Development of toroidal bending magnets for Hadron Beam Therapy

L. Bromberg, P. Michael, J.V. Minervini
MIT
E. Pearson, E. Forton
IBA

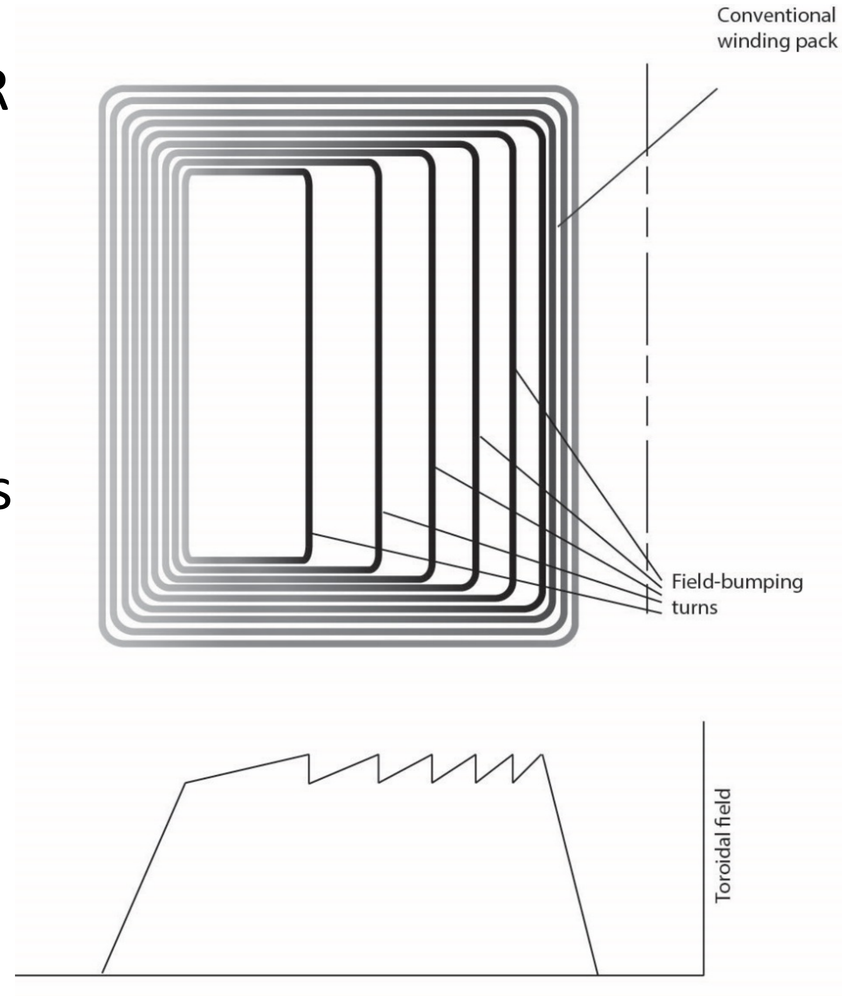
Introduction

- Toroidal magnets
  - Array of identical coils, revolved around central axis
  - Self-contained magnetic field topology that does not require additional magnetic shielding
  - Can generate high fields for beam bending, with negligible magnetic field away from the toroid
  - The toroidal geometry is structurally efficient (low weight)
- To our knowledge, toroidal magnets have not been considered for HBT, although they have been used for
  - KEK spectrometer (proton synchrotron; pions, 100-300 MeV/c)
  - CEBAF CLAS spectrometer
  - JINR STORS
  - LHC ATLAS (barrel torus and end-cap torus)

The innovation:

Constant field toroidal bending magnet

- Toroidal magnets typically have 1/R field dependence
  - Beam defocuses in the non-uniform magnetic field
- Proposed solution:
  1. Distribute current inside the torus to improve field homogeneity
  2. Beam entrance/exit at either inner or outer leg of magnets
     - Strong SYMMETRY



Control of radial field distribution

- It is possible to shape the radial field profile in a torus by controlling its current distribution

$$B(r) = 1/r \,\mathrm{int}(\mu_0\, J(r)\, r\, dr)$$

Assuming $J(r) \sim 1/r$, $B(r)$ = constant in r

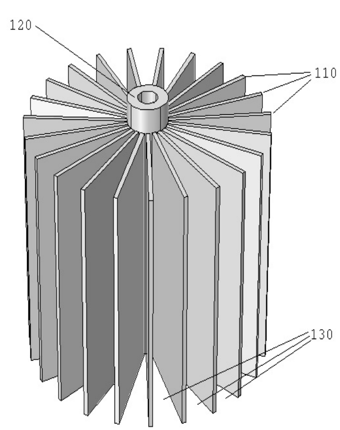
If using constant thickness radial plates, J constant in plate

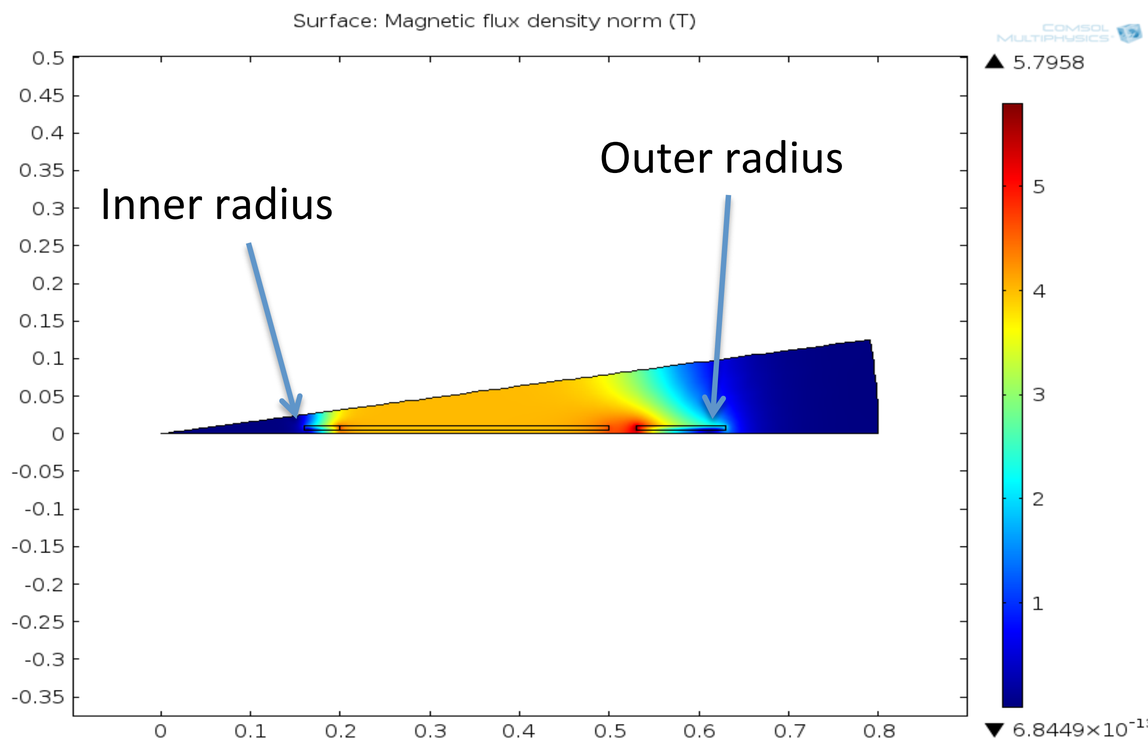
Result easily achieved using

conductor-in-plate toroidal geometry

Worked example

- Assume 20 plates (double pancakes per plate), producing 4 T, using NbTi, at 4 K
- Use symmetry across radial boundaries to simplify calculation
  (i.e., simulating only 9 degrees, symmetric about both boundaries)
- Good shielding properties



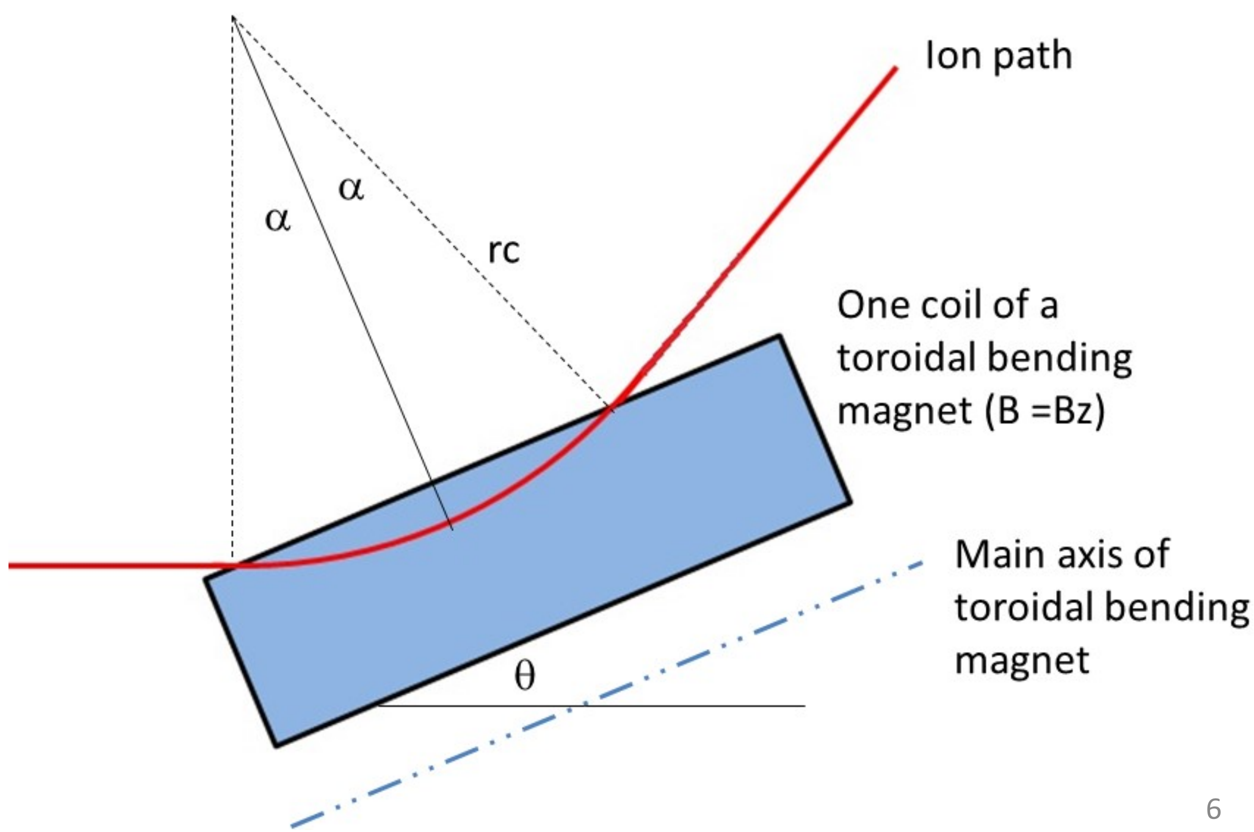


Nominal beam trajectory

$2\, rc \sin\alpha \sin\theta = rc\,(1 - \cos 2\alpha)$

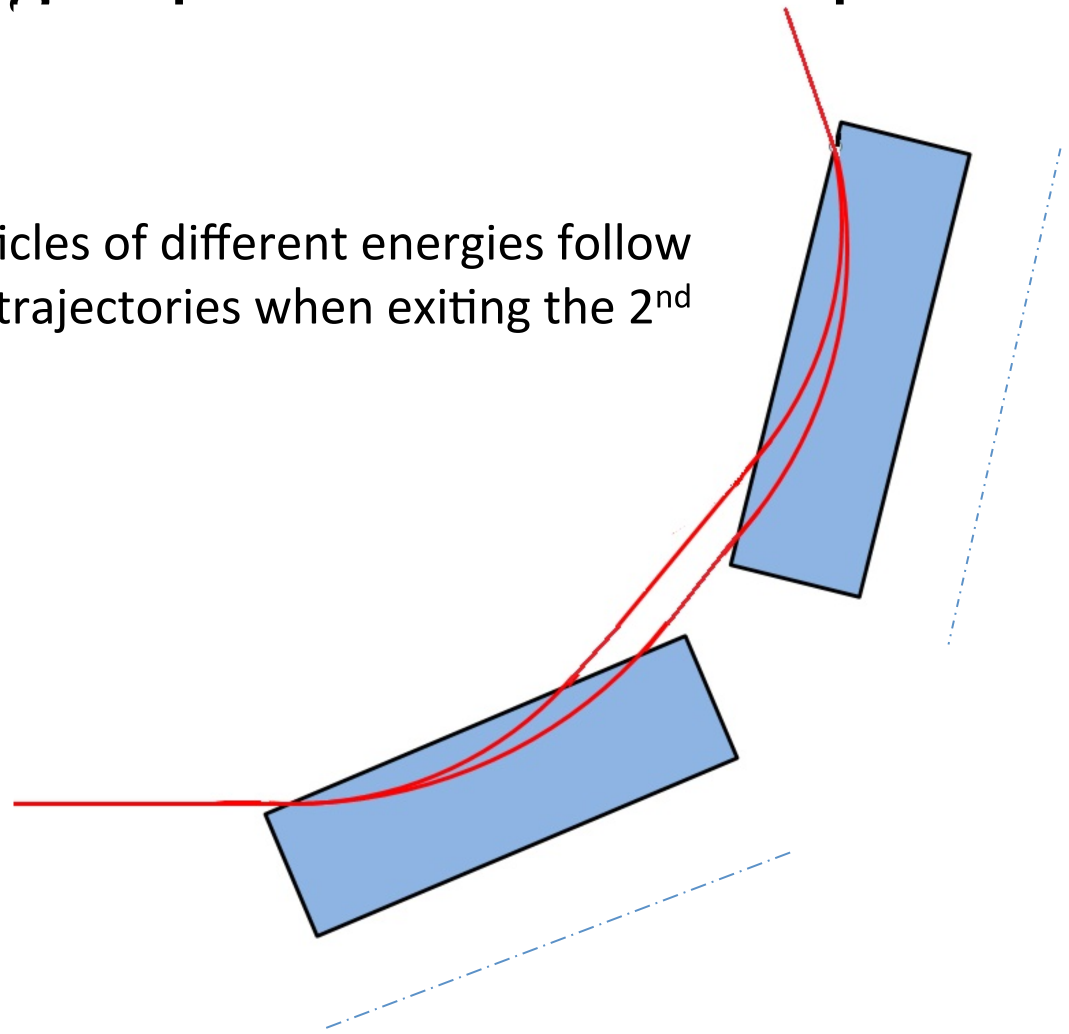
The angle of departure is independent of rc!!!

At fixed field, particles of different energies leave at different locations but parallel to each other!

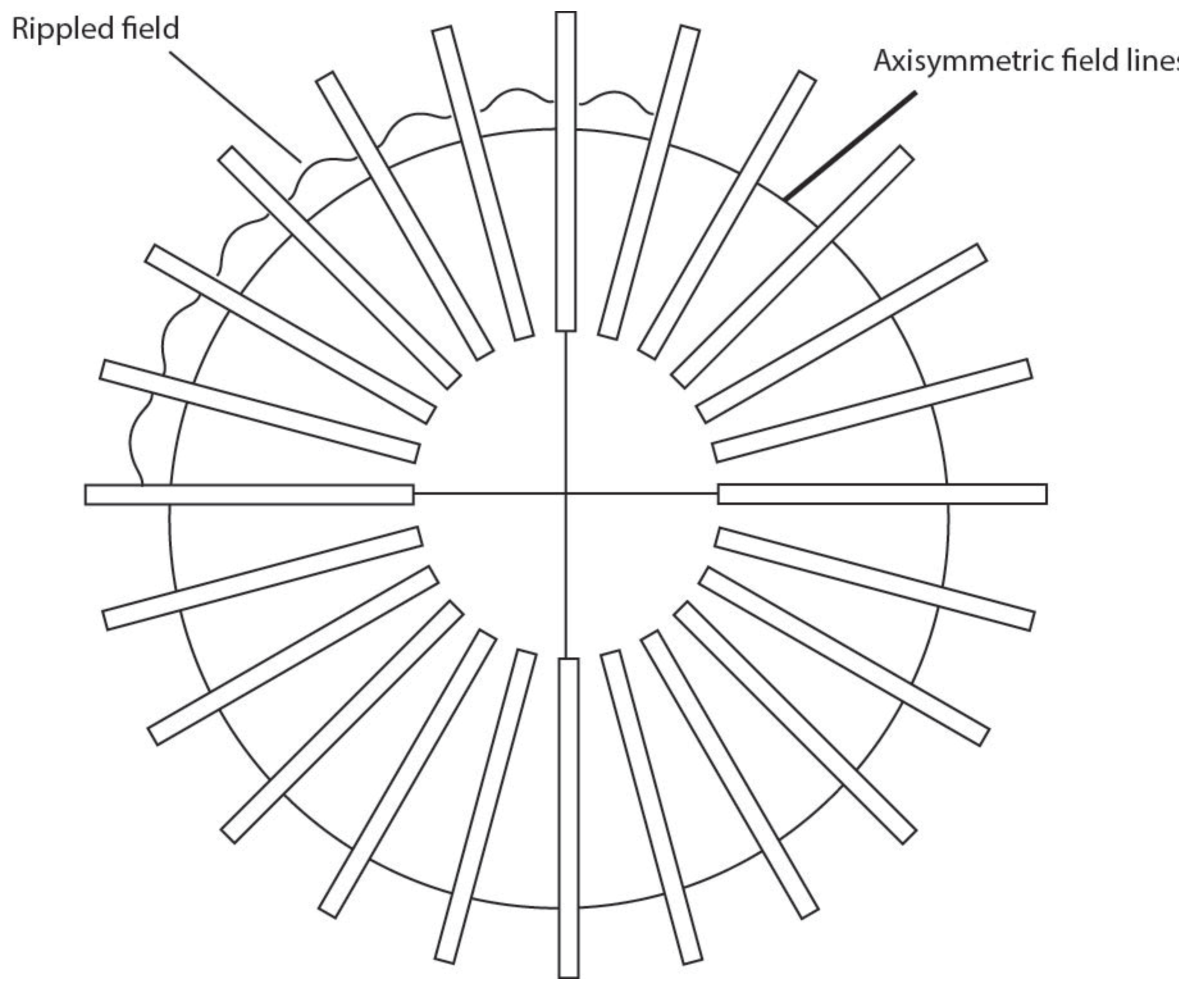


Achromatic bending at fixed field with 2 balanced toroidal magnets large aperture and acceptance

At fixed field, particles of different energies follow identical in-plane trajectories when exiting the 2nd toroid

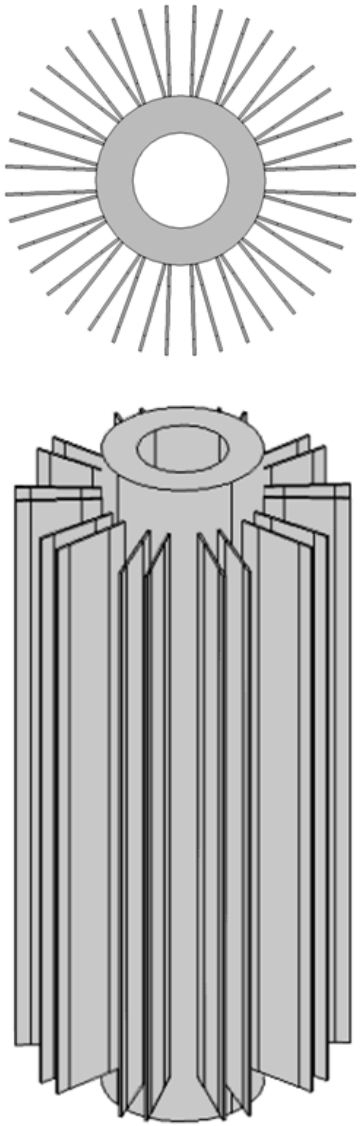


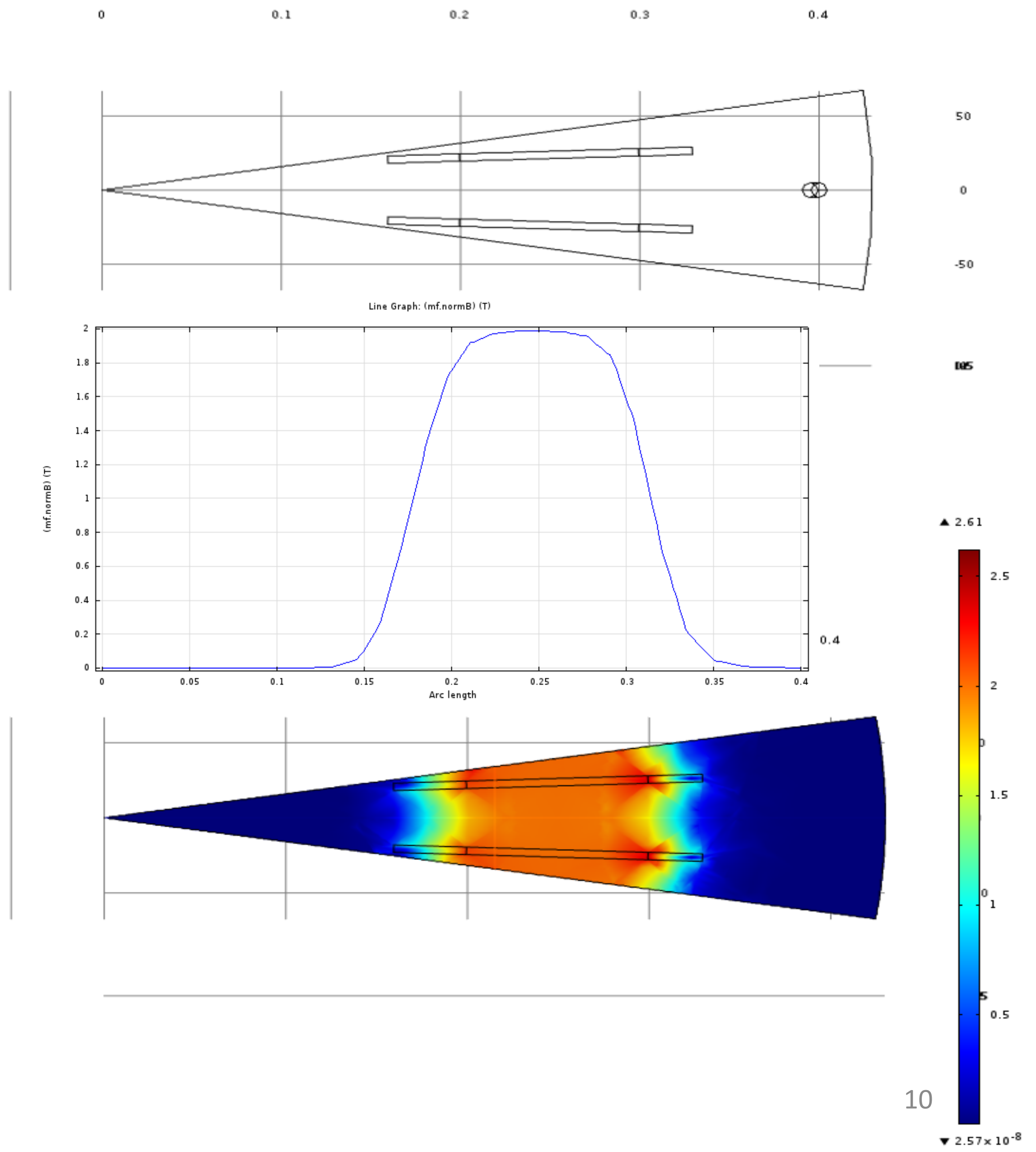
Azimuthally defocusing ripple (for outward deflecting beam)



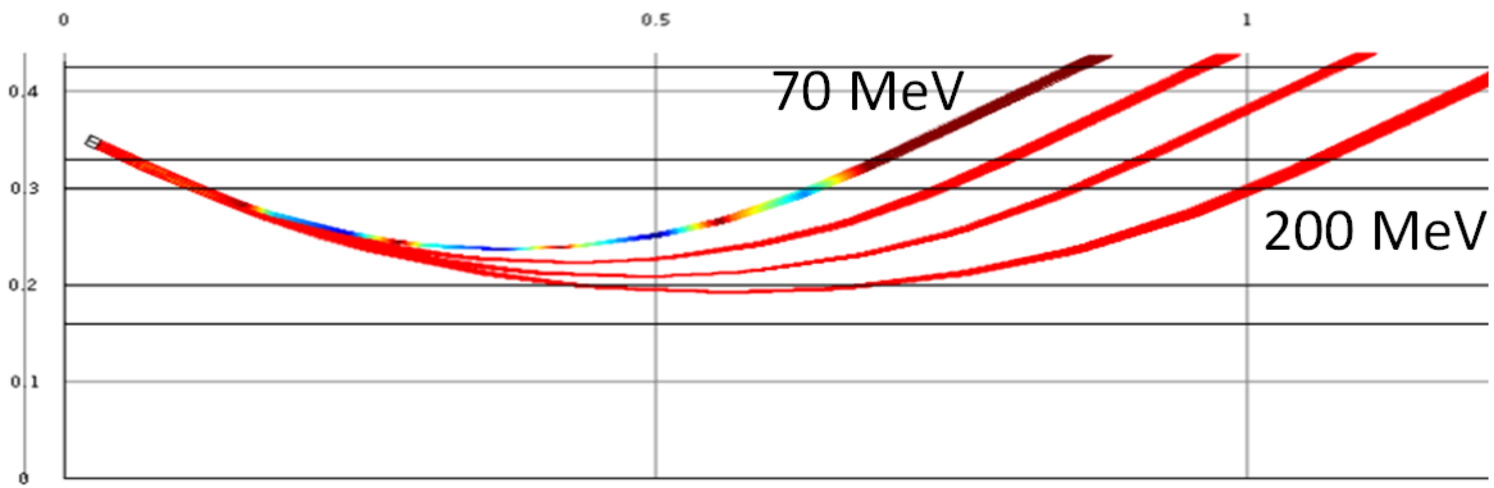
Beam calculations

Toroidal magnet, with azimuthally distributed pairs of parallel plates



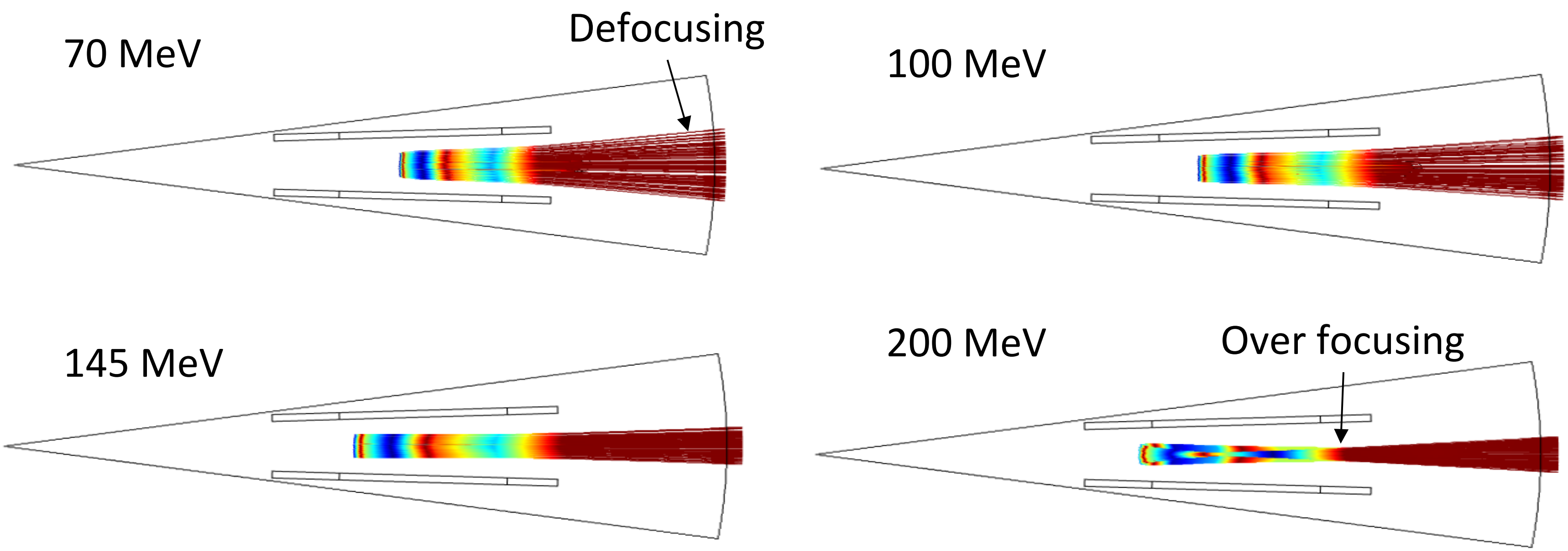


Beam trajectories in r-z plane at fixed field for various proton energies



Beam trajectories projected on r-θ plane at various proton energies

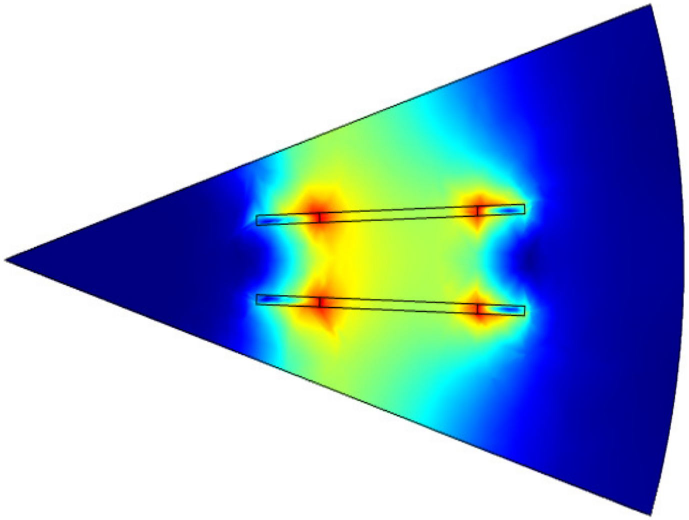
Potential for "COMBINED FUNCTION"



Beam can be either focused or defocused in transverse direction depending on beam energy and magnetic field

Optimal combination of field and energy minimizes beam divergence

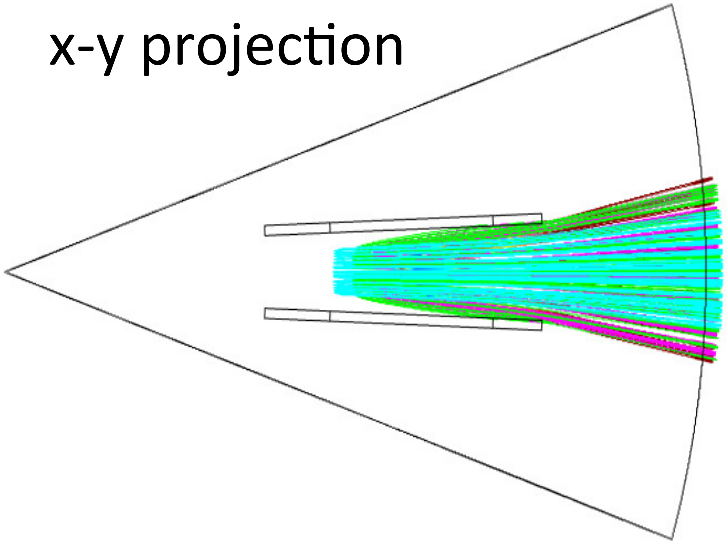
WHAT IF CONVENTIONAL TOROIDAL MAGNETS WERE USED?



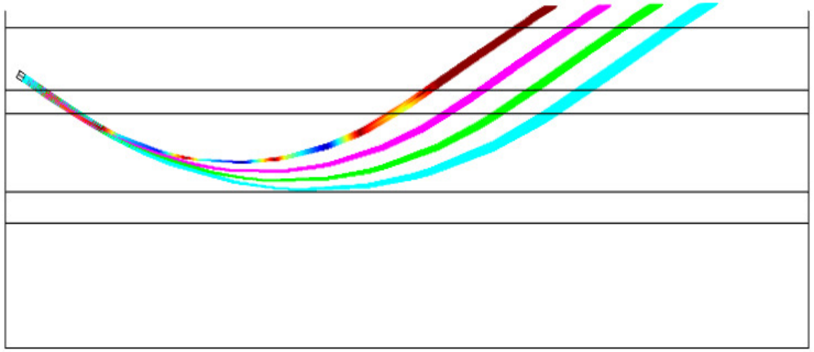
Beam trajectories at various proton energies
With 1/r field

Beam diverges strongly; may be addressable by focusing

x-y projection

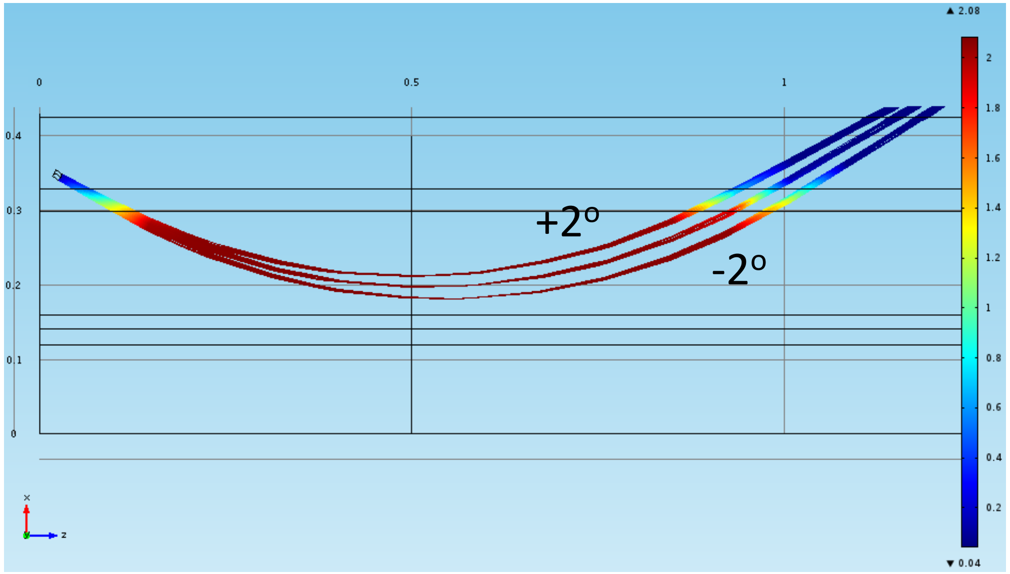


x-z projection



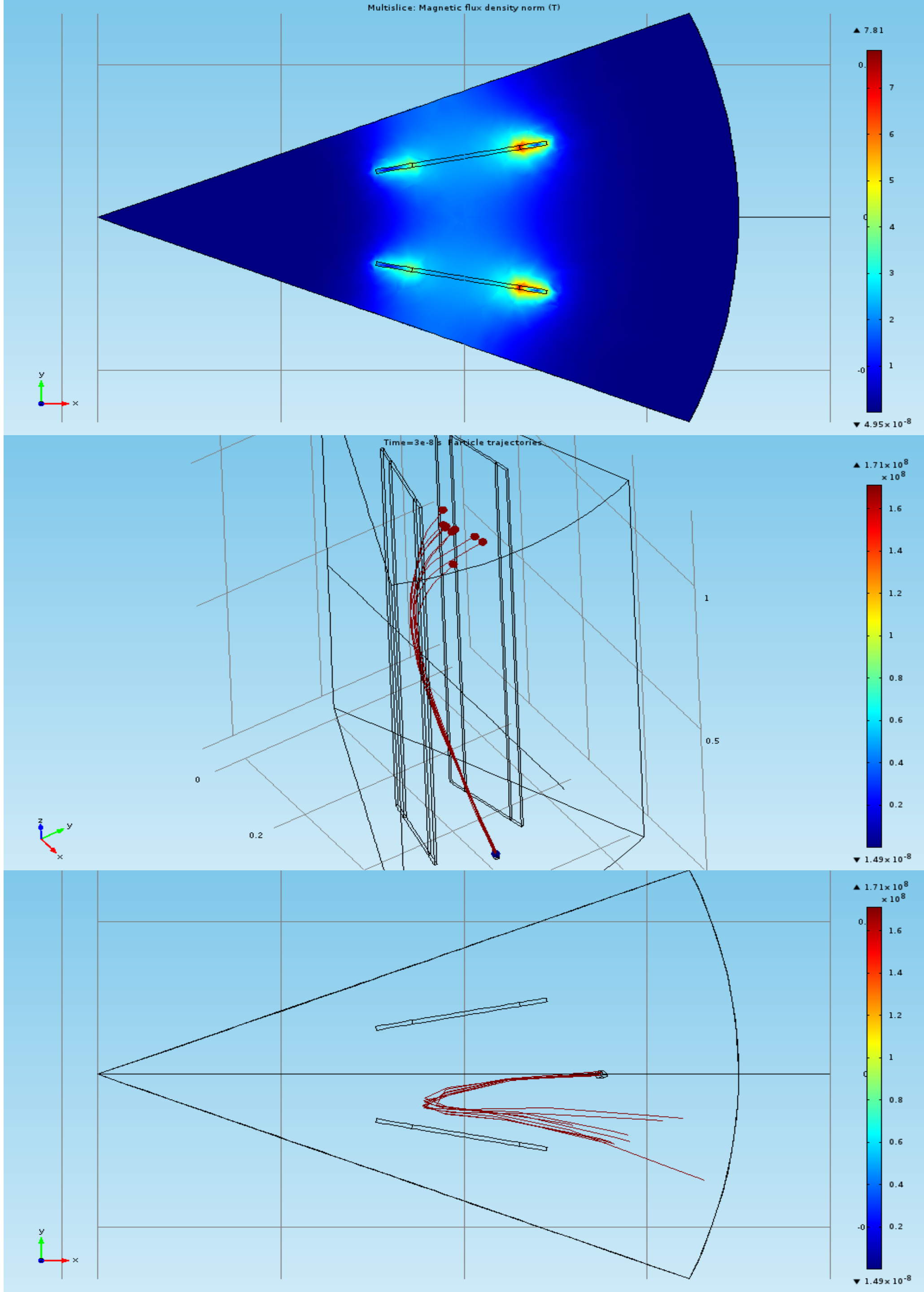
Pencil beam scanning

- Scanning in the axial direction
  - Easy to scan (large aperture)
  - However, needs further optimization to achieve required range at gantry isocenter



Normal to axis Scanning

- Goal is 20 cm in the normal direction
- Need larger gap between plates
  - Increases field inhomogeneity
  - Challenging beam optics



Magnets

Constant field toroidal magnet

- Toroidal magnet details
  - Conductor
    - 93.6 kg, total conductor mass
    - NbTi, 4.2 K, 3 T, Jc ~ 3000-4000 A/mm^2 , 60% Ic operation
  - Structure
    - 40 plates, 1m tall by 0.2m~0.35m radial plate
    - ~40 kg minimum (2mm thick, 0.2m i.d. 0.35m o.d, 1m tall plates)
    - ~40 kg for 2.5cm thick, 0.2m o.d. 1m tall bucking cylinder
    - ~20 kg for tension links between the winding plates
- Stored magnetic energy ~ 500 kJ

Constant Toroidal field magnet

- NbTi magnet
- Cryocooled
- Plate structure
- Compared with equivalent iron-shielded magnet
  - ~ 3-4 times more conductor
  - ~ 3-4 times more energy
  - 1/5 of the electrical power

Magnet characteristics

outer radius	m	0.7
length	m	1
average field	T	2
peak field	T	3
Stored magnetic energy	kJ	400
magnet current	A	400
Current sharing temperature	K	6.2
Max gap at outer region	m	0.1

Magnet weight

Conductor	kg	90
Structure	kg	100
Cryostat	kg	165
Cryocooler head	kg	50
Total weight	kg	~500

Cryostat

- Single vacuum for magnet and cryostat
- Charged beam through beam pipe
  - Radiation shield
    - cylinder with 1/16” copper at o.d. and bottom, with ¼” copper plate at upper end for cold head, current lead, gravity support, functions
    - 73 cm i.d. 103 cm inside length
    - ~60 kg total radiation shield mass
  - Vacuum can has wall thickness similar to test vessel at MIT
    - 2 cm gaps on cylindrical sides and bottom from radiation shield to vacuum can (for rough size)
    - 10 cm gap between top plate of vac. Vessel and radiation shield (for leads, cold head stem)
    - 165 kg, based on simple scaling from existing vessel at MIT

Near term development

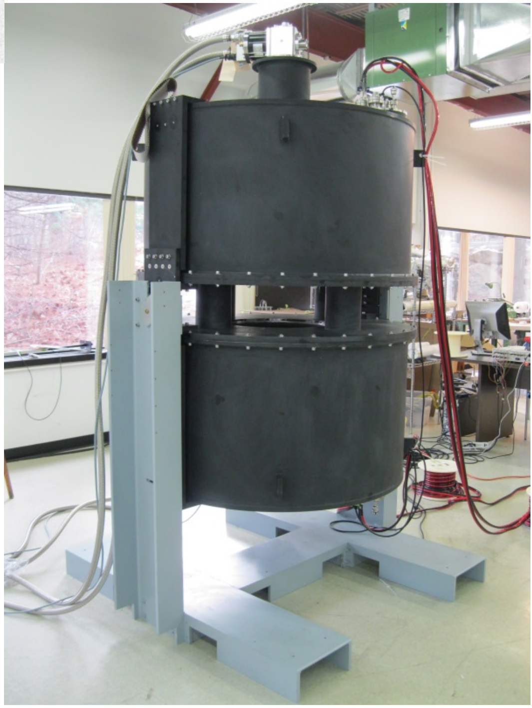
- Working with Superconducting Systems Inc (SSI) and IBA to evaluate the concept
  - Optimize, design, build and test bending magnet
- NIH-funded 18 month program starting mid-September 2015 incorporating Smart Superconducting Magnet™ technology into toroidal bending magnet design

Superconducting Systems, Inc.

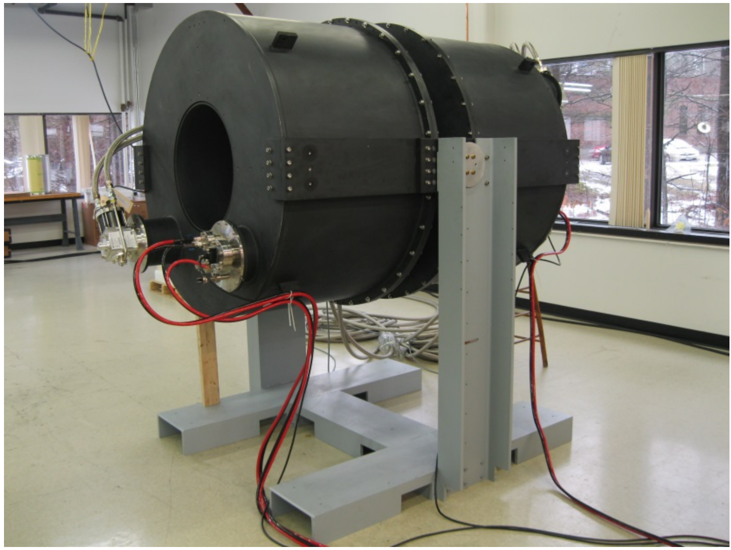
Home of Smart Superconducting Magnets

Rotating magnets technology

- SSI/MIT have built dry, light, high field SC magnets, rotatable, with fast transients
  - "dusty plasma" experiments, for Auburn University
  - Cooling at 30 K for power saving during stand-by operation



Dusty plasma magnet, 2 ton

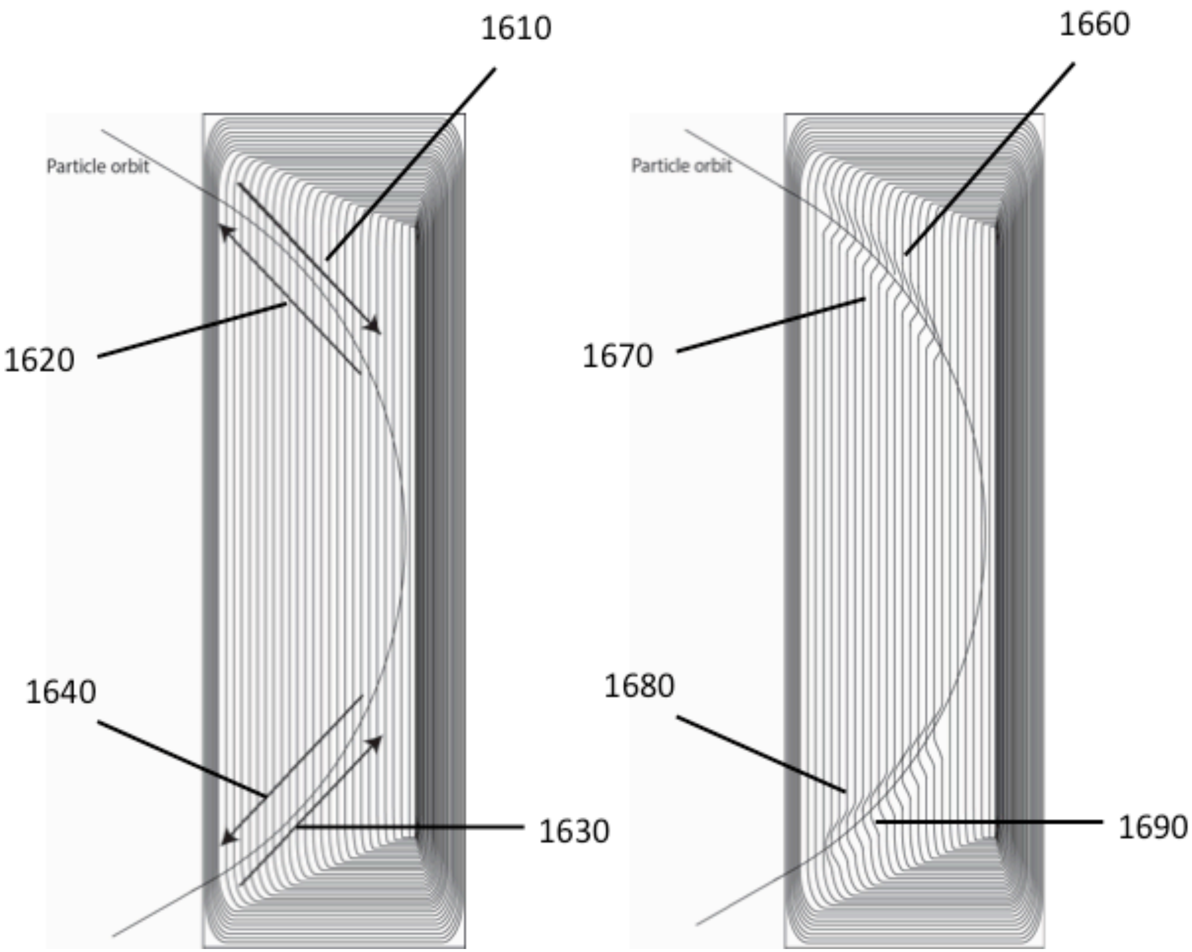


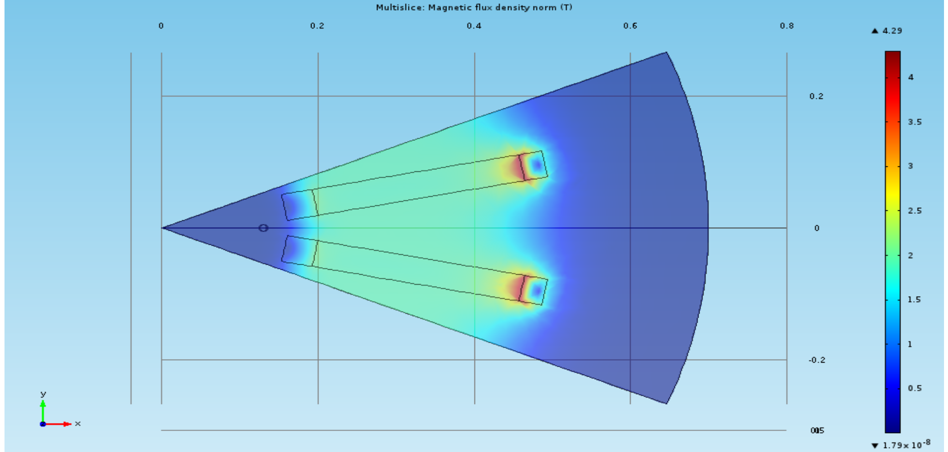
Constant field Toroidal bending magnet Summary

- Advantages
  - Self-shielded, light weight
  - Simple, effective structure
  - High symmetry properties: potential for achromatic magnet with large aperture in 1 direction and high momentum acceptance
  - Good prospects for conduction-cooled, dry magnet
- Disadvantages
  - Increased conductor and stored energy vs iron system
- Challenges
  - Field homogeneity/beam optics
  - Scanning normal to main axis
    - second direction scanning maybe downstream?

Additional slides

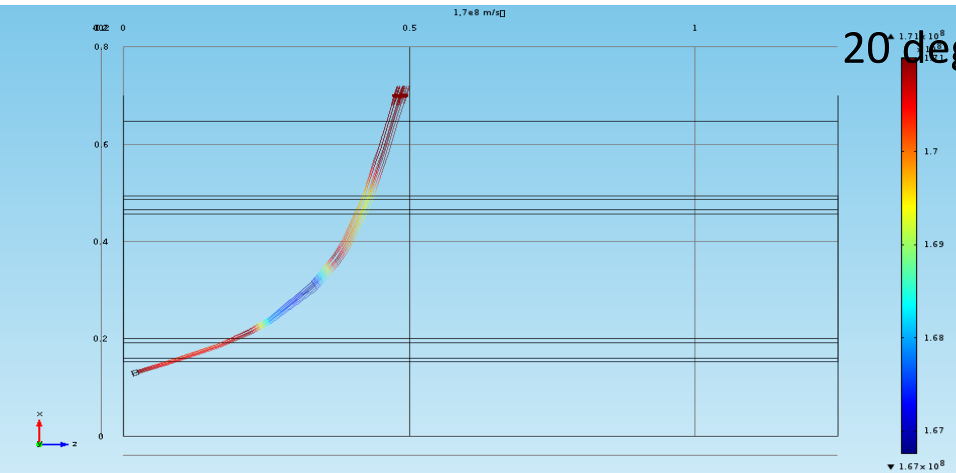
Combined function constant toroidal field magnet

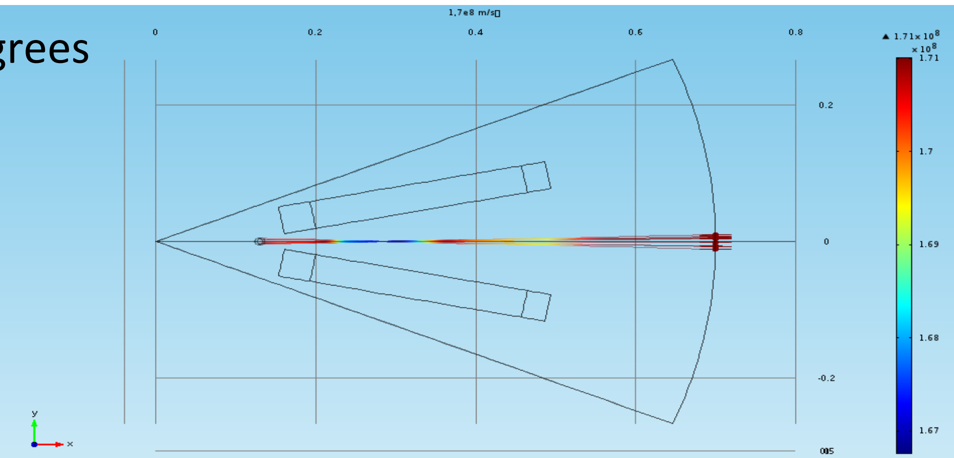




Injection in the inner bore
2 T nominal

20 degrees





30 degrees