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 Design

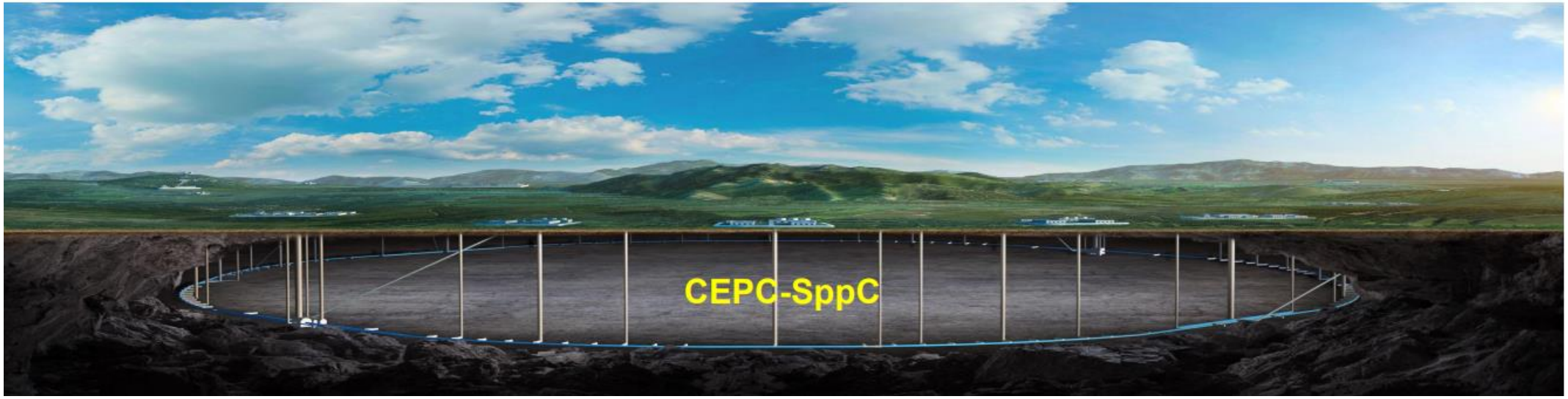
CEPC Workshop 2021

C. Meng

on behalf of CEPC AP group, IHEP

Outline

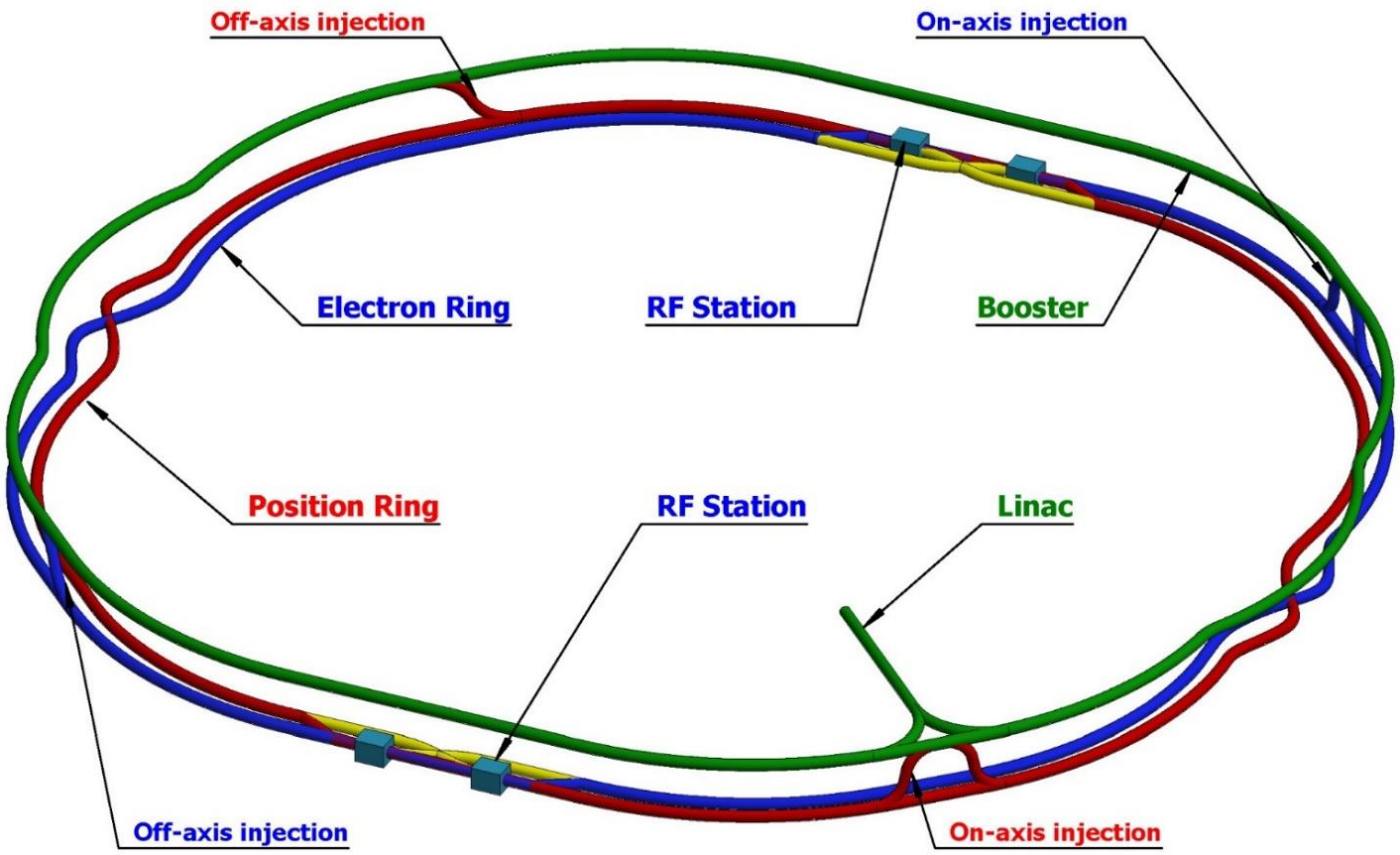
- Introduction
- Progress on CEPC Linac design
- Summary



Introduction

CEPC layout

- CEPC as a Higgs (W, Z) Factory
  - ~100 km
- CEPC layout
  - Linac
  - Full energy Booster
  - Collider
  - Transport lines
- Linac design
  - High Availability and Reliability



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

Introduction

Baseline scheme

➢Baseline scheme (2021.5)

- Energy: →20 GeV
  - ✓Motivation:
    - ☐Low magnetic field & large magnetic field range
  - ✓C-band accelerating structure
    - ☐Higher gradient → Shorter linac tunnel length
    - ☐Small aperture & Strong wakefield
- Emittance: 10 nm
  - ✓High luminosity for Higgs
- Repetition rate:
  - ✓High luminosity Z need faster injection process
    - ☐200 Hz
    - ☐100 Hz & two-bunch-per-pulse
      - 200 Hz & two-bunch-per-pulse
- Availability (Redundancy): 10%~15% accelerating units backup

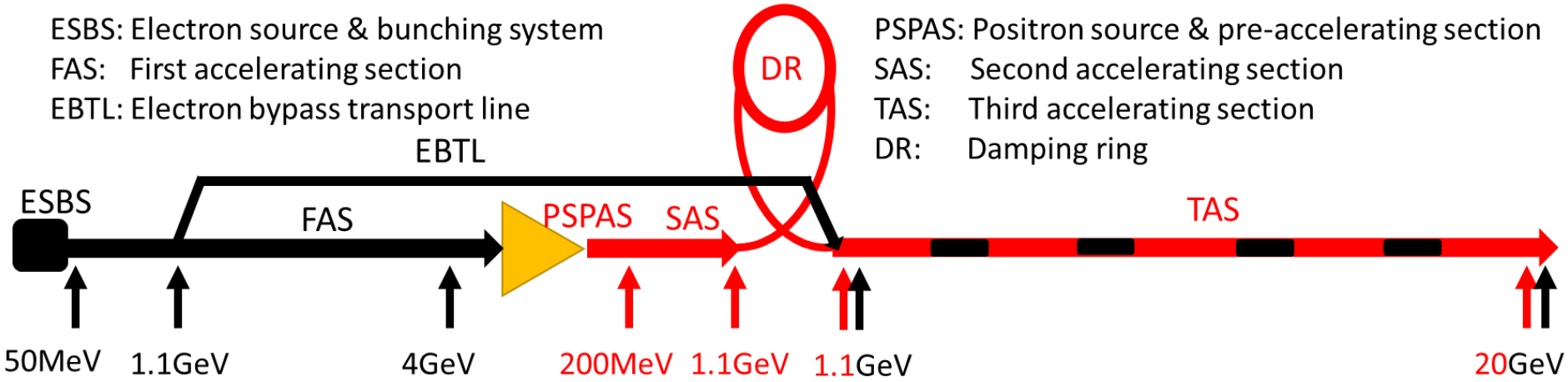
Parameter	Symbol	Unit	Baseline
e^-/e^+ beam energy	E_{e-}/E_{e+}	GeV	**20**
Repetition rate	f_{rep}	Hz	100
e^-/e^+ bunch population	*Ne-/Ne+*	$\times 10^{10}$	0.94(1.88)
		nC	1.5 (3)
Energy spread (e^-/e^+)	σ_E		1.5×10^{-3}
Emittance (e^-/e^+)	ε_r	nm	10

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	21	**45**

Introduction

Linac layout

- Electron Linac
  - ESBS+FAS(1.1GeV)+ETBL+TAC(1.1GeV→20GeV,C-band Acc.)
  - EBTL is in vertical plane with 1.2 m separation
    - ✓ Avoid interference with energy analyzing station, transport lines between the Linac and damping ring, waveguide and positron source
- Positron Linac
  - ESBS+FAS(4GeV)+PSPAS+SAS+DR+TAS(1.1GeV→20GeV,C-band Acc.)
  - Retain the potential to generate 3nC bunch charge for positron source



Introduction

Linac evolution

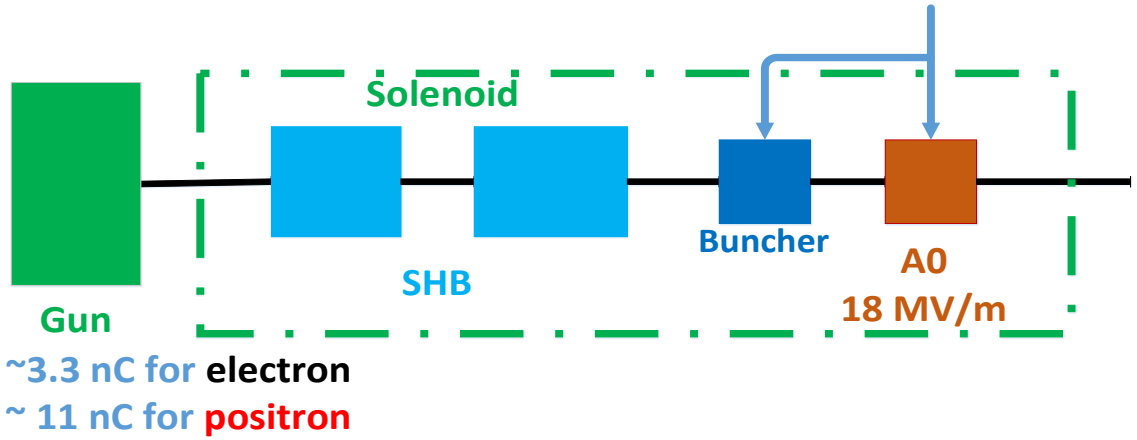
➢Meet the design requirements of Booster: Energy/Emittance

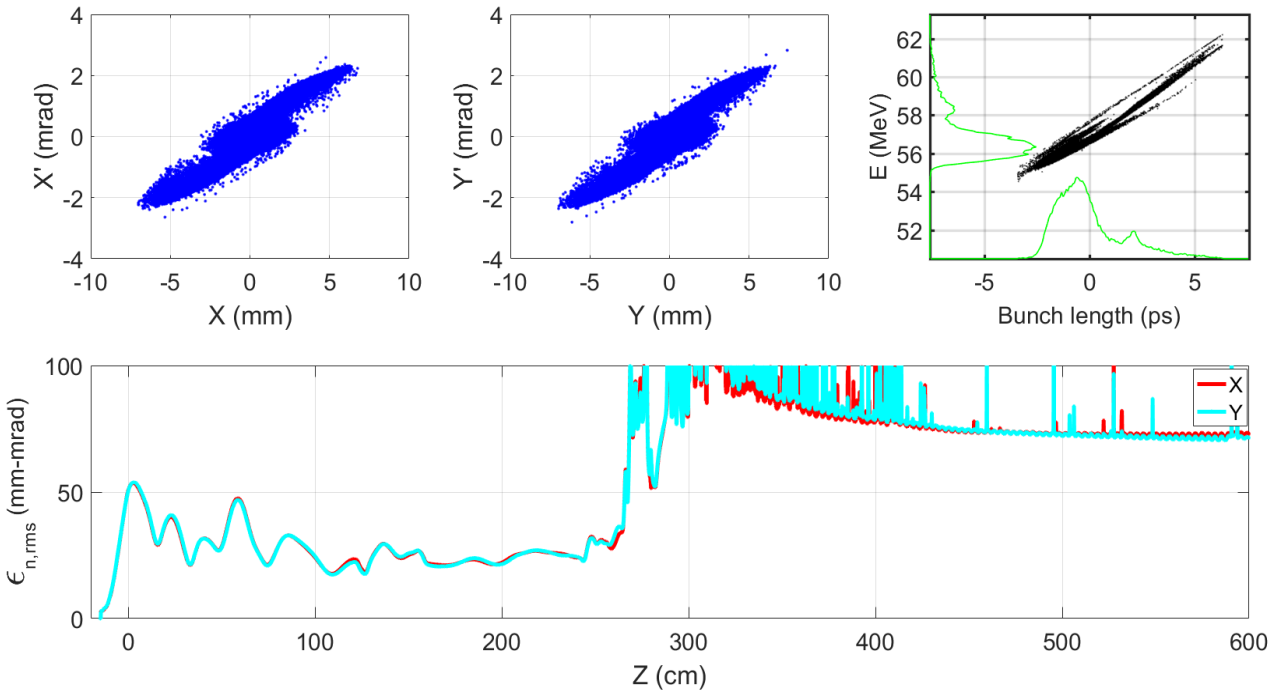
			Pre-CDR	CDR								TDR			
Parameter		Unit	V1	V2			V3							V4	
				V2.1	V2.2	V2.3	V3.1	V3.2	V3.3	V3.4	V3.5	V3.6	V3.7	V3.8	V4.1	V4.2
Beam energy (e+/e-)	E_{e-}/E_{e+}	GeV	6	10					4	10			20	10/20	20	
Repetition rate	f_{rep}	Hz	50				100									100 or. 200
Bunch number per pulse			1													1 or.2
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	
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	
Bunch compressor			No							Yes	No		Yes			
Accelerating strucutre			S-band										S+C-band			
RF frequency	f_{RF}	MHz	2856.75									2860	2860/5720			
Accelerating gradient		MV/m	15/27	18/27 or. 18/21			21						21/45			
Klystron-2-ACC			1-t-2	1-t-2 or. 1-t-4			1-t-4						1-t-4(S)/1-t-2(C)			
Shared Linac Energy range		MeV	200-1100	No												
Collider circumference		km	54 & 61	61			100									
Layout			pre-CDR	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	Aug-21

Linac design

Electron Linac

- ESBS
  - Thermionic Electron gun
  - 2SHB(147MHz/572MHz)+Buncher(2860MHz)+A1(2860MHz)
  - Solenoid for transverse focusing
  - Energy: 50MeV
  - Norm.Rms.Emittance:80mm-mrad
  - Transmission > 90%

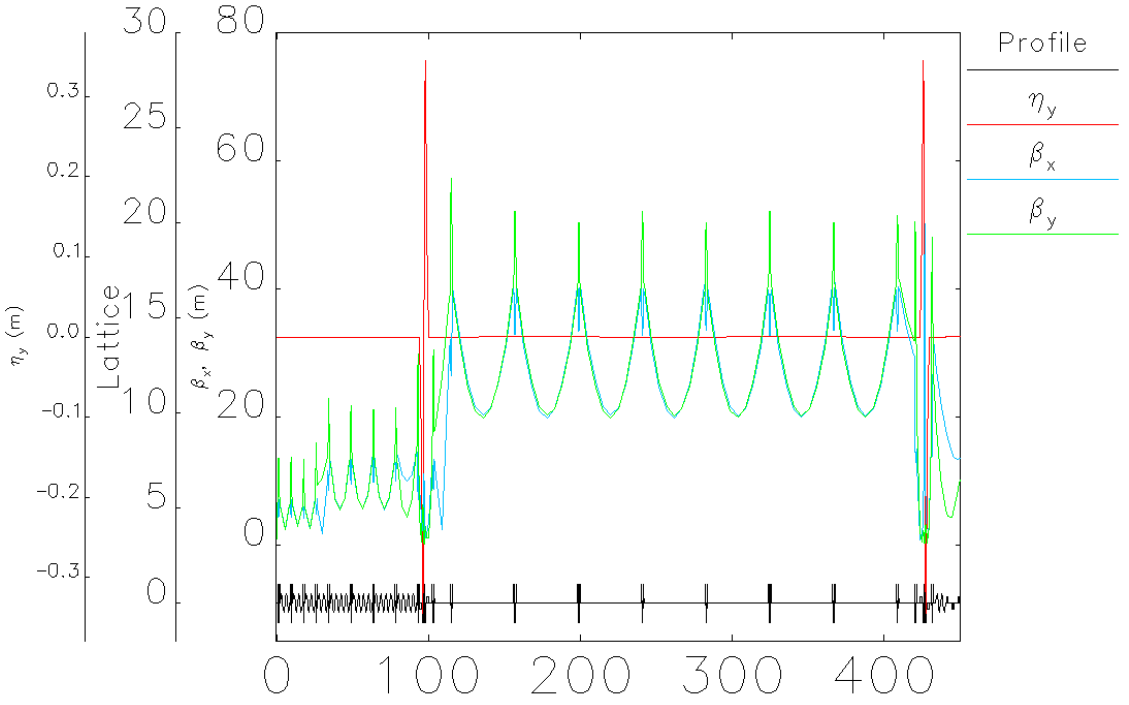


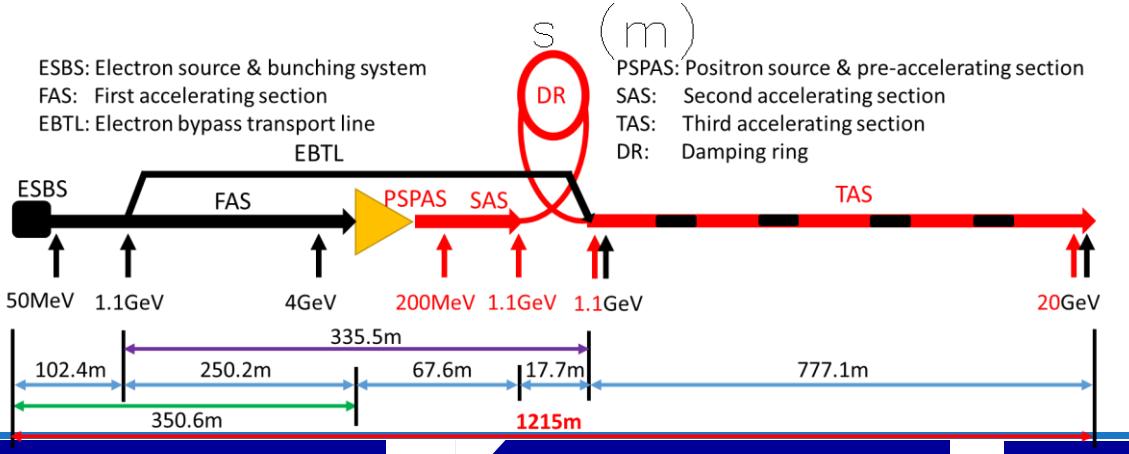


Linac design

Electron Linac

- FAS
  - Energy:50MeV→1.1GeV
    - ✓ S-band accelerating structure
  - Lattice: 2 period structures
    - ✓ Triplet + 2 Acc.Struc [4]
      - ☐ 1 klystron → 2 Acc.Struc
      - ☐ A pair of correctors and one BPM
    - ✓ Triplet + 4 Acc.Struc [3+1]
      - ☐ 1 klystron → 4 Acc.Struc
      - ☐ one klystron is redundancy
      - ☐ A pair of correctors and one BPM
    - ✓ ~14% redundancy
- EBTL
  - Energy:1.1GeV
  - Achromatic design
  - Match the length ~ 335.5m
    - ✓ FAS: from 1.1GeV→4GeV
    - ✓ PSPAS
    - ✓ SAS



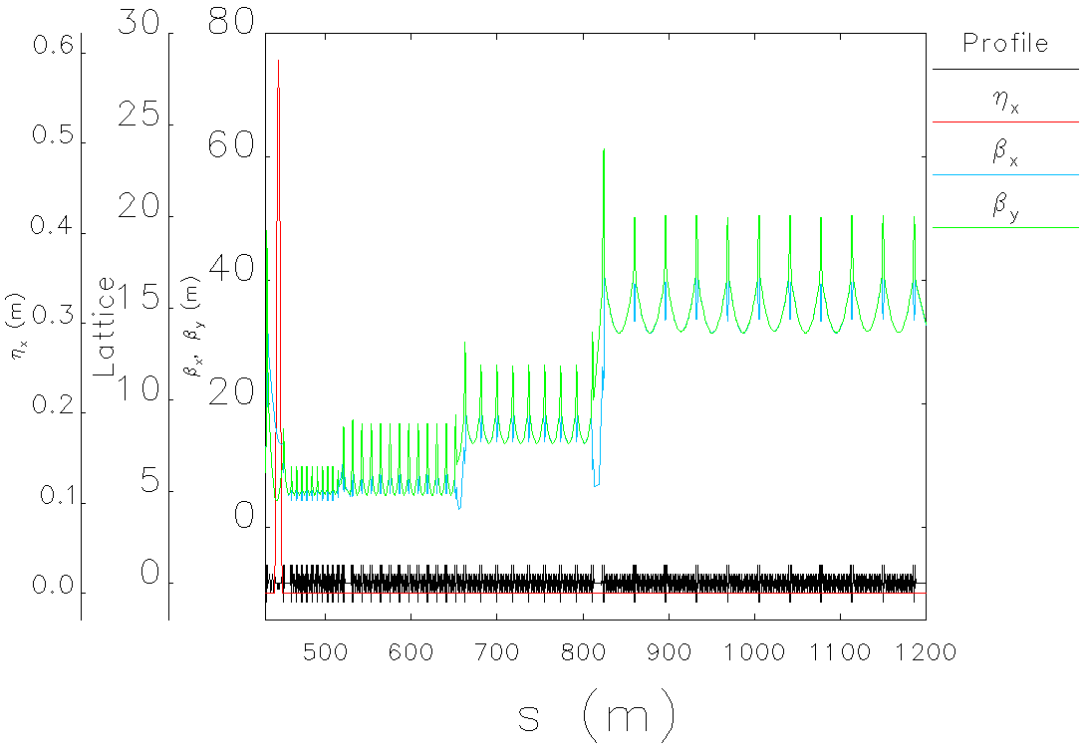


Linac design

Electron Linac

➢TAS

- Energy:1.1GeV→20GeV
  - ✓C-band accelerating structure
    - ☐1 klystron → 2 Acc.Struc
  - ✓Shorter bunch length→ bunch compressor
- Lattice: 4 period structures
  - ✓Triplet + 2 Acc.Struc [10]
    - ☐A pair of correctors and one BPM
  - ✓Triplet + 4 Acc.Struc [12]
    - ☐A pair of correctors and one BPM
  - ✓Triplet + 8 Acc.Struc [6+2]
    - ☐8 klystron are redundancy
    - ☐A pair of correctors and one BPM
  - ✓Triplet + 16 Acc.Struc [8+2]
    - ☐16 klystron are redundancy
    - ☐Tow pair of correctors and two BPM
  - ✓~20% redundancy



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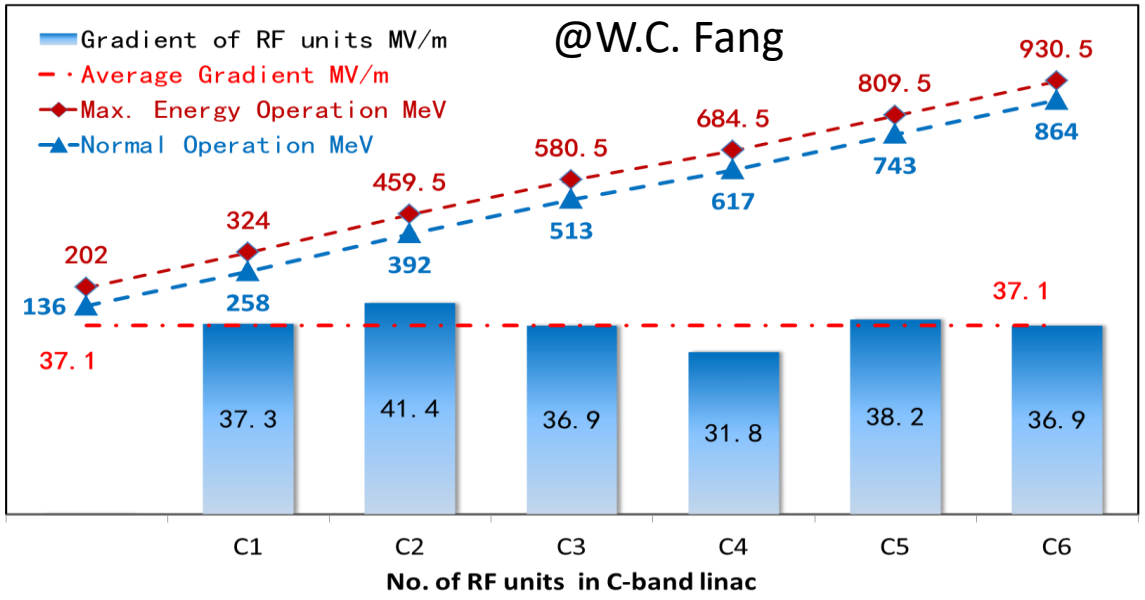
Frequency	MHz	2860	5720
Length	m	3.1	1.8
Cavity mode		2π/3	3π/4
Aperture diameter	mm	20~24	11.8~16
Gradient	MV/m	21	**45**

Linac design

Electron Linac

➢TAS

- C band RF structures at SARI (SXFEL)
  - ✓6 RF units at SXFEL
  - ✓Mode： 4π/5
  - ✓Average gradient 37.1 MV/m.
  - ✓Maximum gradient 41.7 MV/m
- If the accelerating gradient is 40MV/m?
  - ✓Triplet + 2 Acc.Struc [10]
  - ✓Triplet + 4 Acc.Struc [12]
  - ✓Triplet + 8 Acc.Struc [7+1]
    - ☐4 klystron are redundancy
  - ✓Triplet + 16 Acc.Struc [9+1]
    - ☐8 klystron are redundancy
  - ✓**~9% 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	21	**40**

Linac design

Bunch compressor

- Bunch compressor
  - Angle: 10°
  - Voltage
    - ✓120MV
  - Momentum tail

$$\left(1+R_{56}^{ch}R_{65}^{rf}\right)R_{65}^{rf}\left\langle z_0^2\right\rangle+R_{56}^{ch}R_{66}^{rf\,2}\left\langle \delta_0^2\right\rangle=0$$

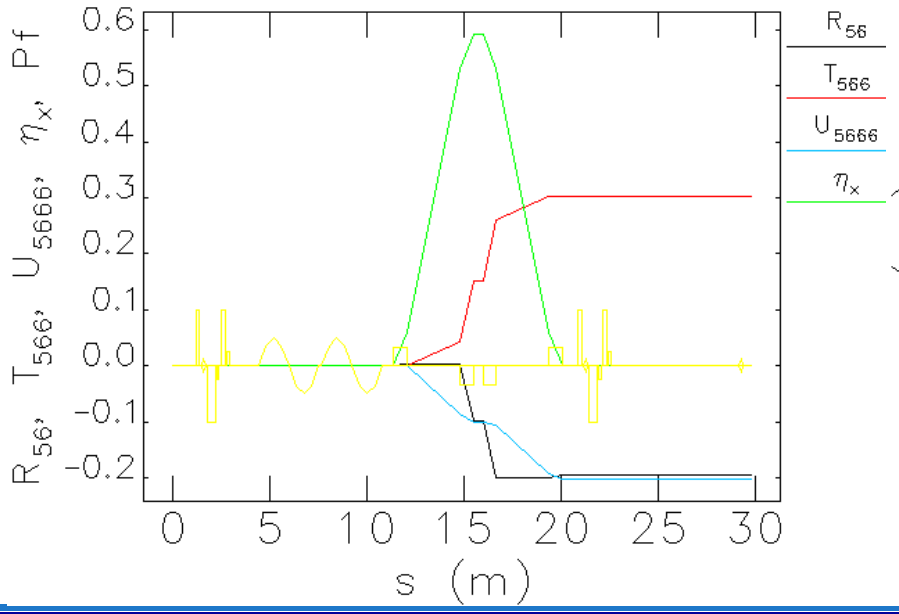
$$\left\langle z_1^2\right\rangle/\left\langle z_0^2\right\rangle=\left(1+R_{56}^{ch}R_{65}^{rf}\right)$$

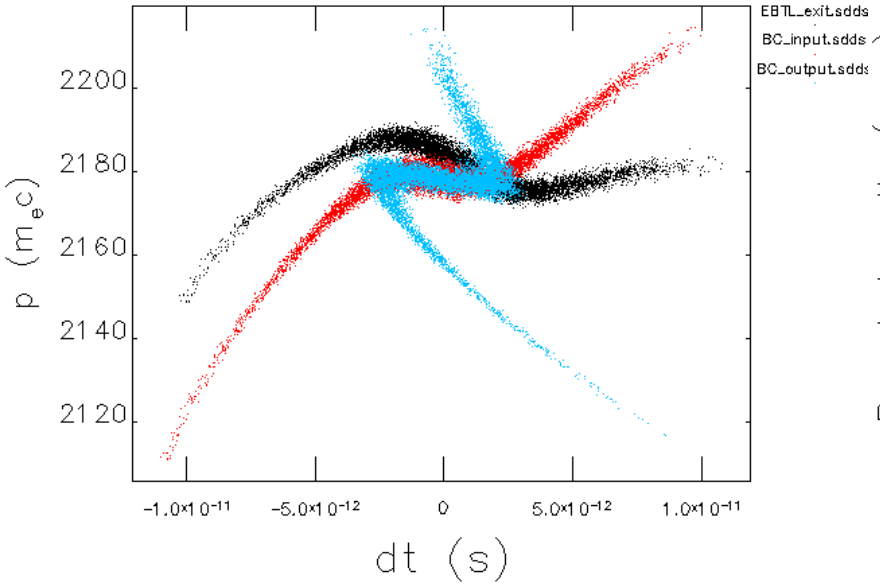
$$R_{56}^{ch}T_{655}^{rf}+R_{65}^{rf\,2}T_{566}^{ch}=0$$

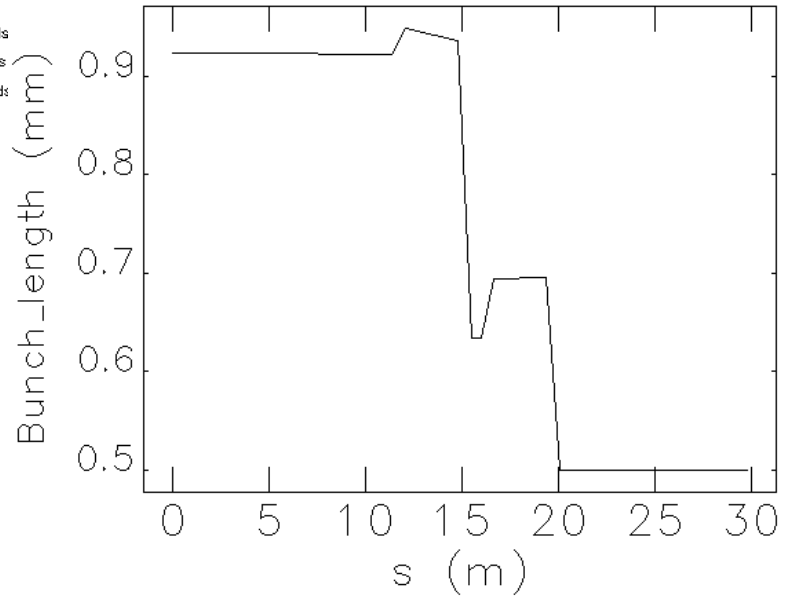
$$R_{56}^{ch}=-\frac{1}{R_{66}^{rf}}\frac{\sqrt{\left\langle z_1^2\right\rangle}}{\sqrt{\left\langle \delta_0^2\right\rangle}}\sqrt{1-\frac{\left\langle z_1^2\right\rangle}{\left\langle z_0^2\right\rangle}}=-0.196\ \mathrm{m}$$

$$R_{65}^{rf}=3.827\ \mathrm{m}^{-1}$$

		Value	Units
Initial rms bunch length	$\sqrt{\langle z_0^2\rangle}$	0.923	mm
Initial rms energy spread	$\sqrt{\langle \delta_0^2\rangle}$	0.235%	
Final rms bunch length	$\sqrt{\langle z_1^2\rangle}$	$\sqrt{\langle z_0^2\rangle}/2$	mm
Initial energy	E_0	1.1	GeV





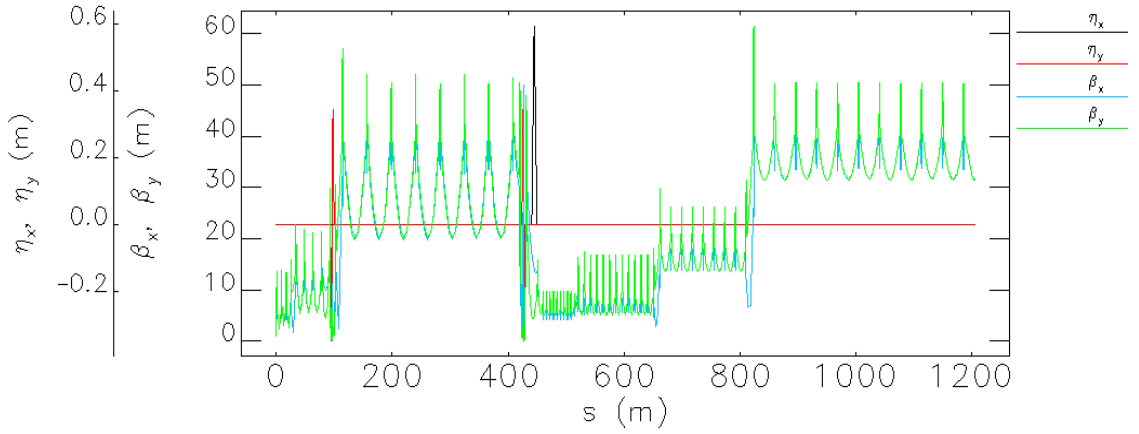


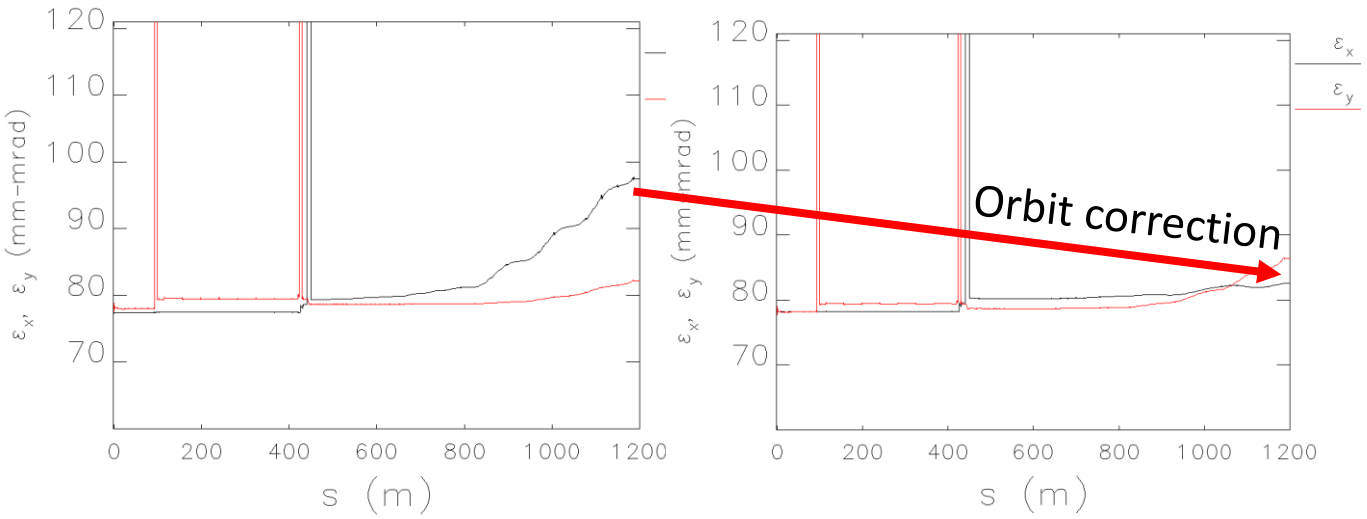
Linac design

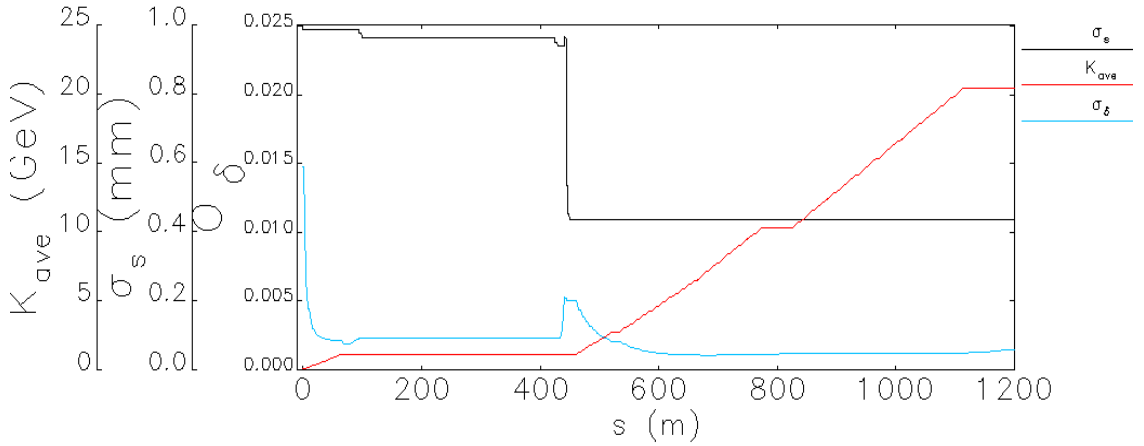
Electron linac

➢Simulation results(including Wakefield & CSR)

Parameter	Unit	Baseline	Achieved
e^-/e^+ beam energy	GeV	20	20.38
Repetition rate	Hz	100	100
e^-/e^+ bunch population	$\times 10^{10}$	0.94(1.88)	1.88
	nC	1.5 (3)	3
Energy spread (e^-/e^+)		1.5×10^{-3}	1.45×10^{-3}
Emittance (e^-/e^+)	nm	10	2.5
Bunch length (RMS)	mm	/	0.45





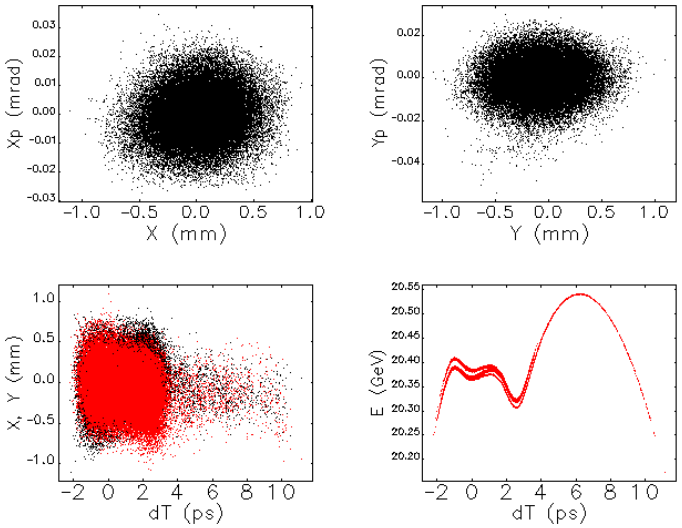


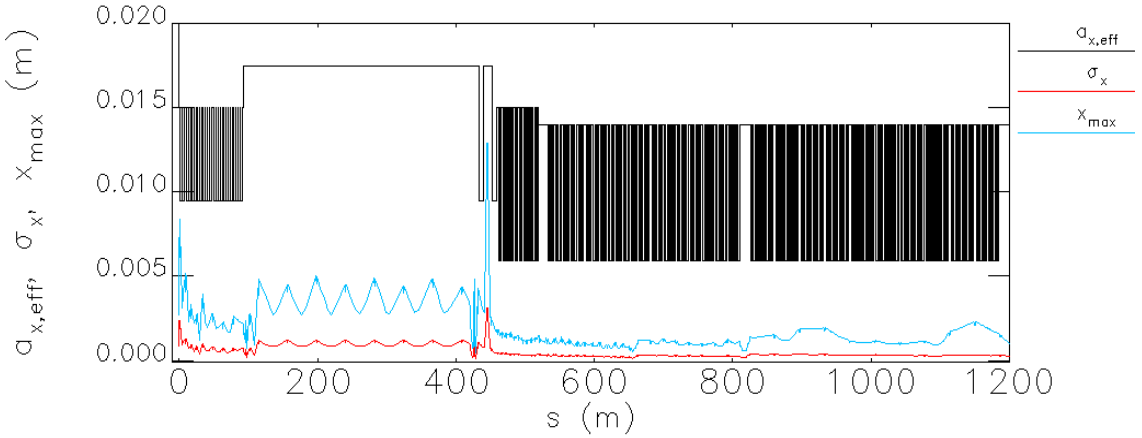
Linac design

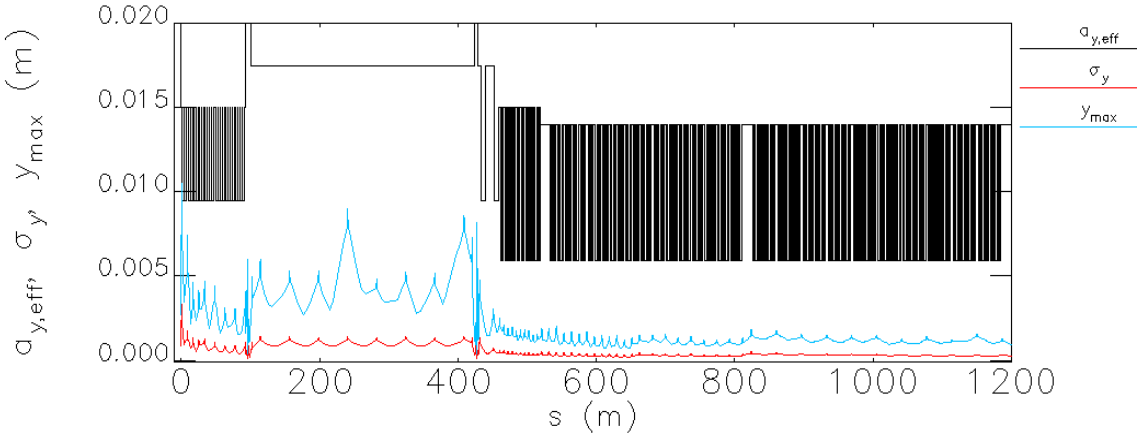
Electron linac

➢Simulation results(including Wakefield & CSR)

Parameter	Unit	Baseline	Achieved
e^-/e^+ beam energy	GeV	20	20.38
Repetition rate	Hz	100	100
e^-/e^+ bunch population	$\times 10^{10}$	0.94(1.88)	1.88
	nC	1.5 (3)	3
Energy spread (e^-/e^+)		1.5×10^{-3}	1.45×10^{-3}
Emittance (e^-/e^+)	nm	10	2.5
Bunch length (RMS)	mm	/	0.45

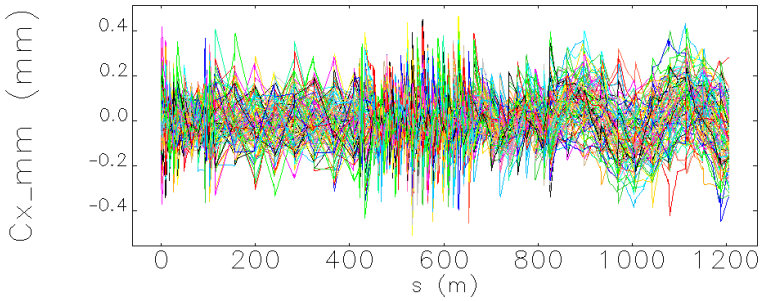


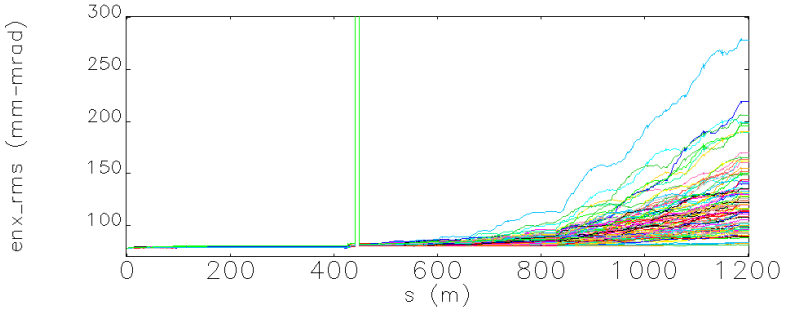


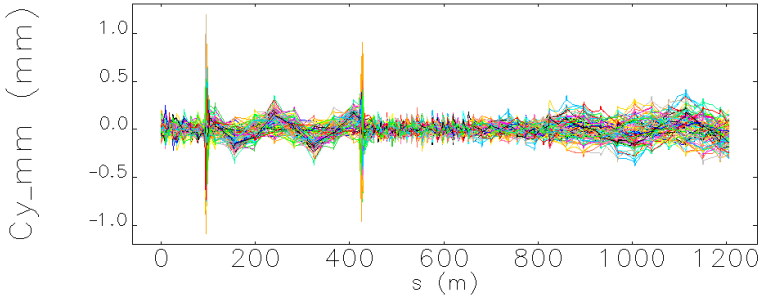


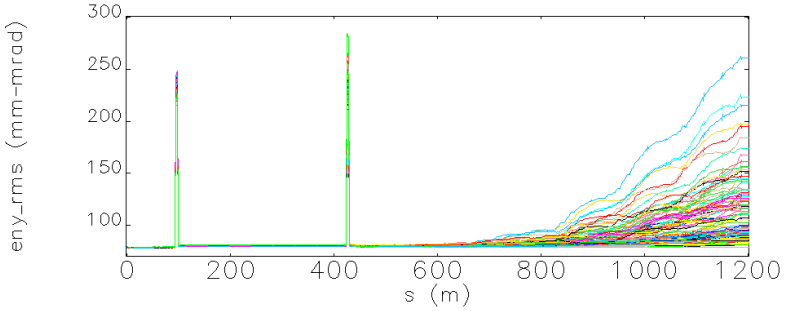
- Error study (100seeds)
  - errors: Magnets/Accelerating structure/BPM
  - Trajectory correction: beam orbit <1mm
    - ✓ C-band section should be smaller than 0.4mm
  - Emittance growth: meet the requirement (10nm)
    - ✓ X: 3.1nm + 0.9nm(std)
    - ✓ Y: 2.9nm + 0.9nm(std)

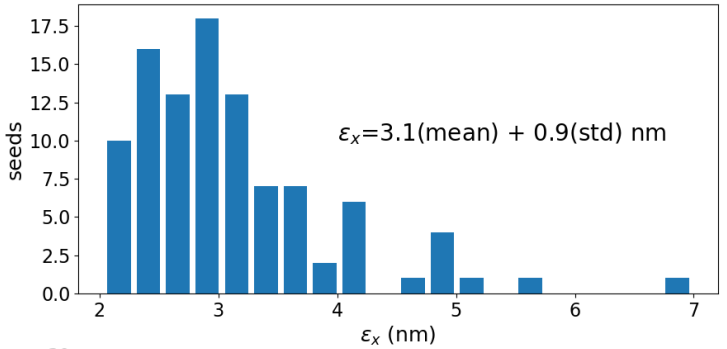
Error description	Unit	Value
Misalignment error	mm	0.1
Rotation error	mrad	0.2
Magnetic element field error	%	0.1
BPM uncertainty	μm	30

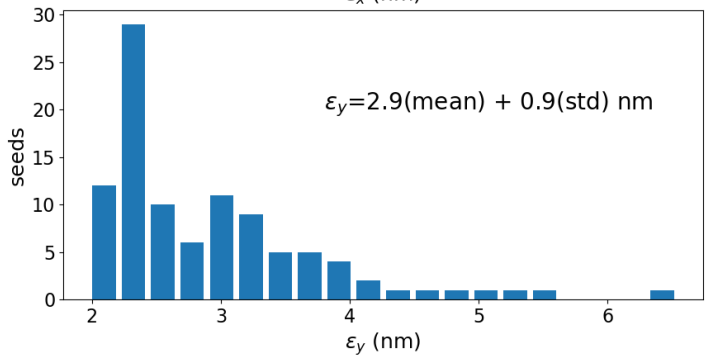








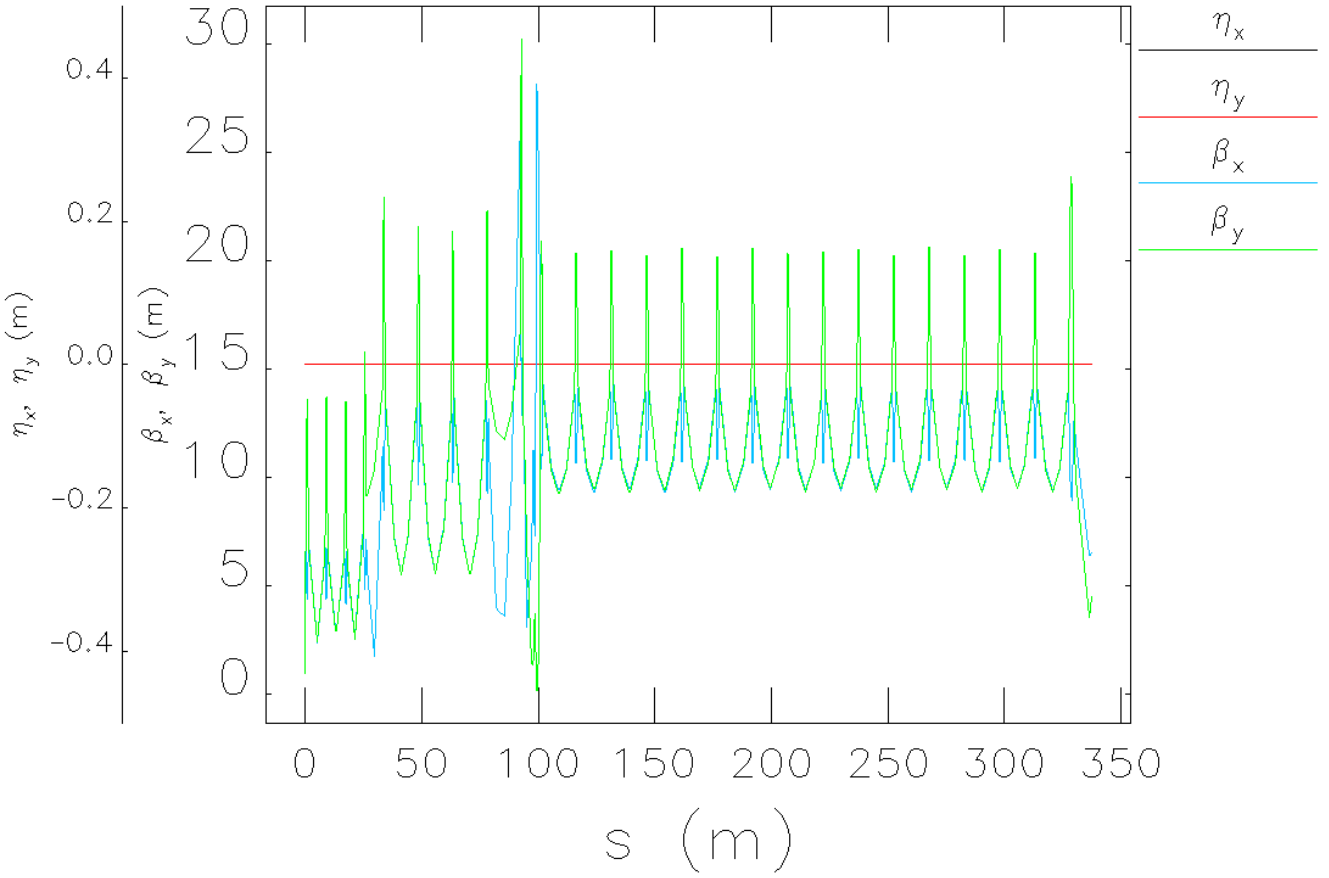




Linac design

Electron Linac

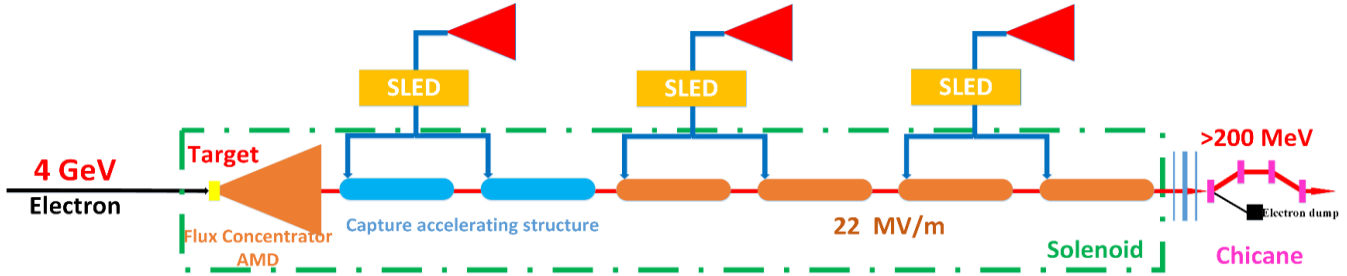
- FAS
  - Energy:50MeV→4.0GeV
    - ✓S-band accelerating structure
  - Lattice: 2 period structures
    - ✓Triplet + 2 Acc.Struc [4]
      - ☐1 klystron → 2 Acc.Struc
      - ☐A pair of correctors and one BPM
    - ✓Triplet + 4 Acc.Struc [16+3]
      - ☐1 klystron → 4 Acc.Struc
      - ☐three klystron is redundancy
      - ☐A pair of correctors and one BPM
    - ✓~15% redundancy
  - Bunch charge: 10nC

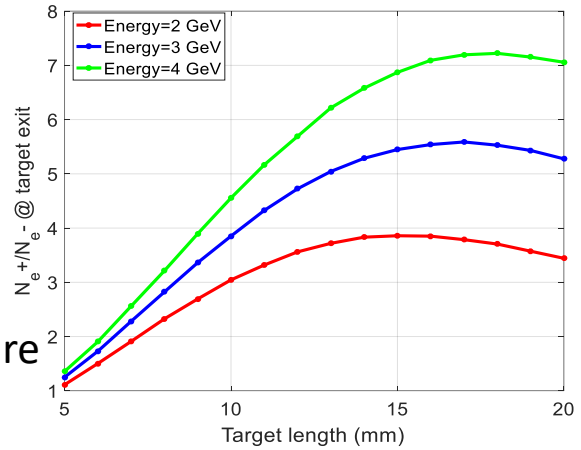


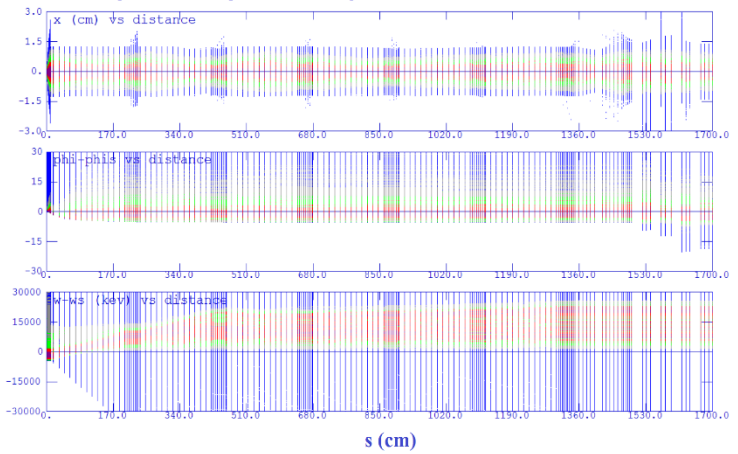
Linac design

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







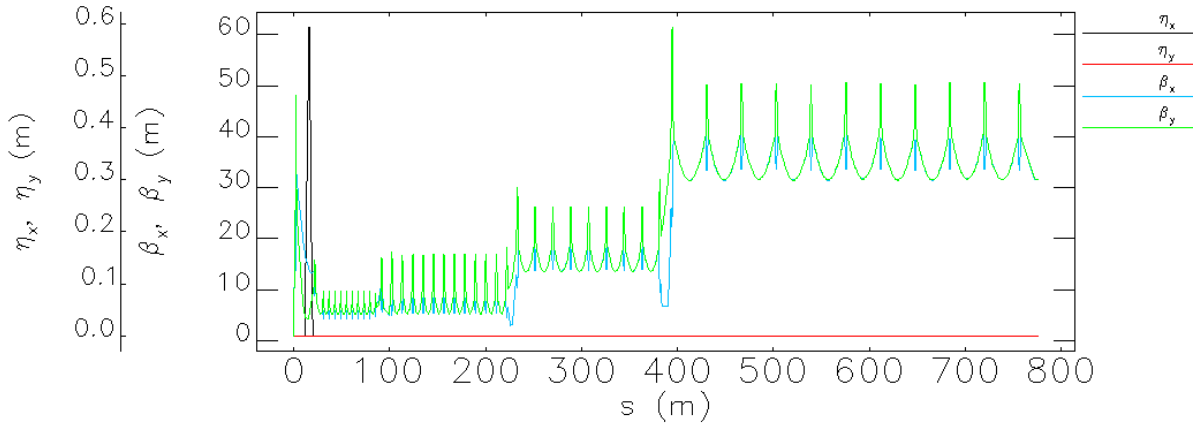
Positron source	Unit	Requirement	Simulation results
e^- beam energy on the target	GeV		4
e^- bunch charge on the target	nC		10
e^+ bunch charge	nC	≥3	~5.5
e^+ Energy	MeV	≥200	250
e^+ Norm. RMS emittance	mm-mrad	≤2400	2370

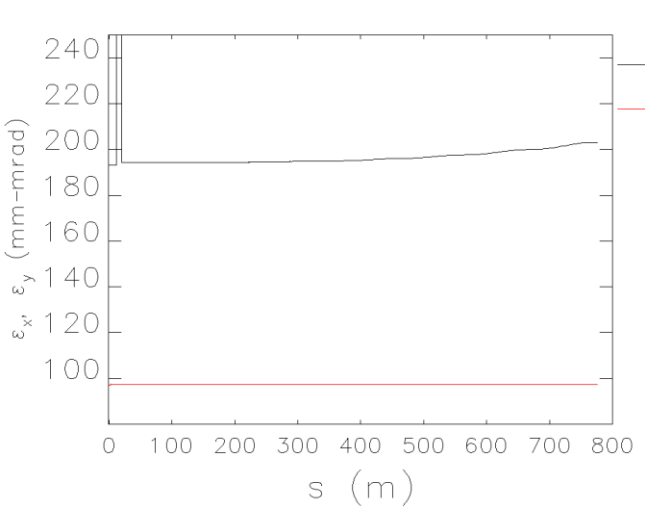
Linac design

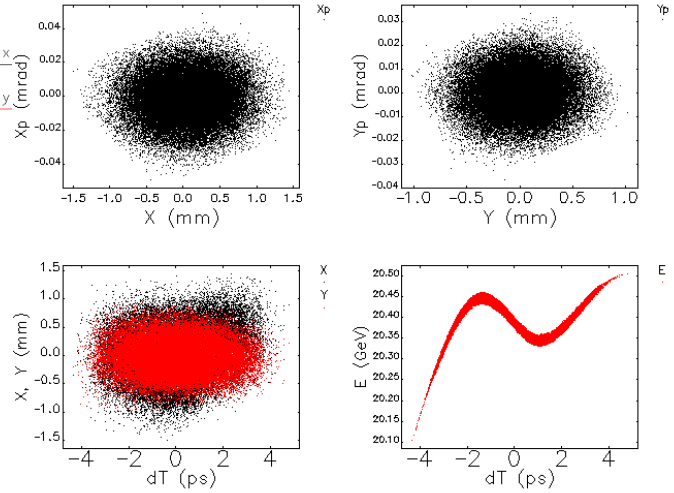
Positron Linac

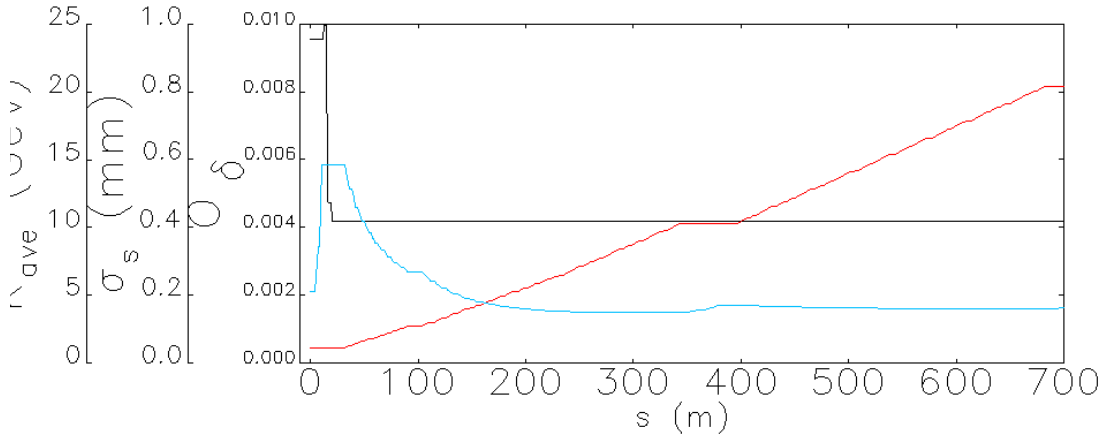
➢Simulation results(including Wakefield & CSR)

Parameter	Unit	Baseline	Achieved
e^-/e^+ beam energy	GeV	20	20.37
Repetition rate	Hz	100	100
e^-/e^+ bunch population	$\times 10^{10}$	0.94(1.88)	1.88
	nC	1.5 (3)	3
Energy spread (e^-/e^+)		1.5×10^{-3}	1.9×10^{-3}
Emittance (e^-/e^+)	nm	10	5.0(H)/2.5(V)
Bunch length	mm	/	0.4







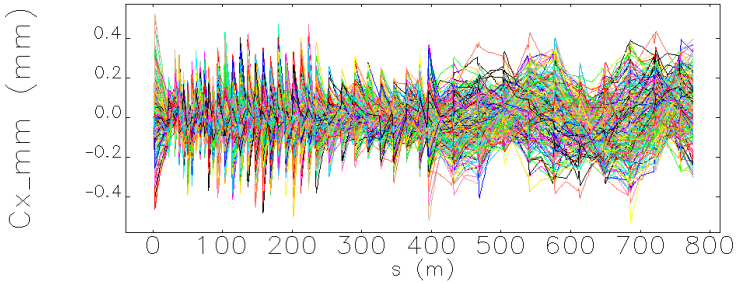


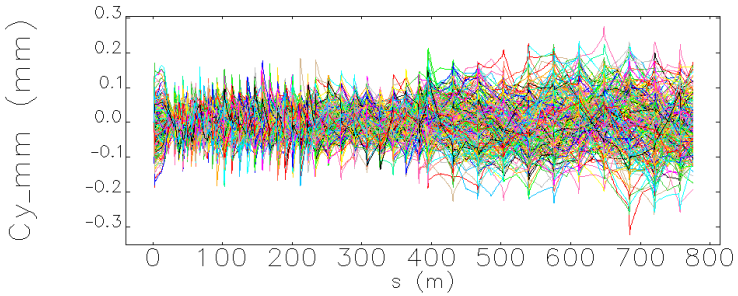
Linac design

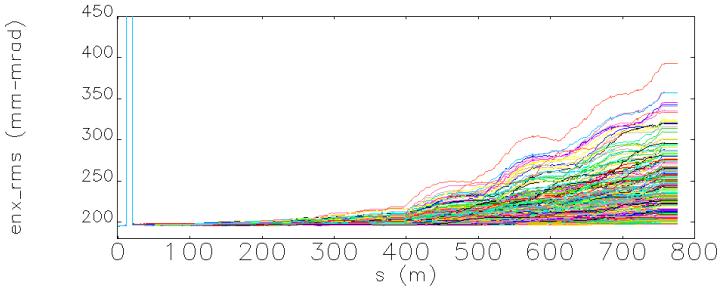
Positron Linac

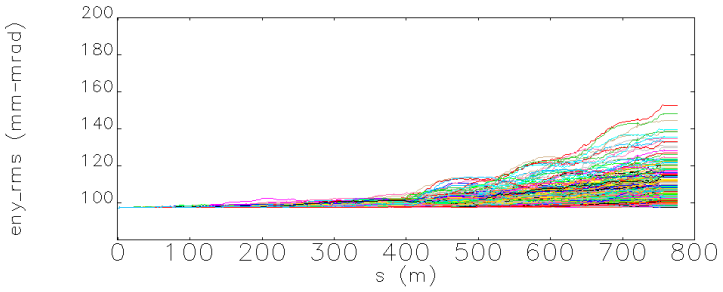
- Error study (200seeds)
  - errors: Magnets/Accelerating structure/BPM
  - Trajectory correction: beam orbit <0.5mm
  - Emittance growth: meet the requirement
    - ✓ X: 6.1nm + 0.9nm(std)
    - ✓ Y: 2.7nm + 0.3nm(std)

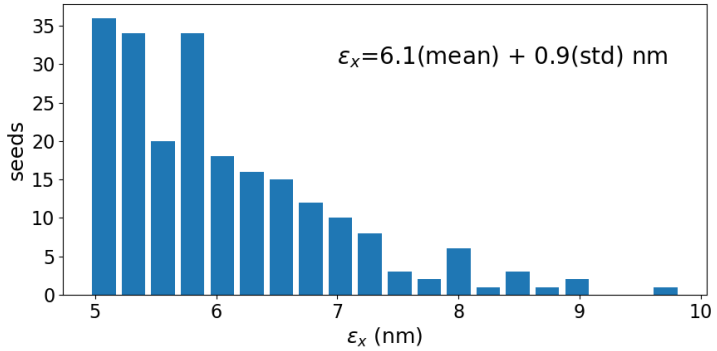
Error description	Unit	Value
Misalignment error	mm	0.1
Rotation error	mrad	0.2
Magnetic element field error	%	0.1
BPM uncertainty	μm	30

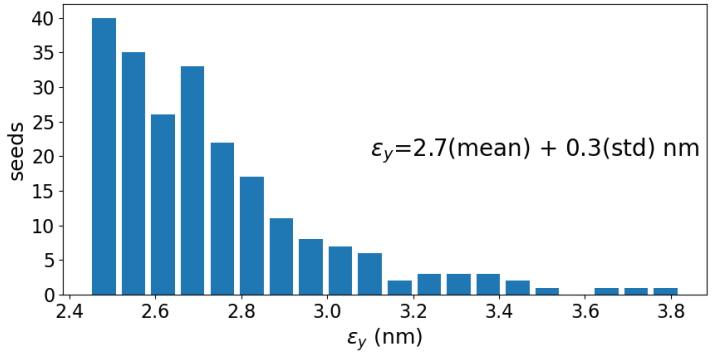










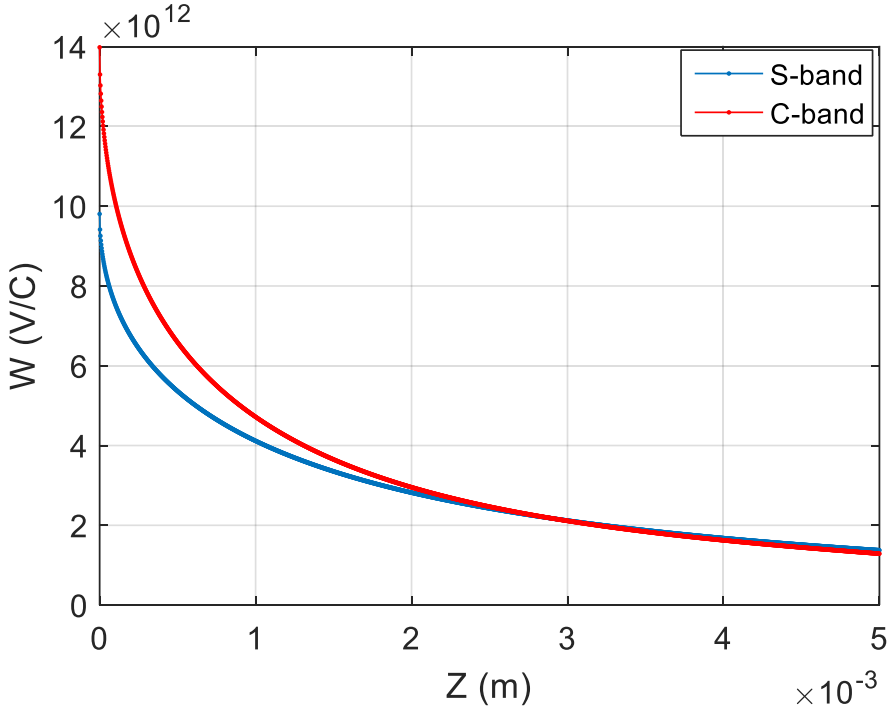


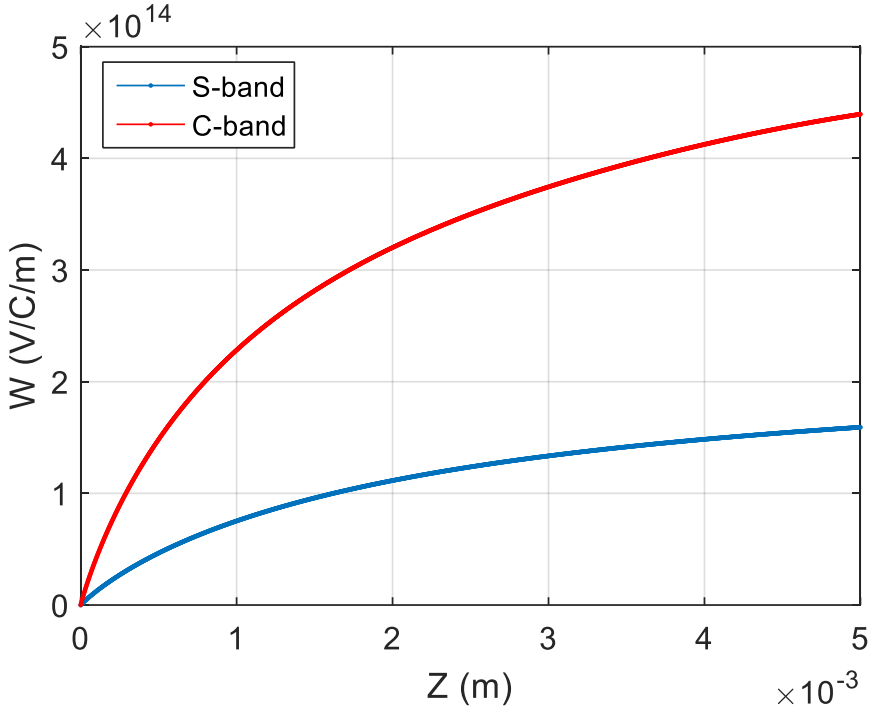
Summary

- The new baseline scheme of the Linac was proposed at May 2021
- The Linac energy is increased to 20 GeV to ease the booster magnet design difficulties (low field at injection energy and large magnetic field range) and the emittance is decreased to 10 nm for high luminosity Higgs scheme.
- The C-band accelerating structure is used from 1.1 GeV to 20 GeV.
- The lattice design and dynamic simulation have been finished, until now, the design can meet the requirements of booster.
- More optimization are still in progress.

Thank you for your attention!

Wakefield


×10^12
14
12
10
8
6
4
2
0
W (V/C)
0
1
2
3
4
5
Z (m)
×10^-3
S-band
C-band


×10^14
5
4
3
2
1
0
W (V/C/m)
0
1
2
3
4
5
Z (m)
×10^-3
S-band
C-band