Electron Cooler Design

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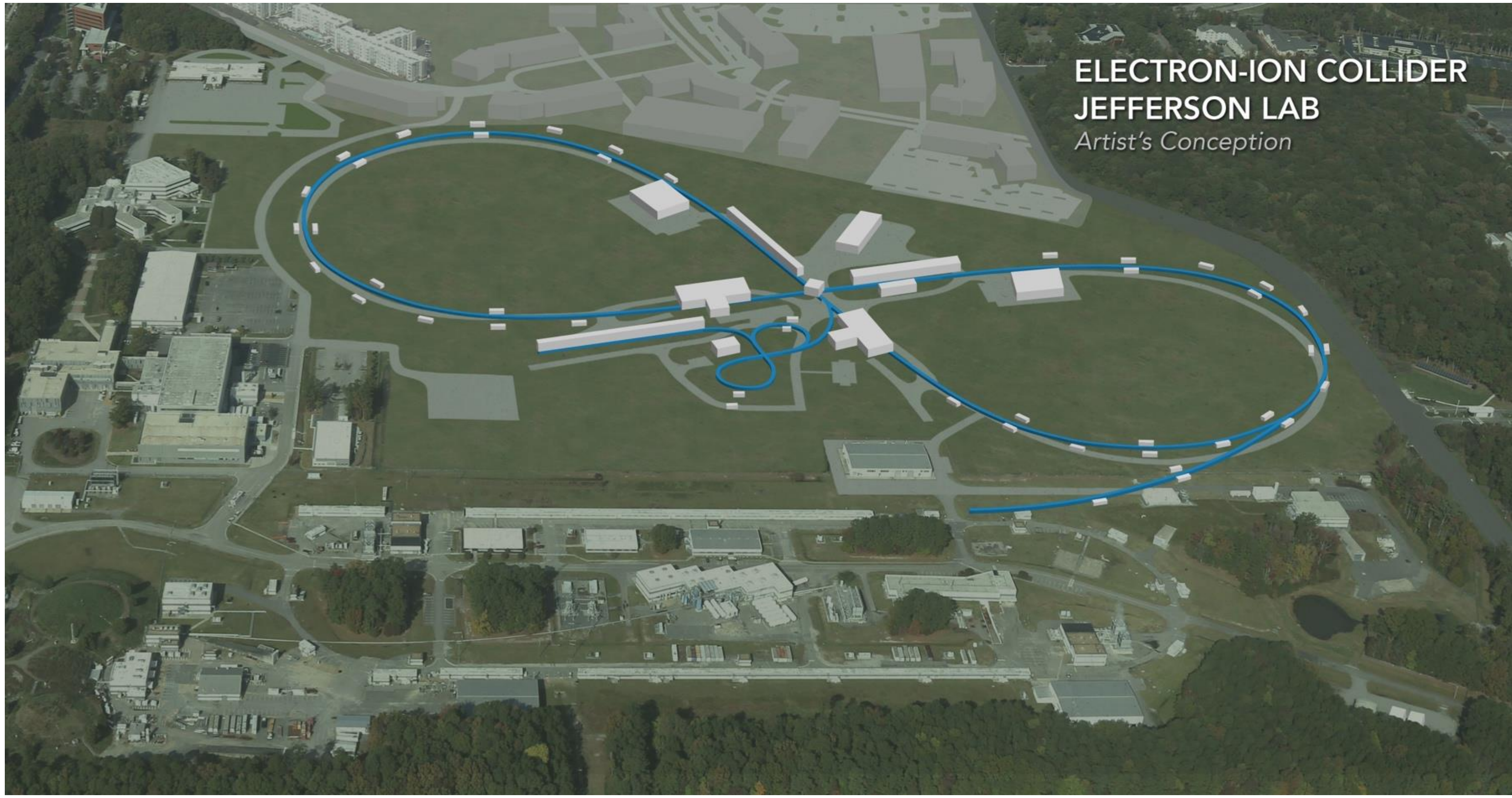


Nuclear Physics Accelerator R&D PI Meeting

November 13-14, 2018

Outline

- Goals and Milestones and description of the project
- Simulation codes
- Injector design.
- CCR strong cooling solution
- Current Status

Electron Cooler Design Project

- Description
  - This project will develop software and methods, that allow the completion of a full (start-to-end) cooler design for the JLEIC collider. The cooler must provide strong cooling to the proton or ion beam in the collider, allowing the highest possible luminosity
- Status
  - Performance from injector to dump is acceptable for 1.6 nC. Injector magnetization is preserved but the bunch profile is not acceptable.
- Main goal
  - Develop a start-to-end simulation of a strong cooler using a circulating cooler ring driven by an energy recovery linac.
- Supported by JLab's Baseline DoE NP Accelerator R&D funding
- The project's funding is not continued by the FY'18 NP Accelerator R&D FOA. The new funding is used to continue other aspects of the cooler ring design as well as experimental benchmarking.

Electron Cooler Design Project Budget

- Budget

	FY'17	Totals
a) Funds allocated	$453,000	$453,000
b) Actual costs to date	$453,000	$453,000

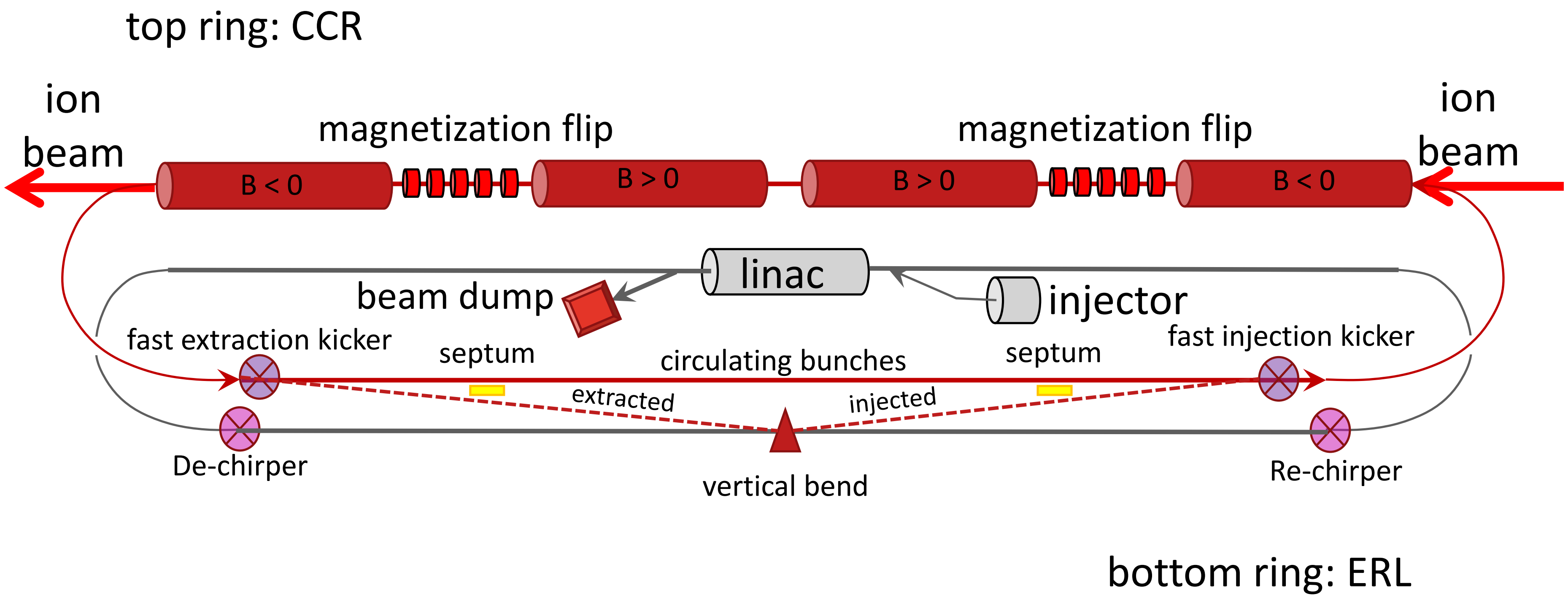
- Deliverables and schedule

Task	FY'17 Q1	FY'17 Q2	FY'17 Q3	FY'17 Q4
Find appropriate simulation codes	×			
Design and optimize the injector				×
Design the ERL and CCR necessary to cool the proton beam in JLEIC				×

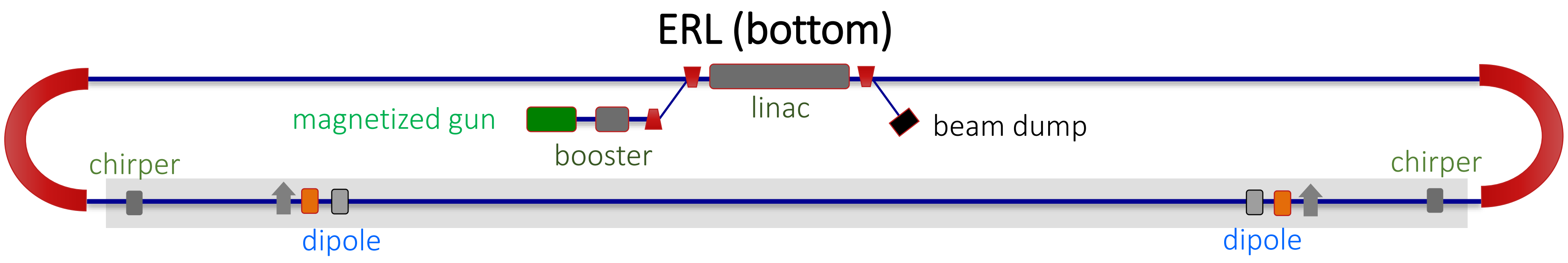
- The project corresponds to Lines 2 and 3, "High-current single-pass ERL for hadron ring" and "Strong hadron cooling" Priority High-A of the Jones' Panel report

Baseline Design is Cooling Ring Fed by ERL

- Same-cell energy recovery in 952.6 MHz SRF cavities
- Uses harmonic kicker to inject and extract from CCR (divide by 11)
- Assumes high charge, low rep-rate injector (w/ subharmonic acceleration and bunching)
- Use magnetization flips to compensate ion spin effects



ERL and CCR Layout



Strong Cooler Specifications (Electrons)

Energy	20–55 MeV
Charge	1.6 (3.2) nC
CCR pulse frequency	476.3 MHz
Gun frequency	43.3 MHz
Bunch length (tophat)	2 cm (23°)
Thermal (Larmor) emittance	<19 mm-mrad
Cathode spot radius	3.1 mm
Cathode field	0.05 T [3]
Normalized hor. drift emittance	36 mm-mrad
rms Energy spread (uncorr.)*	3x10^{-4}
Energy spread (p-p corr.)*	<6x10^{-4}
Solenoid field	1 T
Electron beta in cooler	37.6 cm
Solenoid length	4x15 m
Bunch shape	beer can

Cooler Specifications (protons)

Case 1 – 63.3 GeV center of mass energy

• Energy	100 GeV
• Particles/bunch	4.0 $\times 10^{10}$
• Repetition rate	119 MHz
• Bunch length (rms)	2.2 cm
• Normalized emittance (x/y)	0.9/0.18 mm-mrad
• Betatron function in cooler	100 m (at point between solenoids)

Case 2 – 44.7 GeV center of mass energy

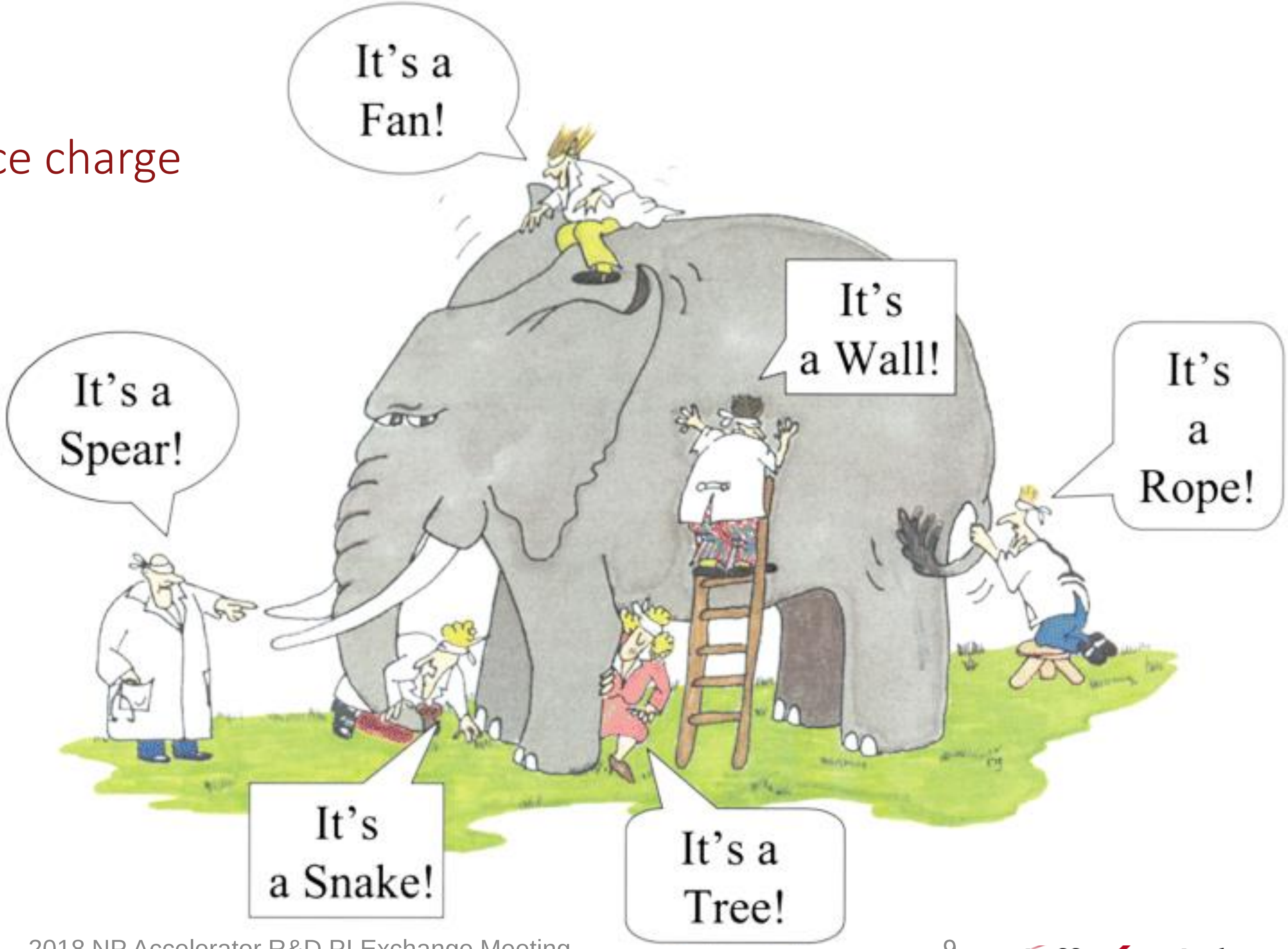
• Energy	100 GeV
• Particles/bunch	1.0$\times 10^{10}$
• Repetition rate	476.3 MHz
• Bunch length (rms)	1.0 cm
• Normalized emittance (x/y)	0.5/0.1 mm-mrad
• Betatron function in cooler	100 m (at point between solenoids)

Ion ring lattice may be coupled or dispersed in solenoid. Ion beam may be partially offset from the electron beam.

Probing a New Parameter Space

- DIMAD
  - ✓ lattice design
- elegant
  - ✓ CSR
- GPT
  - ✓ space charge
  - ✓ CSR
- Bmad
  - ✓ CSR
  - ✓ CSR shielding
- Vlasov-Solver
  - ✓ microbunching

- TStep
  - ✓ space charge
  - ✓ CSR



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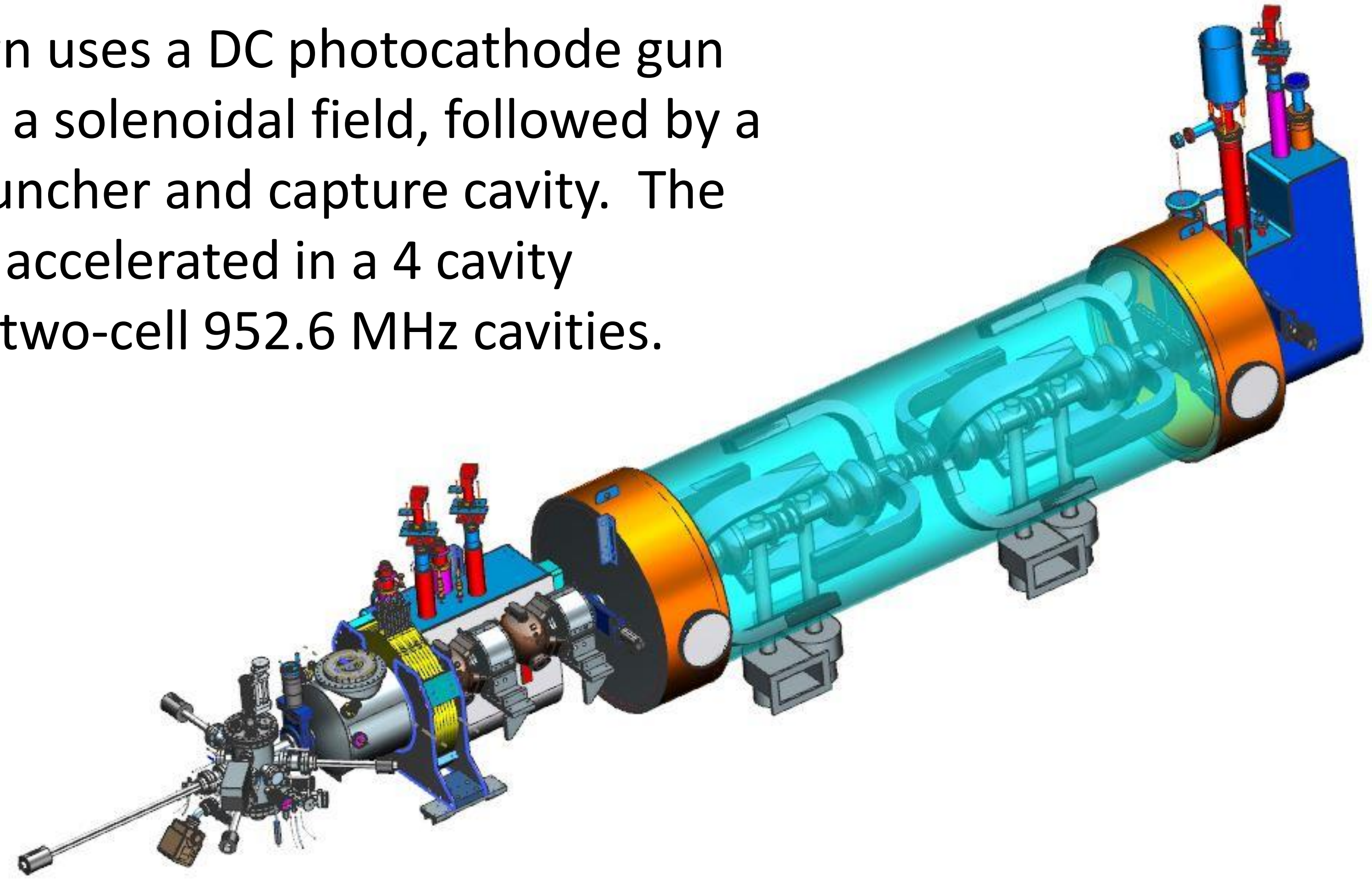
Magnetized Injector Design

Current design uses a DC photocathode gun embedded in a solenoidal field, followed by a 476.3 MHz buncher and capture cavity. The beam is then accelerated in a 4 cavity booster with two-cell 952.6 MHz cavities.



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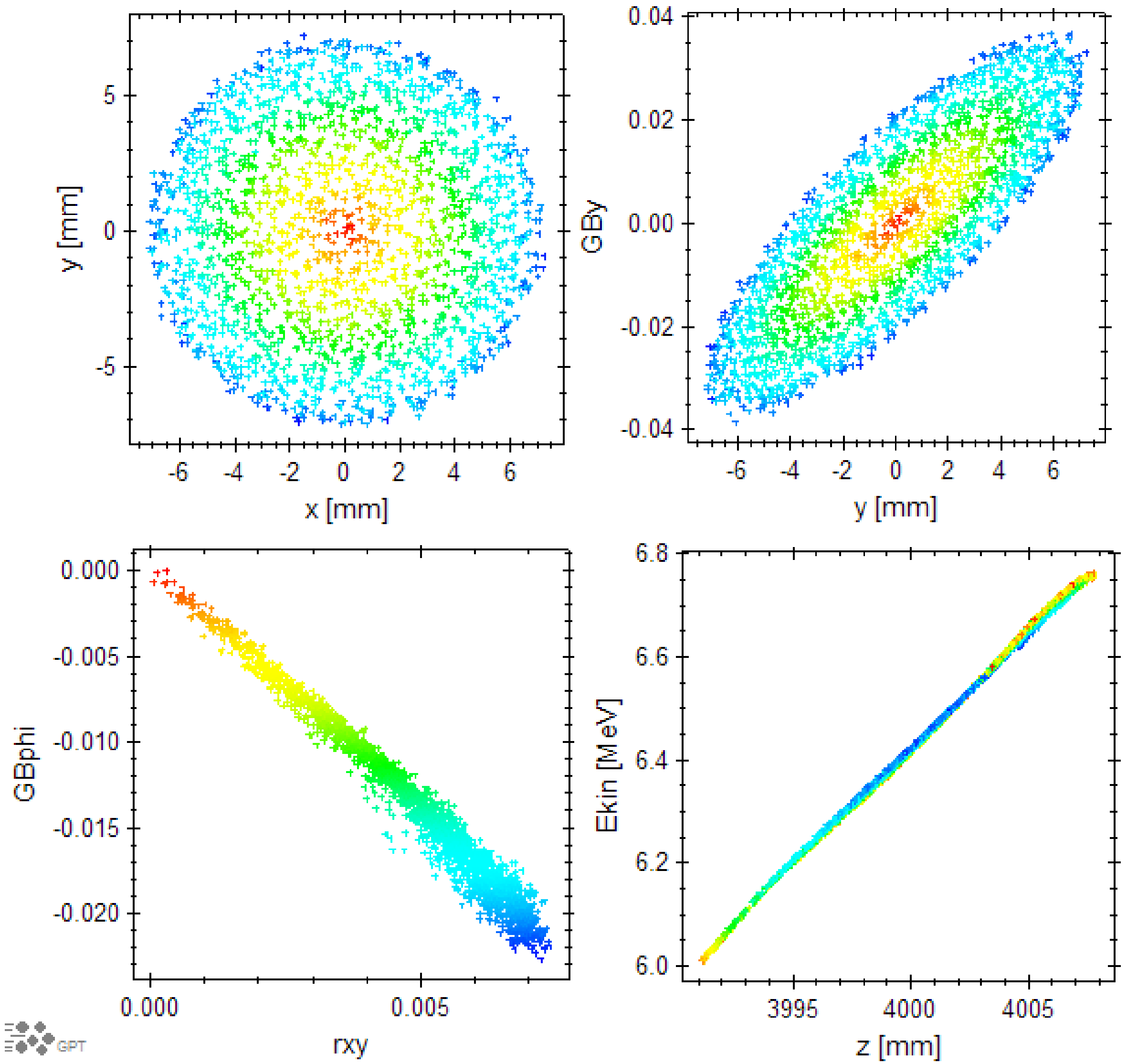
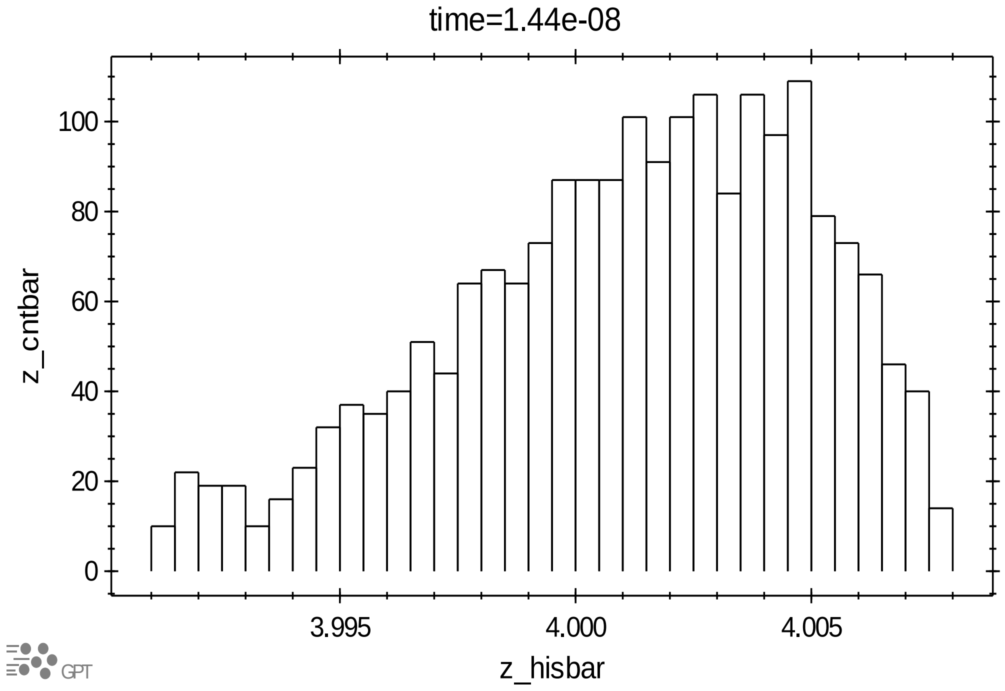
Start to Merge Simulation

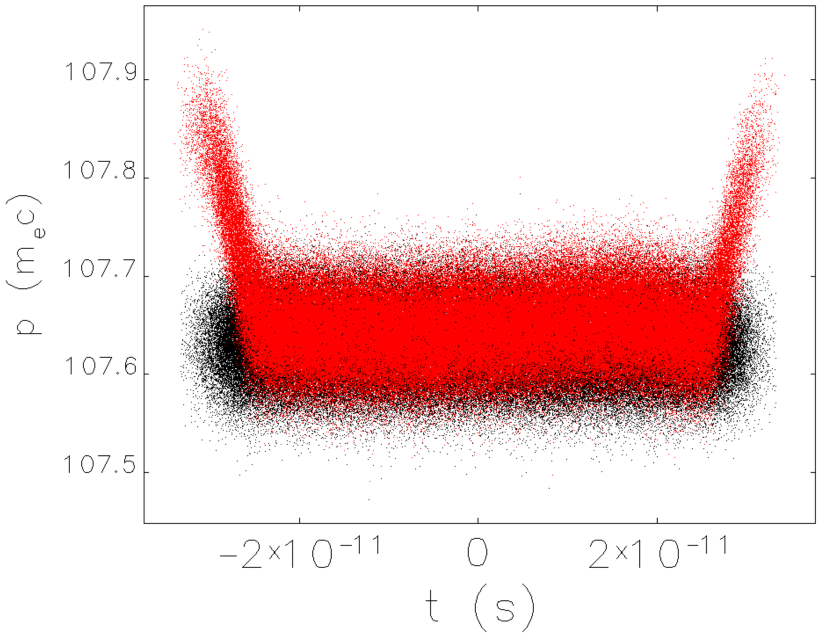


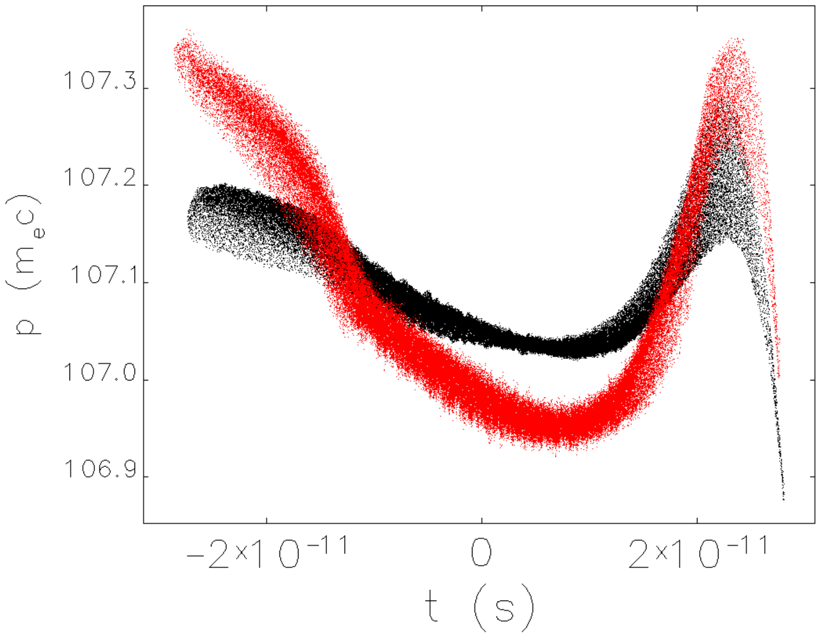


Magnetization is preserved but the longitudinal shape is not

The Problem With a Non-Top-Hat Bunch

- With a uniform bunch, the CSR effects on the longitudinal phase space can be "undone" by running near zero-crossing in an RF cavity
  - ✓ i.e. the CSR imposes a near linear energy chirp across the bunch which can be removed by appropriate choice of phase and gradient of an RF cavity
- current injector solution is not a uniform distribution
- The non-uniform distribution will exacerbate CSR issues.





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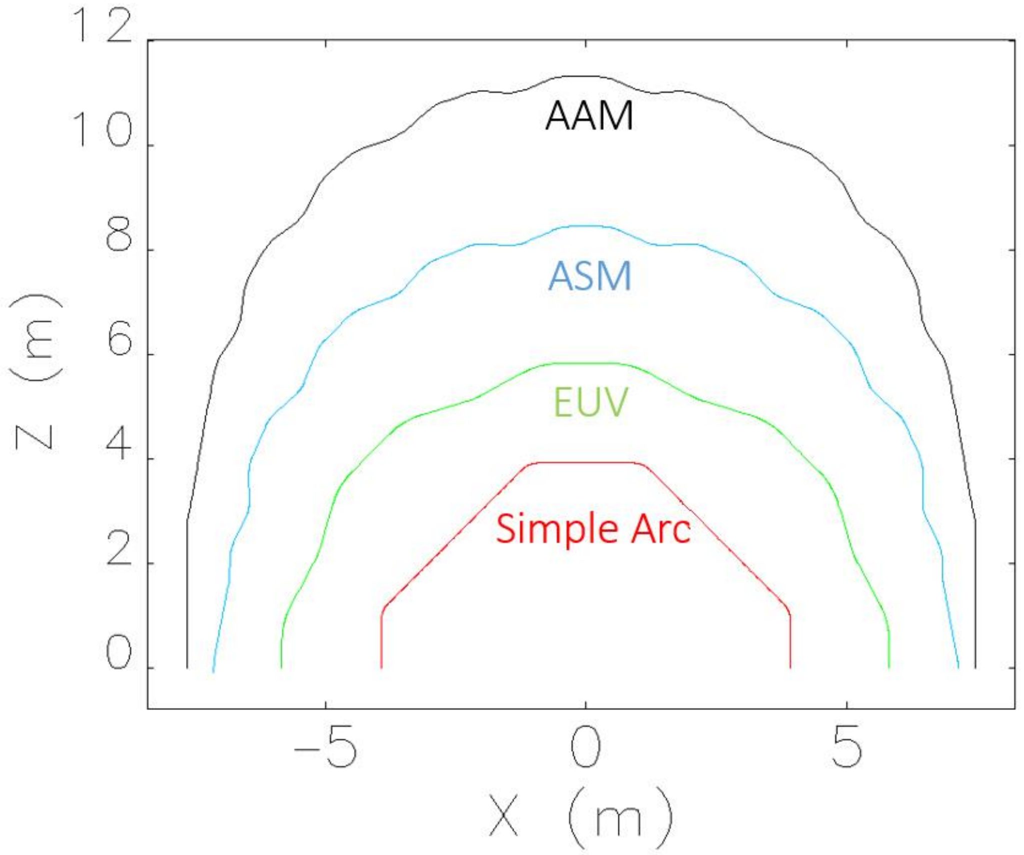
Recirculation Arcs

- ERL has 360° of bending
- CCR has 11 × 360° of bending
- the CCR arc has the following requirements:
  - ✓local axial symmetry – *preserve magnetization*
  - ✓globally isochronous – *longitudinal match*
  - ✓locally isochronous - *manage CSR and mBI*
  - ✓locally achromatic – *manage CSR and mBI*
  - ✓high periodicity – *suppress aberrations and error sensitivities*
  - ✓moderate size – *avoid space charge degradation*
- not easy to satisfy all conditions simultaneously



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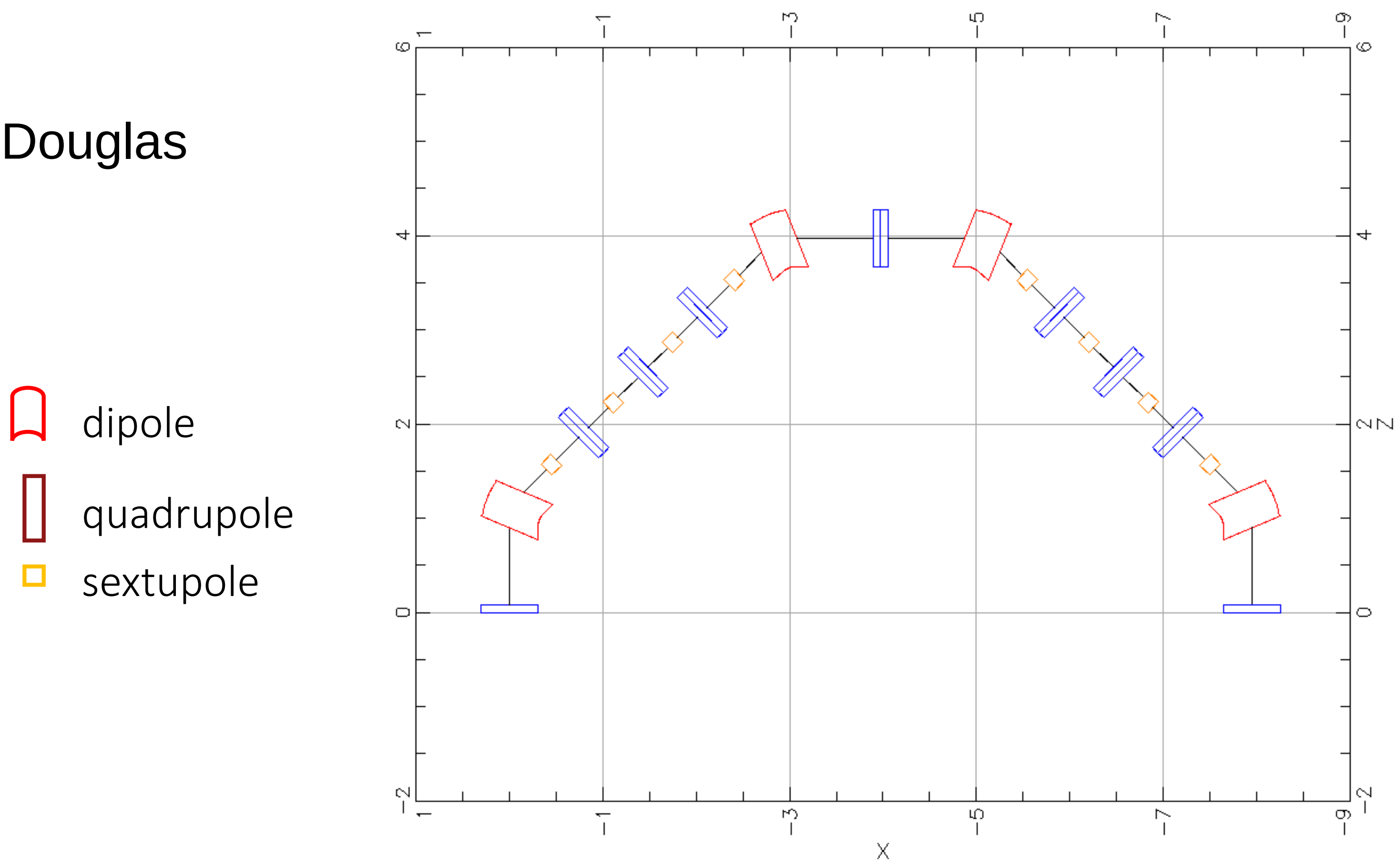
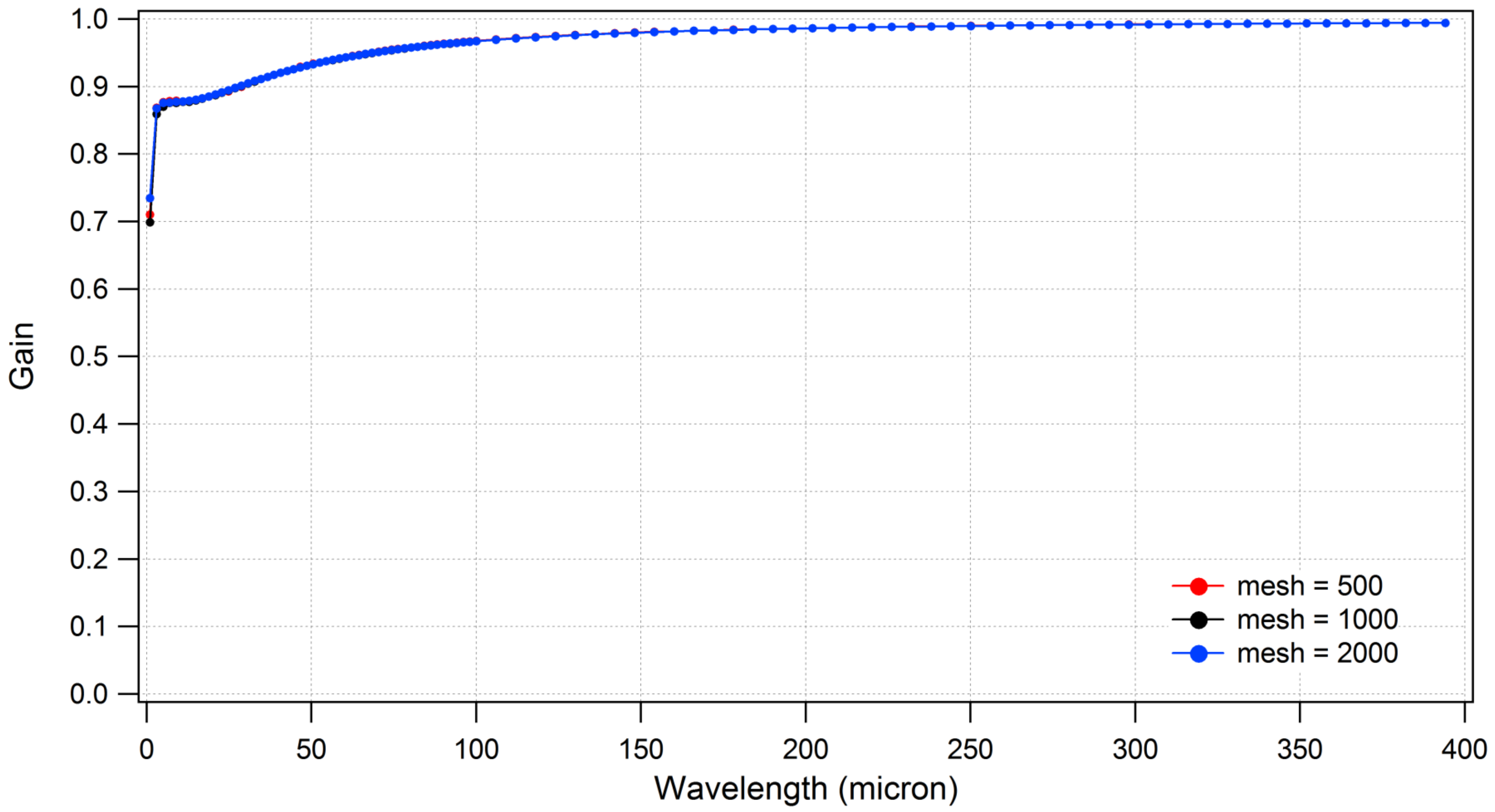
Simple Arc Layout

- design by D. Douglas



Microbunching Gain for Simple bend

- μBI gain is ≤ unity
- <u>needs</u> to be less than unity for multiple passes (gain grows exponentially)



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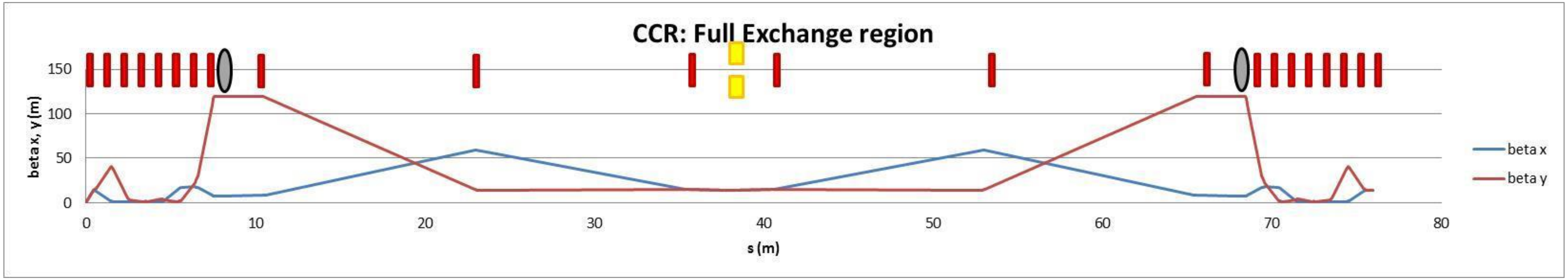
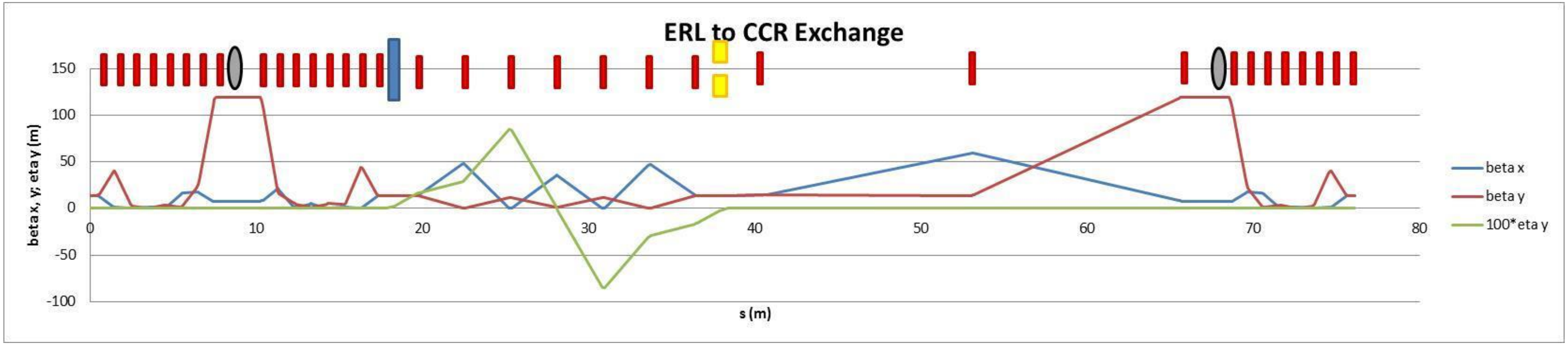
Exchange Region Layout

- CCR back leg





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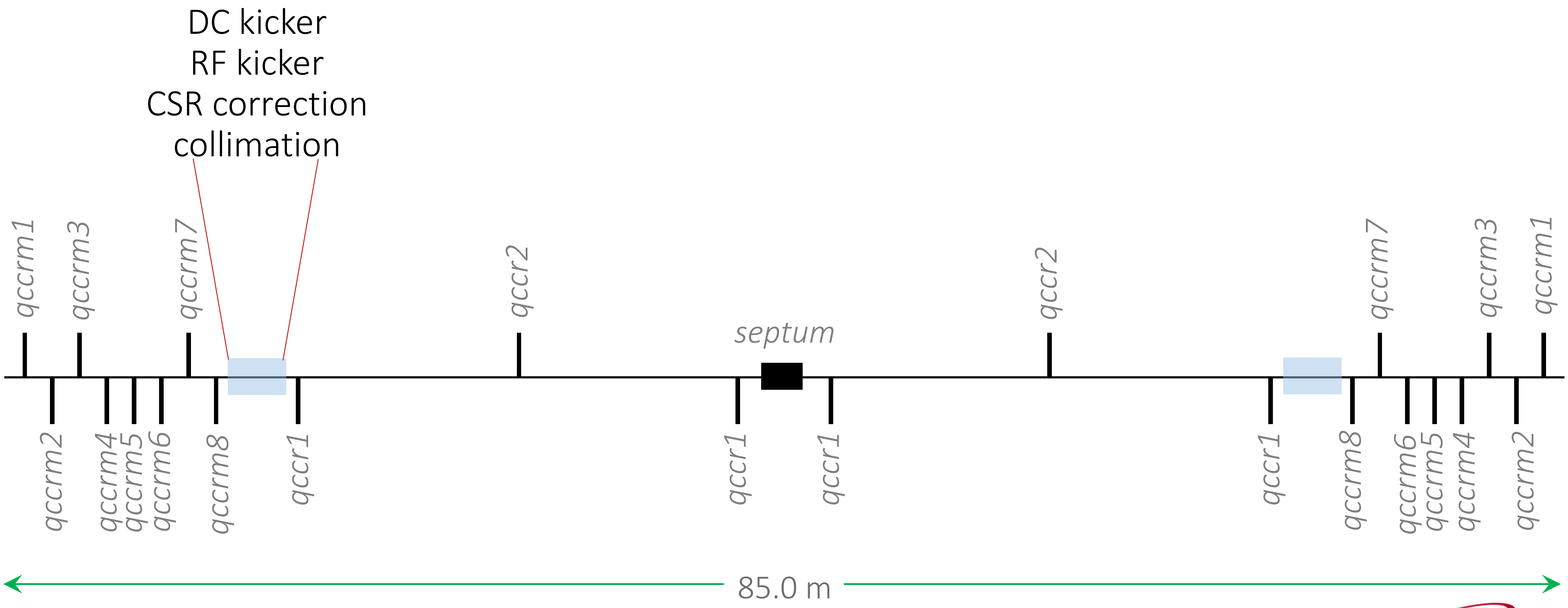
CCR Backleg

- requires idealized systems and mitigation schemes to transport bunch 11-turns
  - ✓ CSR correction cavity modeled as a matrix to fix longitudinal phase space (R_{65} = 0.025 m, T_{655} = 2.5 m) plus an energy shift (33 keV)
  - ✓ “collimator” used to filter high energy tails (*deltaLimit* = 3×10^{-3})



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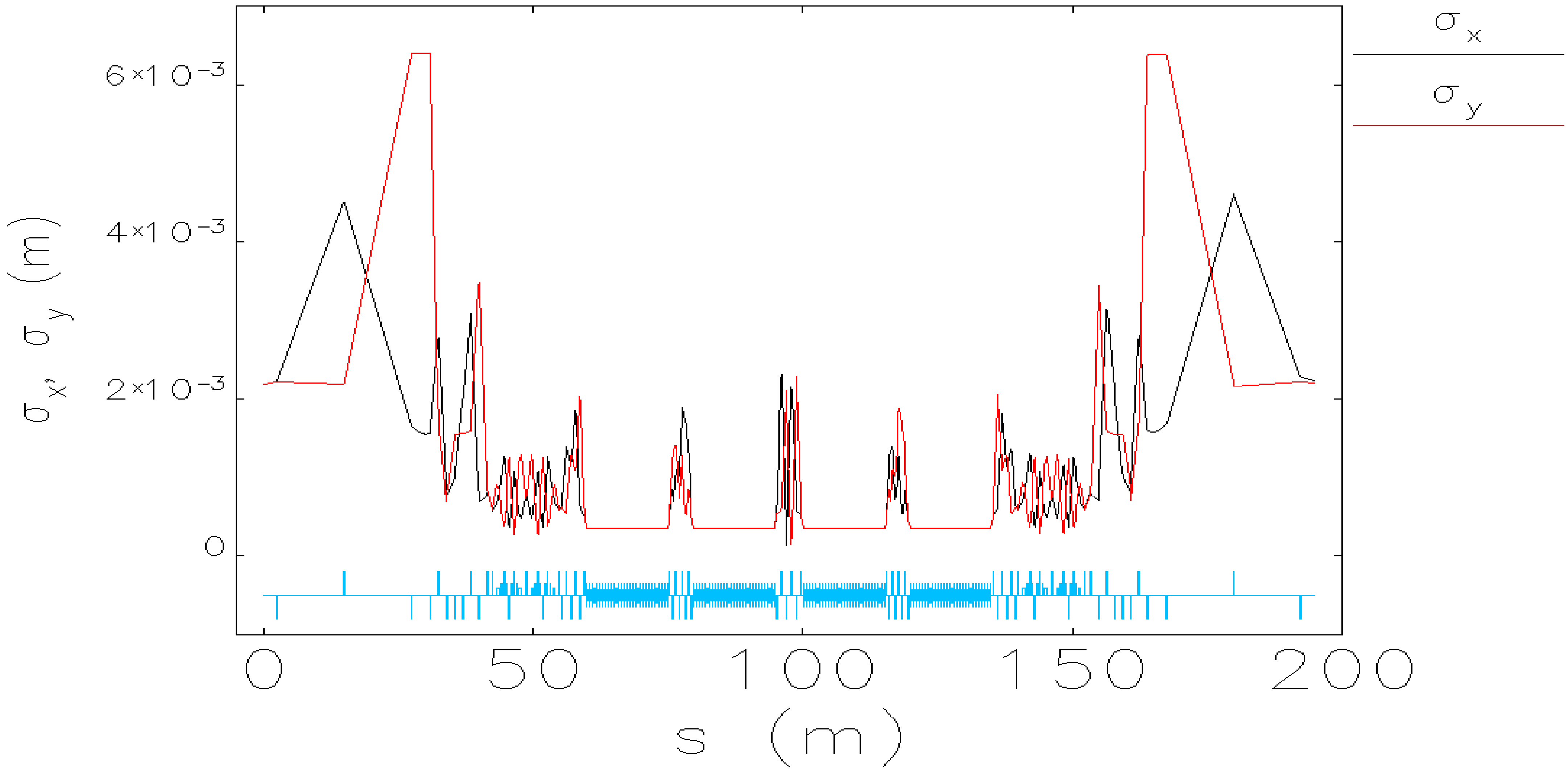
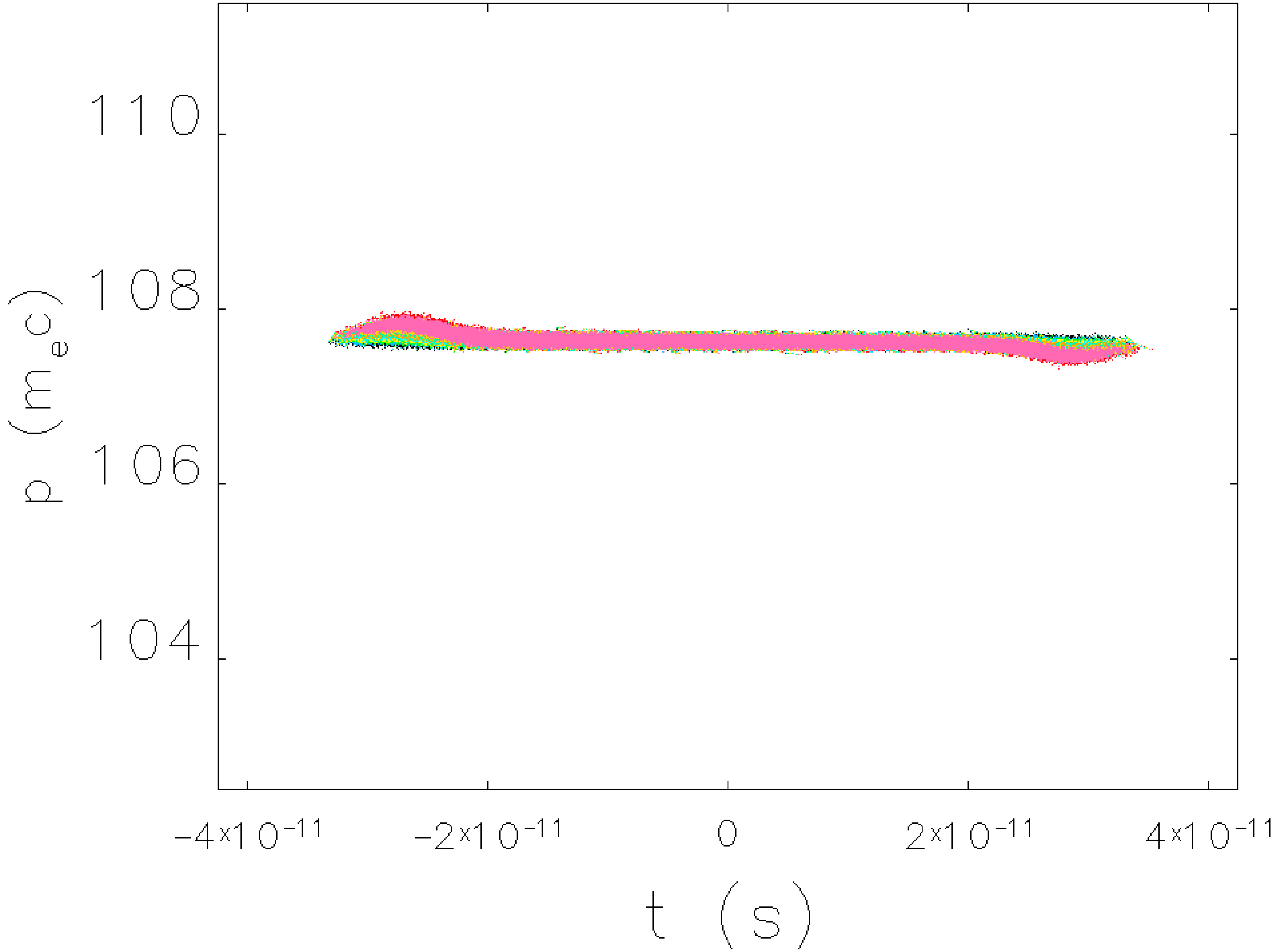
Lattice for Entire CCR

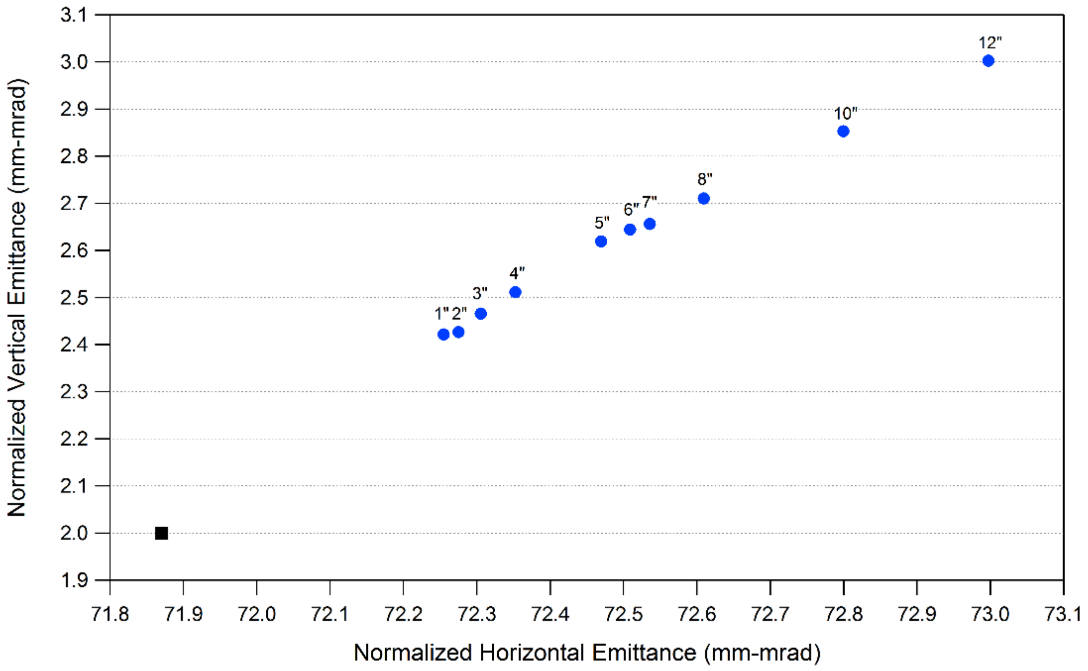


Effects of Space Charge on Longitudinal Phase Space is Negligible

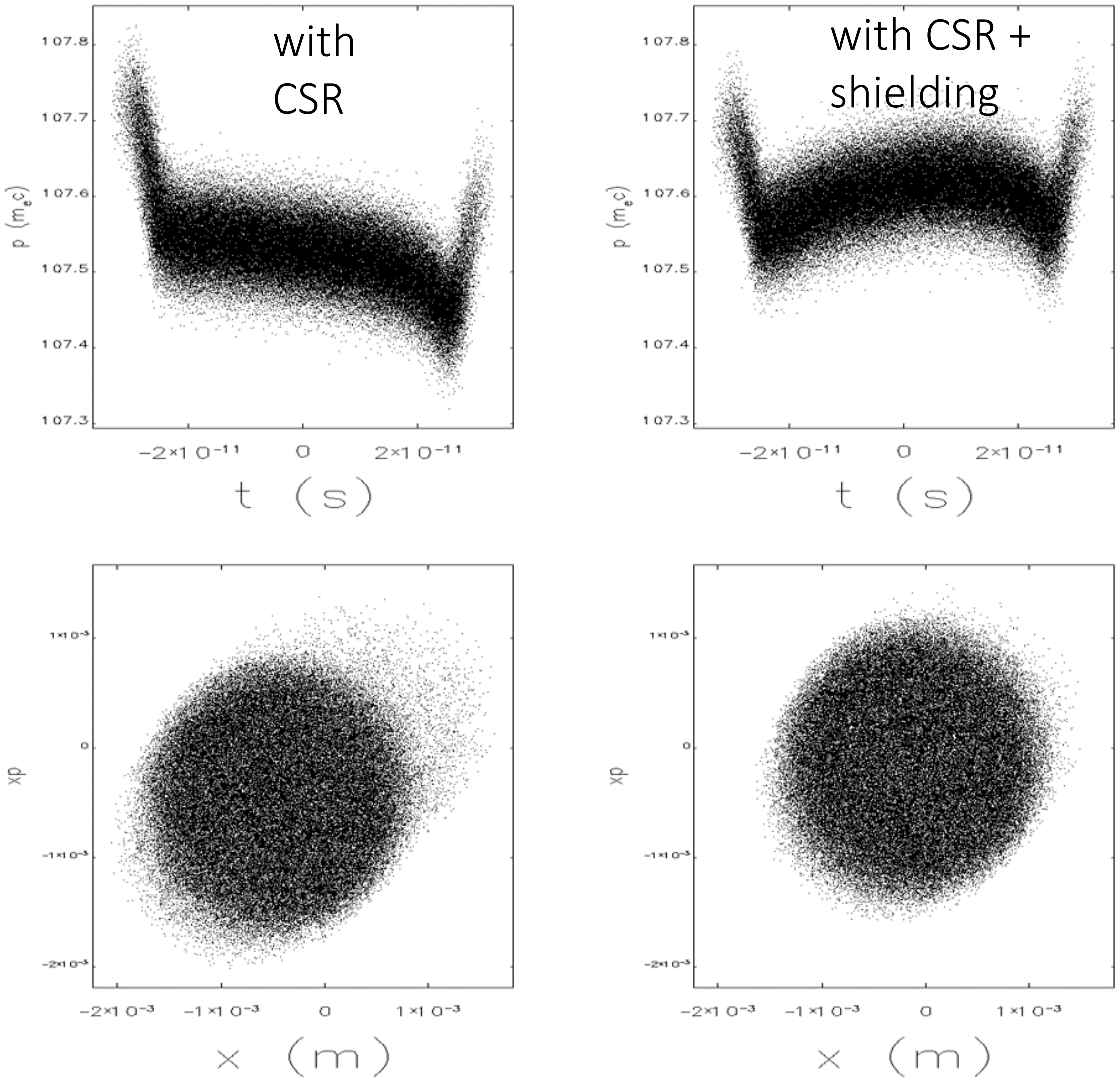
- This simulation uses Tstep, which includes space charge but no CSR. The overlay of 11 passes is shown. The ends are slightly affected but the core is fine.



Bmad with CSR and Shielding

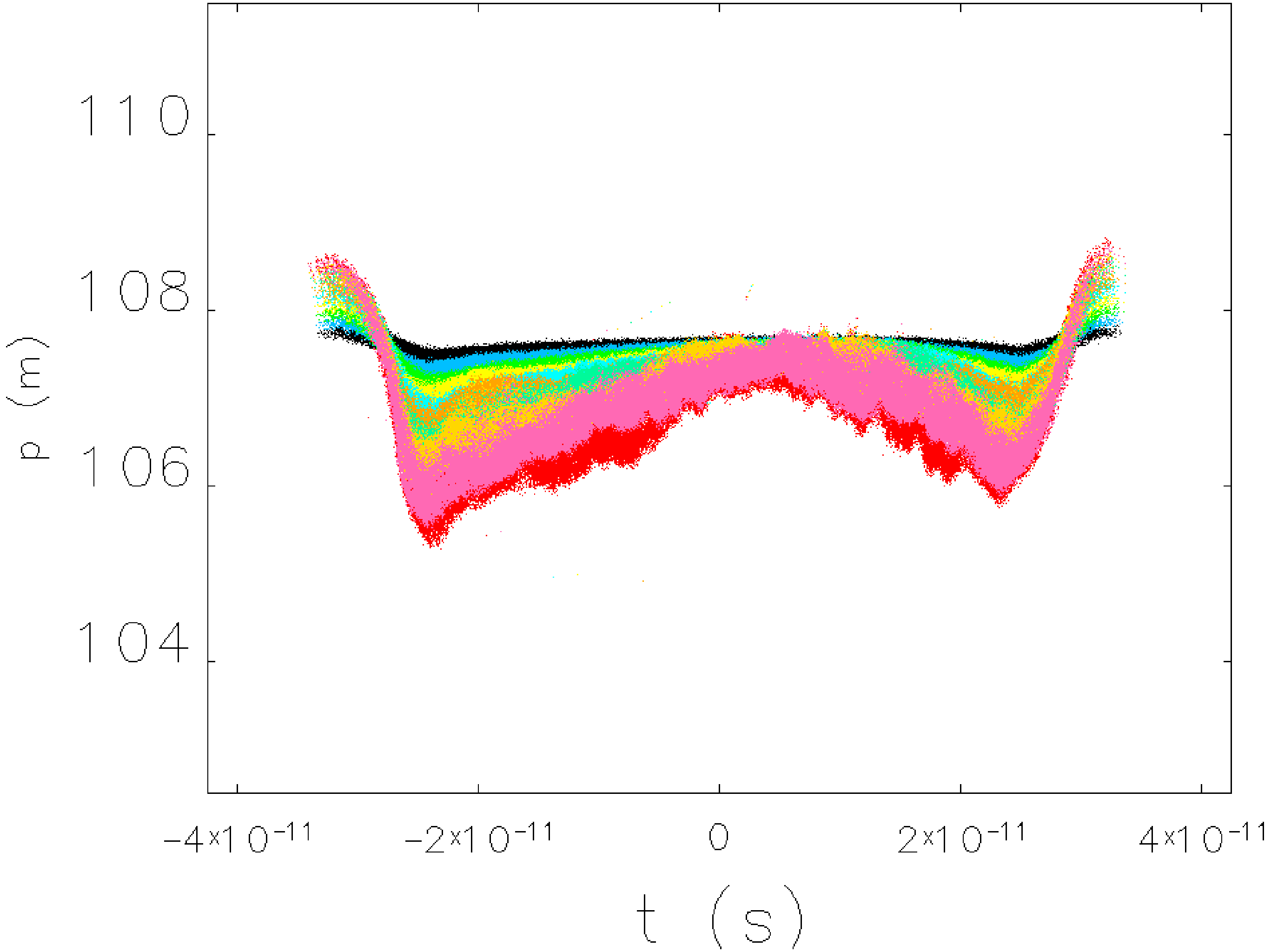


With 3.2 nC bunches, the Larmor emittance grows by 50% with a 12" chamber height. One must reduce the chamber height to 2" to get a 20% emittance growth.



Bmad – Multiturn Tracking

- Bmad with CSR shielding



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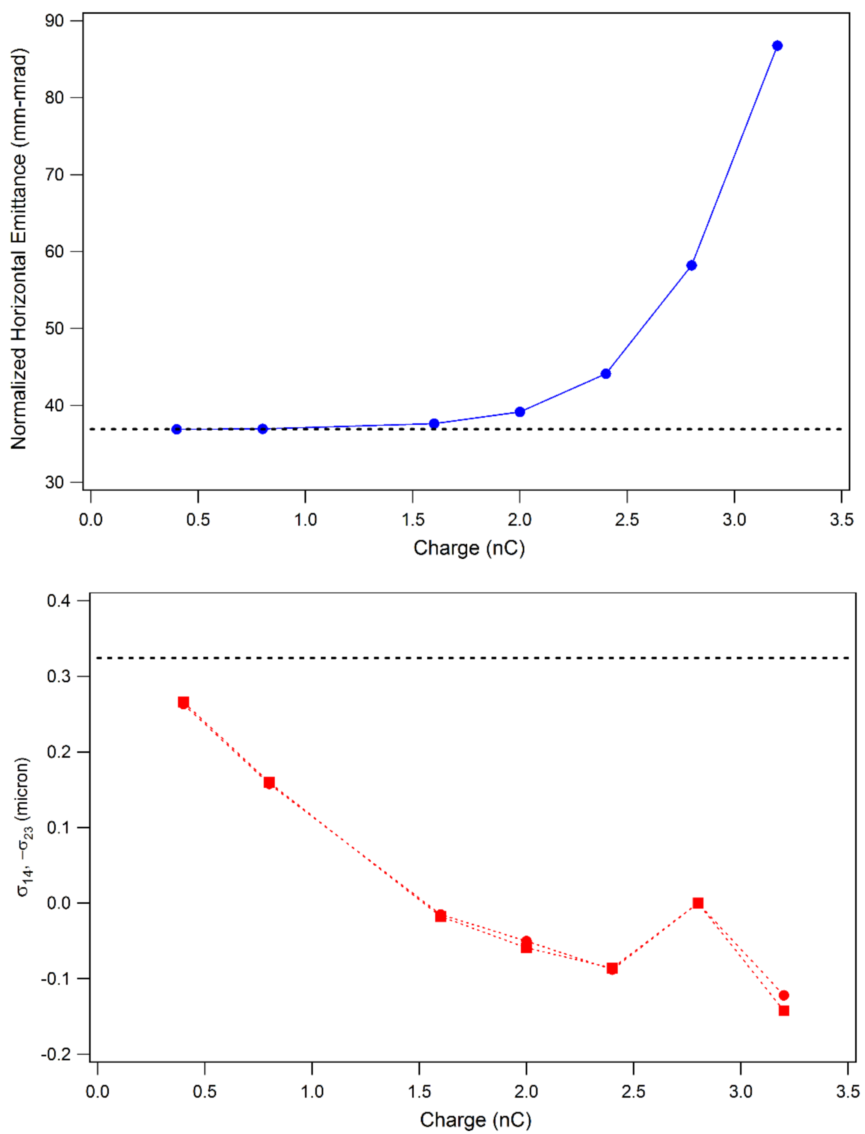
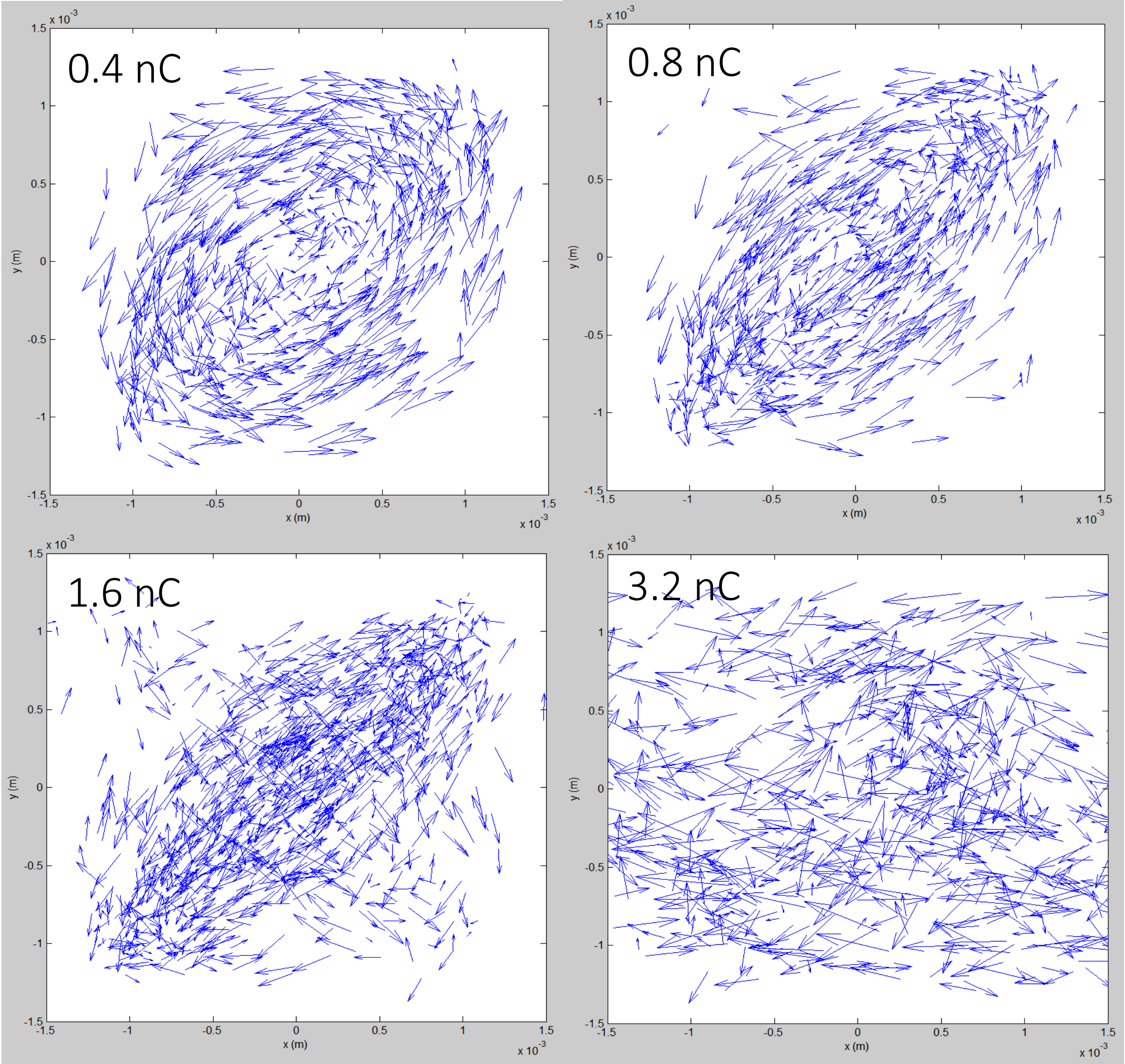
Emittance vs. charge





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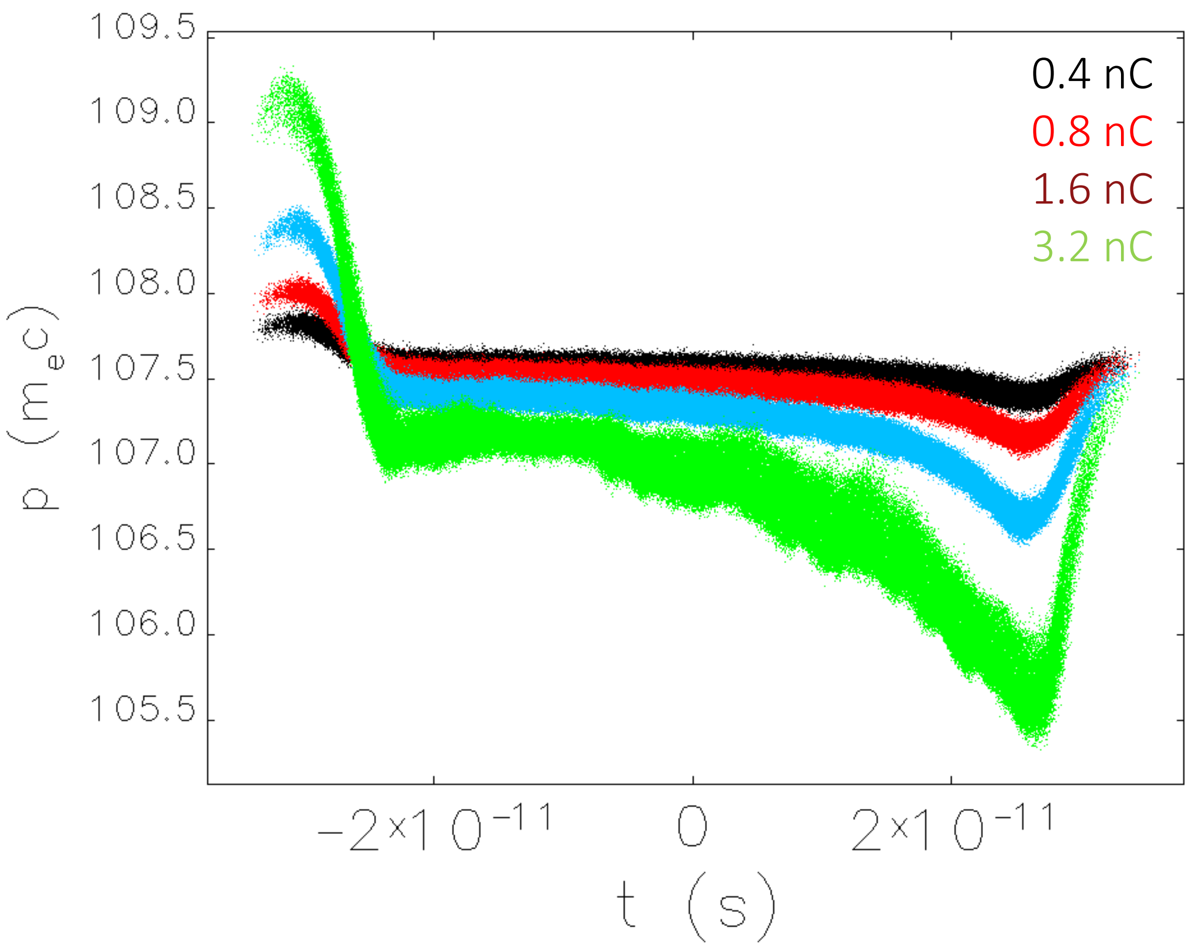
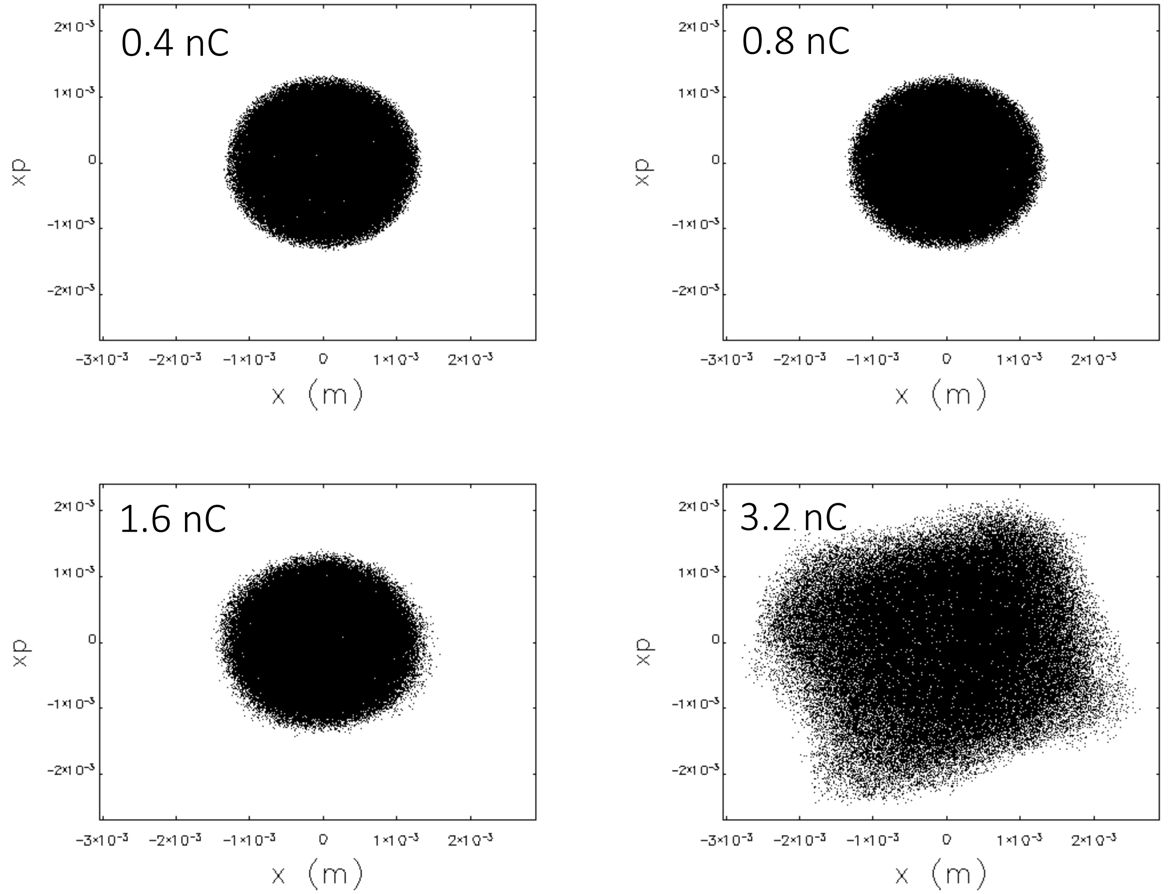
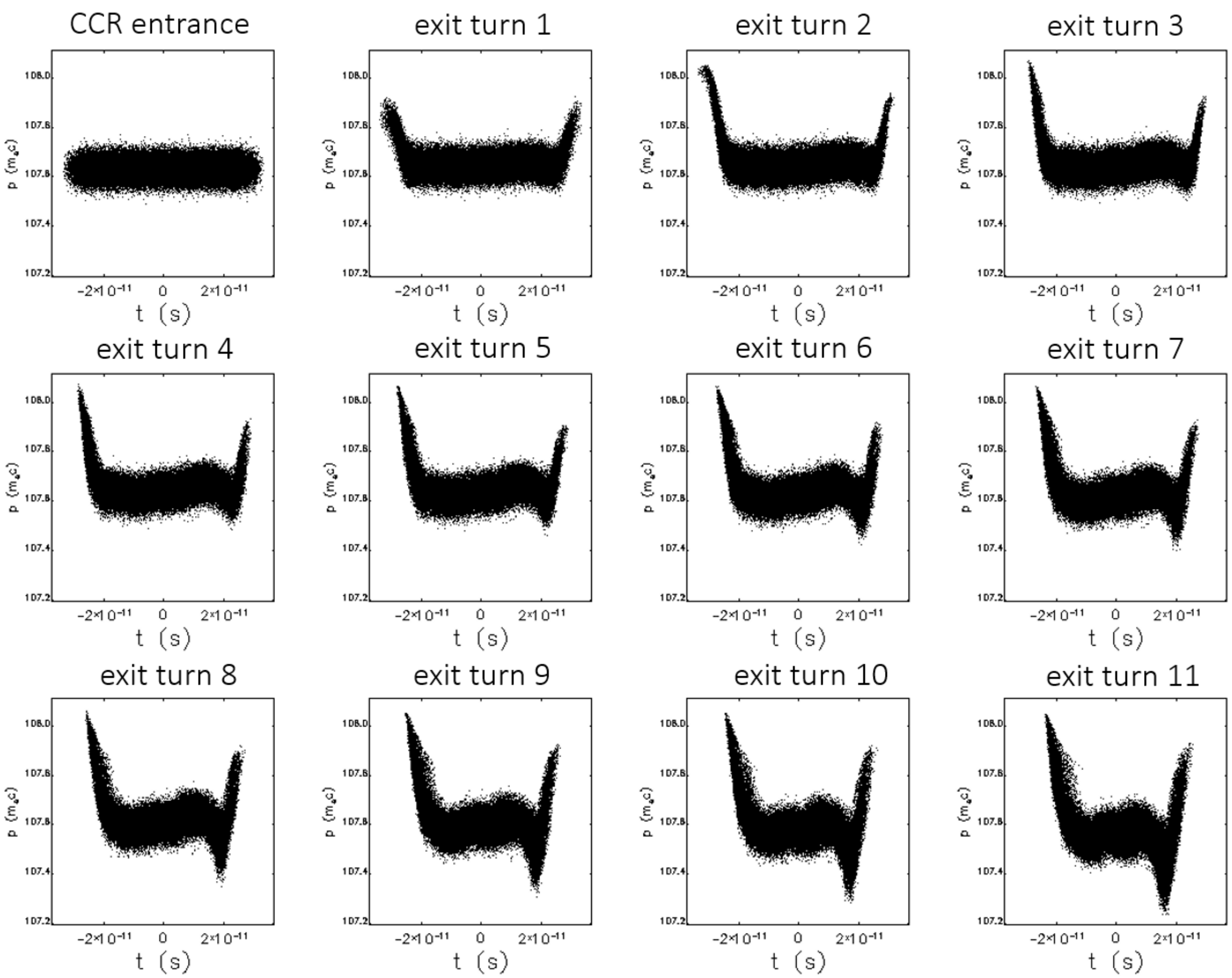
elegant – Charge Scan





Performance of CCR at 1.6 nC

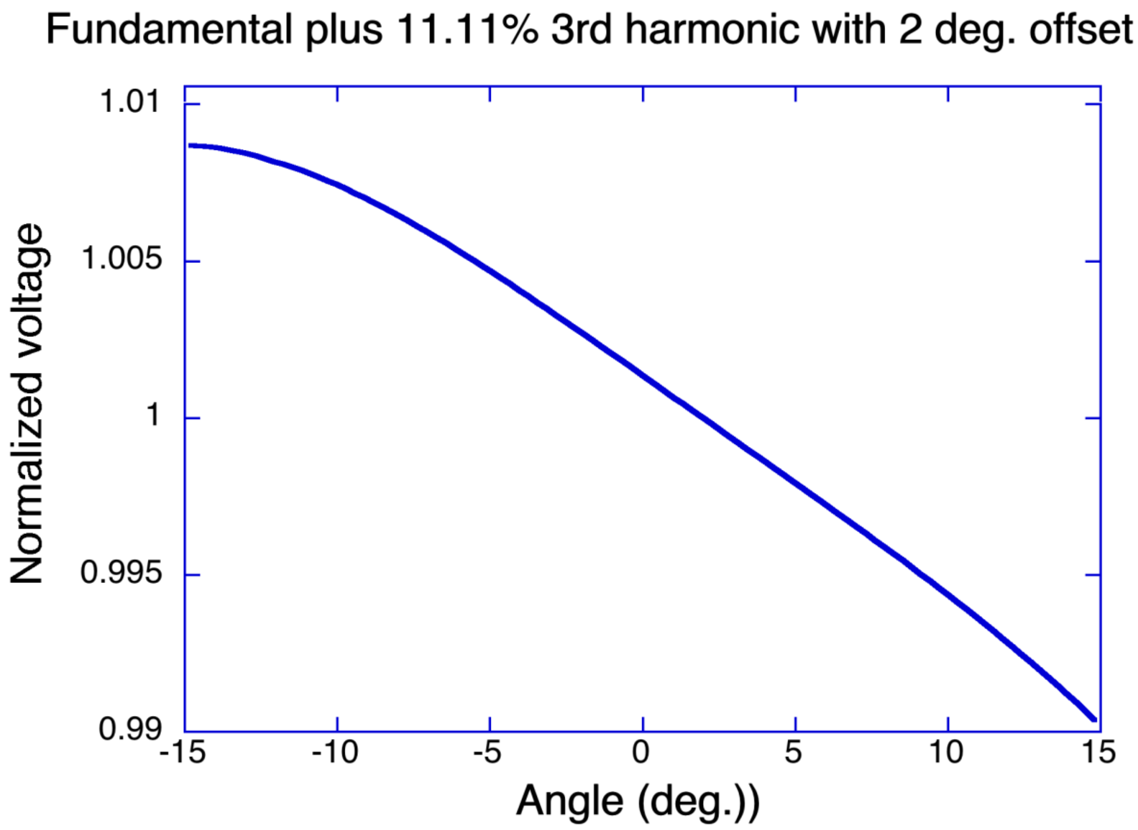


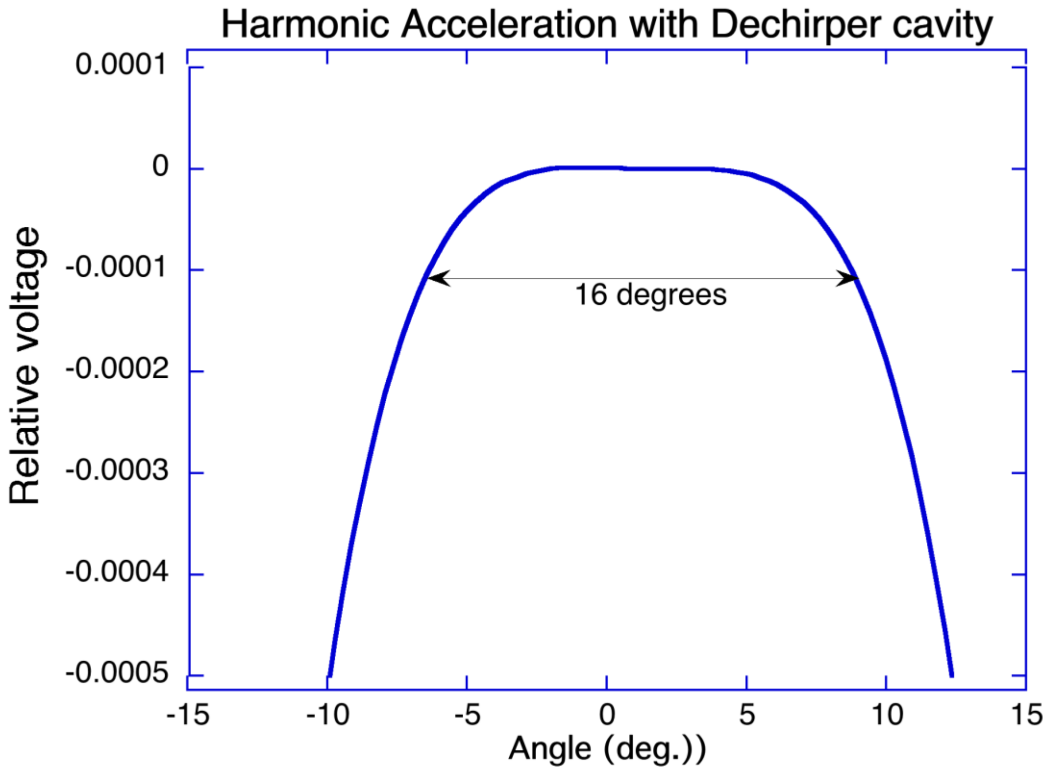
Issues and Potential Solutions

- Injector bunch is not a top hat
  - Lower frequency and add harmonic RF
- Linac acceptance is too small
  - Lower frequency and add harmonic RF
- CSR and space charge accelerate the bunch ends
  - Go to longer bunch
- Simple arc does not preserve magnetization
  - Try FFFAG arc if microbunching gain can be reduced.
  - Try Flat-to-Round transitions at entrance and exit

Voltage with 3rd Harmonic and phase and amplitude offsets

If we want to accelerate a very long bunch and then stretch it out even more we can use 3rd harmonic cavities in the linac.





Before going into the CCR, take out the slope using a 952.6 MHz de-chirper.

We can also put in a quartic correction if necessary by changing the amplitude

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Summary: Where are We, and Where Do We Go?

✓Beam exchange design

✓Cooling Insertion

- Specify solenoid tolerances

✓ Linac design

- Lower frequency and add 3rd harmonic cavities
- Optimize HOM damping.

✓CCR Design

- Microbunching gain is low but magnetization preservation is only fair. Needs to work at higher charge.
- Optimize vs. tune and explore FFFAG
- Calculate collective effects (ion trapping, wakes, resonances)

○ Injector design

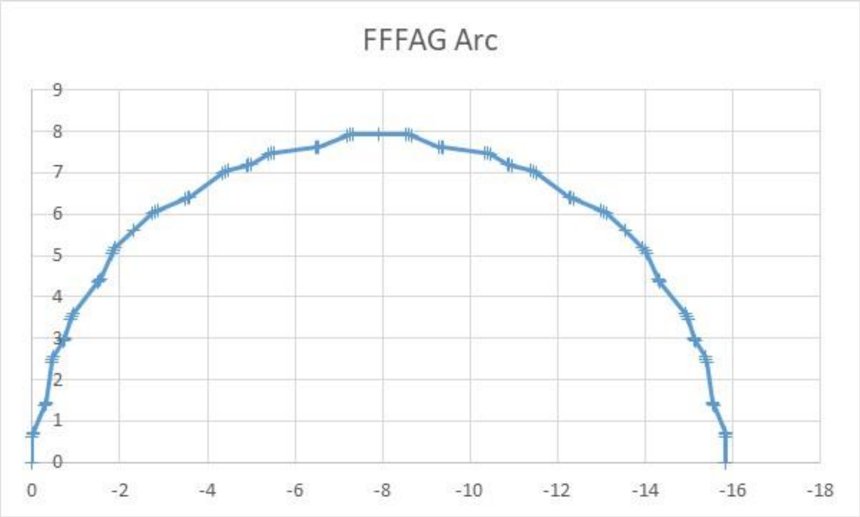
- Magnetization is preserved up to end of booster
- Need to try lower frequency and harmonic RF

○ Merger Design

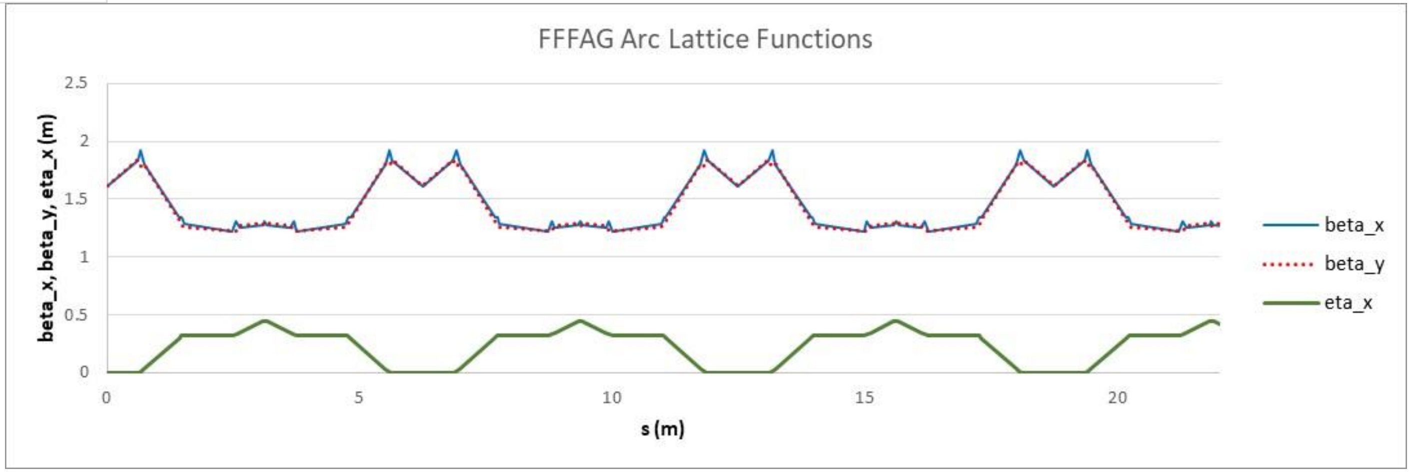
- Still many options to explore.

Thank You

FFFAG Design

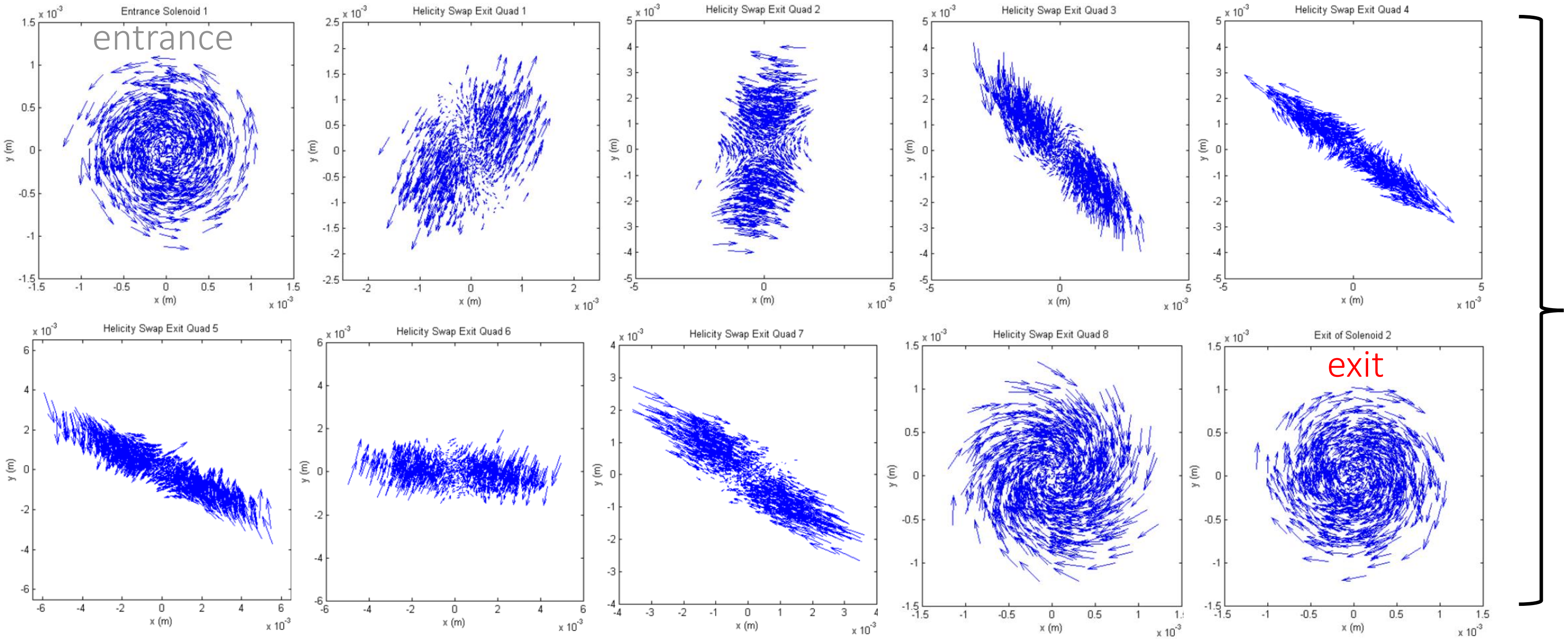


FFFAG is Faux Fixed Focus Alternating Gradient lattice



Magnetization Flip Transformation

- preserving ion polarization requires running solenoids with opposite signs
- however, electron beam has a specific sign of angular momentum which must be matched to the sign of the solenoid
- need to flip the magnetization between solenoids *and* ensure appropriate transverse match



$$\left(\begin{array}{cc|cc} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ \hline 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{array}\right)$$