中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

CEPC Injector

Linac beam dynamics

International Workshop on
High Energy Circular Electron Positron Collider
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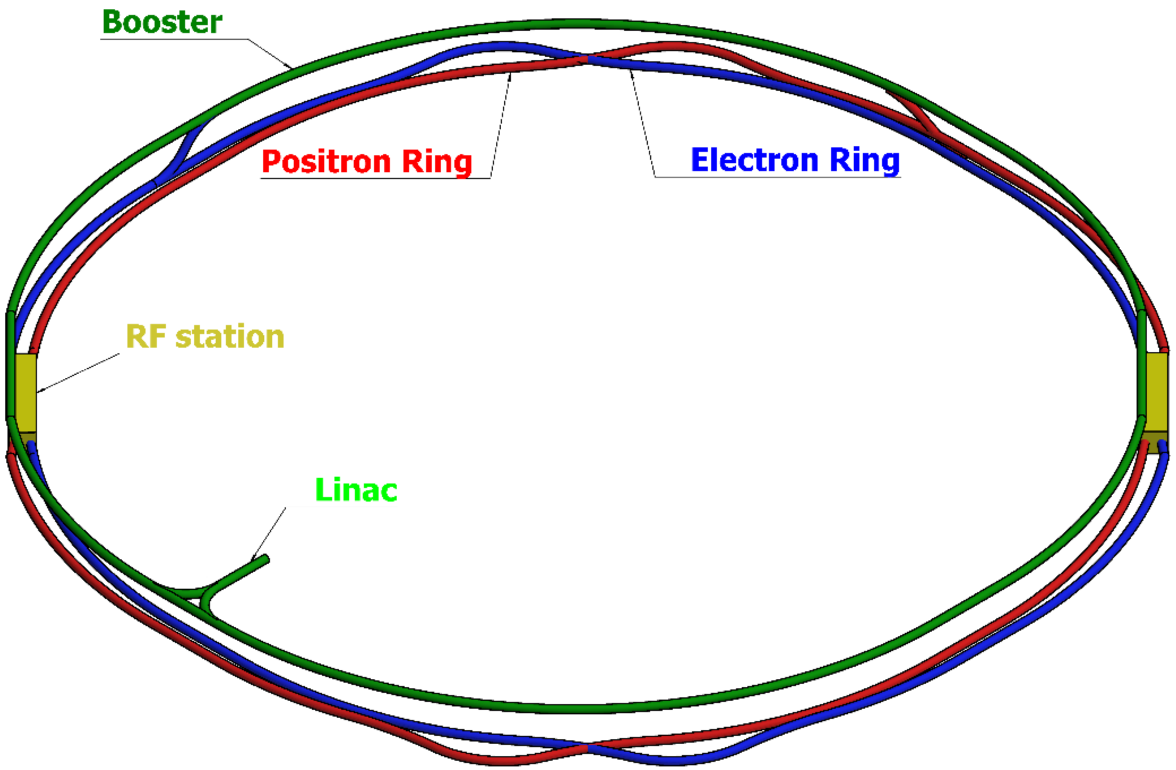
Outline

- Introduction
  - Main parameters
  - Linac layout
- Positron source design
- Linac design
  - Electron linac
  - Positron linac
  - Error study
- Summary



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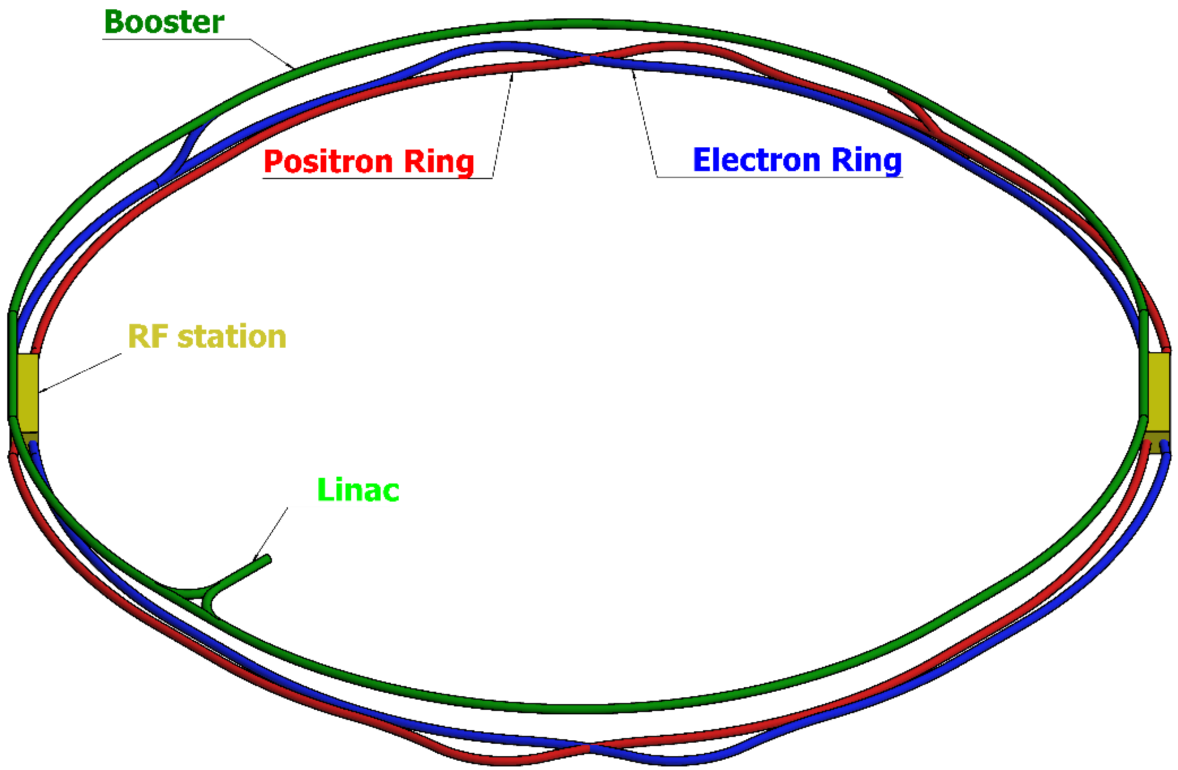

Introduction

Main parameters

- Linac design goal and principles
  - **S**implicity
  - High **A**vailability (necessary hot-standby backups,10%-20%) and **R**eliability
  - Always providing beams that can **meet requirements** of Booster

Parameter	Symbol	Unit	Value
e^-/e^+ beam energy	E_{e-}/E_{e+}	GeV	10
Repetition rate	f_{rep}	Hz	100
e^-/e^+ bunch population	$Ne-/Ne+$		$>6.25\times10^9$
		nC	>1.0
Energy spread (e^-/e^+)	σ_E		$<2\times10^{-3}$
Emittance (e^-/e^+)	ε_r	nm· rad	<300
e^- beam energy on Target		GeV	4
e^- bunch charge on Target		nC	10

Introduction

Main parameters

- Parameters
  - Layout
    - *Emittance and energy spread is too small , no need Damping Ring*
    - *Lower emittance requirement possibility → Damping Ring for positron linac*
  - Bunch charge
    - Positron bunch charge decide the layout of linac and is difficult to upgrade if not keep the potential
    - Enough allowance and high bunch charge requirement possibility or potential, designed ***3 nC***
  - One-bunch-per-pulse
    - Only ***short-range Wakefield*** need to be considered
  - Frequency
    - Collider: 650 MHz
    - Booster: 1300MHz
    - *Linac: 2856.75MHz (s-band)*
      - 2856.75MHz =3.25MHz × 879
      - 650 MHz =3.25MHz × 200MHz
      - 1300 MHz =3.25MHz × 400MHz

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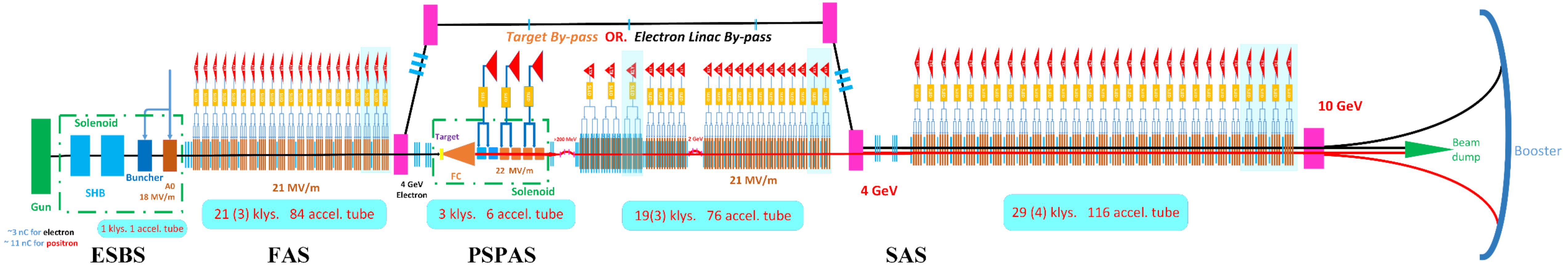
e^- bunch charge on Target		nC	10

Introduction

Layout of Linac (I)

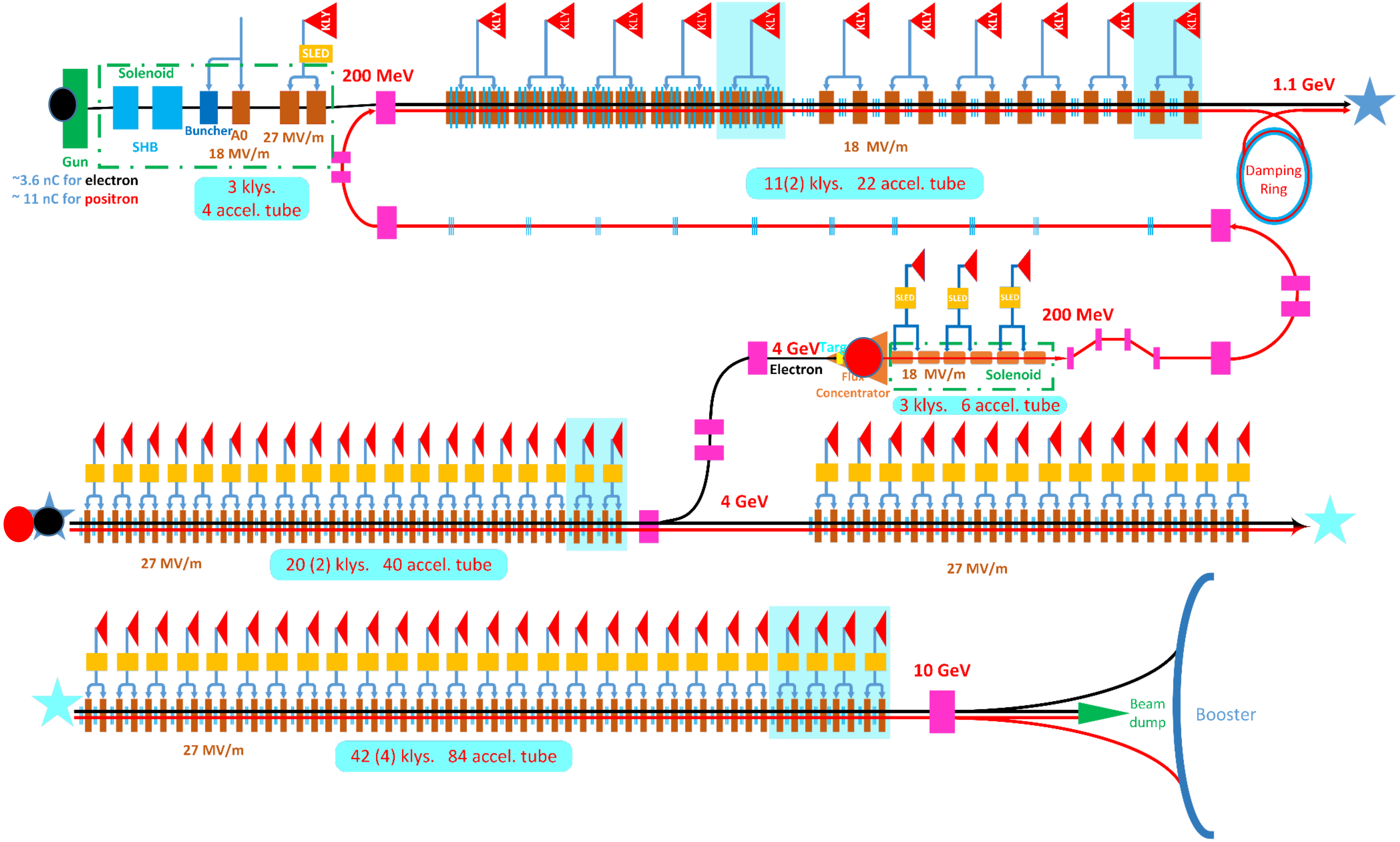


- ESBS (*Electron Source and Bunching System*)
  - Electron energy: 50 MeV
  - Electron bunch charge: 3 nC for electron injection/ 11nC for positron production
- FAS (*the First accelerating section*)
  - Electron beam to 4 GeV
  - High charge mode/ Low charge mode
- PSPAS (*Positron Source and Pre-Accelerating Section*)
  - Positron beam production and capture
- SAS (*the Second accelerating section*)
  - Energy to 10 GeV
- Electron bypass
  - Transport line bypass scheme
  - Target bypass scheme

Introduction

Layout of Linac (II)

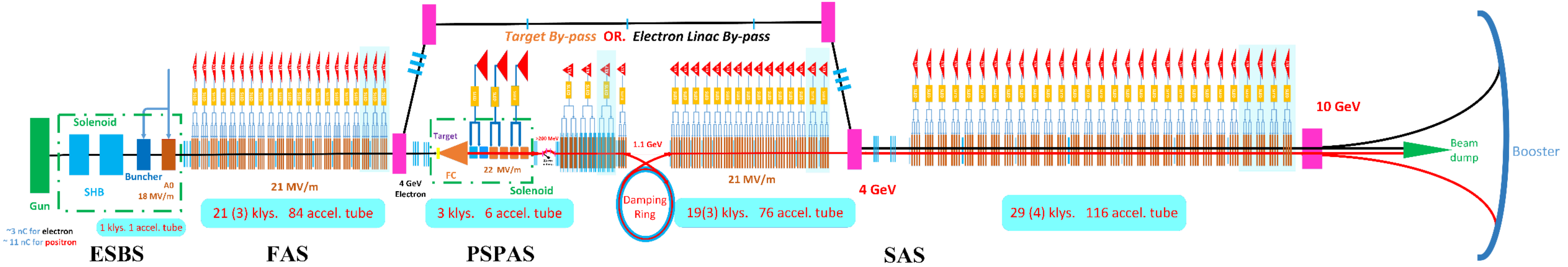
- Damping Ring
  - Timing
  - emittance



alternative

Introduction

Layout of Linac (III)



alternative

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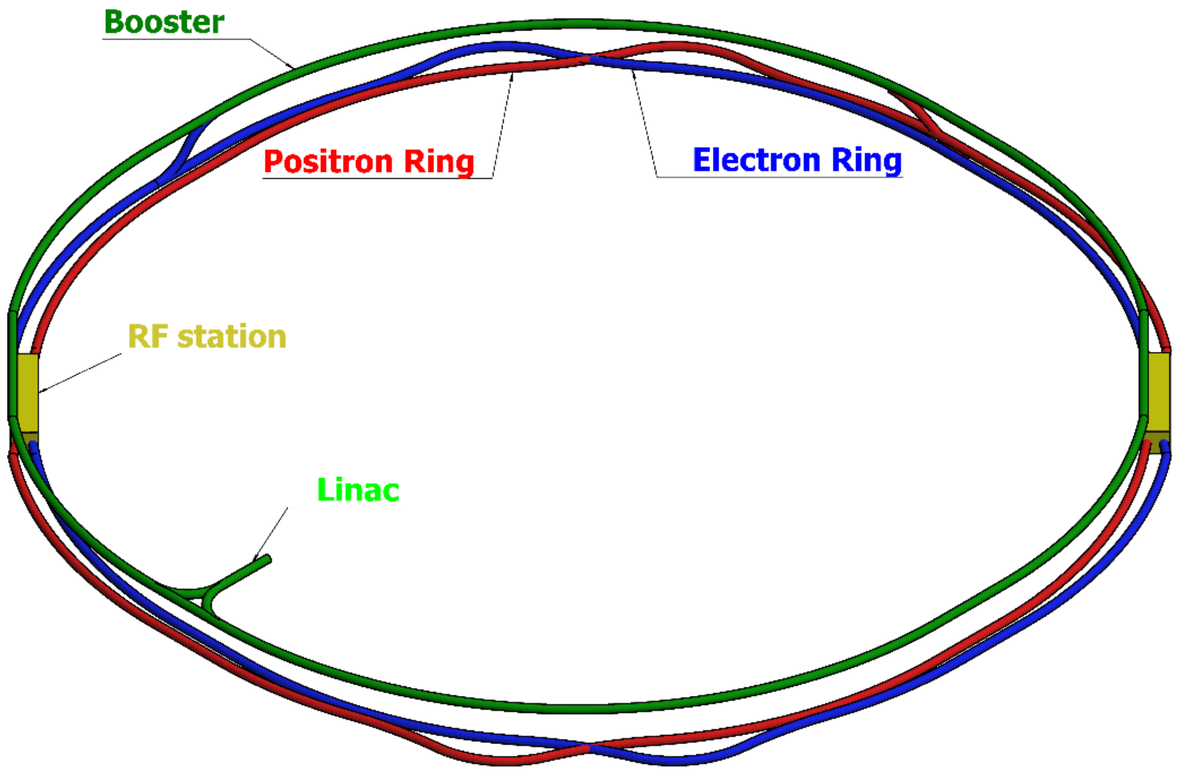
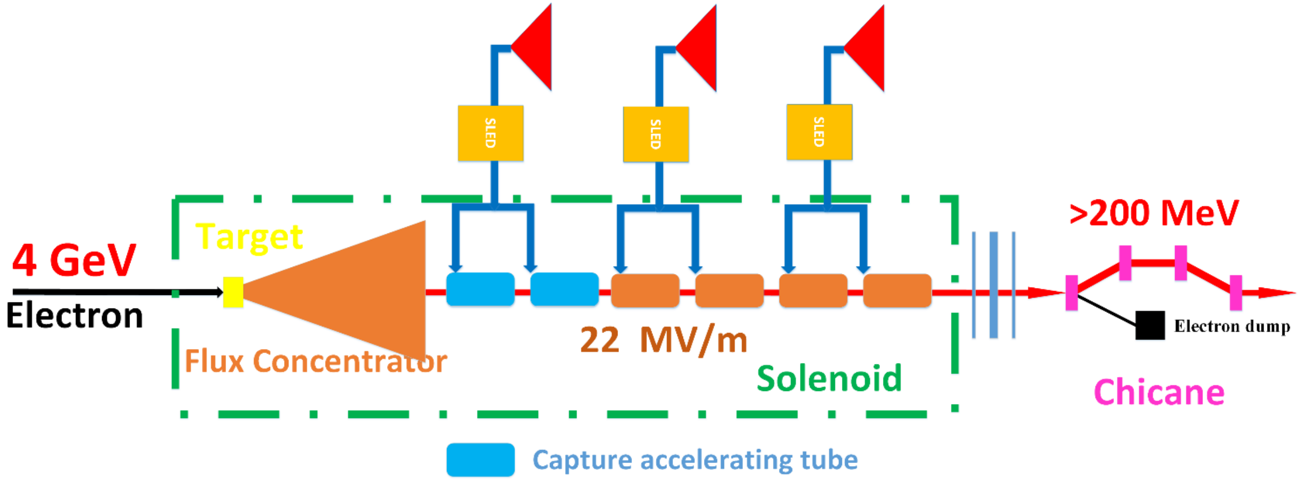
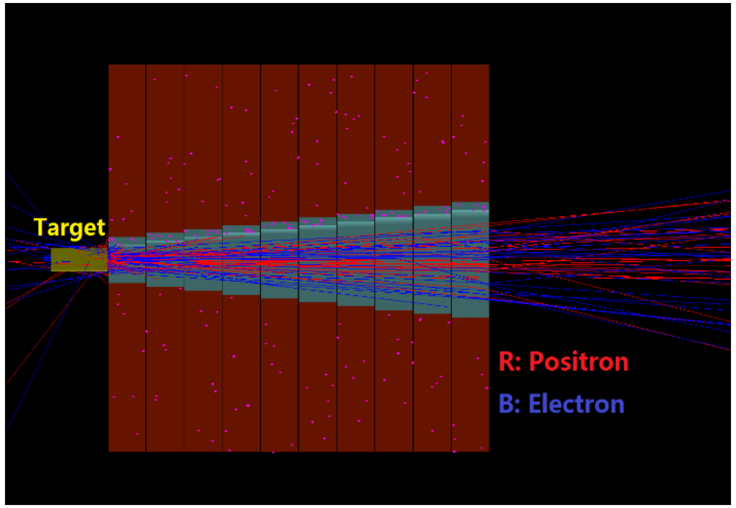


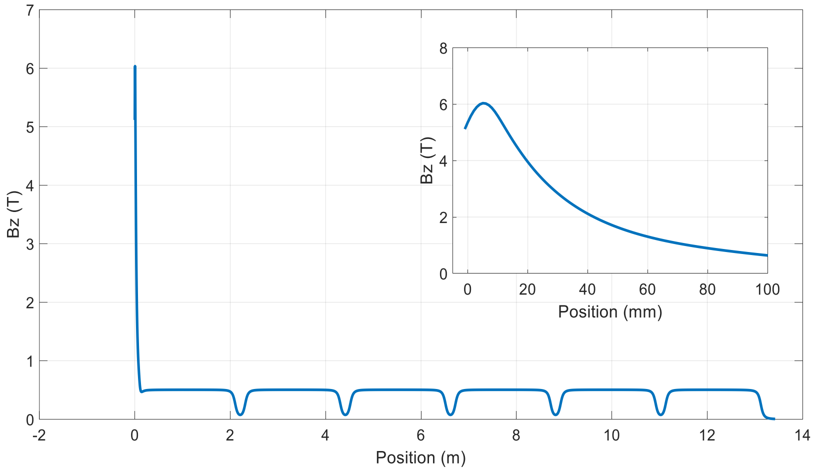
Positron source

Layout of PSPAS

- Layout of positron source
  - Target：
    - W@15mm
    - Rms electron beam size:0.5mm
  - AMD
    - Length: 100mm
    - Aperture: 8mm→26mm
  - Capture & Pre-accelerating section
    - Length:2 m
    - Aperture:25 mm
    - Gradient: 22 MV/m
  - Chicane
    - Wasted electron separation
    - Bunch length compression
- Magnetic field of the positron source and pre-accelerating section
  - 6T→0.5T

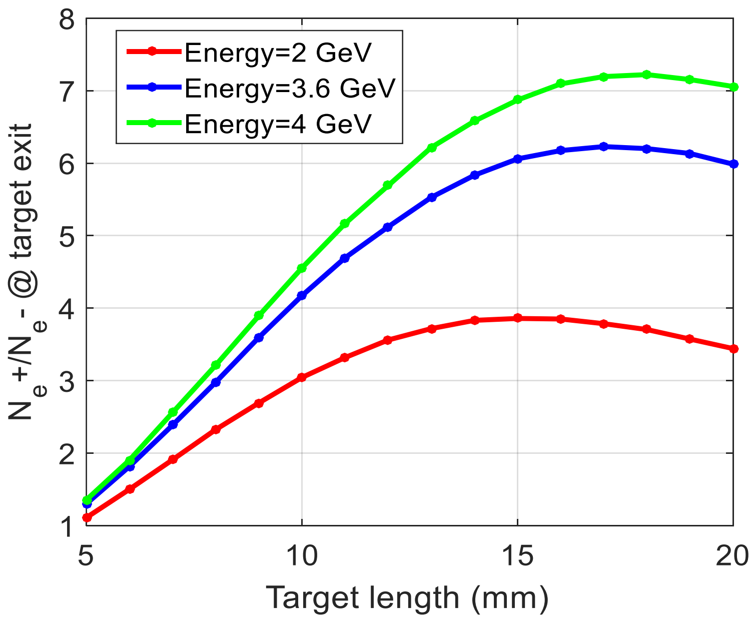


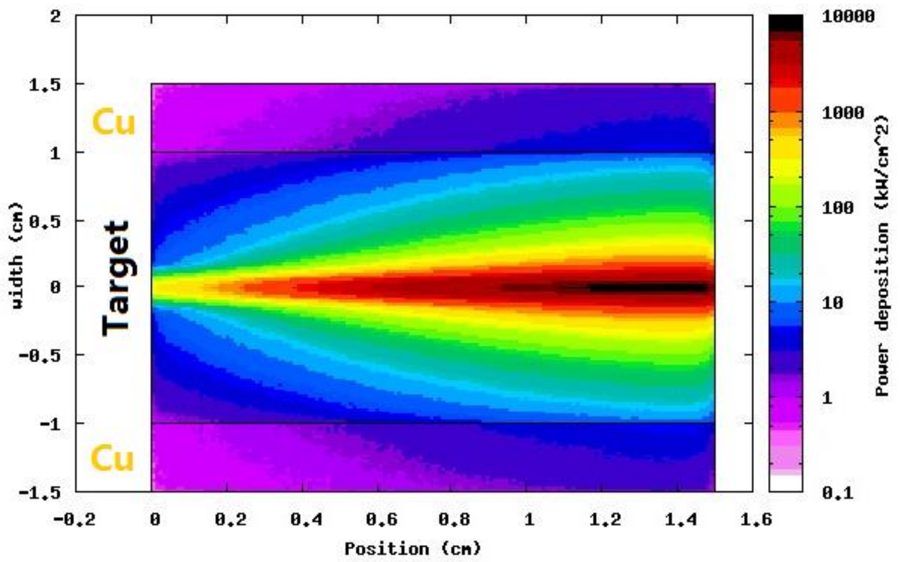




Positron source   Target design

- SuperKEKB positron linac commissioning (3.3 GeV)
  - 2014, N(e+)/N(e-)~20%
  - 2015, N(e+)/N(e-)~30% [designed 50%]
- CEPC positron
  - Positron bunch charge > 3 nC
  - Electron beam:
    - 4GeV (not optimization)
    - 10nC/bunch (maybe lower)
  - Electron beam: 4 kW
- Energy deposition
  - 0.784 GeV/e- @ FLUKA
  - 784 W → water cooling
- Target
  - tungsten
  - 15 mm
  - Beam size: 0.5 mm

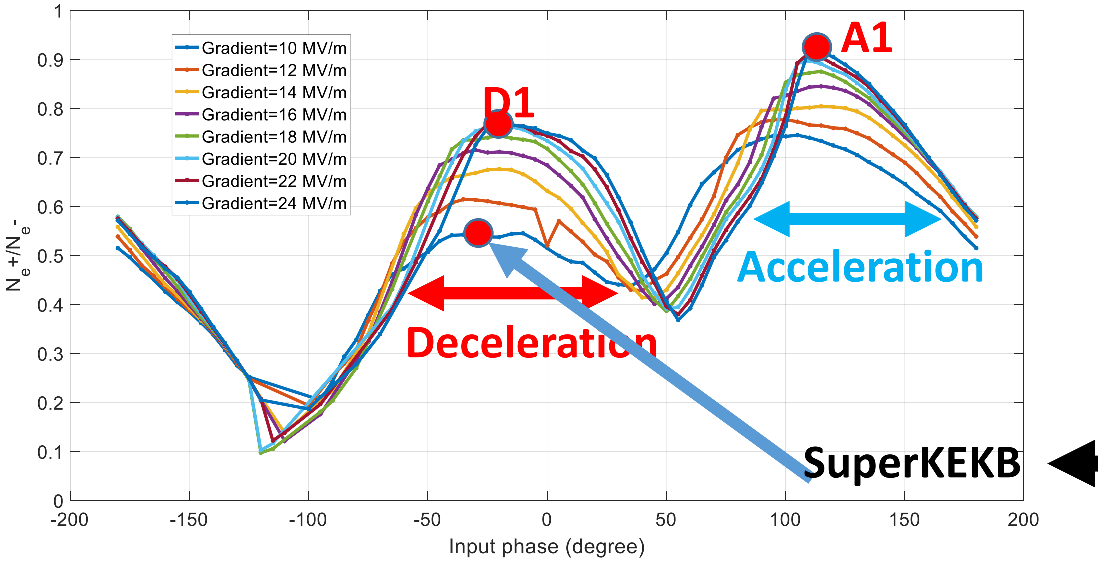




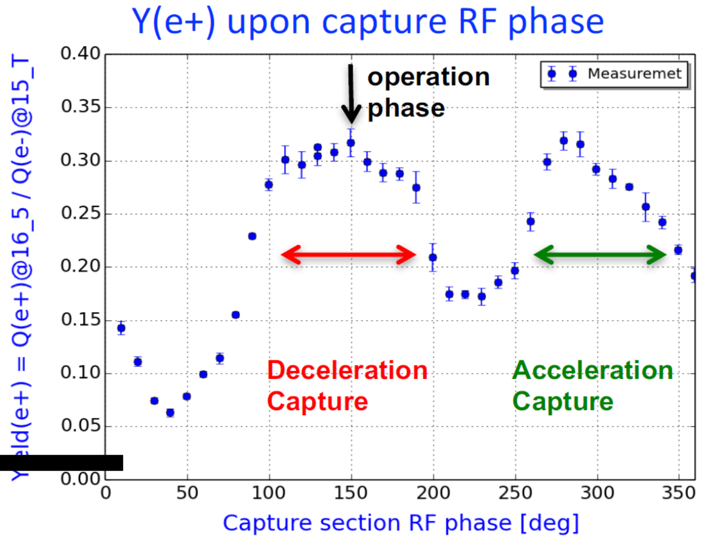
Positron source

Capture accelerating tubes

- Positron yield(@ capture accelerating tube exit) within some energy range with different **capture** accelerating tube **phase** (or different input phase for pre-accelerating section) and different accelerating gradient
  - Deceleration mode (D1)
  - Acceleration mode (A1)
  - 22 MV/m (Considering **energy** and positron yield, lower accelerating gradient have acceptable positron yield decrease)



Only energy cutoff $\Delta E < 15$ MeV

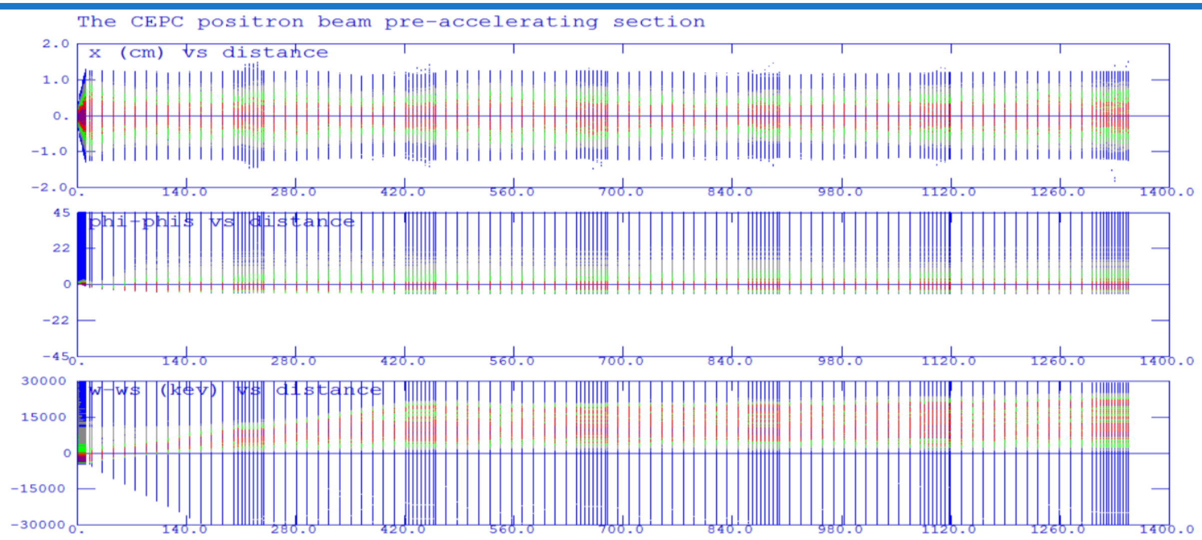


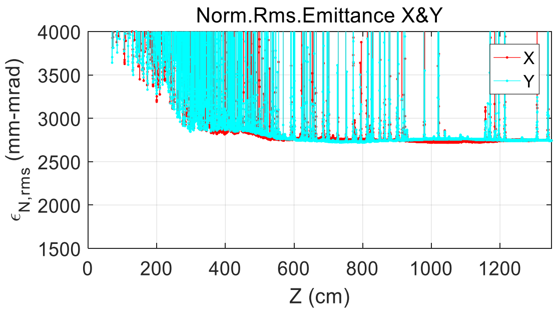
SuperKEKB commissioning results

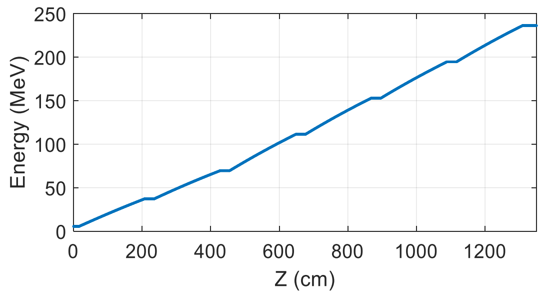
Positron source

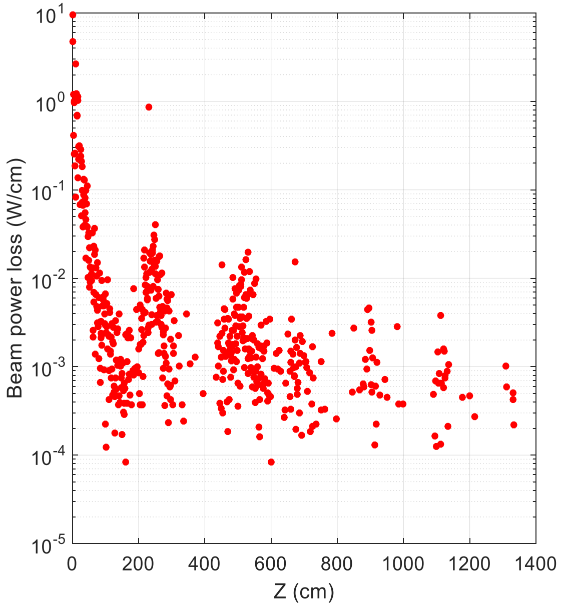
Dynamic results of PSPAS

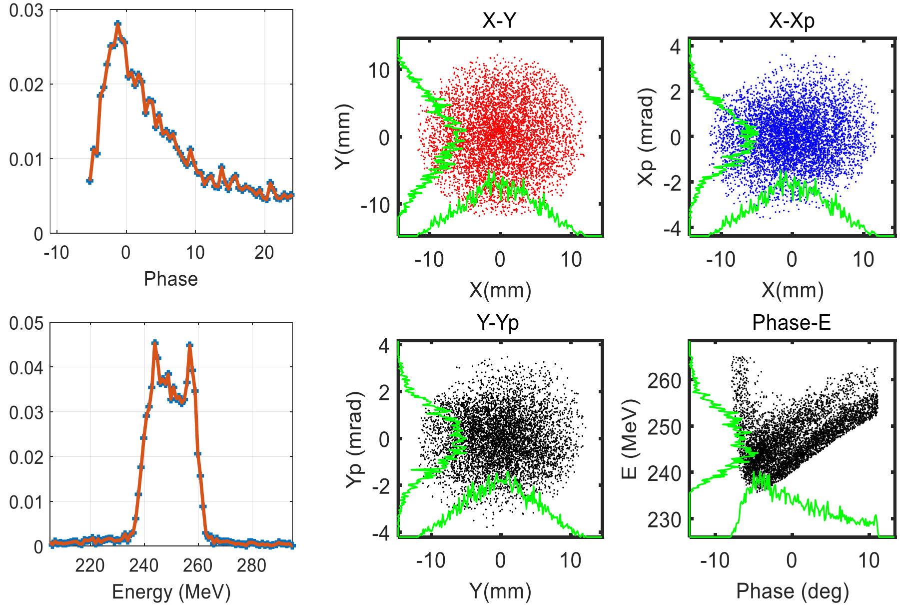
- Pre-accelerating section
  - RF phase
- Norm. RMS. Emittance
  - 2700 mm-mrad → 2400 mm-mrad
- Energy: >200 MeV
- Positron yield
  - Ne+/Ne- ~=**0.55** [-6°, 14°, 235 MeV, 265 MeV]











Positron source   Parameters

	SLC	LEP (LIL)	KEKB/SUPER KEKB	FCC-ee (conv.)*	CEPC
Incident e- beam energy	33 GeV	200 MeV	3.3/3.3 GeV	4.46 GeV	**4 GeV**
e-/bunch [10^{10}]	3-5	0.5 - 30 (20 ns pulse)	6.25/6.25	5.53	**6.25**
Bunch/pulse	1	1	2/2	2	**1**
Rep. rate	120 Hz	100 Hz	50 Hz/50 Hz	200 Hz	**100Hz**
Incident Beam power	~20 kW	1 kW (max)	3.3 kW	15 kW	**4 kW**
Beam size @ target	0.6 - 0.8 mm	< 2 mm	/>0.7 mm	0.5 mm	**0.5 mm**
Target thickness	6X0	2X0	/4X0	4.5X0	**4.3X0**
Target size	70 mm	5 mm	14 mm		**10mm**
Target	Moving	Fixed	Fixed/Fixed		**Moving**/Fixed
Deposited power	4.4 kW		/0.6 kW	2.7 kW	**0.78kW**
Capture system	AMD	λ/4 transformer	/AMD	AMD	**AMD**
Magnetic field	6.8T->0.5T	1 T->0.3T	/4.5T->0.4T	7.5T->0.5T	**6T->0.5T**
Aperture of 1st cavity	18 mm	25mm/18 mm	/30 mm	20 mm	**25 mm**
Gradient of 1st cavity	30-40 MV/m	~10 MV/m	/10 MV/m	30 MV/m	**22 MV/m**
length of 1st cavity	1m	3m	2m	3m	**2m**
Linac frequency	2855.98 MHz	2998.55 MHz	2855.98 MHz	2855.98 MHz	**2856.75 MHz**
e+ yield @ CS exit	~1.6 e+/e-	~0.003 e+/e- (linac exit)	/~0.5 e+/e-	~0.7 e+/e-	**~0.55 e+/e-**

Tungsten radiation length X_0 is 0.35 cm.

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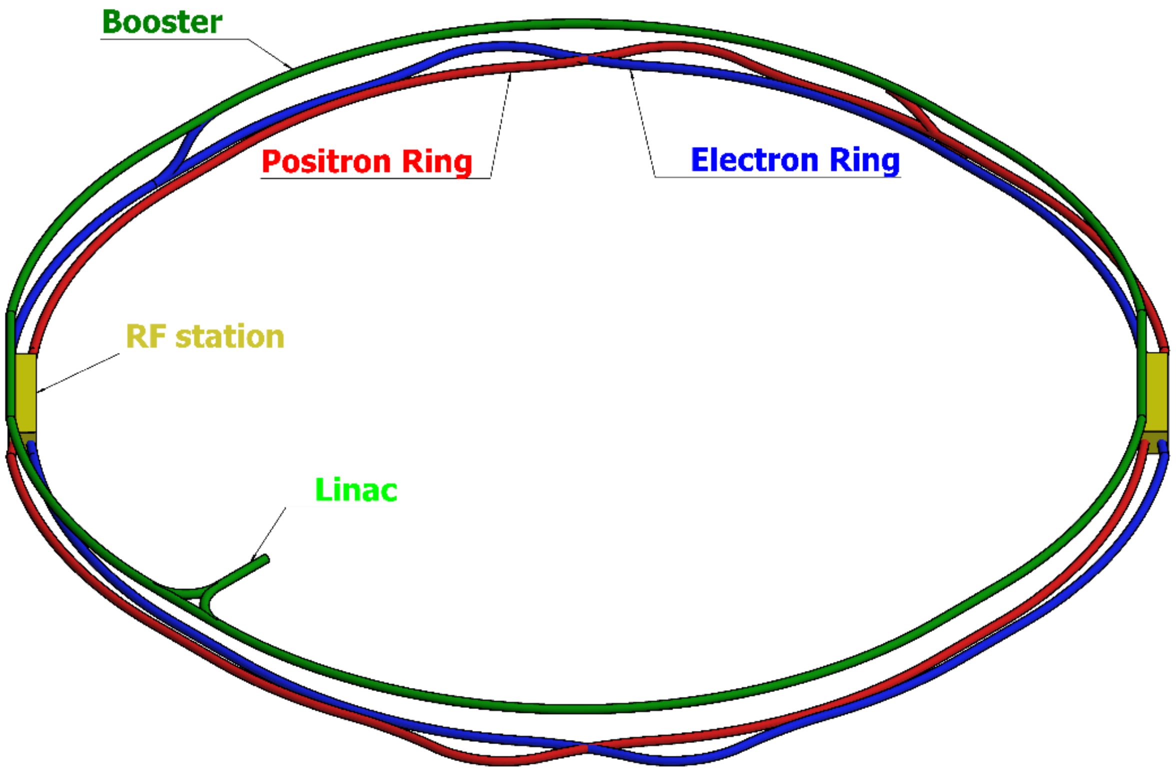
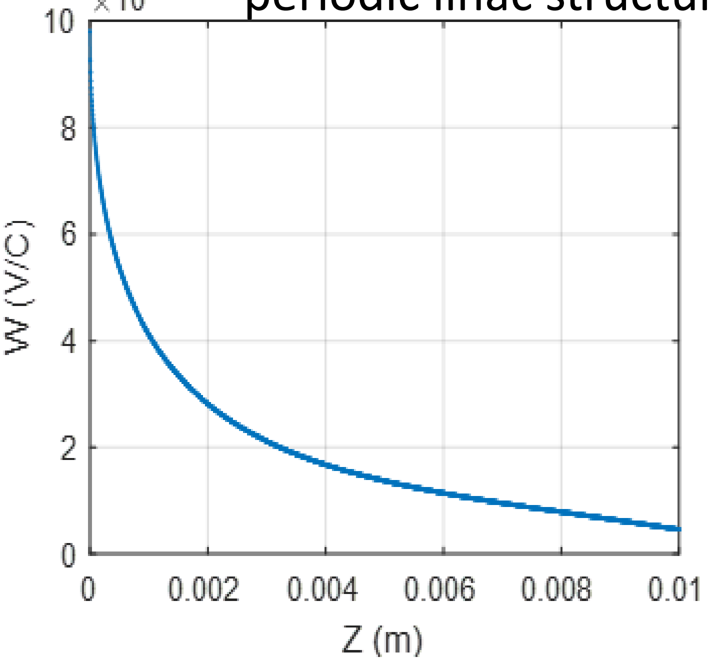
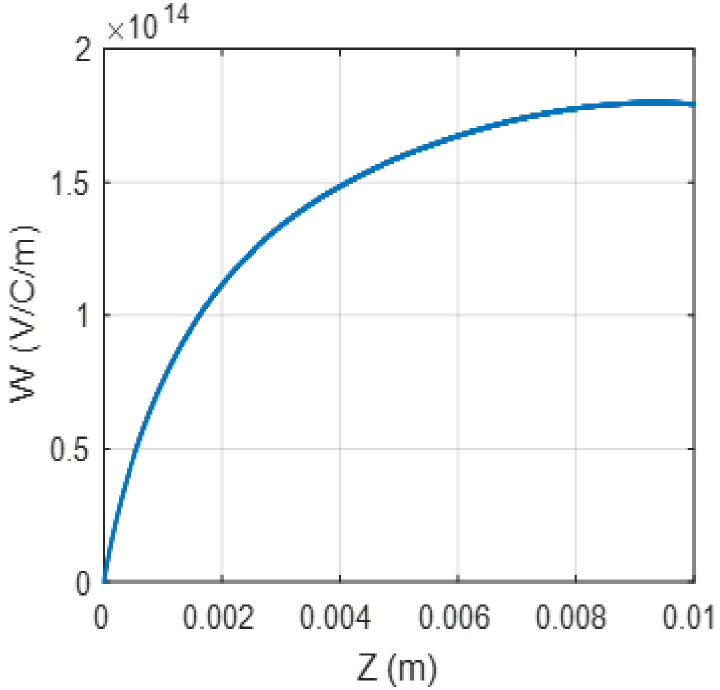


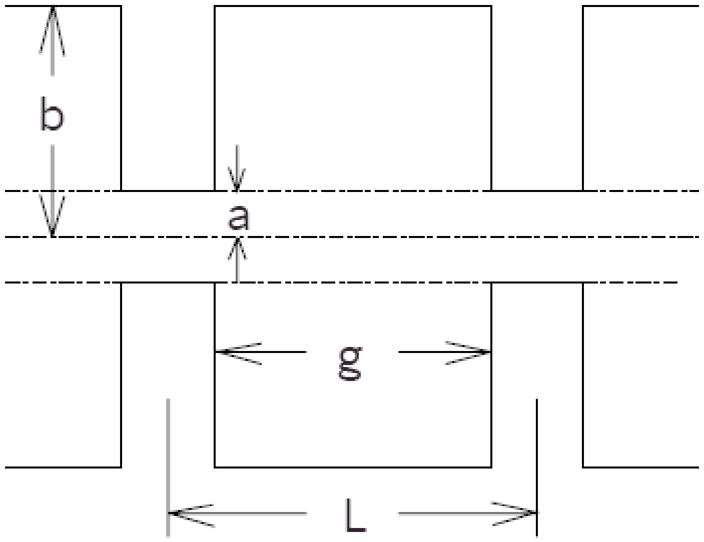
Linac design

Short-Range Wakefield

- k. Yokoya and K. bane's Wakefield model
  - periodic linac structure







The short-range wake is obtained by Inverse Fourier transforming:

$$W_L(s) = \frac{Z_0 c}{\pi} \exp\left(\frac{\pi s}{4 s_{00}}\right) erfc\left(\sqrt{\frac{\pi s}{4 s_{00}}}\right)$$

with $s_{00} = \frac{g}{8}\left(\frac{a}{\left(1-0.465\sqrt{g/p}-0.07\,g/p\right)p}\right)^2$ for $s>0$ and $W_L(s)=0$ for $s<0$.

For short s (1) can be rewritten in the following simpler way:

$$W_L(s) \approx \frac{Z_0 c}{\pi a^2} \exp\left(-\sqrt{\frac{s}{s_{00}}}\right)$$

$$W_x(s) = \frac{4 Z_0 c s_{00}}{\pi a^4}\left[1-\left(1+\sqrt{\frac{s}{s_{00}}}\right)\exp\left(-\sqrt{\frac{s}{s_{00}}}\right)\right]$$

$$S_{00} = 0.169 \frac{a^{1.79} g^{0.38}}{L^{1.17}}$$

$$W_L(s) = \frac{cZ_0}{\pi a^2}\left[1 + W_{L1}\sqrt{\zeta} + W_{L2}\zeta + W_{L3}\zeta\sqrt{\zeta}\right]$$

$$W_T(s) = \frac{cZ_0}{\pi a^4} s\left[2 + W_{T1}\sqrt{\zeta} + W_{T2}\zeta + W_{T3}\zeta\sqrt{\zeta}\right]$$

$$W_{L1} = -1.614 r^{0.122}, \quad W_{L2} = +1.012 r^{0.169}, \quad W_{L3} = -0.231 r^{0.111}$$

$$W_{T1} = -2.781 r^{0.217}, \quad W_{T2} = +1.637 r^{0.511}, \quad W_{T3} = -0.364 r^{0.793}$$

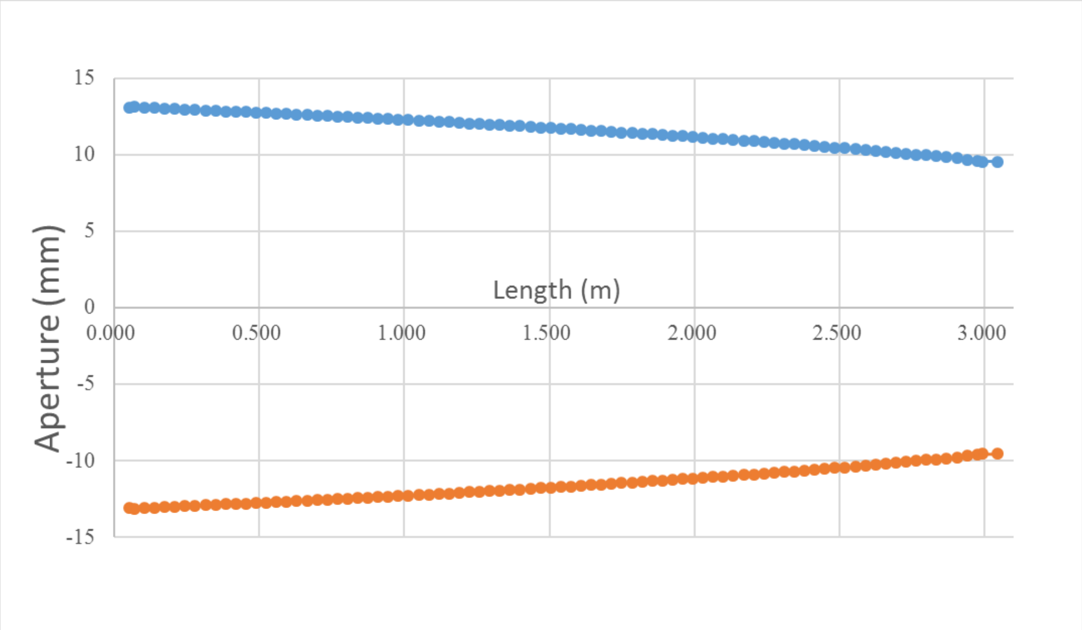
$$\zeta = \frac{Ls}{a^2} \qquad r = \frac{a/\lambda}{0.15}.$$

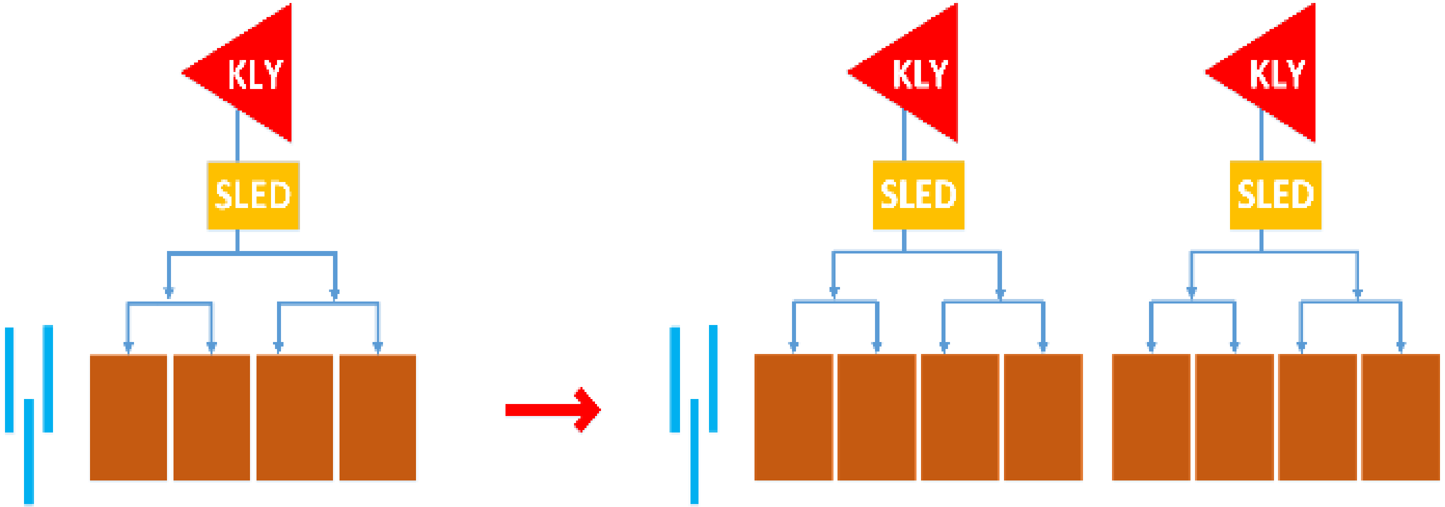
k. Yokoya and K. bane, "The longitudinal high-frequency impedance of a periodic accelerating structure", Proceedings of the 1999 IEEE Particle Accelerator Conference Vol. 3 pag. 1725, New York, March 1999

Linac design

Electron linac

- Focusing structure: ***Triplet***
  - Long drift length for accelerating tubes
  - Beam size in Acc. tubes is small and controllable
  - Same beam envelopes at X/Y planes
  - *1 triplet+4 Acc. tubes→1 triplet+8 Acc. tubes*
- Operation mode :
  - High charge mode (positron production)
    - 4GeV & 10 nC
  - Low charge mode (electron injection)
    - 10 GeV & 3 nC

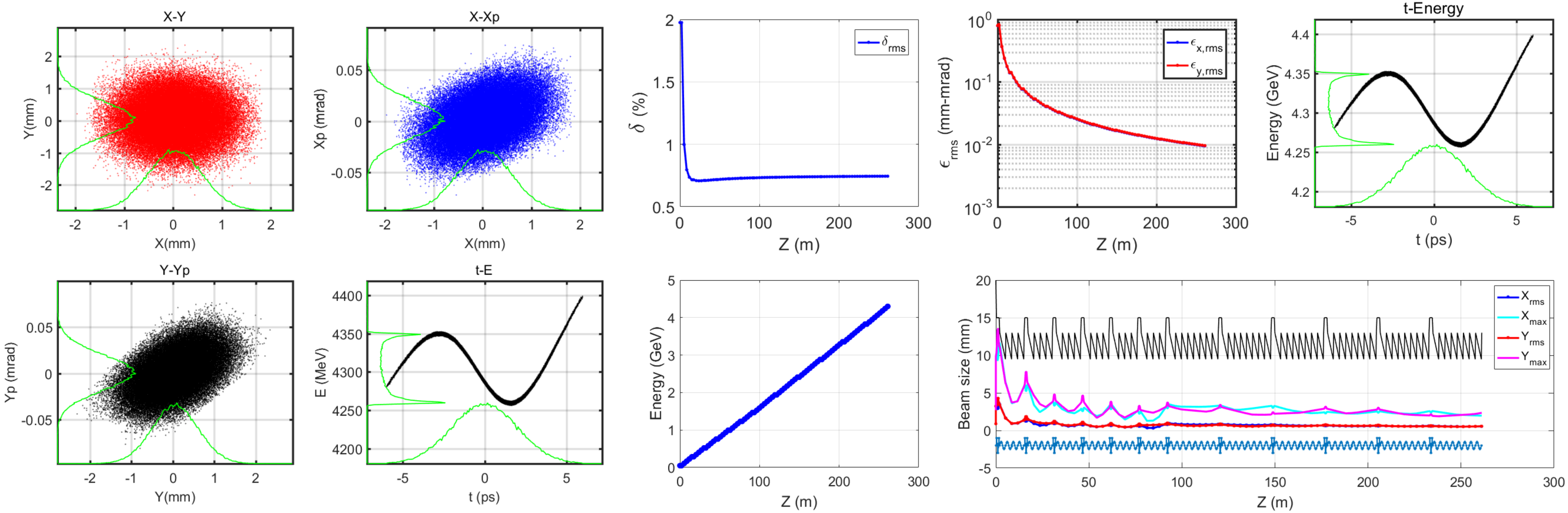




Linac design

Electron linac

- High charge mode
  - 10 nC && 4 GeV
  - Energy spread (rms): 0.8%
  - Emittance growth (challenge with errors and correction)

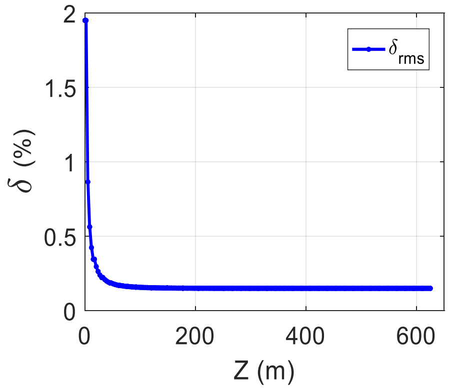


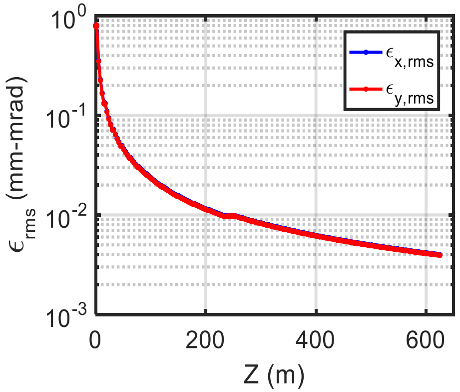
Linac design

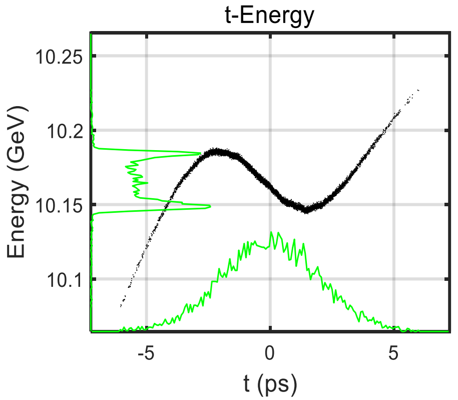
Electron linac

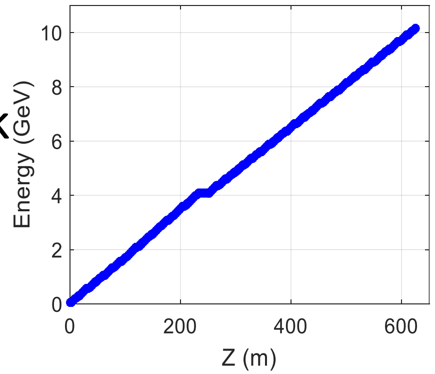
- Low charge mode
  - 3 nC && 10 GeV without bypass
  - Energy spread (rms): 0.15%
  - Emittance (rms): 5 nm
- Bypass scheme
  - electron transport line bypass
    - ***Simplicity***
    - A bit higher cost, more magnets
  - target bypass
    - Moveable target: alignment & mechanics
    - Low energy part for positron linac is week focusing for high energy electron, e.g. quadrupoles and correctors

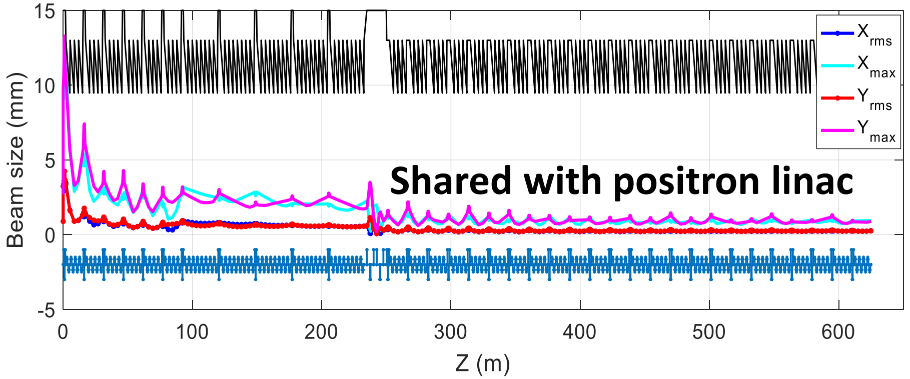
Energy spread (e^- /e^+)	σ_E		<2×10^{-3}
Emittance (e^- /e^+)	ε_r	mm· mrad	<0.3







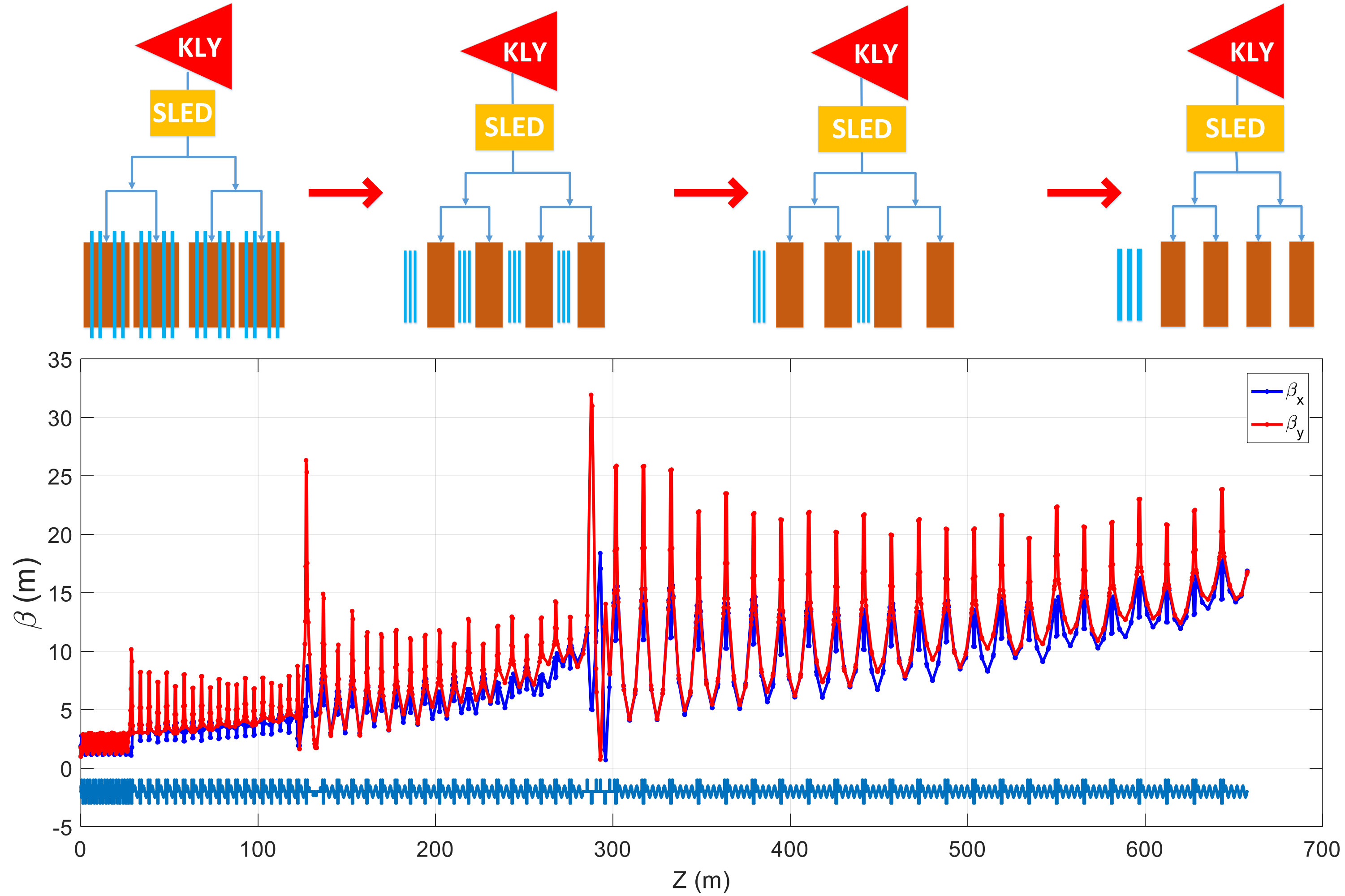




Linac design

Positron linac

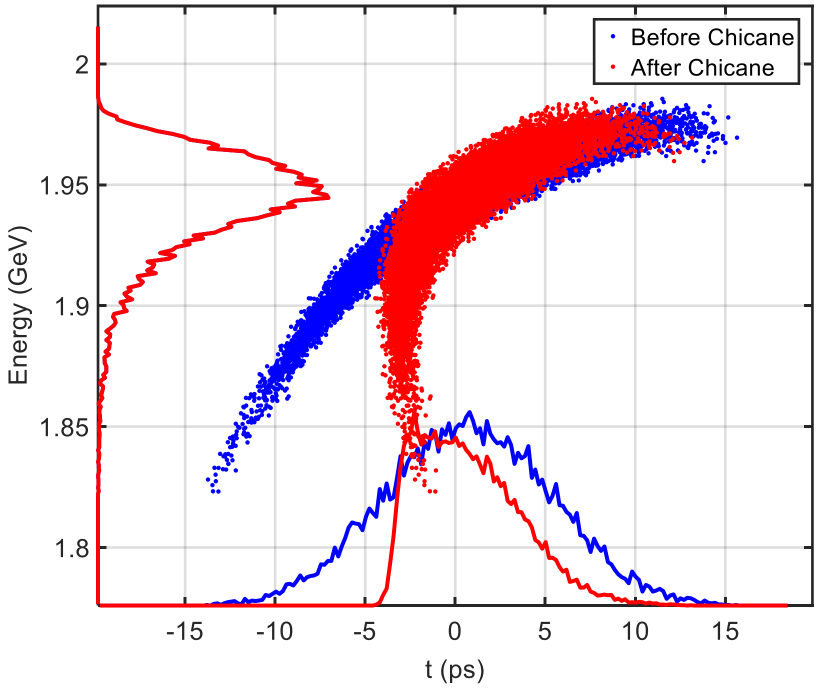
- Because of the larger emittance of positron beam, the lattice design of shared linac is focused on positron beam, especially the transverse focusing structure.
- Transverse focusing structure
  - **FODO, nesting on Acc. tubes**
  - **Triplet**
- Positron linac
  - Controlled β function
  - Large emittance
    - Need smaller β
  - Longer period length
    - Reduce quadrupole number
    - Cause larger β
  - Triplet number
    - Further optimization

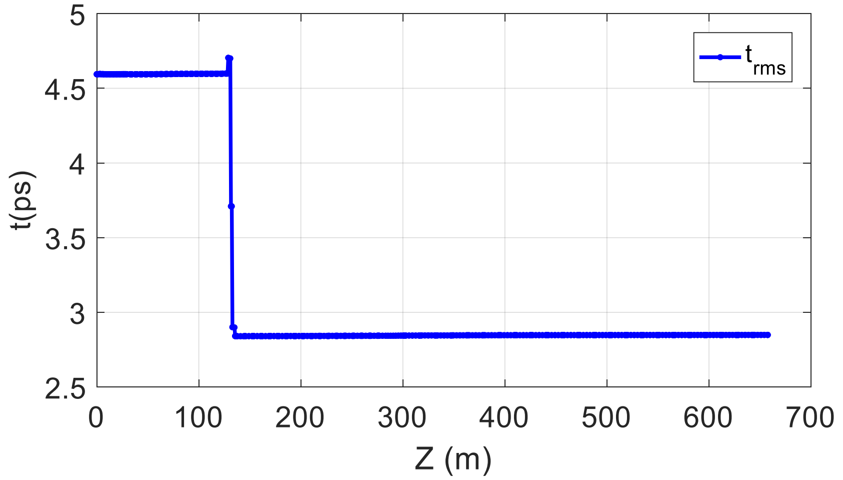


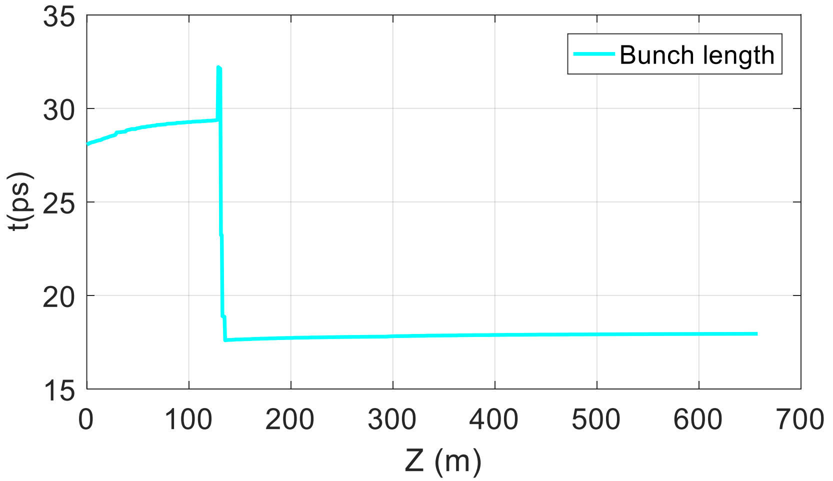
Linac design

Positron linac

- Bunch length is large for positron beam and energy spread cannot meet the requirement of Booster
  - Bunch length compressor: chicane
    - Higher energy: smaller beam size and reduce beam loss
    - Lower energy: smaller chicane
  - Chicane
    - Energy: ~ 2GeV
    - RF phase: 80 degree
    - Bending angle: 6 degree
    - Rectangular magnet:
      - achromatic structure
    - R_{56}=-57.3 mm





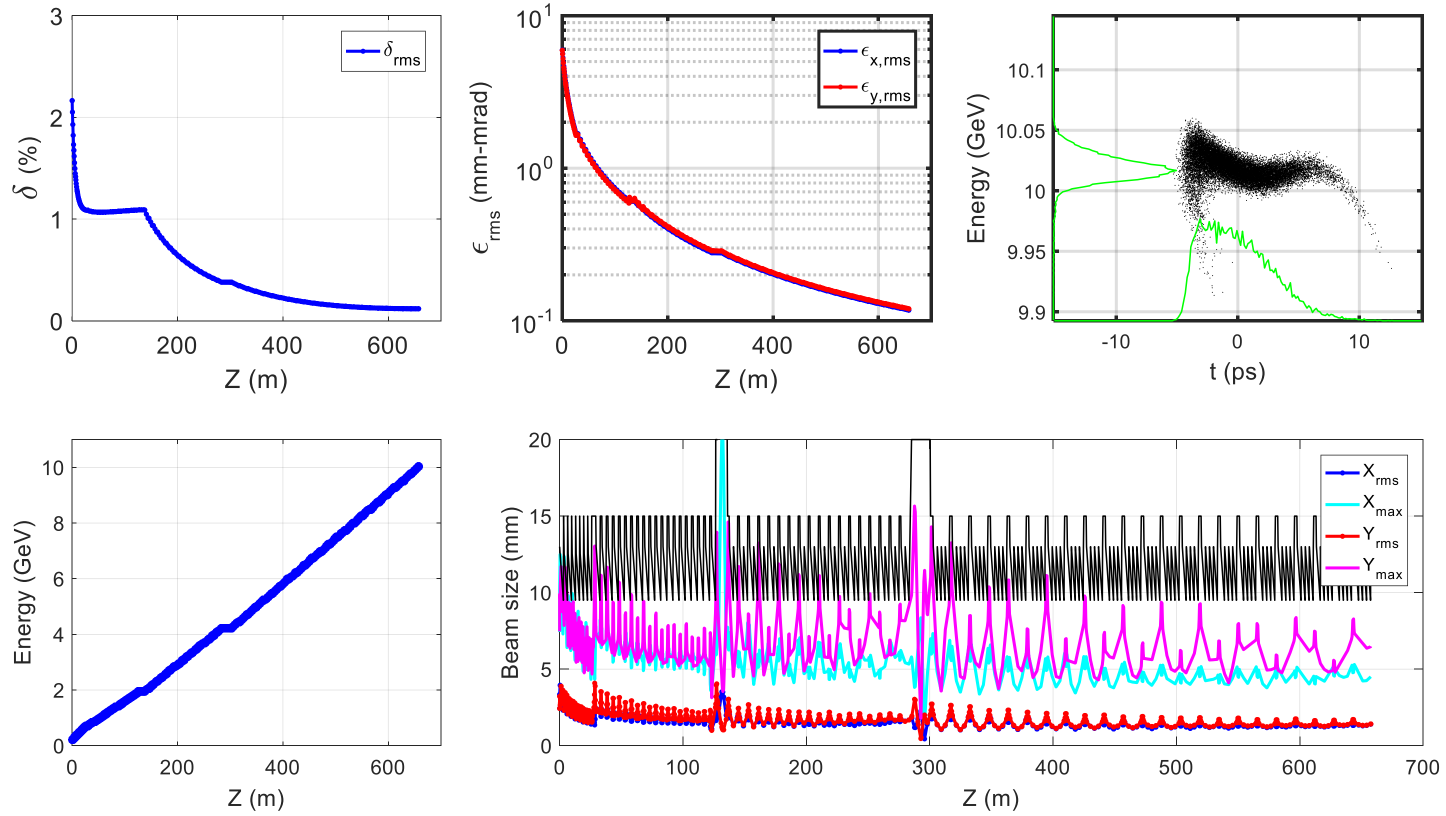


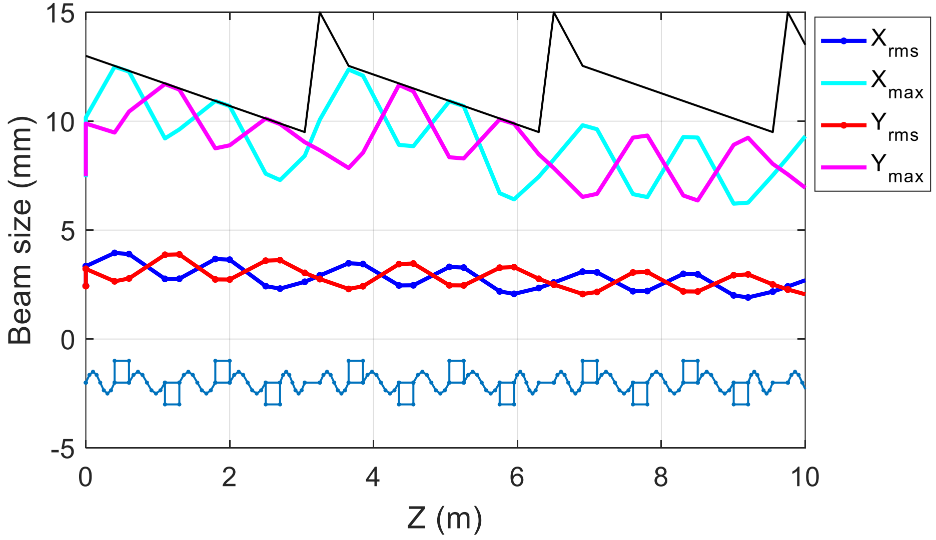
Linac design

Positron linac

- Positron linac
  - 3 nC && 10 GeV
  - Energy spread (rms): 0.12%
  - Emittance (rms): 120 nm

Energy spread (e^- /e^+)	σ_E		<2×10^{-3}
Emittance (e^- /e^+)	ε_r	mm· mrad	<0.3





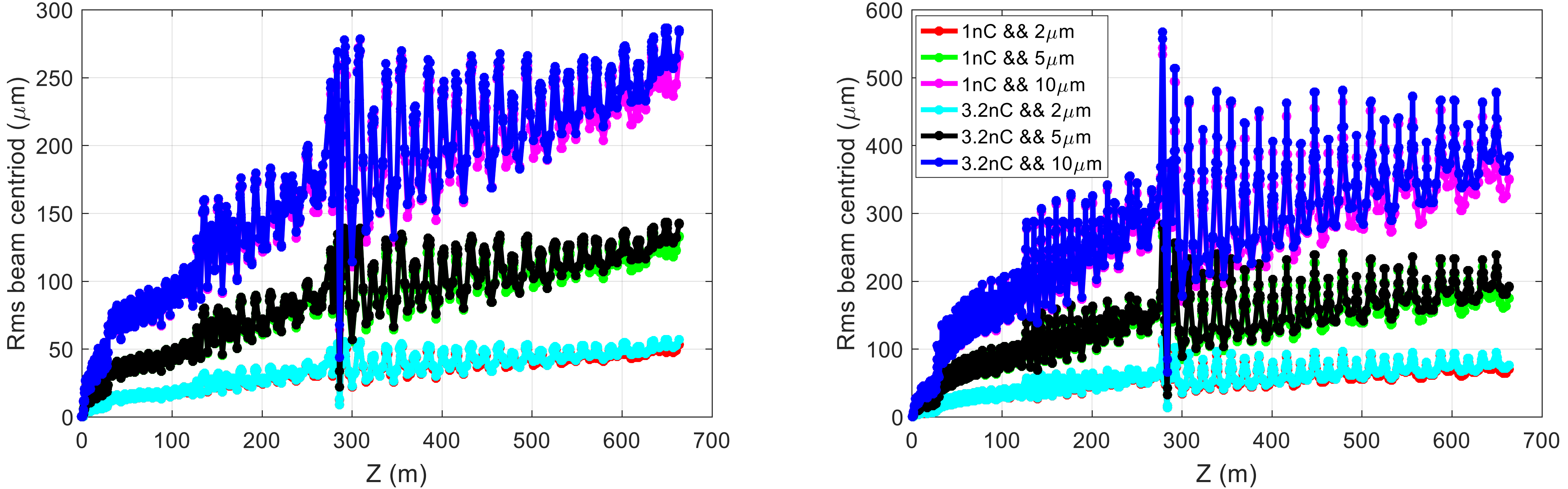
Beam loss: 2%

Error study

Vibration

- Simulation condition
  - 10k particles
  - 100 seeds
  - Dynamic errors:
    - Quadrupole transverse vibration
      - 2 μm、5 μm、10 μm
    - Uniform distribution

- Simulation results
  - If rms beam obit jitter <0.1 mm, the dynamic vibration <2 μm
  - **If rms beam obit (dynamic) <0.2 mm, the dynamic vibration <5 μm**
    - Normal value

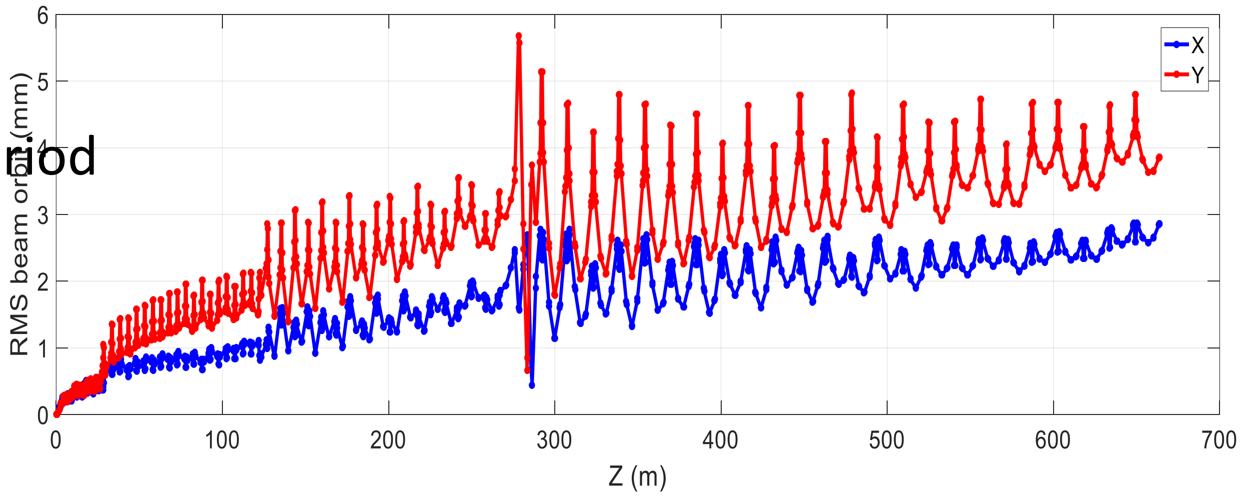


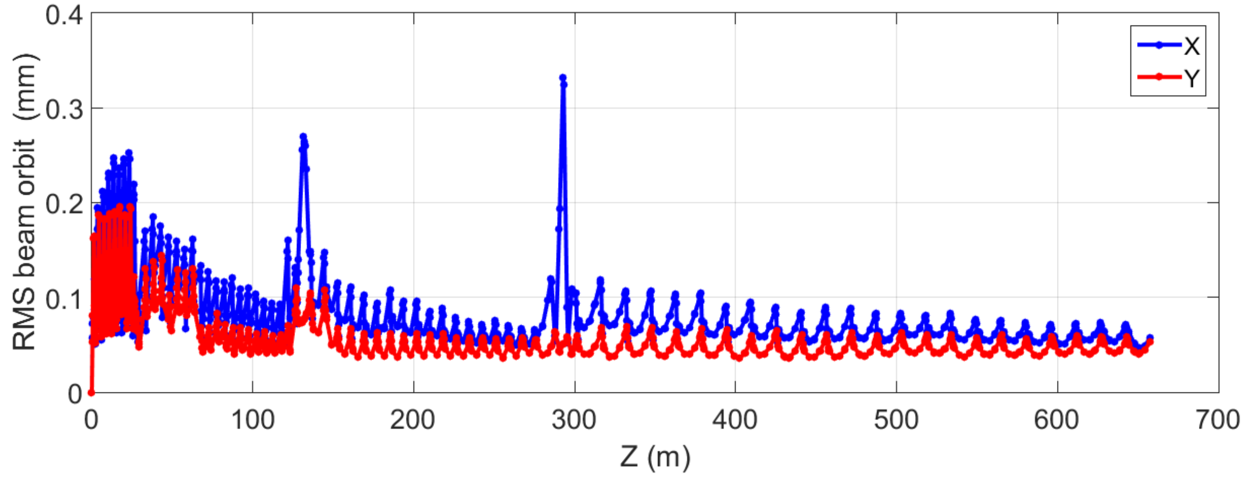
Error study

Misalignment errors with correction

- **Positron linac**
  - 500 seeds with correction
    - One-to-one correction scheme for each period
  - Errors:
    - Gaussian distribution, 3σ truncated
- Beam orbit
  - RMS value< 0.3 mm
  - Rms value< 0.1 mm (high energy part)

Error description	Unit	Value
Translational error	mm	0.1
Rotation error	mrad	0.2
Magnetic element field error	%	0.1
BPM uncertainty	mm	0.1

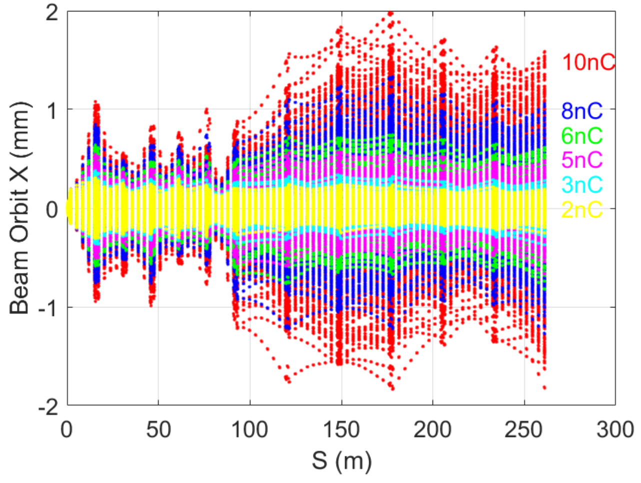


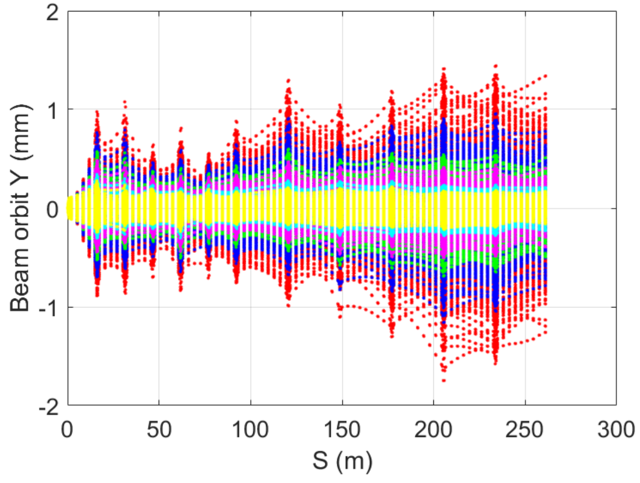


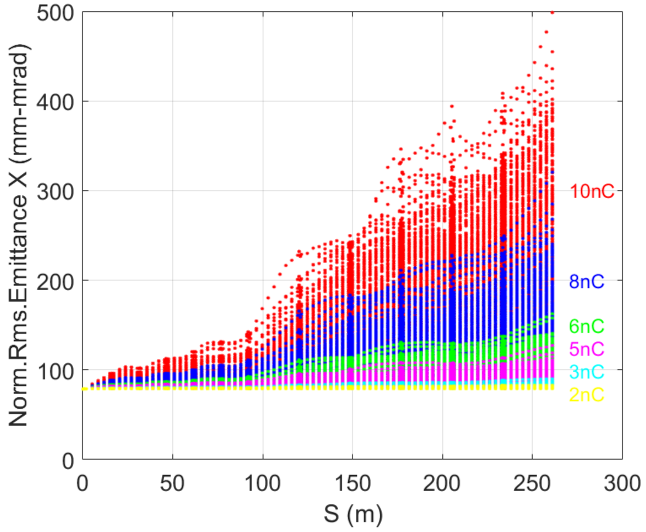
Error study

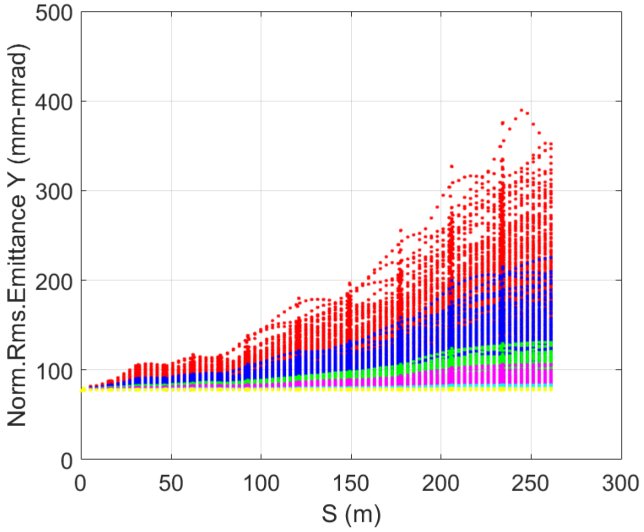
Misalignment errors with correction

- Electron linac
  - First orbit correction + multi-particles simulation
  - Low charge
    - Beam orbit can be controlled well
  - High charge
    - Misalignments of Acc. Tubes
    - BPM noisy
    - **Wakefield**
  - In operation, the orbit and emittance growth can be controlled better. Correction is based on multi-particles orbit
  - Meet the requirements for positron production





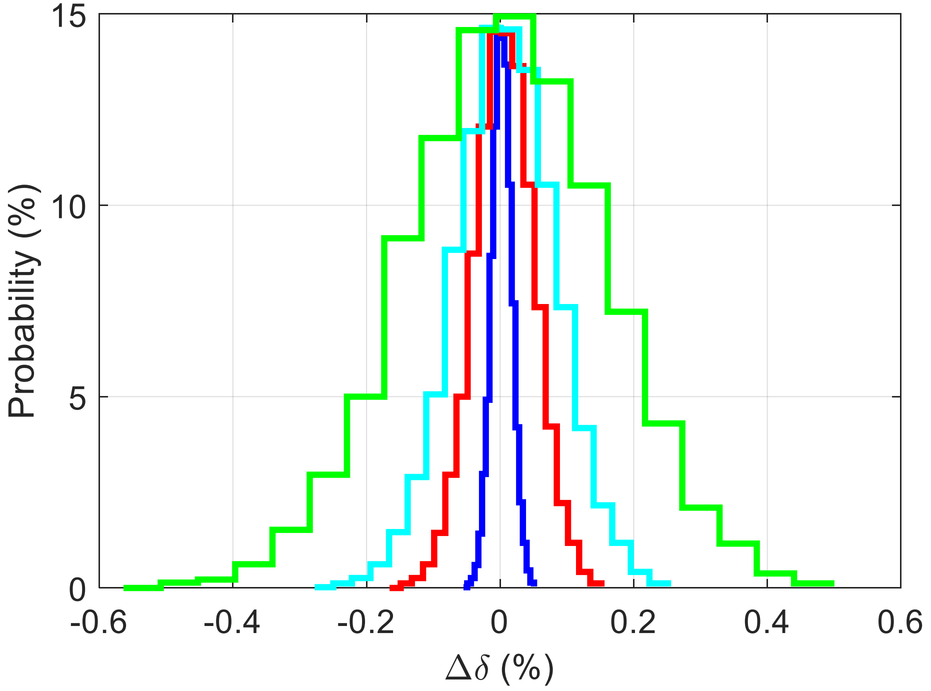




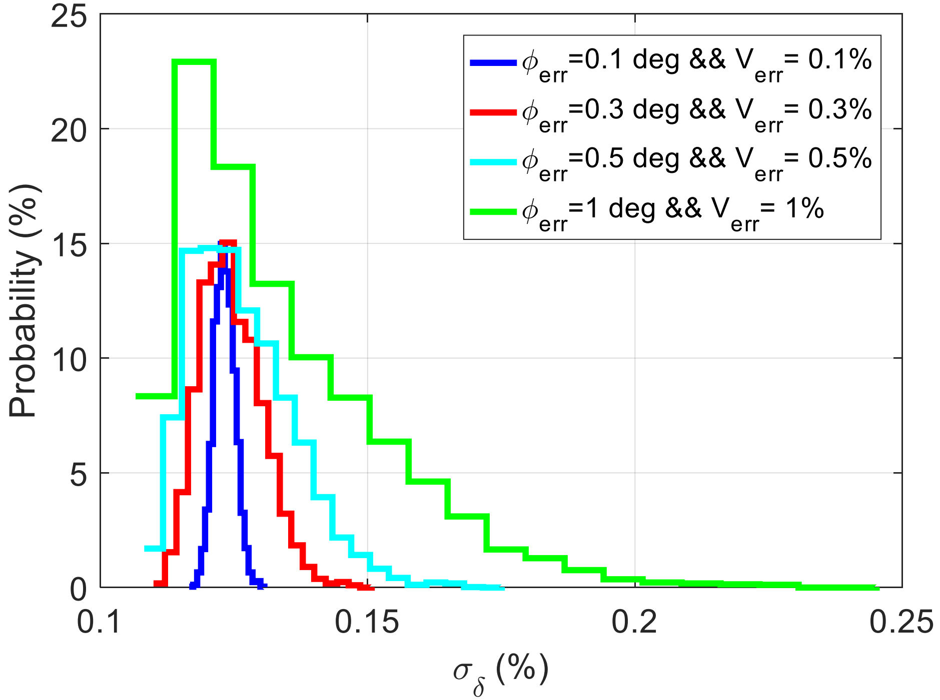
Linac design

Energy jitter

- Simulation condition
  - 5000 seeds
  - Accelerating tubes
    - phase errors and amp errors
    - 4 in 1 KLY, 4 accelerating tubes in one group
    - 3σ--Gaussian



- Energy spread < 0.2%
  - Phase errors: 0.5 degree (rms)
  - Amp errors: 0.5% (rms)
- Energy jitter: 0.2%



Linac design

Parameter	Symbol	Unit	Goal	Status
e^-/e^+ beam energy	E_{e-}/E_{e+}	GeV	10	10/10
Repetition rate	f_{rep}	Hz	100	100
e^-/e^+ bunch population	*Ne-/Ne+*		$>6.25\times10^9$	1.9×10^{10} 1.9×10^{10}
	Ne-/Ne+	nC	>1.0	>3.0/3.0*
Energy spread (e^-/e^+)	σ_E		$<2\times10^{-3}$	1.5×10^{-3} 1.2×10^{-3}
Emittance (e^-/e^+)		mm· mrad	<0.3	0.005/0.12**
e^- beam energy on Target		GeV	4	4
e^- bunch charge on Target		nC	10	10

* Enough allowance and high bunch charge requirement possibility or potential

** Without errors

Summary

- The physics design of CEPC Linac have been proposed and the simulated beam dynamics results can meet the requirements of Booster.
- The general design of positron source have been proposed.
- There are no issue that defies solution for CEPC linac.
- Further optimization are undergoing.