Cooling Software Mini-Workshop
BDSIM

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Beam Delivery Simulation (BDSIM)

- Based on Geant4
  - Access to all Geant4 physical processes
- Matrix and numerical tracking
  - Tracking of all particle types and production of secondaries
- Supports custom beamline elements / geometries
- Recently a 'muon cooler' beam line element has been developed:
  - Absorbers
  - RF cavities
  - Solenoid coils
  - **Dipole coils under development** (for 6d cooling)

- Refs:
  - https://indico.stfc.ac.uk/event/362/contributions/2280/attachments/716/1251/2021-09-27-bdsim-for-muon-cooling.pdf
  - https://www.pp.rhul.ac.uk/bdsim/manual/index.html

Absorber

Passed 10^6 on-axis muons through MICE-like lithium hydride and liquid hydrogen absorbers, for different beam momenta

Parameter	Unit	Magnitude
Material		LiH
Thickness	mm	65.37
Density	$g\ cm^{-3}$	0.69
Li6 Fraction	by mass	0.814
Li7 Fraction	by mass	0.043
H Fraction	by mass	0.143
Momenta		171.55, 199.93, 239.76
Material		liquid H_2
Thickness	mm	349.6
Density	$g\ cm^{-3}$	0.07053
Momenta	$MeV\ c^{-1}$	164.9, 199.0, 237.1
Material		liquid H_2
Thickness	mm	10
Density	$g\ cm^{-3}$	0.07053
Momenta	$MeV\ c^{-1}$	30
Number of particles		10^6

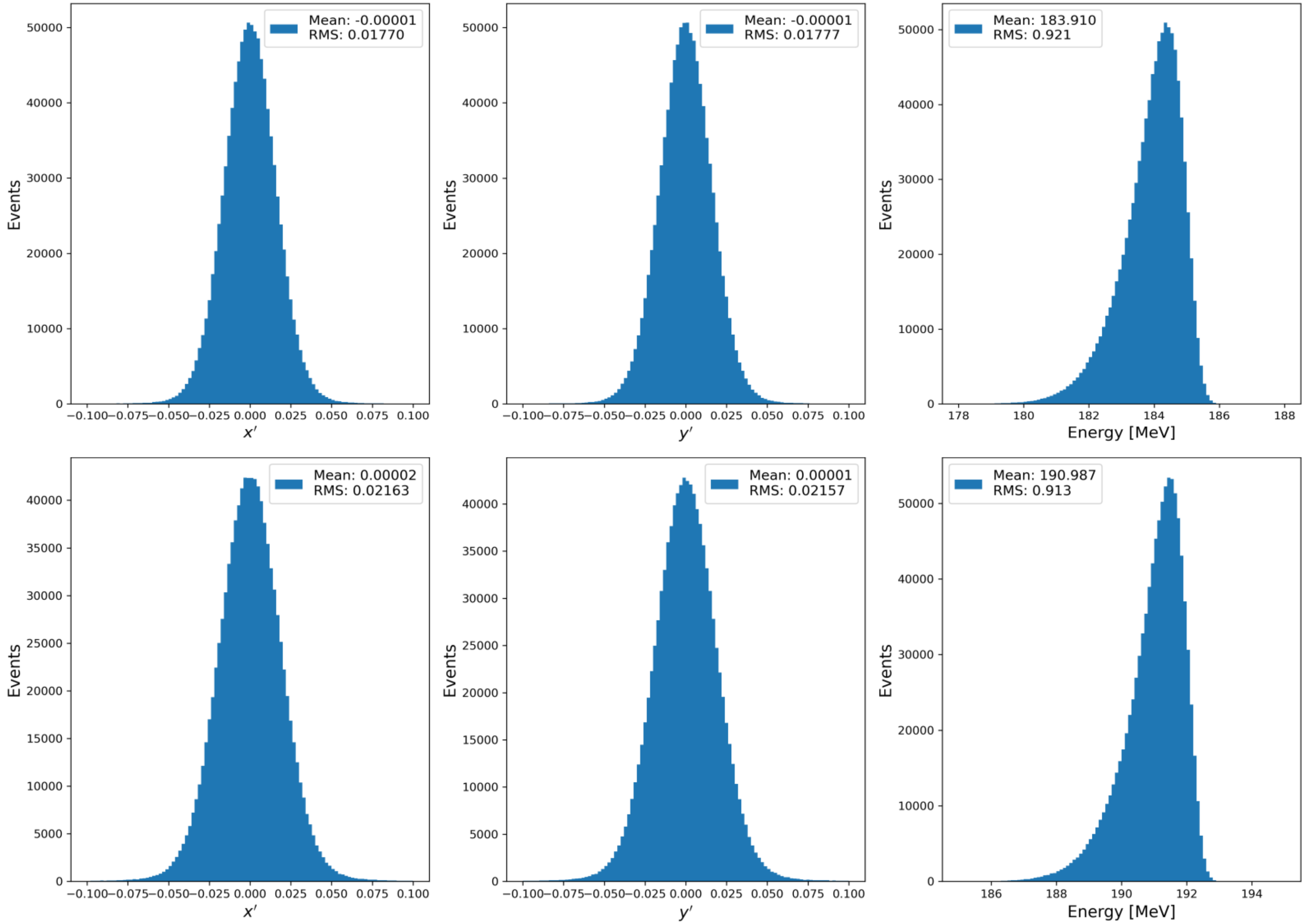
Table 1: Reference absorbers and associated momenta.

Absorber

170 MeV/c

lH2

LiH

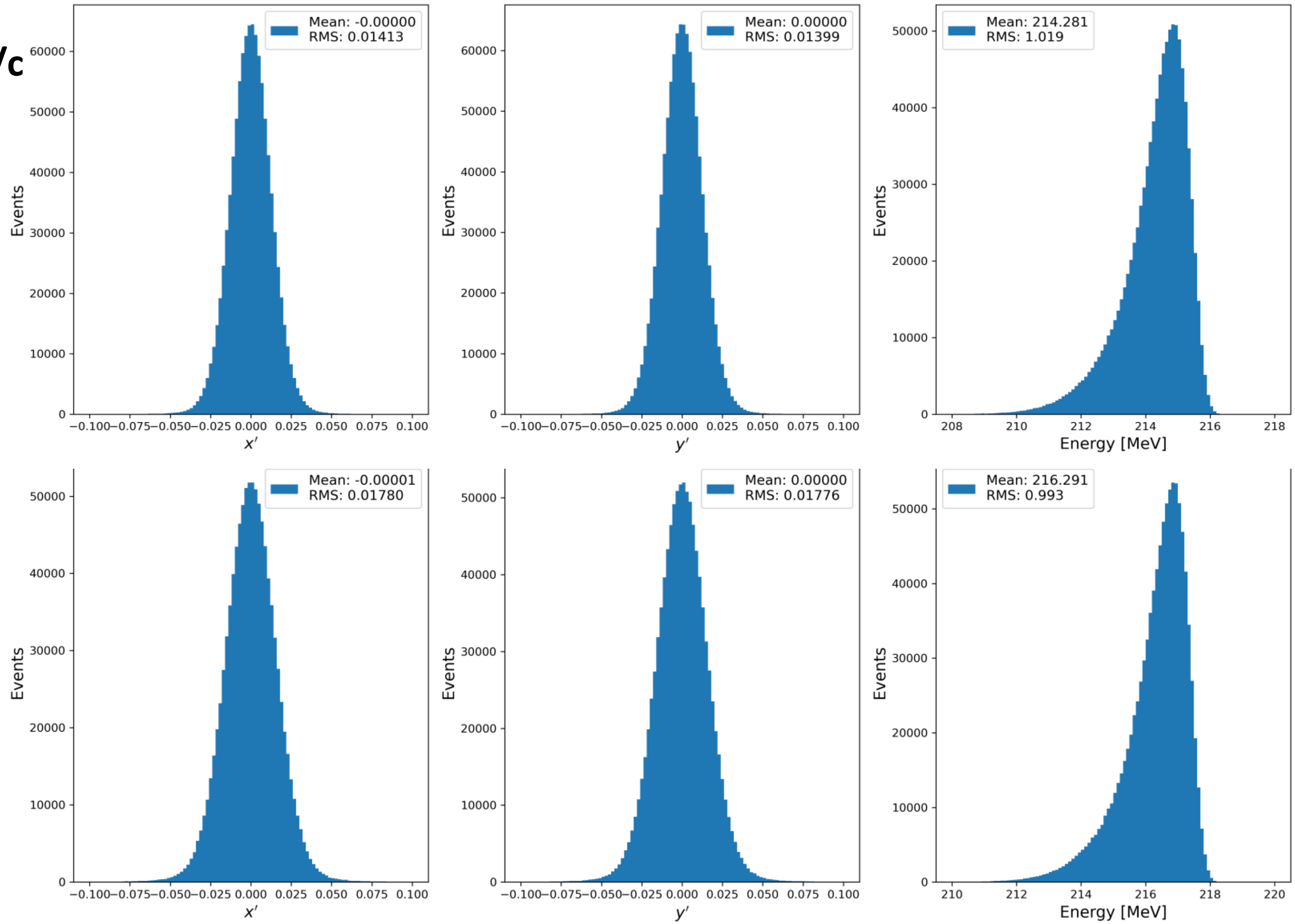


Absorber

200 MeV/c

lH2

LiH

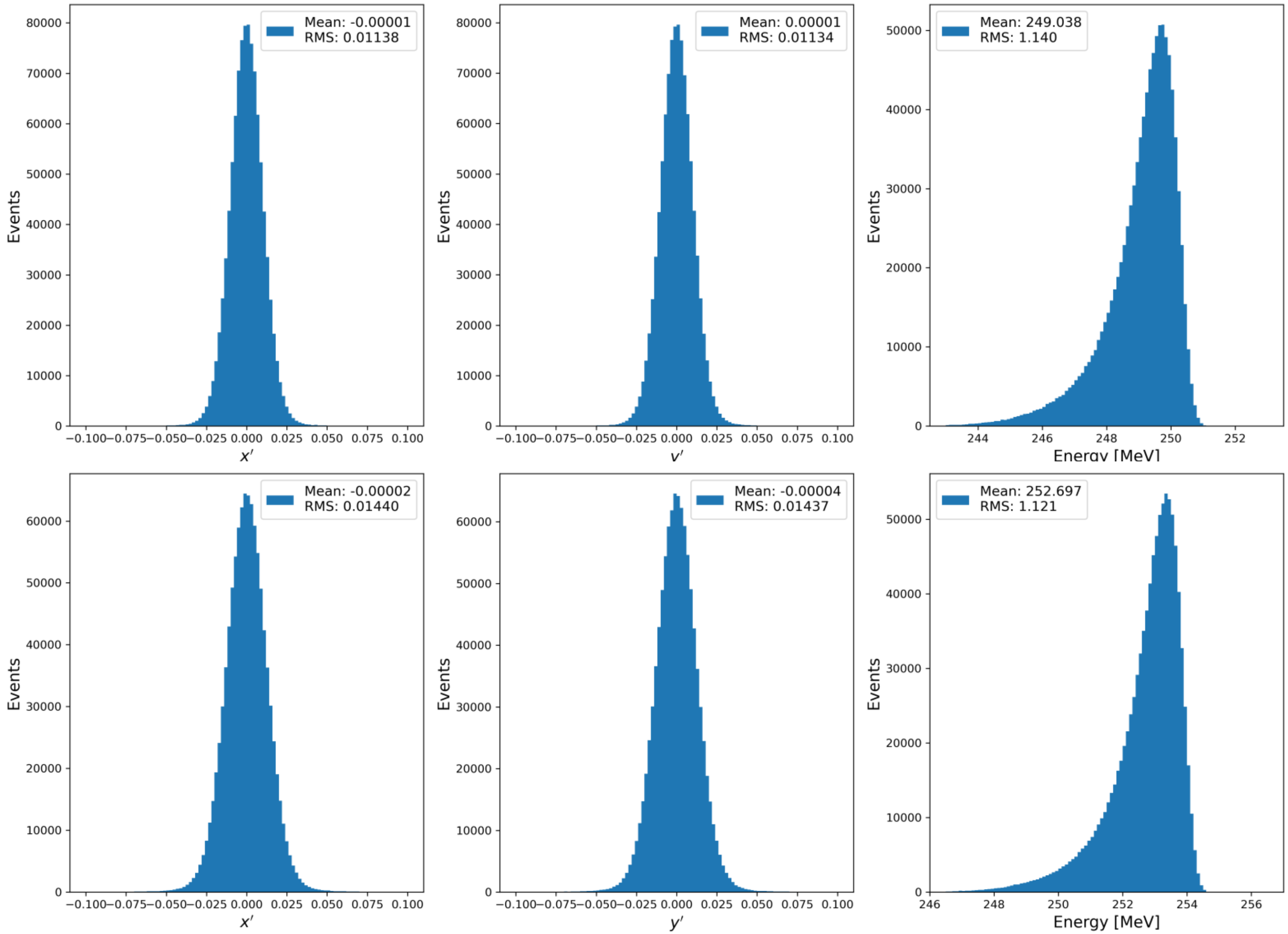


Absorber

240 MeV/c

lH2

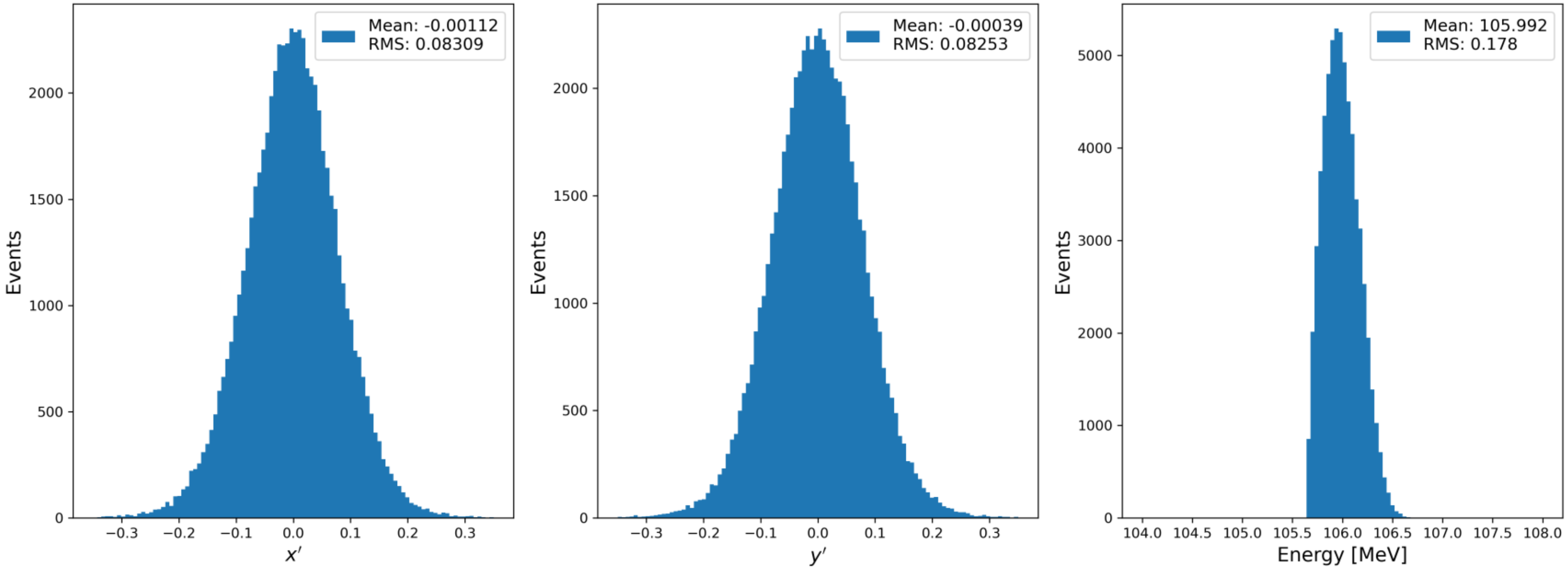
LiH



Absorber

30 MeV/c

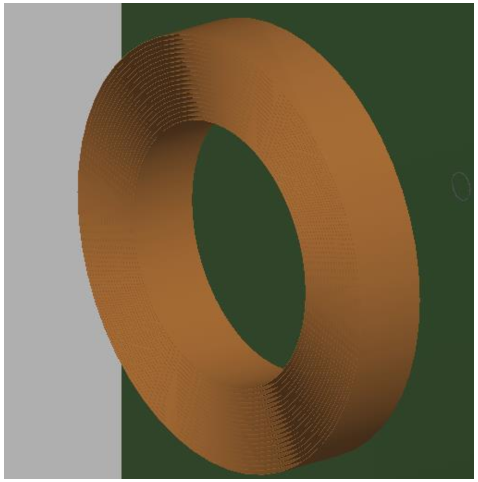
lH2



Solenoid

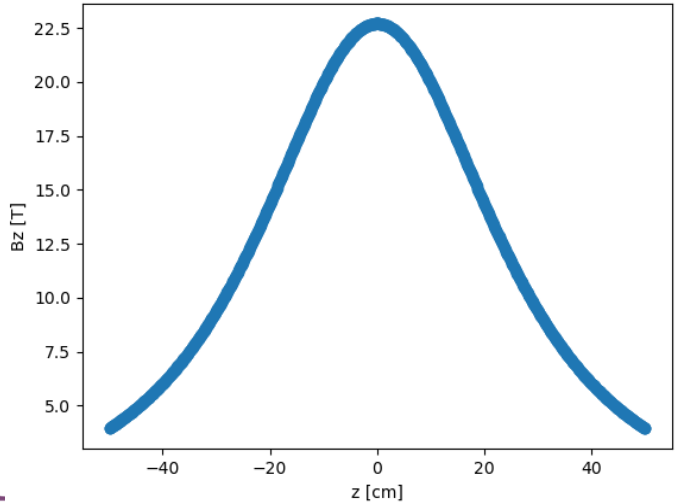
- BDSIM does not yet have an option to model the field from a block of current
  - Only solenoid sheet

- Here, the G4Beamline recipe was followed, i. e., modeled the block as a stack of sheets (in this case 20 sheets)
- Numerical intergrators:
  - G4ClassicalRK4
  - G4DormandPrince745
- Max integ. step lengths:
  - 0.1, 0.2, 0.5, 1, 2, 5, 10, 20 mm



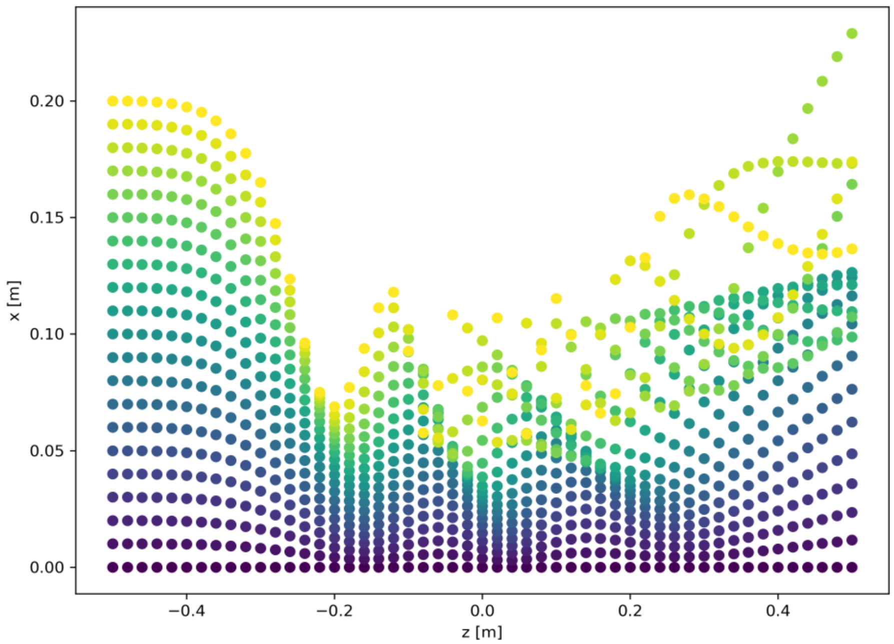
Parameter	Unit	Magnitude
Coil inner radius	mm	250.0
Coil radial thickness	mm	169.3
Coil outer radius	mm	419.3
Coil length	mm	140.0
Current density	A/mm^2	500.0
Particle species		$\mu+$
Particle momentum	MeV/c	200.0
Particle z start	mm	-500.0
Particle z end	mm	500.0
Particle radial step	mm	10.0
Particle maximum radius	mm	200.0

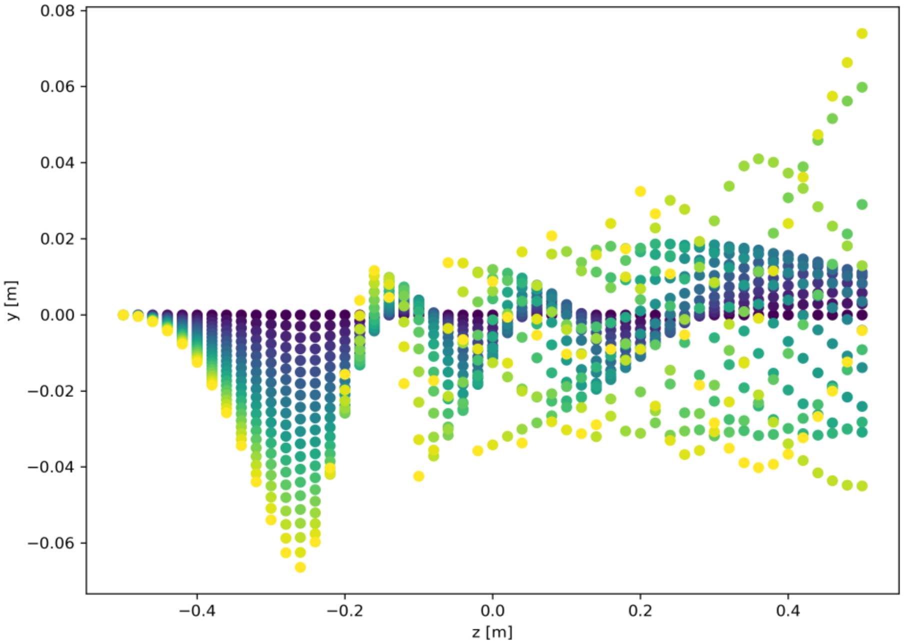
Table 2: Coil and test particles.



Solenoid

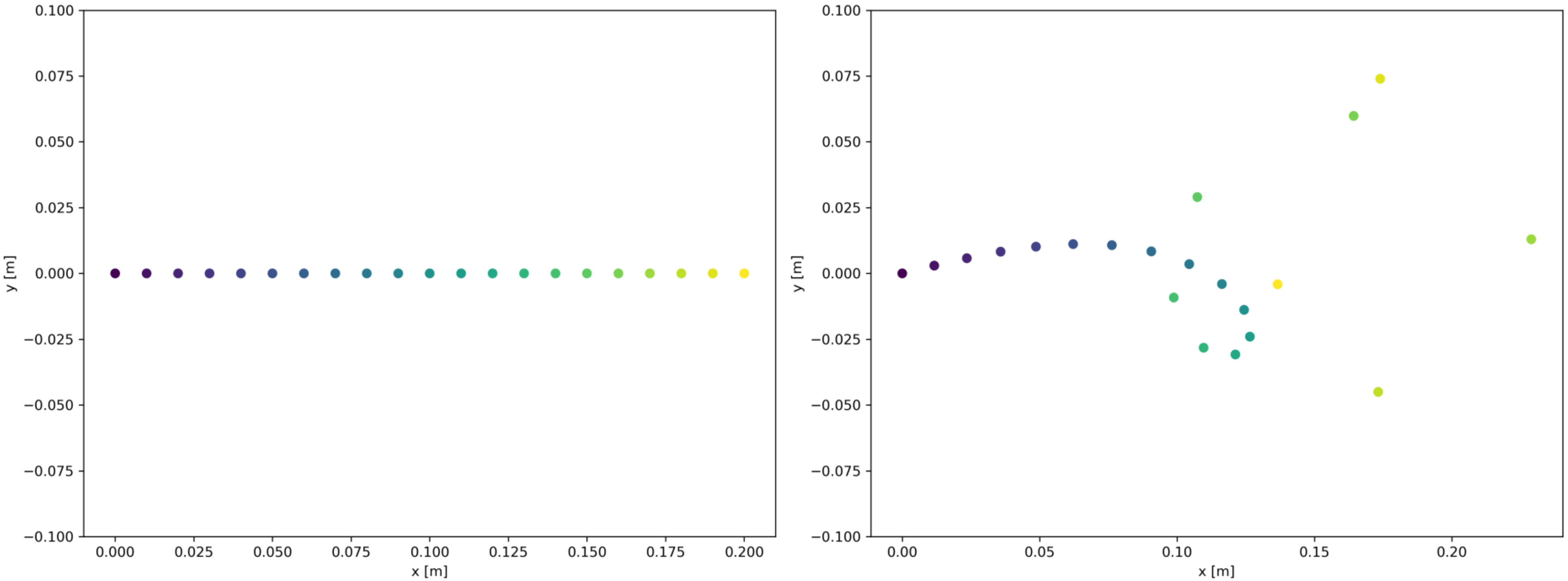
x, y trajectories, G4ClassicalRK4, 10 mm max step





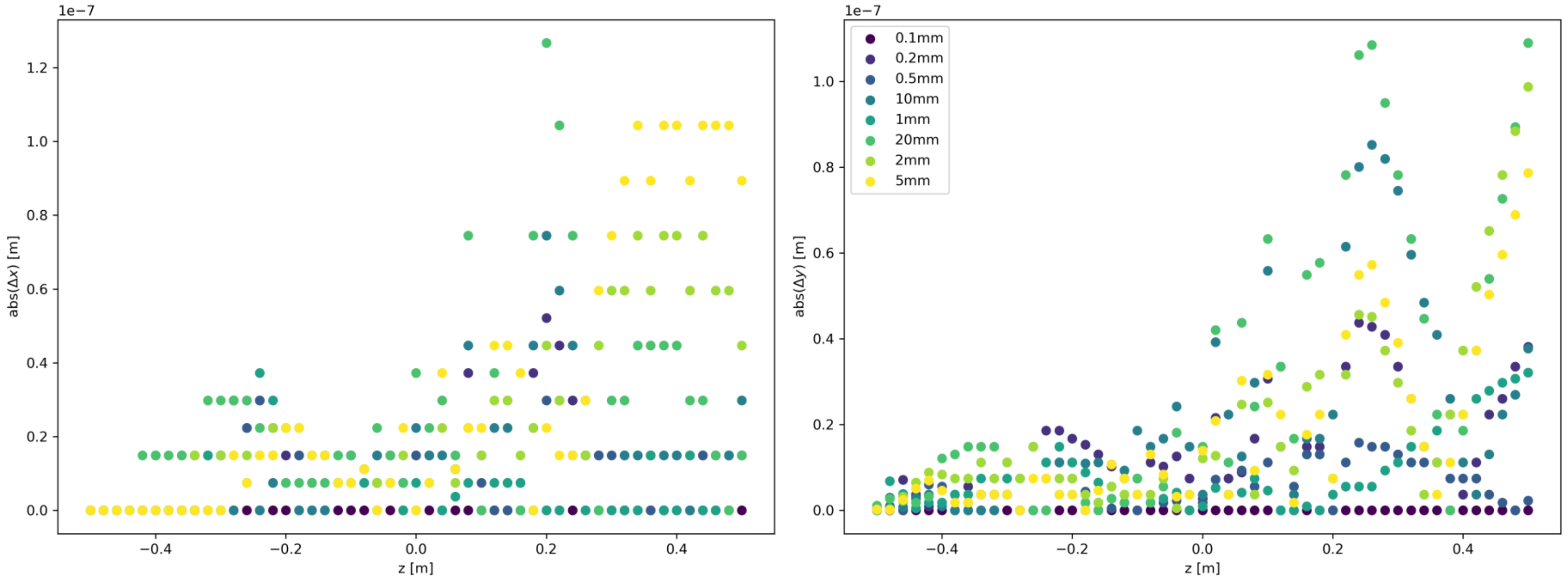
Solenoid

Initial and final particle position, G4ClassicalRK4, 10 mm max step



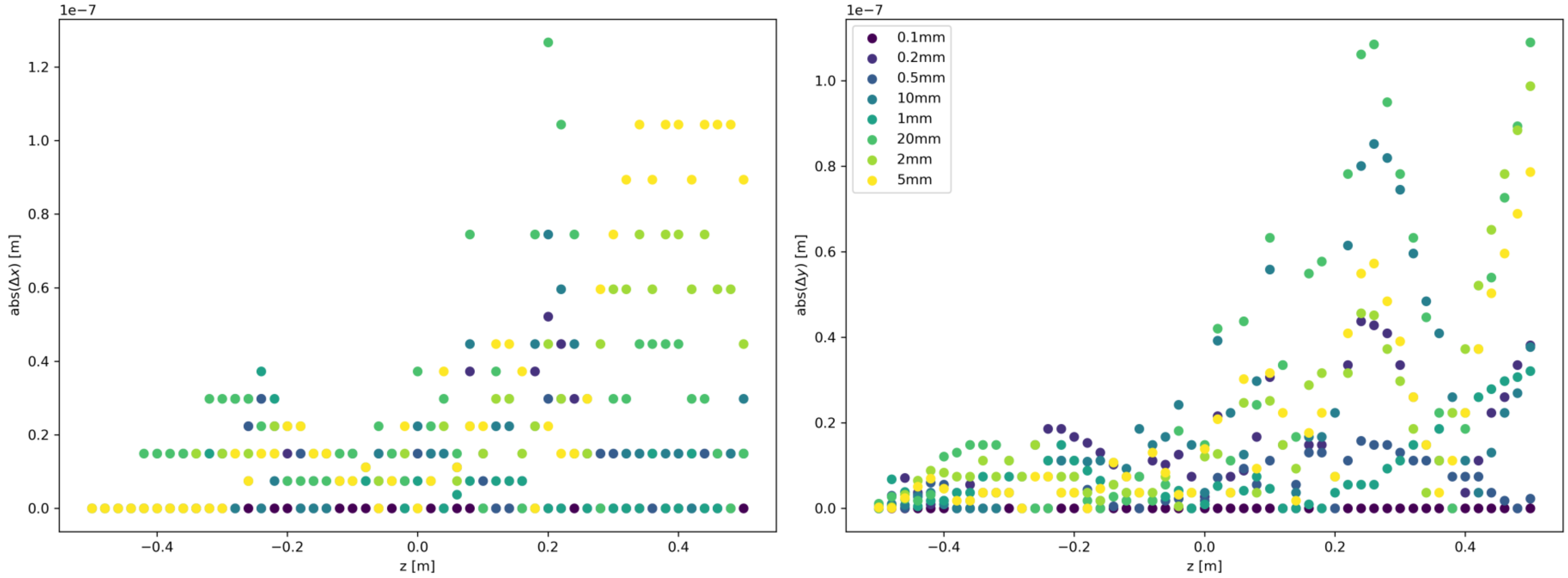
Solenoid

Trajectory residuals, G4ClassicalRK4



Solenoid

Trajectory residuals, G4DormandPrince745



No apparent difference between the two integrators (to double check)

RF

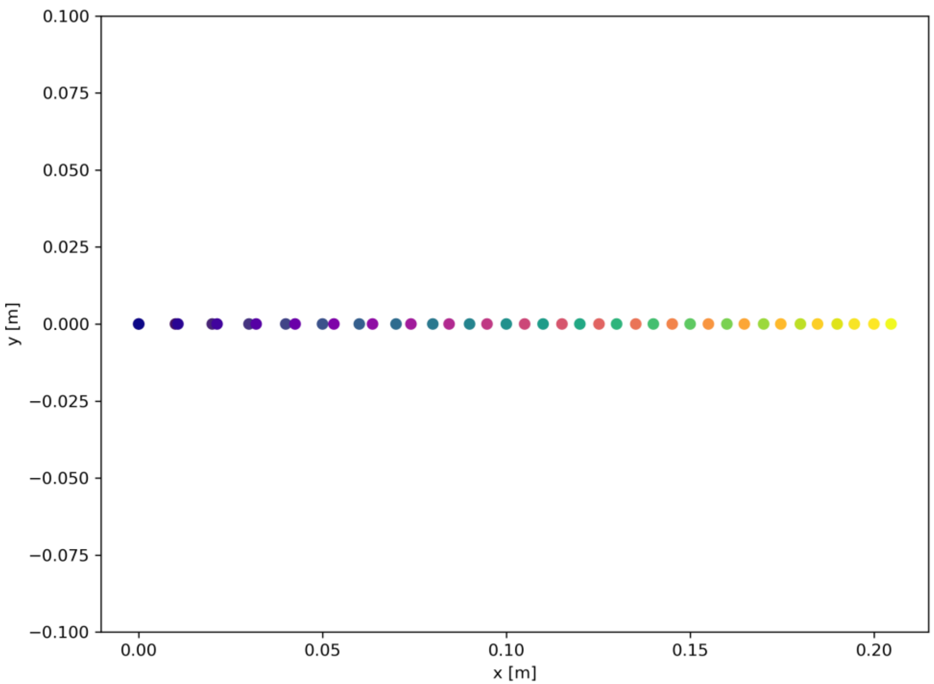
- Cavity in TM_{010} mode
- Timed such that the field is 0 when the 200 MeV/c particles arrive at the cavity center
- Only results using the G4ClassicalRK4 integrator with 10 mm max integ. step are shown

Parameter	Unit	Magnitude
Frequency	MHz	704.0
Peak electric field	MV/m	30.0
Length	mm	183.6
Window thickness	mm	0.0
Phase relative to bunching mode	$^\circ$	0.0
Particle species		$\mu+$
Particle momentum	MeV/c	200.0
Particle z start	mm	-500.0
Particle z end	mm	500.0
Particle radial step	mm	10.0
Particle maximum radius	mm	200.0
Particle time step	ns	0.1/0.704
Particle maximum time	ns	1/0.704

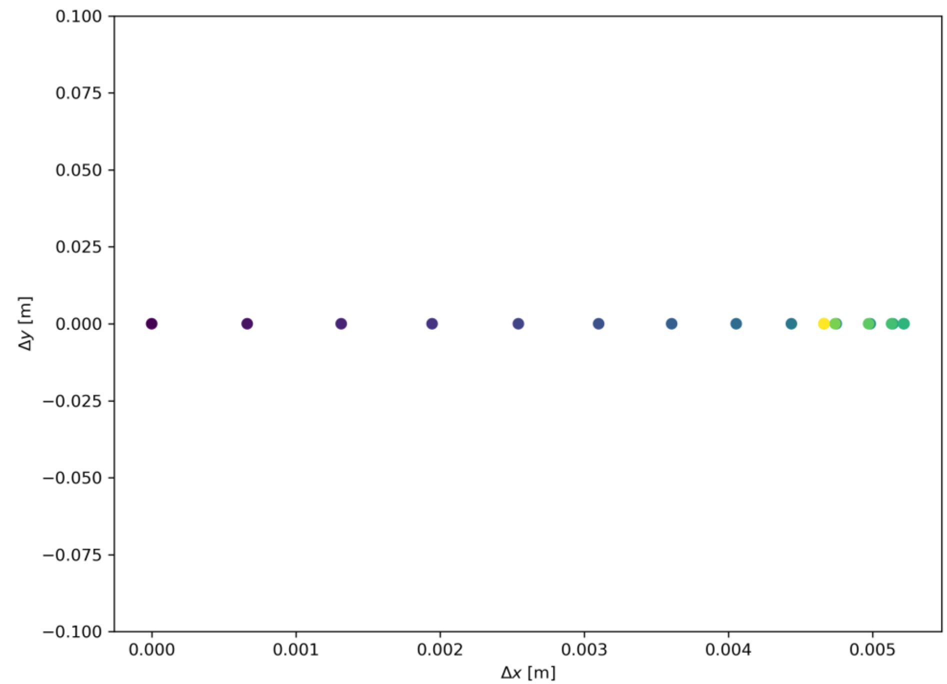
Table 3: RF Cell and test particles.

RF

t = 0 ns



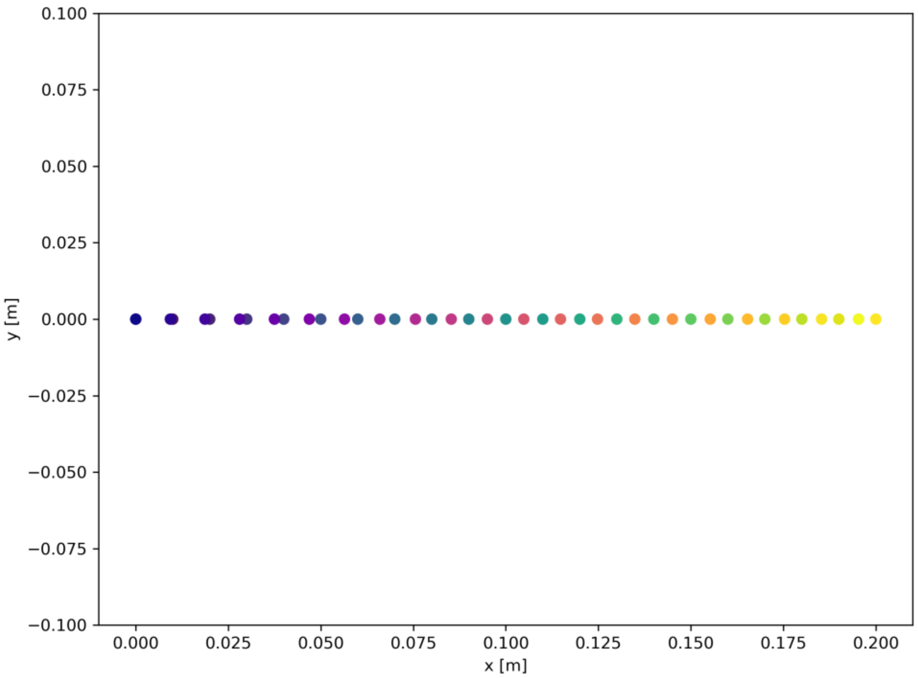
(x, y) position start/end



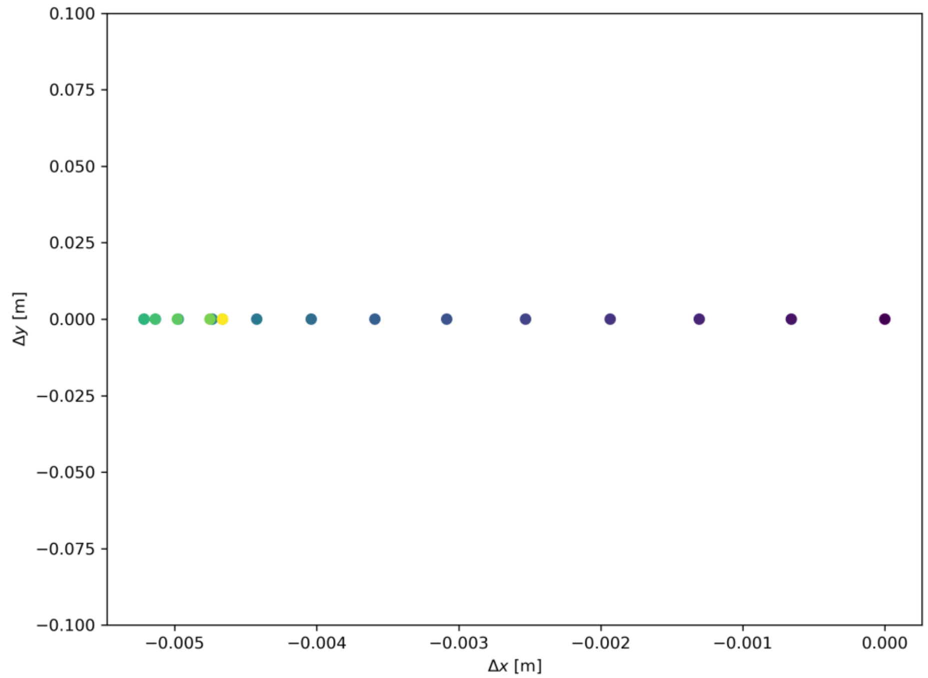
Δ(x, y) position start/end

RF

t = 0.71 ns



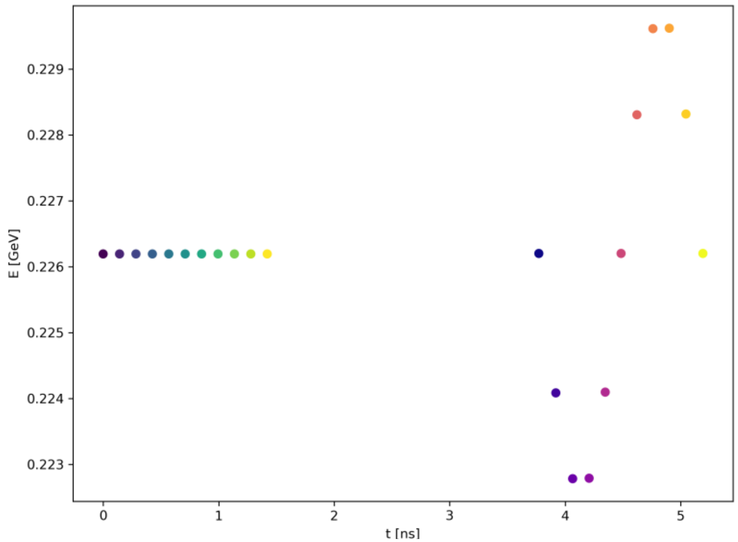
(x, y) position start/end

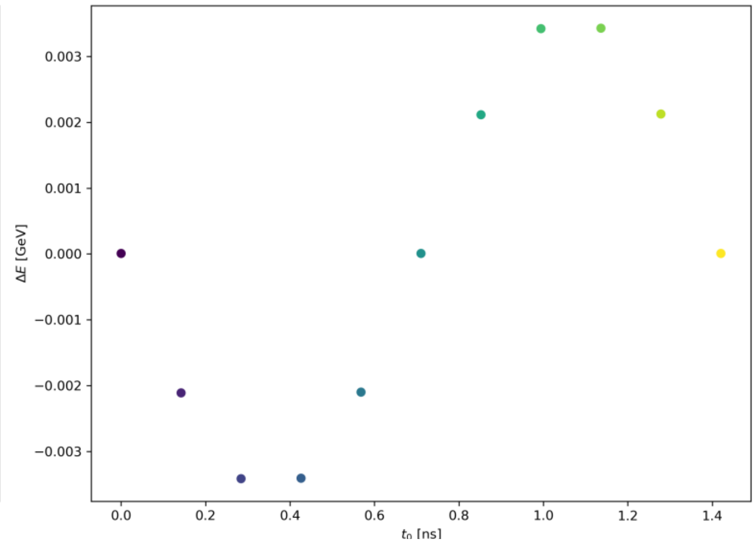


Δ(x, y) position start/end

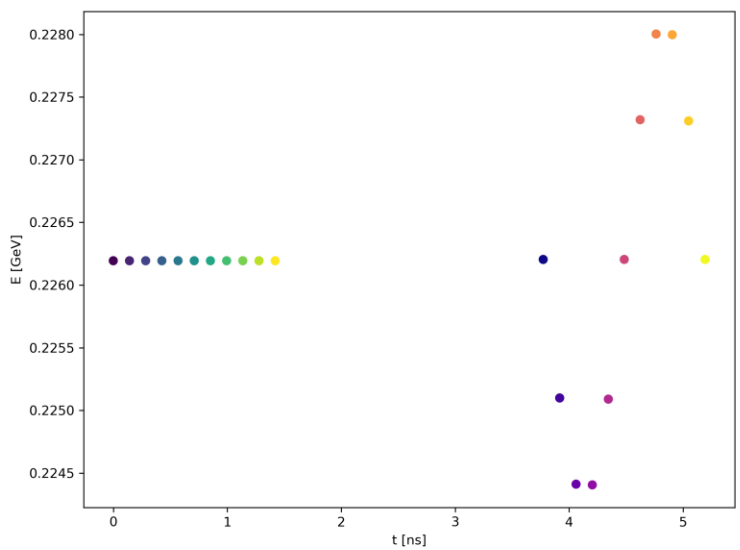
RF

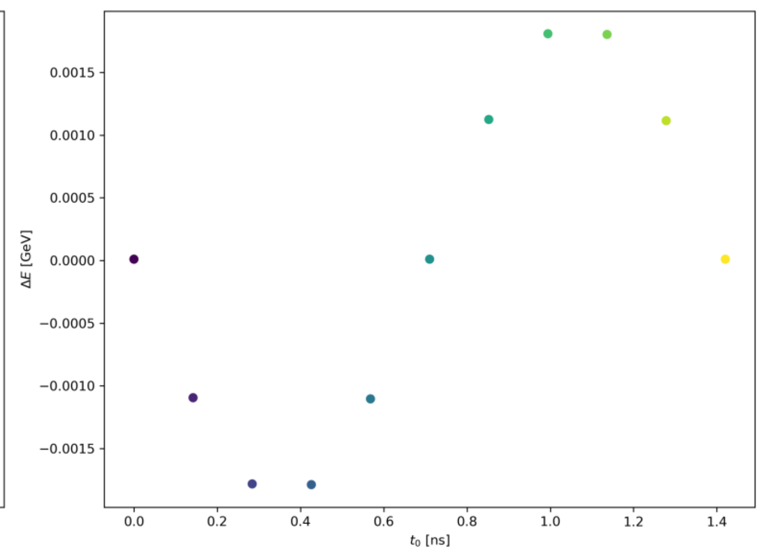
x = 0 m


E [GeV]
0.229
0.228
0.227
0.226
0.225
0.224
0.223
0
1
2
3
4
5
t [ns]


ΔE [GeV]
0.003
0.002
0.001
0.000
−0.001
−0.002
−0.003
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
t₀ [ns]

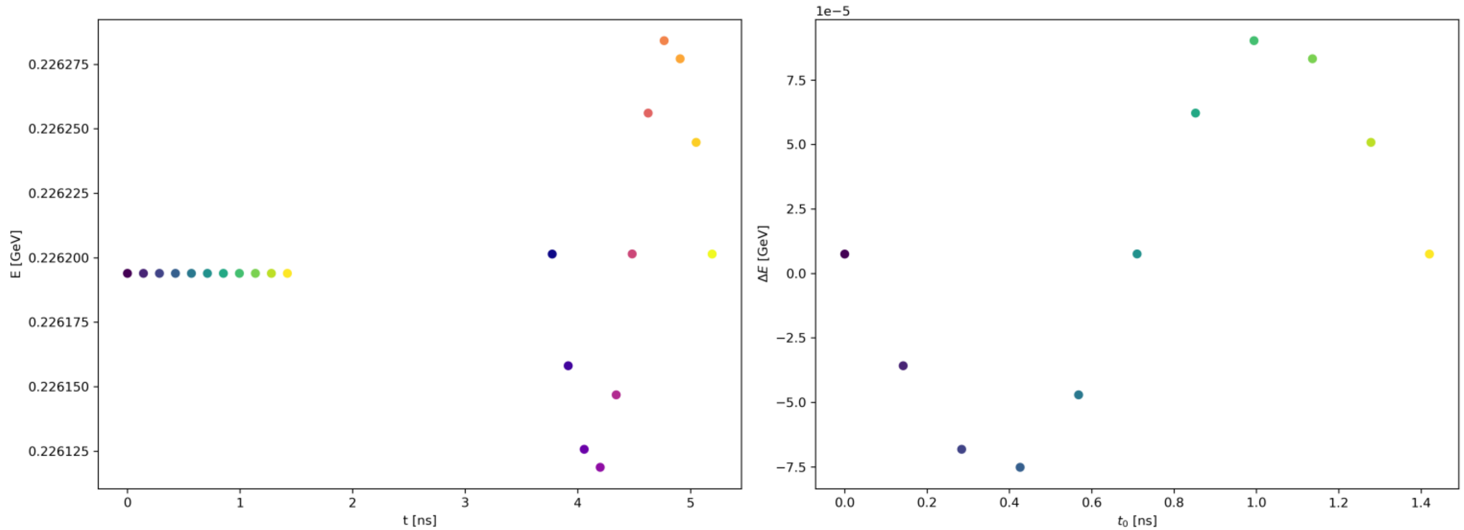
x = 0.1 m


E [GeV]
0.2280
0.2275
0.2270
0.2265
0.2260
0.2255
0.2250
0.2245
0
1
2
3
4
5
t [ns]

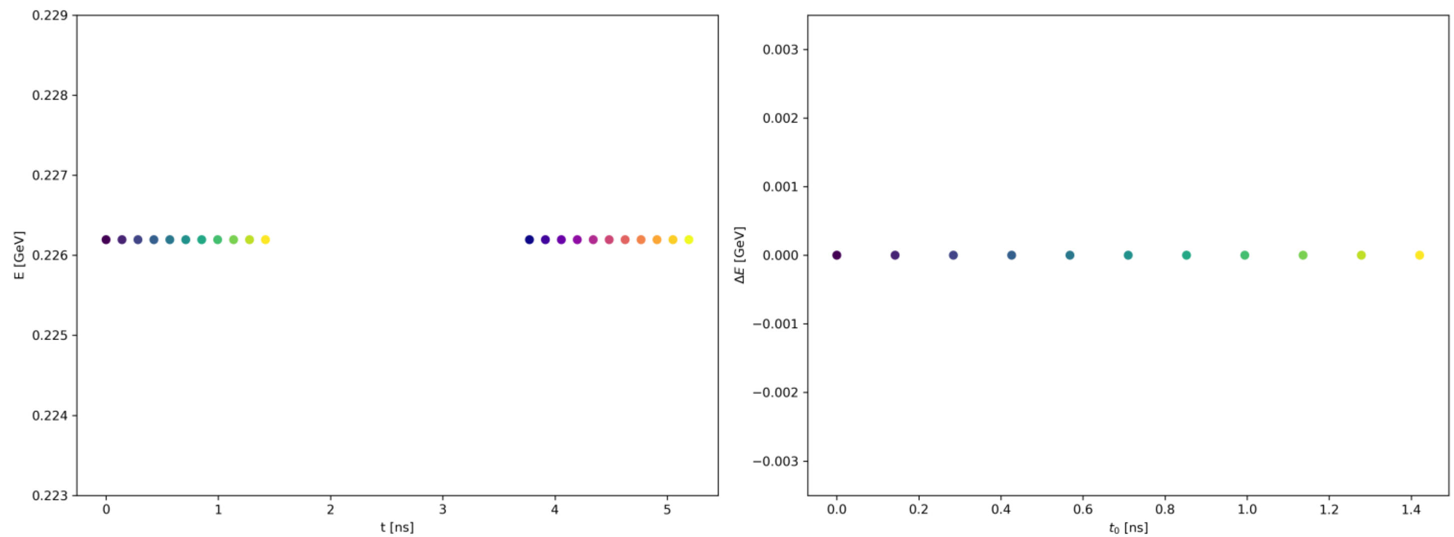

ΔE [GeV]
0.0015
0.0010
0.0005
0.0000
−0.0005
−0.0010
−0.0015
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
t₀ [ns]

RF

x = 0.16 m

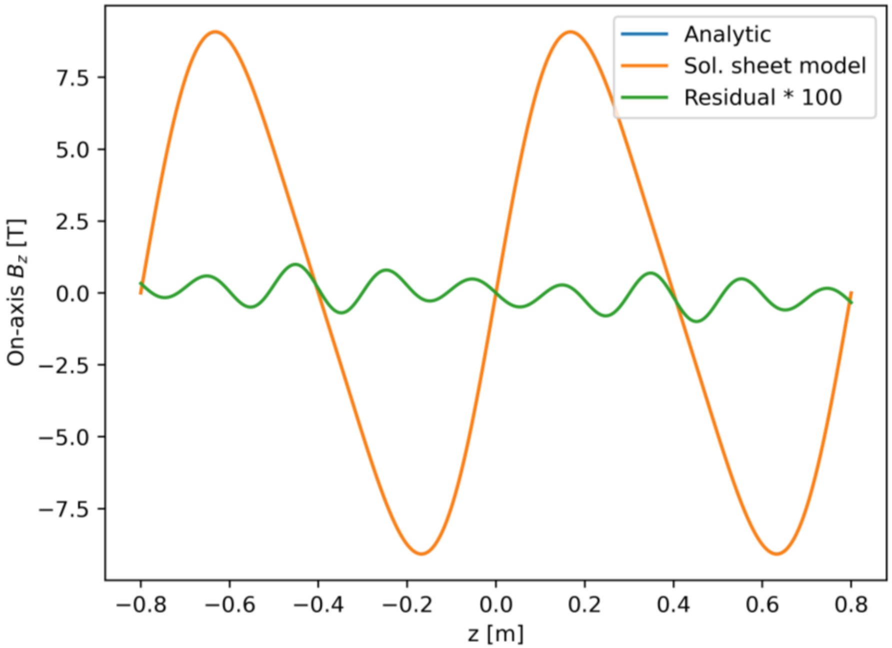


x = 0.2 m



Cooling Cell – Low Emittance

- Field on-axis from cylindrical current sheets instead of blocks
- Fitted the BDSIM current sheet model to the analytic on-axis field



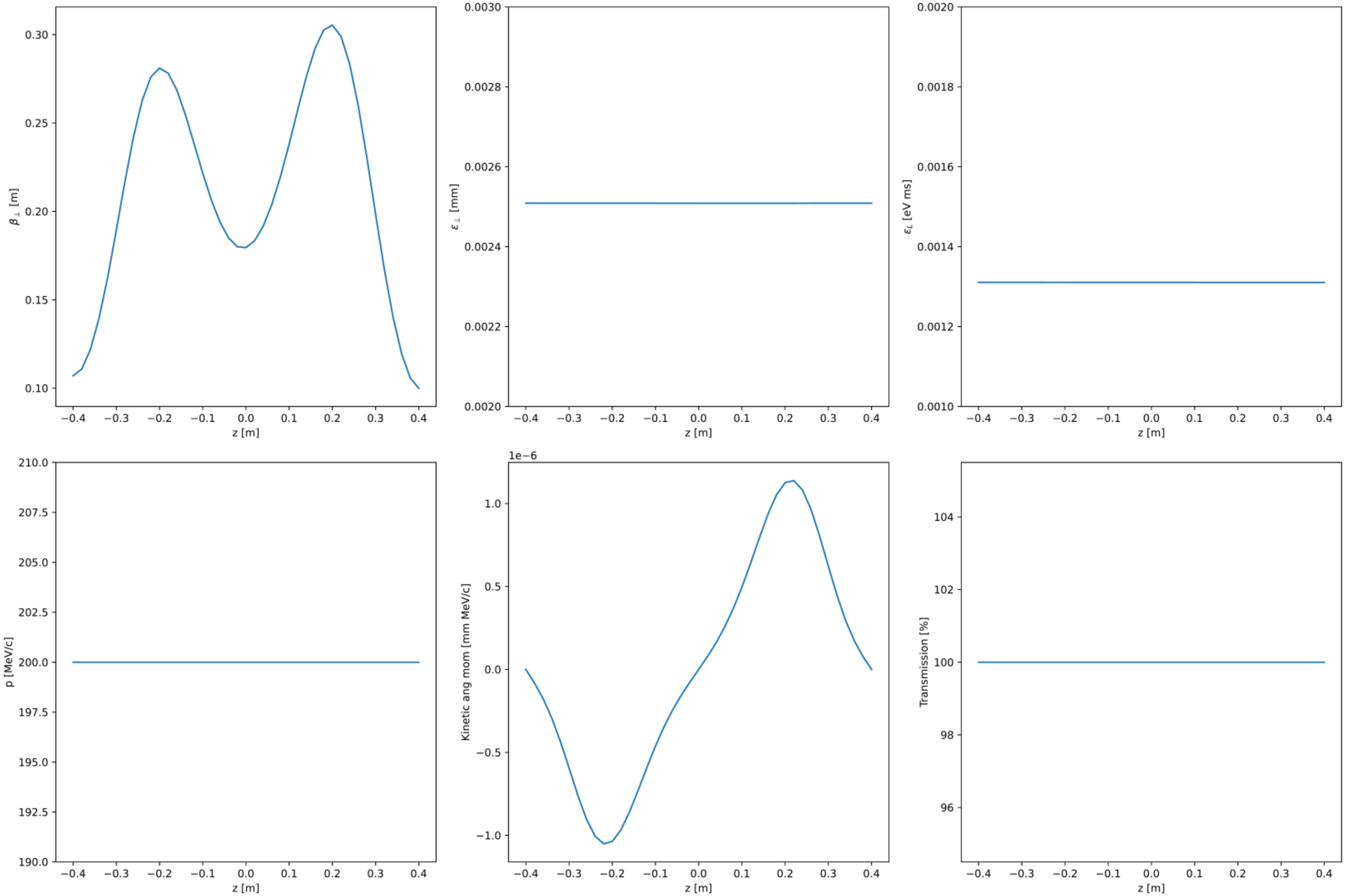
Parameter	Unit	Magnitude
Beam pipe radius	mm	81.6
Cooling cell length	mm	800.0
RF Cavity as Table 3		
Phase relative to bunching mode	°	20.0
RF cell separation	mm	5
RF centre-to-centre distance	mm	188.6
Iris radius	mm	81.6
Solenoid as Table 2		
Coil Z centre position	mm	100.7
No absorber		
Beam momentum	MeV/c	200.0
Beam distribution		Gaussian
Beam longitudinal emittance	eV ms	1.3×10^{-3}
Beam transverse emittance	mm	2.5×10^{-3}
σ_t	ns	0.003532
σ_E	MeV	0.3692
Beam $\beta_\perp$	mm	107
Beam $\alpha_\perp$		0
Beam L_{kin}	mm MeV/c	0

Table 4: Cooling Cell definition - with a low emittance beam.

Cooling Cell – Low Emittance

No RF

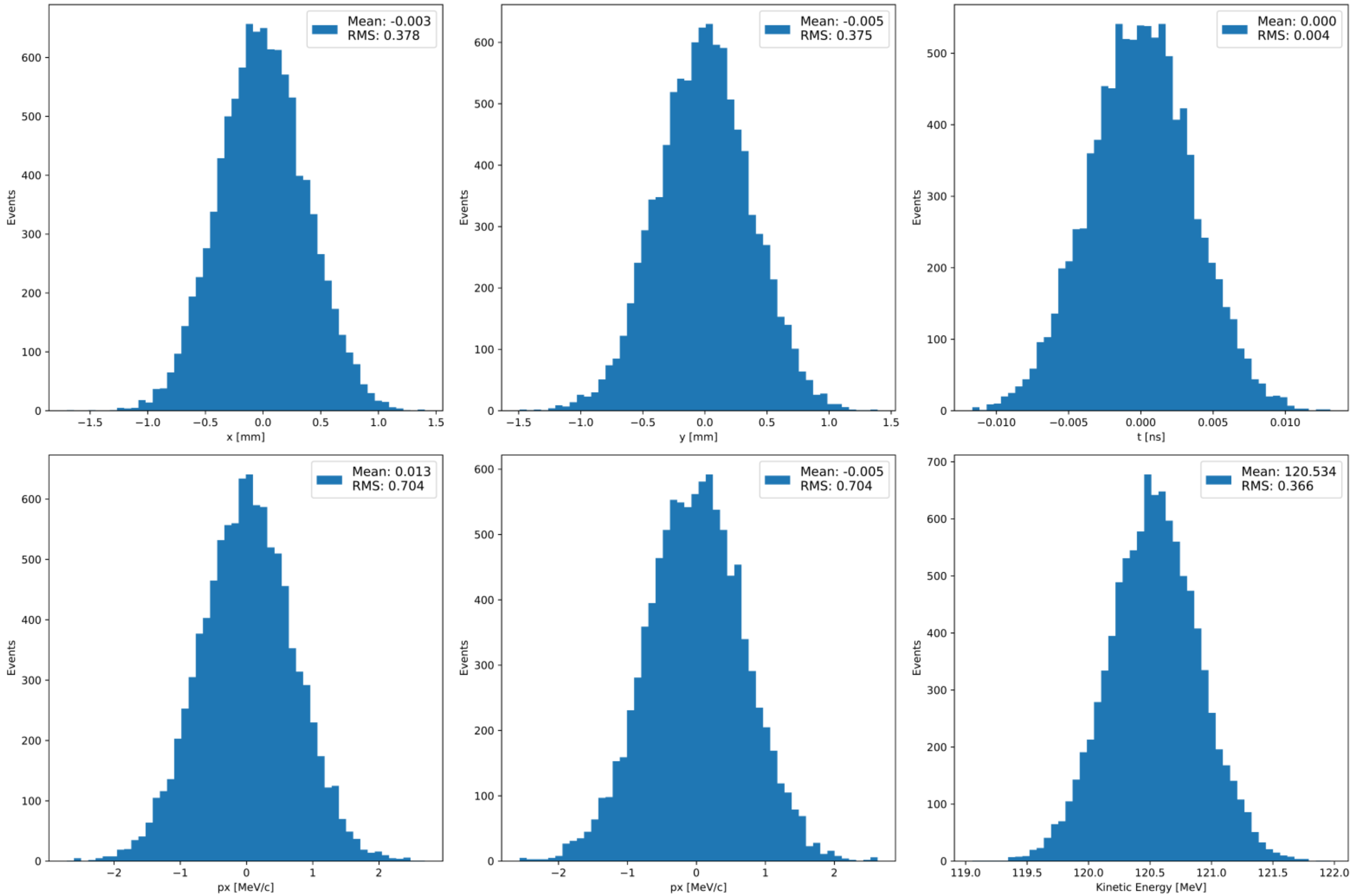
Beta asymmetric!



Cooling Cell – Low Emittance

No RF

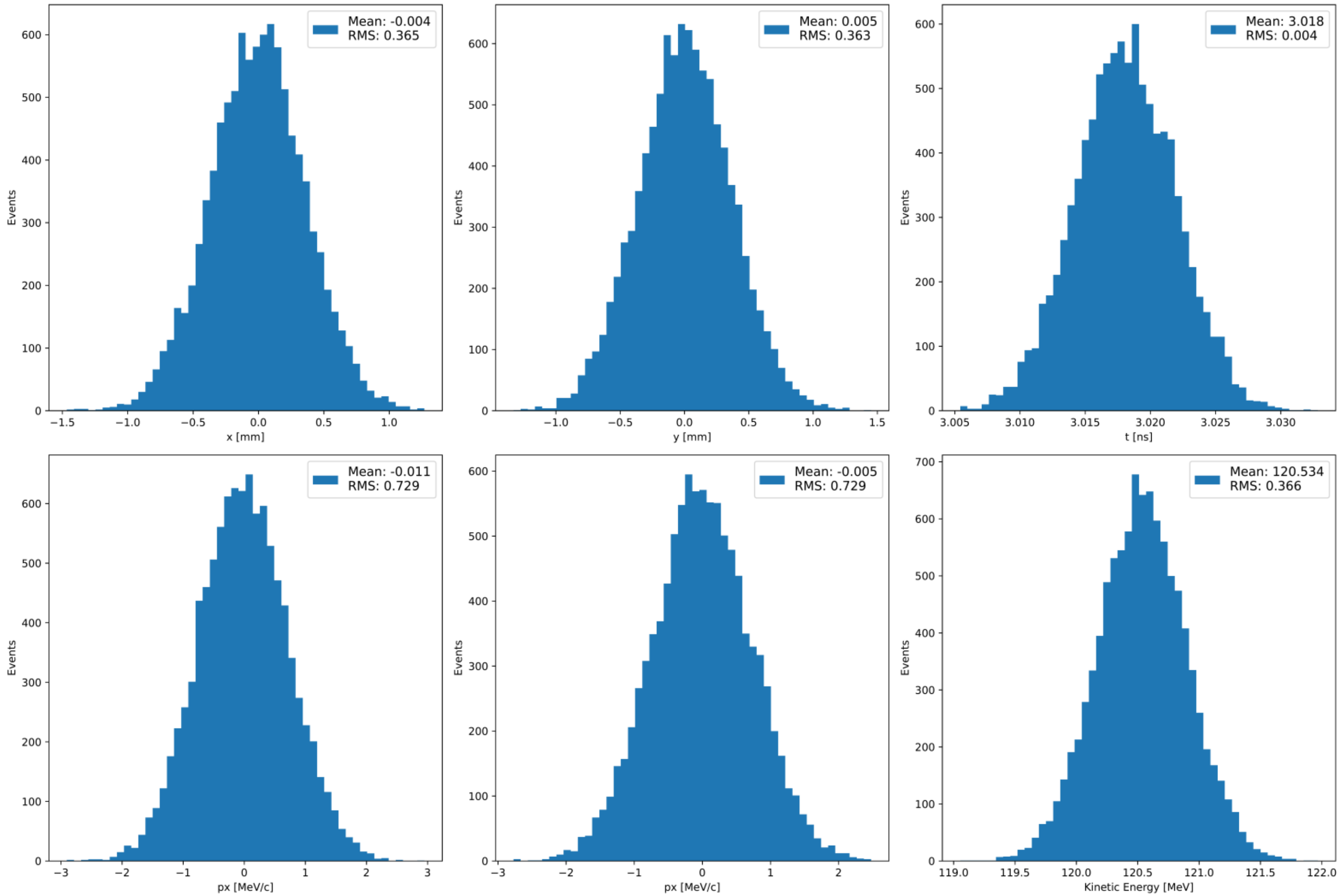
Start profiles



Cooling Cell – Low Emittance

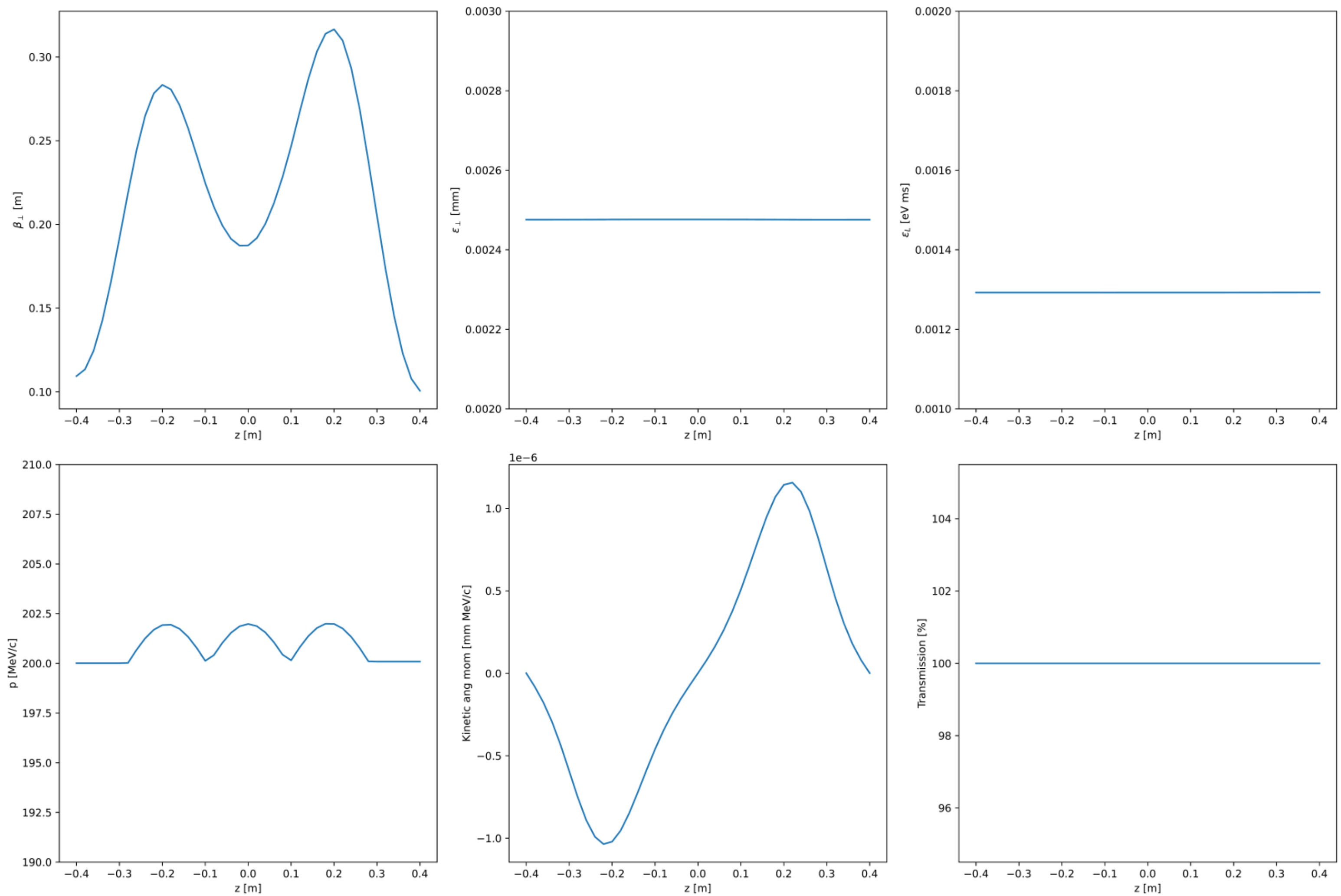
No RF

End profiles



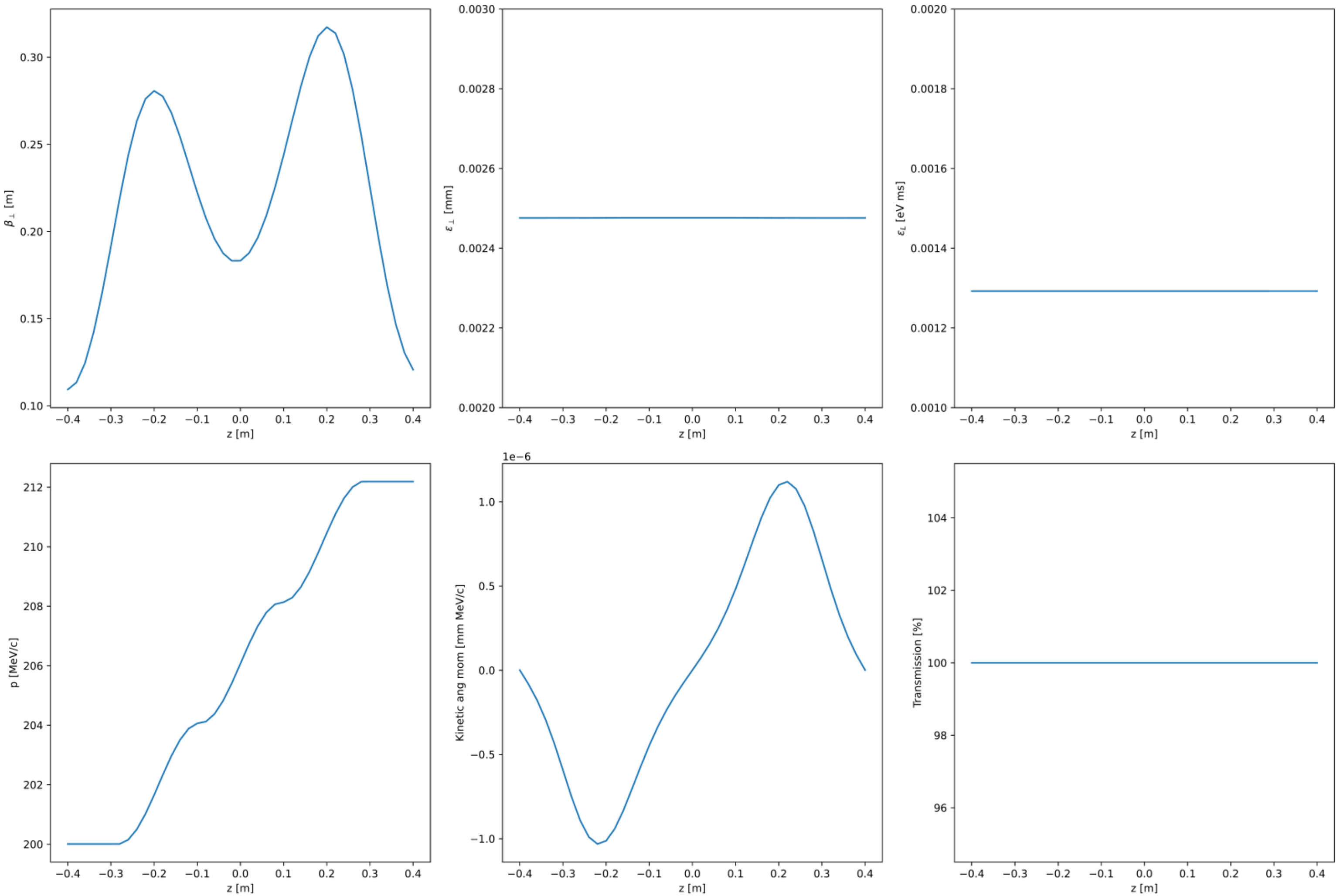
Cooling Cell – Low Emittance

Bunching mode



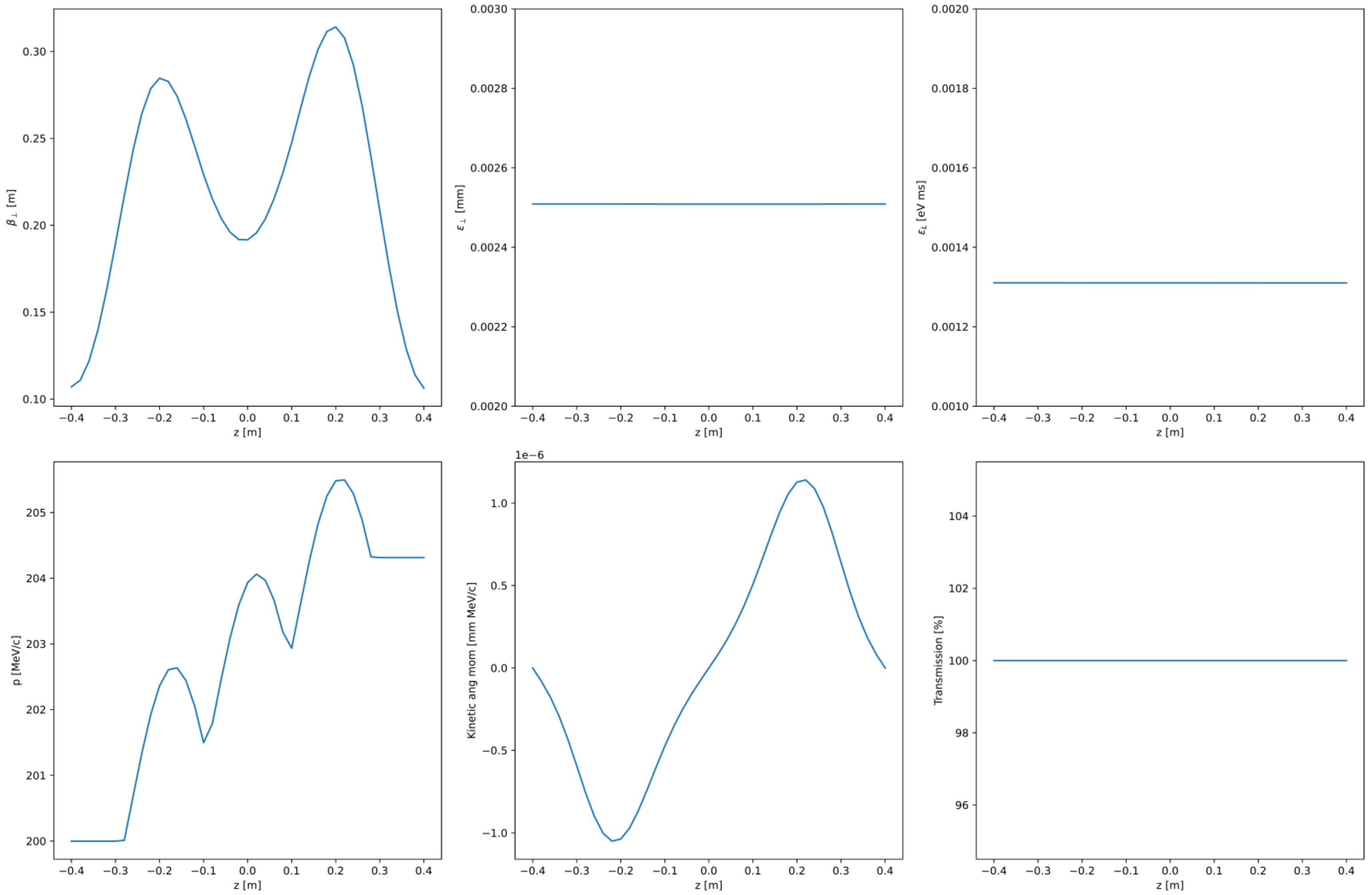
Cooling Cell – Low Emittance

Acc Mode



Cooling Cell – Low Emittance

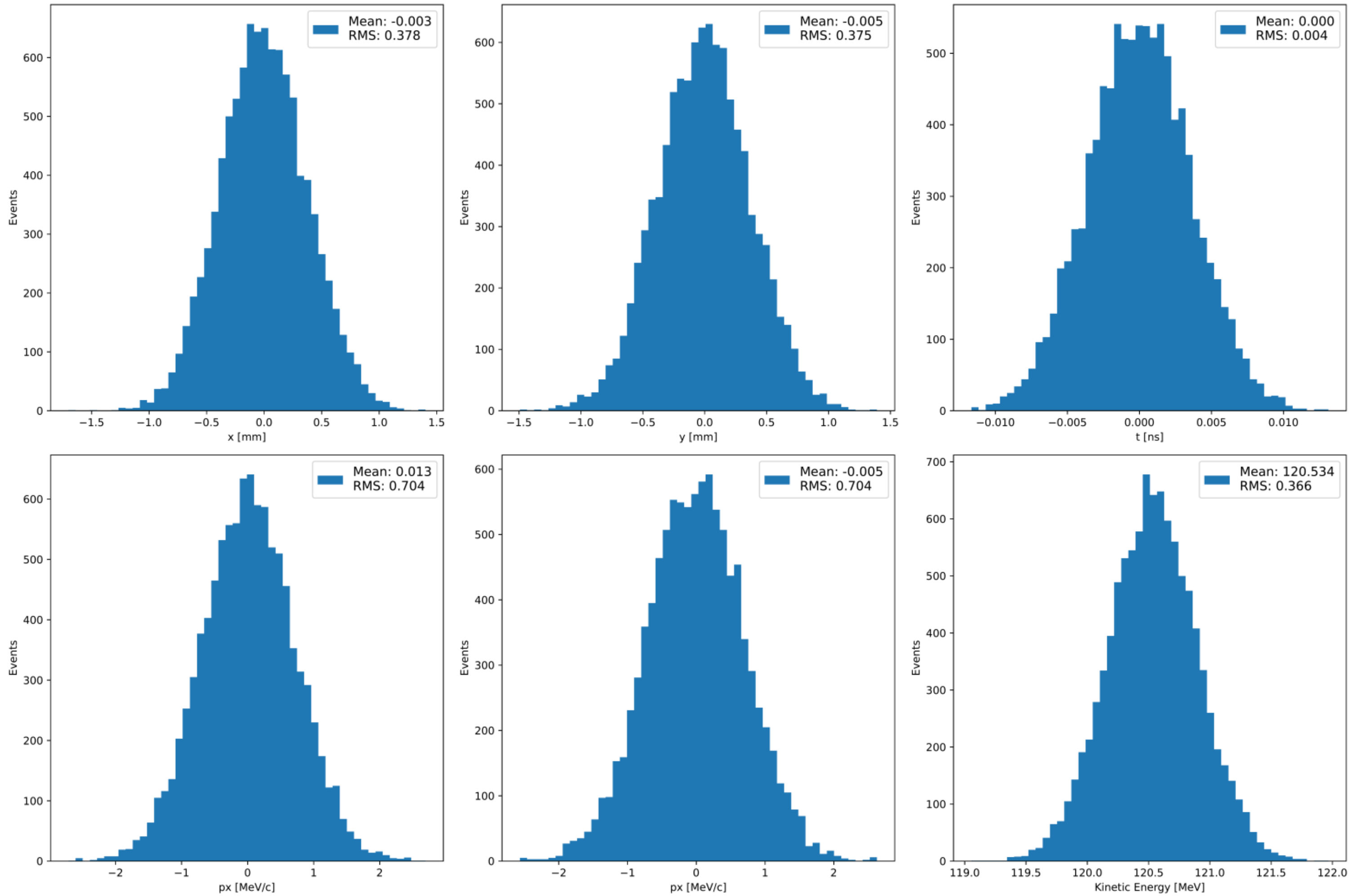
RF phase
20° relative to bunching mode



Cooling Cell – Low Emittance

RF phase
20° relative to bunching mode

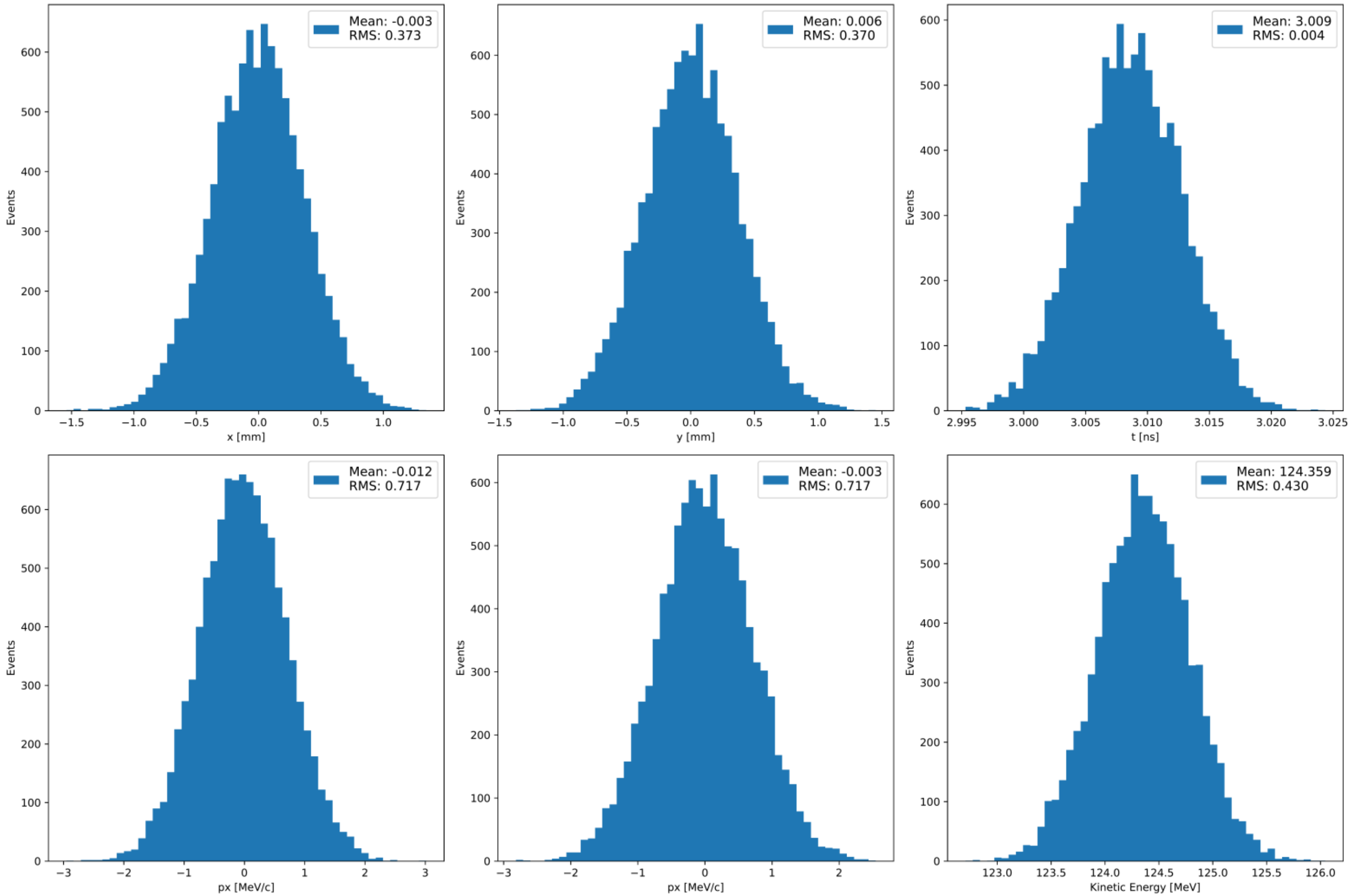
Start profiles



Cooling Cell – Low Emittance

RF phase
20° relative to
bunching mode

End profiles



Cooling Cell – High Emittance

- At 2.5 mm transverse emittance, some particles start scraping, some go backwards
  - Still working on processing and cleaning the virtual detector data
- **To be continued..**
- Simulated a 1 mm transverse emittance beam through (see backup)
  - Fully transmitted
  - Just below equilibrium emittance so no cooling
- **Note**: previously shown transverse cooling using an earlier iteration of the cooling cell (see backup)

Parameter	Unit	Magnitude
Cooling cell as Table 4 except absorber and beam		
Absorber as LiH from Table 1 except thickness		
Thickness	mm	10
Beam momentum	MeV/c	200.0
Beam distribution		Gaussian
Beam longitudinal emittance	eV ms	1.3
σ_t	ns	0.1117
σ_E	MeV	11.68
Beam transverse emittance	mm	2.5
Beam $\beta_\perp$	mm	107
Beam $\alpha_\perp$		0
Beam L_{kin}	mm MeV/c	0

Table 5: Cooling Cell definition - with a high emittance beam.

Thank you

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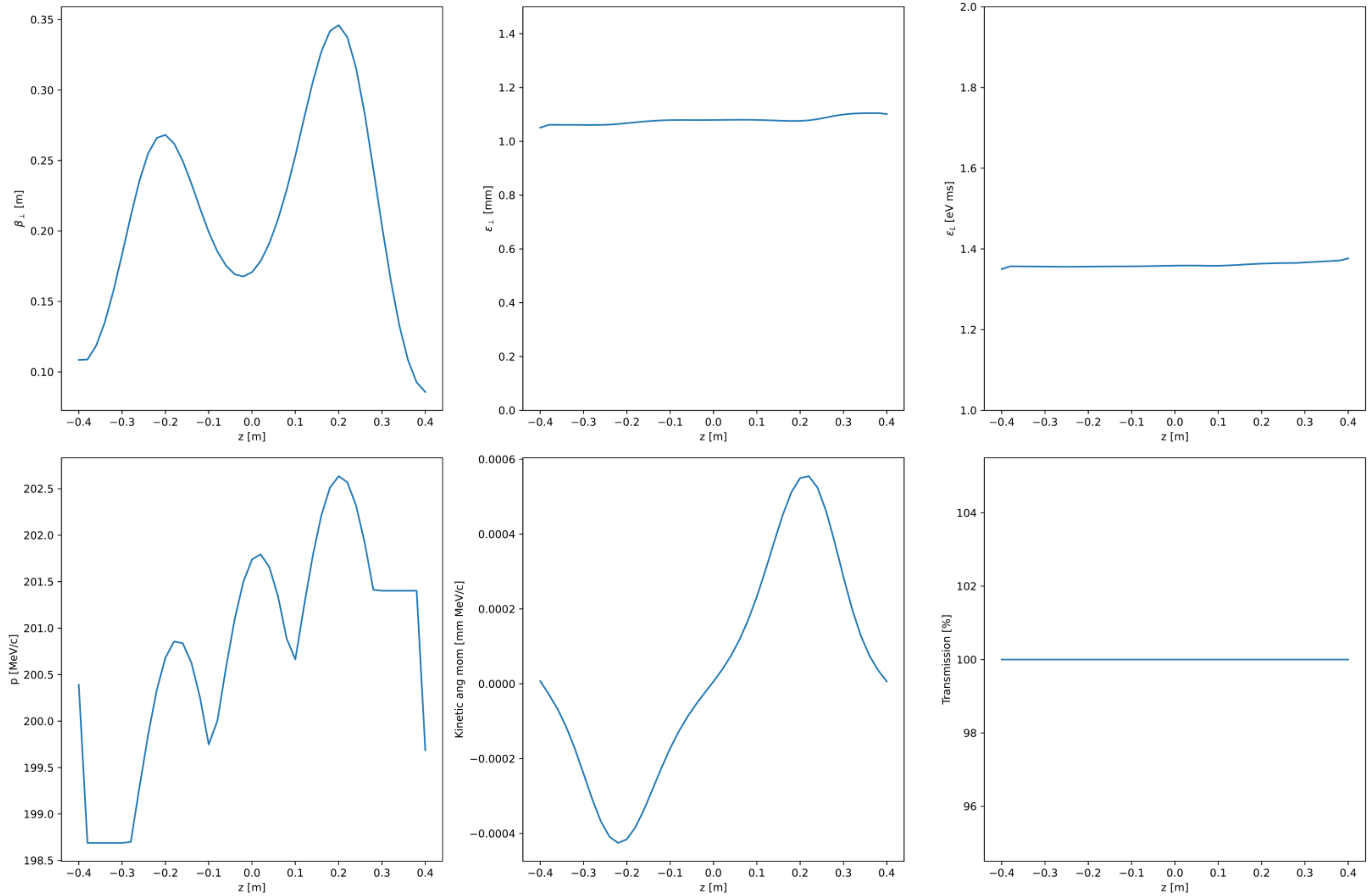
Back Up

Cooling Cell – High Emittance

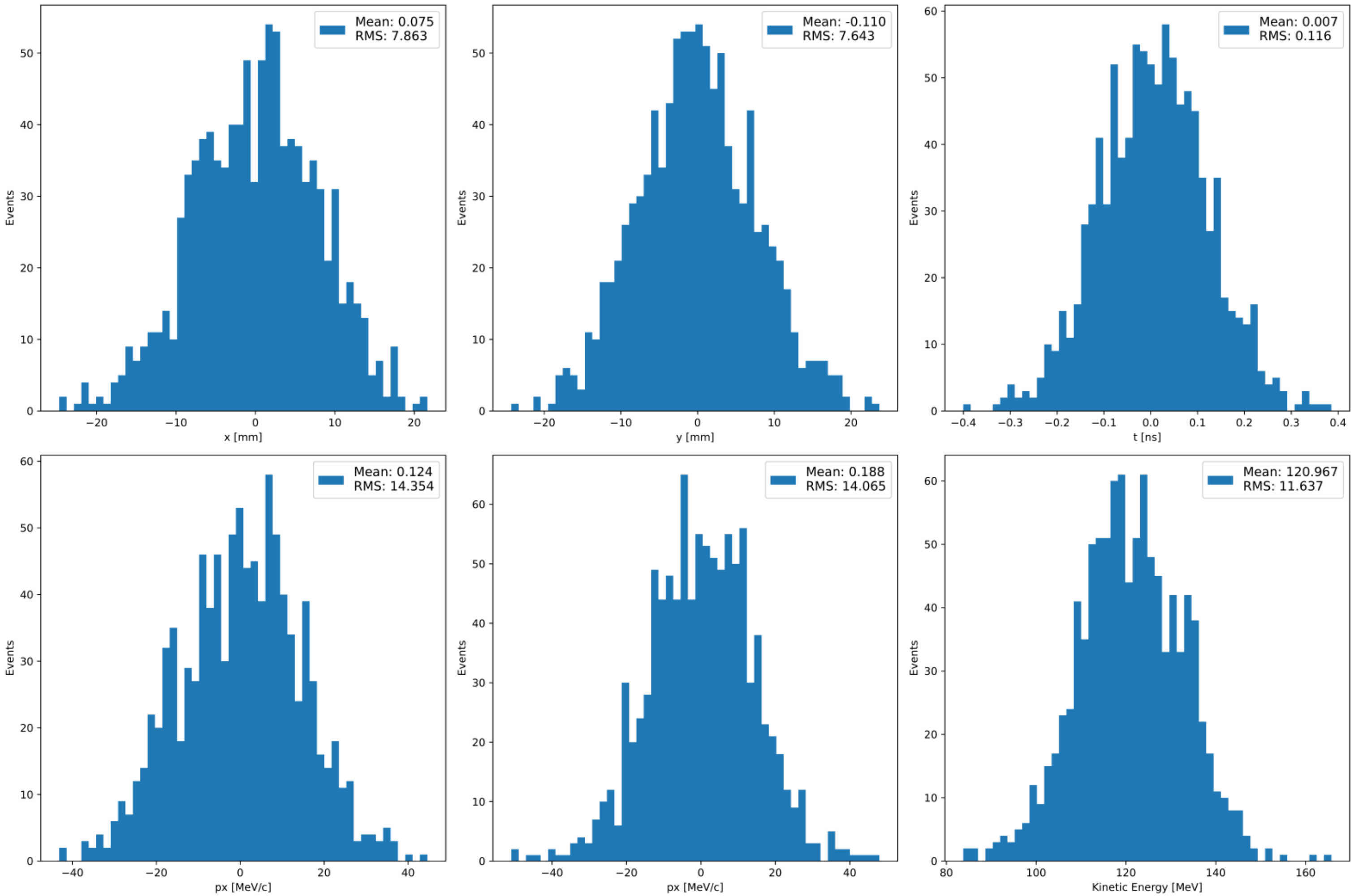
Transverse Emittance: 1 mm



Cooling Cell – High Emittance

Transverse Emittance: 1 mm

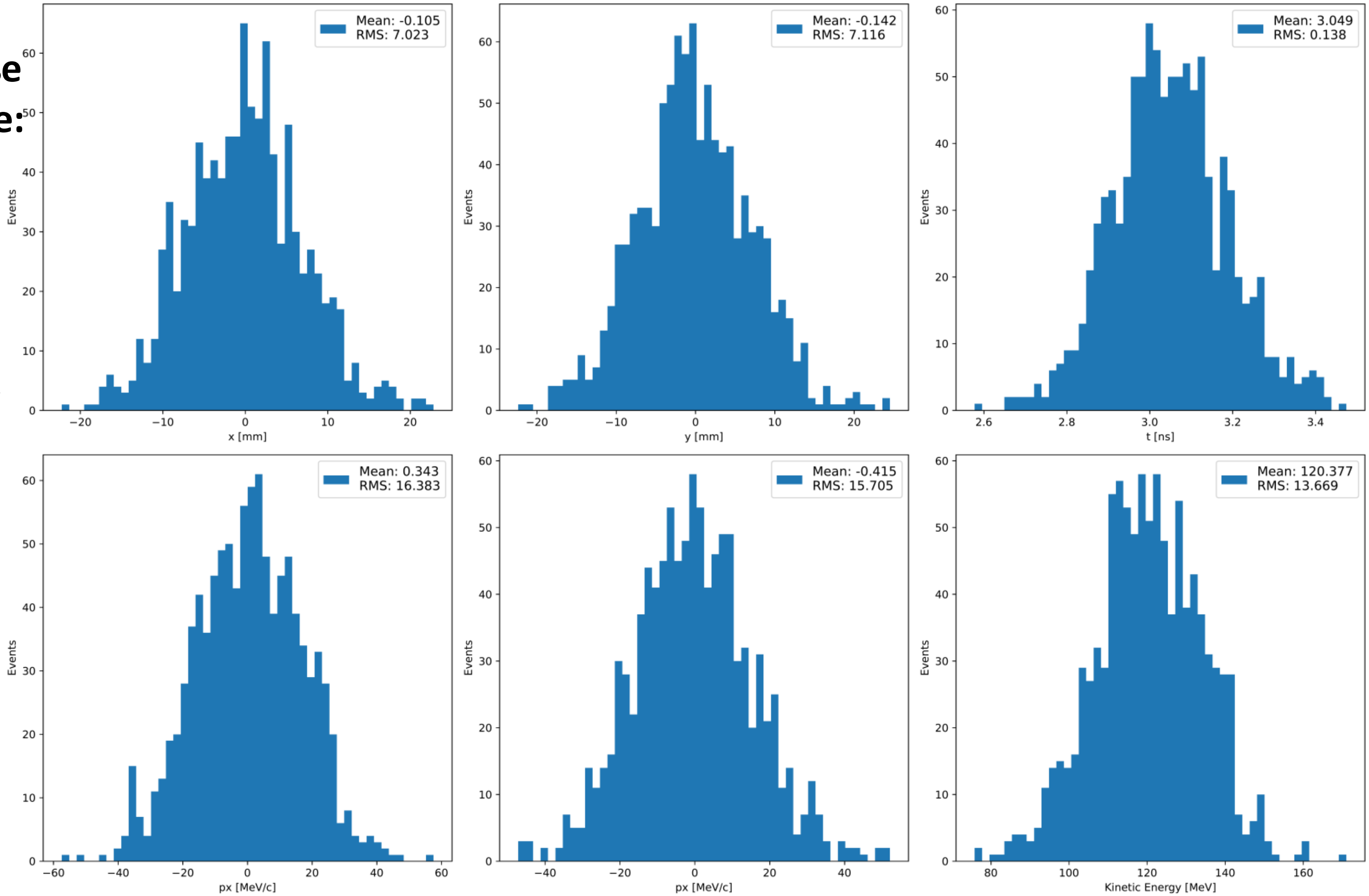
Start profiles



Cooling Cell – High Emittance

Transverse Emittance: 1 mm

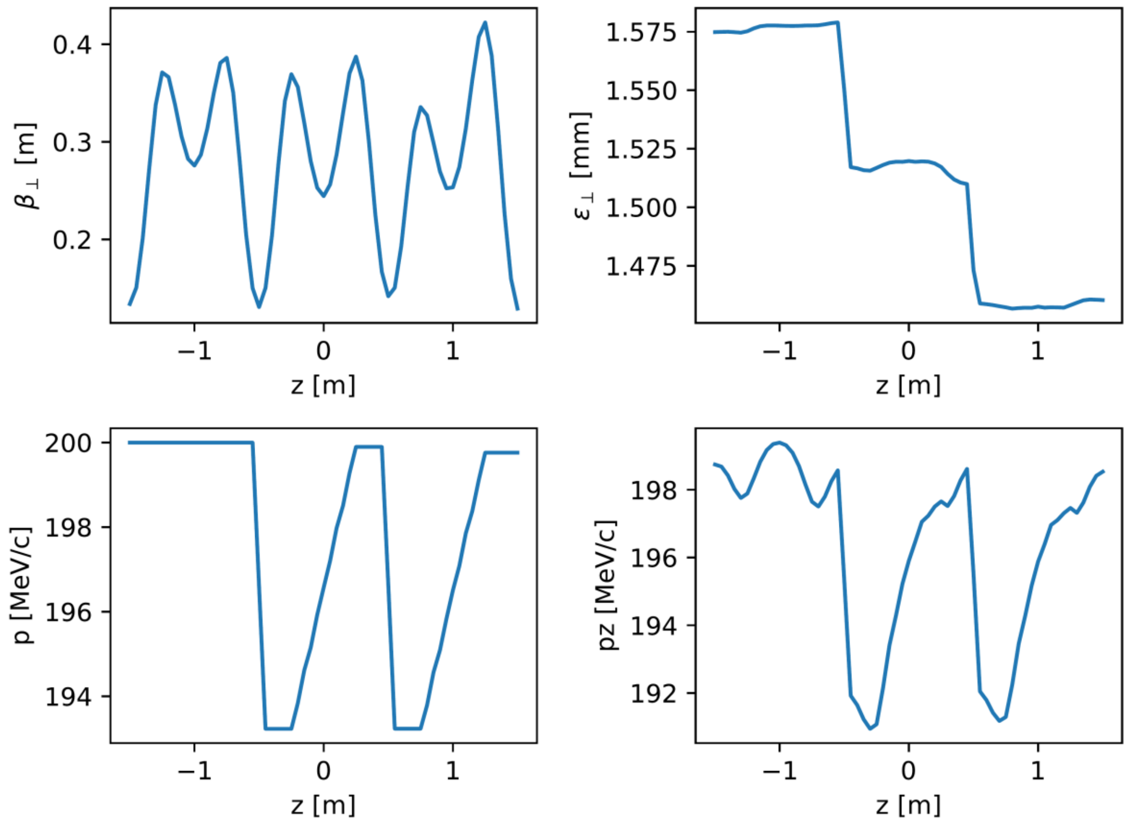
End profiles



Cooling Cell – High Emittance

Cooling cell version:2022-11-01 release

Transverse cooling observed 200 MeV/c beam with ~1.6 mm 4D emittance



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