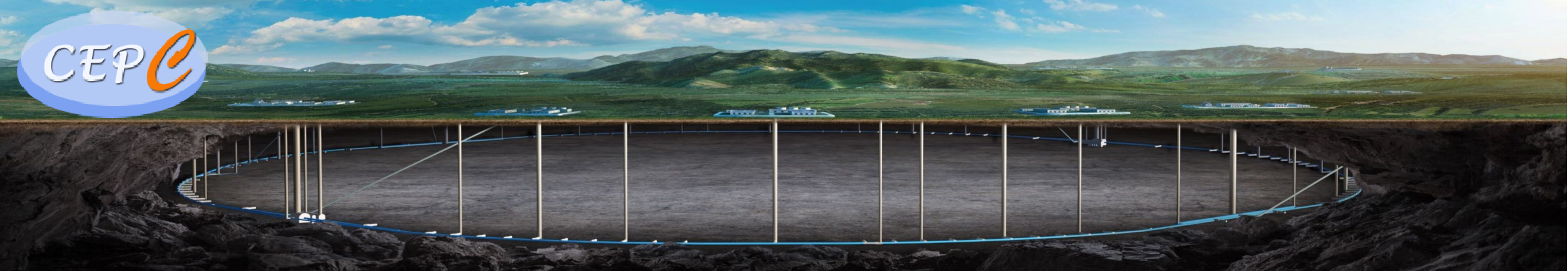

CEPC Linac design

CEPC International Workshop 2023, 3-6. July. 2023

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Acknowledgement:
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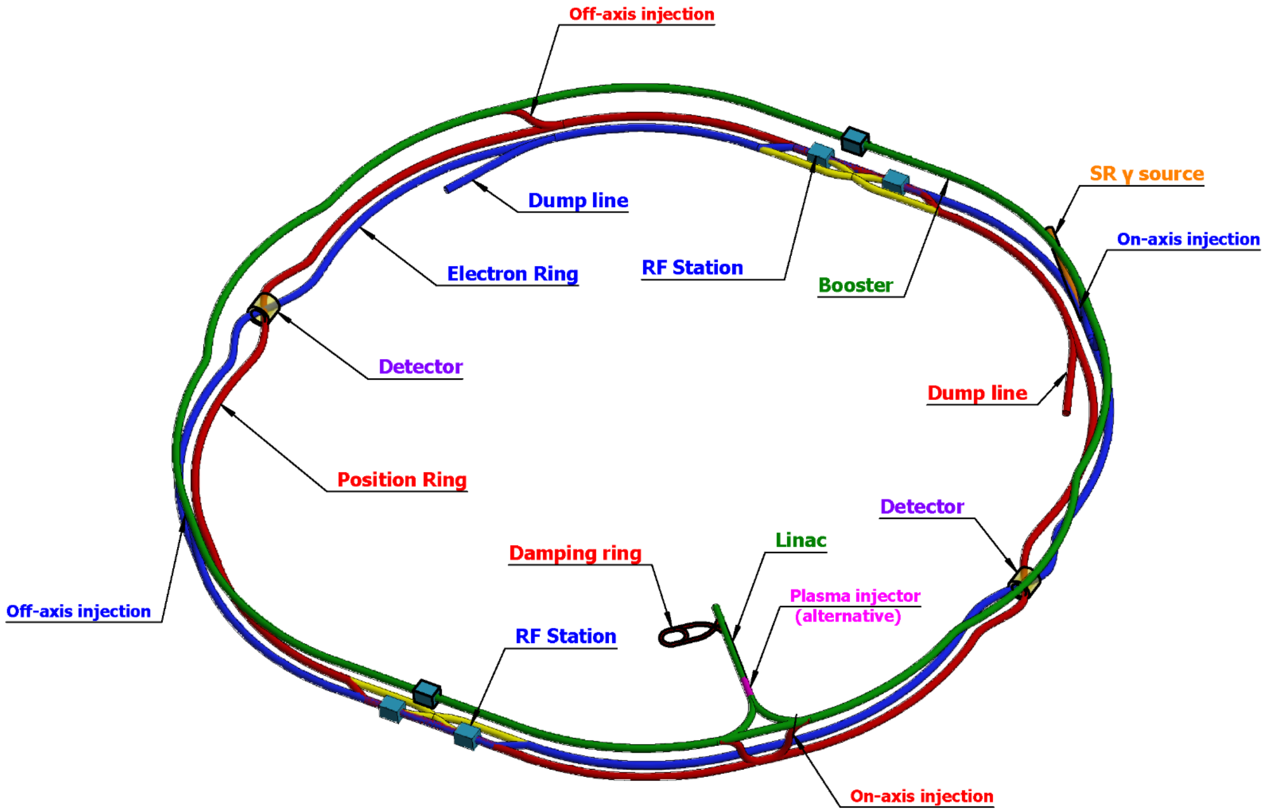
Content

- **Introduction of the CEPC Linac**
- **Physics design of the CEPC Linac**
  - Basic consideration
  - Electron Linac
  - Positron Linac
  - Error study
  - Double-bunch acceleration scheme
- **Experimental study on emittance growth in high bunch charge beam**
- **Summary**

Introduction: CEPC 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: Linac parameters

- CEPC Linac is a high energy electron and positron linear accelerator

Required		$t\bar{t}$ (180GeV)	Higgs (120GeV)	W (80GeV)	Z (45.5GeV)
Bunch charge	nC	1.38	1.0	1.0	1.1
Bunch number per pulse		1	1	1	2
Repetition rate	Hz	100			
Switch time for electron and positron	s	3.5			

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
Switch time for electron and positron		s	3.0

Introduction: Why is 30-GeV needed?

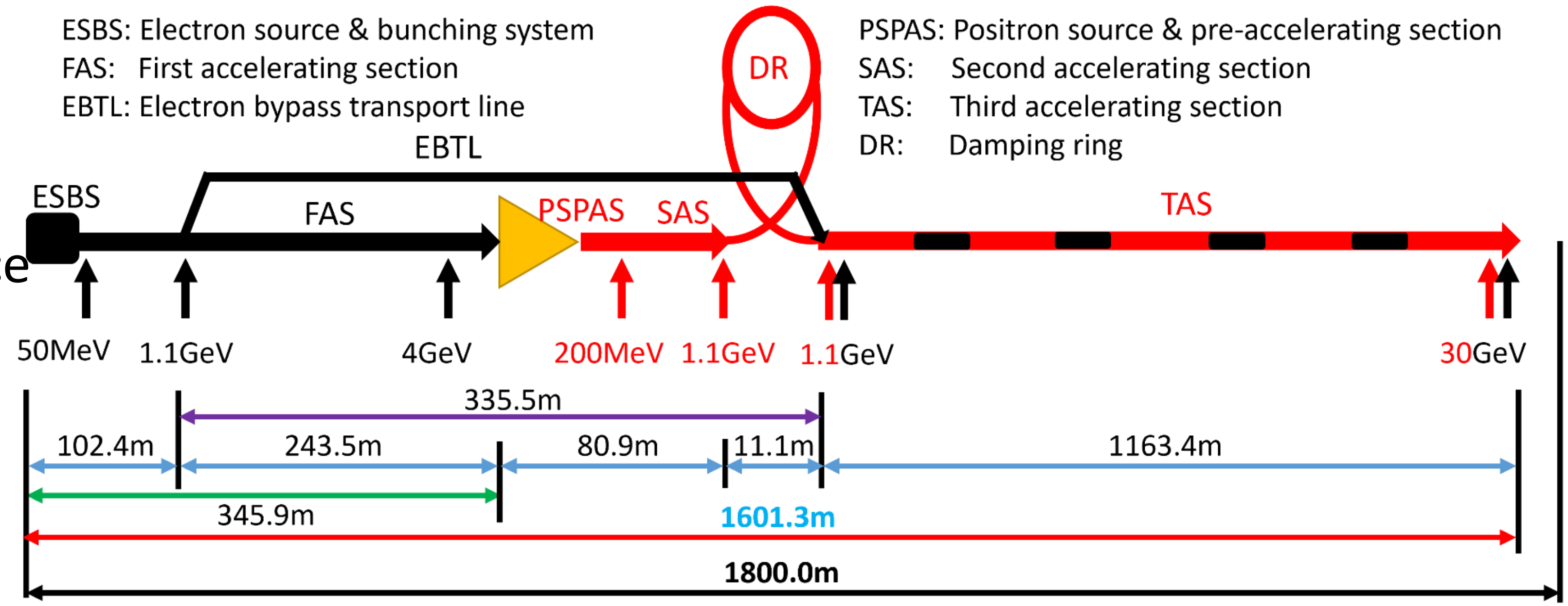
- The maximum energy of booster is 180GeV and circumference is 100 km
  - Large circumference & Low injection energy → Low magnetic field
    - design difficulty in magnet (*field*) and power supply (*stability*)
  - Large extraction energy → Large field range
    - design difficulty in magnet (*excitation efficiency*) and power supply (*power*)
- Increasing the energy of the Linac is the easiest way: 30 GeV

Magnet		Low injection energy			Max. Extraction energy	Cost
		10GeV	20GeV	30GeV	180GeV	
CT Air-core coil		Yes	Yes	Yes	No	Very 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: How to achieve 30-GeV

- Acceleration:
  - S-band accelerating structure
  - C-band accelerating structure @TAS (1.1GeV→30GeV)
    - **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



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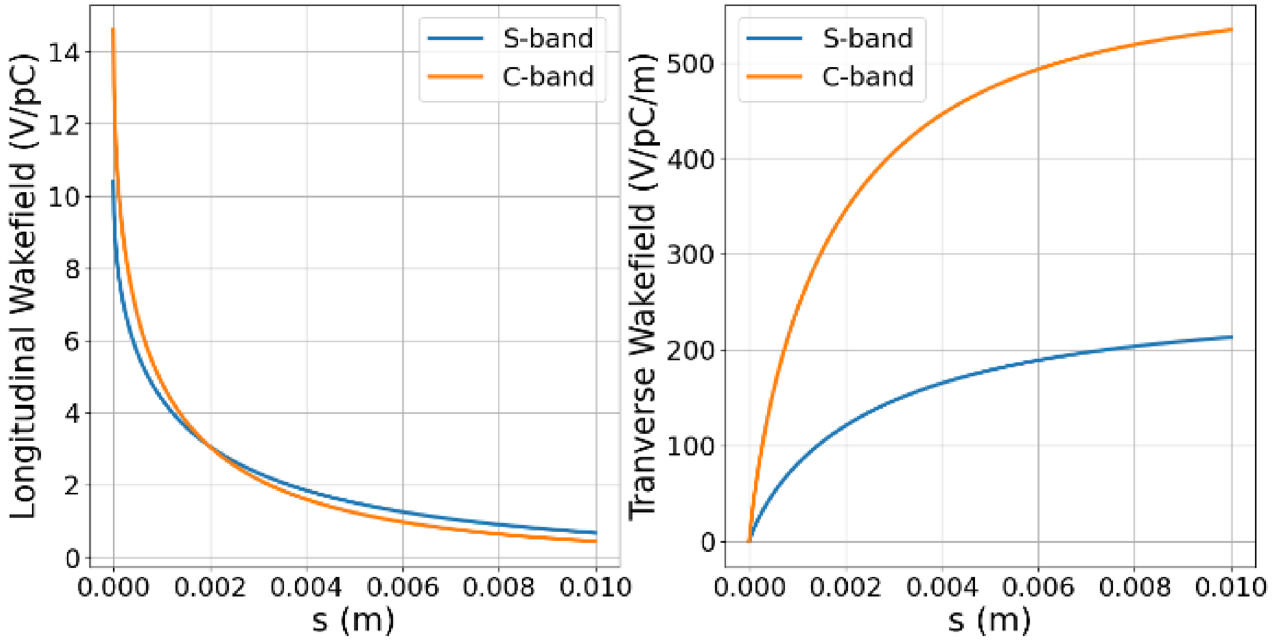
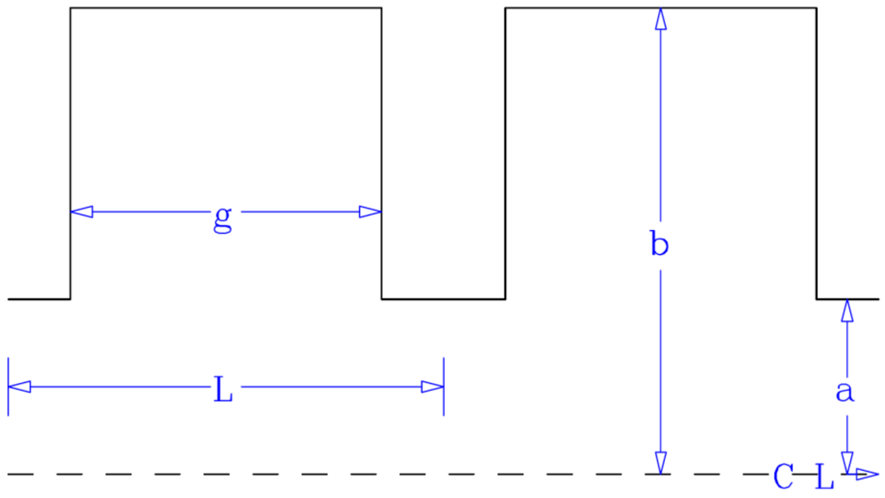
- Brief introduction of the HEPS Linac beam commissioning
- Summary

Basic consideration: Wakefield

- Wakefield
  - Emittance growth
  - Energy spread

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 (include coupler cells)		86	55	89
Number of Acc. Stru.		93	16	470
Number of Klystron		34		236
Klystron Power	MW	80		50

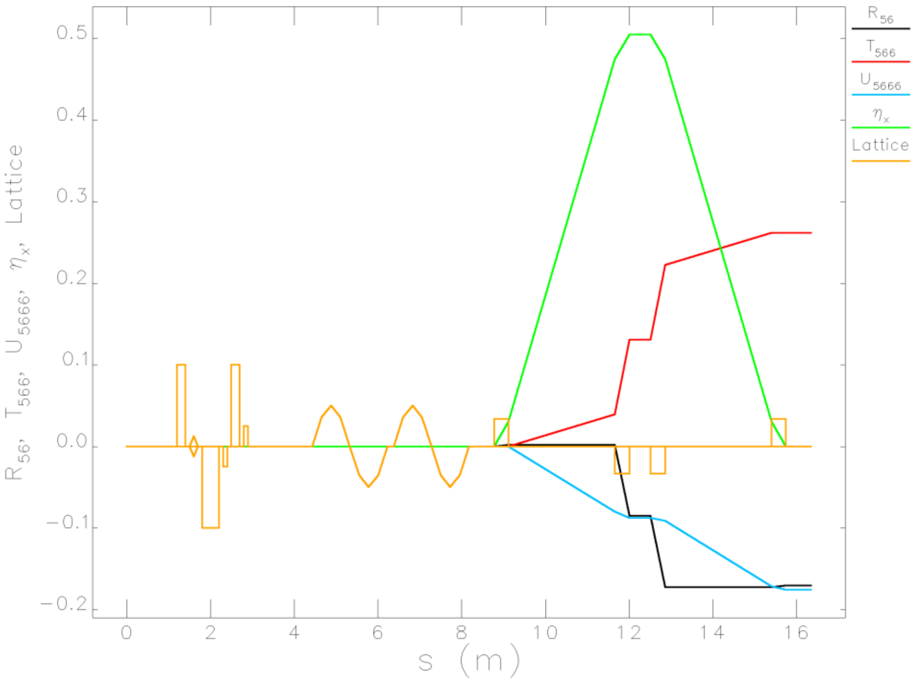


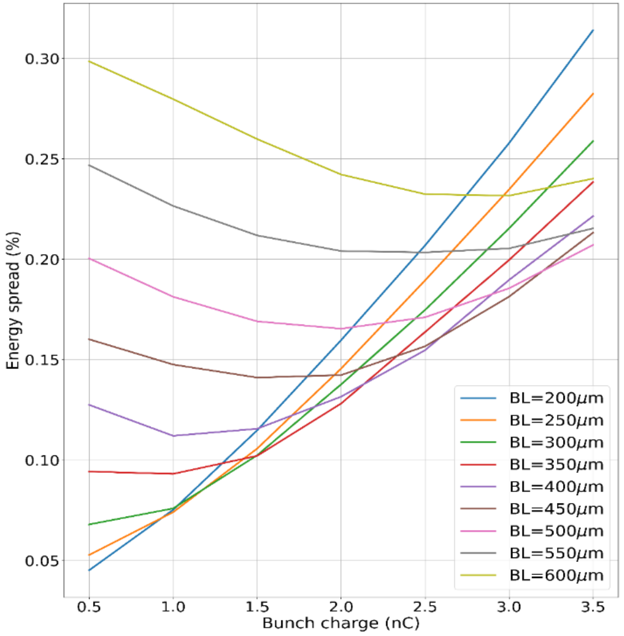


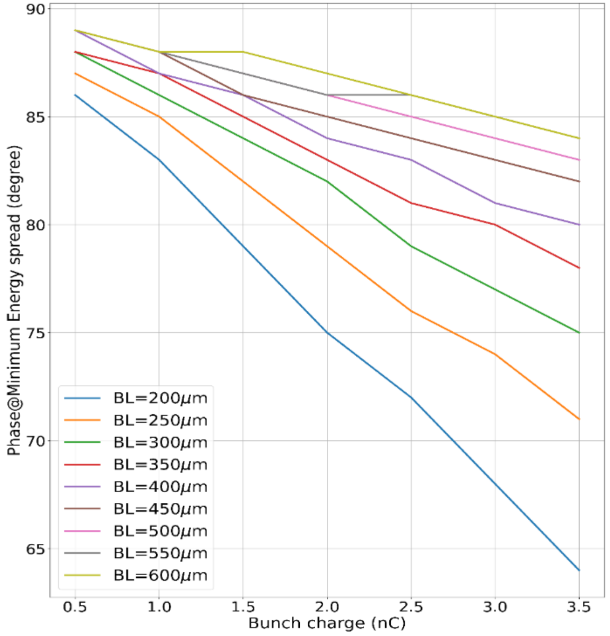
K. Yokoya and K. Bane, in *Proceedings of the 1999 IEEE Particle Accelerator Conference, New York, NY* (Piscataway, NJ, 1999), p. 1725.
Karl Bane, LCC-0116, SLAC-PUB-9663, March 2003

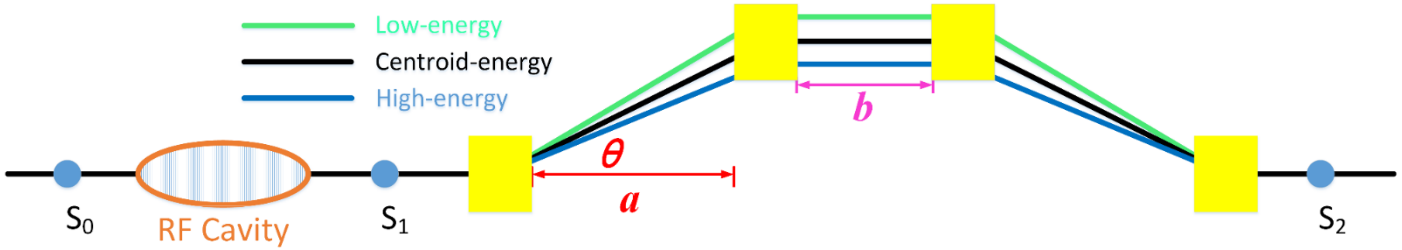
Basic consideration: Bunch length

- Energy spread is determined by Wakefield and bunch length of TAS
  - 400 μm
- Bunch compressor
  - Chicane-type
  - 1.0~1.2 mm → 0.4 mm









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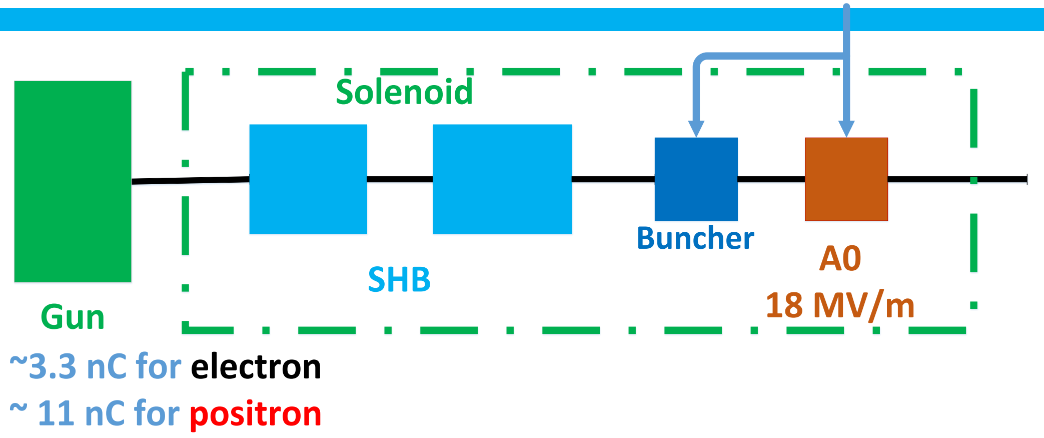
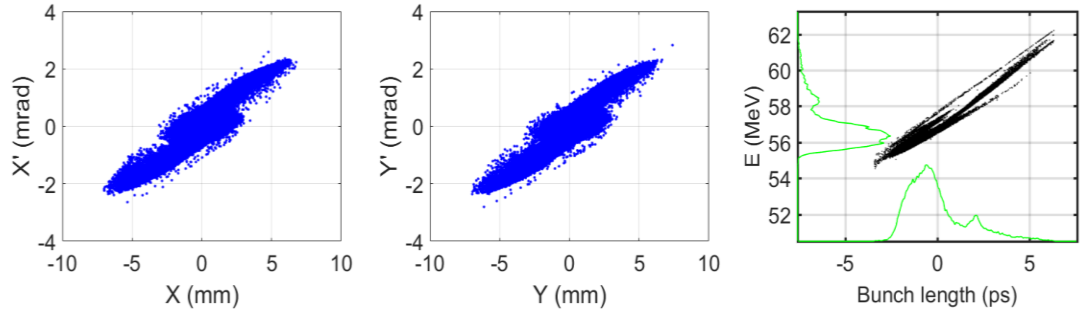
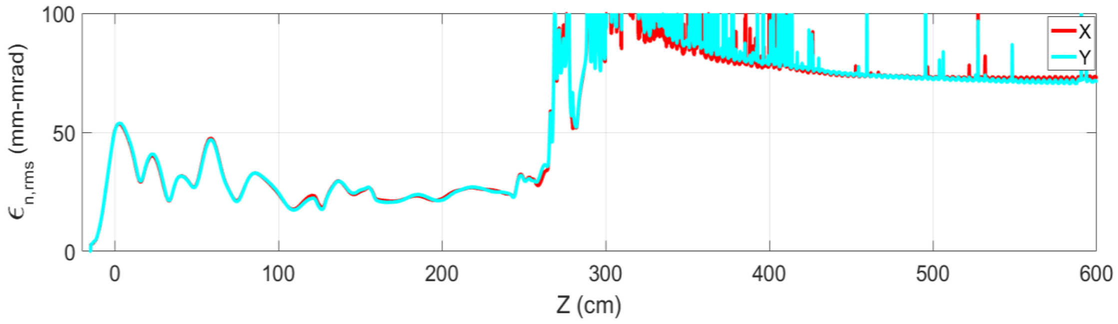
Electron Linac: Electron source and bunching system

- Layout
  - Thermionic cathode electron gun
  - bunching
    - 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%
    - required bunch charge: 6.7nC @ 3nC positron beam

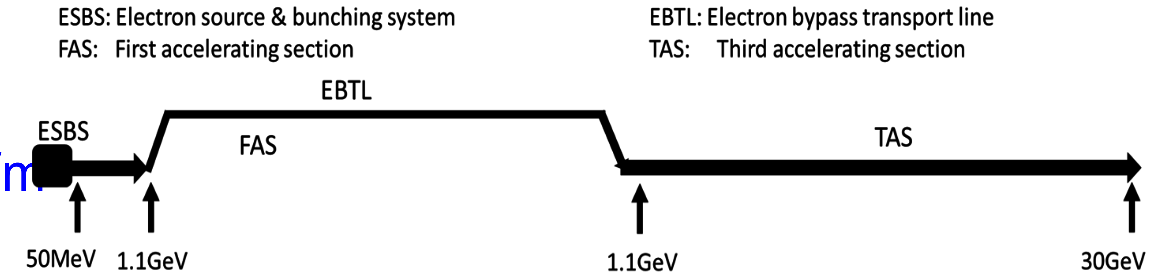


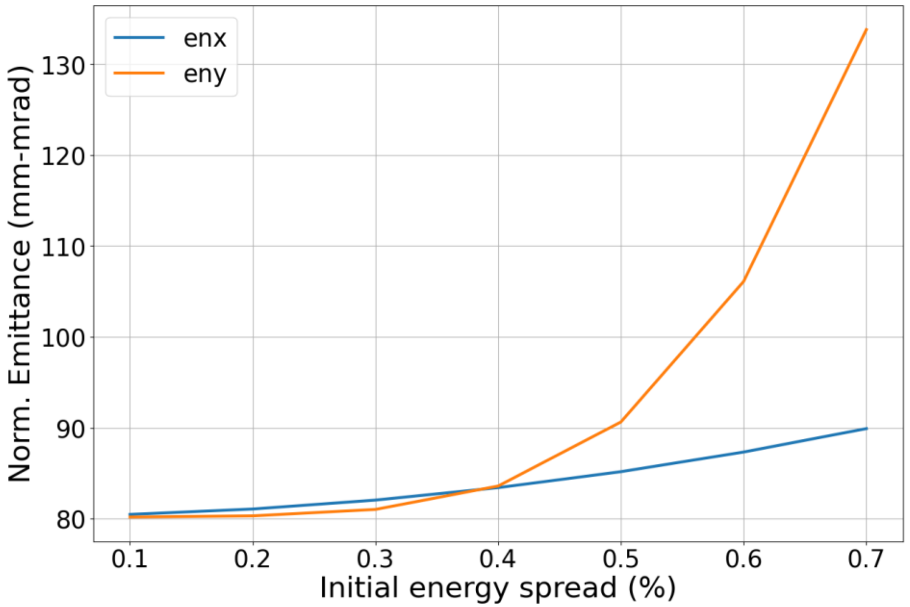




Electron Linac: Acceleration section

- FAS:50MeV→1.1GeV
  - 5+1(redundancy) S-band klystron
  - 1 klystron →4 accelerating structures @22MV/m
- EBTL
  - Vertical separation
  - Local achromatic design
  - Emittance growth (T366 and U3666)
    - energy spread < 0.4%
    - In the design, energy spread is 0.2%
- TAS: 1.1GeV→30GeV
  - Bunch compressor
  - 191+45(redundancy) C-band klystron
    - 1 klystron →2 accelerating structures@45MV/m
    - 19% backups

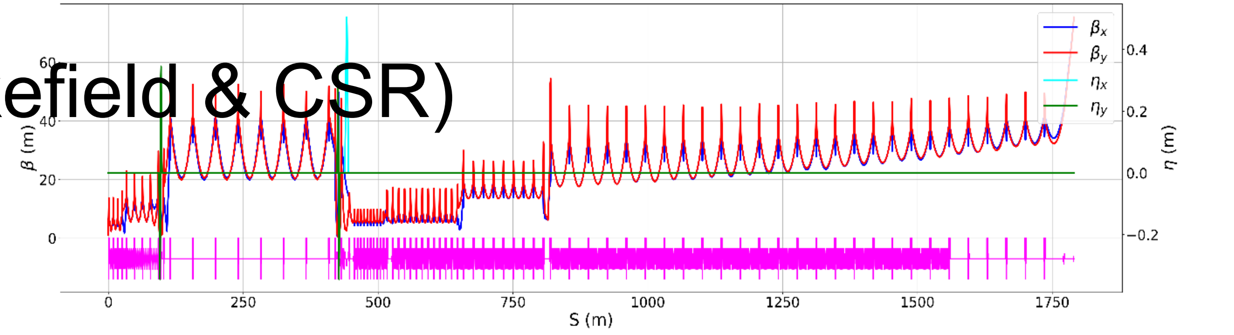


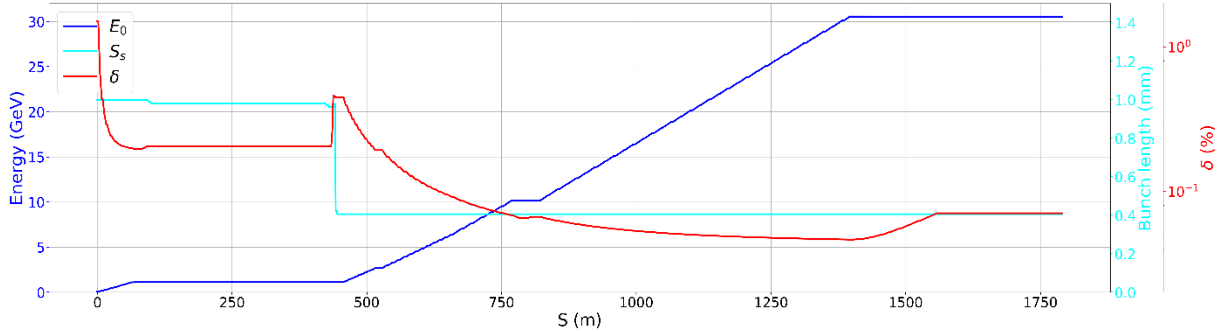


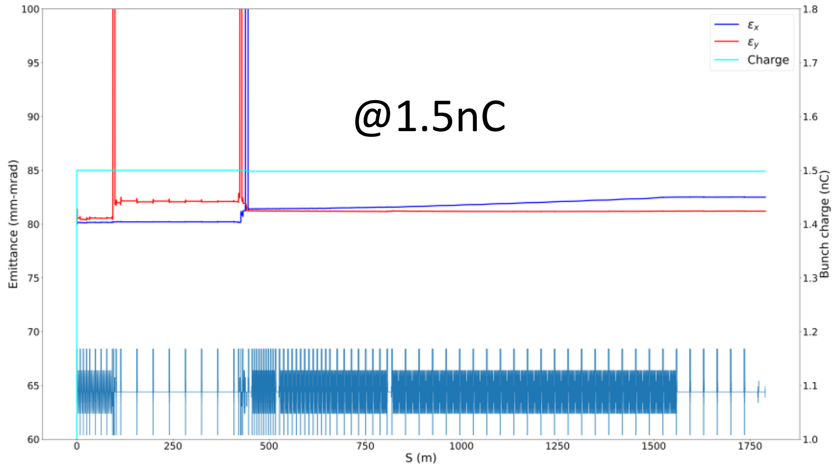
Electron Linac: Beam dynamics results

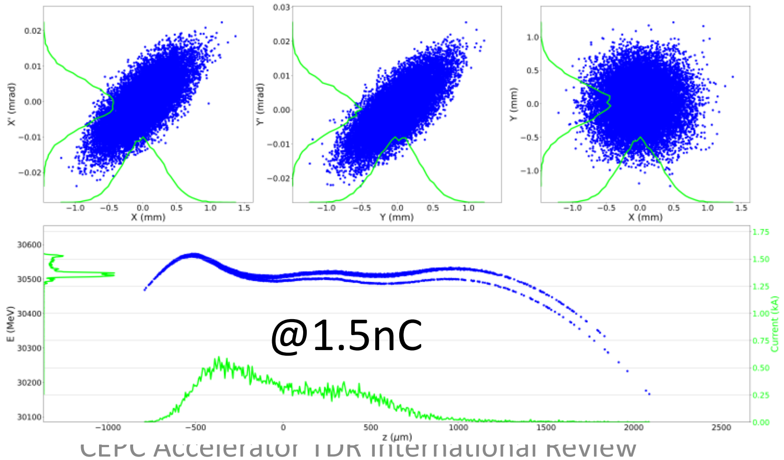
- Simulation results(including Wakefield & CSR)

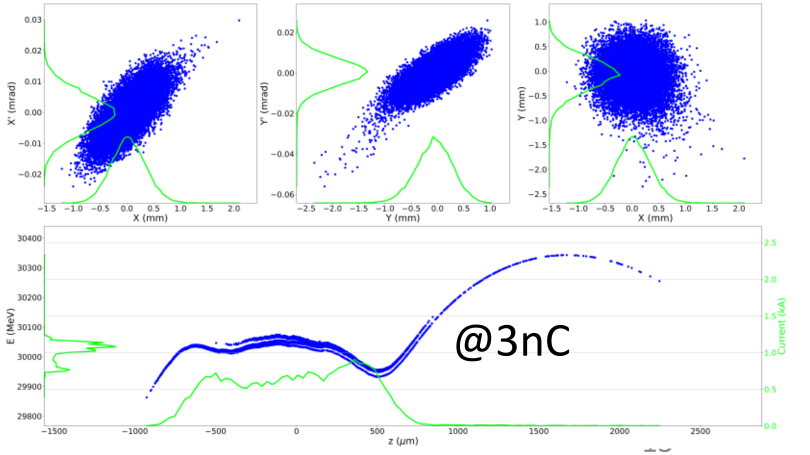
Parameter	Unit	Value	Simulated	
			Electron	
Beam energy	GeV	30	30.52	30.02
Repetition rate	Hz	100		
Bunch charge	nC	1.5	1.5	3.0
Energy spread	10^{-3}	1.5	0.71	1.29
Emittance(x/y)	nm	6.5	1.38/1.36	1.44/1.63
Bunch length (RMS)	mm	/	0.4	0.4





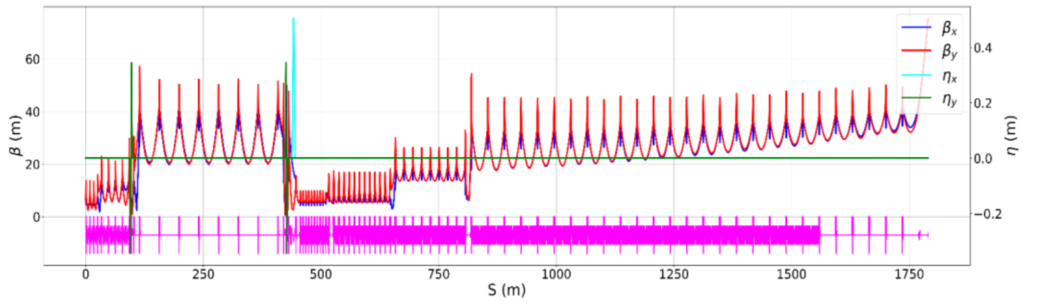


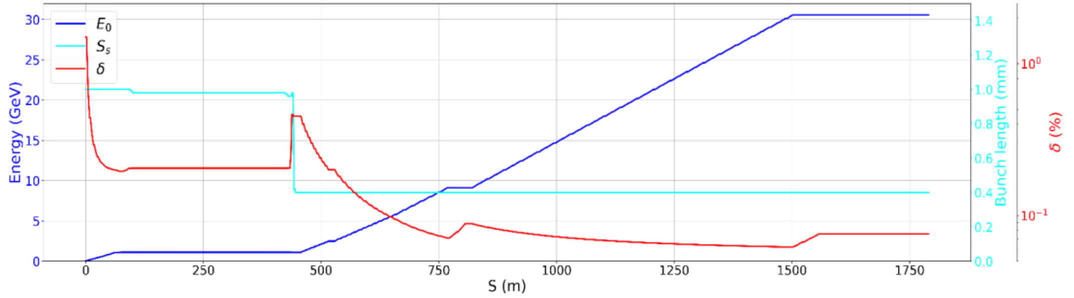




Electron Linac: Beam dynamics results

- One risk is that the accelerating gradient of C-band structure is high in the baseline scheme
  - If the accelerating gradient is 40 MV/m, it still work
    - 215+21(redundancy) C-band klystron, 9% backups
  - If no backups, the accelerating gradient is 36 MV/m, which is safe operating gradient
    - The reserved space can provide an additional 4.5GeV of energy as a further backup
  - Maybe baseline value will be redefined as 40MV/m





Parameter	Acc. Grad.	Backups	Reserved Linac tunnel for acceleration
	MV/m	%	GeV
Baseline design	45	19	5.6
Alternative Case-1	40	9	5.0
Alternative Case-2	36	0	4.5

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

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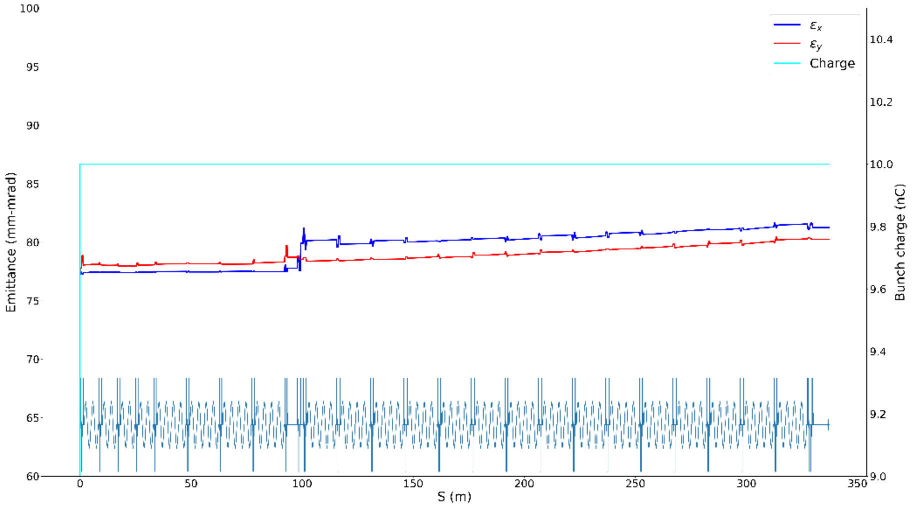
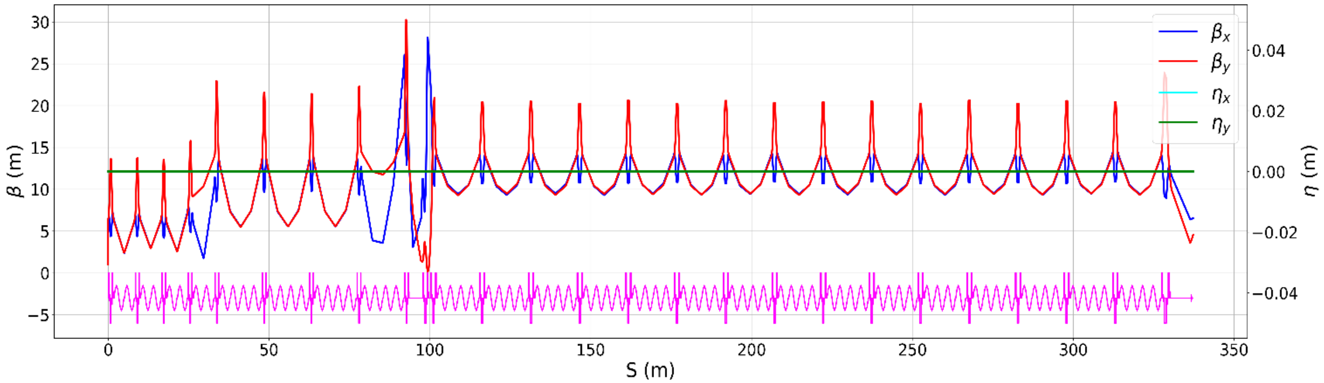
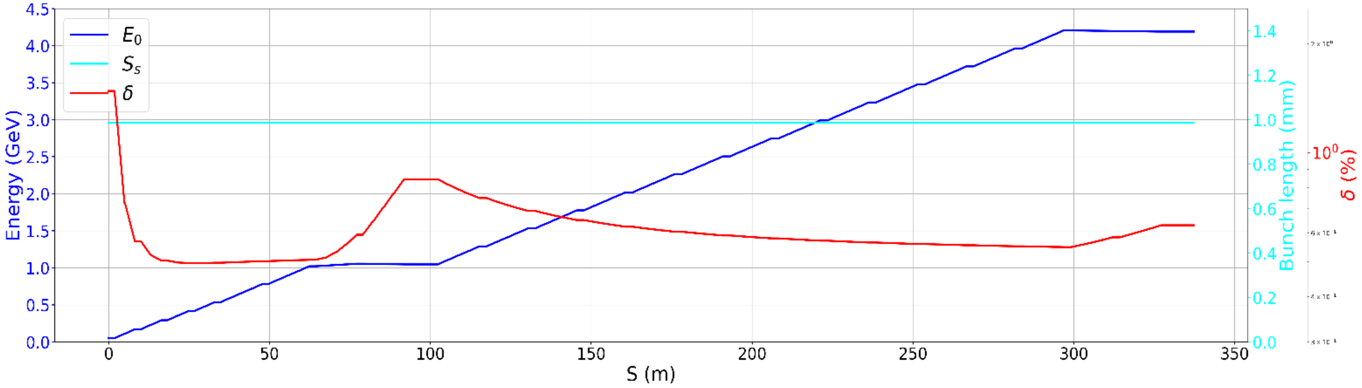
Positron Linac： FAS for positron production

- 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%

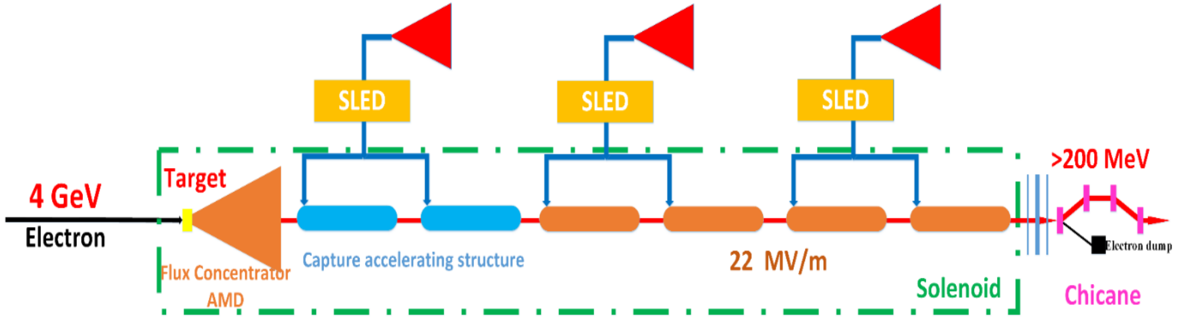


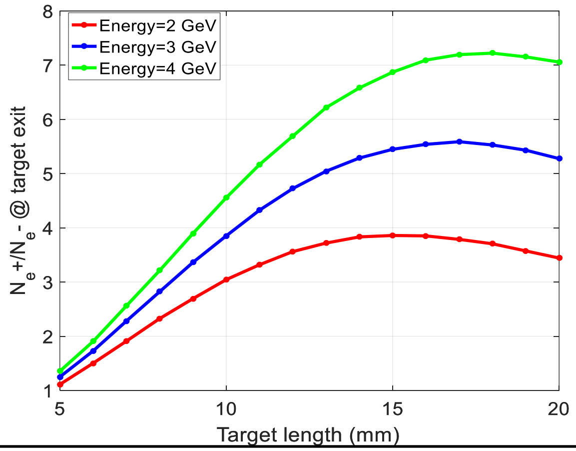


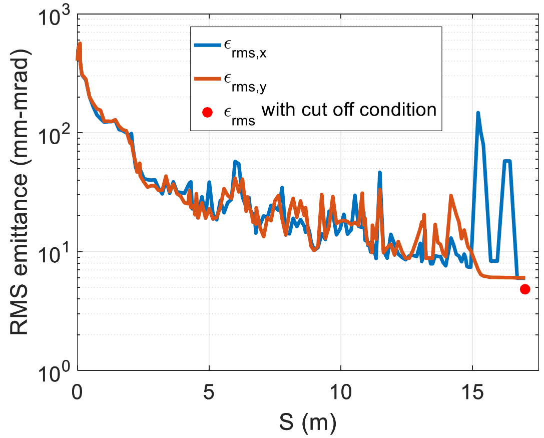


Positron Linac: PSPAS

- Positron source
  - Target (Conventional)
    - tungsten@15 mm
    - Beam size: 0.5 mm
      - Online beam size monitor
- AMD (Adiabatic Matching Device)
  - Length: 100mm
  - Aperture: 8mm→26mm
  - Magnetic field: (5.5T→0T) + 0.5T
- Capture & Pre-accelerating structure
  - 1 klystron → 2 accelerating structures
    - Larger aperture S-band accelerating structure with aperture is 25 mm, gradient is 22 MV/m and length is 2 m
  - Solenoid
- Chicane
  - Wasted electron separation



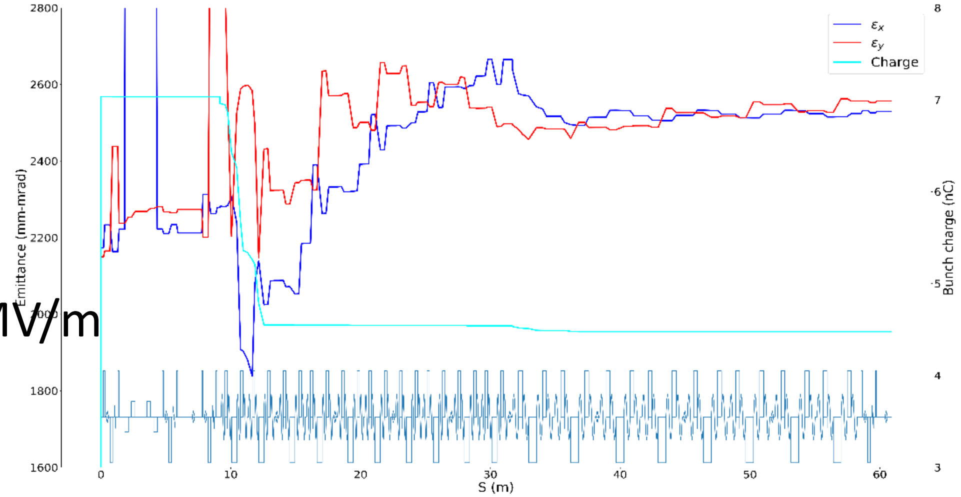


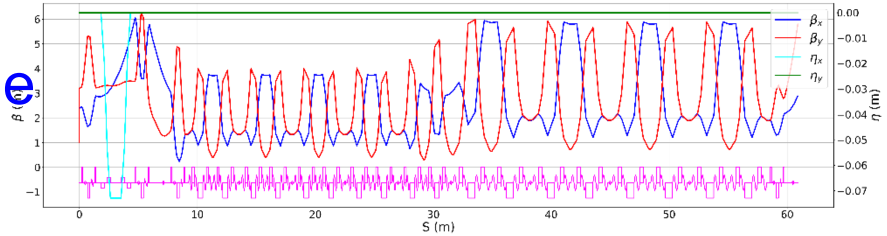


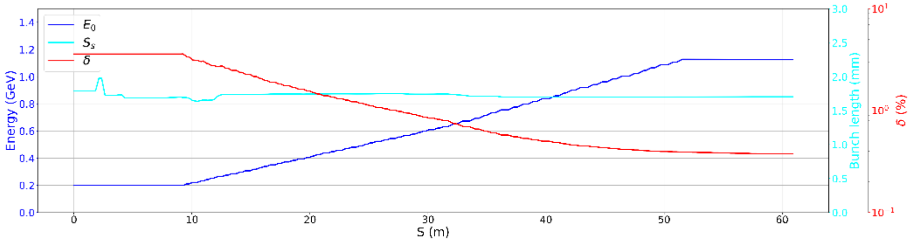
Positron source	Unit	Requirement	Simulation results
e^- beam energy on the target	GeV	4	
e^- bunch charge on the target	nC	10	
e^+ bunch charge	nC	≥3	~5.5
e^+ Energy	MeV	≥200	250
e^+ Norm. RMS emittance	mm-mrad	≤2400	2370

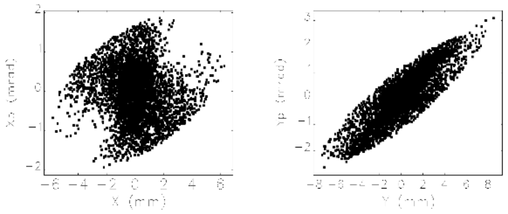
Positron source: SAS

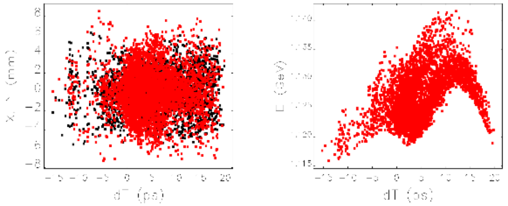
- Acceleration： 200MeV→1.1GeV
  - 8+1(redundancy) S-band klystron
  - 1 klystron →2 accelerating structures
    - 10 Larger aperture S-band accelerating structure@22MV/m
    - 8 normal S-band accelerating structure@27MV/m
    - HEPS: 26MV/m with beam (limit by power source)
- Transverse focusing
  - 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







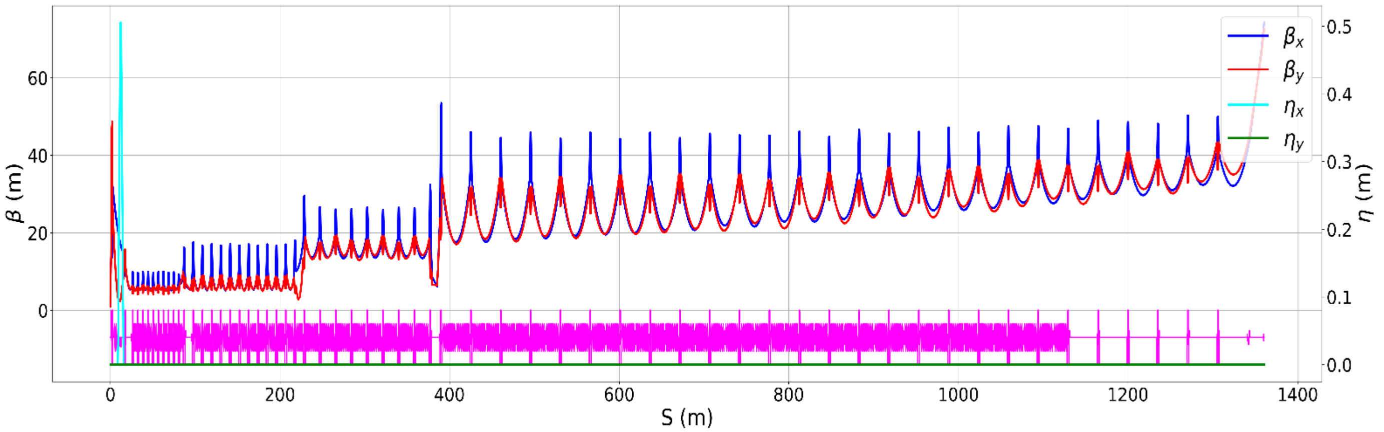


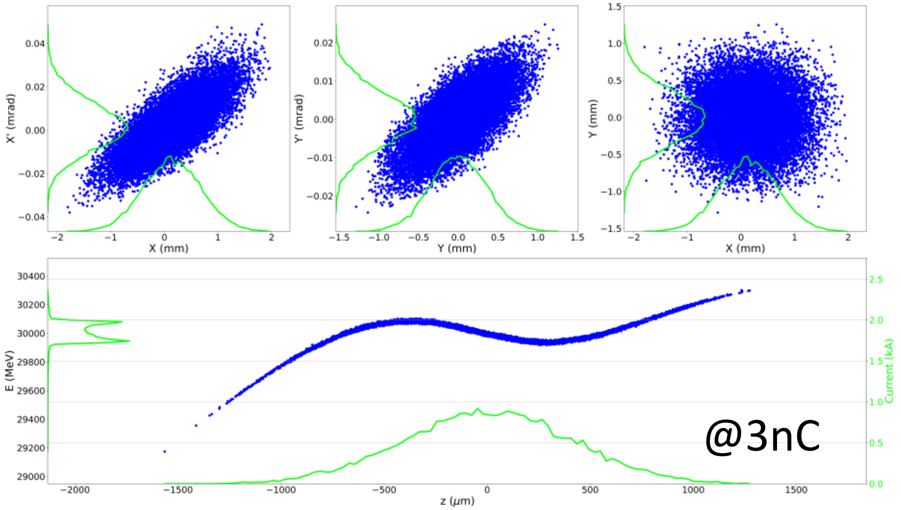


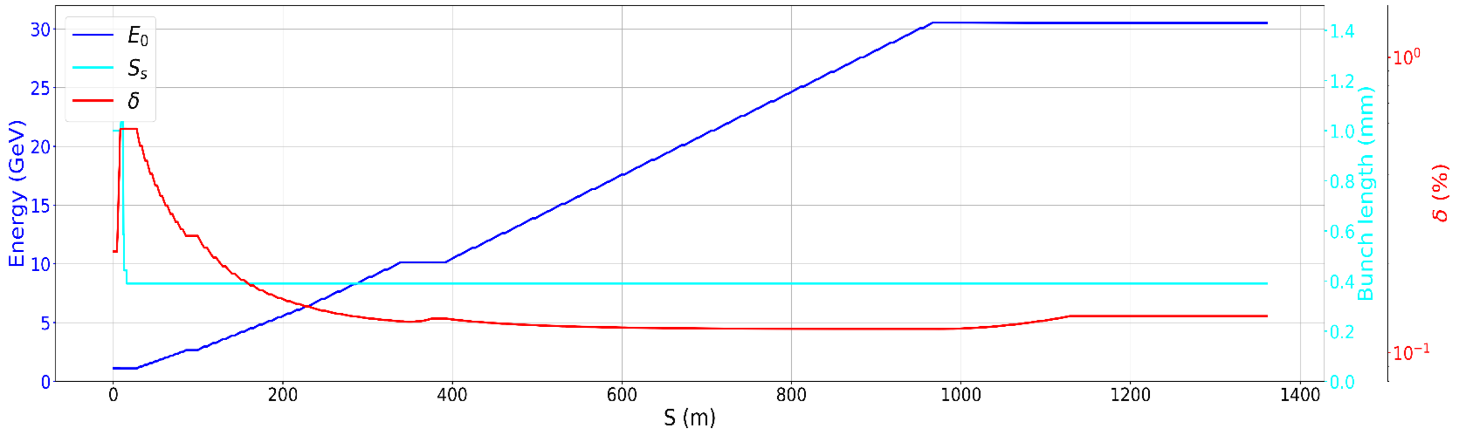
Positron Linac: TAS

- 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







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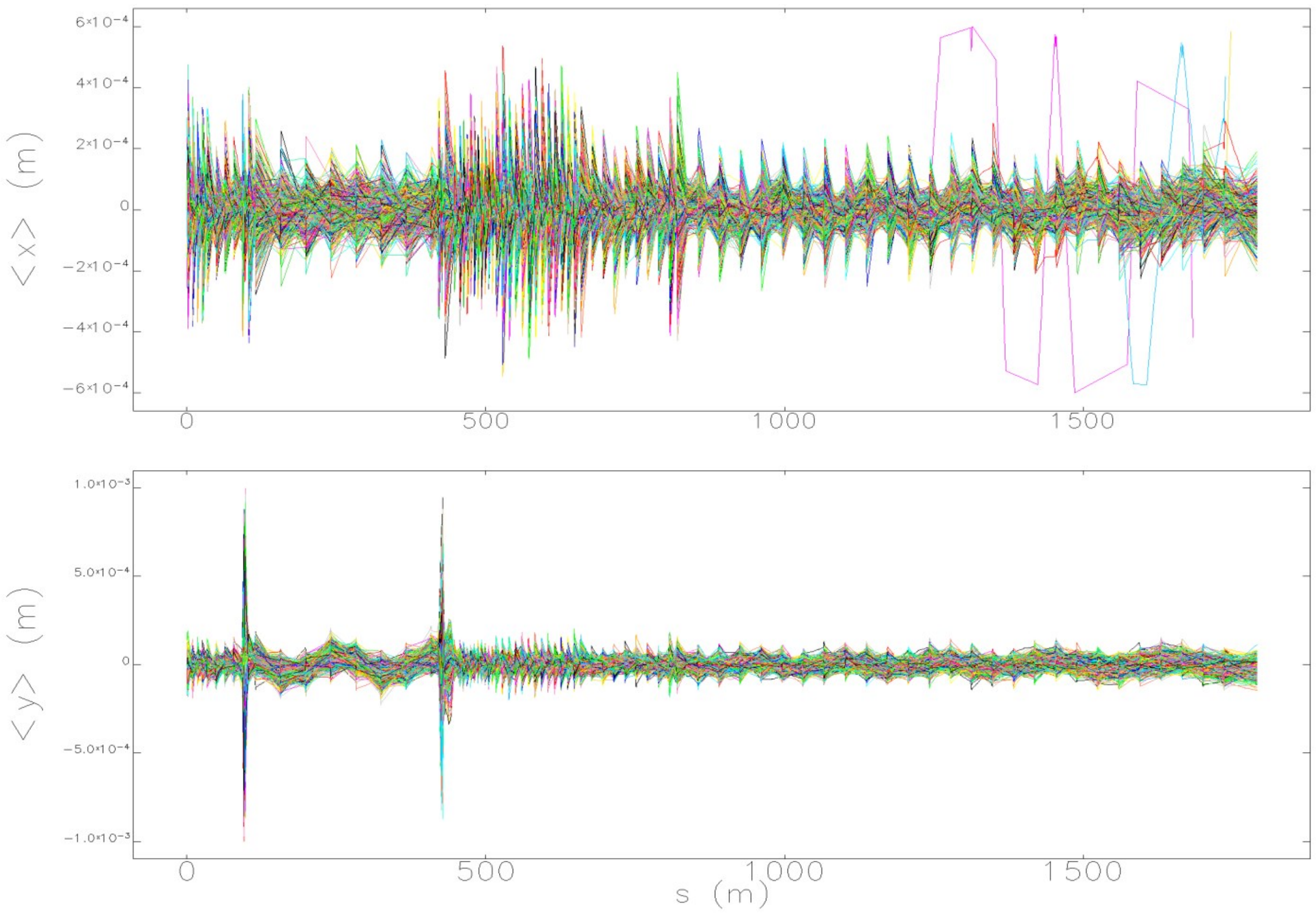
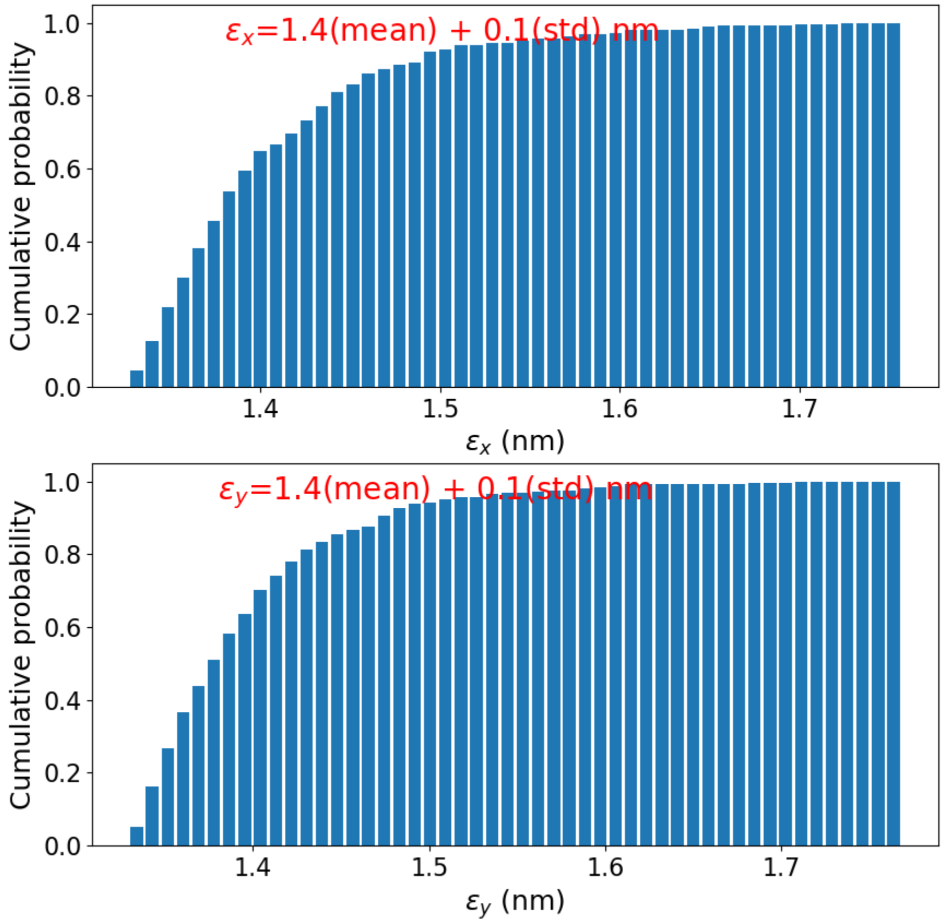
Error study: Misalignment errors

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 (10μm)	150	0.1	0.2	0.2
PR	30	0.15	0.2	0.2

Error study: Orbit correction

- Orbit correction

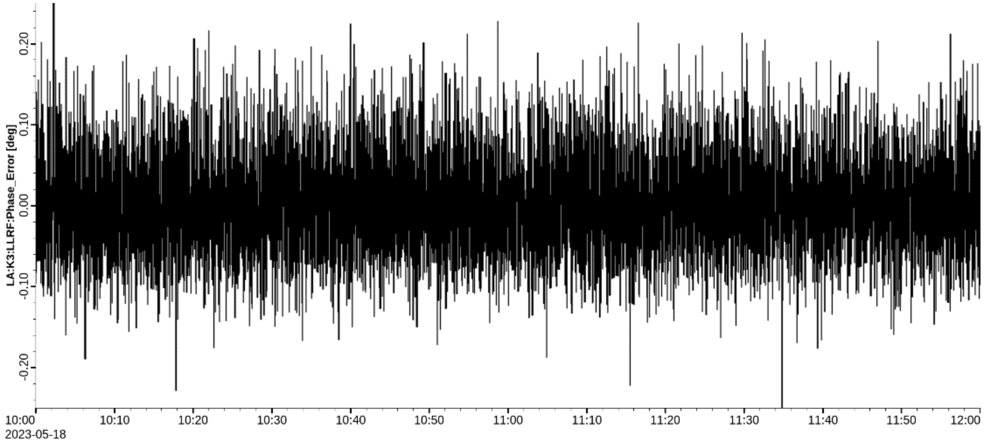


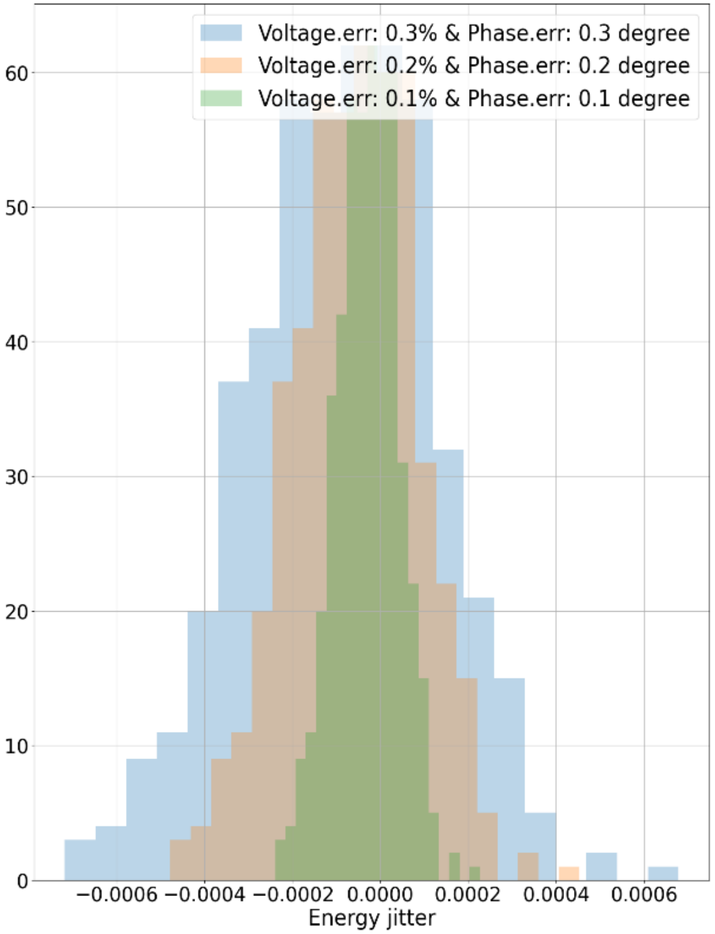


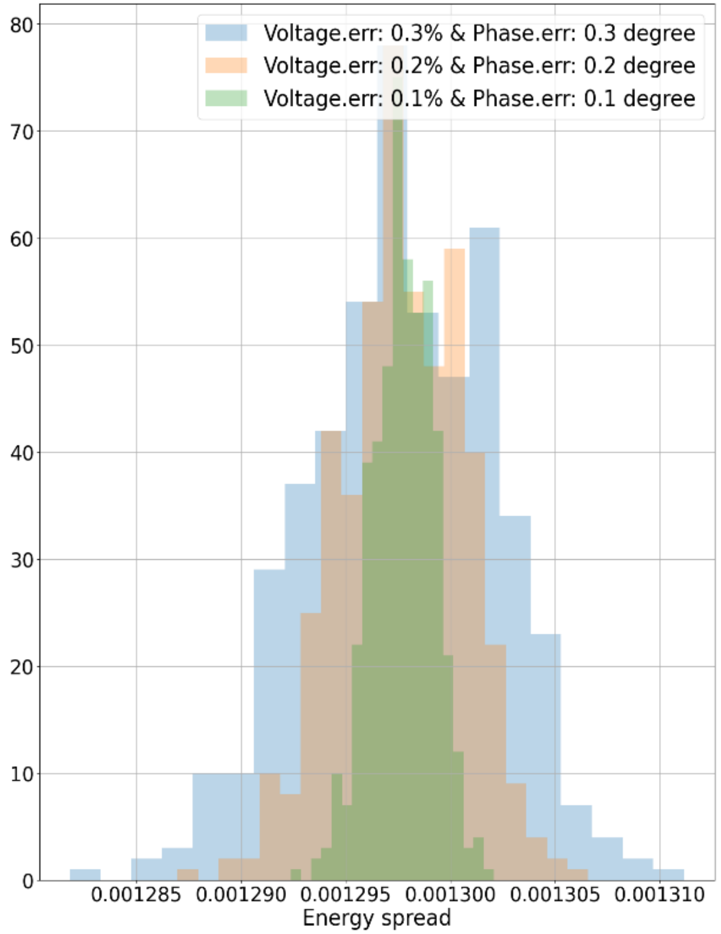
Error study: Energy jitter

- Energy jitter
  - 0.3% & 0.3 degree
  - <±0.1%

HEPS Linac:
Phase jitter is 0.08 degree (std) and 0.4 degree (peak-to-peak) (2 hours)







Error study: simulation results

- 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

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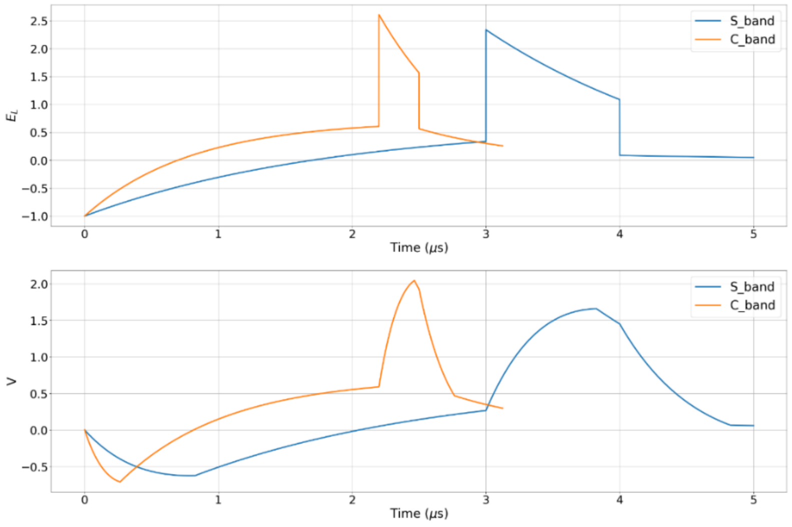
Z scheme: Double-bunch acceleration scheme

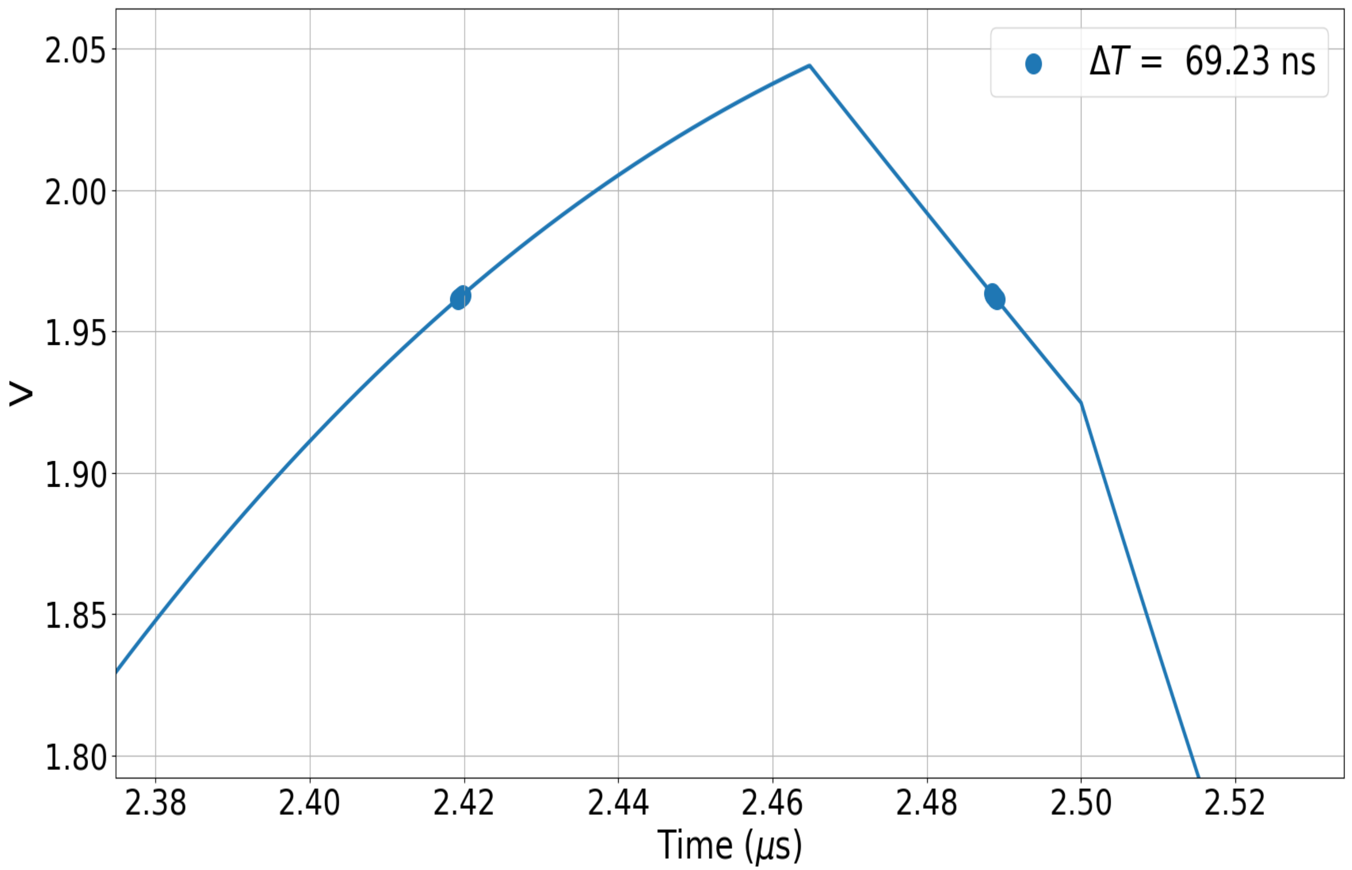
- In order to meet the injection requirement of high luminosity Z scheme, one should increase the injection speed of the Linac to the booster.
  - Double-bunch acceleration scheme
    - To filling the required bucket pattern, the SHB RF frequency should be checked
    - Pulse compressor
  - RF frequency of the Linac, booster and ring is 2860MHz,1300MHz and 650MHz
    - Greatest common divisor (GCD) is 130MHz
  - 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

Z scheme： Double-bunch acceleration scheme

- Energy multiplication factor can meet the requirements
  - S-band:
    - RF pulse is about 4.0μs
    - Filling time is about 0.83 μs
  - C-band: 95% Acc. Eff.
    - RF pulse maybe is about 2.5μs
    - Filling time is about 0.27 μs

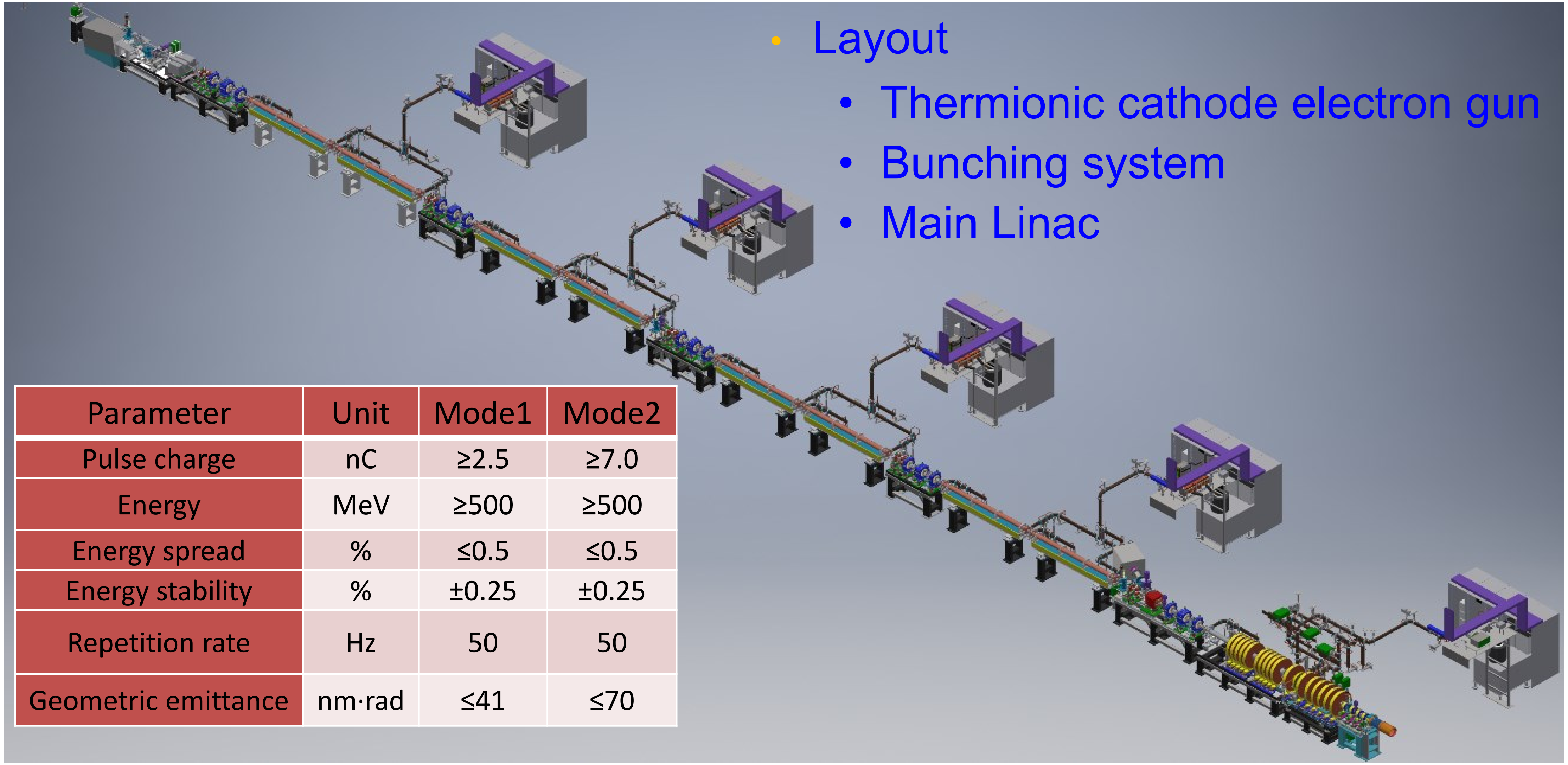




Content

- Introduction of the CEPC Linac
- Physics design of the CEPC Linac
  - Basic consideration
  - Electron Linac
  - Positron Linac
  - Error study
  - Double-bunch acceleration scheme
- **Experimental study on emittance growth in high bunch charge beam**
- Summary

HEPS Linac beam commissioning



- Layout
  - Thermionic cathode electron gun
  - Bunching system
  - Main Linac

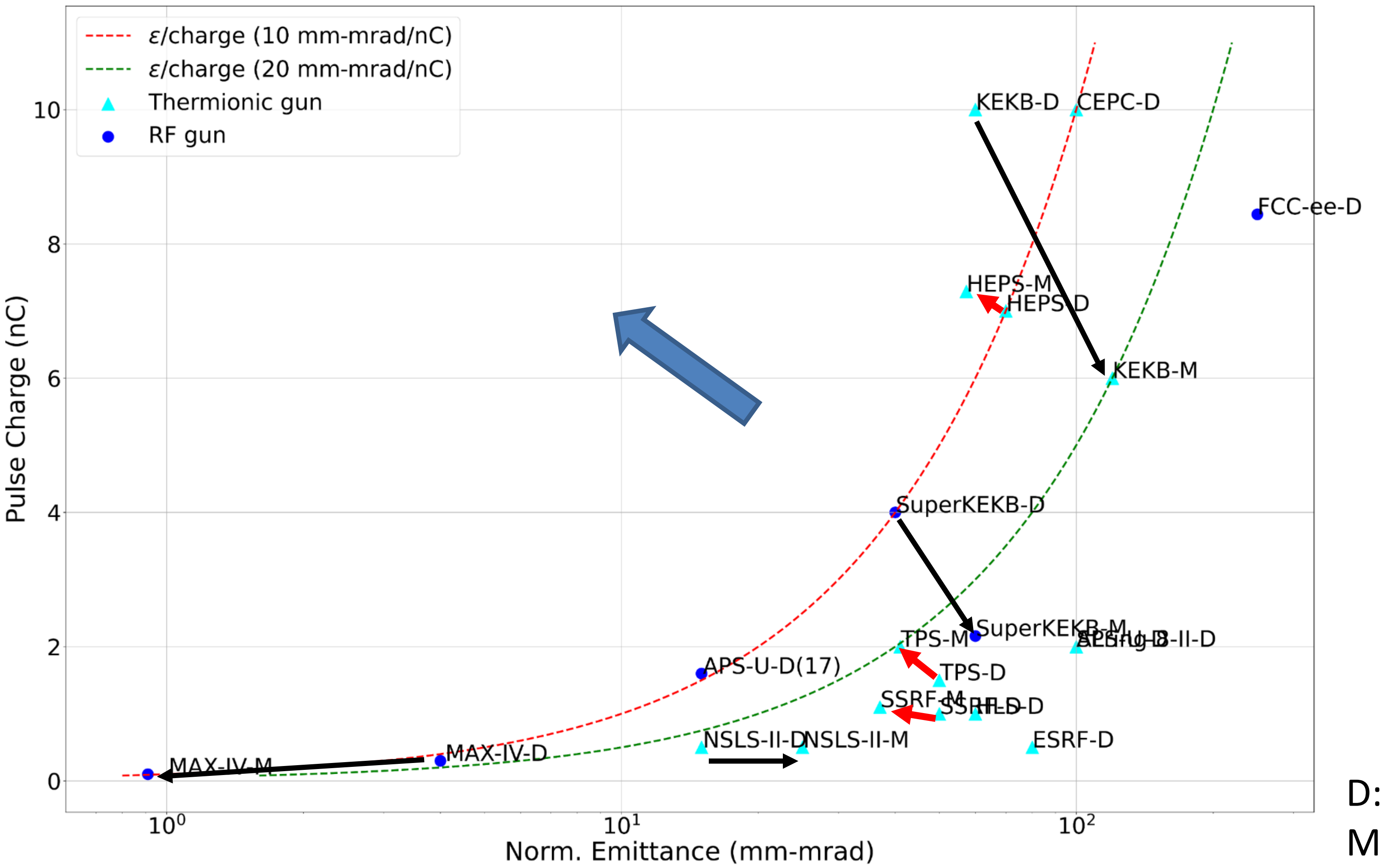
Parameter	Unit	Mode1	Mode2
Pulse charge	nC	≥2.5	≥7.0
Energy	MeV	≥500	≥500
Energy spread	%	≤0.5	≤0.5
Energy stability	%	±0.25	±0.25
Repetition rate	Hz	50	50
Geometric emittance	nm·rad	≤41	≤70

HEPS Linac beam commissioning

- Klystron gallery and Linac tunnel

HEPS Linac beam commissioning

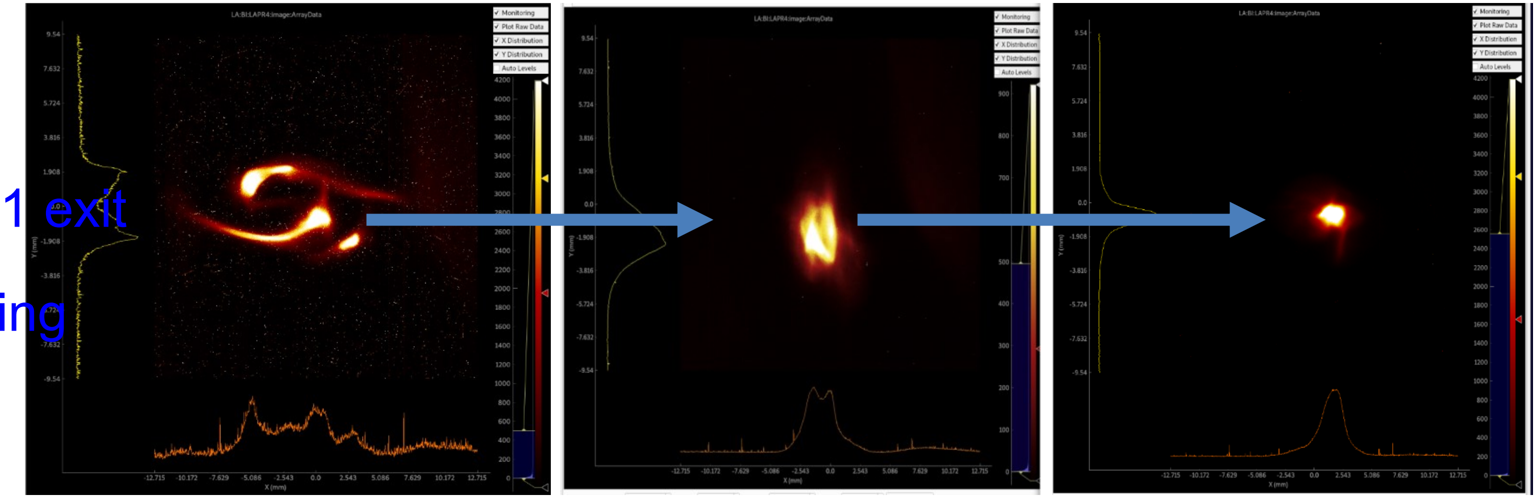
- High bunch charge Linac

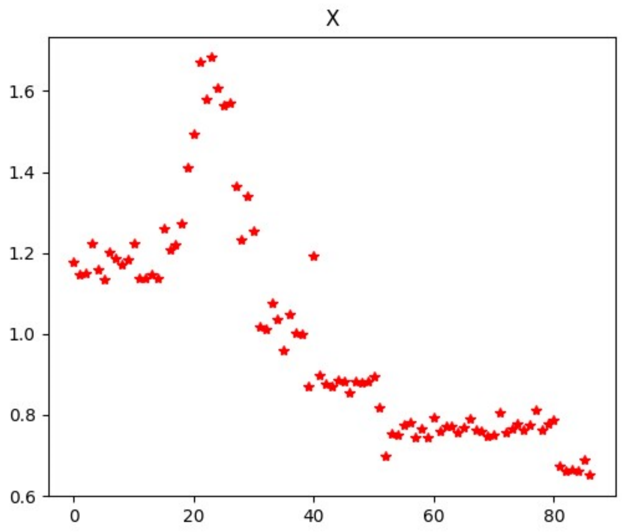


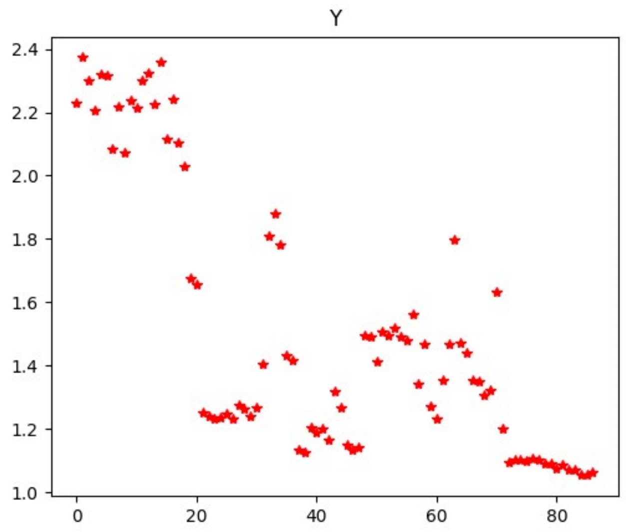
D: Design
M: Measurement

Emittance optimization: Wakefield effect

- Reasonable Lattice
  - Measured Twiss parameters@AS1 exit
  - Matched Lattice with strong focusing
- Reasonable orbit
  - Maintain transmission efficiency
  - Target： Beam size @PR4
  - Adjustment amounts： corrector
  - Method： as small as possible beam size







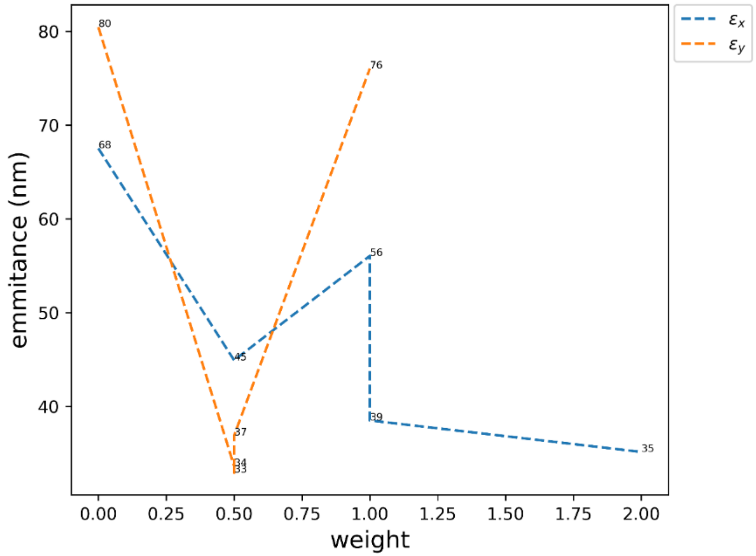
Emittance optimization: Wakefield effect

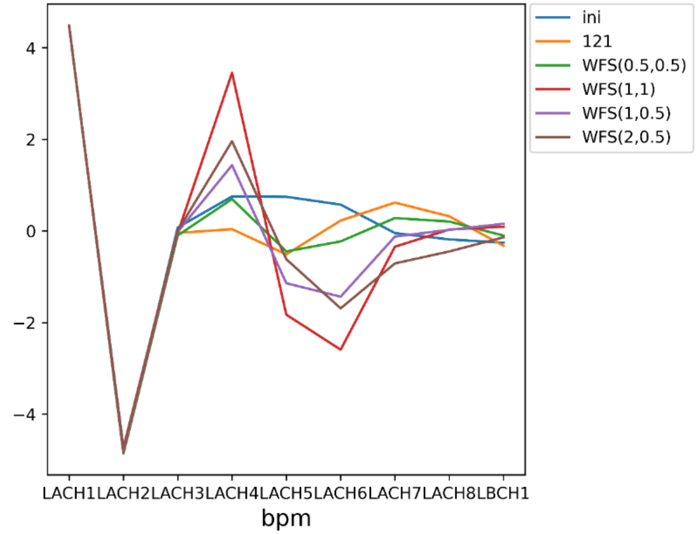
- Reasonable orbit
  - Maintain transmission efficiency
  - Target: orbit
  - Adjustment amounts: corrector
  - Method: Wakefield-free steering correction (WFS)
- The effectiveness of the method has been preliminarily verified

Orbit and response matrix @ 2.6nC and 1nC

	α_x	β_x	$\varepsilon_x(nm)$	α_y	β_y	$\varepsilon_y(nm)$
initial	-0.237	4.27	67.52	-0.567	6.393	80.46
$\omega = 0.5$	0.021	4.645	44.93	-0.304	6.189	53.64
$\omega = 1$	-0.18	5.188	56.06	-0.527	9.857	76.03
(1.0, 0.5)	0.13	6.093	38.51	-0.117	3.894	32.94
(2.0, 0.5)	0.156	6.121	35.15	0.076	4.725	36.90

$$\begin{pmatrix} \boldsymbol{x} \\ \omega_w \Delta \boldsymbol{x} \end{pmatrix} = \begin{pmatrix} \boldsymbol{R} \\ \omega_w [\boldsymbol{R} - \boldsymbol{R_w}] \end{pmatrix} \boldsymbol{\theta}$$

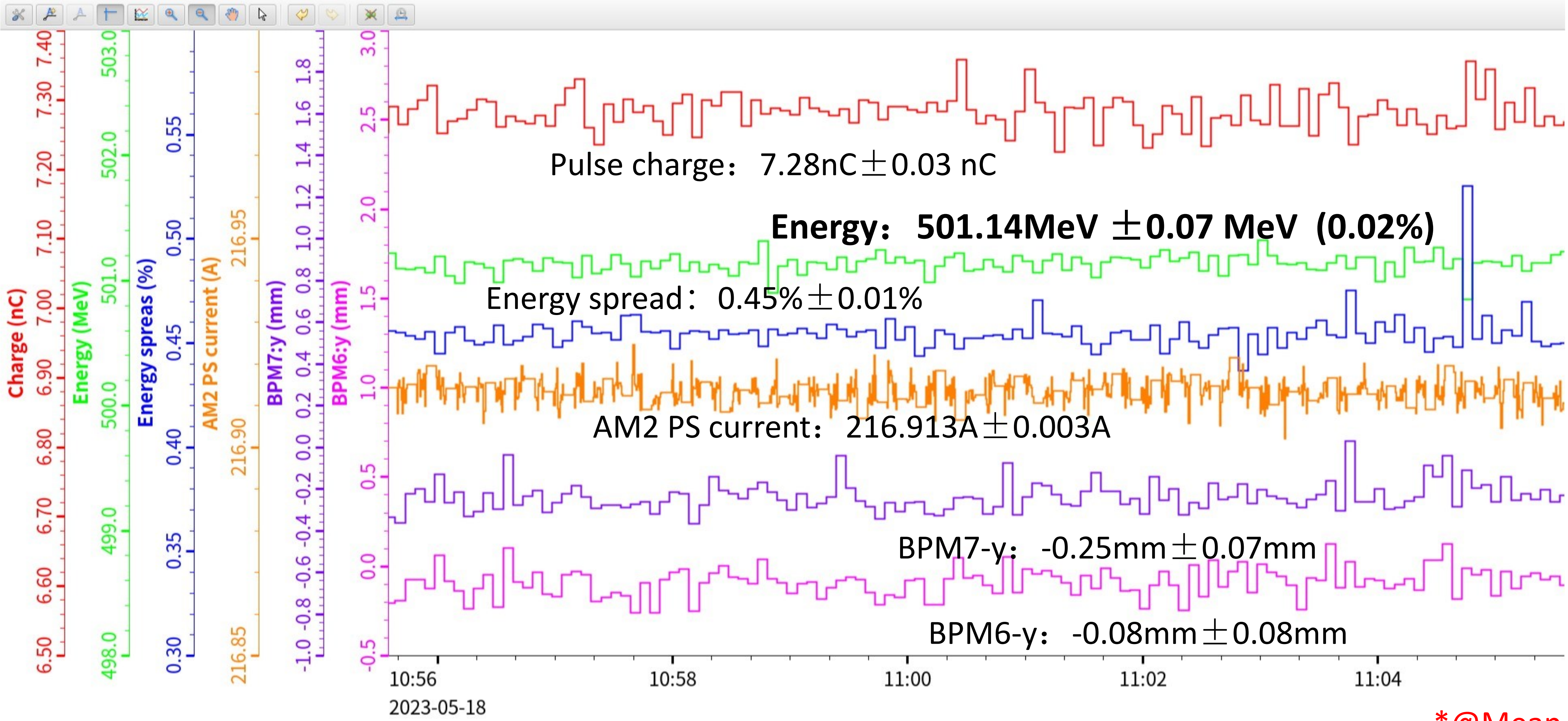




Stability: Excellent performance

- Energy jitter is smaller than 0.02% @ 7.28nC

$$\frac{\Delta E}{E} = \frac{1}{\sqrt{N}}\sqrt{\left(\frac{\Delta V}{V}\right)^2 + \left(\frac{\Delta\theta}{\tan\theta}\right)^2} \approx \frac{1}{\sqrt{N}}\frac{\Delta V}{V}$$

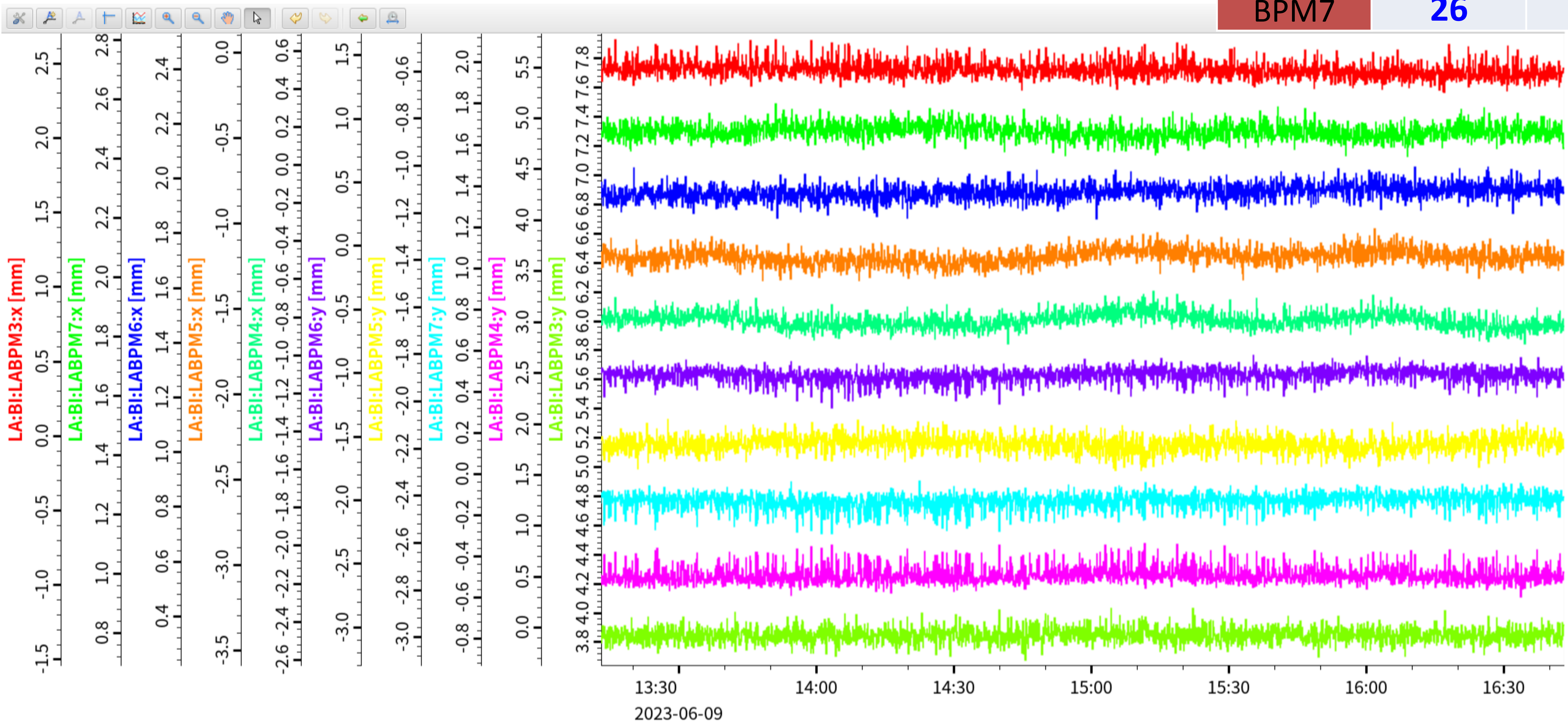


*@Mean ± std

Stability: orbit jitter

BPM	X	Y
	µm	
BPM3	53	50
BPM4	39	79
BPM5	45	34
BPM6	27	54
BPM7	**26**	**38**

- Average beam orbit jitter is 45 µm @ 2.5nC (4 hours)



Measurement results

- Measurement results can meet the design requirements.

		Designed		Measured	
Parameter	Unit	Mode1	Mode2	Mode1	Mode2
Pulse charge	nC	≥2.5	≥7.0	2.84±0.02	7.29±0.02
Energy	MeV	≥500	≥500	501.4	501.2
Energy spread	%	≤0.5	≤0.5	0.31	0.45
Energy stability	%	±0.25	±0.25	σ=0.014 Peak-peak=±0.04	σ=0.014 Peak-peak=±0.05
Geometric emittance	nm·rad	≤41	≤70	37.2(H) 36.9(V)	56.4(H) 58.5(V)

Summary

- The Linac energy is designed 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, double-bunch-per-pulse is need and the baseline scheme can meet the requirements.
- The successful beam commissioning of the HEPS Linac gives us experience.

CEPC

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Thank you for your attention!