Recirculating Superconducting Proton Linac

Ji Qiang

Accelerator Modeling Program, ATAP, LBNL

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BERKELEY LAB

U.S. DEPARTMENT OF ENERGY | Office of Science

ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION ATAP

Outline

- Introduction
- Multi-GeV recirculating superconducting proton linac
- Beam dynamics design/simulation of a double pass proton linac
- Effects of overtaking collision in the CW double pass proton linac
- Field error sensitivity
- Conclusions and future work

High Power GeV Superconducting Proton Linac Can Have Many Applications in Science and Industry

- Accelerator driven tritium production
- Driver for spallation neutron sources
- Driver for high energy physics studies
- Accelerator driven nuclear energy production
- …

Accelerator Production of Tritium

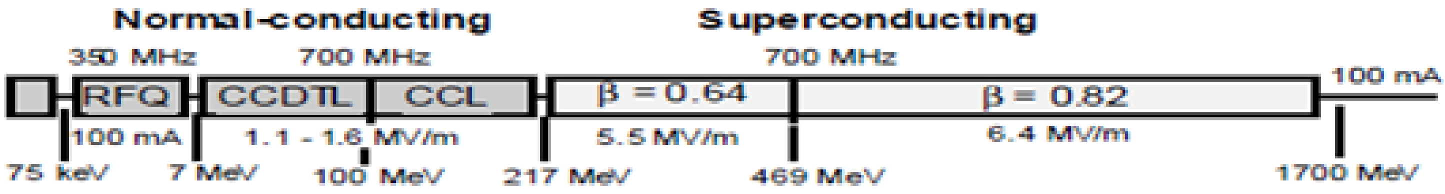
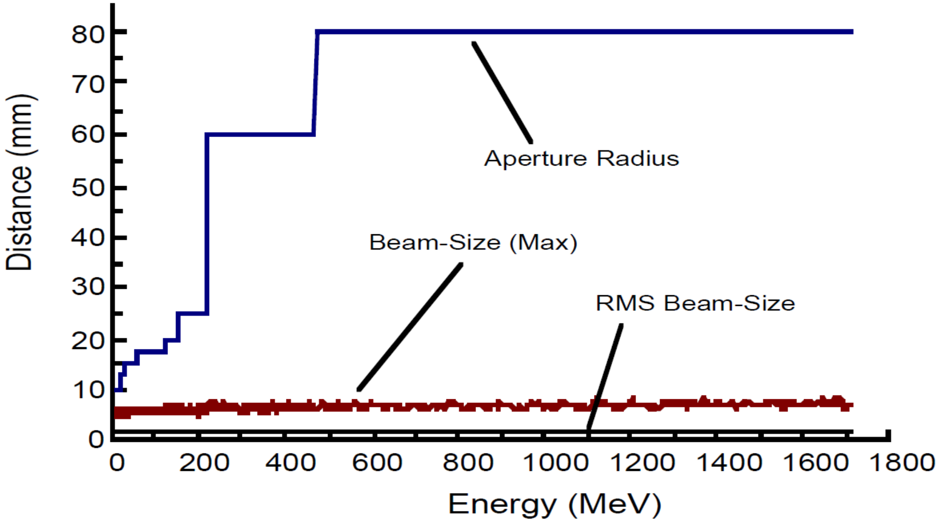


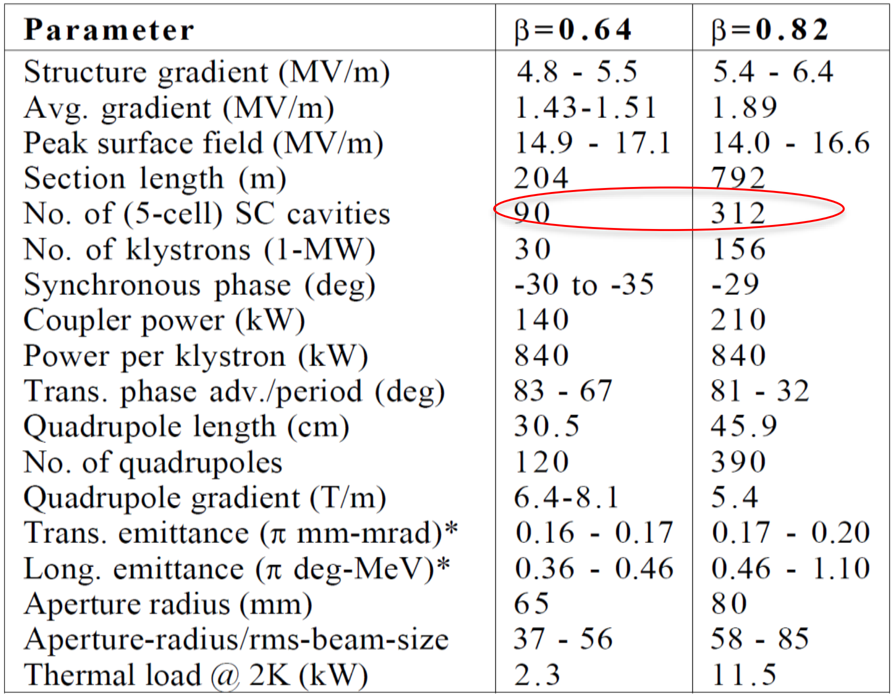
Fig. 1. Architecture of APT integrated NC/SC linac.

Superconducting Linac:

- Significant power savings and lower operating and capital cost
- Allow much larger aperture at high energies
- Permits greater operational flexibility

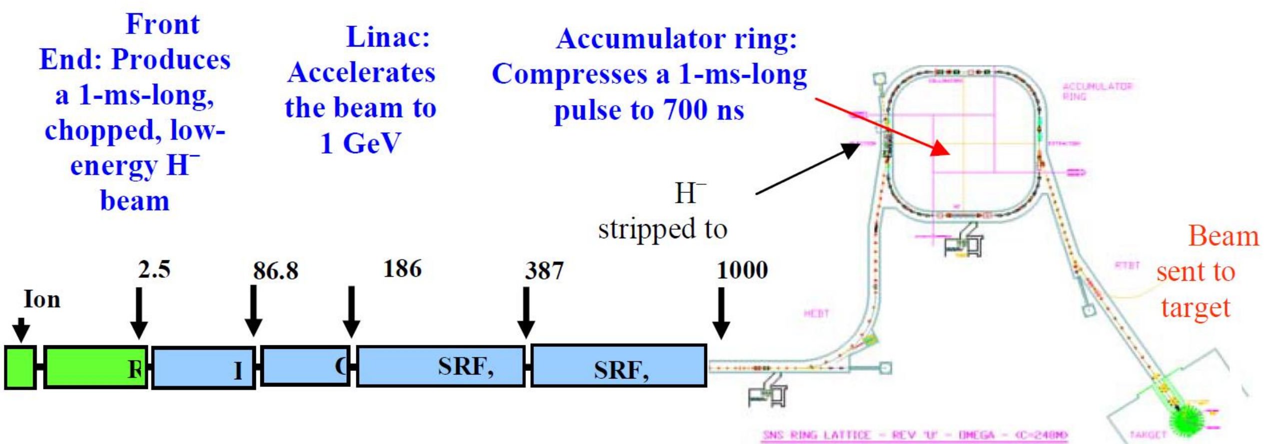


Ref: G. Lawrence and T. Wrangler, 1998.



Parameter	β=0.64	β=0.82
Structure gradient (MV/m)	4.8 - 5.5	5.4 - 6.4
Avg. gradient (MV/m)	1.43-1.51	1.89
Peak surface field (MV/m)	14.9 - 17.1	14.0 - 16.6
Section length (m)	204	792
No. of (5-cell) SC cavities	90	312
No. of klystrons (1-MW)	30	156
Synchronous phase (deg)	-30 to -35	-29
Coupler power (kW)	140	210
Power per klystron (kW)	840	840
Trans. phase adv./period (deg)	83 - 67	81 - 32
Quadrupole length (cm)	30.5	45.9
No. of quadrupoles	120	390
Quadrupole gradient (T/m)	6.4-8.1	5.4
Trans. emittance (π mm-mrad)*	0.16 - 0.17	0.17 - 0.20
Long. emittance (π deg-MeV)*	0.36 - 0.46	0.46 - 1.10
Aperture radius (mm)	65	80
Aperture-radius/rms-beam-size	37 - 56	58 - 85
Thermal load @ 2K (kW)	2.3	11.5

Accelerator Driven Spallation Neutron Sources



Front End: Produces a 1-ms-long, chopped, low-energy H^- beam

Linac: Accelerates the beam to 1 GeV

Accumulator ring: Compresses a 1-ms-long pulse to 700 ns

H^- stripped to

Beam sent to target

Spallation Neutron Source Project Completion Report, 2006.

Baseline parameters for the SNS accelerator

Kinetic energy	GeV	1.0
Beam power on target	MW	1.4
Average current on target	mA	1.4
Linac beam macropulse duty factor	%	6
Average macropulse H^- current	mA	26
Peak linac current	mA	38
Linac average beam current	mA	1.6
SRF cryomodule number		11 + 12
SRF cavity number		33 + 48
Peak gradient medium beta	MV/m	27.5
Peak gradient high beta	MV/m	35

Table 1: ESS Main Parameters

Parameter	2012 Baseline	2013 Baseline
Ion species	Proton	Proton
Energy [GeV]	2.5	2.0
Beam power [MW]	5	5
Repetition rate [Hz]	14	14
Beam current [mA]	50	62.5
Beam pulse [ms]	2.86	2.86
Duty cycle [%]	4	4

M. Eshraqi et al., 2014.

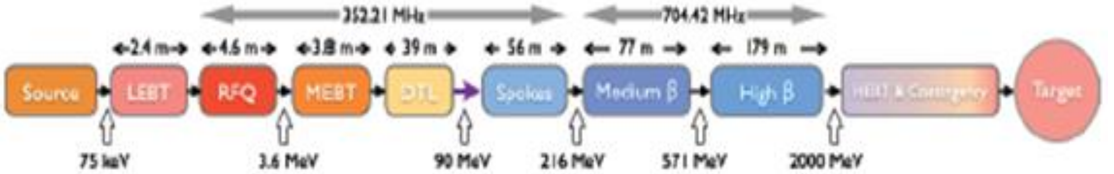


Figure 1: Block layout of the ESS baseline linac 2013, OptimusPlus (not to scale). Warm colored boxes represent the normal conducting components and cold color boxes the superconducting sections.

Accelerator Driver for High Energy Physics Applications

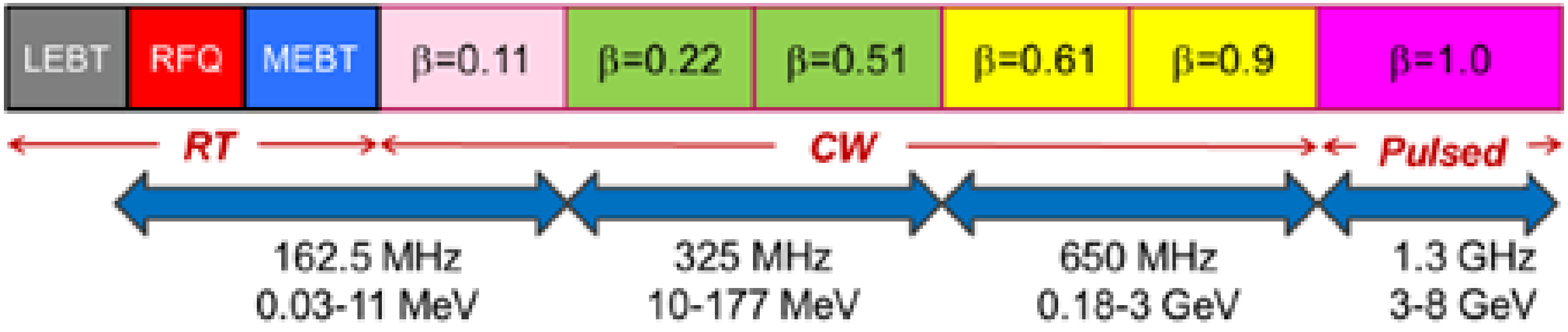


Figure III-1: The Project X Linacs

S. Holmes, et al., Project X Reference Design Report, Project X-document 776-v7, 2013.

SPL

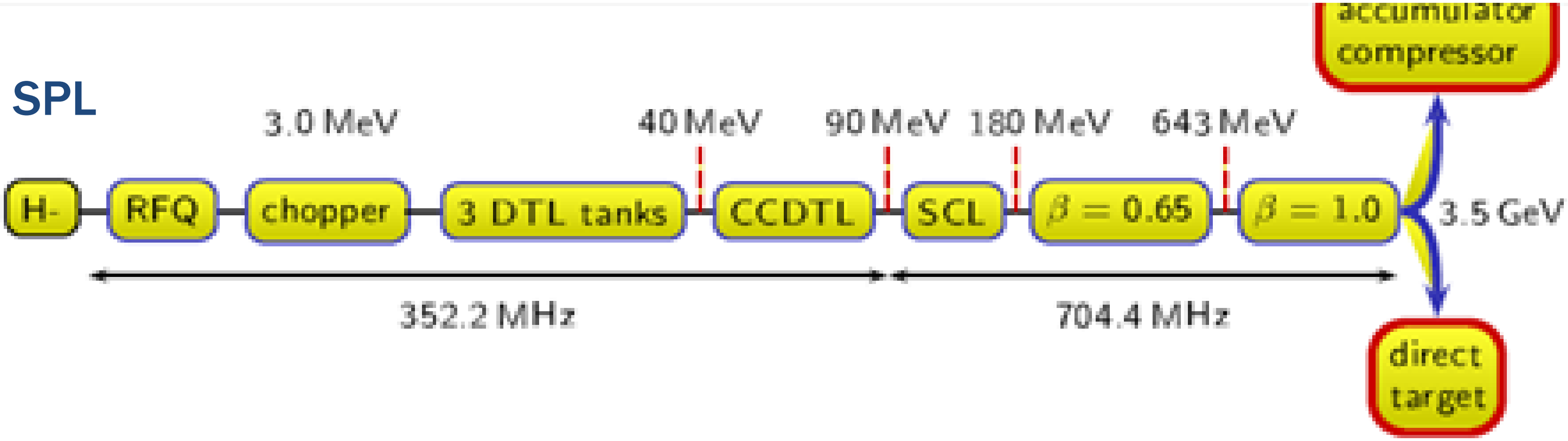
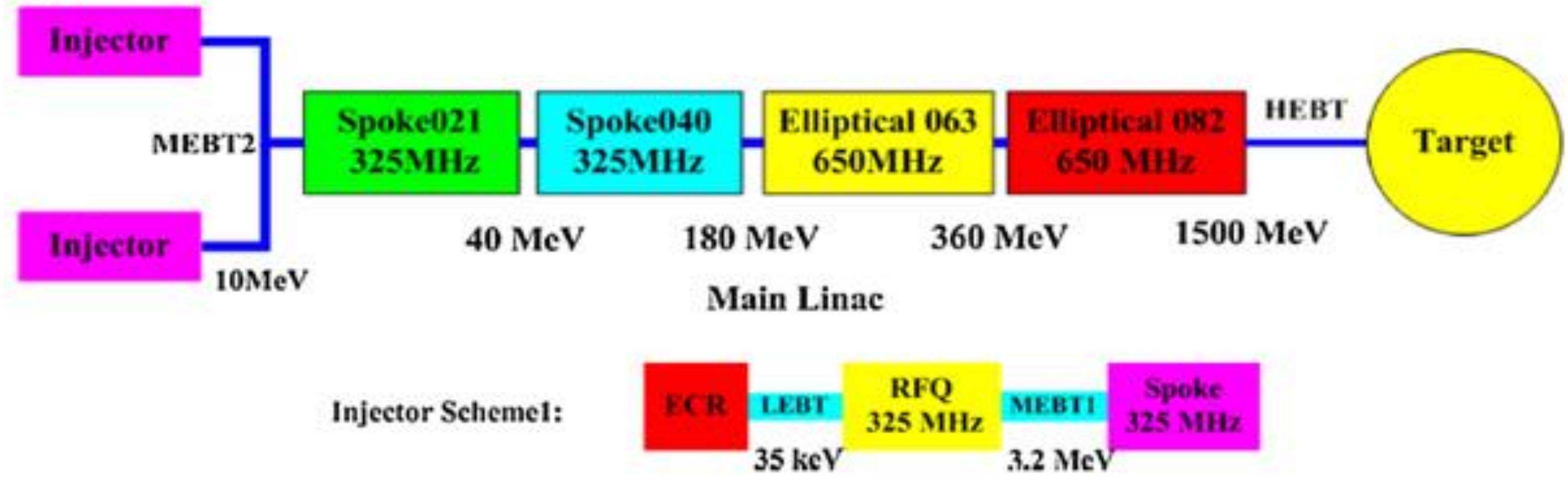


Fig. 2.3: Schematic layout of the linac

F. Gerigk, et al., Conceptual Design of the SPL II, CERN-2006-006, 2006.

Accelerator Driven System for Nuclear Energy Production



Z. Li, et al., Physical Review ST Accelerators and Beams 16 (2013) 080101.

FIG. 3. Layout of the C-ADS driver accelerators.

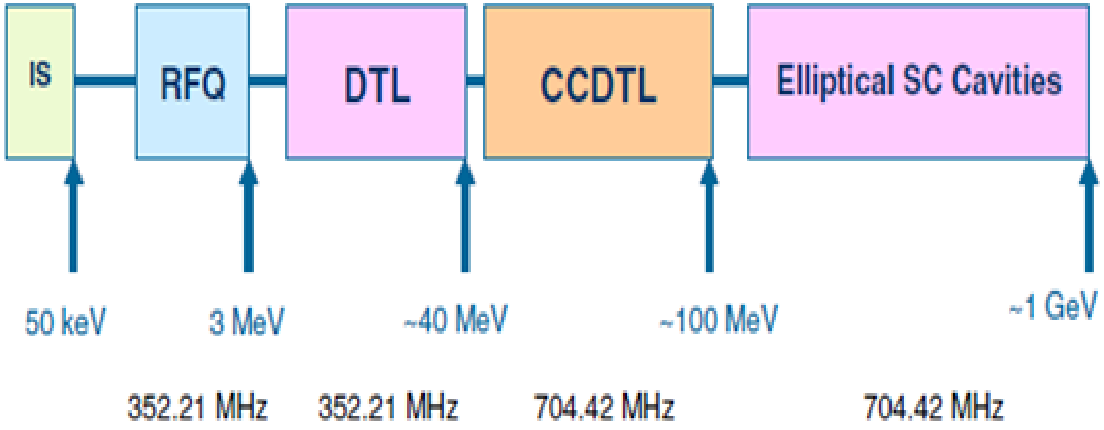
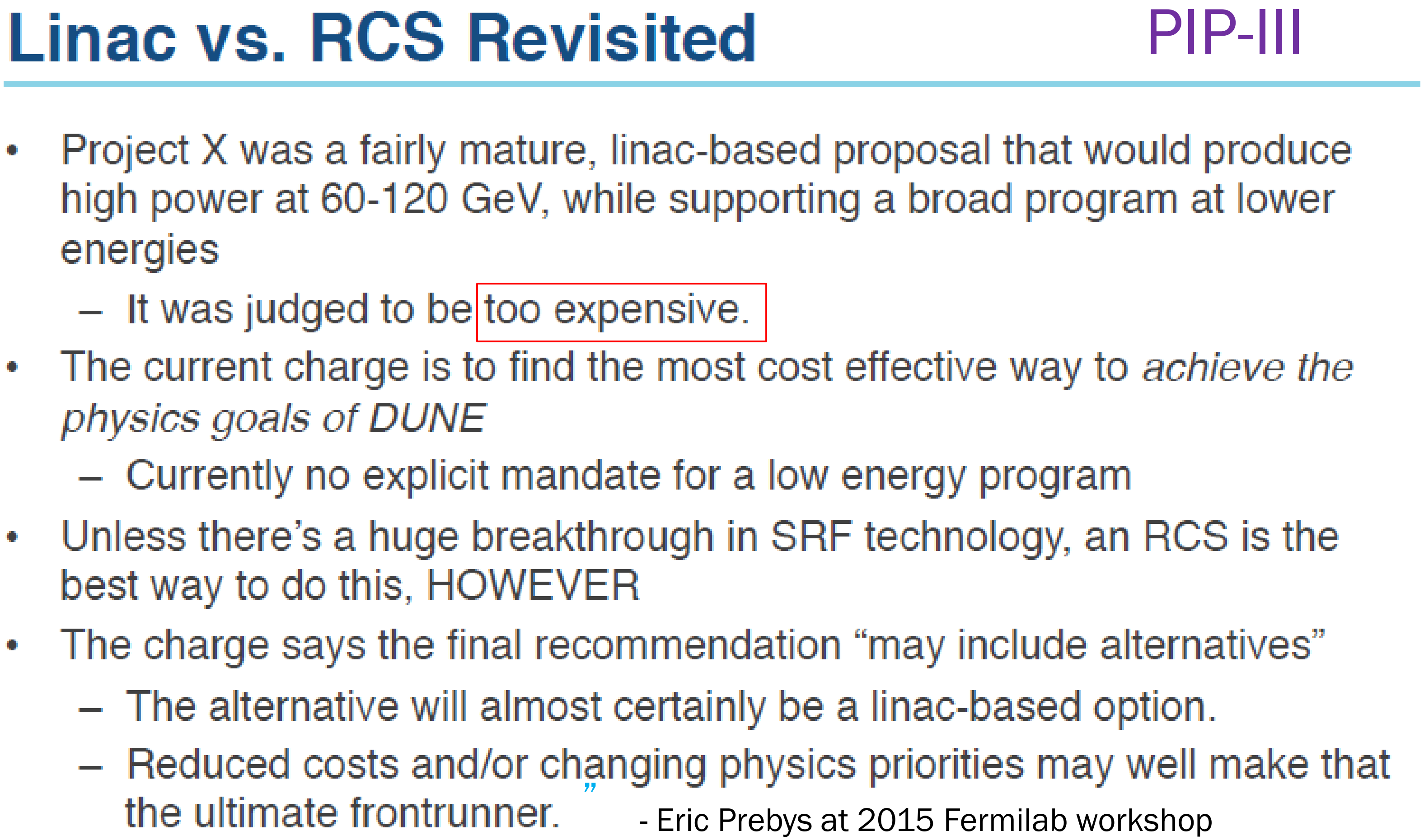


Figure 1. Lay-out of the 1 GeV Linac.

R. Pande,etal.,Pramana—Journal ofPhysics78(2012)247.

But Superconducting Proton Linac is Expensive…



Linac vs. RCS Revisited

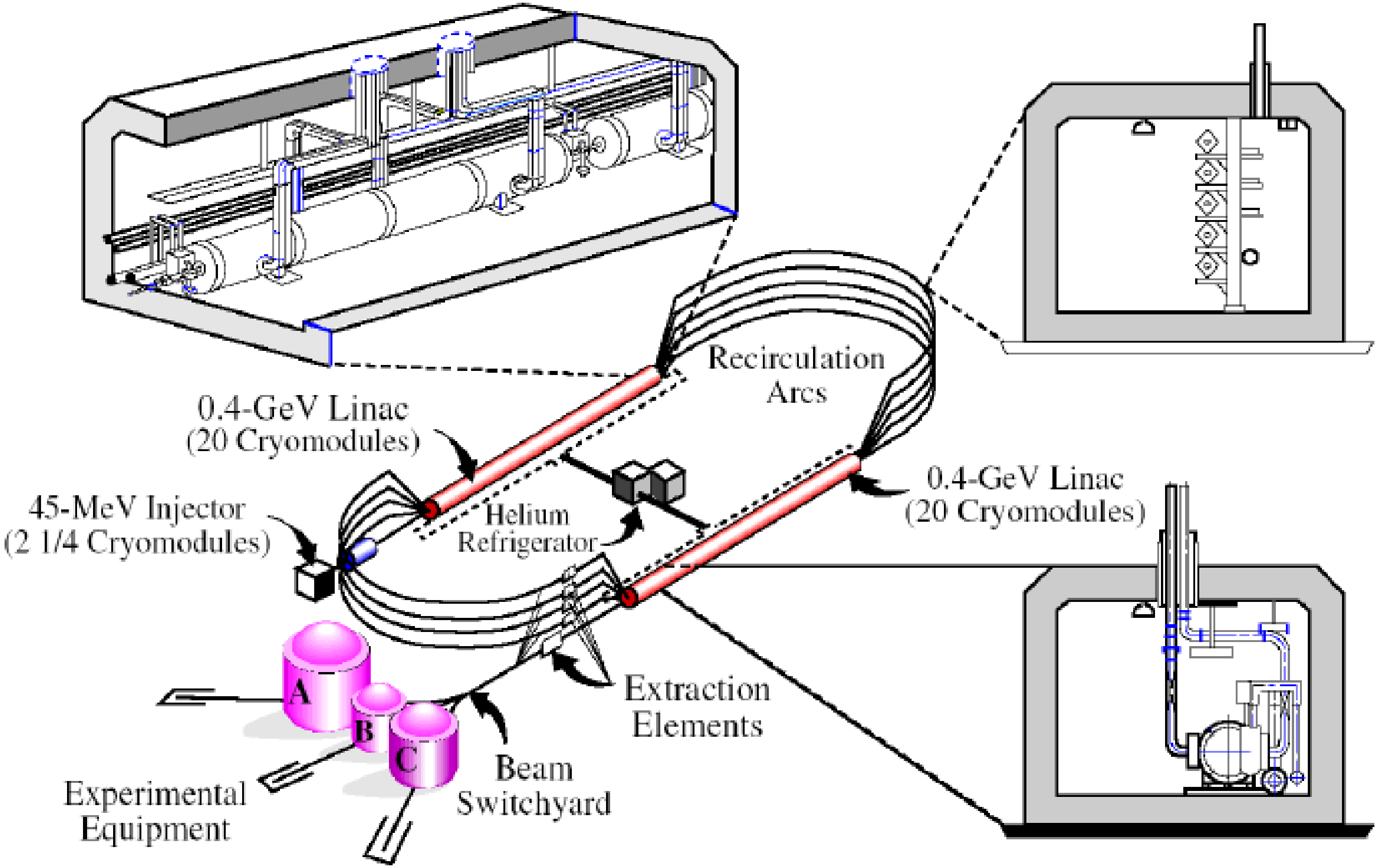
PIP-III

“
- Project X was a fairly mature, linac-based proposal that would produce high power at 60-120 GeV, while supporting a broad program at lower energies
  - It was judged to be too expensive.
- The current charge is to find the most cost effective way to *achieve the physics goals of DUNE*
  - Currently no explicit mandate for a low energy program
- Unless there’s a huge breakthrough in SRF technology, an RCS is the best way to do this, HOWEVER
- The charge says the final recommendation “may include alternatives”
  - The alternative will almost certainly be a linac-based option.
  - Reduced costs and/or changing physics priorities may well make that the ultimate frontrunner. ”

- Eric Prebys at 2015 Fermilab workshop

A Potential Lower Cost Solution: Recirculating Proton Linac

Recirculating Electron Linac has been built and under operation (e.g. JLAB Recirculating Electron Linac)



But there is no recirculating proton linac in the world…

Significant Differences between Proton Linac and Electron Linac

- Electron velocity approaches to speed of light over a few MeVs
- Acceleration efficiency (transit time factor) independent of energy
- Typical electron linac consists of a single type of RF cavity (C band or S band or SC or ...)

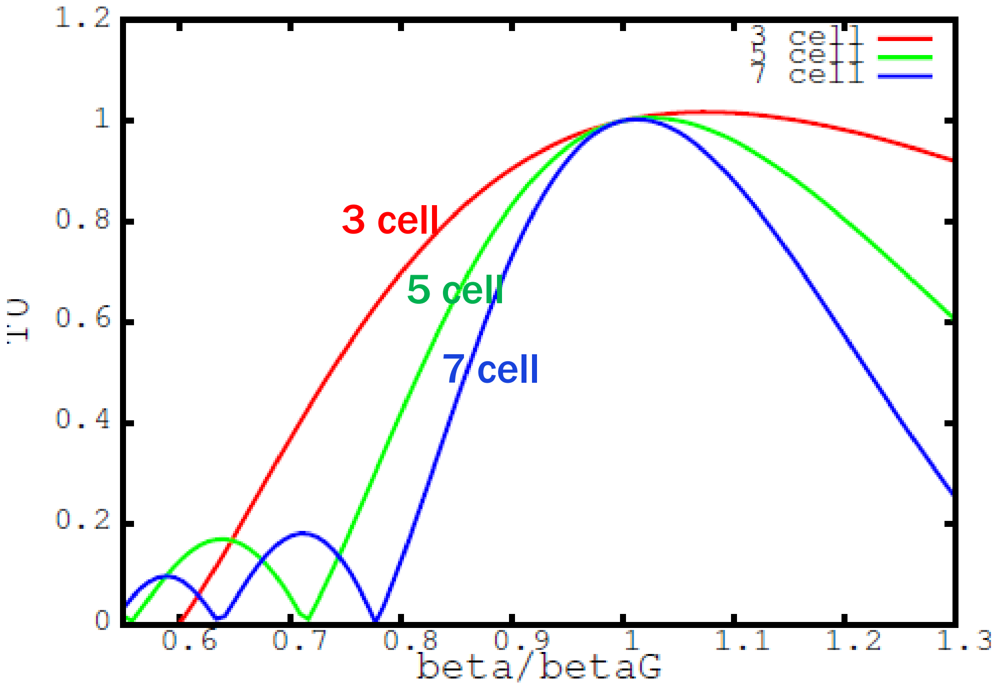
- Proton velocity varies during the process of acceleration up to GeV
- Acceleration efficiency depends on the proton energy
- Typical proton linac consists of many type of RF cavities with different geometries (DTL, CCL, CCDTL, SC,...)

recirculating linac uses a single type of RF cavity for multiple energy beam

A Reasonable Proton Energy Bandwidth Can Be Achieved with Appropriate Choice of RF Cavity Structure

$$\Delta E_c = qVT\cos(\phi)$$

$$T_0(\beta) = \frac{2\beta}{\pi n}\left(\frac{\sin(\pi n(\beta-\beta_G)/(2\beta))}{\beta-\beta_G} - (-1)^n\frac{\sin(\pi n(\beta+\beta_G)/(2\beta))}{\beta+\beta_G}\right)$$



- A single type of cavity can cover a range of proton energy with appropriate cell numbers
- A multi-GeV recirculating proton linac could be realized with multiple energy sections

The Total Number of RF Cavities Can Be Optimized w.r.p the Cavity Geometry Beta and Transition Energy

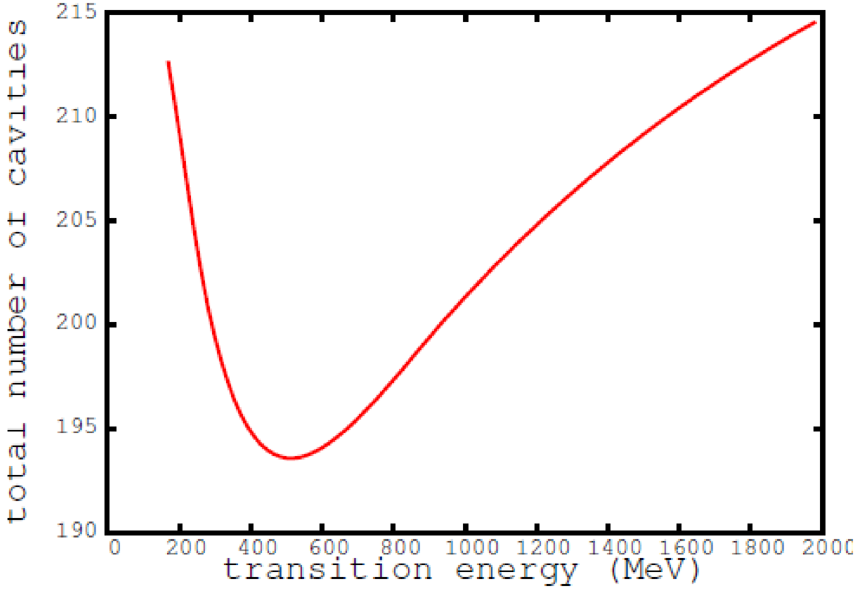
Energy Averaged Transit Time Factor:

$$\bar{T}(\beta_G) = \frac{mc^2}{\Delta E_{max}} \int_{\beta_{in}}^{\beta_{out}} \frac{T(\beta,\beta_G)\beta}{(1-\beta^2)^{3/2}} d\beta$$

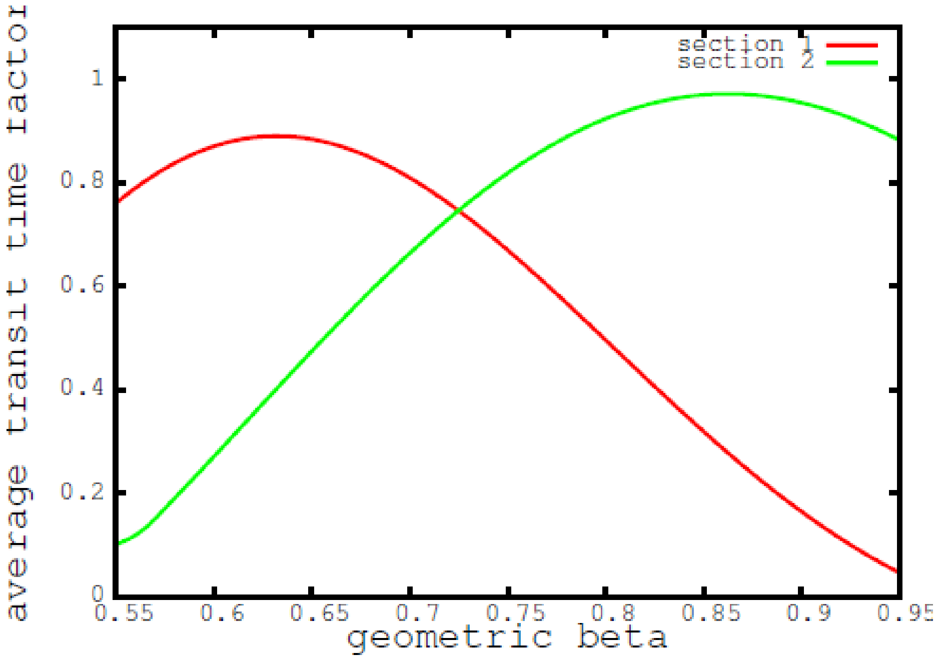
Maximum Energy Gain in Two Sections:

$$\Delta E_{1,2max} = qV_1N_1\bar{T}_1 + qV_2N_2\bar{T}_2$$

total # of cavities vs. transition energy

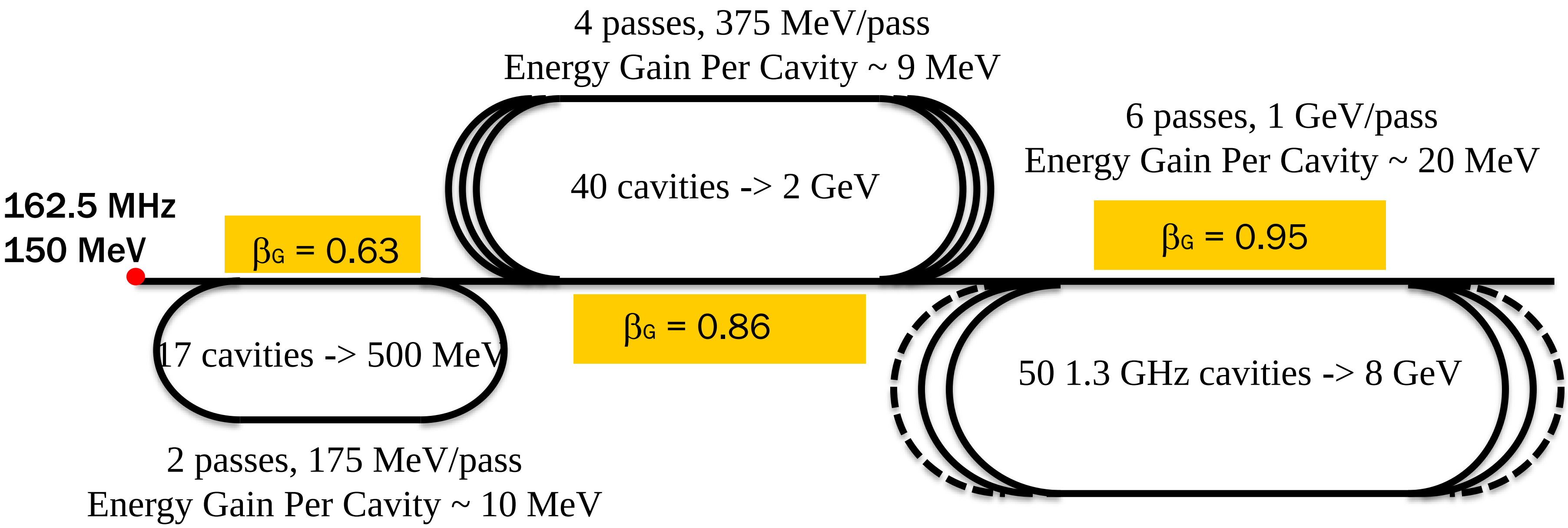


average transit time factor vs. geom. beta



Two sections, Ein = 150 MeV, Eout = 2 GeV, $V_1 = V_2$ = 13 MV

A Multi-Section Multi-GeV Recirculating Proton Linac (~a factor of 5 reduction of superconducting cavities)

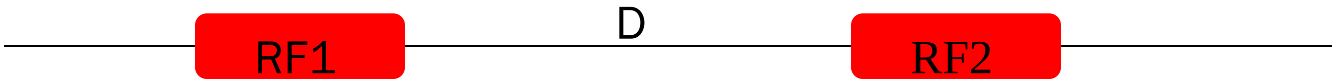


- Total number of superconducting cavities: 494 -> 107
- Shorten the distance of straight accelerating section

Fermilab 650 MHz 5 cell superconducting cavity (CW): $E_{acc} \geq 15MV/m$

J. Qiang, Nuclear Instruments & Methods in Physics Research A 795, p. 77 (2015).

Relative RF Acceleration Phase Changes in Multiple Beam Passes



$$\Delta E_1 = V_1 T_1 \cos(\omega t + \phi_1) \qquad \Delta E_2 = V_2 T_2 \cos(\omega t + \phi_2)$$

Phase slippage with proton energy:

$$\delta\phi = \omega \frac{D}{V}$$

D → distance between RF1 and RF2

V → proton velocity after RF1

Possible solutions:

- Fast adjustment of RF cavity driven phase versus energy
- Fast adjustment of RF cavity frequency versus energy

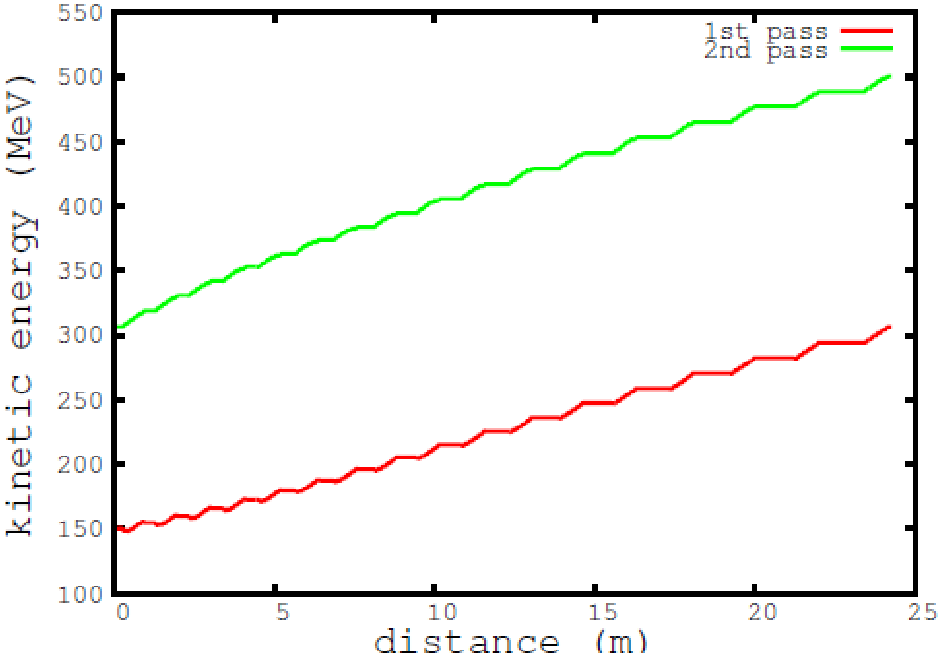
- Use of synchronous acceleration condition:

$$\boxed{t_i^m - t_i^n \quad = \quad \pm k T_{rf}, \quad k = 0, 1, 2, 3, \cdots}$$

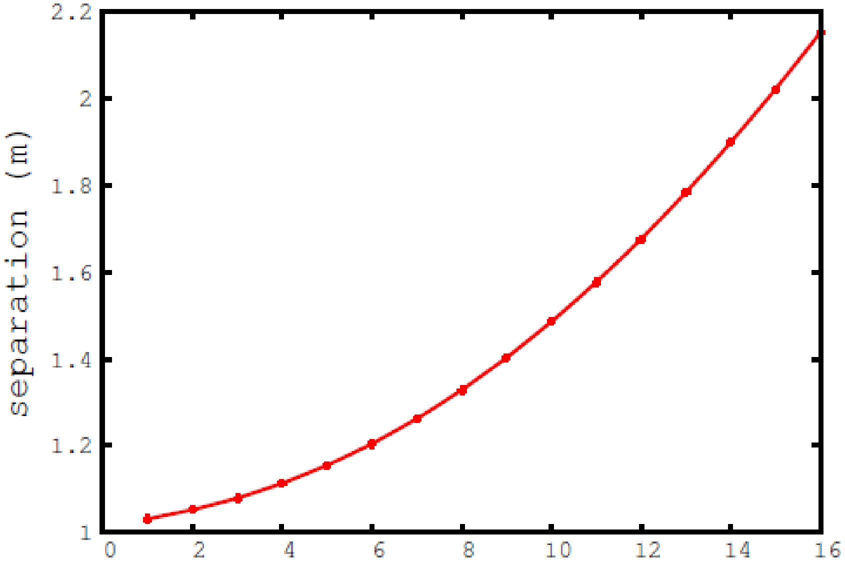
Synchronous Condition Can be Met with Variable Separation of Cavities in the Two Pass Section

No need to adjust RF cavity phase/frequency during the two pass acceleration

Proton Kinetic Energy vs. Distance

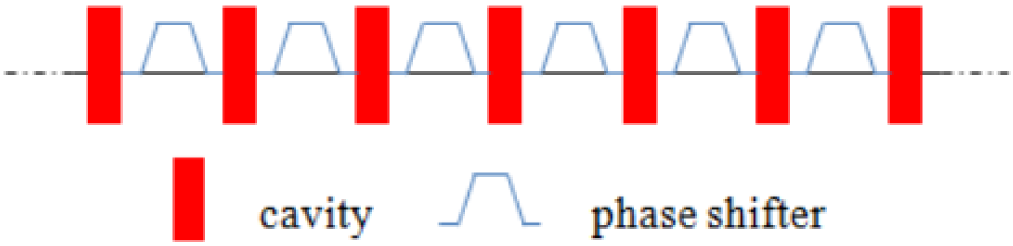


Separation Distance vs. Cavity Number



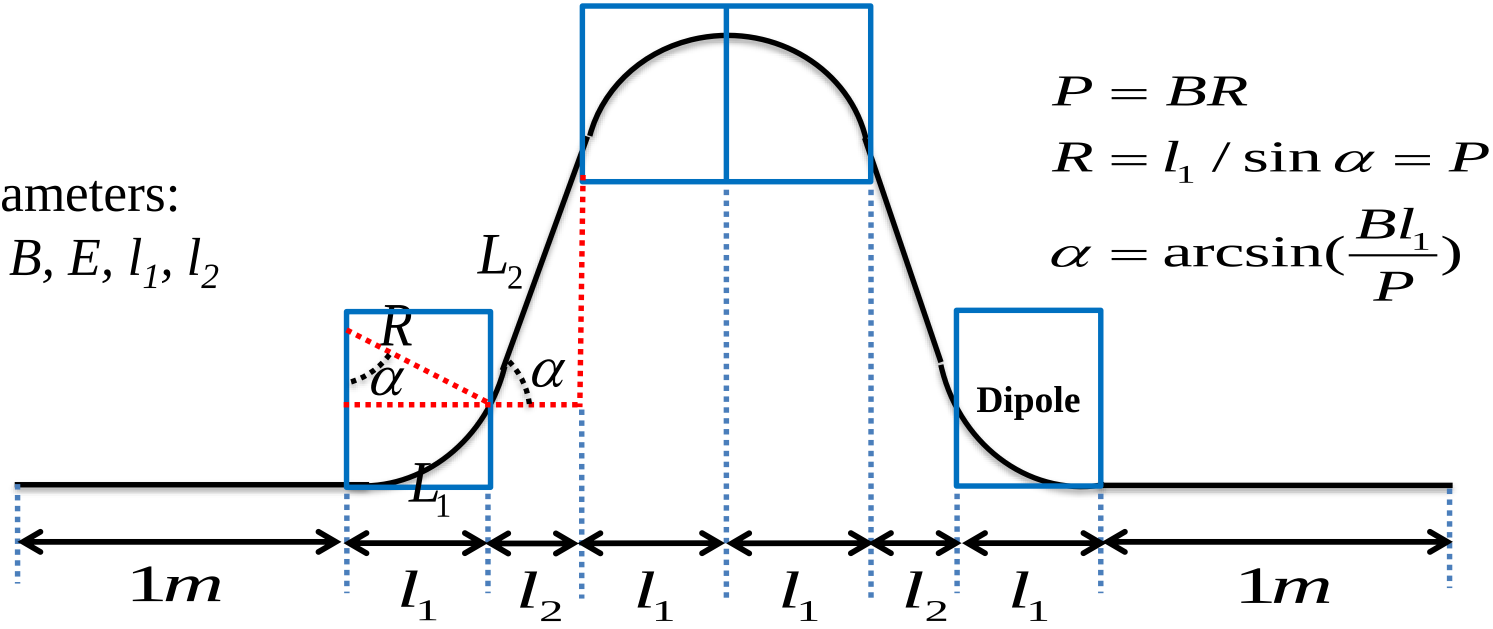
cavity separation number

Phase Shifter Can be Used for Multiple Proton Beam Passes



Parameters:

B, E, l_1, l_2



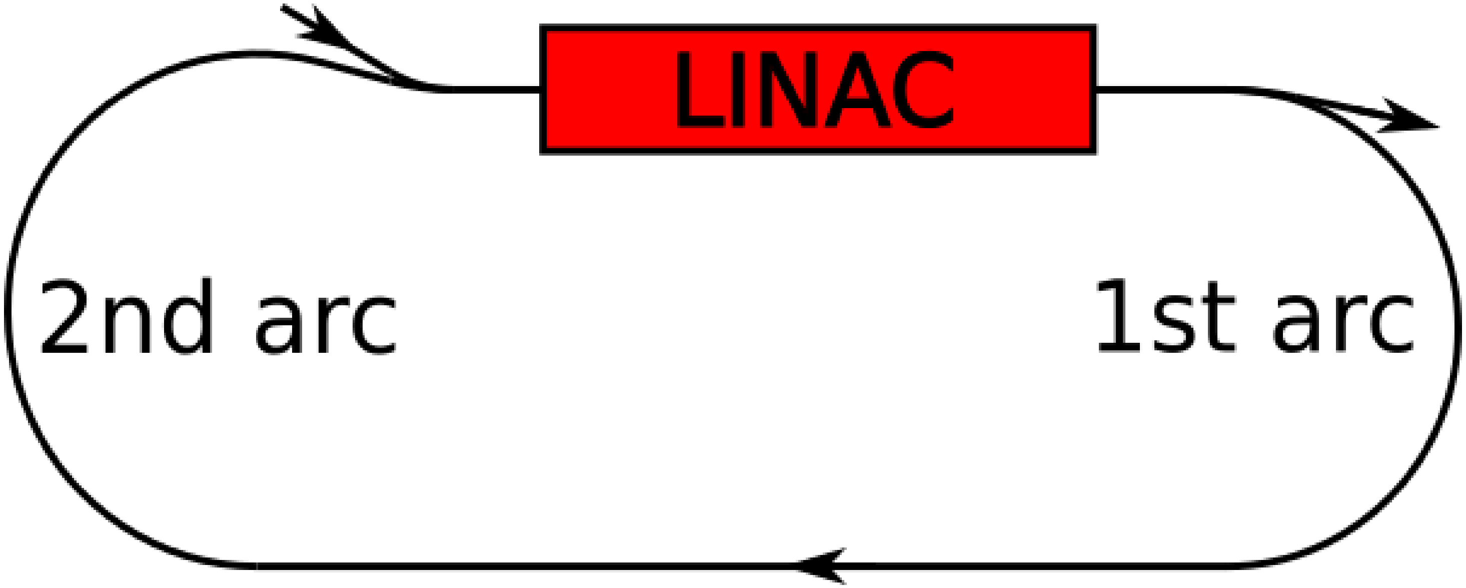
$$P = BR$$

$$R = l_1 / \sin\alpha = P / B$$

$$\alpha = \arcsin\left(\frac{Bl_1}{P}\right)$$

$$\text{path} = 2 + 4\arcsin\left(\frac{B\,l_1}{P}\right)\cdot\frac{P}{B} + 2\,\frac{l_2}{\sqrt{1-(B\,l_1/P)^2}}$$

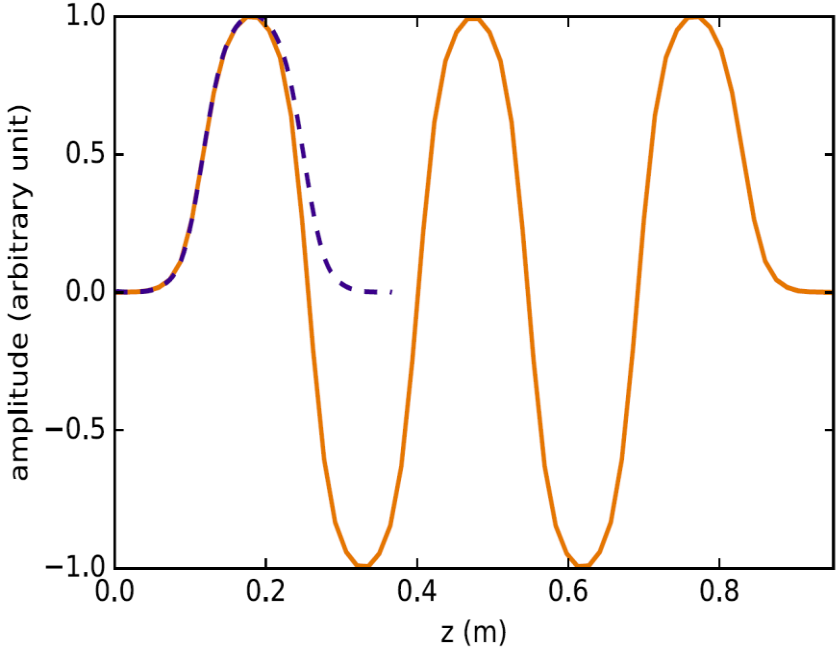
Beam Dynamics Design/Simulation of the Double Pass Section



K. Hwang and J. Qiang, Phys. Rev. Accel. Beams 20, 040401 (2017).

On-Axis Field Distribution of the RF Cavity and Other Parameters

Item	Value
Bunch current	20, 40 mA
Normalized transverse emittance	0.23 mm mrad
Normalized longitudinal emittance	3.0° MeV
Radio frequency	650 MHz
Radio-frequency geometric beta β_G	0.63
Accelerating gradient	14 MV/m
Radio-frequency phase	−30°


on-axis field profile of the SC cavity and the buncher cavity

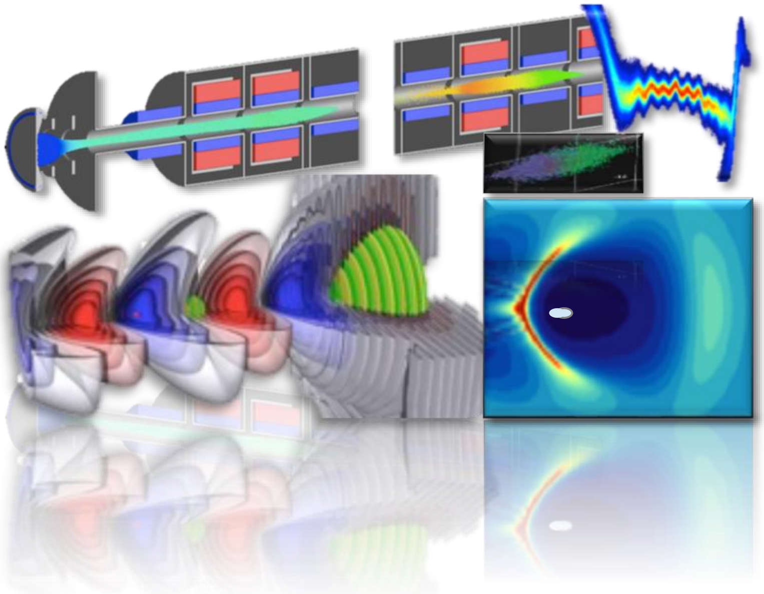
Non-Periodic Lattice Design by Optimizing the Envelope Oscilation and Emittance Growth w.r.p Quadrupole Settings

- Alternative phase focusing is used to enhance the transverse focusing for the 1st four cavities
- Integrate the Differential Evolution optimizer with self-consistent beam-dynamics simulation using the IMPACT(Z) code.
- Maintain smooth envelope oscillation evolution.
- Control emittance growth.

$$\begin{aligned}\text{cost} \quad &= \quad w_\sigma \sum_{i=0}^{N} \sum_{j=x,y} \left(\sigma_j\left(i\right) - \sigma\right)^{p_\sigma} \\ &\quad +w_\epsilon \sum_{j=x,y,z} \left(\epsilon_j\left(L\right) - \epsilon_j(0)\right)^{p_\epsilon}\end{aligned}$$

Berkeley Lab Accelerator Simulation Toolkit

BLAST
BERKELEY LAB ACCELERATOR SIMULATION TOOLKIT



http://blast.lbl.gov

Detailed modeling of:

- beams, plasmas, laser-plasma inter., linacs, rings, injectors, plasma accelerators, traps, …

Using state-of-the-art codes:

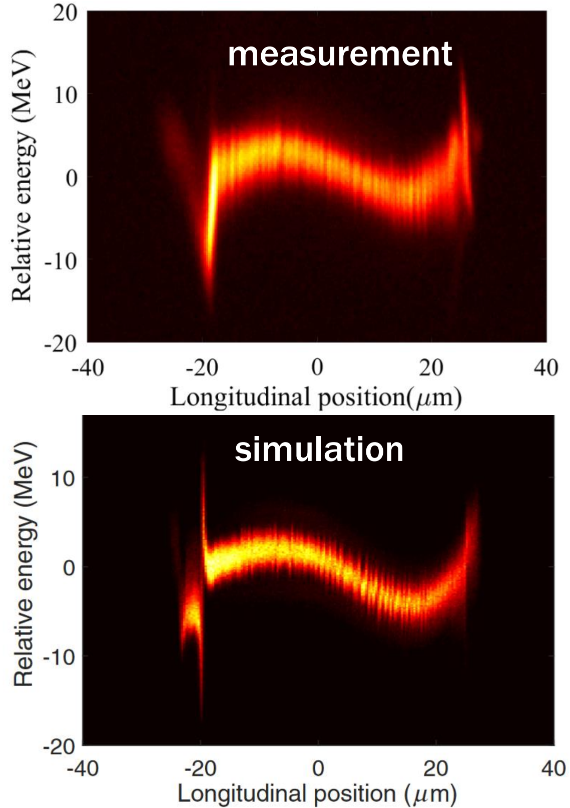
- BEAMBEAM3D, IMPACT, INF&RNO, POSINST, WARP.

With original advanced algorithms:

- boosted frame, IGF, laser envelope, SEY, AMR, relativ. particle pusher, symplectic space-charge model, EM spectral Circ, …

IMPACT Code Suite (IMPACT-Z/IMPACT-T): A Multi-Physics High-Intensity/High Brightness Beam Dynamics Code

- Key Features include:
  - Time-dependent and position dependent
  - Serial and massive parallelization
  - Detailed 3D RF accelerating and focusing model, dipole, solenoid, multipole, …
  - Multiple charge states, multiple bunches
  - 3D space-charge effects
  - Structure + resistive wall wakefields
  - Coherent synchrotron radiation (CSR)
  - Incoherent synchrotron radiation (ISR)
  - Gas ionization
  - Photo-electron emssion
  - Machine errors and steering
- Can be used to model beam dynamics in:
  - Photoinjectors
  - Ion beam formation and extraction
  - RF linacs
  - Rings



J. Qiang et al., PRAB 20, 054402, 2017.

IMPACT Includes Multiple Fast Poisson Solvers for Space-Charge Modeling under Different Boundary/Beam Conditions

FFT based Green function method:

- Standard Green function: low aspect ratio beam
- Shifted Green function: separated particle and field domain
- Integrated Green function: large aspect ratio beam
- Non-uniform grid Green function: 2D radial non-uniform beam

Fully open boundary conditions

Spectral-finite difference method:

2D open boundary
Transverse regular pipe with longitudinal open

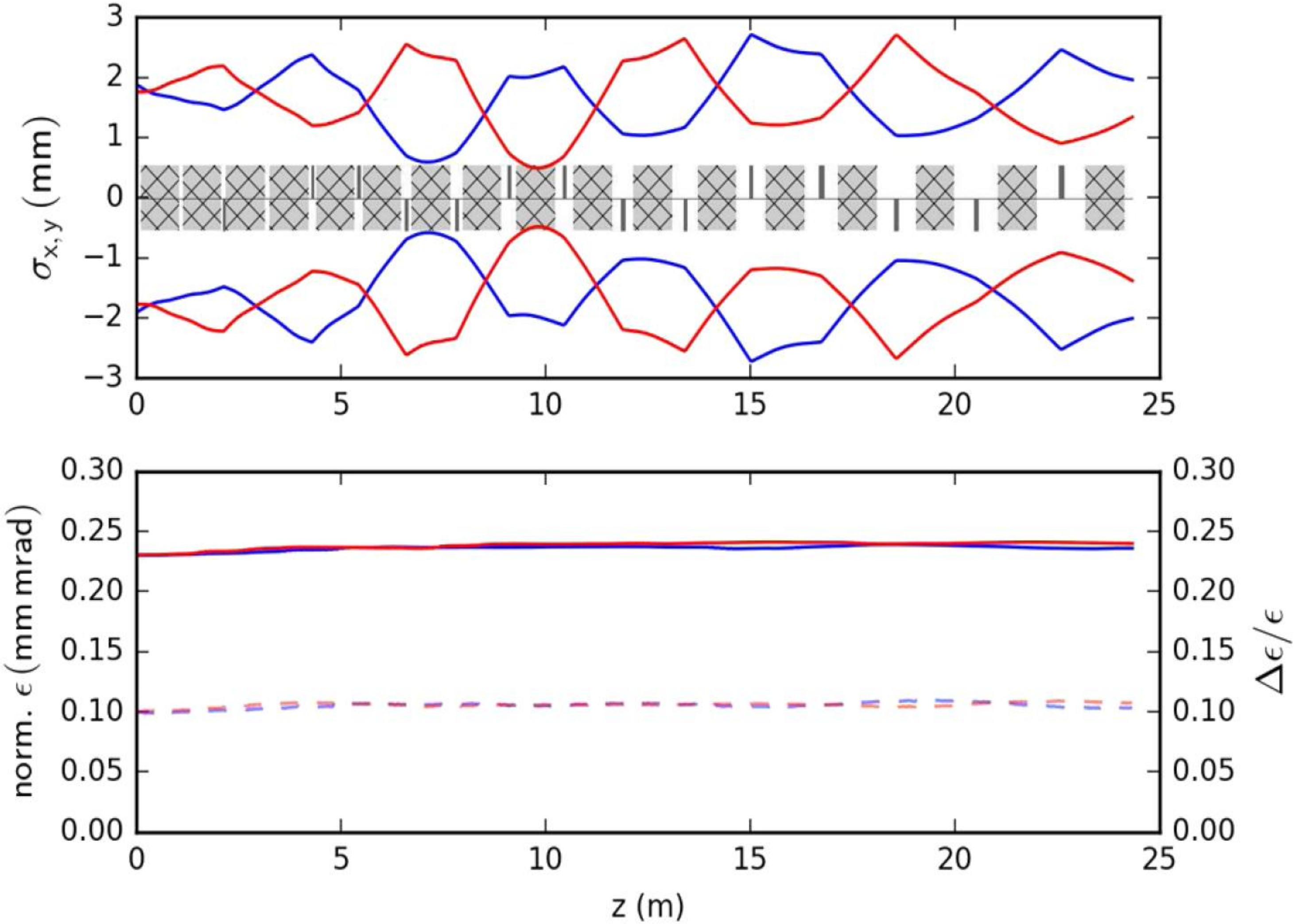
Multigrid spectral-finite difference method:

Transverse irregular pipe

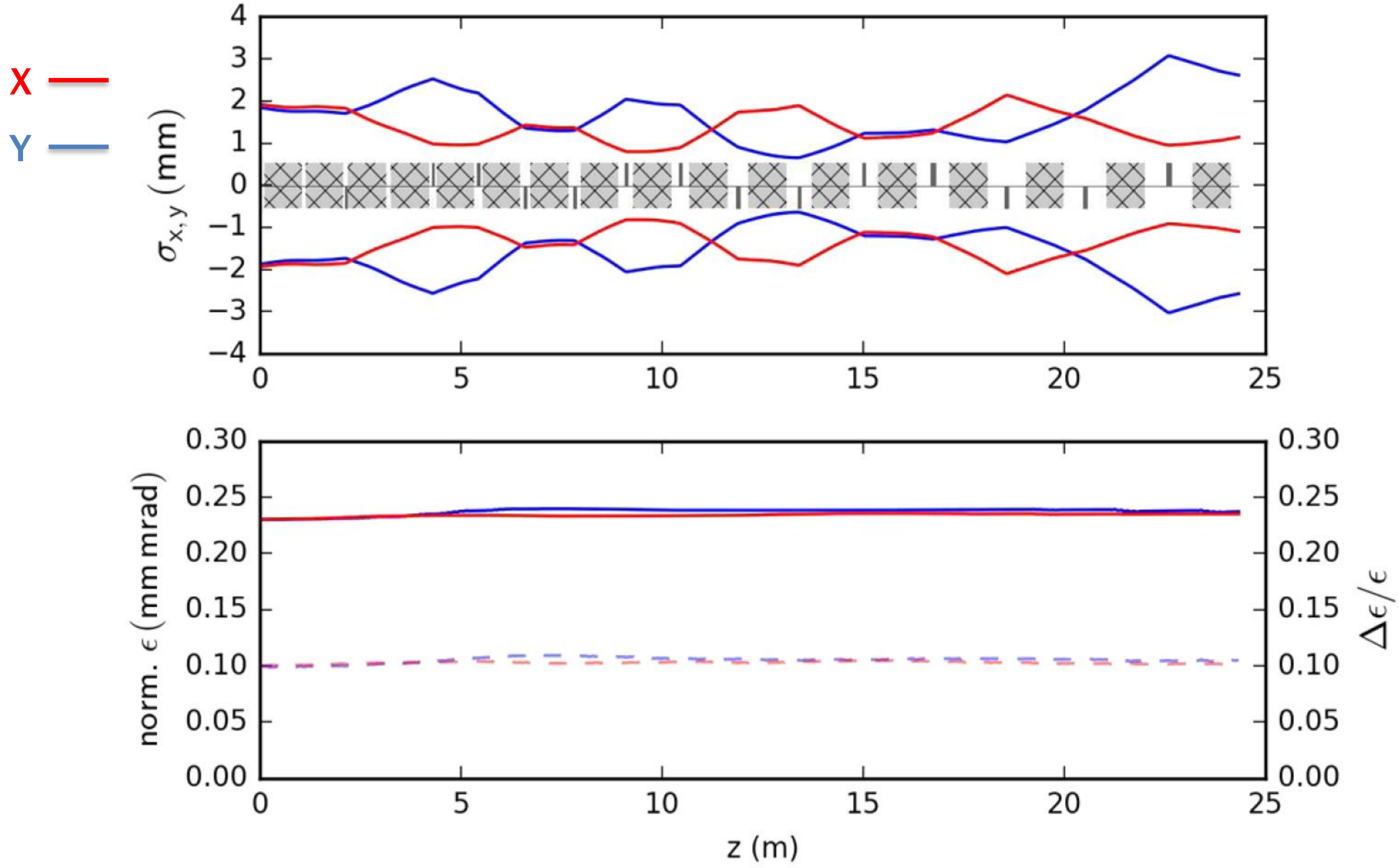
Reasonably Smooth Envelope Oscilation Evolution and Small Emittance Growth in the 1st Pass

X —

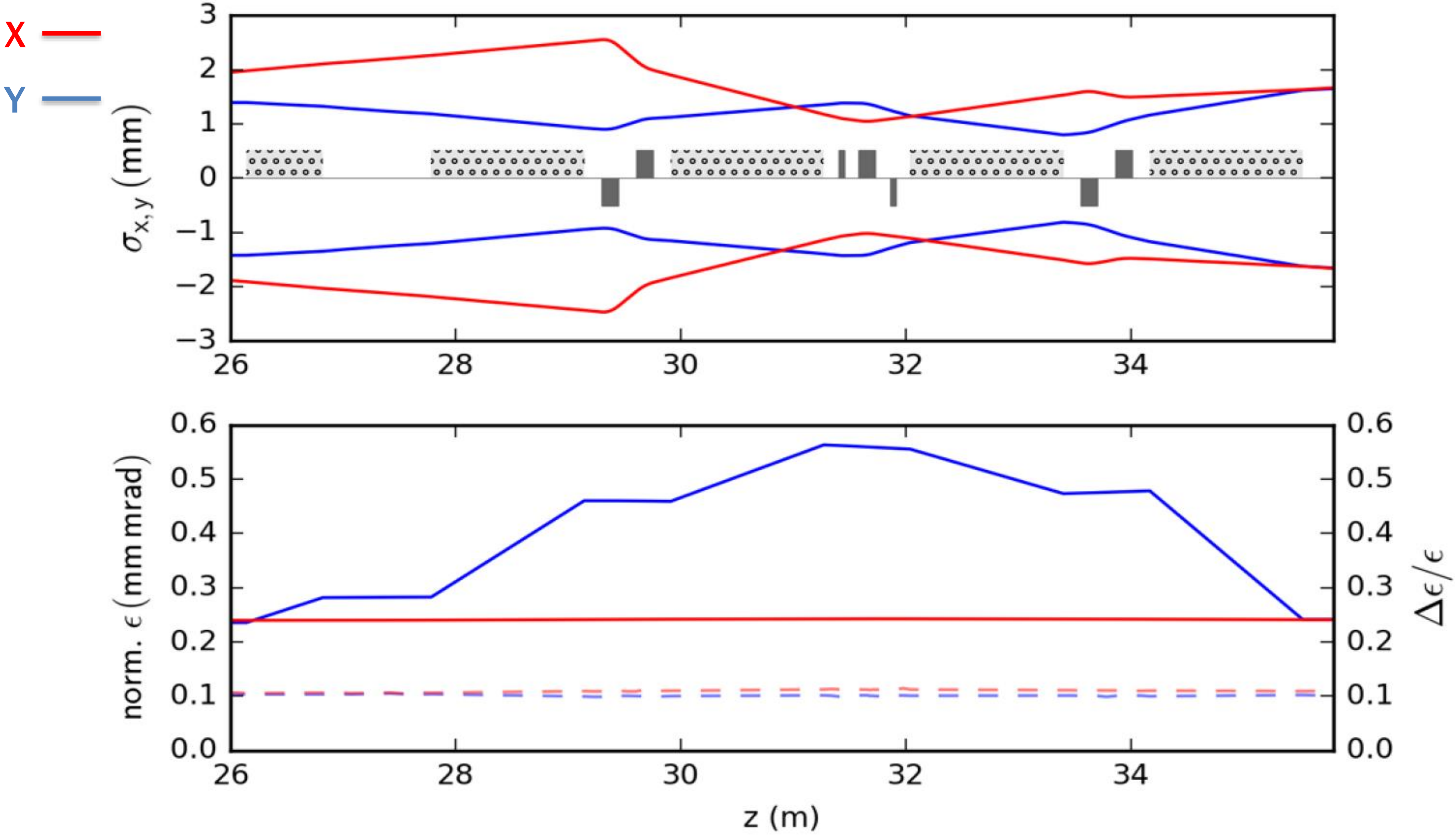
Y —



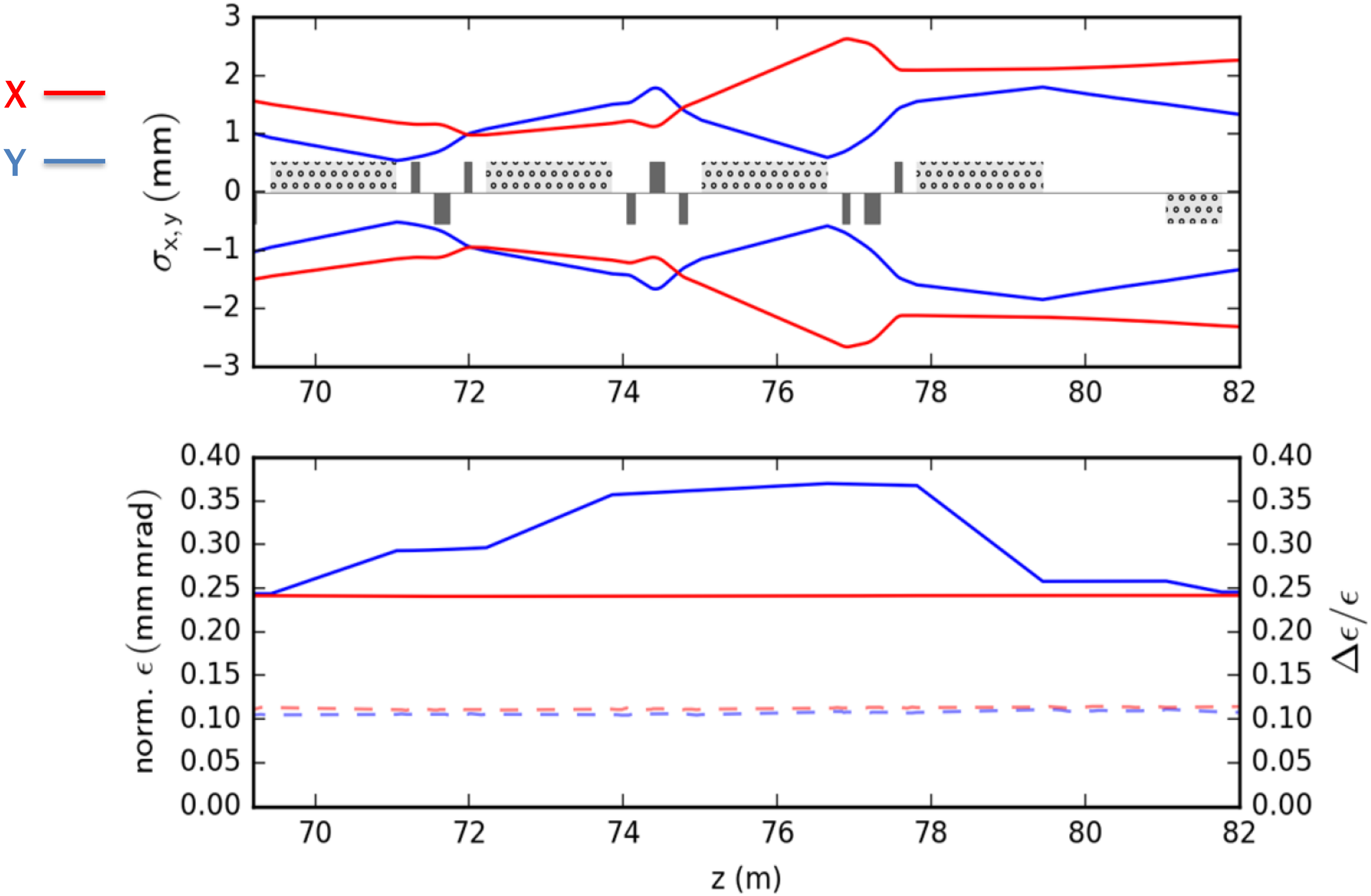
Smooth Envelope Oscilation Evolution and Small Emittance Growth in the 2nd Pass



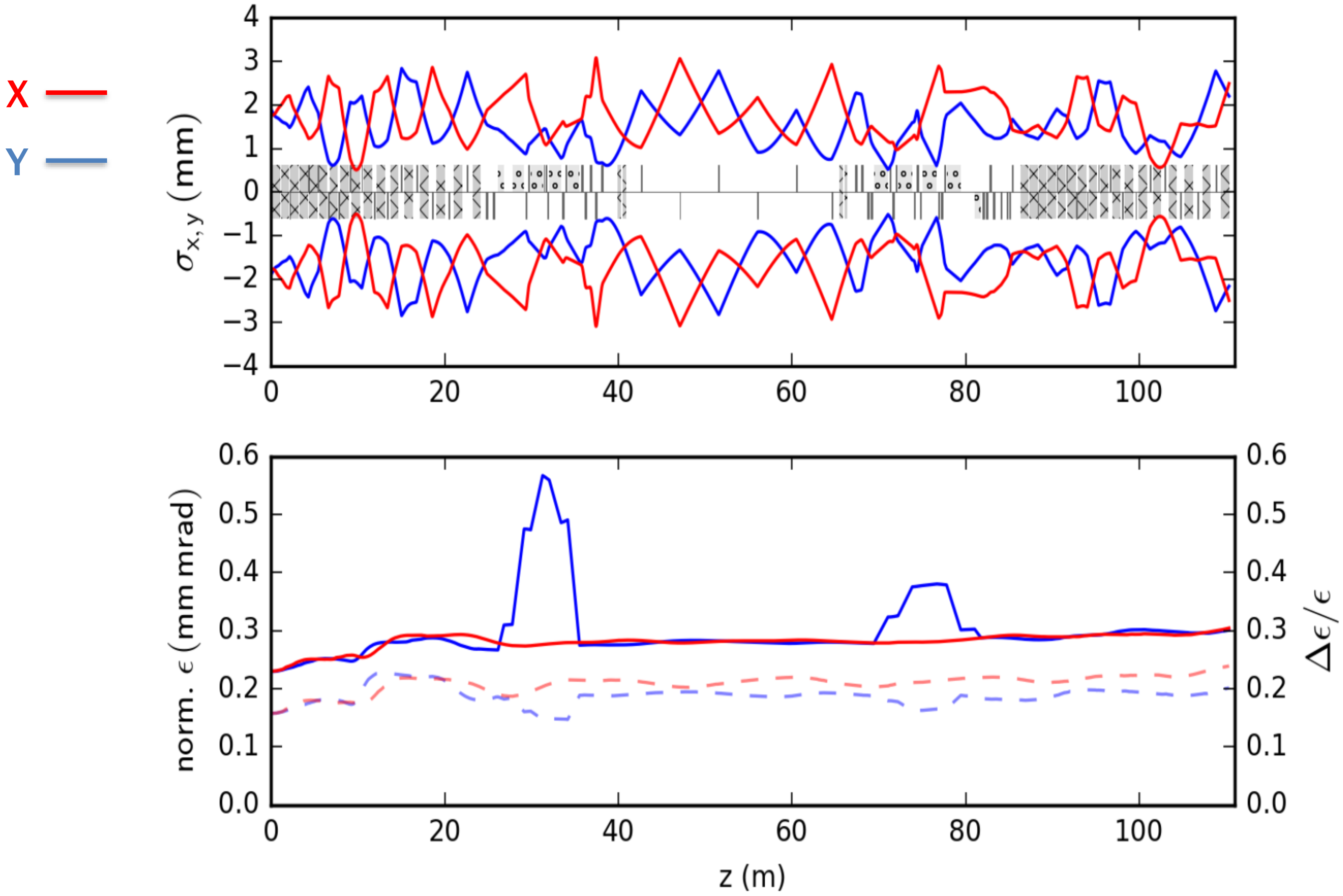
Reasonable RMS Sizes and Emittance Evolution in the 1st Arc



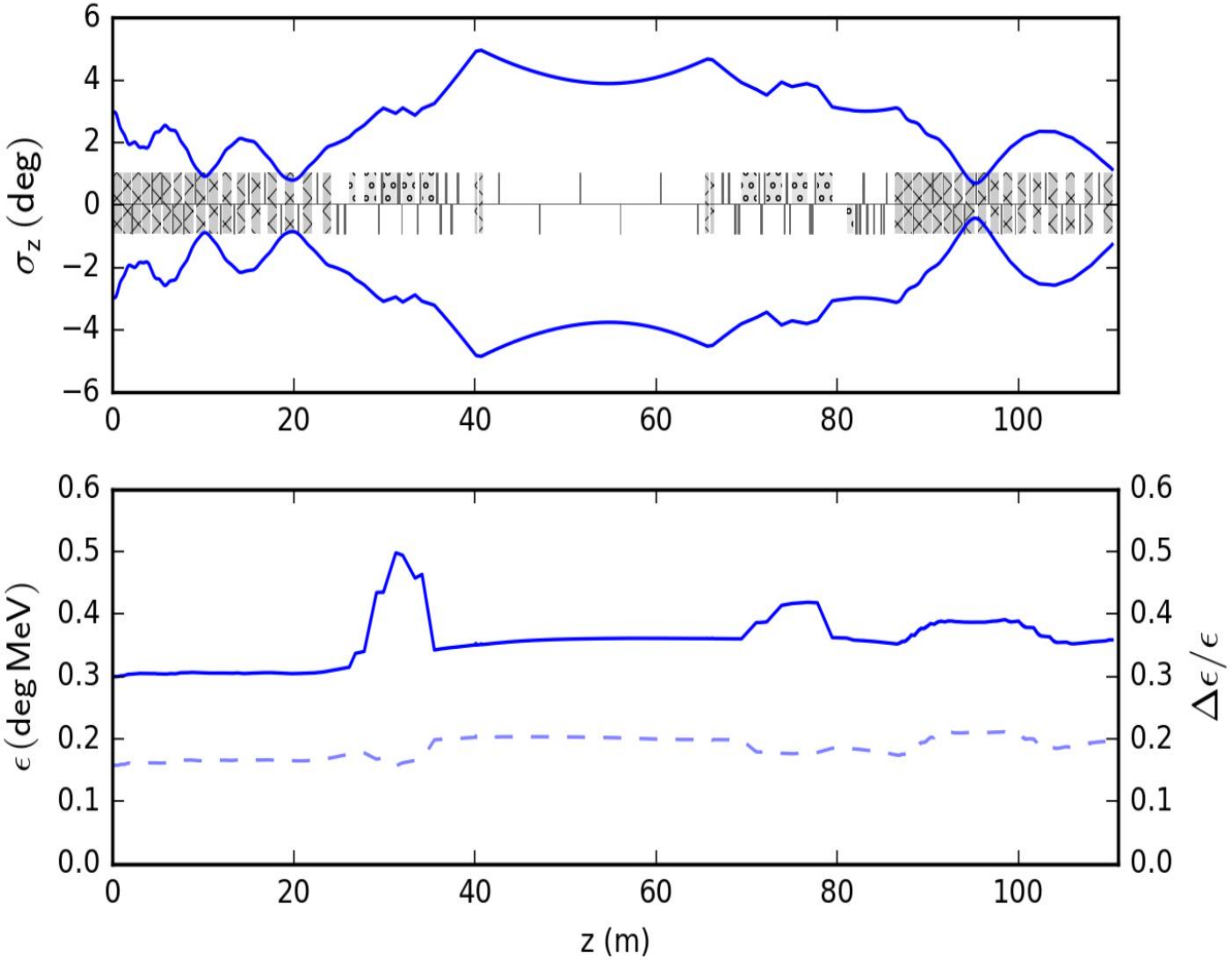
Reasonable RMS Sizes and Emittance Evolution in the 2nd Arc



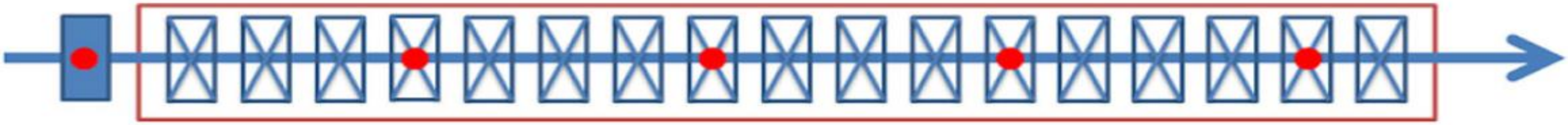
Reasonable Transverse RMS Sizes and Emittances Evolution through the Double Pass Proton Linac from S-2-E Simulation



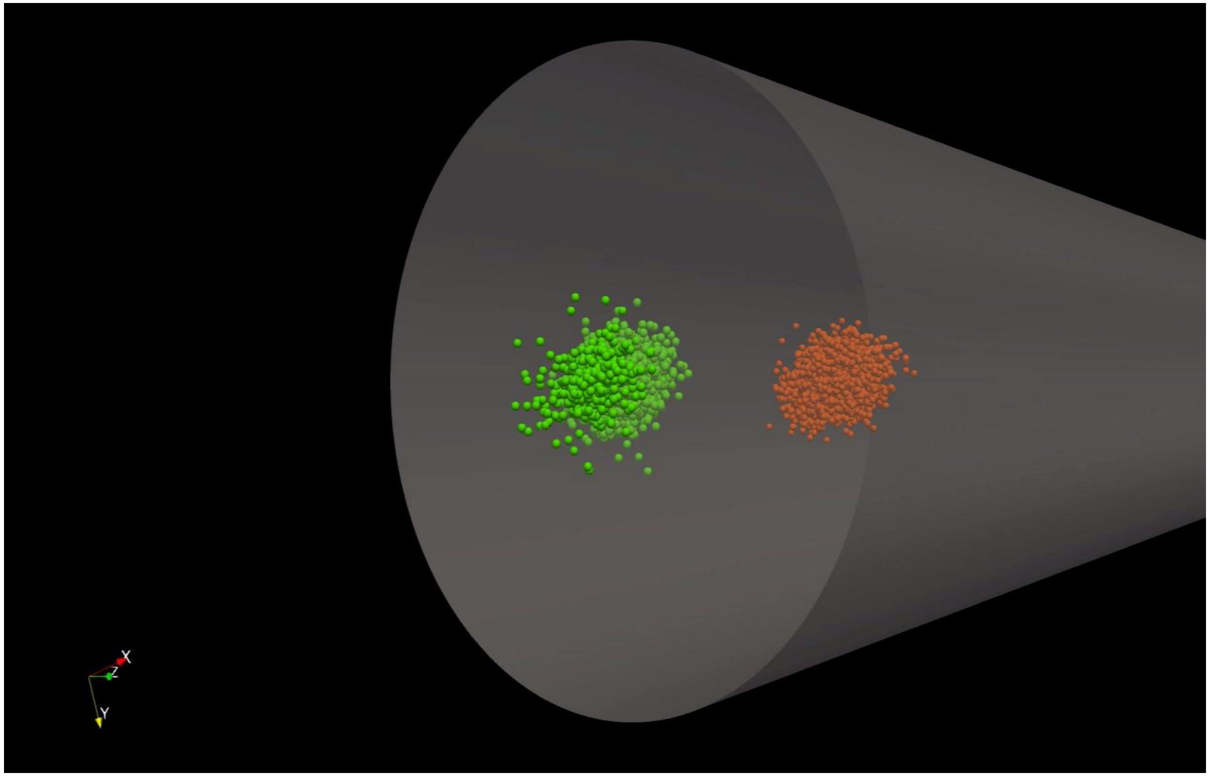
Reasonable Longitudinal RMS Size and Emittance Evolution through the Double Pass Proton Linac from the S-2-E Simulation



Effects of Overtaking Collision in CW Double Pass Proton Linac



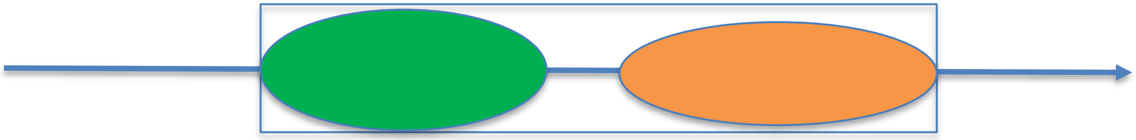
Injector frequency 162.5 MHz, SC frequency 650 MHz, 10 collisions



Y. Tao, J. Qiang, K. Hwang, linac, Phys. Rev. Accel. Beams 20, 124202 (2017).

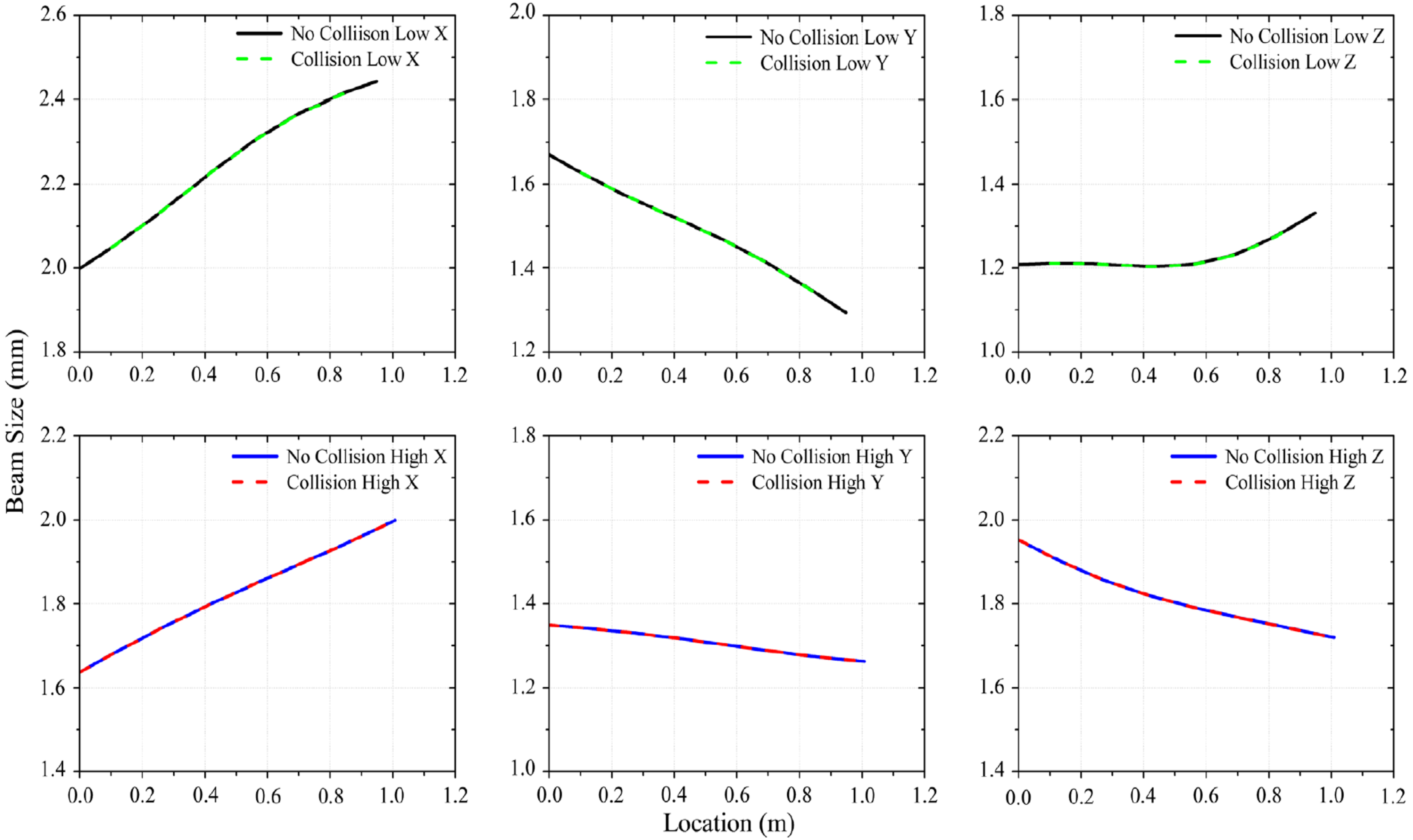
Simulation of the Overtaking Collision Effects Using the IMPACT-T Code Including Space-Charge Forces of Both Energy Bunches

- Convert the particle distributions from Z to T.
- Calculate the space-charge forces from itself and the space-charge forces from the other energy bunch.
- Advance protons with both space-charge forces and external forces.

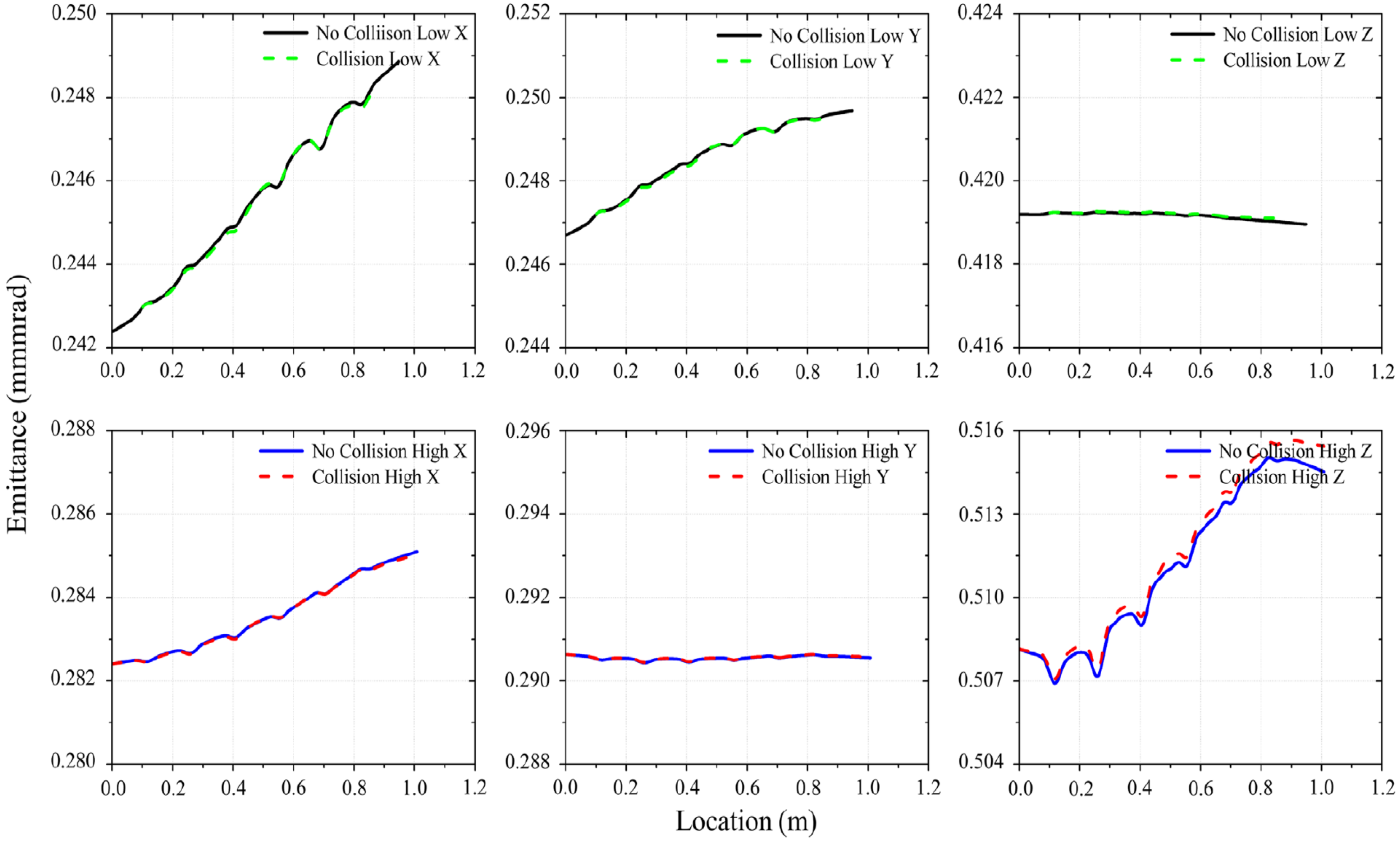


computation domain

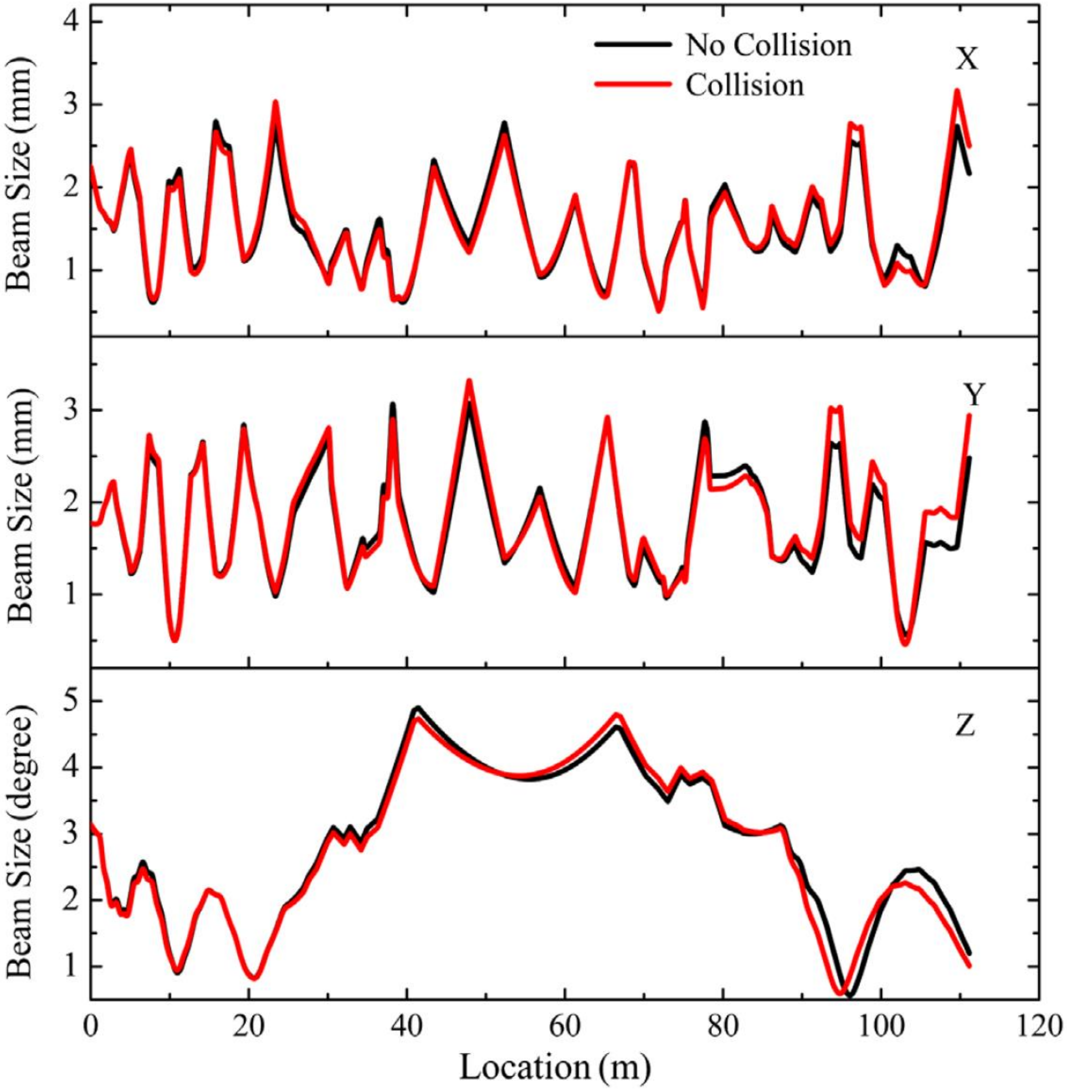
RMS Sizes Evolution w/o Collision through the 1st Cavity



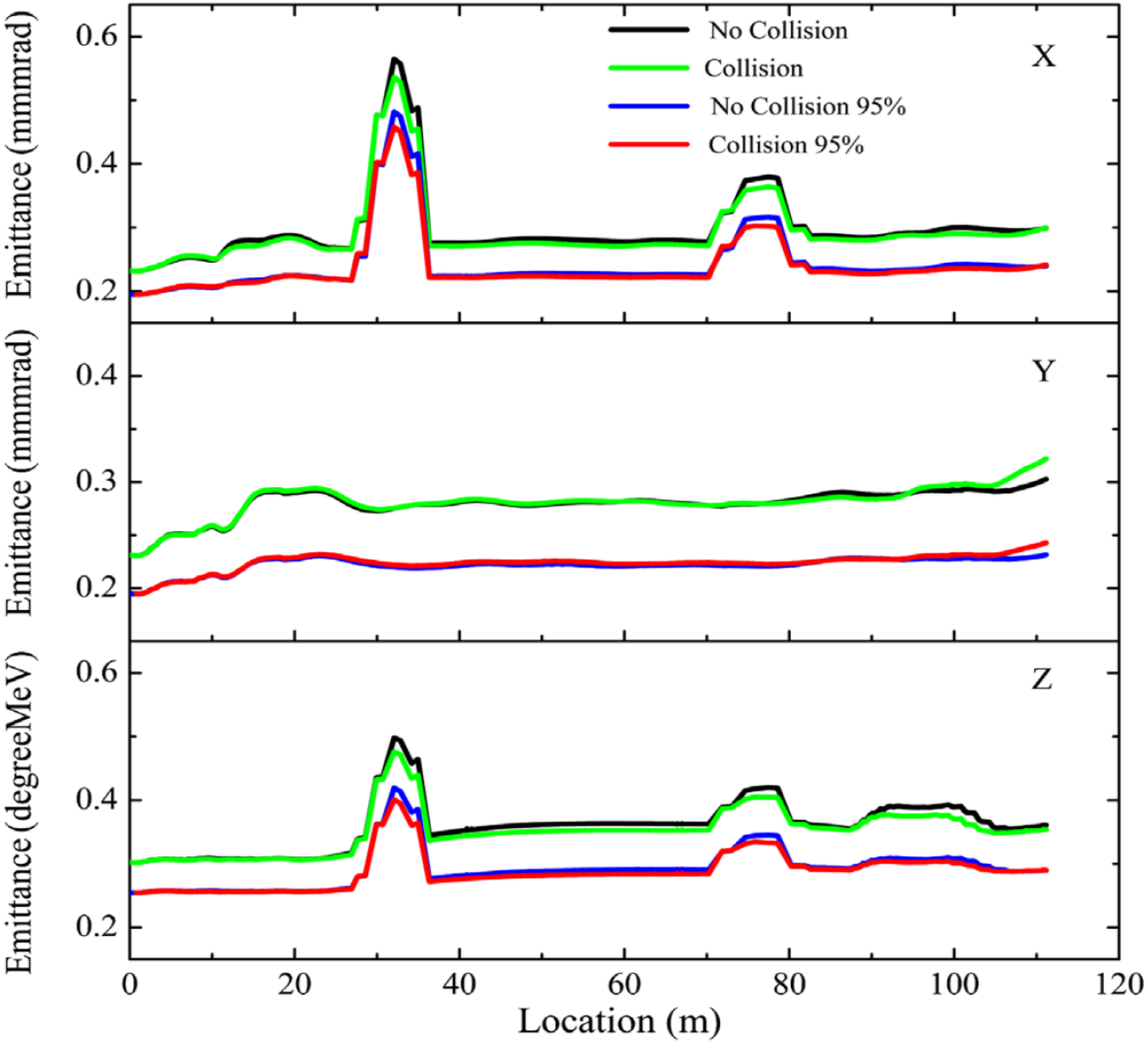
RMS Emittances Evolution w/o Collision through the 1st Cavity



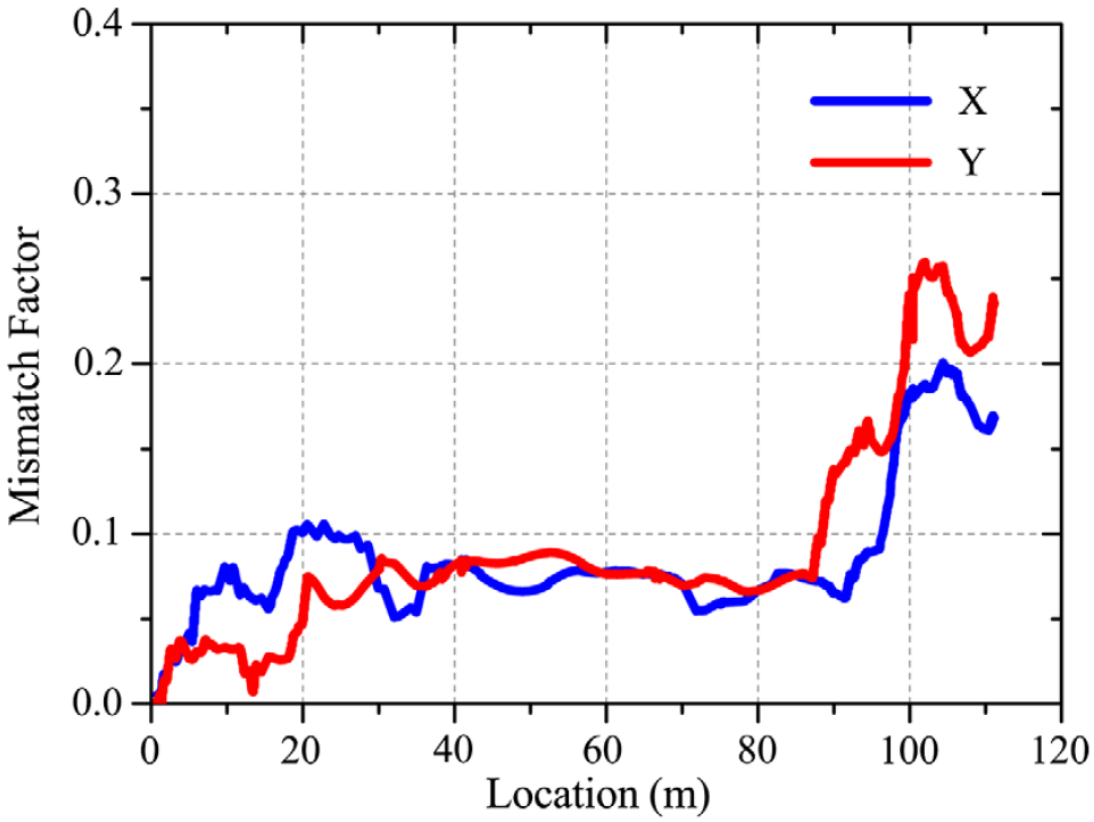
RMS Sizes Evolution w/o Collision through the Double Pass Linac



RMS Emittances Evolution w/o Collision through the Double Pass Linac



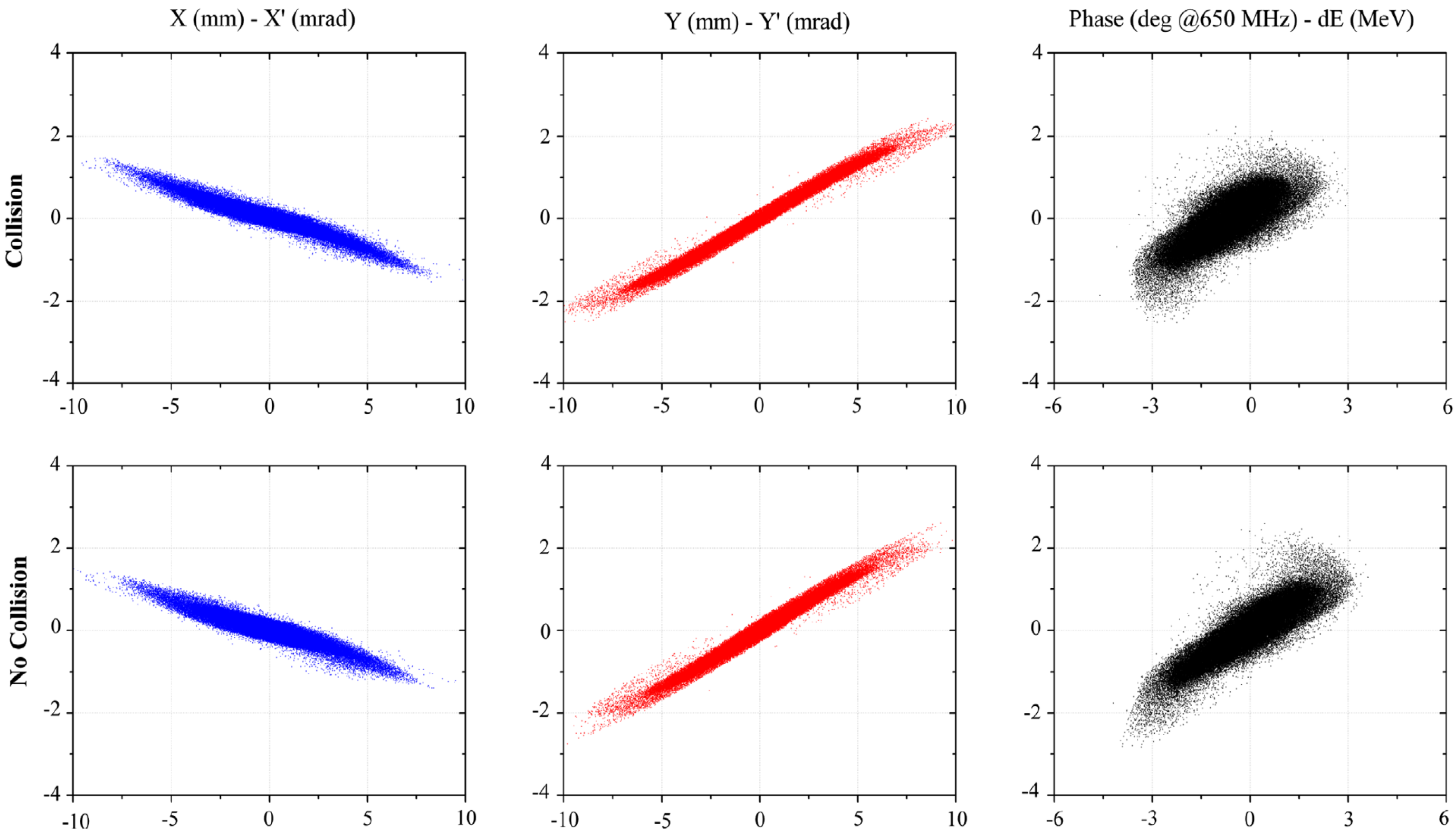
Mismatch Factor Evolution of No-Collision and Two-Bunch Collision through the Double Pass Linac



$$M = \sqrt{1 + \frac{\Delta + \sqrt{\Delta(\Delta + 4)}}{2}} - 1$$

$$\Delta = (\delta\alpha)^2 - \delta\beta\delta\gamma$$

Similar Phase Space Distributions at the Exit of the Linac w/o Collisions



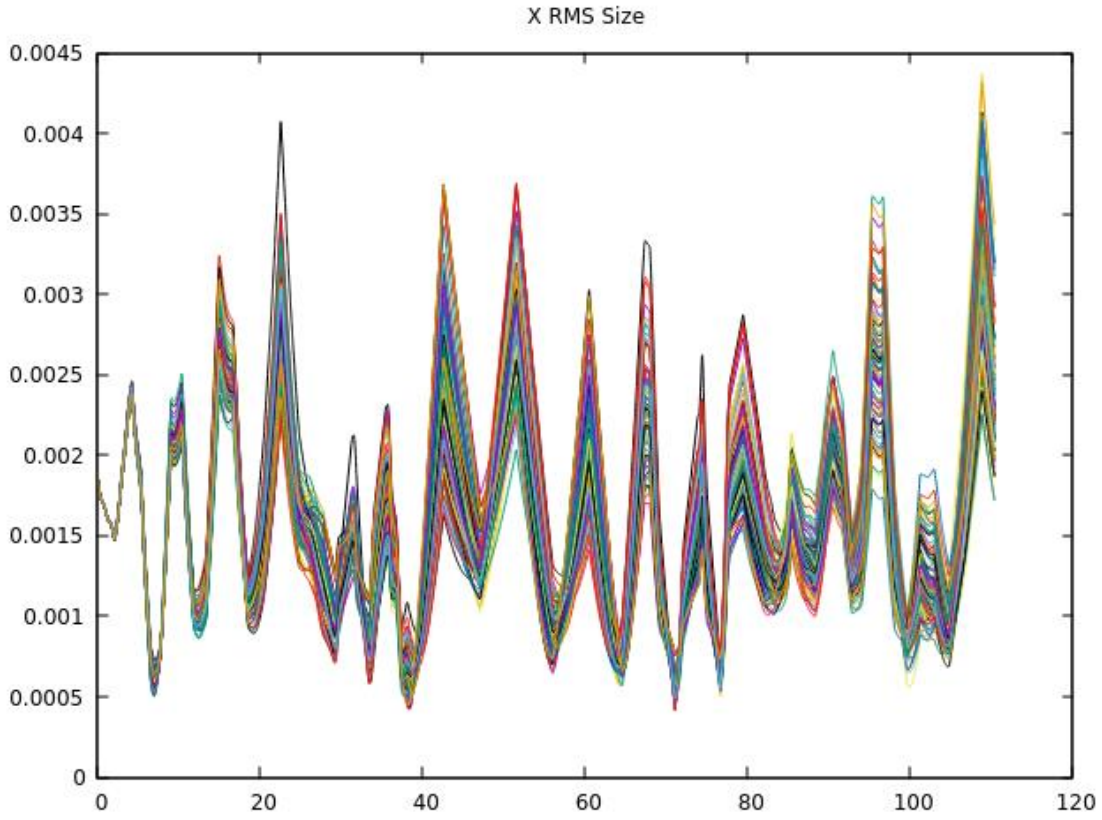
less than 20% differences in all Twiss parameters

Effects of Random Field Errors in the Double Pass Proton Linac

Cavity	Static Errors	Dynamic Errors
Phase	± 1°	± 0.5°
Amplitude	± 1%	± 0.5%

Quad	Static Errors	Dynamic Errors
gradient	± 0.5%	± 0.05%

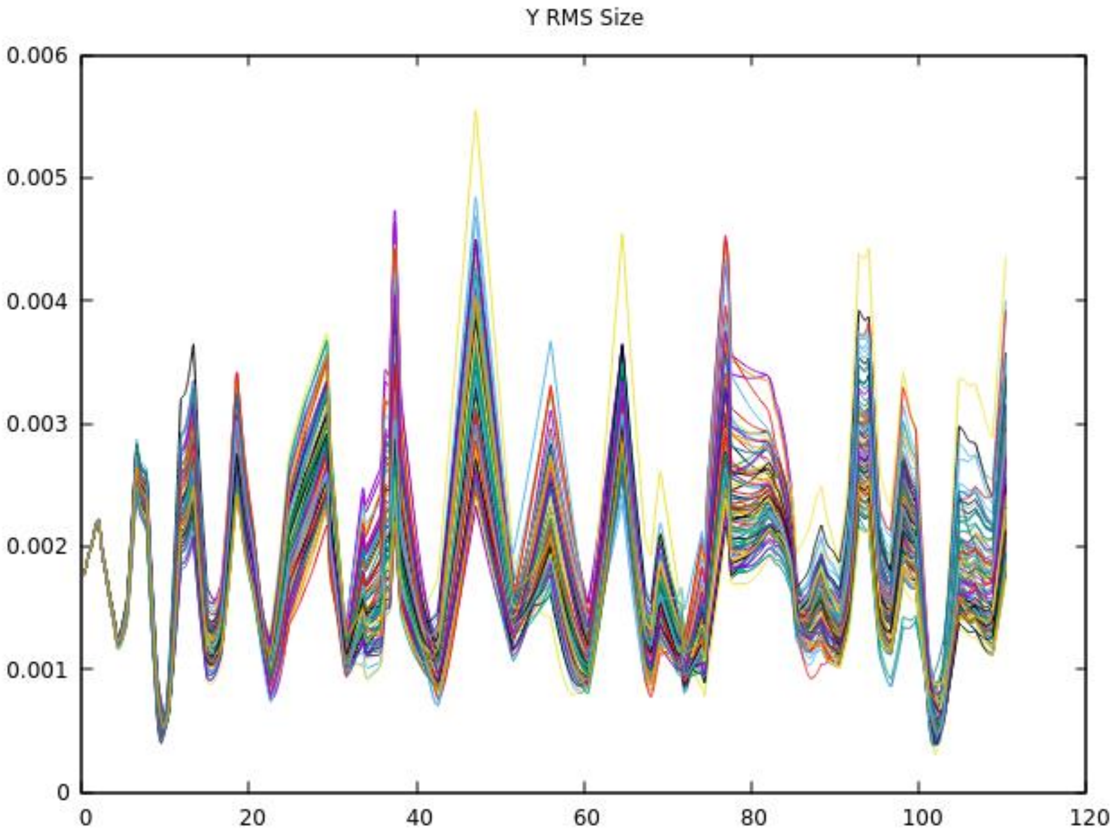
Horizontal RMS Size Evolution with 100 Set of Random Errors



Final RMS Size:

- Reference: 2.17 mm
- With Errors Avg : 2.37 mm
- Growth : 9.2%

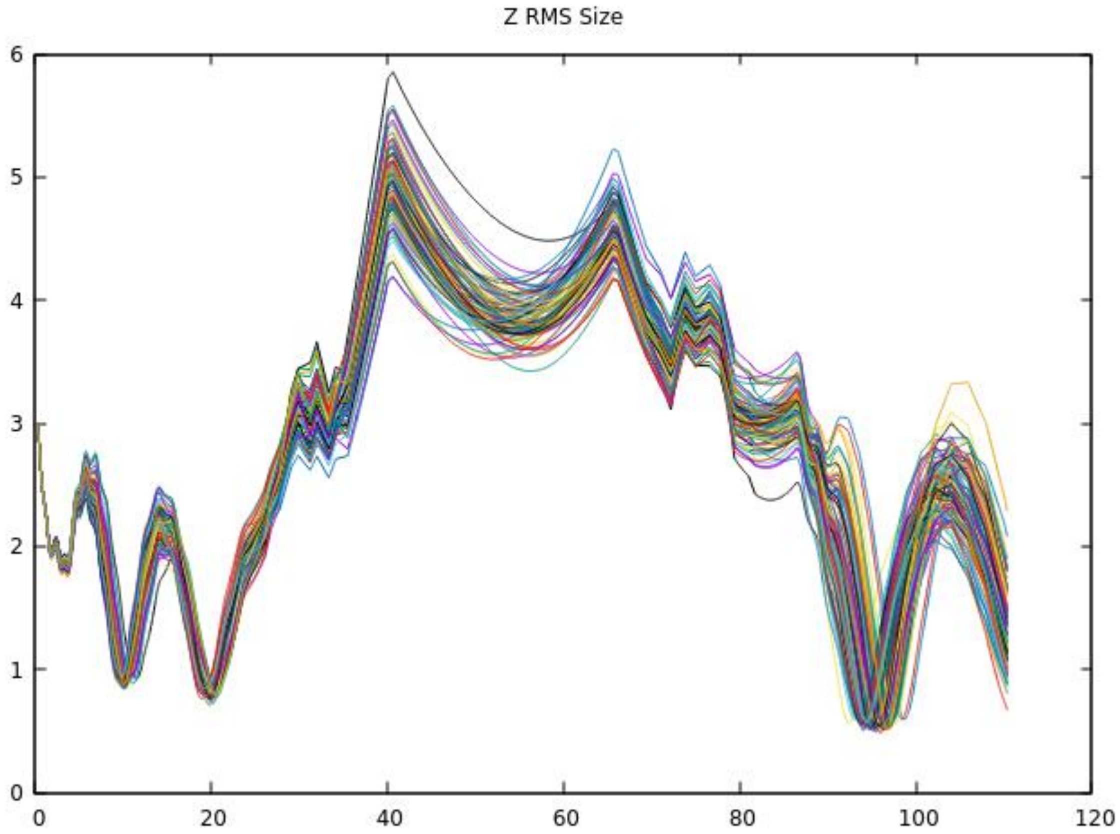
Vertical RMS Size Evolution with 100 Set of Random Errors



Final RMS Size:

- Reference : 2.48 mm
- With Errors Avg : 2.65 mm
- Growth : 6.9%

Longitudinal RMS Size Evolution with 100 Set of Random Errors



Final RMS Size:

- Reference: 1.2 degree
- With Errors avg : 1.29 degree
- Growth : 7.5%

Conclusions and Future Work

- *A multi-GeV multi-section recirculating superconducting proton linac can substantially save the accelerator construction and operation costs.*
- *Beam dynamics simulation in the two-pass section demonstrates the simultaneously accelerating and focusing of two energy beams.*
- *Overtaking collisional effect between the low energy bunch and the high energy bunch is small and would not preclude the CW operation of the accelerator.*
- *Field sensitive study suggests that the accelerator would be insensitive to these errors.*

- ➢ Beam steering with misalignment errors
- ➢ Design of multiple pass phase shifter
- ➢ Design of multiple pass arcs
- ➢ Failure mode study

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Kilean
Hwang

Yue
Tao

Thank You!