Simulation of Beam Dynamics in a Strong Focusing Cyclotron

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NAPAC October 11, 2016

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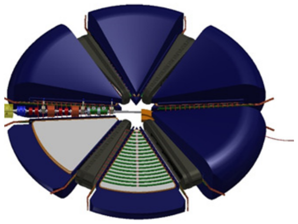
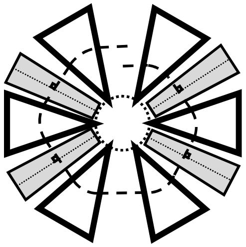
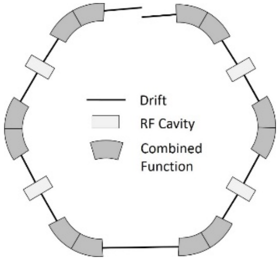
Outline

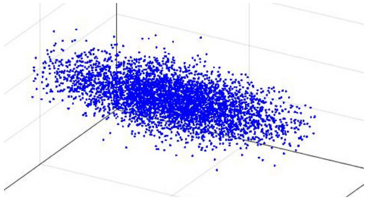
Motivation:
Develop proton accelerator capable of ~10 mA and 100-1000 MeV

- *Strong-Focusing Cyclotron*
  - *RF Cavity*
  - *Sector Dipoles*
  - *Beam Transport Channel*
- *Beam Dynamics*
  - *Isochronous Orbit*
  - *MAD-X*
    - *Linear Optics*
    - *Modified MAD-X-PTC*
  - *Synergia*
    - *SYNERGIA*
    - *Space Charge*

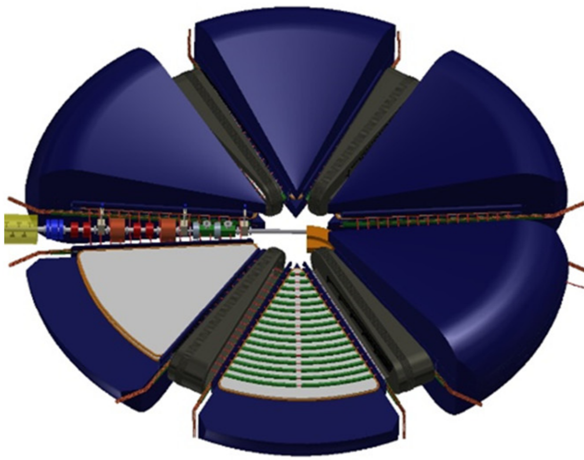




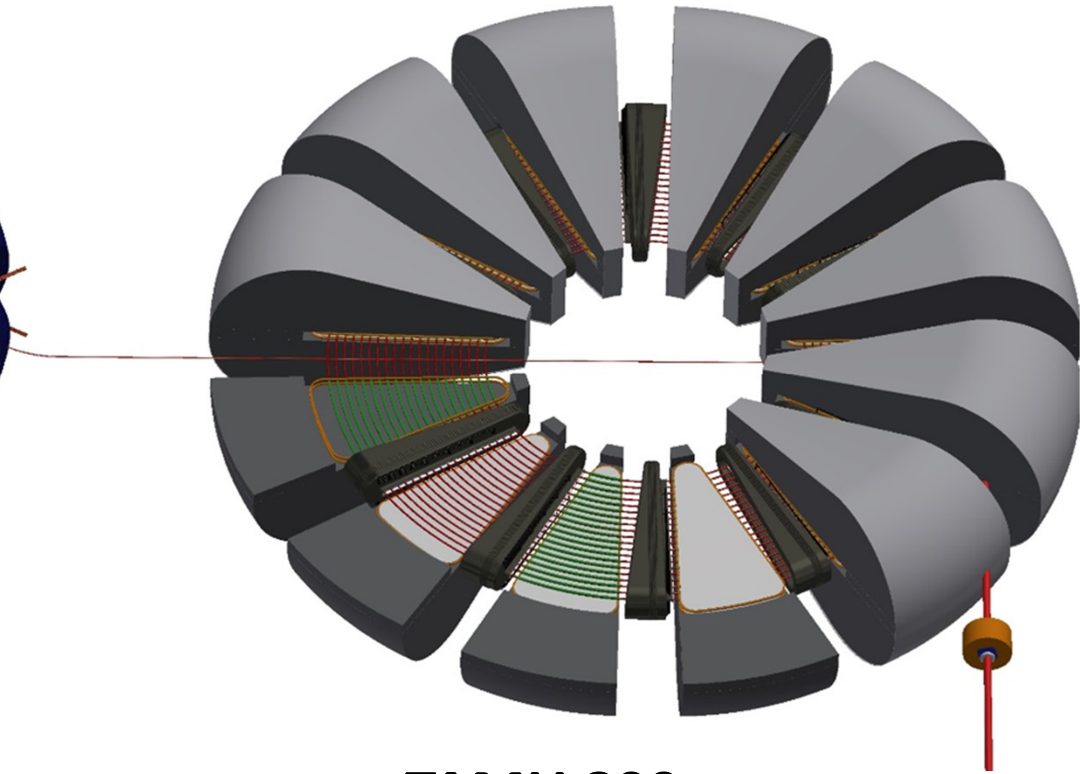




Accelerator System

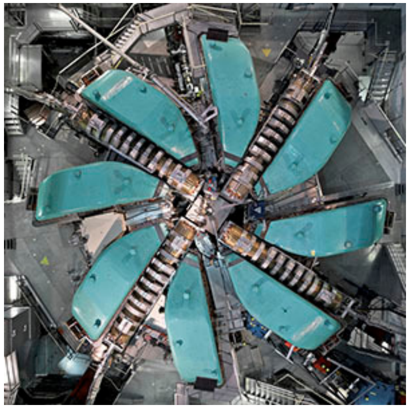


TAMU 100
Booster cyclotron
6.5 MeV to 100MeV
6 Sectors
4 RF Cavities



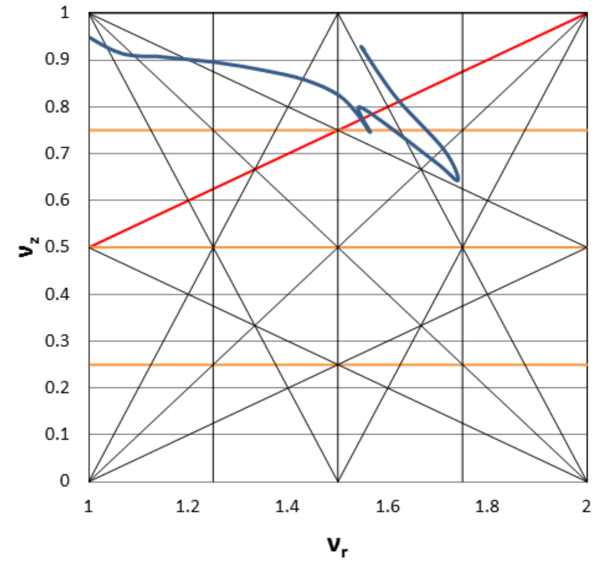
TAMU 800
100MeV to 800MeV
12 Sectors
10 RF Cavities

High Current Issues

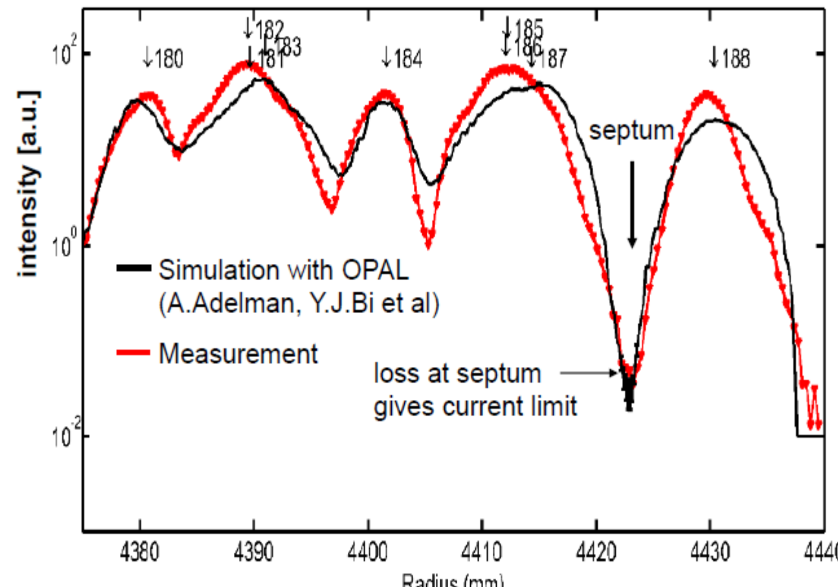


PSI Cyclotron- highest power proton accelerator

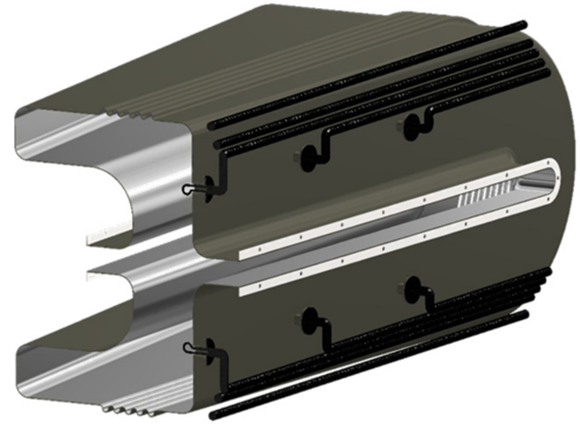
Tune diagram PSI



- *Avoid Beam Overlap*
  - *Large energy gain per turn to fully separate beam*
- *Avoid resonance crossing*
  - *Hold tune constant*
- *Space Charge*
  - *Use strong focusing*



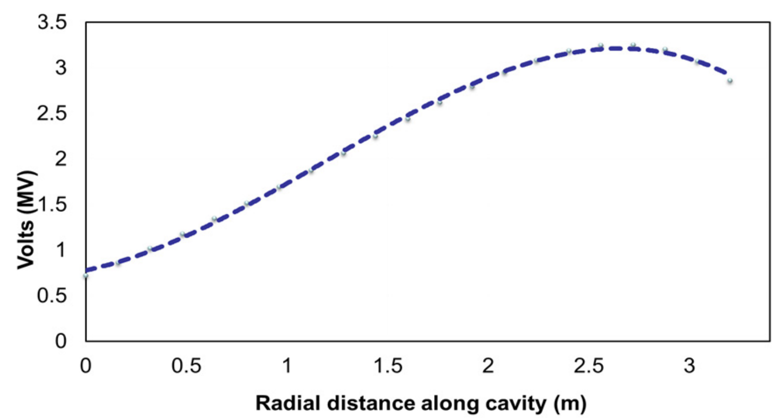
Superconducting RF Cavities

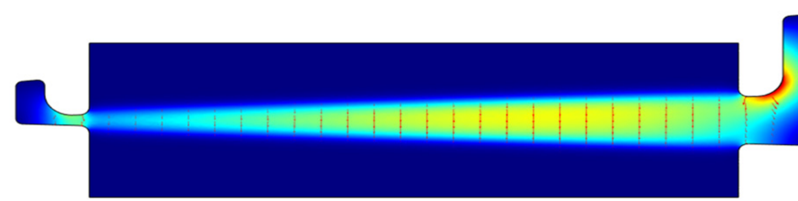


117MHz

Large energy gain per turn

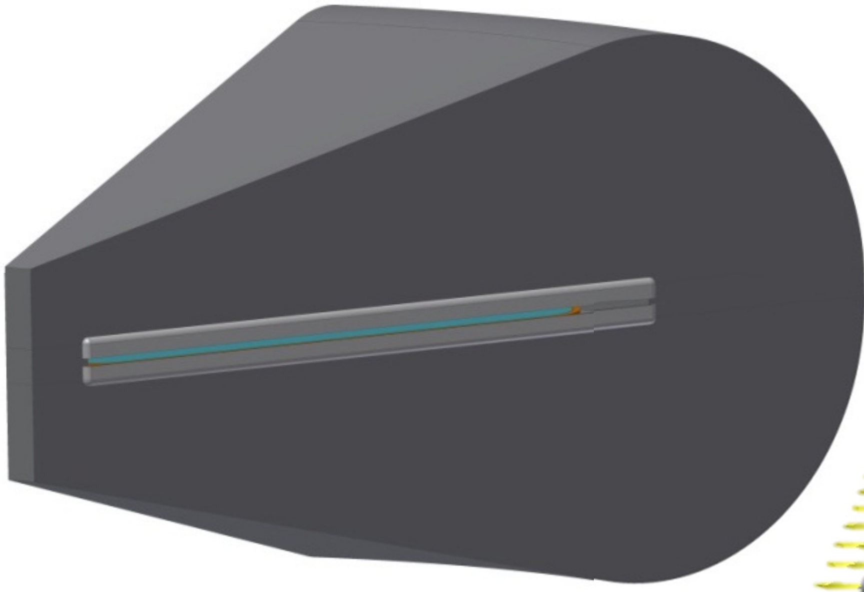
Tapered to reduce footprint

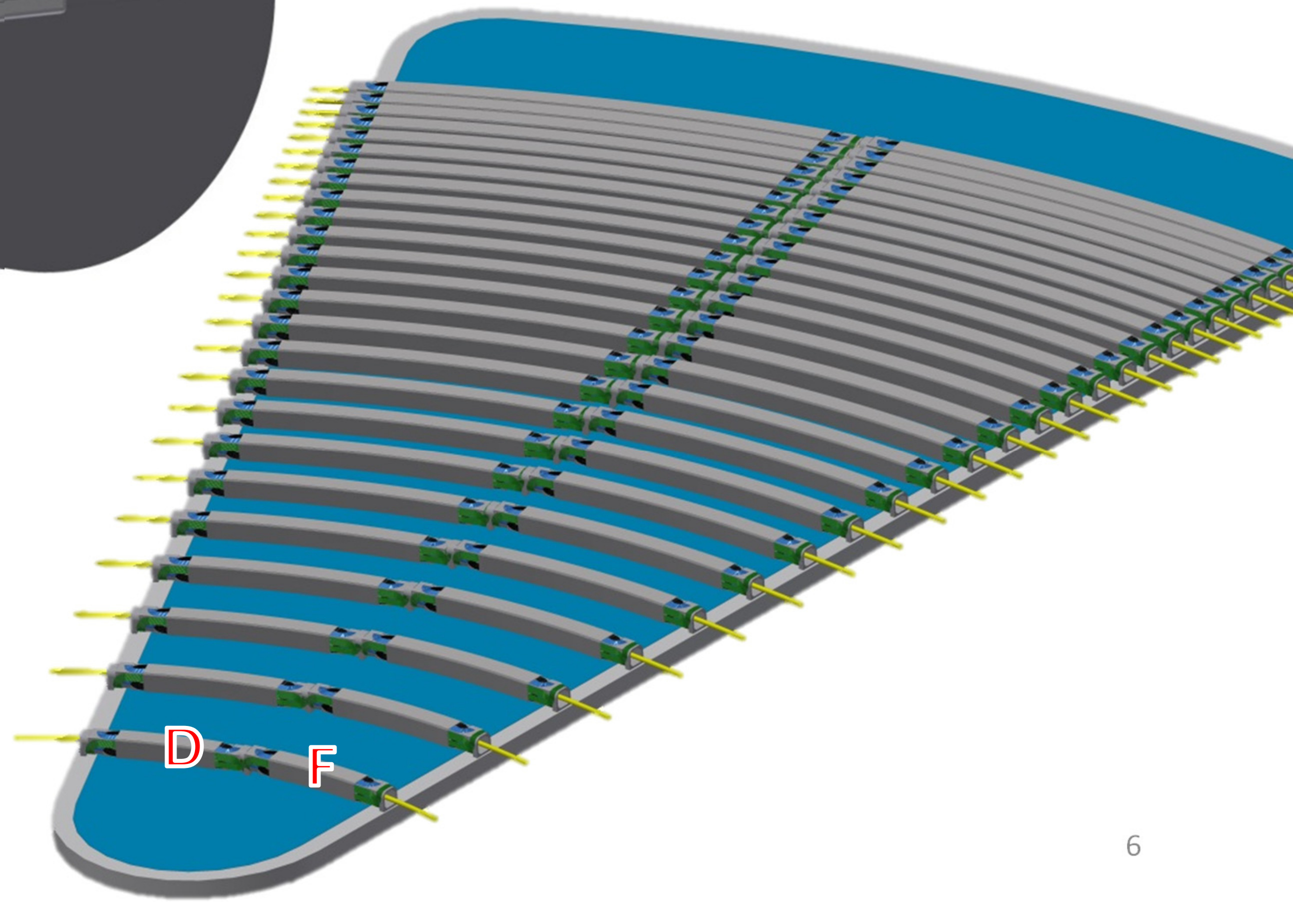




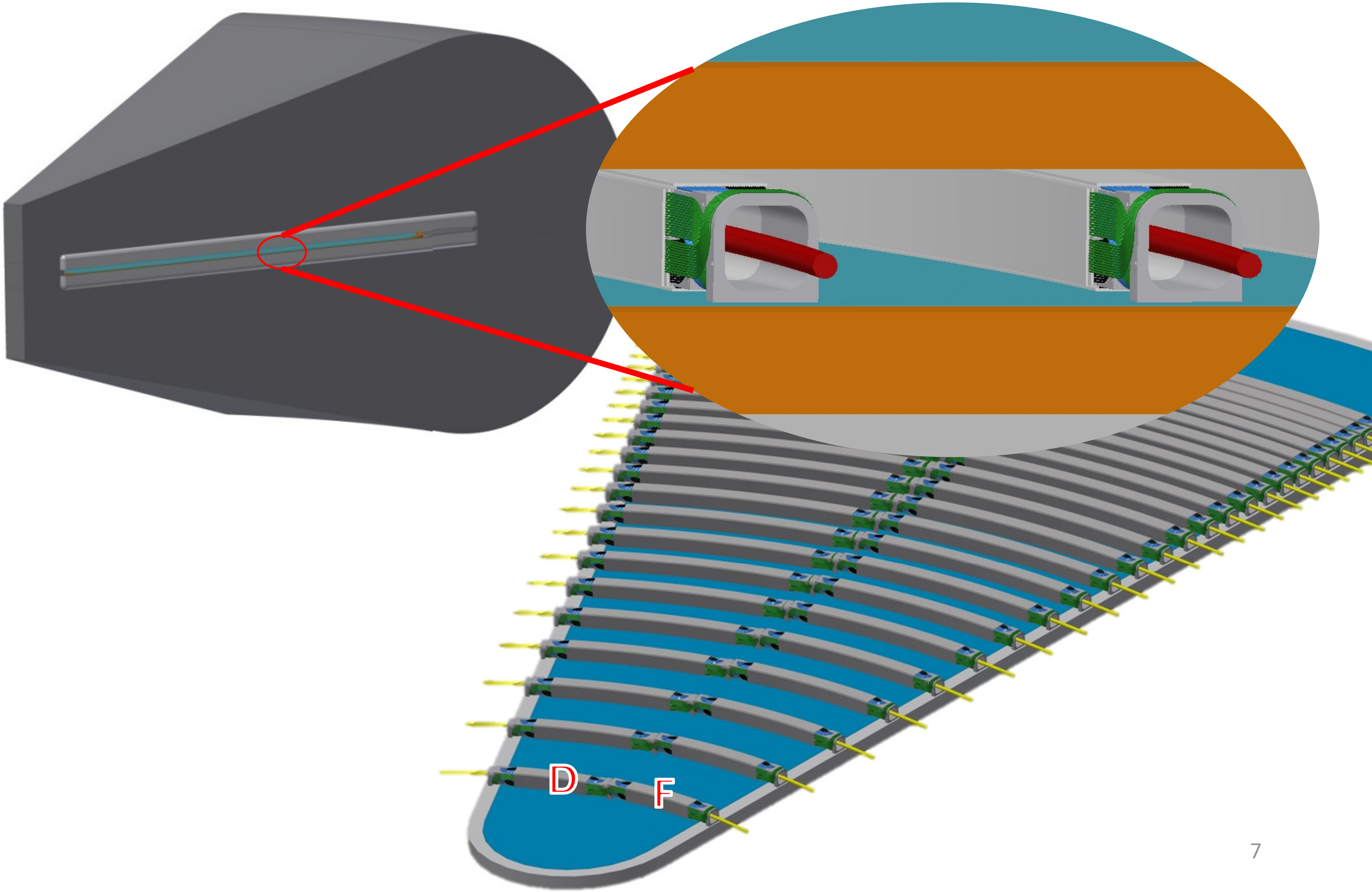
SRF modeling- N. Pogue

Sector with Beam Transport Channels

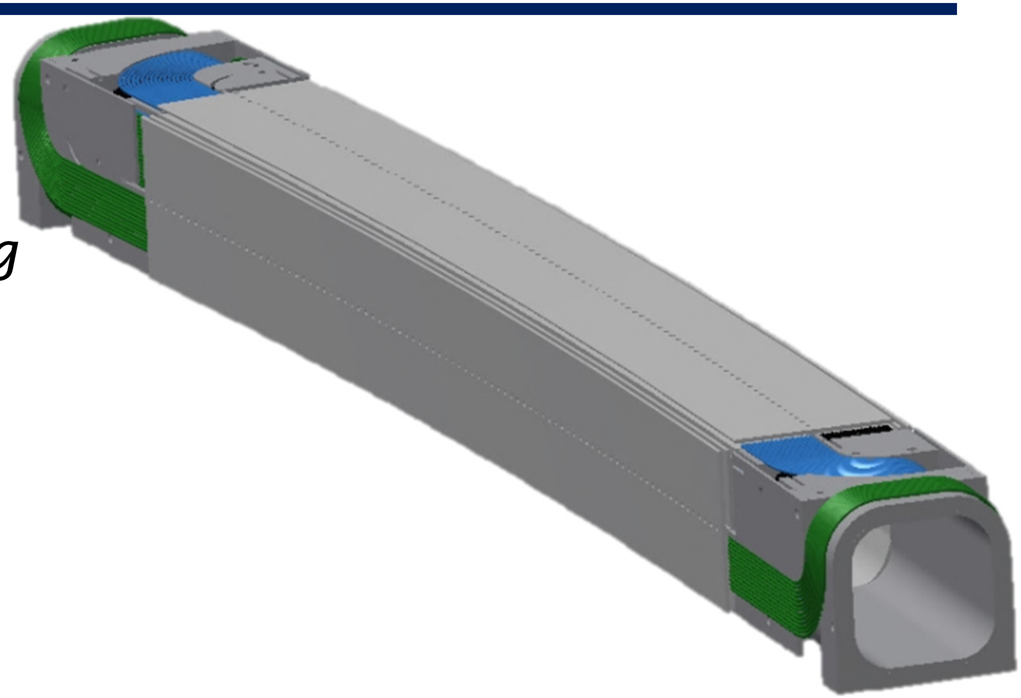




Sector with Beam Transport Channels

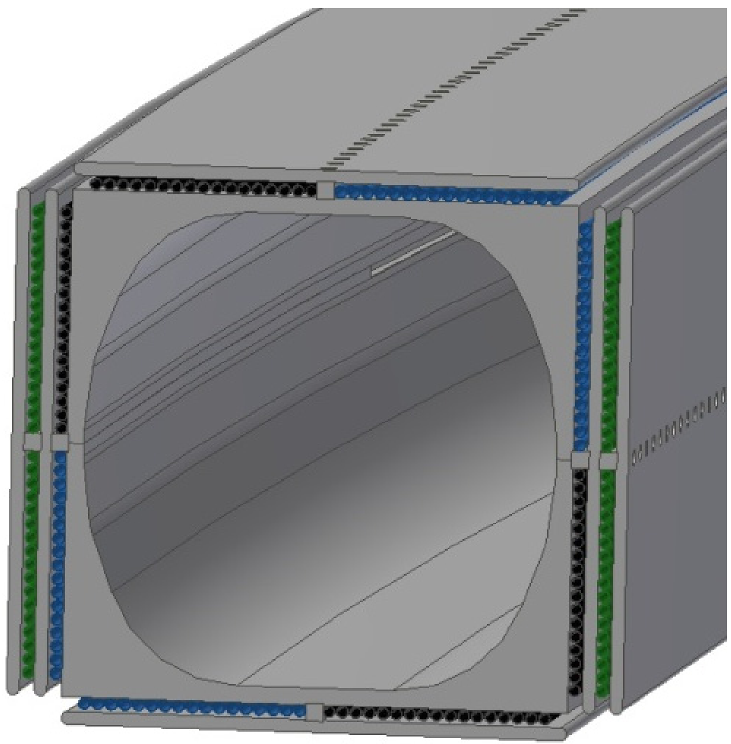


Beam Transport Channel (BTC)



Quadrupole Windings

- *Panofsky style*
- *Alternating gradient focusing*
- *Up to 6 T/m*

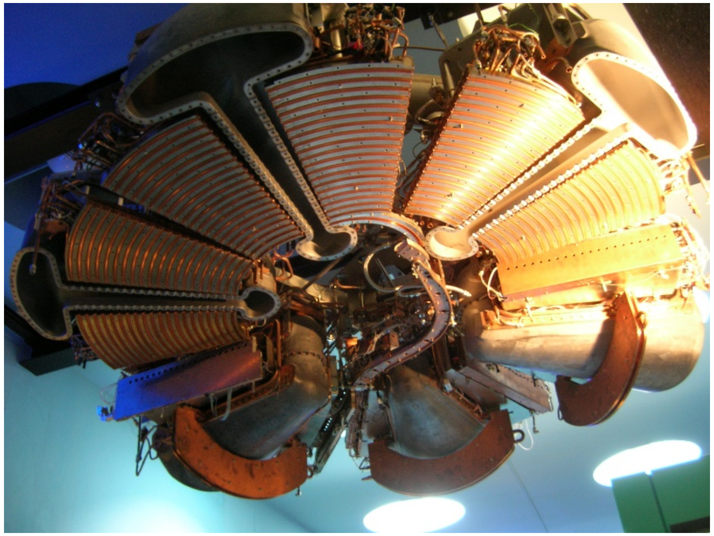


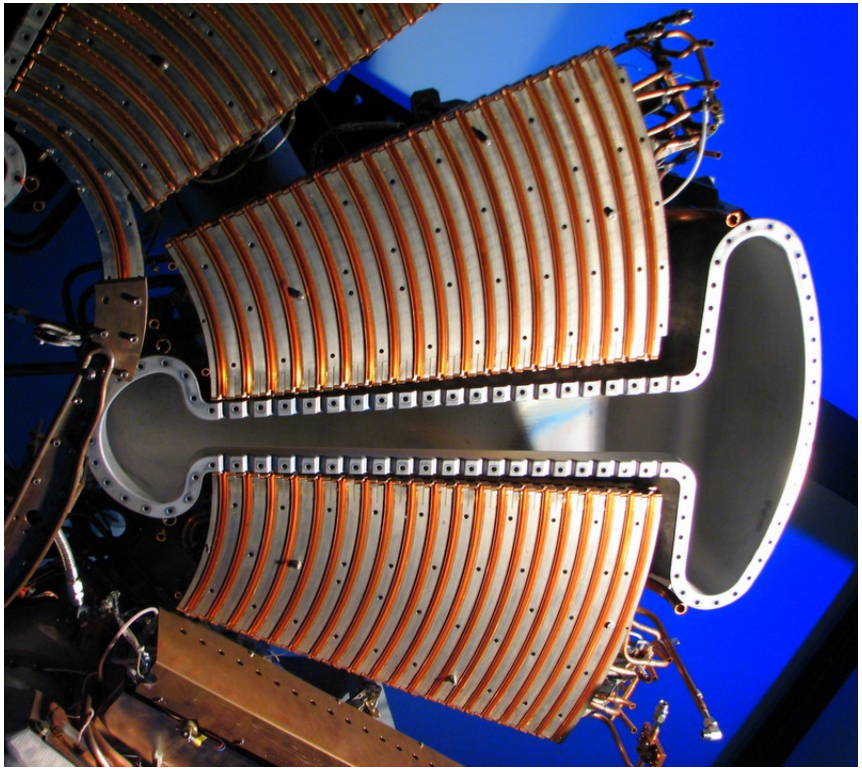
Window Frame Dipole Windings

- *Up to 20 mT*
- *Act as corrector for isochronicity*

TRITRON

Separated sector cyclotron with tapered superconducting RF cavities





Had edge focusing and gradient windings along the sectors

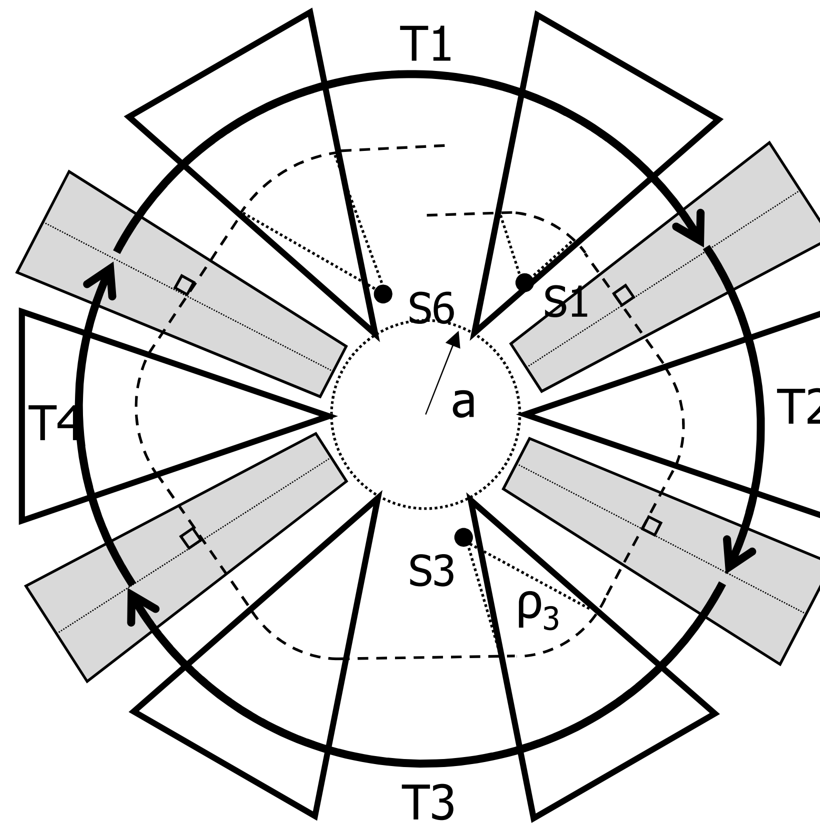
"Future separated orbit cyclotrons can be planned with enlarged turn separation…With a geometrical aperture for the beam of about 5cm"

Equilibrium Isochronous Orbit

- *Cyclotron "closed orbit" approximation does not confine beam to specific paths*
- *Available codes designed for circular machines or linacs, not a "spiral linac"*
- *Developed a set of parametric equations to be optimized*

Assumptions:

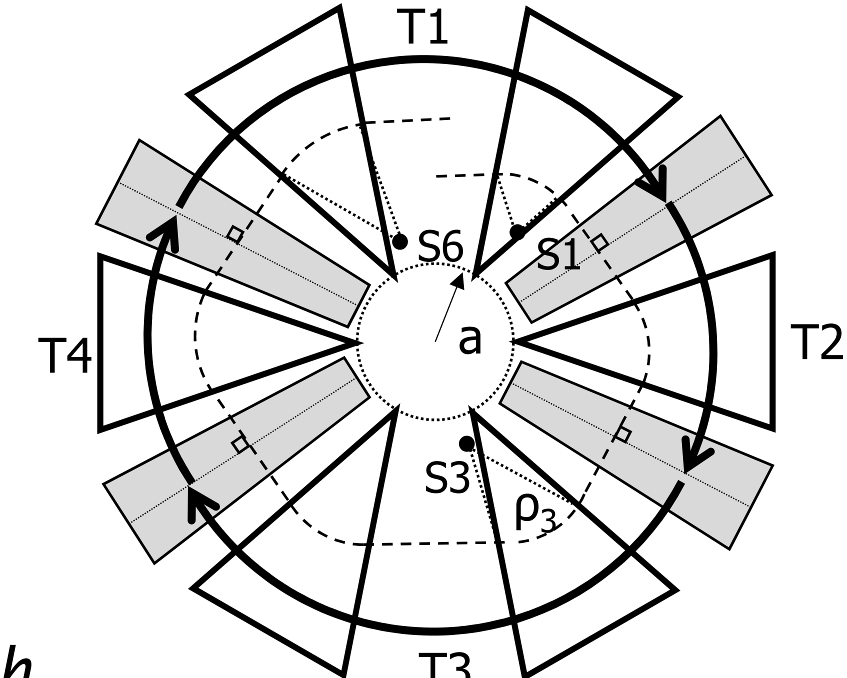
- *Sectors centered on multiple of 60°*
- *Cavity size determines radial offset of the sectors*
- *Perpendicular to cavity*
- *Isochronous time set by RF frequency and harmonic number*



Equilibrium Isochronous Orbit

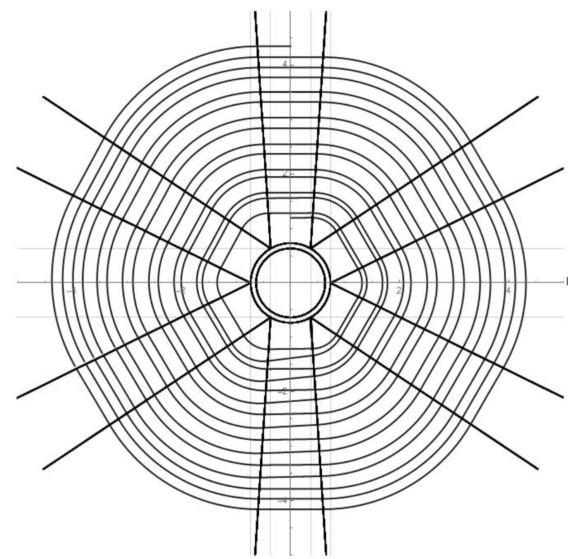
Inputs:

- *Injection energy, radius and angle*
- *minimum orbit separation.*

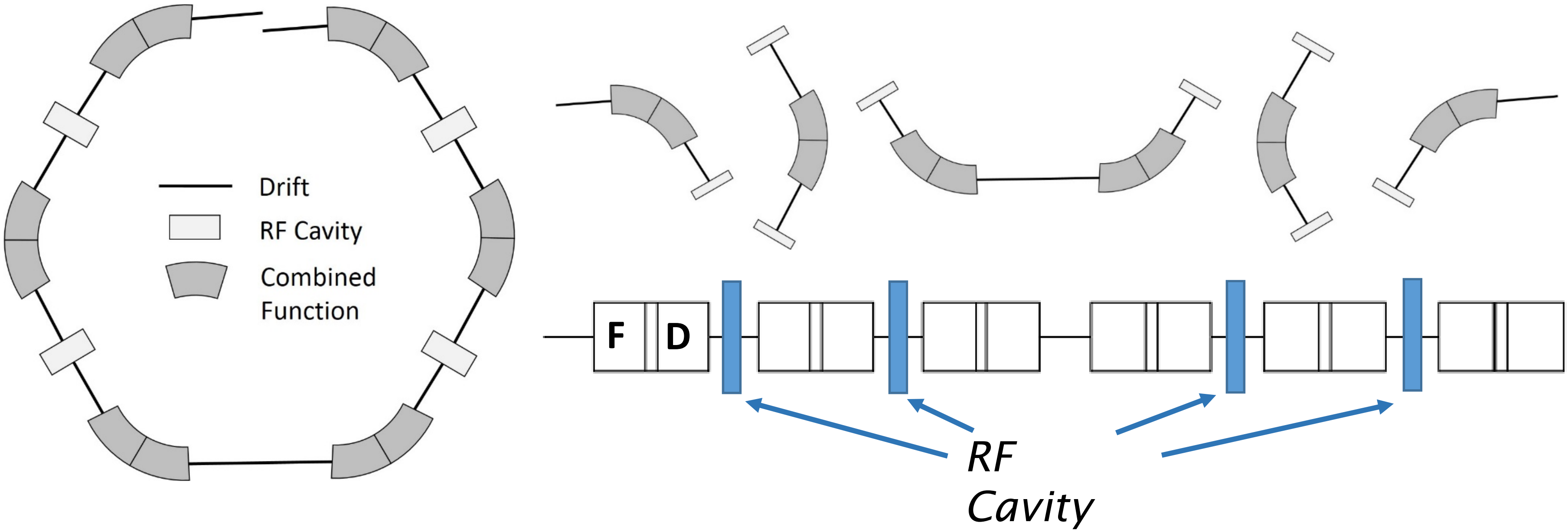


Code outputs*:*

- *Length of drift spaces*
- *Angle and arc length through sectors*
- *Energy after each cavity*
- *Magnetic field profile of each sector (all different)*
- *Global phase of each cavity*
- *Number of turns*



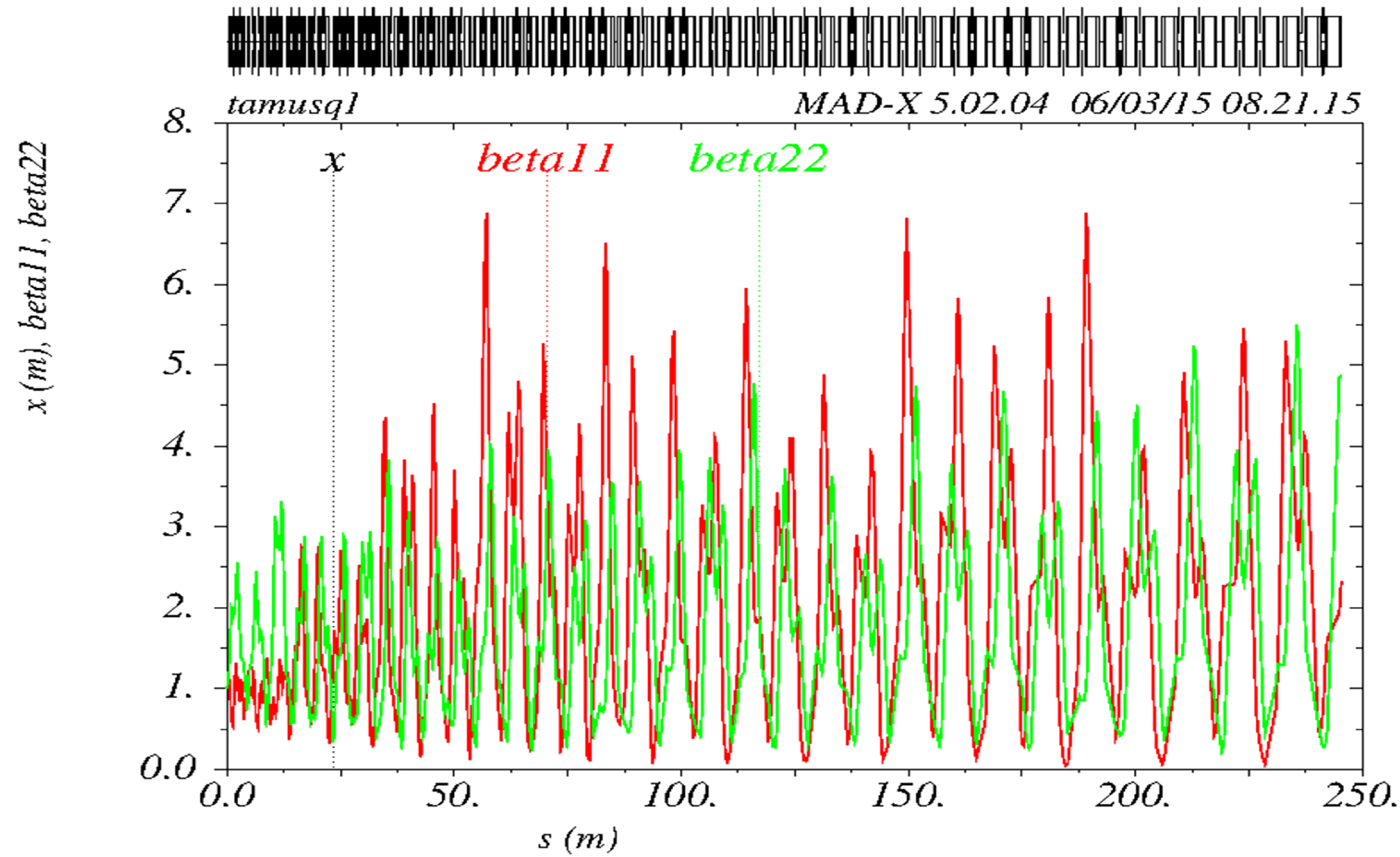
MAD-X



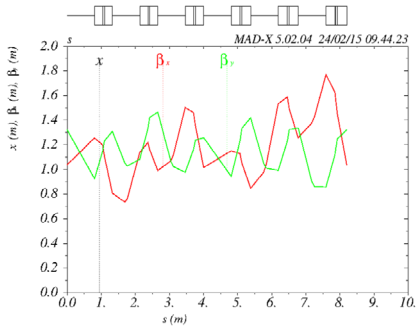
- *Each section of the cyclotron with a different energy must be entered as its own sequence.*
- *Adjust quadrupole strengths to maintain desired tune and beta*
- *Optimization only within sequence*

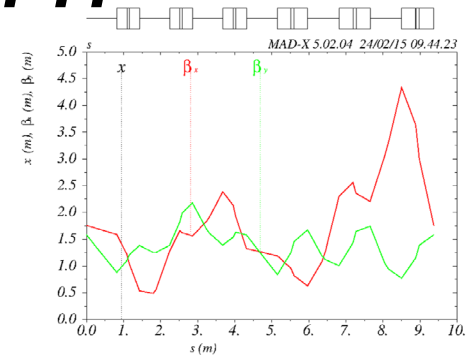
14 turns x 6 sectors=84 calls to MAD-X !

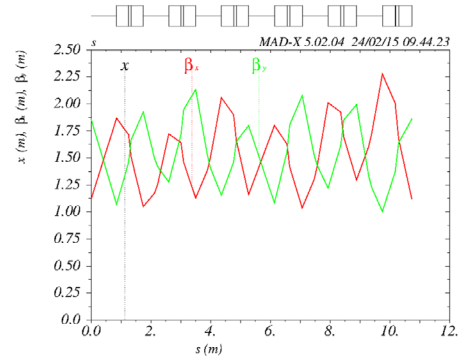
Whole System

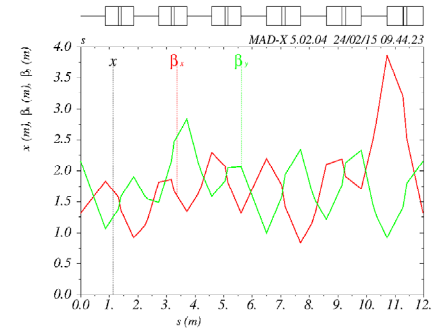


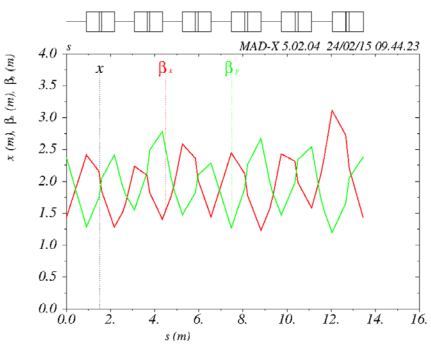
Each Turn

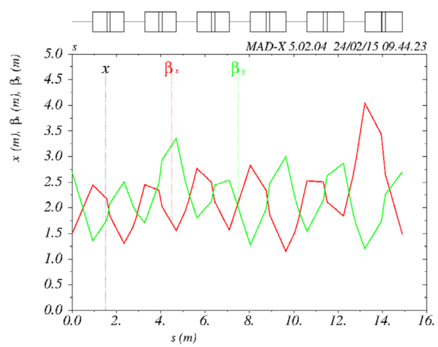


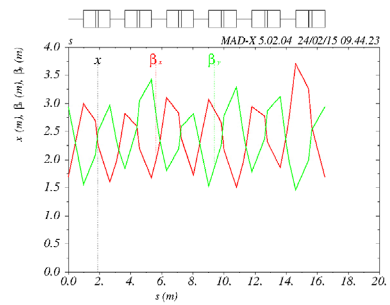


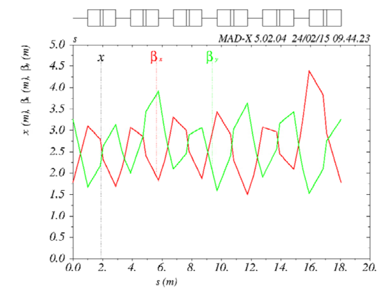


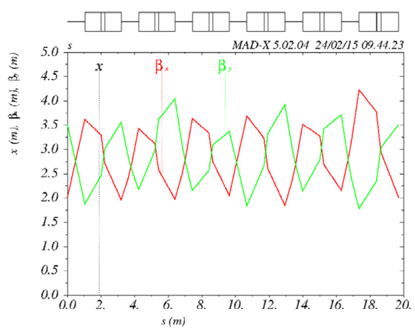


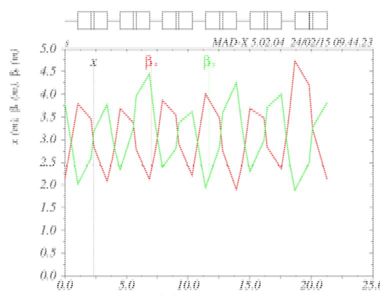


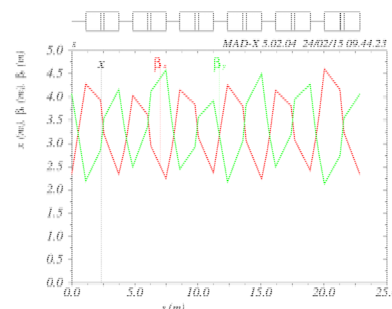


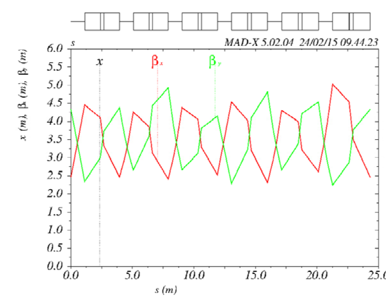


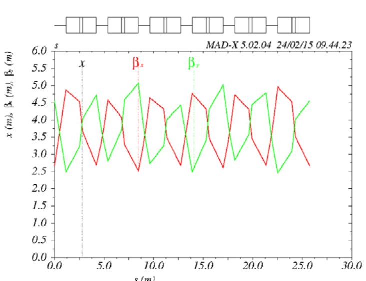


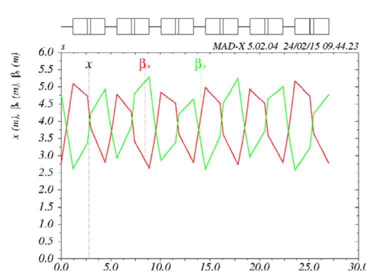










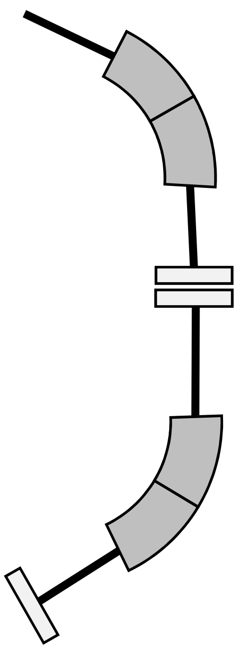


Must be further divided into cells…

Modified MAD-X-PTC

- *Single particle thick element tracking*
- *Lacks required cavity type, requires multiple sequence files*

Matlab script written to keep track of particle data and add energy gain when a cavity is encountered

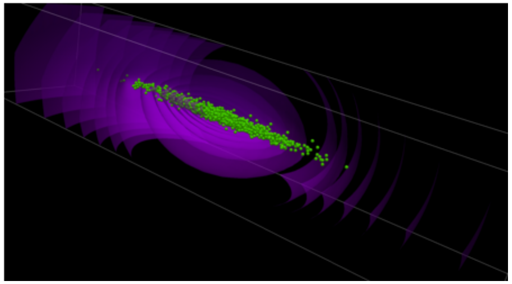


$$\Delta E_n \approx qV_n \left[2\beta c \frac{\sin\left(\frac{\omega_{RF} L_n}{2\beta c}\right)}{\omega_{RF} L_n} \right] \cos(\omega T_n - \varphi_n)$$

Particles travel through half the cavity with one energy, get energy kick, and travel through second cavity half with new energy

Synergia

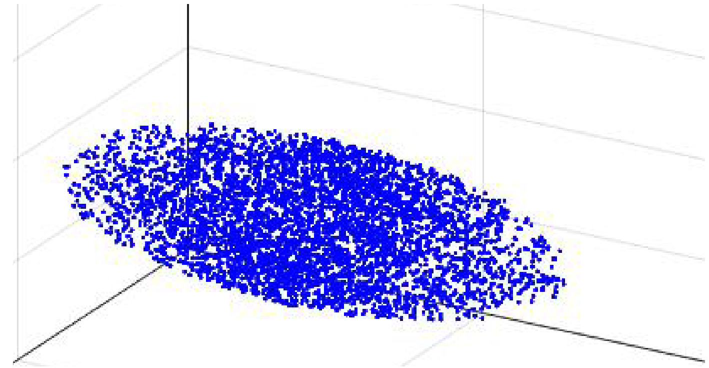
Particle In Cell (PIC) Code out of Fermilab

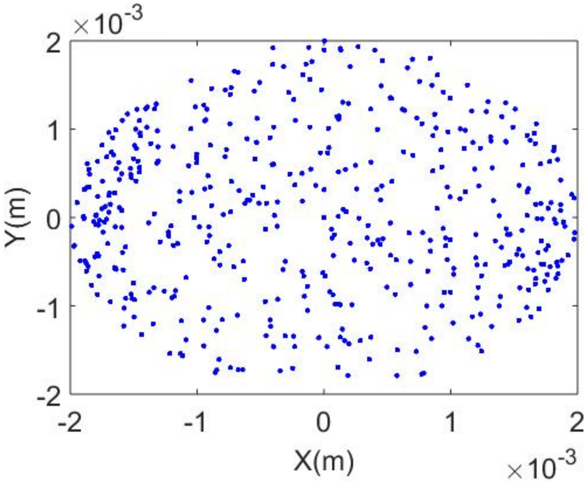


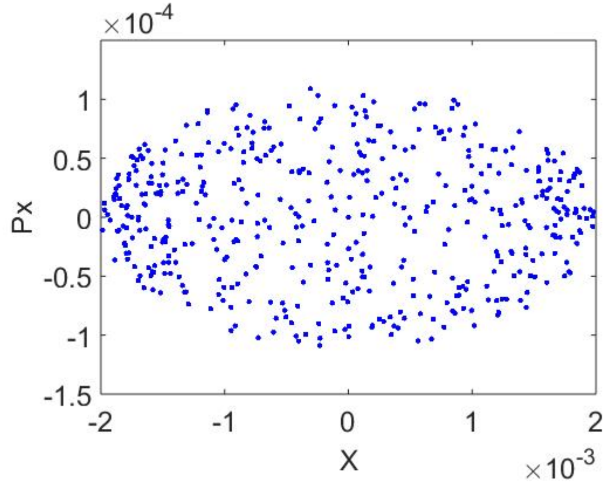
- *MAD sequence file input*
- *Single particle thick element tracking*
- *Space charge*
- *Scales magnet strengths to energy gained in RF cavities*
- *RF module was modified to account for transit time factor*
  - *Same energy gain kick was used as in the Matlab modified MAD-X*

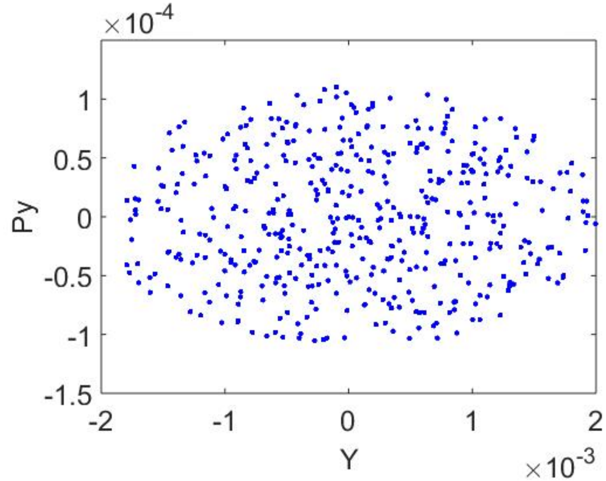
Particle Tracking

Using 2 mm-mrad waterbag distribution



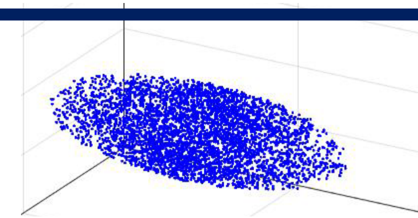




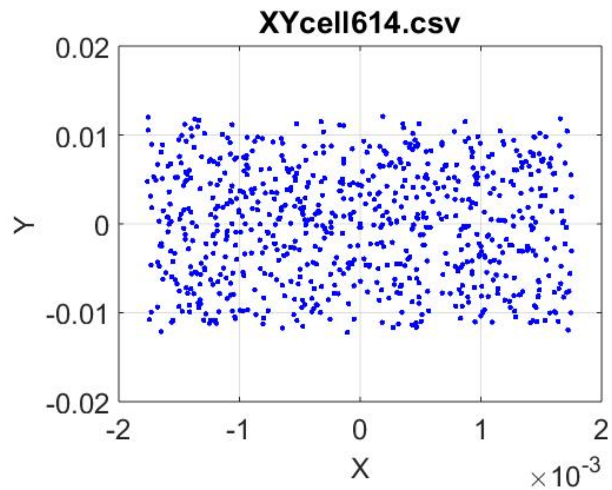


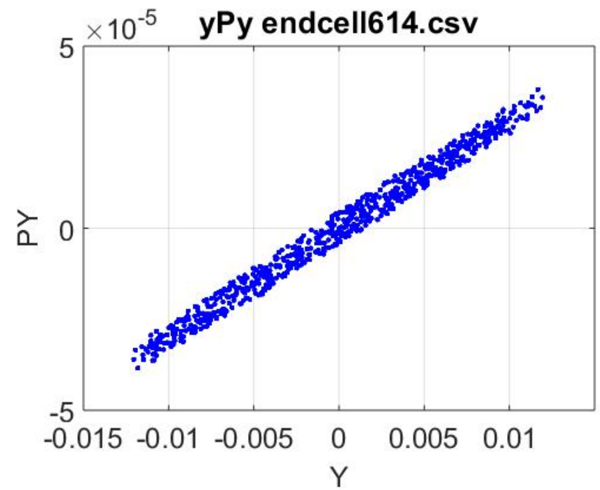
Benchmarking Synergia / MAD-X-PTC

Quadrupole strengths set to ~zero

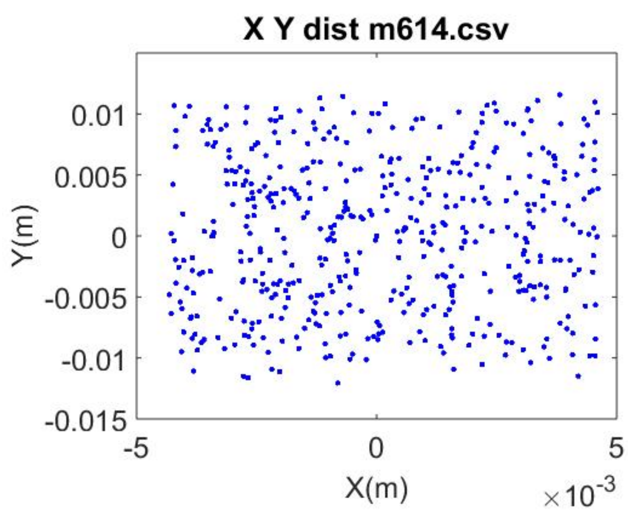


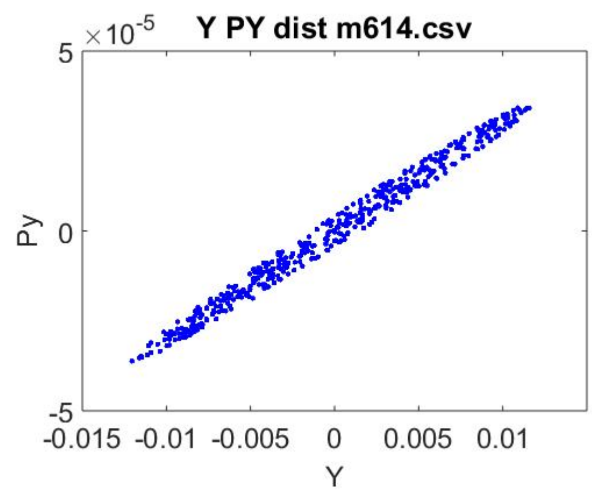
MAD-X-PTC





Synergia



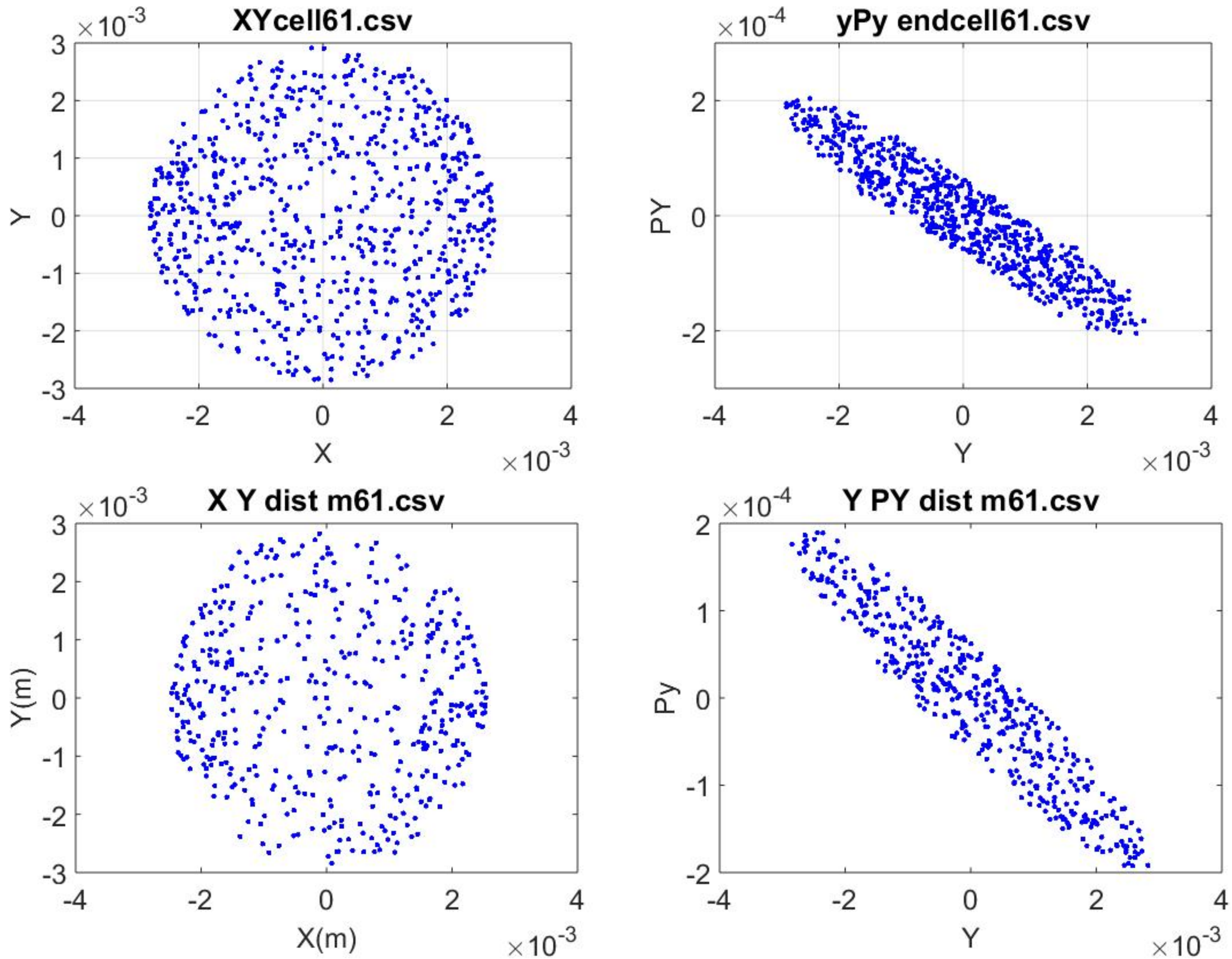


Turn on Quads (1st turn)

Quadrupole strengths from MAD runs to hold tune

MAD-X-PTC

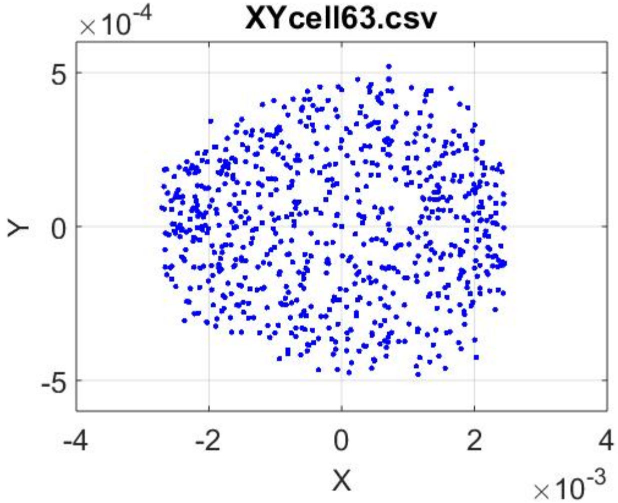
Synergia

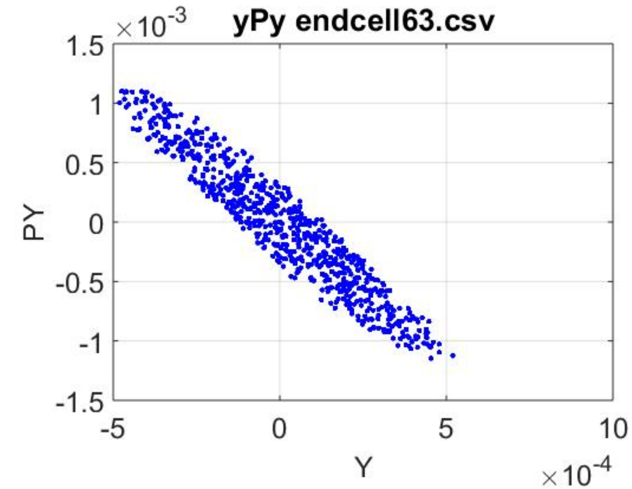


Turn on Quads (3^{rd} turn)

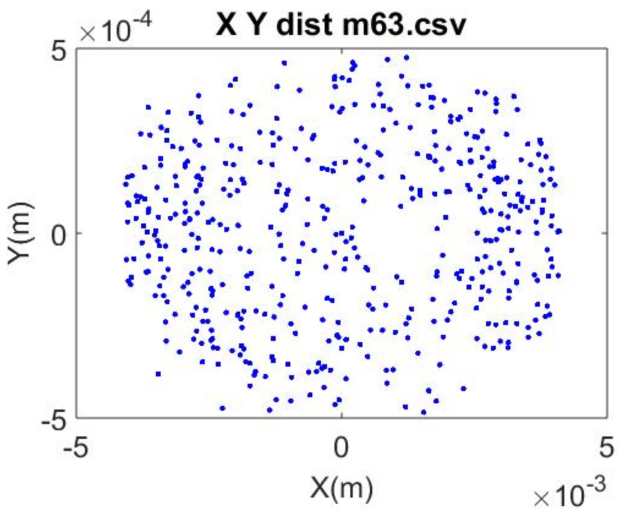
Quadrupole strengths from MAD runs to hold tune

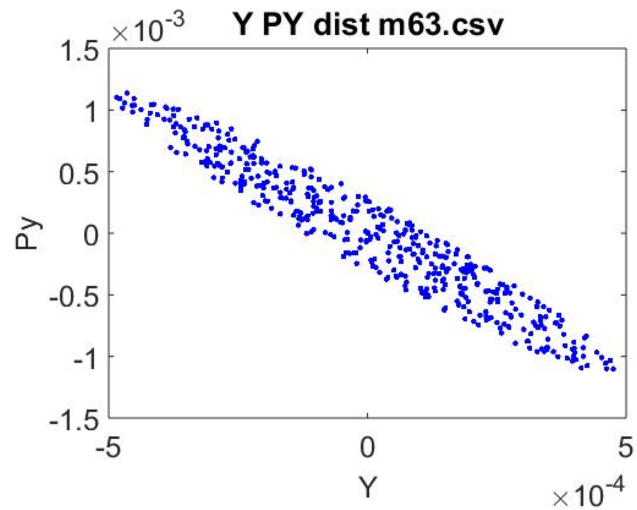
MAD-X-PTC





Synergia

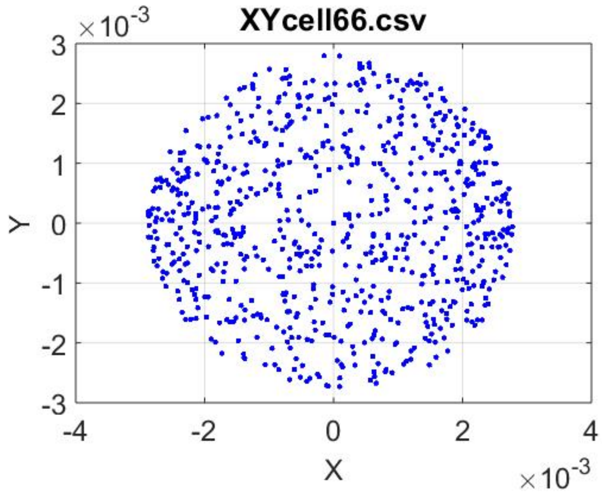


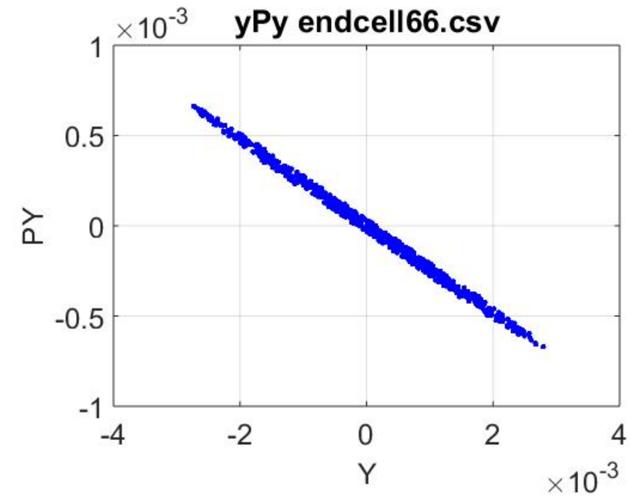


Turn on Quads (6^{th} turn)

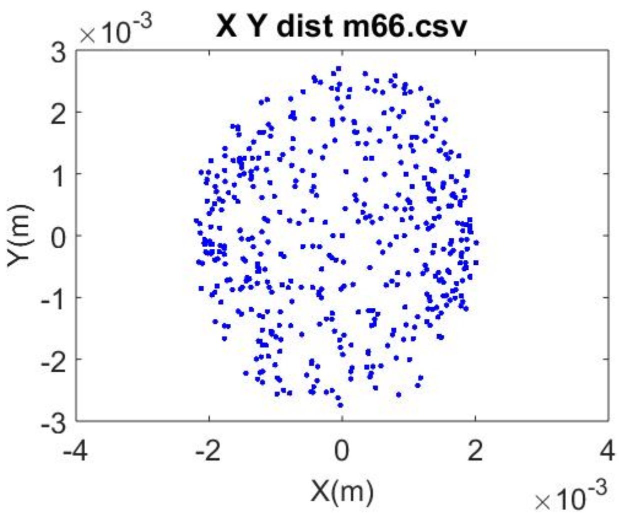
Quadrupole strengths from MAD runs to hold tune

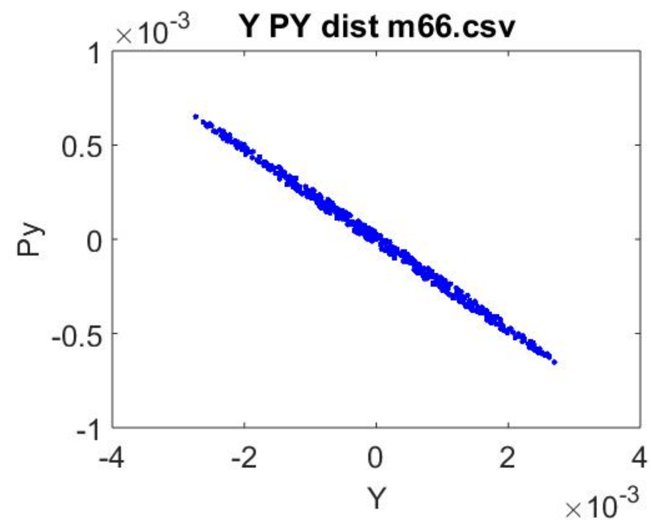
MAD-X-PTC





Synergia

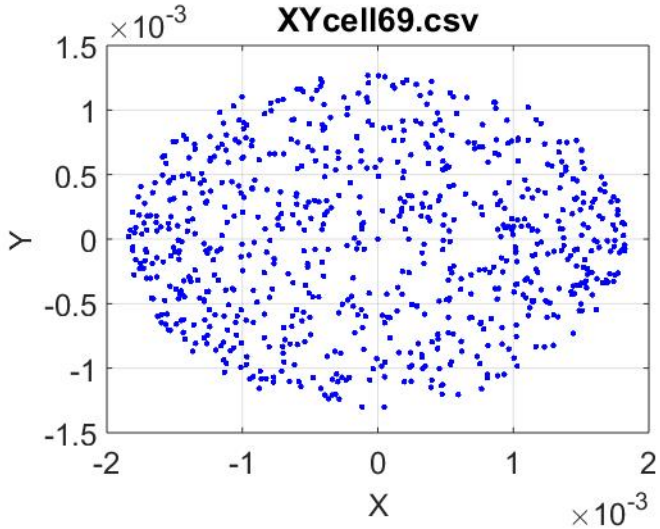


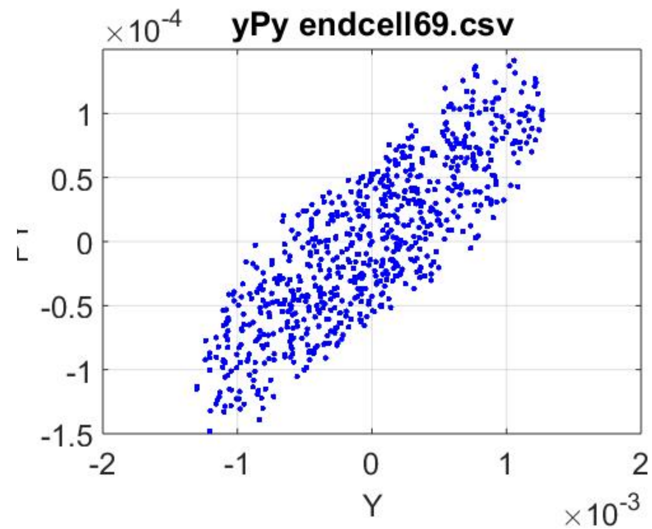


Turn on Quads (9^{th} turn)

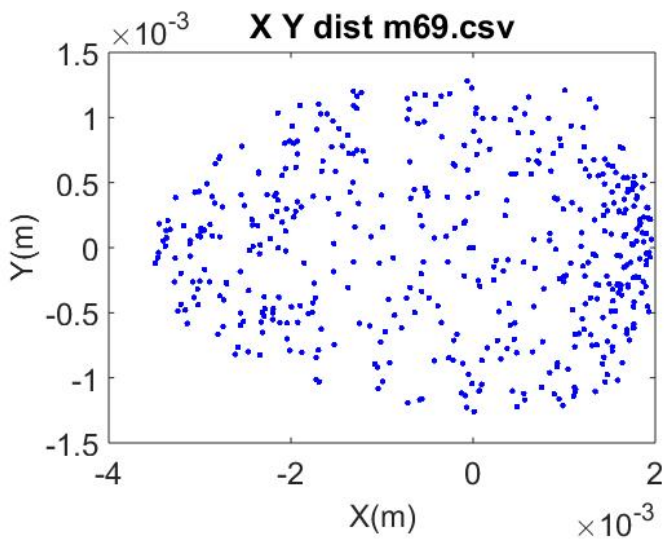
Quadrupole strengths from MAD runs to hold tune

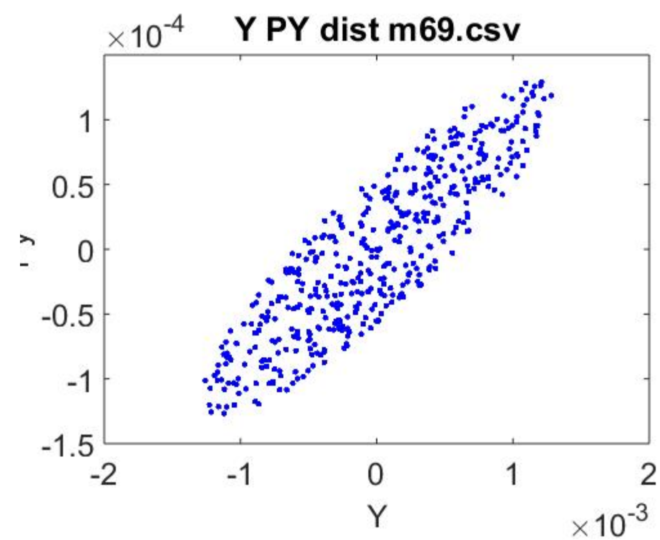
MAD-X-PTC





Synergia



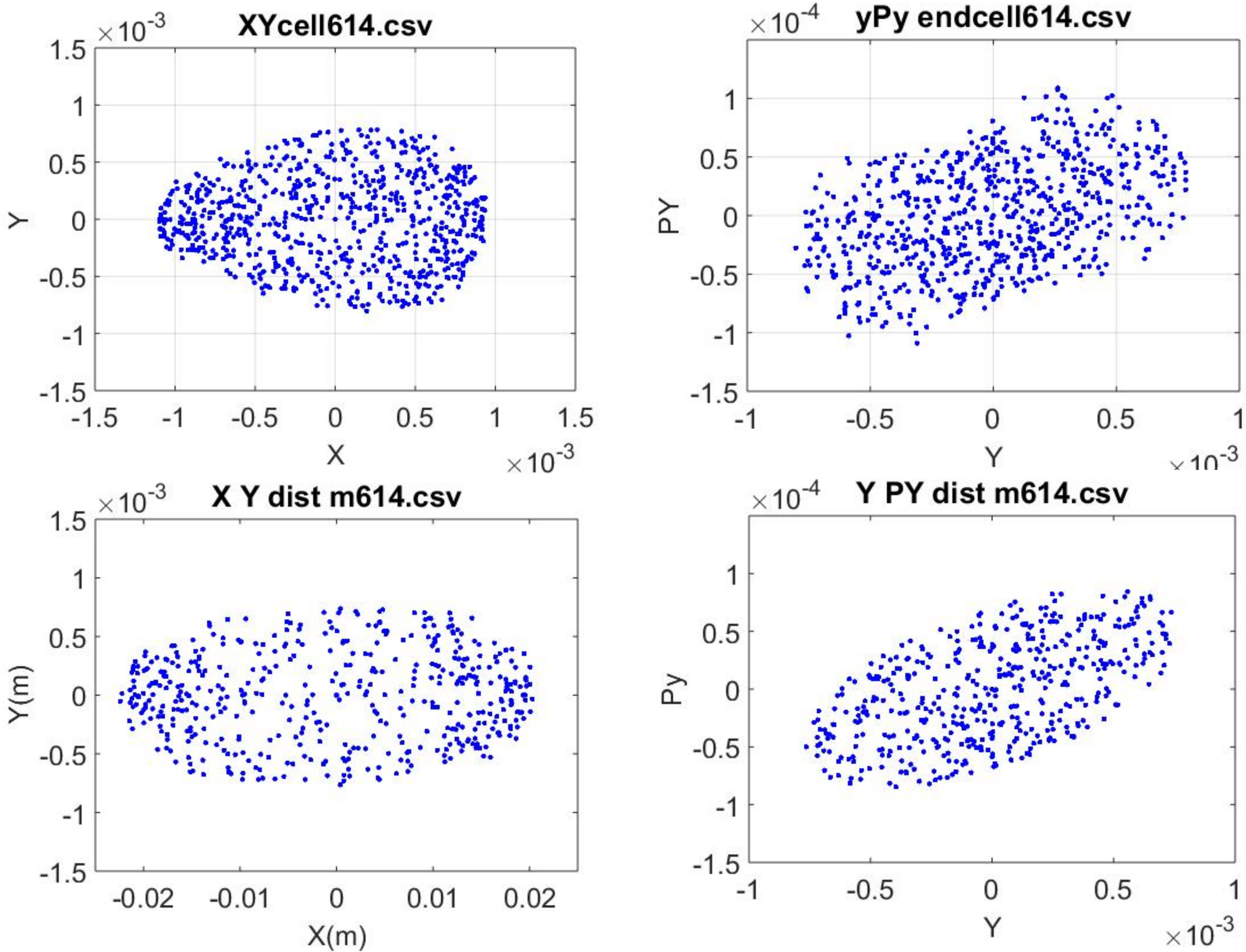


Turn on Quads (last turn)

Quadrupole strengths from MAD runs to hold tune

MAD-X-PTC

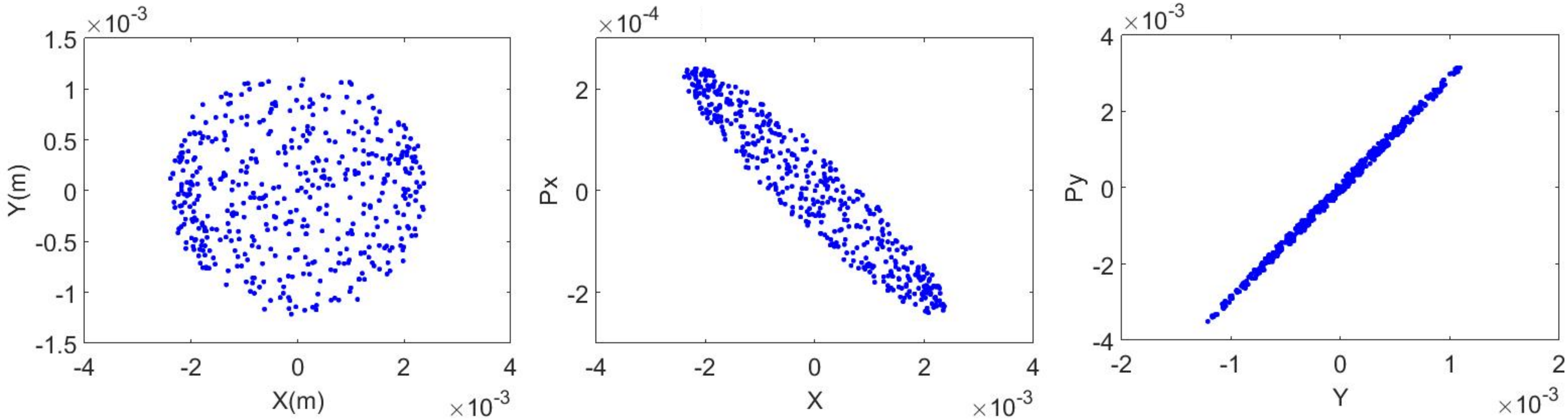
Synergia



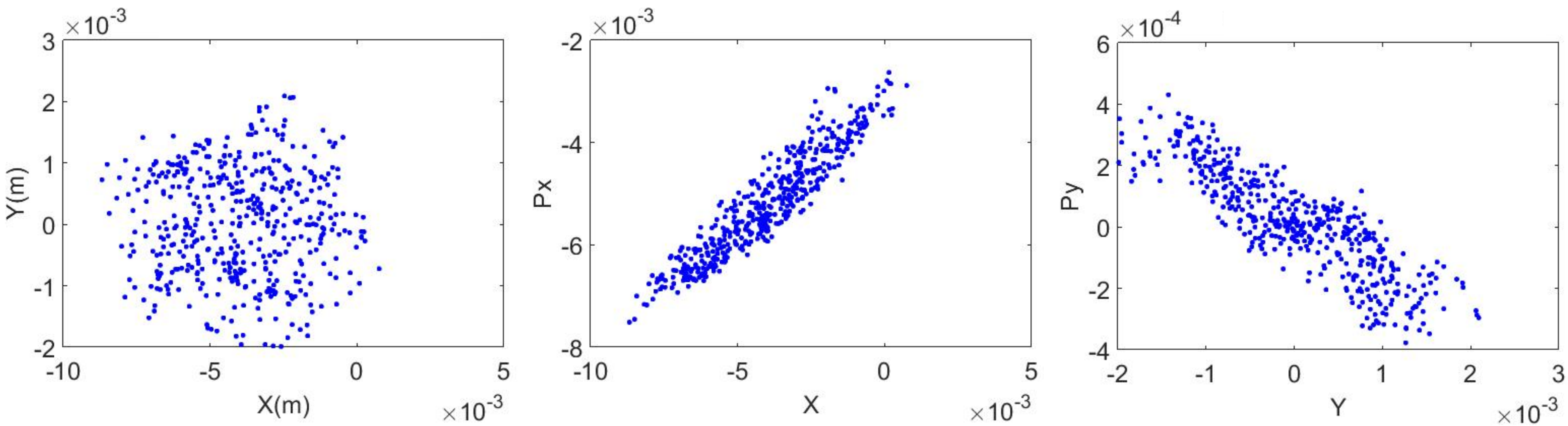
Synergia- Space Charge (1st sector)

Using the same quad strengths, lose ~60% particles

No Space charge



Space charge



Conclusion

- *SFC*
  - *RF cavity provides sufficient turn separation*
  - *Sector dipoles modeled*
  - *BTC*
- *Beam Dynamics*
  - *Isochronous reference orbit obtained*
  - *Quadrupole used as knob to fix tune*
  - *Particle tracking in MAD-X-PTC and SYNERGIA*

Future Work

- *Combined function magnet closure*
- *Implement more realistic energy gain in RF modules*
- *Use space charge to determine current limit*