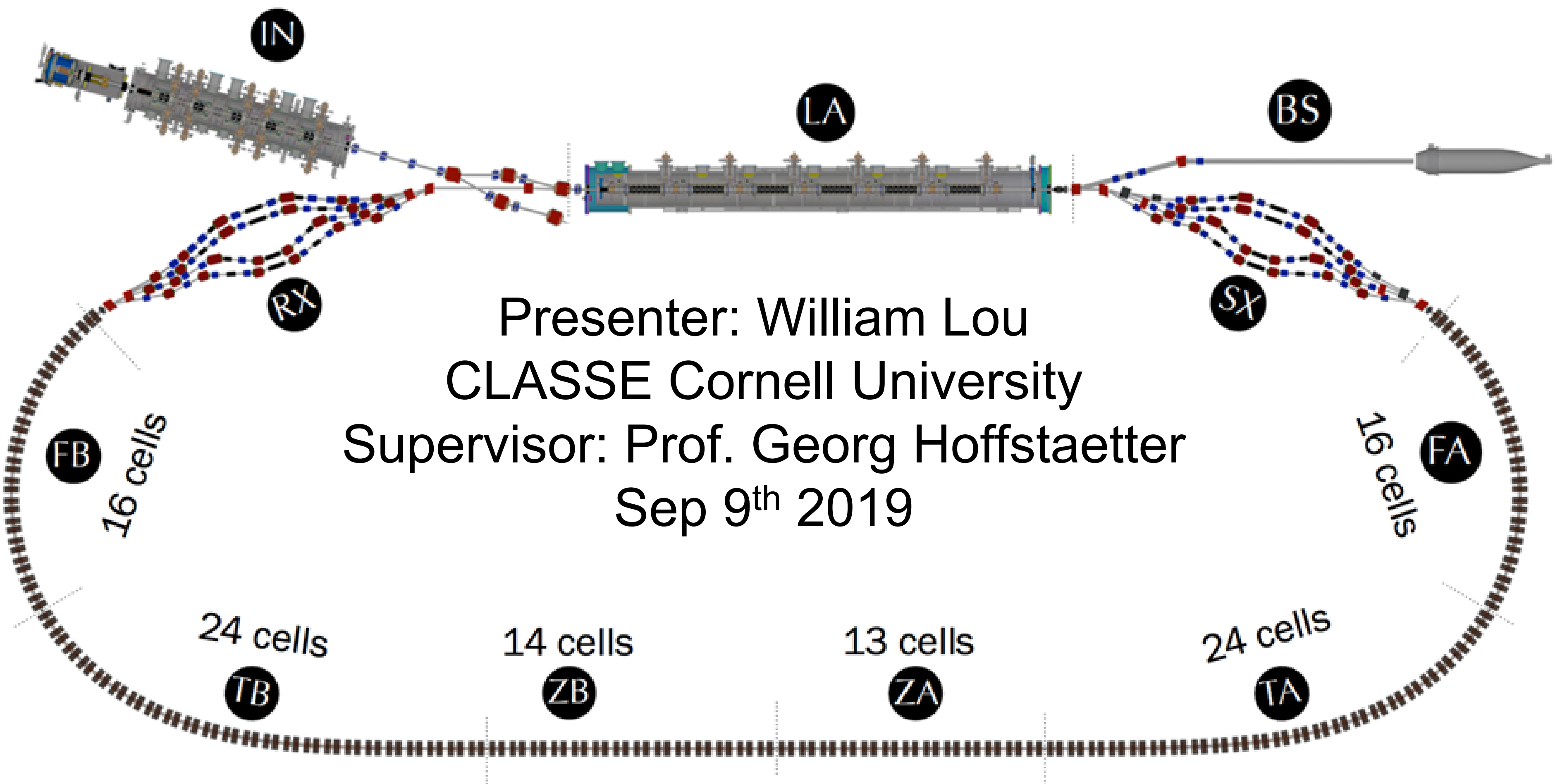
CSR Phase Space Dilution in CBETA



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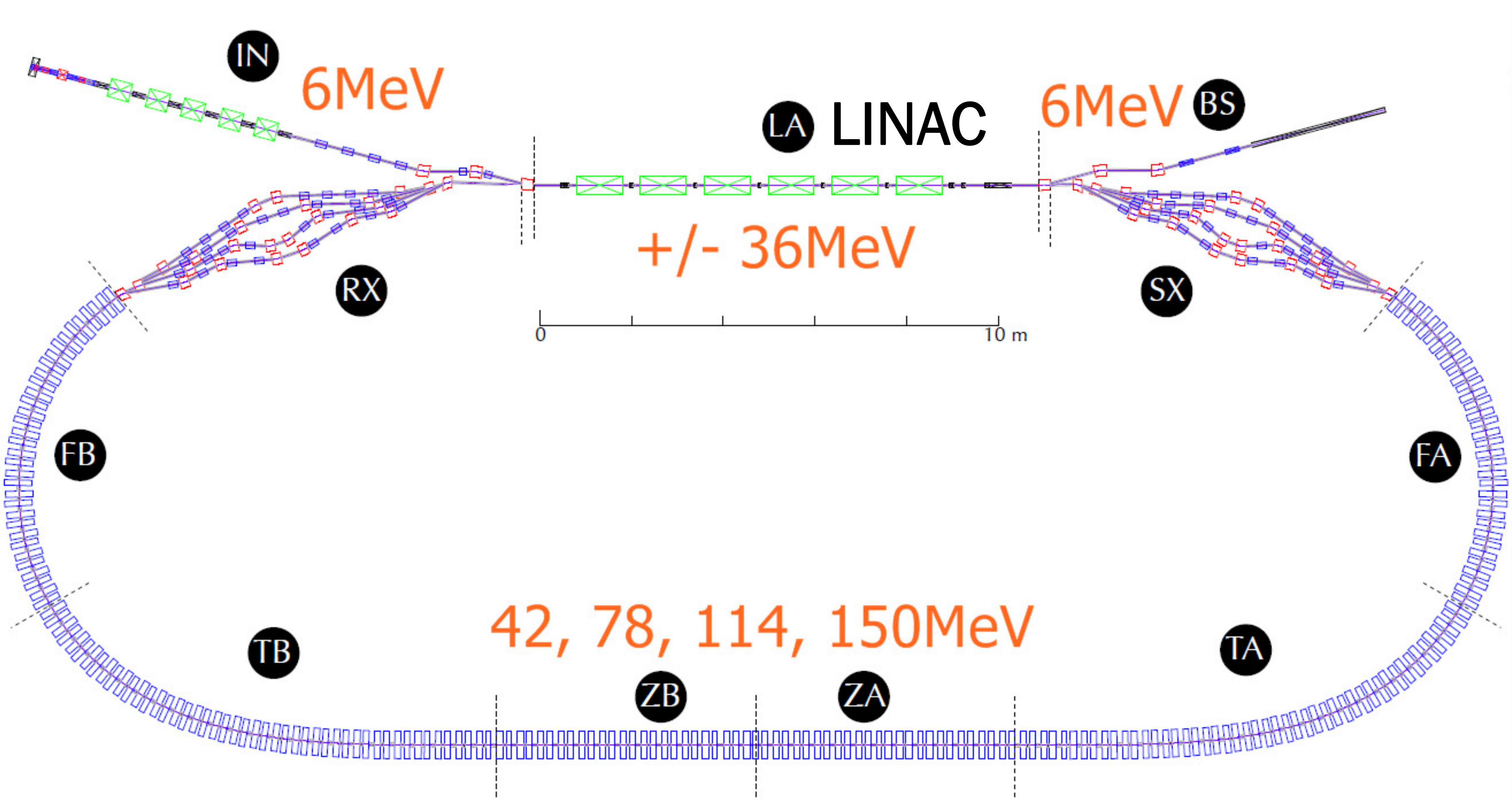
CLASSE Cornell University
Supervisor: Prof. Georg Hoffstaetter
Sep 9th 2019

What is CBETA?

Cornell BNL ERL Test Accelerator



Fixed Field Alternating gradient (FFA) beamline

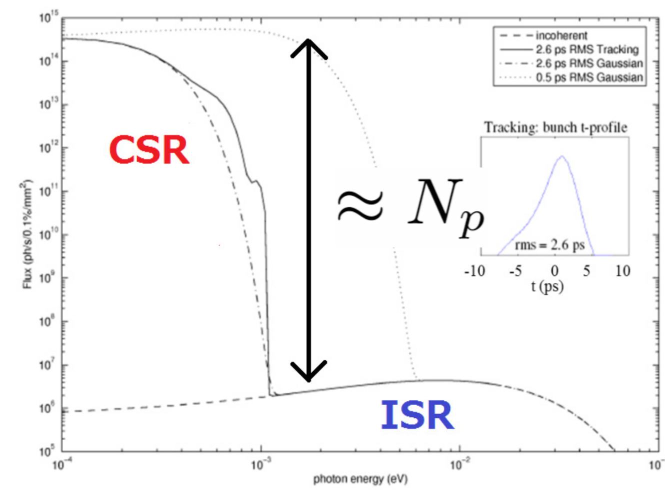
What is CSR?

- **Synchrotron Radiation** (SR) emitted by an electron "kicks" other electrons in the same bunch.

- The radiation at long wavelengths (on the order of the bunch length) can add **coherently**.

- The radiation intensity scales as N_p^2

SR Power spectrum of a 70pC Bunch through a dipole magnet



Courtesy of I.V. Bazarov

Effects on beam
- Increase energy spread and emittance
- Energy loss
- Potential micro-bunching Instability

See Helper slide #1 for detailed description

Bmad Simulation Overview

Two particle interaction

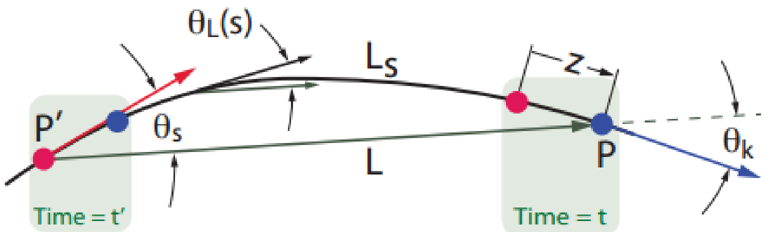


Figure 1: CSR calculation geometry. A "source" particle (red dots) is a distance z behind the "kicked" particle (blue dots). The radiation from the "source" particle at point P' and time t' interacts at some later time t with the kicked particle at point P.

$$\left(\frac{d\mathcal{E}}{ds}\right)_{\text{CSR}} = \int_{-\infty}^{\infty} ds' \, \frac{d\lambda(s')}{ds'} \, I_{\text{CSR}}(s - s')$$

$$I_{\text{CSR}} = -r_e m c^2 \left(\frac{2\,\epsilon_L}{z\,L} + \frac{2}{L} \frac{\gamma^2\,\theta_s\,\theta_k}{1 + \gamma^2\,\theta_s^2} \right)$$

1D Model in Bmad

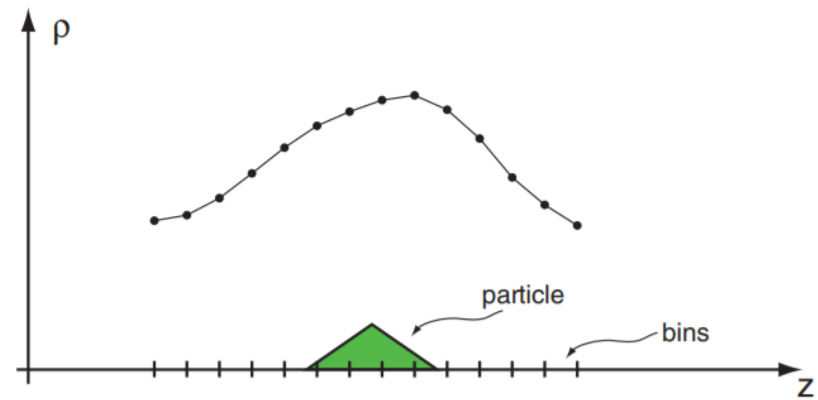


FIG. 6. (Color) Bmad implementation of the CSR algorithm. The beam of particles is divided up into a number of bins. The contribution of a particle to a bin's total charge is determined by the overlap of the particle's triangular charge distribution and the bin.

$$d\mathcal{E}_j = ds_{\text{slice}} \sum_{i=1}^{N_b} (\lambda_i - \lambda_{i-1}) \, \frac{I_{\text{CSR}}(j-i) + I_{\text{CSR}}(j-i+1)}{2}$$

Important parameters:

- Np (# particles)
- Nb (# bins)
- Q (bunch charge)

Extra features:

- Can include Space Charge at high energy
- Can include shielding effect
- Can handle the case when design orbit is not the reference orbit (like FFA cells)

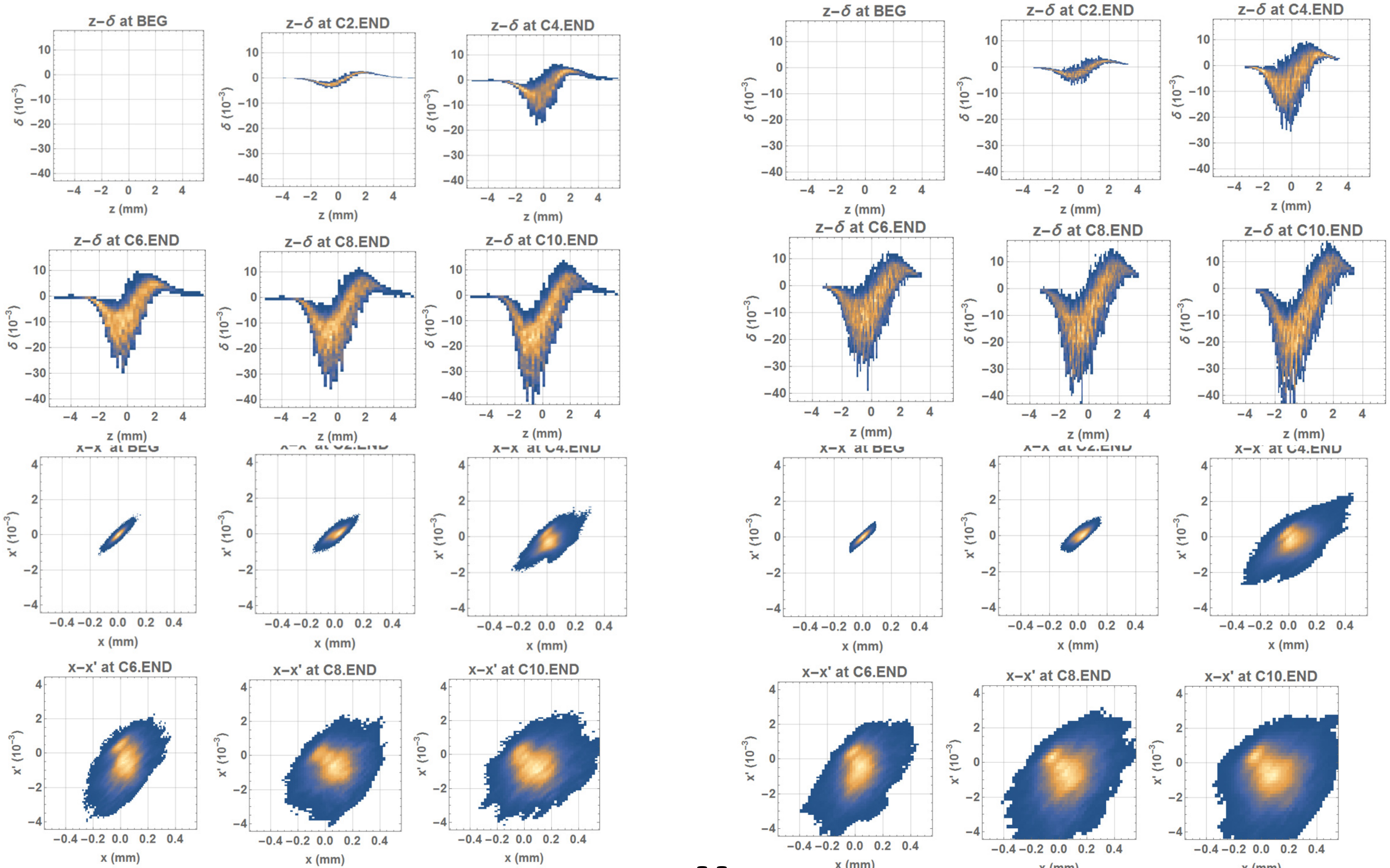
Benchmarking with Elegant

(10 equivalent FA cells, Np = 1M, Nb = 3000, Q = 5nC)

Bmad *Elegant*

z-pz

x-px

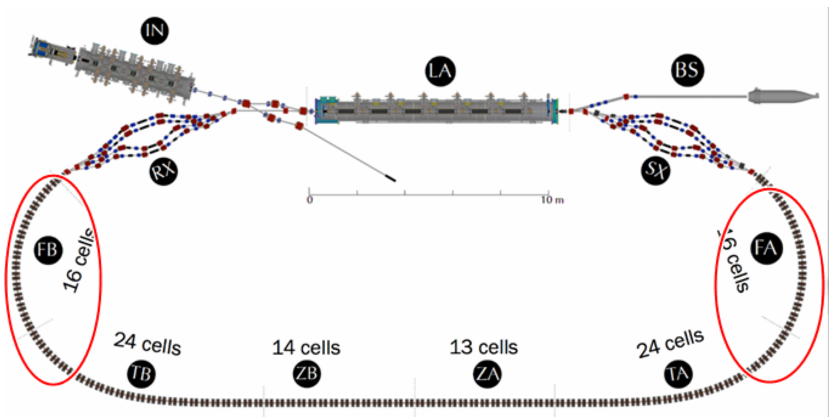


The two programs agree well

Note: Elegant CSR cannot handle FFA cells (design ≠ reference orbit), so FA cells were converted into equivalent bends and drifts for comparison

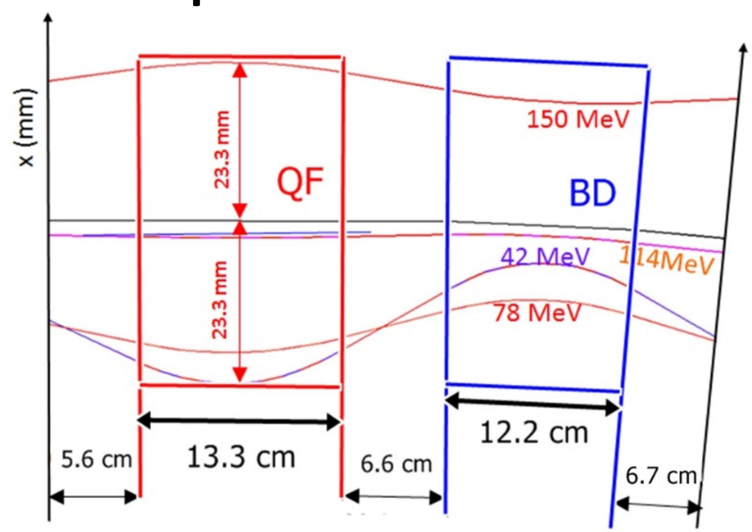
Which section(s) in CBETA contribute the most CSR ?

CBETA layout



The bunch undergoes the most “bending” in FA and FB

One periodic FA cell

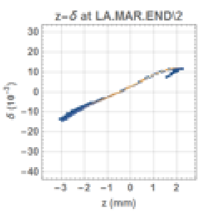
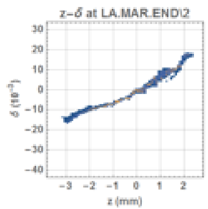
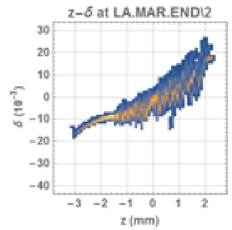
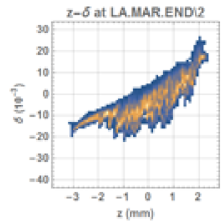
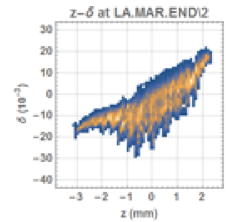
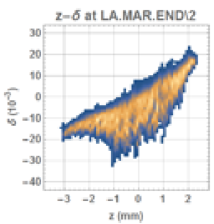
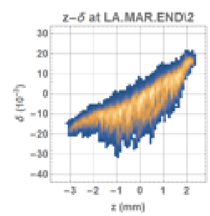
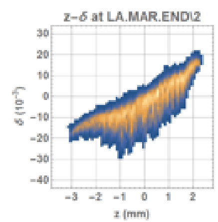
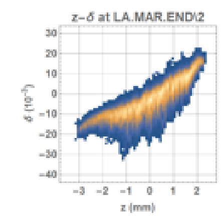
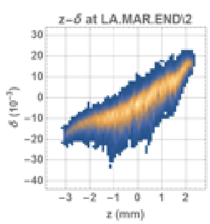
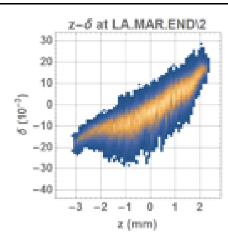
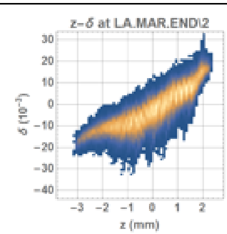
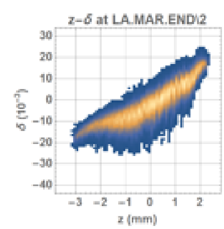


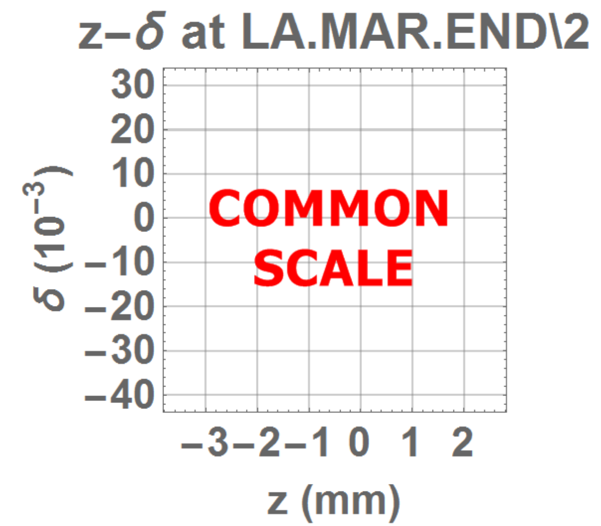
The bending is different for the four design orbits

Effect of varying Nb

CBETA 1-pass (Np = 600k, Q=25pC)

z-pz phase space at the end of LINAC pass 2 (6 MeV)

No CSR	100	400	700	1000
				
	1500	2000	2500	3000
				
	3500	4000	4500	5000
				



Np/Nb cannot be too small

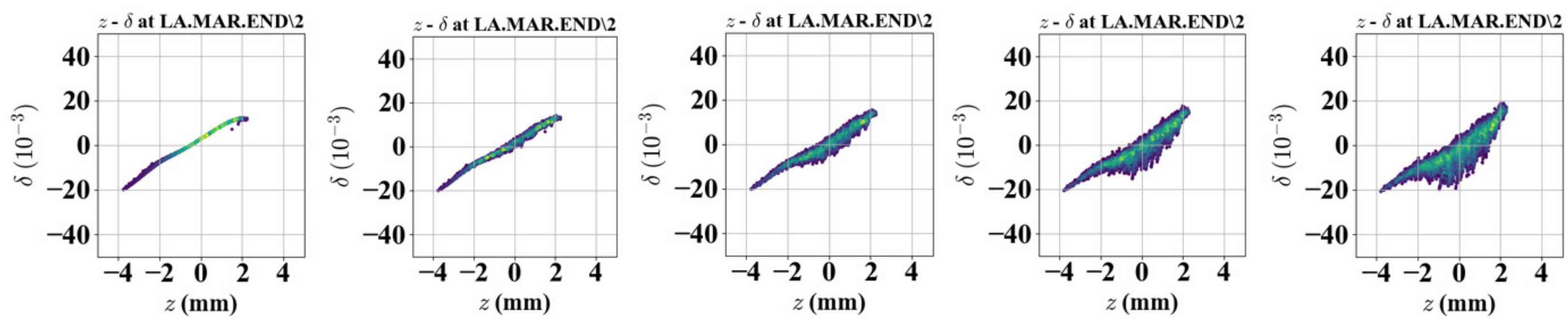
Picked Nb = 2500

Effect of varying Q

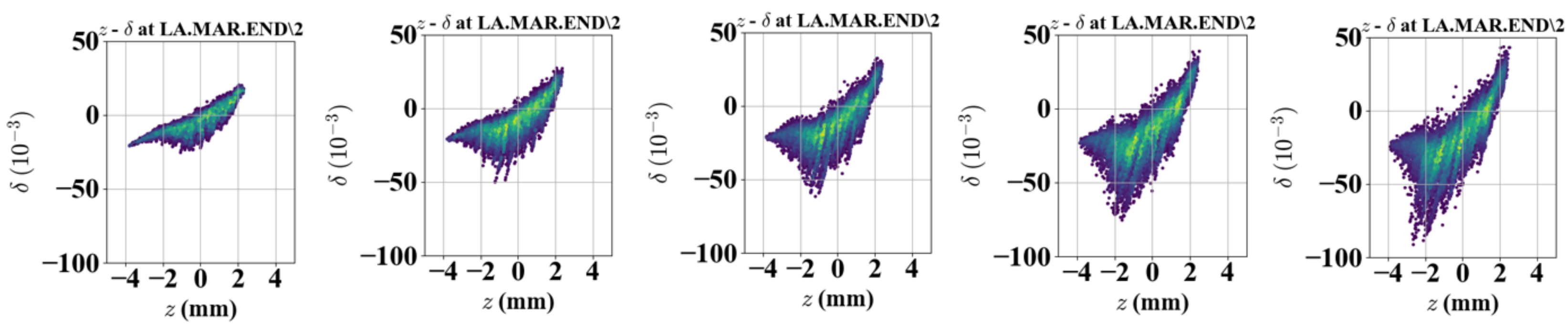
CBETA 1-pass (Np = 1M, Nb = 2500)

z-pz phase space at the end of LINAC pass 2 (6 MeV)

No CSR	5pC	10pC	15pC	20pC



25pC	50pC	75pC	100pC	125pC



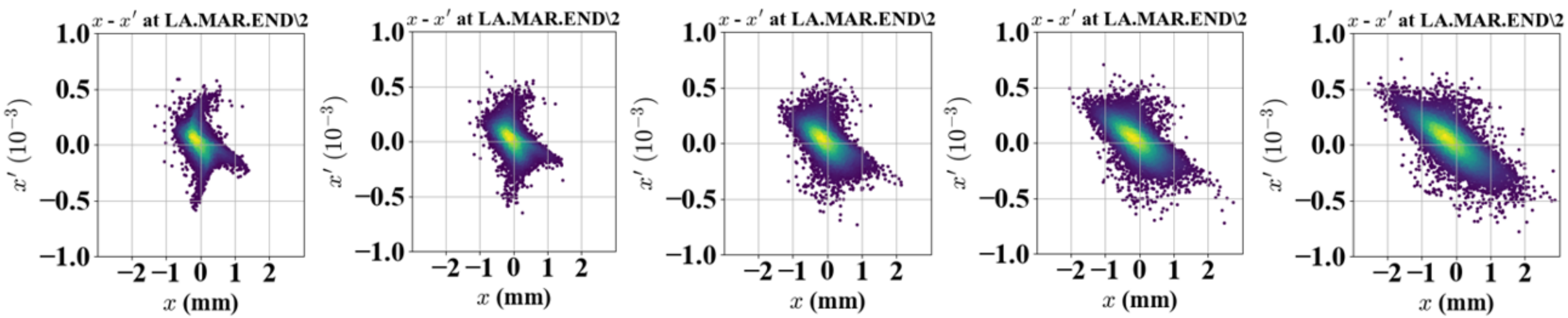
For Q=50pC, max energy spread exceeds ±5.0%

Effect of varying Q

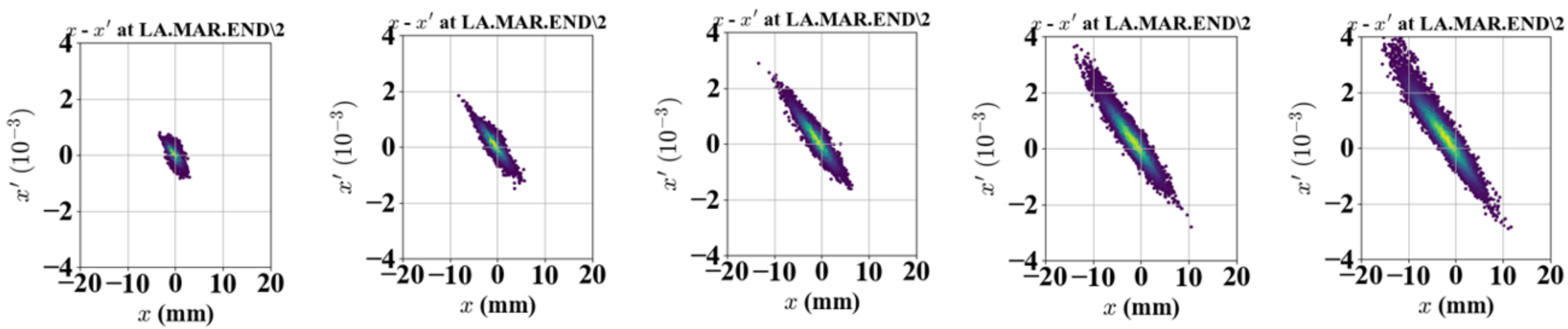
CBETA 1-pass (Np = 1M, Nb=2500)

x-px phase space as the end of LINAC pass 2 (6 MeV)

No CSR	5pC	10pC	15pC	20pC



25pC	50pC	75pC	100pC	125pC



For Q>75pC, max x beam size exceeds 15mm

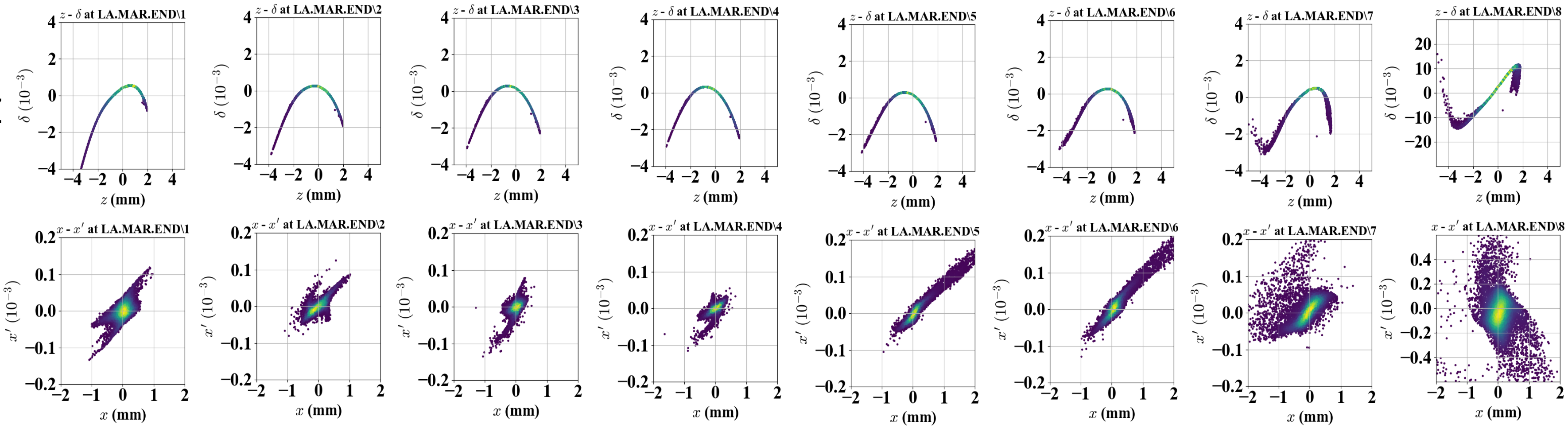
CBETA 4-pass (Np = 1M, Nb=2500)

No CSR

Final $\sigma_\delta \approx$ 6.94E-3, Final $\sigma_x \approx$ 0.58 mm

z-pz

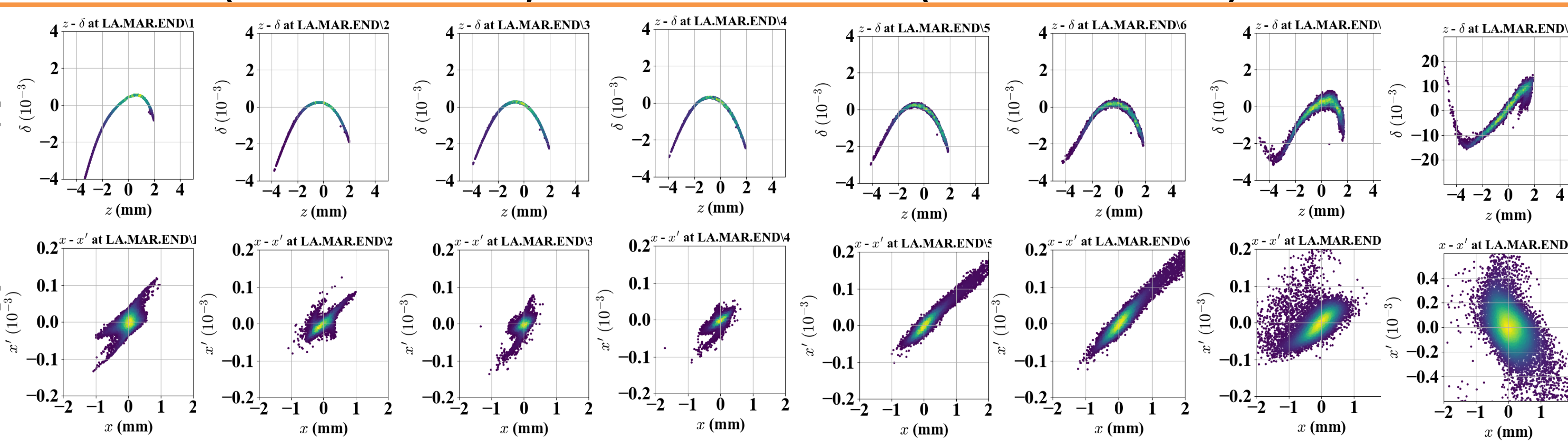
x-px



End of LINAC Pass	1	2	3	4	5	6	7	8
	(Acceleration)				(Deceleration)			

z-pz

x-px



Q = 1 pC

Particle loss = 215 / 1M, Final $\sigma_\delta \approx$ 7.00E-3, Final $\sigma_x \approx$ 0.67 mm

CBETA 4-pass (Np = 1M, Nb=2500)

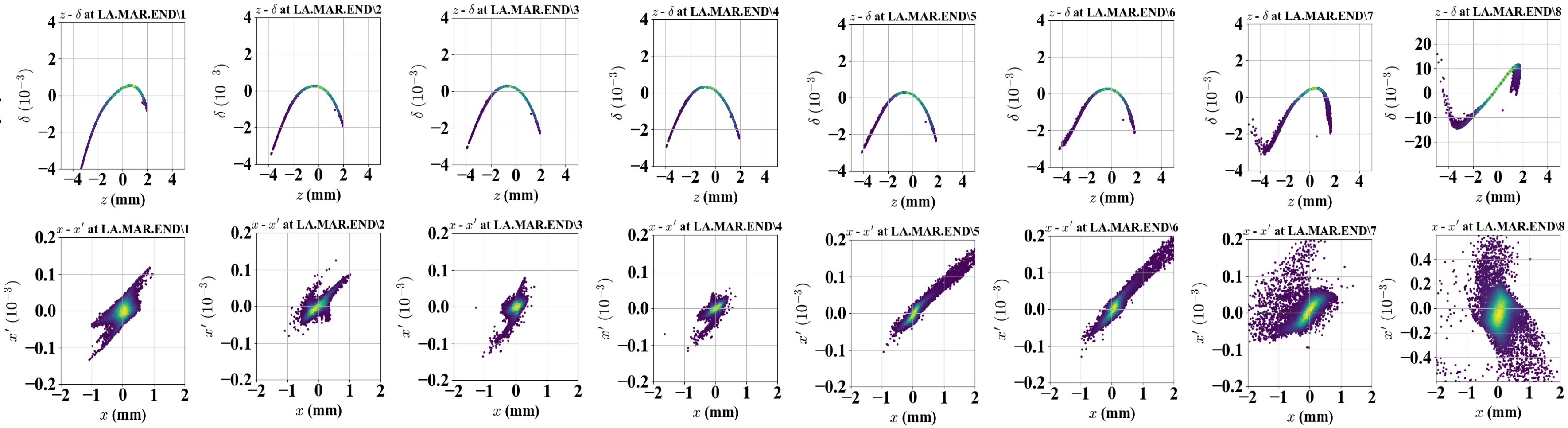
CBETA

No CSR

Final $\sigma_\delta \approx$ 6.94E-3, Final $\sigma_x \approx$ 0.58 mm

z-pz

x-px



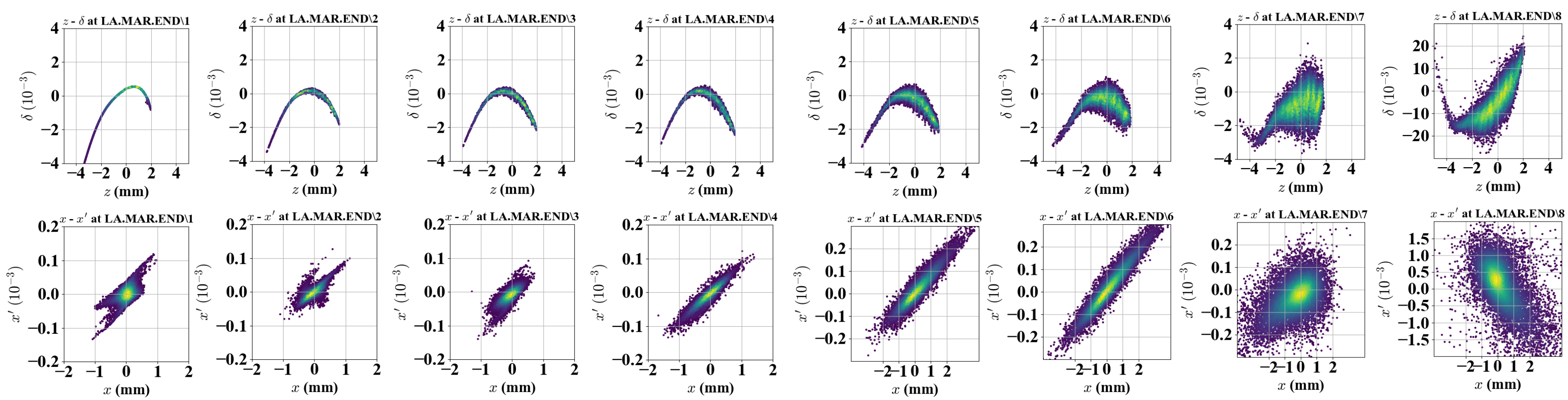
End of LINAC Pass

1 2 3 4 5 6 7 8

(Acceleration) (Deceleration)

z-pz

x-px



Q = 5 pC

Particle loss = 658 / 1M, Final $\sigma_\delta \approx$ 8.71E-3, Final $\sigma_x \approx$ 1.42 mm

Mitigation

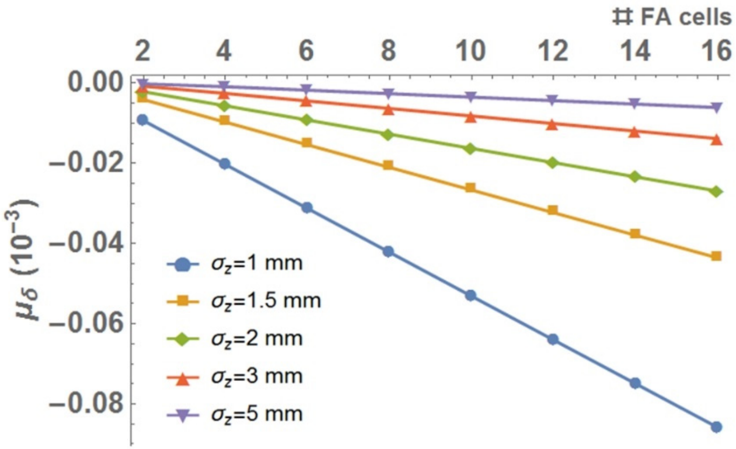
Increase Bunch Length

characteristic CSR energy change per unit length as

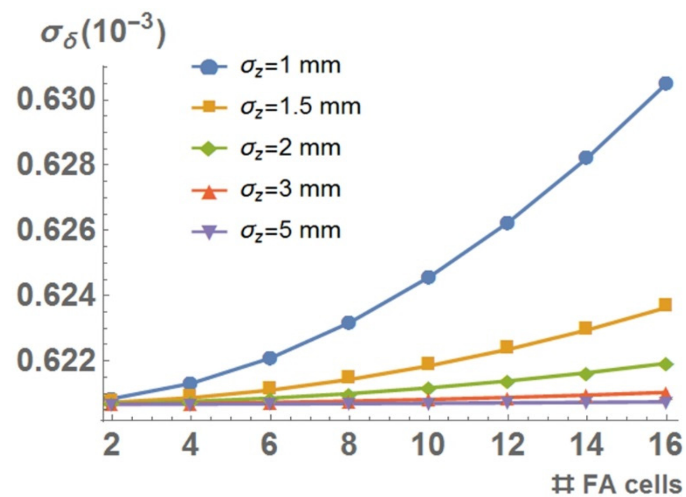
$$W_0 \equiv N r_c m c^2 \frac{(\kappa\sigma)^{2/3}}{\sigma^2}.$$

A Gaussian bunch with various bunch length is tracked down 16 FA cells (42 MeV) with CSR.

Relative energy loss <δ>



Relative energy spread σ_δ

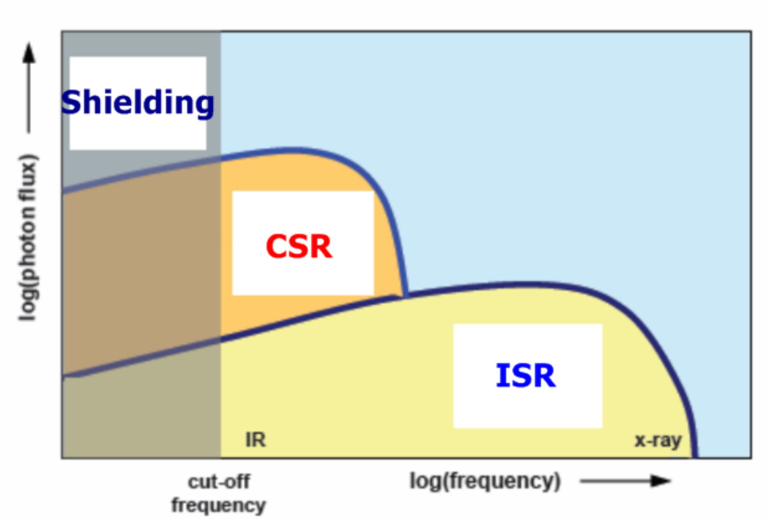


Increasing bunch length mitigates CSR effects of energy loss and increasing energy spread.

Mitigation

Vacuum Chamber Shielding

- Acts like waveguide with cutoff frequency
- Potentially decreases energy loss and spread



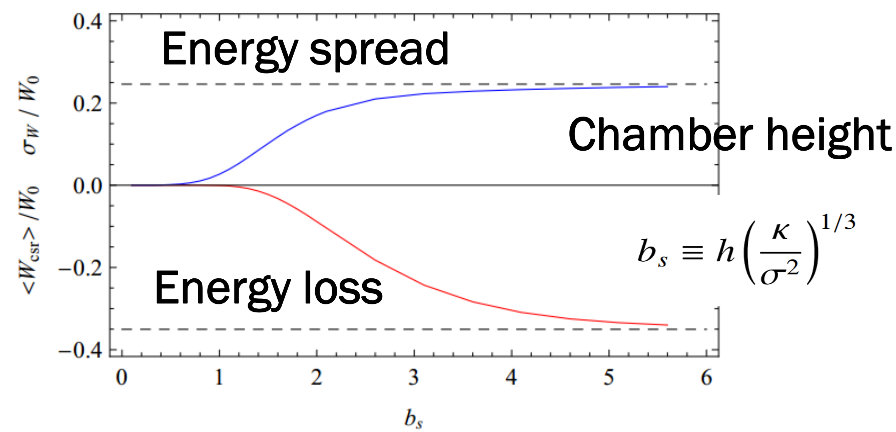


Figure 5.8: Average energy loss and energy spread versus the shielding parameter b_s.

Further simulation for CBETA required

Summary

- CSR could deteriorate CBETA beam quality as bunch charge and number of FFA pass increase.

- For CBETA 1-pass, Q < 50pC is required for final max energy spread < ±5.0%
(Beam stop can ideally take ±7.0%)

- For CBETA 4-pass, Q < 5pC is required for final max energy spread < ±5.0%, but for Q = 1pC 200/1M particles lost with the current lattice

Future Plan

- Investigate particle loss
- Test effect of shielding
- Test effect of increasing bunch length

Acknowledgement

- David Sagan (for Bmad assistance)
- Christopher Mayes (for CSR conceptual clearance)
- Kirsten Deitrick (for Elegant assistance)
- Georg Hoffstaetter (for result interpretation and **everything**)

References

- Bmad Manual
- Elegant Manual
- CBETA Design Report
- http://www.slac.stanford.edu/cgi-wrap/getdoc/slac-pub-14893.pdf

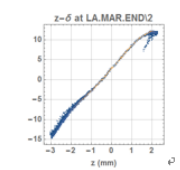
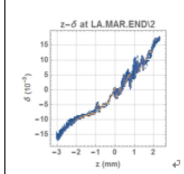
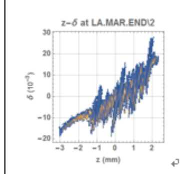
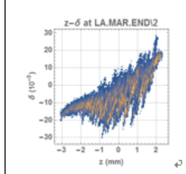
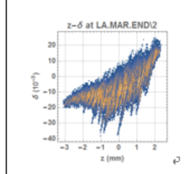
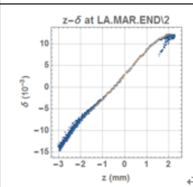
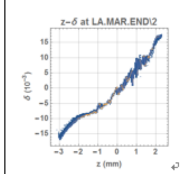
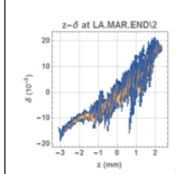
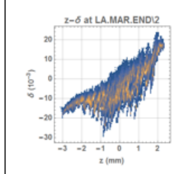
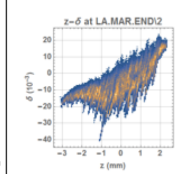
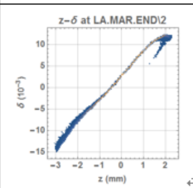
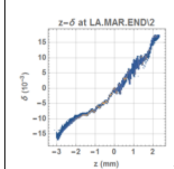
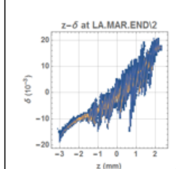
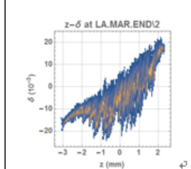
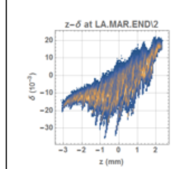
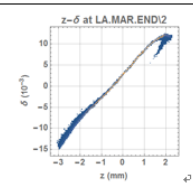
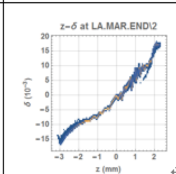
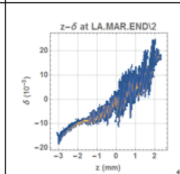
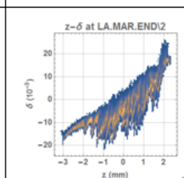
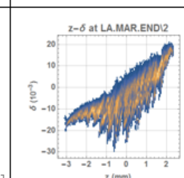
Helper slide #1

Particles are there subject to centripetal acceleration according to the Lorentz force. Radiation emitted by particles accelerated perpendicularly to their velocity is called synchrotron radiation (SR). The low-frequency part of the SR spectrum is amplified w.r.t. the high-frequency one, by the fact that electrons in the bunch are confined to a length scale of the order of, or shorter than, the radiation wavelength. As a consequence, the electric field of radiation produced by individual electrons adds in phase. This gives rise to a total radiation intensity that is proportional to the number of electrons in the bunch *squared*. In contrast, at shorter wavelengths the radiation field adds incoherently, i.e., the total intensity goes linearly with the number of beam particles. For a typical ~100 pC bunch charge, the CSR intensity is amplified by a factor ~5×10^8 w.r.t. the incoherent component.

Helper slide #2

CBETA

Effect of varying Nb (CBETA 1-pass)

Beam distribution at the end of LINAC (6 MeV) (Nb = # bins, Np = # particles, bunch charge = 25nC)					
Nb / Np	**No CSR**	**100**	**300**	**700**	**1000**
100k					
200k					
400k					
600k					

Z-pz phase Space

Spread in delta increases from (-1.5%, 1.0%) to (-2.5%, 2.0%)

Results depend on Nb

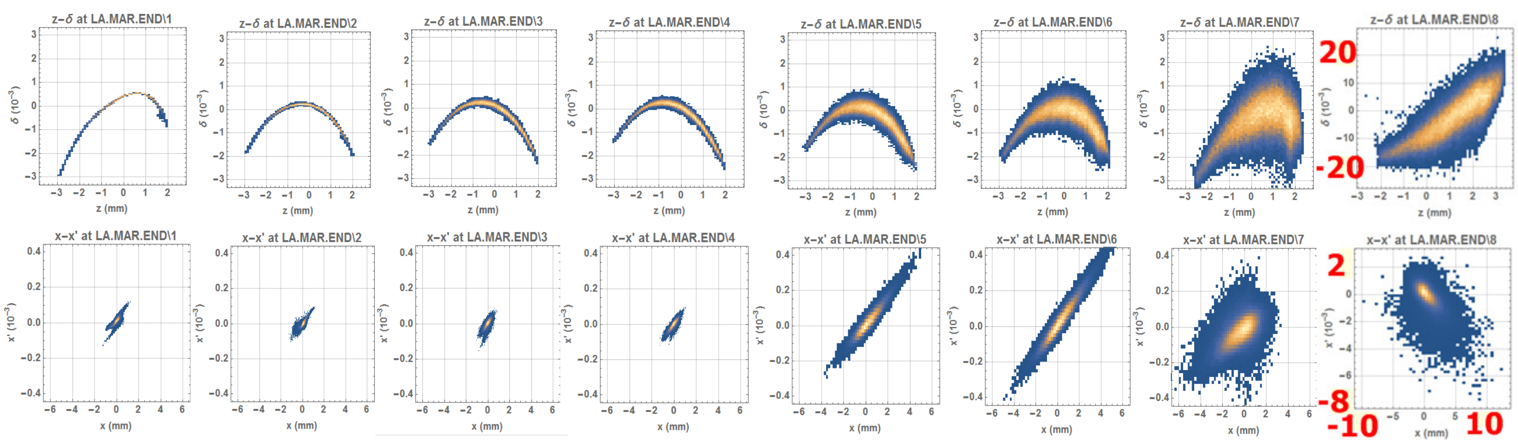
CBETA 4-pass (Np = 100k, Nb=3000)

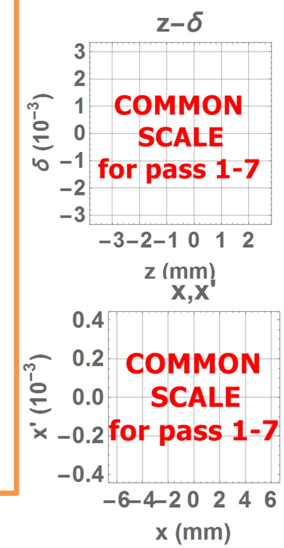
Q = 1 pC

Particle loss = 9 out of 100k
Final energy spread ≈ -2.0% to 2.0%

z-pz

x-px



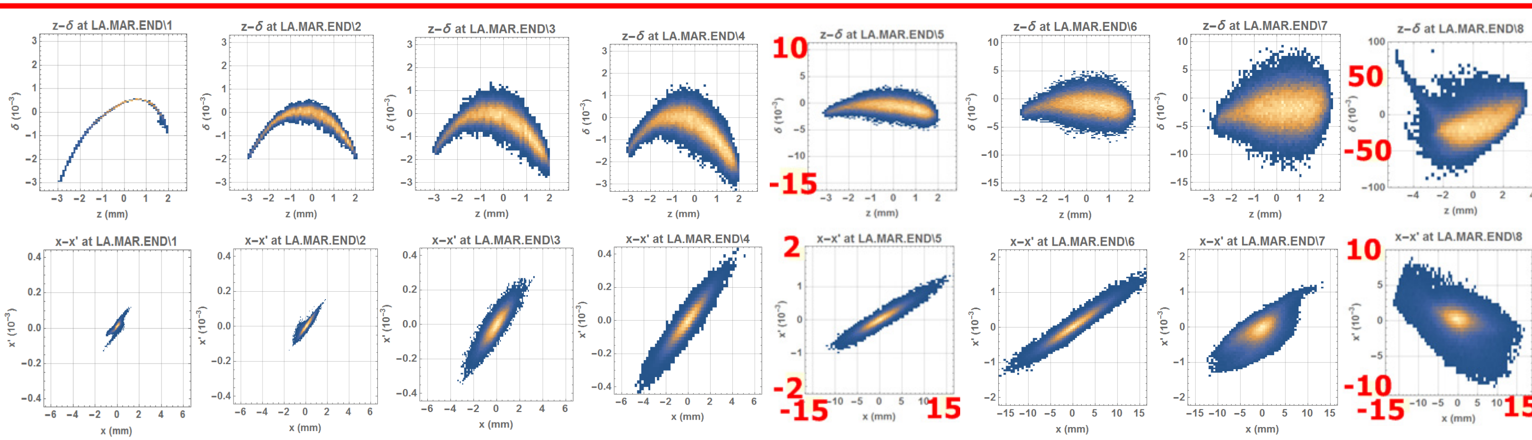


End of LINAC Pass 1 2 3 4 5 6 7 8

(Acceleration) (Deceleration)

z-pz

x-px



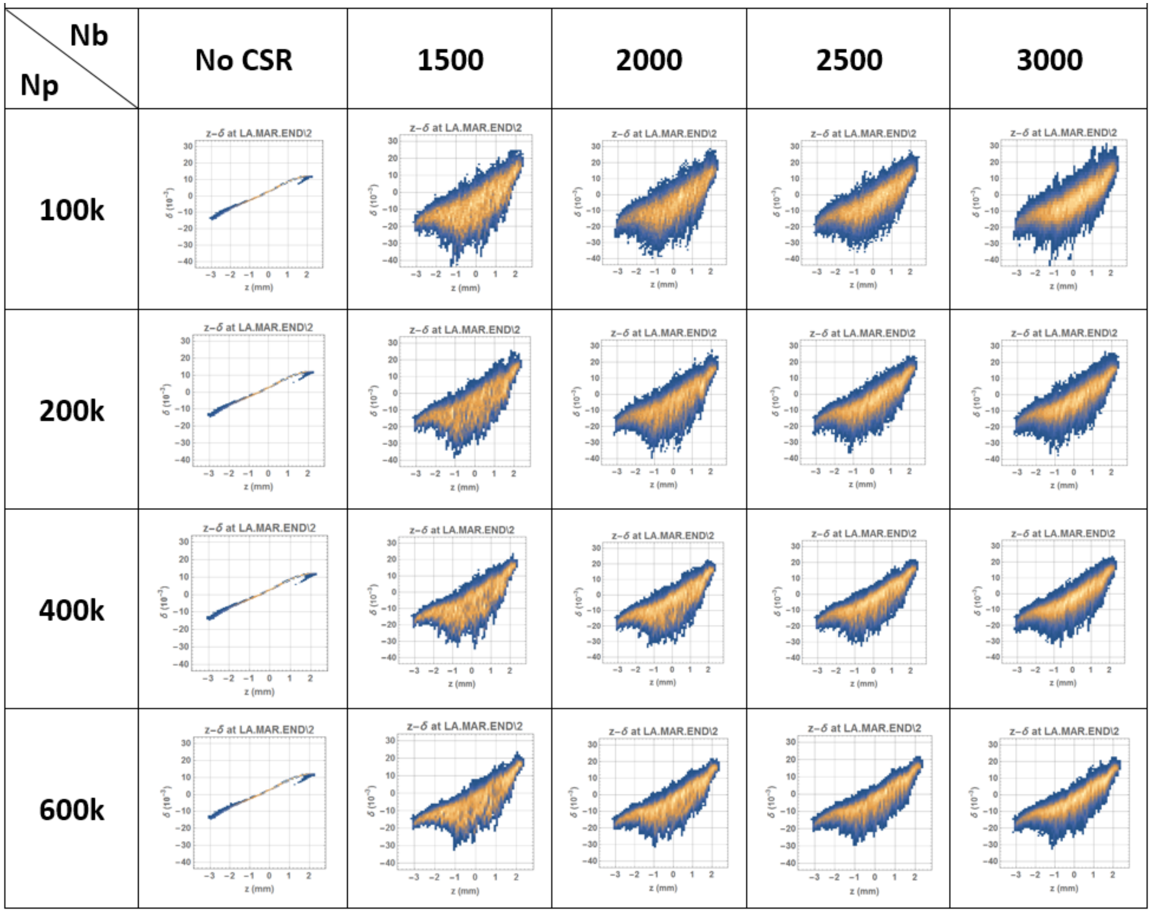
Q = 5 pC

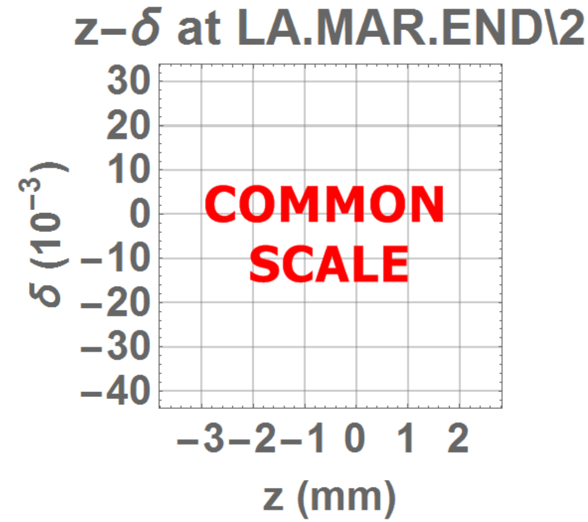
Particle loss = 23k out of 100k
Final energy spread ≈ -6.0% to 6.0%

Effect of varying Nb and Np

CBETA 1-pass (Q=25pC)

z-pz phase space at the end of LINAC pass 2 (6 MeV)



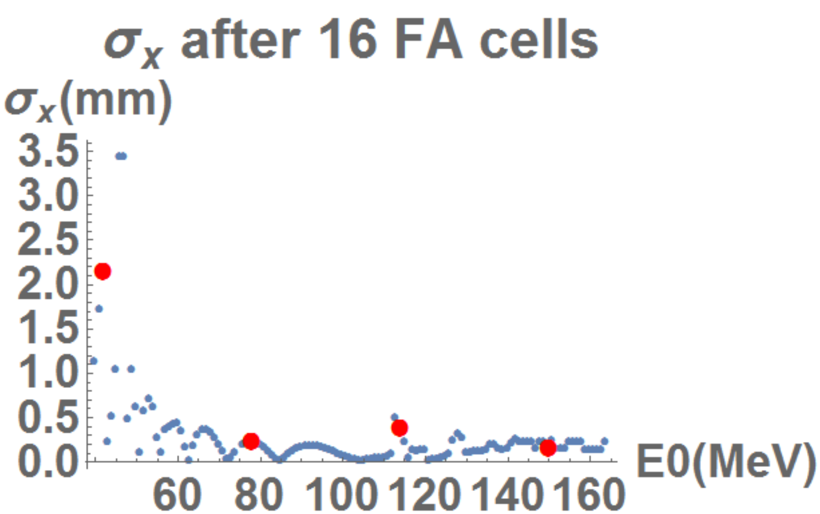


The distribution seems independent of Np...

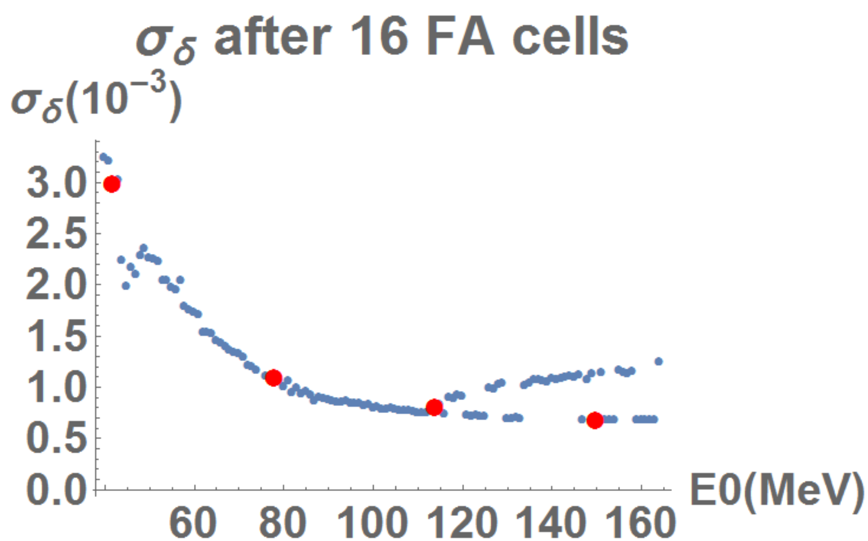
CBETA 4-pass (Np = 10k, Nb=50)

- For testing, track a Gaussian beam (σx = 0.03mm, σδ=0.62E-3) of different energy through 16 FA cells
- Energy acceptance of periodic FA cell is 38 MeV to 164 MeV

X beam size

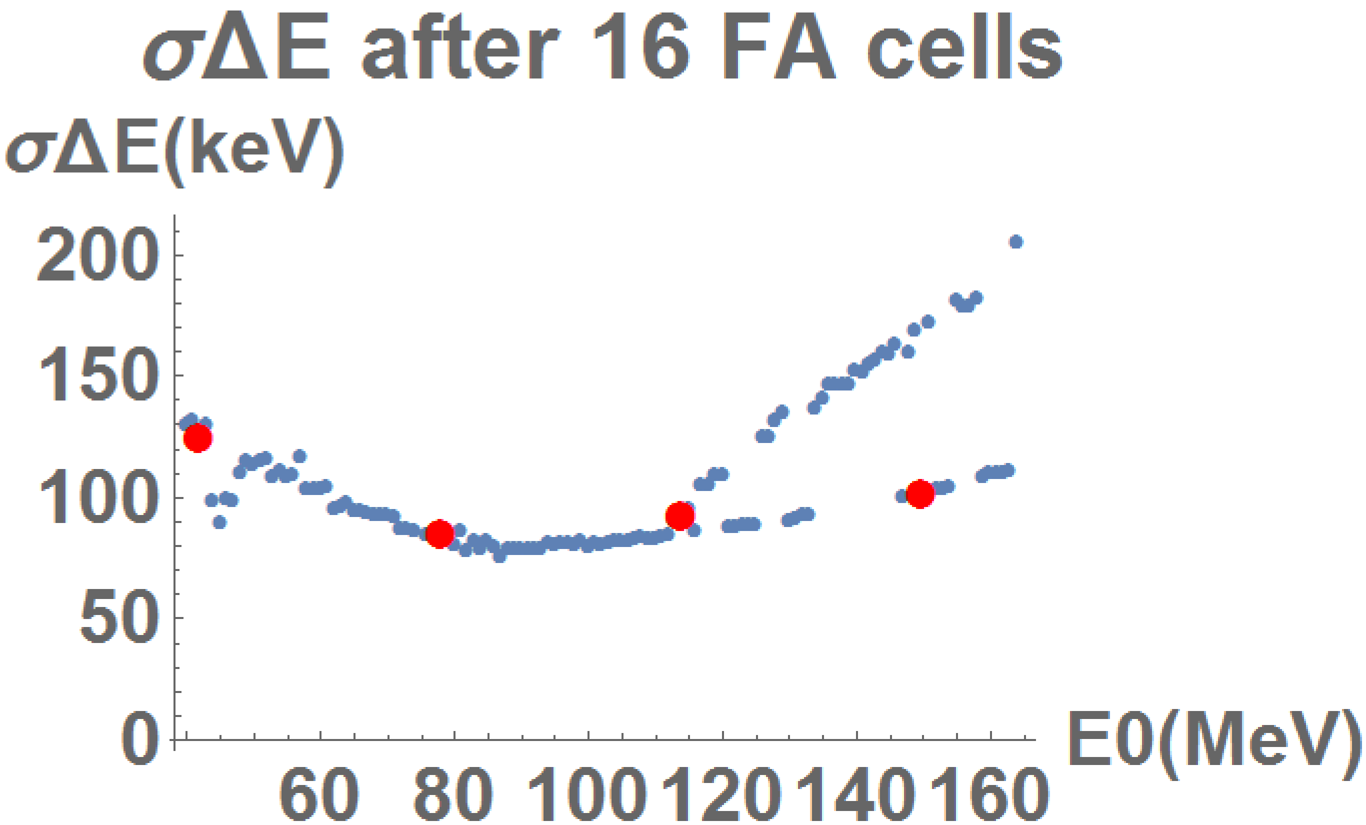


Energy spread



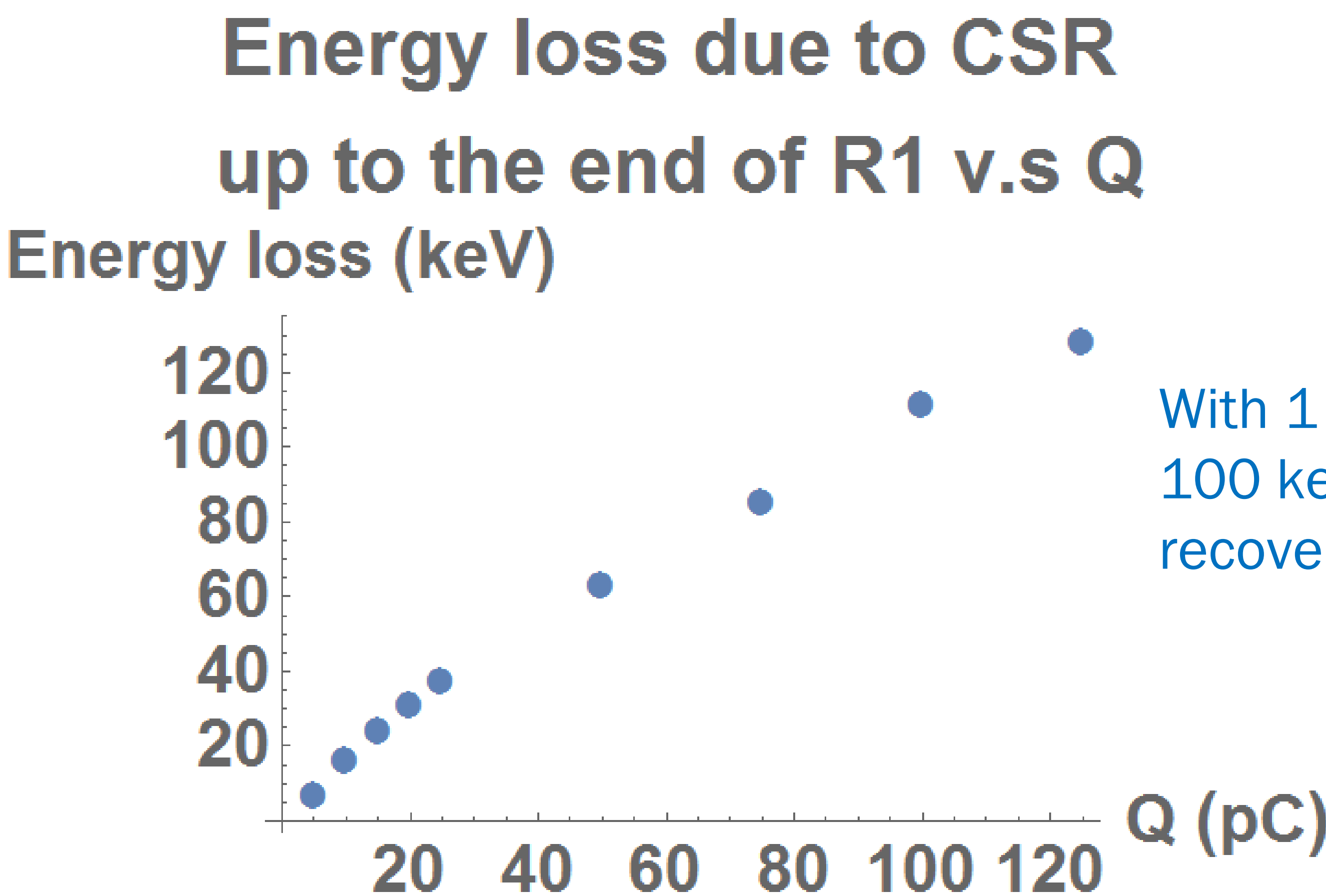
● = four CBETA design energies

Helper slide #5



Effect of varying Q

CBETA 1-pass (Np = 600k, Nb=3000)



With 1 mA, energy loss of 100 keV means 100W loss, recoverable by LINAC