Magnetic Separators

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Outline

- Why need magnetic separators
- Basic principles
- Electromagnets
- Some examples

Why need magnetic separators?

- Nuclear reactions are messy.
  - Beam – 10^9 – 10^{13} particles per second
  - Scattered target material
  - Transfer reaction products
  - Quasi-fission products
  - Fission products
  - Fragmentation products

- Essentially – A lot of the stuff coming out of the target is not the nuclide you want to study

Charged Particle in Magnetic Fields

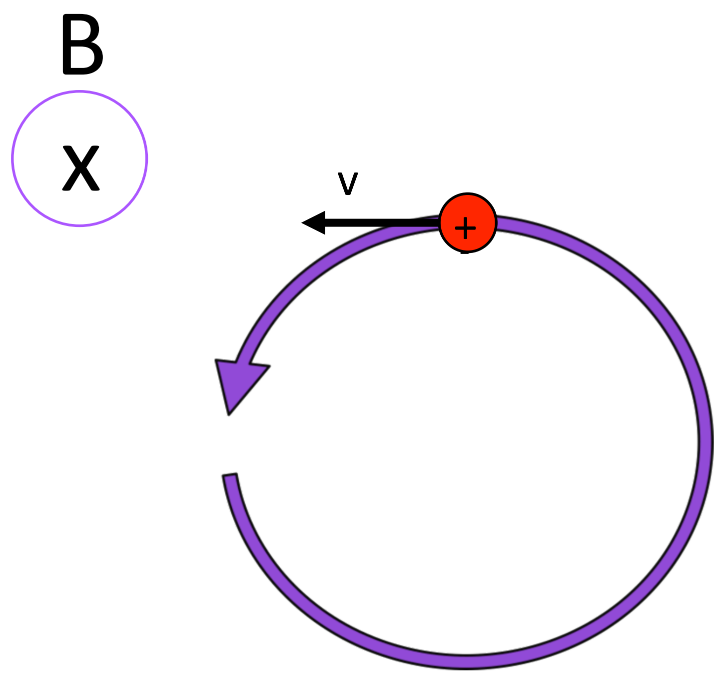
Lorentz force:

- Charged particle moving in a B field experiences a sideways force that is perpendicular to the magnetic fields and the velocity of the particle.

Force, velocity

$$\vec{F} = q(\vec{v} \times \vec{B})$$

charge, Magnetic field



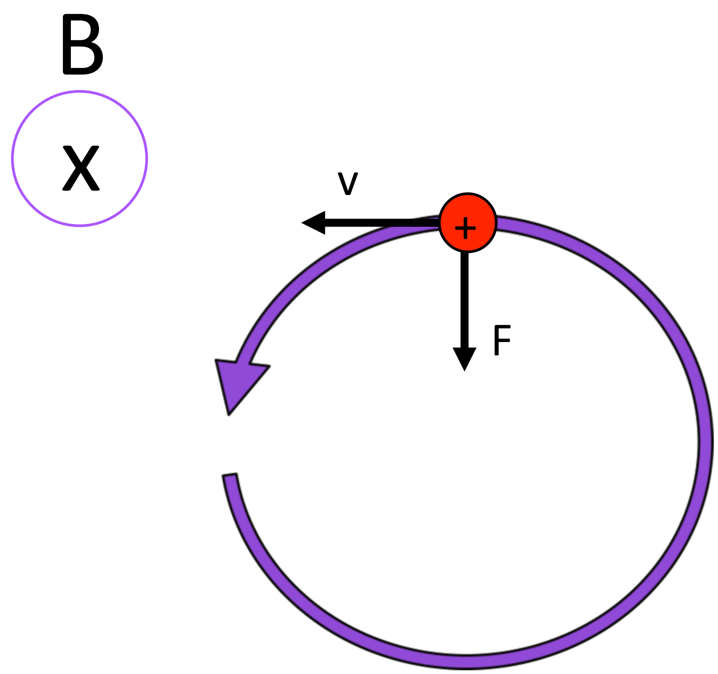
Charged Particle in Magnetic Fields

Centripetal force:

- Force that keeps a body moving with a uniform speed along a circular path and is directed along the radius towards the center.

$$F = \frac{mv^2}{\rho}$$

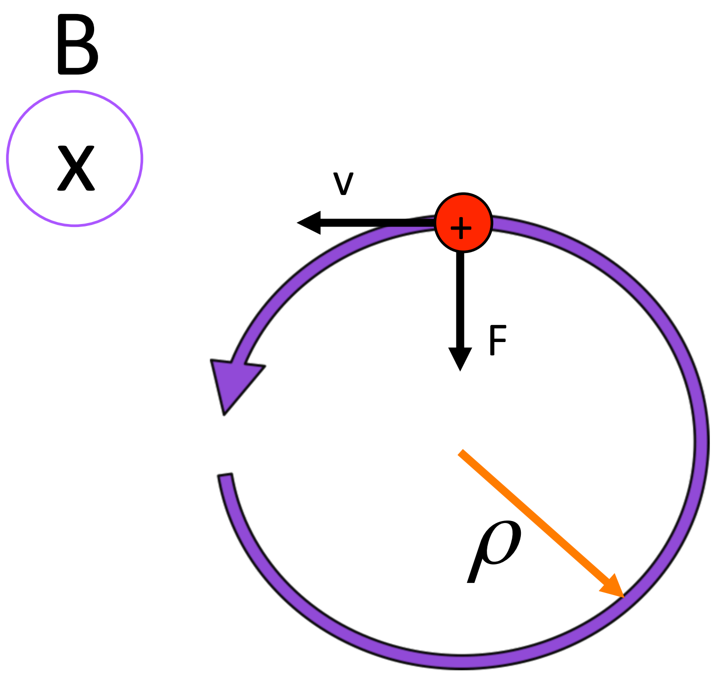
Force; mass; velocity; Radius of curvature



Charged Particle in Magnetic Fields

Lorentz force = centripetal force

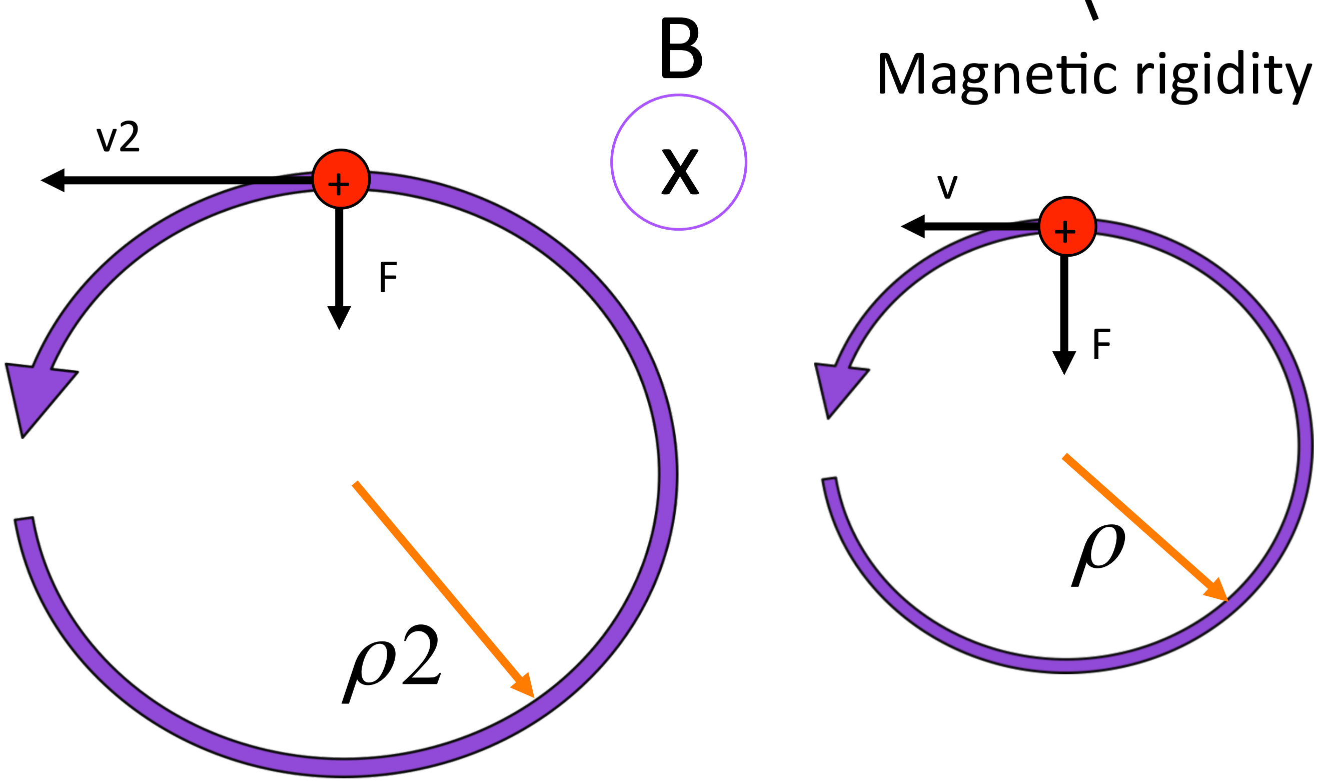
$$qvB = \frac{mv^2}{\rho} \qquad \rho = \frac{mv}{qB}$$



Charged Particle in Magnetic Fields

Lorentz force = centripetal force

$$qvB = \frac{mv^2}{\rho} \qquad \rho = \frac{mv}{qB} \qquad B\rho = \frac{mv}{q}$$



How Separation is Achieved

Lorentz force = centripetal force

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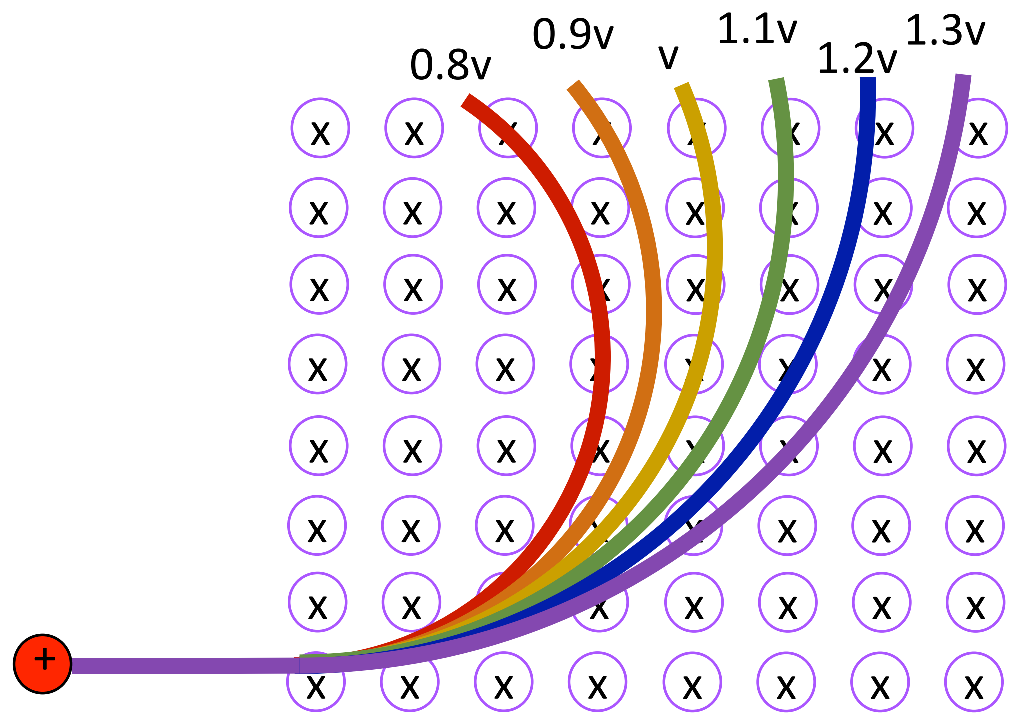

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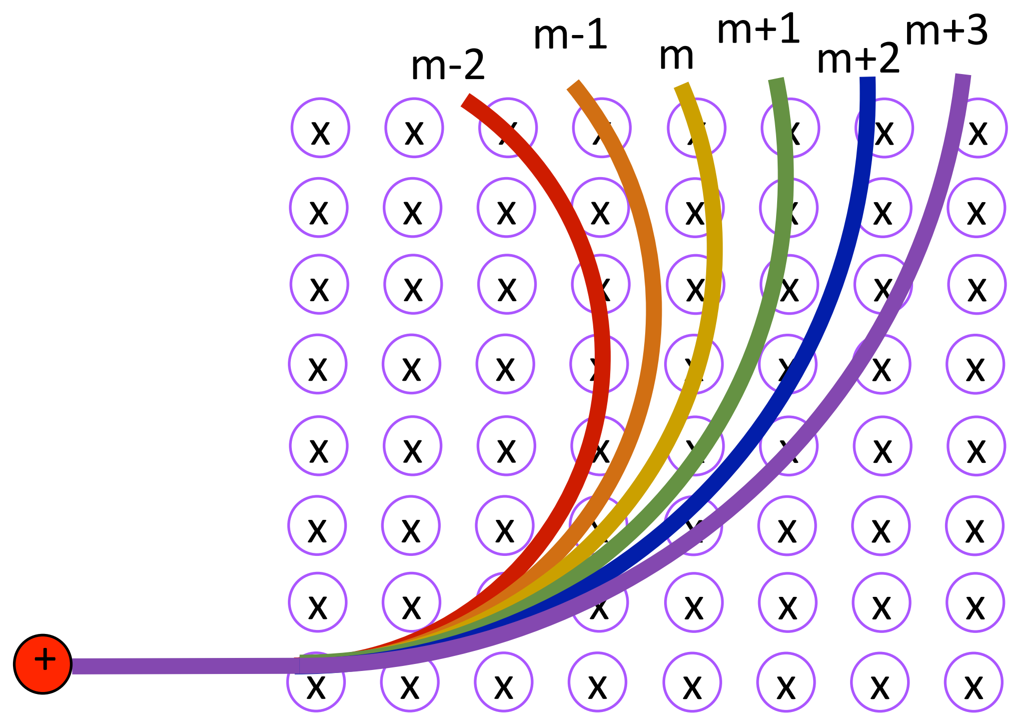

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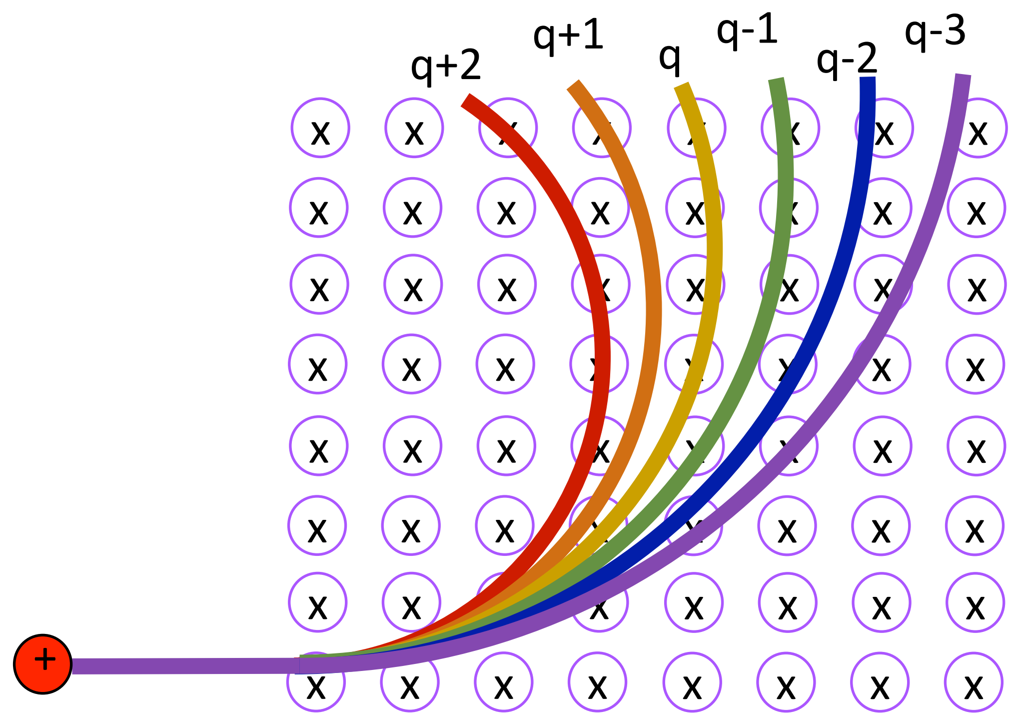
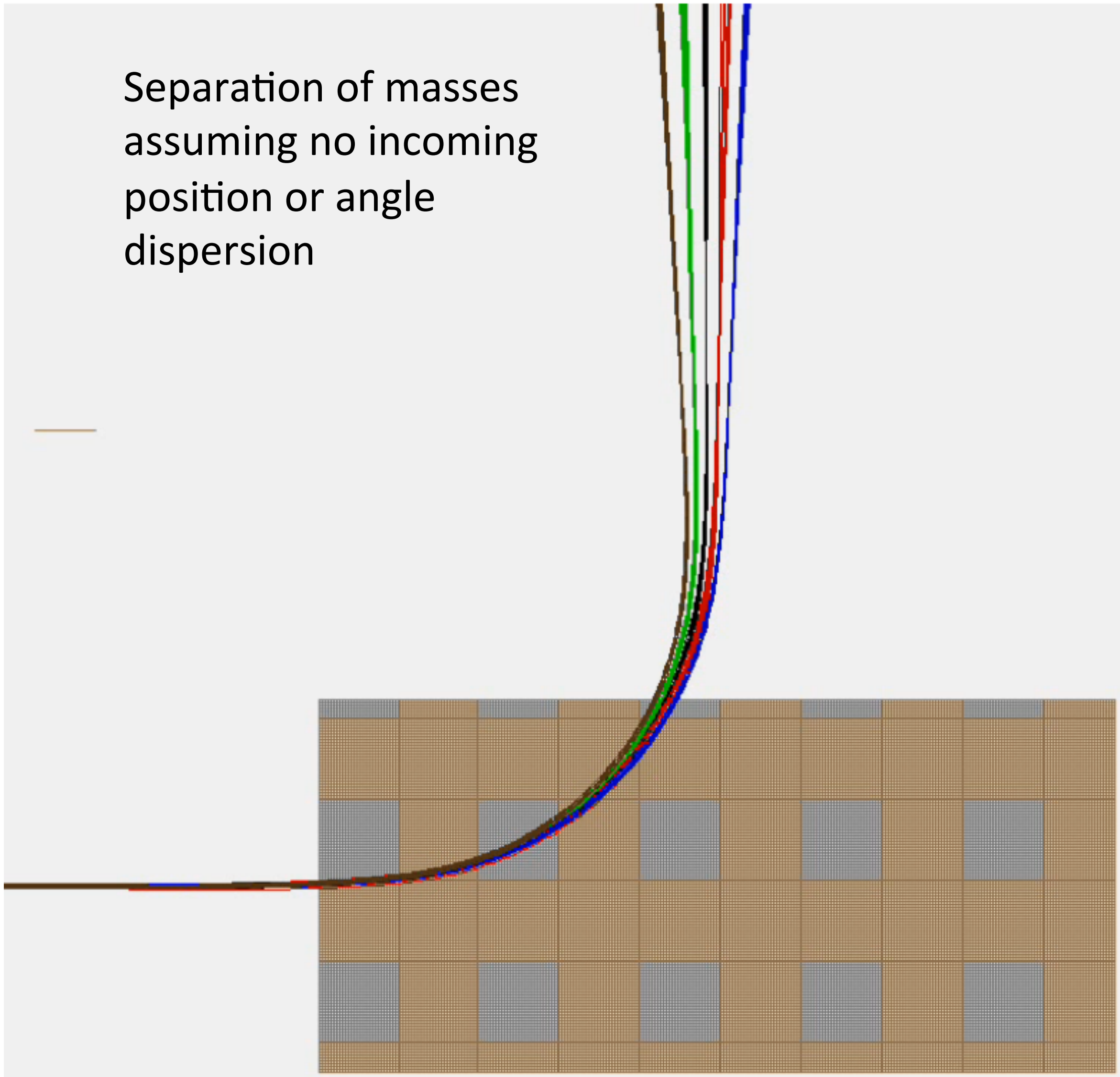
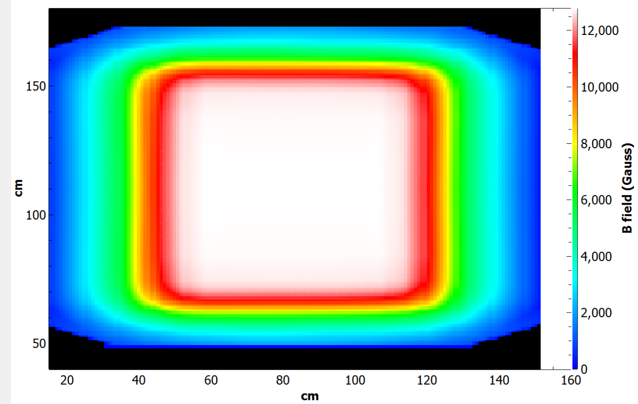


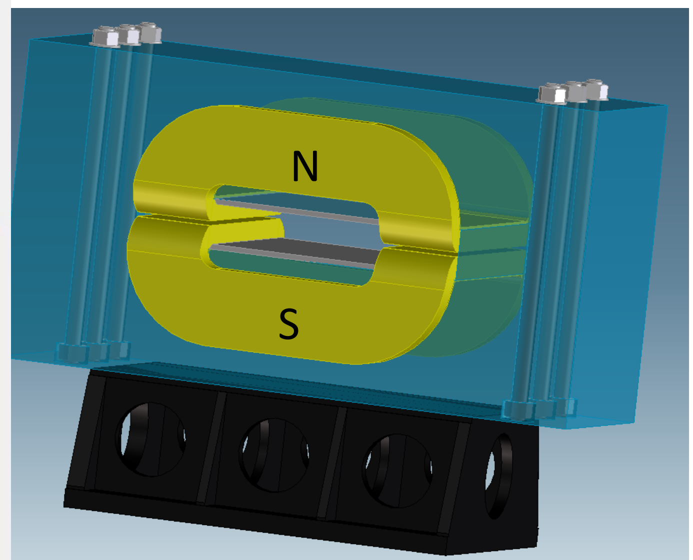
Magnets - Dipole

A=90 A=95 A=100 A=105 A=110

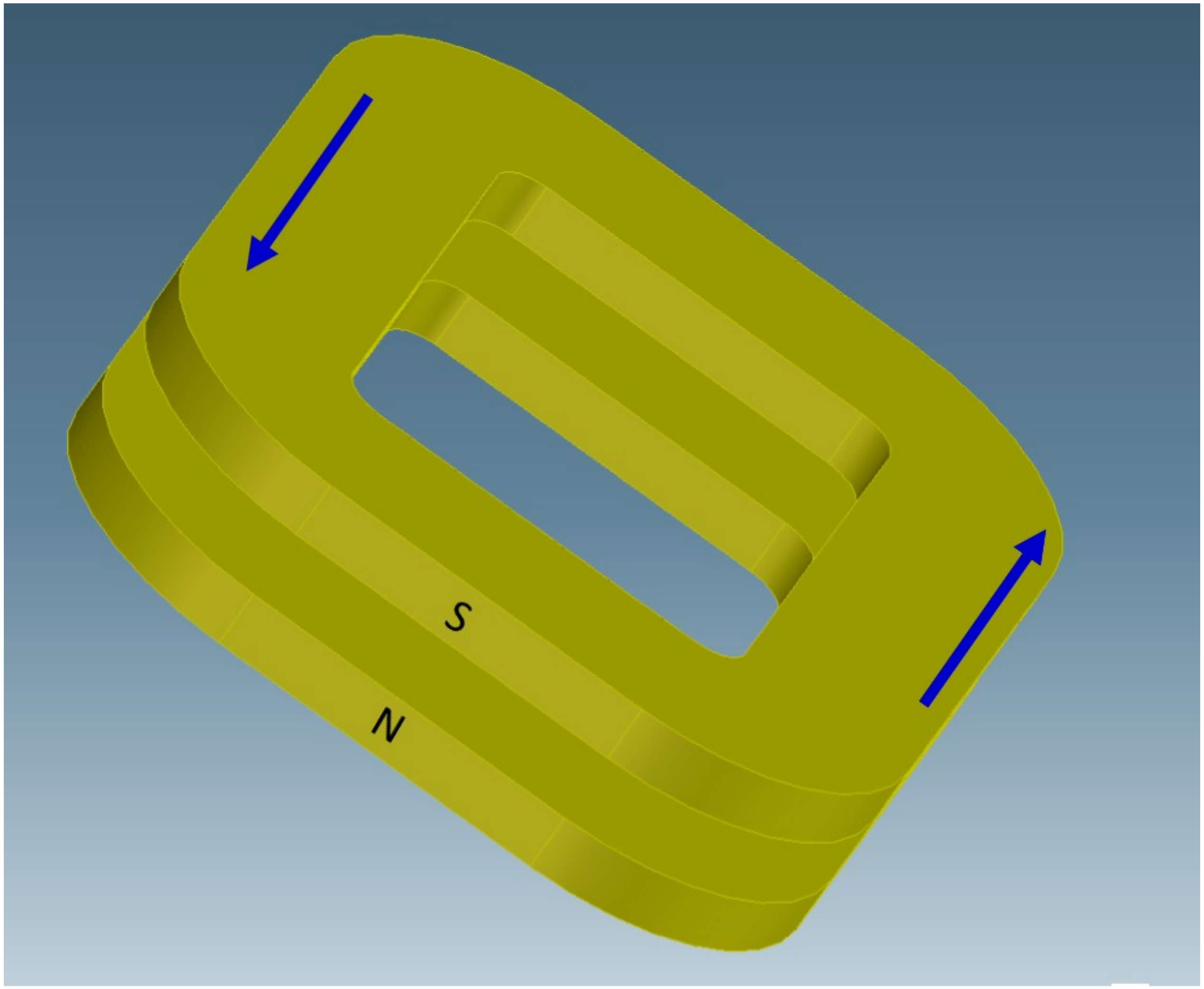
Separation of masses assuming no incoming position or angle dispersion

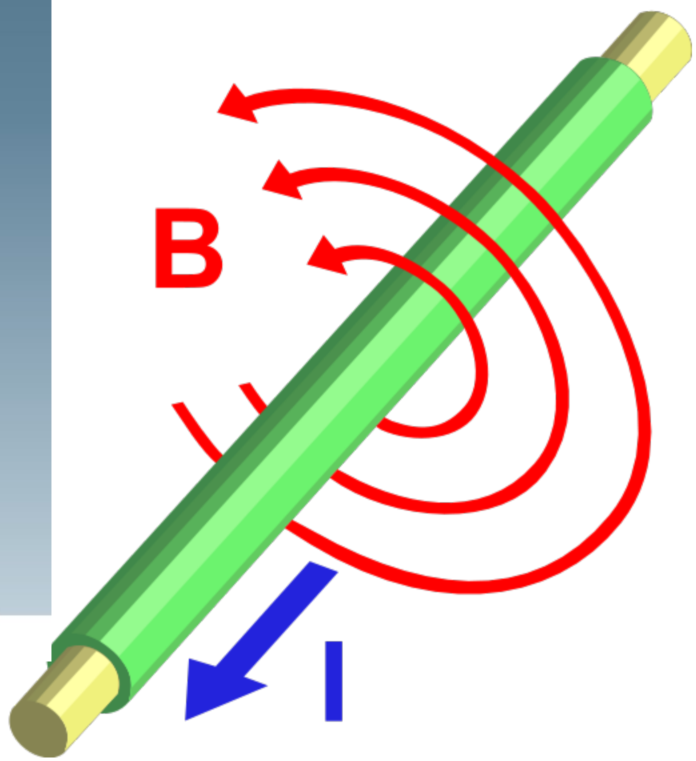






Electromagnetism





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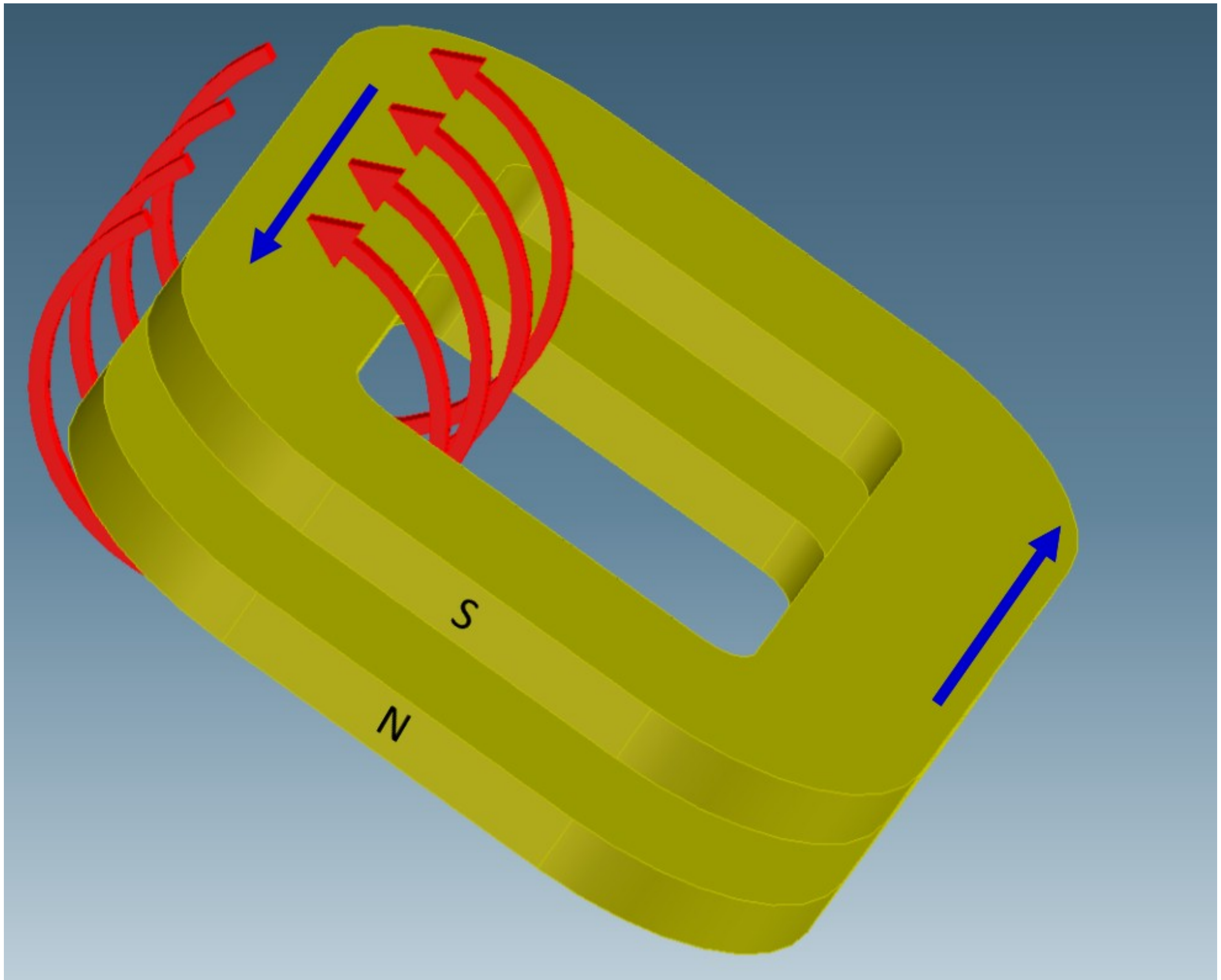

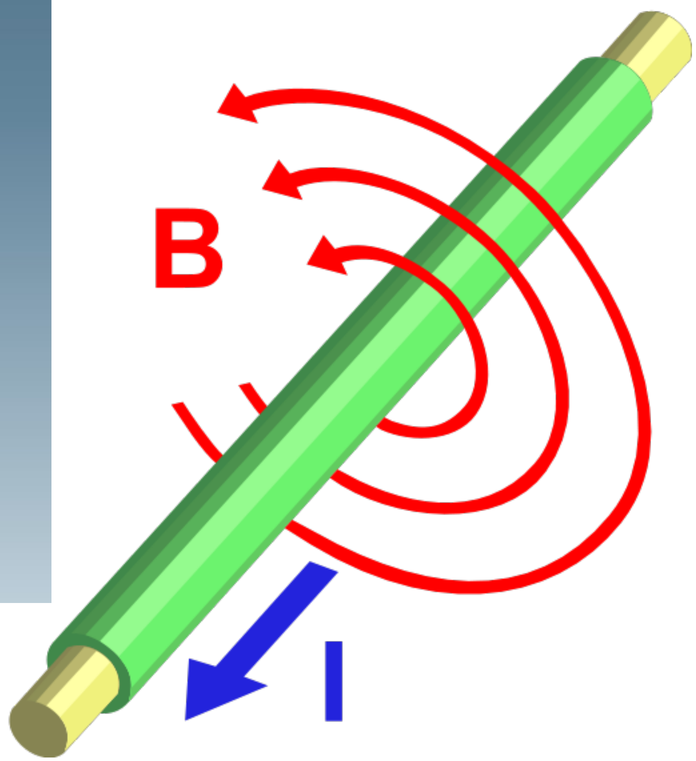

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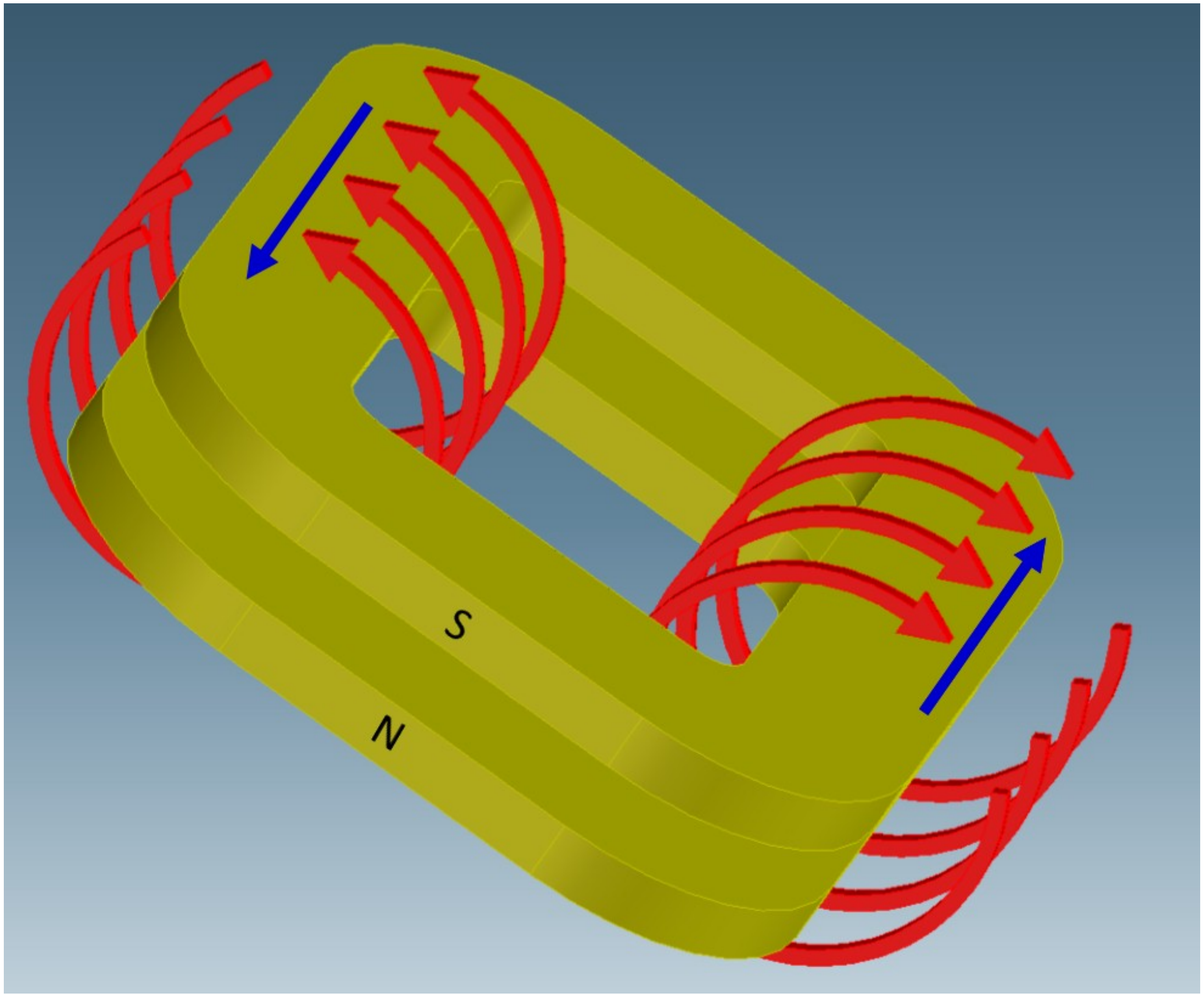

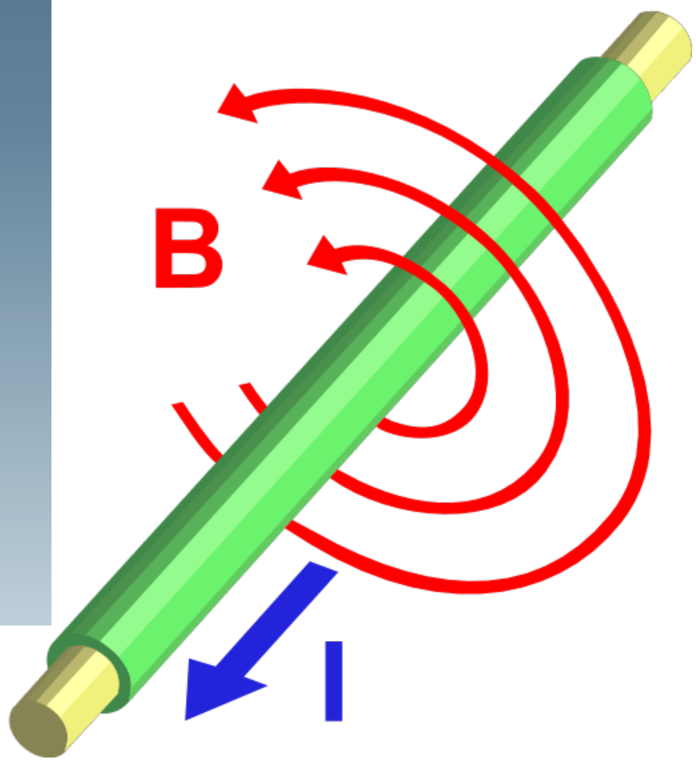

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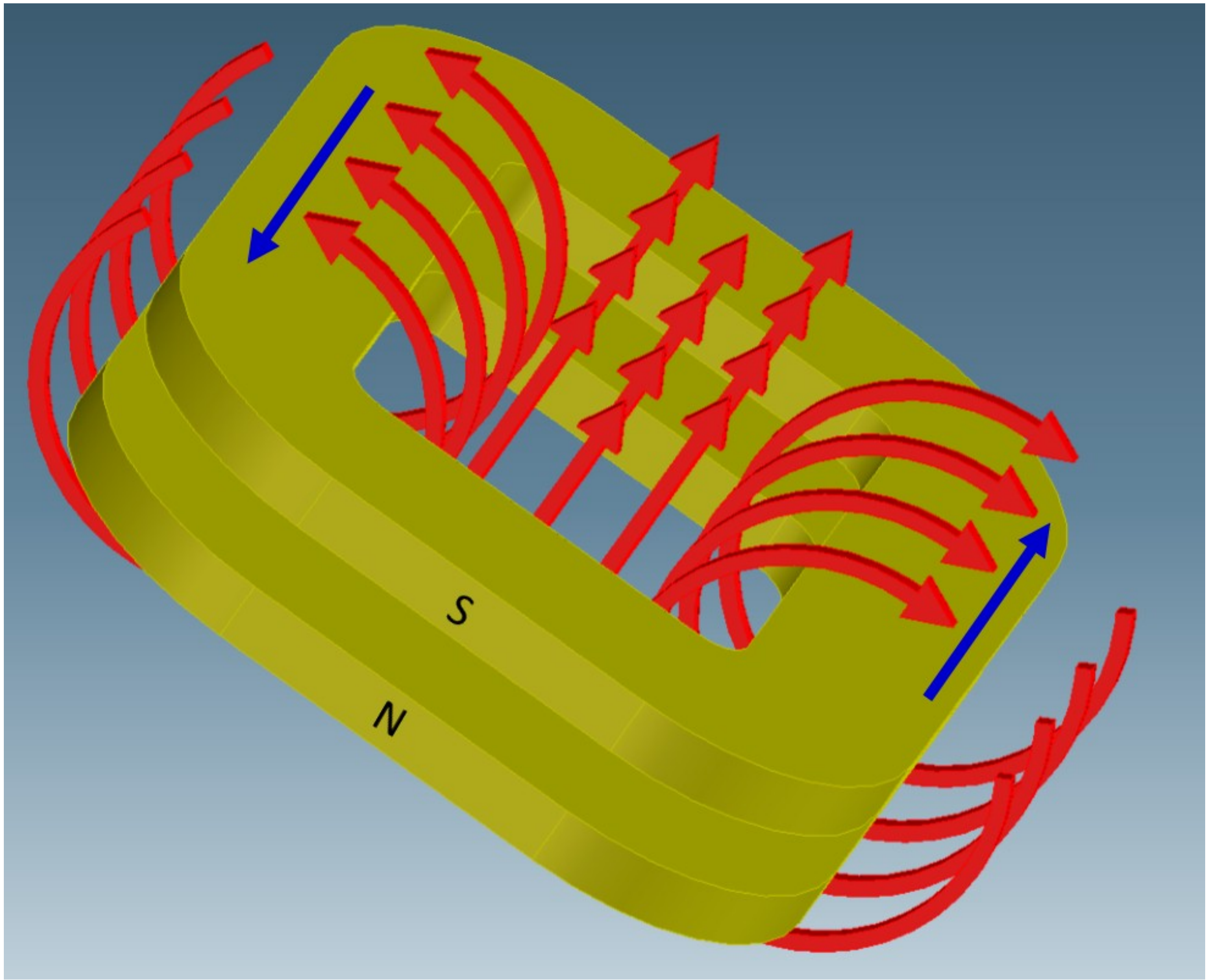
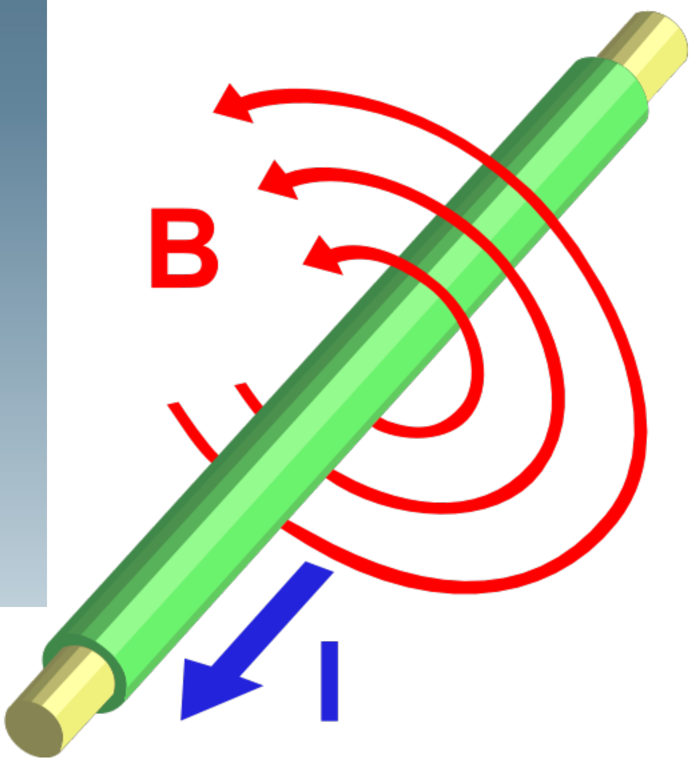
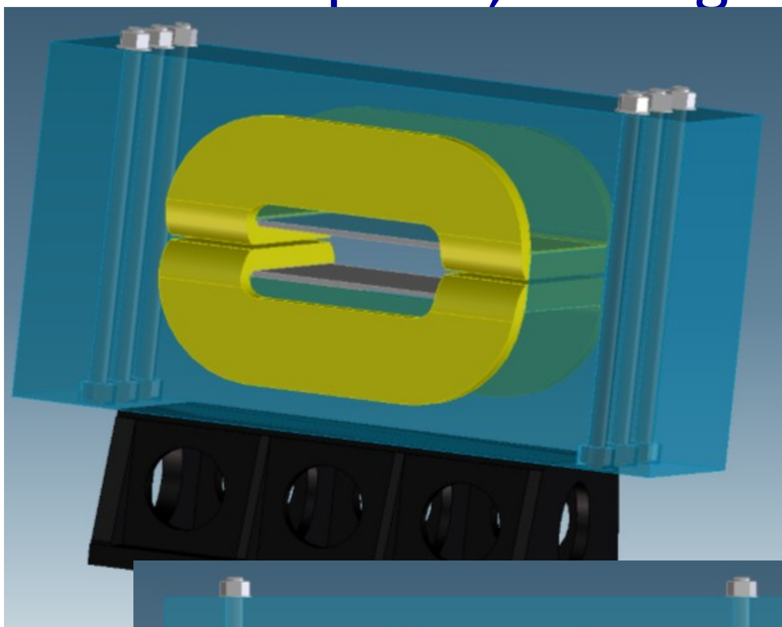
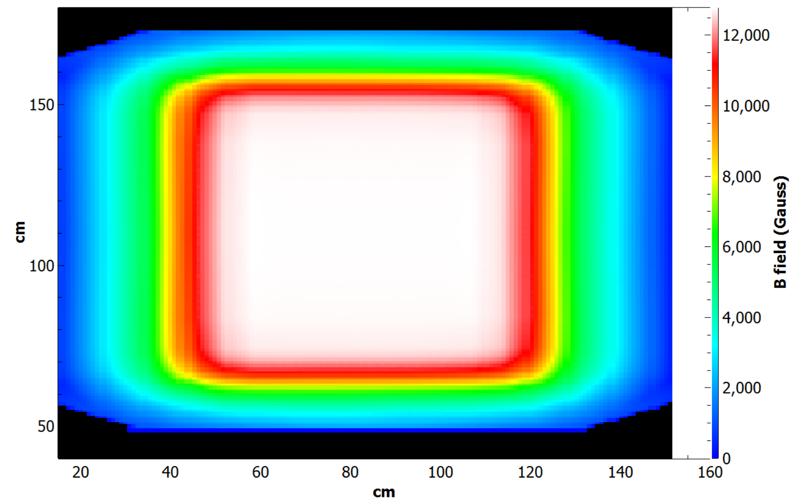


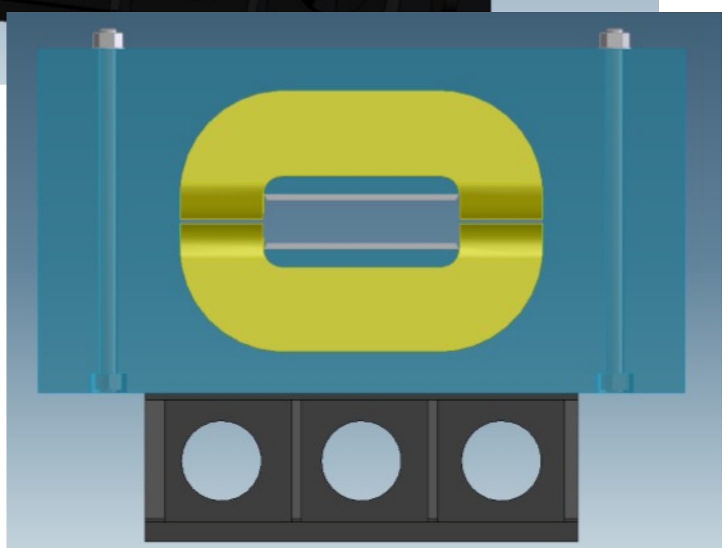


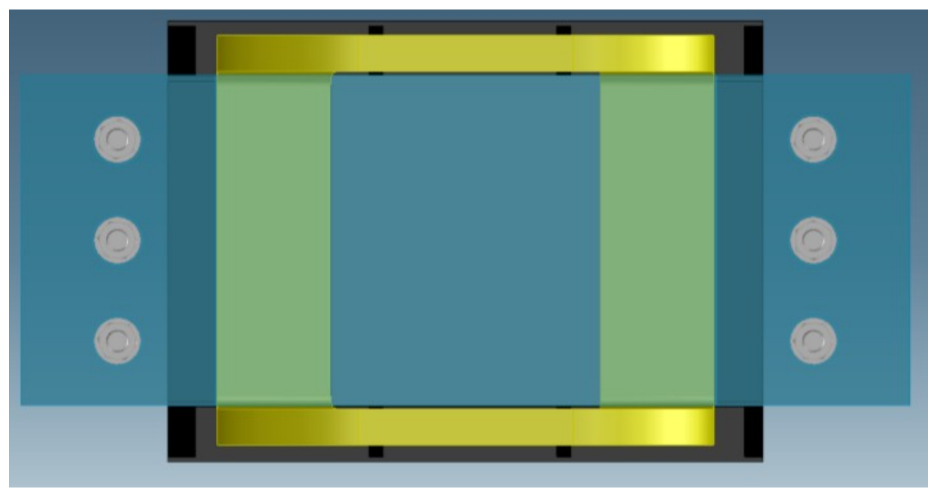
Magnets - Dipole

- Normal dipoles, no edge angles









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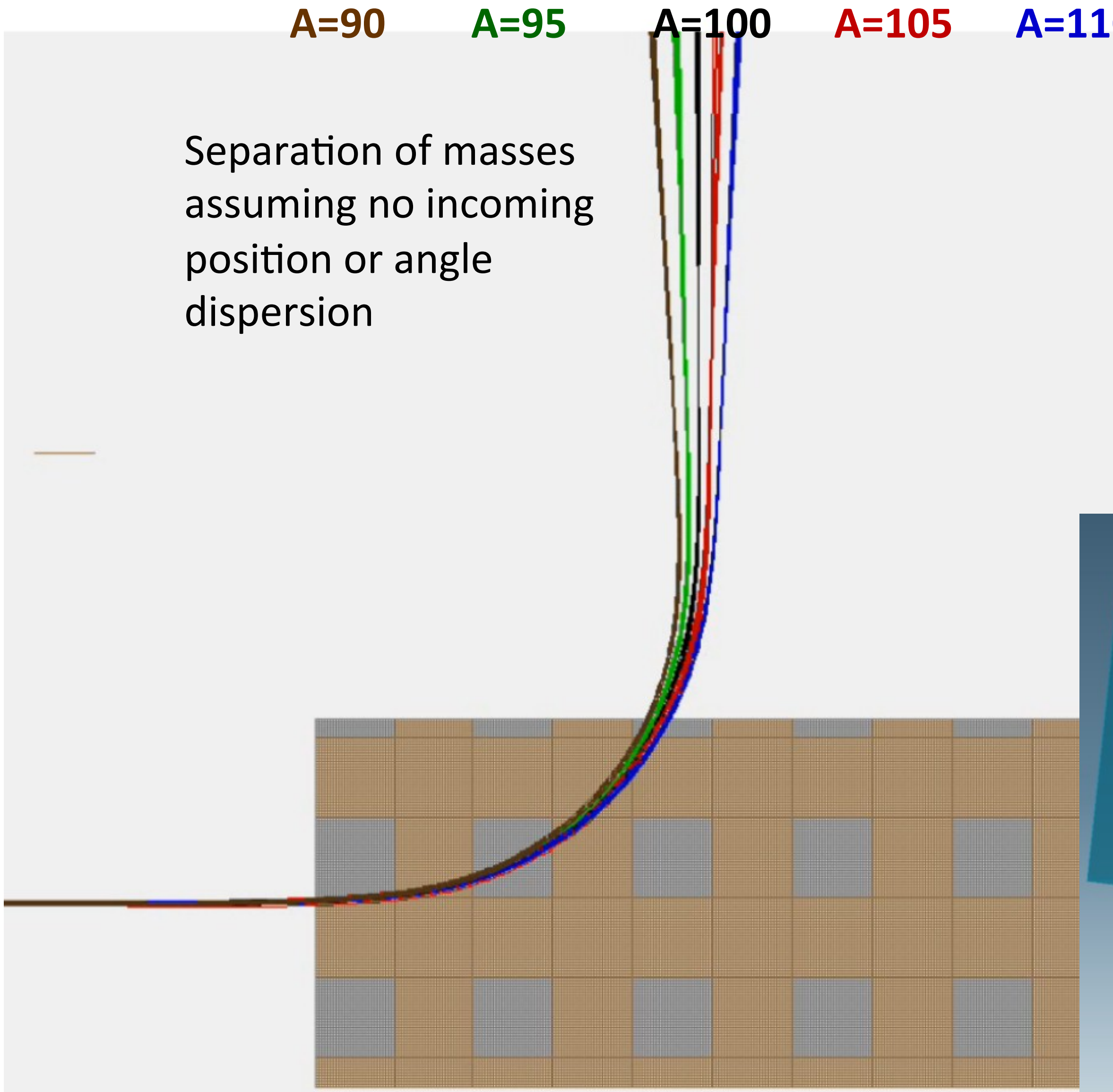

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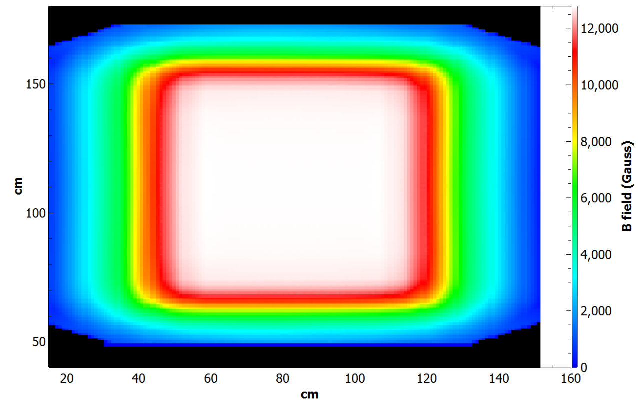

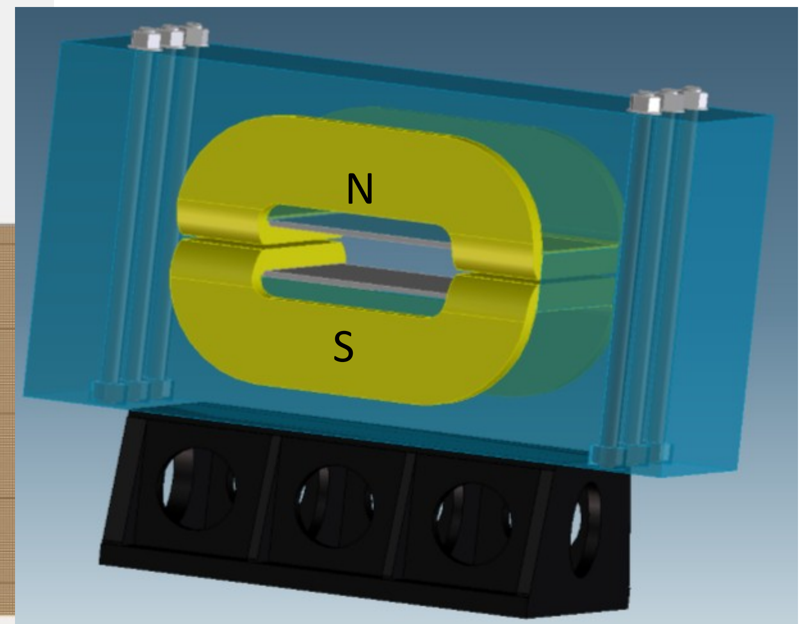

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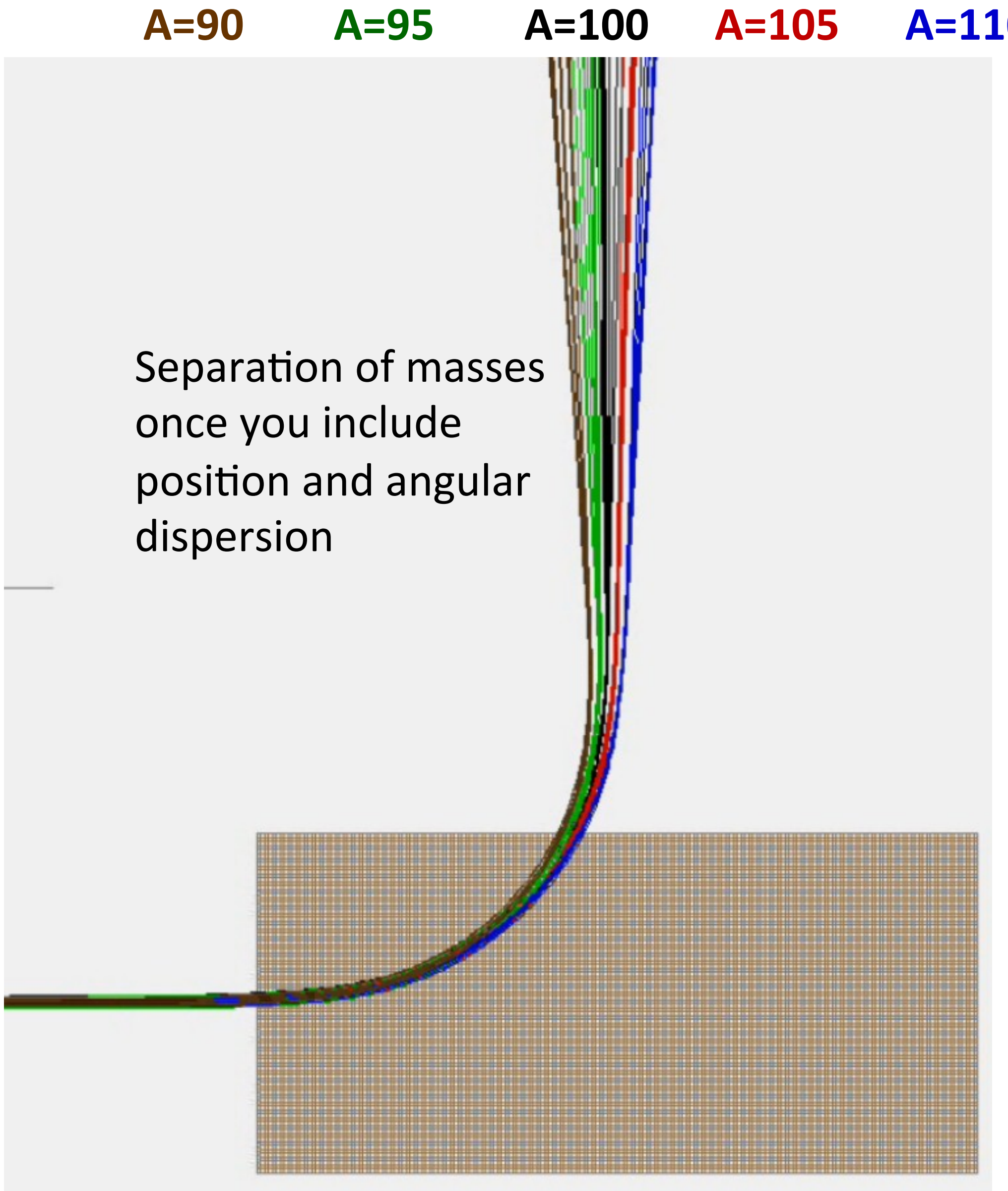
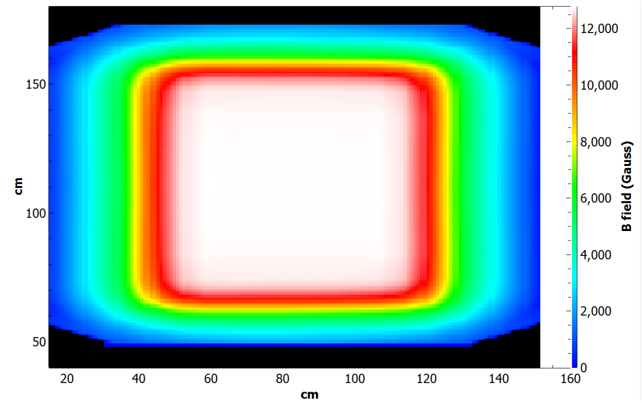
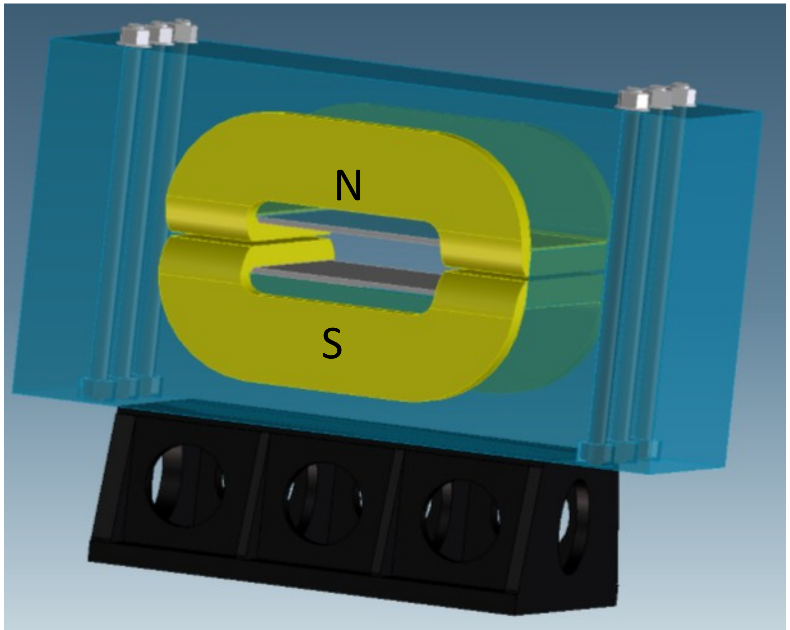
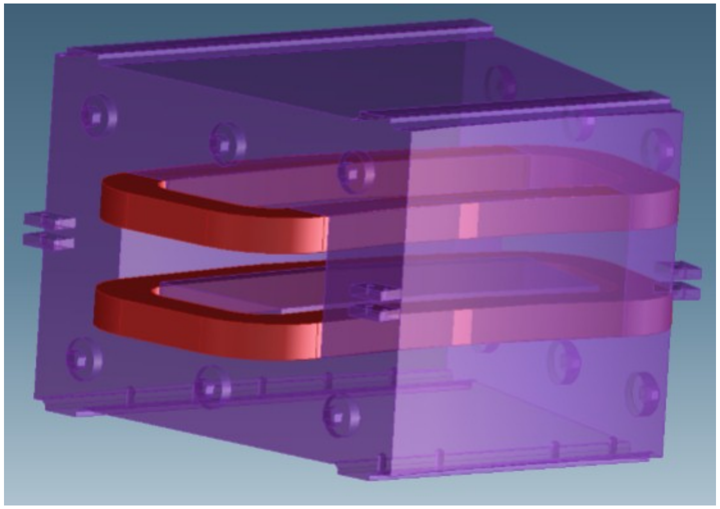


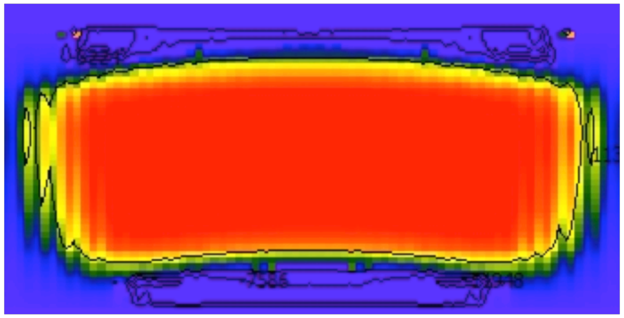


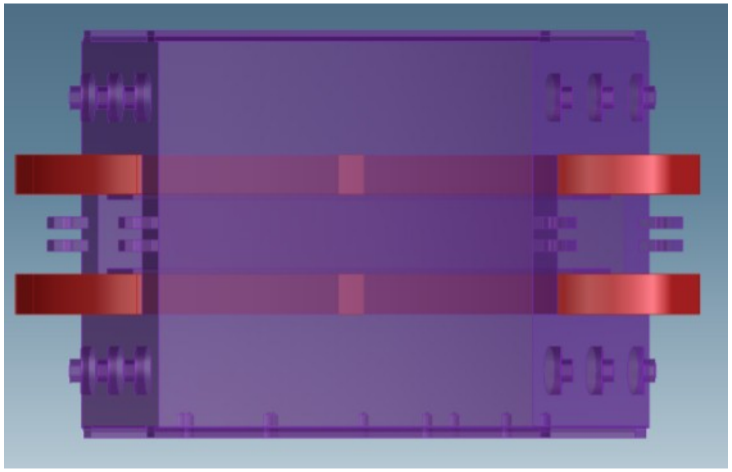


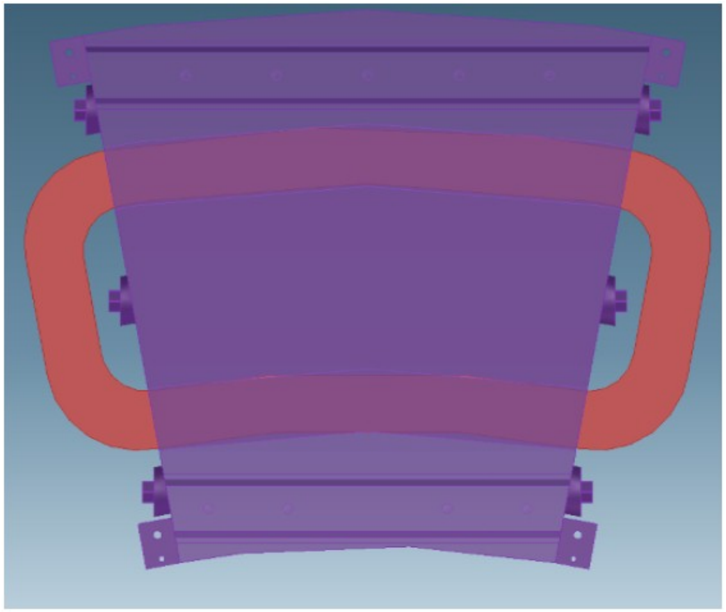
Magnets – Dipoles with Edge Angles

- With focusing – Edge angles









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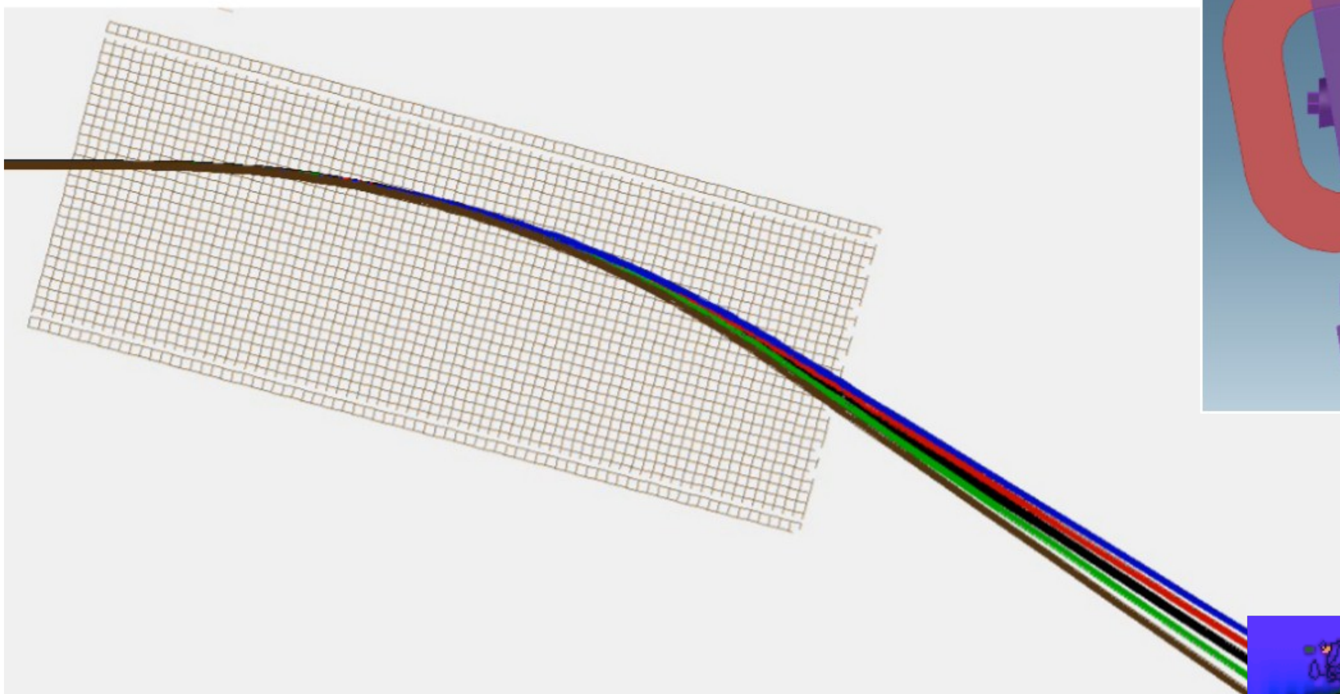
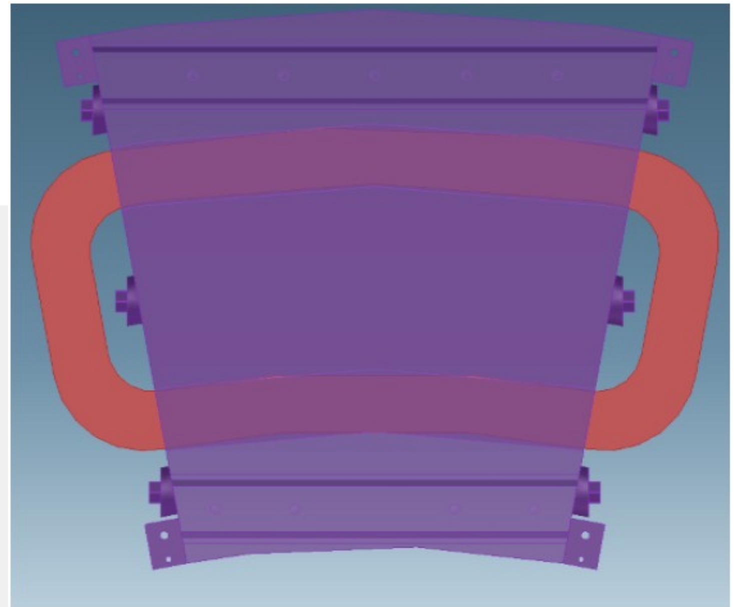
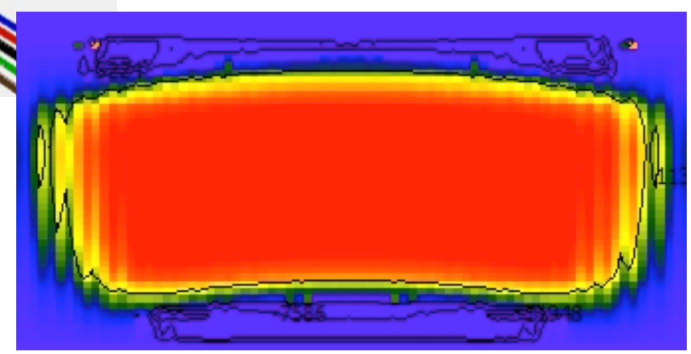
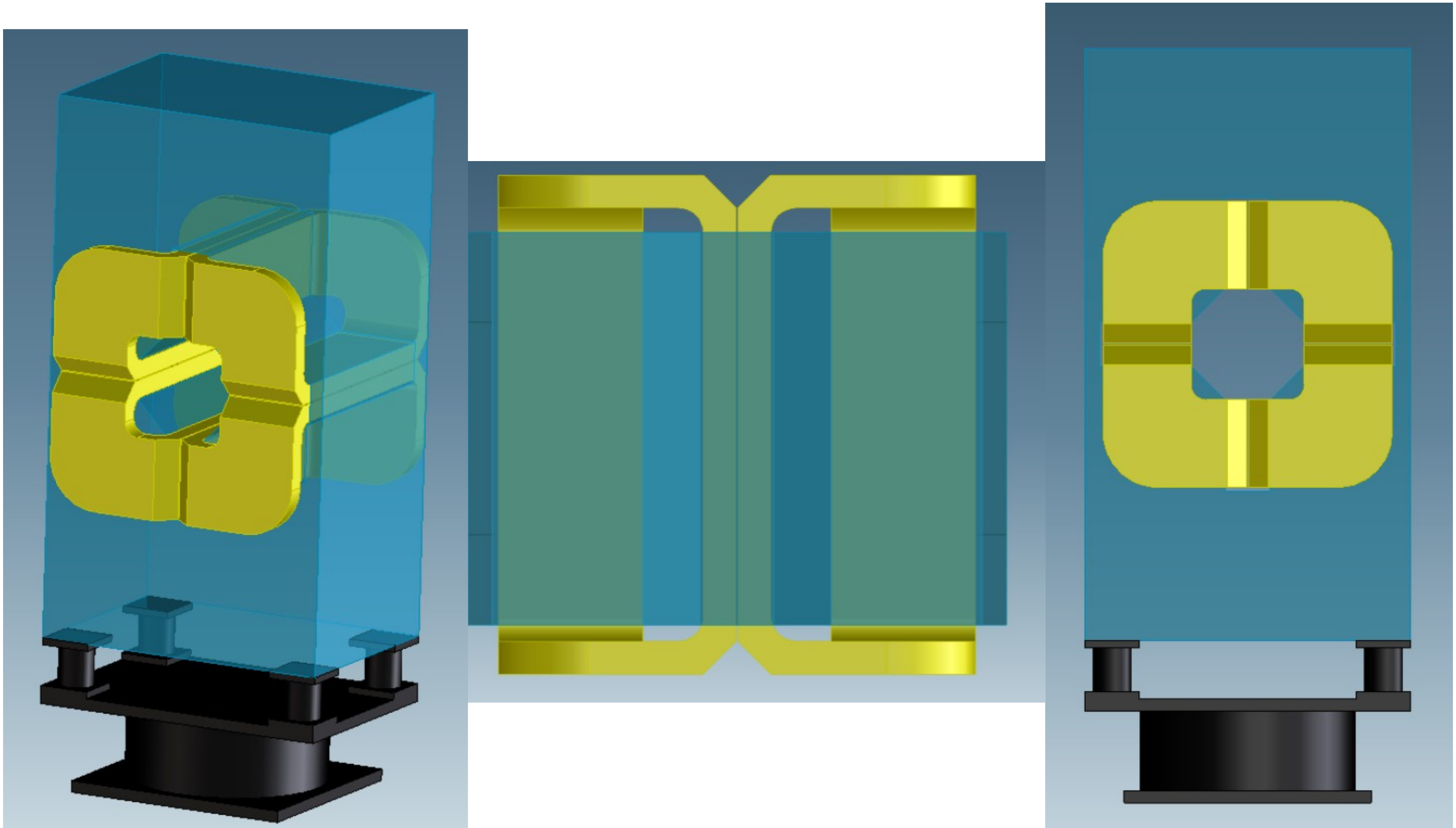






Magnets - Quadrupole



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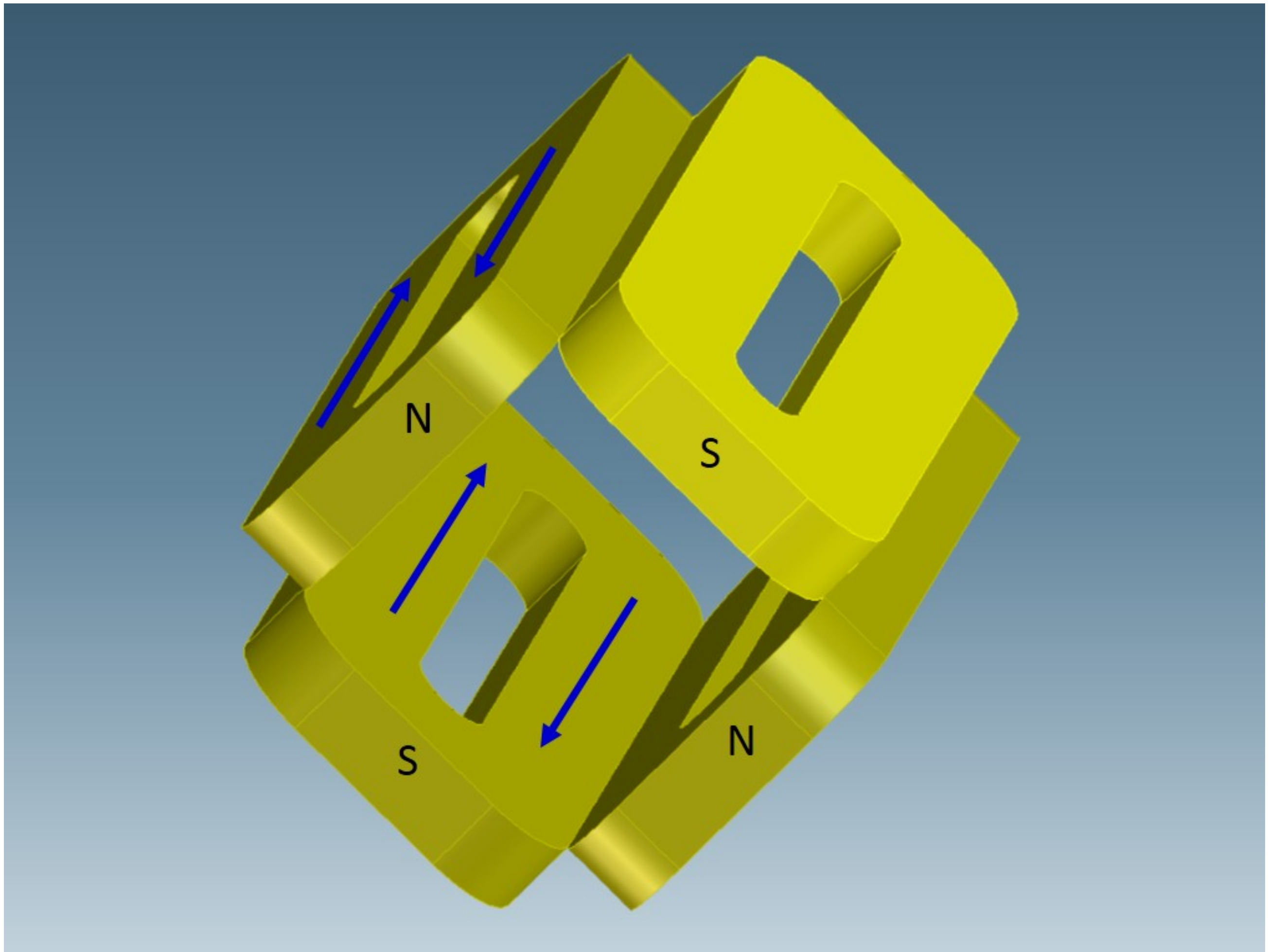

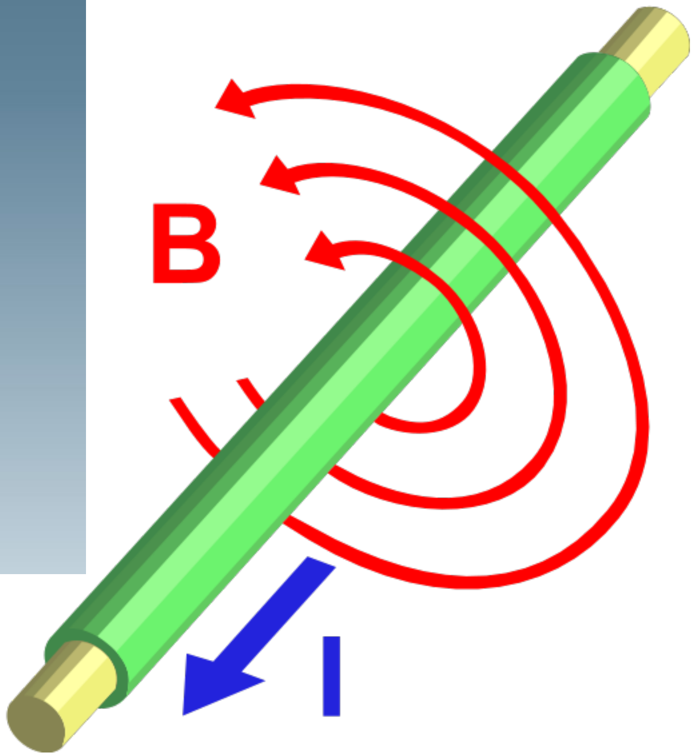

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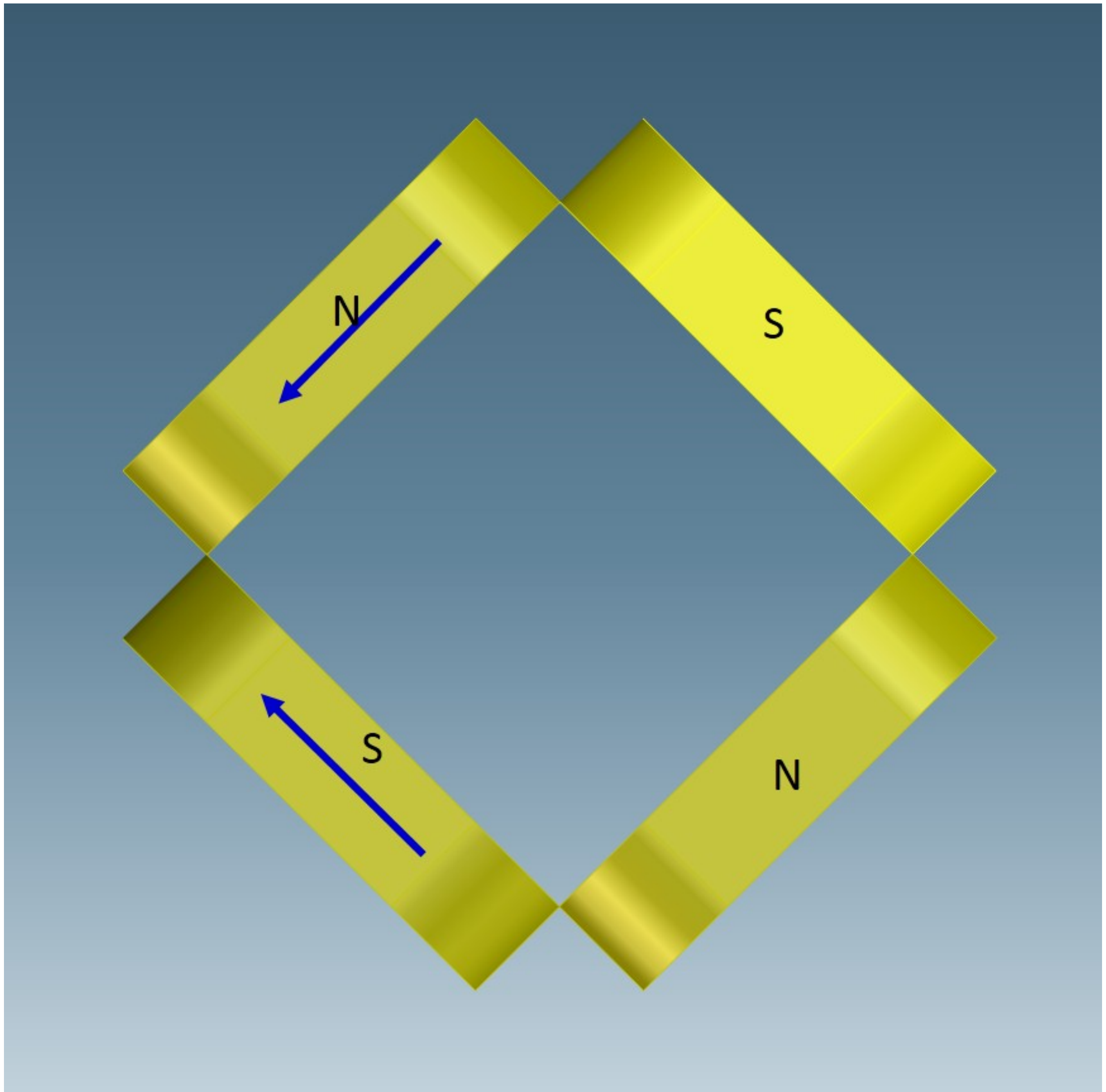

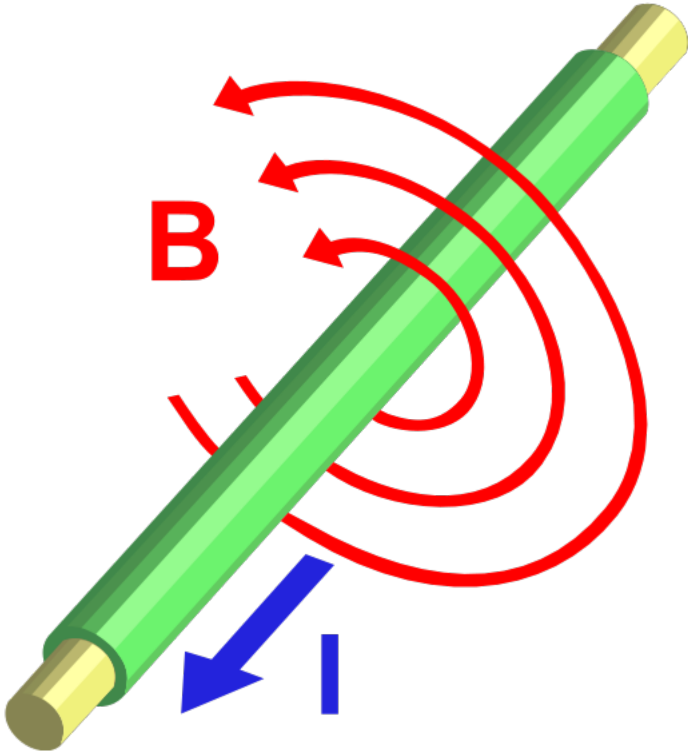

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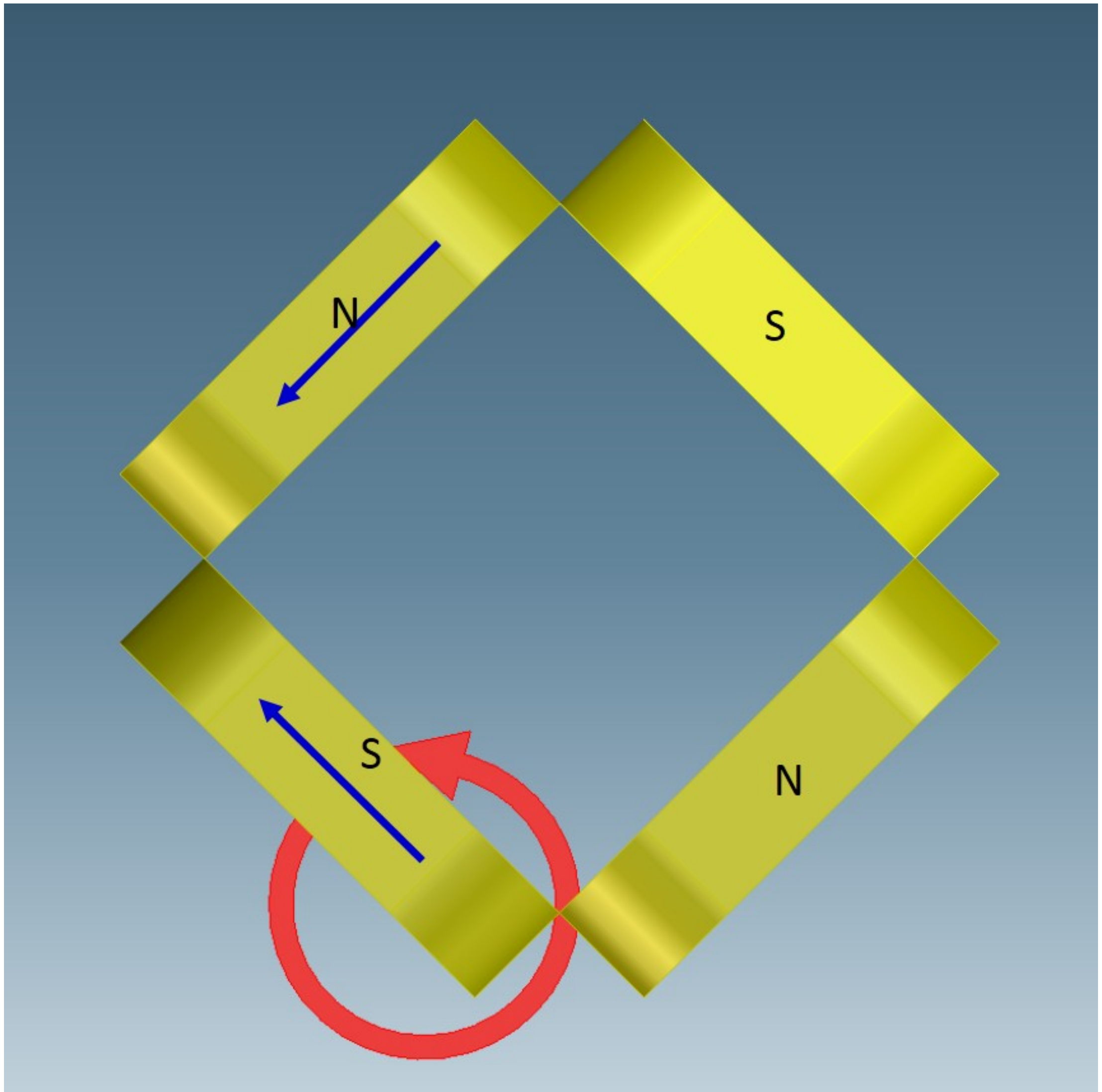

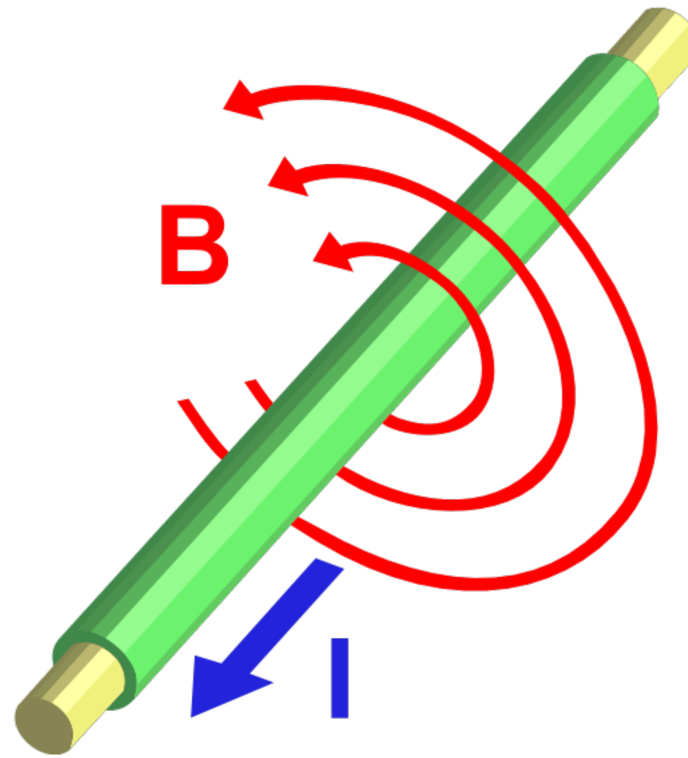

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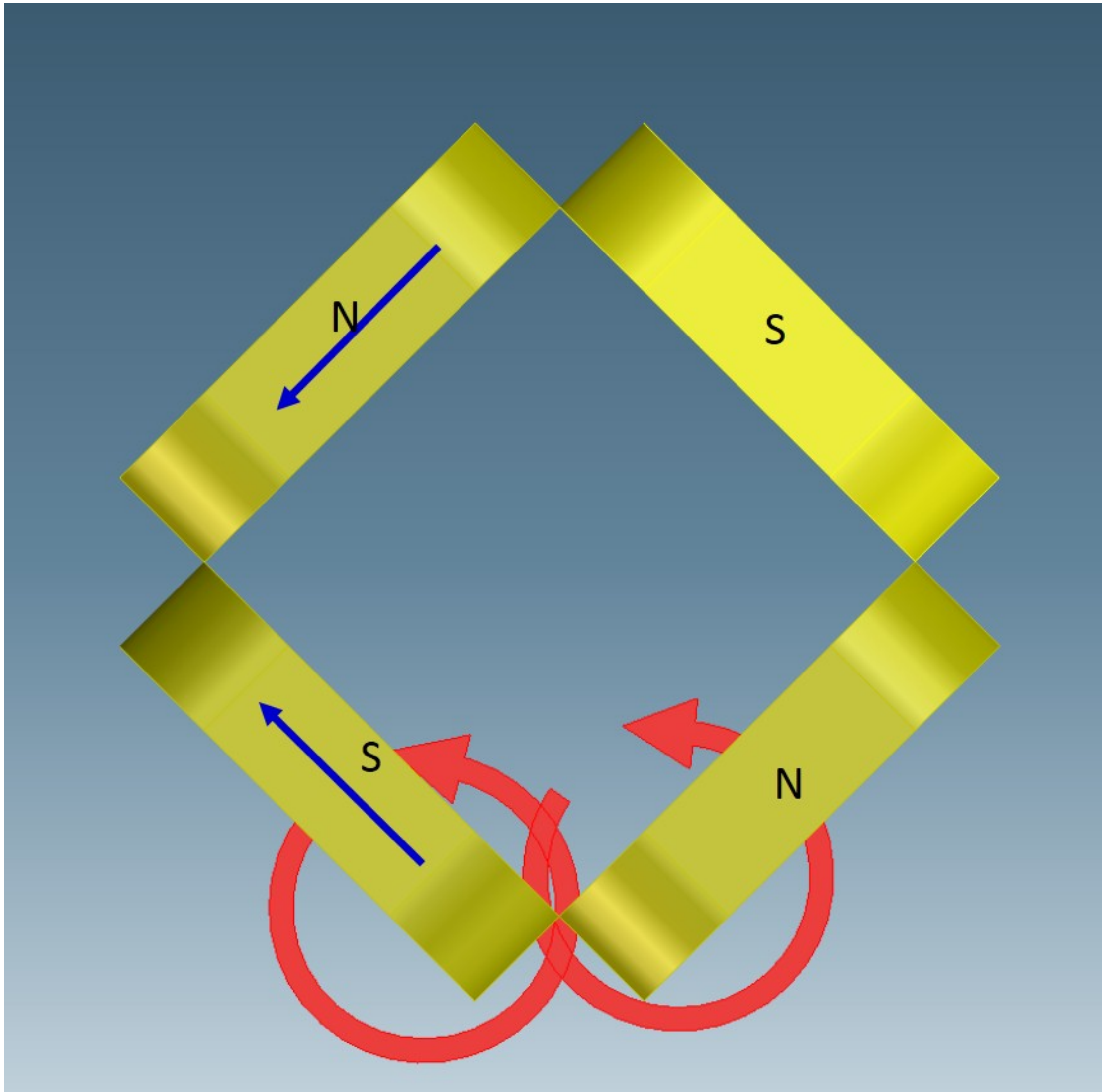

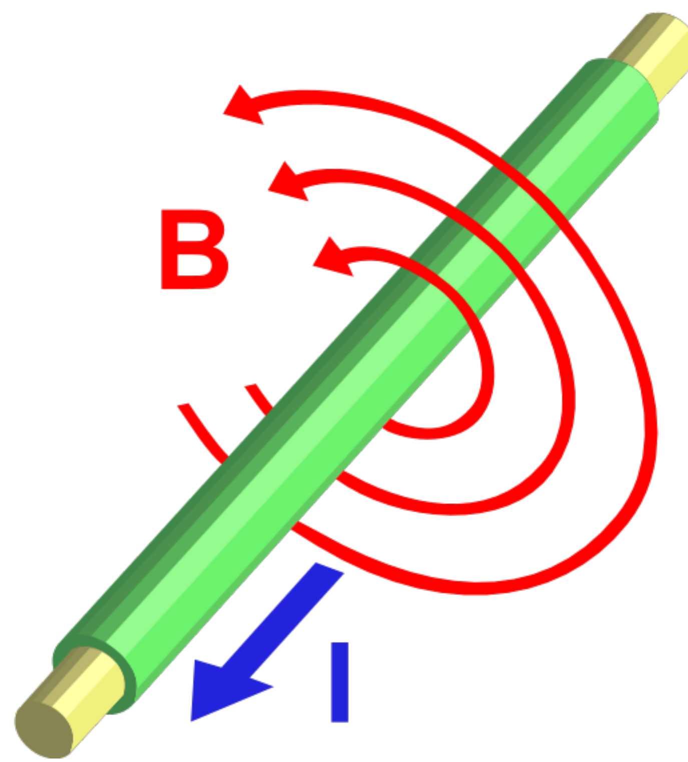

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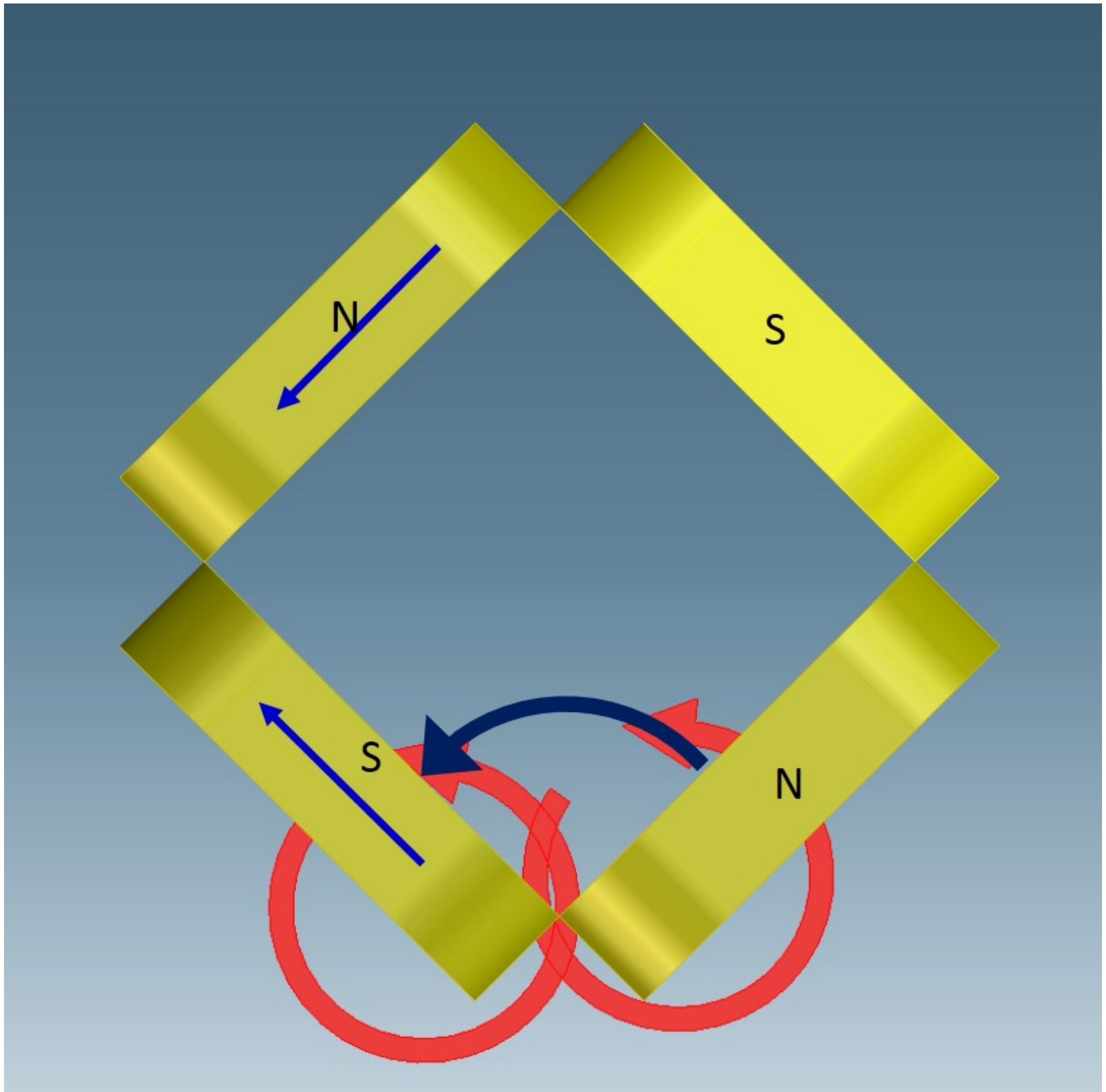

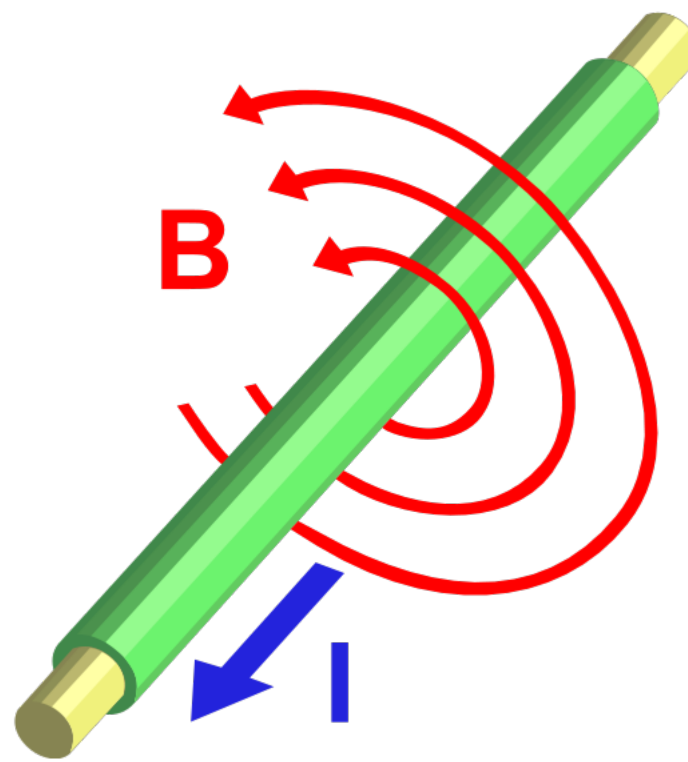

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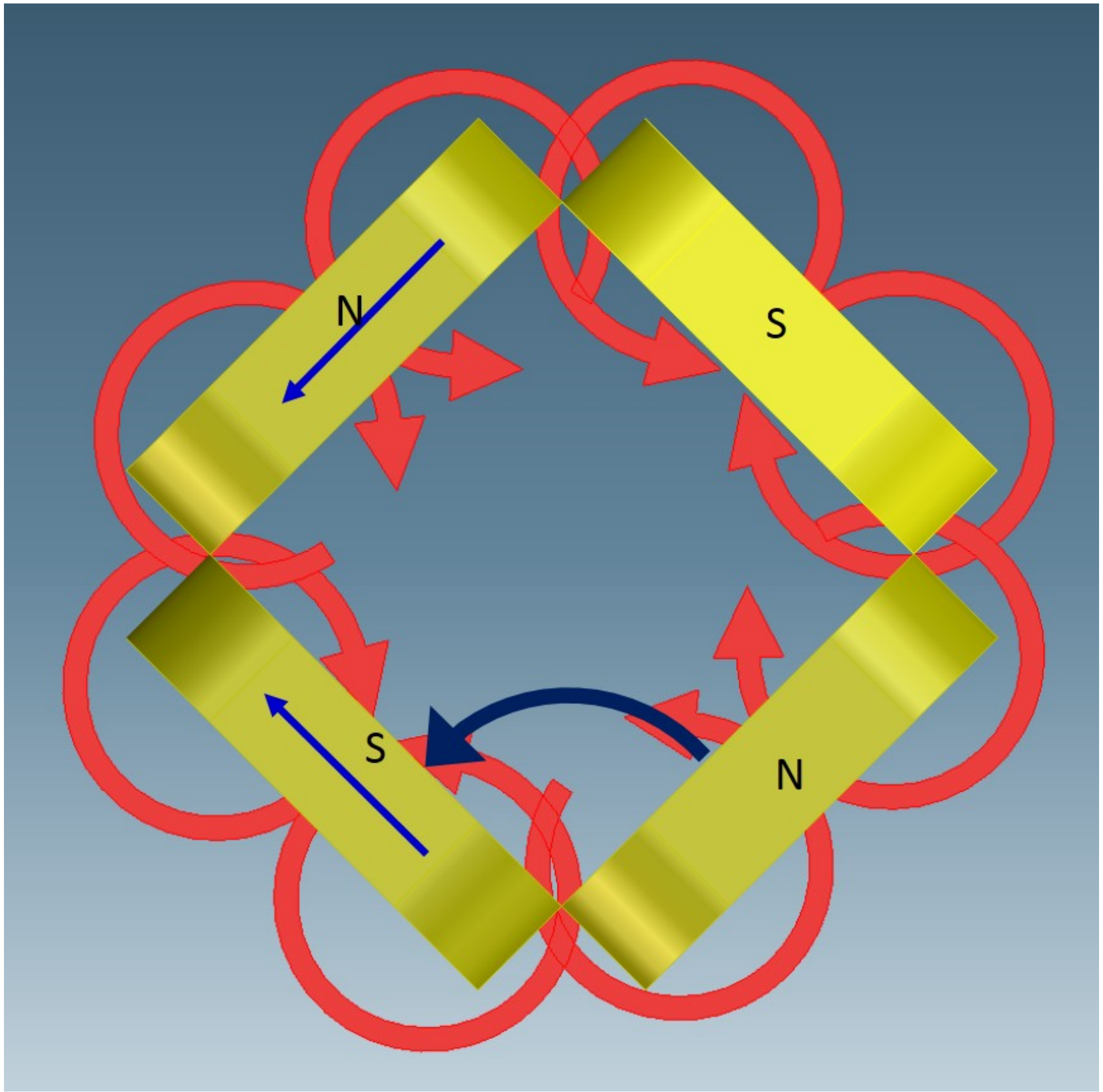

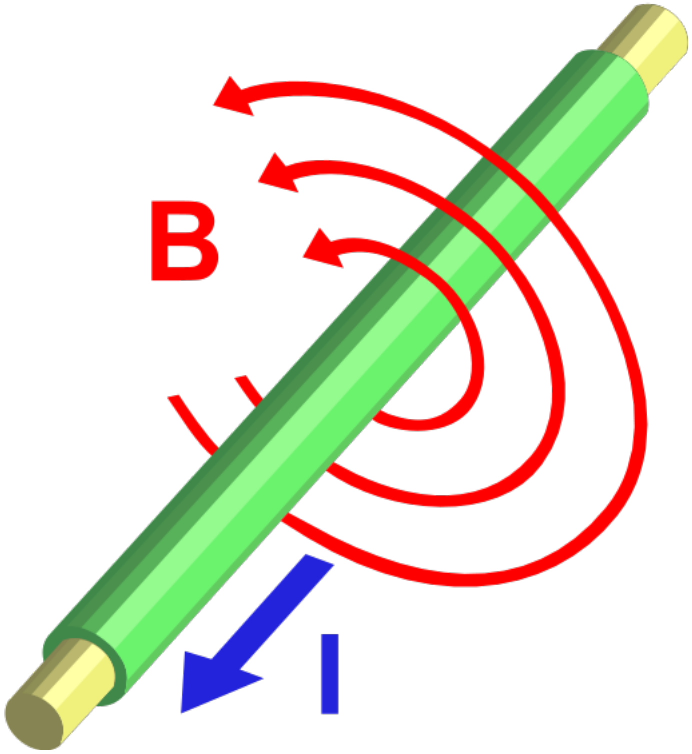

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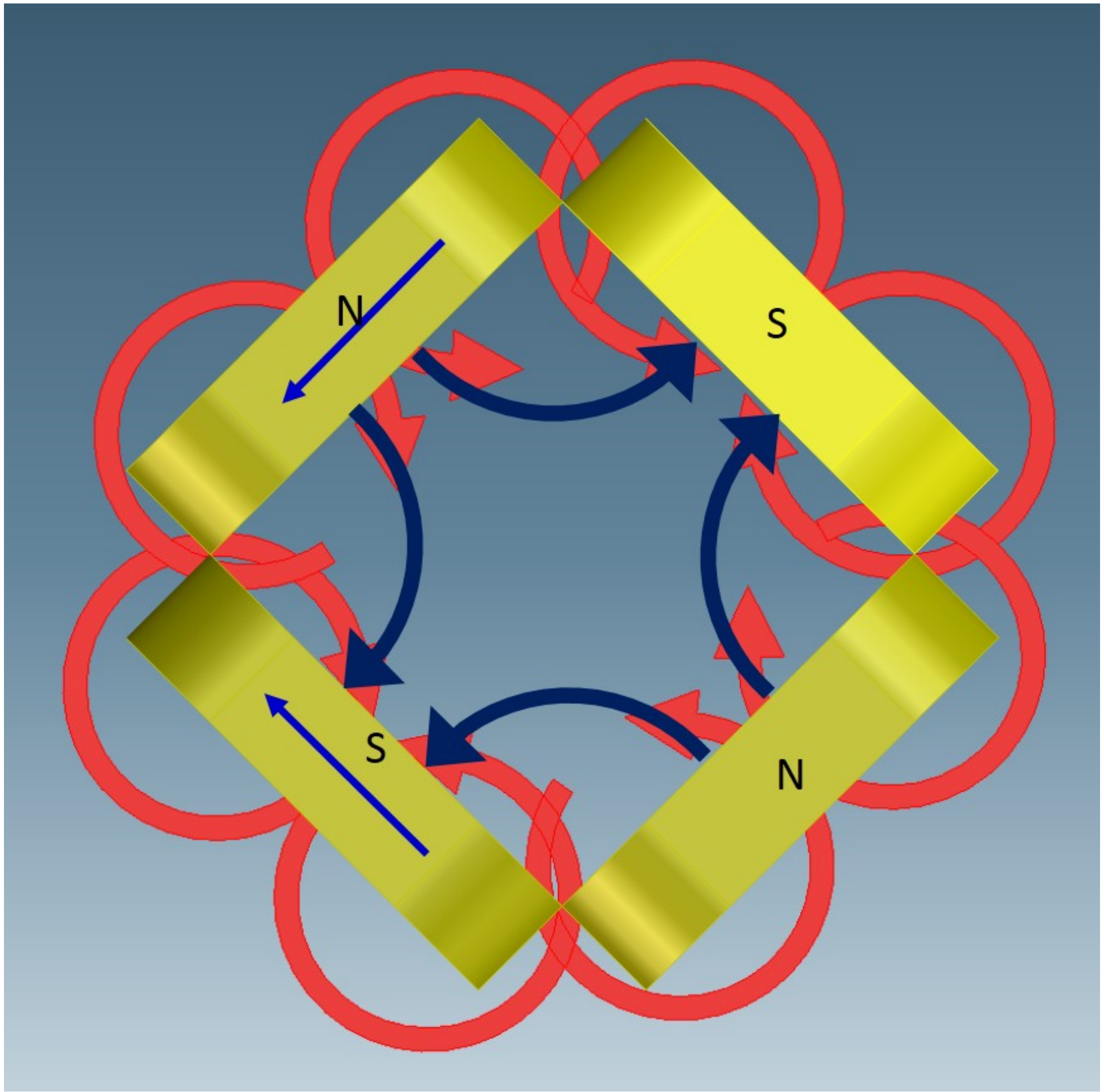

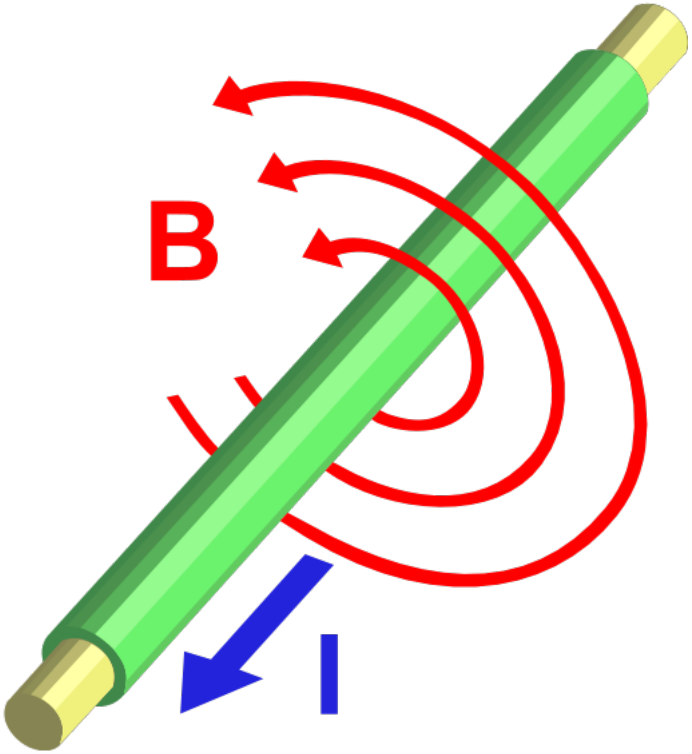

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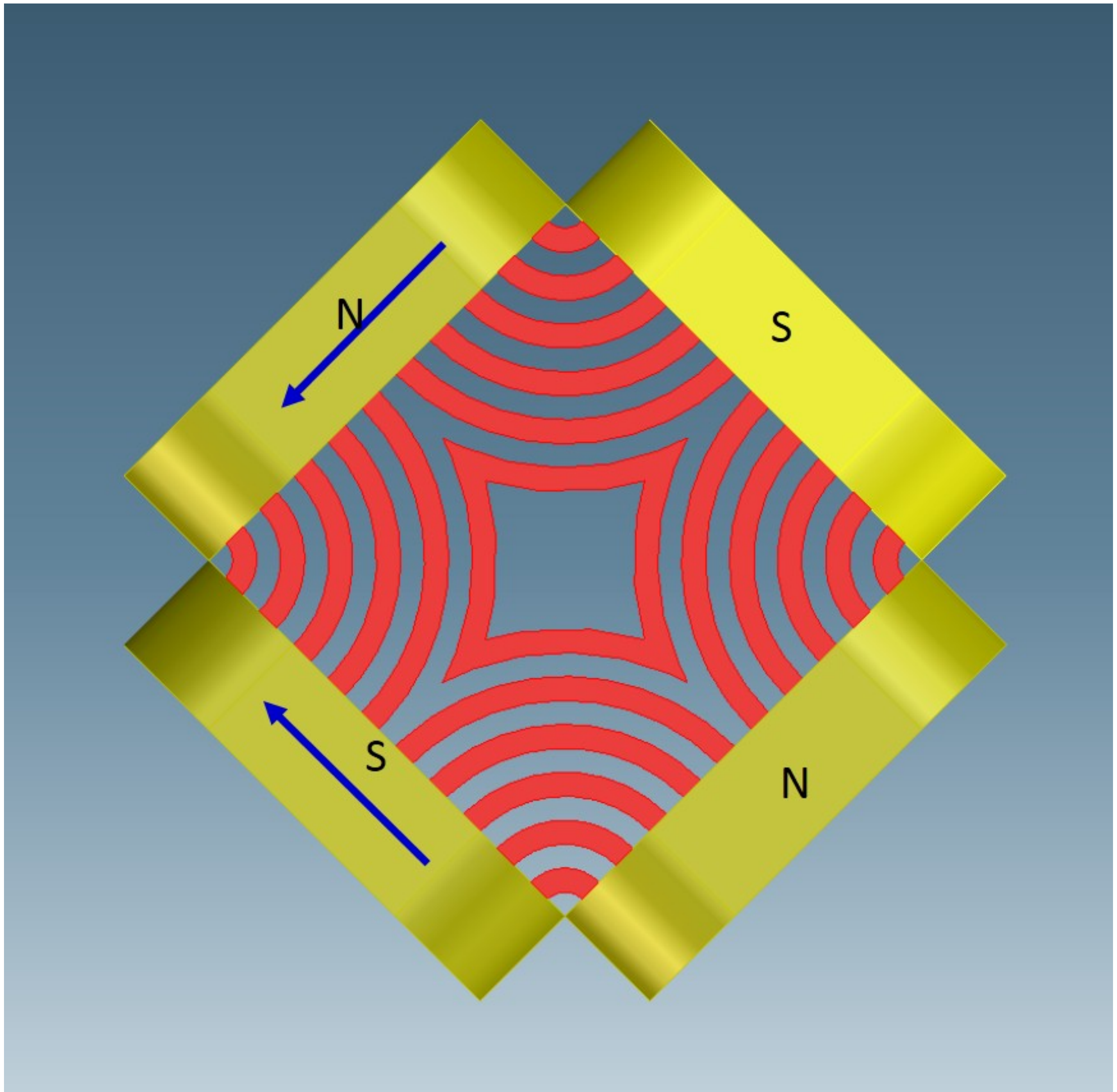

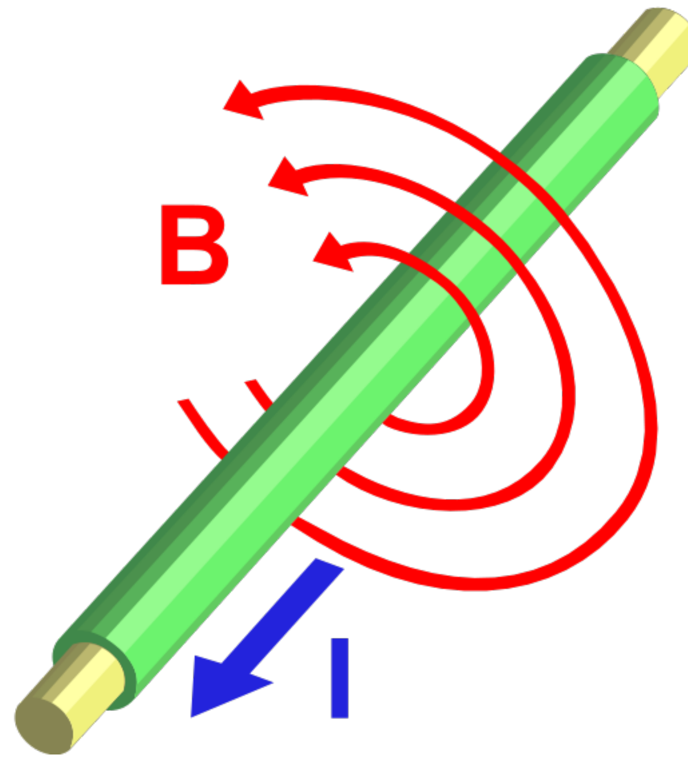

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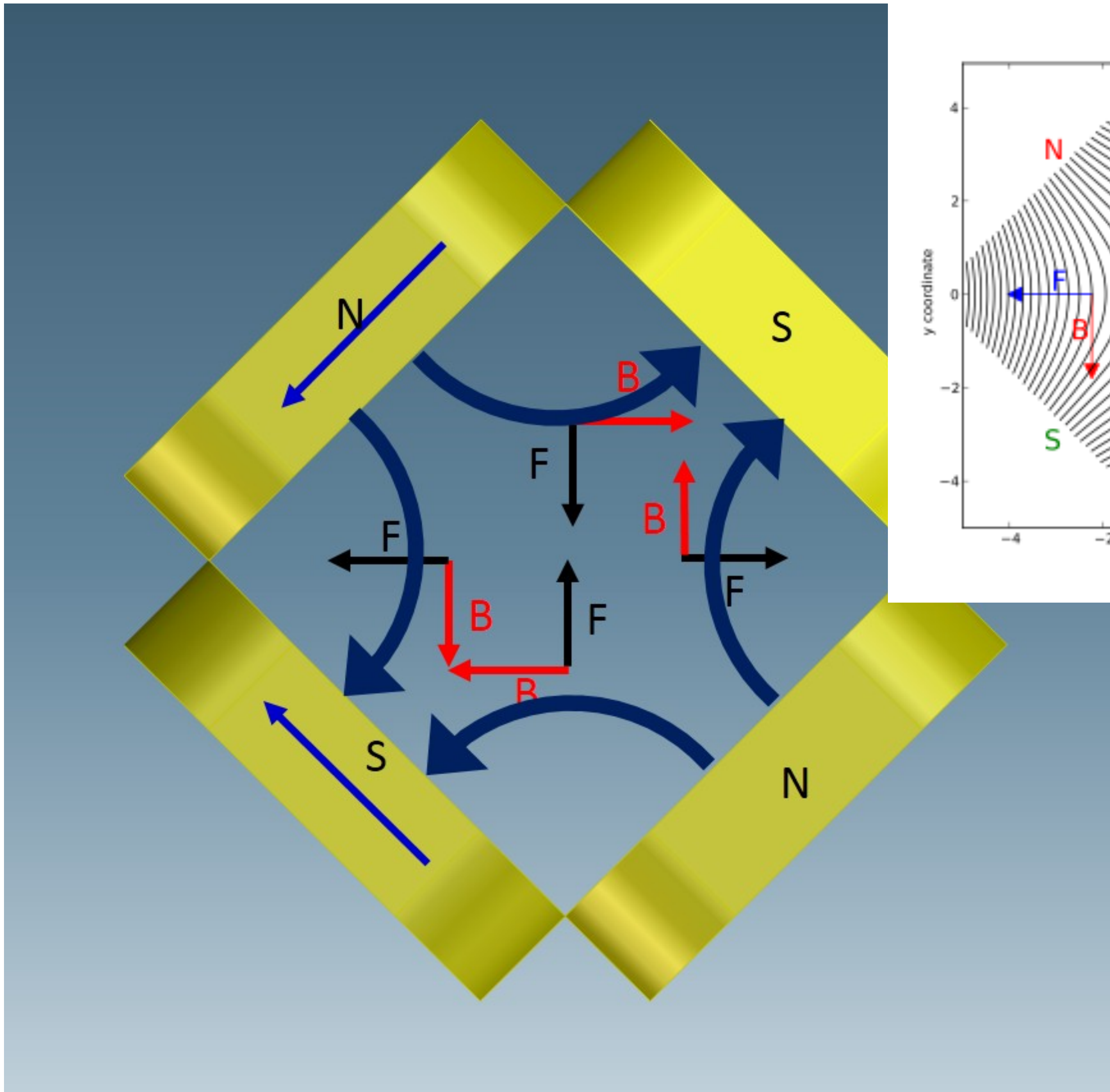

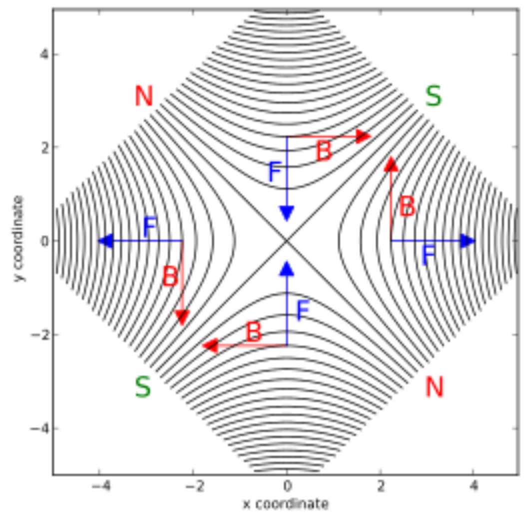

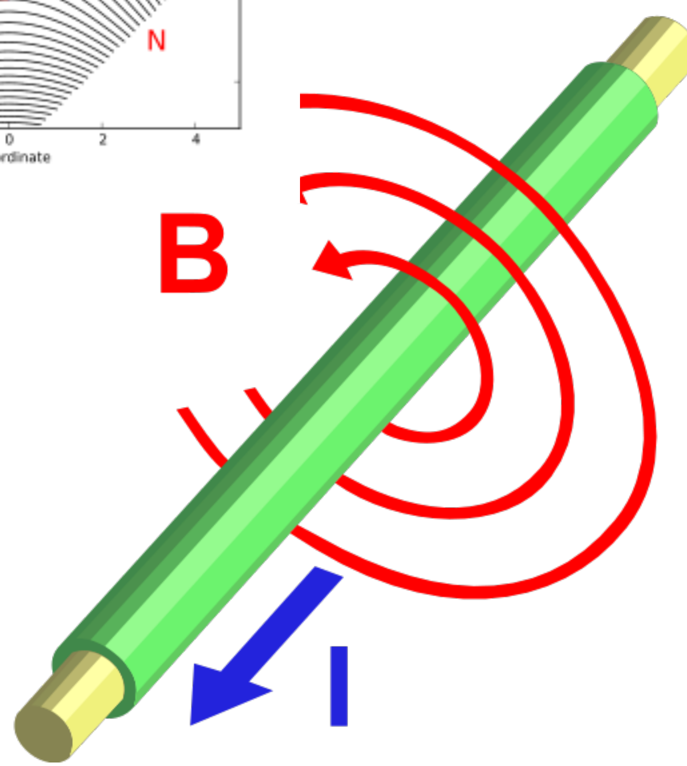

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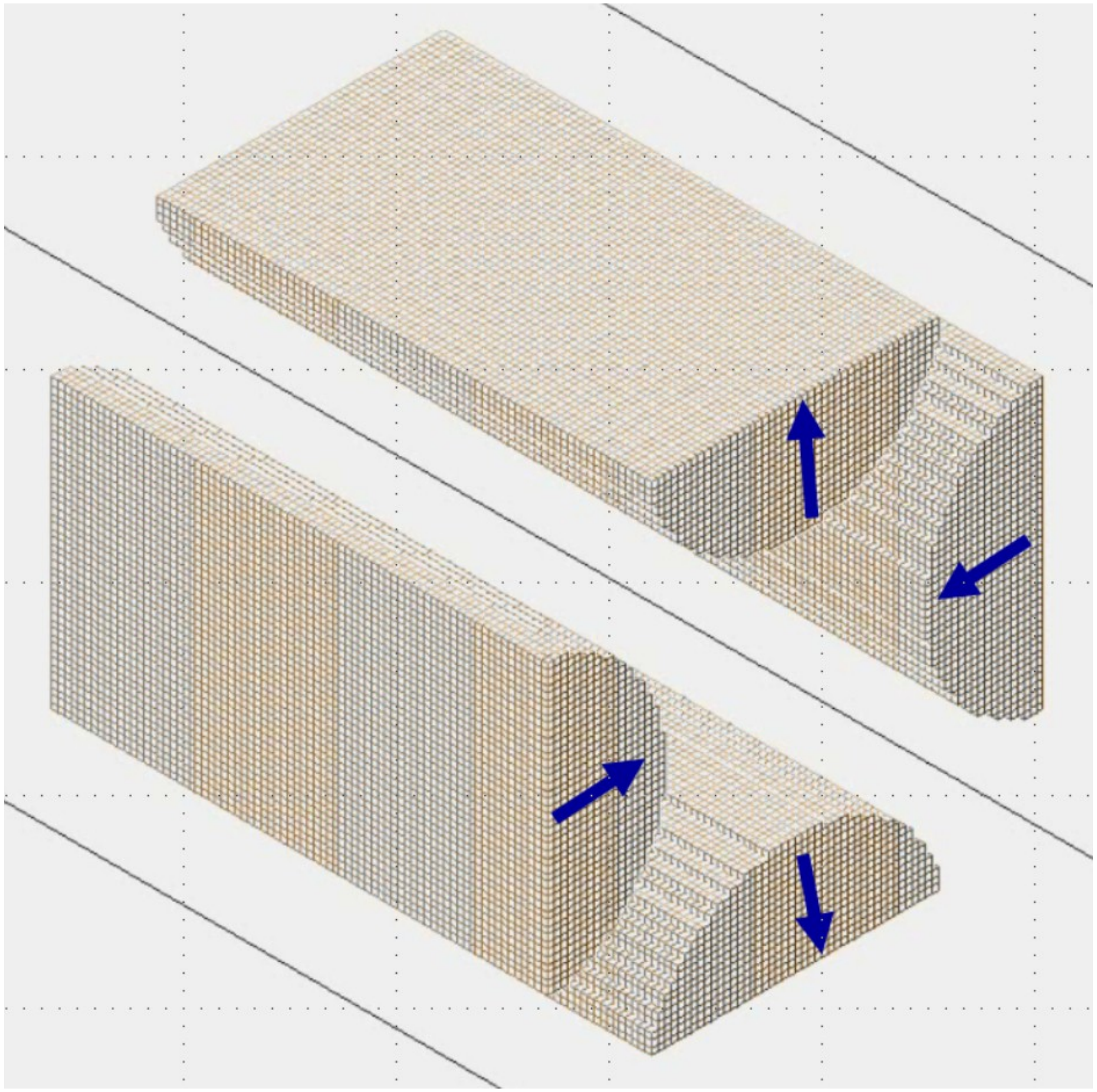
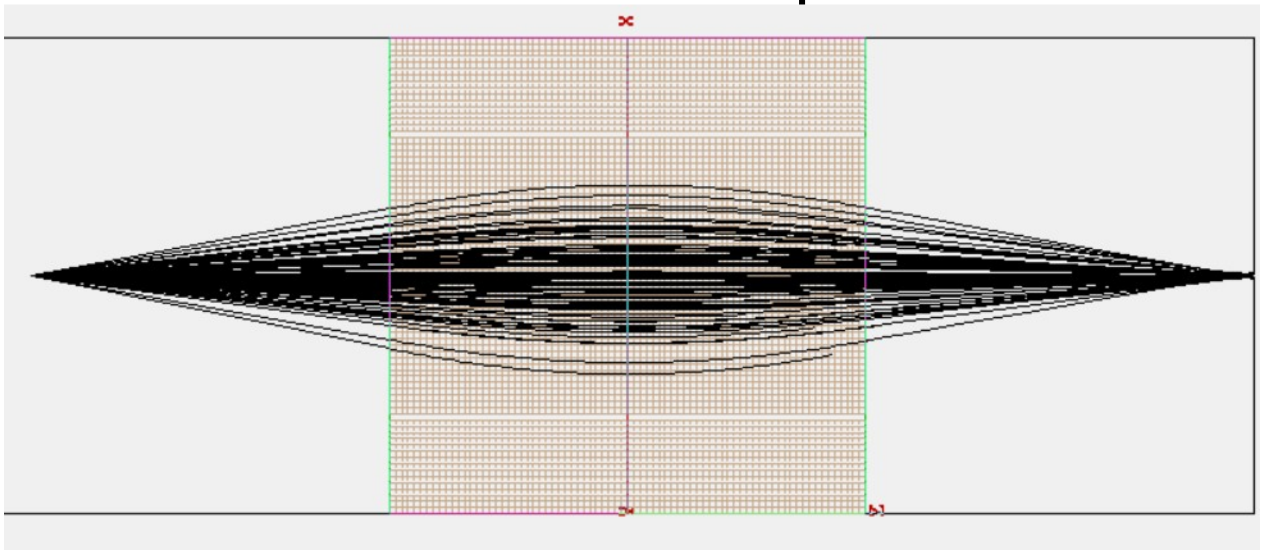
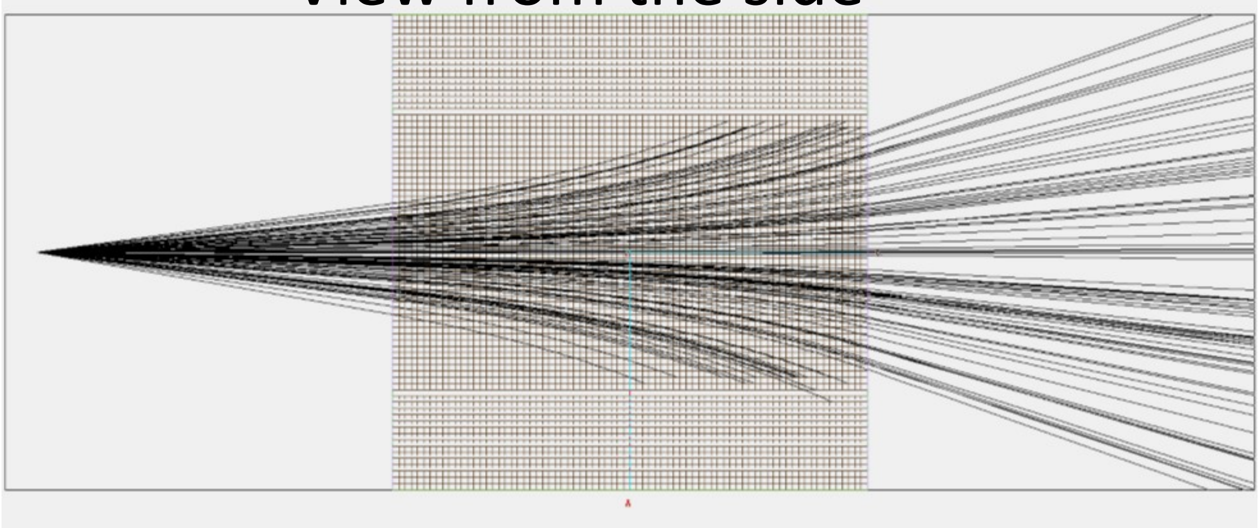


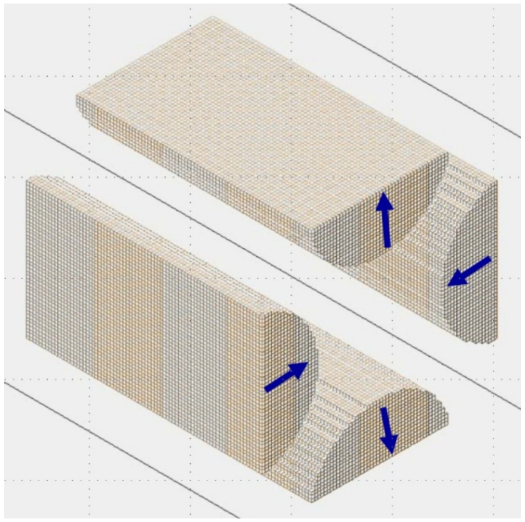
Magnets – Quadrupoles

View from the top

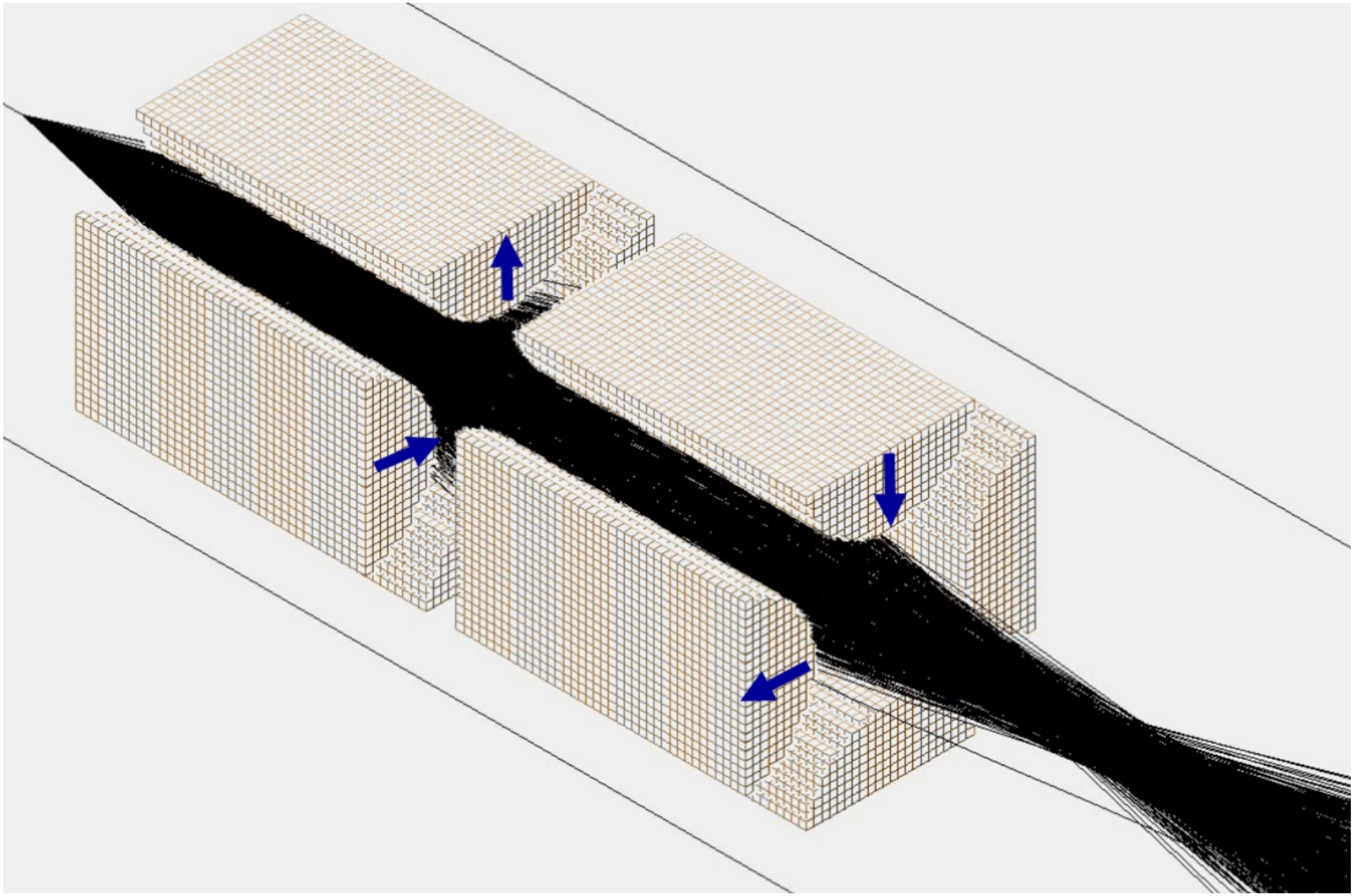


View from the side





Magnets – Quadrupole Doublets



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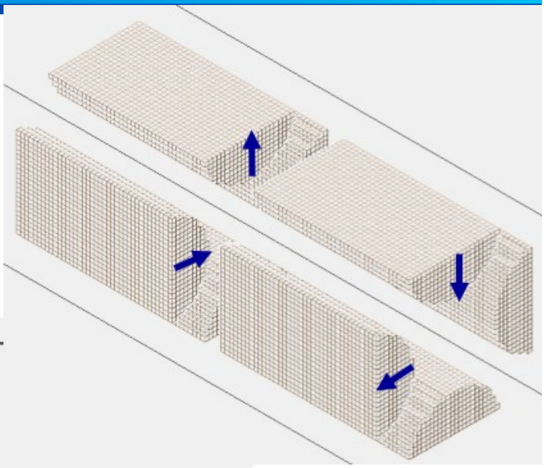

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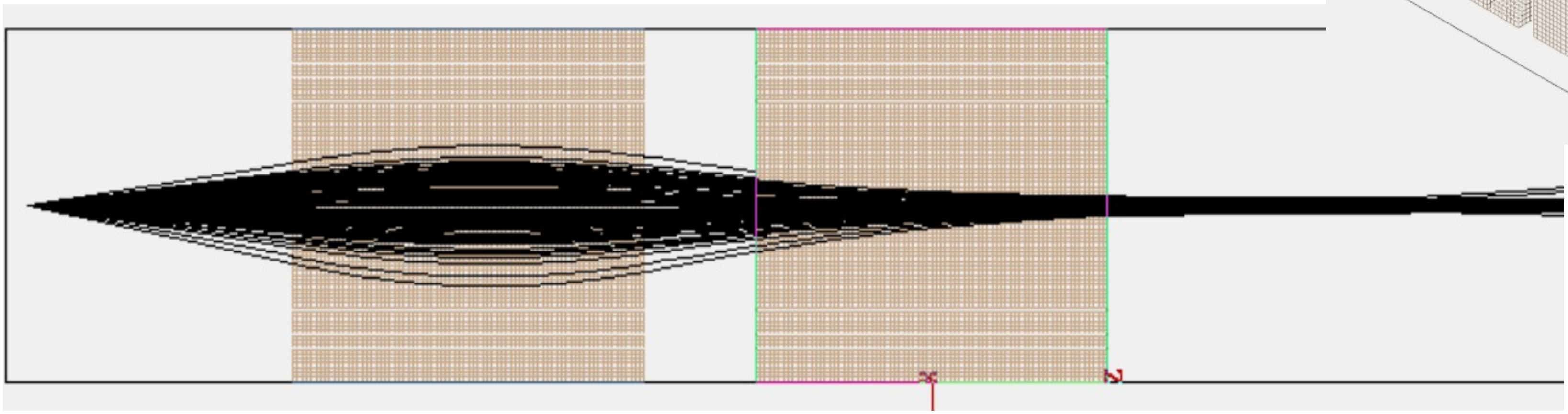

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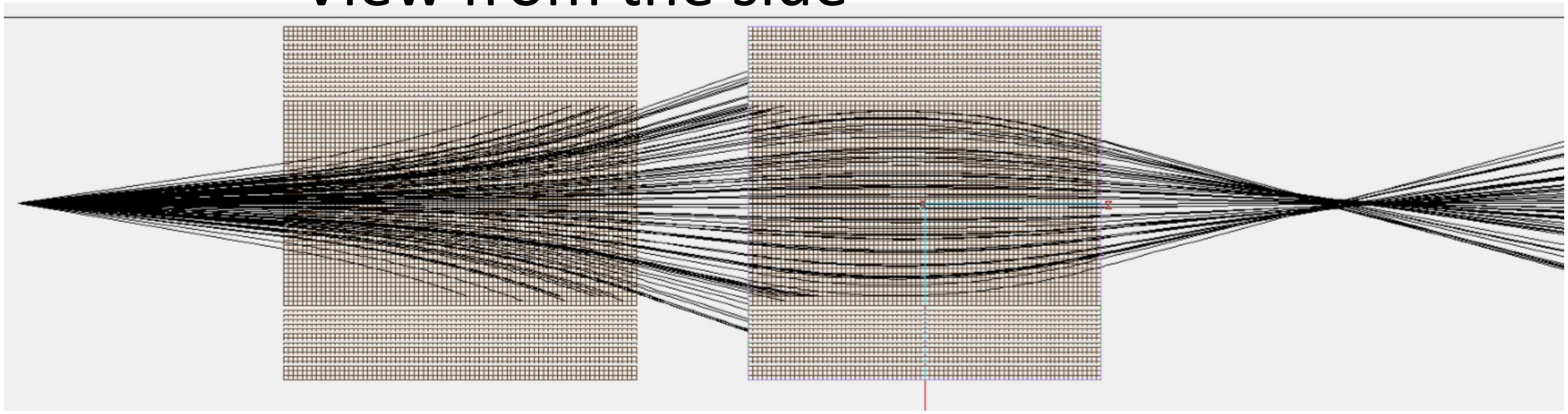
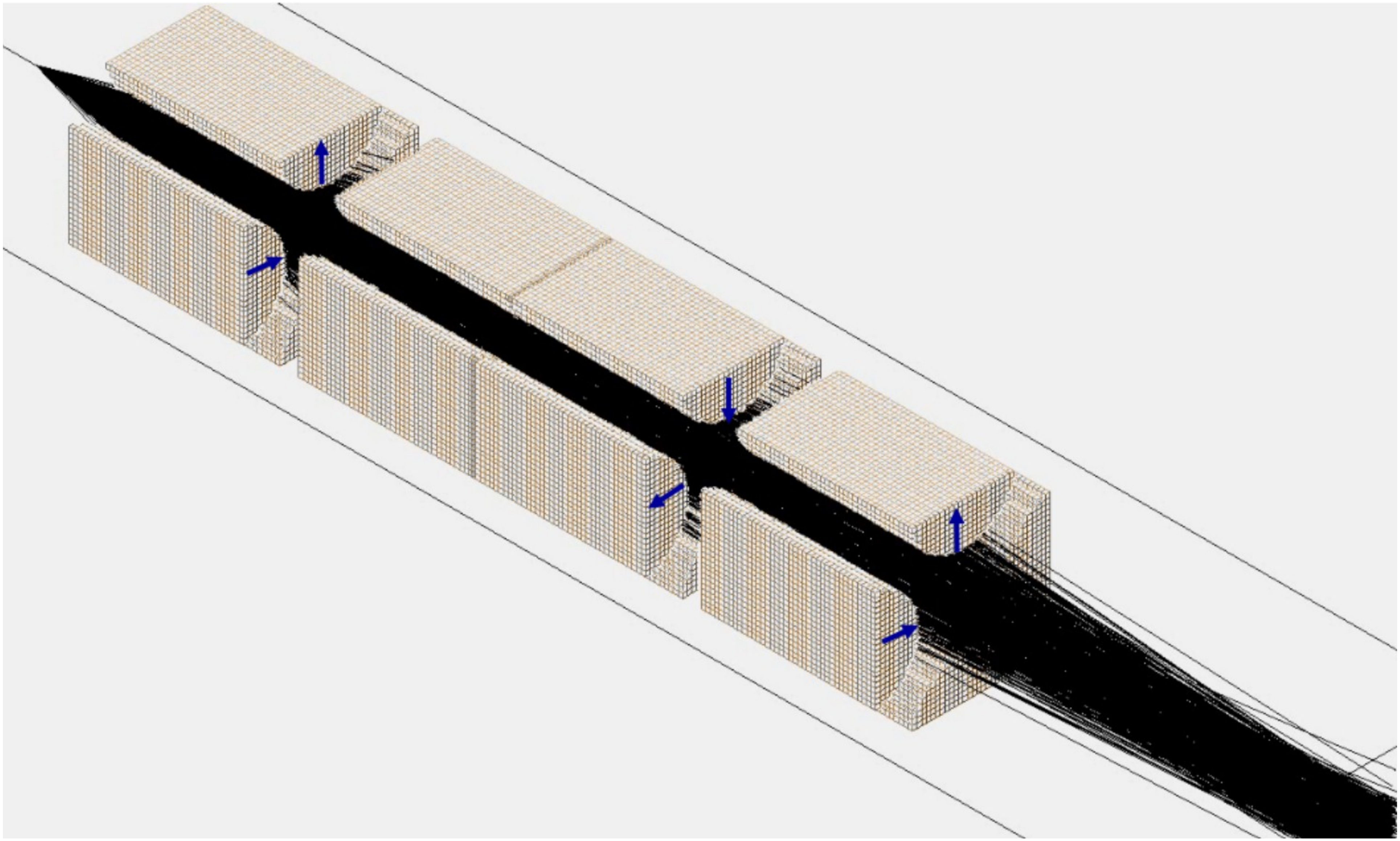


Magnets – Quadrupole Triplets



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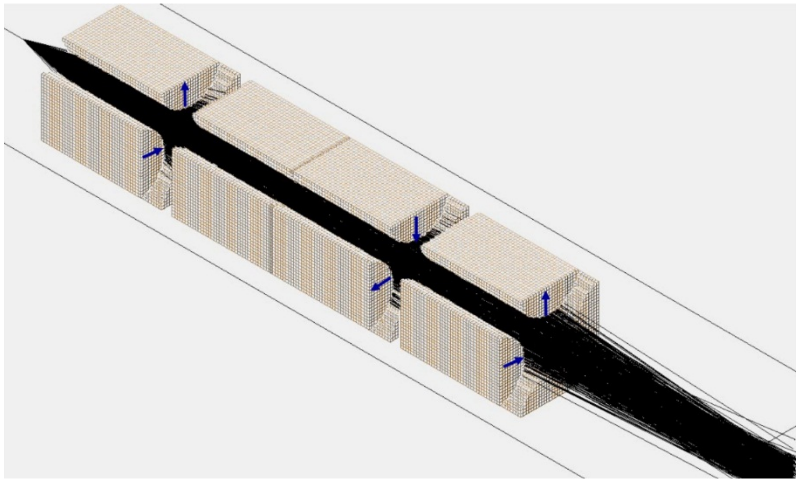

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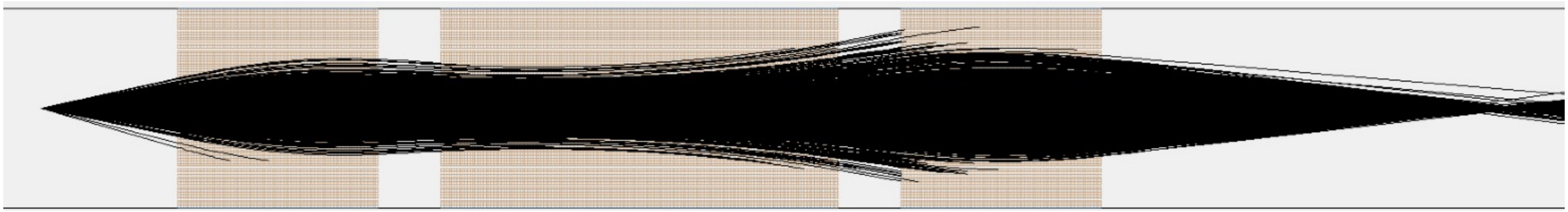

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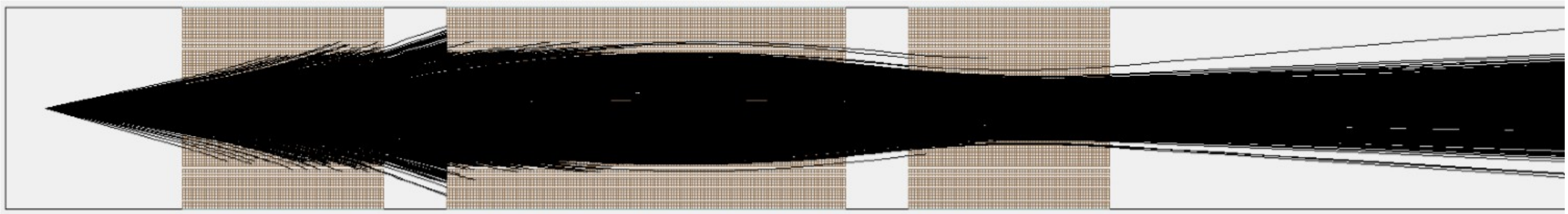
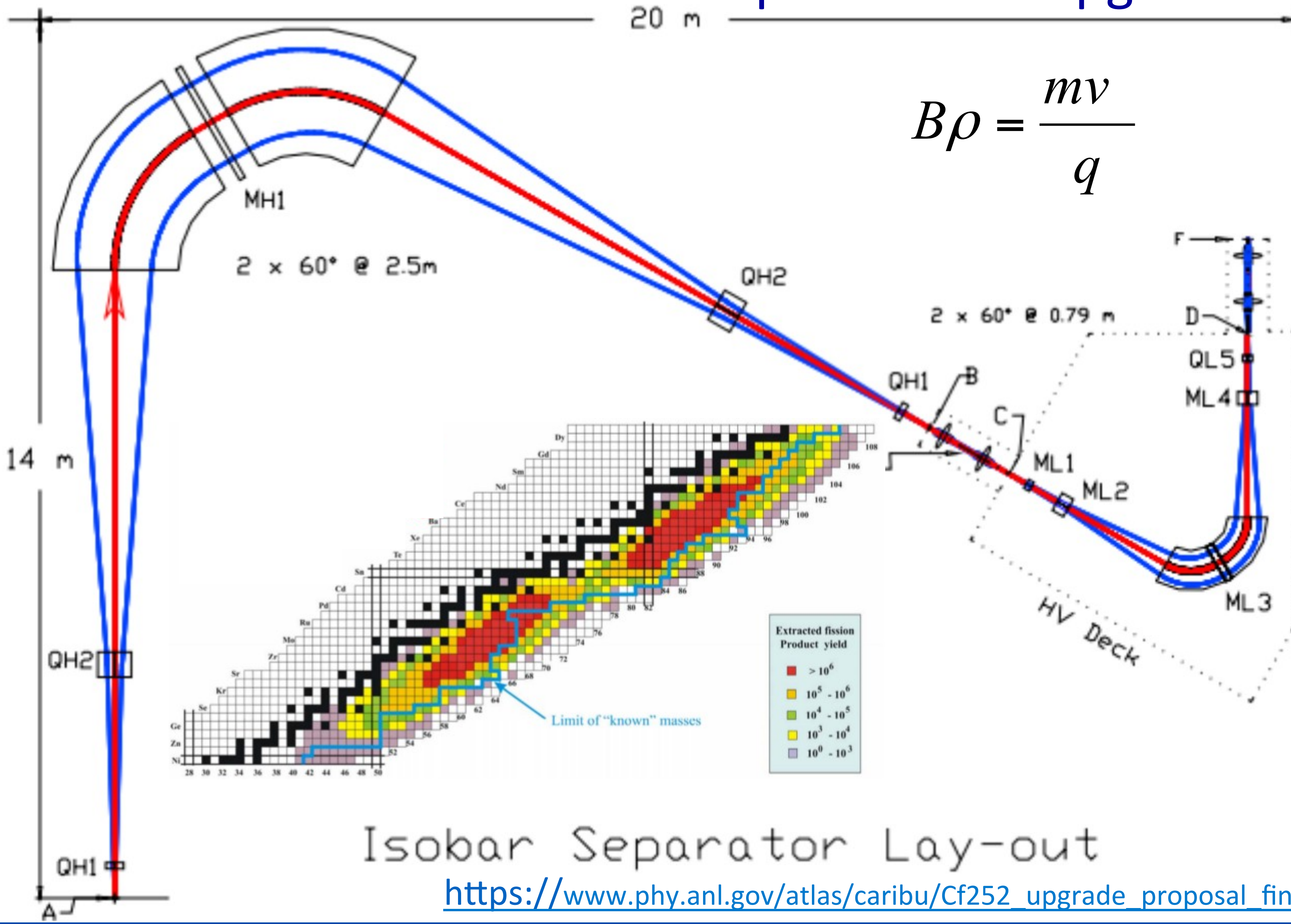


CARIBU – Isobar Separator

- CARIBU – Californium Rare Isotope Breeder Upgrade



$$B\rho = \frac{mv}{q}$$

Isobar Separator Lay-out

https://www.phy.anl.gov/atlas/caribu/Cf252_upgrade_proposal_final_Rev4.pdf

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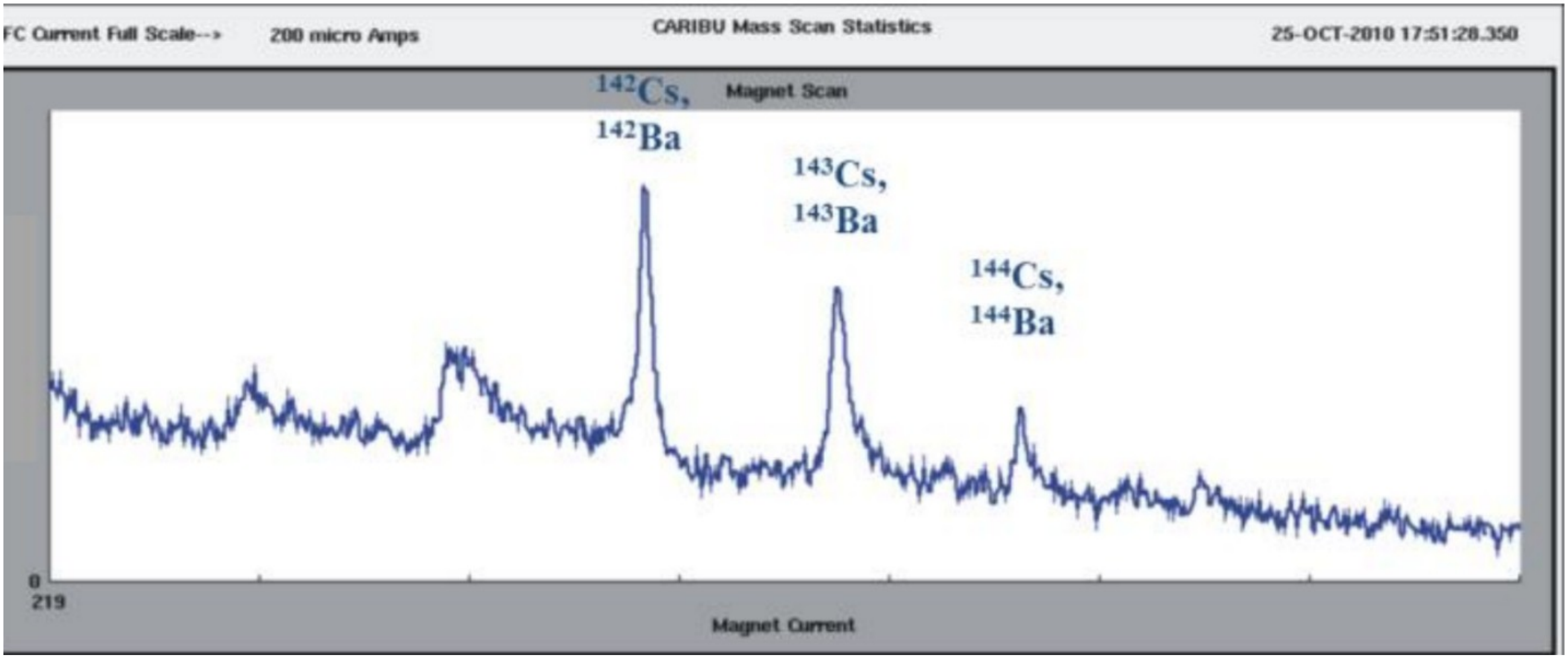
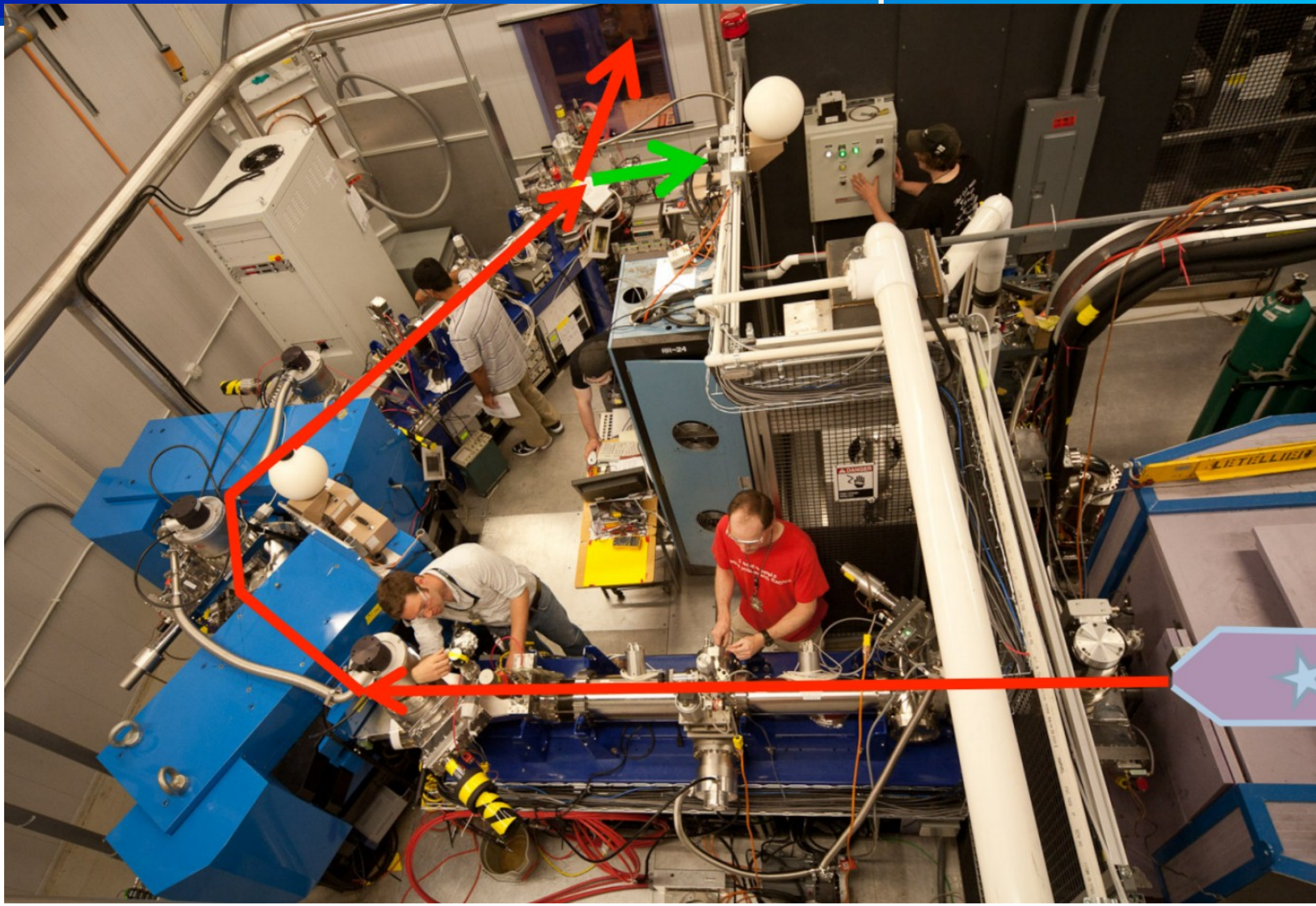


https://www.phy.anl.gov/atlas/caribu/Cf252_upgrade_proposal_final_Rev4.pdf

CARIBU – Isobar Separator

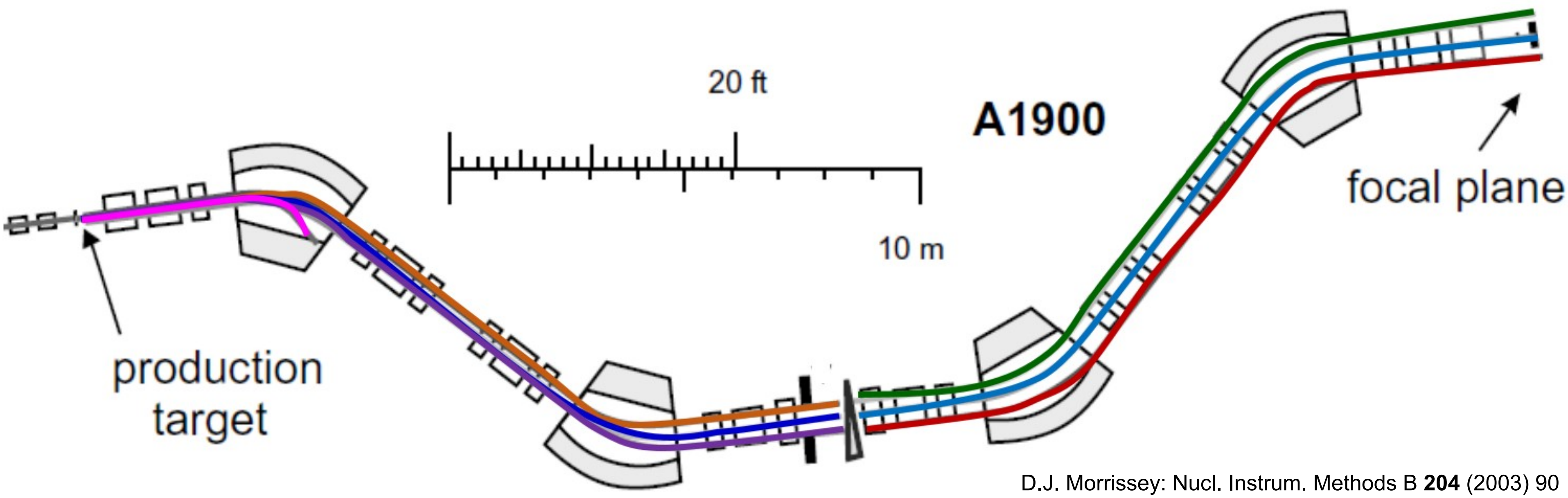


http://ns12.anl.gov/pdfs/presentations/Mondaytalks/2012_0813_1600_Savard.pdf

A1900 – Projectile Fragment Separator

The National Superconducting Cyclotron Laboratory (NSCL)

- Fragment Separator
- Main scientific roles
  - prepare secondary beams of radioactive ions for transport to RIB factories
  - dripline nuclides

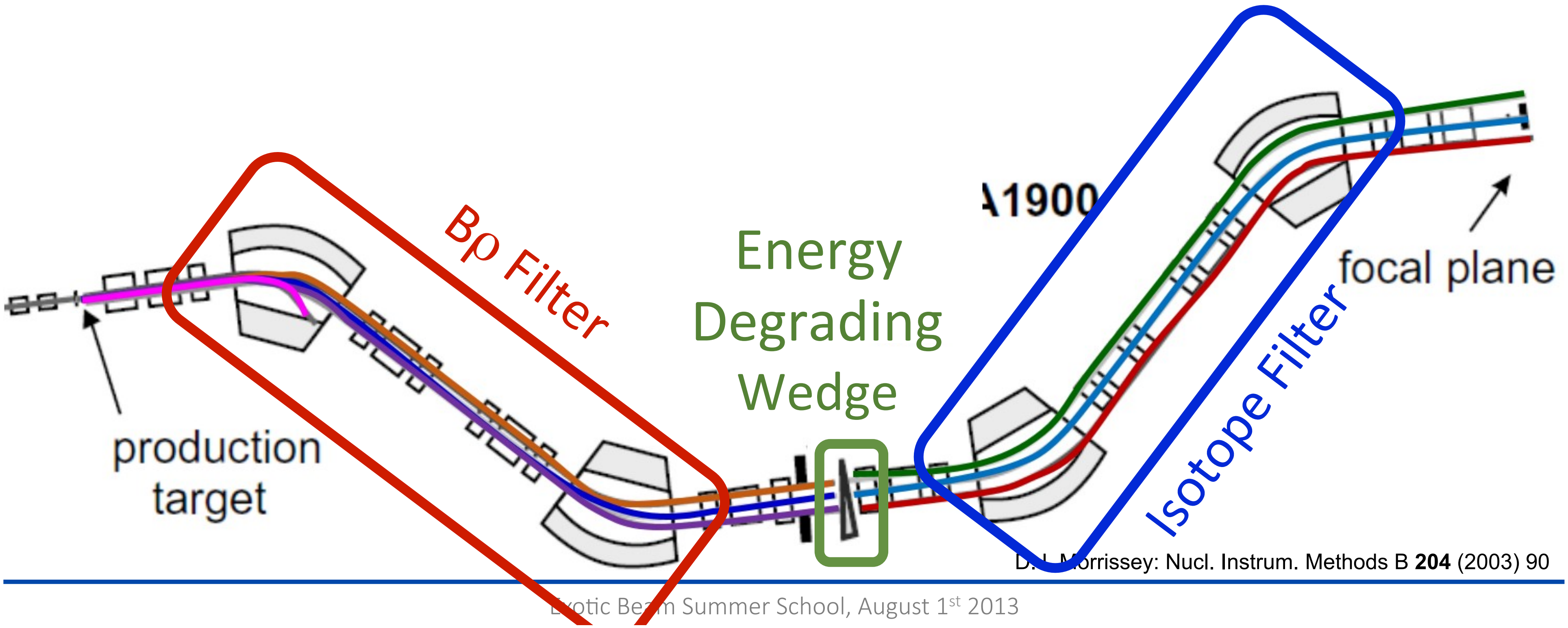


D.J. Morrissey: Nucl. Instrum. Methods B **204** (2003) 90

A1900 – Projectile Fragment Separator

The National Superconducting Cyclotron Laboratory (NSCL)

- Three stages:
  - Bρ Filter
  - Energy Degrading Wedge
  - Isotope Filter



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A1900 – Projectile Fragment Separator

dΩ = 8 msr

Δp/p = 5%

Dispersion = 5 cm/%

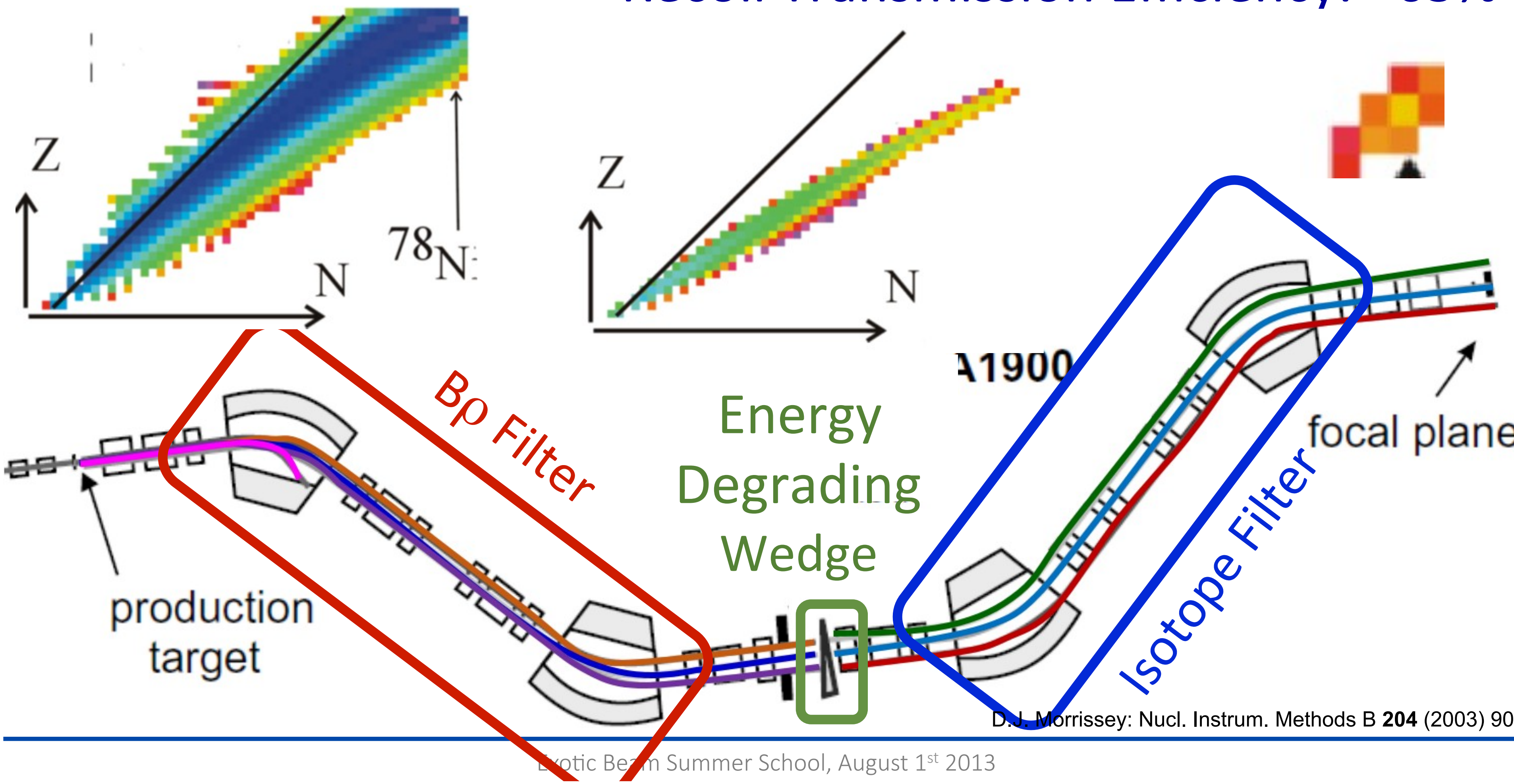
Resolution = 2500 p/Δp

An Example Reaction: $^{86}Kr \rightarrow ^{78}Ni$

Beam Energy: ~155 MeV/A

Recoil Energy: ~170 MeV/A

Recoil Transmission Efficiency: ~65%



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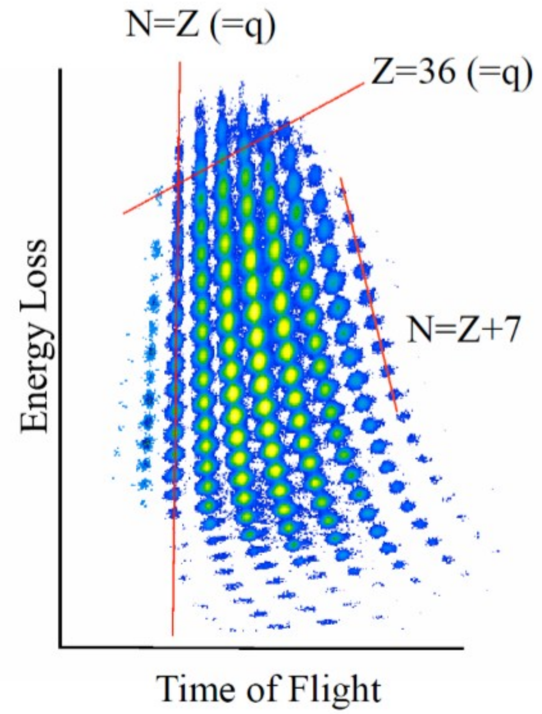
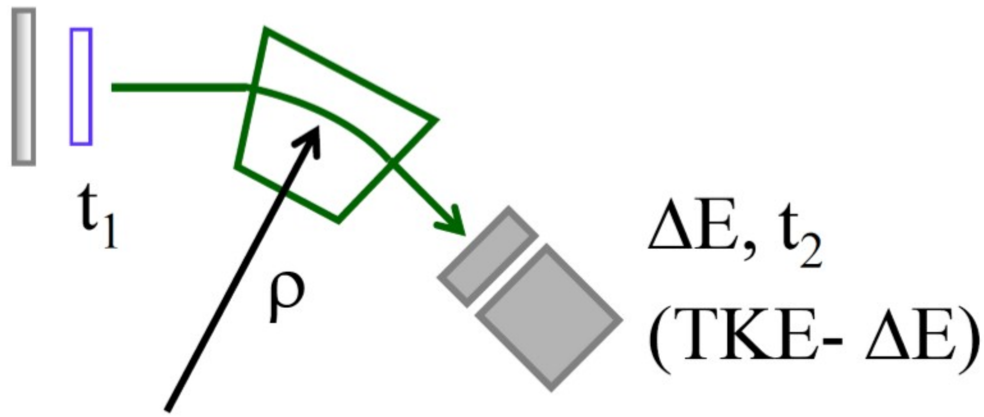
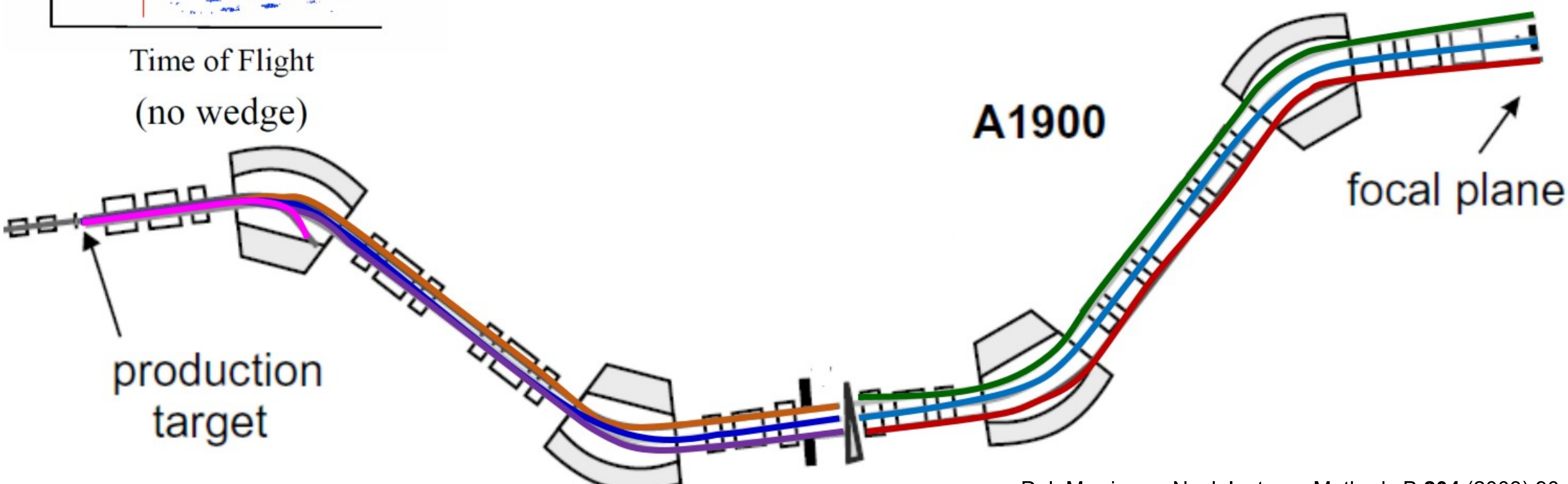
A1900 – Projectile Fragment Separator



(no wedge)

Particle Identification

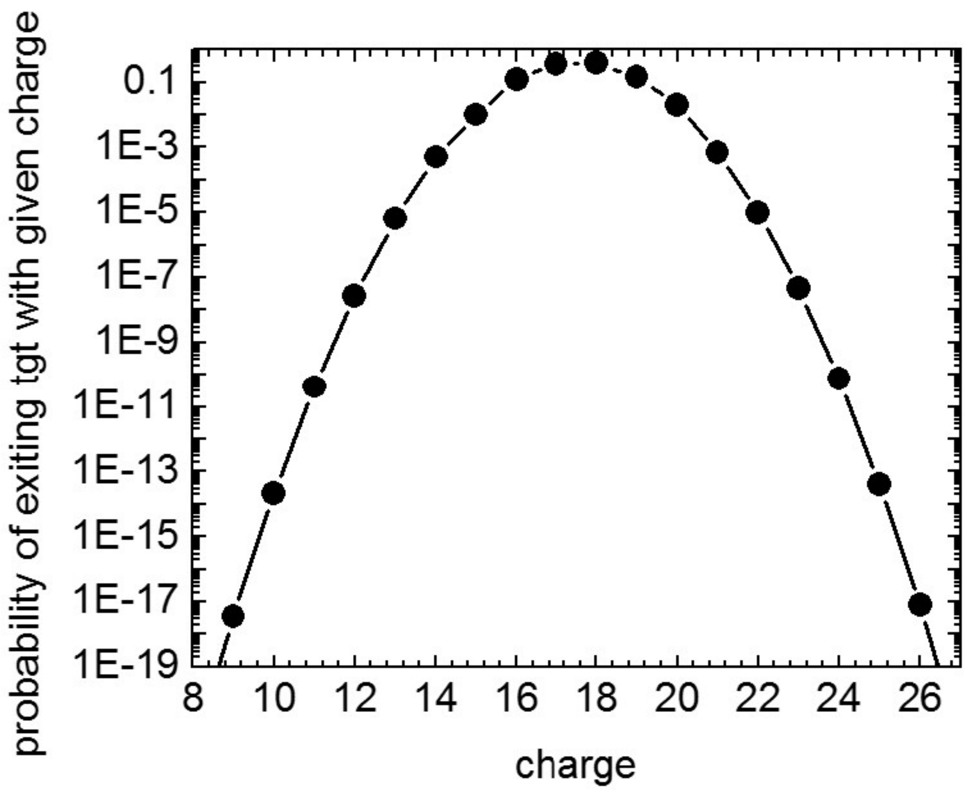




D.J. Morrissey: Nucl. Instrum. Methods B **204** (2003) 90

What about with 'slow' (5 MeV/A) Beams?

- Recoils exit the target with a distribution of charge states
- $B\rho = mv/q$



An Example Reaction: $^{48}Ca + ^{243}Am \rightarrow ^{288}115$
Beam Energy: ~5 MeV/A
Recoil Energy: ~0.8 MeV/A

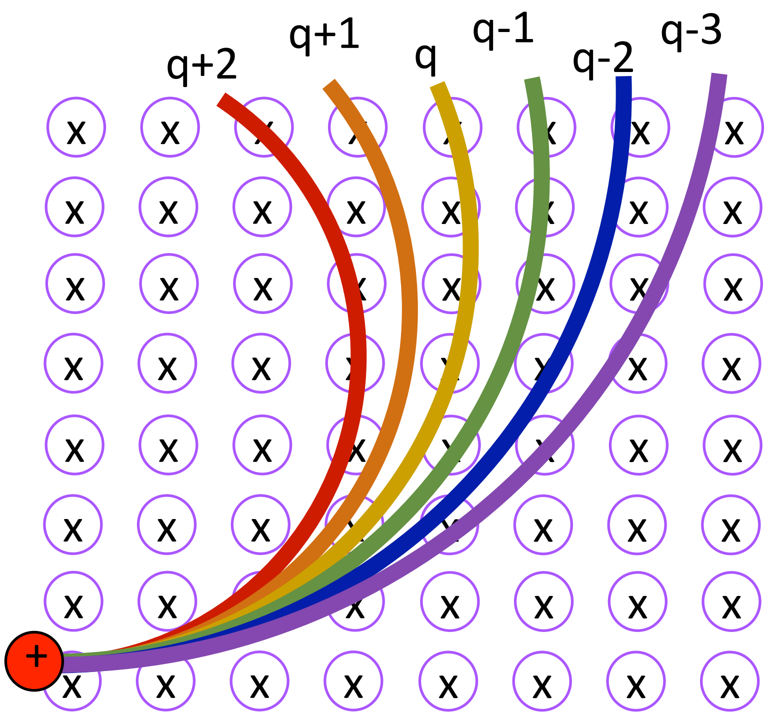
Maximum efficiency in vacuum separators limited to less than the fraction that exits in one charge state or ~30%

Parameterization from Phys. Lett. A, 28 (1968) 277

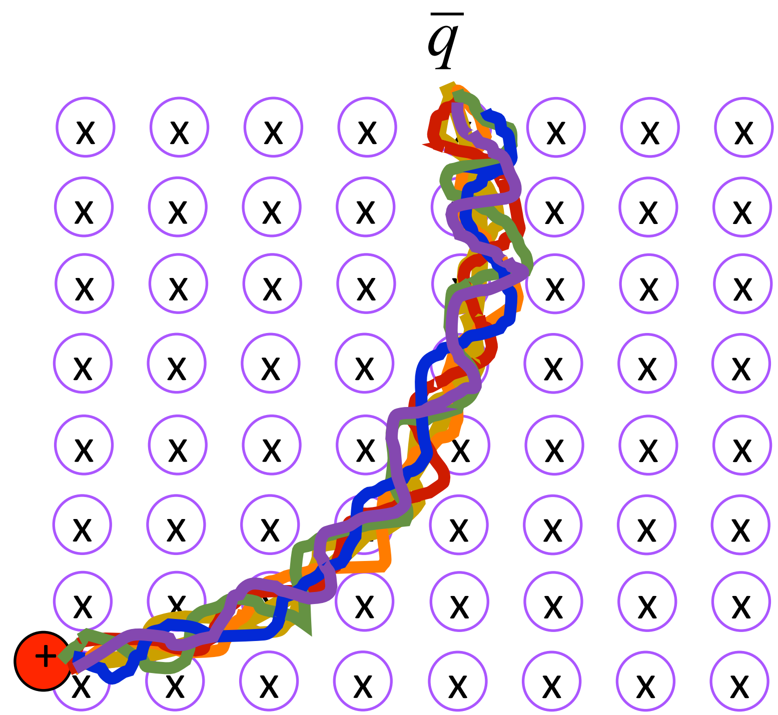
Why a Gas-Filled Magnetic Separator?

$$B\rho = \frac{mv^2}{q}$$

In Vacuum



In Gas



Why a Gas-Filled Magnetic Separator?

- Recoils exit the target with a distribution of charge states
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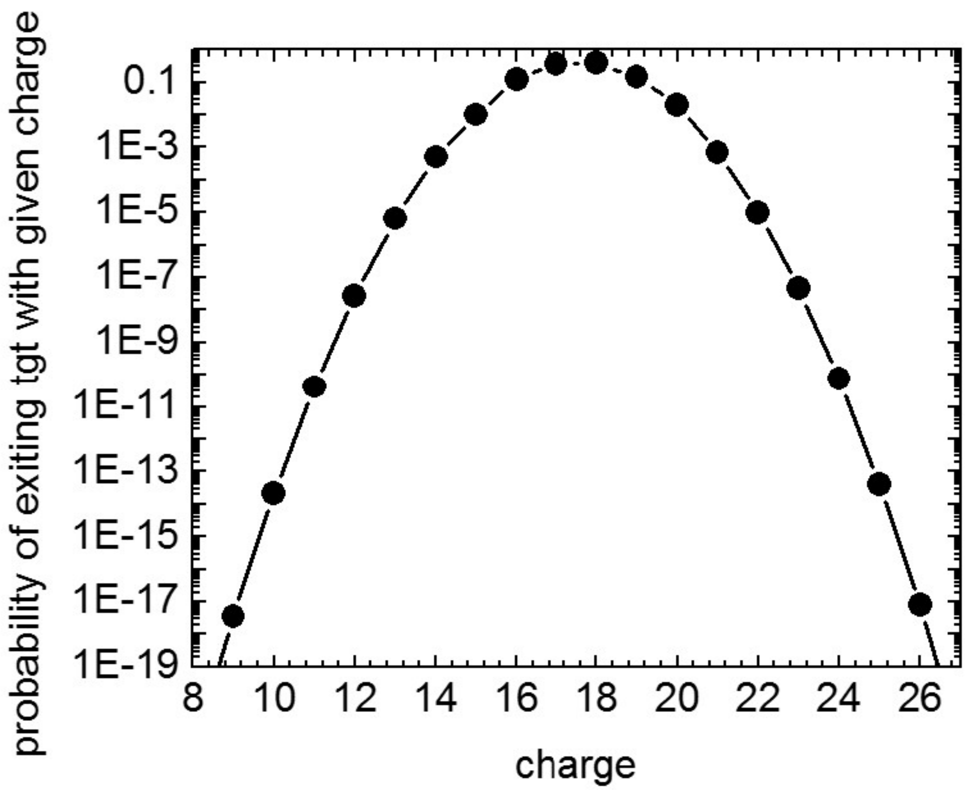


- Reason #1: Recoils passing through He take on a well-defined average charge state.

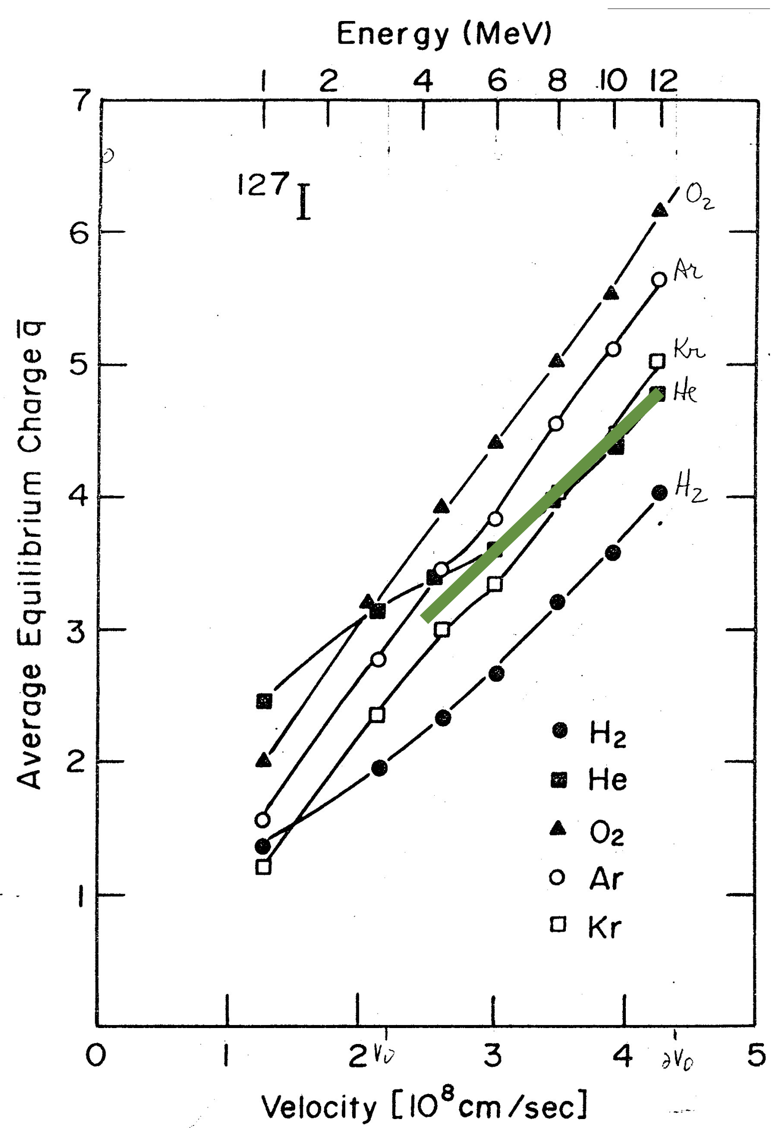
(100% charge acceptance)

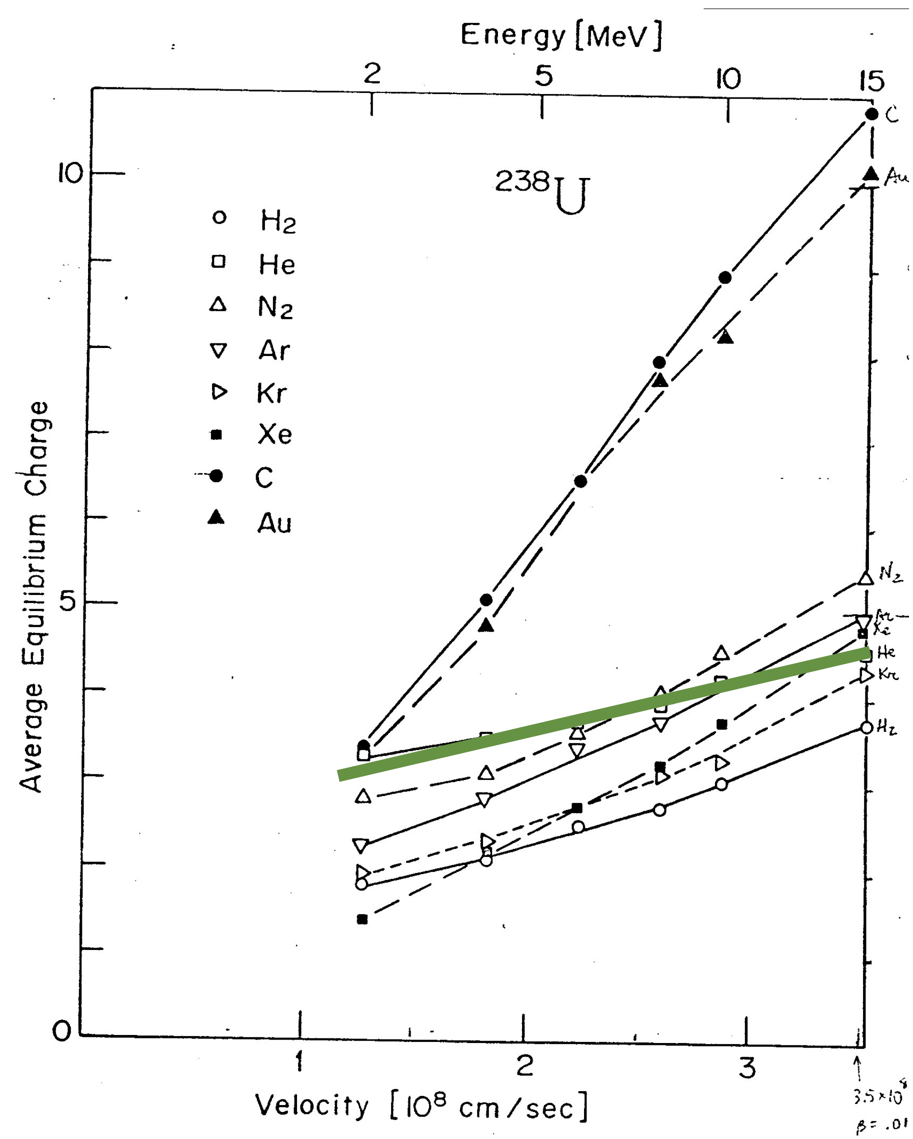
- Reason #2: The average charge state is nearly proportional to velocity.

(large velocity/energy acceptance)

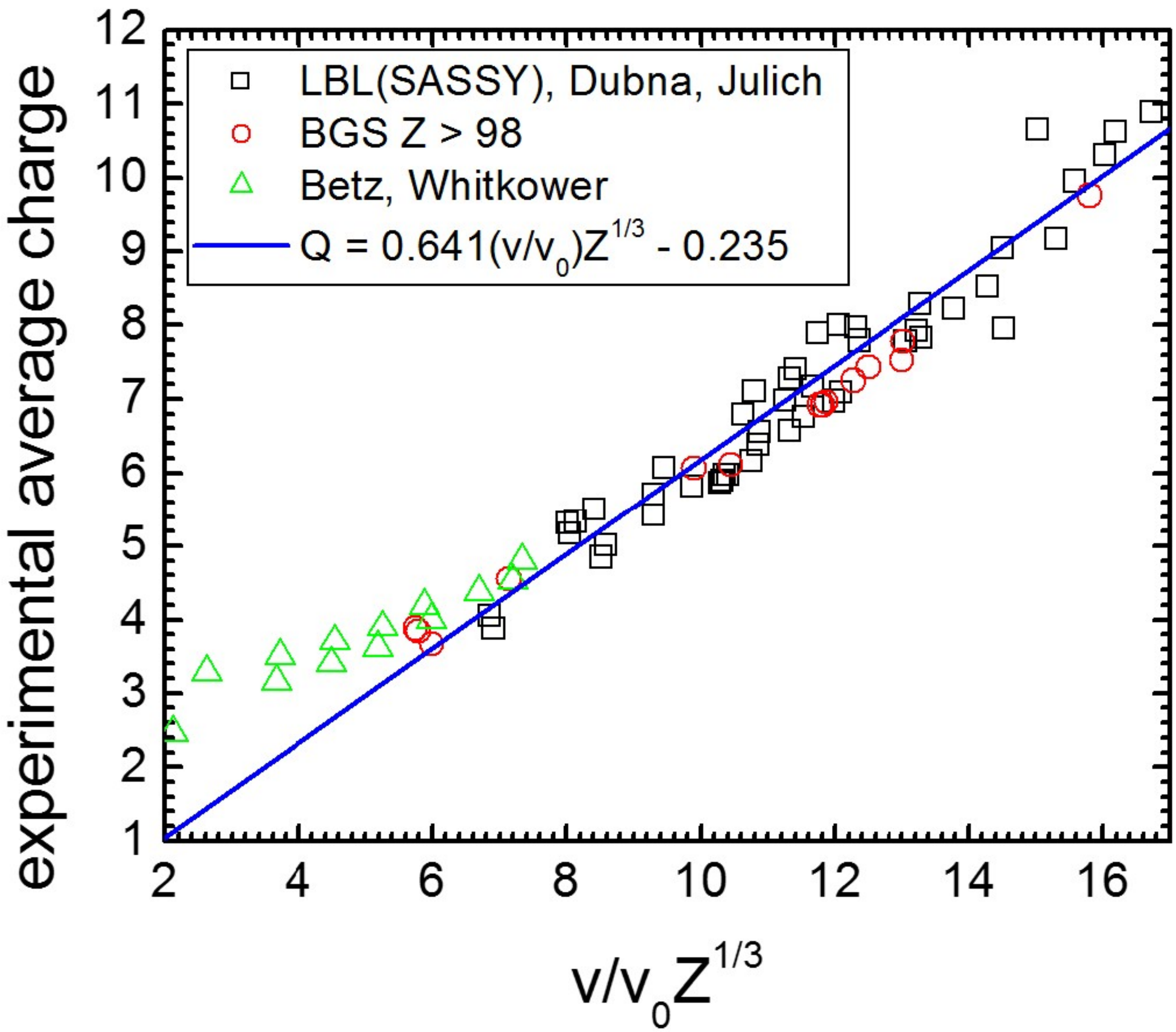
Parameterization from Phys. Lett. A, 28 (1968) 277

Old Average Charge Data from Betz and Whitkower





Gas



Back in 1948, Neils Bohr suggested a

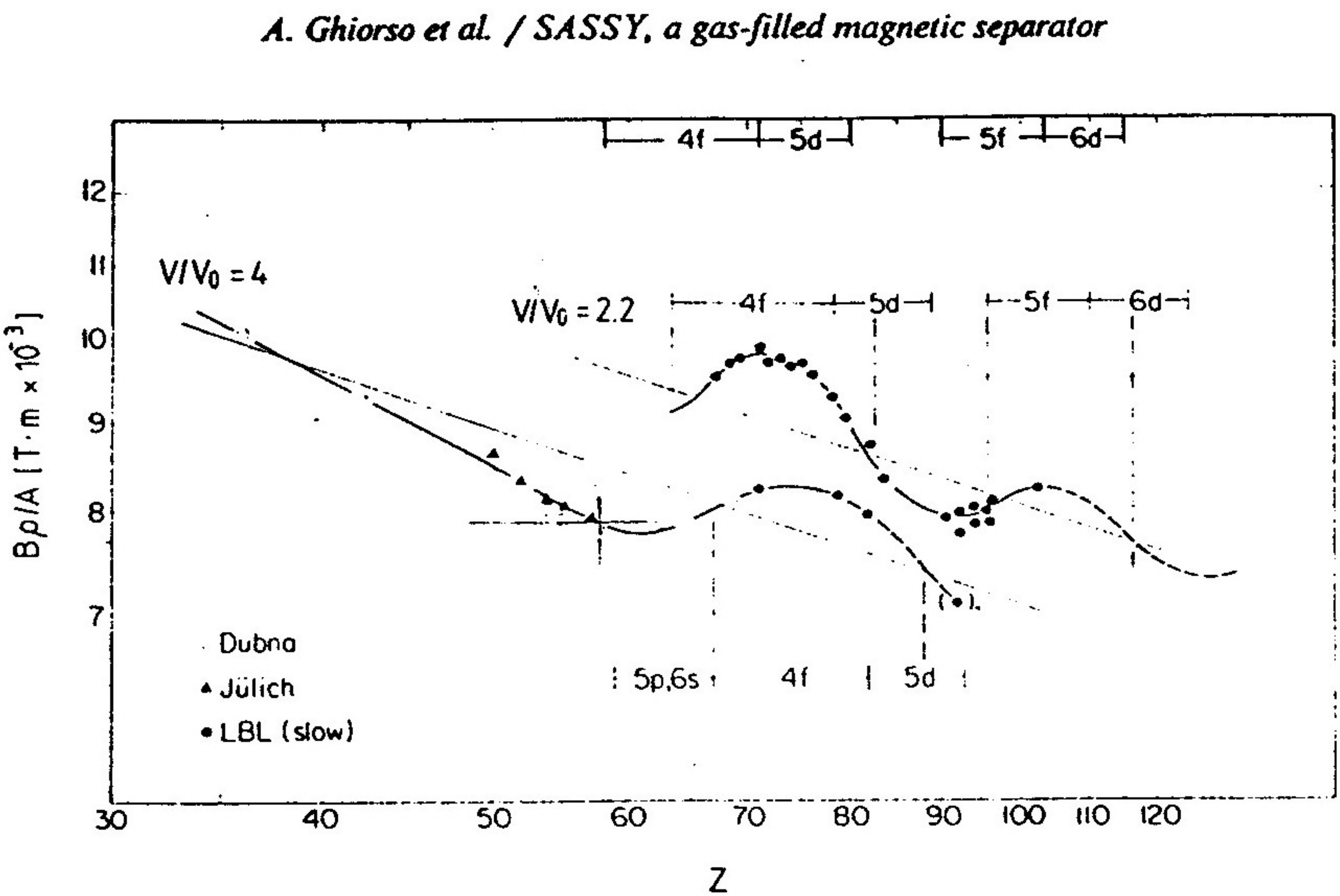
$q = vZ^{1/3}$ dependence

Two problems:

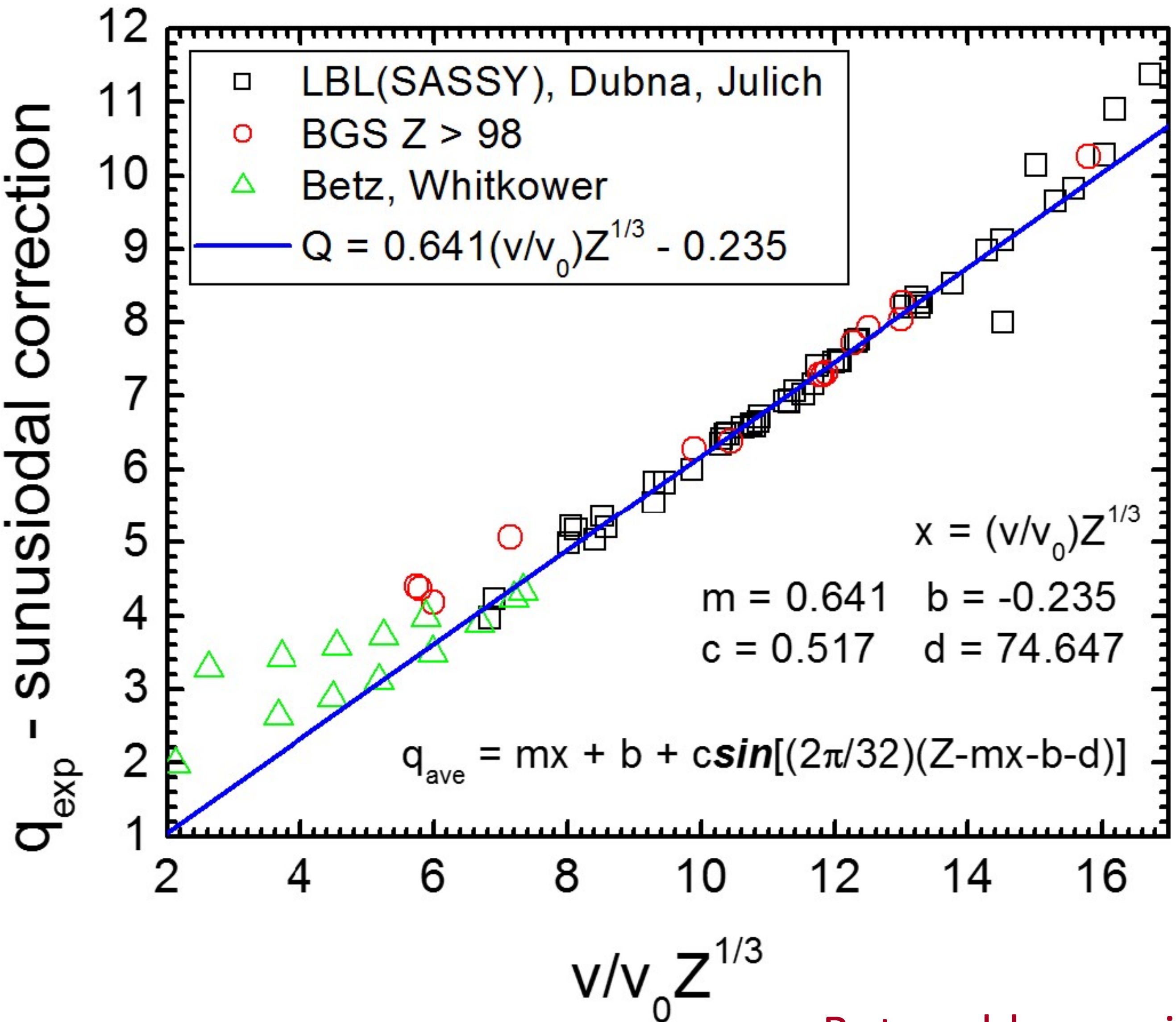
1) There is lots of scatter. Deviations are +/- 10%. Can this be understood in terms of the electronic shell structure of the stripped ions?

2) Strong deviations at low velocities due to the High ionization potential of He.

Ghiorso and Armbruster suggest that deviations are due to electronic shell structure of stripped ions



Understanding Magnetic Rigidity in He Gas
Sinusoidal correction based on electronic structure of stripped ion . . .



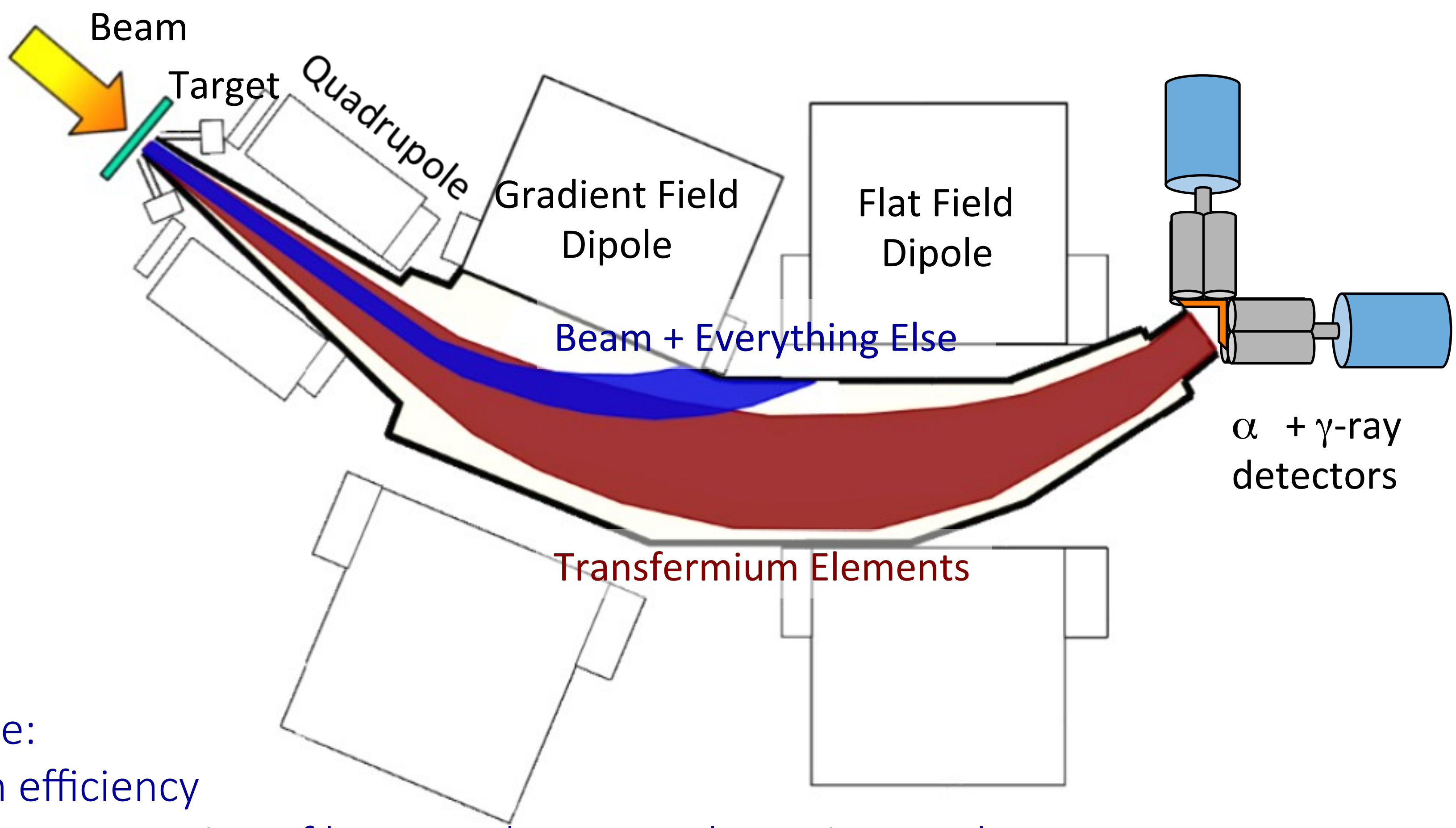
Semi-empirical understanding of why this works:

If the stripped ion is in an f-orbital, the most loosely bound electrons are inner electrons, and are less available for stripping by the gas, giving a lower q.

If the stripped ion is in a p-orbital, the most loosely bound electrons are outer electrons, and are readily available for stripping by the gas, giving a higher q.

But problems arise at low velocities!

Berkeley Gas-filled Separator (BGS)



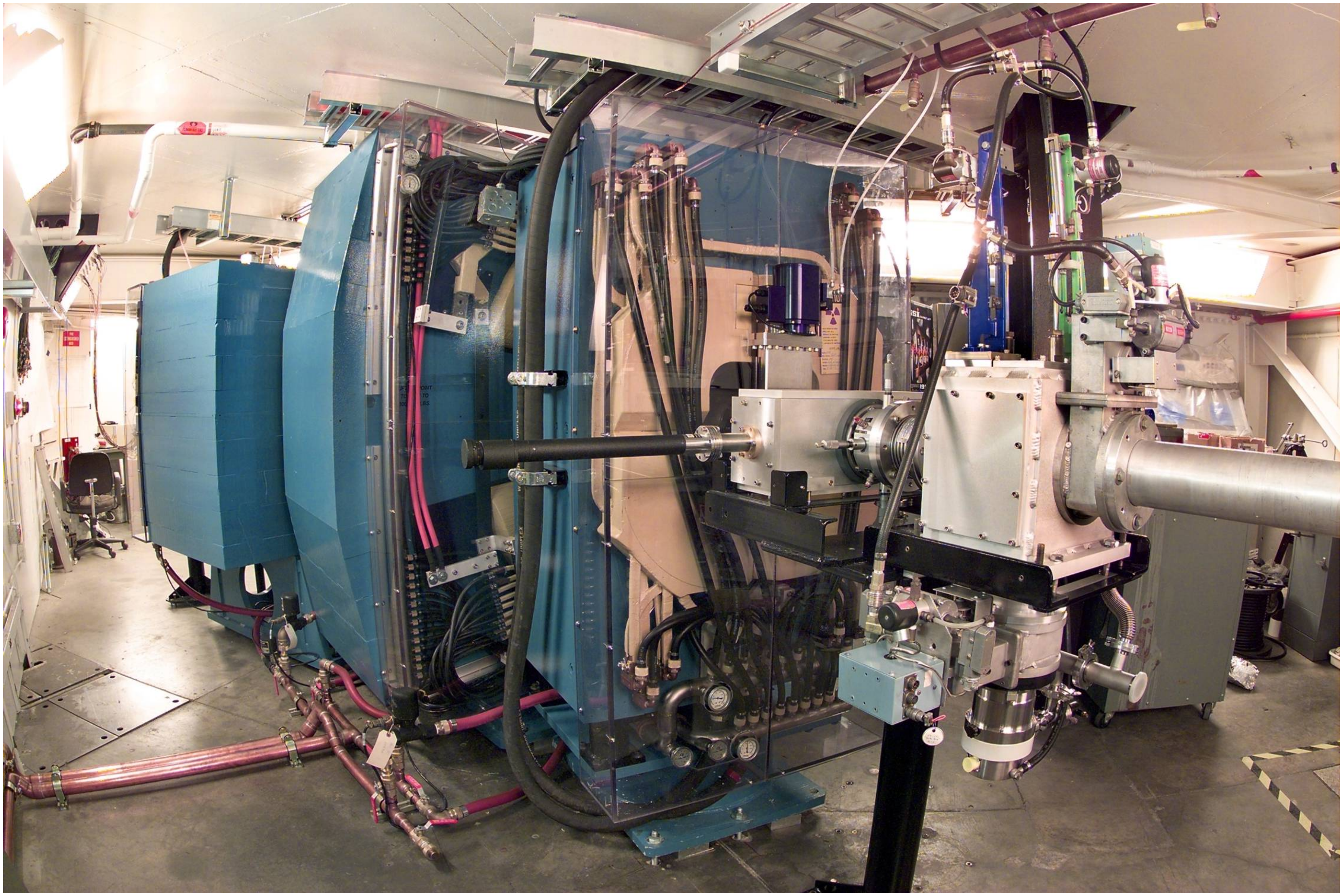
Positive:

- High efficiency
- Large suppression of beam and unwanted reaction products

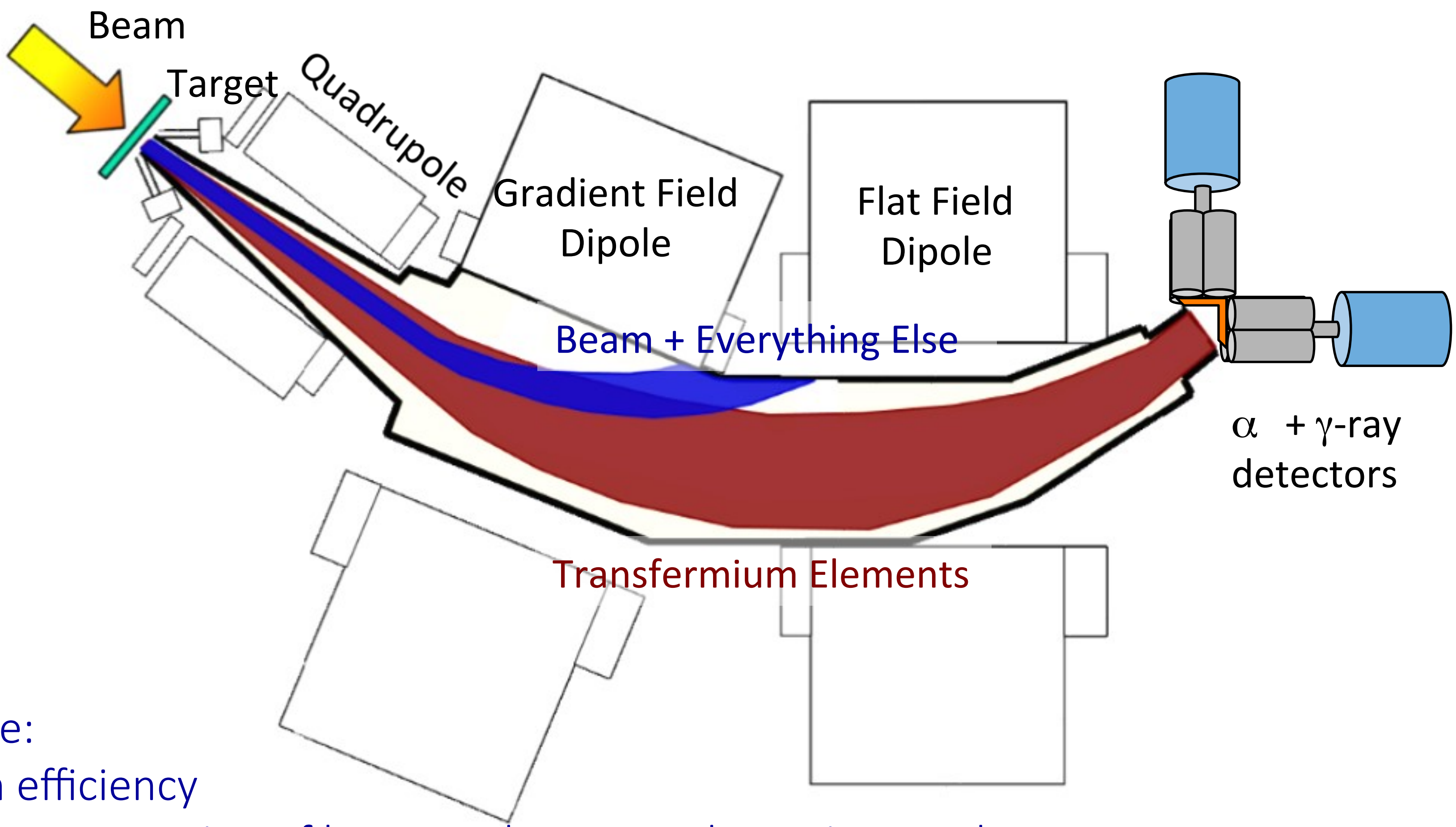
Negatives:

- Large focal plane image
- Poor mass resolution
- High gamma background at focal plane

Berkeley Gas-filled Separator (BGS)



Berkeley Gas-filled Separator (BGS)



Positive:

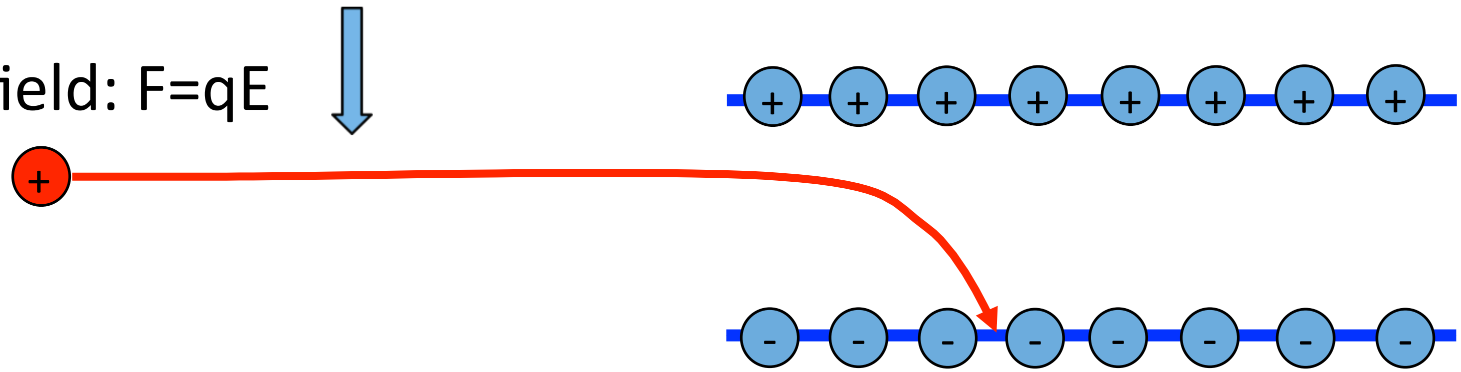
- High efficiency
- Large suppression of beam and unwanted reaction products

Negatives:

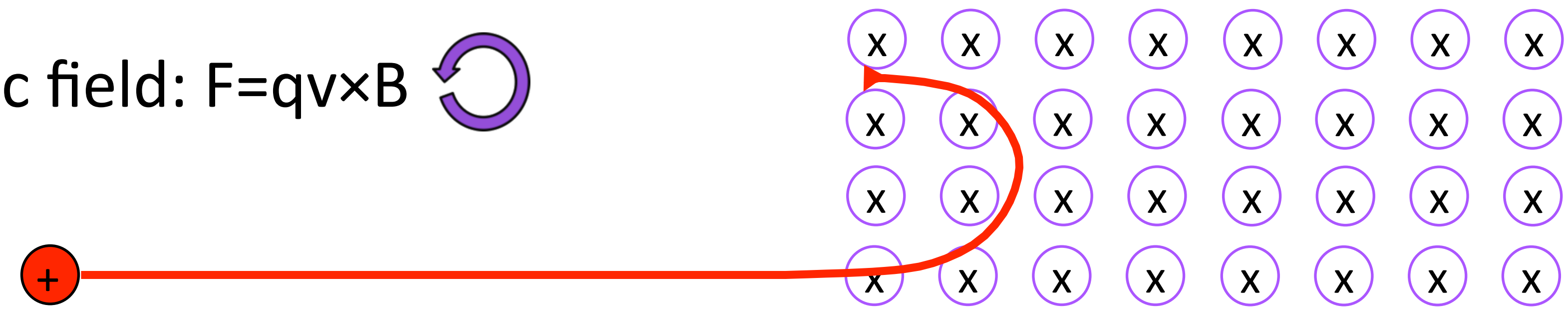
- Large focal plane image
- Poor mass resolution
- High gamma background at focal plane

Electromagnetic Separators

Electric field: F=qE



Magnetic field: F=qv×B

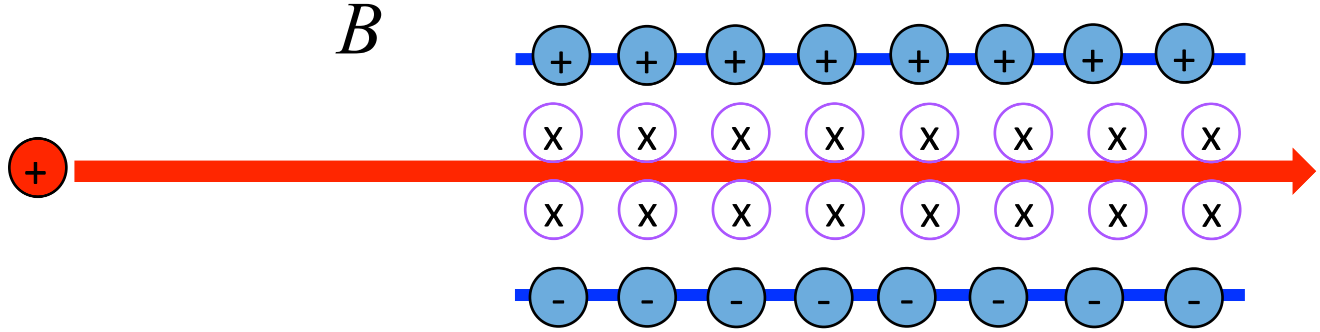


Electromagnetic Separators - Wien

Balance electric and magnetic fields:

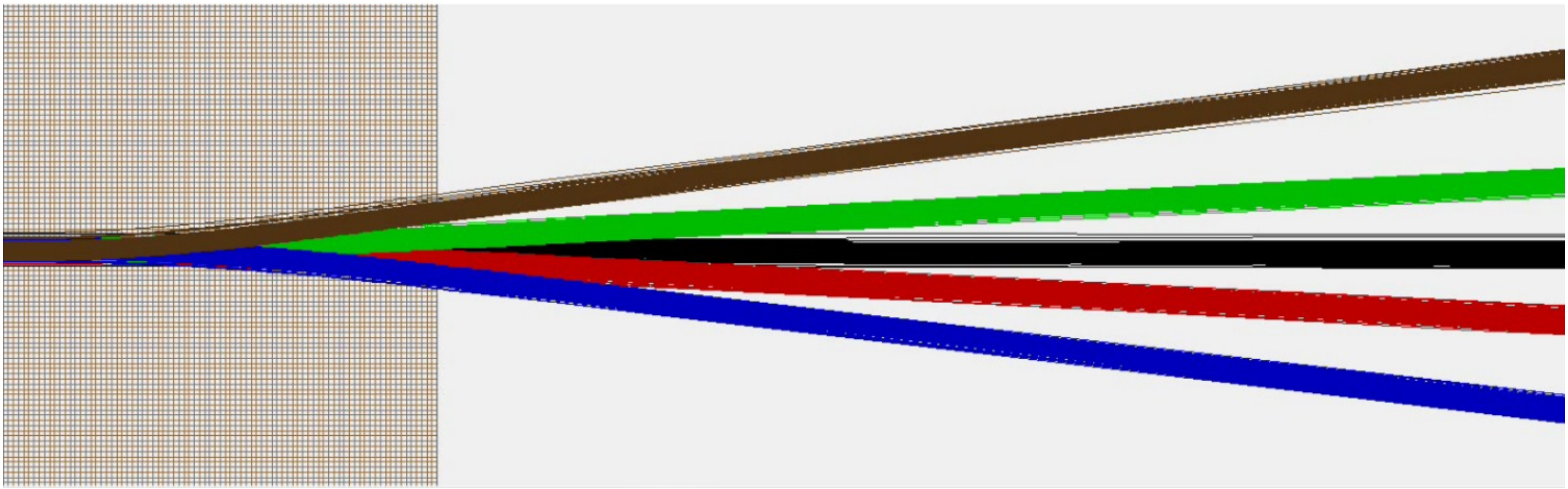
$F_E = F_B$: $qE = qvB$

$$v = \frac{E}{B}$$

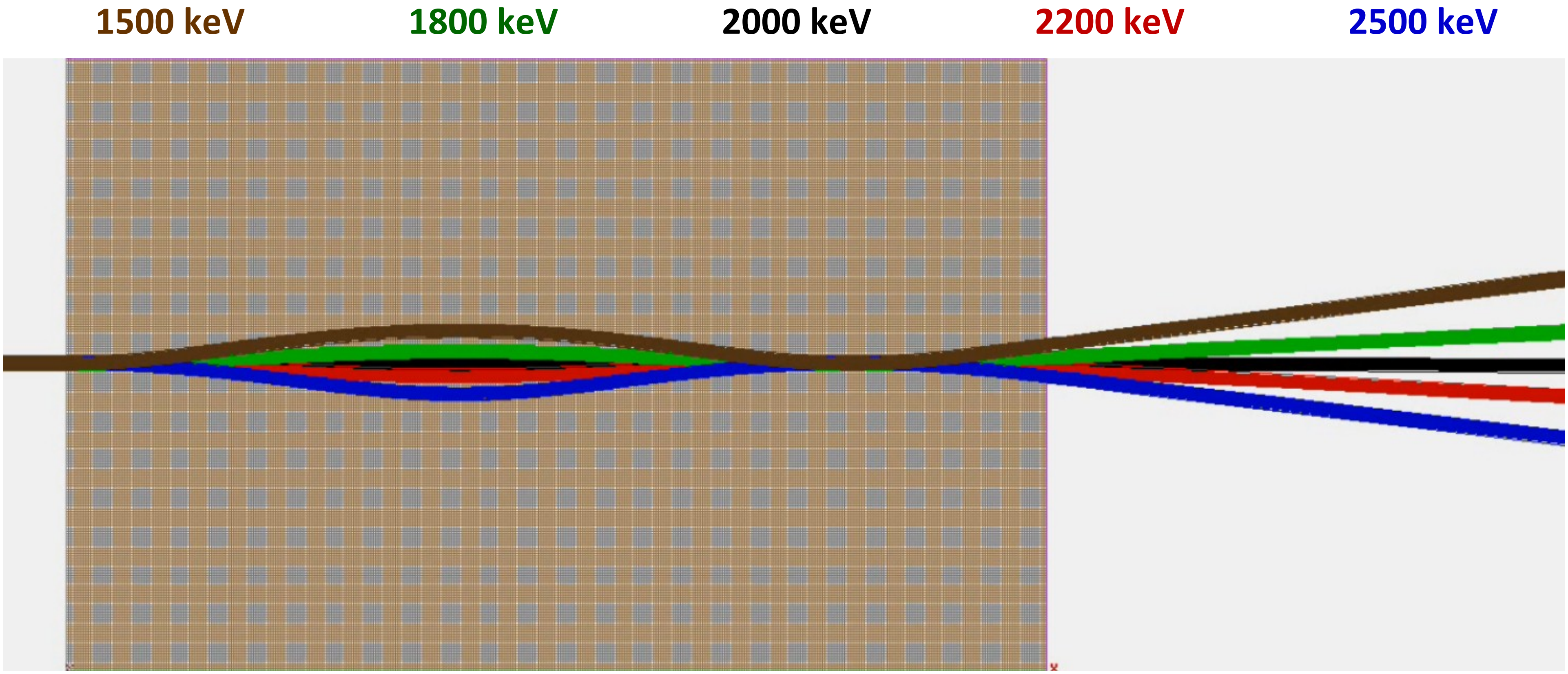


Electromagnetic Separators - Wien

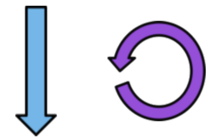
1500 keV **1800 keV** **2000 keV** **2200 keV** **2500 keV**



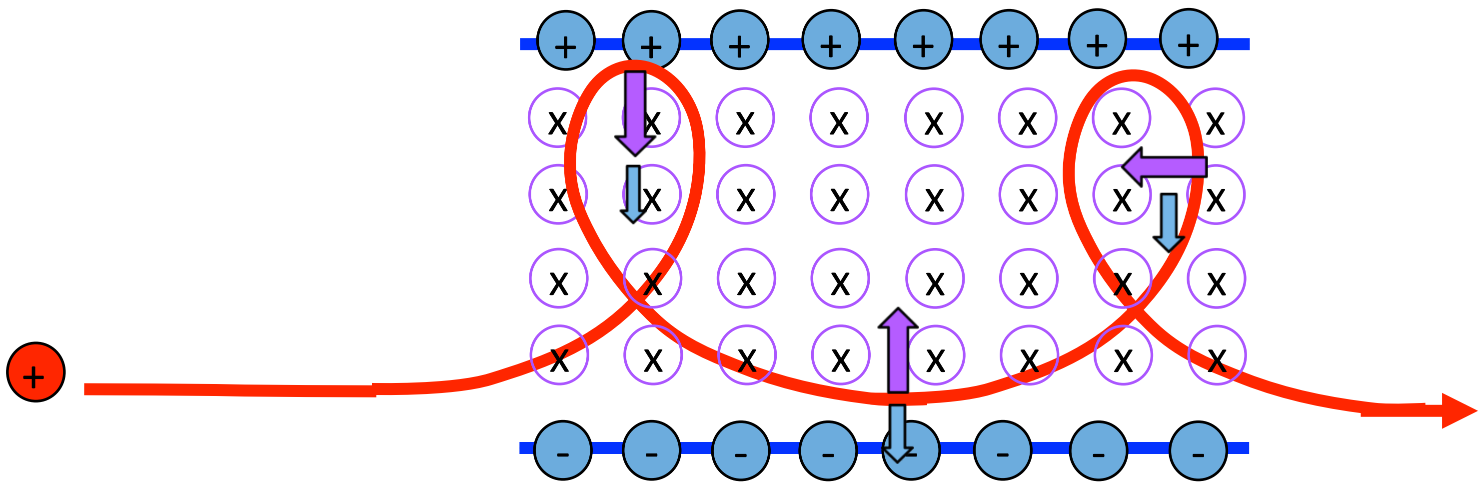
But what if you made it longer?



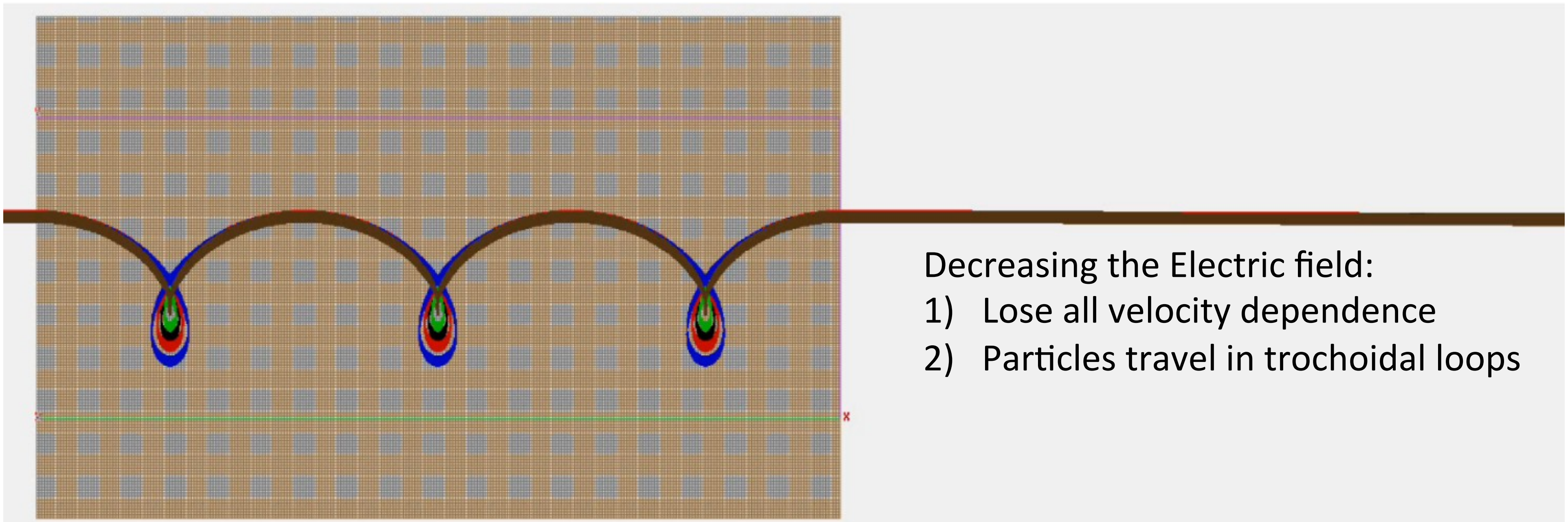
Mass Analyzer: The Idea

Unbalance electric and magnetic fields: 

$$r = \frac{mv_{\perp}}{qB}$$



Unbalancing the Fields

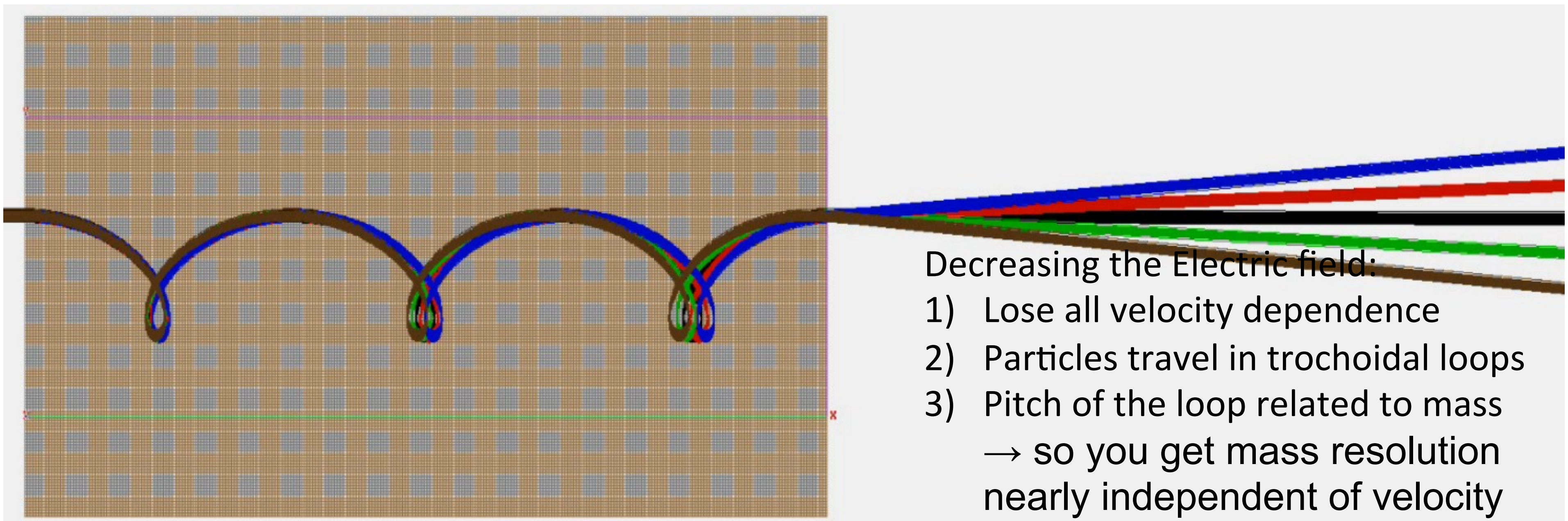


Decreasing the Electric field:

1) Lose all velocity dependence
2) Particles travel in trochoidal loops

1500 keV **1800 keV** **2000 keV** **2200 keV** **2500 keV**

Unbalancing the Fields



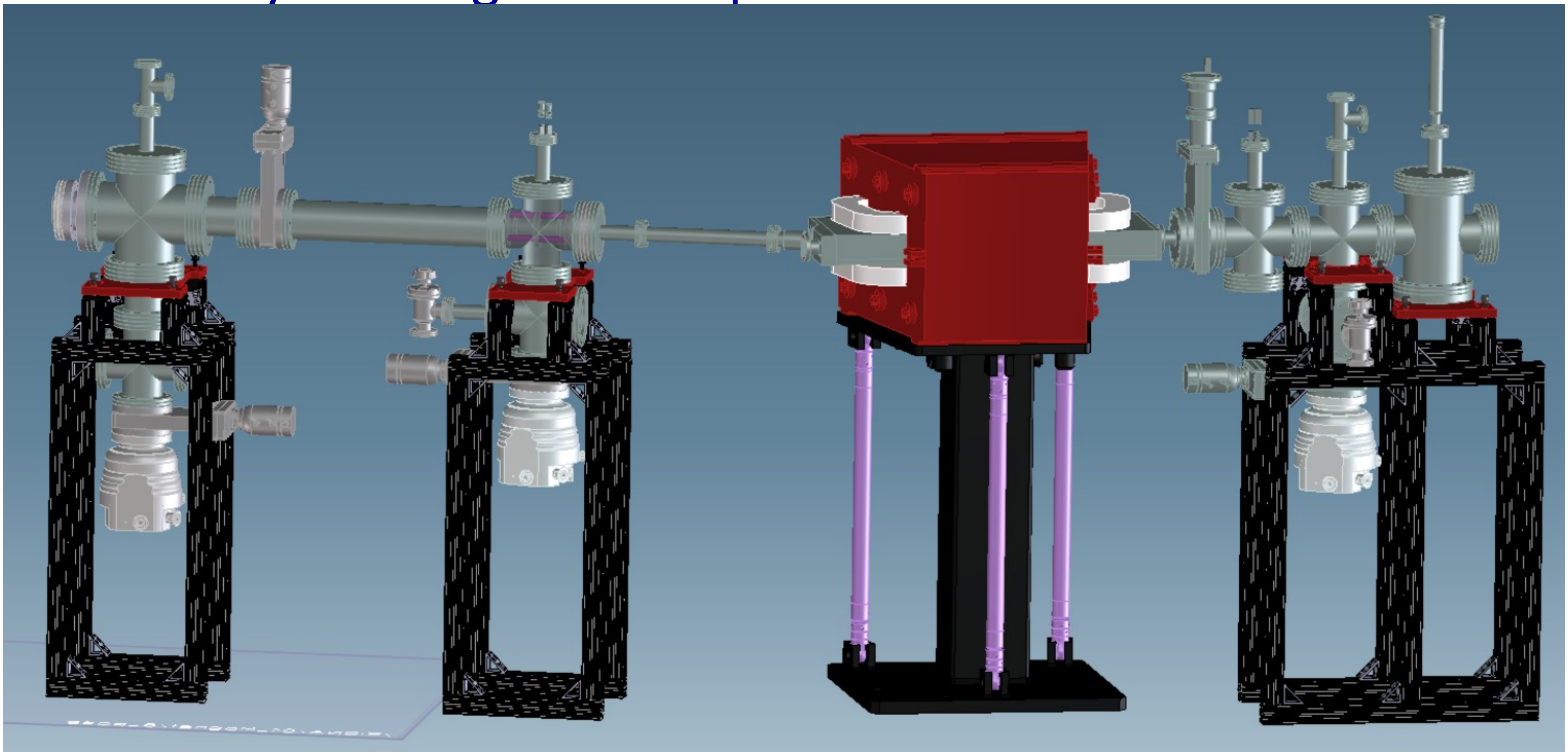
Decreasing the Electric field:

1) Lose all velocity dependence
2) Particles travel in trochoidal loops
3) Pitch of the loop related to mass → so you get mass resolution nearly independent of velocity

A=98 **A=99** **A=100** **A=101** **A=102**

Status and Future

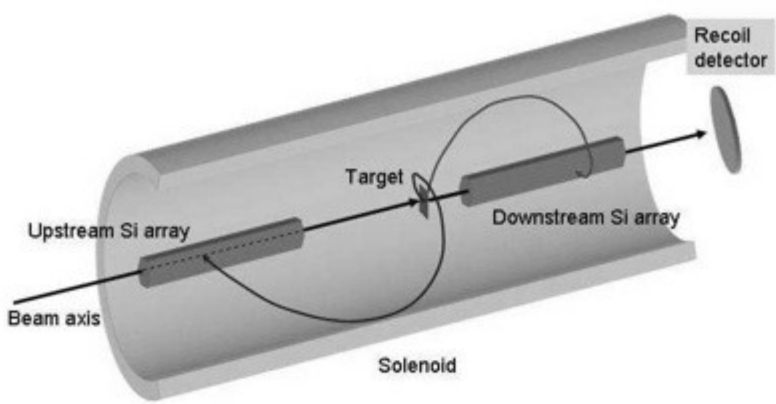
- Currently building test setup

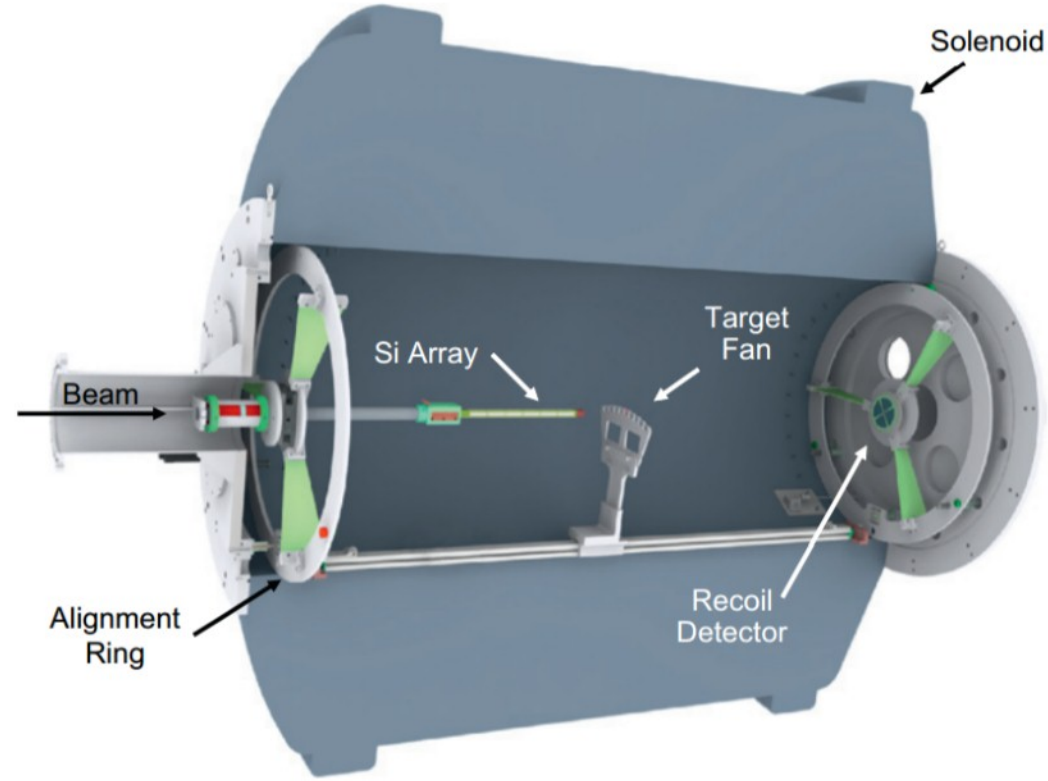


Ion Source Focusing Element Magnet + Electrode MCP Detector

Solenoids - Helios

- HELIcal Orbit Spectrometer at Argonne National Laboratory
- Drip-line nuclei produced in inverse kinematic reactions





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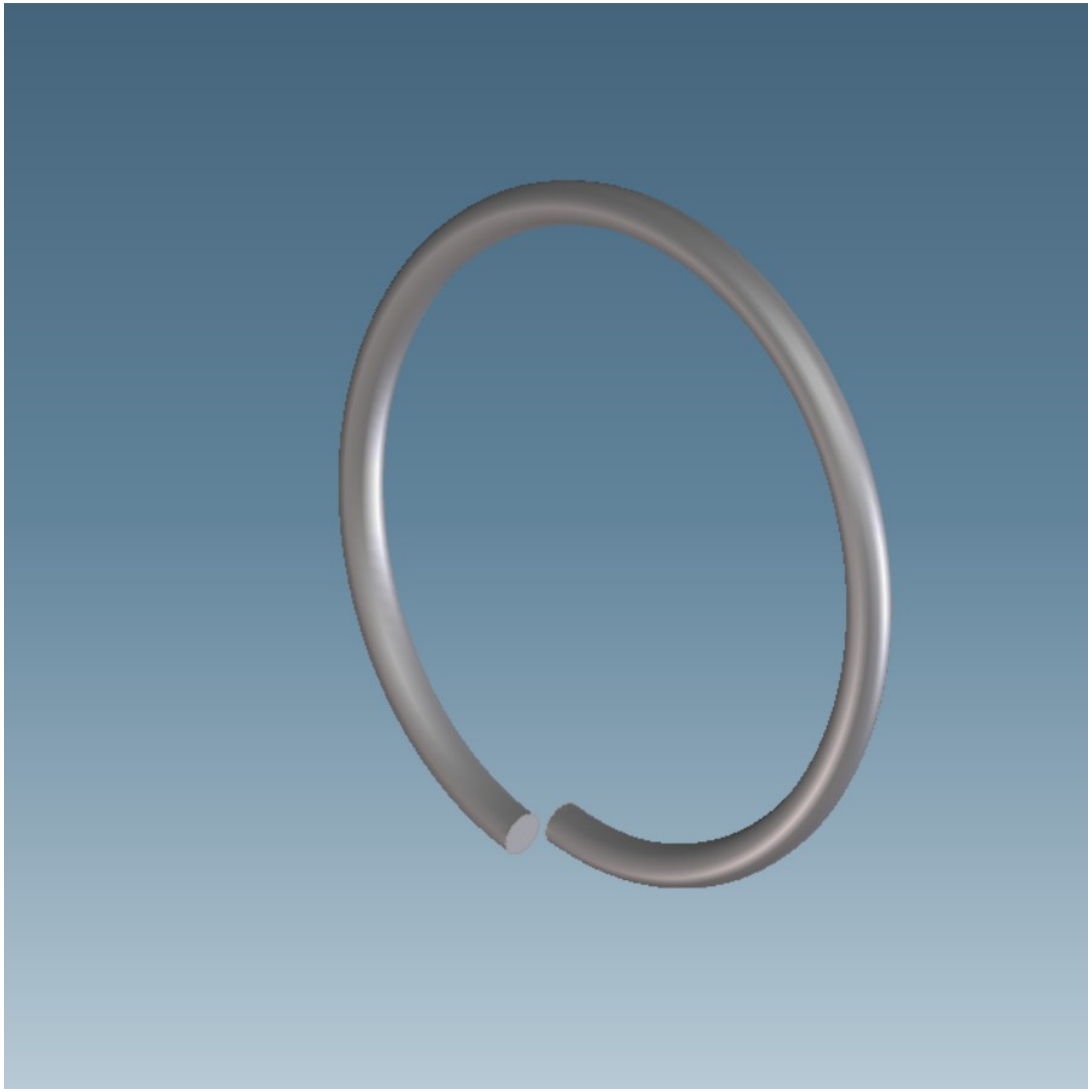
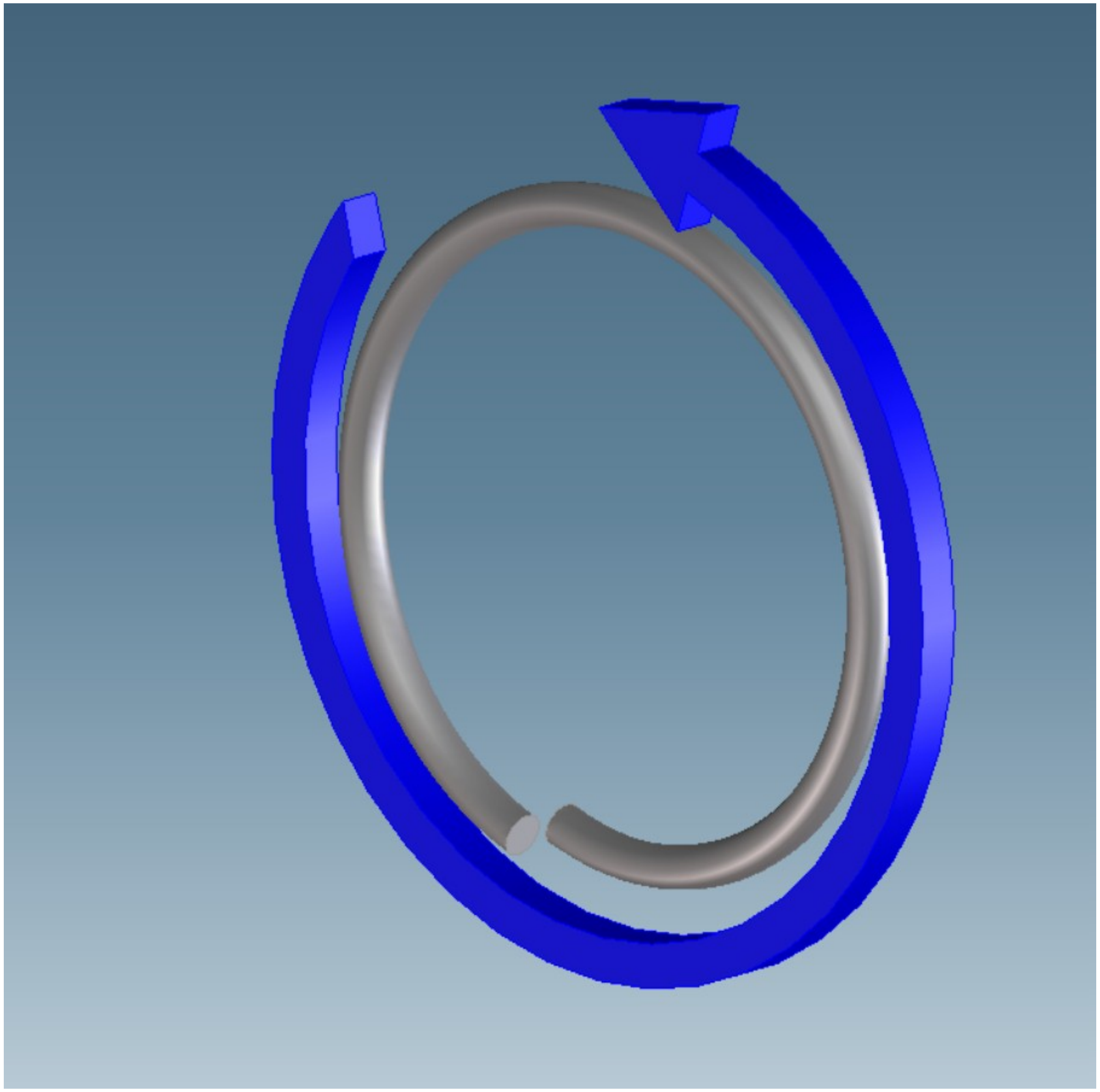
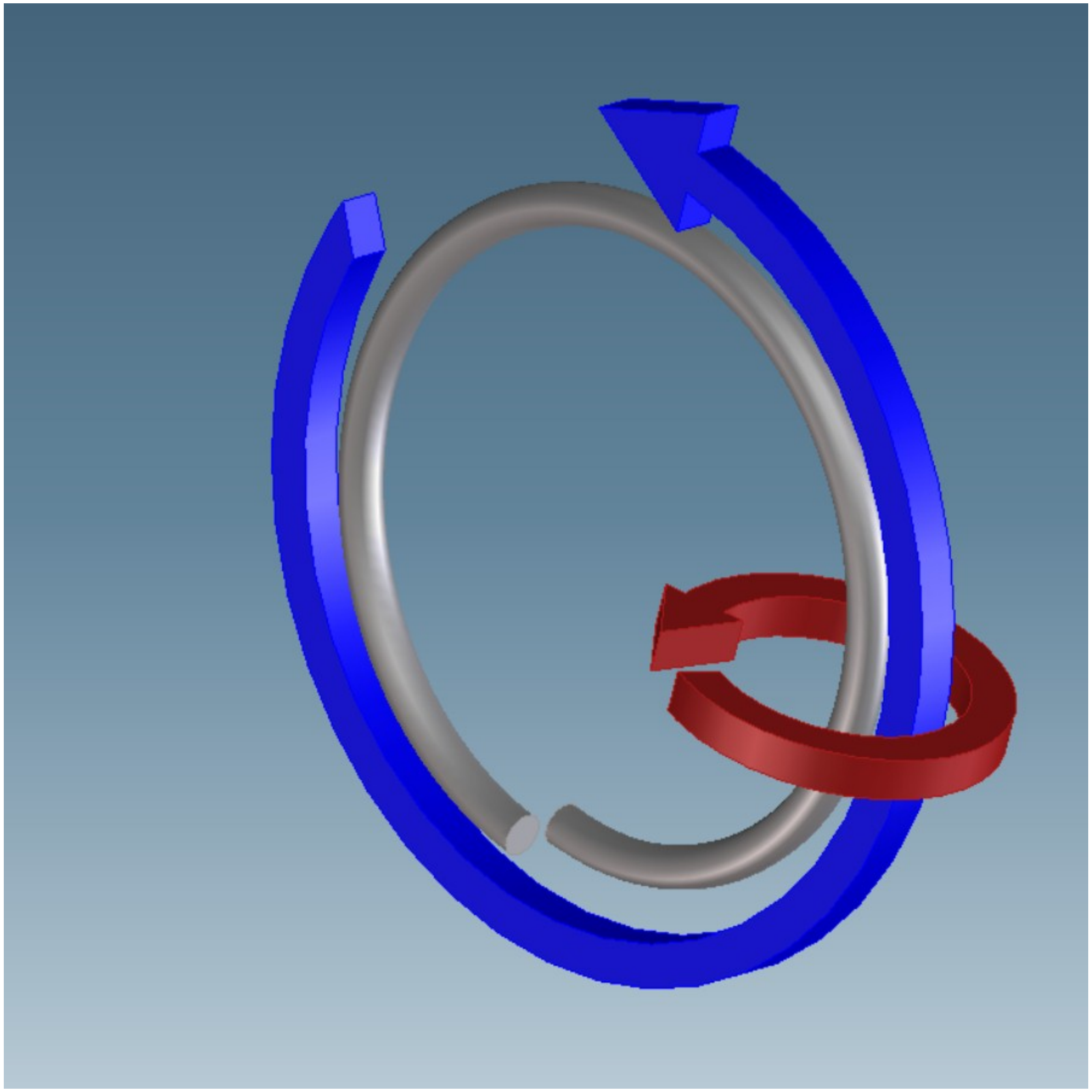
Magnets - Solenoids



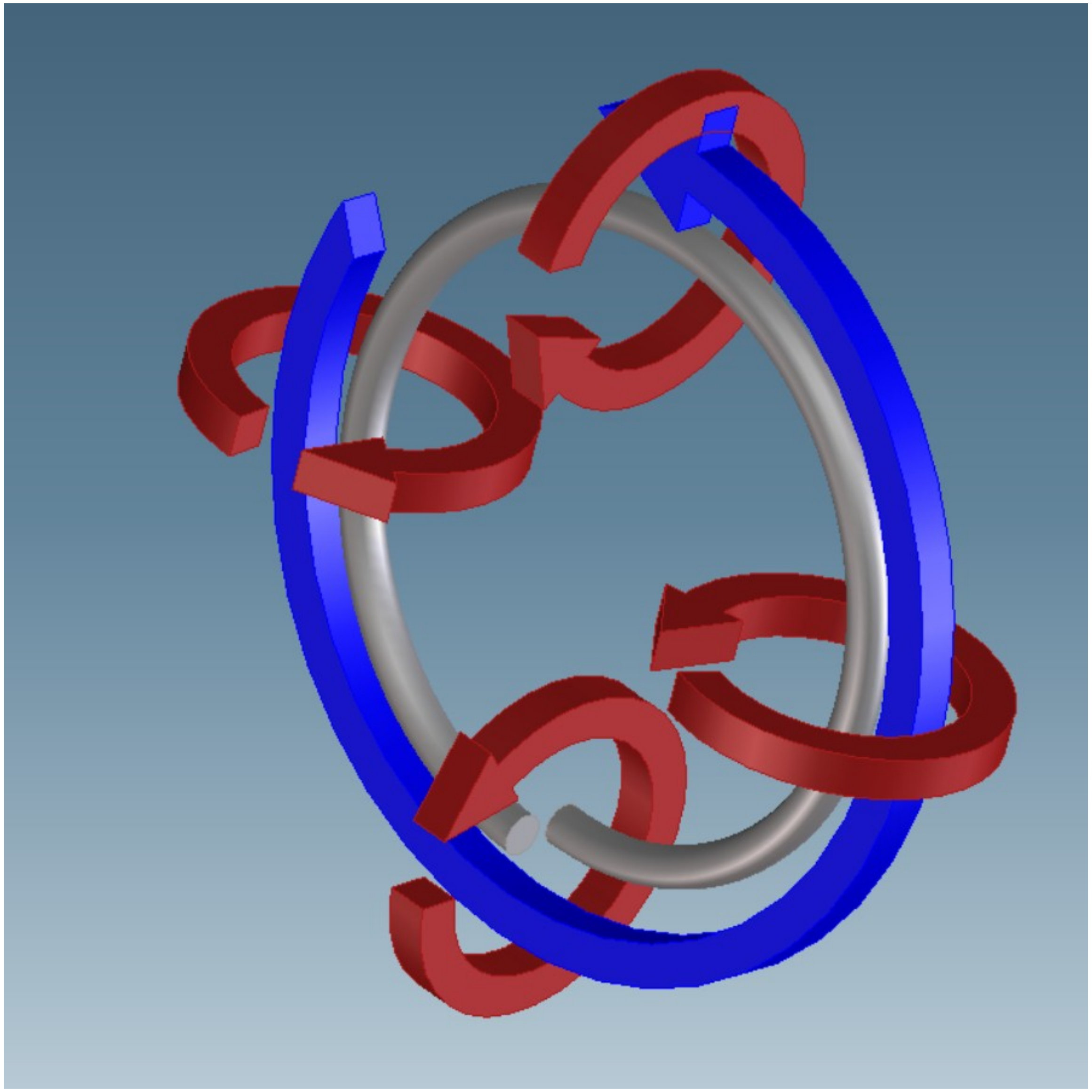
Magnets - Solenoids



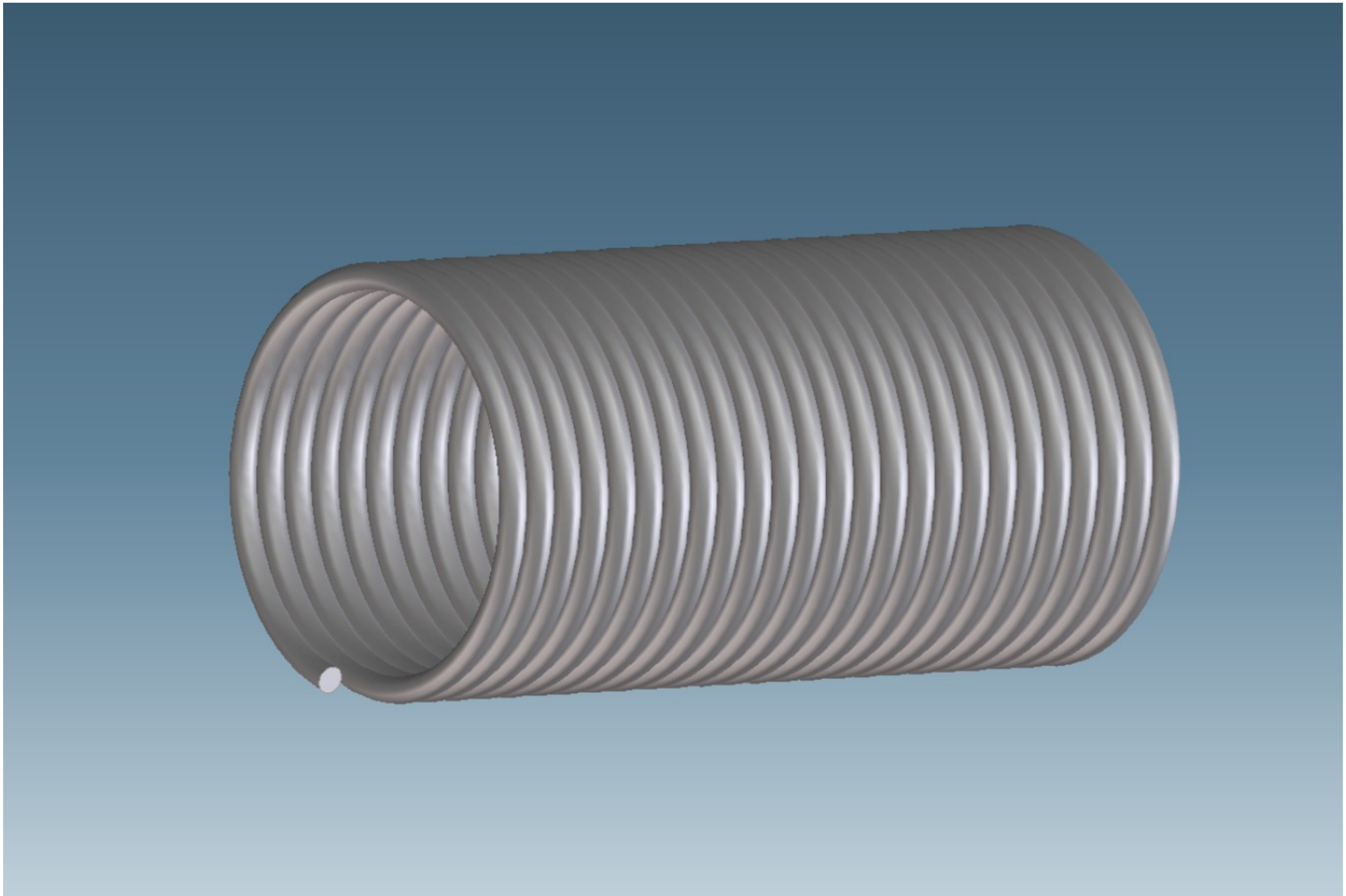
Magnets - Solenoids



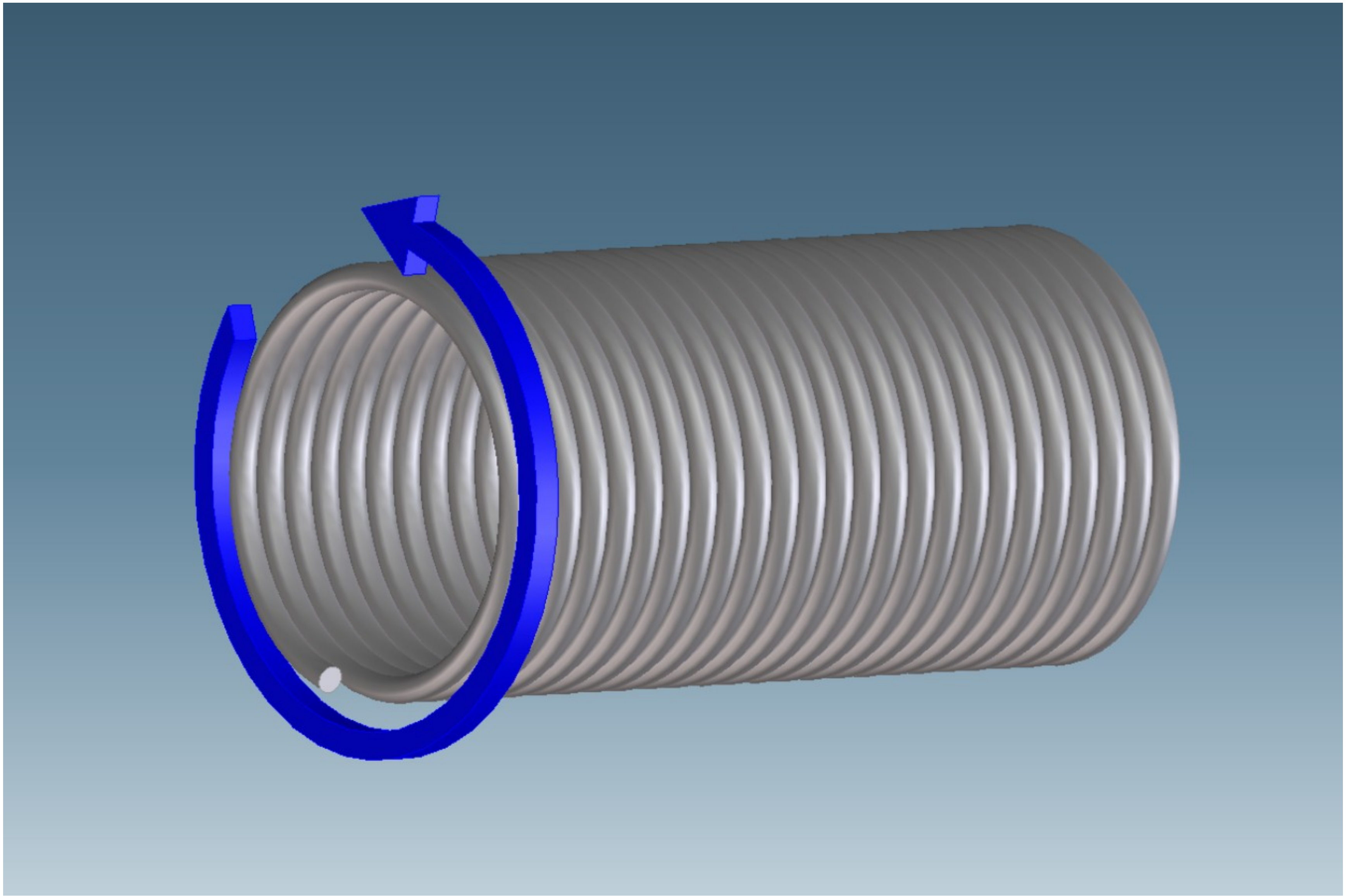
Magnets - Solenoids



Magnets - Solenoids



Magnets - Solenoids



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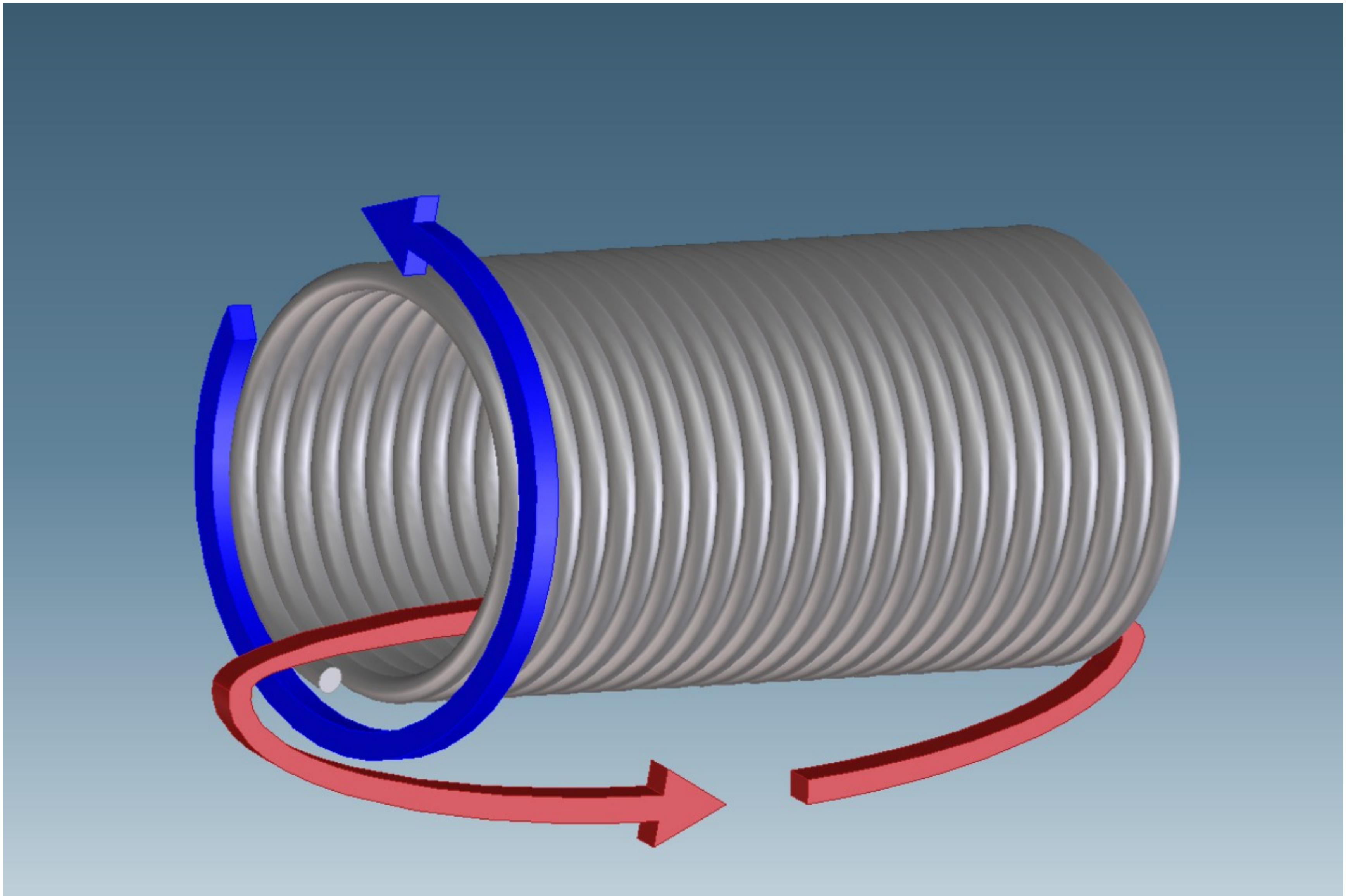

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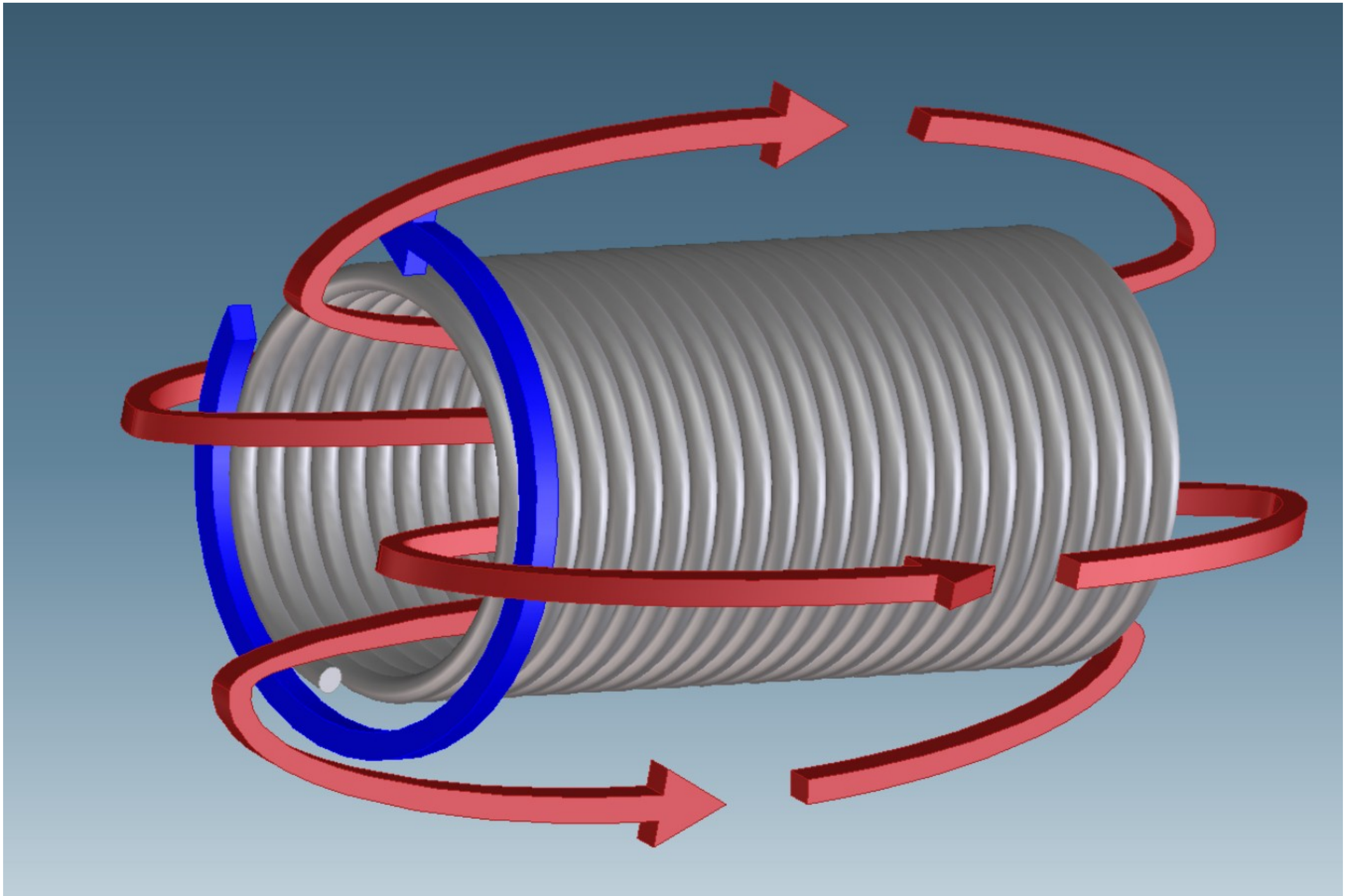
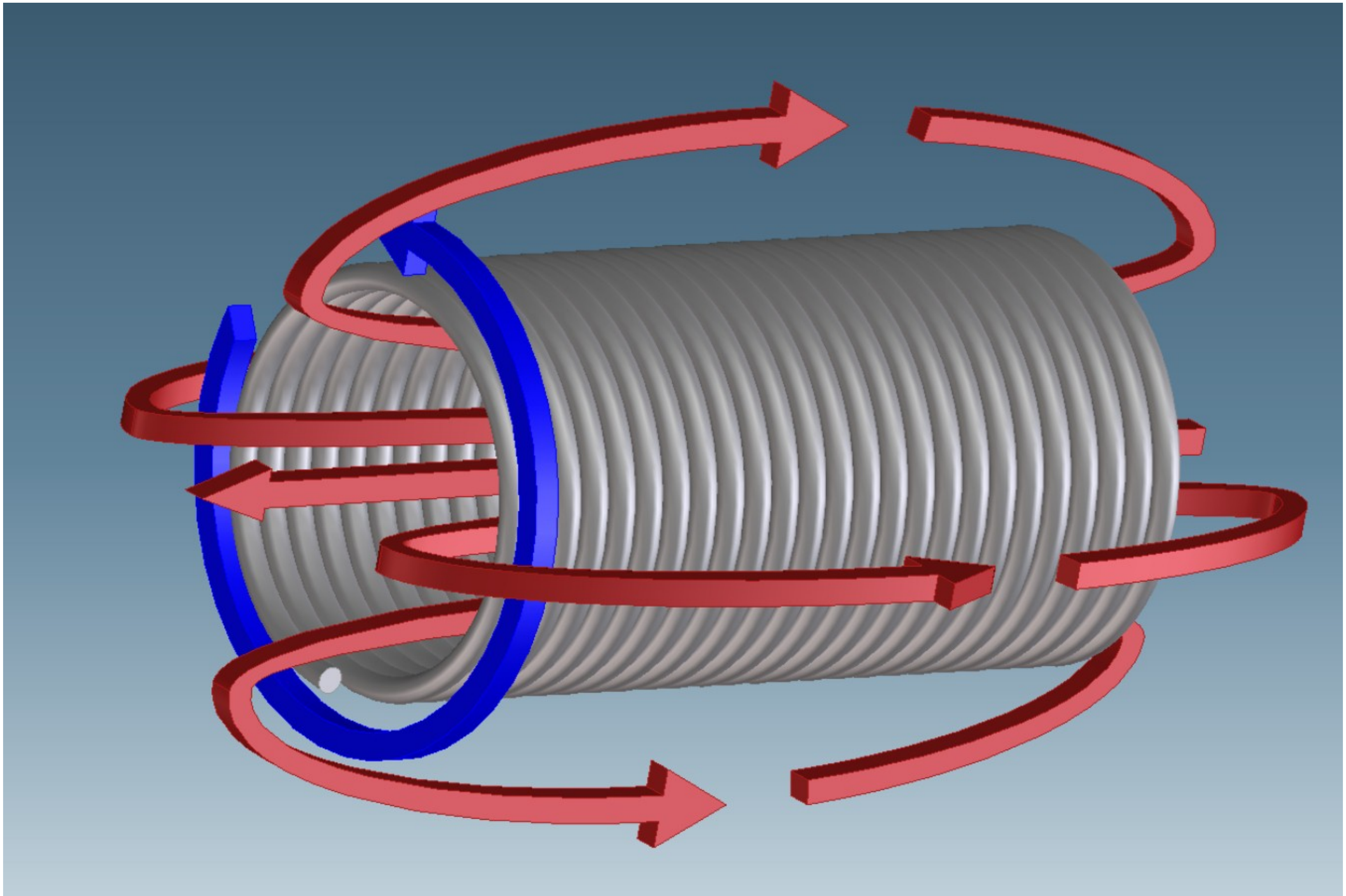
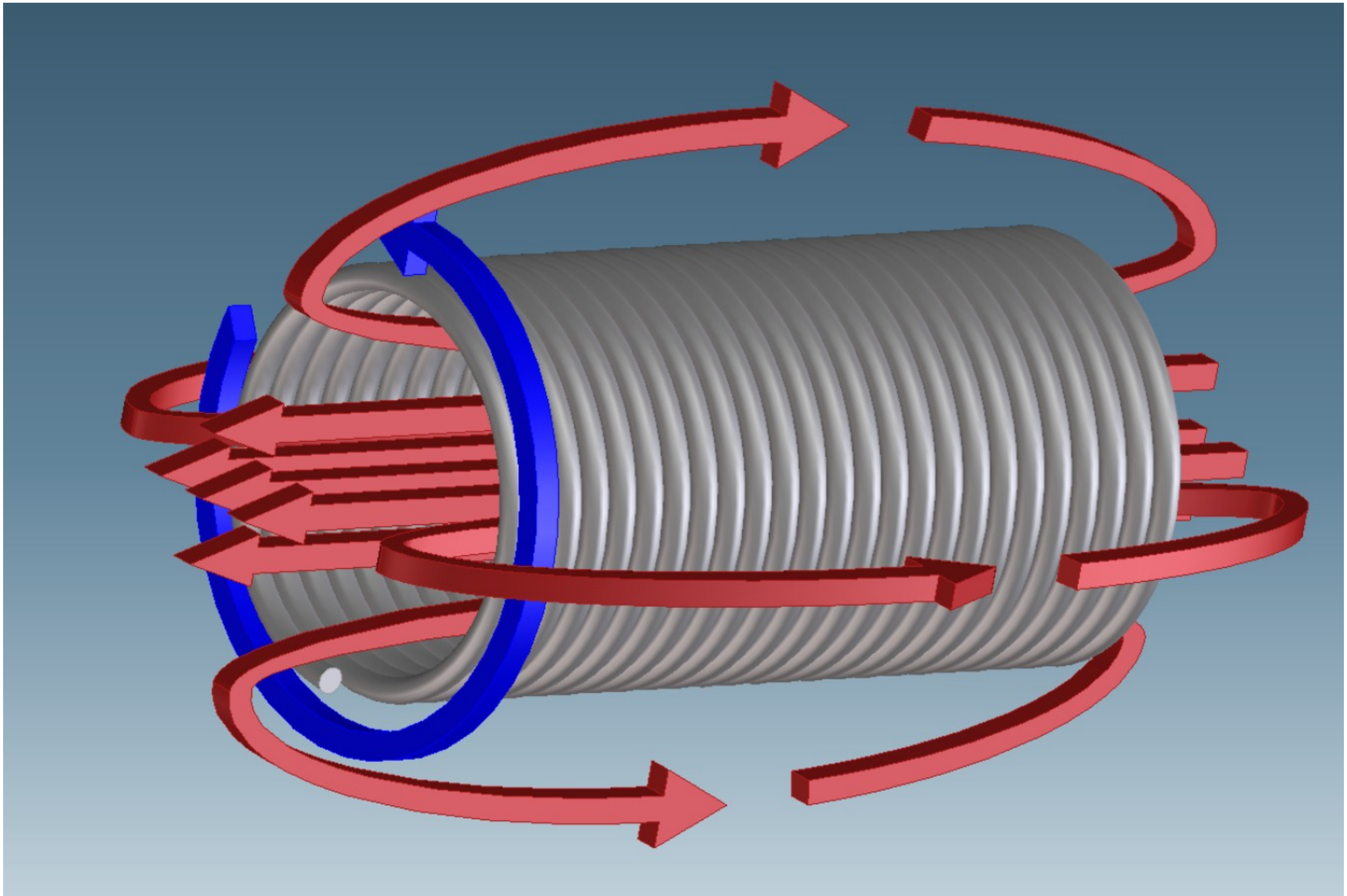


Magnets - Solenoids



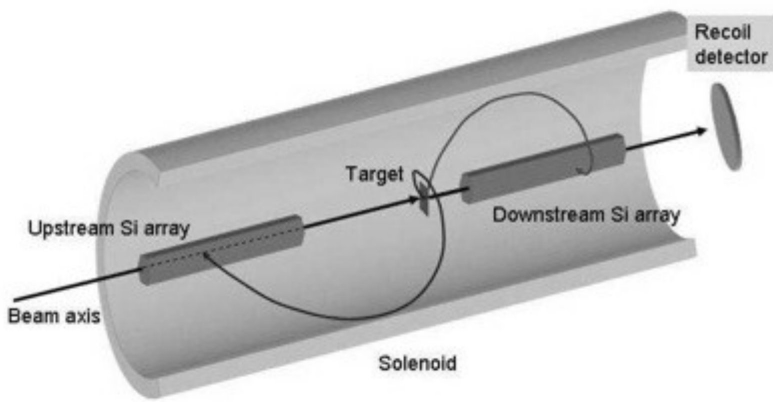
Magnets - Solenoids

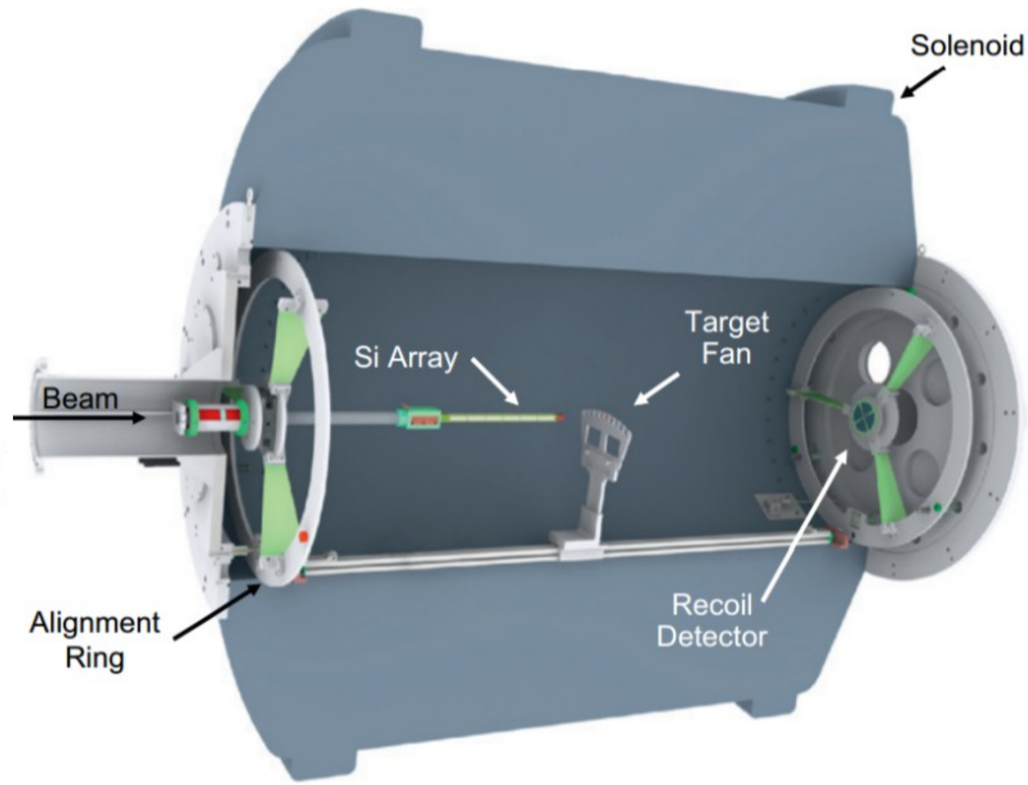


Solenoids - Helios

- Particles emitted from the target follow helical trajectories in the magnetic field

$$\rho = \frac{mv_\perp}{qB}$$





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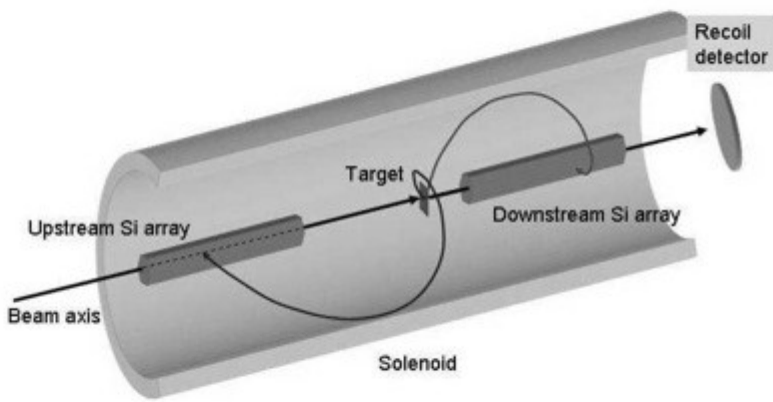
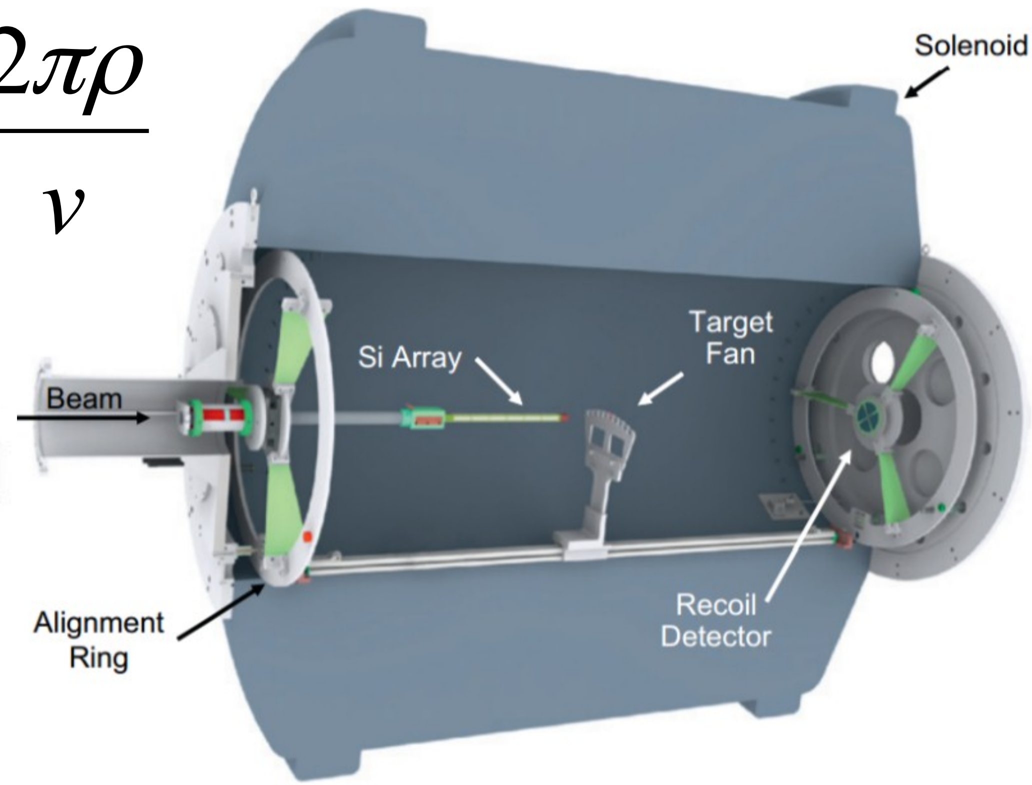
Solenoids - Helios

- Particles emitted from the target follow helical trajectories in the magnetic field

$$\rho = \frac{mv_{\perp}}{qB} \qquad T_{cyc} = \frac{2\pi\rho}{v}$$





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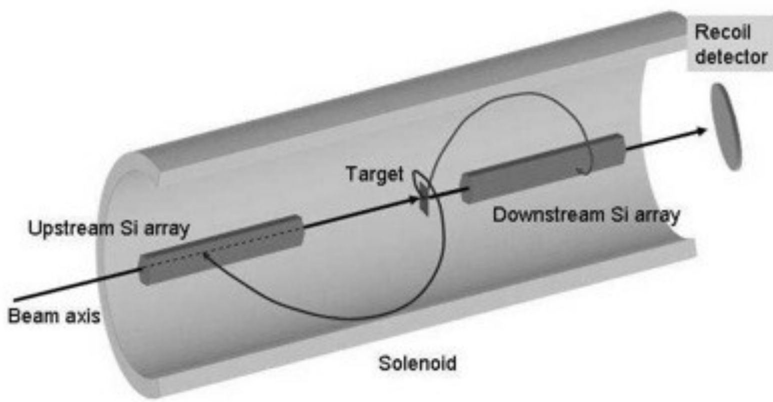
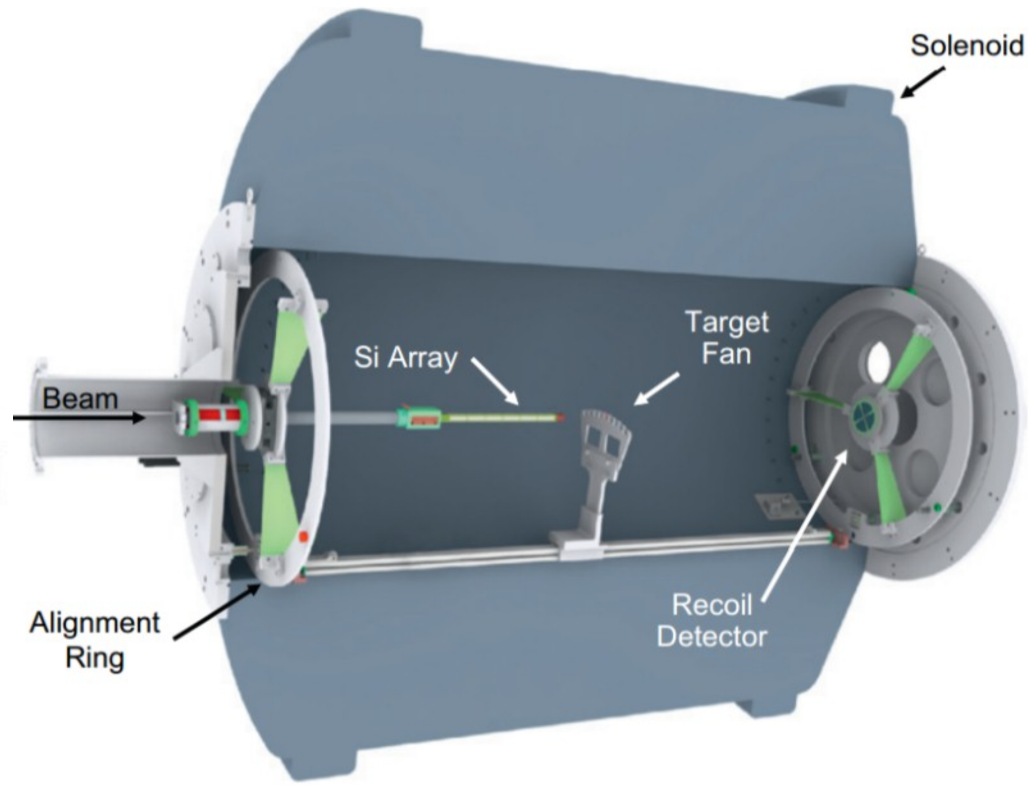
Solenoids - Helios

- After a single orbit, they return to the solenoid axis where they can be detected

$$T_{cyc} = \frac{2\pi m}{Bq}$$





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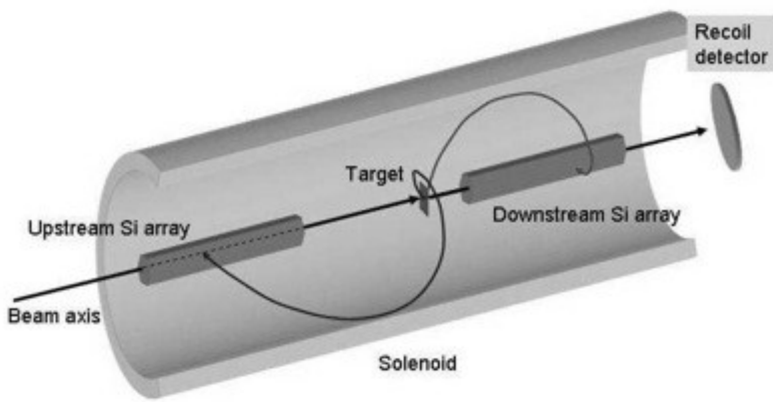
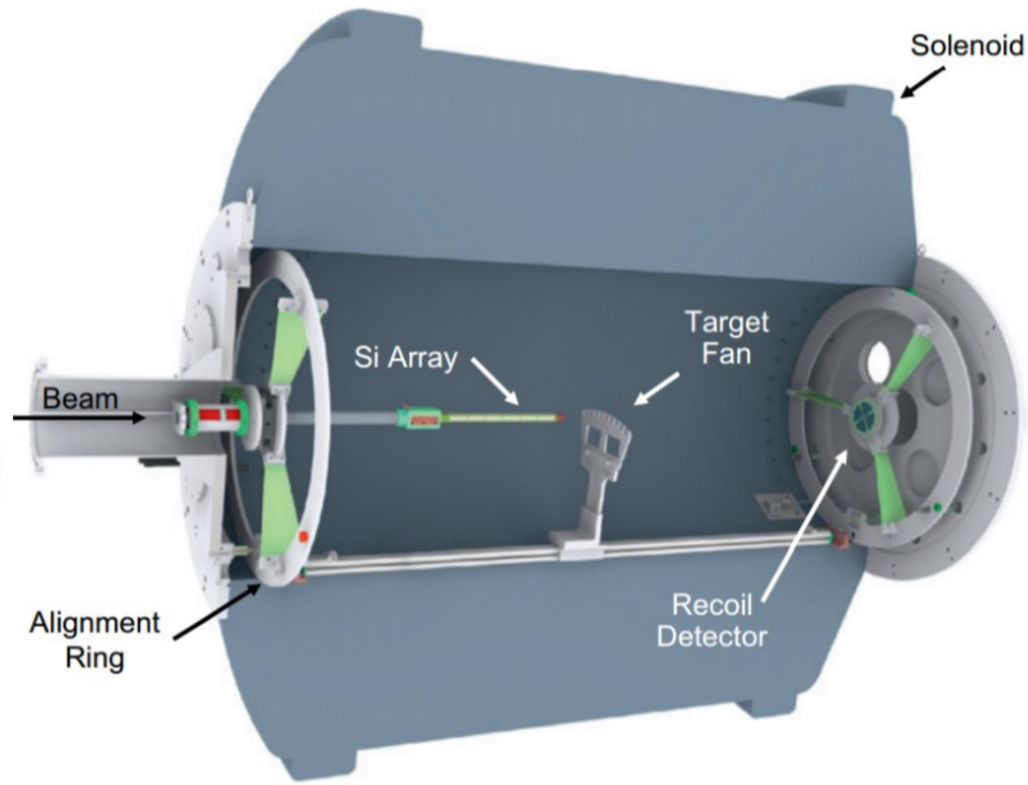
Solenoids - Helios

- After a single orbit, they return to the solenoid axis where they can be detected

$$z = v_{ll} T_{cyc}$$





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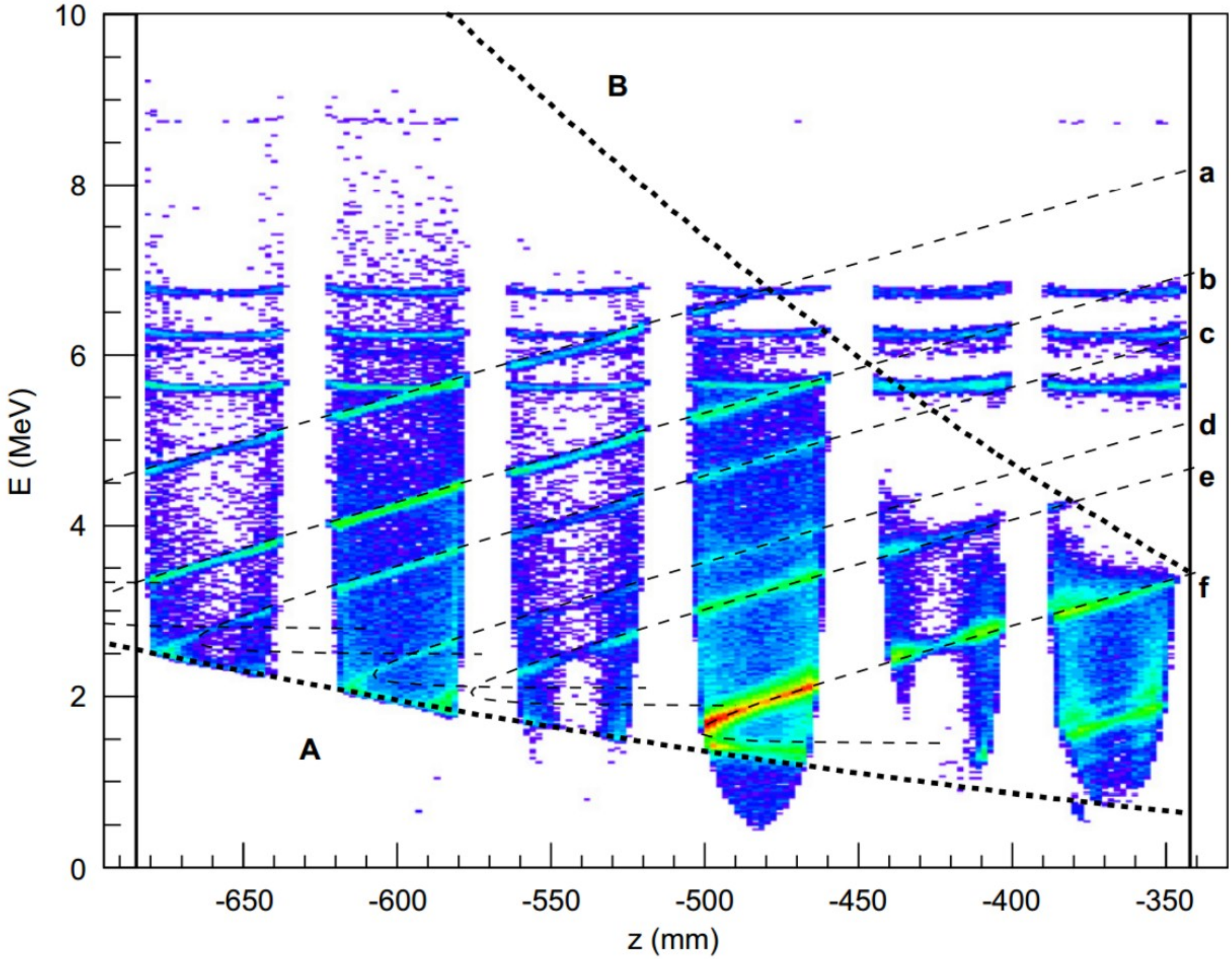
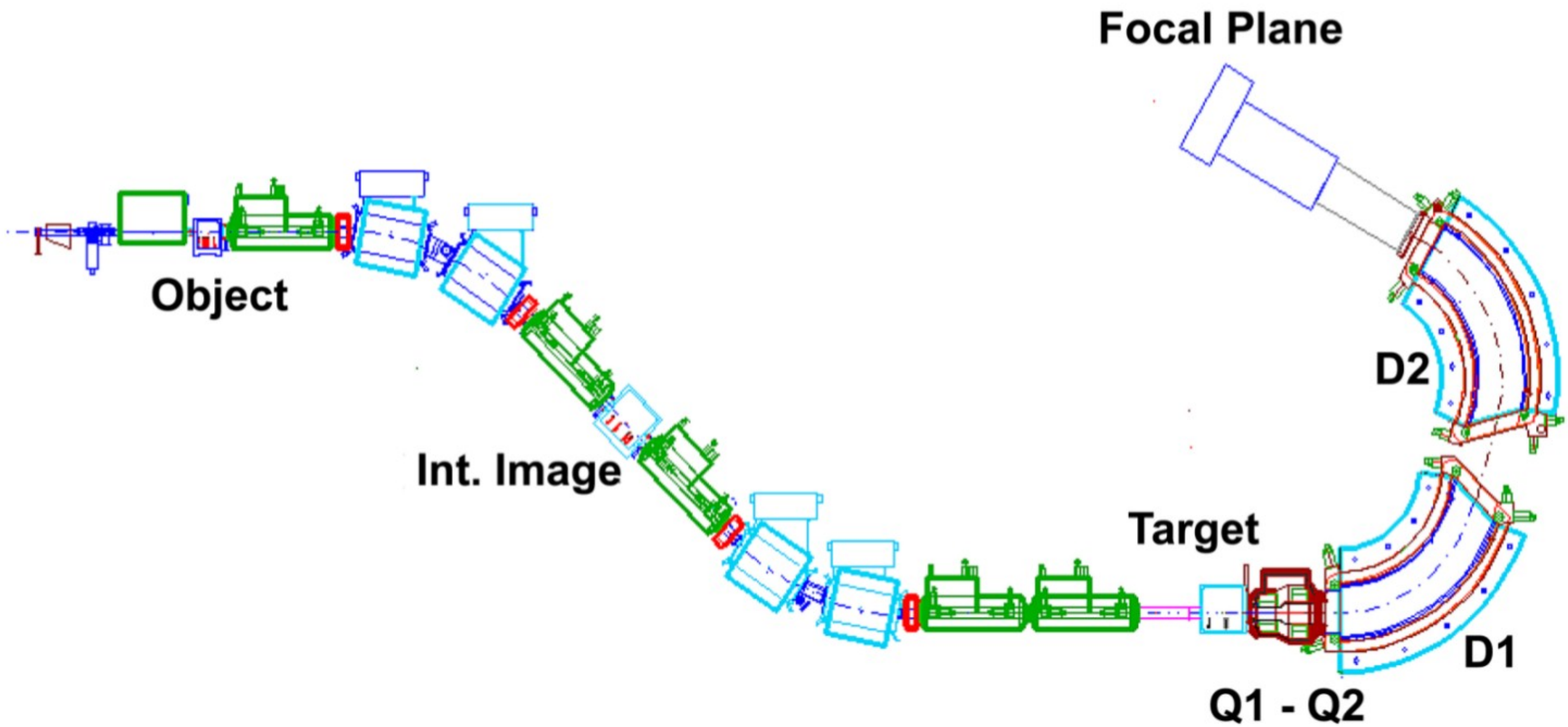
HELIOS

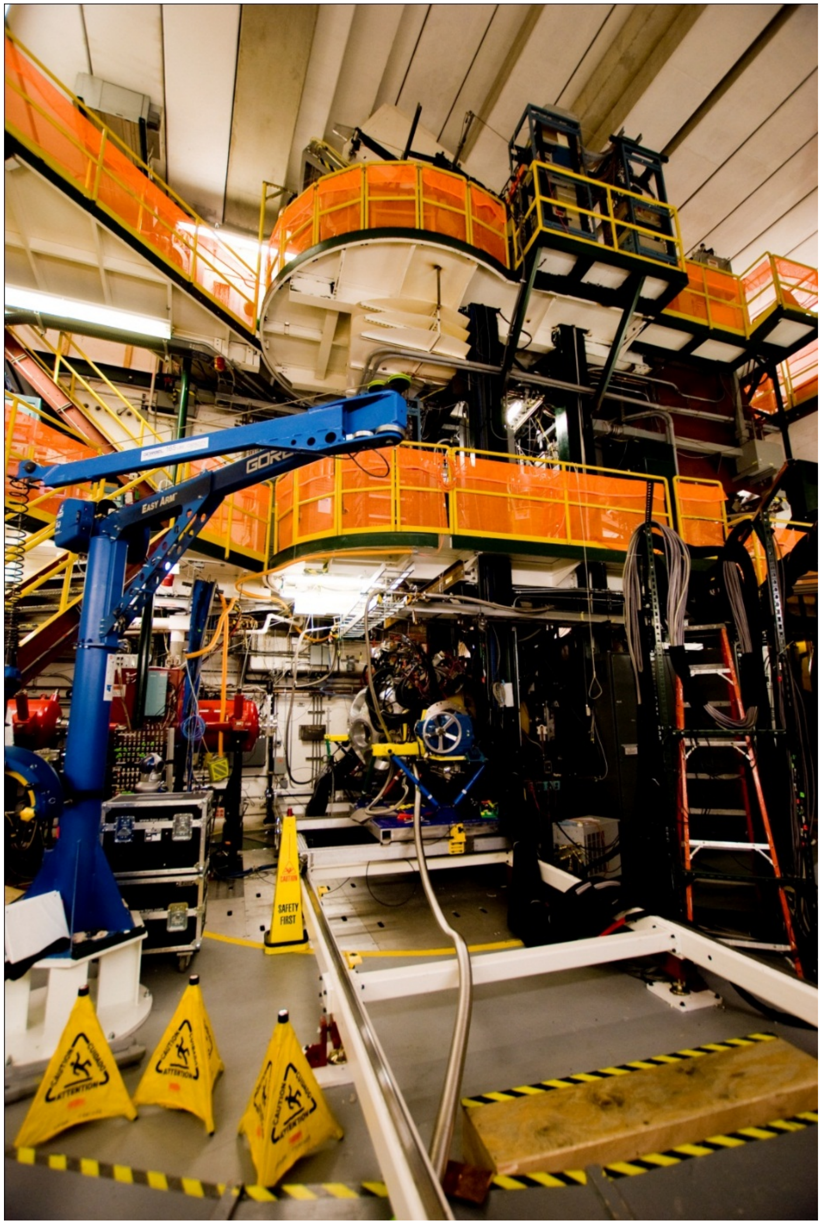


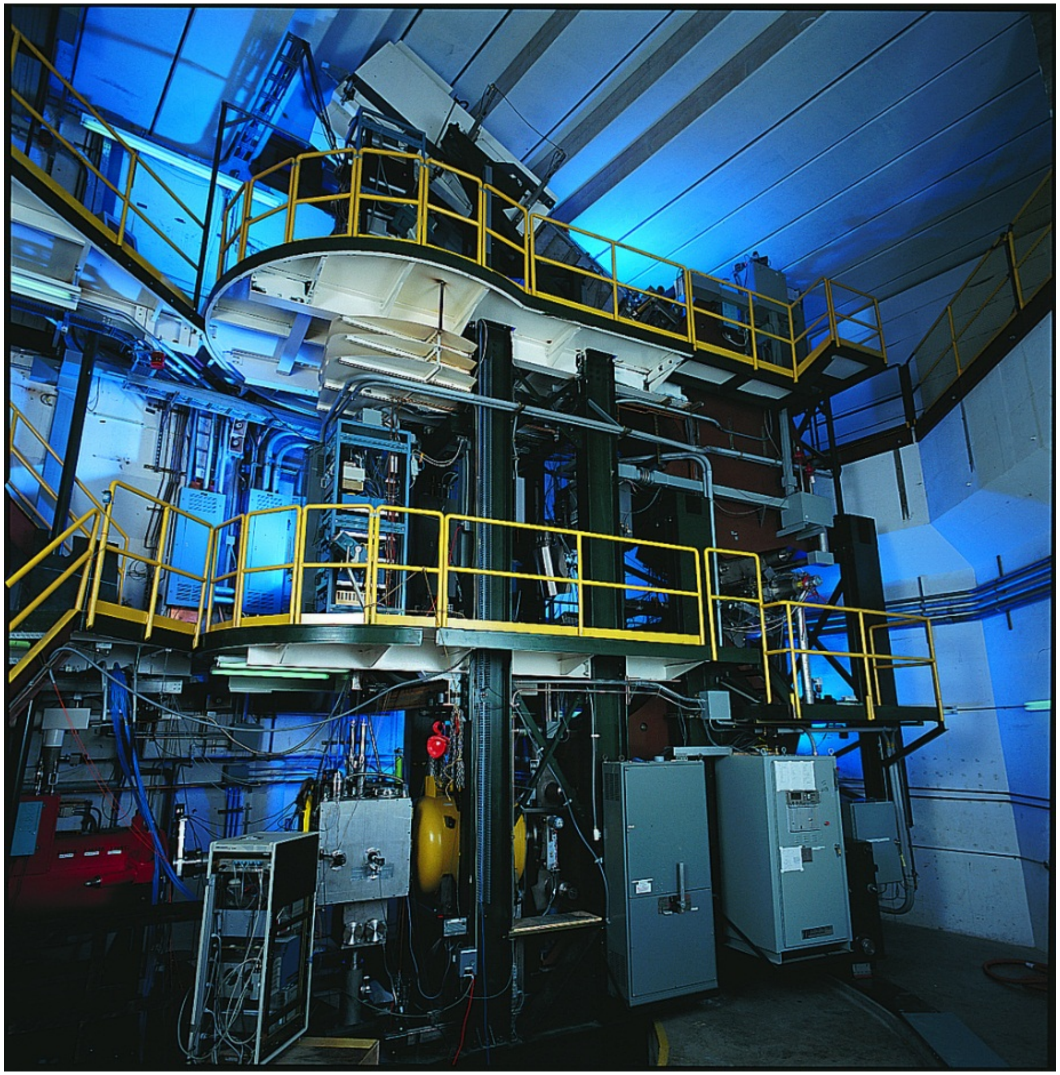
S800

- National Superconducting Cyclotron Laboratory



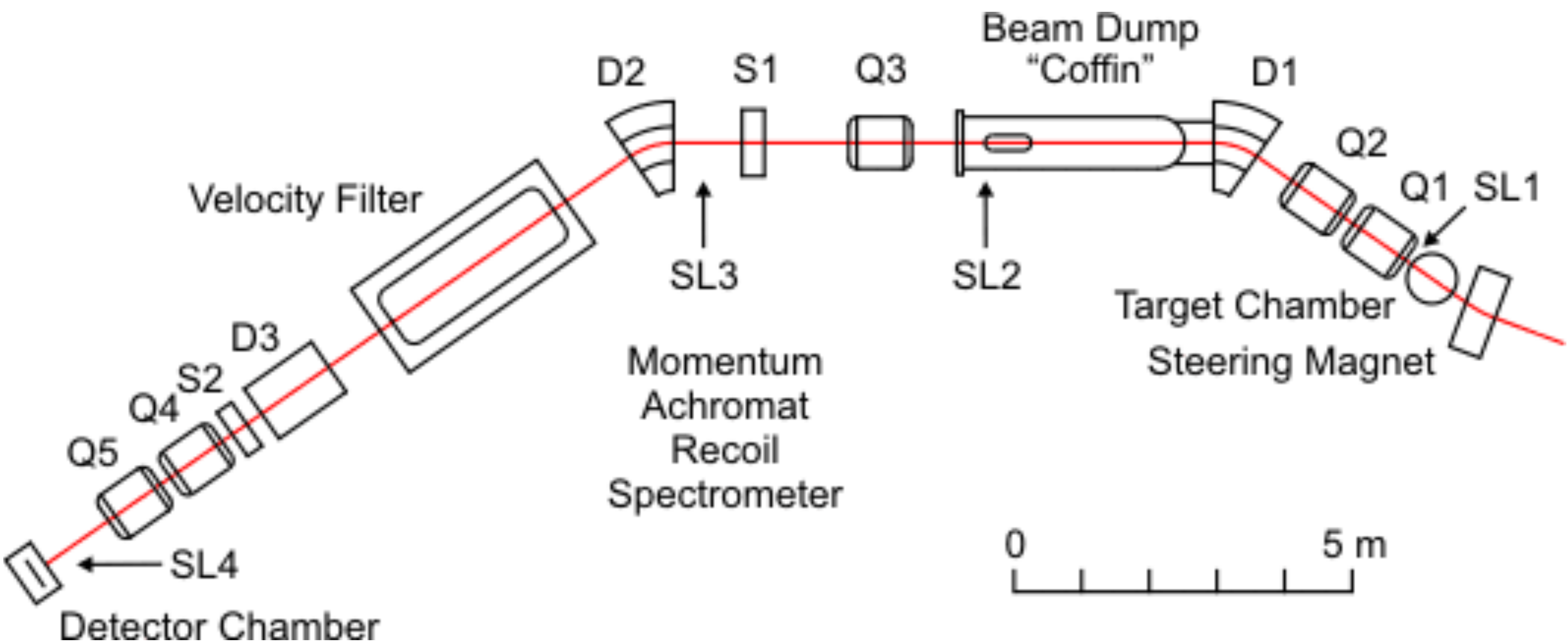
S800





MARS – Projectile Fragment Separator

- Used to produce and separate exotic nuclei via inverse kinematics for radioactive beams or nuclear decay studies



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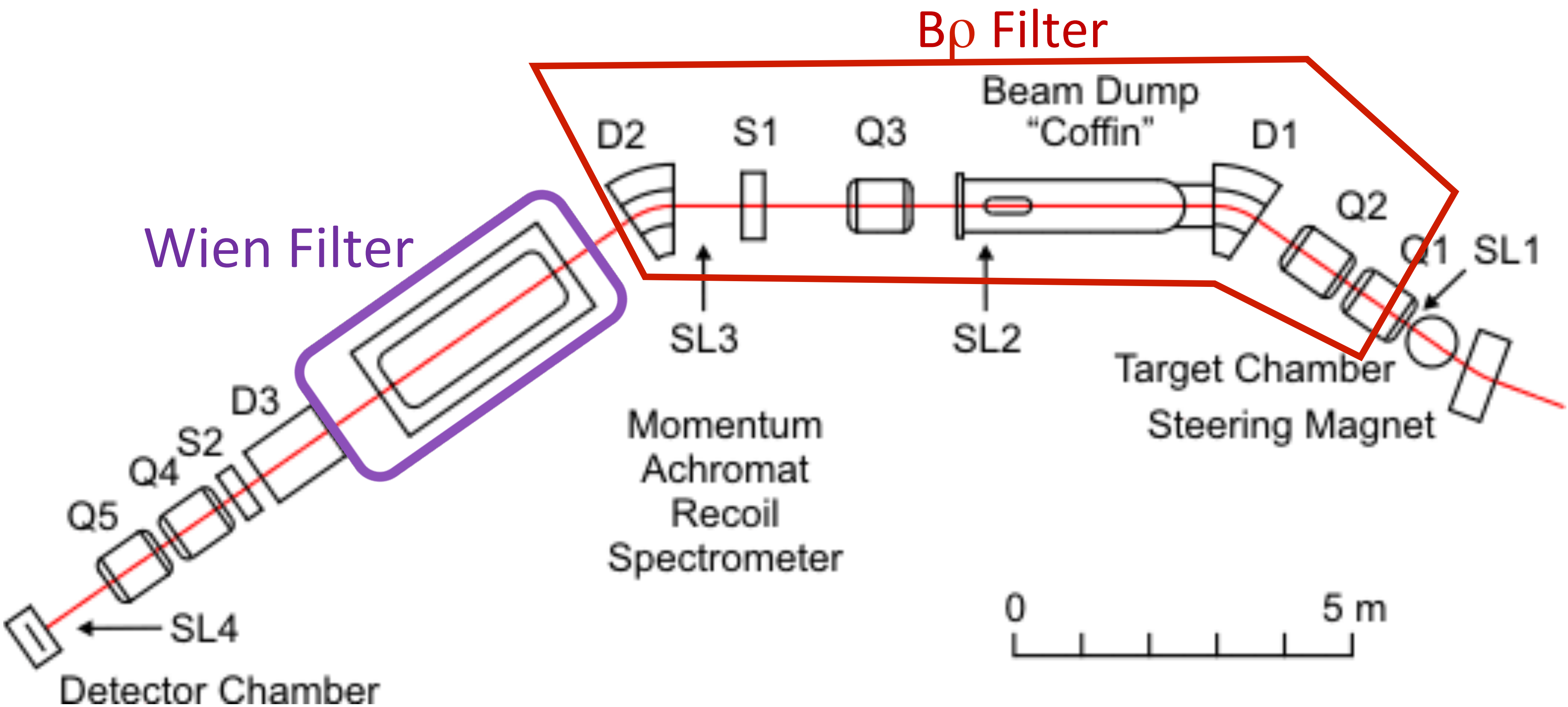
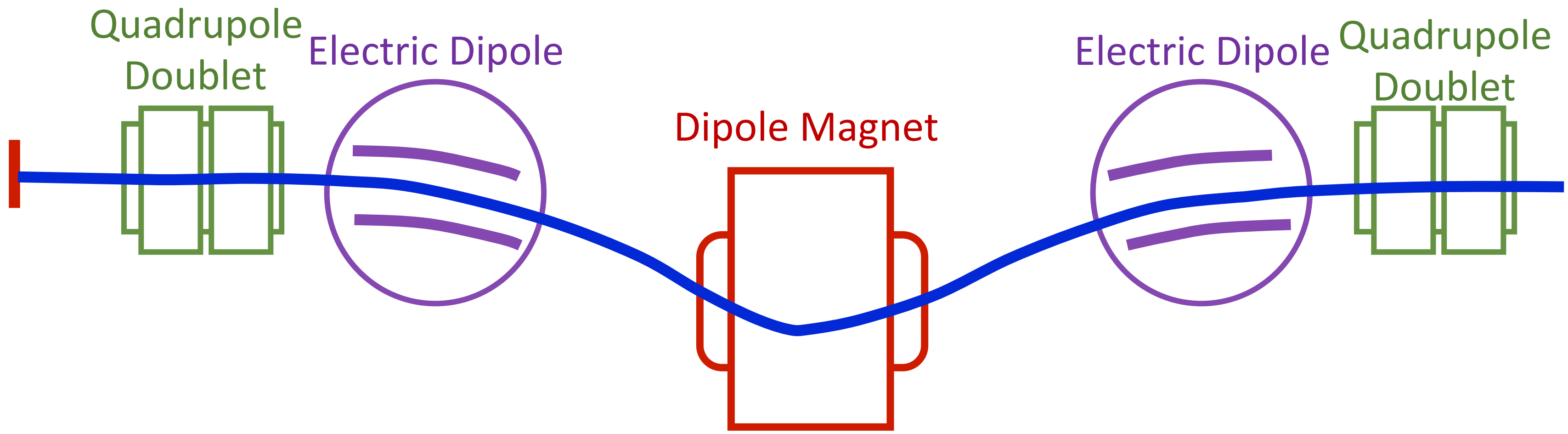


FMA – Fragment Mass Analyzer

- High mass resolution
- Good background suppression
- Efficiency limited by angular acceptance



FMA – Fragment Mass Analyzer

Conclusion

- Magnetic separators are useful for a variety of purposes
- Separation is based on m/q or mv/q
- Nearly endless configurations
- Most rely on series of dipoles for separation and quadrupoles for focusing
- Magnetic separators will become more important with FRIB and the next generation radioactive beam facility

Thanks For Your Attention

B E R K E L E Y , C A L I F O R N I A