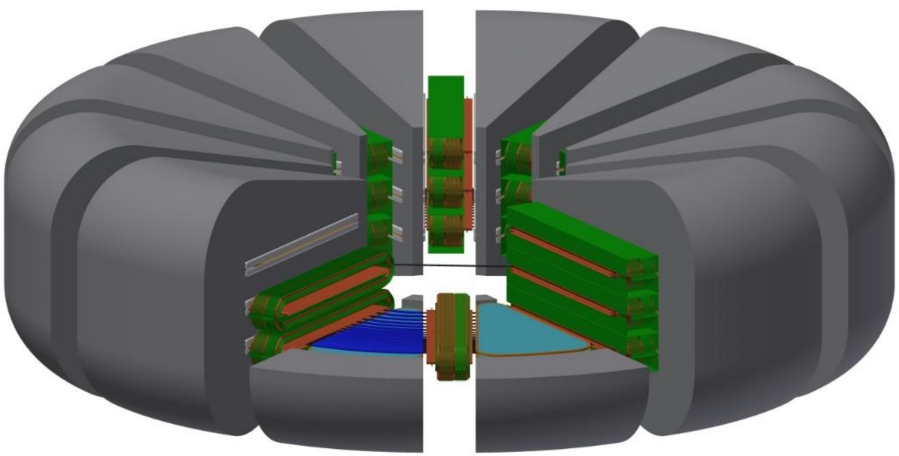
Department of Physics and Astronomy, Texas A&M University

Superconducting Beam Transport Channel for a Strong-Focusing Cyclotron

J. Kellams, S. Assadi, K.C. Damborsky, P. McIntyre, K. Melconian, N. Pogue, and A. Sattarov



Outline

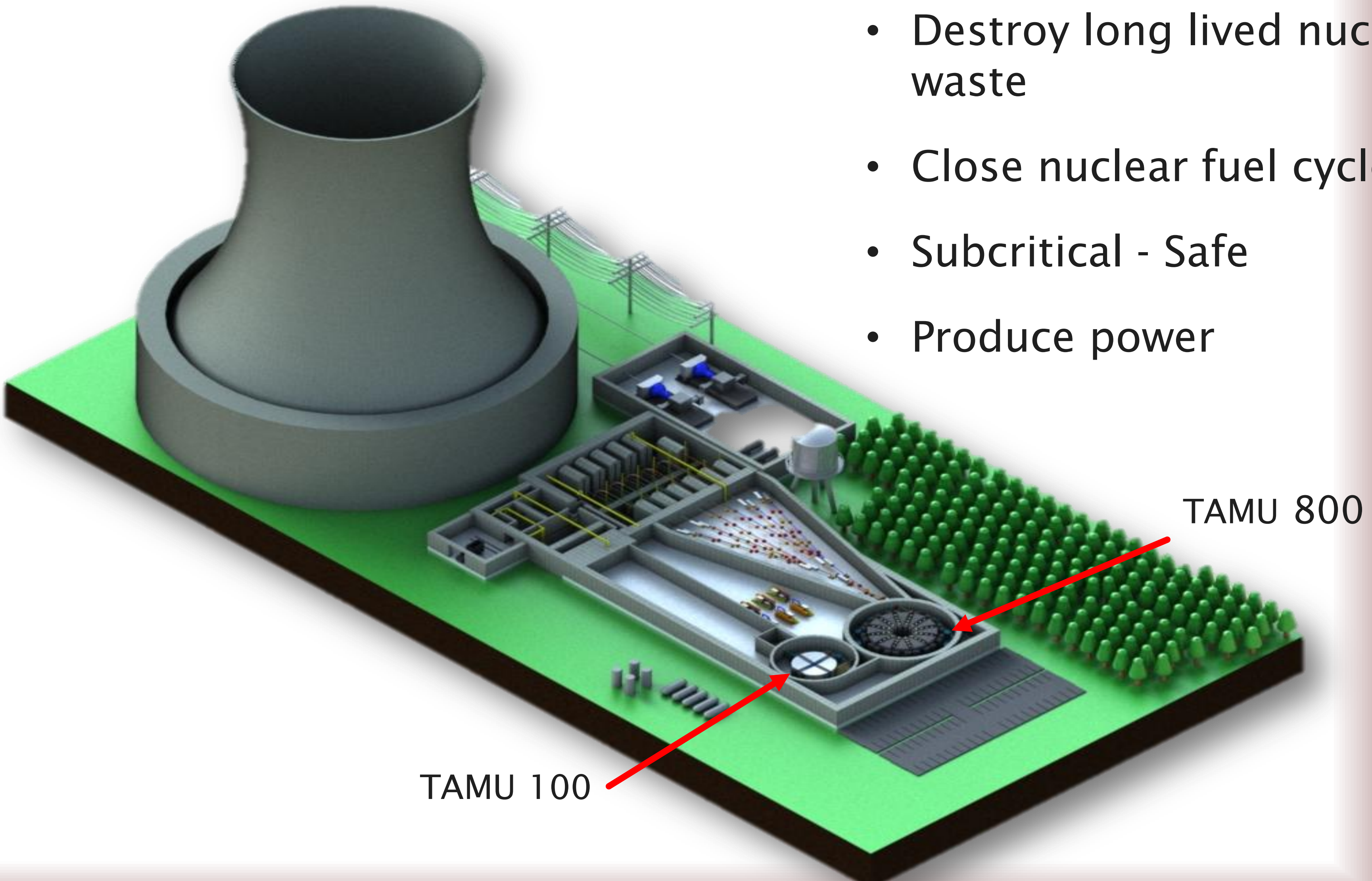
- Motivation
  - Proton driver for Accelerator-Driven Subcritical Fission
  - What limits beam current in cyclotrons
- Superconducting RF Cavity
  - Fully separate all orbits
- Beam Transport Channel
  - Control betatron tunes throughout acceleration
  - Magnetic design
  - Winding prototype
- Sector Dipoles
  - Flux-coupled stack
  - Fringe field reduction
- Beam Dynamics
- Future Work

Outline

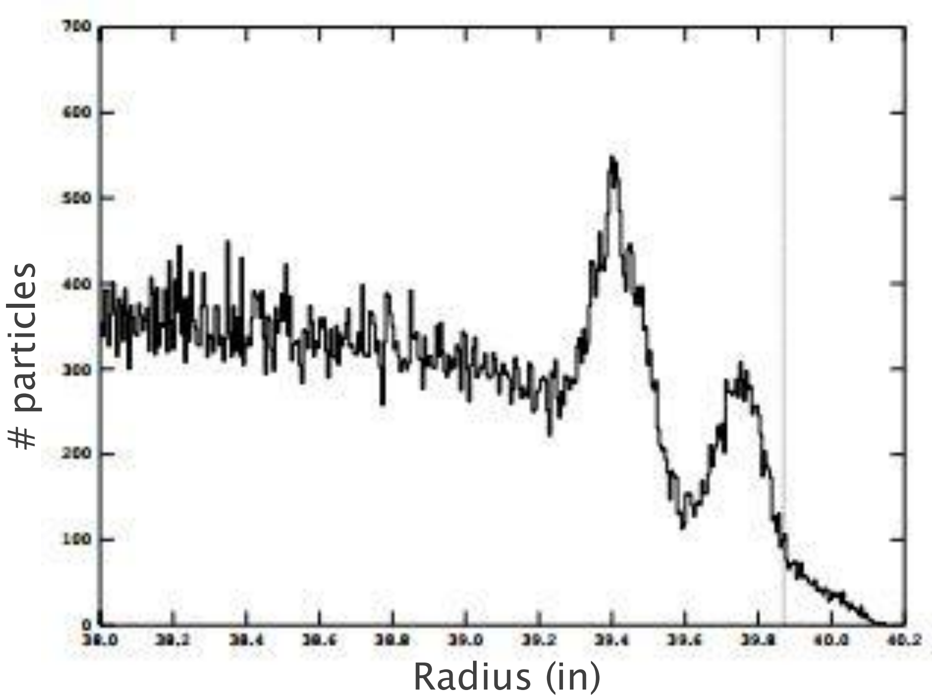
- Motivation
  - Proton driver for Accelerator-Driven Subcritical Fission
  - What limits beam current in cyclotrons
- Superconducting RF Cavity
  - Fully separate all orbits
- Beam Transport Channel
  - Control betatron tunes throughout acceleration
  - Magnetic design
  - Winding prototype
- Sector Dipoles
  - Flux-coupled stack
  - Fringe field reduction
- Beam Dynamics
- Future Work

Accelerator Driven Molten Salt System

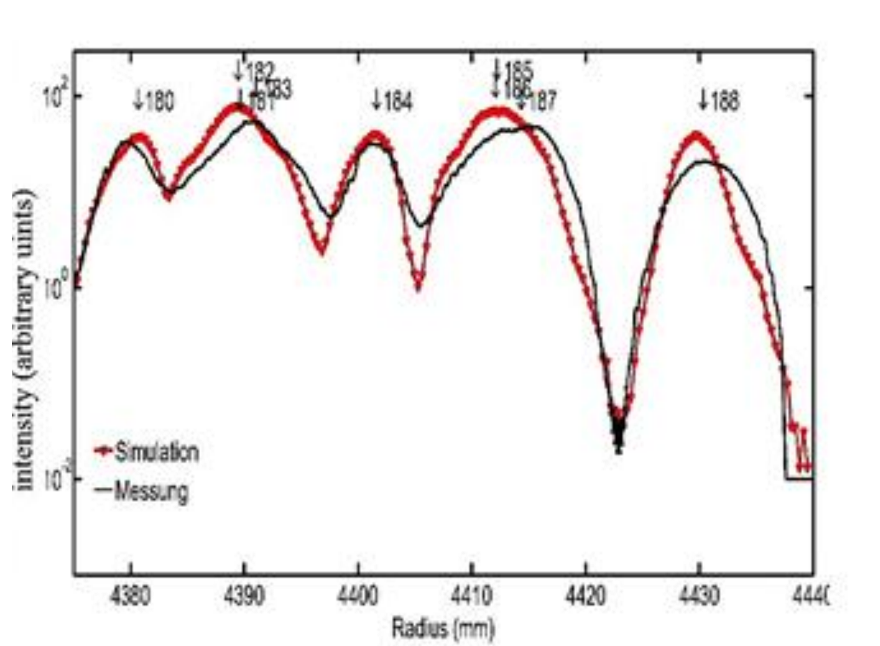
- Destroy long lived nuclear waste
- Close nuclear fuel cycle
- Subcritical - Safe
- Produce power



Current limits in cyclotrons:
1) Overlapping bunches in successive orbits



http://www.nscl.msu.edu/~marti/publications/beamdynamics_ganil_98/beamdynamics_final.pdf



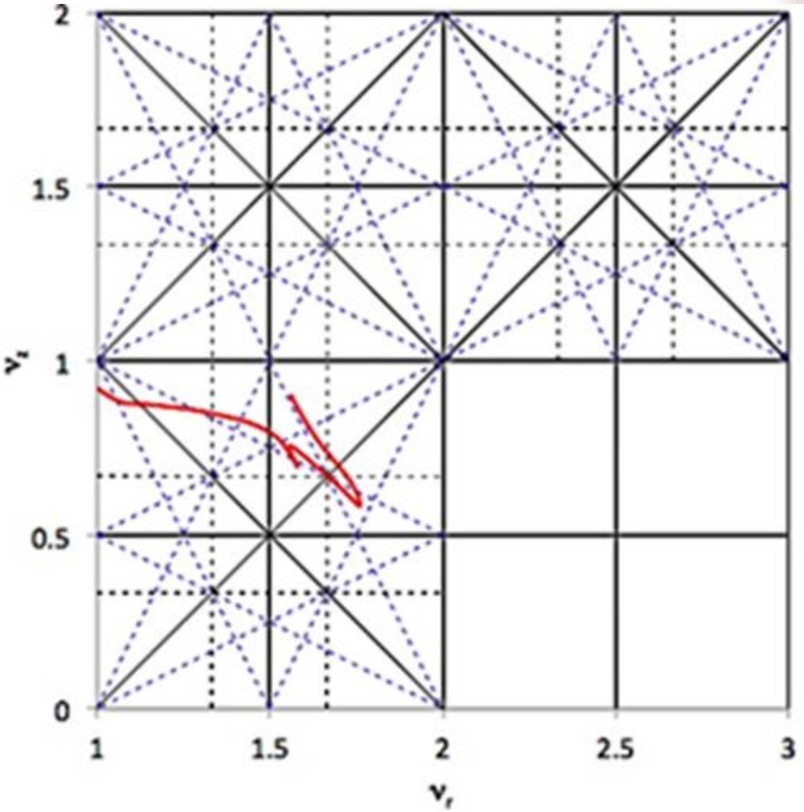
http://cas.web.cern.ch/cas/Bilbao-2011/Lectures/Seidel.pdf

Overlap of N bunches on successive orbits produces N x greater space charge tune shift,.

2) Weak focusing, Resonance crossing

Cyclotrons are intrinsically weak-focusing accelerators

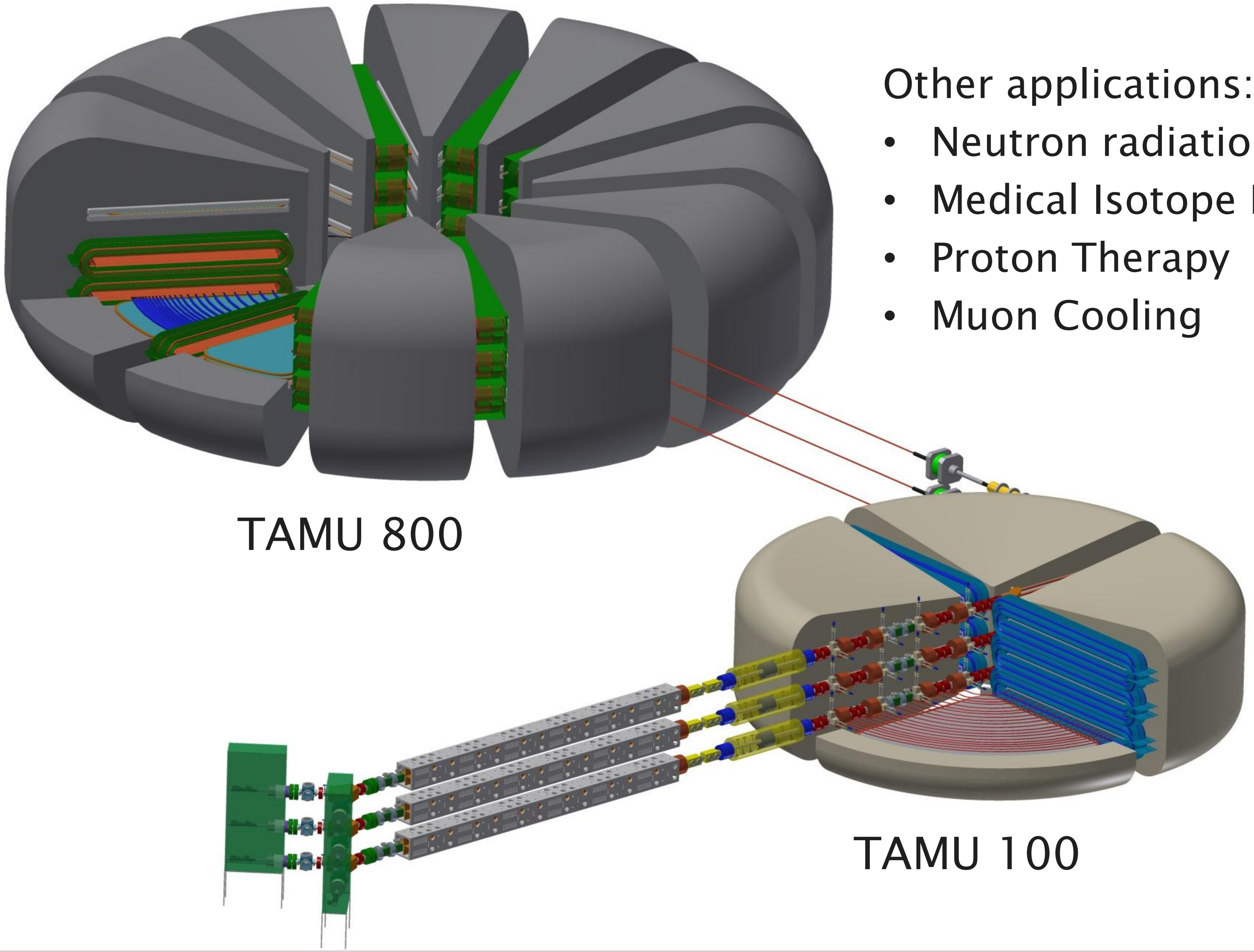
- Rely upon fringe fields
- Low tune requires larger aperture
- Tune evolves during acceleration
- Crosses resonances



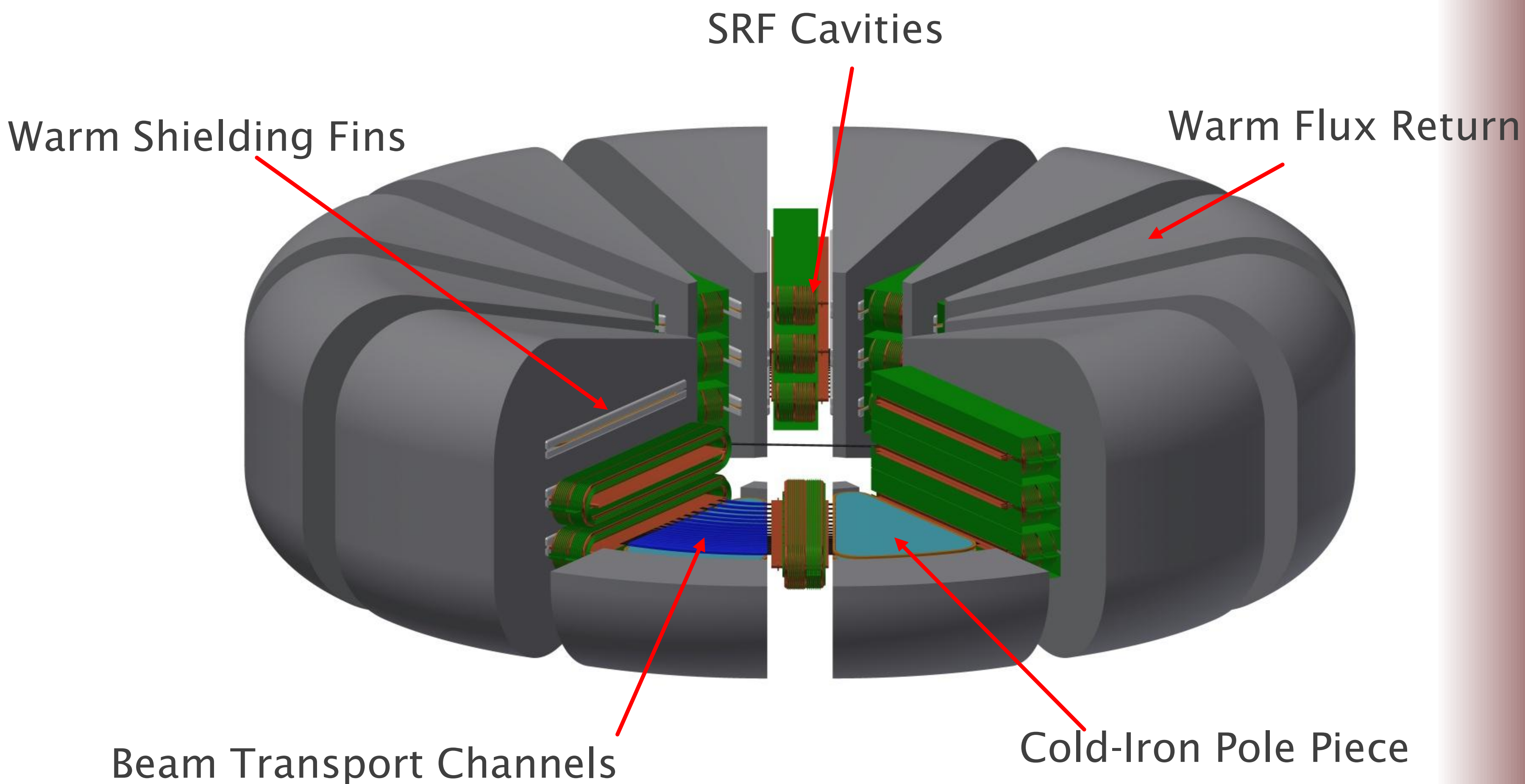
Strong-Focusing Cyclotron

Other applications:

- Neutron radiation damage
- Medical Isotope Production
- Proton Therapy
- Muon Cooling



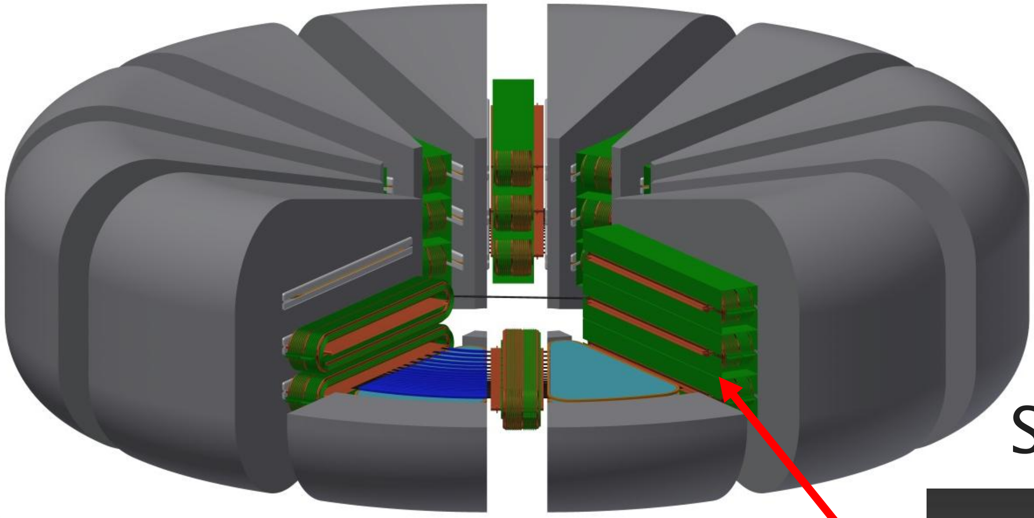
SFC Components



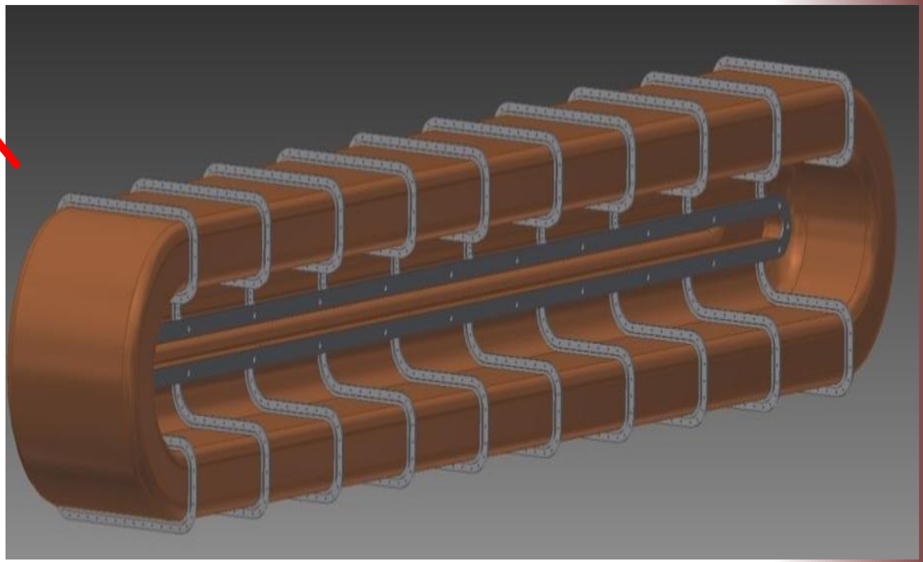
Outline

- Motivation
  - Proton driver for Accelerator-Driven Subcritical Fission
  - What limits beam current in cyclotrons
- Superconducting RF Cavity
  - Fully separate all orbits
- Beam Transport Channel
  - Control betatron tunes throughout acceleration
  - Magnetic design
  - Winding prototype
- Sector Dipoles
  - Flux-coupled stack
  - Fringe field reduction
- Beam Dynamics
- Future Work

Slot-geometry ¼-wave SRF Cavities

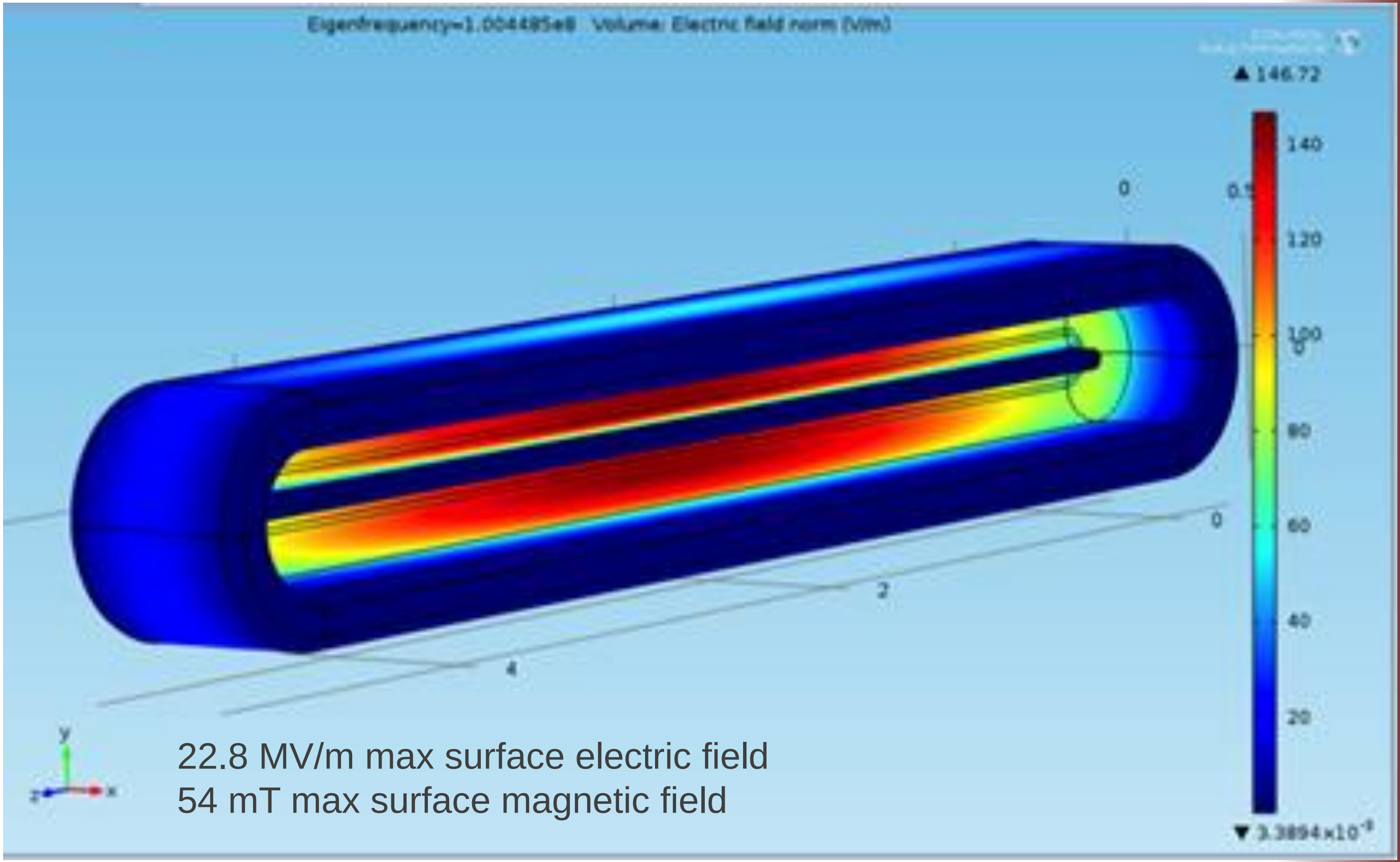


Superconducting RF cavities



- 100 MHz
- 2 MV/cavity energy gain
- 20 MV/turn fully separates orbits

Example SRF Cavity Model

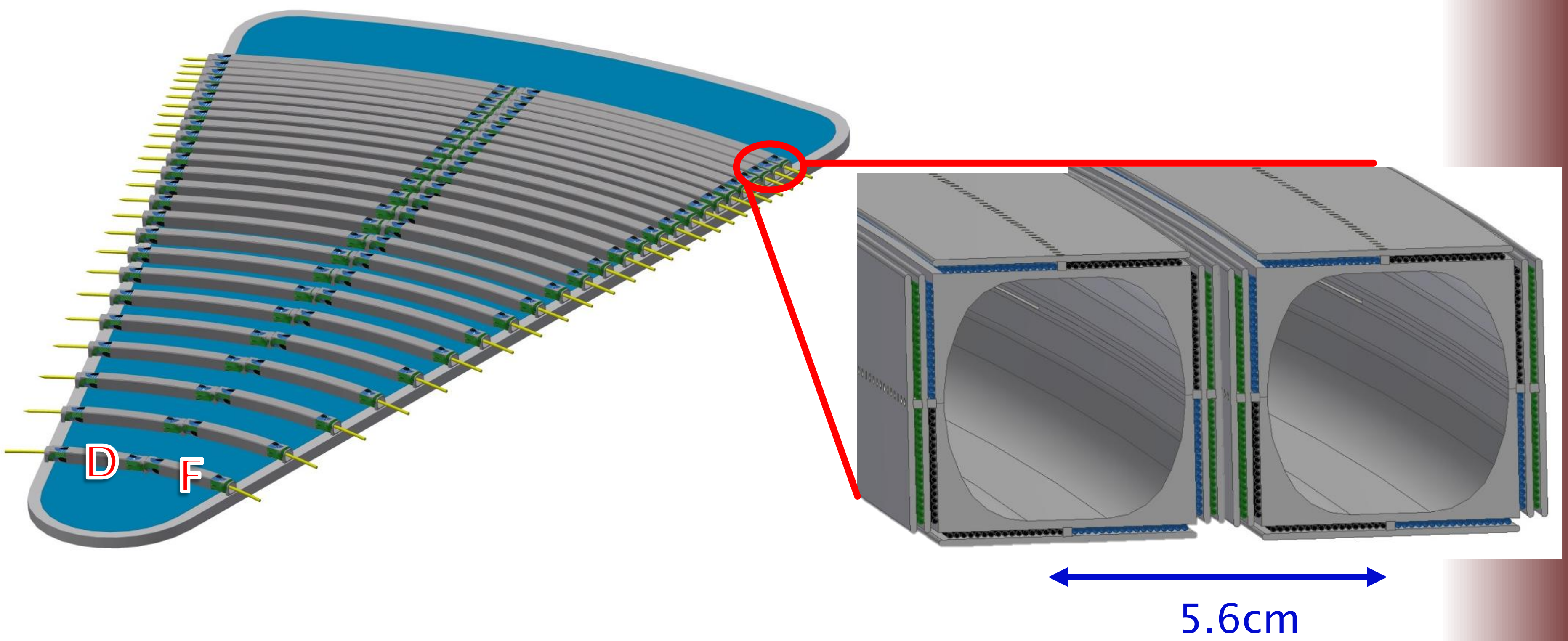


22.8 MV/m max surface electric field
54 mT max surface magnetic field

Outline

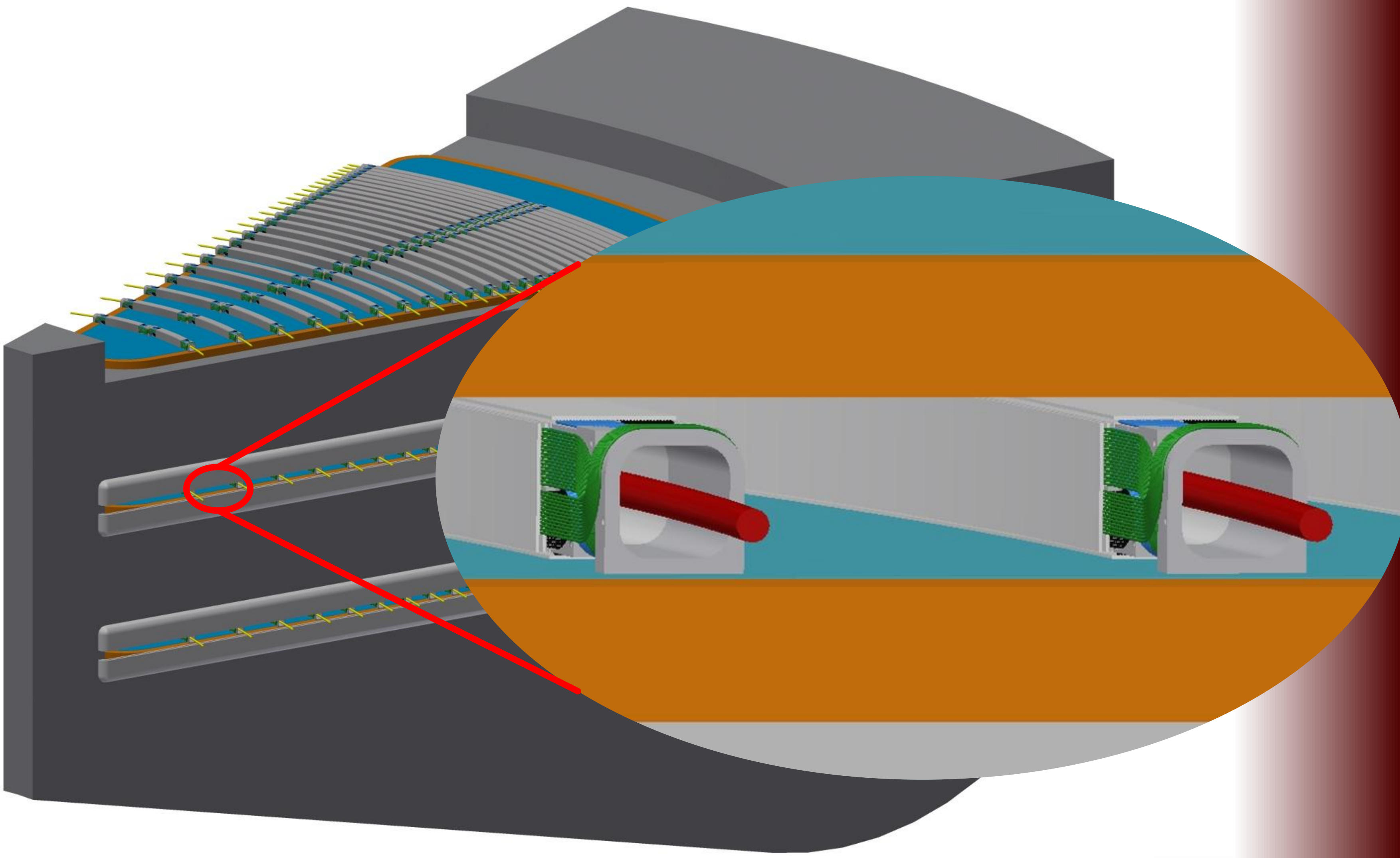
- Motivation
  - Proton driver for Accelerator-Driven Subcritical Fission
  - What limits beam current in cyclotrons
- Superconducting RF Cavity
  - Fully separate all orbits
- Beam Transport Channel
  - Control betatron tunes throughout acceleration
  - Magnetic design
  - Winding prototype
- Sector Dipoles
  - Flux-coupled stack
  - Fringe field reduction
- Beam Dynamics
- Future Work

F-D doublet on each orbit in each sector



BTC dimension set by beam separation at extraction

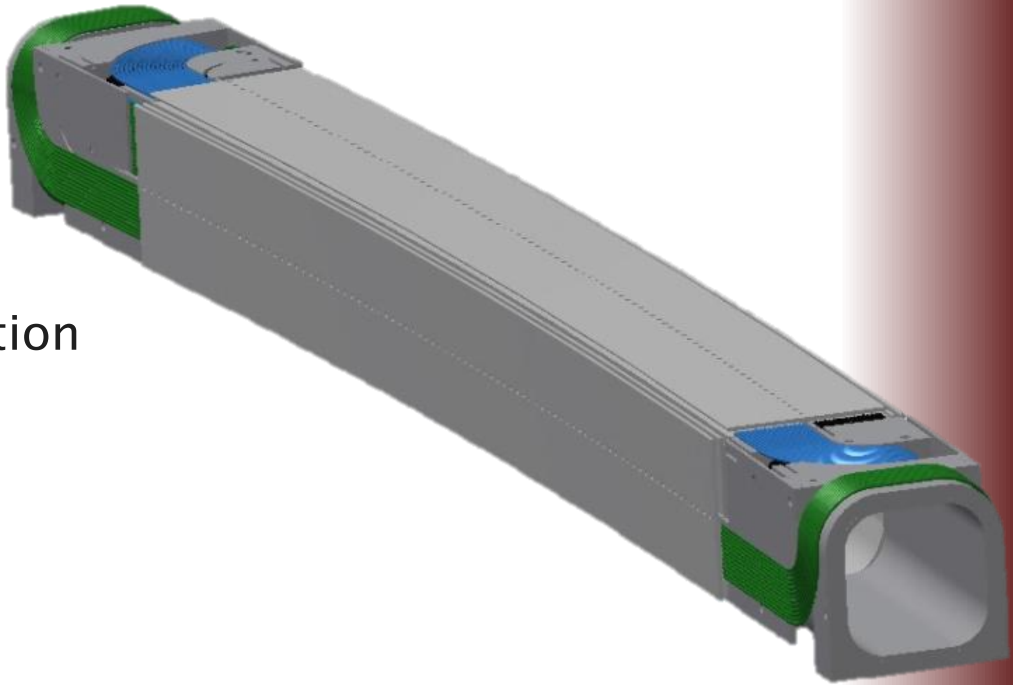
Beam Transport Channel at injection

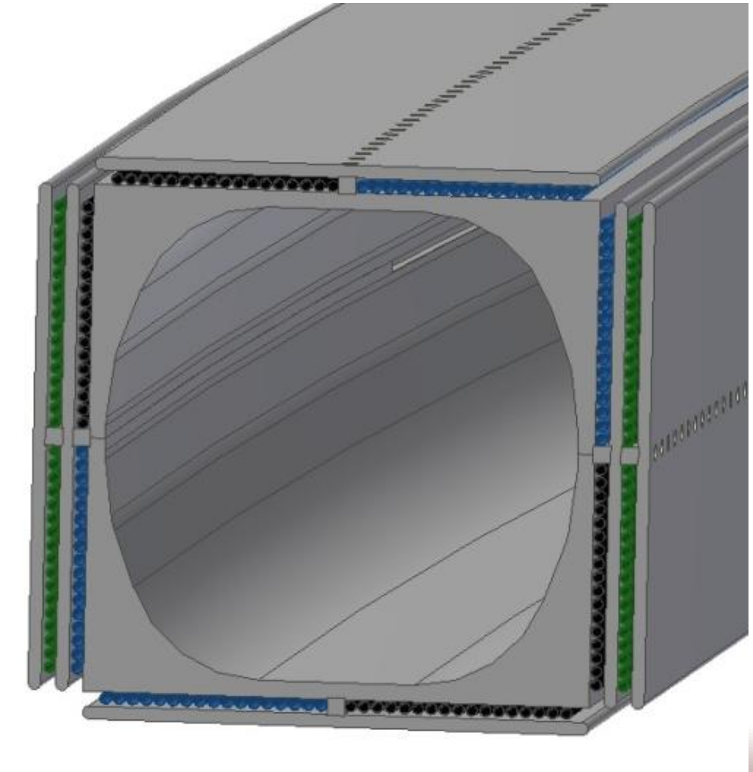


Beam Transport Channel (BTC)

Dipole Windings

- Up to 20 mT
- Act as corrector for isochronicity,
- Septum for injection/extraction

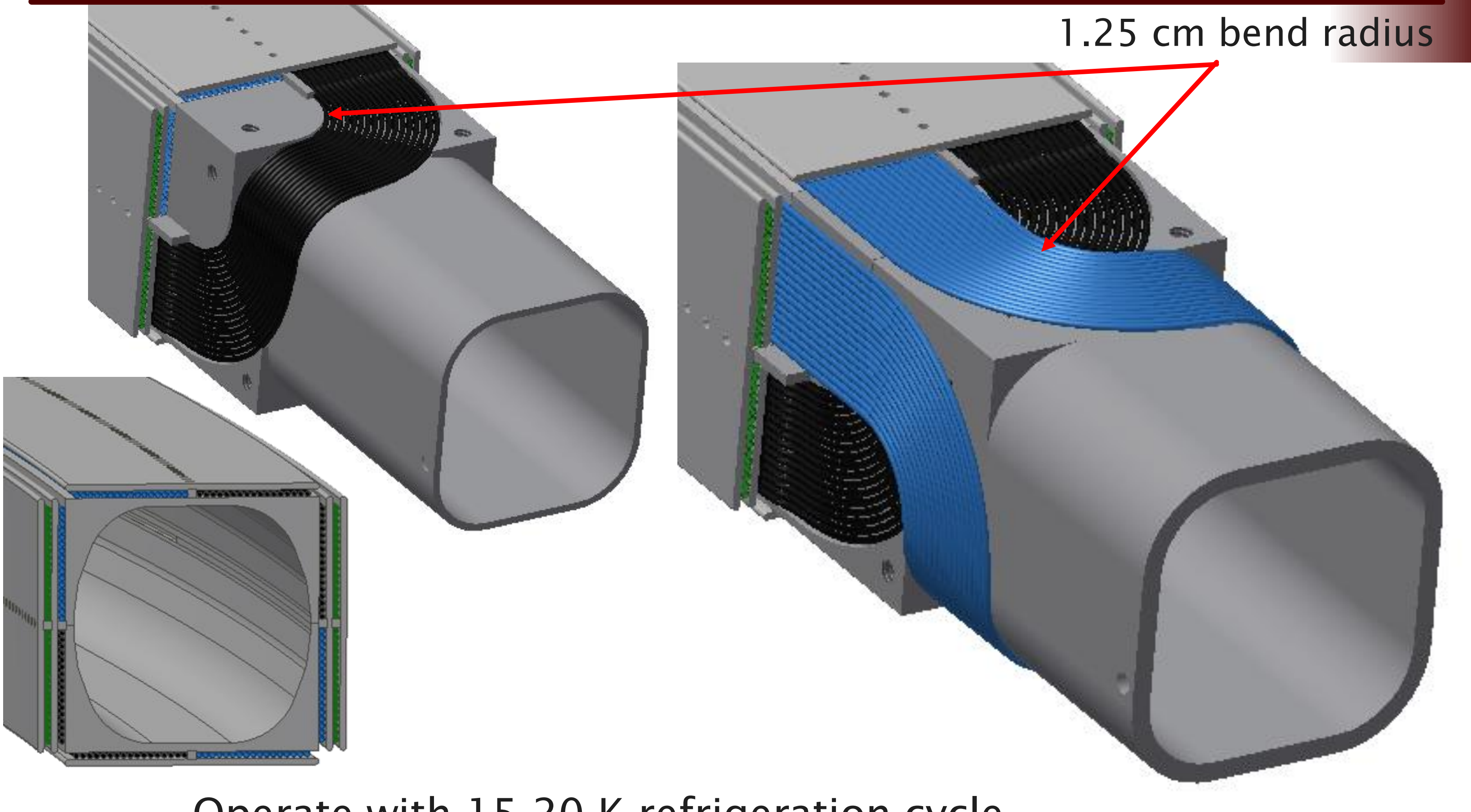




Quadrupole Windings

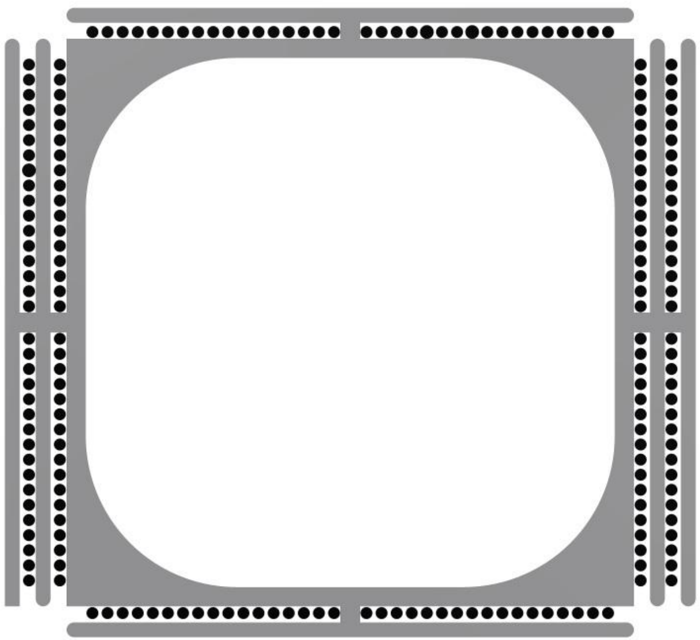
- Up to 6 T/m
- Panofsky style
- Alternating-gradient focusing
- Powered in 6 families to provide total tune control

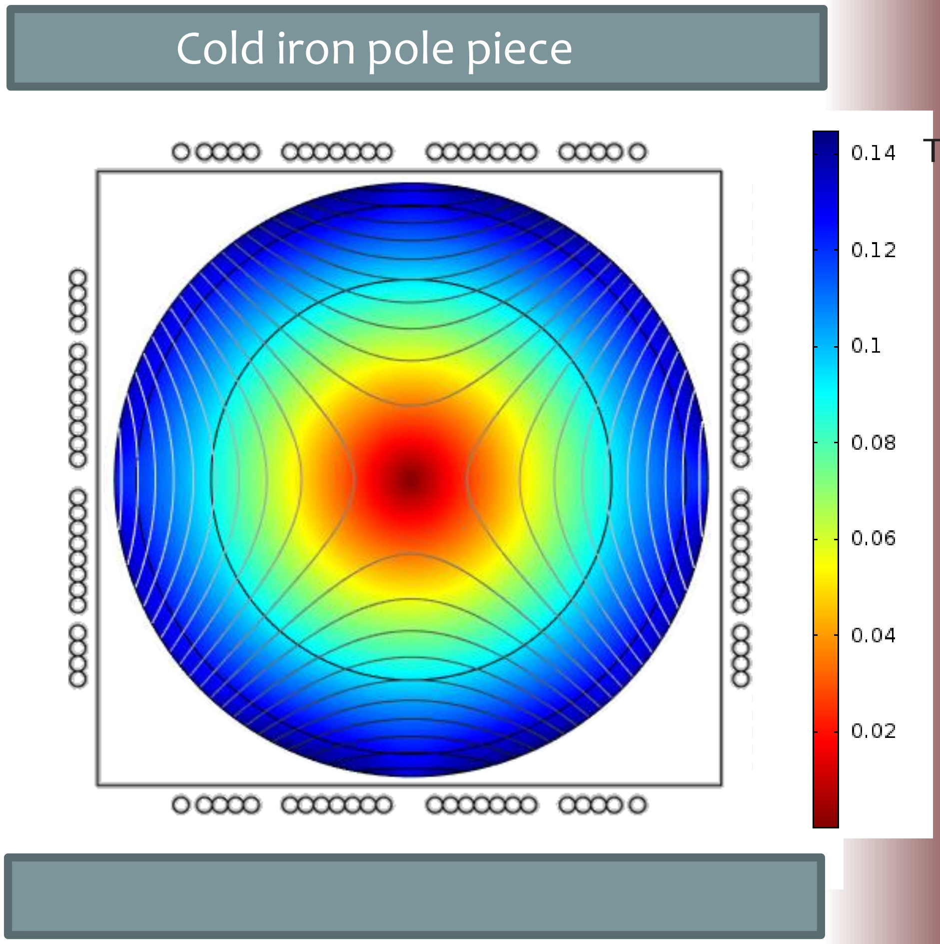
All BTC windings use MgB_2



Operate with 15-20 K refrigeration cycle

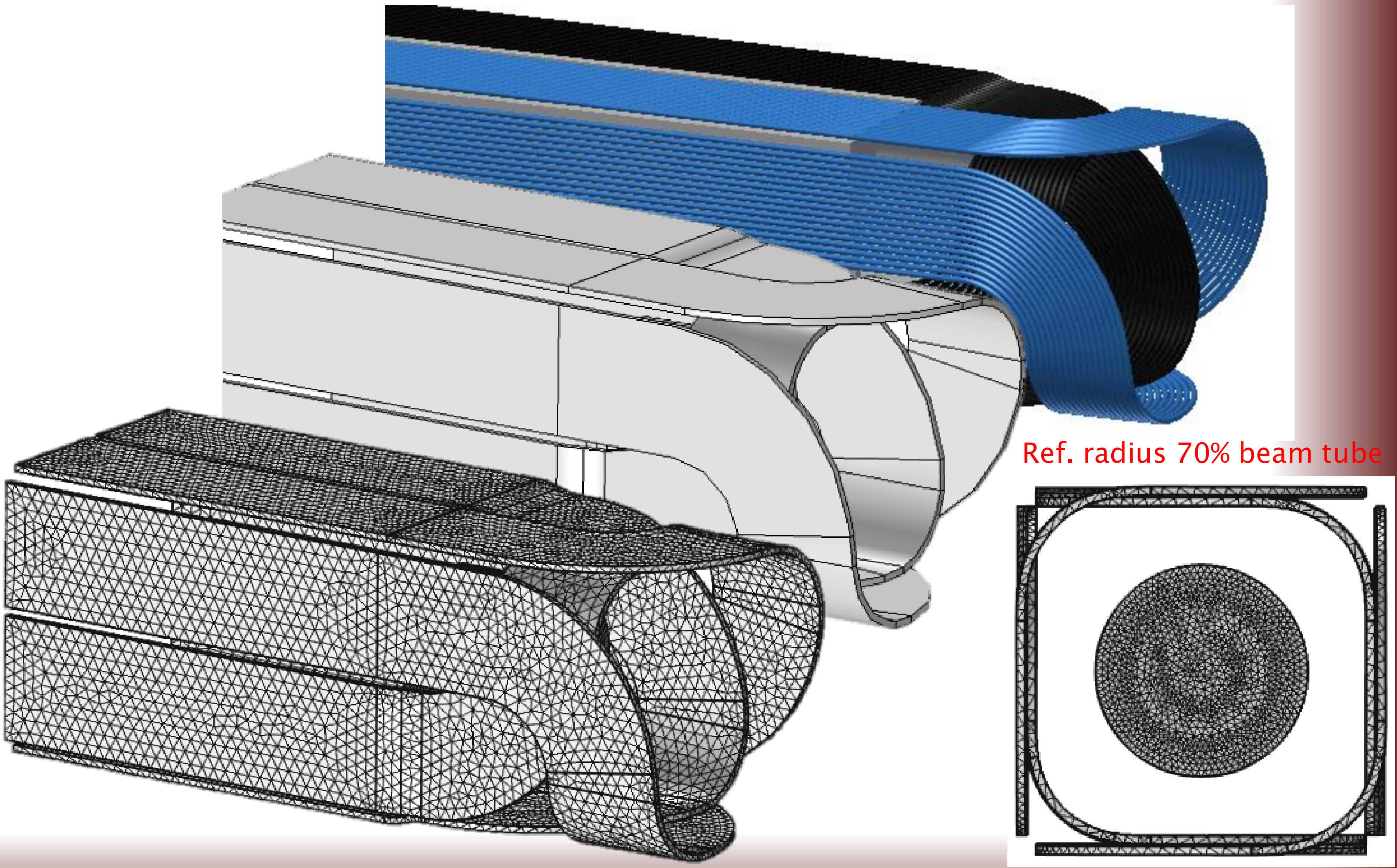
2D Field Modeling



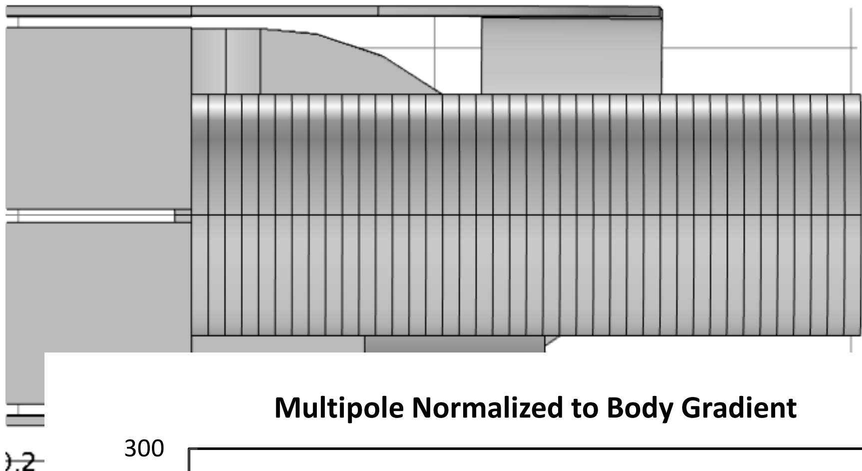


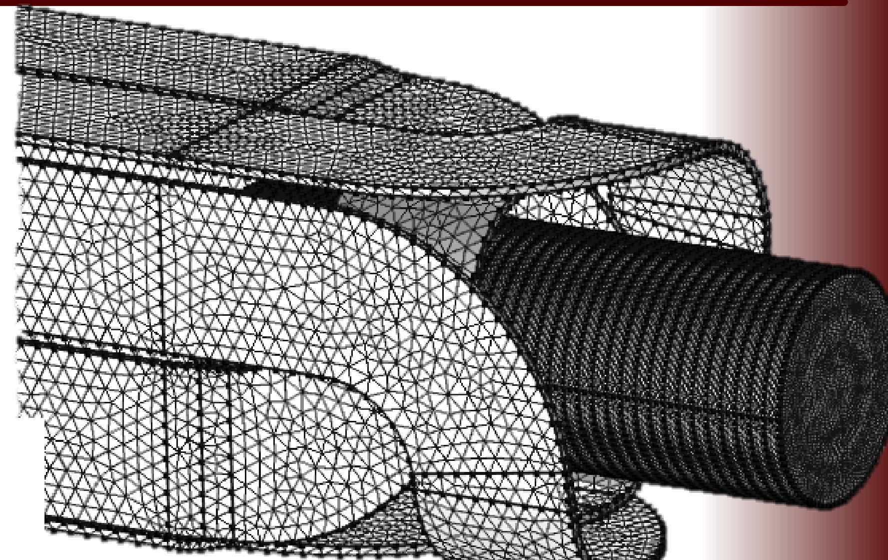
Wire spacing adjusted to kill multipoles
Current density required for 6T/m ~ 235 A

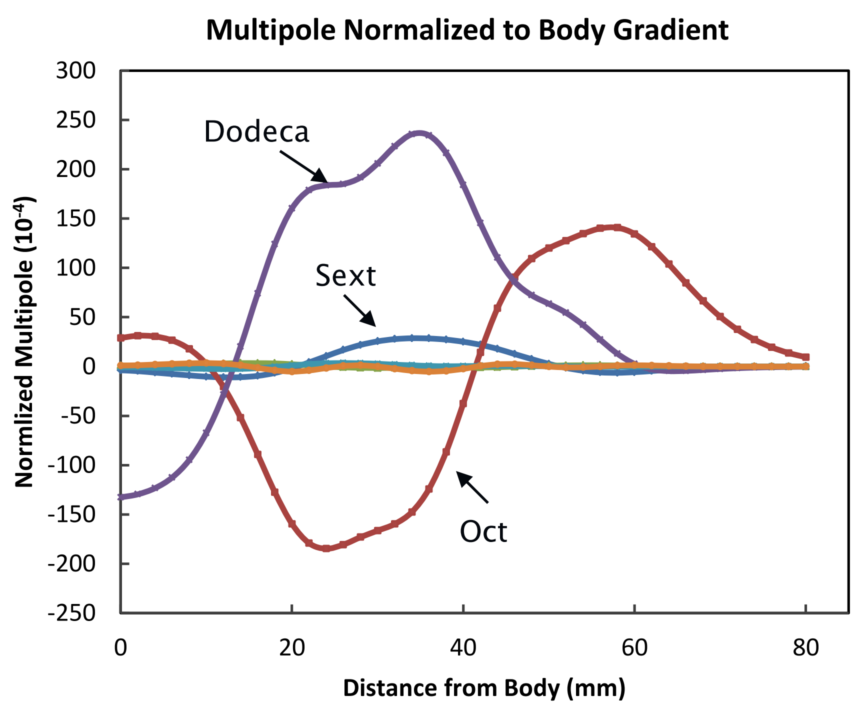
BTC Endcap modeling

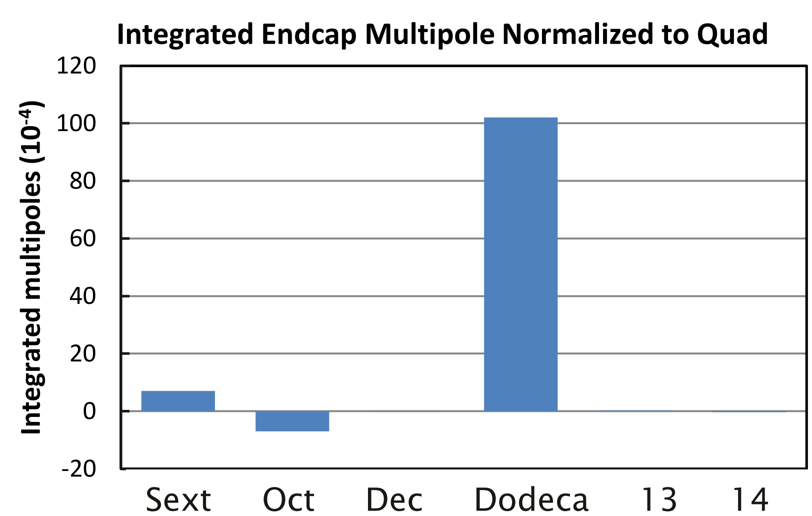


Endcap modeling

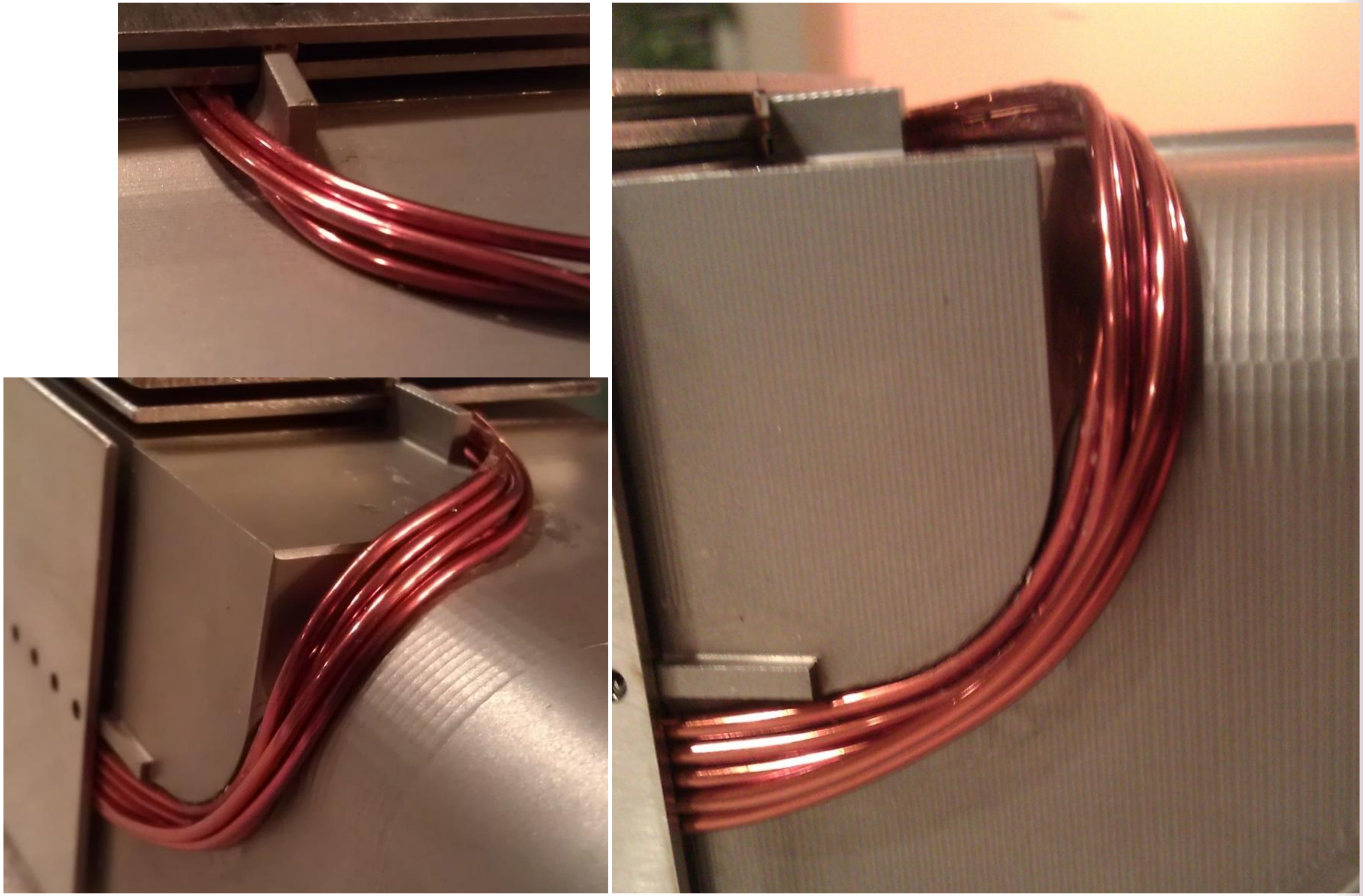




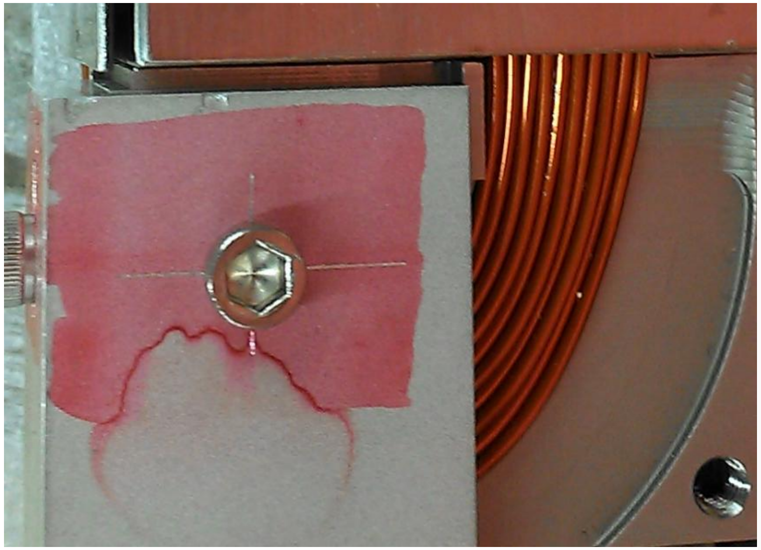


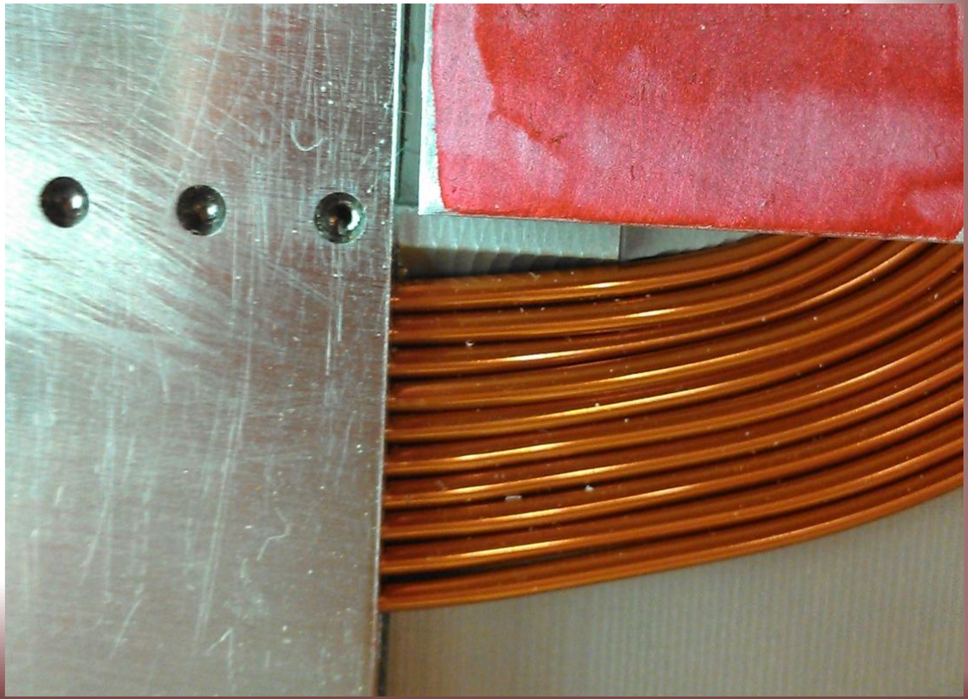


Copper Prototype

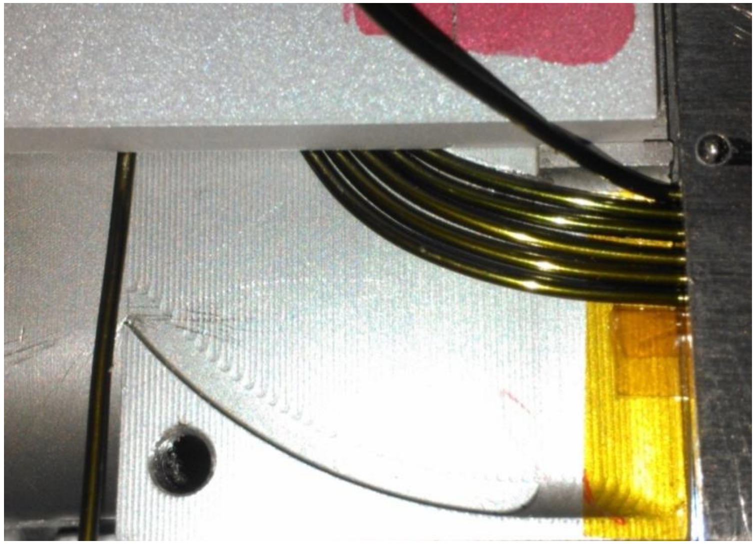


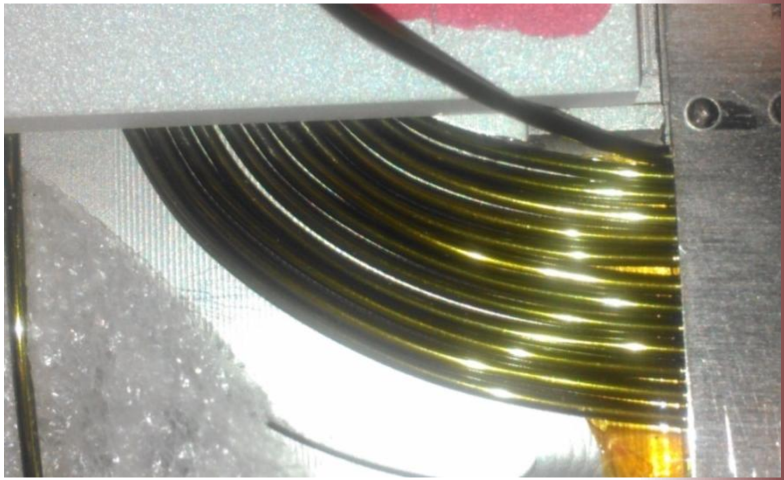
Winding Guides





Spacers



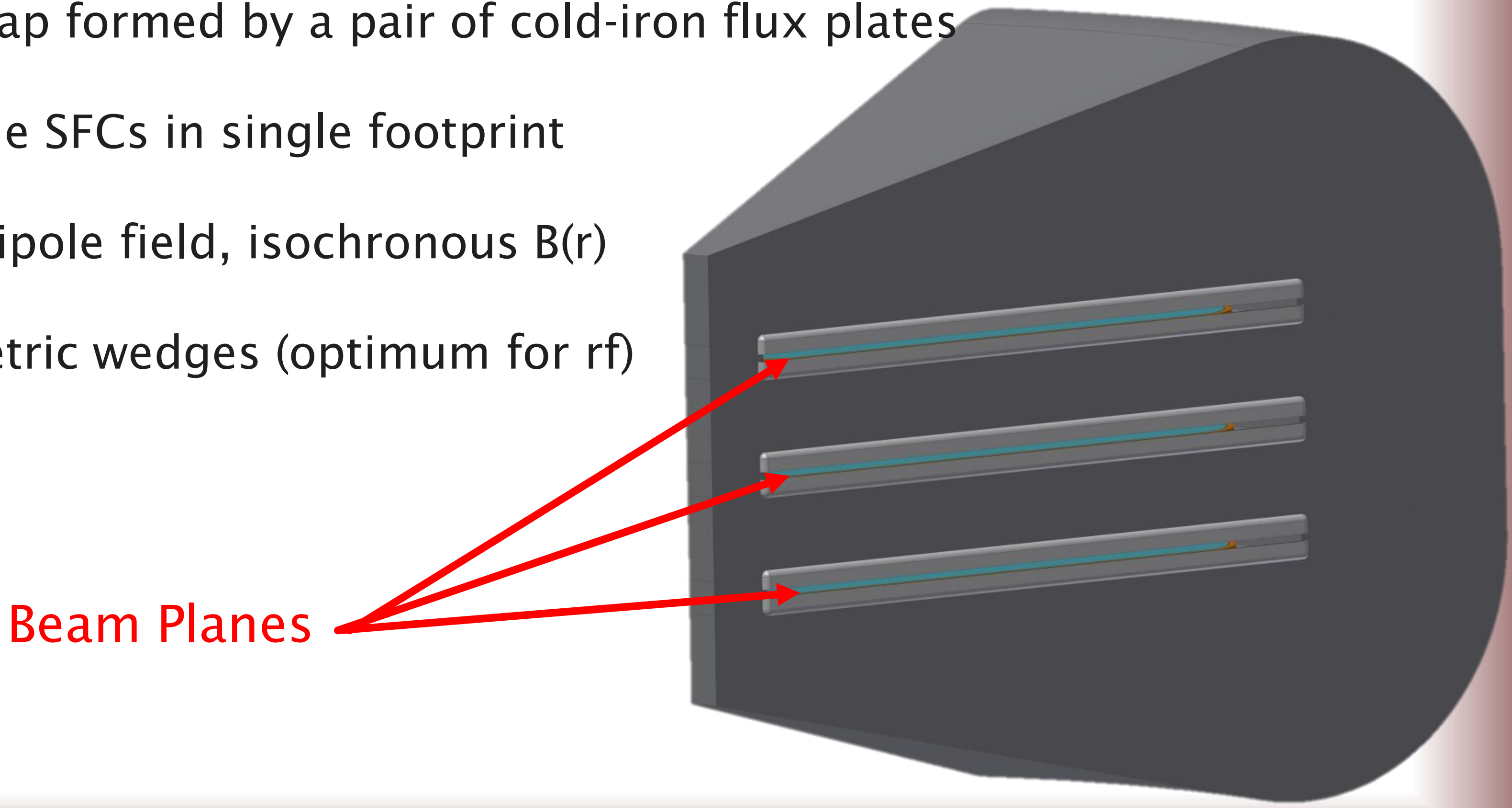


Outline

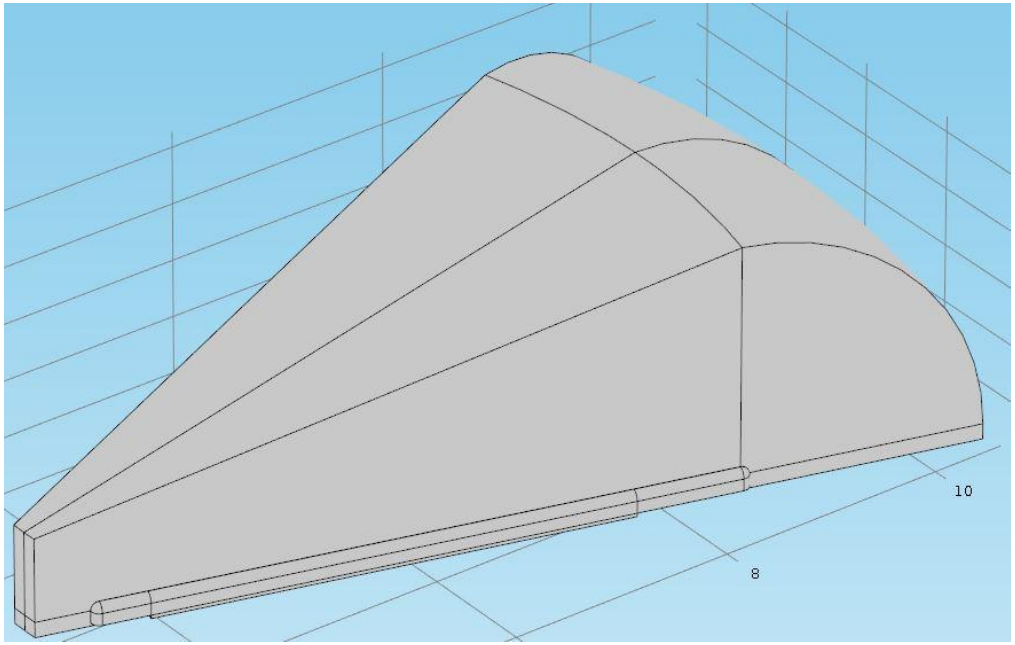
- Motivation
  - Proton driver for Accelerator-Driven Subcritical Fission
  - What limits beam current in cyclotrons
- Superconducting RF Cavity
  - Fully separate all orbits
- Beam Transport Channel
  - Control betatron tunes throughout acceleration
  - Magnetic design
  - Winding prototype
- Sector Dipoles
  - Flux-coupled stack
  - Fringe field reduction
- Beam Dynamics
- Future Work

Sector dipoles - Flux-Coupled Stack

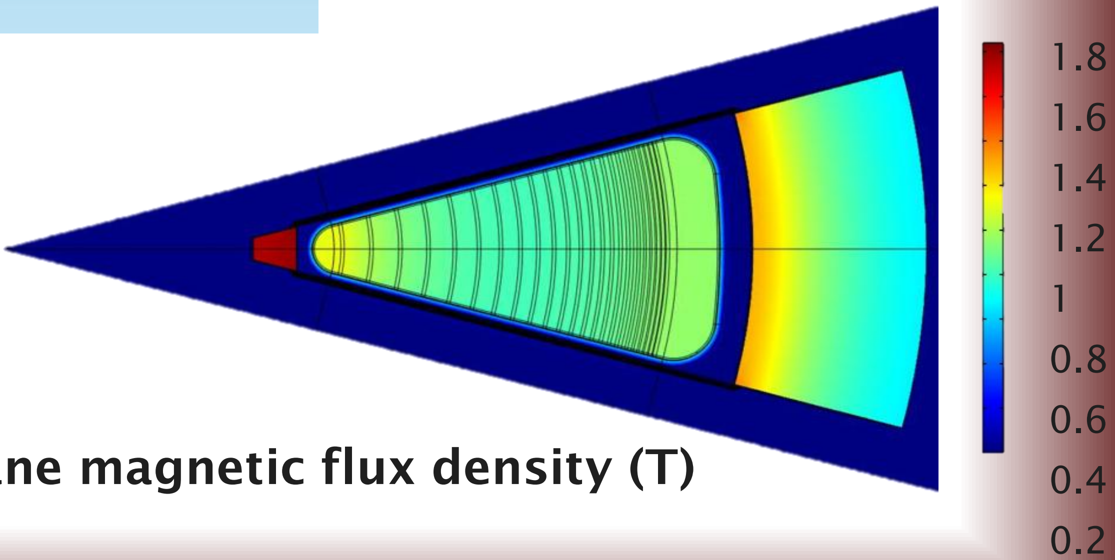
- Levitated-pole design originated at Riken
- Common warm-iron flux return
- Each gap formed by a pair of cold-iron flux plates
- Multiple SFCs in single footprint
- ~1 T dipole field, isochronous B(r)
- Geometric wedges (optimum for rf)



Sector Dipole Modeling



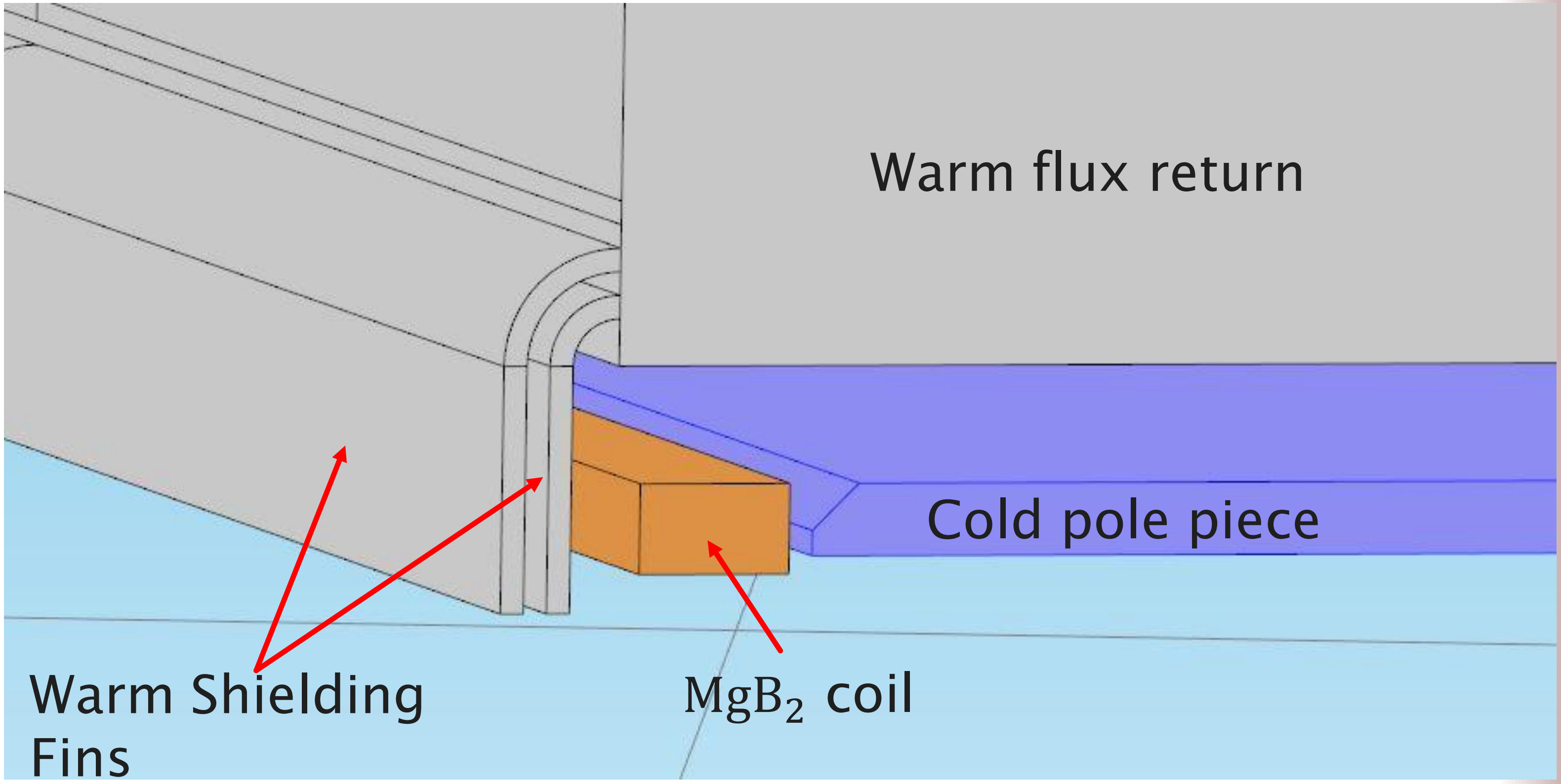
Top half of single stack cyclotron for modeling



Mid-plane magnetic flux density (T)

Fringe Field Reduction

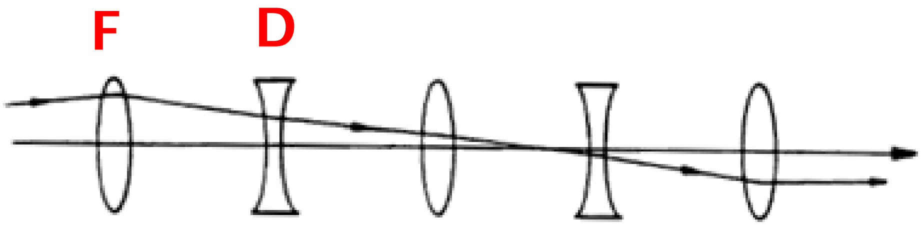
Superconducting cavities require the magnetic flux density to be less than 40 mT 10 cm from the warm iron flux return.

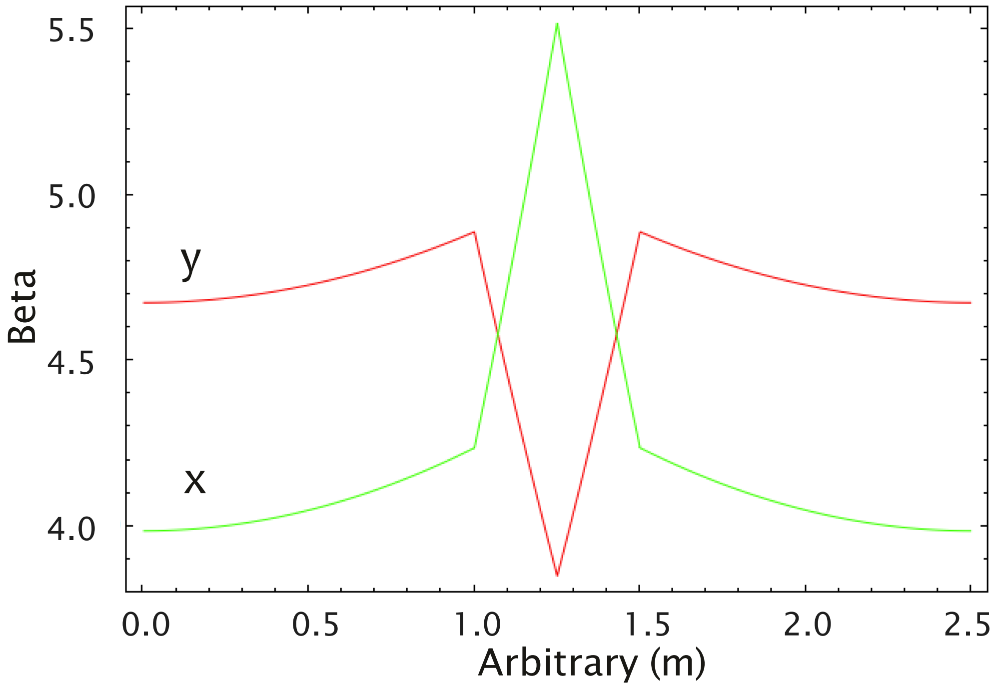


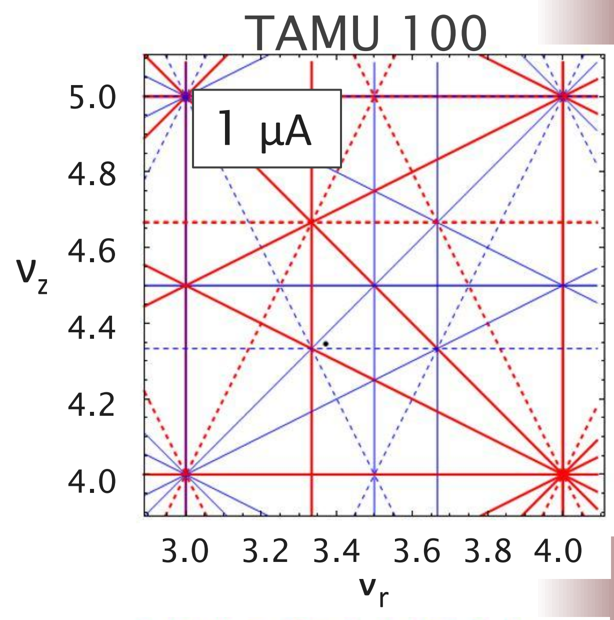
Outline

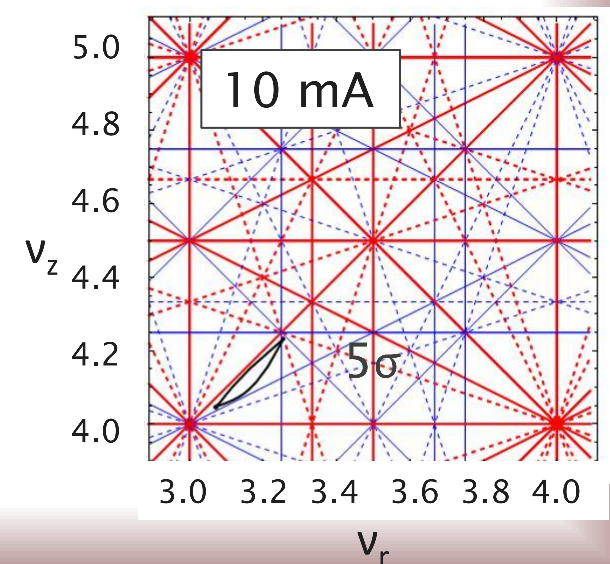
- Motivation
  - Proton driver for Accelerator-Driven Subcritical Fission
  - What limits beam current in cyclotrons
- Superconducting RF Cavity
  - Fully separate all orbits
- Beam Transport Channel
  - Control betatron tunes throughout acceleration
  - Magnetic design
  - Winding prototype
- Sector Dipoles
  - Flux-coupled stack
  - Fringe field reduction
- Beam Dynamics
- Future Work

Use BTC to Hold Tunes at Desirable Values









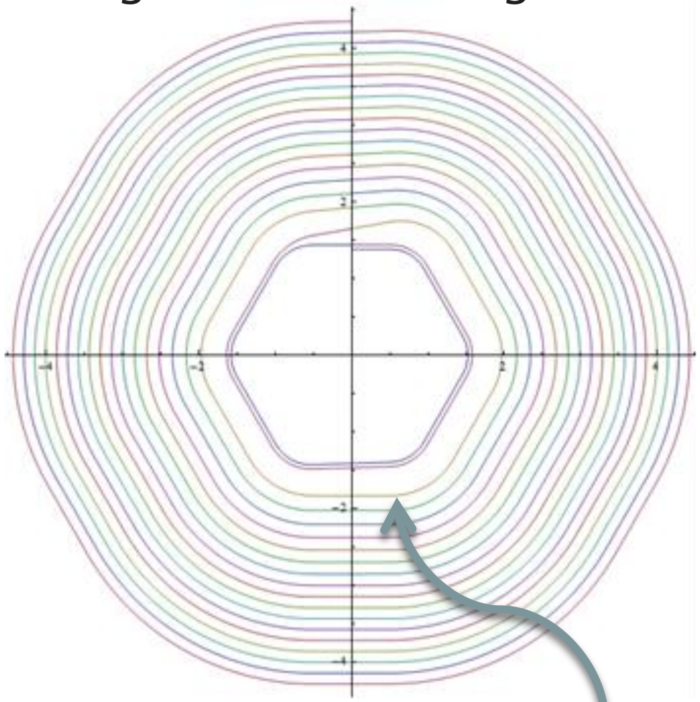
Avoid resonance crossing

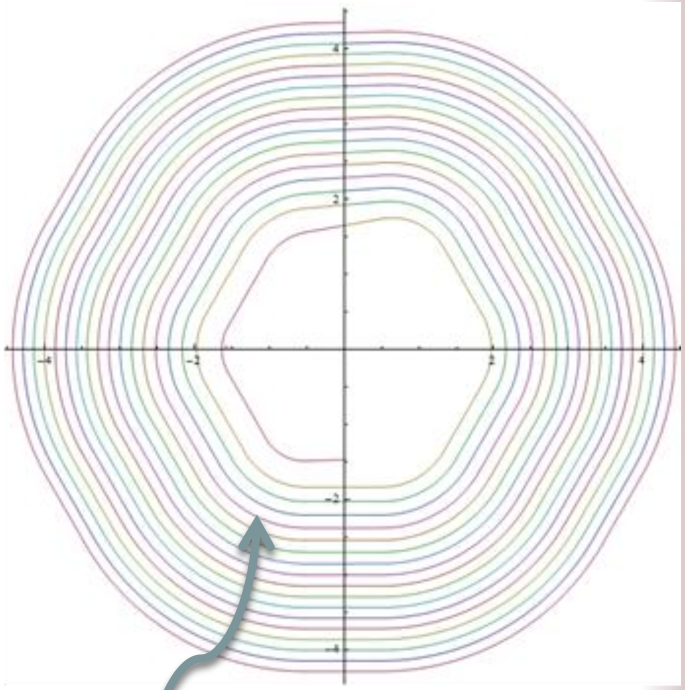
Dipole Corrector

The BTC dipole correctors can be used to maintain isochronicity as well as adjust beam spacing

Example of ability to adjust orbits to optimize design (from a 6 sector 100 MeV SFC design):

Design orbits working in from extraction:



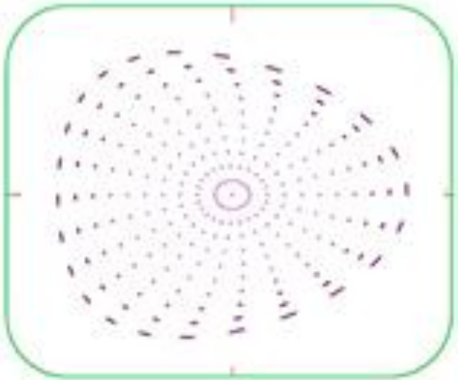


First try gave problematic orbits at injection
Then adjust orbit pattern using dipole correctors – ideal accommodation for injection

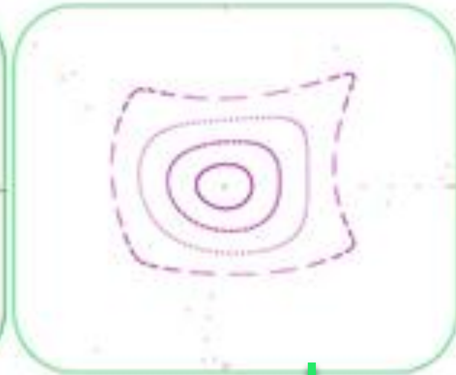
Poincare Plots of 5 σ contours

$(\nu_x, \nu_y) = (3.196, 3.241)$

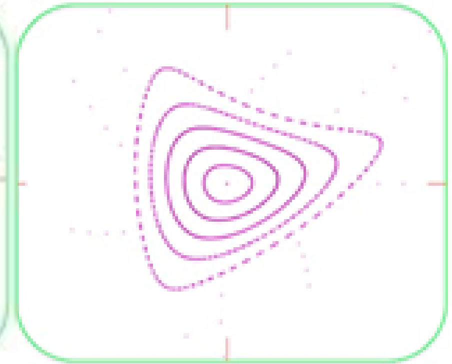
3.5 mA beam



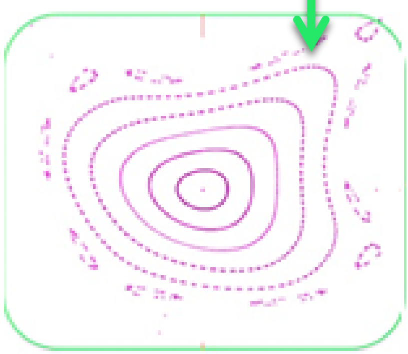
Injection



40 MeV



Extraction



Now change the tune to excite a 7th order resonance

Conclusion and Future plans

- The Strong-Focusing Cyclotron opens the possibility for high current
  - Beam separation: ~1T dipole, Superconducting RF cavities
  - Strong focusing: Beam Transport Channels

To Do:

Beam Transport Channel

- Finalize copper test wind
- Quench modeling and protection
- MgB_2 winding

Sector Magnet

- Continue to refine pole piece and shielding fins FEA models

Acknowledgements

Thank you!

- Al McInturff
- Chase Collins

- HyperTech
- John Buttles & Bailey tool

Graduate Students

- Justin Comeaux
- Kyle Damborsky
- Karie Melconian