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

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

Issues related to CEPC e+/e- injection

eeFACT2022

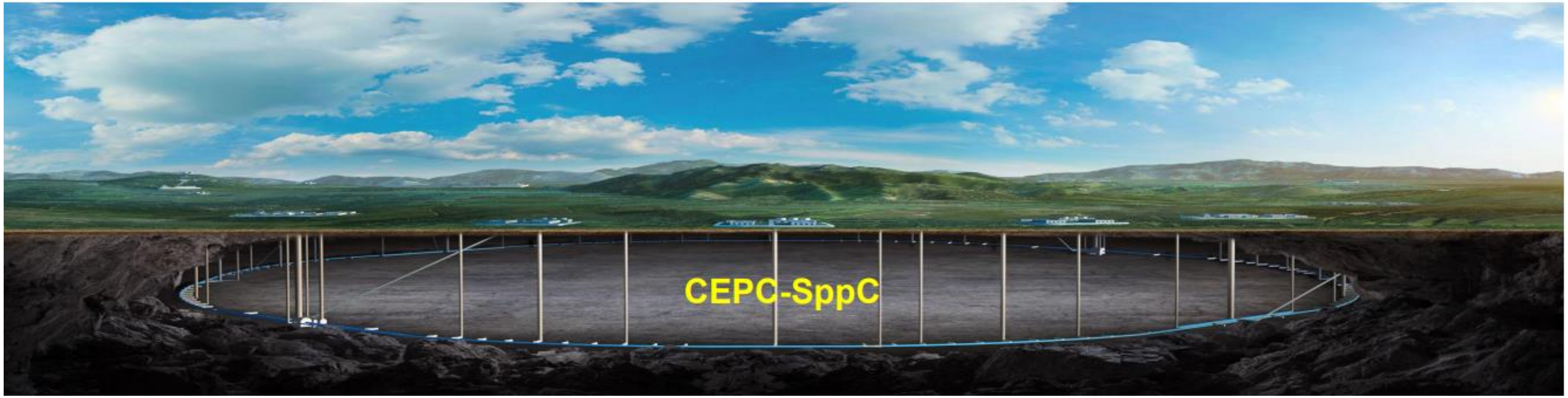
Sep. 12~15, 2022

C. Meng

on behalf of CEPC AP group, IHEP

Outline

- Introduction
- Progress on CEPC Linac design
- Summary

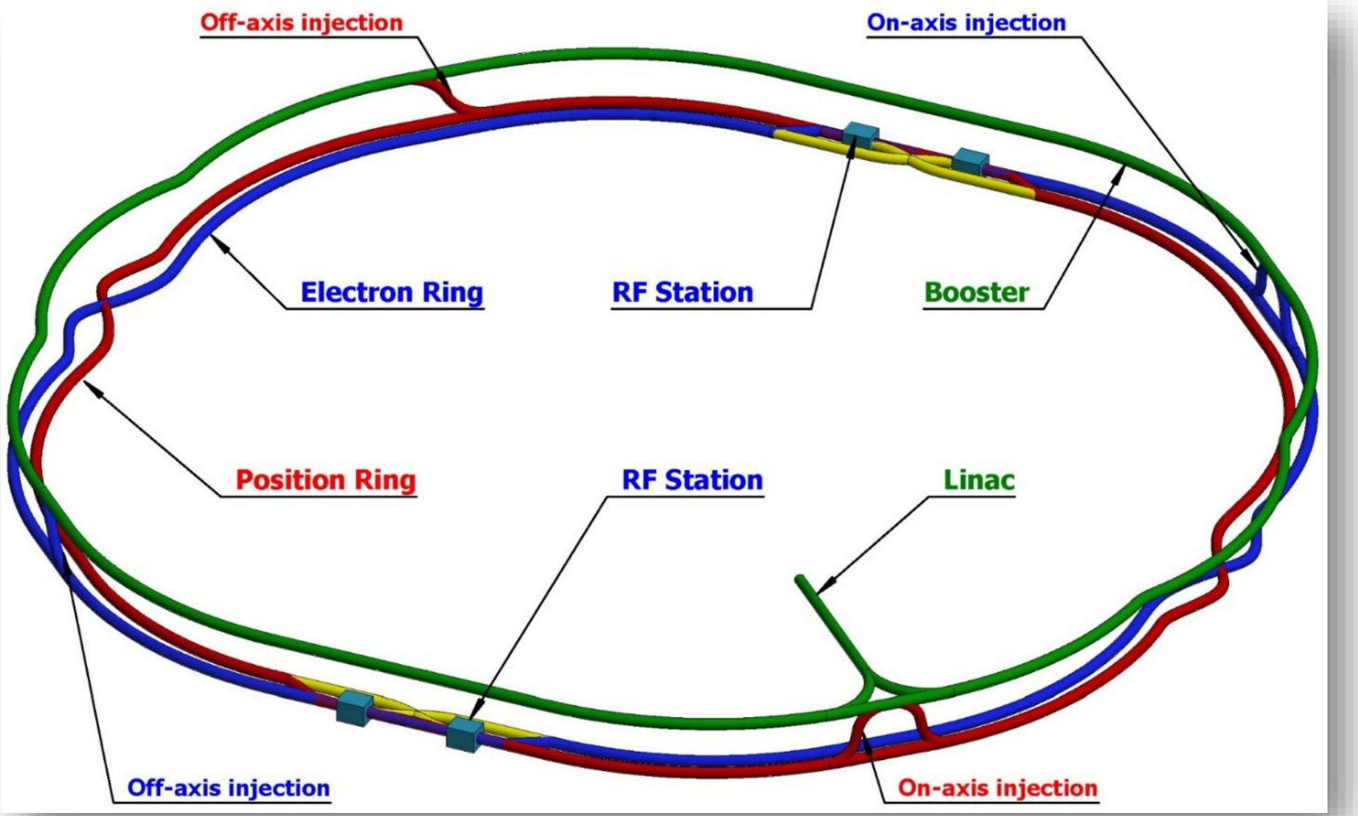


Introduction

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

Linac evolution

➢Meet the design requirements of Booster: Energy/Emittance

Stage			PreCDR	CDR									TDR				
Parameter		Unit	V1	V2			V3								V4		
				V2.1	V2.2	V2.3	V3.1	V3.2	V3.3	V3.4	V3.5	V3.6	V3.7	V3.8	**V4.1**	V4.2	V4.3
Beam energy (e+/e-)	E_{e-}/E_{e+}	**GeV**	**6**	**10**					**4**	**10**			**20**	**10/20**	**20**		**30**
Repetition rate	f_{rep}	Hz	50					100									
Bunch number per pulse			1													**1&2**	
Bunch population (e+/e-)	N_{e-}/N_{e+}	$\times10^{9}$	20				6.25			6.25(18.8)	**9.4 (18.8)**						
		nC	3.2				1			1(3)	**1.5 (3)**						
Energy spread (e^{+}/e^{-})	σ_E	$\times10^{-3}$	1				2								**1.5**		
e^{-} bunch charge at target		nC	**10**														
e^{-} beam energy at target		GeV	4						2	**4**							
Emittance	ε	**nm**	**300**								**120**		**60**	**40**	**10**		**6.5**
Damping Ring			Yes			No					Yes	Yes			**Yes**		
	E_{e+}	GeV	1.1								1.1	1.1			**1.1**		
	C	m	58.5								58.5	75.4			**147**		
	ε_0	mm-mrad	287								287	377			**94**		
Bunch compressor			No							Yes	No		**Yes**				
Accelerating strucutre			S-band										**S-band+C-band**				
RF frequency	f_{RF}	MHz	2856.75									2860	**2860/5720**				
Accelerating gradient		MV/m	15/27	18/27 or. 18/21			21						**22 & 27/45**				
Klystron-to-ACC.Struc.			1-t-2	1-t-2 or. 1-t-4			1-t-4						**1-t-4 & 1-t-2(S)/1-t-2(C)**				
Shared Linac Energy range		MeV	200-1100		**No**												
Linac tunnel length		km	600	1200					500	1200			1400				**1800**
Collider circumference		km	54 & 61	61			**100**										
Layout			shared Linac	3 layout schemes			TGB or EBTL		Pre-BST	**EBTL**							
Date			Apr-16	Nov-16			Dec-16	Apr-17	Aug-17	Oct-17	Dec-17	Jul-18	Mar-19	Sep-19	**May-21**	**Mar-22**	Jun-22

Introduction

Baseline scheme

- Latest Baseline scheme (2021.5)
  - Motivation: Energy →20 GeV
    - "Low magnetic field & large magnetic field range"
      - 30Gs@10GeV
      - 10GeV→180GeV
    - Air-core coil can used at low injection energy but not suitable for high energy;
    - iron-corn magnet can meet the requirement of large magnetic field range but can not meet the magnetic field at low injection energy
  - High Luminosity for Higgs
    - Emittance → 10nm
  - High luminosity for Z
    - need faster injection speed
      - 200 Hz
      - 100 Hz & double-bunch acceleration

- Latest Baseline scheme (2022.6)
  - Motivation: *Energy →30 GeV*
    - In order to reduce the effect of residual magnetism at low injection energy, oriented silicon steel sheet is required for the booster dipole magnet material, however this is very expensive
    - Non-oriented silicon steel sheet instead of oriented silicon steel sheet can save a lot of cost, even considering the Linac cost increase
  - High luminosity for Z
    - need faster injection speed
      - 100 Hz & double-bunch acceleration

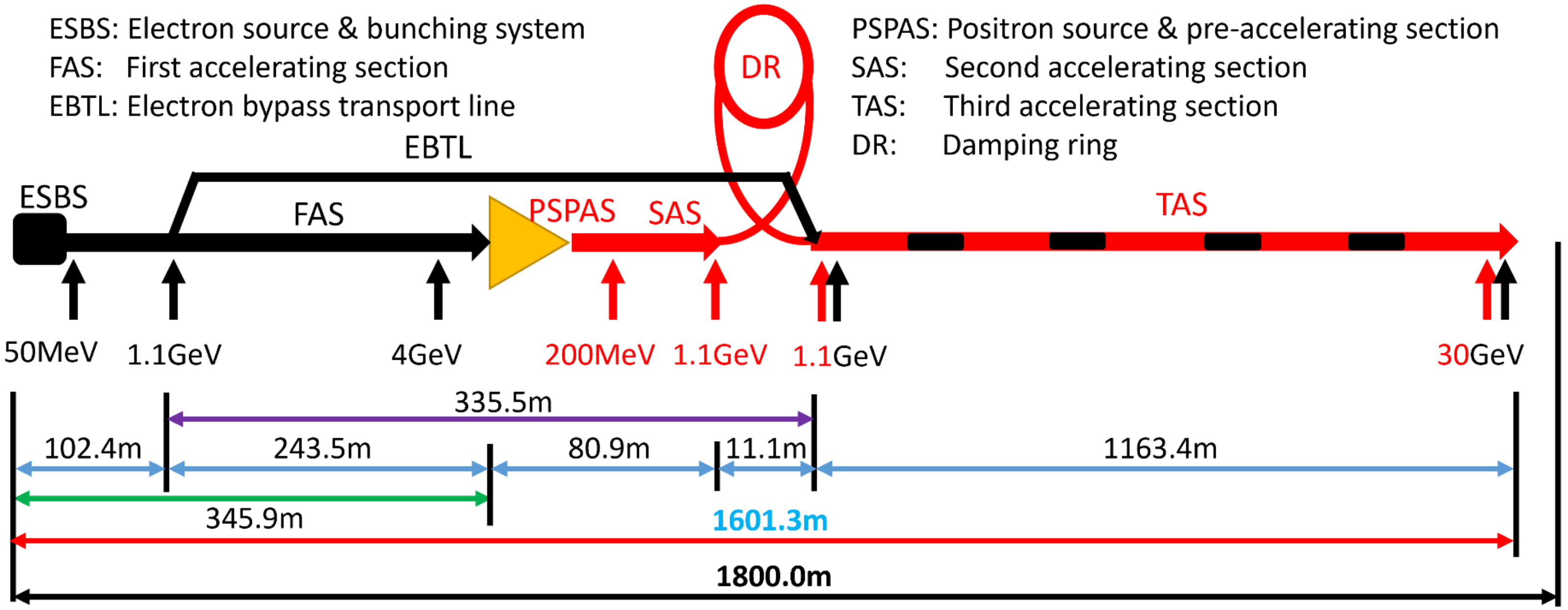
Introduction

Baseline scheme

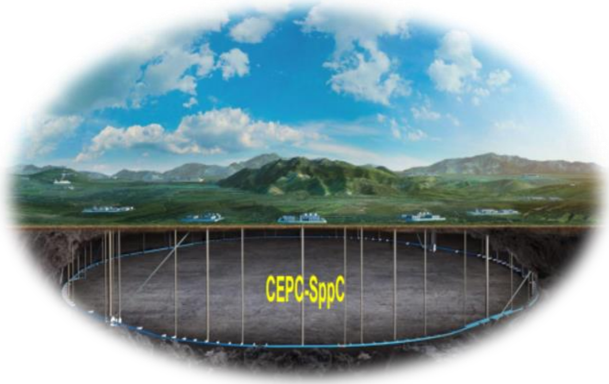
- Latest Baseline scheme (2022.6)
  - Energy: →30 GeV
    - ✓ C-band accelerating structure @TAS
      - ☐ Higher gradient → Shorter linac tunnel length
      - ☐ Small aperture & Strong wakefield

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

- Layout
  - The tunnel is 1.8km
    - ✓ Linac is about 1.6 km
    - ✓ 200 m as reserved space



Progress on CEPC Linac design

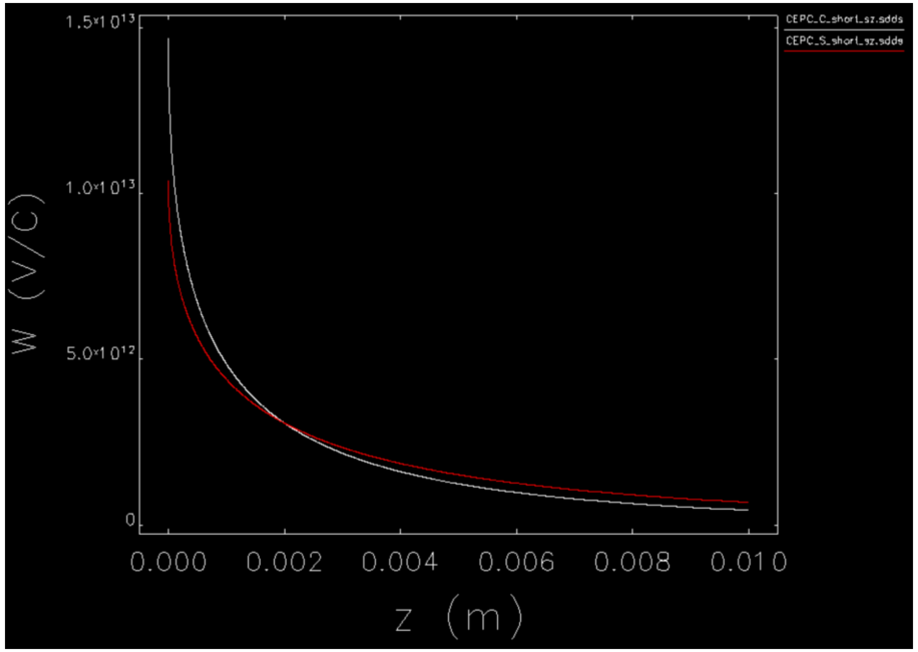


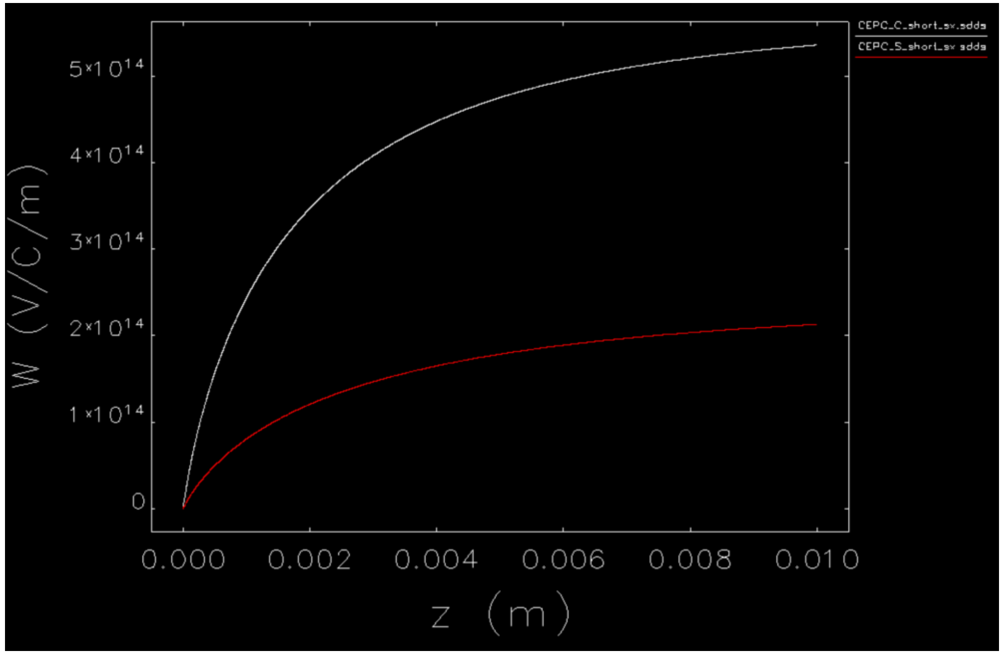
1. Basic consideration
2. Electron source and bunching system
3. Electron Linac
4. Positron Linac
   - First accelerating section(FAS)@4GeV & 10nC
   - Positron source and pre-accelerating section(PSPAS)
   - Second accelerating section(SAS)
5. High luminosity for Z scheme consideration

Basic consideration

Short-range Wakefield

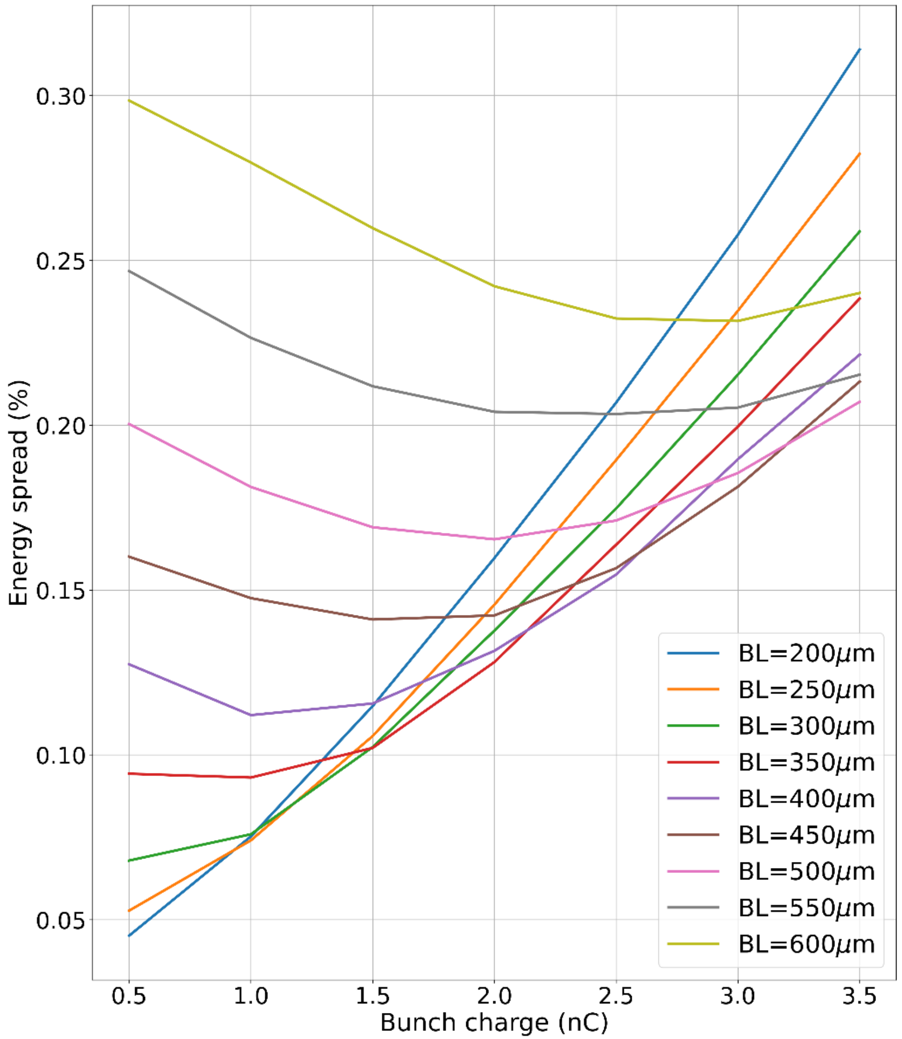
Parameter	Unit	S-band	C-band
Frequency	MHz	2860	5720
Length	m	3.1	1.8
Cavity mode		2π/3	3π/4
Aperture diameter	mm	20~24	11.8~16
Gradient		22/27	45

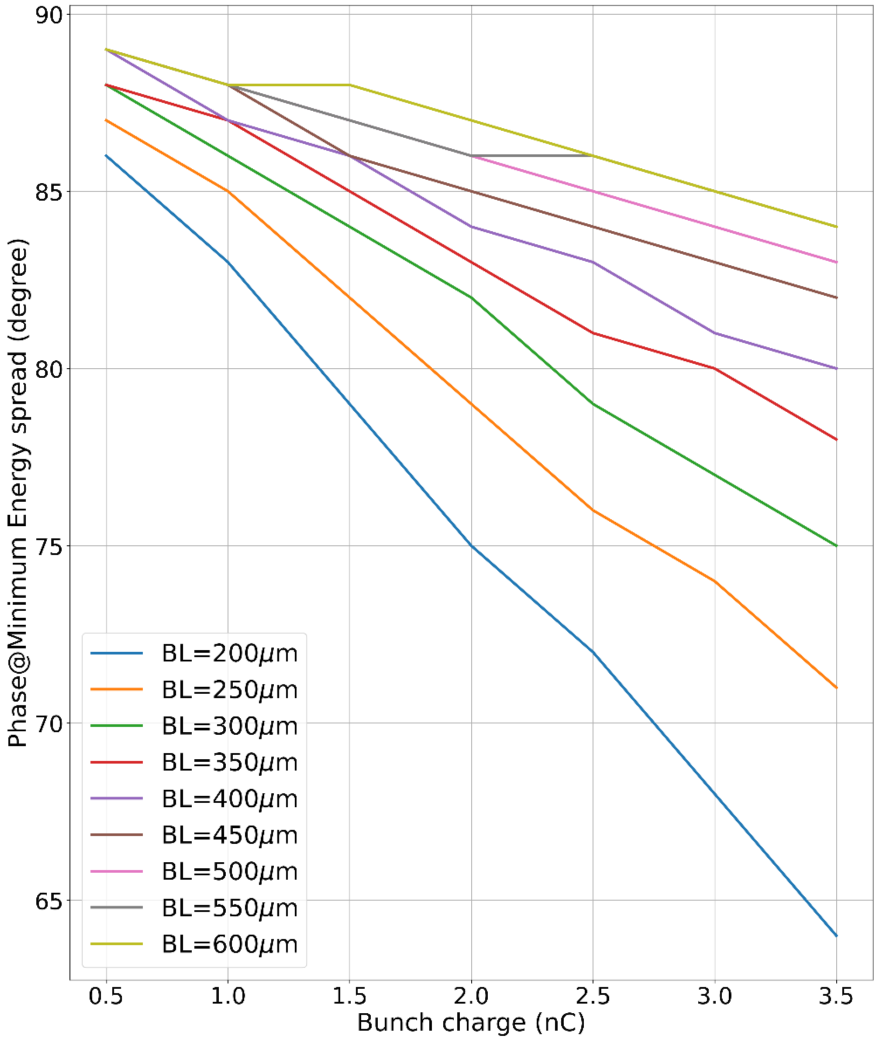




Basic consideration

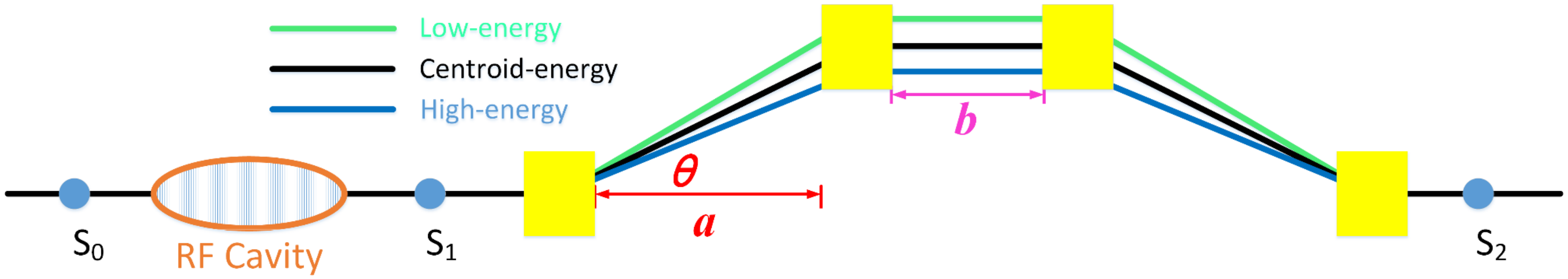
Phase scan @ TAS





Bunch Length: 400μm

Basic consideration Bunch compressor



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

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

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

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

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

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

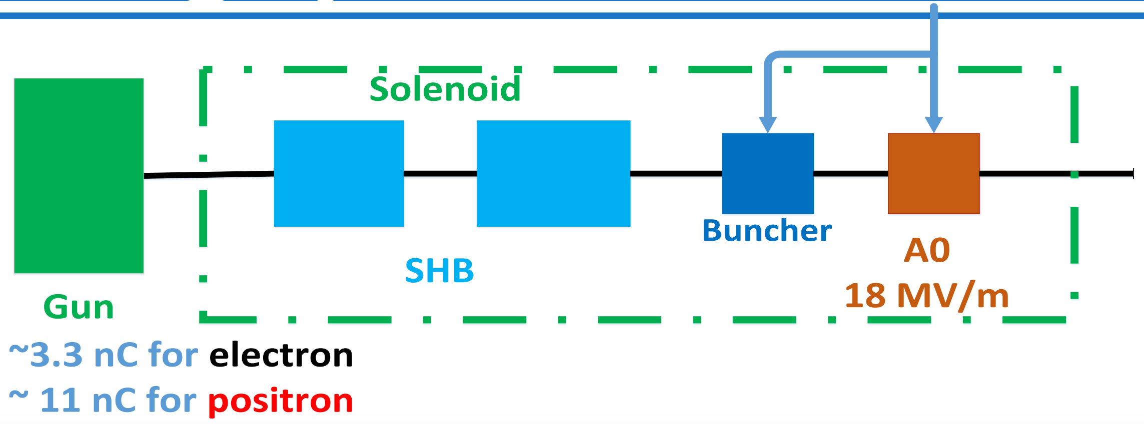
$$\phi_0 = \arctan\left(\sqrt{\frac{k^2}{4F} - 3} - \frac{k}{2\sqrt{F}} \right)$$

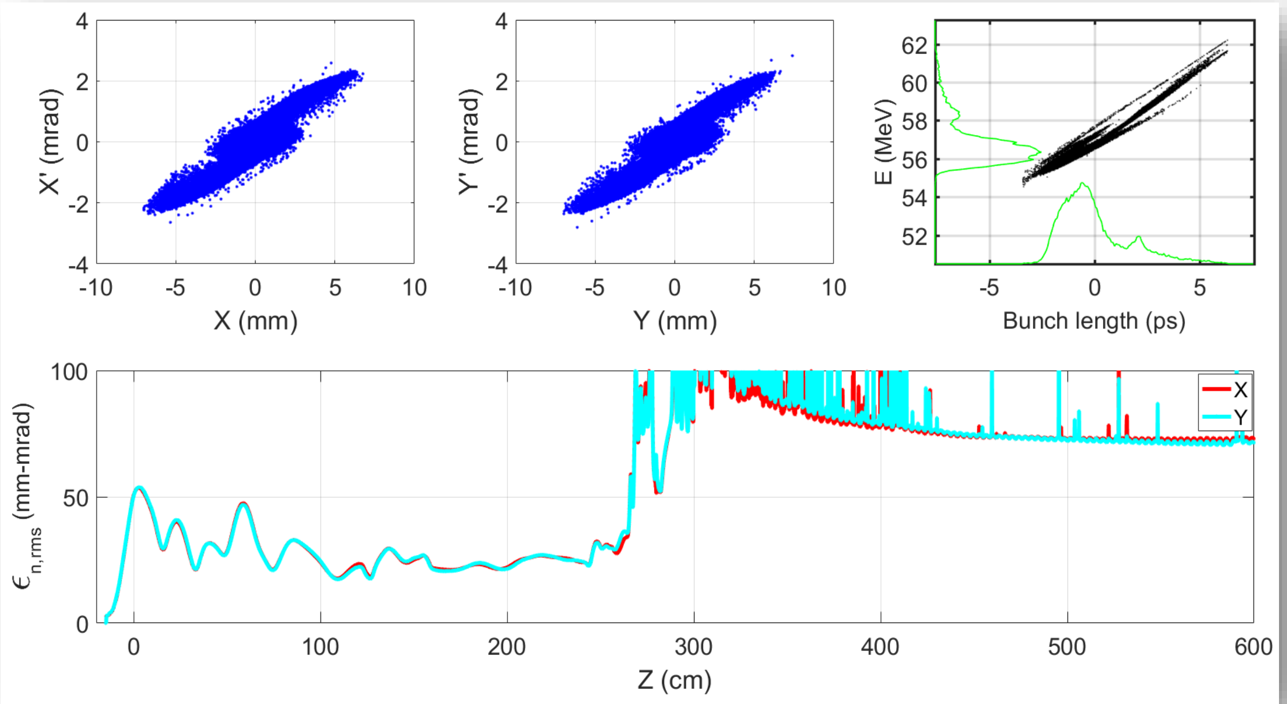
$$V = \frac{\sqrt{F} E_0}{k \cos\phi_0} ,$$

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

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%

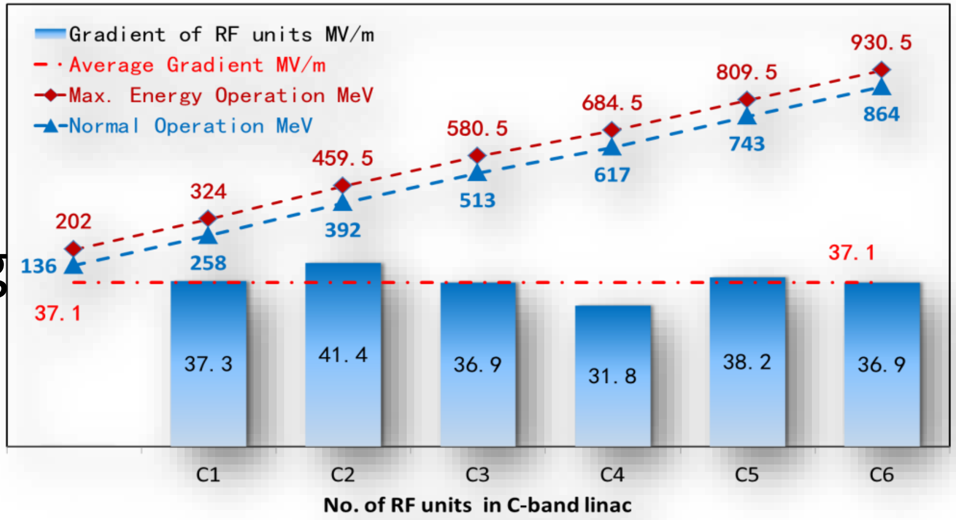




Electron Linac Acceleration

- FAS:50MeV→1.1GeV
  - 5+1(redundancy) S-band klystron
  - 1 klystron →4 accelerating structures
  - Gradient: 22MV/m
- TAS: 1.1GeV→30GeV
  - 195+40(redundancy) C-band klystron
  - 1 klystron →2 accelerating structures
  - Gradient: 45MV/m
- If the operation gradient of C-band accelerating structure is 40MV/m
  - Still works
  - 219+16(redundancy) C-band klystron
  - About 7% redundancy

Parameter	Unit	S-band	C-band
Frequency	MHz	2860	5720
Length	m	3.1	1.8
Cavity mode		2π/3	3π/4
Aperture diameter	mm	20~24	11.8~16
Gradient	MV/m	22	45 or 40



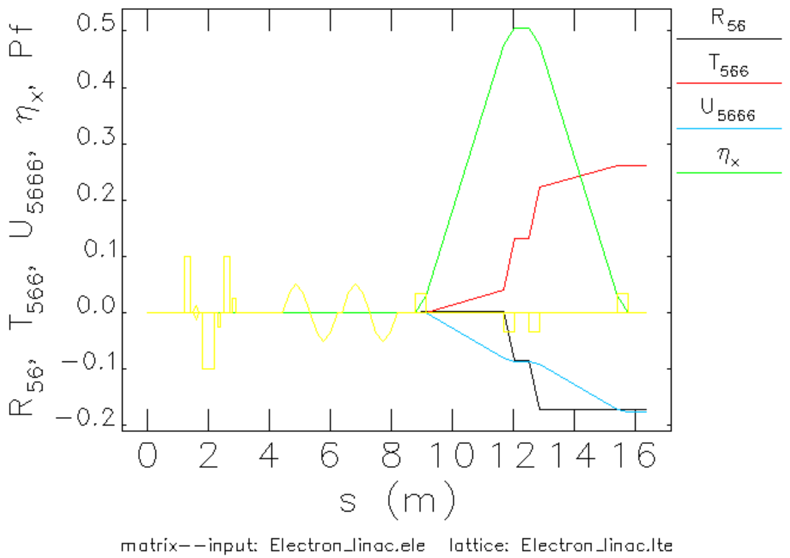
SXFEL @W.C. Fang

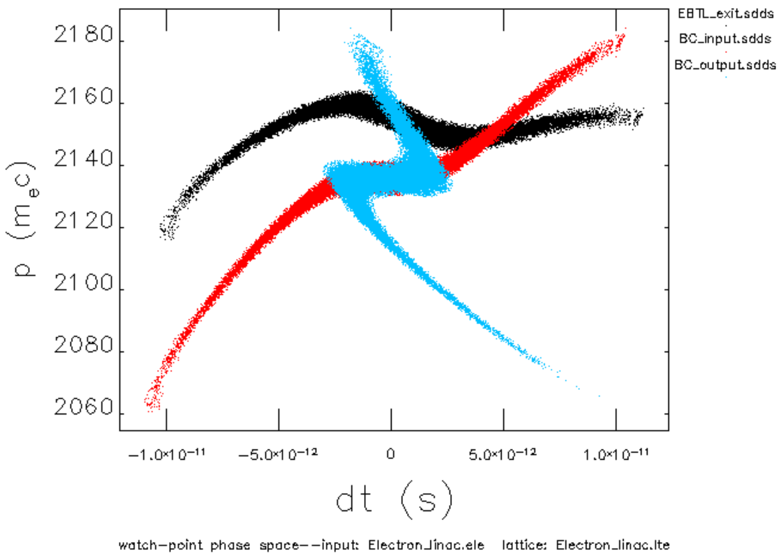
Electron Linac

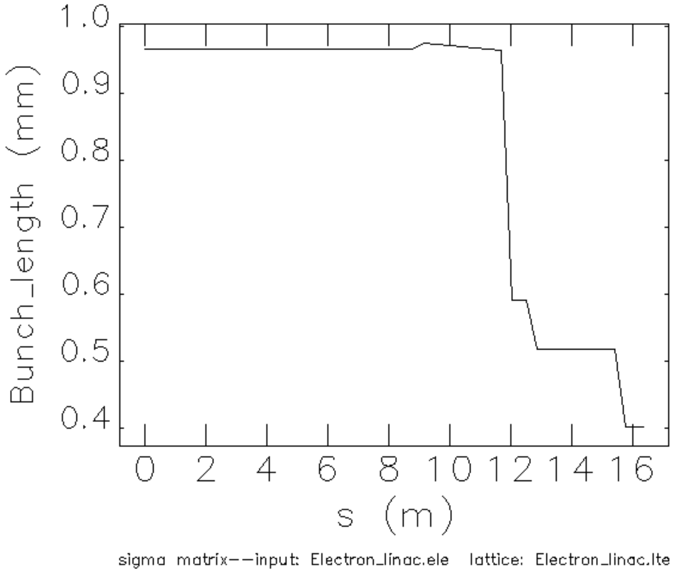
Bunch compressor

- The bunch length is compressed to match the C-band accelerating structure
  - Angle: 10°
  - R56=-0.171m
  - V=51MV
  - Phase=-7°

		Value	Units
Initial rms bunch length	$\sqrt{\langle z_0^2 \rangle}$	0.966	mm
Initial rms energy spread	$\sqrt{\langle \delta_0^2 \rangle}$	0.221%	
Final rms bunch length	$\sqrt{\langle z_1^2 \rangle}$	0.4	mm
Initial energy	E_0	1.1	GeV

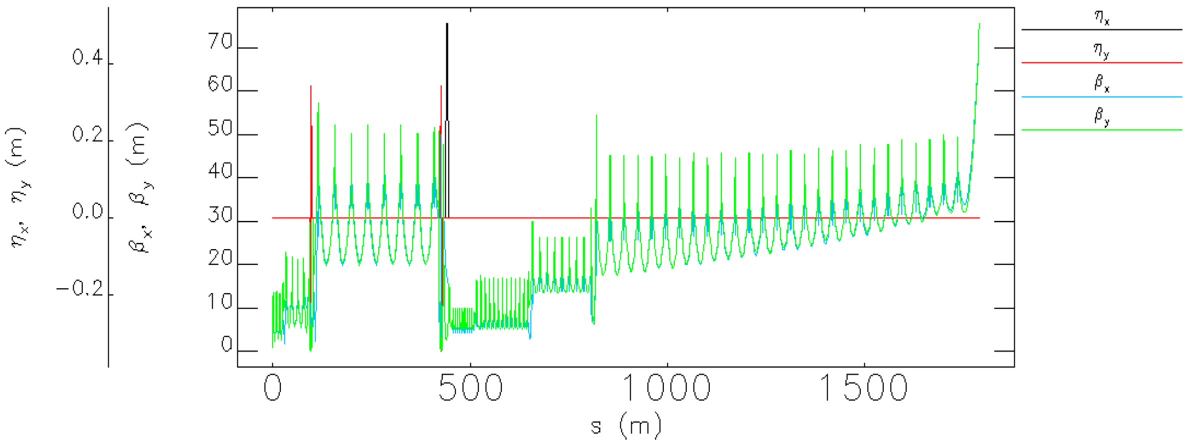


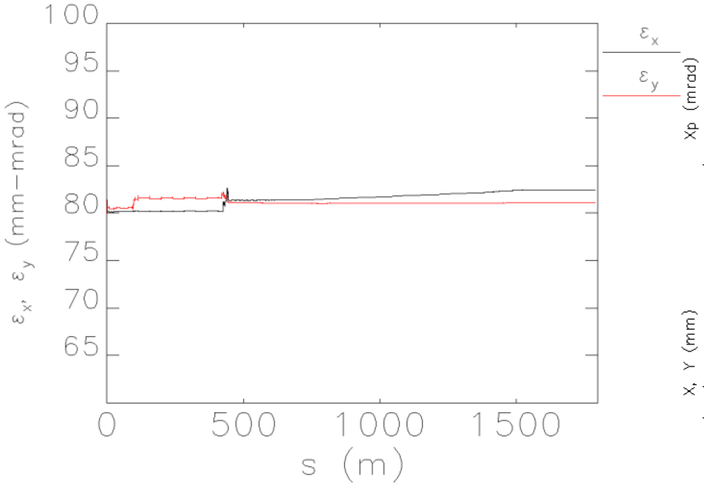


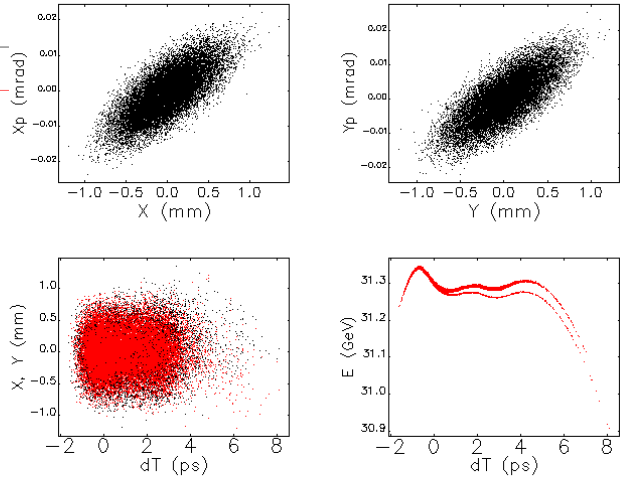


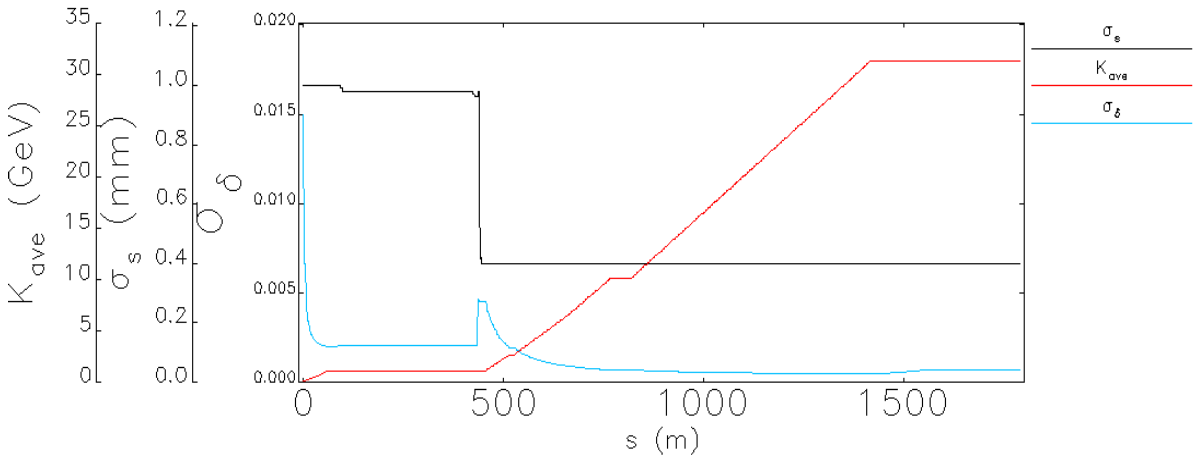
➢Simulation results(including Wakefield & CSR)

Parameter	Unit	Value	Simulated	
			Electron	
Beam energy	GeV	30	31.3	30.8
Repetition rate	Hz	100	/	
Bunch charge	nC	1.5	1.5	3.0
Energy spread		1.5×10^{-3}	0.68×10^{-3}	1.37×10^{-3}
Emittance(x/y)	nm	6.5	1.35/1.33	1.4/1.6
Bunch length (RMS)	mm	/	0.4	0.4





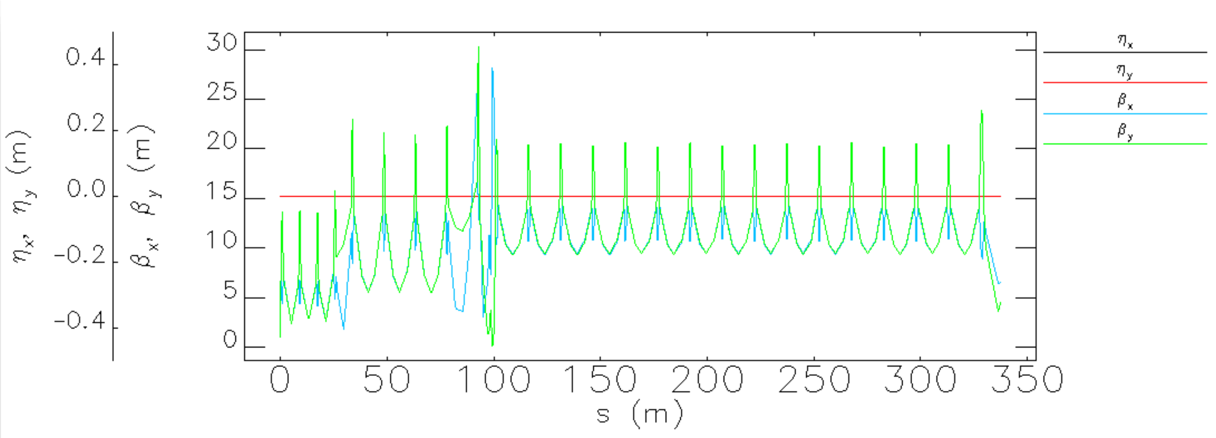


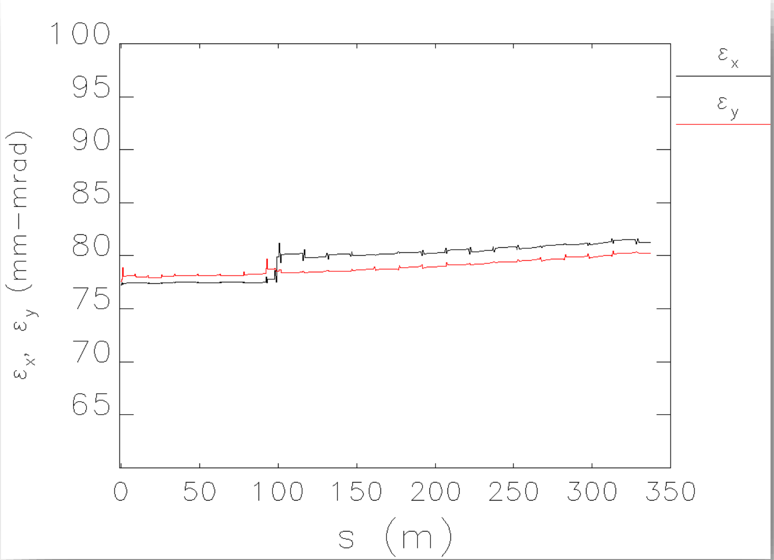


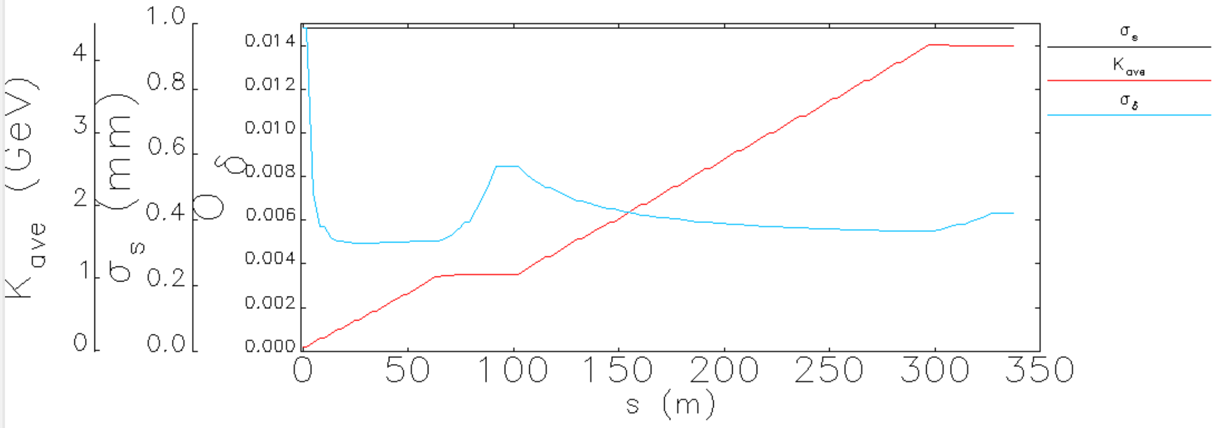
Positron Linac

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: 0.7%

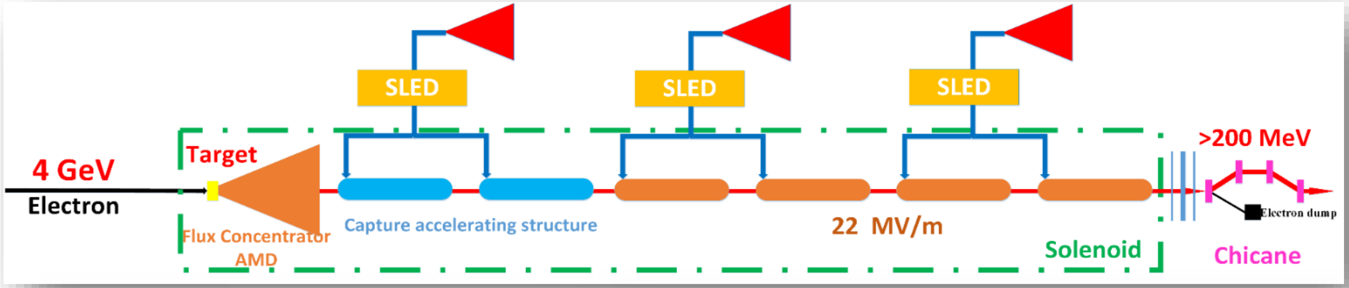


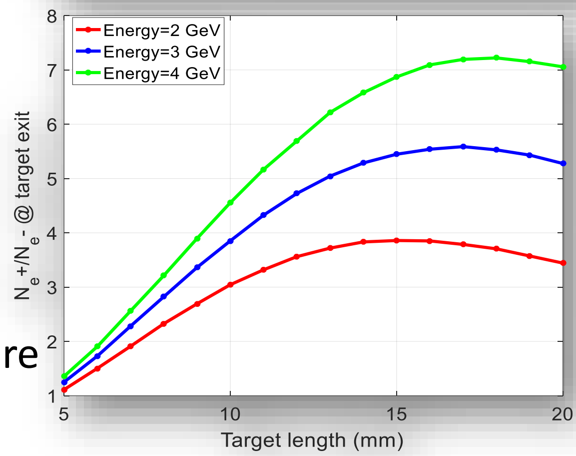


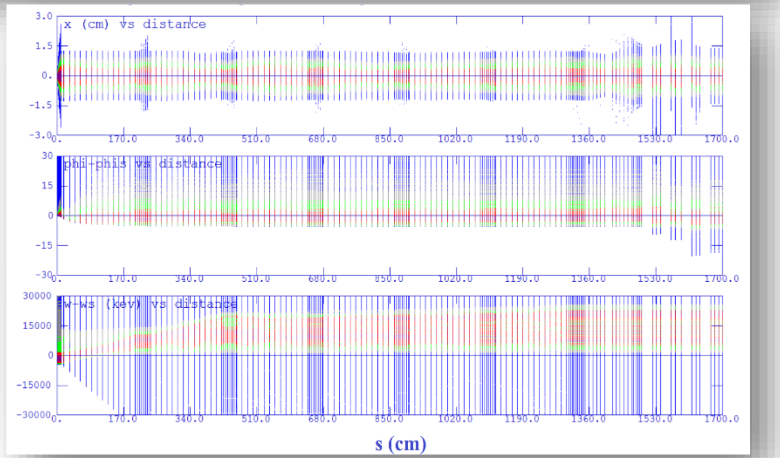


Positron Linac PSPAS

- 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





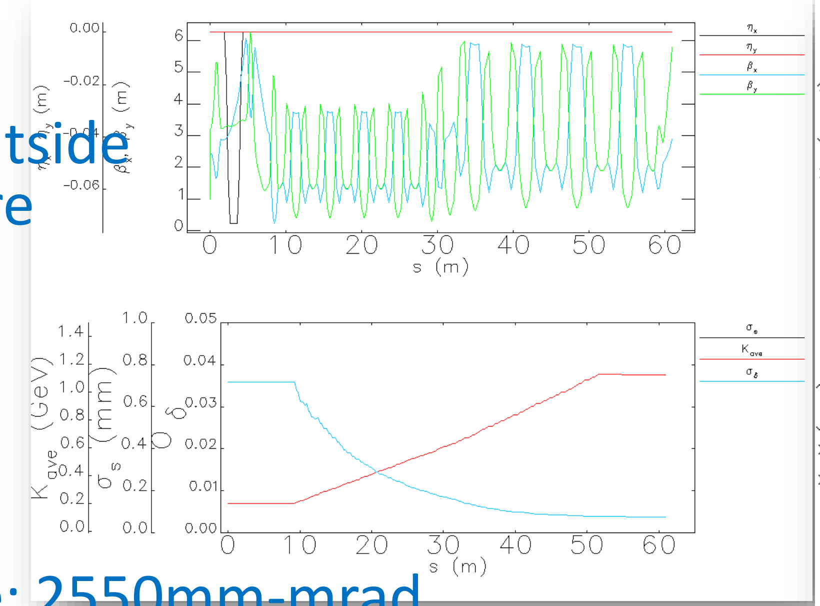


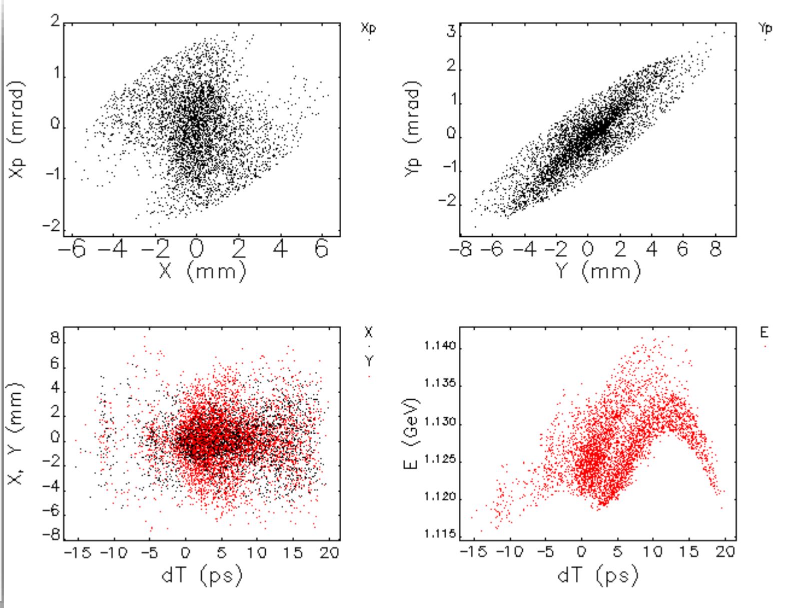
Positron source	Unit	Requirement	Simulation results
e^- beam energy on the target	GeV	4	
e^- bunch charge on the target	nC	10	
e^+ bunch charge	nC	≥3	~5.5
e^+ Energy	MeV	≥200	250
e^+ Norm. RMS emittance	mm-mrad	≤2400	2370

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
- 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: 2550mm-mrad

Parameter	Unit	S-band	
Frequency	MHz	2860	
Length	m	3.1	2.0
Cavity mode		2π/3	2π/3
Aperture diameter	mm	20~24	25
Gradient	MV/m	22	

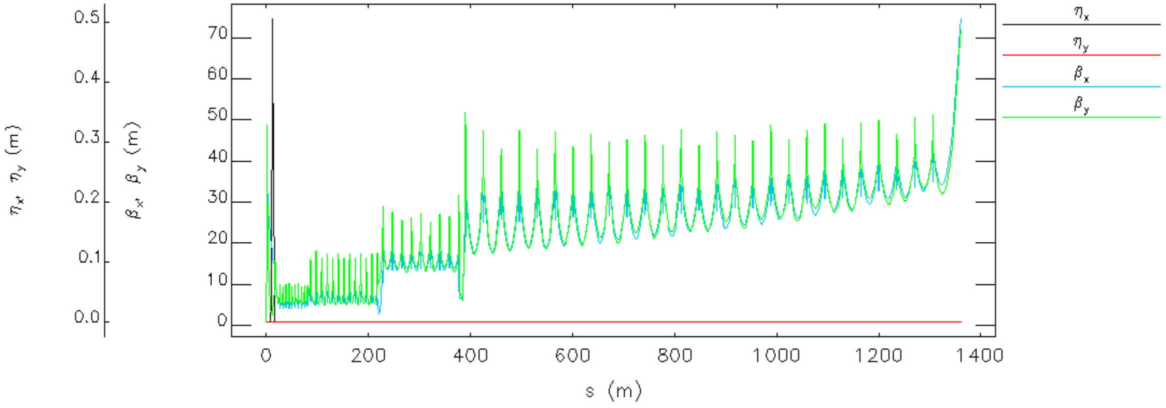


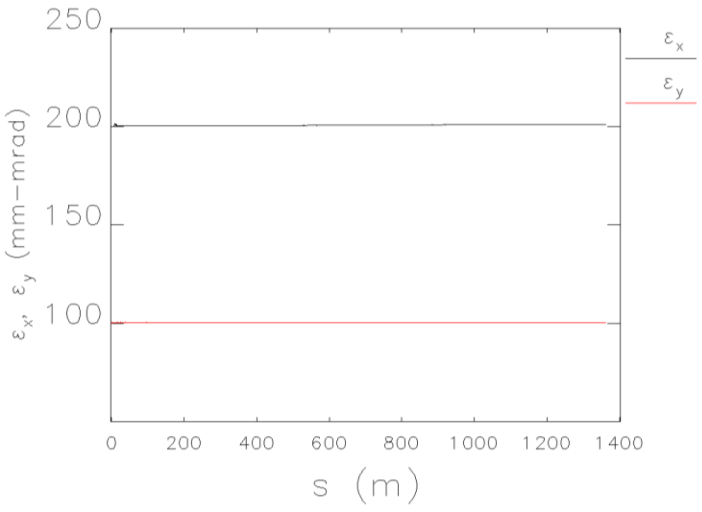


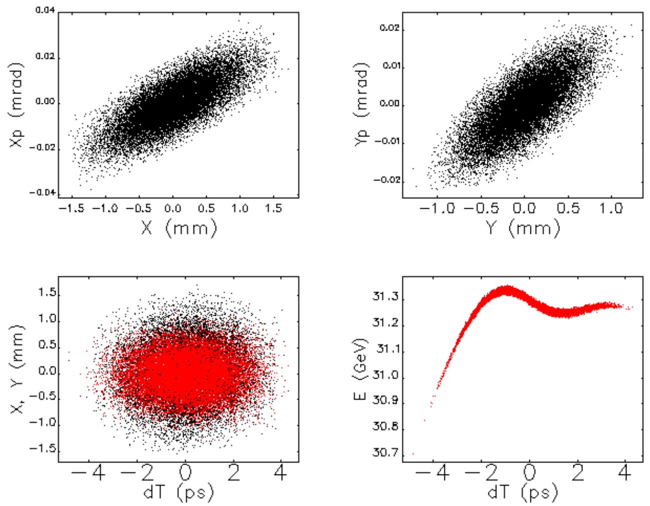
Linac design — Beam dynamics results

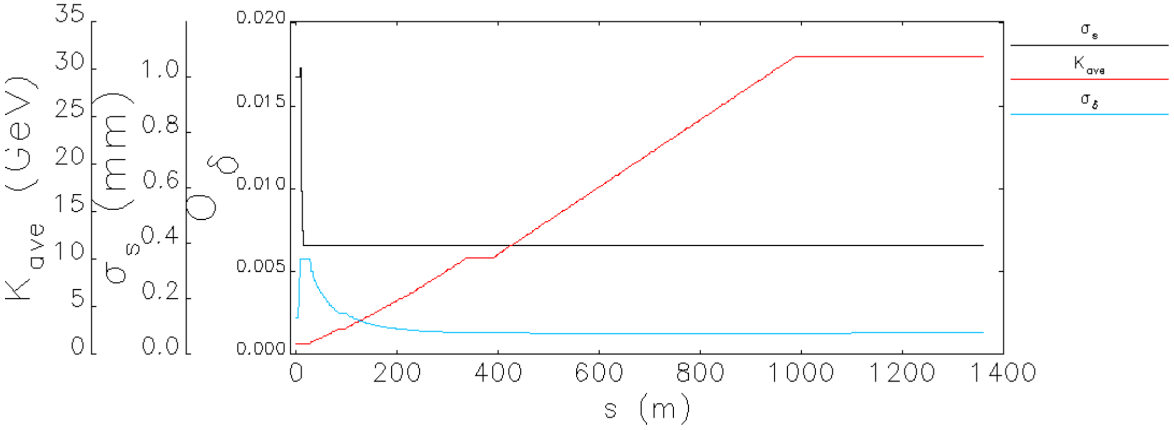
➢Simulation results(including Wakefield & CSR)

Parameter	Unit	Value	Simulated	
			Positron	
Beam energy	GeV	30	31.3	30.8
Repetition rate	Hz	100	/	
Bunch charge	nC	1.5	1.5	3.0
Energy spread		1.5×10^{-3}	1.29×10^{-3}	2.16×10^{-3}
Emittance(x/y)	nm	6.5	3.29/1.64	3.80/1.66
Bunch length (RMS)	mm	/	0.4	0.4









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:
  - Increase the repetition frequency from 100Hz to 200Hz
    - ✓ Power source, modulator and so on
  - Double-bunch acceleration scheme
    - ✓ To filling the required bucket pattern, the SHB frequency should be checked
    - ✓ **Flat-top pulser compressor**
    - ✓ Difficulties on BPM, LLRF, commissioning
    - ✓ RF gun
      - ☐ More flexible injection scheme
      - ☐ The Linac have better potential in terms of compatibility

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
- Thermionic cathode electron gun + subharmonic buncher
  - There are two SHB with different RF frequency
  - More frequency should be considered for bunch frequency
    - ✓ The bunch interval should be an integer multiple, **n**, of the time corresponding to the common frequency, $f_{bunch} = f_{cm}/n$
    - ✓ SHB1 frequency is an integer multiple, **m1**, of bunch frequency, $f_{shb1} = m1 \times f_{bunch}$
    - ✓ SHB2 frequency is an integer multiple, **m2**, of SHB1 frequency, $f_{shb2} = m2 \times f_{shb1}$
    - ✓ Linac frequency is an integer multiple, **m3**, of SHB2 frequency, $f_{linac} = m3 \times f_{shb2}$
    - ✓ $f_{linac} = m3 \times m2 \times m1 \times f_{cm}/n$ → **22*n=m3*m2*m1**
- RF gun
    - ✓ The bunch interval should be an integer multiple, **n**, of the time corresponding to the common frequency, $f_{bunch} = f_{cm}/n$
    - ✓ Linac frequency is an integer multiple, **m3**, of bunch frequency, $f_{linac} = m3 \times f_{bunch}$
    - ✓ $f_{linac} = m3 \times f_{cm}/n$ → **22*n=m3**

Timing consideration

➢ Frequency

- n=9, m1=11, m2=3, m3=6
- Divide the common frequency to 14.44MHz, then multiply to the corresponding RF frequency
- Frequency multiplication to 2860MHz, 5720MHz by common frequency

	Frequency			Multiple	Period		
Repetition frequency	f_{rep}	100	Hz	/	t_{rep}	10.0	ms
Common frequency	f_{cm}	130	MHz	9	t_{cm}	7.6923	ns
Minimum Bunch frequency	f_{bunch_min}	14.44	MHz	1	t_{bunch}	69.23	ns
Bunch frequency	f_{bunch}	14.44	MHz	1	t_{bunch}	69.23	ns
SHB1 RF frequency	f_{shb1}	158.89	MHz	11	t_{shb1}	6.2937	ns
SHB2 RF frequency	f_{shb2}	476.76	MHz	33	t_{shb2}	2.0979	ns
LINAC RF frequency	f_{linac}	2860	MHz	198	t_{linac}	0.3497	ns
	f_{linac2}	5720	MHz	396	t_{linac2}	0.1748	ns
Damping ring RF frequency	f_{DR}	650	MHz	45	t_{DR}	1.5385	ns
Booster RF frequency	$f_{booster}$	1300	MHz	90	$t_{booster}$	0.7692	ns
Ring RF frequency	f_{ring}	650	MHz	45	t_{ring}	1.5385	ns

Timing consideration

Parameter	Unit	High luminosity Z mode				Comments
		30MW		50MW		
		Baseline scheme	RF gun scheme	Baseline scheme	RF gun scheme	
Repetition frequency	Hz	100				
Common frequency	MHz	130				
Linac common frequency	MHz	14.44	130	14.44	130	
Bunch frequency	MHz	14.44	43.33	7.22	65.00	
SHB1 RF frequency	MHz	**158.89**	/	**158.89**	/	
SHB2 RF frequency	MHz	**476.67**	/	**476.67**	/	
LINAC RF frequency	MHz	2860.00				
	MHz	5720.00				
Damping ring RF frequency	MHz	650.00				
Booster RF frequency	MHz	1300.00				
Ring RF frequency	MHz	650.00				
Bunch spacing @ Collider	ns	23.08	23.08	15.38	15.38	
Bunch spacing @ Linac	ns	69.23	23.08	138.46	15.38	
Injection scheme		bunch-by-bunch	pulse-by-pulse bunch-by-bunch	bunch-by-bunch	pulse-by-pulse bunch-by-bunch	
Harmonic number		45*(2k) + [10, 20, 40]	5(2k)+ [2,4]	45*(2k) + [10, 20, 40]	5(2k)+ [2,4]	k is an integer
		45*(2k+1) + [5, 25]	5(2k+1) + [1,3]	45*(2k+1) + [5, 25]	5(2k+1) + [1,3]	
Bunch number per train		**6n**	**2n**	**18n**	**2n**	n is an integer

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 of booster.
- For high luminosity Z scheme, tow-bunch-per-pulse is need and the baseline scheme can meet the requirements, some key technologies need further research and development, such as flat-top pulser compressor, BPM, LLRF, and so on.

Thank you for your attention!