Strong-Focusing Cyclotron As a High-Current Ion Driver for MEIC

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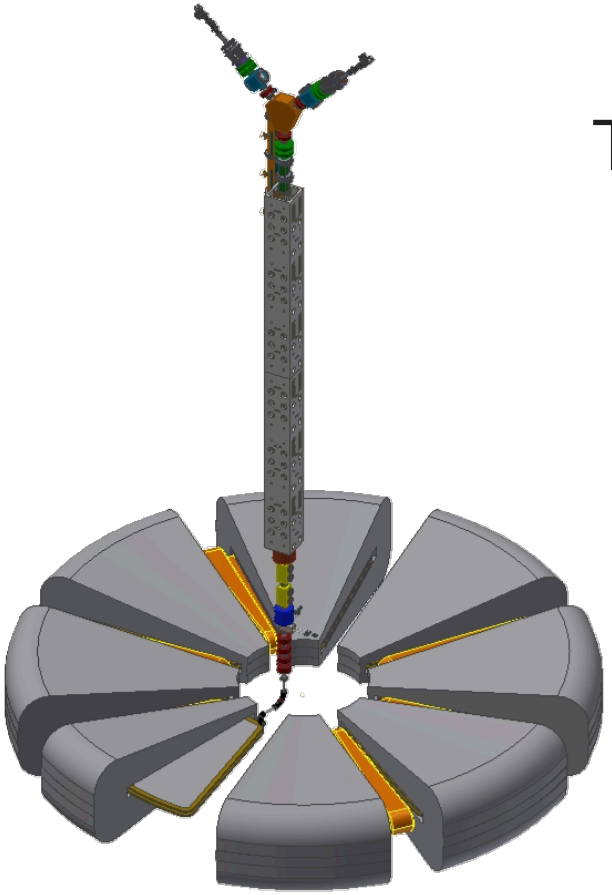


Outline

- Motivation
  - Requirements for MEIC Ion Driver
  - Cyclotron as a MEIC Driver
  - 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
- Beam Dynamics Simulations

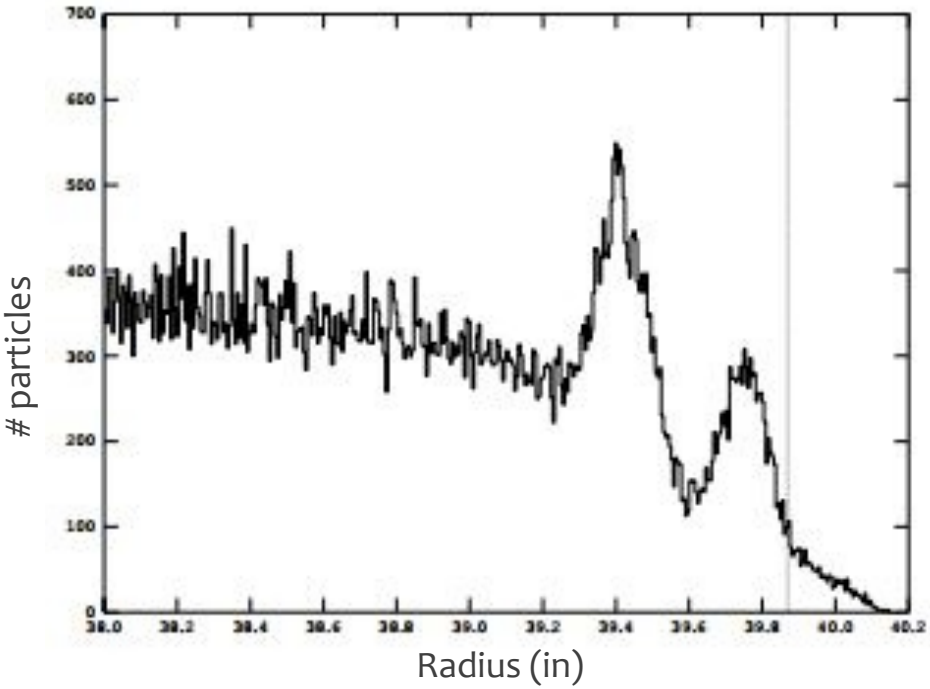
MEIC requirements

- *Polarized protons: >10 mA*
- *Polarized deuterons: >10 mA*
- *Polarized $^{3}He^{++}$: ~1 mA*
- *Polarized $^{6}Li^{+++}$: ~0.1 mA*

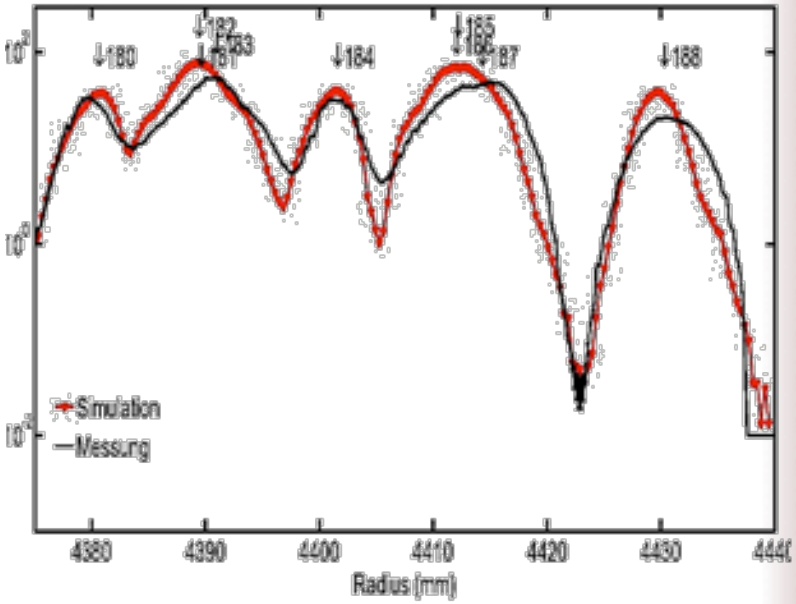
- *We need an injector that can accelerate ions with mass/charge spanning the range 1 ➔ 2*
- *and current spanning the range 0.1 – 10 mA.*
- *We must preserve polarization.*

- *One can do the job using an RFQ and drift tube linac, but spanning the 2:1 range of m/q and the 100:1 range of beam current is challenging…*
- *And DTL is expensive, whether it is normal or superconducting.*

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



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



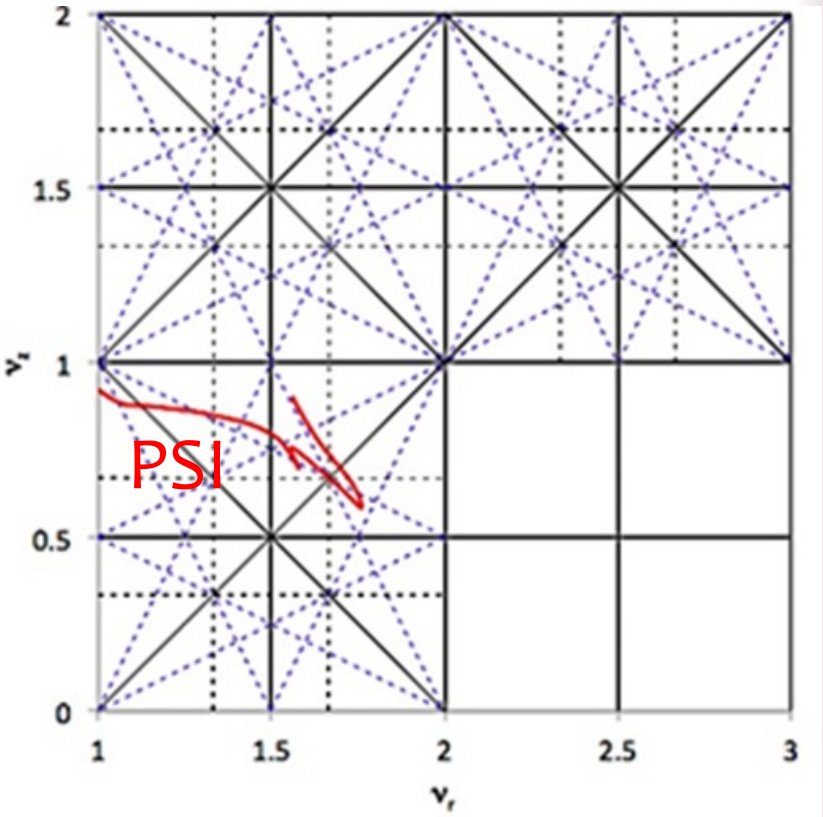
http://cas.web.cern.ch/cas/Bilbao-2011/Lectures/Seidel.pdf

Overlap of N bunches on successive orbits produces N x greater space charge tune shift, non-linear effects at edges of overlap.

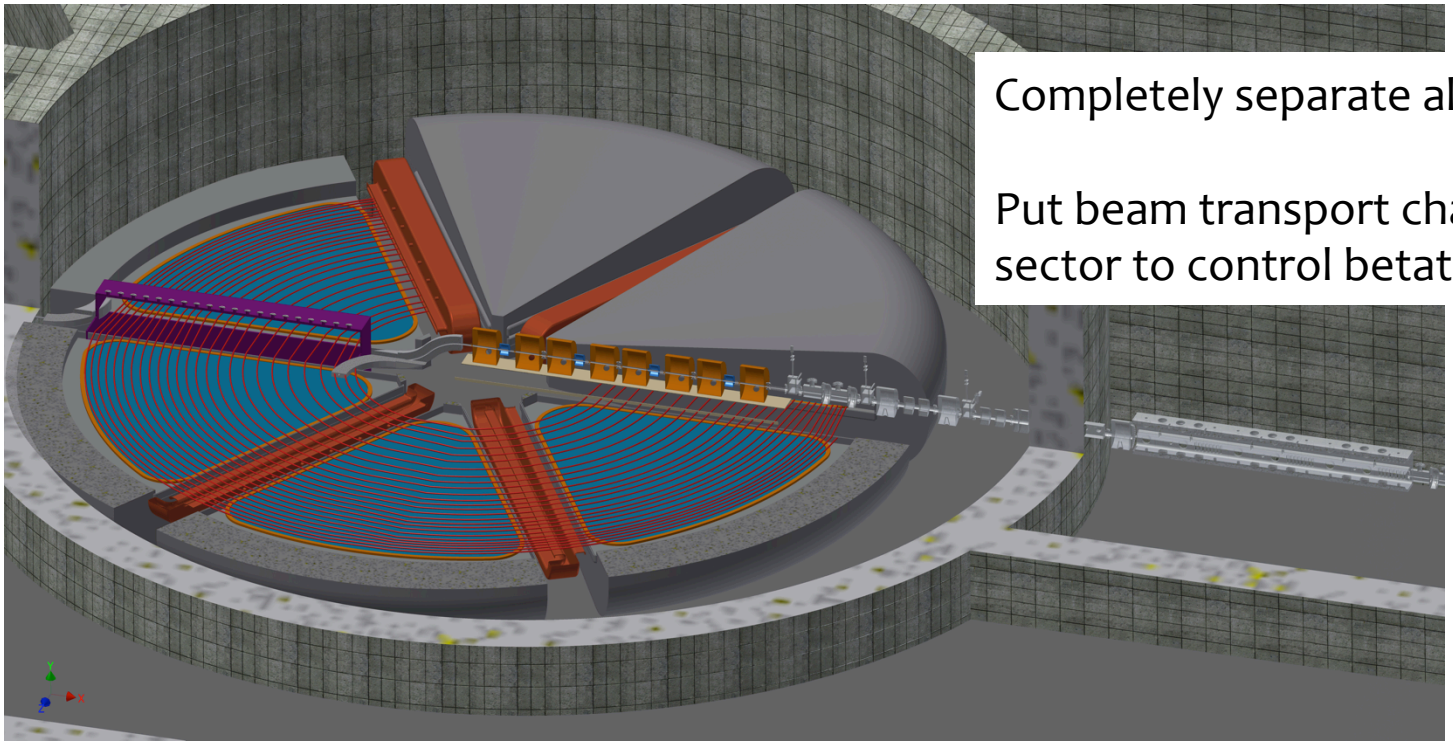
2) Weak focusing, Resonance crossing

Cyclotrons are intrinsically weak-focusing accelerators

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



Strong-Focusing Cyclotron



Completely separate all orbits.

Put beam transport channels in each sector to control betatron tunes

Curing the limits of overlapping orbits and controlling tunes opens the high-current frontier:

- Ion injector for MEIC
- Proton driver for ADS fission
- Medical Isotope Production
- Ion beam therapy

SFC Components

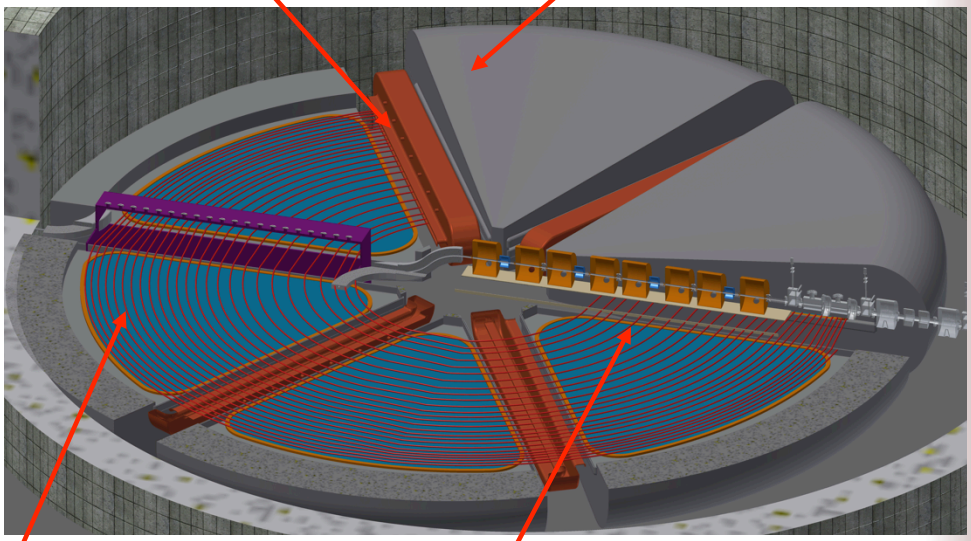
Slot-Geometry Half-Wave Cavities:
Superconducting for CW applications
Cryo-copper for pulsed operation - MEIC

Warm Flux Return

Ohm meets Carnot…

One SFC pulse dissipates ~2 kJ in cryo-Cu cavities.

Boils ~20 g = 25 cc LN2.



Beam Transport Channels

Cold-Iron Pole Piece

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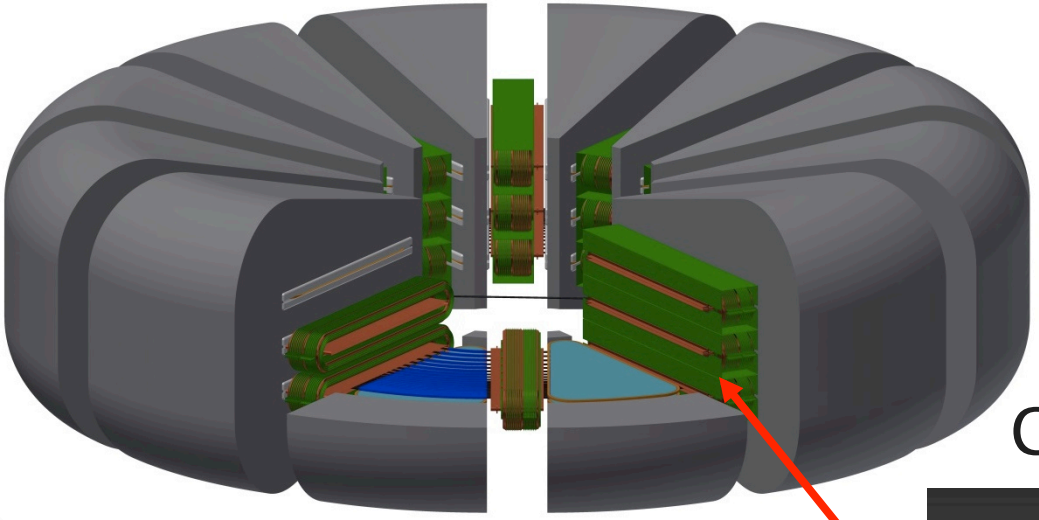
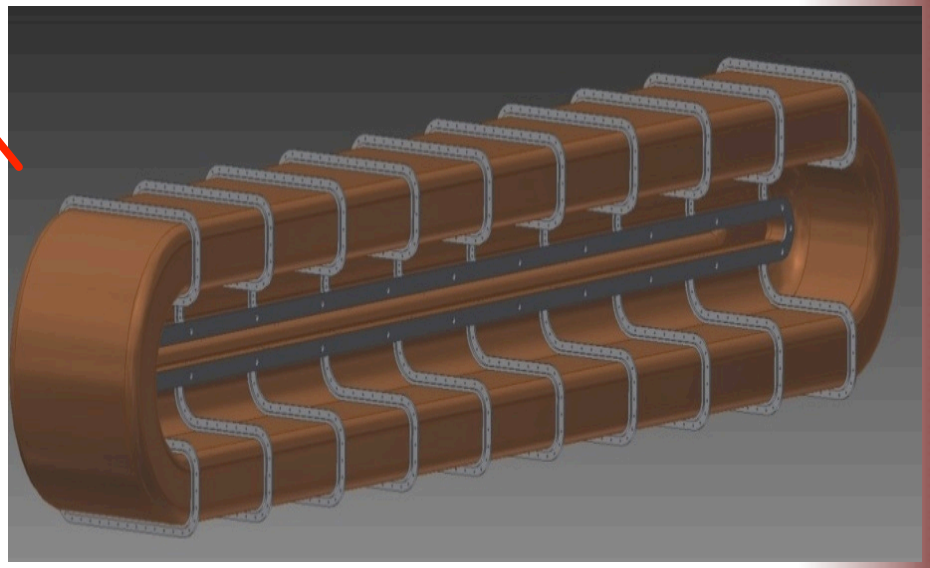
Slot-geometry ¼-wave SRF Cavities

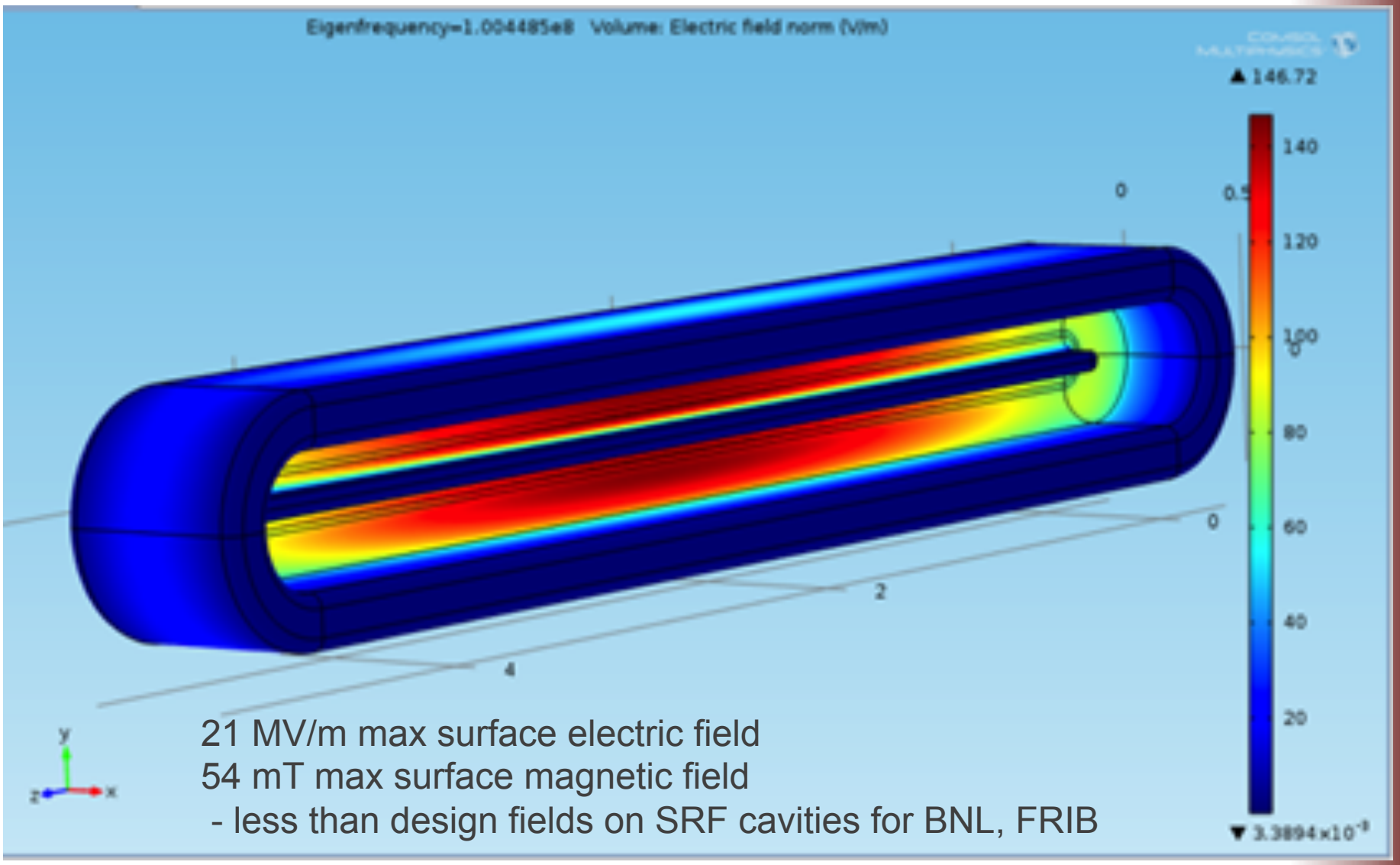


Cryo-copper RF cavities



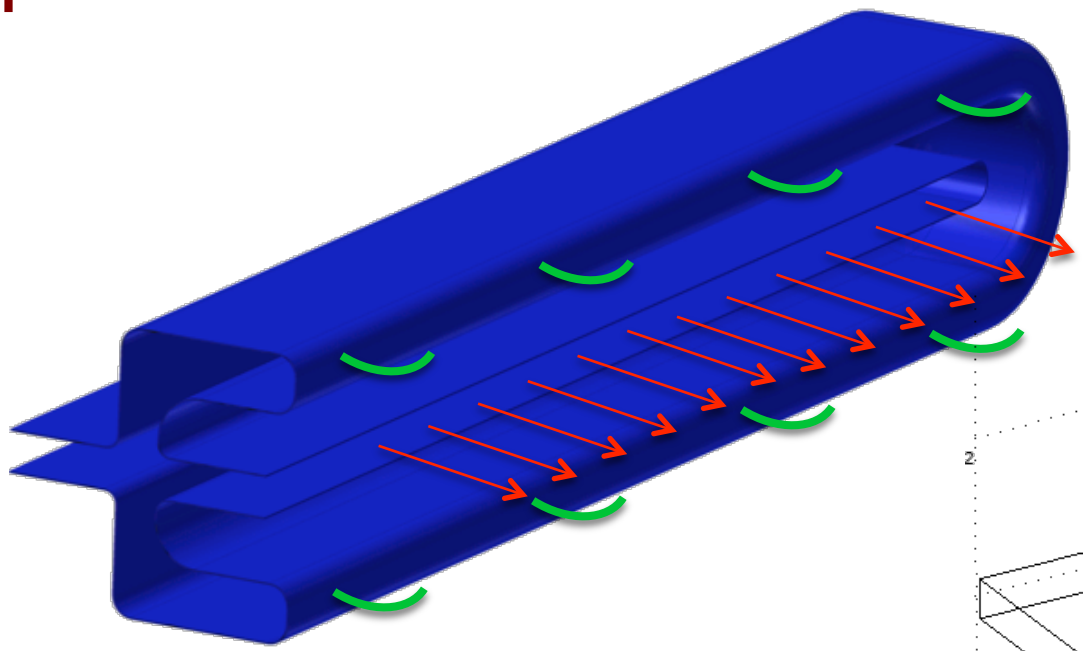
- 100 MHz
- 2 MV/cavity energy gain
- 20 MV/turn fully separates orbits

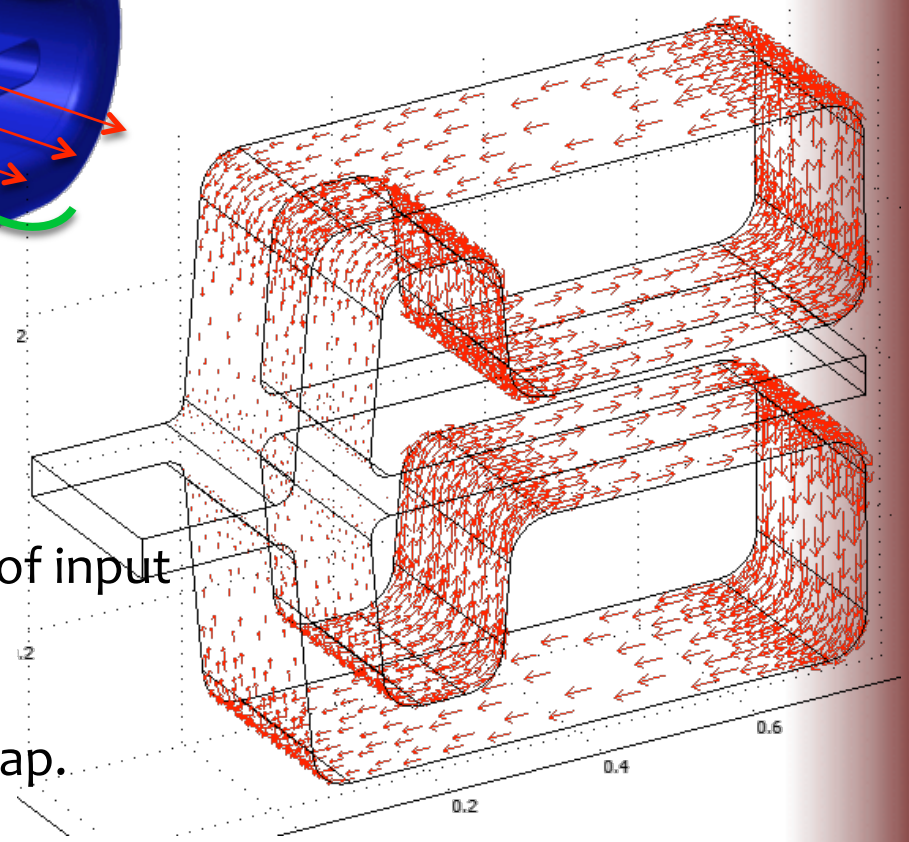
Example SRF Cavity Model



21 MV/m max surface electric field
54 mT max surface magnetic field
- less than design fields on SRF cavities for BNL, FRIB

Slot-geometry ¼ wave cavity structure and distributed RF drive suppresses perturbations from wake fields





RF power is coupled to the cavity by rows of input couplers along the top/bottom lobes.

RF power is coupled from the cavity to the synchronous bunches traversing the slot gap.

The cavity serves as a linear transformer:

Its geometry accommodates transverse mode suppression

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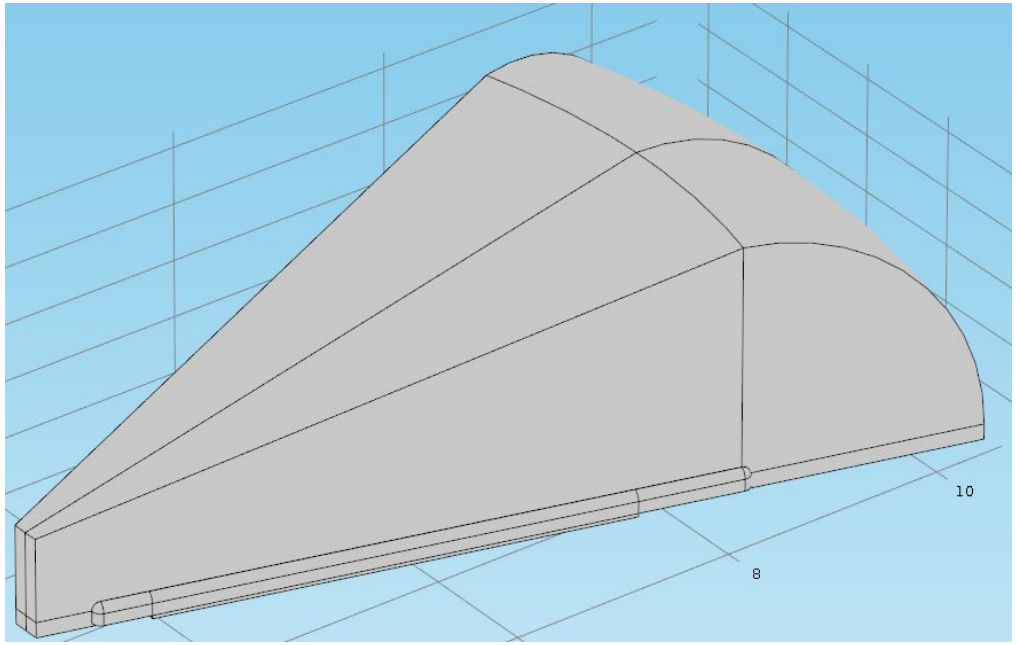
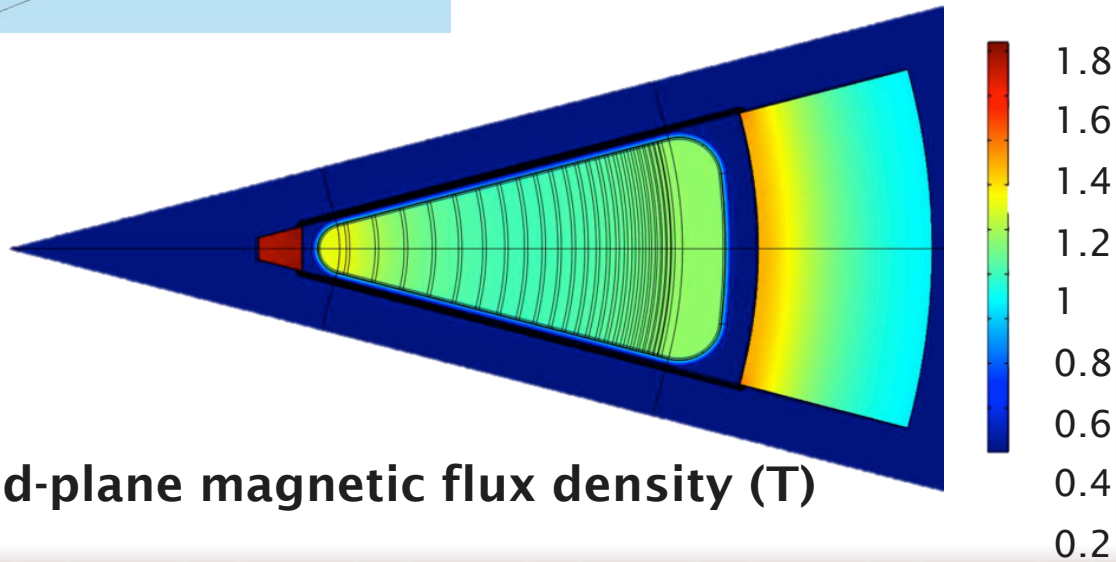
  - Flux-coupled stack
  - Fringe field reduction
- Beam Dynamics
- Future Work

Sector Dipole Modeling



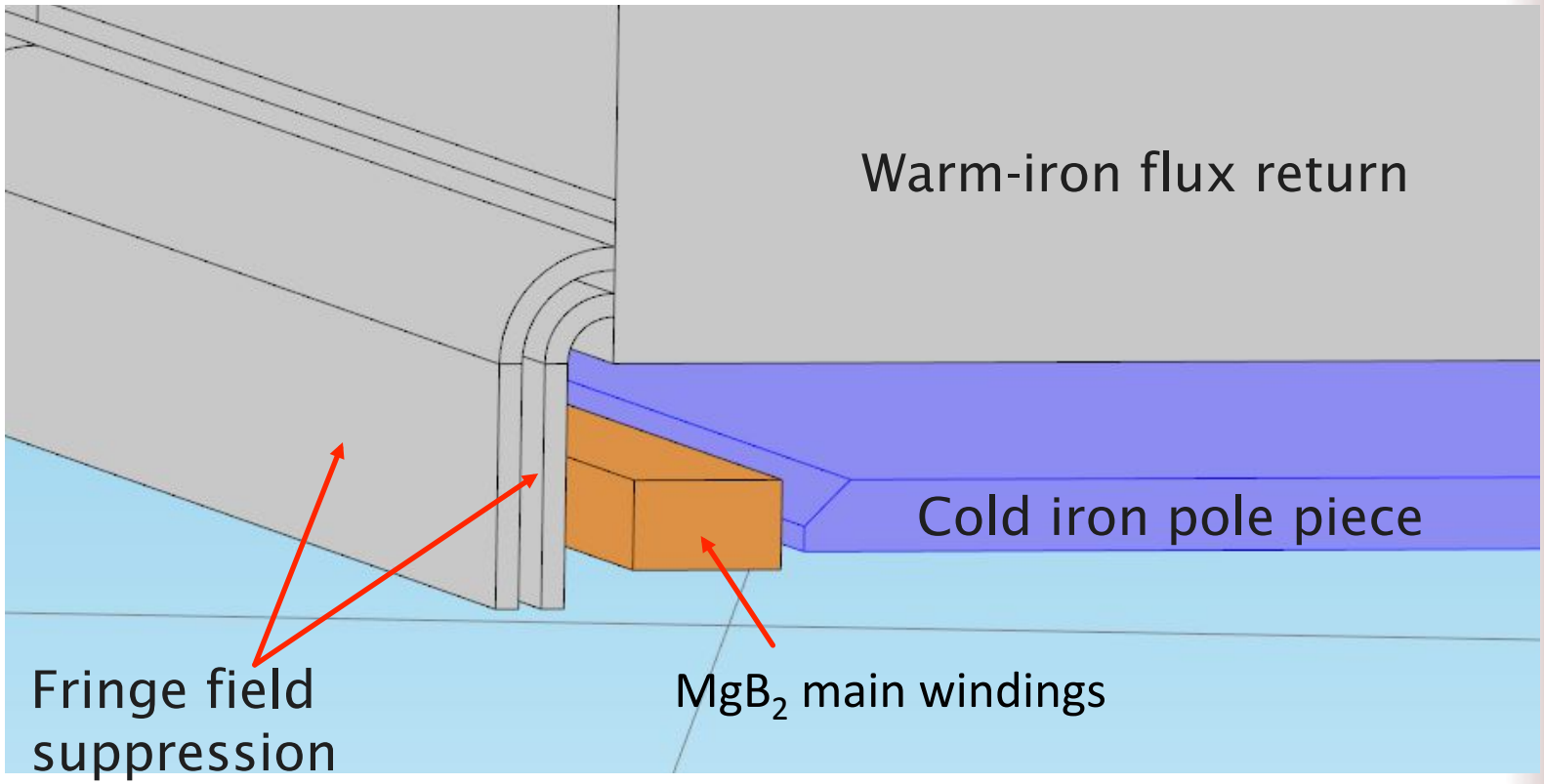
Top half of single stack cyclotron for modeling



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.



Levitated pole method first pioneered at Riken

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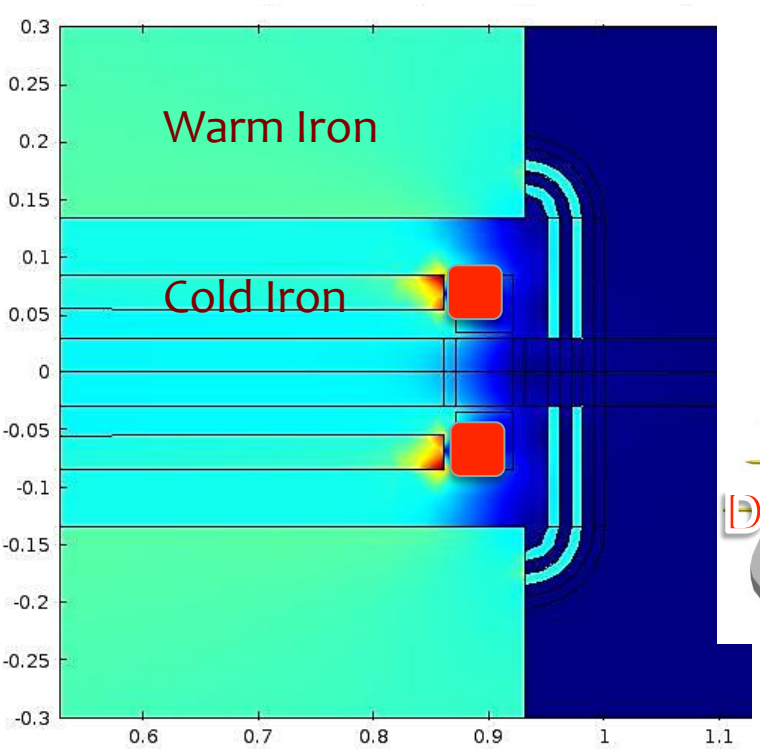
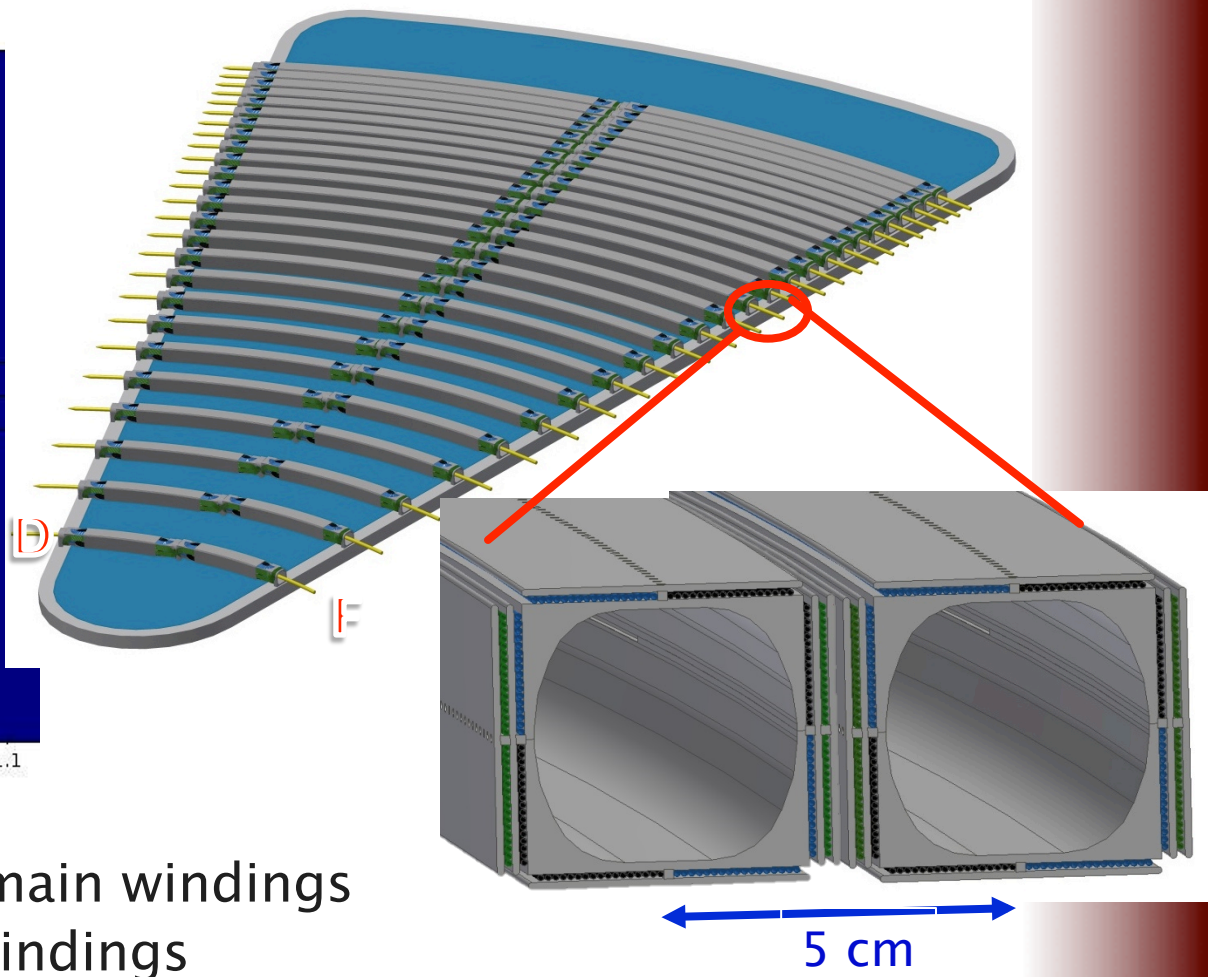
F-D doublet on each orbit, each sector





Cable-in-conduit MgB_2 main windings
Wirewound MgB_2 BTC windings
Tailor B(r) to provide match isochronicity condition.
BTC dimension set by beam separation at extraction.

The beam transport channels define the trajectories of all orbits. But we need to accelerate ions with different values of m/q

If we keep the bending radius ρ for a given (energy/amu) $\tilde{E}$ the same, and if we add the same $\tilde{E}$ to successive orbits, the pattern of spiral orbits will be invariant:

$$\rho = (\gamma v)(m / qB)$$

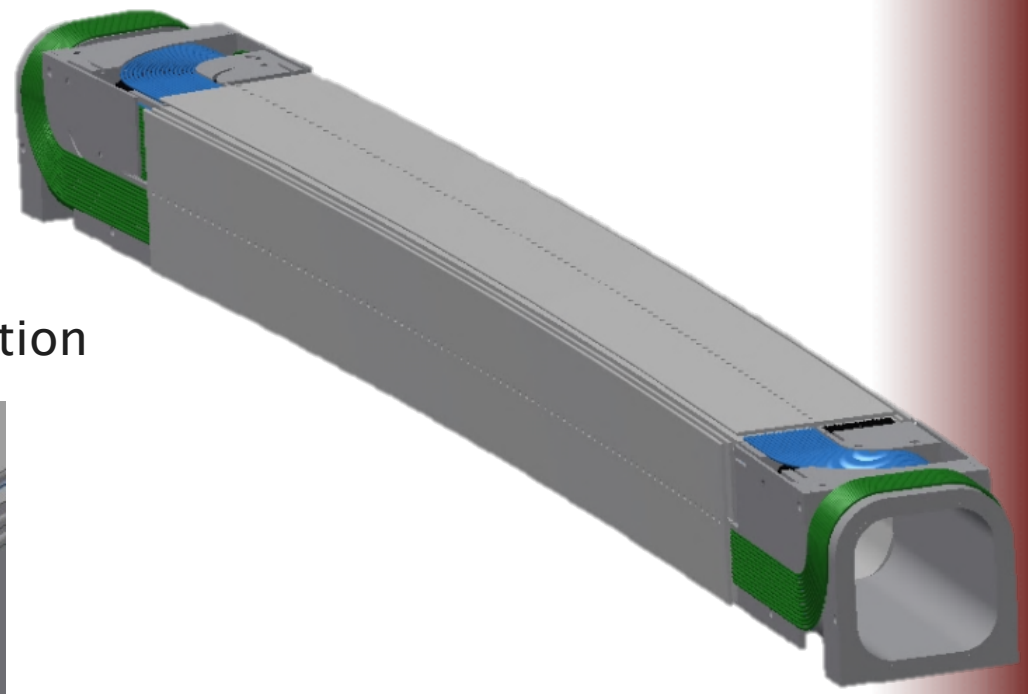
$$\tilde{E} / m = (qV / m)$$

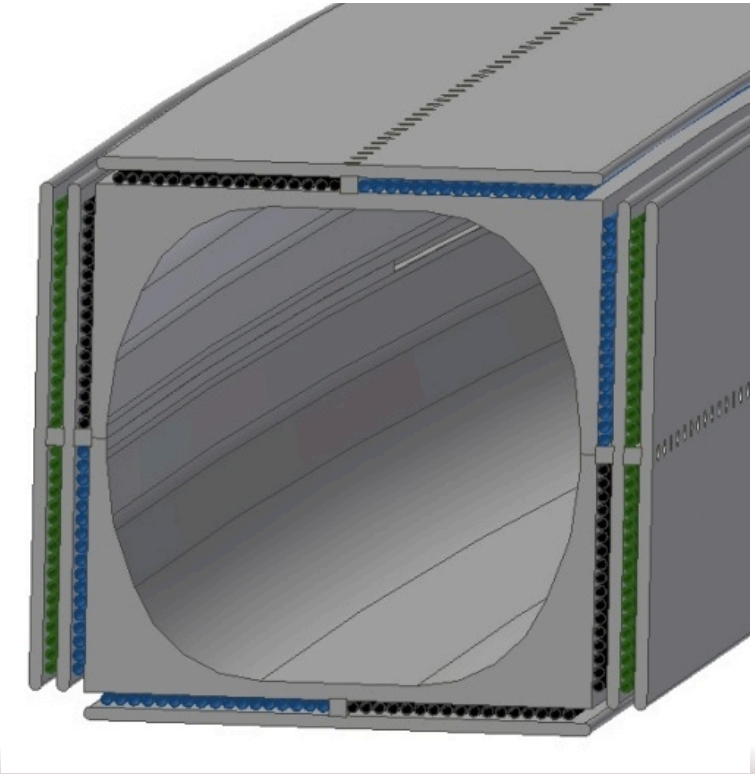
So the SFC will accelerate ions of any (m/q) providing we scale the cavity voltage V and the magnetic field B in proportion to (m/q).

Beam Transport Channel (BTC)

Dipole Windings

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

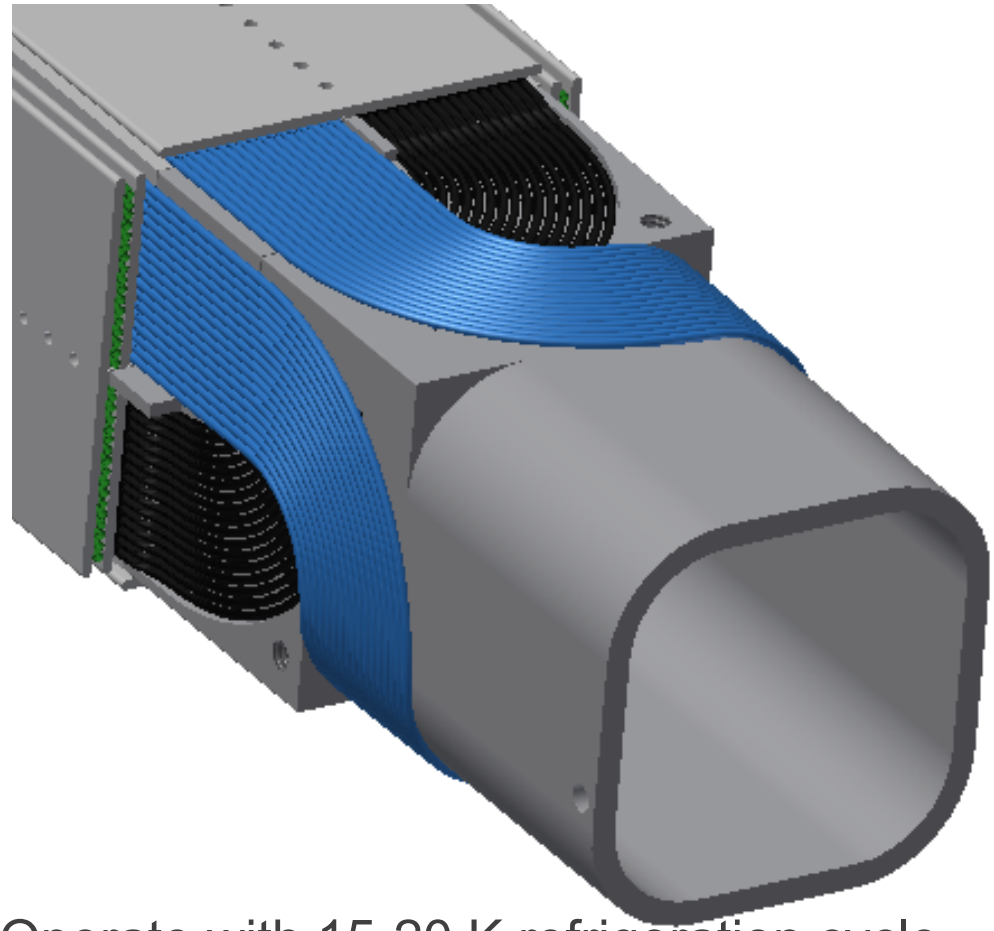




Quadrupole Windings

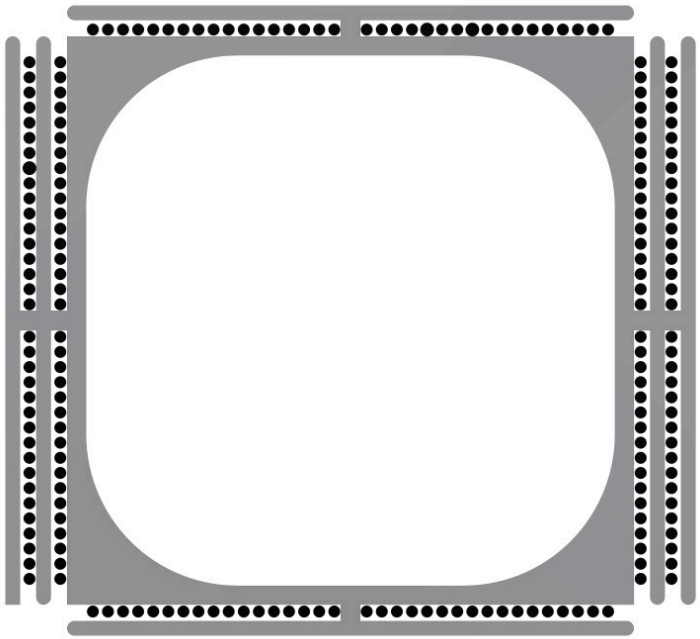
- Up to 6 T/m with single wire layer
- Panofsky style
- Alternating-gradient focusing
- Powered in 6 families to provide total tune control

All BTC windings use MgB_2

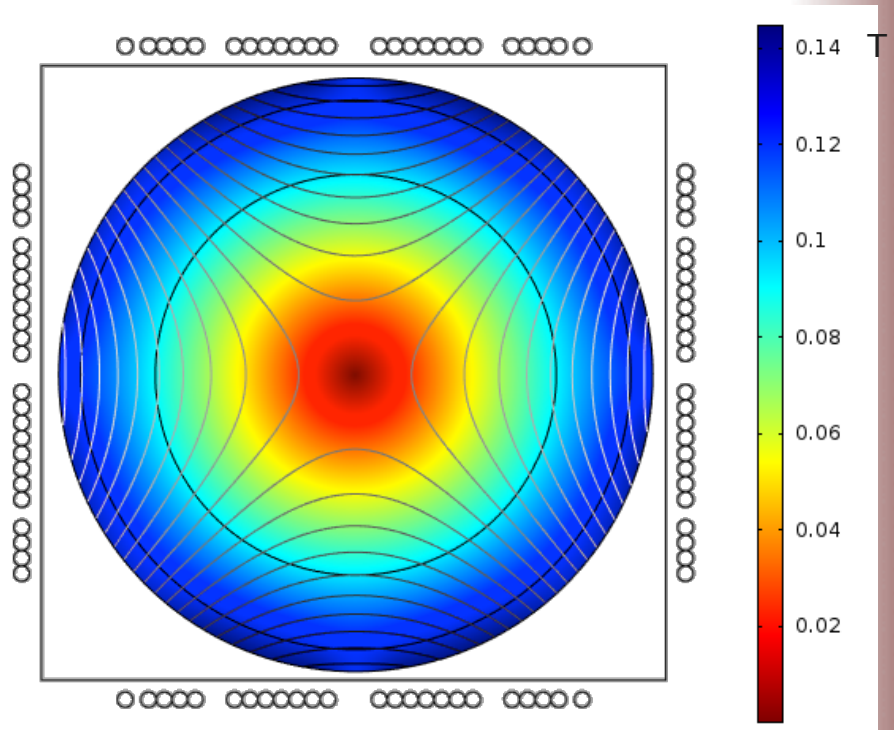


Operate with 15-20 K refrigeration cycle
10 x less AC power to refrigerate,
50 x more heat capacity compared to NbTi @ 4.2 K

2D Field Modeling



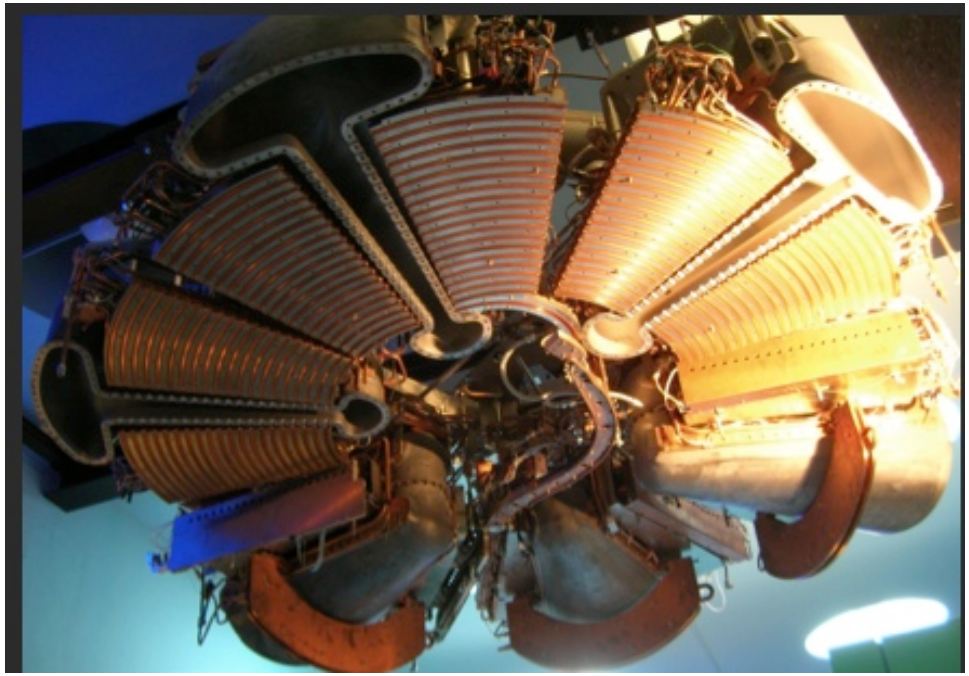
Cold iron pole piece

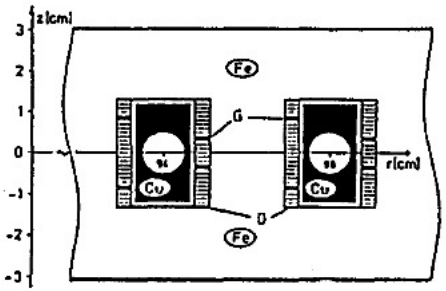


Wire spacing adjusted to kill multipoles

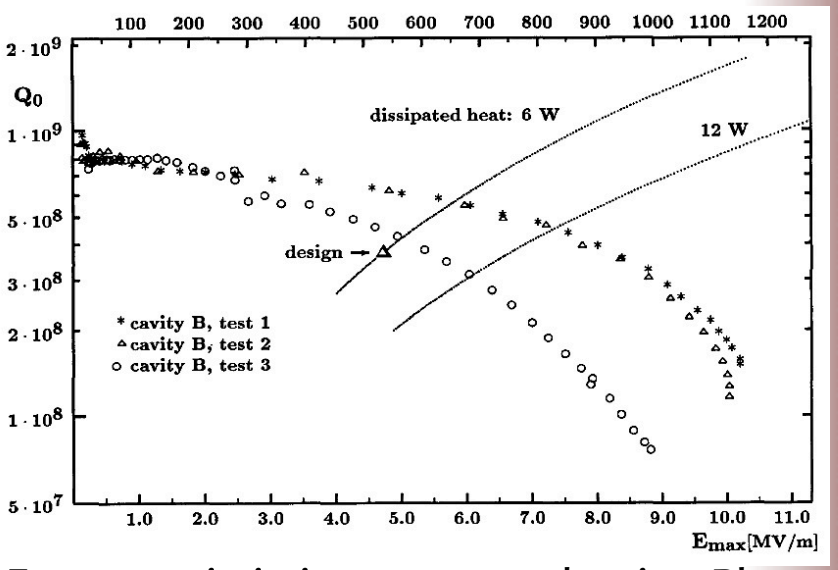
Current density required for 6T/m ~ 235 A

TRITRON was the first to attempt to make a separated orbit cyclotron





The good-field fraction of radial aperture was <50% for each orbit, so admittance was limited.

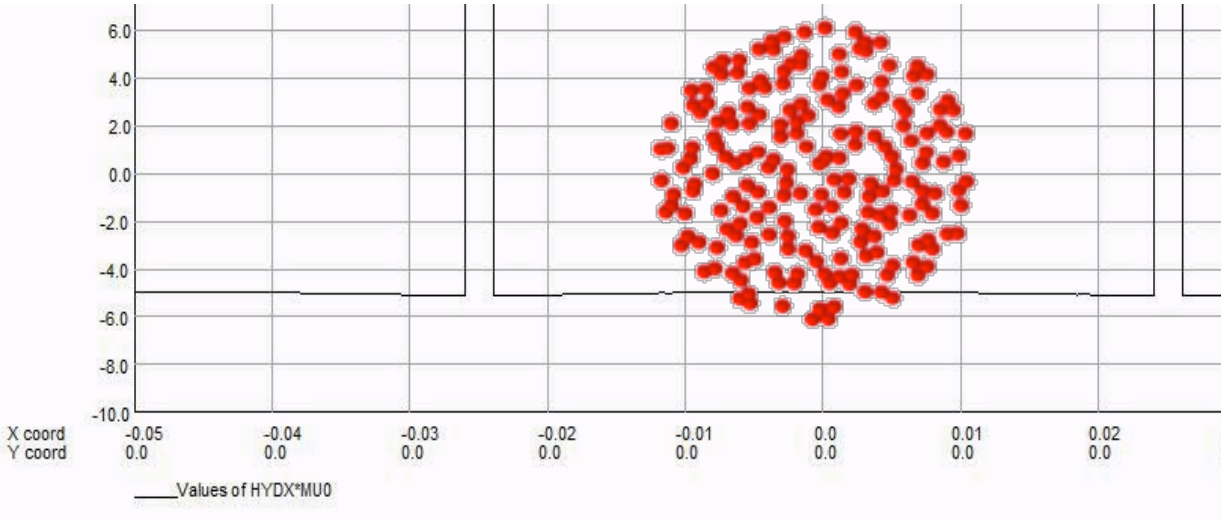


Energy gain in its superconducting Pb cavities was limited by multipacting.

The intervening years of superferric magnet technology (and now MgB_2) and Nb cavity technology make this a fertile time to make a strong-focusing cyclotron for high current.

F-D quads control betatron motion

Uniform gradient in each channel: excellent linear dynamics.

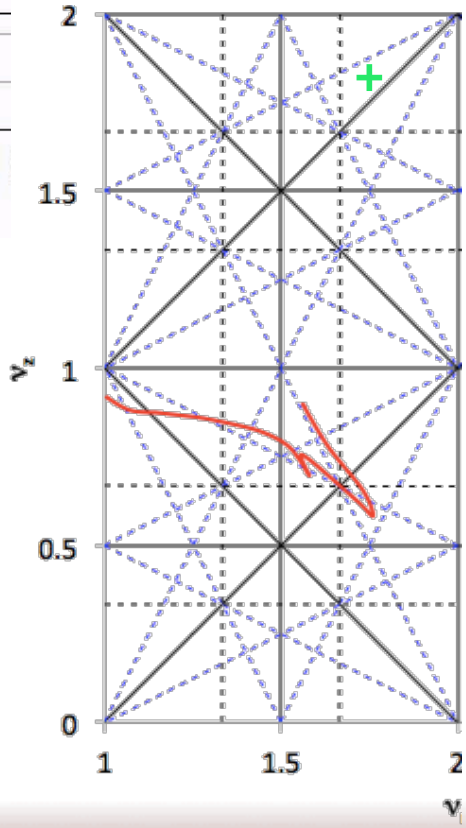


We can lock ν_x, ν_y to any desired operating point.

BTC quads are tuned in 2 x 5 families.

Sextupole correctors at exit of each BTC are tuned in 2 x 6 families.

First 2 turns each have dedicated families so that they can be tuned first for rational commissioning.

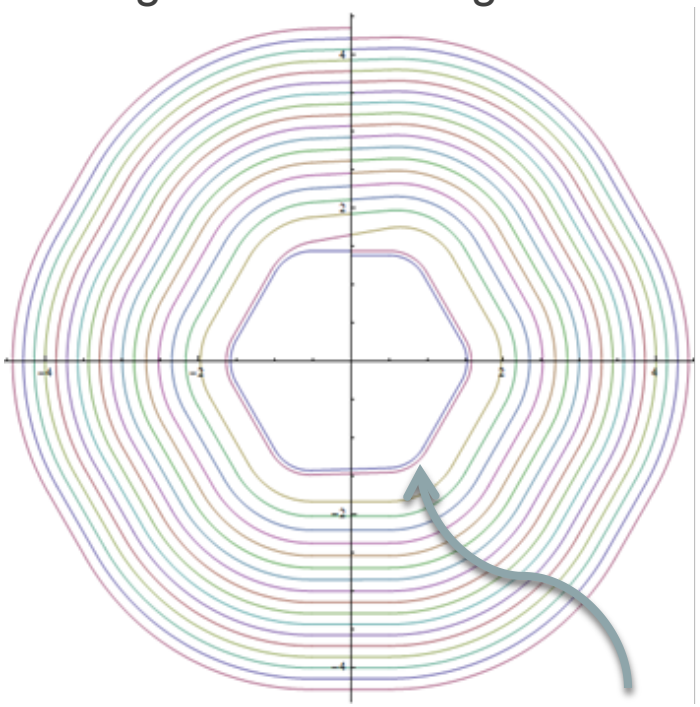


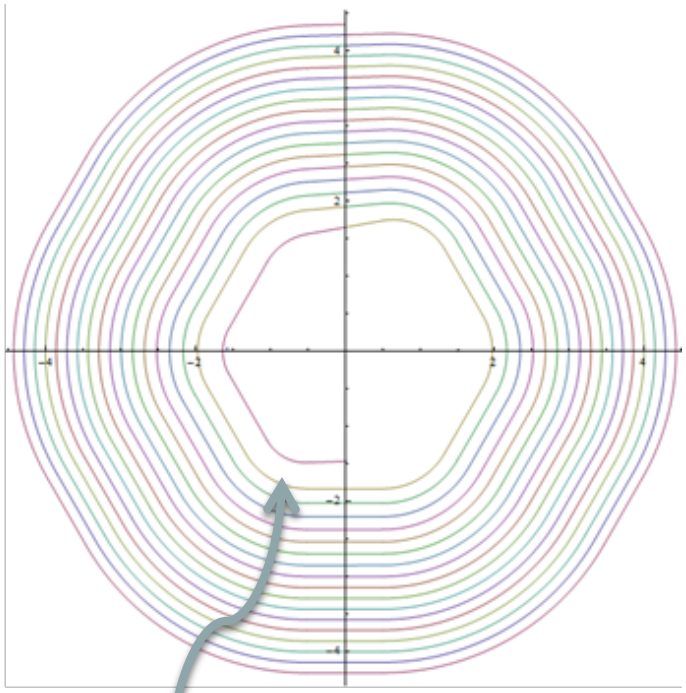
Dipole Corrector

The BTC dipole correctors can be used to maintain isochronicity and locally manage beam spacing at injection, extraction.

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

Design orbits working in from extraction:

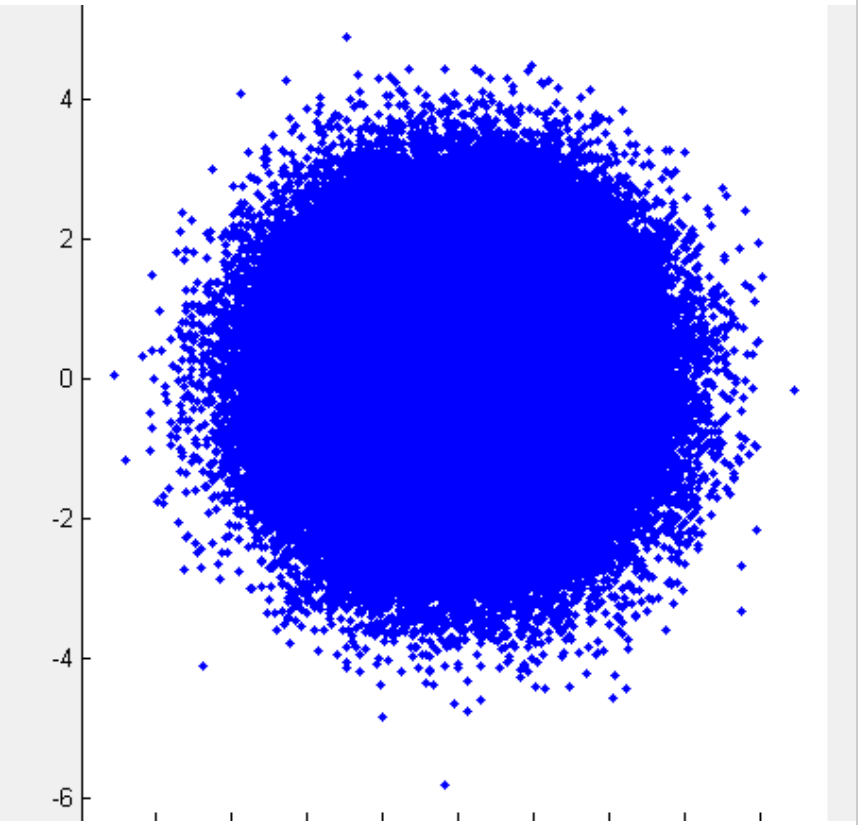




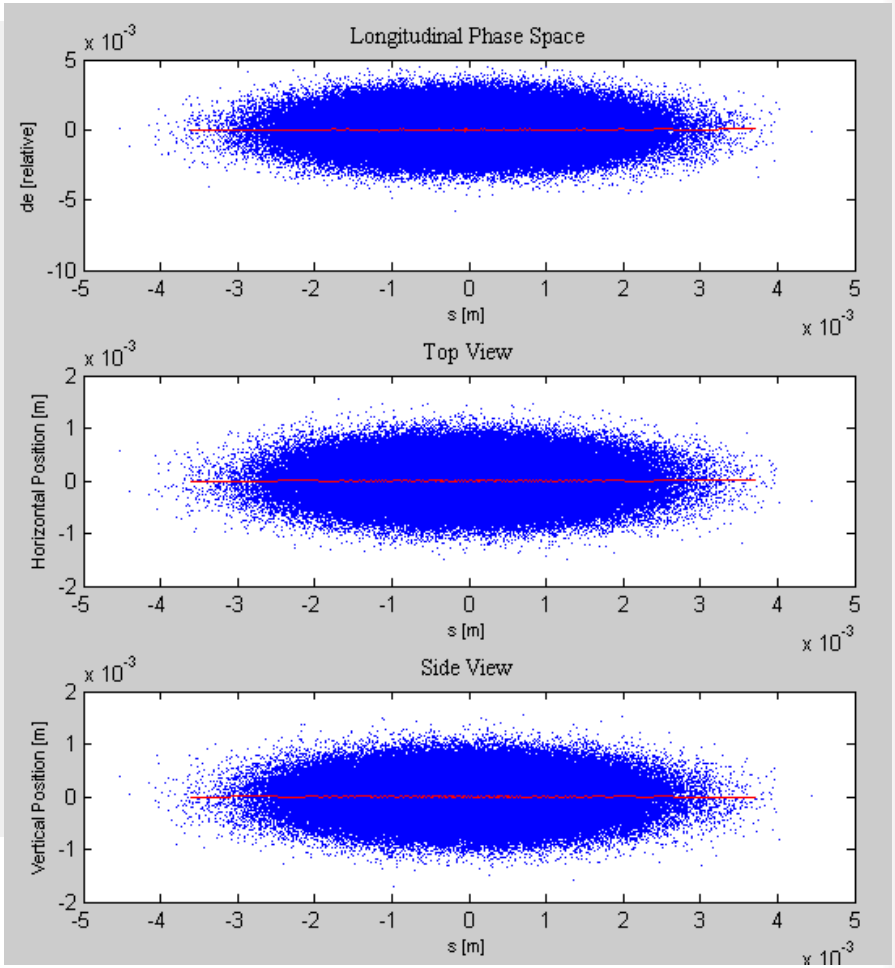
First try gave problematic orbits @ injection

Then adjust orbit pattern using dipole correctors – ideal accommodation for injection

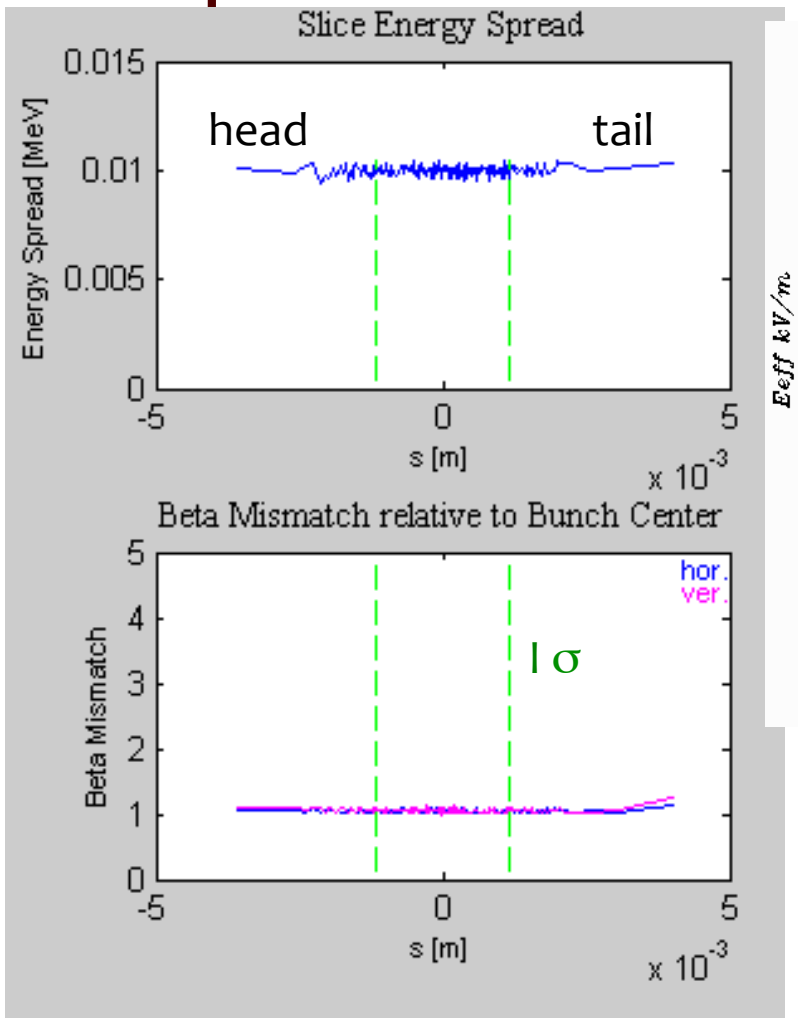
We are modeling 6-D transport through the SFC including effects of x/y coupling, synchrobetatron, and space charge

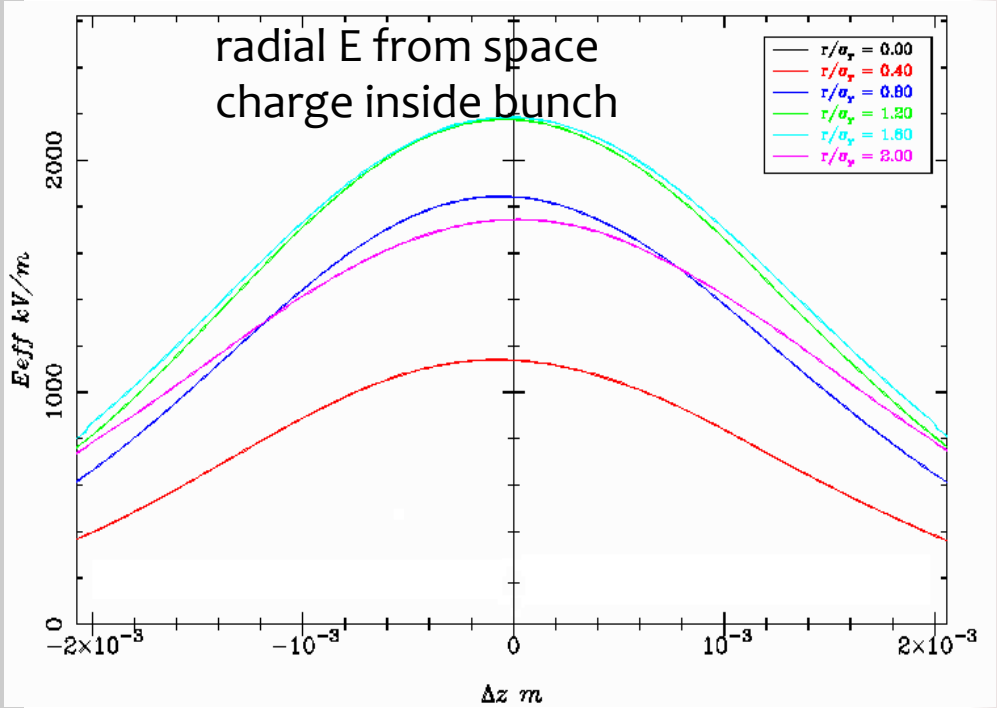


300k particle simulation



Matched optics from injection to extraction. Left pictures shows how a bunch transfers

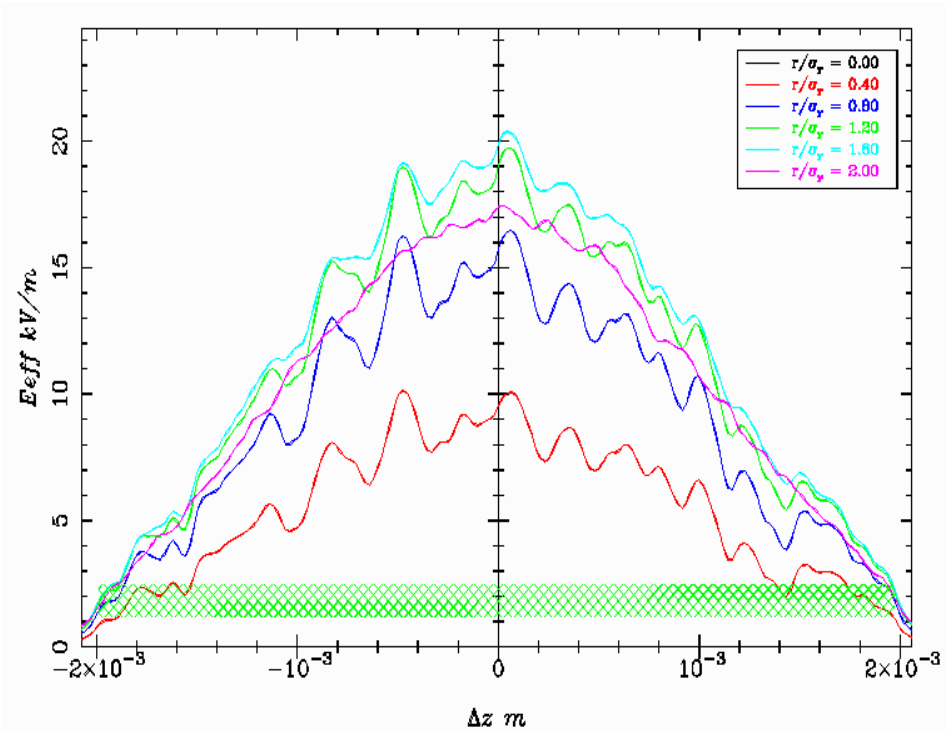


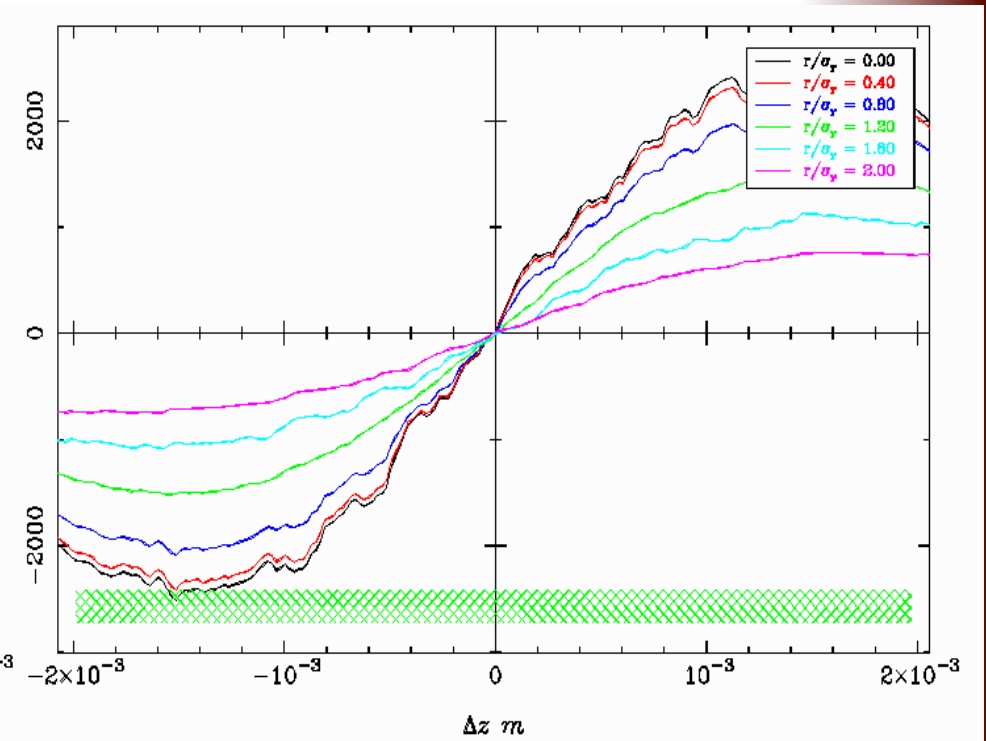


10 mA beam, ± 5° total phase width

Plots of slice energy spread and β mismatch after first turn, sensitive to bunch length – no hourglass from synchrobetatron

Effect of ±.3 MeV energy mismatch on a bunch injected at 9 MeV



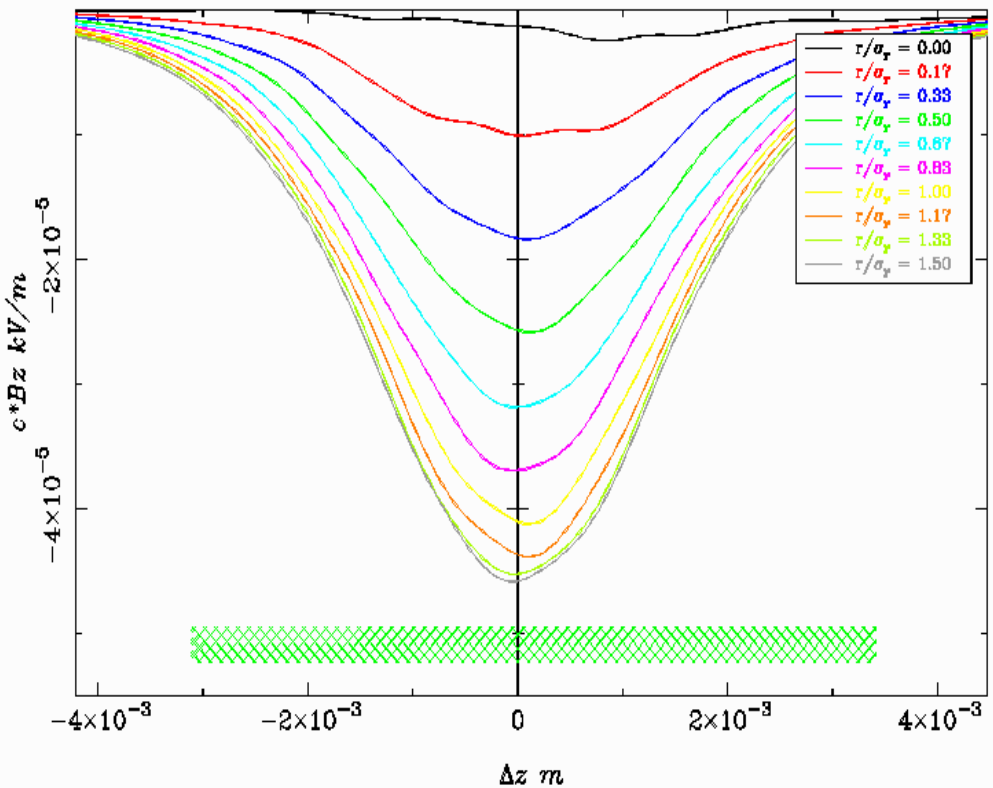


bunch is clumping after half-turn (after 2 cavities)

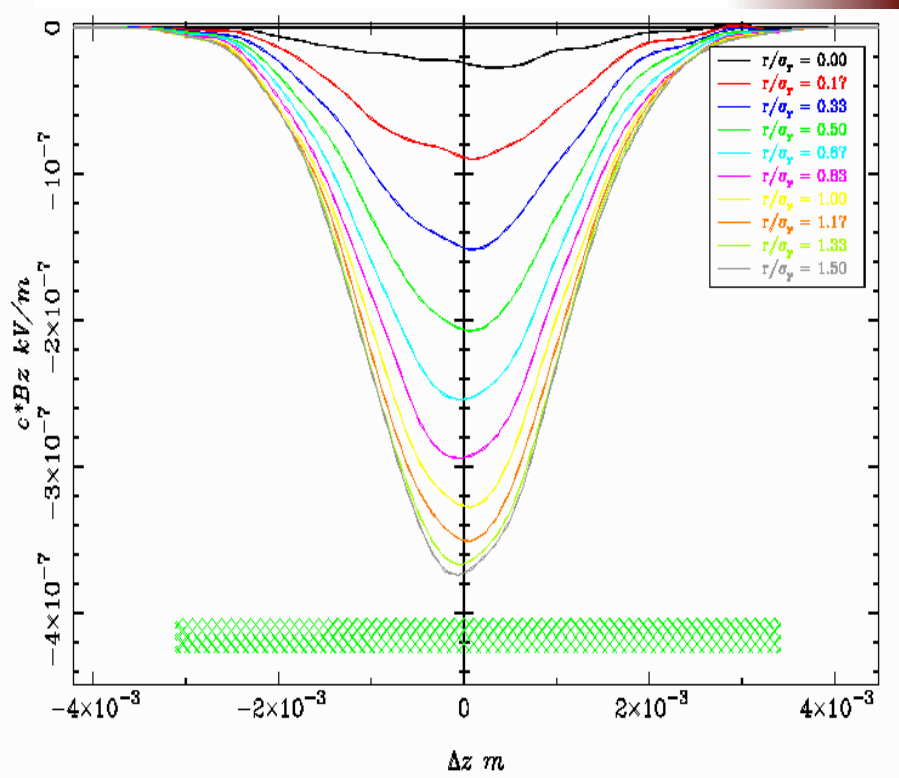
Longitudinal line charges along a bunch - 10 mA beam, injected at 9 MeV.

Radial E from space charge

Distortion in distribution comes from the space charge



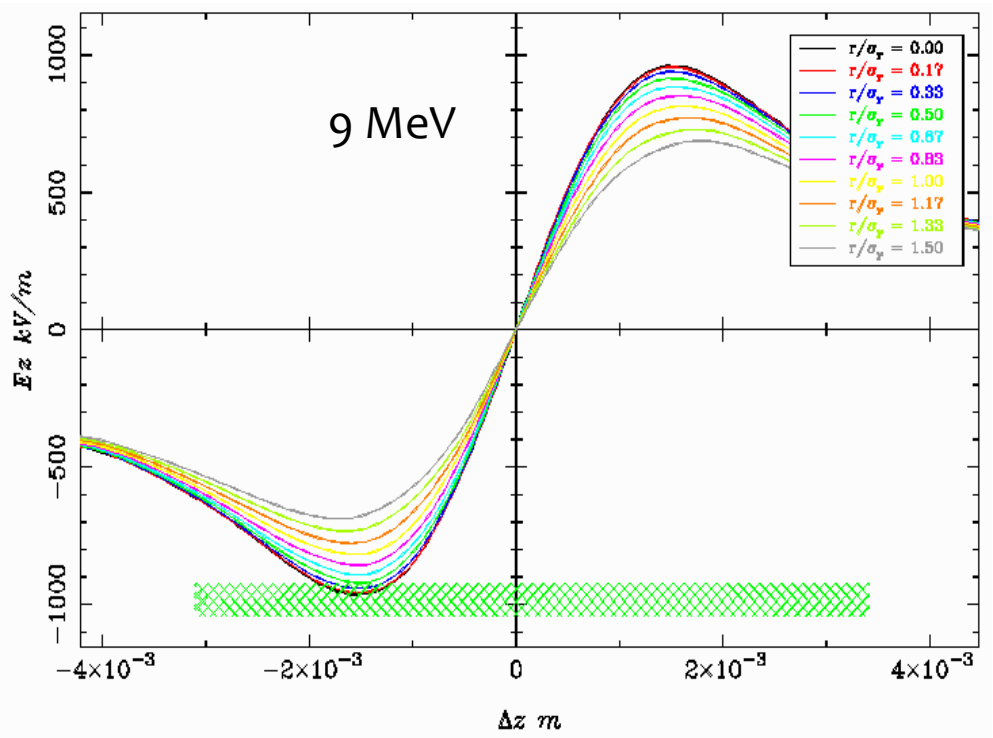
After first cavity

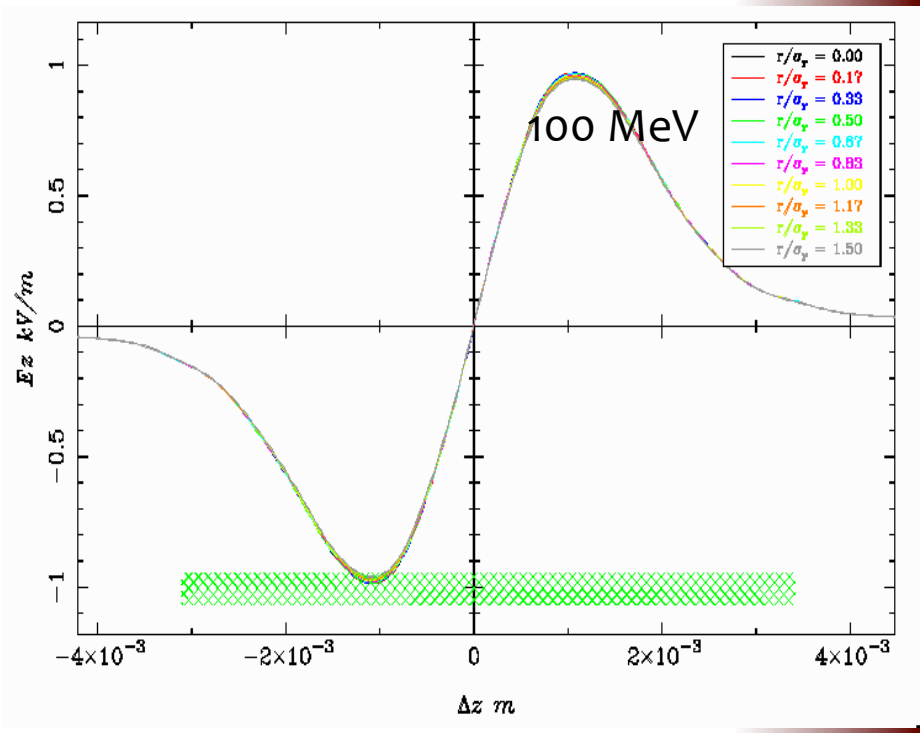


just before extraction

Accelerating bunch at injection, extraction

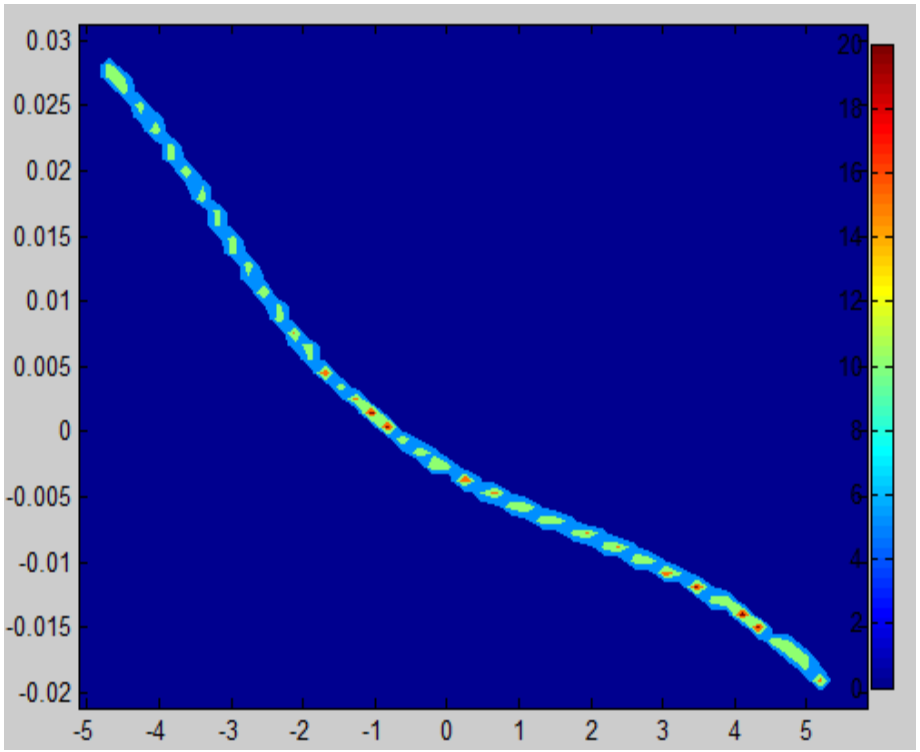
Axial E from space charge





Longitudinal phase space with 10 mA

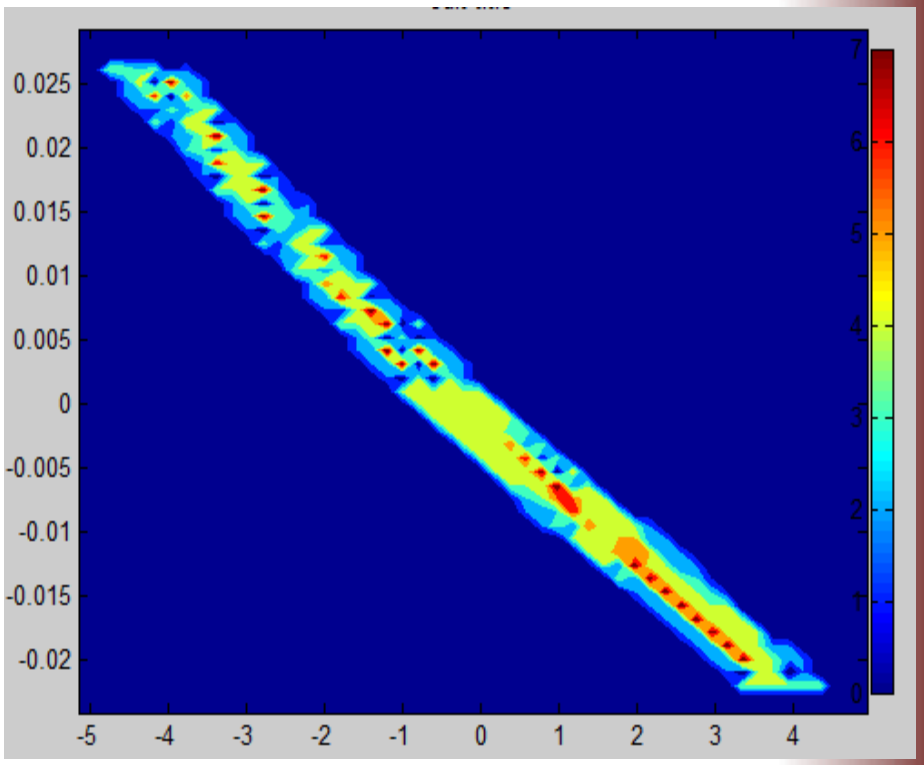
9 MeV injection



±5° phase width

Energy width increases ~30%.

100 MeV extraction

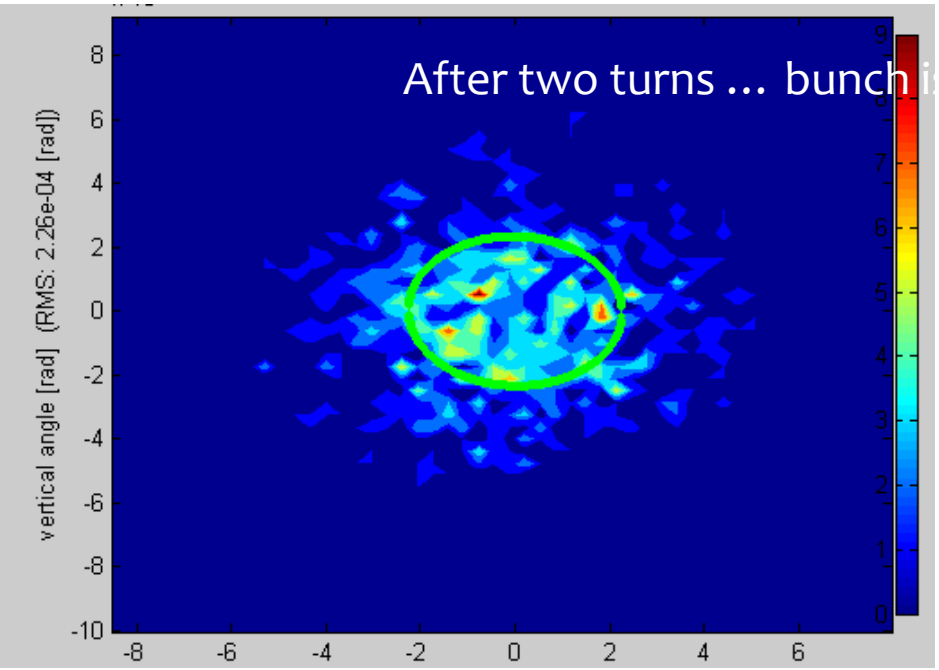


±6° phase width

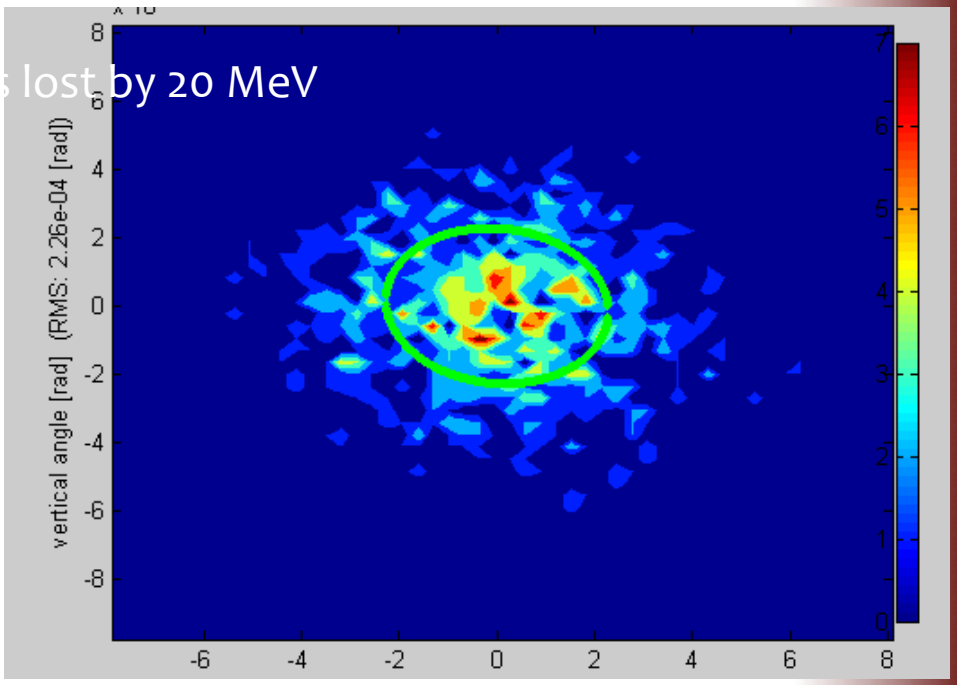
Sextupole correction at exit from each BTC (2 x 6 families)

Effects of synchrobetatron and space charge with 10 mA at extraction:

Move tunes near integer fraction resonances to observe growth of islands:



1/3 order integer effect

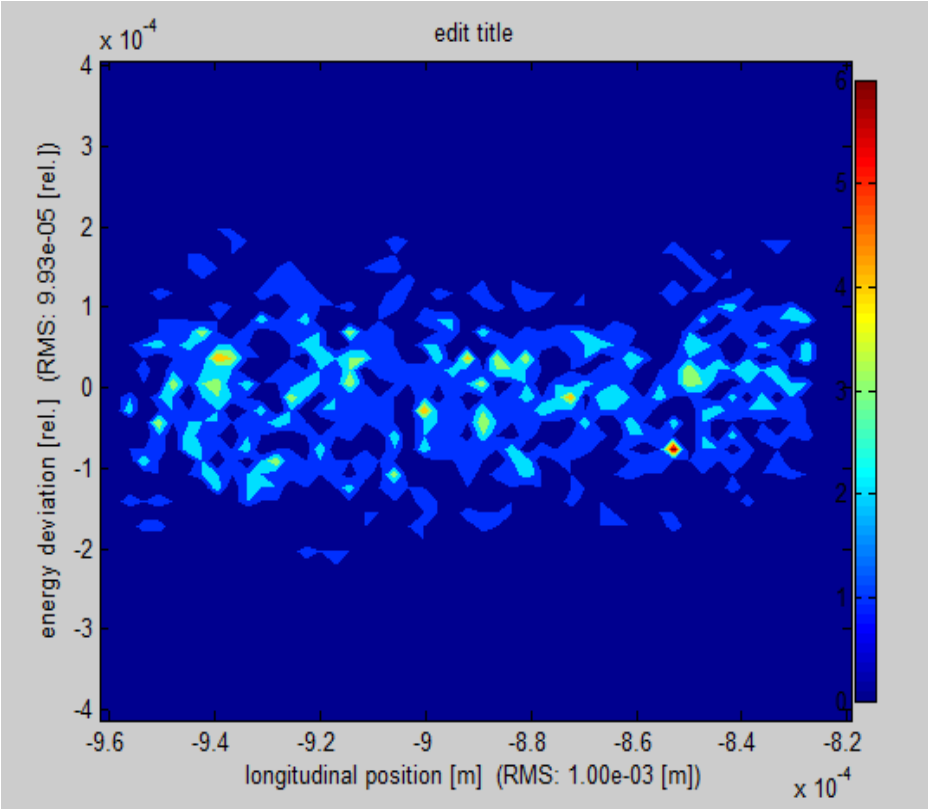


1/5 order integer effect

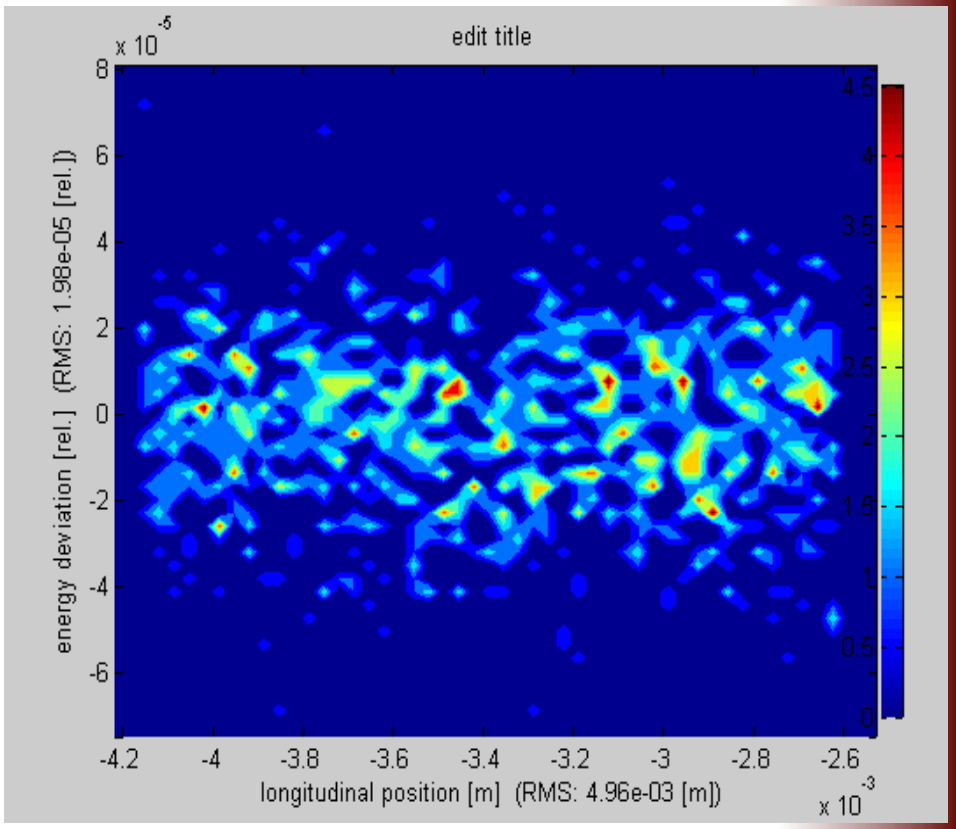
1/5-order islands stay clumped, 1/3-order islands are being driven.
Likely driving term is edge fields of sectors (6-fold sector geometry).
We are evaluating use of sextupoles at sector edges to suppress growth.

Synchrobetatron/space charge in longitudinal phase space:

Tunes again moved to approach resonances, but retaining transmission through lattice



Injection

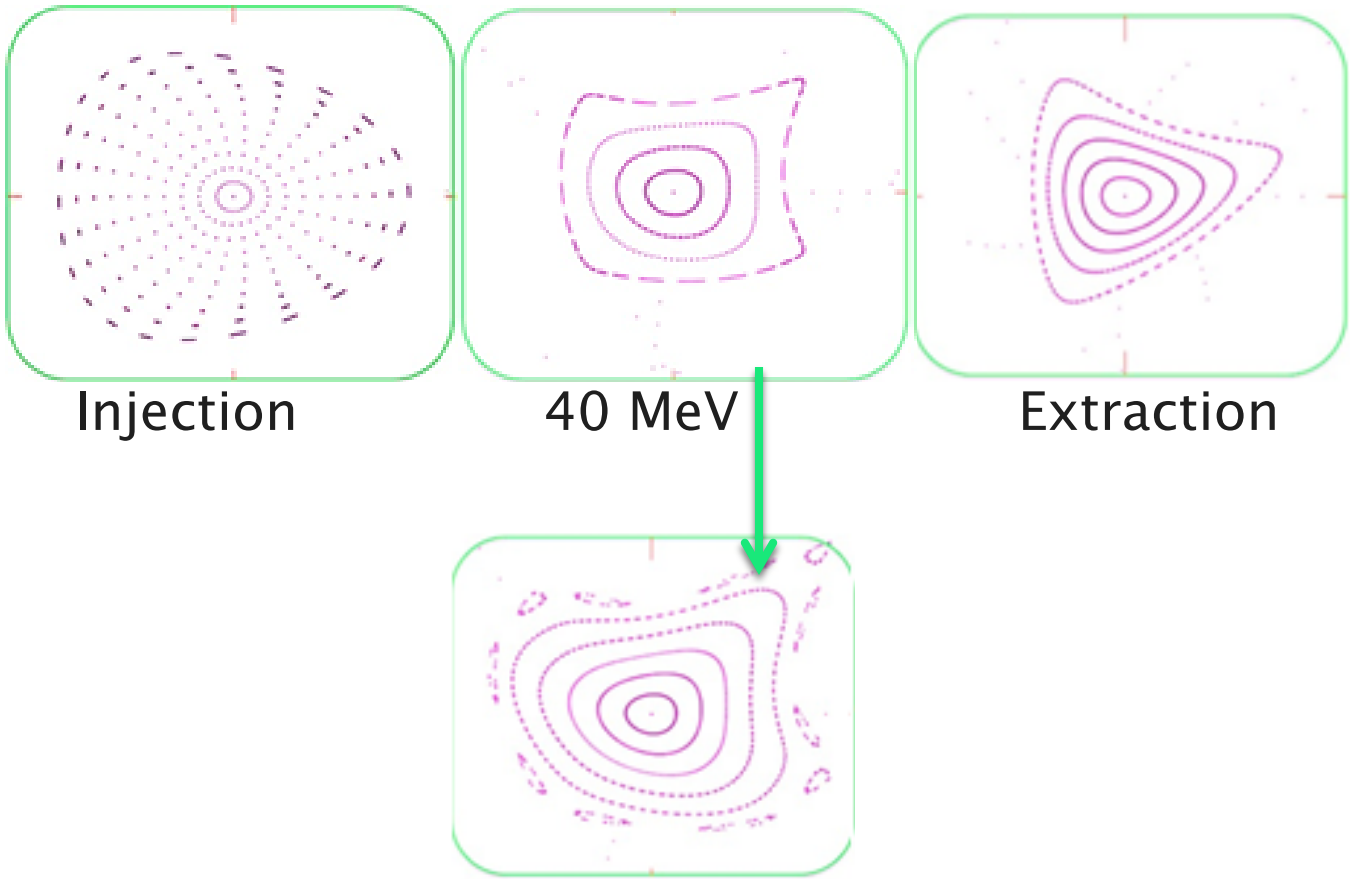


extraction

Phase width grows x5 at extraction.

Poincare Plots through acceleration

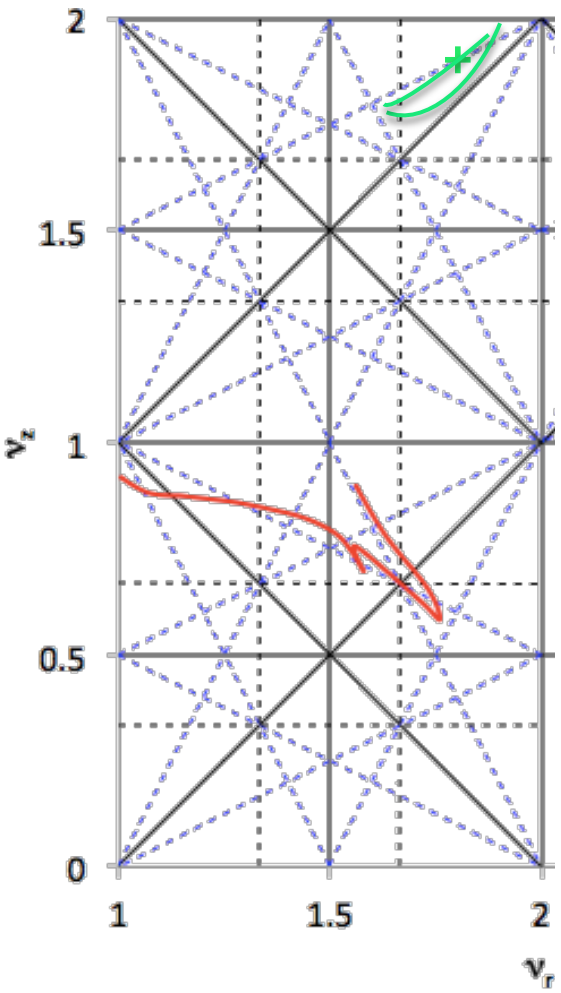
3.5 mA beam



Now change the tune to excite a 7th order resonance

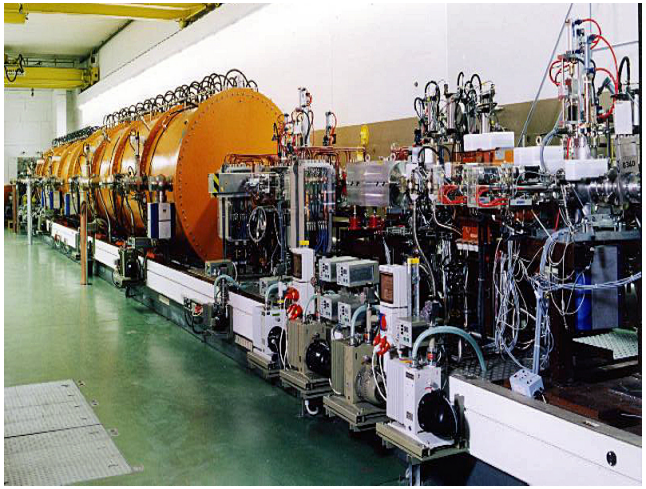
The SFC gives us the tools to control space charge tune shift

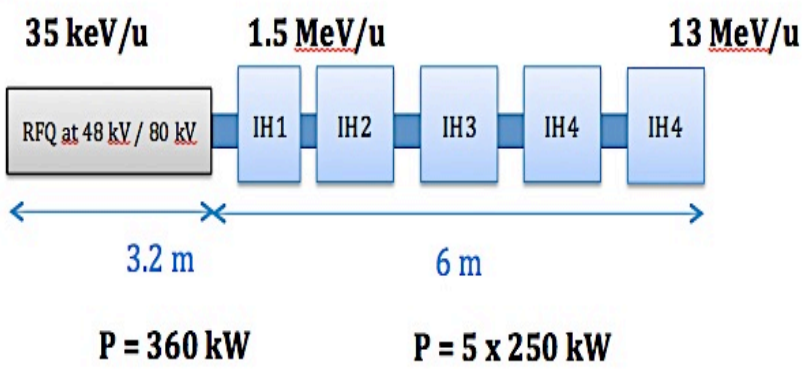
Space charge produces a tune shift that depends upon the location of each particle in the bunch. We can choose an operating point that gives maximum room for the entire envelope of tunes out to 5 σ in the Poincare plot are contained within a region with no low-order resonances.



Preliminary parameters for MEIC SFC:

Injection: NTG has prepared a candidate design for an RFQ and IH structure that could accelerate 0.1 – 10 mA of beam over the range m/q = 1-2.

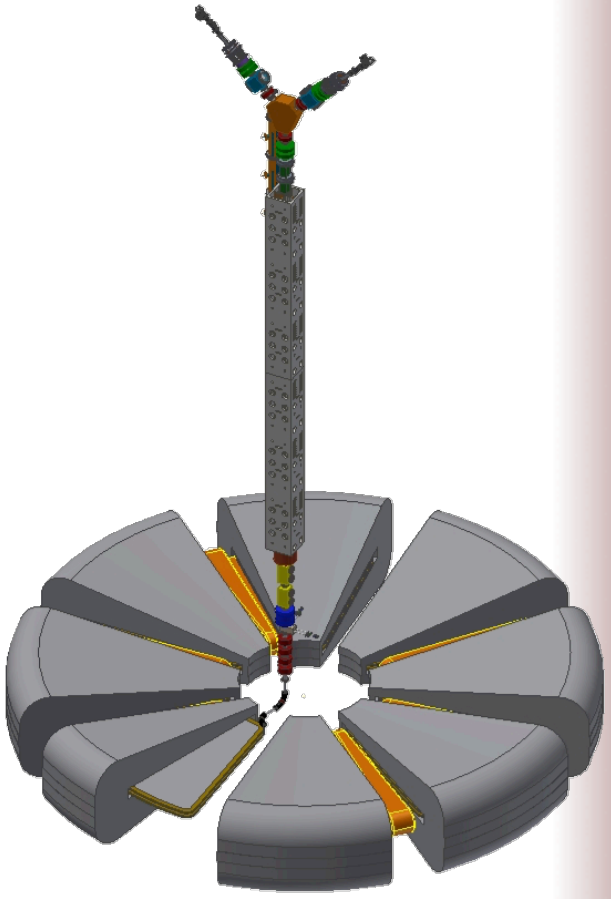




They have given a budgetary price of $8 M, exclusive of rf power.

MEIC SFC:

- *Injection energy* — *13 MeV/u*
- *Extraction energy* — *100 MeV/u*
- *m/q range* — *1-2*
- *Overall diameter* — *10 m*
- *Max dipole field (d)* — *1.4 T*
- *Max cavity surface field (d)* — *22 kV/m*
- *# orbits* — *30*
- *Injection/Extraction radius* — *1.5 m / 4.0 m*
- *# Sectors, Cavities, Orbits* — *8, 6, 24*
- *Normalized emittance* — *1 p 10^{-6} m*
- *Momentum spread* — *10^{-3}*
- *Injection/extraction bunch length .008/.024 m*
- *Total peak rf power* — *24 MW*
- *Rf frequency* — *204 MHz* = β(100 MeV/u) x 476 MHz



The most expensive component system is the rf power. We have obtained a budgetary quotation from Continental Electronics = $37 M. Next most expensive components are rf cavities. We would use cryo-copper cavities for an SFC for MEIC. Budgetary estimate = $1 M each.

Conclusion and Future plans

- ***One SFC can provide efficient acceleration of ions for MEIC over the full range of beam current and for all ions in range m/q = .1 – 10 MA.***
- ***Extraction energy is 100 MeV/u. Cannot give higher energy for p.***
- The SFC gives the separation of orbits and focusing control to accelerate high-current beams without beam breakup or filamentation.
- The Texas A&M group has received funding from the Accelerator Stewardship Program to develop simulations of beam dynamics for the SFC, and design tools for its optimization.
- We have obtained budgetary estimates for the most expensive components for a SFC designed for the MEIC injector.
- ***Total projected cost for RFQ + IH + SFC is ~$75 million.***
- We request encouragement from MEIC to develop the SFC design further and to carry cost estimation to a next level of detail.
- **<u>SBIR topics:</u>** **Cryo-copper slot-geometry half-wave cavity**

  Levitated-pole Superconducting Sector Dipole

  Superconducting Beam Transport Channel

Acknowledgements

Thank you!