Permanent Magnet Multipole for Hadron Beam Transportation

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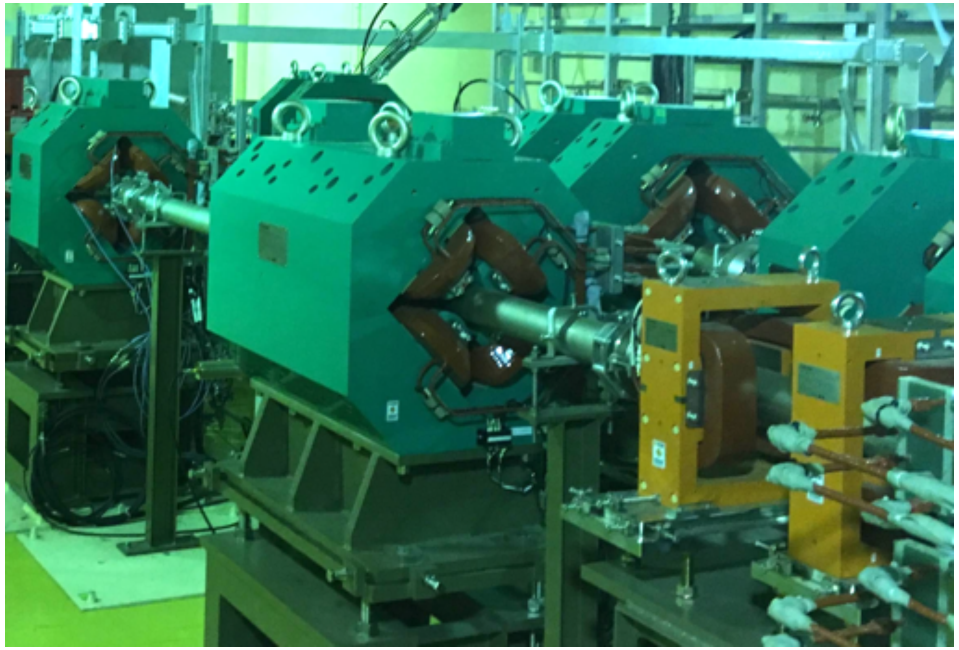
Contents

Magnetic Elements for Beam Transportation

Magnetic elements are essential device for beam experiments for transporting (bending or focusing) quantum beam. With the diversification of beam usage purposes, from intense ion beam to neutron beam with no electric charge, more sophisticated magnetic elements are demanded.

One of the key technologies, to satisfy such requirements, is developing <u>compact multipole</u> magnetic elements with variable strength.



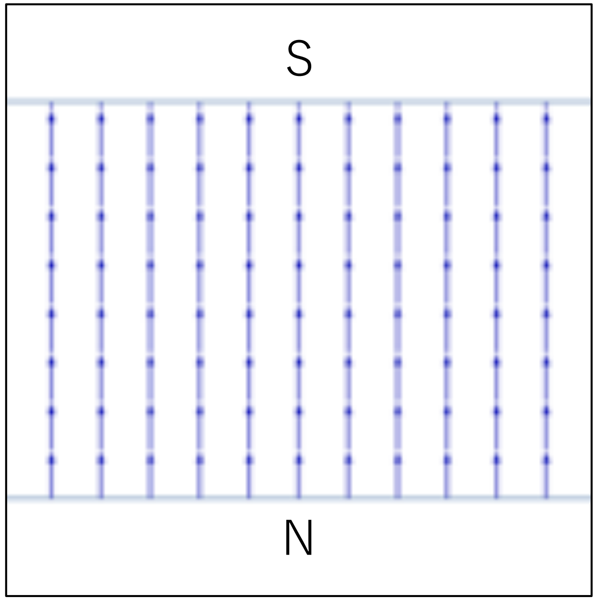
Typical image of beam line

Multipole Magnetic

- Multipole expansion of magnetic field

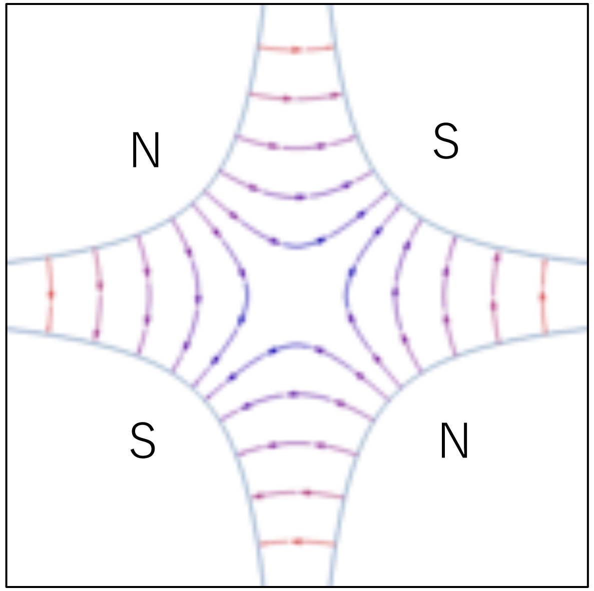
$$B_y(x,y) + iB_x(x,y) = \sum_{n=1}^{\infty} (B_n + iA_n) \left(\frac{x+iy}{R} \right)^{n-1}$$

A_n: Skew Part
B_n: Normal Part



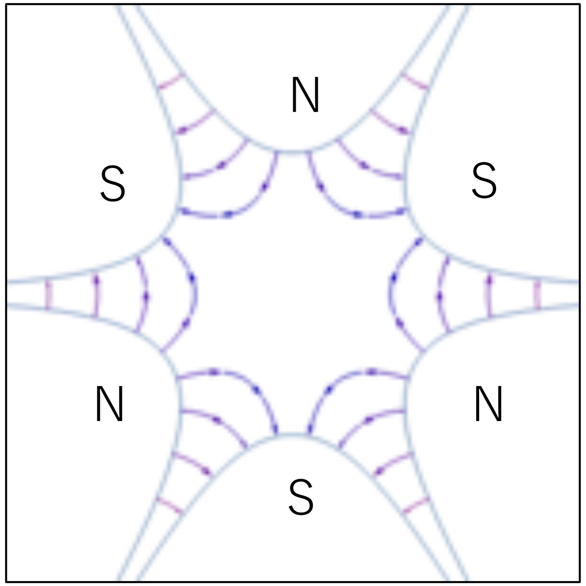
B_1: dipole

$B_y(x,y) = (\text{const.})$



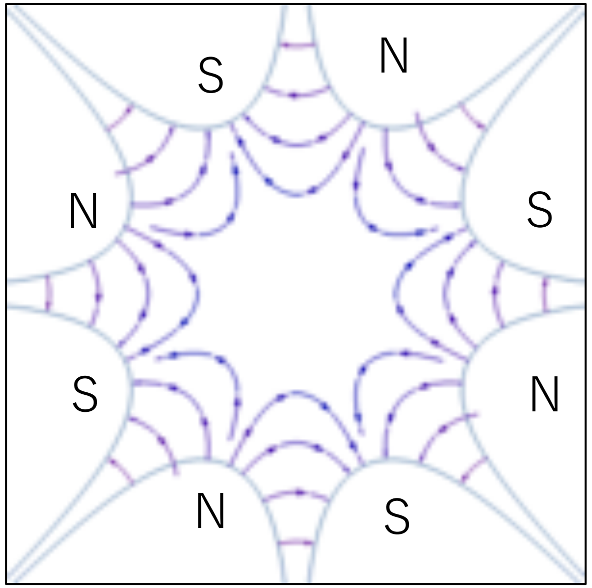
B_2: quadrupole

$B_y(x,0) \propto x$



B_3: sextupole

$B_y(x,0) \propto x^2$



B_4: octupole

$B_y(x,0) \propto x^3$

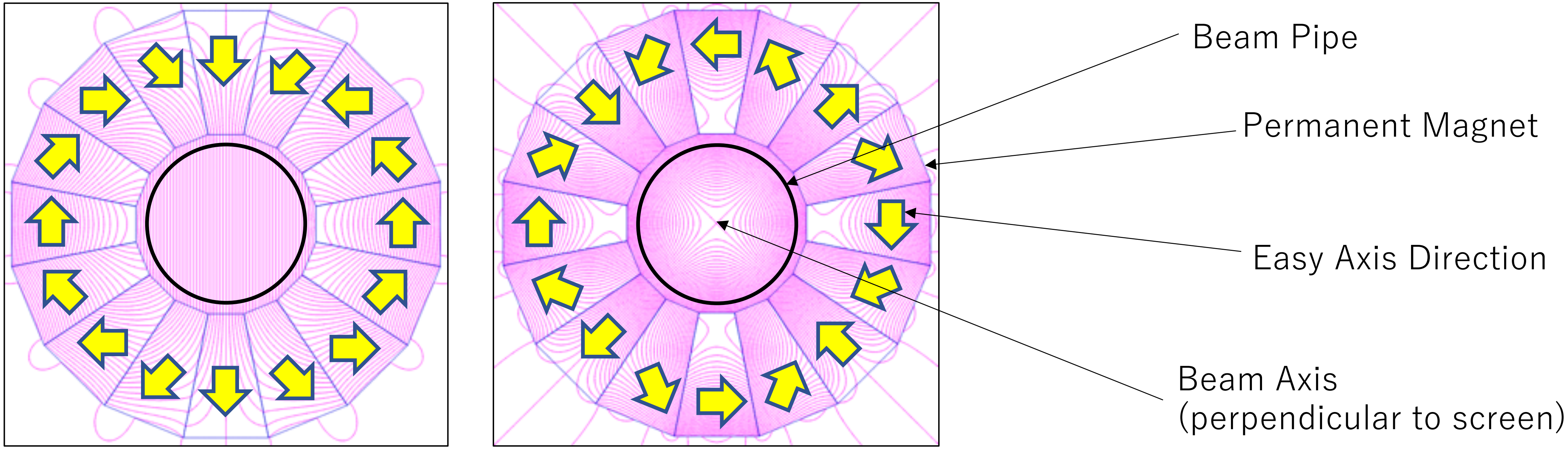
Permanent Magnet Multipole

In order to make strong multipole magnets with compact size, application of permanent magnet materials is one of solutions.

Permanent magnet multipoles can be stronger than electromagnets (normal-conducting ones and superconducting ones), because there are no bulky coils and current density limitations for permanent magnet materials. Furthermore, applying the permanent magnets are cost effective permanent magnets have no power consumption and heat loss to be cooled.

Halbach Configuration

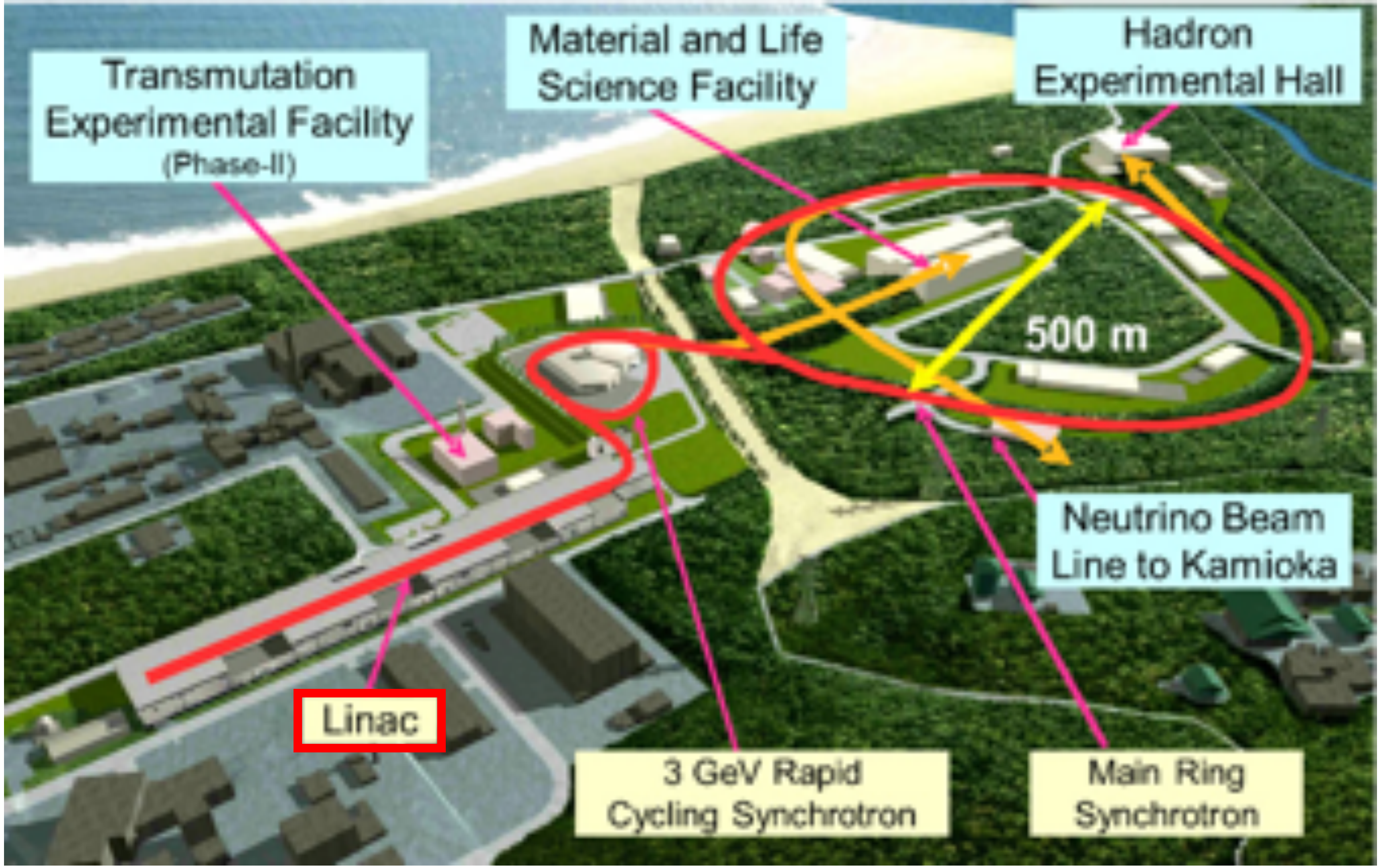
As a design recipe to generate fairly strong multipole field with compact size using permanent magnets, Halbach configuration [1] is well-known. Figures below are examples of the permanent magnet multipoles with standard Halbach configurations.



[1] K. Halbach, NIM, 169 (1980) 1, NIM 187 (1981) 109, and NIM, 198 (1982) 213

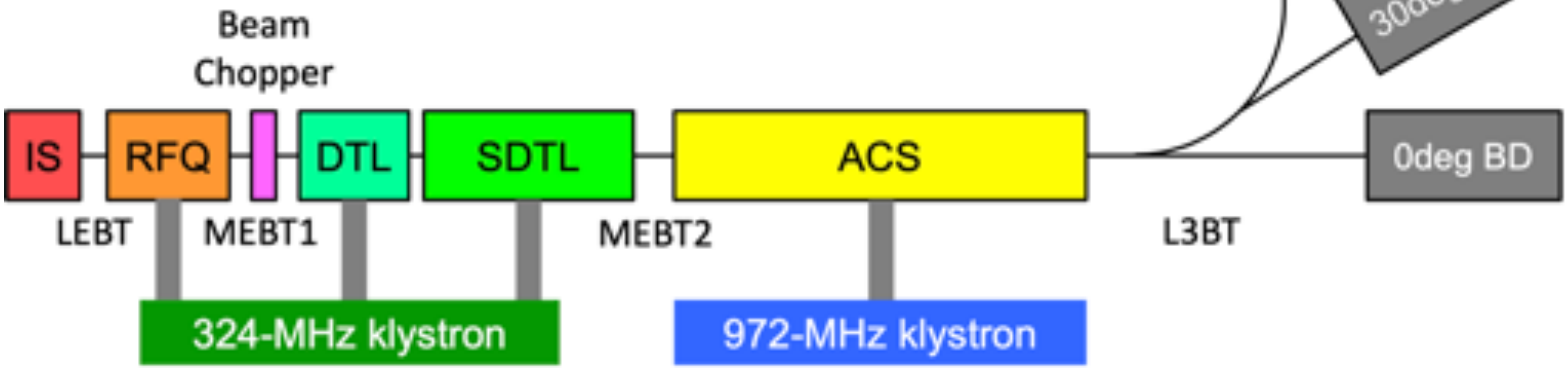
Combined Quadrupole and Octupole Magnet for Intense Ion Beam Transportation

J-PARC Accelerator Complex Overview



J-PARC LINAC

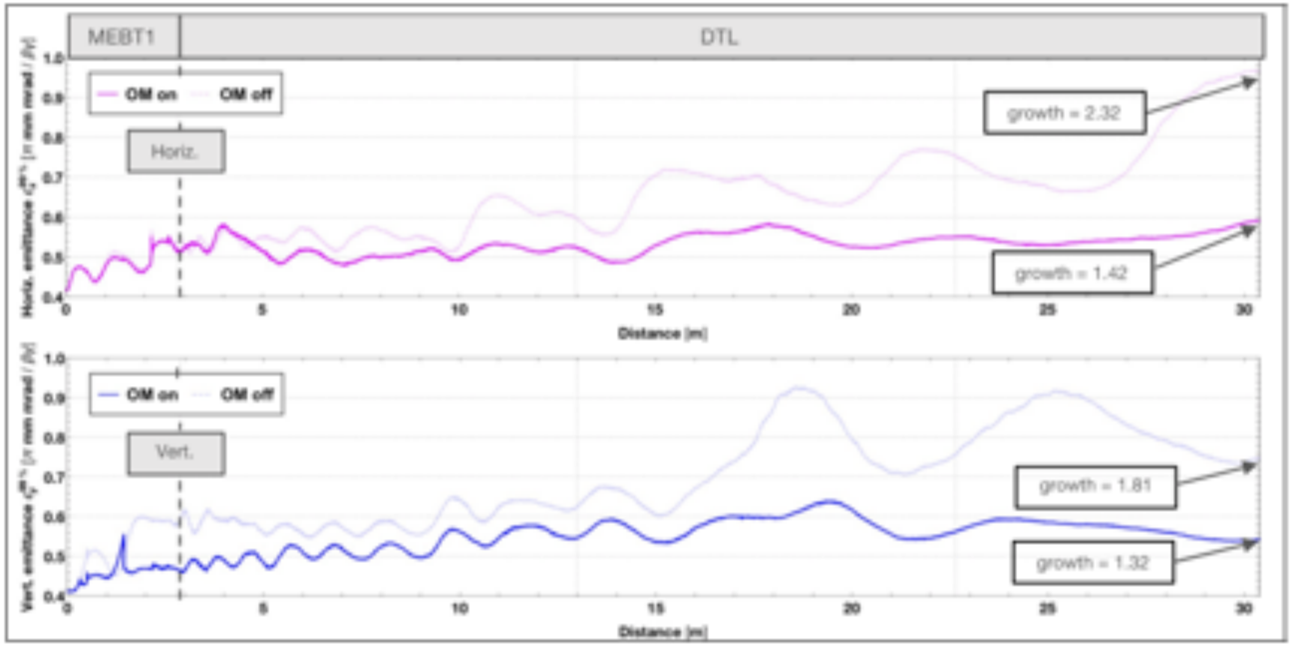
- Acceleration particle: Negative hydrogen ion (H^-)
- Energy: 400 MeV
- Peak current: 50 mA
- Pulse width/ repetition: 0.5 msec/ 25 Hz

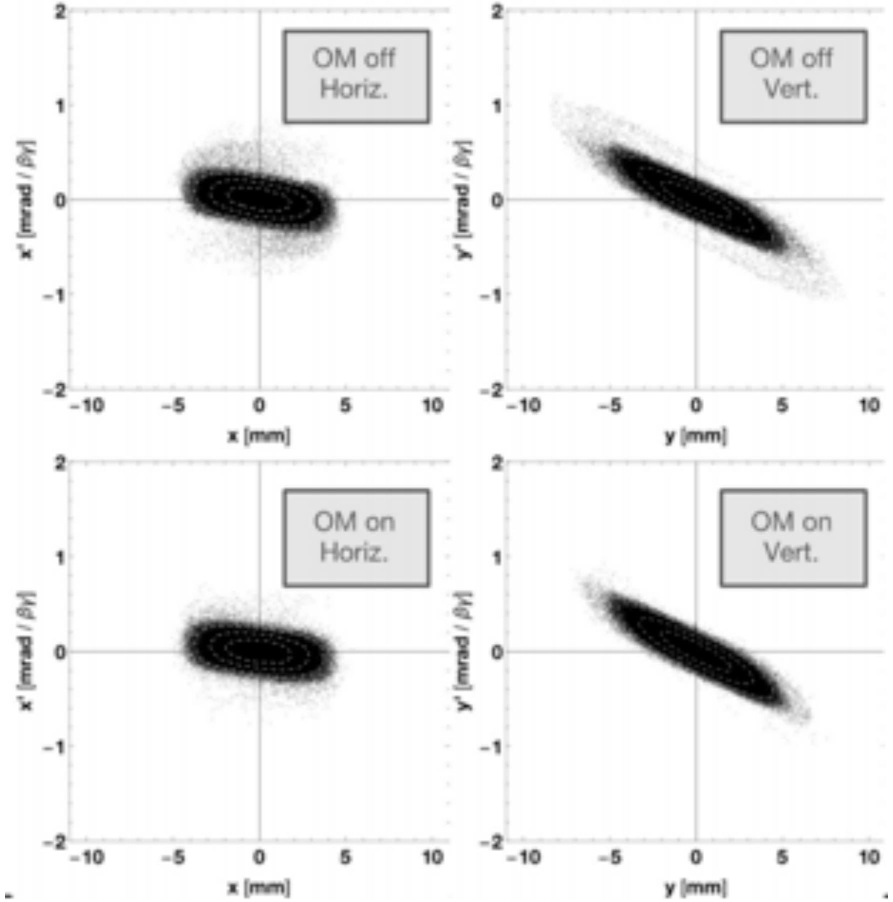


Because of relatively low velocity of the bean in MEBT1 and DTL region, beam halo formation and emittance growth due to space charge effect is severe and lead beam losses in the accelerator.

Compensation of Space Charge Effects with Octupole Focusing Field

Compensation technique for emittance growth with octupole focusing component was proposed in J-PARC LINAC [2]. The octupole focusing components can suppress beam halo formation.





[2] M. Chimura et al, 16th Annual Meeting of Particle Accelerator Society of Japan, THPI008 (2019)

Requirements for Magnets

- Quadrupole Strength: > 30 T/m
- Octupole Strength: 0 ~ 15000 T/m^3 (adjustable)
- Length of the Magnet: 50 mm
- Inner Bore Radius: 42 mm diameter
- Total size: smaller than existing electromagnets (in the right figure)

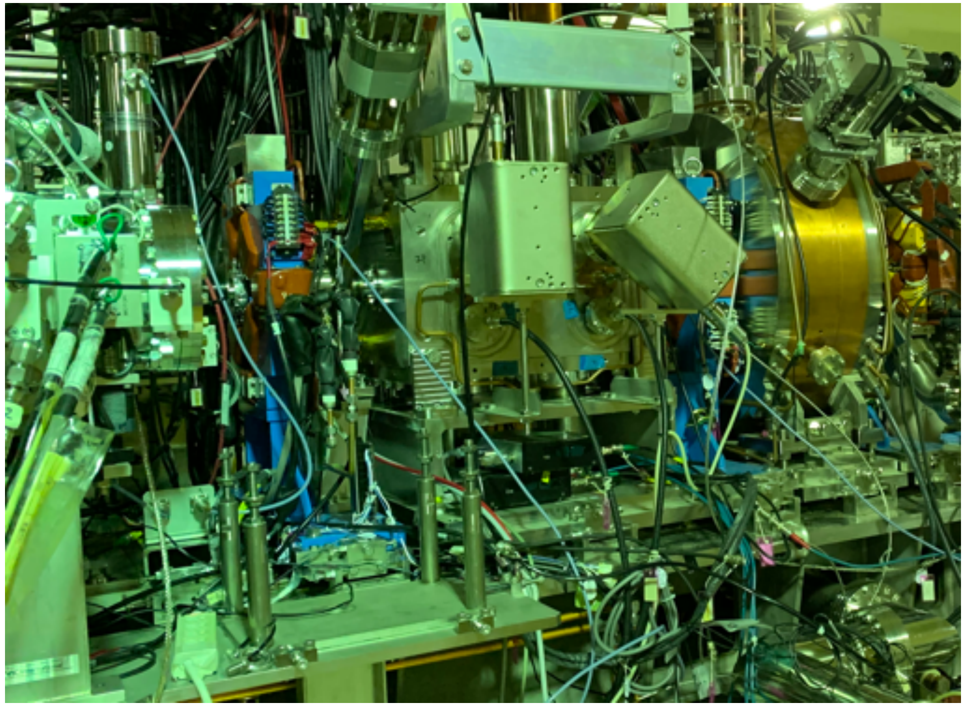
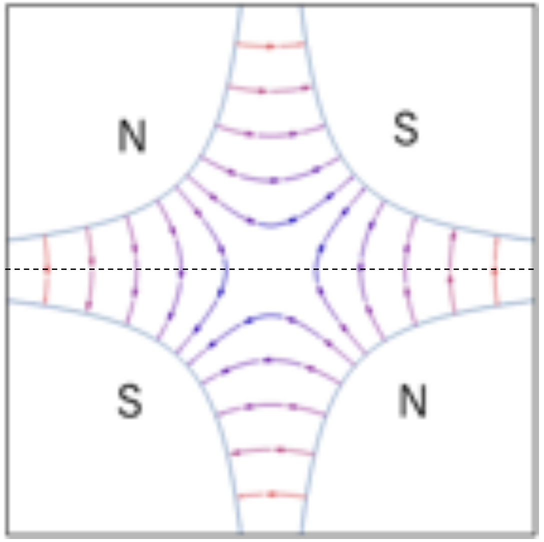


Photo of LINAC MEBT1
(blue components are existing magnets)

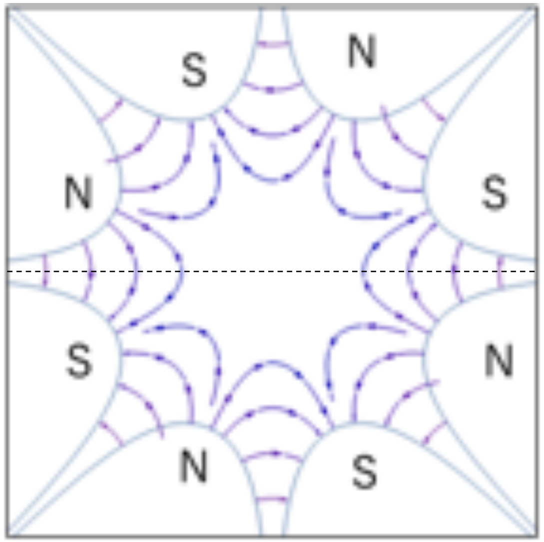
In order to generate quadrupole and octupole field in same region with limited space, applying permanent magnets is a possible solution.
(Neither coil, water, nor power cables are needed.)

Demanded Field Profile



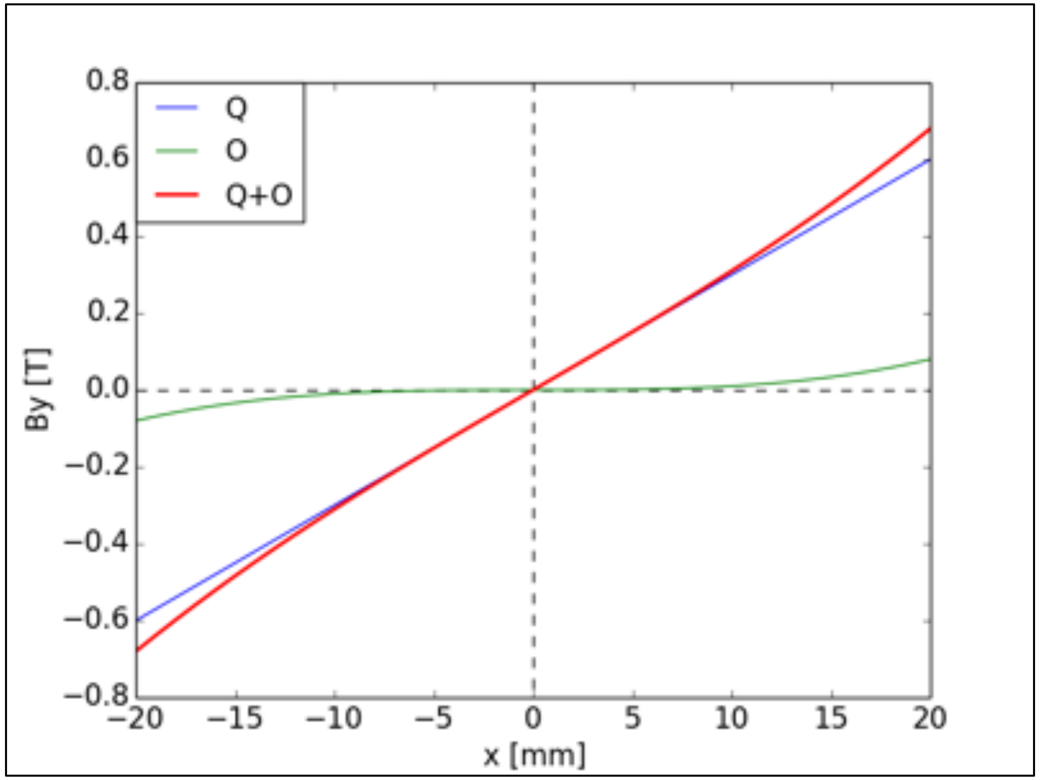
Q: quadrupole

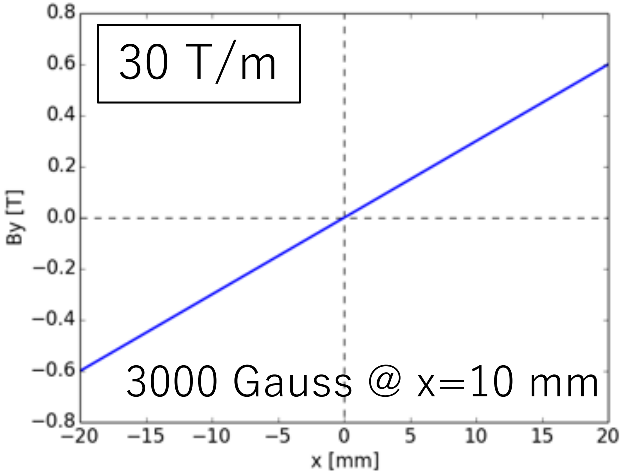
+

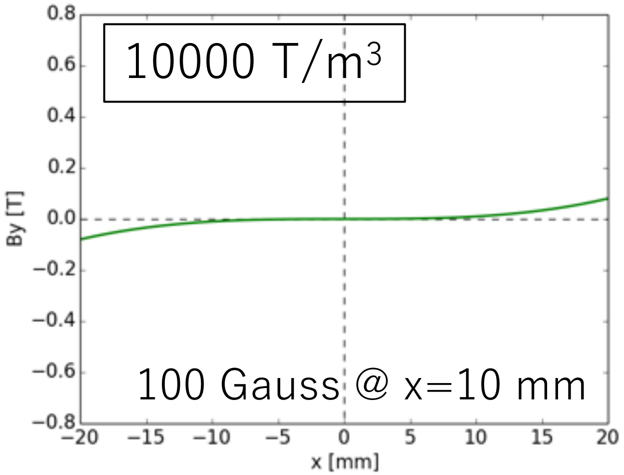


O: Octupole

=





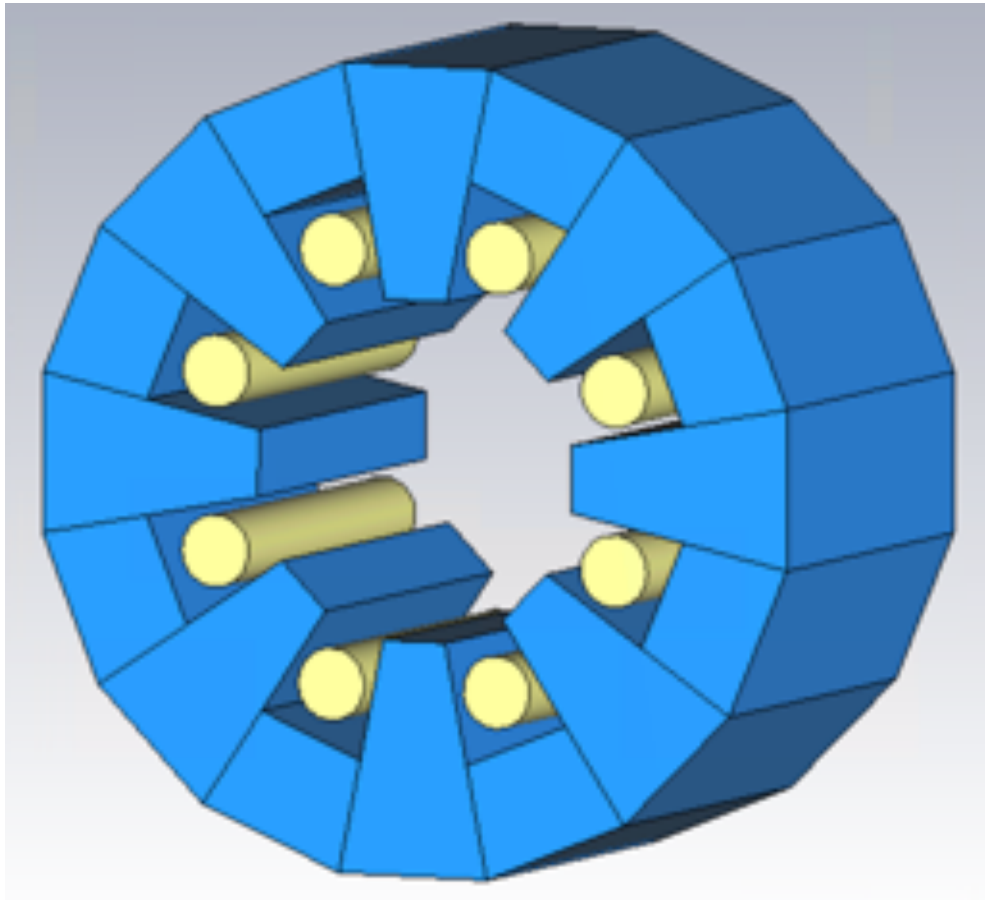


Superposition of two multipole field components must be realized for efficient space charge compensation.

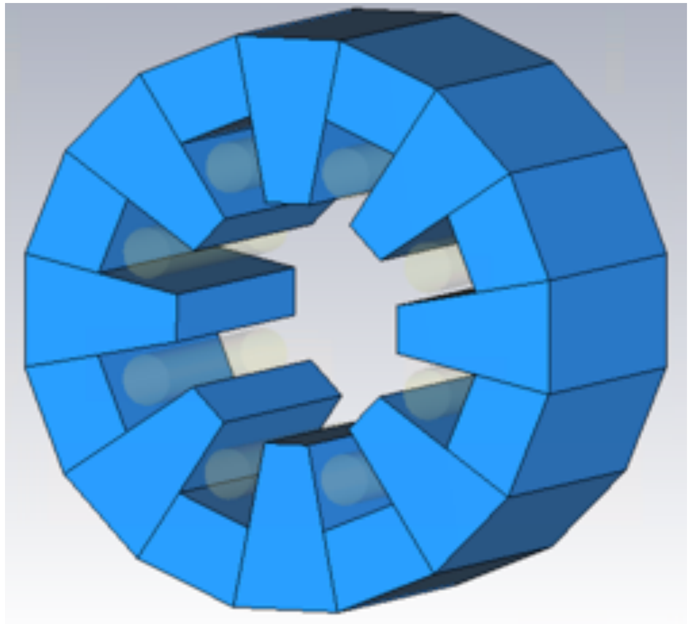
Combined Permanent Magnet Multipole

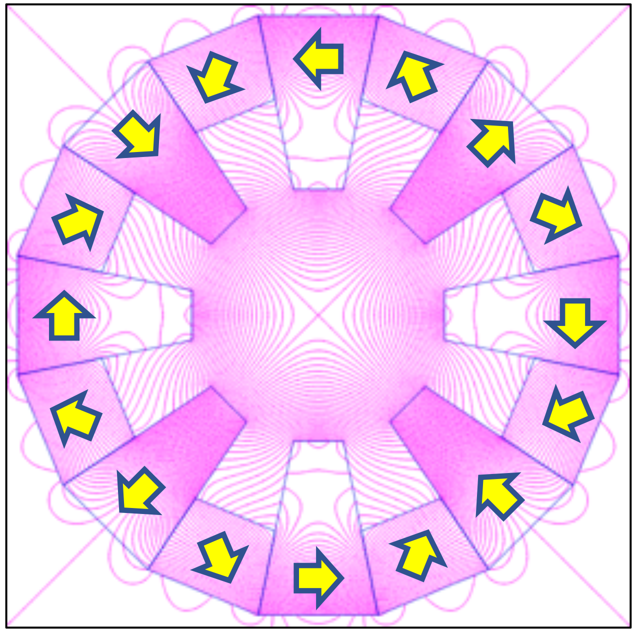
<u>Conceptual Design</u>
Magnetic circuit is composed of two parts: One is a set of trapezoidal magnets aligned as a ring, which generates primary field components (now, it's quadrupole). The other is a set of cylindrical magnets inserted in the outer ring magnets, which produces secondary field components (octupole).

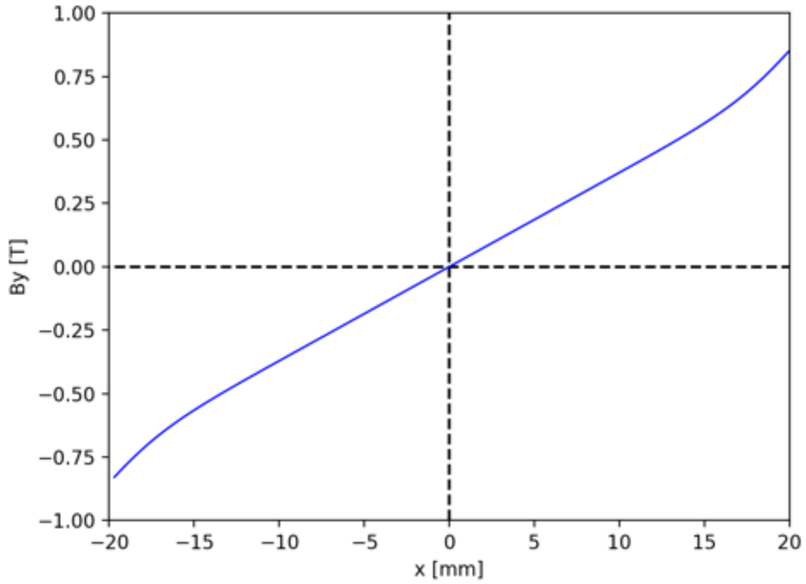
Utilizing hard permanent magnets, such as NdFeB, SmCo magnets, superposition of the field components can be satisfied.

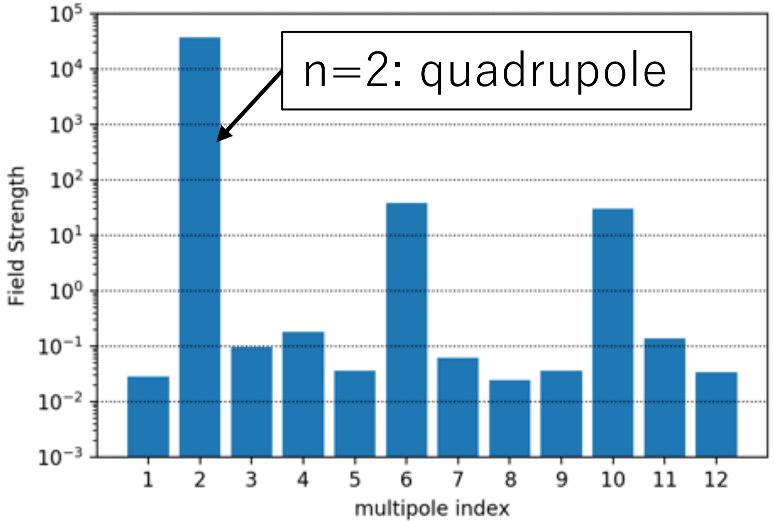


Outer Part: Quadrupole Field Analysis in 2D







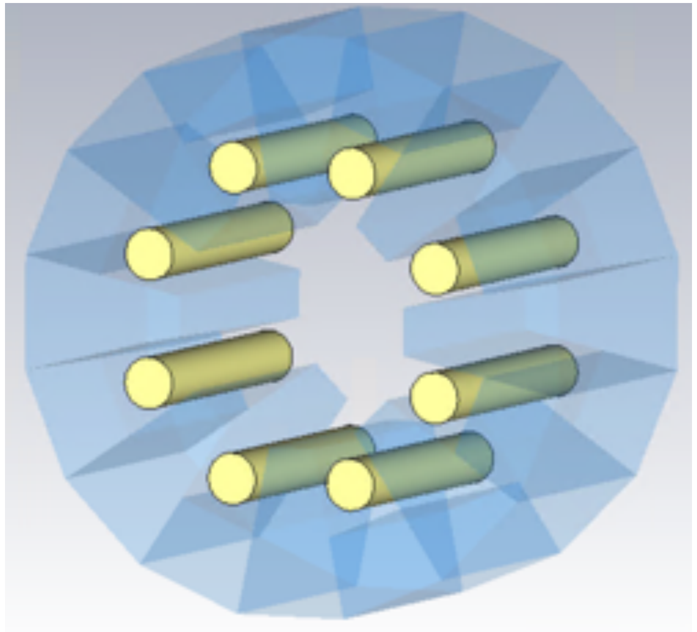


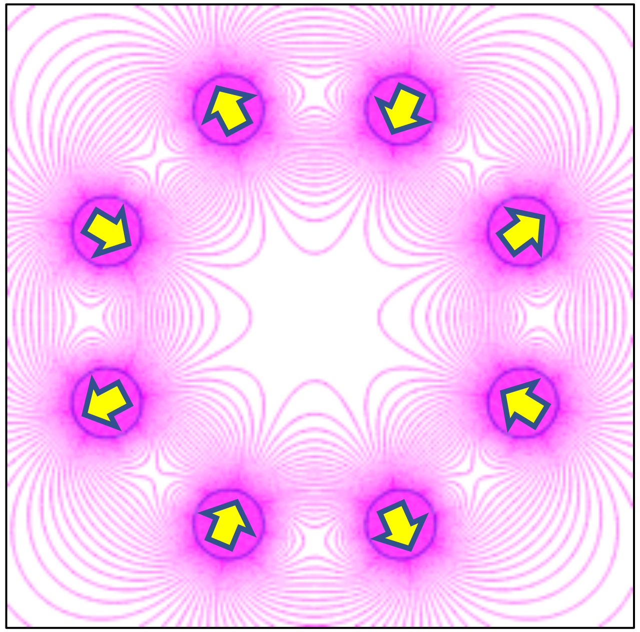
<u>Results of analysis:</u>

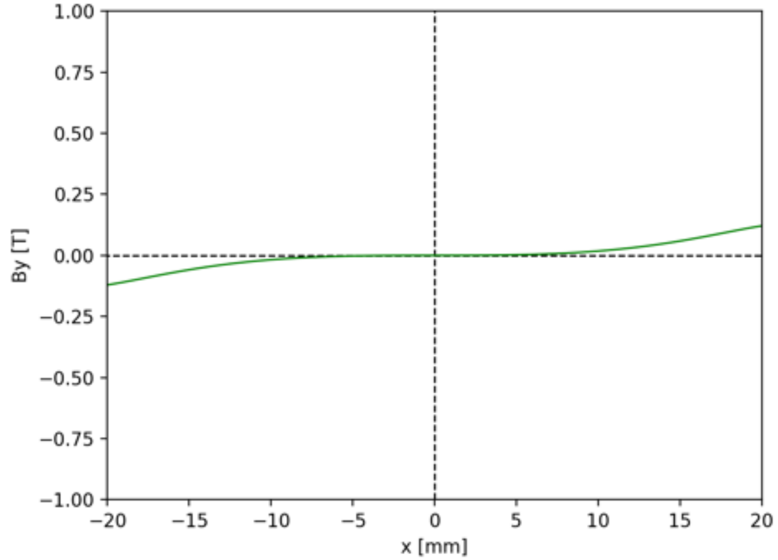
(upper right) Field profile in mid plane
(lower right) Harmonic analysis

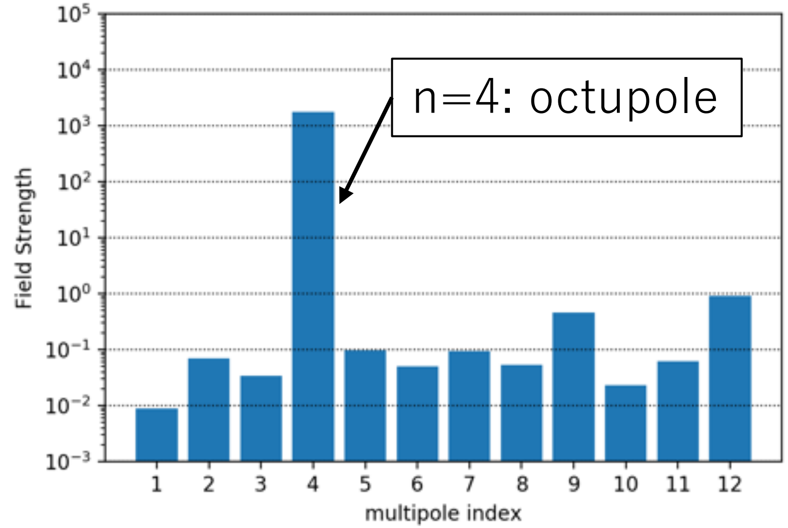
Although parasite components ($n = 6, 10$) exist, their strength are less than 2 order magnitudes.
=> <u>Almost pure quadrupole can be obtained.</u>

Inner Part: Octupole Field Generation in 2D









Results of analysis:

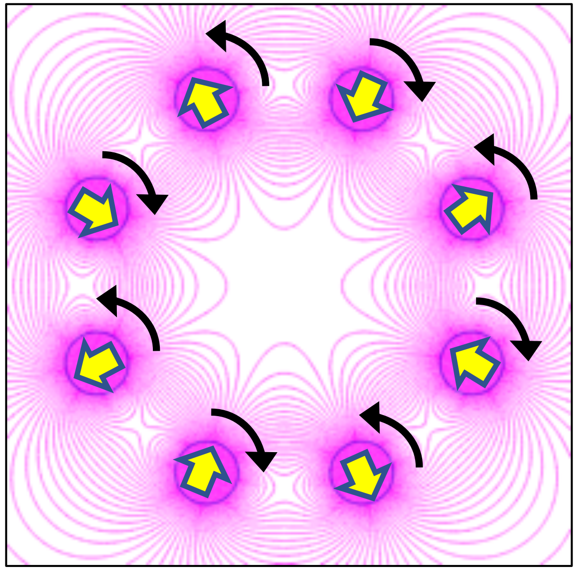
(upper right) Field profile in mid plane

(lower right) Harmonic analysis

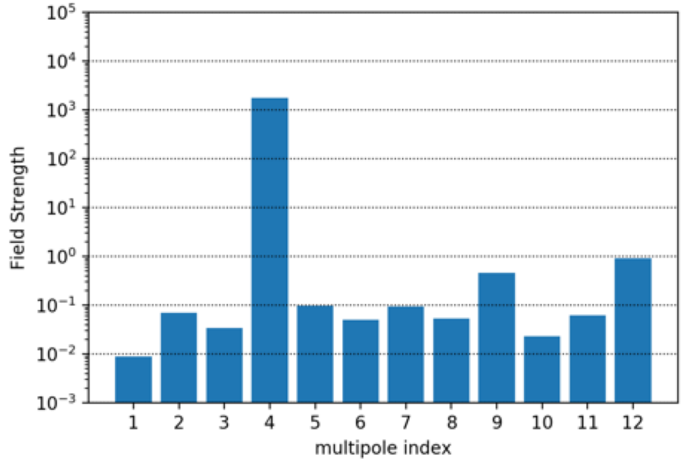
Almost pure octupole components can be obtained.

Octupole Strength: 17700 T/m^3 (10000 T/m^3 required)

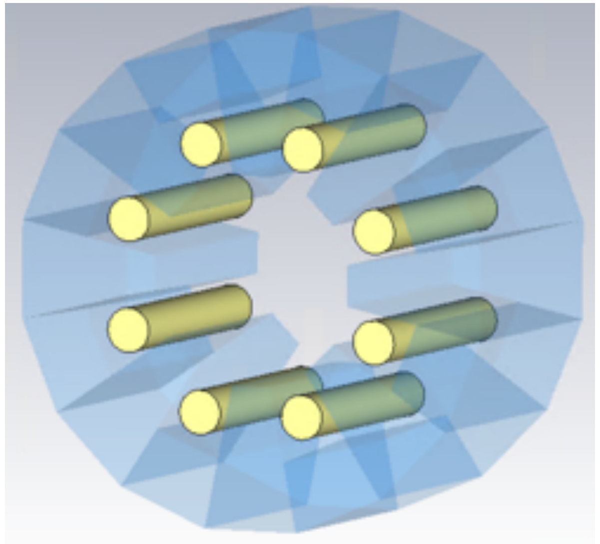
Tunability of Octupole Field Strength (1)

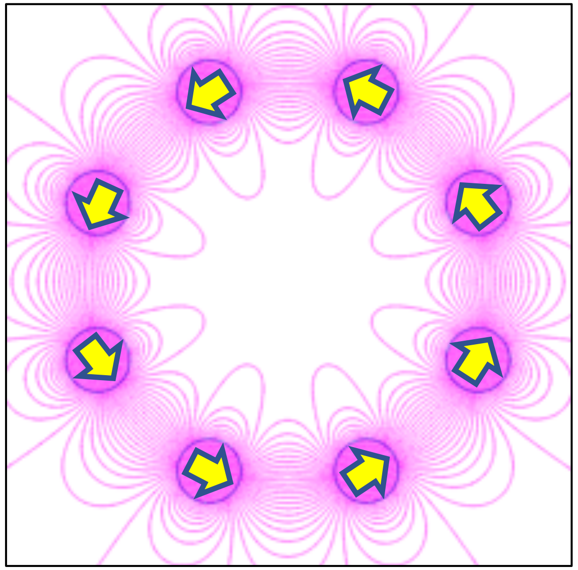


Octupole ON

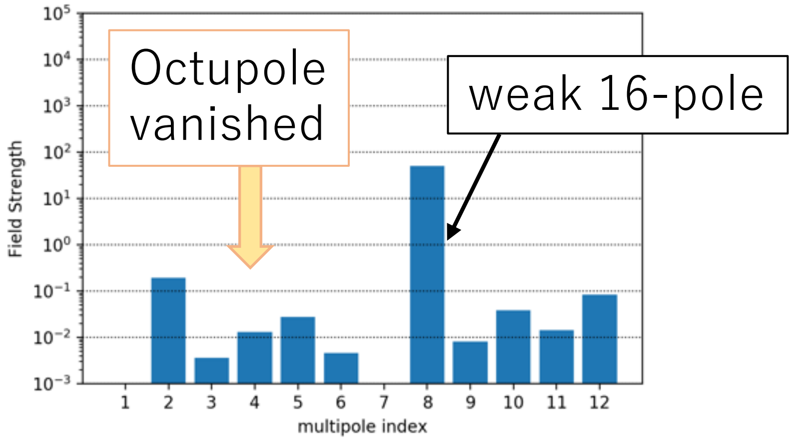


Rotating the
cylindrical Magnets

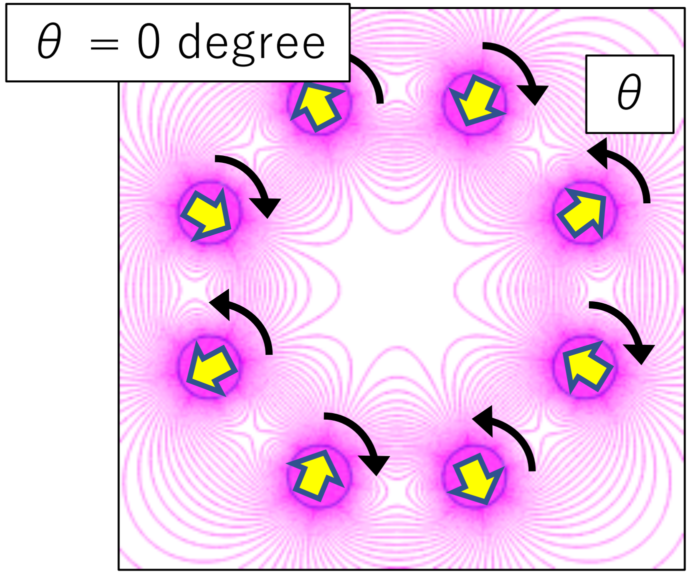


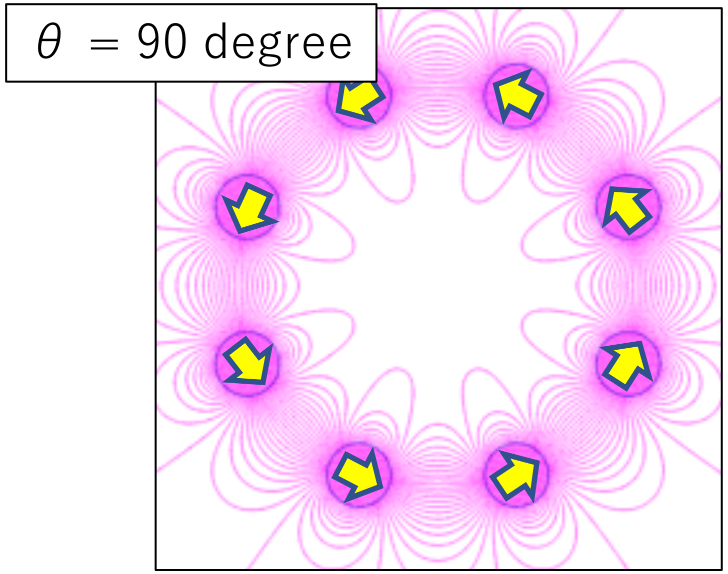


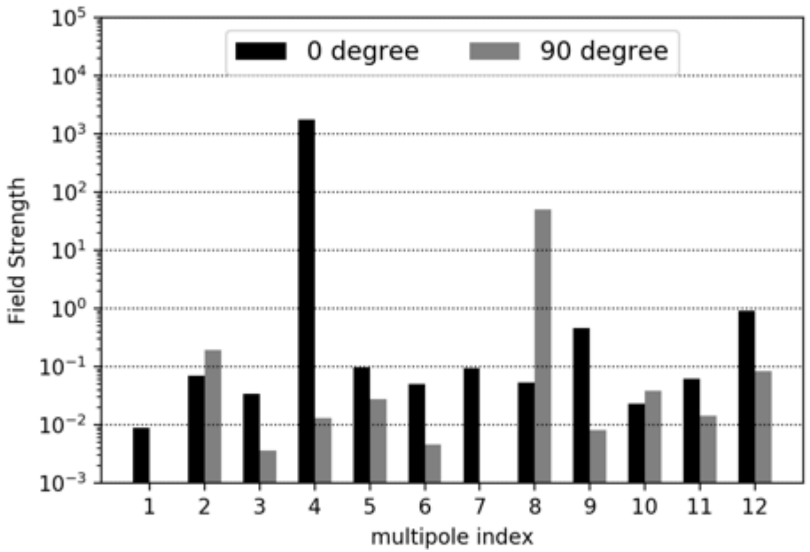
Octupole OFF

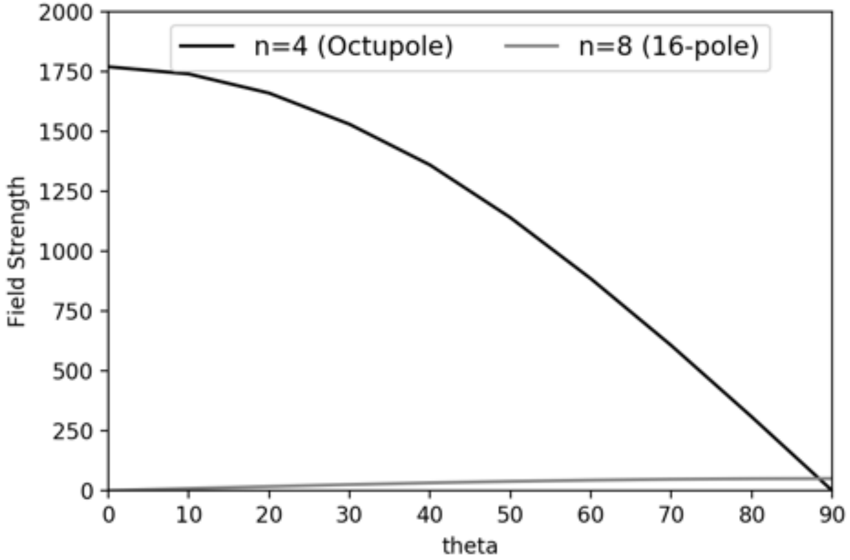


Tunability of Octupole Field Strength (2)







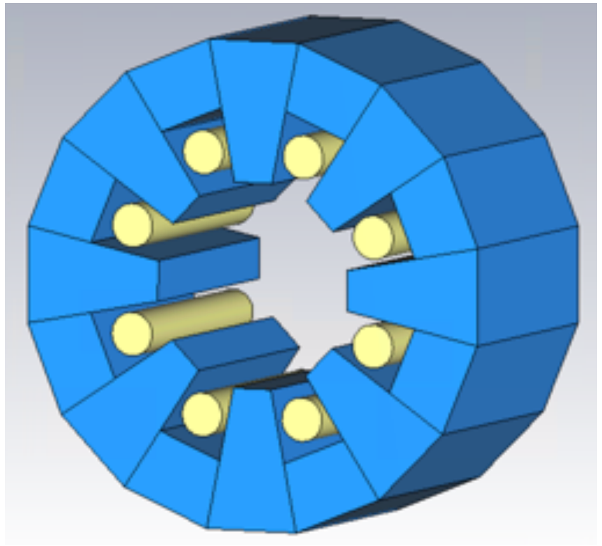


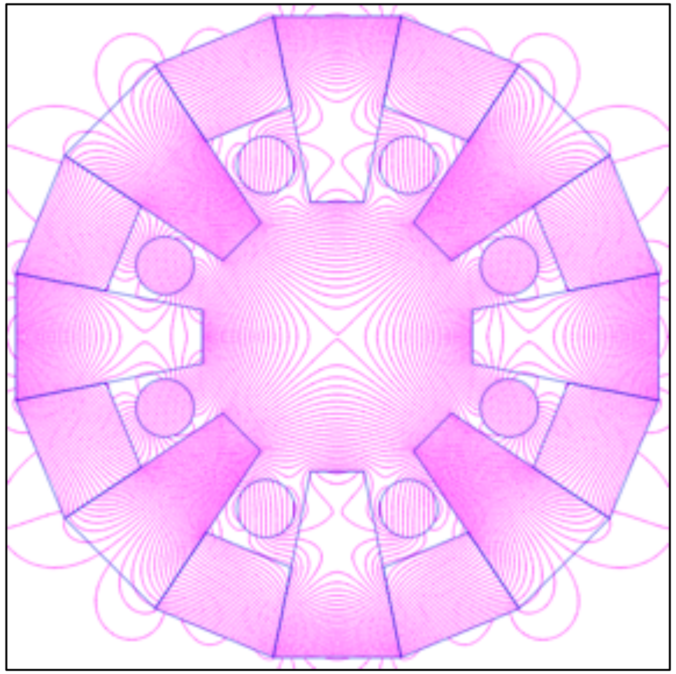
<u>Tunable region of Octupole Field Strength</u>

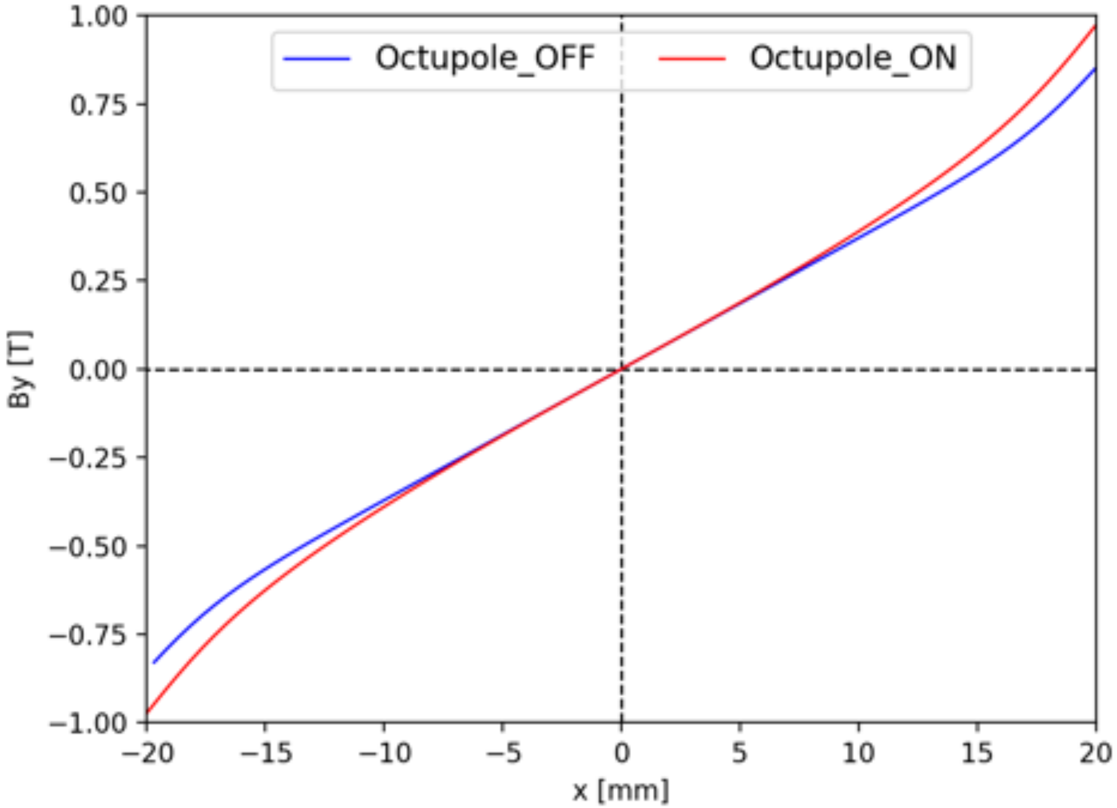
0 ~ 17700 T/m^3 [required range: 0 ~ 15000 T/m^3]

(Parasitic 16-pole field (n = 8) is ignorable to transport beams.)

Magnetic Circuit Configuration Generating Quadrupole and Octupole Fields

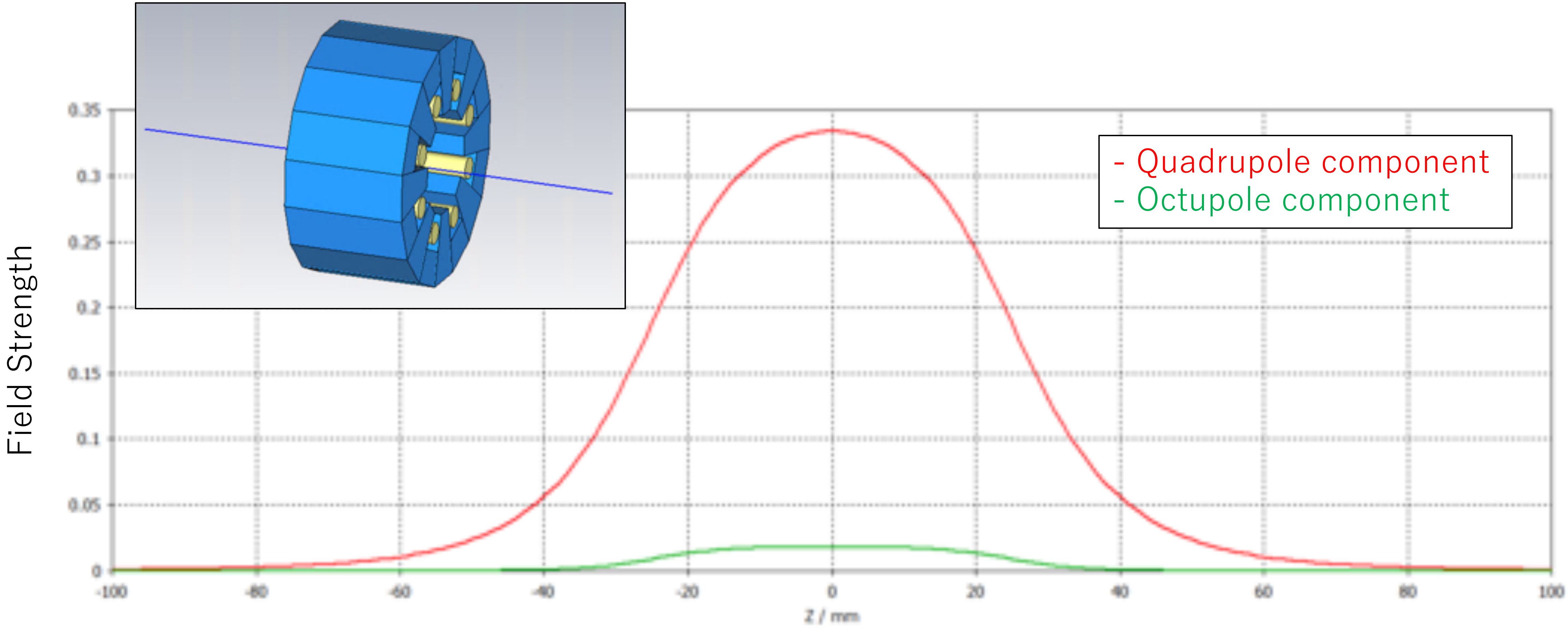






Superposition of quadrupole and octupole field components can be successfully achieved.

Results of 3D field analysis



3D magnetic field analysis was performed, and longitudinal distribution of multipole field componentswas calculated.

Fabrication of Prototype

- Fabrication of Prototype magnet is in progress.
- Manual tunable mechanism for octupole field strength will be installed in the prototype.

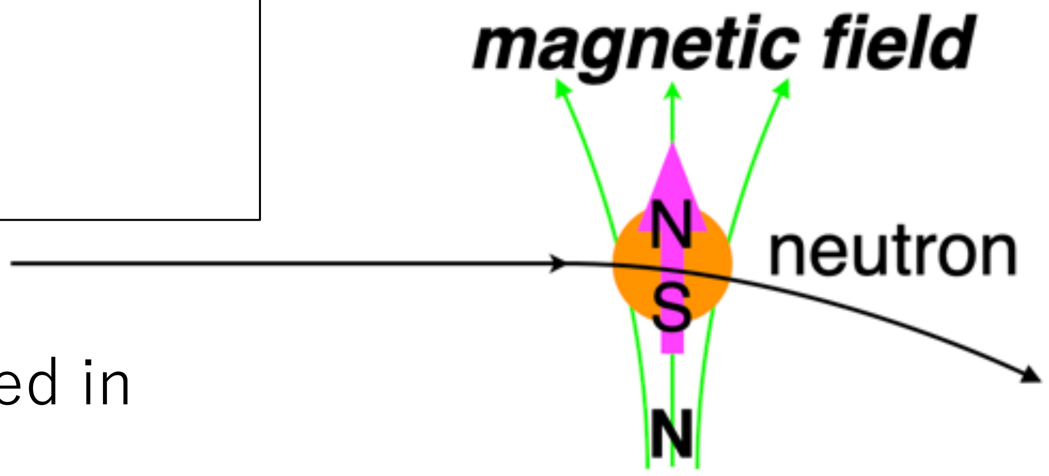
- Field measurement of the fabricated prototype will be performed by the end of 2021.

Modulating Sextupole Magnet for Neutron Beam Focusing

Neutron Beam Manipulation

Equation of Motion for a particle with magnetic moment (μ) in External Magnetic Field (**B**)

$$F = M\frac{d^2\mathbf{r}}{dt^2} = \mp|\mu|\ \nabla|\mathbf{B}|$$



Neutron has a magnetic moment.
Therefore, neutron beam can be deflected in a magnetic field with a high gradient.

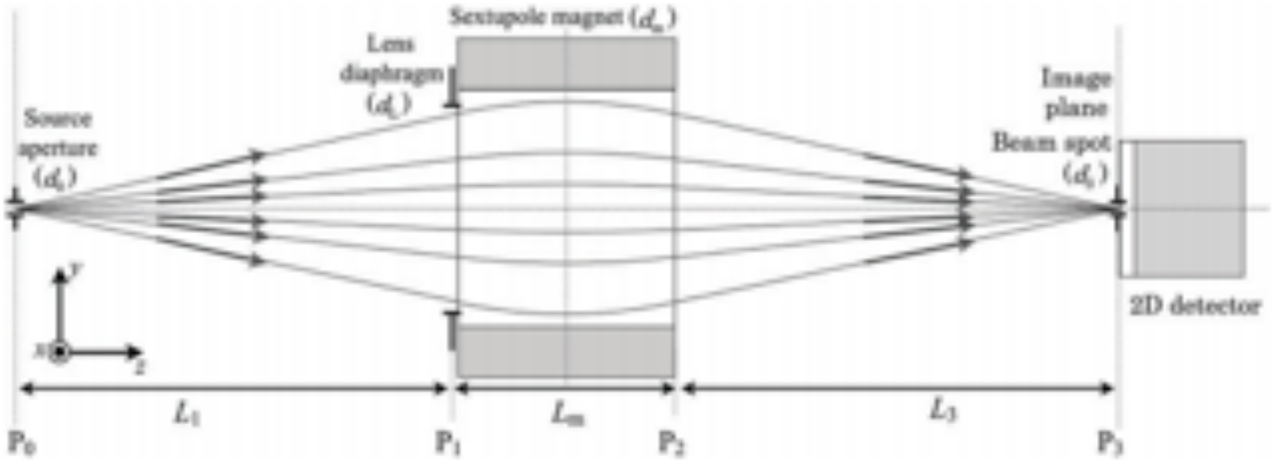
<u>Neutron Beam Focusing</u>

For beam focusing, the force should be proportional to the length between the position from the beam axis.

$$\nabla|\mathbf{B}| \propto |\mathbf{r}| \quad \Rightarrow \quad |\mathbf{B}| \propto r^2$$

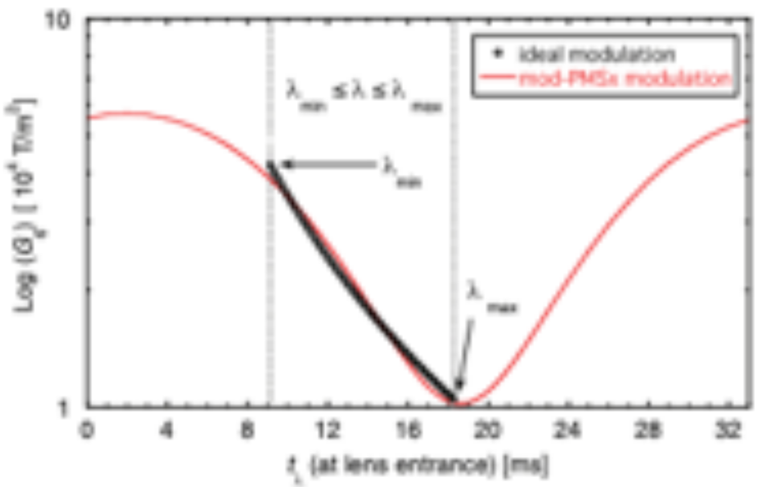
<u>Sextupole Field is worked as a lens!!</u>

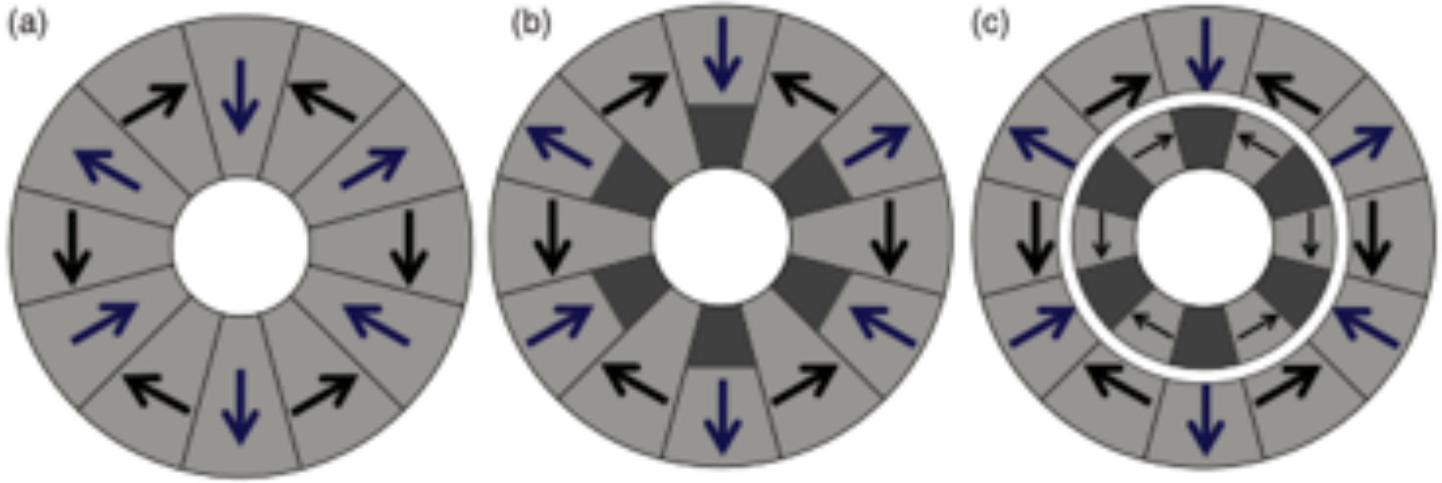
Neutron Focusing Lens with Sextupole



In order to focus neutrons with various energy (velocity) focusing strength must be modulated depending on the ToF of neutrons.

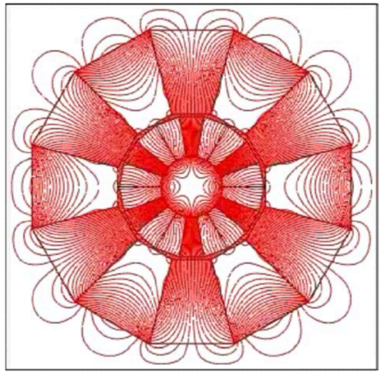
<u>To synchronize with repetition rateof pulsed neutron source such as J-PARC MLF, Rapid Modulating (25 Hz) sextupole magnet is needed.</u>
=> nested sextupole magnet



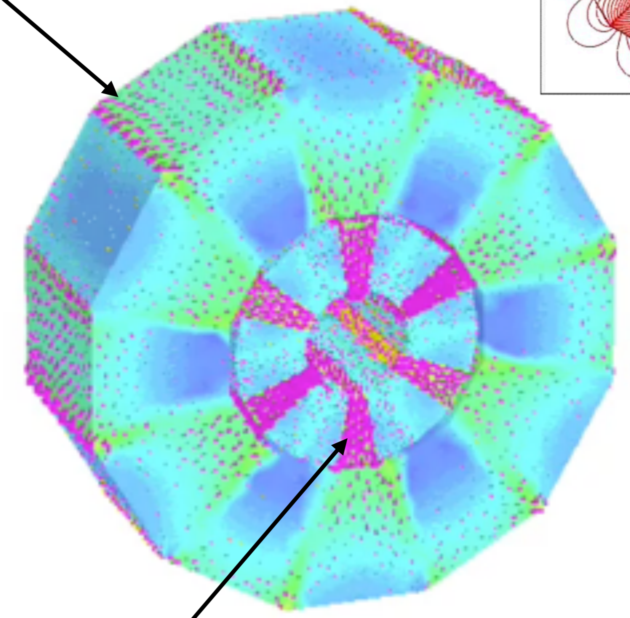


[3] M. Yamada et al, PTEP 2015, 043G01

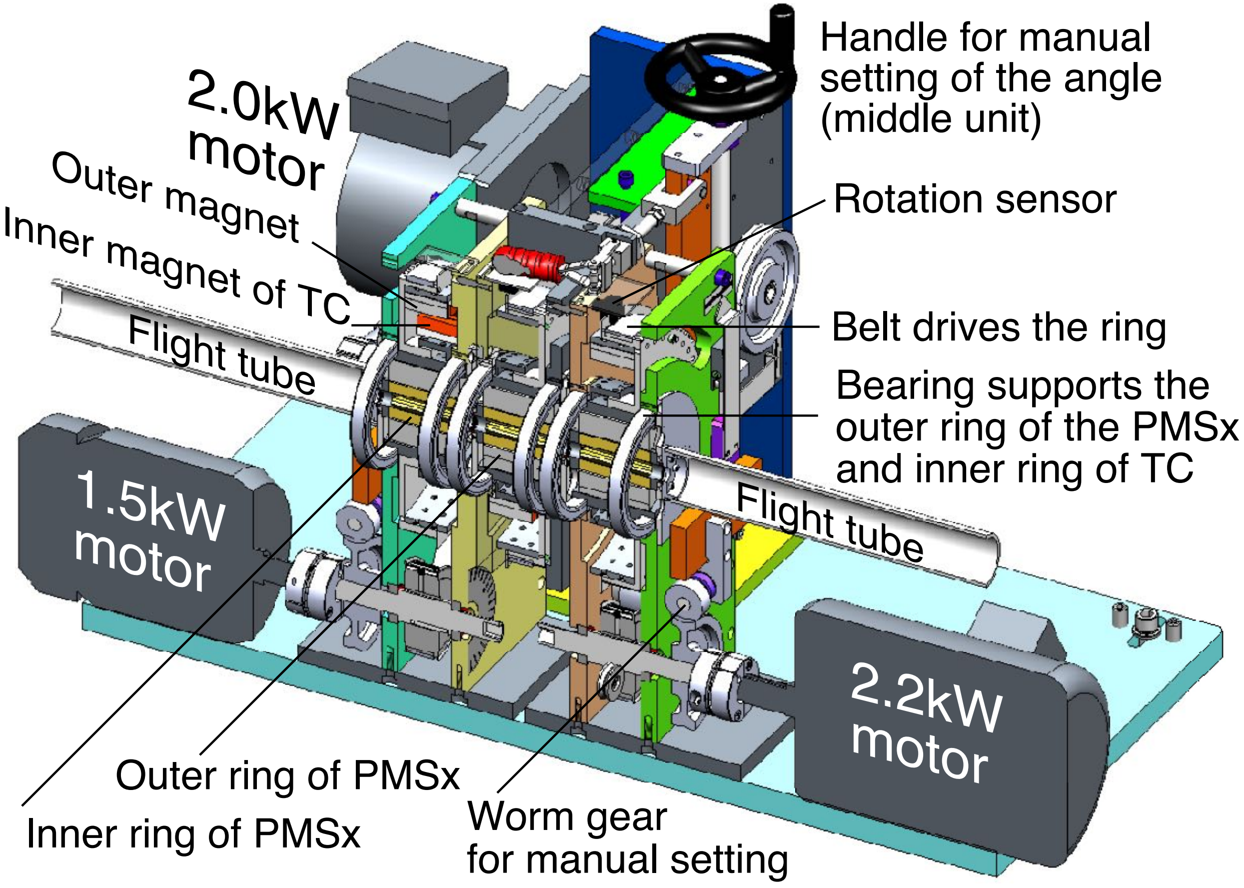
Modulation of Focusing Strength



Rotating Outer Ring Magnet

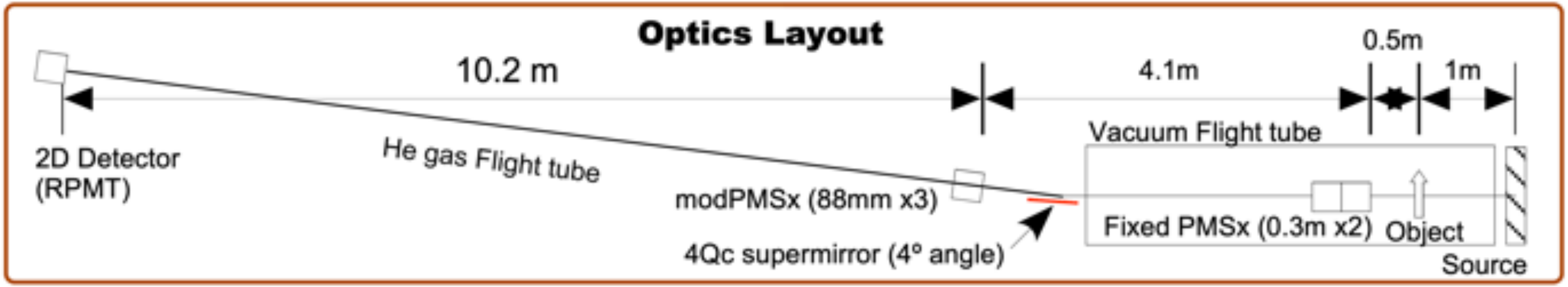


Fixed Inner Ring Magnet with soft iron poles

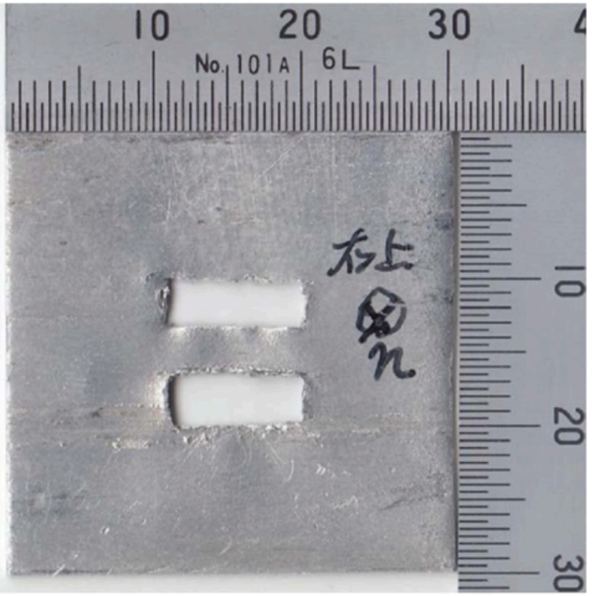


Demonstration Imaging Experiment

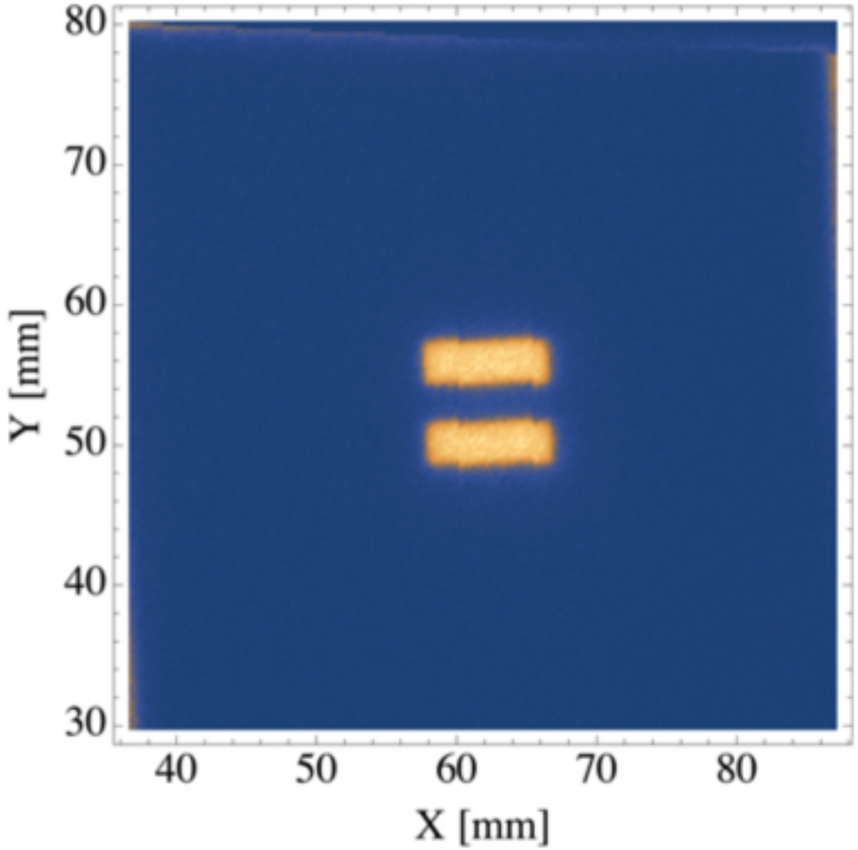
Utilizing the lens effect, Magnified imaging experiment was performed a Hokkaido University.



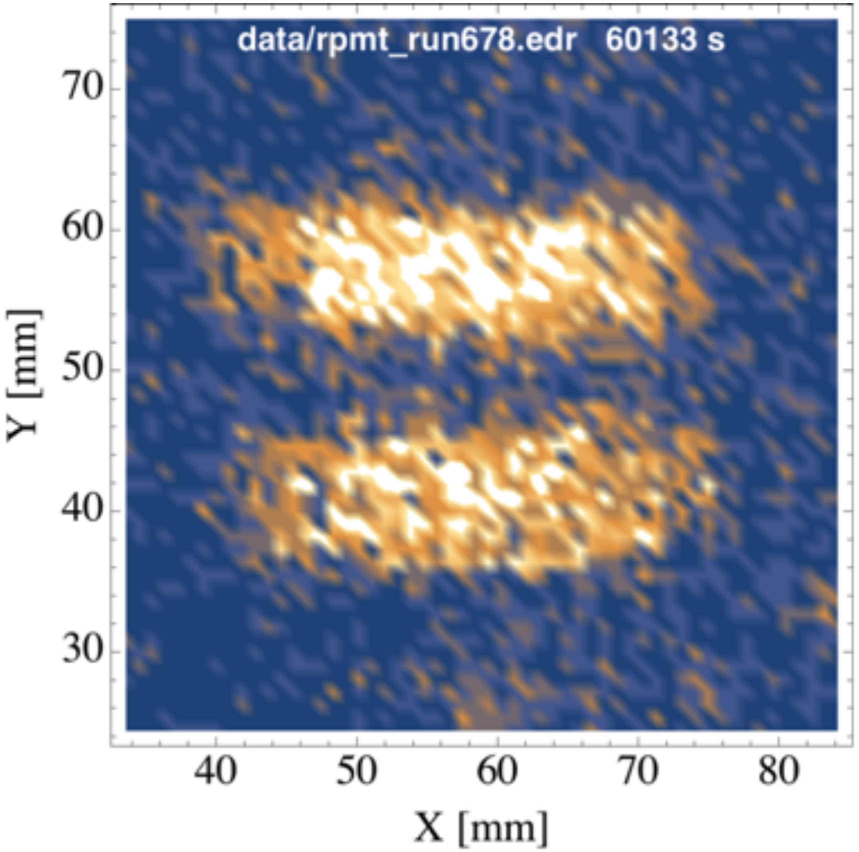
Result of Magnified Imaging



Object



Direct Image



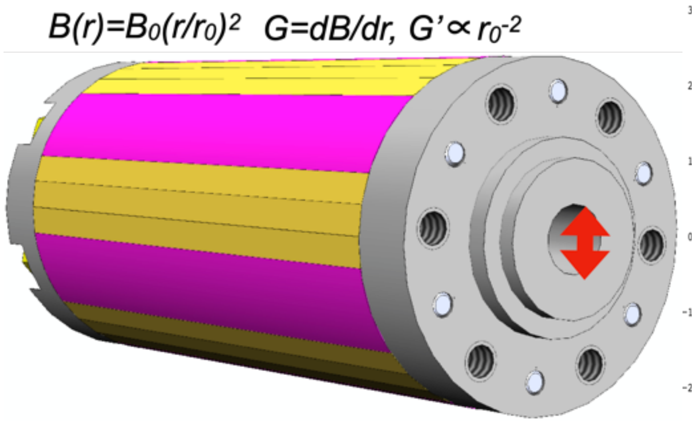
Magnified Image

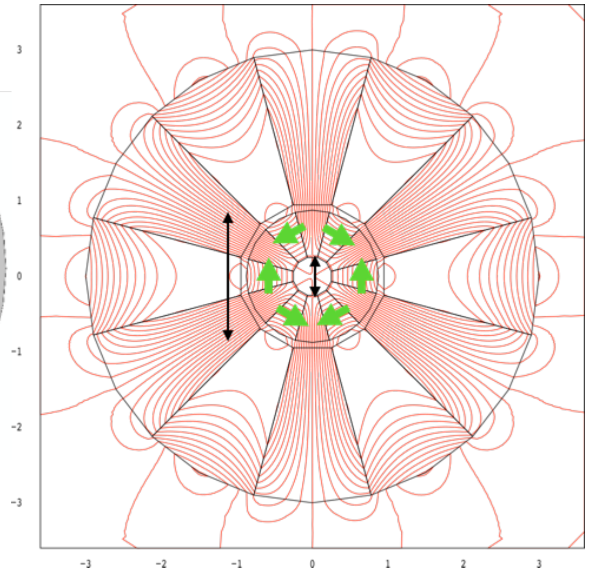
Proof of Principle experiment was successfully performed.

Next Experiment:

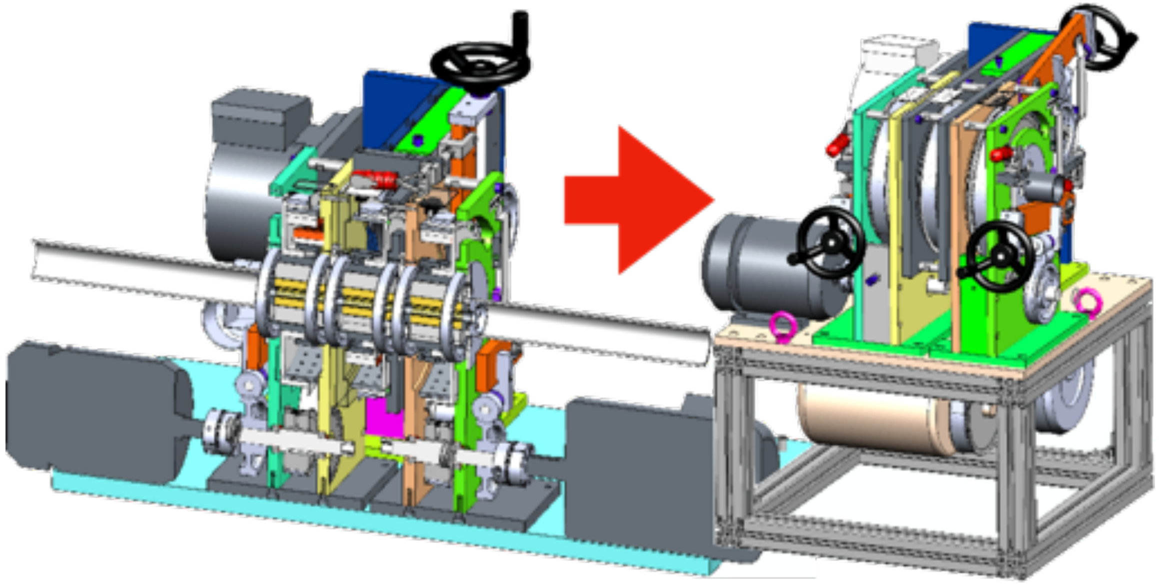
- Neutron Beamline in Hokkaido-U was reduced down to 10m. In order to perform next experiment, improvement of devices is in progress.

Stronger Sextupole Magnet





Compact Configuration



Summary

- Multipole magnet are essential device is beam experiment. Permanent magnet multipoles have great potential for sophisticated handling of particle beams.

- In this presentation, examples below were introduced.
  - Combined multipole (quadrupole and octupole) for compensation of space charge effect in intense ion beams
  - Modulating sextupole magnet for neutron beam focusing