Simulation of Resonant Extraction in the Fermillab Mu2e Project

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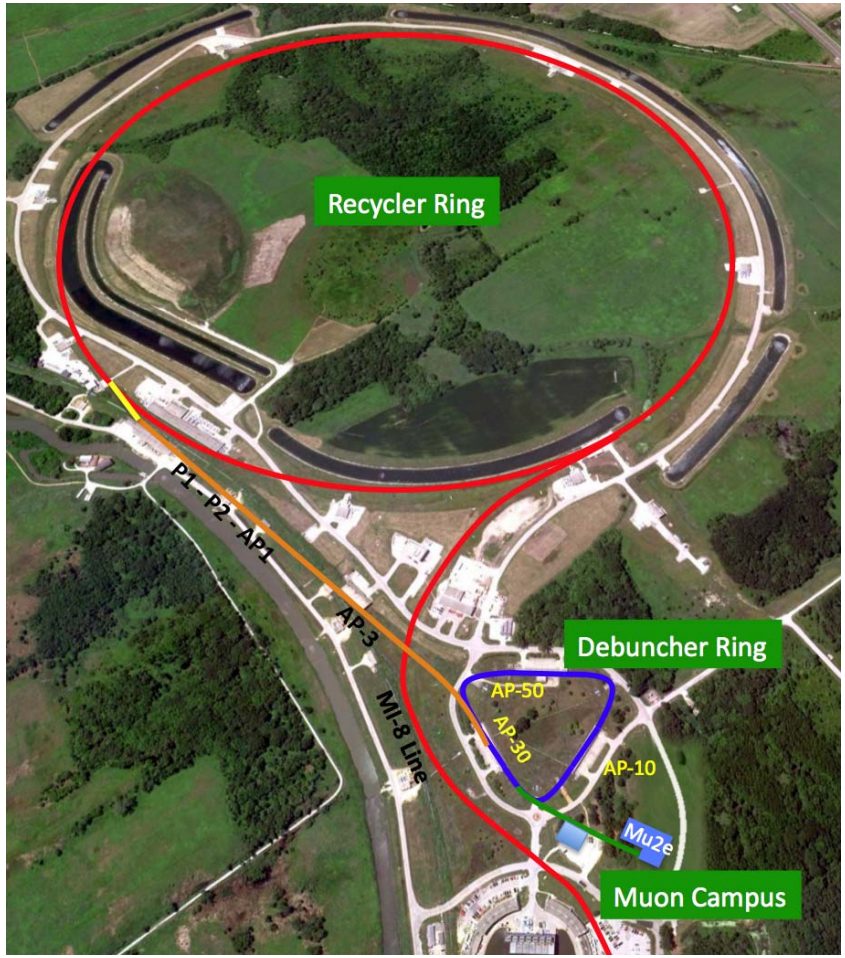
Outline

- General
- Simulation with Synergia
- Work in Progress
- Conclusion

General

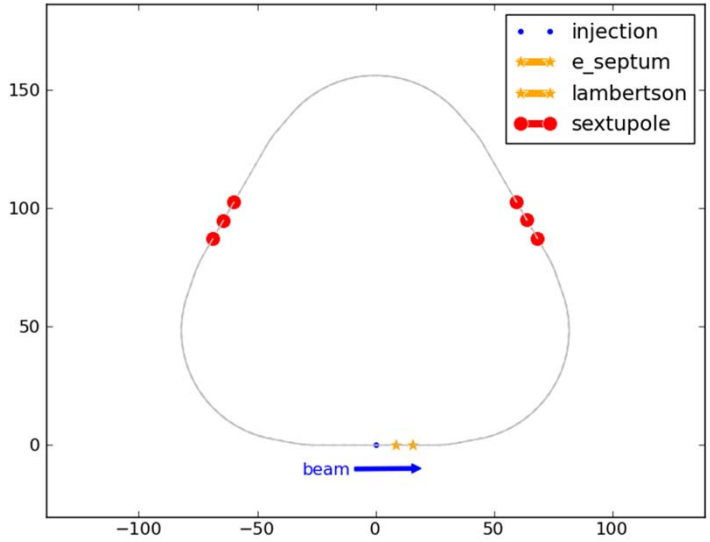
Mu2e Project with Slow Extraction

- Goal of the Mu2e is to search for the Charged Lepton Flavor Violation process of a muon converting to an electron in the field of a nucleus.
- Batches of protons from the Booster are transported to the Recycler Ring where they are rebunched and transported to the Delivery(formerly, Debuncher) Ring
- Beam is slowly extracted from Delivery ring to the Mu2e production target.
- The Delivery Ring will operate with the beam intensity of $1x10^{12}$ protons, which is approximately 4 times larger than present value.
- The Fermilab Delivery Ring has
  - Large acceptance and low chromaticity
  - Three long dispersion-free straight sections
  - Dihedral symmetry



Resonant Extraction

- The third-order resonance extraction is proposed 1) because the delivery ring is dihedral symmetry, and 2) because its current operating tune is already close to the $\nu_x = 29/3$.
- Two nonlinear harmonic sextupole circuits placed in the two of straight sections excite 3rd-order resonance of the beam .
- Tune quad circuits are placed in each straight section to adjust tune.
- Particles are kicked at the electrostatic septa and then extracted a the Lambertson magnets.
- Since its high intensity beam(1×10^{12} protons) is resonantly extracted, space charge effects are important.



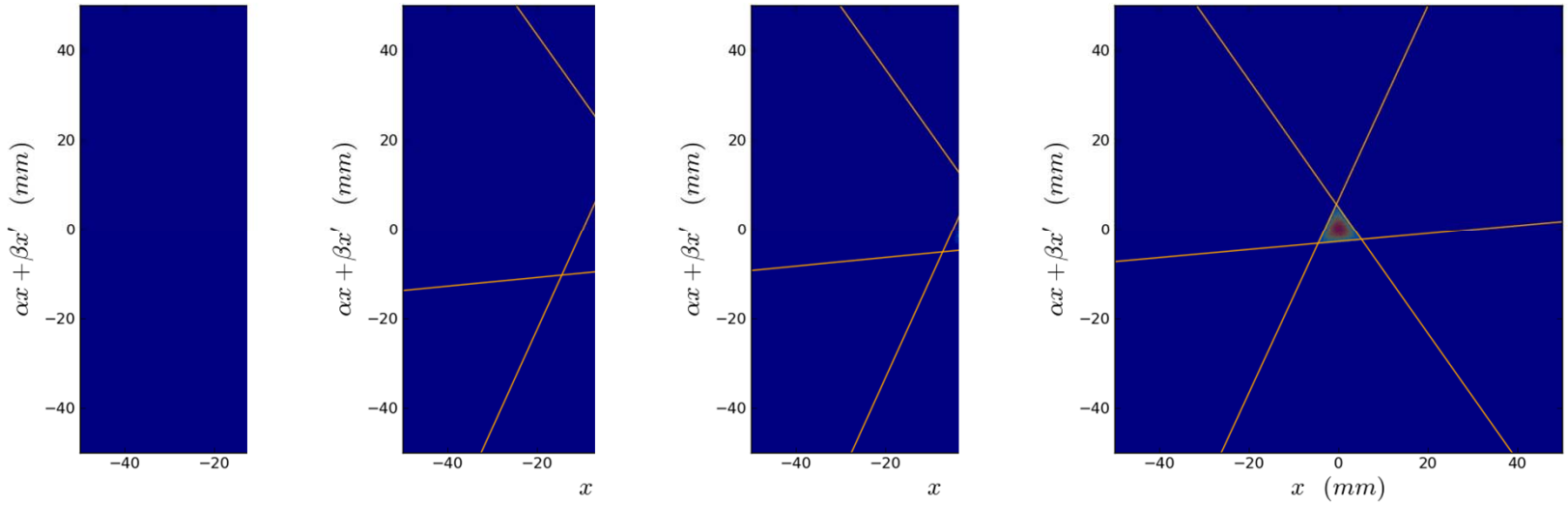
Resonant Extraction Parameters

Quantity	Unit	Value
Beam		
Kinetic Energy	GeV	8
Bunch Length (rms)	nsec	20-50
Initial Emittance(normalized)	π mm-mrad	20-25
Intensity	Tp(10^{12} protons)	1
Ring		
Circumference	m	505.283
Resonant Tune (ν_x)		29/3
Spill Time	msec	53.9 ~ 58.9
N_{turn}/spill		31,795 ~ 34,744
dN_p/N_{turn}	Mp(10^6 protons)	31.5

Simulation with Synergia

Simulation Procedure

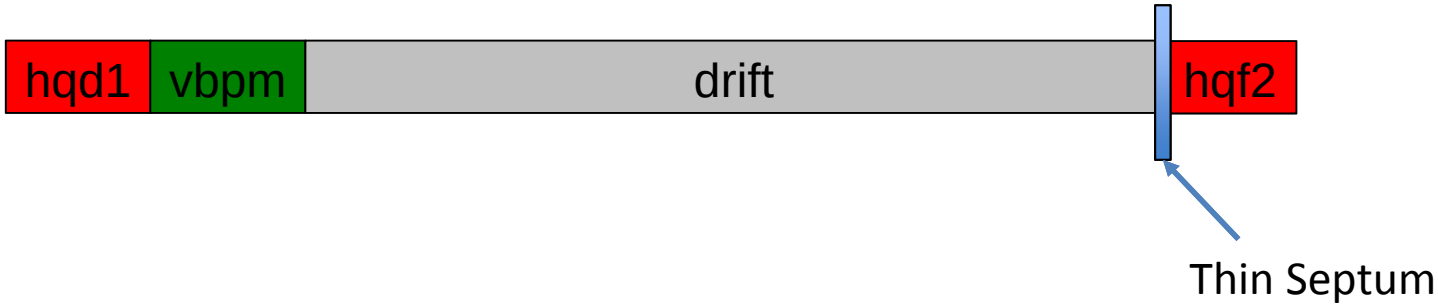
- A matched beam is injected into the Delivery Ring.
- During the first 100 turns, harmonic sextupole circuits are linearly ramped to excite 3rd-order resonance.
- After sextupole field ramping, tune quadrupole circuits are ramped to squeeze separatrix for the extraction.
- Use septum and Lambertson to extract high amplitude particles.
- Synergia is capable of tracking millions of particles with 2-5D/3D space charge effects.



Simulation Parameters

Quantity	Unit	Value
Initial Tune		$(\nu_x, \nu_y) = (9.65, 9.78)$
Macro particles		100k ~ 1 M
Space Charge Kicks		240
Map Order		Hybrid (2nd order + CHEF propagator)
Grids		32x32x128 / 64x64x128
RF cavity	MHz	2.36
RF Voltage	kV	10
Septum Kick Strength	μrad	~ - 100
Septum Wire Position	mm	16
Septum Wire Width	μm	100
Septum Gap	mm	14

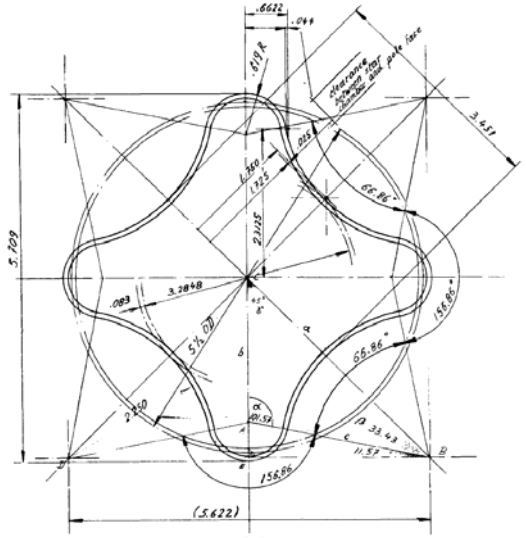
Septum and Lambertson

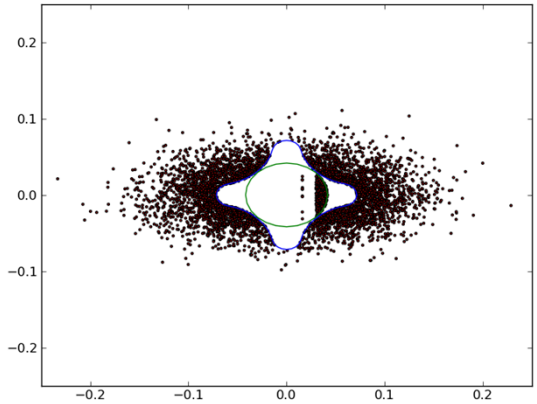


- Place the thin septum element at the upstream of the quads, where β_x ~ 14 m.
- With the thin septum element, particles gain $\Delta x'$ = -0.1 mrad.
- The Lambertson magnet is located one cell downstream of the septum and removes kicked particles.

Apertures

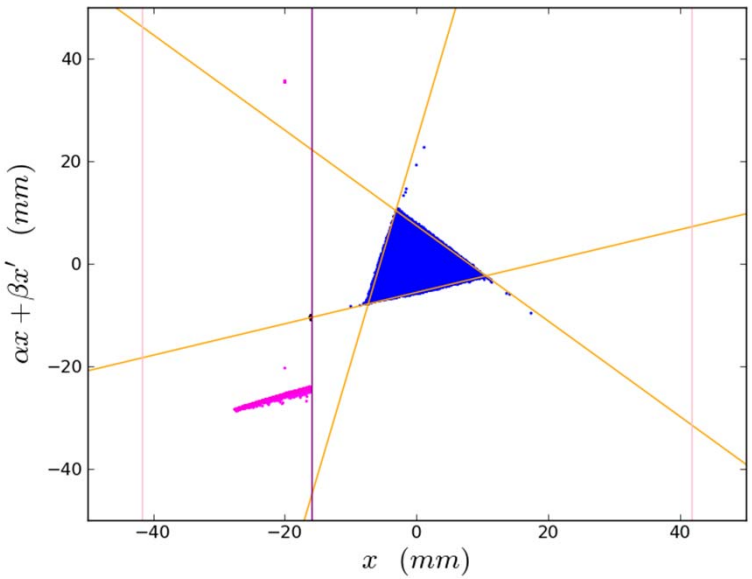
- Various apertures are applied around ring.
- Most of element have circular apertures.
- Quadrupoles have star chambers.
- For a star chamber, we are using polygon-aperture, which is implemented with the winding-number algorithm.
- The Electrostatic Septum has wire_elliptical aperture.
- At the septum, we need to filter particles which hit either the wire or the gap.



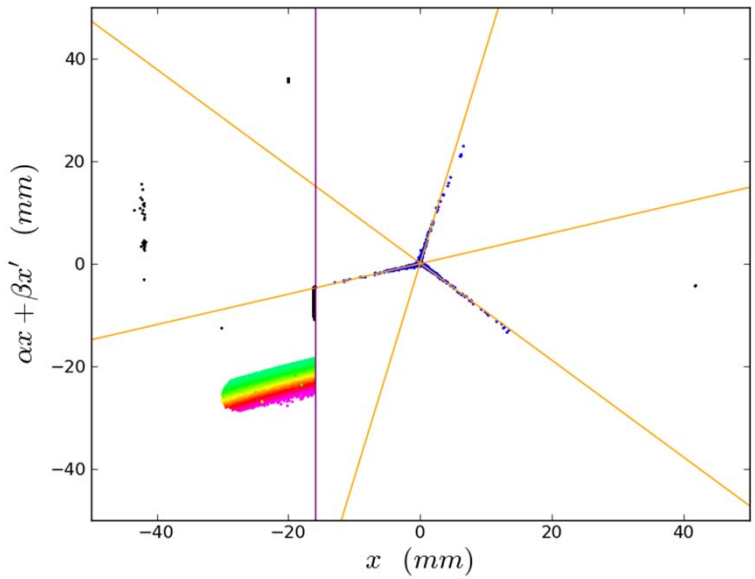


Phase Space

- Normalized phase space plots at the septum.
- Showing accumulation of kicked particles.
- Showing lost particles with apertures (circular/wire)

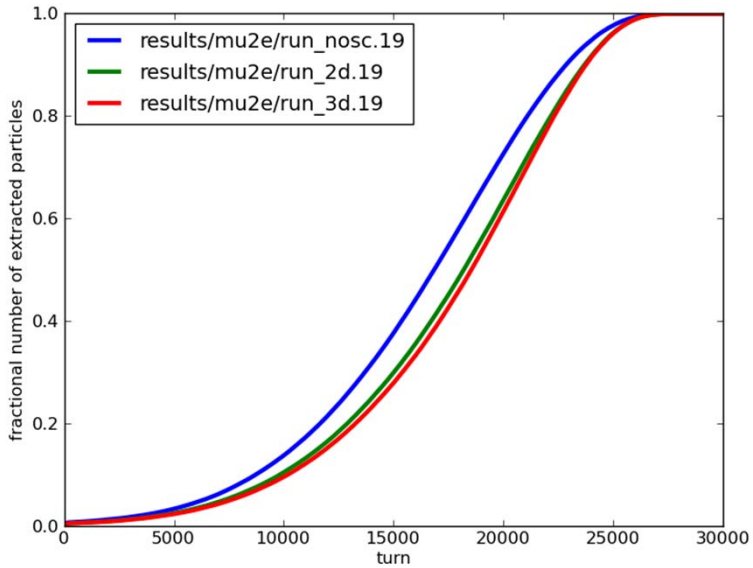


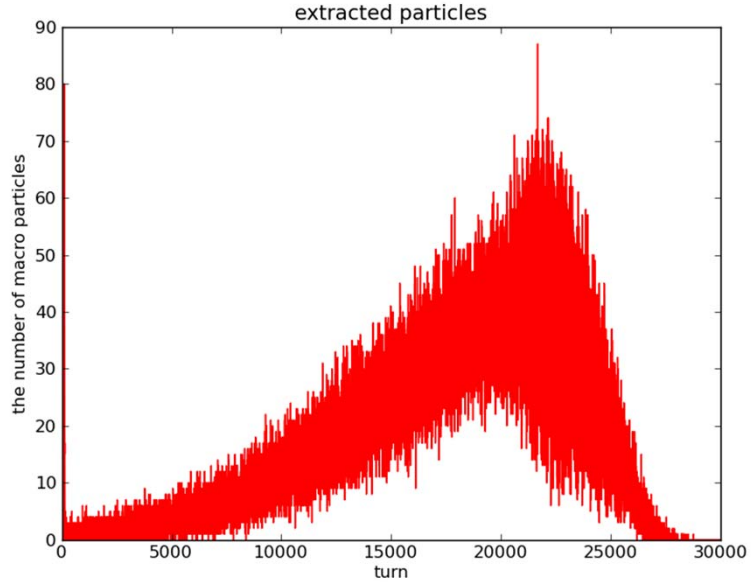
Turn = 1000



Turn = 26000

Spill Structure

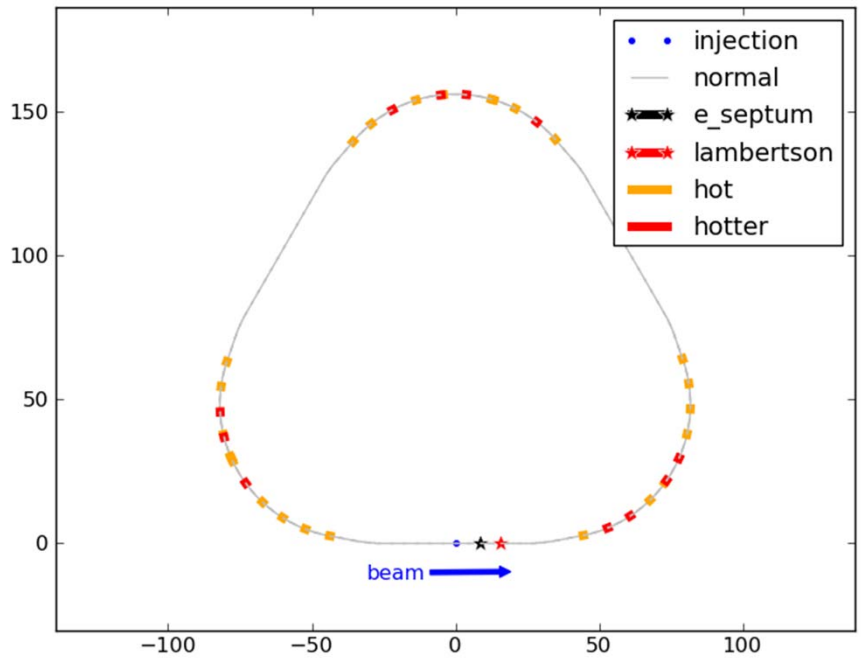




- Required spill rate is ~20 macro-particle per turn ±50%.
- With linear ramping profile of tune-quad circuit strengths.
- Need to find optimal tune ramping profile

Particle Losses

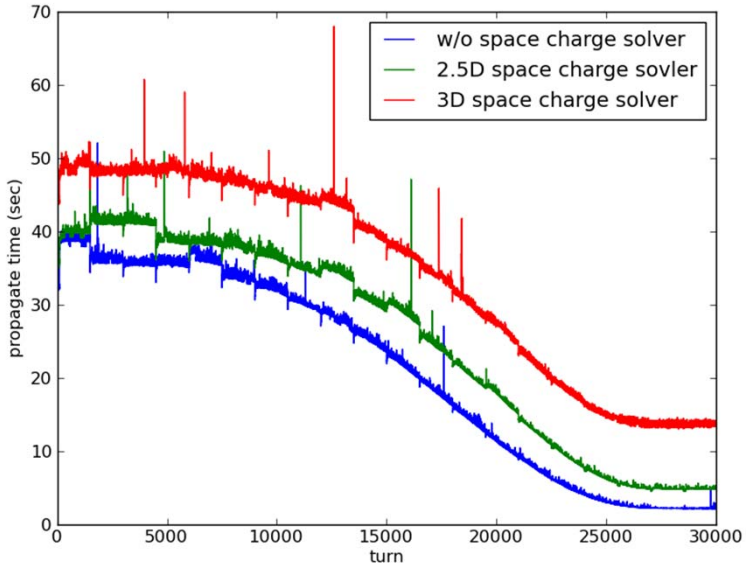
- Roughly, less than 3% protons losses at the septum are desired.
- 1.3 % is achieved with thin septum element.

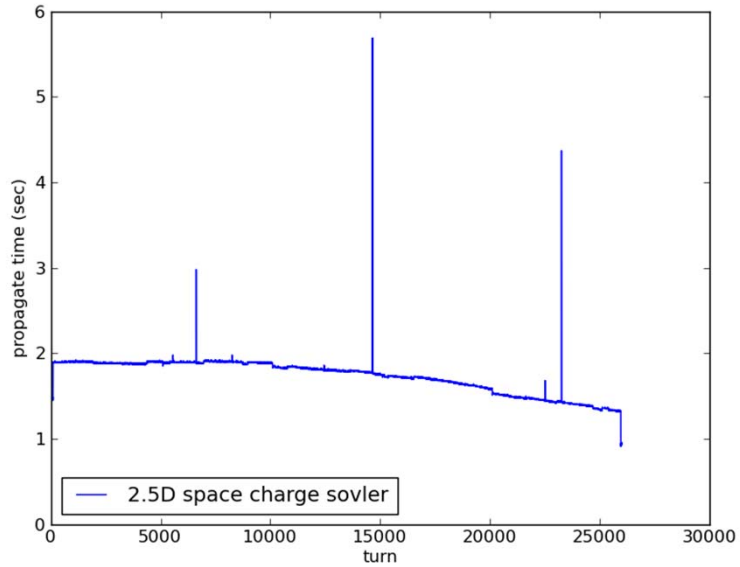


lost particles

e_septum:	1.32960 %
Lambertson:	0.09540 %
subtotal(39 elmts):	2.20920 %
extracted particles	
Lambertson:	97.62080 %
total(39 elmts):	99.83000 %

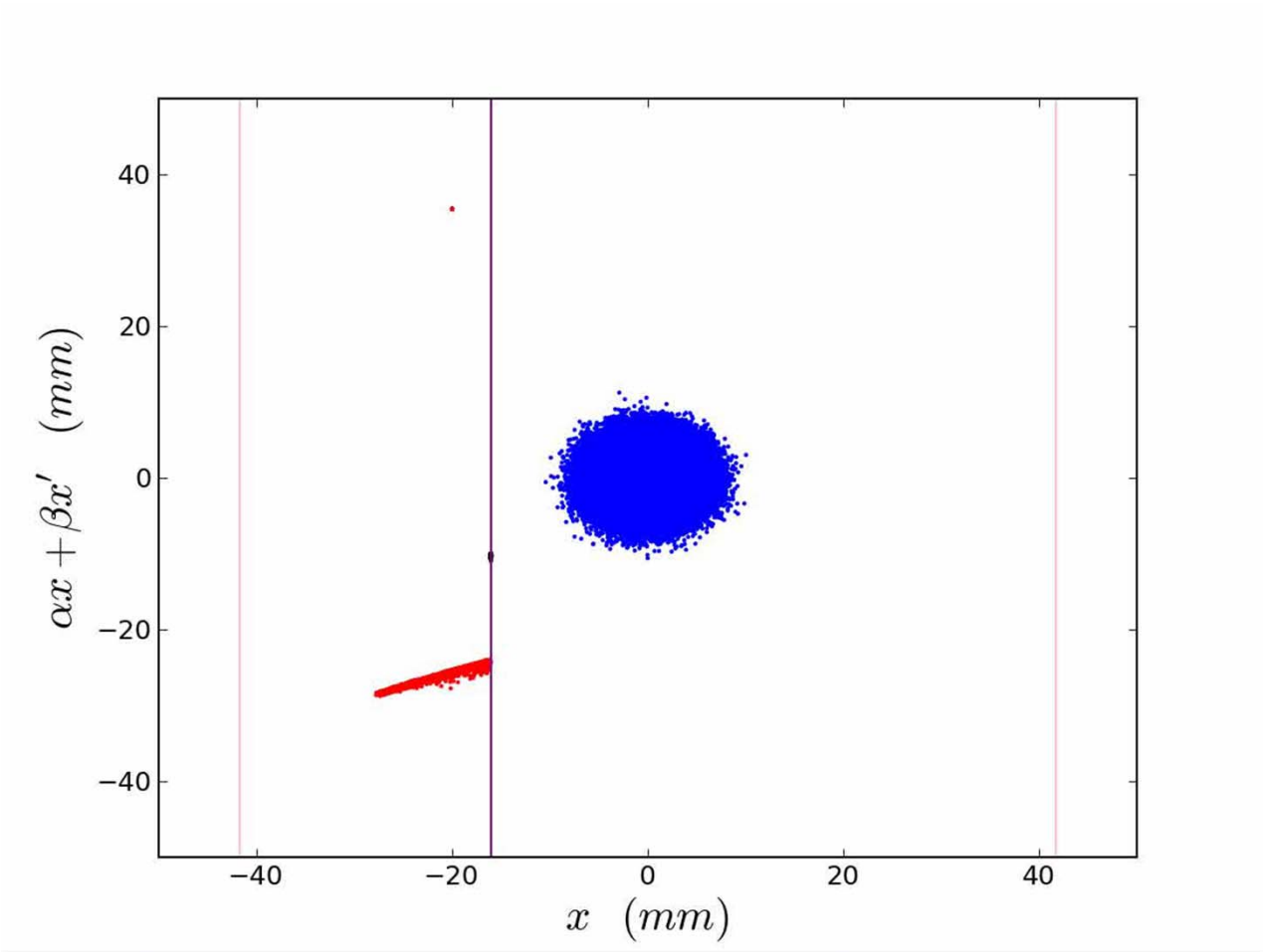
Computational Time





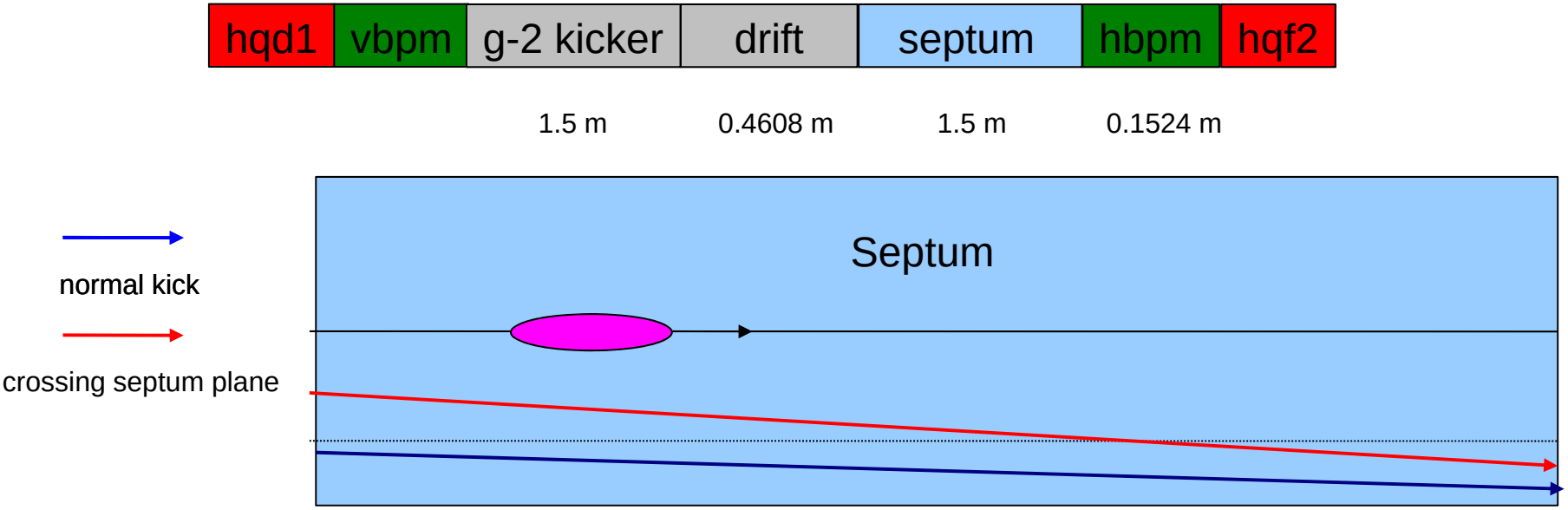
- Synergia has been optimized in the various places.
- Computation time for the entire simulation is reduced from 9 days to 12 hrs.
- More optimizations are in progress.

Phase Space II



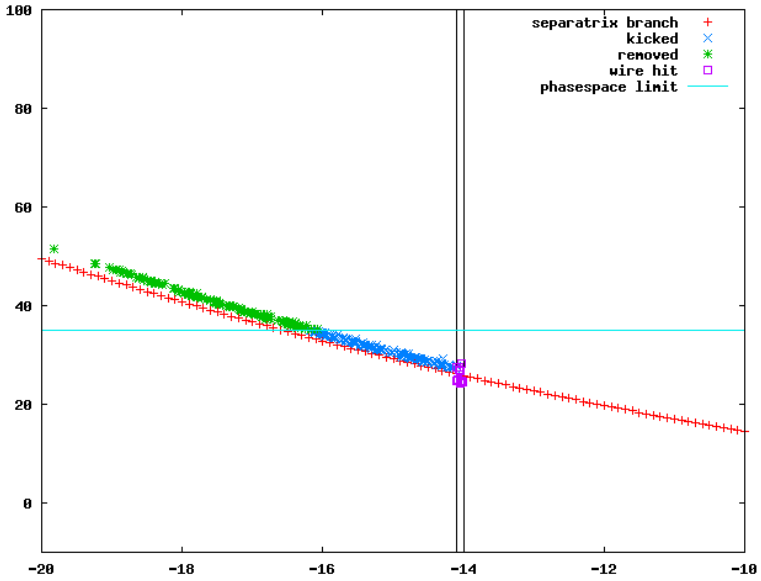
Work in Progress

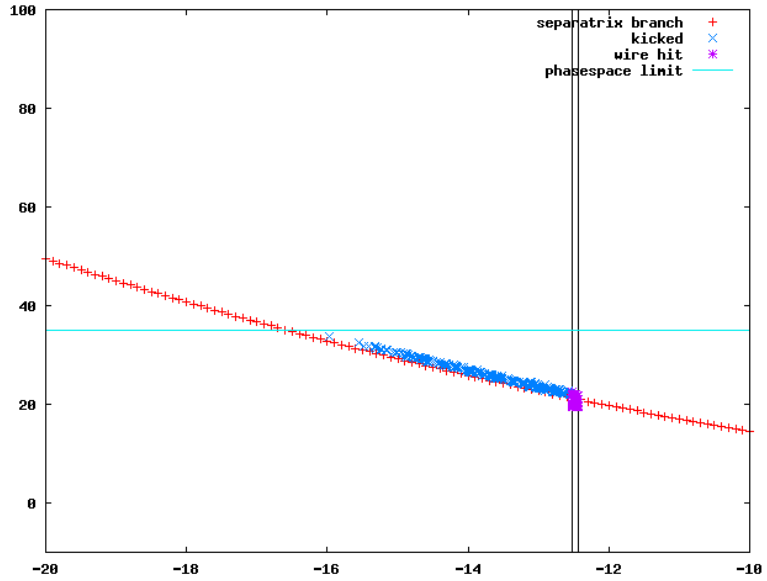
New Septum Geometry



- Septum has finite length (~1.5 m)
- Constant electrostatic field is applied through the element.
- With 100 kV on the wire and 14 mm gap, particles see $\Delta x' = -0.122$ mrad.
- The wire plane has to be rotated to minimize intersecting particles.

Phase Space Aperture



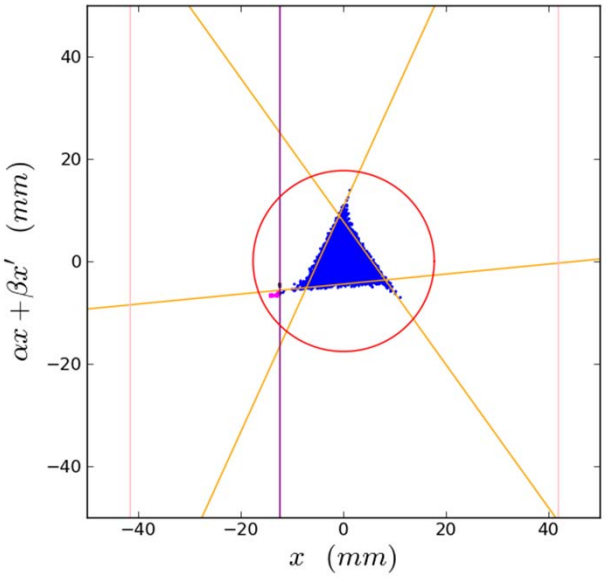


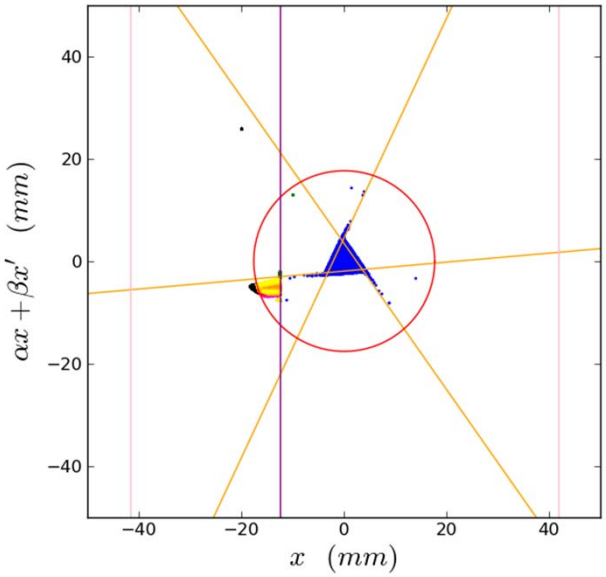
- Machine acceptance of the Delivery ring: 35 π mm-mrad.

$$\varepsilon_{\text{limit}} > \frac{x^2 + (\alpha_x x + \beta_x x')^2}{\beta_x}$$

- Need to find optimal wire position to reduce losses by the phase space aperture

Phase Space Aperture II





- Phase space at the entrance of the septum.
- Losing particles at the larger number of turns by the aperture.

Nonlinear Optimization

- To find the optimal parameters, free/open-source Nonlinear optimization library, NLOpt (http://ab-initio.mit.edu/wiki/index.php/NLopt) will be used.
- With a conjunction of Synergia and NLOpt, we have successfully found optimal strengths of the triplet to minimize the beam profile in the ProtoPlasma beamline simulation.
- For the mu2e simulation, we will use NLOpt
  - To find tune-ramping profile to get a flat spill structure.
  - To optimize septum wire position and its rotating angle.

Conclusion

- The proposed Mu2e project requires slow resonant extraction in the Fermilab Delivery Ring.
- Synergia successfully demonstrates the third-order resonant extraction with space charge effects.
- Septum and Lambertson elements are implemented into Synergia.
- Various apertures (circular, polygon, wire, and phase space) are applied around the ring.
- Synergia has been optimized, so that the computation time is significantly reduced.
- We are working to make stable spill rate and to reduce losses around the ring, especially at the septum.
- To find optimal parameters, we are using nonlinear optimization package, NLOpt.