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

环形正负电子对撞机
Circular Electron Positron Collider

CEPC Linac injector design status

HEP 2023

Feb. 14~16, 2023

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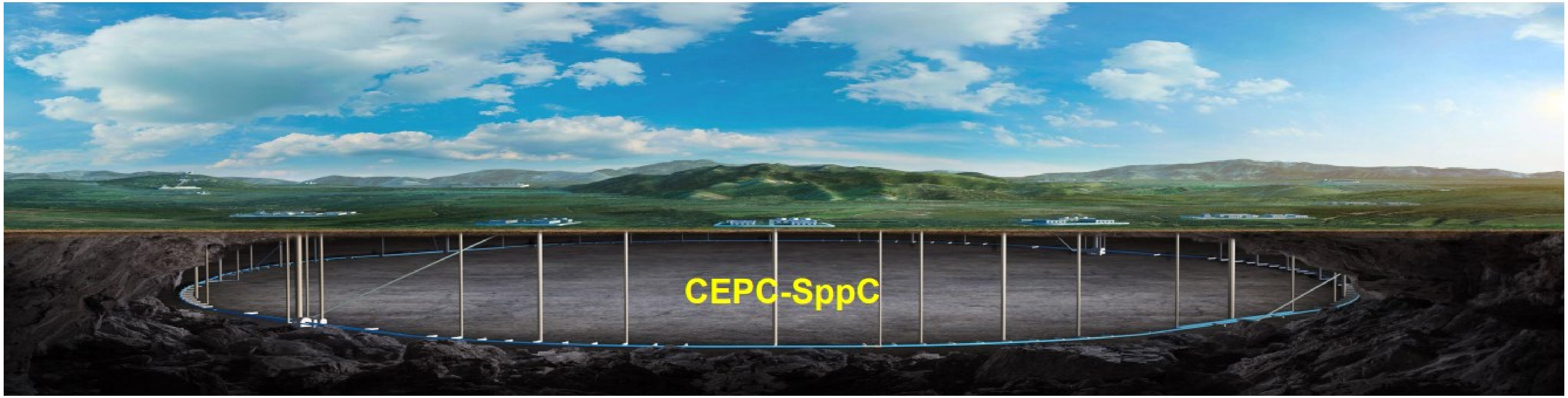
on behalf of CEPC AP group, IHEP

Outline

- ➢Introduction
- ➢CEPC Linac design status
- ➢Summary



Introduction

CEPC TDR layout

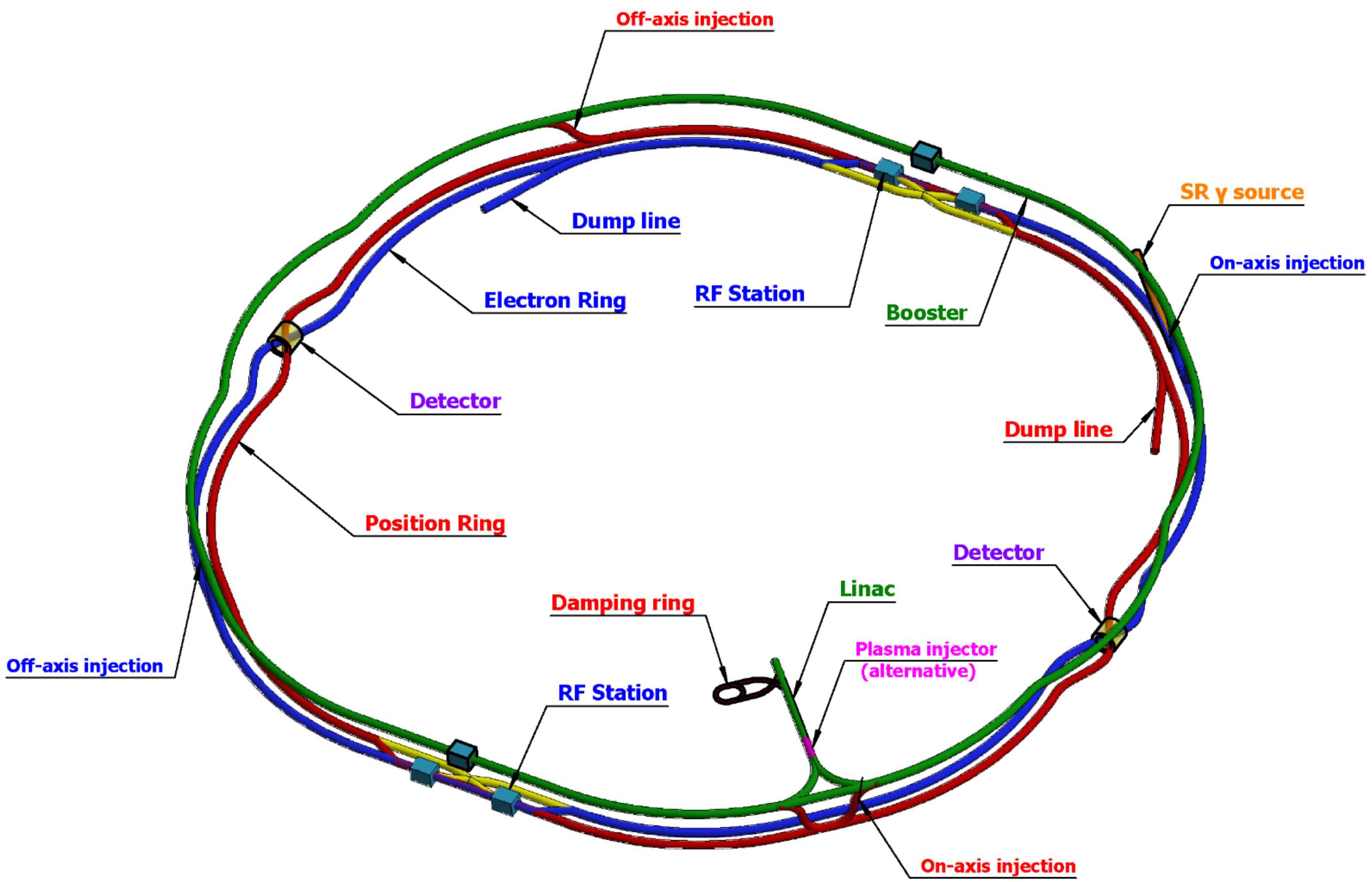
➢CEPC as a Higgs (ttbar,H, W, Z) Factory

- **Linac, 30GeV, 1.8km**
- Full energy Booster, 100km
- Collider, 100 km
- Transport lines

➢Linac design

- Meet requirements
- High availability
- Reserve upgrade potential

$$L_{\text{int}} = \int_0^T L(t)dt = \langle L \rangle \cdot T_s \cdot \eta$$



Introduction

Energy

- The maximum energy of booster is 180GeV and circumference is 100 km
  - Low injection energy & large circumference → Low magnetic field
    - ✓ design difficulty in magnet (field) and power supply (stability)
  - Large extraction energy → Large field range
    - ✓ design difficulty in magnet (excitation efficiency) and power supply (power)
- Increasing the energy of the Linac is the easiest way

Magnet		Low injection energy			Max. Extraction energy	Cost
		10GeV	20GeV	30GeV	180GeV	
Air-core coil		Yes	Yes	Yes	No	high
iron-corn magnet	oriented silicon steel sheet	No	Yes	Yes	Yes	high
	Non-oriented silicon steel sheet	No	No	Yes	Yes	low

effect of residual magnetism

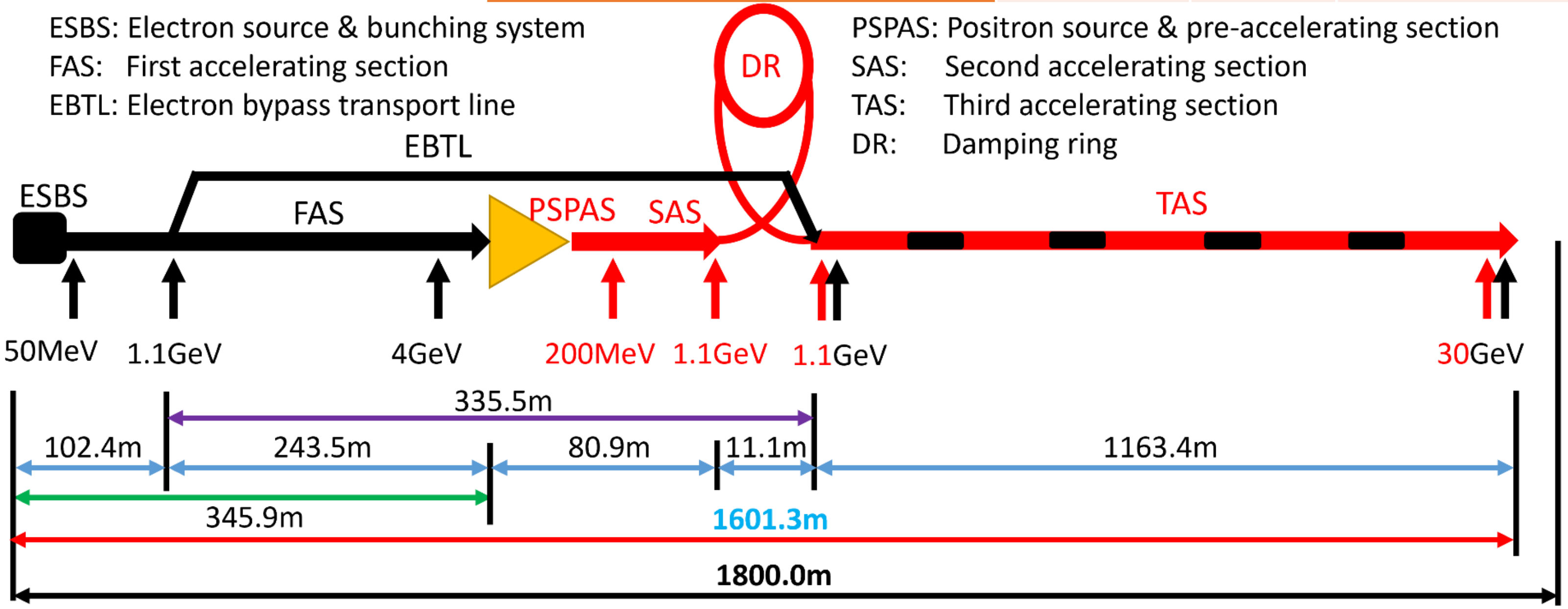
Introduction

Baseline scheme

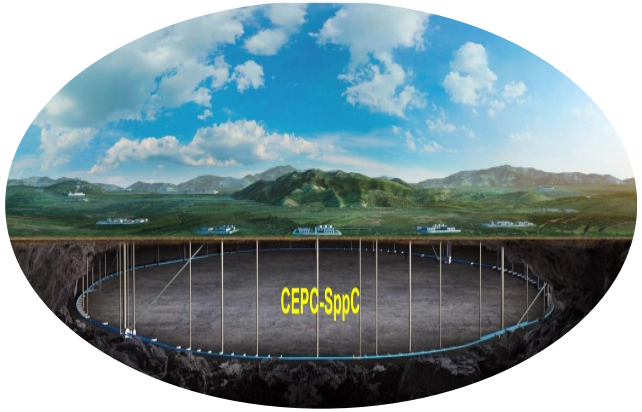
- Latest Baseline scheme (2022.6)
  - Energy: → 30 GeV
    - ✓ C-band accelerating structure @TAS
      - ☐ **Higher gradient** → Shorter linac tunnel length
      - ☐ Small aperture & Strong wakefield
- Layout
  - The tunnel is 1.8km
    - ✓ Linac is about 1.6 km
    - ✓ 200 m as reserved space

Parameter	Symbol	Unit	Baseline
Energy	E_{e-}/E_{e+}	GeV	**30**
Repetition rate	f_{rep}	Hz	100
Bunch number per pulse			1 or 2
Bunch charge		nC	1.5 (3)
Energy spread	σ_E		1.5×10^{-3}
Emittance	ε_r	nm	6.5

ESBS: Electron source & bunching system
FAS: First accelerating section
EBTL: Electron bypass transport line
PSPAS: Positron source & pre-accelerating section
SAS: Second accelerating section
TAS: Third accelerating section
DR: Damping ring



CEPC Linac design status

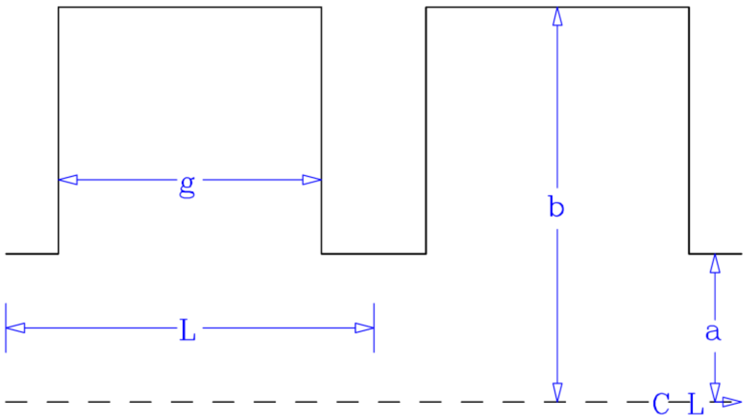


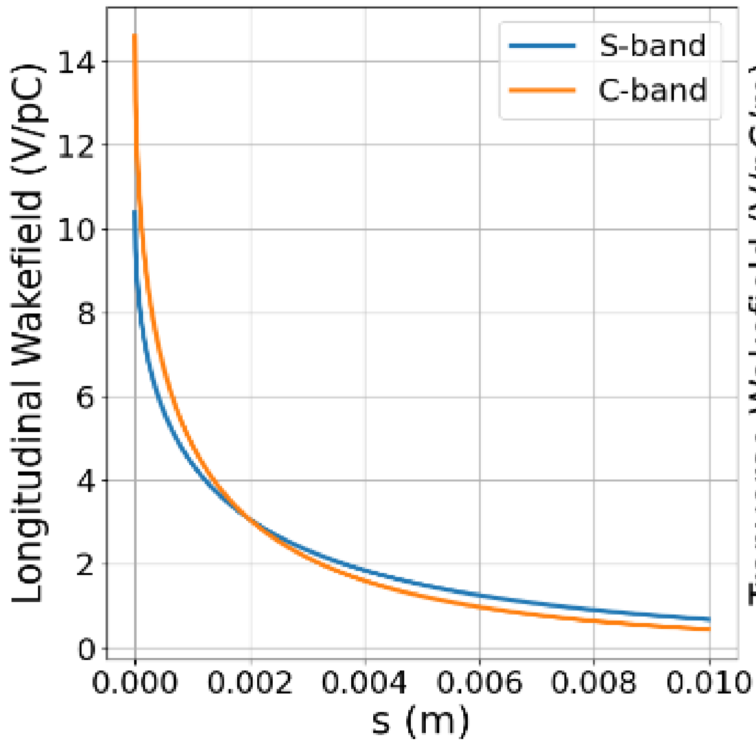
1. Basic consideration
2. Electron source and bunching system
3. Electron Linac
4. Positron Linac
   - First accelerating section(FAS)@4GeV & 10nC
   - Positron source and pre-accelerating section(PSPAS)
   - Second accelerating section(SAS)
5. High luminosity for Z scheme consideration

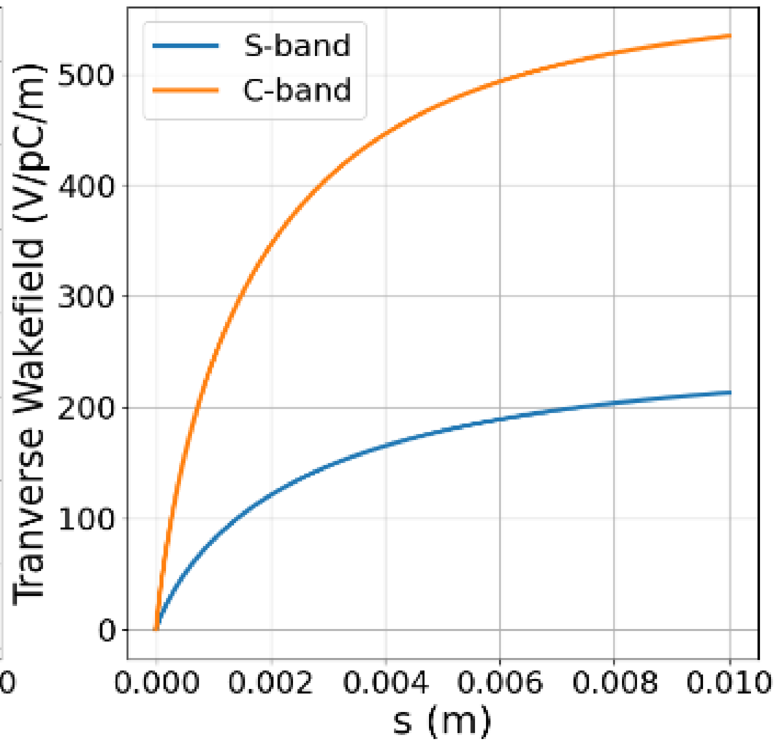
Basic consideration

Short-range Wakefield

Parameter	Unit	S-band		C-band
Frequency	MHz	2860		5720
Length	m	3.1	2.0	1.8
Cavity mode		2π/3		3π/4
Aperture	mm	19~26	25	12~16
Gradient	MV/m	22/27	22	40~45
Cells		86	55	89



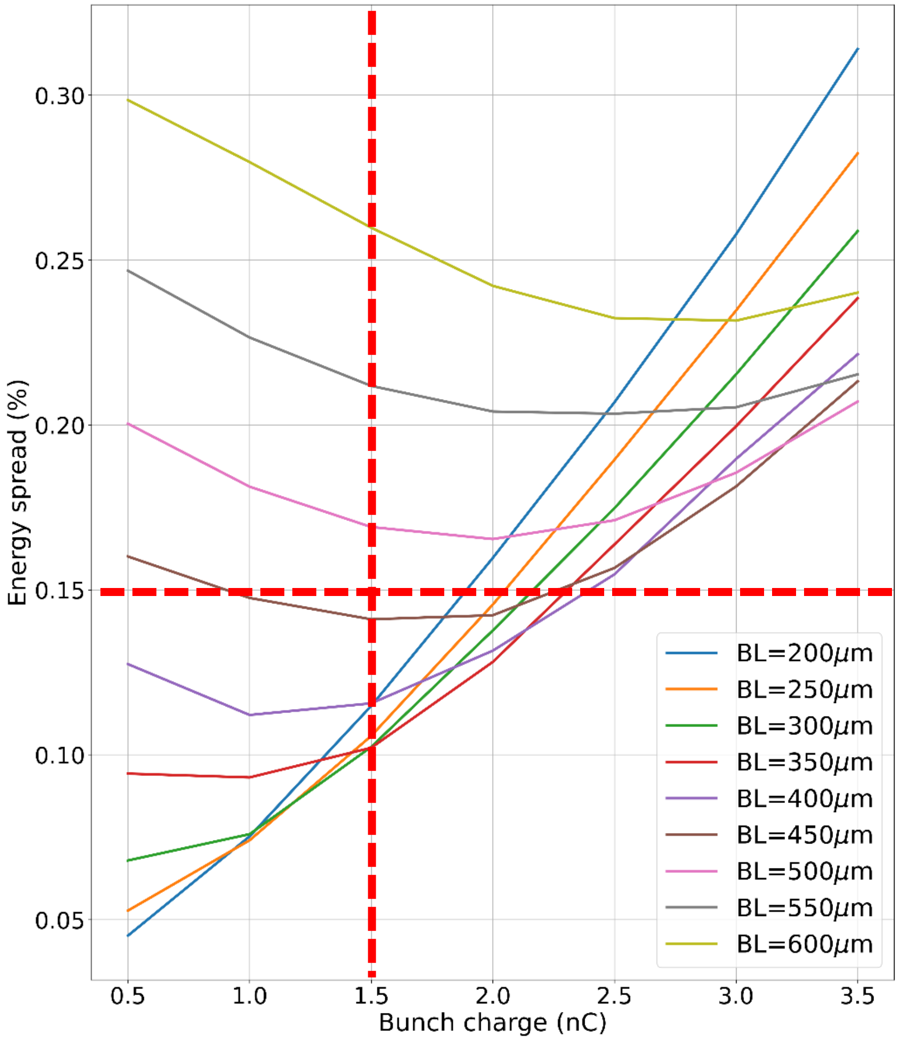


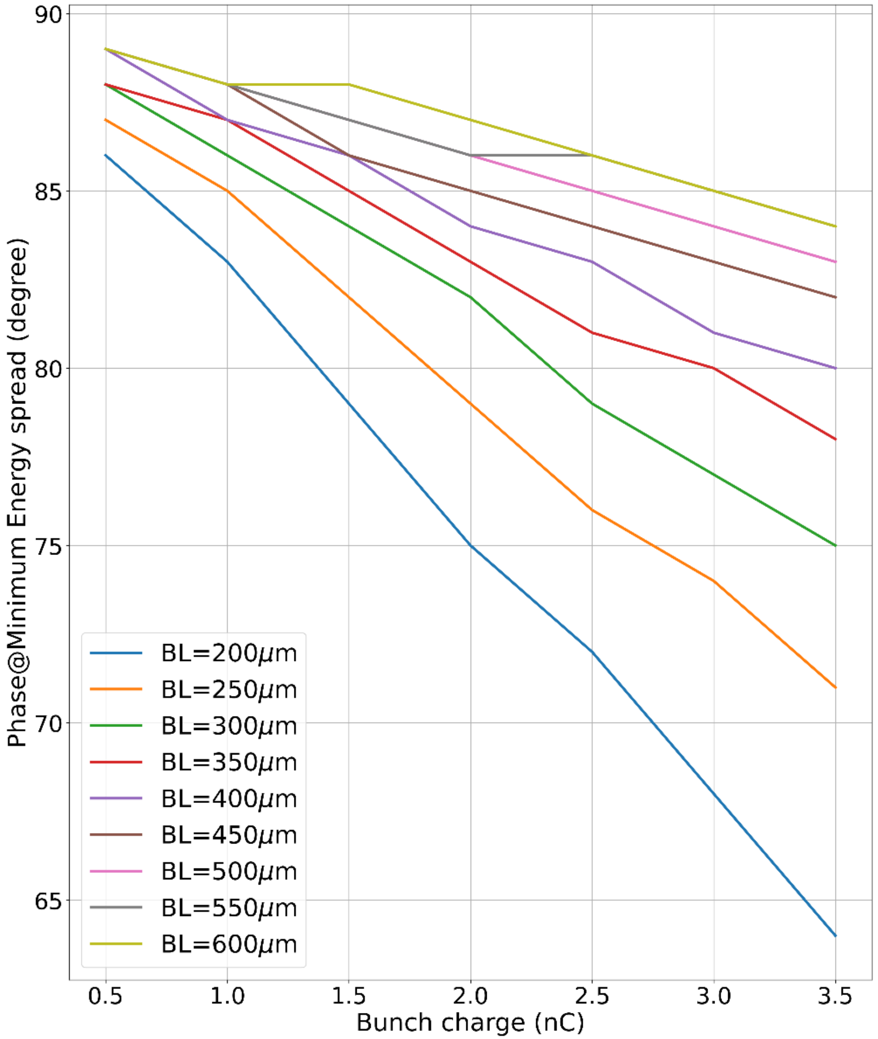


K. Yokoya and K. Bane, in *Proceedings of the 1999 IEEE Particle Accelerator Conference, New York, NY* (Piscataway, NJ, 1999), p. 1725.
Karl Bane, LCC-0116, SLAC-PUB-9663, March 2003

Basic consideration   Phase scan @ TAS

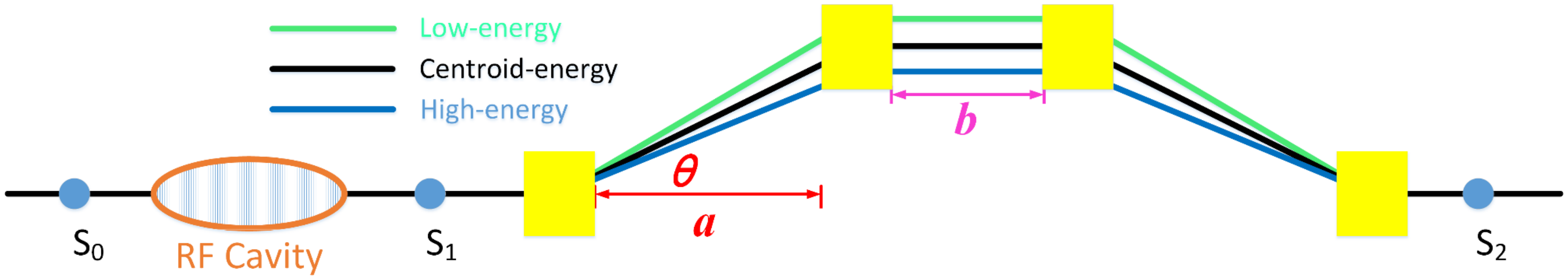
- Energy spread
  - Bunch length
    - ✓ 400μm





Basic consideration

Bunch compressor



$$\begin{pmatrix} z_2 \\ \delta_2 \end{pmatrix} = \begin{pmatrix} 1 & R_{56}^{ch} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} z_1 \\ \delta_1 \end{pmatrix} = \begin{pmatrix} 1 & R_{56}^{ch} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ R_{65}^{rf} & R_{66}^{rf} \end{pmatrix} \begin{pmatrix} z_0 \\ \delta_0 \end{pmatrix}$$

$$= \begin{pmatrix} 1 + R_{56}^{ch} R_{65}^{rf} & R_{56}^{ch} R_{66}^{rf} \\ R_{65}^{rf} & R_{66}^{rf} \end{pmatrix} \begin{pmatrix} z_0 \\ \delta_0 \end{pmatrix} = M \begin{pmatrix} z_0 \\ \delta_0 \end{pmatrix}$$

$$R_{65}^{rf} = \frac{eV}{E_1} k \cos\phi_0, k = \frac{2\pi f}{c}$$

$$R_{66}^{rf} = \frac{E_0}{E_1} = \frac{E_0}{E_0 + eV \sin\phi_0}$$

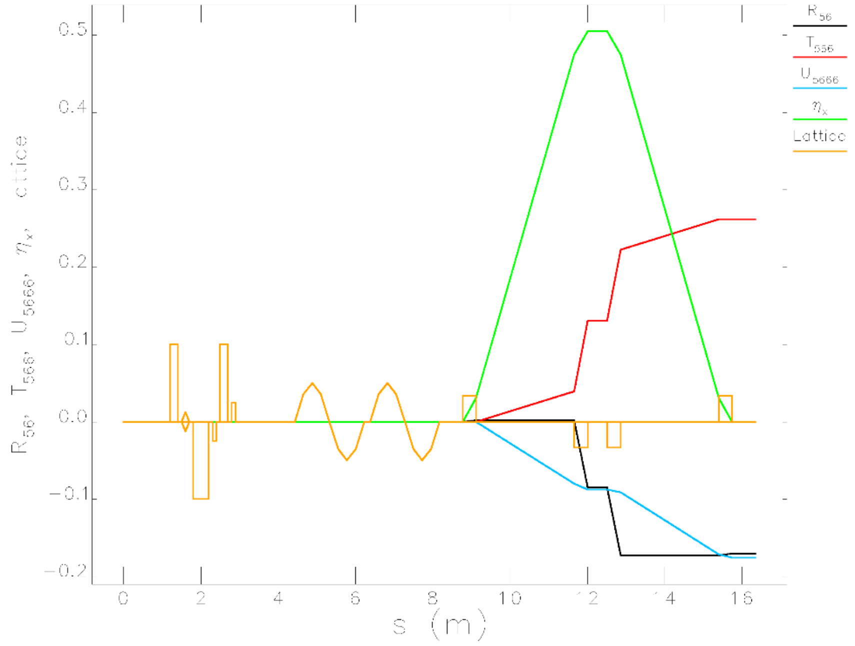
$$R_{56}^{ch} \approx -2\theta^2 (a + \frac{2}{3} L) .$$

$$F = \frac{\langle z_0^2 \rangle - \langle z_2^2 \rangle}{\langle z_0^2 \rangle \langle z_2^2 \rangle} \langle \delta_0^2 \rangle$$

$$\phi_0 = \arctan\left(\sqrt{\frac{k^2}{4F} - 3} - \frac{k}{2\sqrt{F}} \right)$$

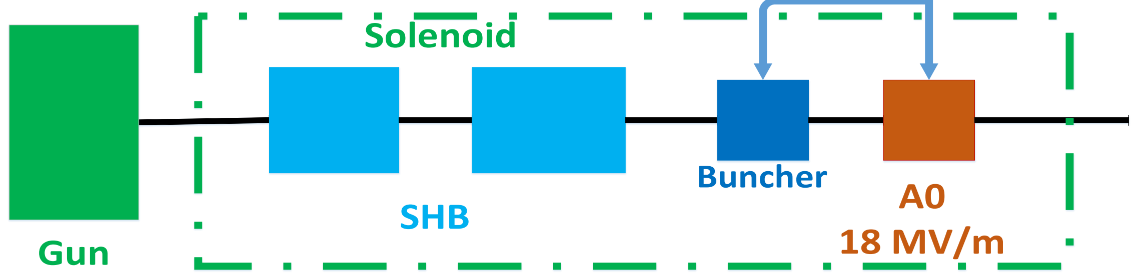
$$V = \frac{\sqrt{F} E_0}{k \cos\phi_0} ,$$

$$R_{56}^{ch} = \frac{(f^2 - 1)}{\sqrt{F}} (1 + \frac{\sqrt{F} \tan\phi_0}{k})$$

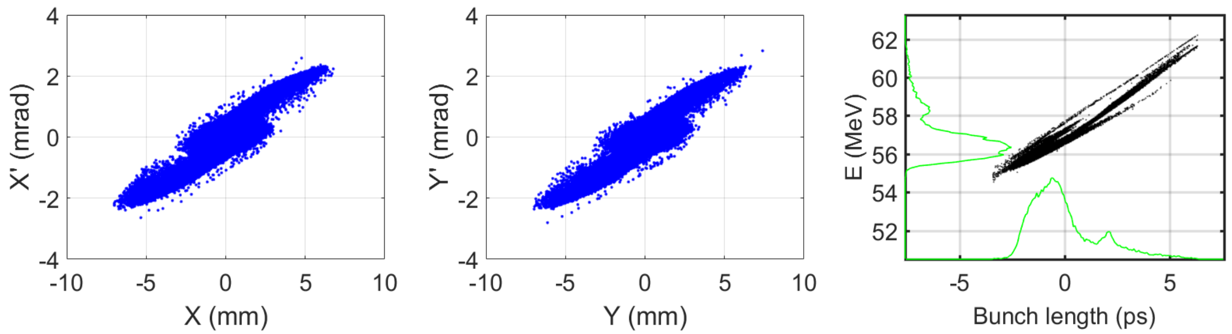


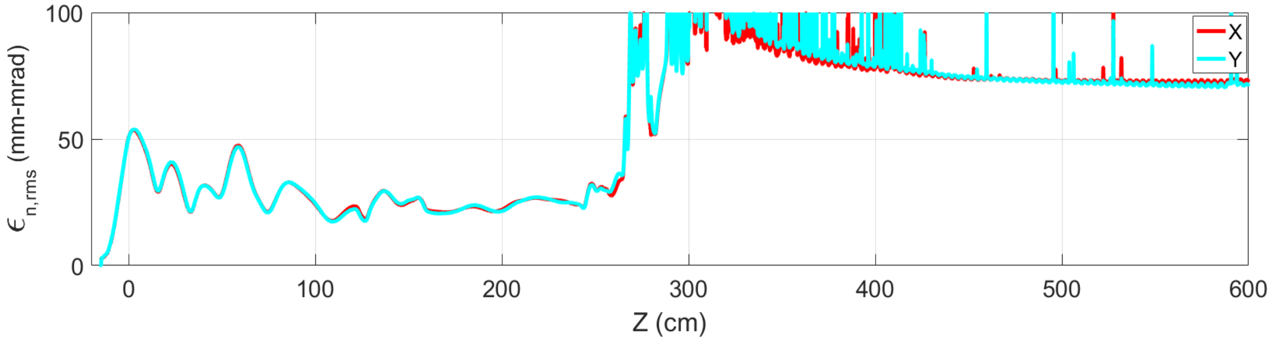
Electron source and bunching system

- Layout
  - Thermal cathode electron gun
  - **Two SHBs (158.89MHz/476.67MHz)**
  - Buncher(2860MHz)
  - Accelerating structure (2860MHz)
  - Solenoid for transverse focusing
- Simulation results
  - Energy: 50MeV
  - Normalized Rms Emittance: 80mm-mrad
  - Transmission > 90%



~3.3 nC for **electron**
~ 11 nC for **positron**

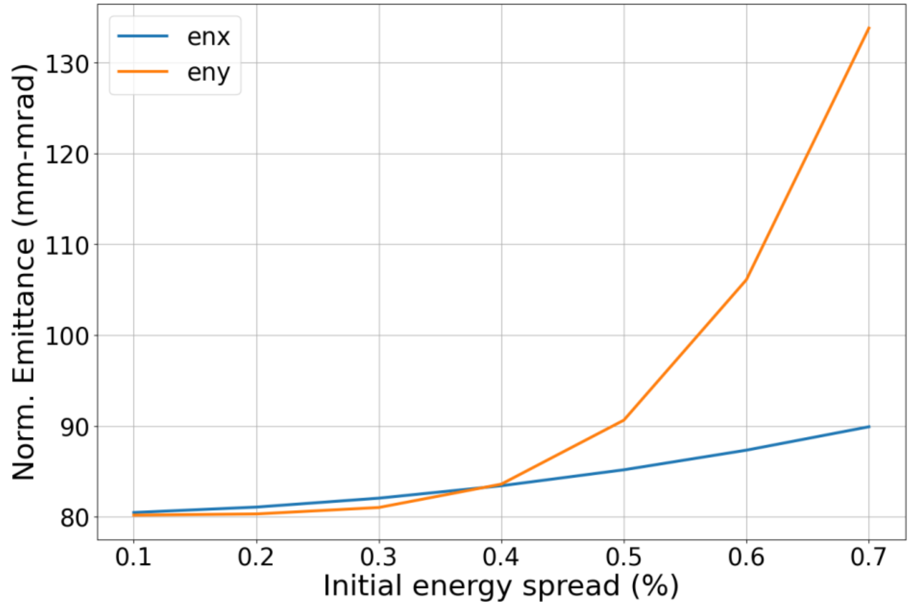




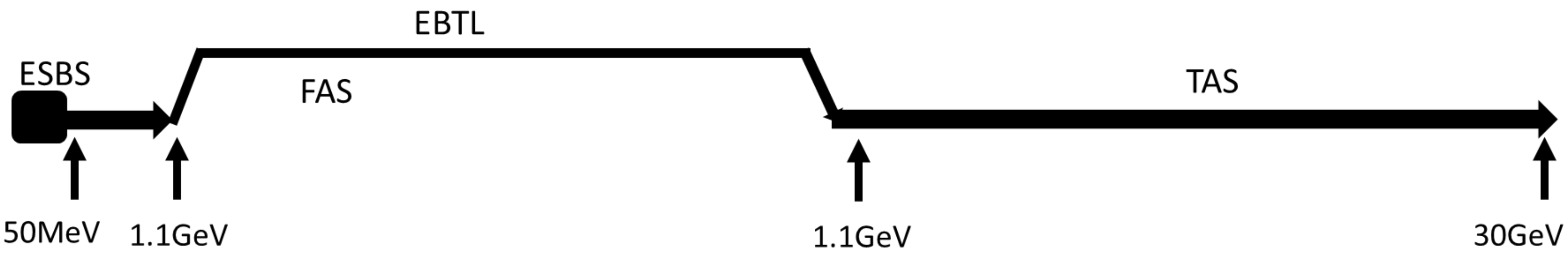
Electron Linac

Acceleration

- FAS:50MeV→1.1GeV
  - 5+1(redundancy) S-band klystron
  - 1 klystron →4 accelerating structures @22MV/m
- EBTL
  - Emittance growth → energy spread < 0.4%
- TAS: 1.1GeV→30GeV
  - Bunch compressor
  - 191+45(redundancy) C-band klystron
    - ✓ 1 klystron →2 accelerating structures@45MV/m



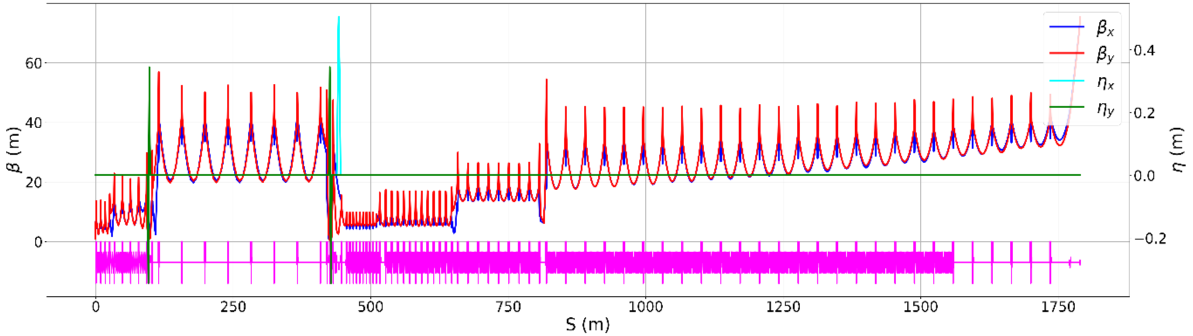
ESBS: Electron source & bunching system
FAS: First accelerating section
EBTL: Electron bypass transport line
TAS: Third accelerating section

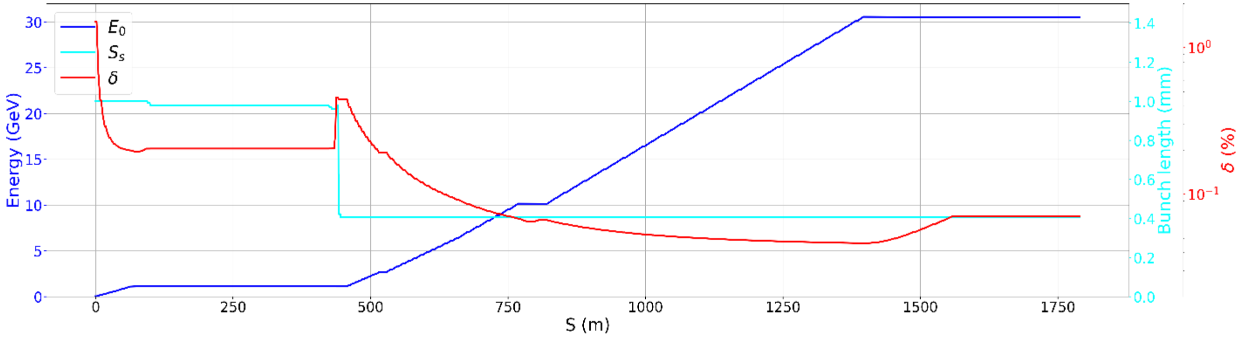


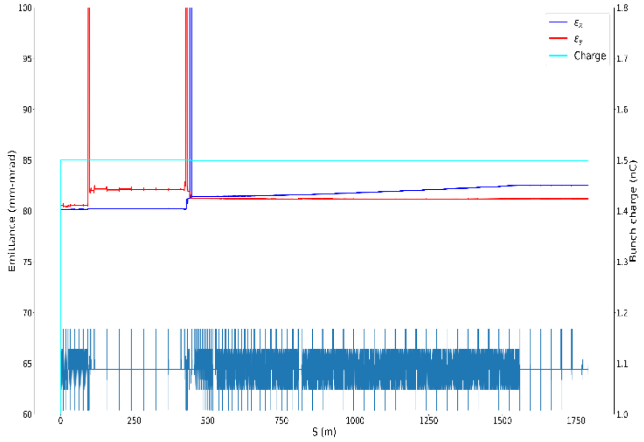
Beam dynamics results

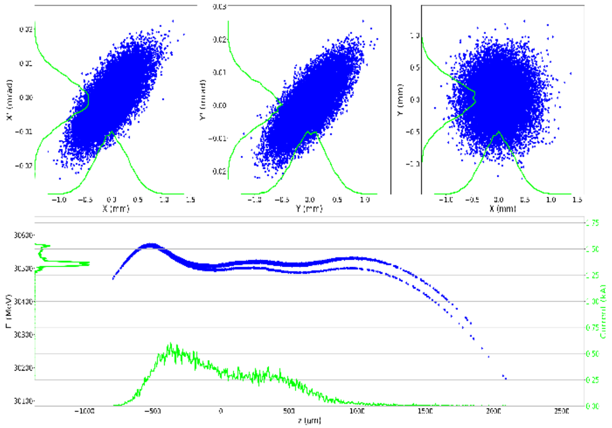
➢Simulation results(including Wakefield & CSR)

Parameter	Unit	Value	Simulated Electron	
Beam energy	GeV	30	30.52	30.02
Repetition rate	Hz	100		
Bunch charge	nC	1.5	1.5	3.0
Energy spread	10^{-3}	1.5	0.71	1.29
Emittance(x/y)	nm	6.5	1.38/1.36	1.44/1.63
Bunch length (RMS)	mm	/	0.4	0.4





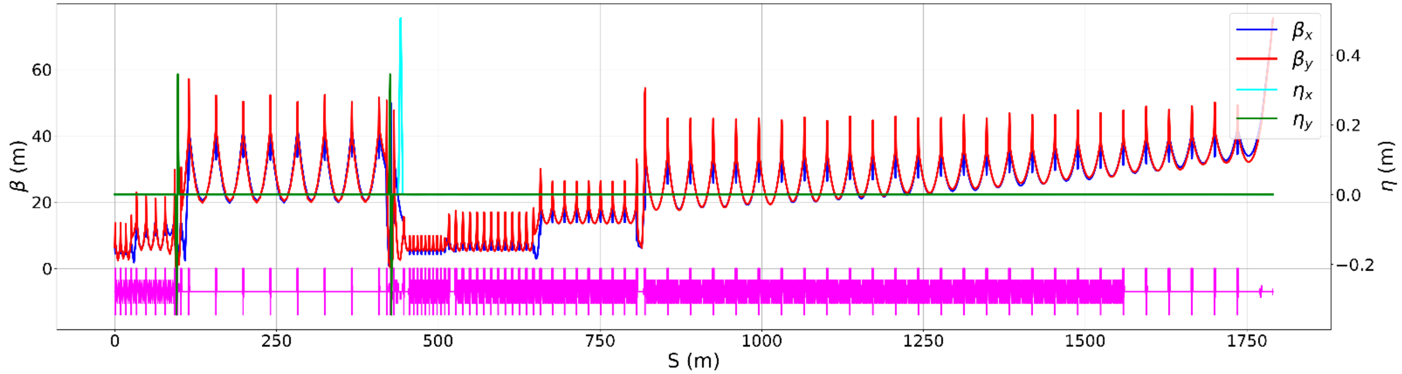


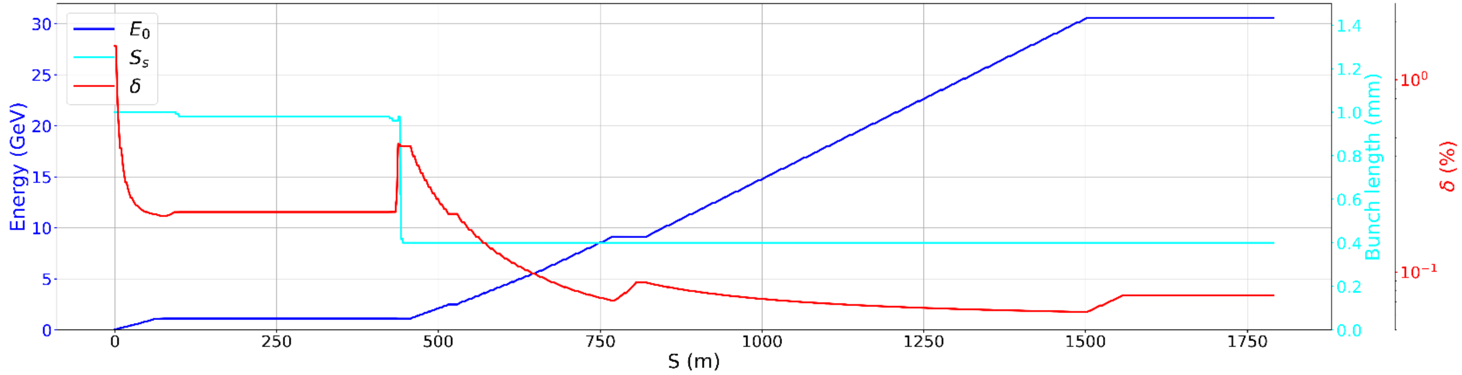


Electron Linac

Beam dynamics results

- TAS: 1.1GeV→30GeV
  - 215+21(redundancy) C-band klystron
    - ✓1 klystron →2 accelerating structures
    - ✓**40MV/m**



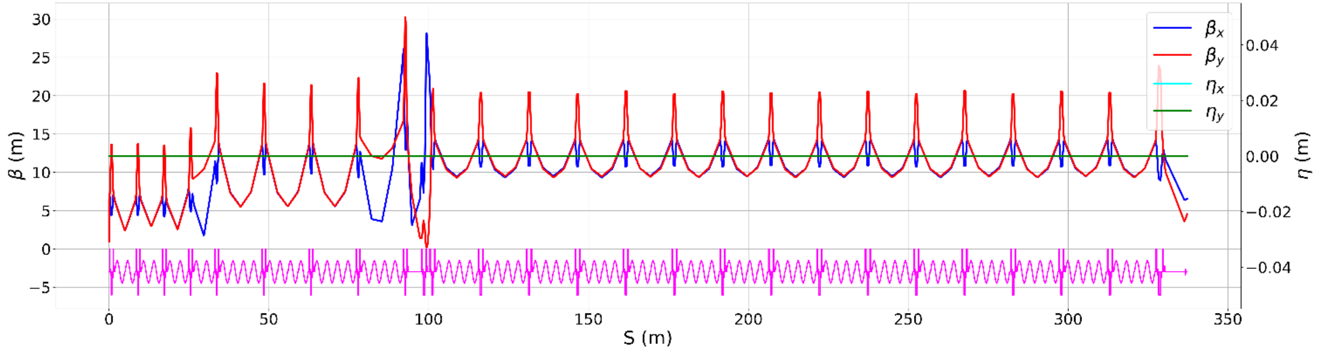


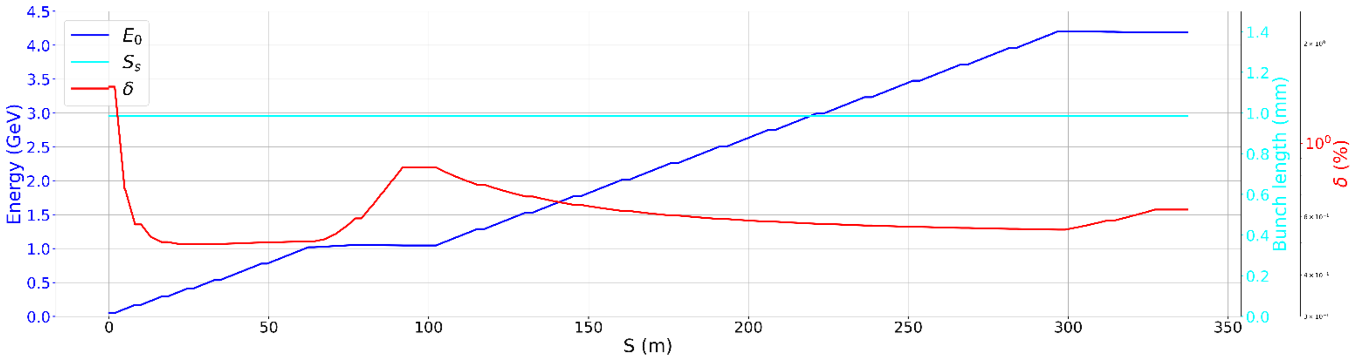
Parameter	Unit	Value	Simulated	
			Electron	
Beam energy	GeV	30	30.56	30.06
Repetition rate	Hz	100		
Bunch charge	nC	1.5	1.5	3.0
Energy spread	10^{-3}	1.5	0.76	1.34
Emittance(x/y)	nm	6.5	1.38/1.36	1.46/1.75
Bunch length (RMS)	mm	/	0.4	0.4

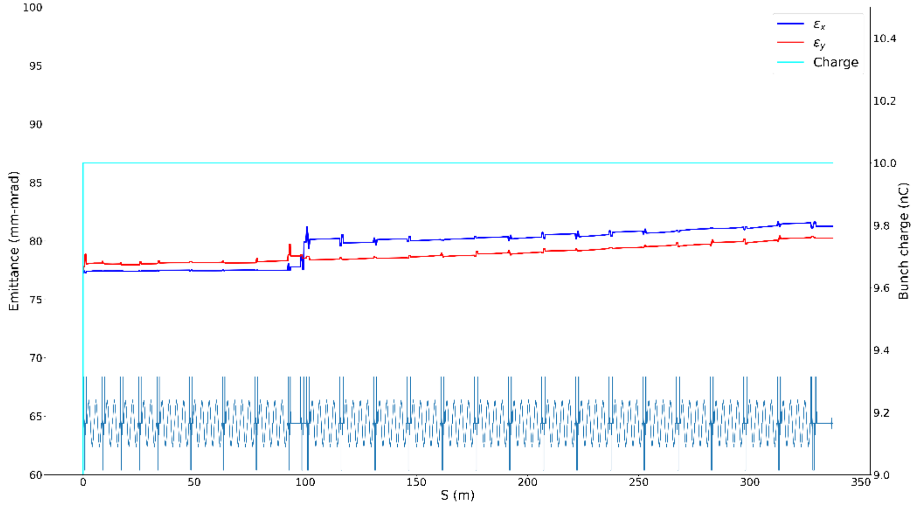
Positron Linac

FAS for positron production

- Acceleration: 50MeV→4GeV @10nC
  - 18+3(redundancy) S-band klystron
  - 1 klystron →4 accelerating structures
  - Gradient: 22MV/m
- Simulation results
  - Energy: 4GeV
  - Energy spread: 0.63%



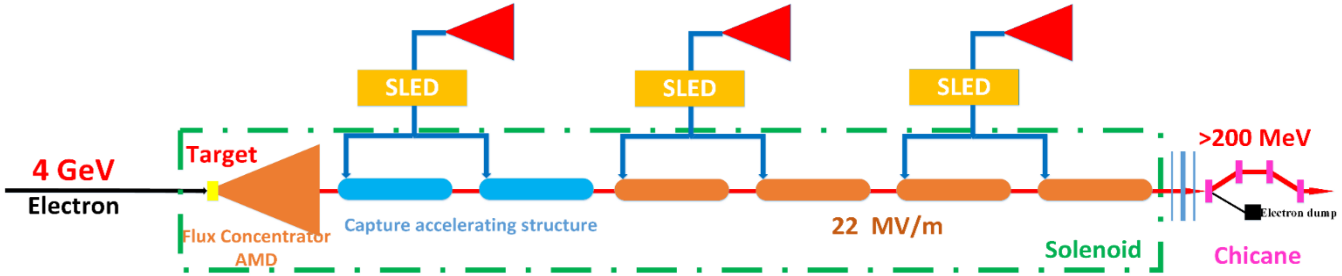


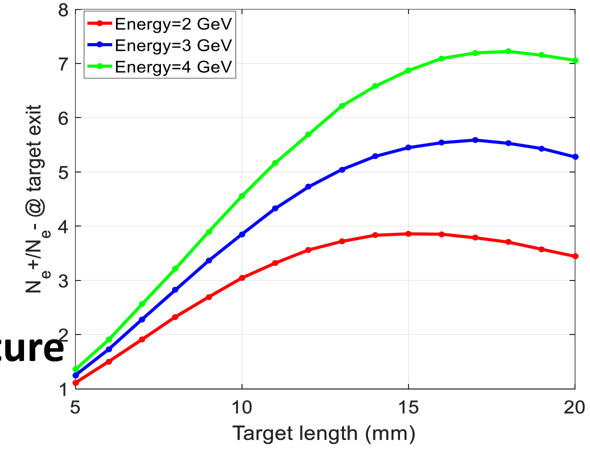


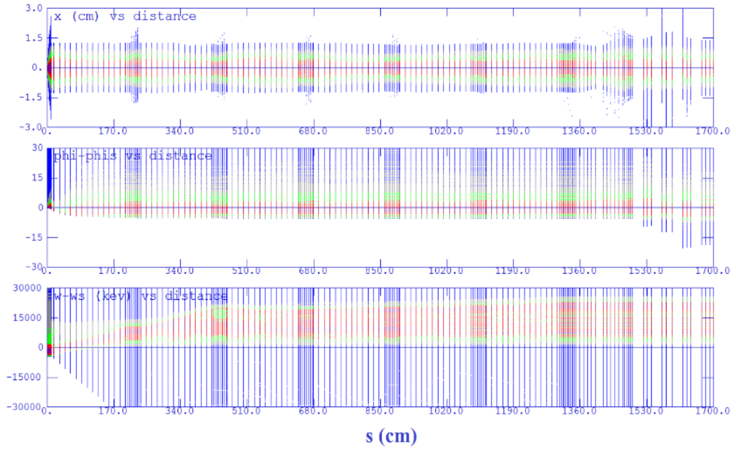
Positron Linac

PSPAS

- Positron source
  - Target (Conventional)
    - ✓ tungsten@15 mm
    - ✓ Beam size: 0.5 mm
- AMD (Adiabatic Matching Device)
  - Length: 100mm
  - Aperture: 8mm→26mm
  - Magnetic field: (5.5T→0T) + 0.5T
- Capture & Pre-accelerating structure
  - 1 klystron → 2 Acc.Struc
    - ✓ **Larger aperture S-band accelerating structure**
      - ☐ Aperture: 25 mm
      - ☐ Gradient: 22 MV/m
      - ☐ Length:2 m
  - Energy:200MeV
  - Solenoid
- Chicane
  - Wasted electron separation







Positron source	Unit	Requirement	Simulation results
e^- beam energy on the target	GeV		4
e^- bunch charge on the target	nC		10
e^+ bunch charge	nC	≥3	~5.5
e^+ Energy	MeV	≥200	250
e^+ Norm. RMS emittance	mm-mrad	≤2400	2370

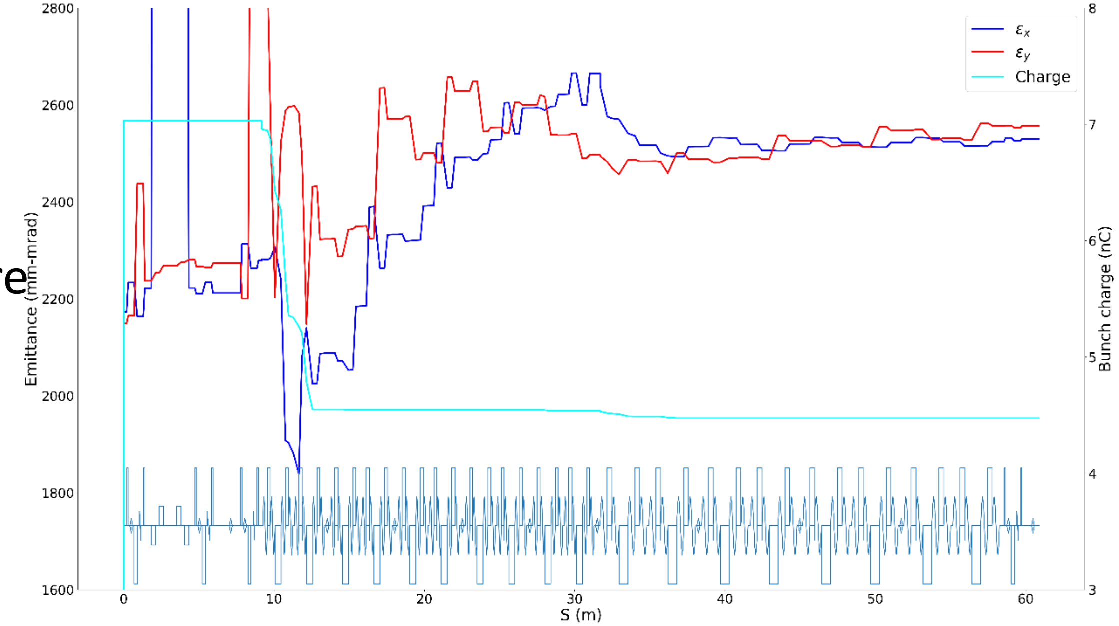
Positron Linac

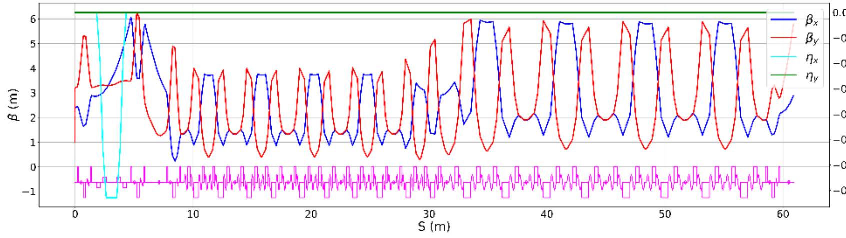
SAS

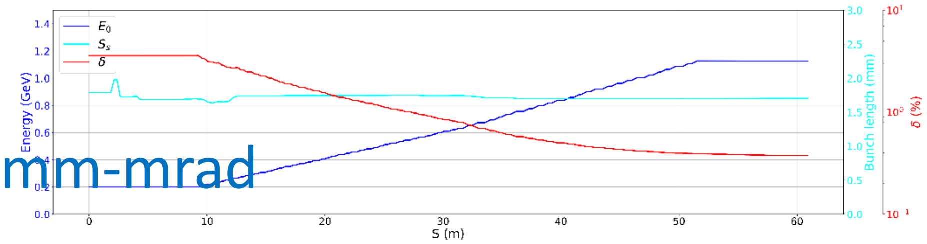
➢ Acceleration
- 8+1(redundancy) S-band klystron
- 1 klystron →2 accelerating structures
  - ✓ 10 Larger aperture S-band accelerating structure
  - ✓ 8 normal S-band accelerating structure
- Gradient: 22MV/m, 27MV/m

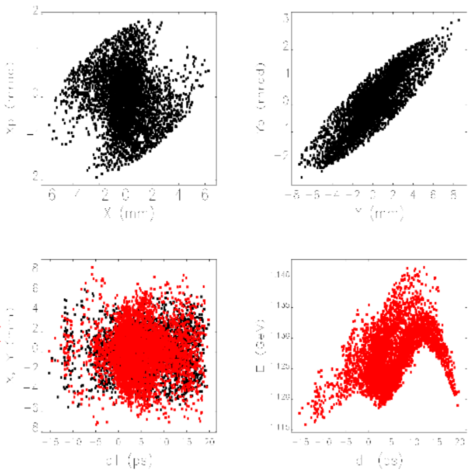
➢ Transverse focusing
- Triplet quadrupoles are outside each accelerating structure

➢ Simulation results
- Energy: 1.1GeV
- Energy spread: 0.4%
- Bunch charge: ~4.5nC
- Normalized rms Emittance: 2500mm-mrad



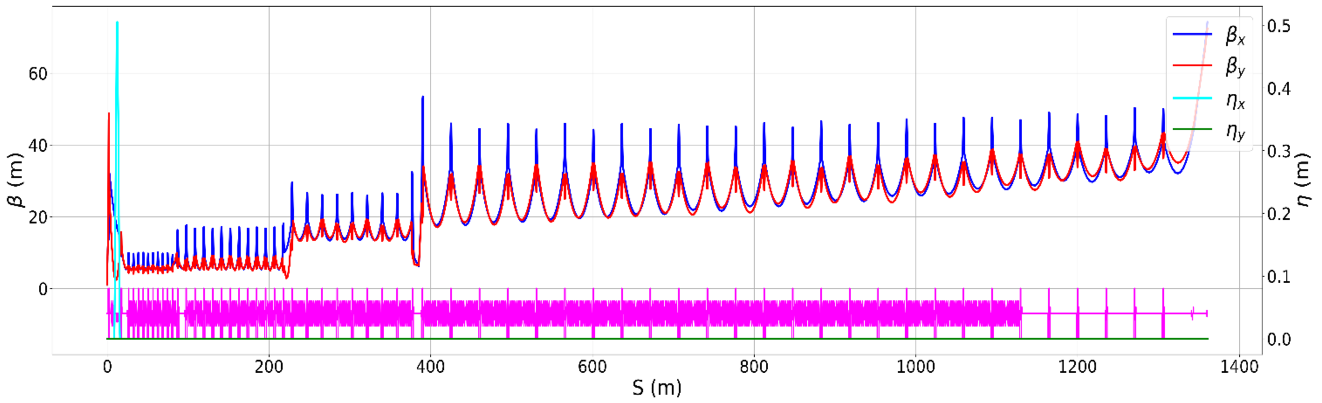


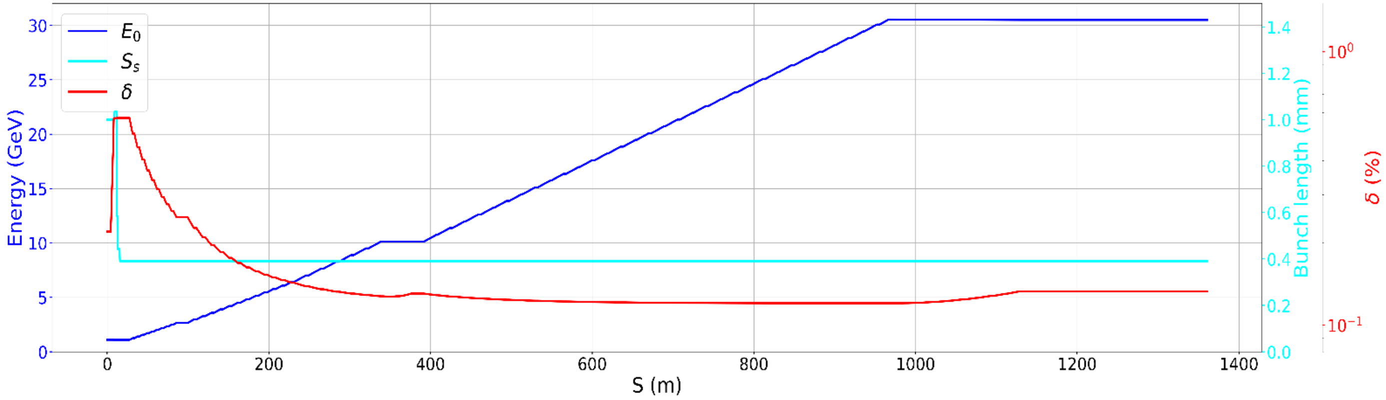




- Simulation results(including Wakefield & CSR)

Parameter	Unit	Value	Simulated	
			Positron	
Beam energy	GeV	30	30.50	30.01
Repetition rate	Hz	100	/	
Bunch charge	nC	1.5	1.5	3.0
Energy spread	10^{-3}	1.5	1.33	2.19
Emittance(x/y)	nm	6.5	3.37/1.68	3.90/1.71
Bunch length (RMS)	mm	/	0.4	0.4





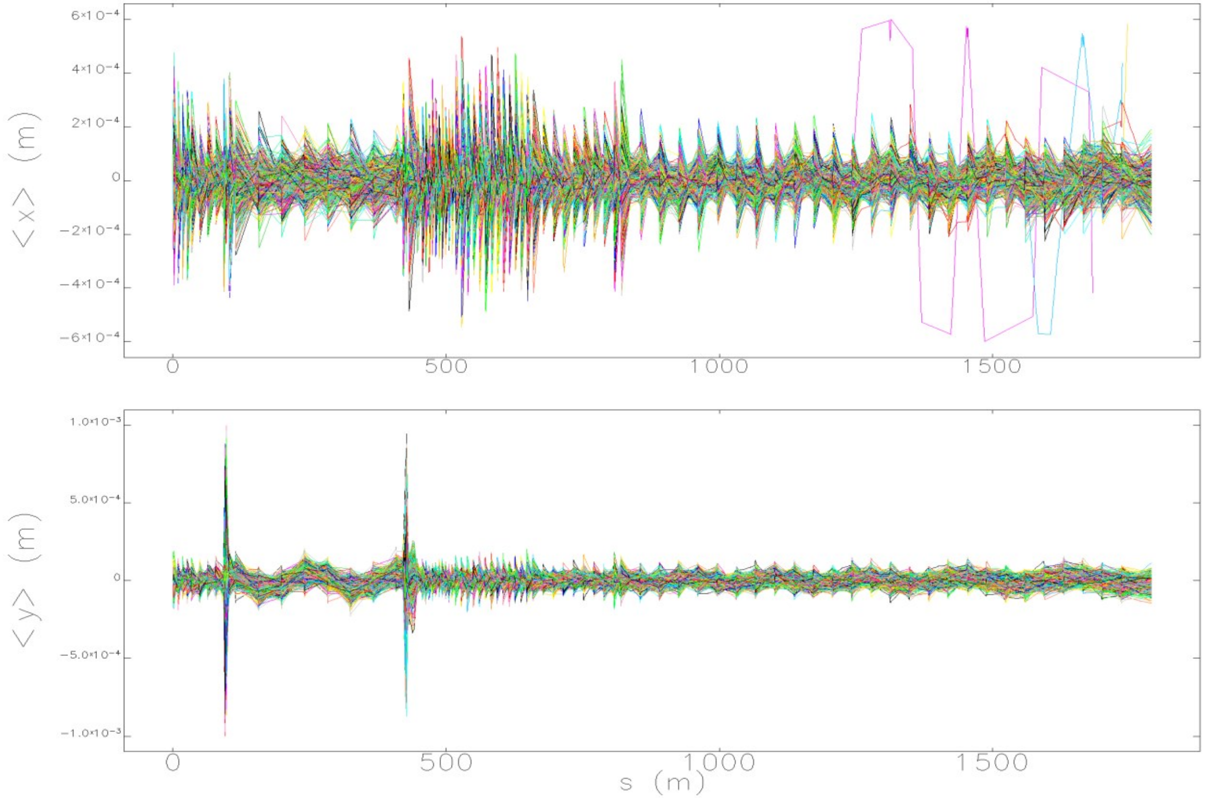
Error study

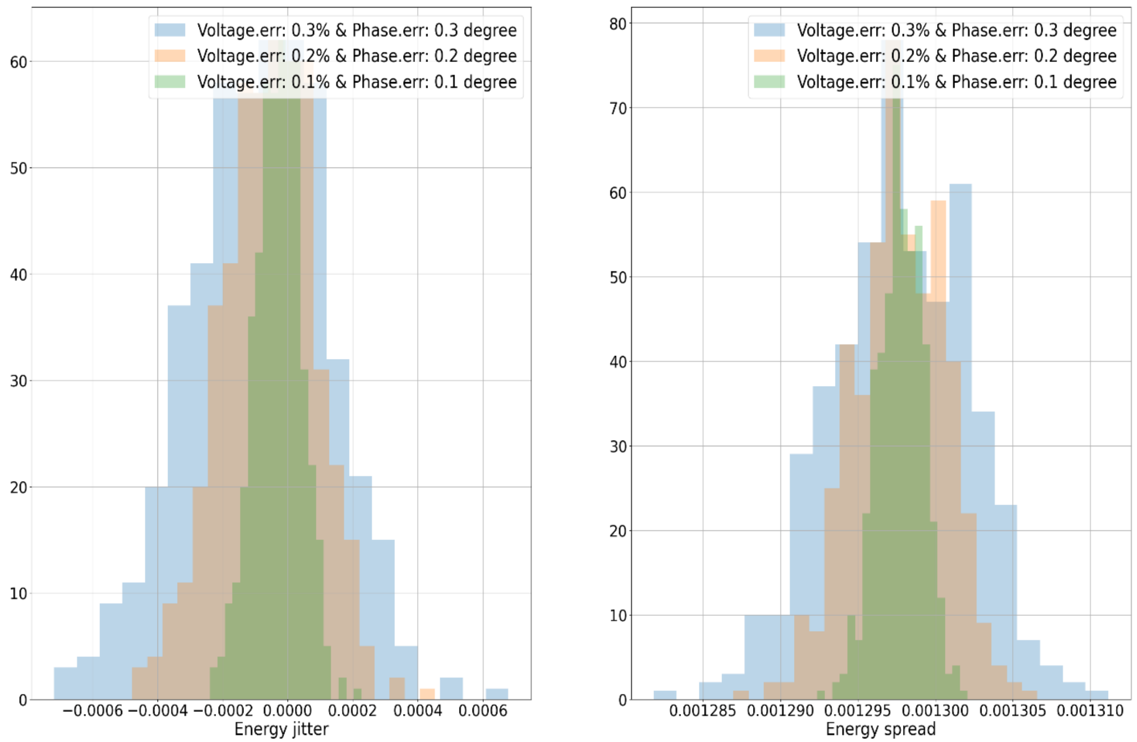
Error settings

Elements	Number	Transverse misalignment	Longitudinal misalignment	Rotation error
		mm	mm	mrad
Electron Gun	1	0.1	0.2	0.2
Positron source	1	0.1	0.2	0.2
Large-aperture S-band Acc. Stru.	16	0.1	0.1	0.2
S-band Acc. Stru.	91	0.1	0.1	0.2
SHB1	1	0.1	0.15	0.2
SHB2	1	0.1	0.15	0.2
BUN	1	0.15	0.15	0.2
C-band Acc. Stru.	470	0.1	0.1	0.2
C-band defecting cavity	1	0.1	0.1	0.2
Solenoid	37	0.15	0.2	0.2
Quadrupole	364	0.1	0.2	0.2
Dipole	15	0.15	0.2	0.2
Corrector	275	0.15	0.2	0.2
BPM	150	0.1	0.2	0.2
PR	30	0.15	0.2	0.2

Error study

Error description	Unit	Value
Magnetic element field error	%	0.1
BPM uncertainty	μm	10





Error study

- According to simulation, the Linac with errors can meet the requirements @ 1.5nC.

Parameter		Unit	Value	Simulated			
				Electron		Positron	
Beam energy		GeV	30	30.5	30.0	30.5	30.0
Bunch charge		nC	1.5	1.5	3.0	1.5	3.0
Energy spread	W/O error	$\times 10^{-3}$	1.5	0.68	1.37	1.29	2.16
	W/ error			0.64±0.14	1.45±0.13	1.30±0.01	2.16±0.01
Energy jitter		$\times 10^{-3}$	1.0	0.22	0.24	0.21	0.22
Emittance(H/V)	W/O error	nm	6.5	1.38 1.36	1.44 1.63	3.37 1.68	3.90 1.71
	W/ error			1.41±0.07 1.40±0.06	1.91±0.30 2.21±0.62	3.39±0.08 1.69±0.03	5.01±1.63 2.18±0.56

High luminosity Z scheme Motivation

- In order to meet the injection requirement of high luminosity Z scheme, one should increase the injection speed of the Linac to the booster.
- Schemes:
  - Double-bunch acceleration scheme
    - ✓ To filling the required bucket pattern, the SHB RF frequency should be checked
    - ✓ **Pulse compressor ?**

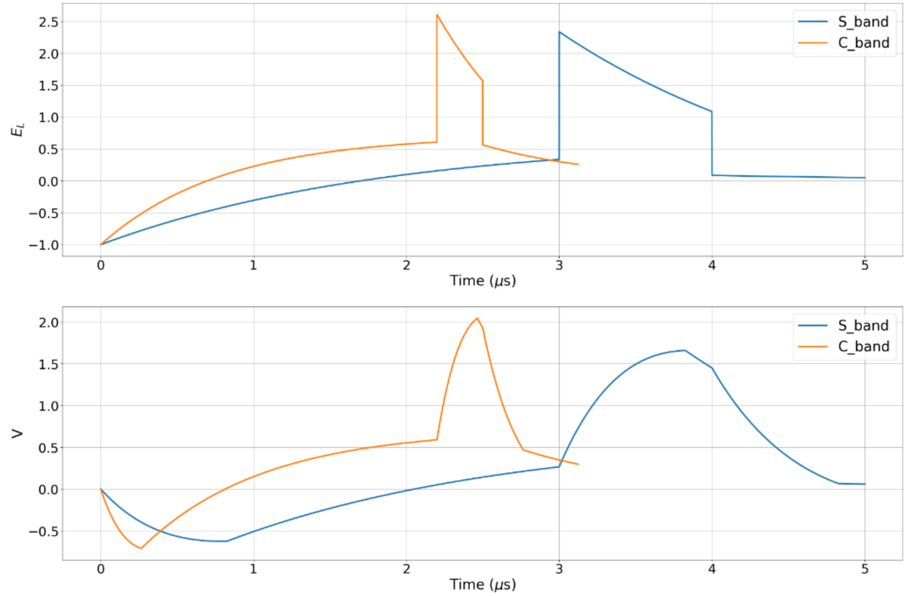
Timing consideration

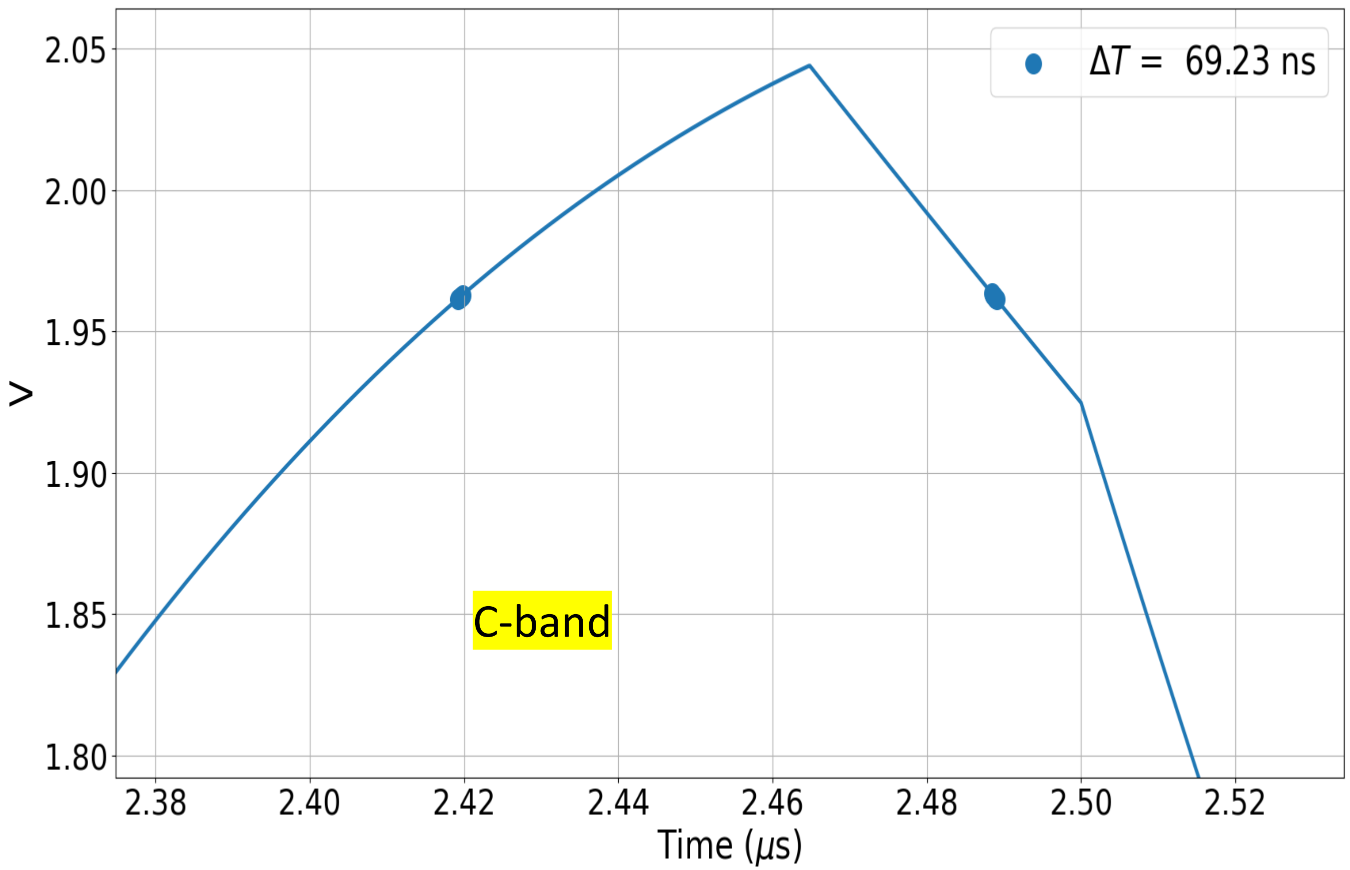
- RF frequency of the Linac, booster and ring is 2860MHz,1300MHz and 650MHz
  - Greatest common divisor (GCD) is 130MHz
  - All RF frequency is based on the common frequency
- Linac RF frequency
  - Divide the common frequency to 14.44MHz, then multiply to the corresponding RF frequency
  - Frequency multiplication to 2860MHz, 5720MHz by common frequency

Parameter	Unit	Design value
Repetition frequency	Hz	100
Common frequency	MHz	130
Linac common frequency	MHz	14.44
Bunch frequency	MHz	14.44
SHB1 RF frequency	MHz	158.89
SHB2 RF frequency	MHz	476.67
LINAC RF frequency	MHz	2860
	MHz	5720
Damping ring RF frequency	MHz	650
Booster RF frequency	MHz	1300
Ring RF frequency	MHz	650
Bunch spacing @Collider	ns	23.08
Bunch spacing @Linac	ns	69.23
Injection scheme		bunch-by-bunch
Harmonic number		45*(2k) + [10, 20, 40]
		45*(2k+1) + [5, 25]
Bunch number per train		6n

Pulse compressor

- Energy multiplication factor can meet the requirements
  - S-band:
    - ✓ RF pulse is about 4.0μs
    - ✓ Filling time is about 0.83 μs
  - C-band:
    - ✓ RF pulse maybe is about 2.5μs
    - ✓ Filling time is about 0.27 μs





Summary

- The Linac energy is increased to 30 GeV to ease the booster magnet design difficulties (low field at injection energy and large magnetic field range) and save the total cost.
- The C-band accelerating structure is used from 1.1 GeV to 30 GeV.
- The lattice design and dynamic simulation have been finished, the design can meet the requirements.
- For high luminosity Z scheme, tow-bunch-per-pulse is need and the baseline scheme can meet the requirements.

Thank you for your attention!