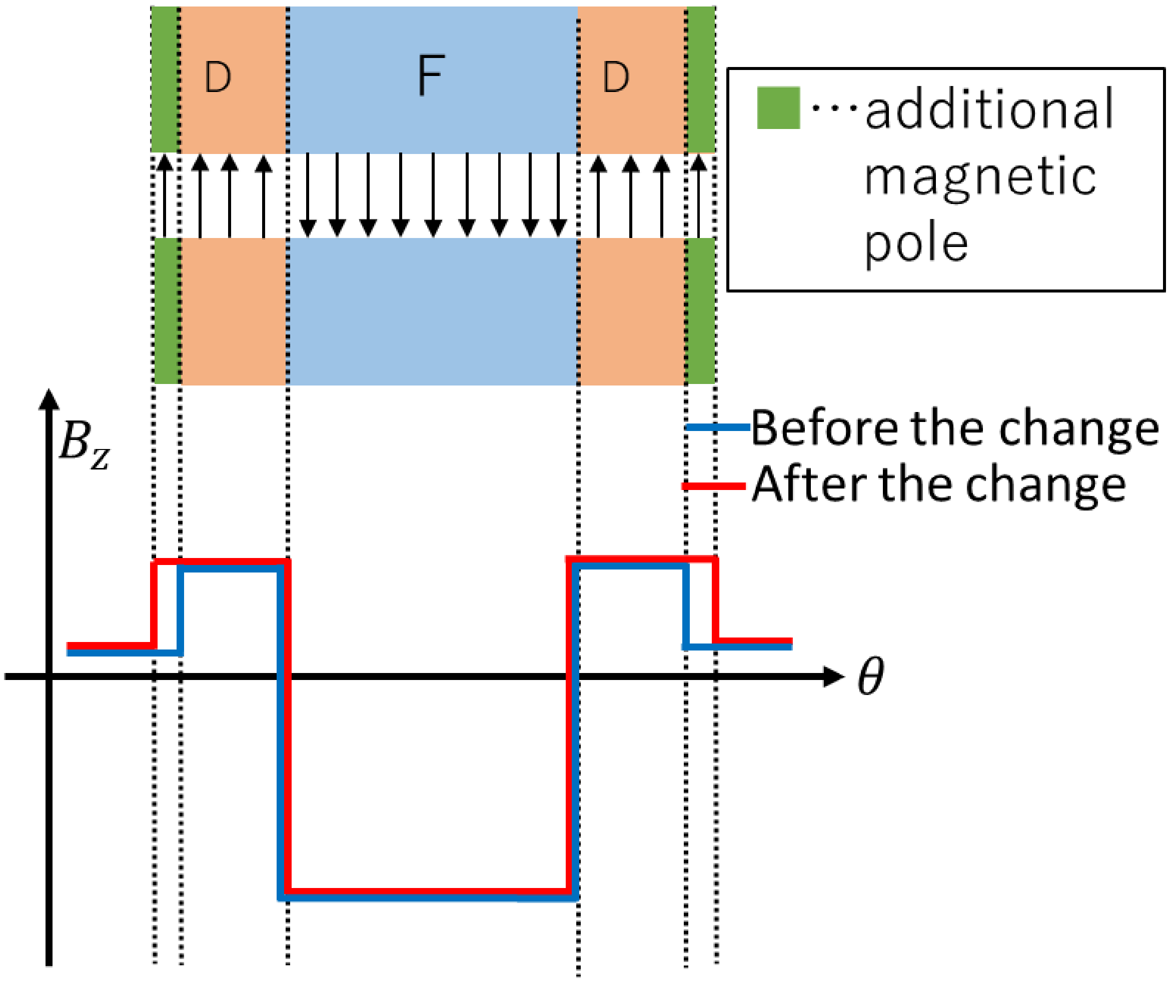
*2 N.Motohashi , FFAG'15 workshop

Purpose

The purpose is to clarify the mechanism by which the focusing force varies with the additional poles in order to enable the systematic design of the additional poles.

->The effect of the additional poles was quantitatively evaluated using indices related to the focusing force.

Principle of changing the focusing force with additional magnetic poles



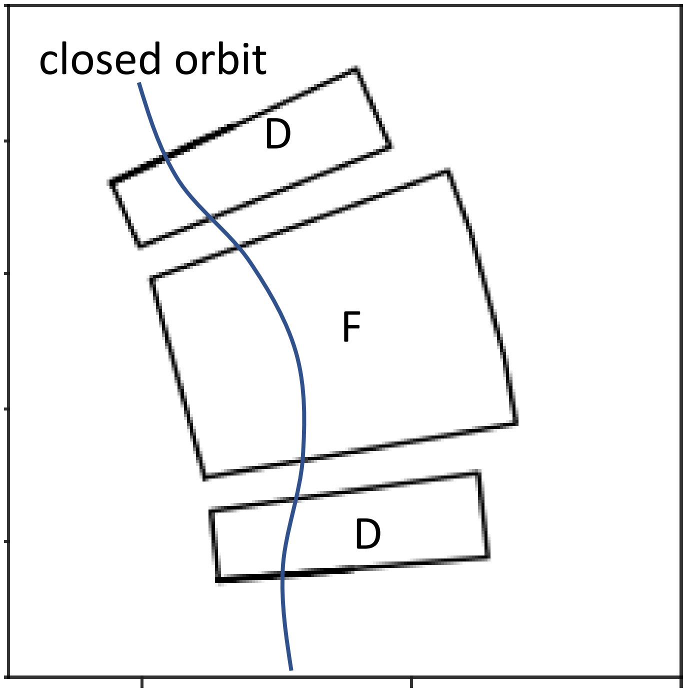
Additional magnetic pole changes magnet length

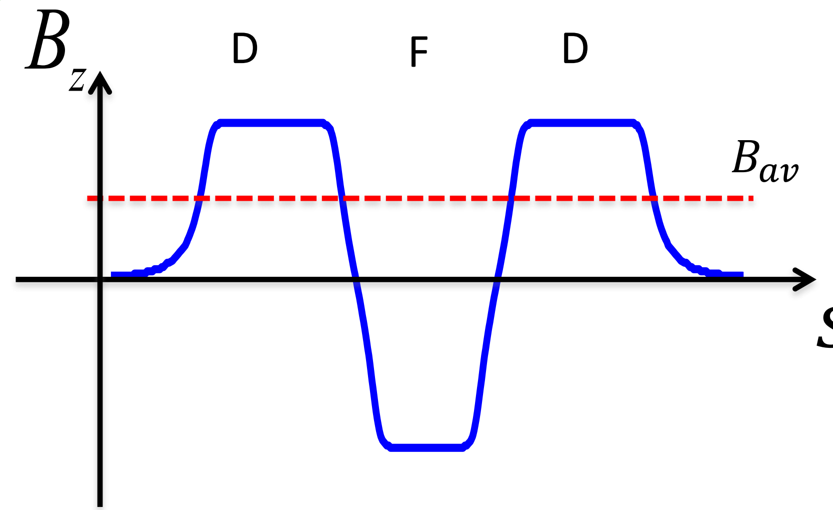
Flutter factor is changed

Vertical tune changed

Evaluation method of Flutter factor

Top view of the poles





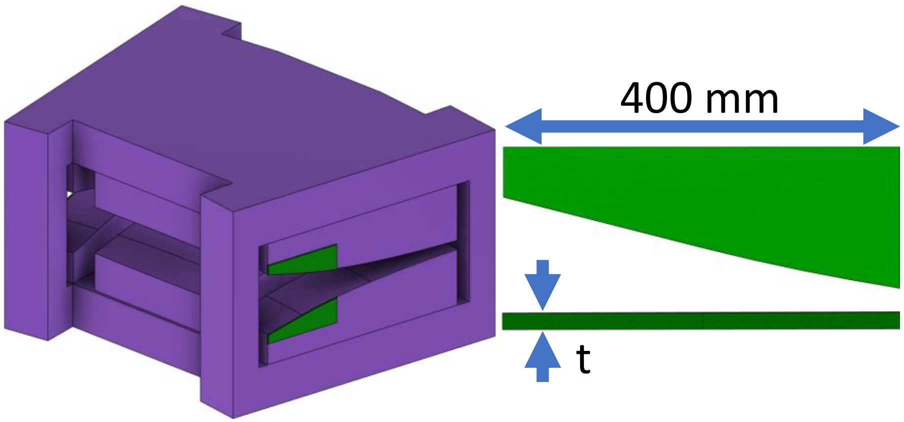
$$F^2 = \left\langle \left(B - B_{av}\right)^2 \right\rangle / B_{av}^2 \quad B_{av} = \left\langle B_{(q)} \right\rangle$$

Steps to calculate the flutter factor

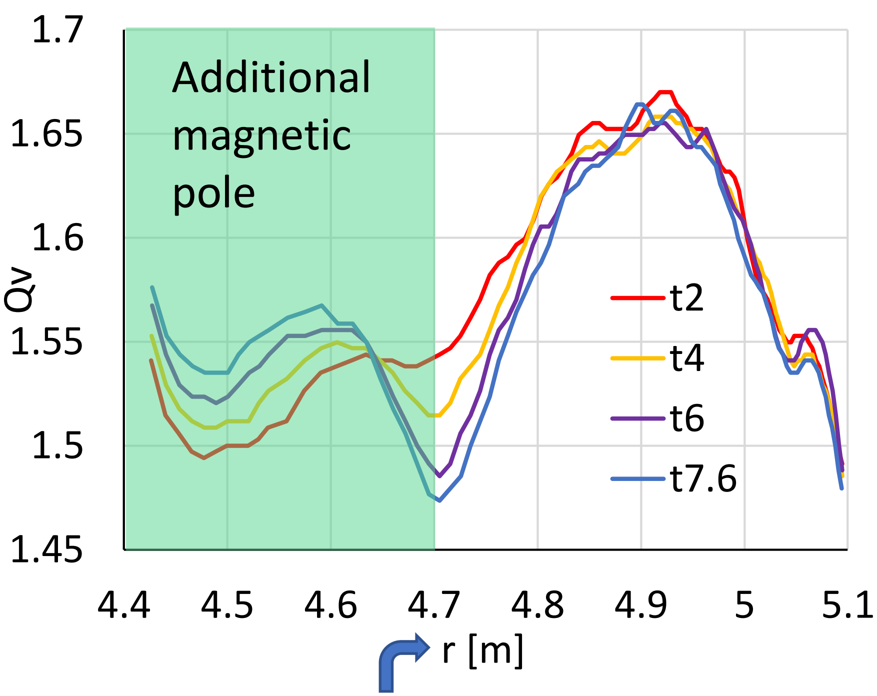
①：Calculation of the closed orbit for each energy in the range of 10 MeV to 100 MeV

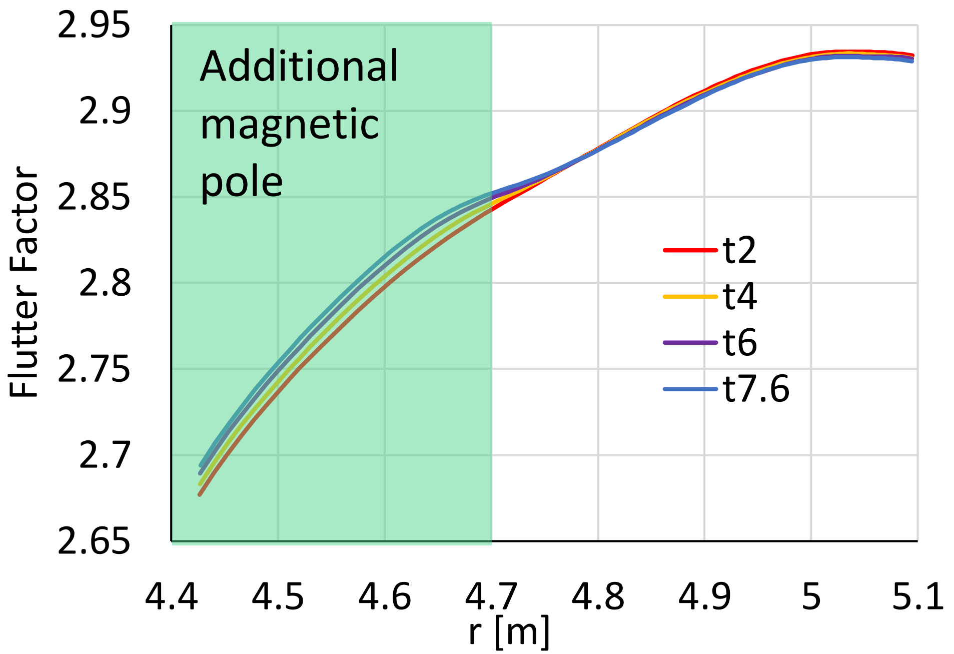
②： flutter factor calculated from Bz along with closed orbit for each energy

Evaluation of Flutter Factor



- For simplicity, the additional magnetic poles in this calculation are used only in the 1st step.
- The flutter factor was evaluated for varying the additional pole thickness.
- The flutter factor and vertical tune are increased in the region of constant thickness of the additional magnetic pole.
- The vertical tune at the edge of the additional pole decreases as the pole thickness increases.





Orbit radius of the beam at the edge of the defocusing magnet

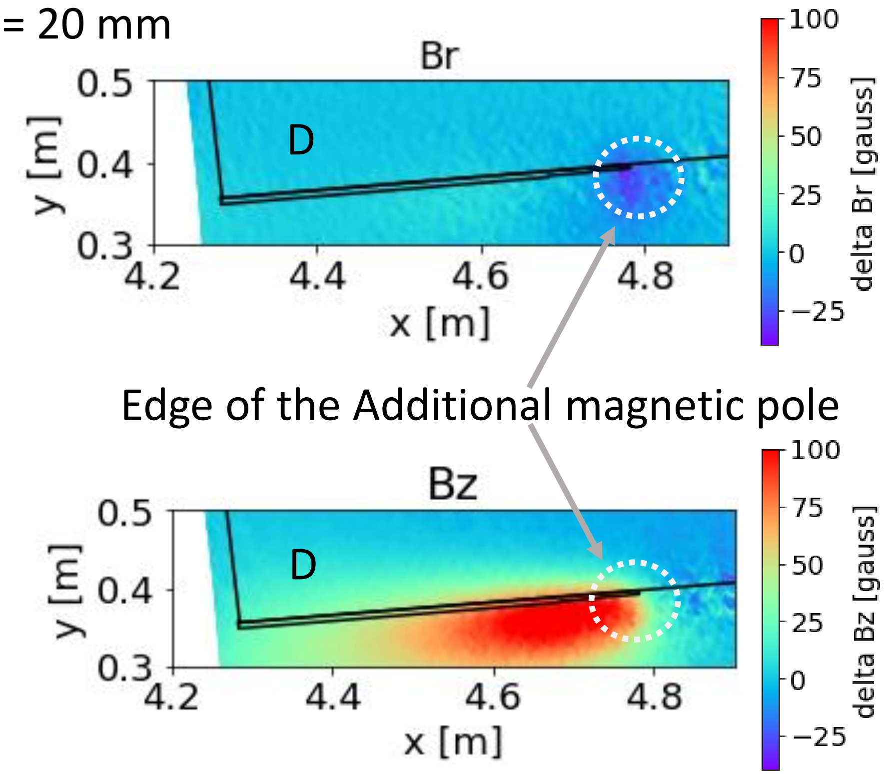
An assumption about the cause of reduced vertical tune at the edges of the additional poles

Assumption At the edge of the additional magnetic poles are generated a quadrupole field

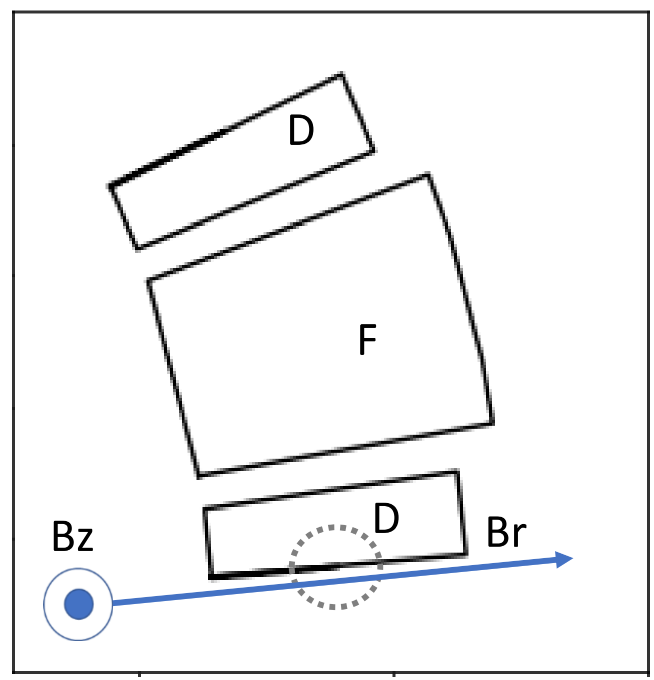
The difference in magnetic field with and without additional poles is plotted.

As shown by the dot circles in the color map below,
it is found that Br and Bz change at the edges of the additional magnetic poles.

Z = 20 mm



Top view



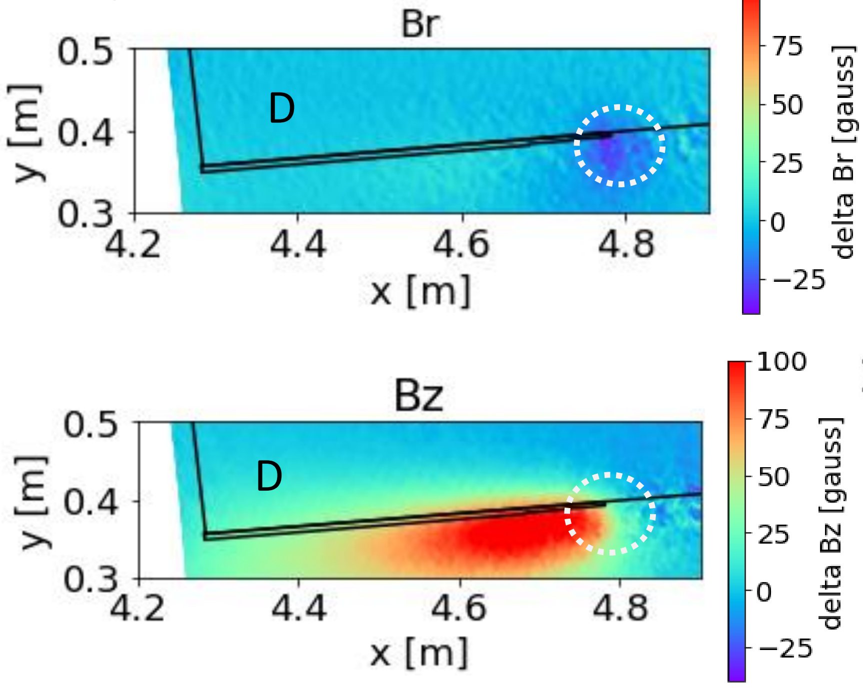
An assumption about the cause of reduced vertical tune at the edges of the additional poles

Assumption At the edge of the additional magnetic poles are generated a quadrupole magnetic field

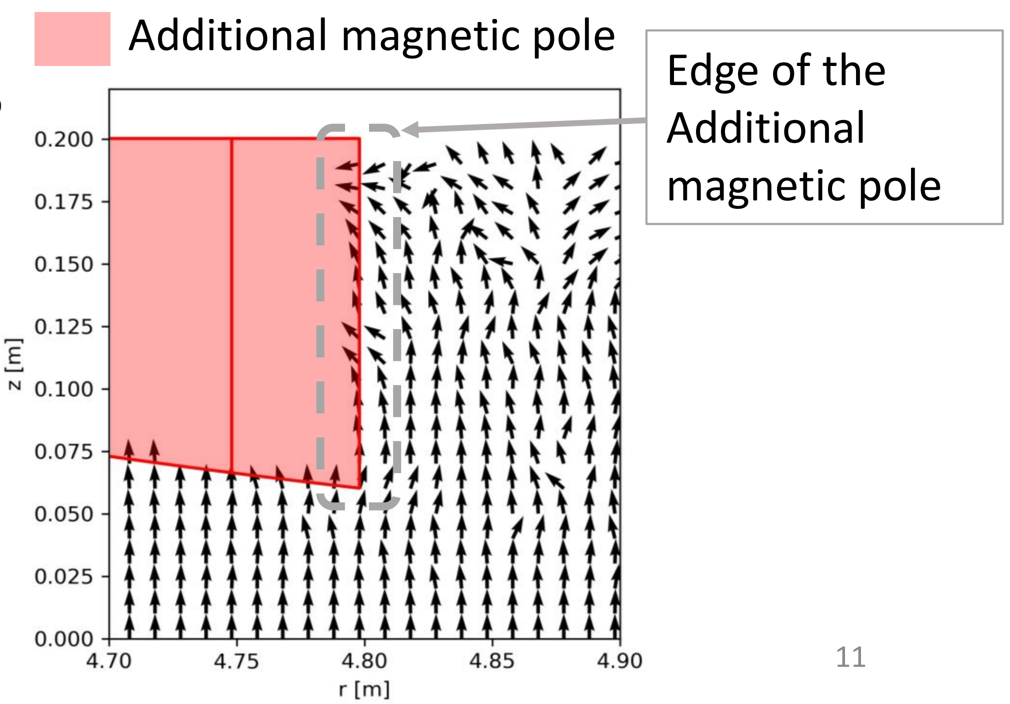
The vector of the magnetic field viewed from the side of the additional magnetic pole was plotted.

A quadrupole magnetic field is generated by the suction of the magnetic field at the edge of the additional magnetic poles.

Z = 20 mm

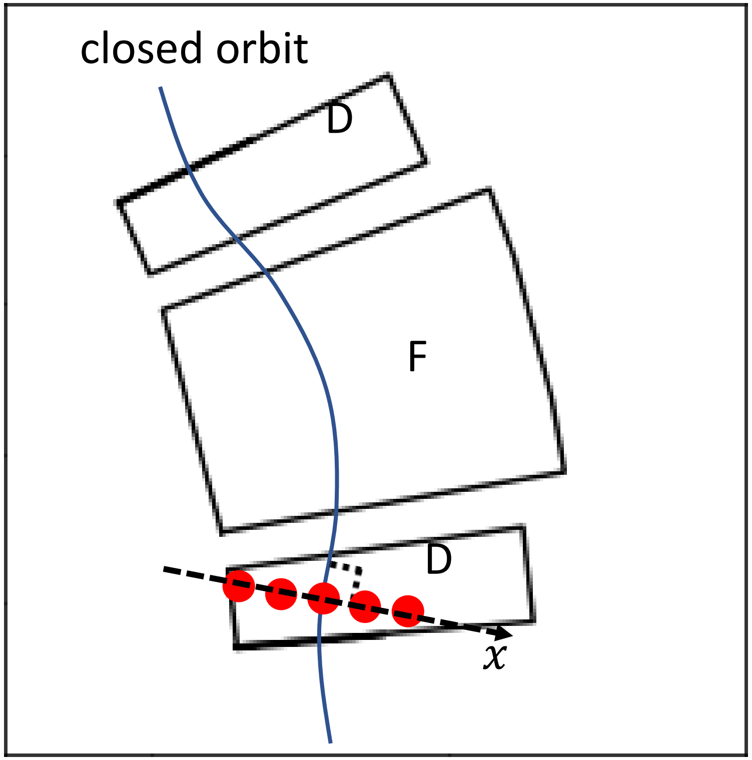


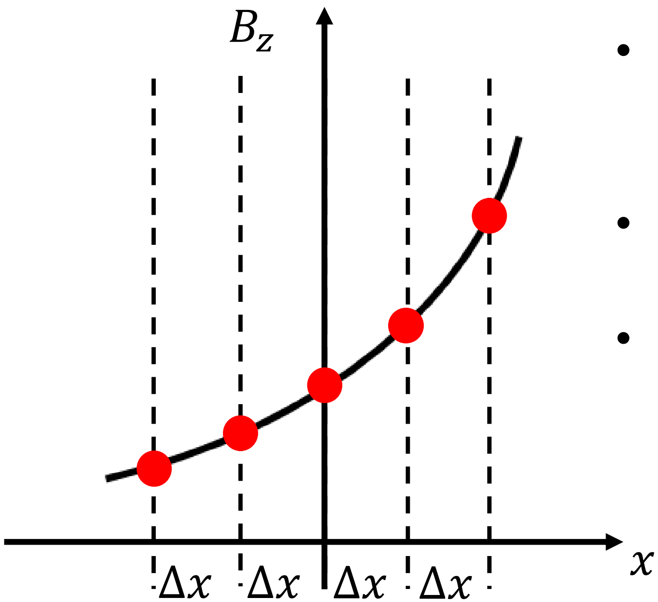
Side view



Evaluation method of kL

Since it was found that the quadrupole field was generated at the edge of the additional poles, the effect of the edge of the additional poles was evaluated using kL,
where kL is the integration of the quadrupole component k along a closed orbit.





Δx = 5 mm

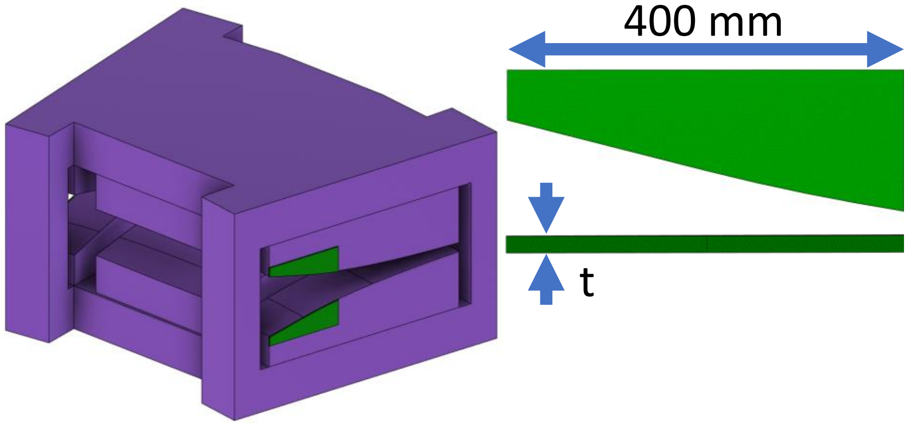
- The x is the axis perpendicular to the closed orbit.
- A point on the closed orbit is set to x=0.
- The quadrupole component k was calculated from five points on the x-axis.

Steps to calculate the kL

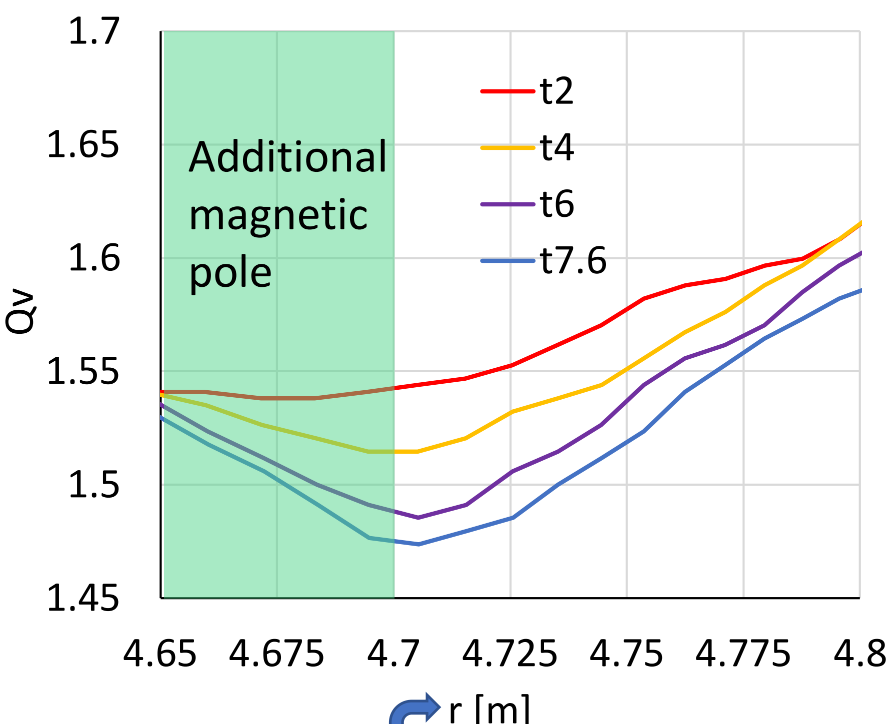
①： k is calculated from Curve fitting $\quad B_z = B_0 + kx + lx^2 + mx^3$

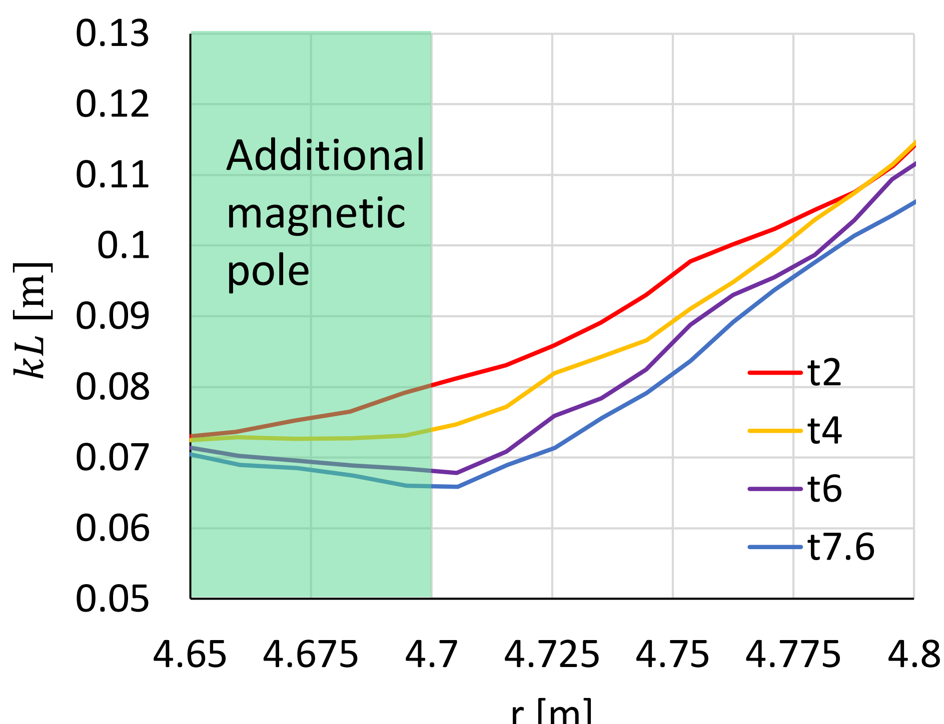
②：kL is integrated from Bz along with closed orbit $\quad kL = \int k dl$

Evaluation method of kL



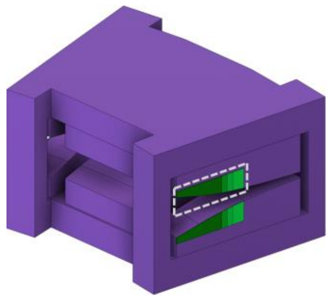
kL changes in the region near the edges of the additional poles.
In the same region, the vertical tune also changes.
Thus, the generation of a quadrupole field at the edge of the additional pole causes a change in the vertical tune.

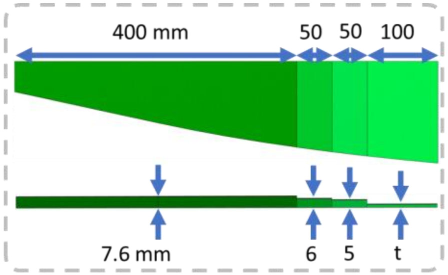




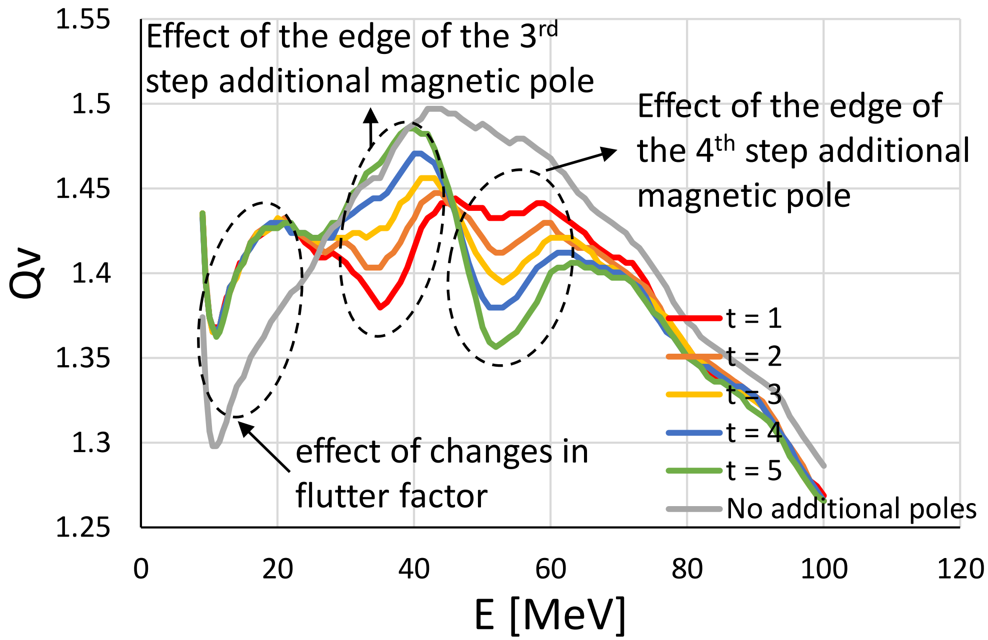
Orbit radius of the beam at the edge of the defocusing magnet

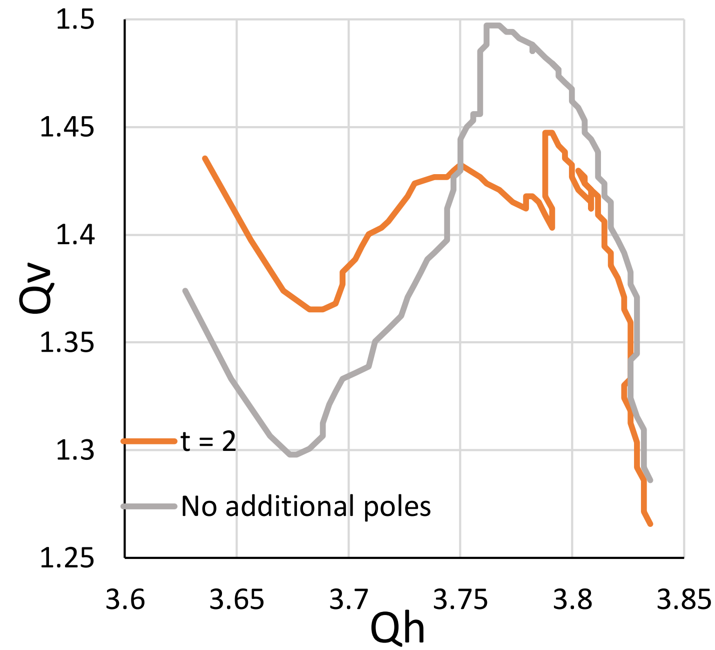
Optimization of the shape of the additional poles





Optimization of the thickness of the 4th step additional magnetic pole was done so that the variation of the vertical tune is minimized.



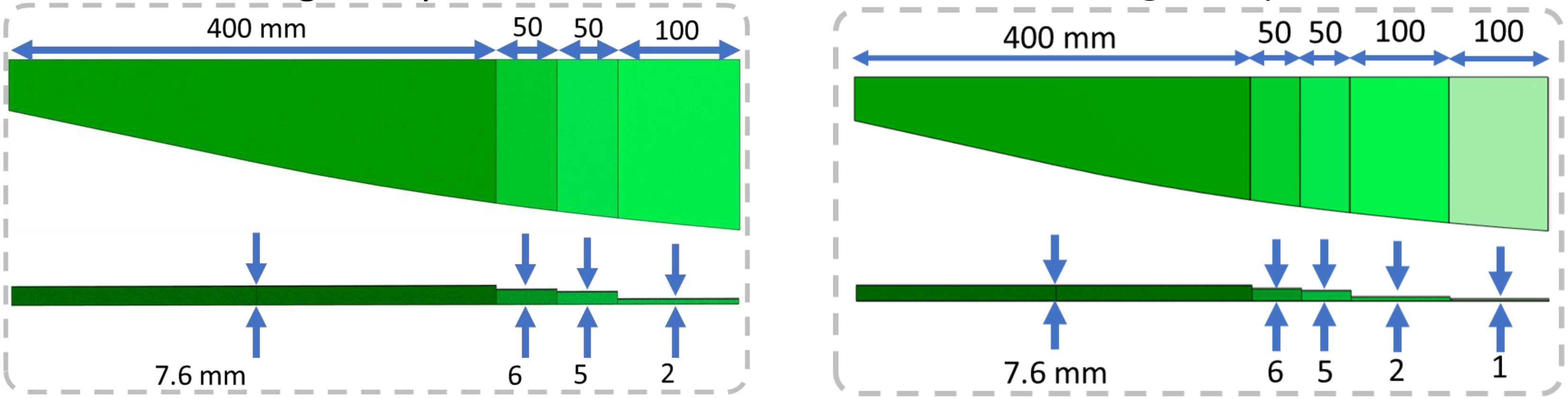


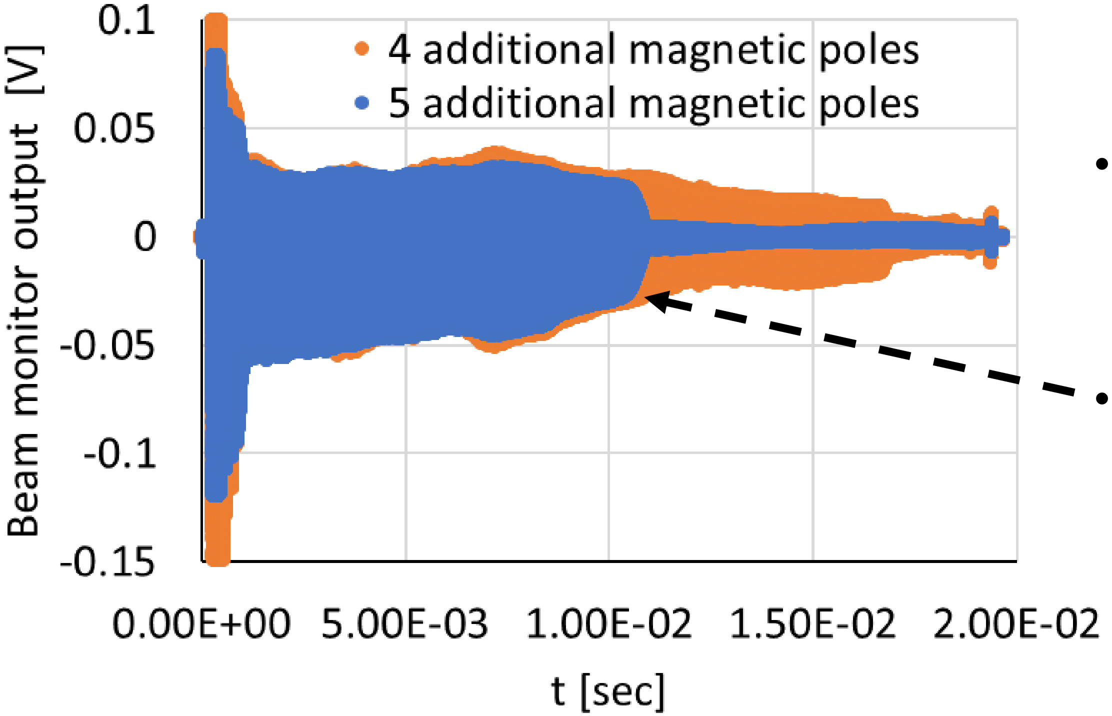
In this calculation, the current value was changed to fit the range of the experimental values of the vertical tune.

By changing the thickness of the 4th step additional pole, the effect of the edge of the 3rd step additional pole also changes.

The case of t=2 had the smallest variation in vertical tune.

Beam Experiment Results





- Beam experiment was done on a 150 MeV FFA with an optimized 4-additional magnetic poles.
- Beam experiment was done with 5-additional poles to change the effect of the 4th step additional magnetic pole edge.
- In the case of five additional poles, the beam loss occurs at the timing when the beam passes through the edge of the 4th step additional pole due to the change in the size of the step.

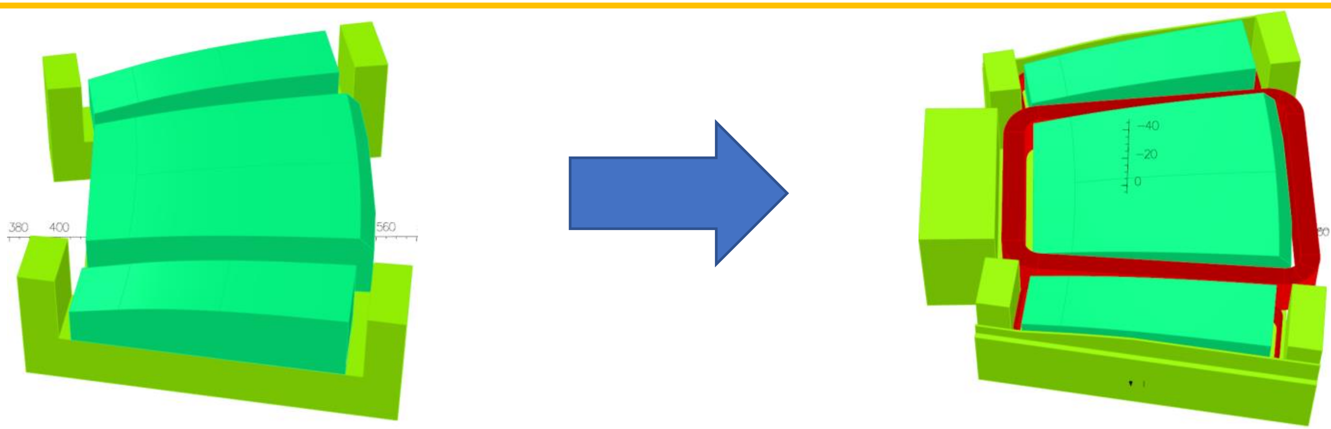
An attempt to radically improve the problem of magnets in the current 150 MeV FFA

The Problems

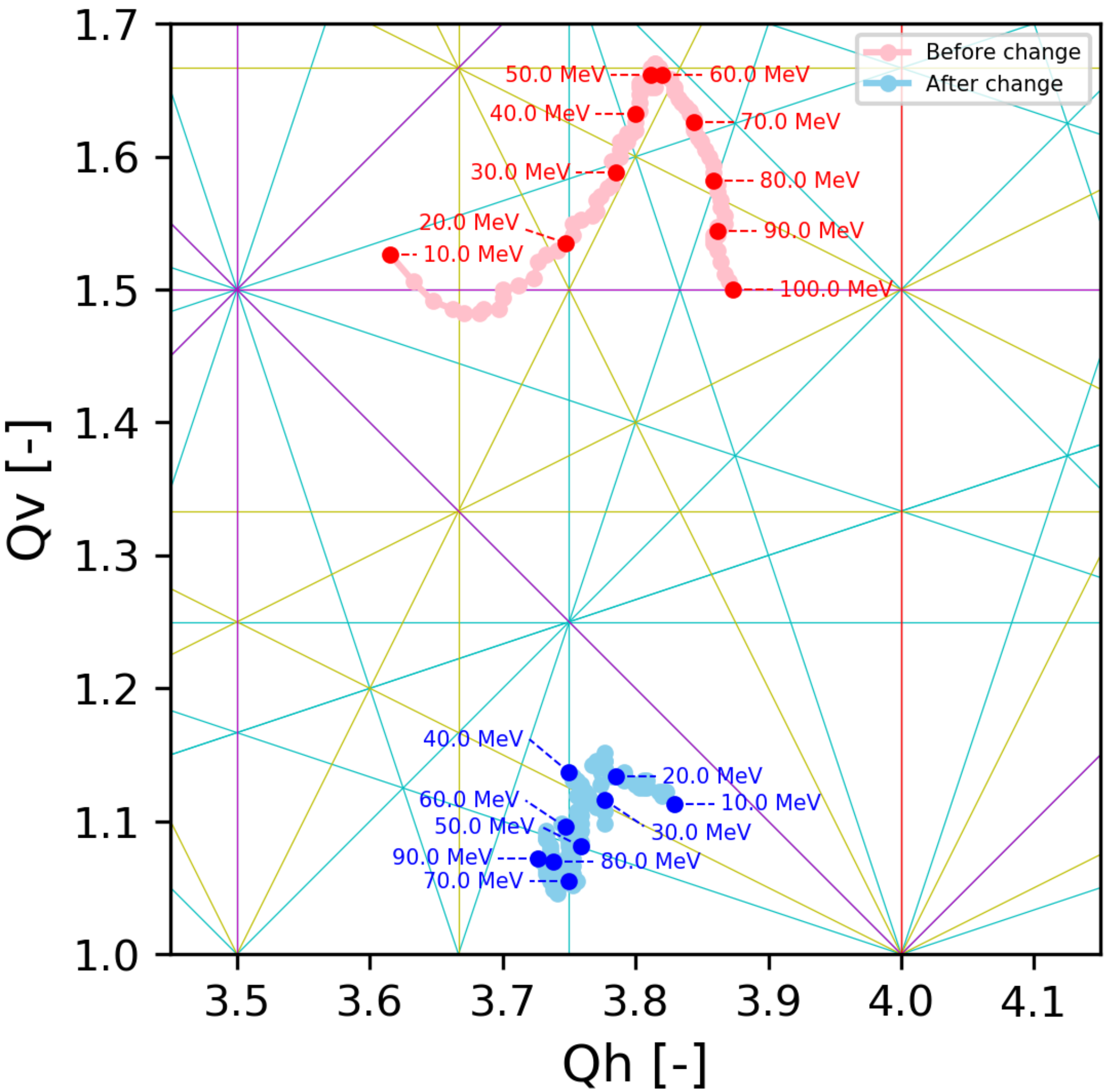
Since the return yoke of defocusing magnet is actively saturated with magnetism, the leakage field into the straight section is large.
→Magnetic material cannot be inserted into the straight section.
The field index k for each radius is not in accordance with the magnetic pole shape.

Improvement Points

- Attach a return yoke to the focusing magnet as well to avoid saturating the defocusing magnet's return yoke.
  The size of the return yoke in focusing magnet was determined so that the return yoke of the defocusing magnet will not be magnetically saturated.
- Attach a magnetic shield.
- Change the magnetic pole shape of the defocusing magnet since the field index k has changed significantly with the radius.



Calculated results of betatron tune



Qh：3.62 ~ 3.87
Qv：1.48 ~ 1.67

Qh：3.73 ~ 3.83
Qv：1.05 ~ 1.15

With the attempts described on the previous page, the range of horizontal and vertical tunes could be significantly reduced.

The optimization of the pole shape of the defocusing magnet and the shape of the magnetic shield is not yet sufficient and there is room for further improvement.

Summary

- kL, which indicates the magnitude of the quadrupole component, and F, which indicates the flutter factor, were used for the evaluation.
- As the thickness of the additional poles increases, the vertical tune increases due to the increase of the flutter factor in the region of constant thickness, and the vertical tune decreases due to the generation of a quadrupole field in the region near the edge.
- Beam experiments with additional magnetic poles mounted on 150 MeV FFA magnets showed that the vertical tune can be controlled by changing the thickness of the additional poles and the size of the edge step.
- By attaching a return yoke to the focusing magnet, attaching a magnetic shield, and changing the pole shape of the defocusing magnet, the range of horizontal and vertical tune of the 150 MeV FFA could be significantly reduced.