Strong-Focusing Cyclotron: Optimum Driver for ADS Fission and Isotope Production

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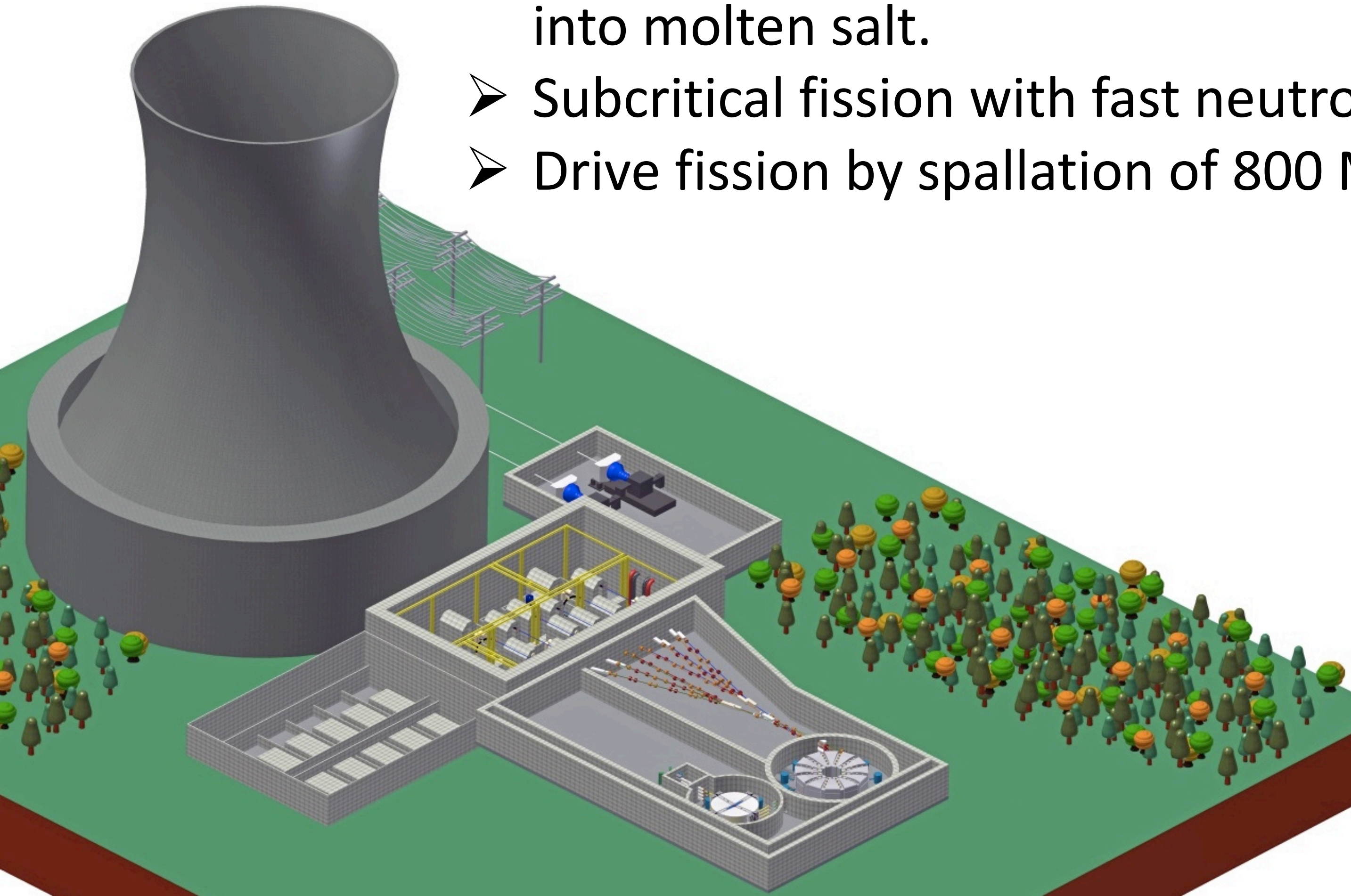
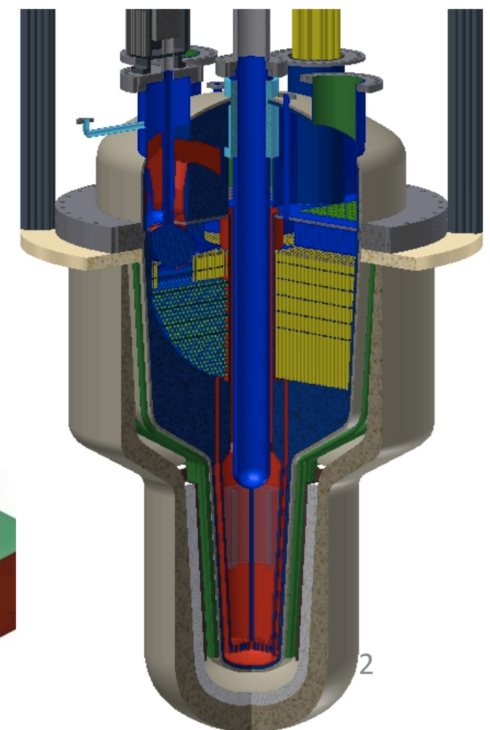
We invented the strong-focusing cyclotron as a proton driver for ADS fission

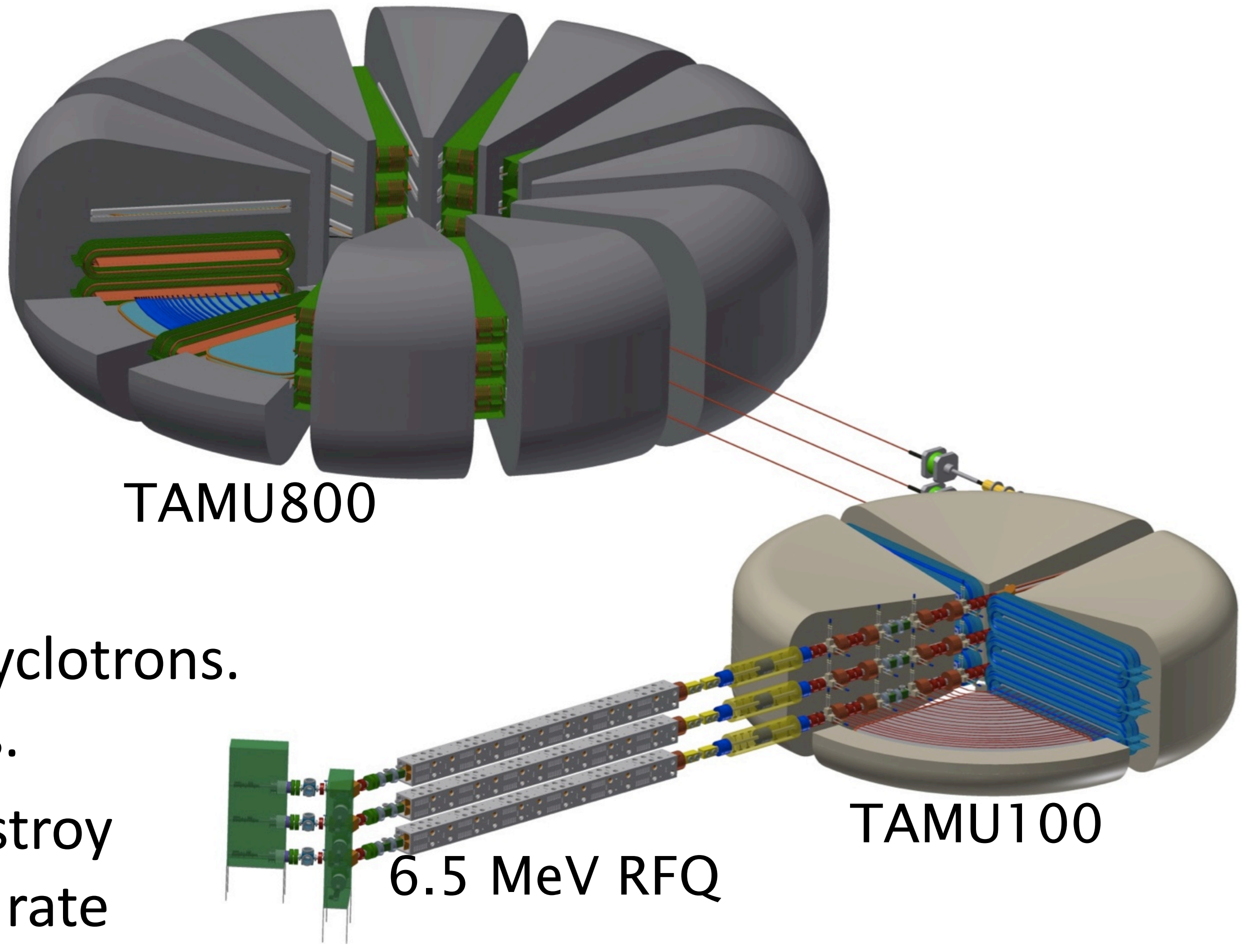
Destroy the transuranics in spent nuclear fuel

- Extract the transuranics from spent nuclear fuel into molten salt.
- Subcritical fission with fast neutronics
- Drive fission by spallation of 800 MeV protons





We need high power CW proton beam for ADS:
Strong-Focusing Cyclotron



Flux-coupled stack of 3 cyclotrons.

10 mA CW proton beams.

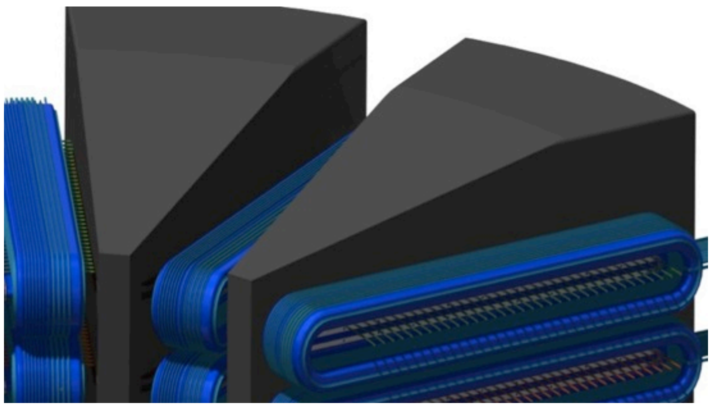
Drives 9 ADS cores to destroy transuranics at the same rate they are made in a GW_e power plant.

Generates power as a 5:1 energy amplifier.

The Strong-Focusing Cyclotron

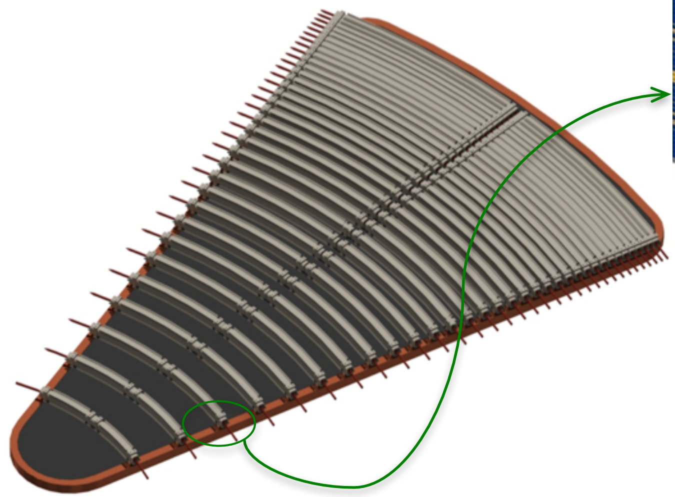
Three key innovations enable us to accelerate 10 mA CW proton drive beam or 1 mA microemittance beam.

Superconducting RF cavities to fully separate orbits



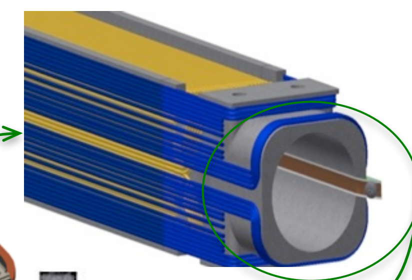
All orbits fully separated, 1.8 MV/cavity energy gain

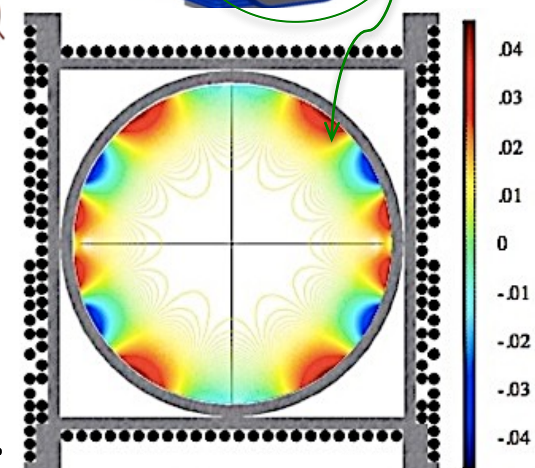
Flux plate dipole = stackable staircase



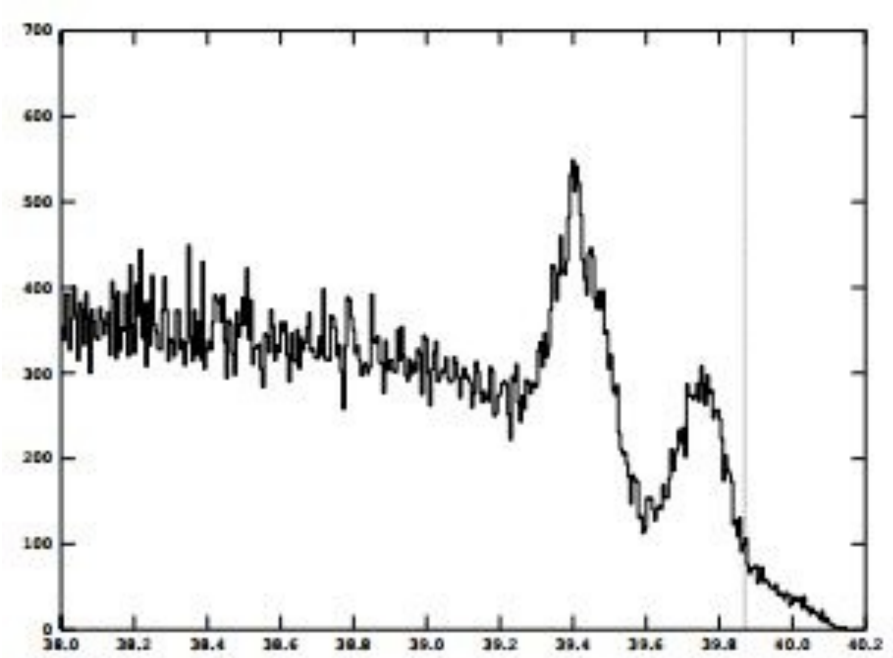
Fix betatron tunes throughout acceleration.

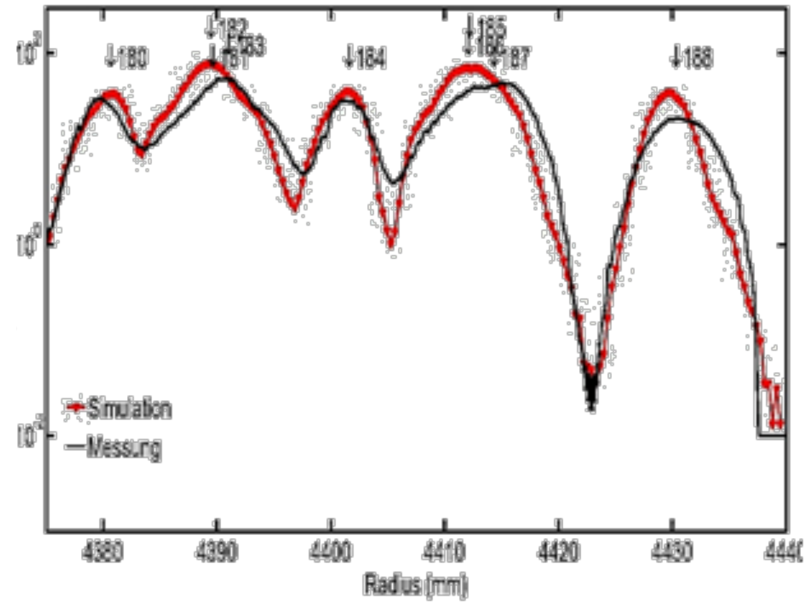
Quadrupole doublet transport channels





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.

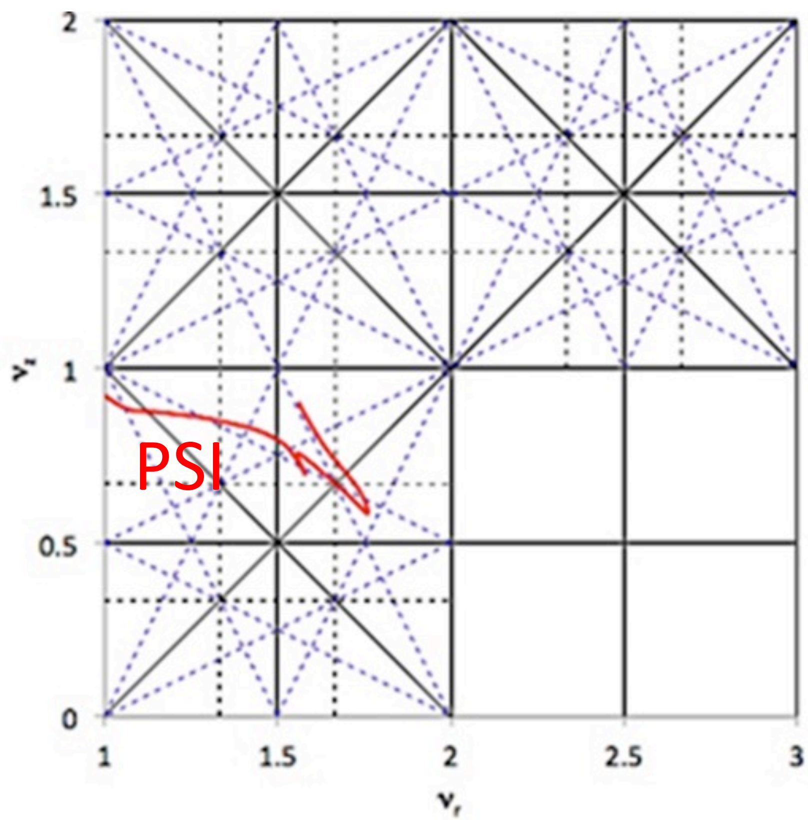
2) Weak focusing, Resonance crossing

Cyclotrons are intrinsically weak-focusing accelerators

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

Scaling, Non-scaling FFAG utilize non-linear fields

- Rich spectrum of unstable fixed pts



Space charge shifts, broadens resonances, feeds synchro-betatron
Even if a low-charge bunch accelerates smoothly, a high-charge bunch may undergo breakup even during rapid acceleration

The motivations for the SFC…

- Fully separate successive orbits
  - Minimize bunch coupling
  - Minimize/control space charge tune shifts
- Maintain tight control of isochromaticity
  - Maintain maximum longitudinal admittance
- Provide strong-focusing with tight control of betatron tunes
  - Prevent resonance crossings
  - Maximum transverse admittance

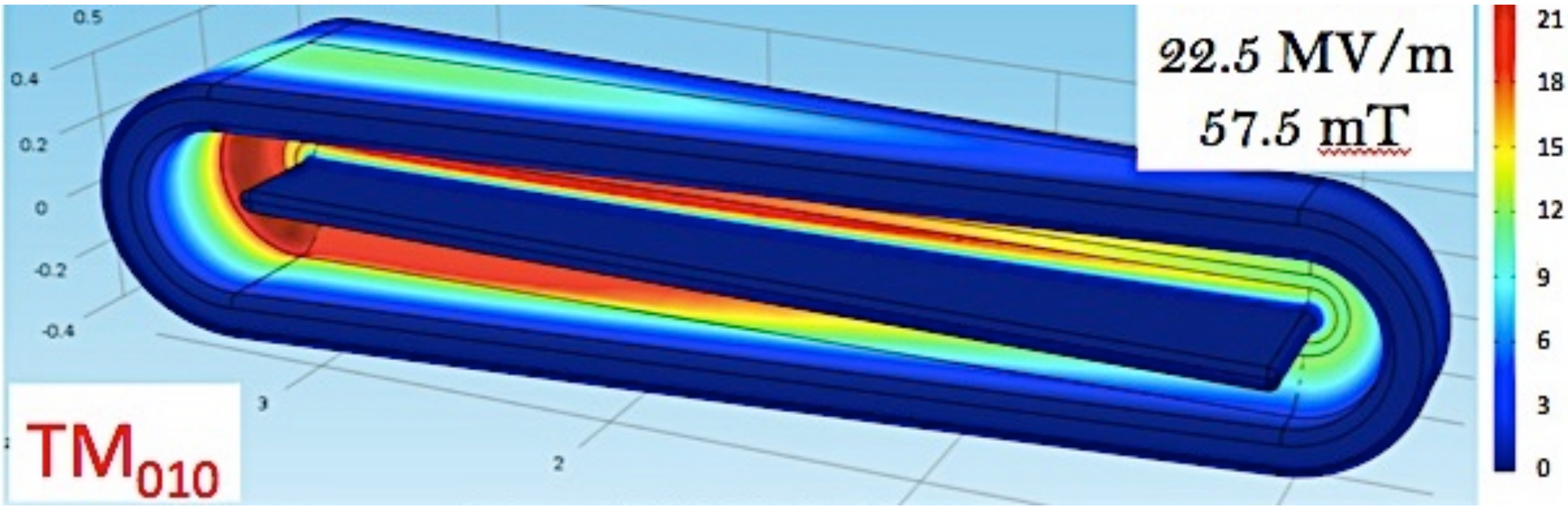
We have just completed Year 2 of a systematic effort to simulate and optimize beam dynamics in an SFC

Funded by DOE Accelerator Stewardship Program

- Derive isochronous reference trajectory using realistic (extracted from FEA models) magnetic and electric fields.
- Determine quad doublet strengths of the strong focusing channels using single-particle linear optics.
- Simulate high current beam in the strong focusing cyclotron using OPAL-T drift and combined function dipoles. Adjust operating point of the cyclotron for beam currents ≥10 mA.
- Model sector magnets with channel quad coils in place for OPAL cyclotron calculations.
- Model strong focusing cyclotron using realistic 3D fields from sector magnets and RF-cavities.

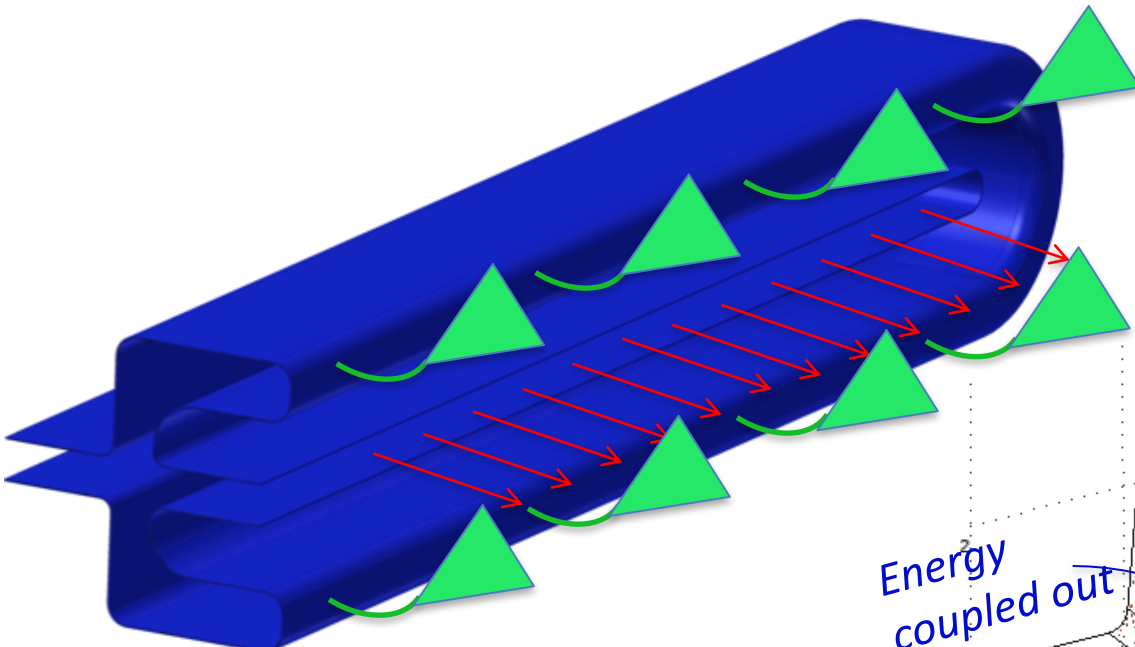
SRF Cavity: slot-geometry ¼-wave structure

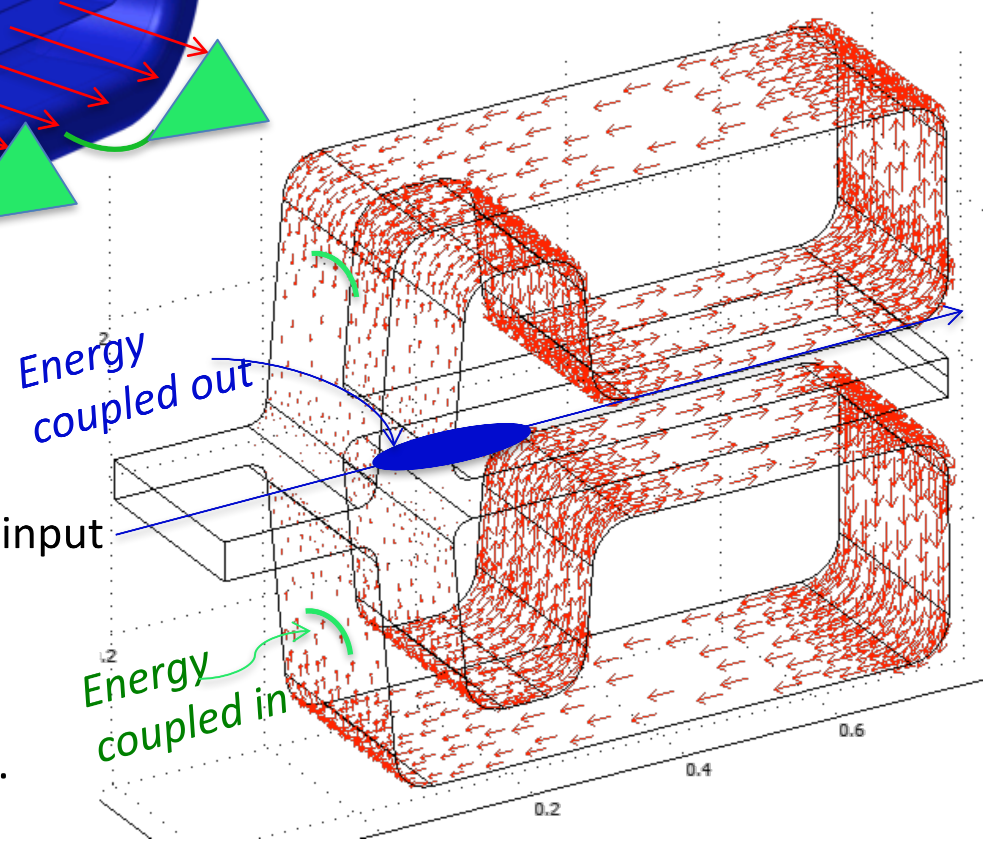
Ends close topologically top/bottom so accelerating mode is not shorted out: smooth fields to end.



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

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

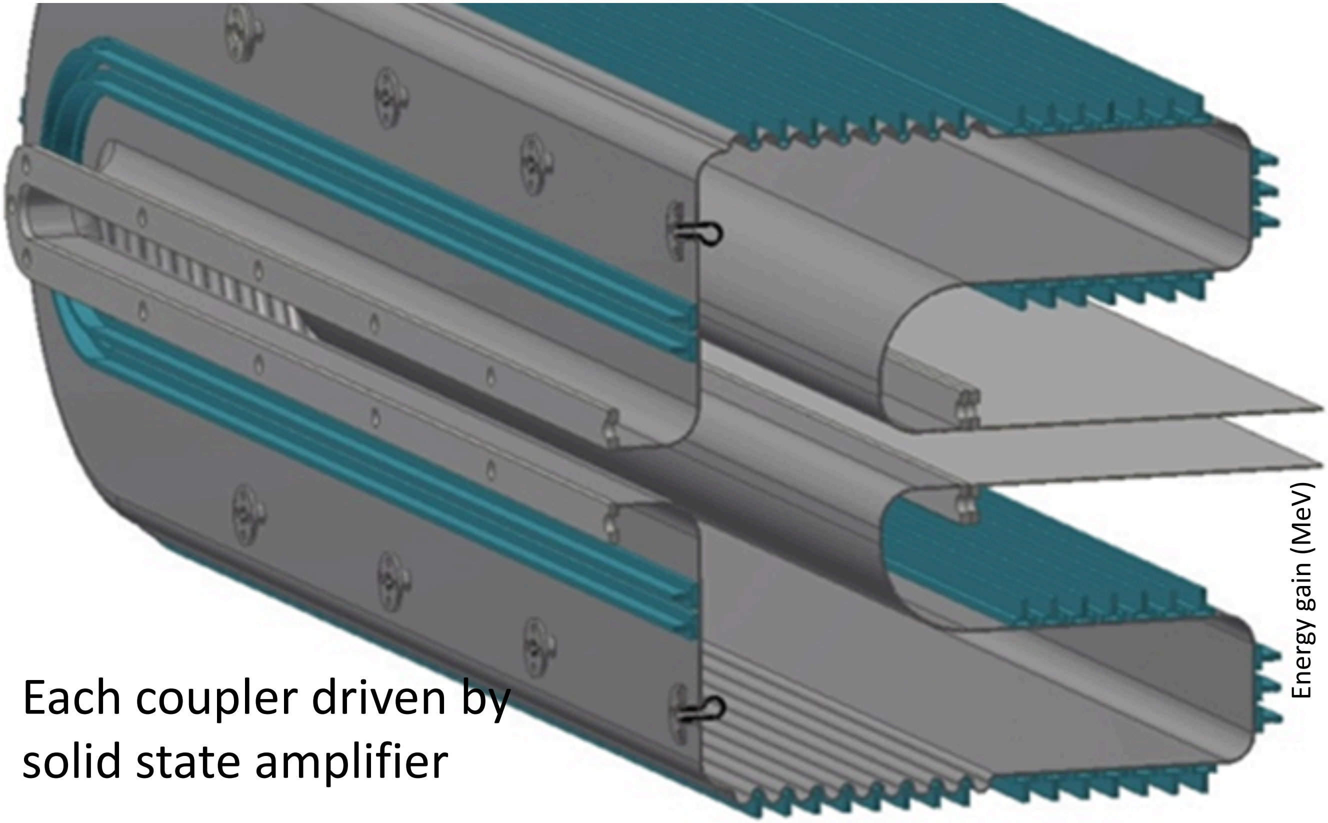




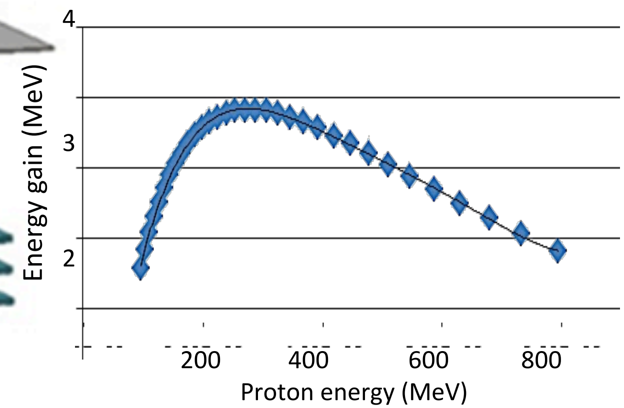
RF power is coupled to the cavity by rows of input couplers along the top/bottom lobes.

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

Linear coupler array to match drive to beam loading, convolutes to suppress multipacting



Each coupler driven by solid state amplifier

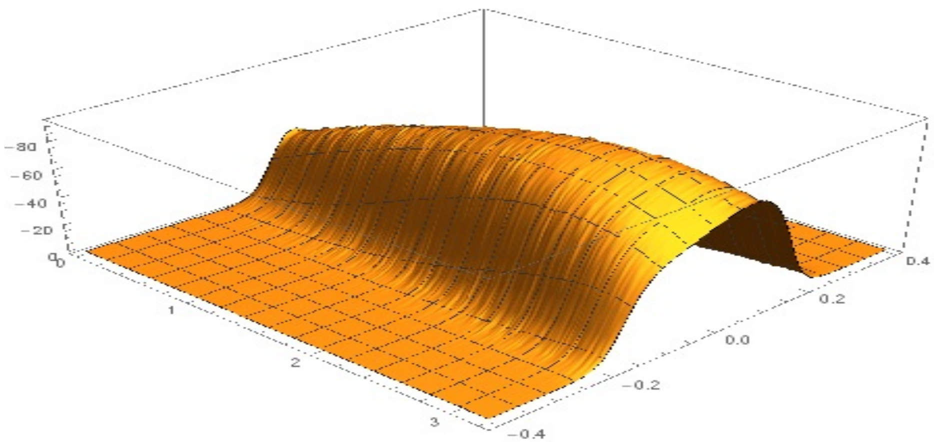


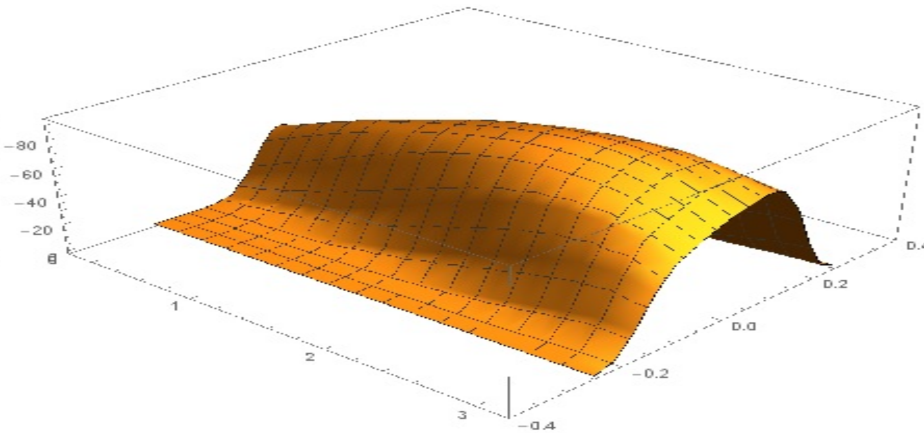
Distributed drive matches to distributed beam loading for stability under high beam loading.

Note: this requires that all orbits are made very close to isochronicity…

Calculate cavity fields in 3-D FEA (COMSOL)

Midplane $E_s(s,x)$

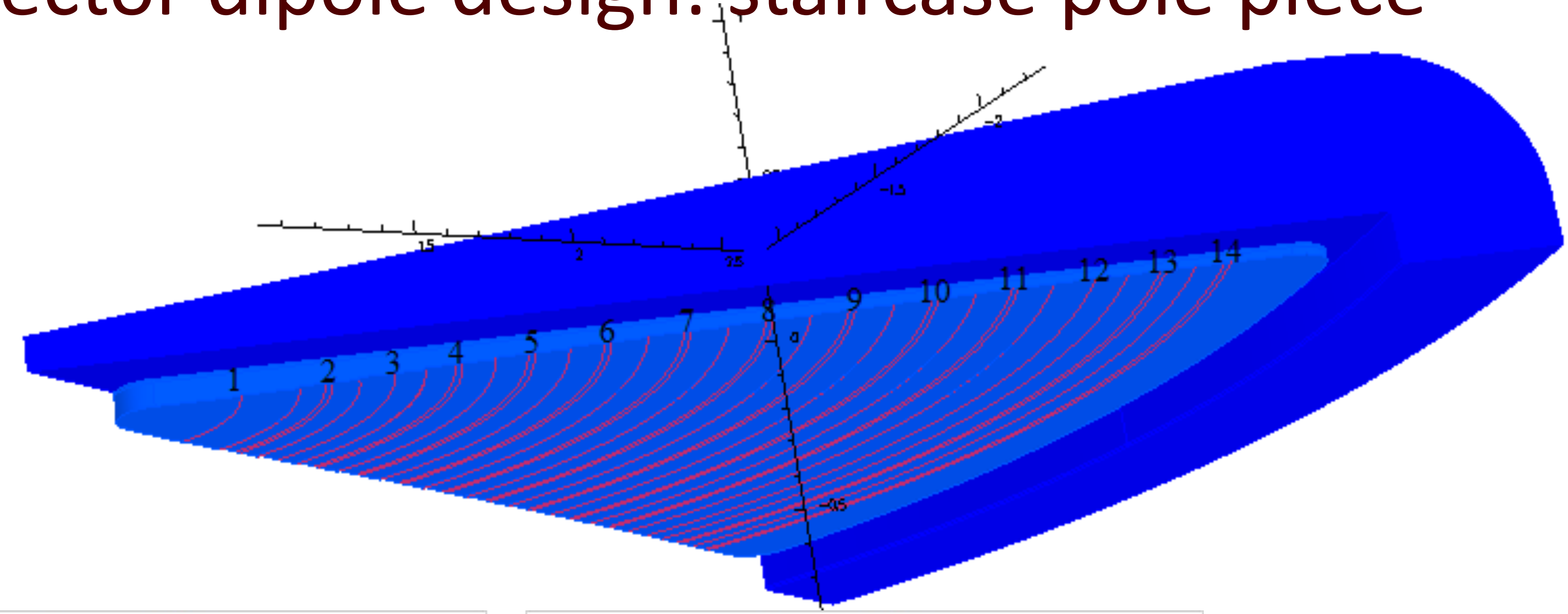


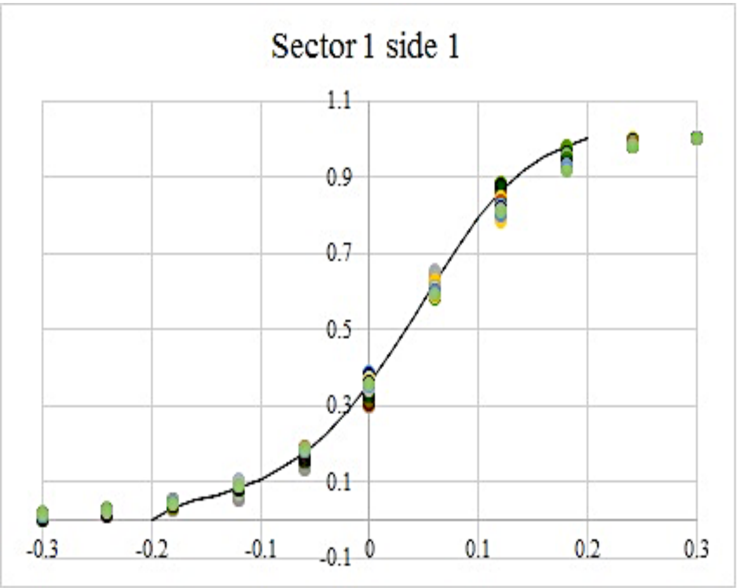


from FEA model…

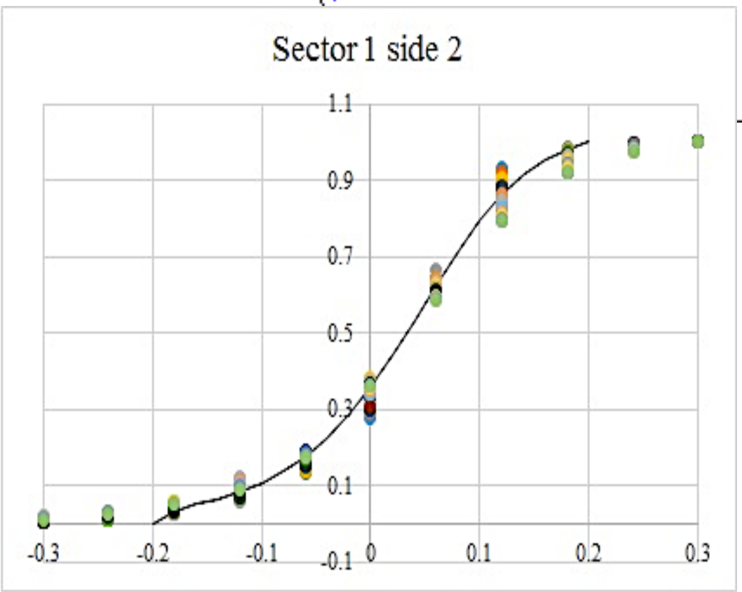
smoothed Runge-Kutta parametrization

Sector dipole design: staircase pole piece





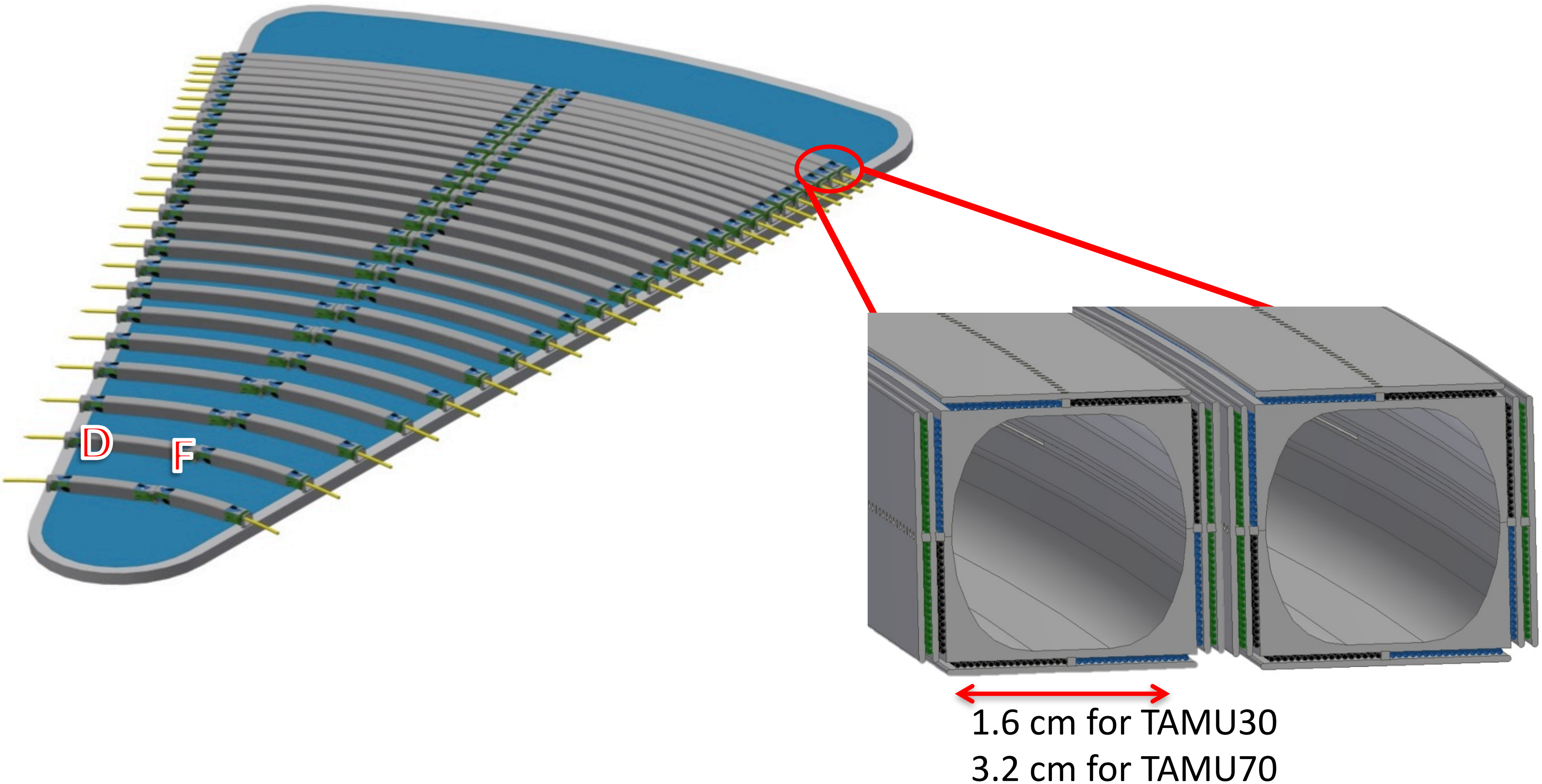
3-D FEA (mid-plane field @ edge…



parametrized fields

Vector Fields
software for electromagnetic design

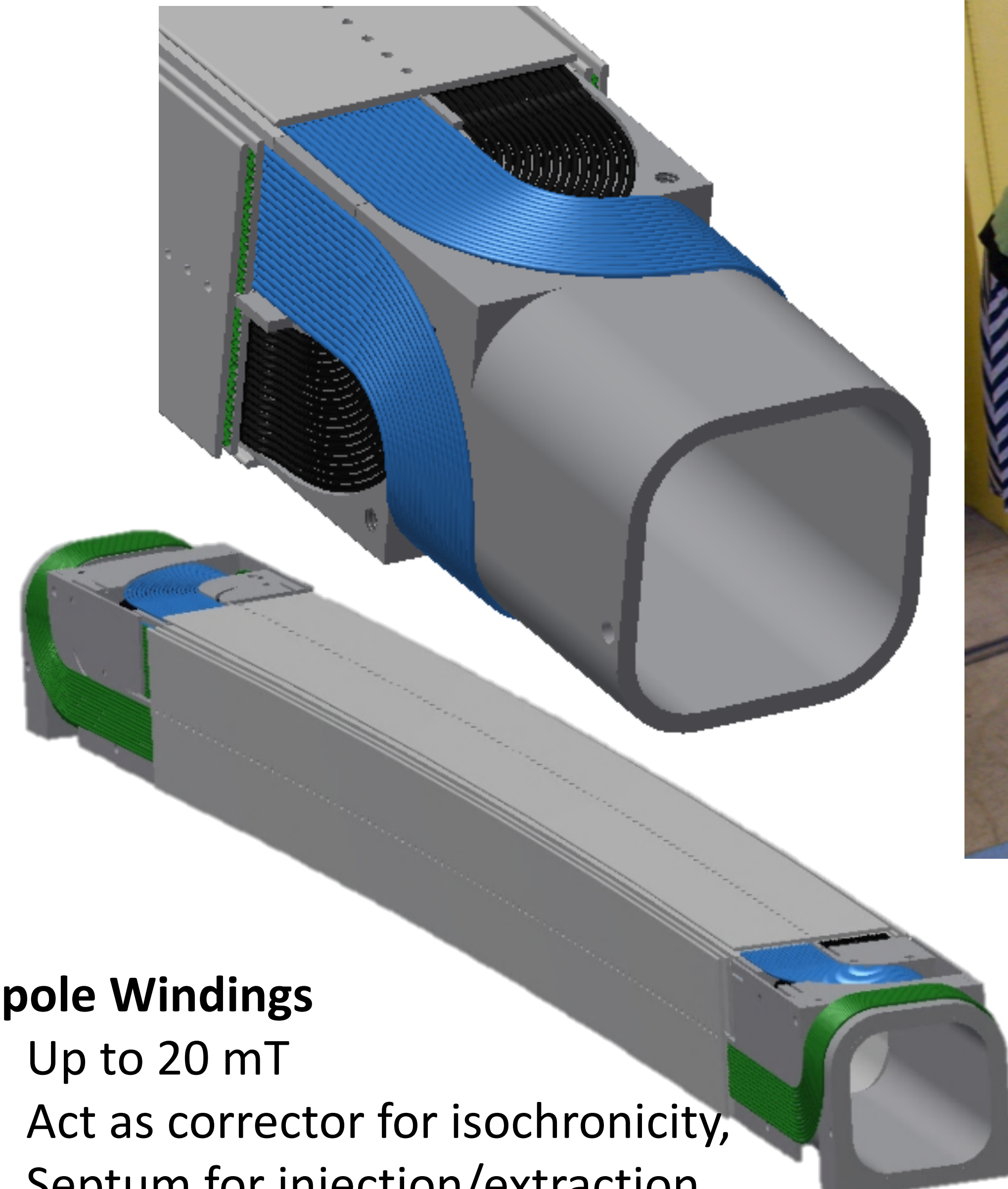
F-D doublet in each orbit, each sector



BTC dimensions are set by the requirements for beam separation at extraction.

>80% of horizontal aperture is useful for orbits.

MgB_2 windings on beam transport channels

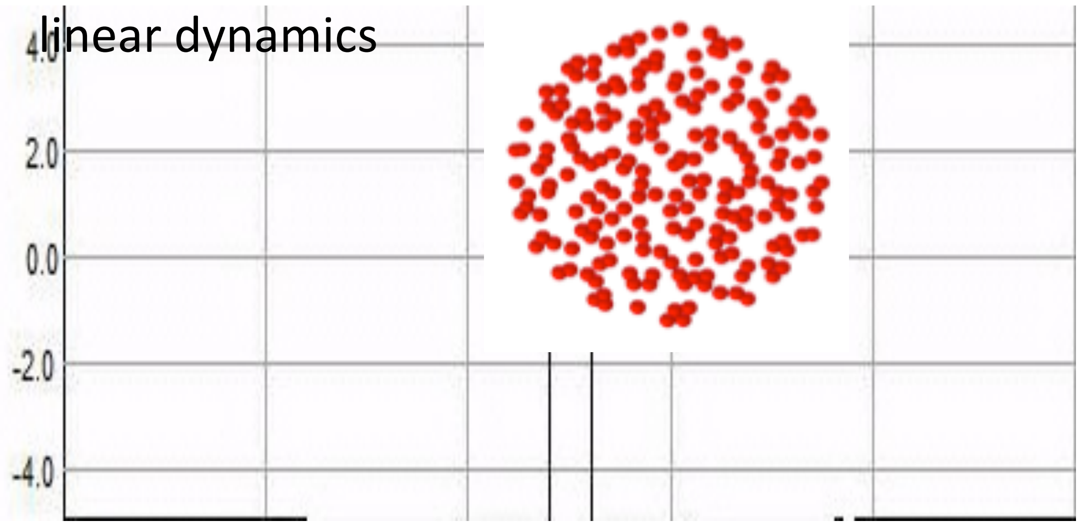


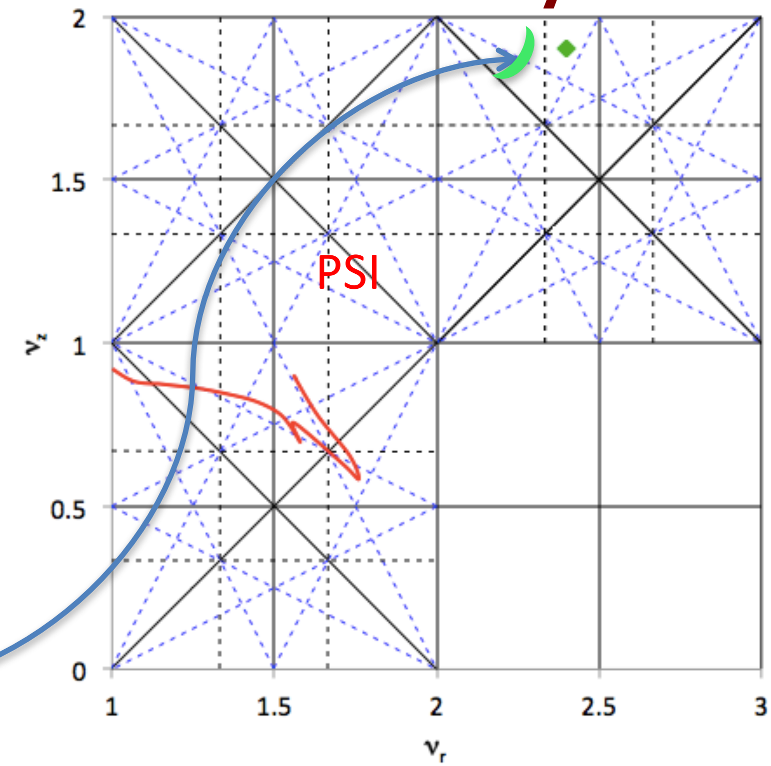
Quadrupole Windings
- Up to 6 T/m
- Panofsky style
- Alternating-gradient focusing
- 6 families provide tune control

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

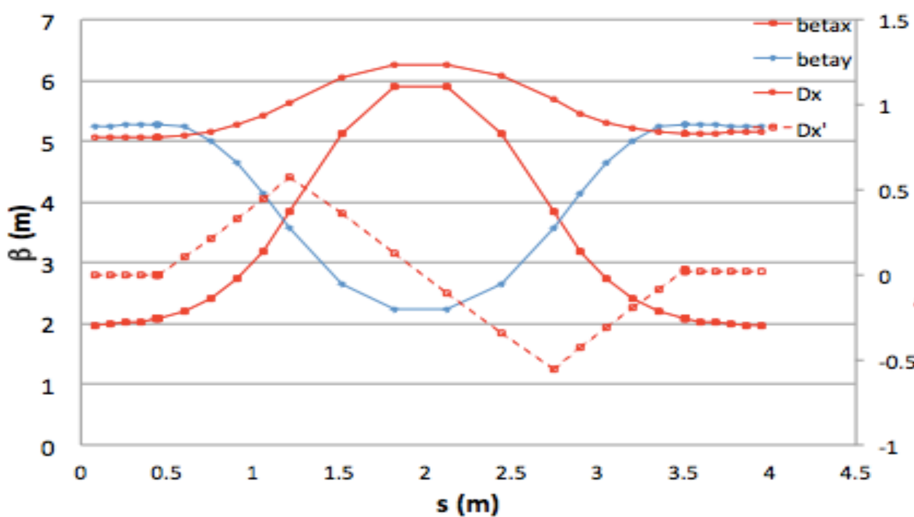
BTCs control tune, isochronicity

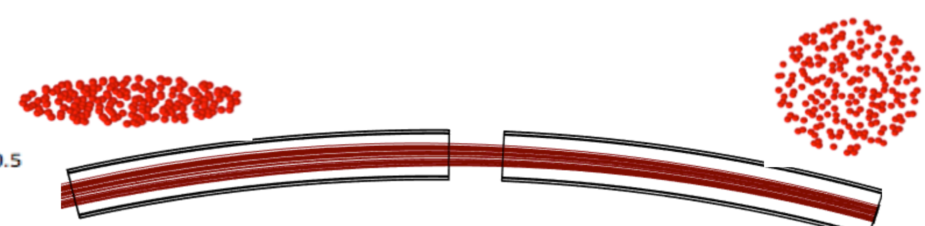
Uniform gradient in each channel: excellent linear dynamics





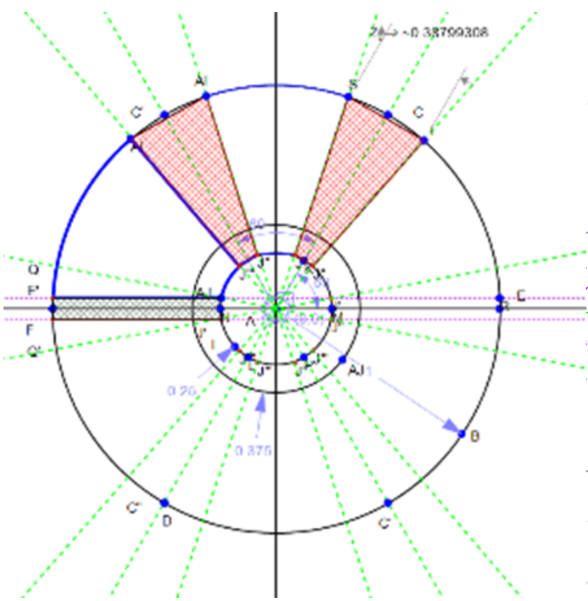
Select desired operating tune, use quad focusing to lock the tune for all energies

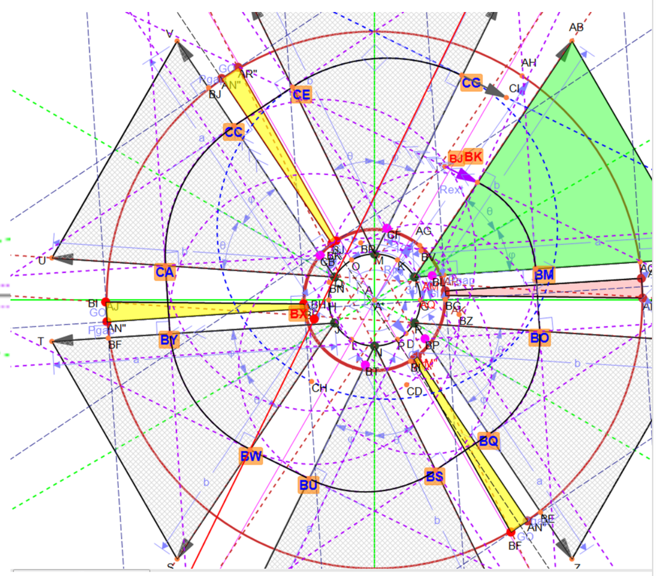


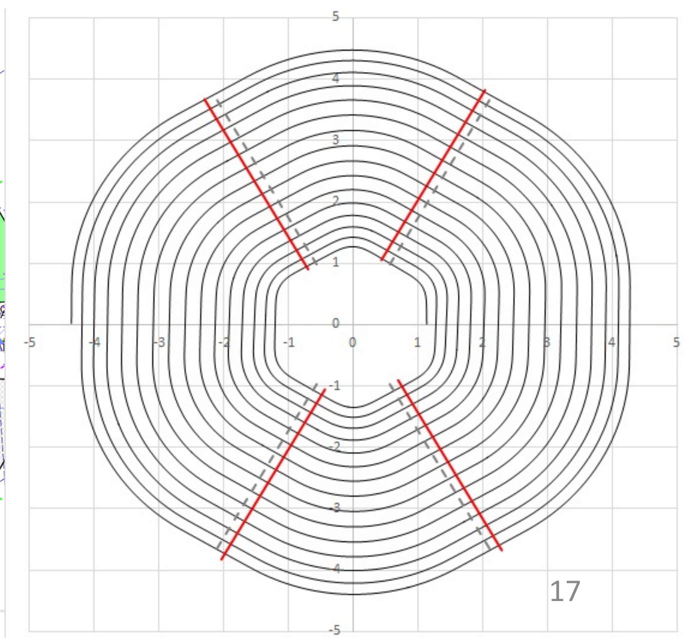


Design Linear Transport

- Start with a few simple parameters; generate geometry; solve for isochronicity
- Z-transfer of live beam can be measured.
- The 6D beam monitors will be located on every turn – connected to fast feedback for corrections.

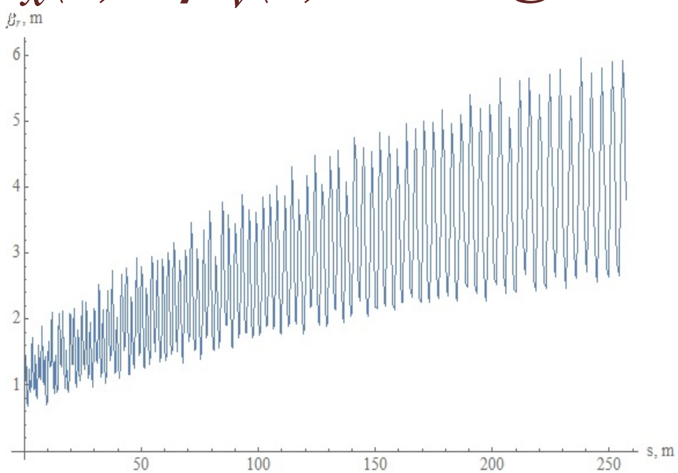


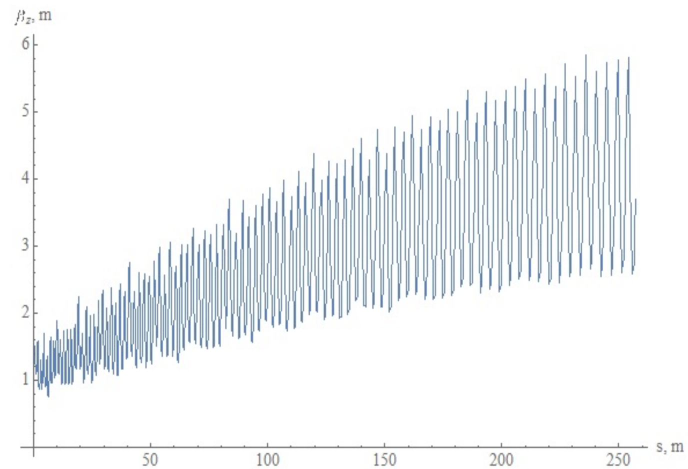




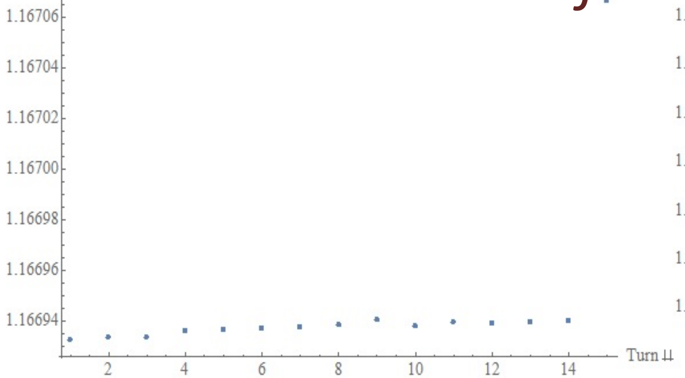
Start with weak focusing, step ΔE

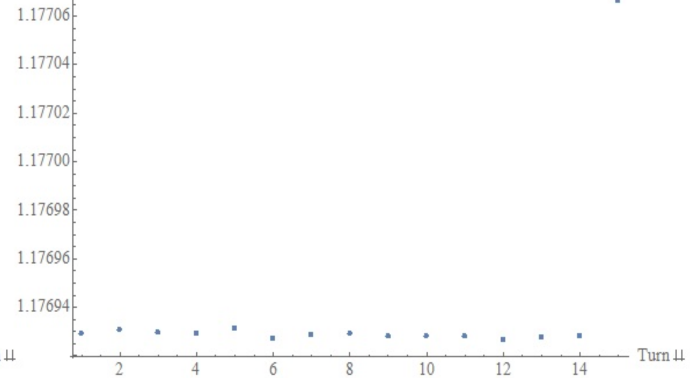
$\beta_x(s)$, $\beta_v(s)$ along all sectors, all orbits



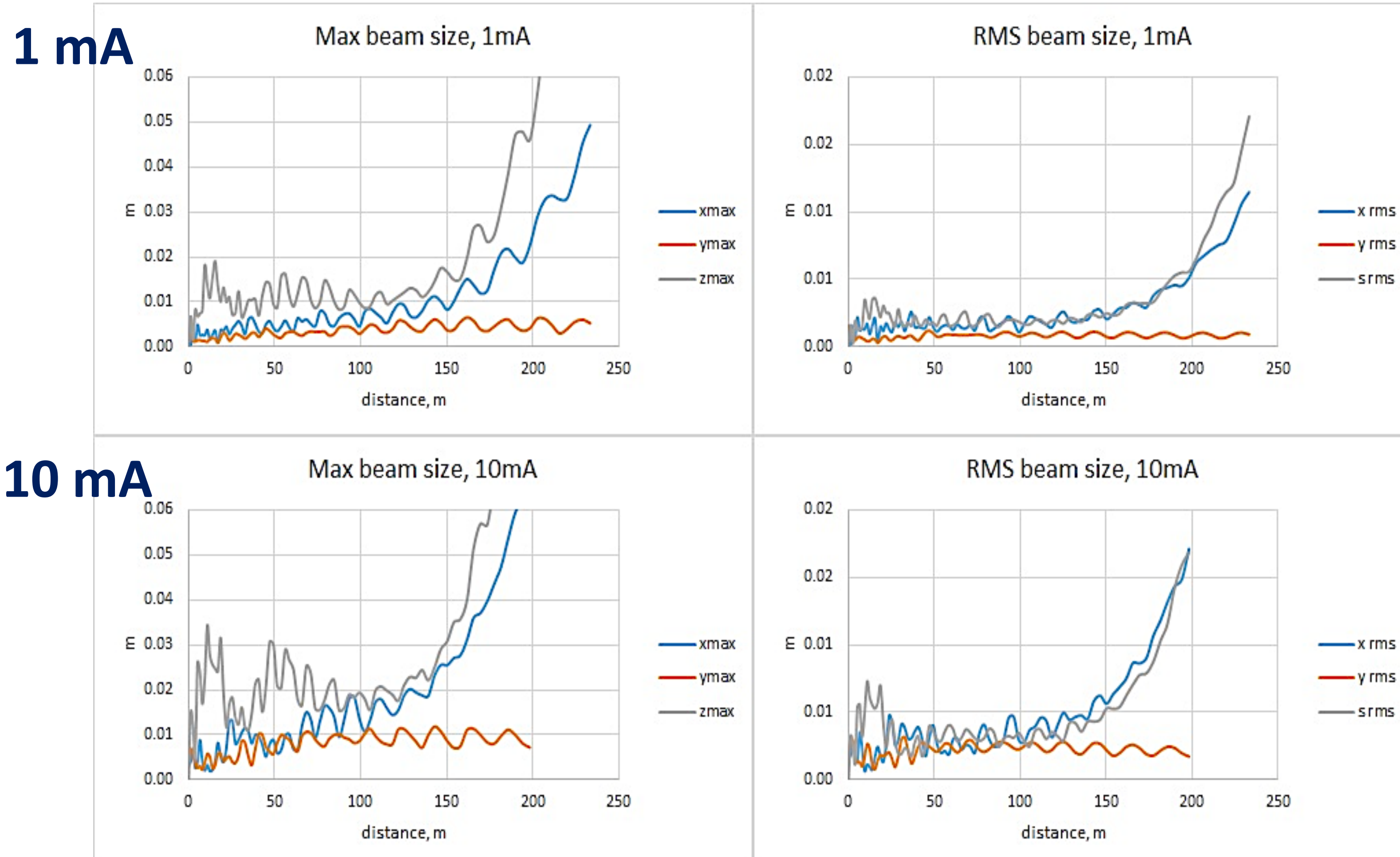


Tunes for each orbit





Simplest starting point: weak focusing, ΔE step function from $E_{iso}(r)$



Now use ~real rf fields and strong focusing

$$\Delta E = dE_{iso}\frac{\cos\left[\delta_{RF} + \omega(t - t_{iso})\right]}{\cos\left(\delta_{RF}\right)}$$

10 mA CW

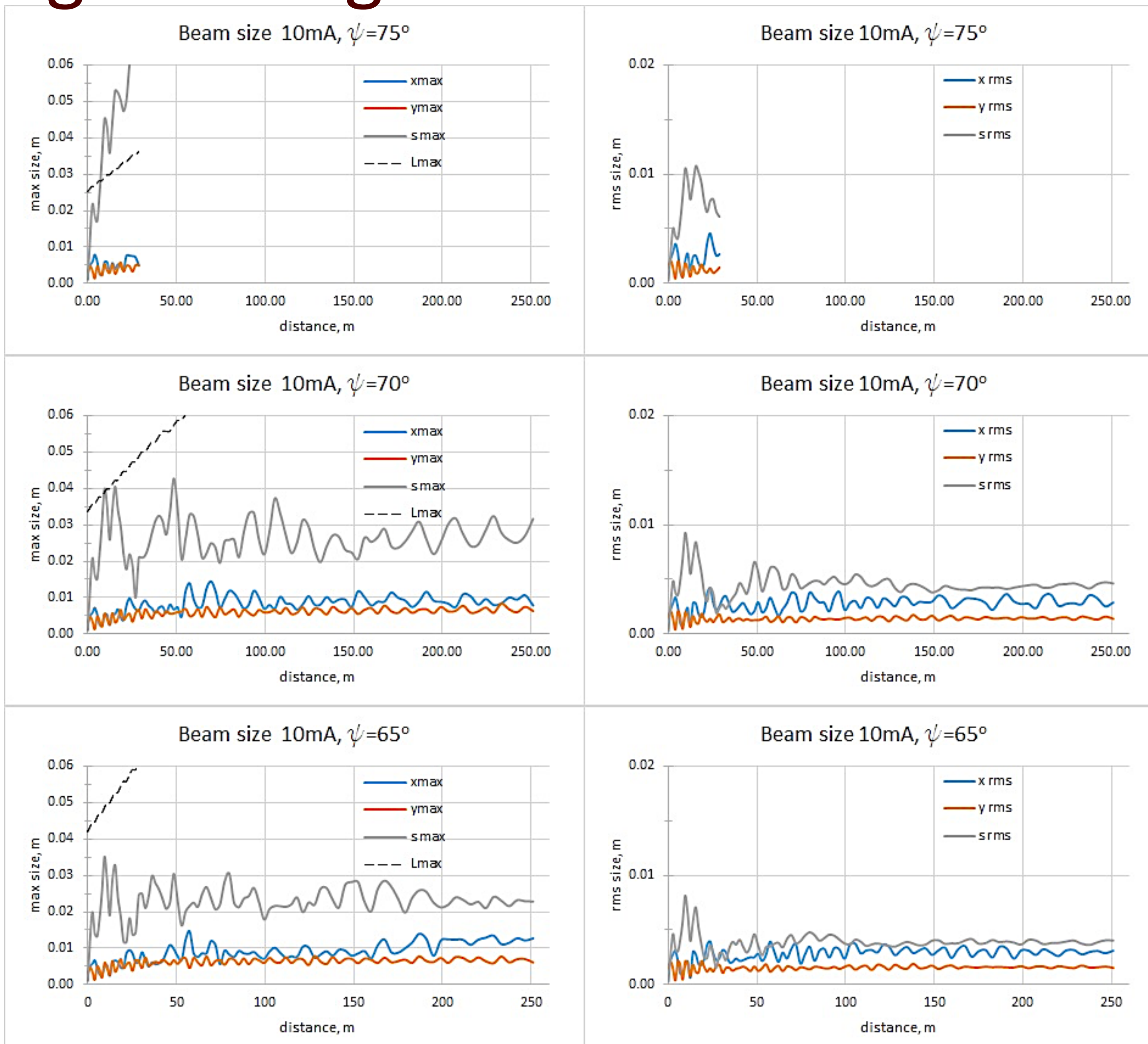
ψ=75°

10 mA CW

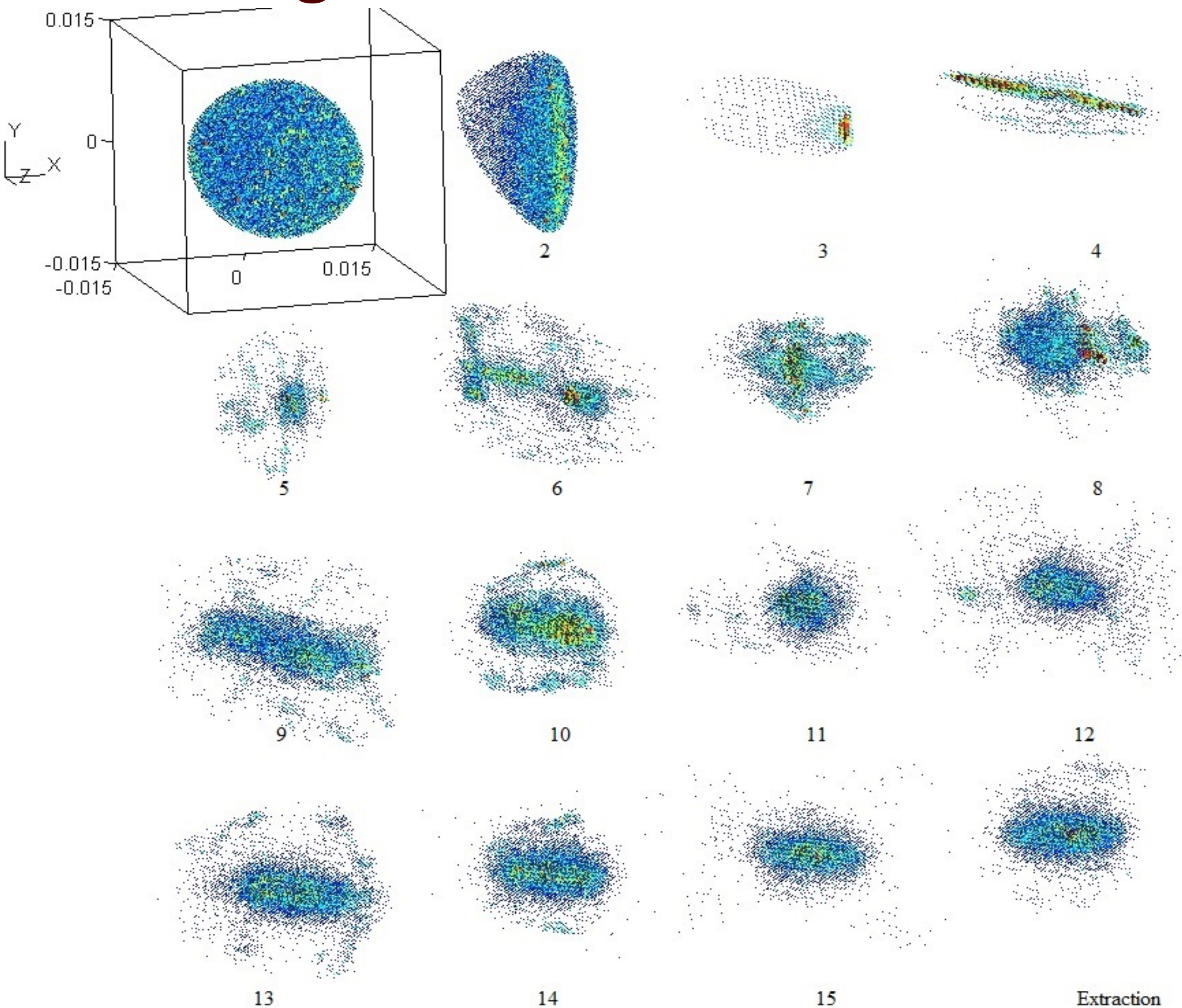
ψ=70°

10 mA CW

ψ=65°



Now follow a 10 mA bunch through in 3D through the whole 100 MeV SFC

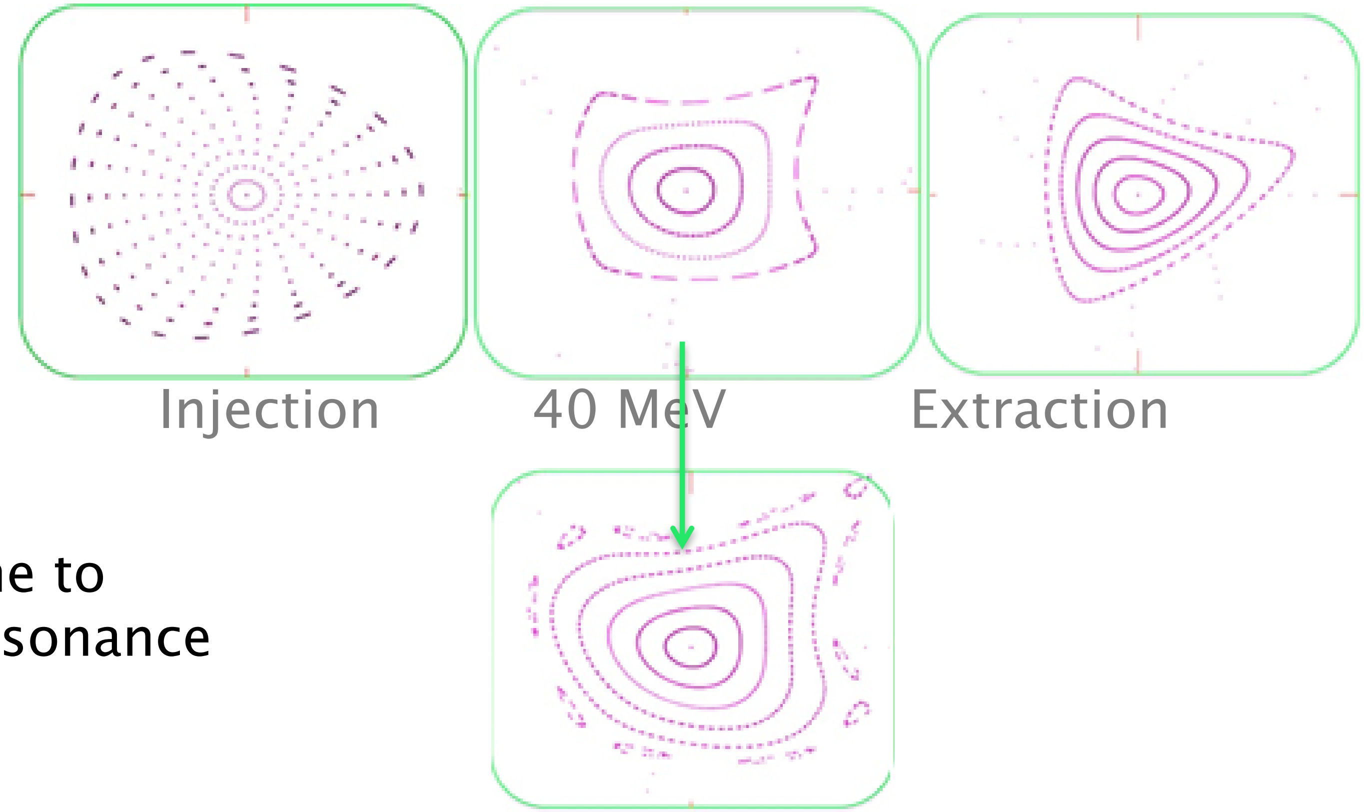


Now transport beam that fills much of aperture. Poincare Plots of 1-5 σ contours in TAMU100

3.5 mA beam

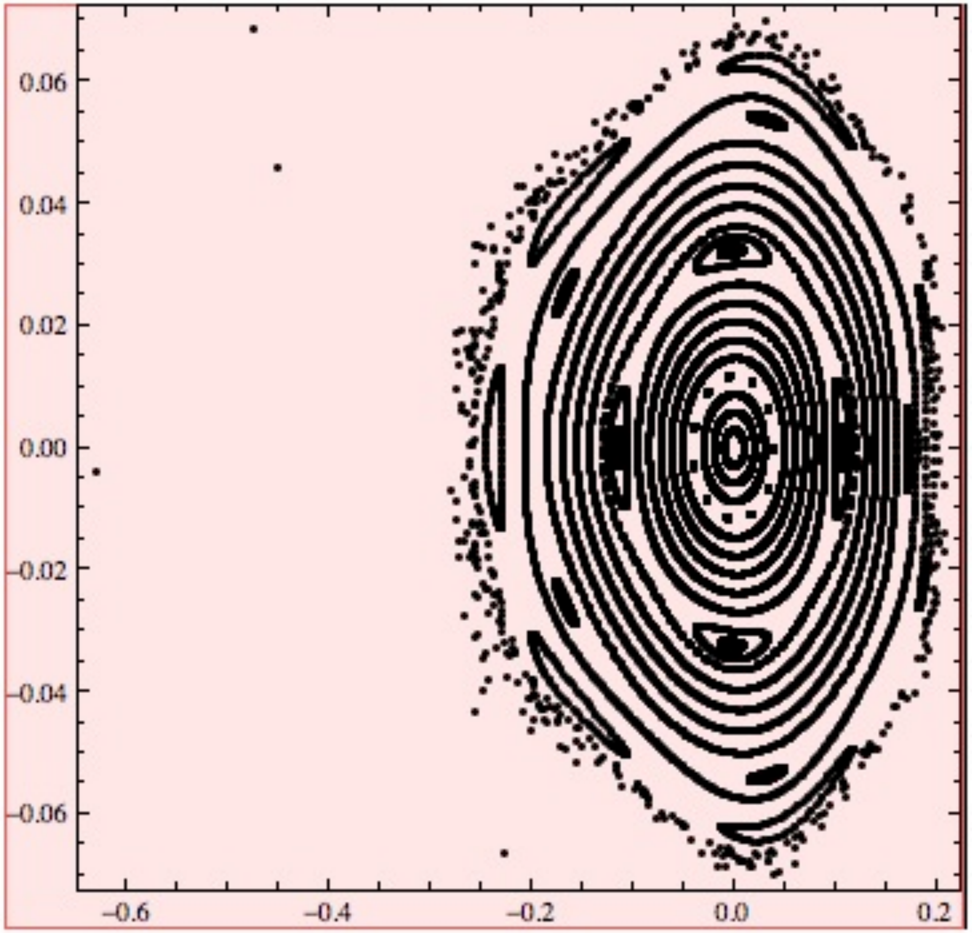
First lock tune to favorable operating point:

Now change the tune to excite a 7th order resonance



We are seeing the origins of the current limits in PSI from overlapping bunches, tune trajectory. Both are cured in the SFC.

Offset a 2 mA bunch to one side of the beam transport channel. Observe the driving of instabilities.



Instabilities start due to non-linearities in cavity and quad fields.
Plots stable for 1 mA bunch.
Space charge effects show up @ 2 mA.

Back to our report card…

1. **Derive isochronous reference trajectory using realistic (extracted from FEA models) magnetic and electric fields.**
2. **Determine quad doublet strengths of the strong focusing channels using single-particle linear optics.**
3. **Simulate high current beam in the strong focusing cyclotron using OPAL's drift and combined function dipoles. Adjust operating point of the cyclotron for beam currents ≥10 mA.**
4. **Model sector magnets with channel quad coils in place for OPAL cyclotron calculations.**
5. **Model strong focusing cyclotron using realistic 3D fields from sector magnets and RF-cavities.**

Codes are very challenging for many standard codes:

- MAD-X has problems with strong-curvature combined function, strong RF acceleration
- Synergia has similar problems – efforts to fix by Fermilab team and ours team not there..
- OPAL-T has been very successful at the present level of simulation.
- We are trying to stage in OPAL-Cyclotron, but its field map calls are prone to go crazy…

We would love to woo collaborators into the fun…

The Strong-Focusing Cyclotron offers enhanced performance as a high-current driver for ADS, medical isotope production,…

Thanks to DOE Accelerator Stewardship Program for sustained support of our simulation efforts.