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

FCCWEEK2018

CEPC Linac design

FCCWEEK2018
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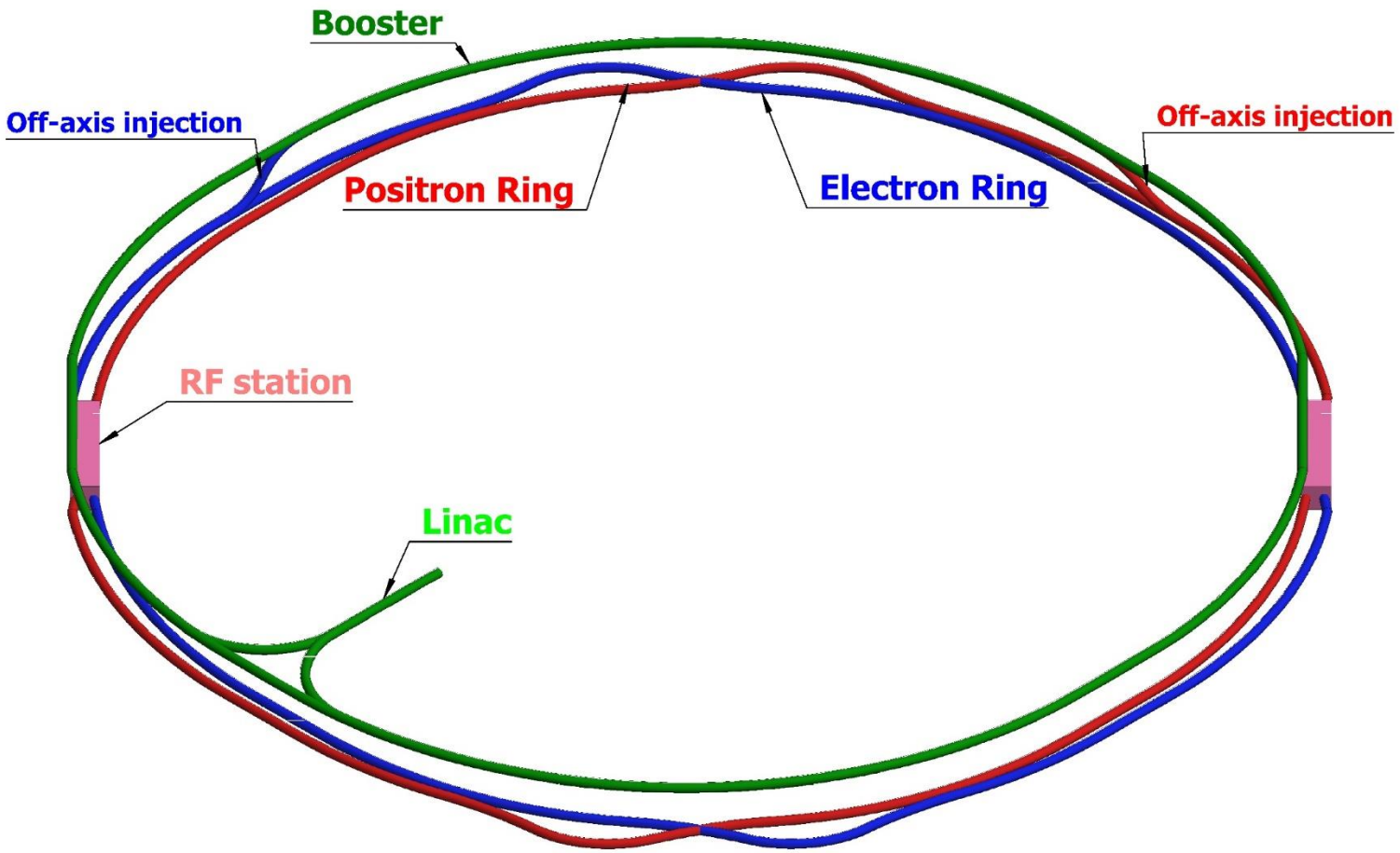
Outline

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



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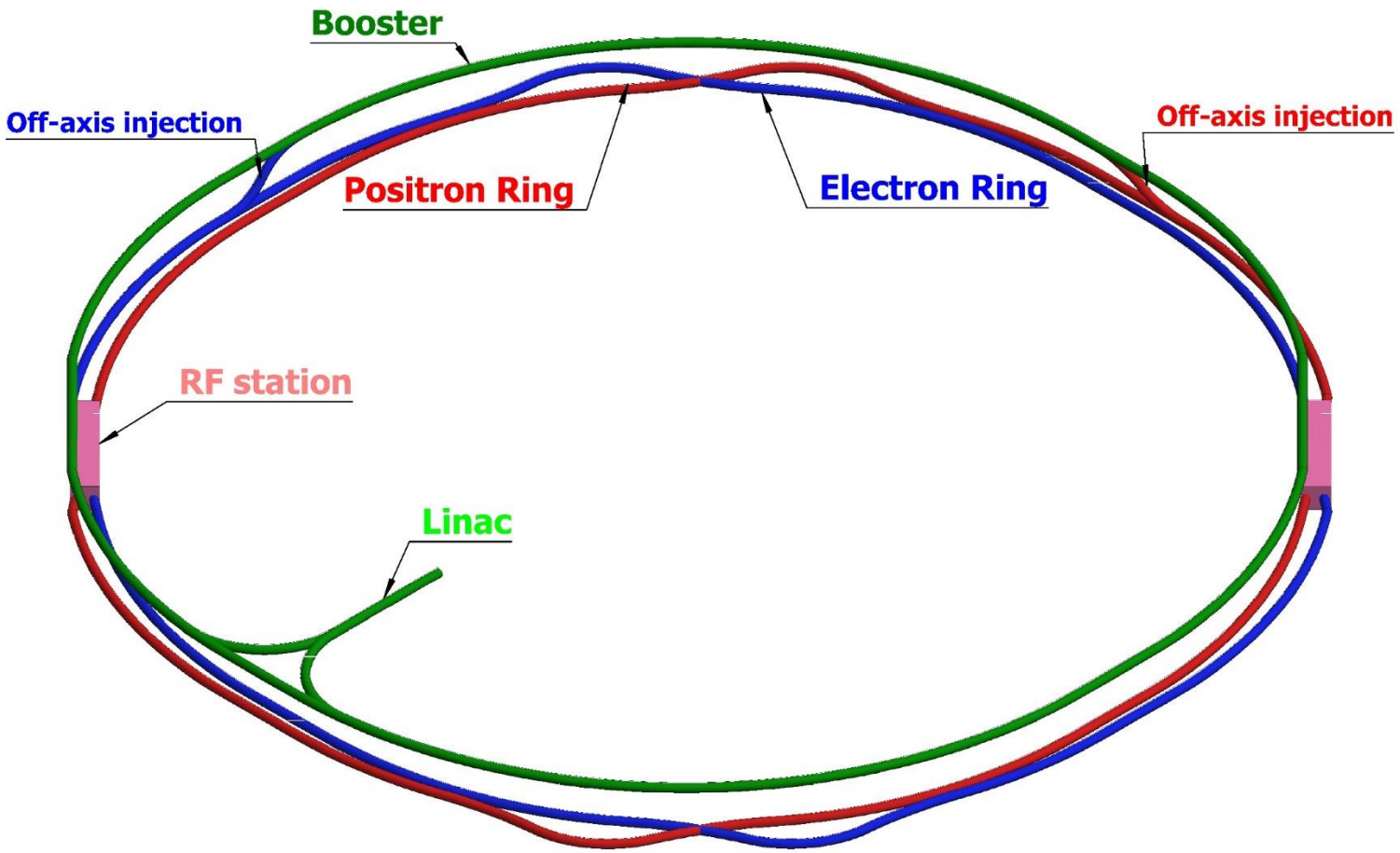


Introduction

Main parameters

- Linac design goal and principles
  - **Simplicity**
    - Layout
    - S-band accelerating structure (2856.75MHz)
      - 2856.75MHz =3.25MHz×879, Linac
      - 650 MHz =3.25MHz×200, Booster
      - 1300 MHz =3.25MHz×400, Collider
  - **High Availability and Reliability**
    - ~ 15% backups for Klystrons and accelerating structure
  - 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+*		$>9.4\times10^9$
		nC	>1.5
Energy spread (e^-/e^+)	σ_E		$<2\times10^{-3}$
Emittance (e^-/e^+)	ε_r	nm	<120
e^- beam energy on Target		GeV	4
e^- bunch charge on Target		nC	10

Introduction

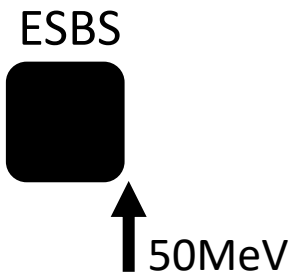
Main parameters

- Layout
  - Smaller emittance requirement **possibility** and high **potential**
    - **Damping Ring** for positron beam
      - **Larger errors tolerance**
      - Higher injection efficiency, easier injection design
      - Shorter damping time to damp the extraction beam of booster to collider
- Bunch charge: ***3nC***
  - Enough redundancy and high bunch charge requirement possibility or potential
    - High electron beam energy ~4 GeV for positron production
- One-bunch-per-pulse
  - Only ***short-range Wakefield*** need to be considered

✓Two-bunch-per-pulse

Layout of Linac

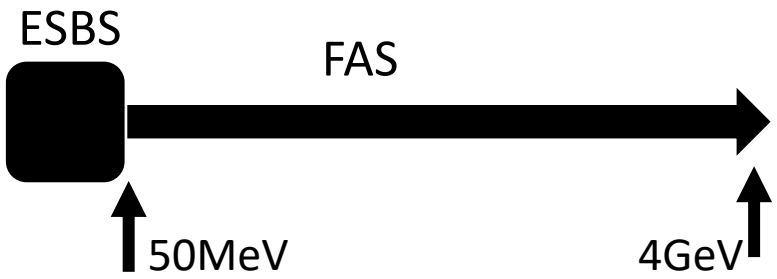
Positron Linac



- ESBS (*Electron Source and Bunching System*)
  - 50 MeV && 11nC for positron production

Layout of Linac

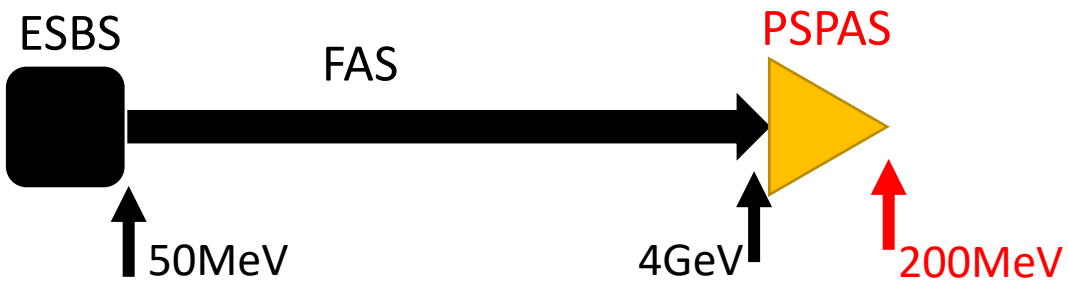
Positron Linac



- ESBS (*Electron Source and Bunching System*)
  - 50 MeV && 11nC for positron production
- FAS (*the First Accelerating Section*)
  - Electron beam to 4 GeV && 10nC for positron production

Layout of Linac

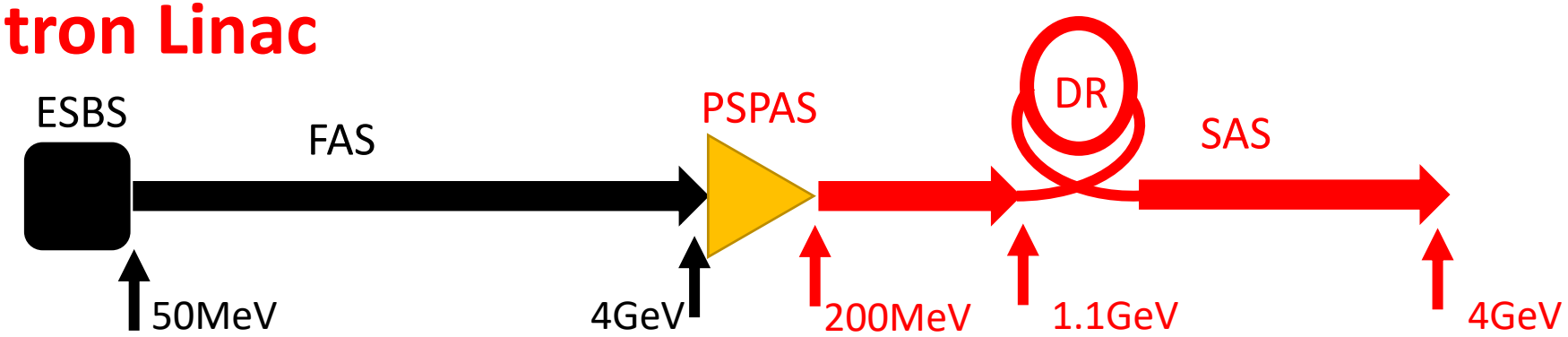
Positron Linac



- ESBS (*Electron Source and Bunching System*)
  - 50 MeV && 11nC for positron production
- FAS (*the First Accelerating Section*)
  - Electron beam to 4 GeV && 10nC for positron production
- PSPAS (*Positron Source and Pre-Accelerating Section*)
  - Positron beam larger than 200 MeV && larger than 3 nC

Layout of Linac

Positron Linac



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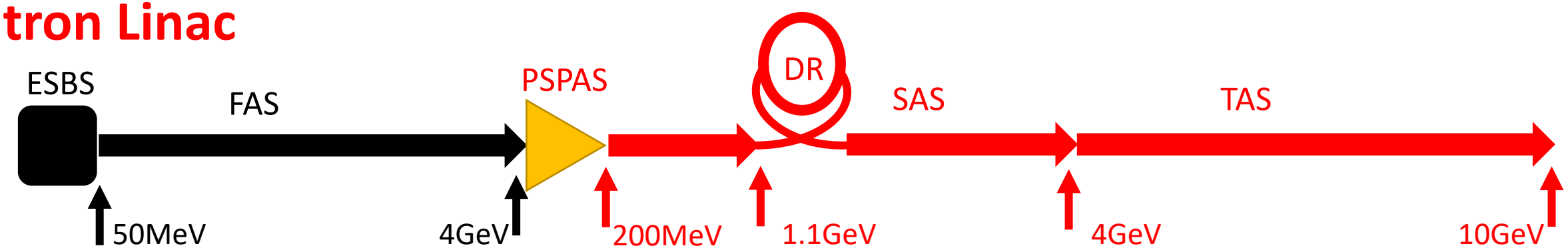
  - Positron beam larger than 200 MeV && larger than 3 nC
- SAS (*the Second Accelerating Section*)
  - Positron beam to 4 GeV && 3 nC
- DR (Damping Ring)
  - Positron beam 1.1GeV/60m

Layout of Linac

Positron Linac



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- FAS (*the First Accelerating Section*)
  - Electron beam to 4 GeV && 10nC for positron production
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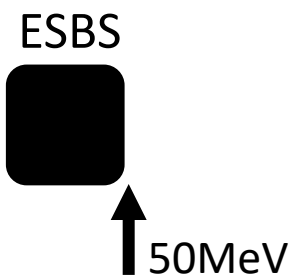
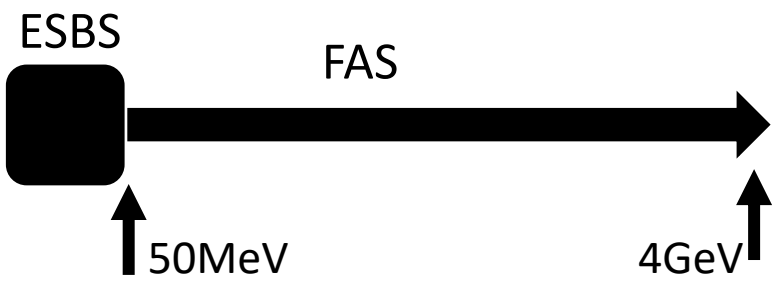
  - Positron beam larger than 200 MeV && larger than 3 nC
- SAS (*the Second Accelerating Section*)
  - Positron beam to 4 GeV && 3 nC
- DR (Damping Ring)
  - Positron beam 1.1GeV/60m
- TAS (*the Third Accelerating Section*)
  - Positron beam to 10 GeV && 3 nC

Electron Linac



- ESBS (*Electron Source and Bunching System*)
  - 50 MeV && 3.3 nC

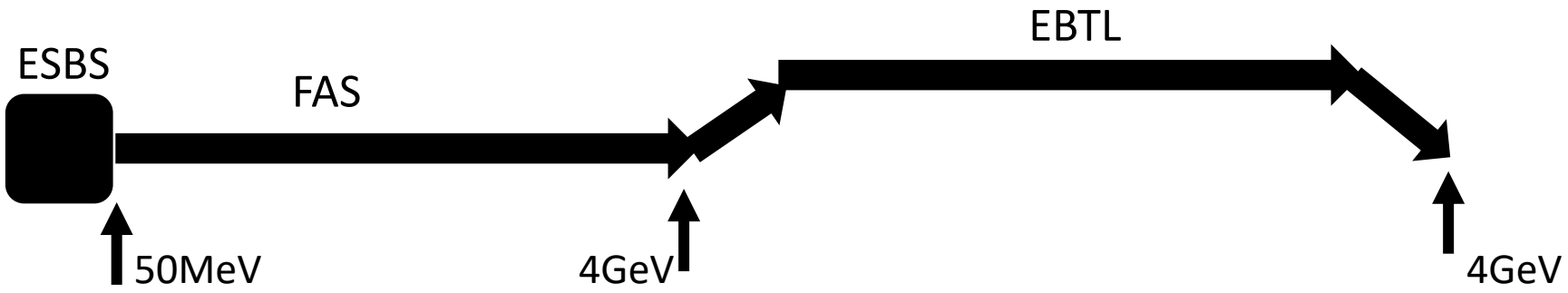
Electron Linac



- ESBS (*Electron Source and Bunching System*)
  - 50 MeV && 3.3 nC
- FAS (*the First Accelerating Section*)
  - Electron beam to 4 GeV && 3 nC

Layout of Linac

Electron Linac



- ESBS (*Electron Source and Bunching System*)
  - 50 MeV && 3.3 nC
- FAS (*the First Accelerating Section*)
  - Electron beam to 4 GeV && 3 nC
- EBTL (*Electron Bypass Transport Line*)
  - Electron beam @ 4 GeV && 3 nC

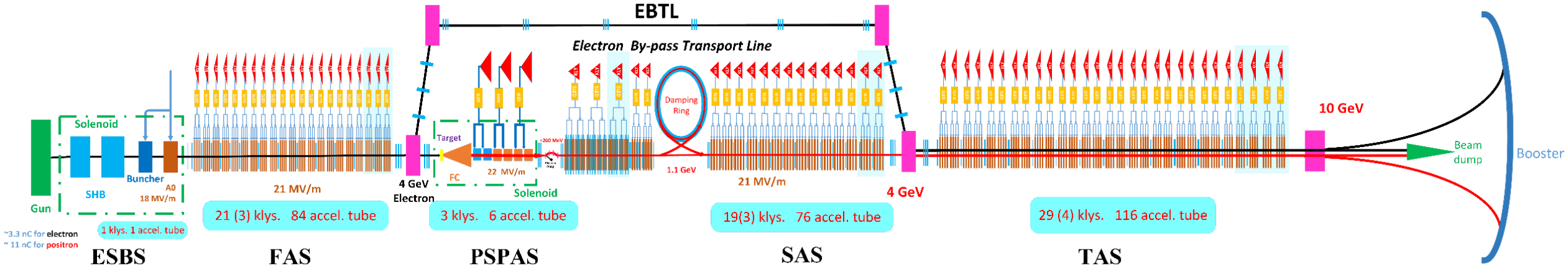
Layout of Linac

Electron Linac

- ESBS (*Electron Source and Bunching System*)
  - 50 MeV && 3.3 nC
- FAS (*the First Accelerating Section*)
  - Electron beam to 4 GeV && 3 nC
- EBTL (*Electron Bypass Transport Line*)
  - Electron beam @ 4 GeV && 3 nC
- TAS (*the Third Accelerating Section*)
  - Electron beam to 10 GeV && 3 nC

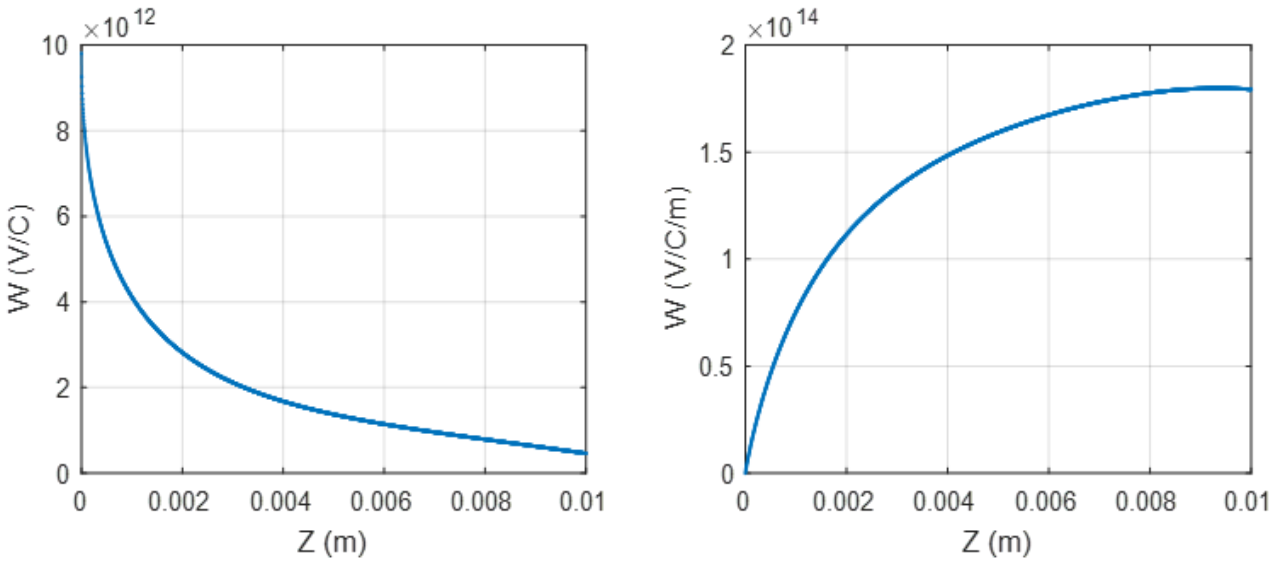
Introduction

Layout of Linac



Accelerating structure

Length	m	~3
Frequency	MHz	S-band/2856.75
Aperture	mm	>19
Acc. Gradient	MV/m	21
SLED		Yes
Mode		1 (Kly.)->4 (Acc. tube)



K. Yokoya and and K. Bane, The longitudinal high–frequency impedance of a periodic accelerating structure, Proceedings of the 1999 PAC, New York, 1999.

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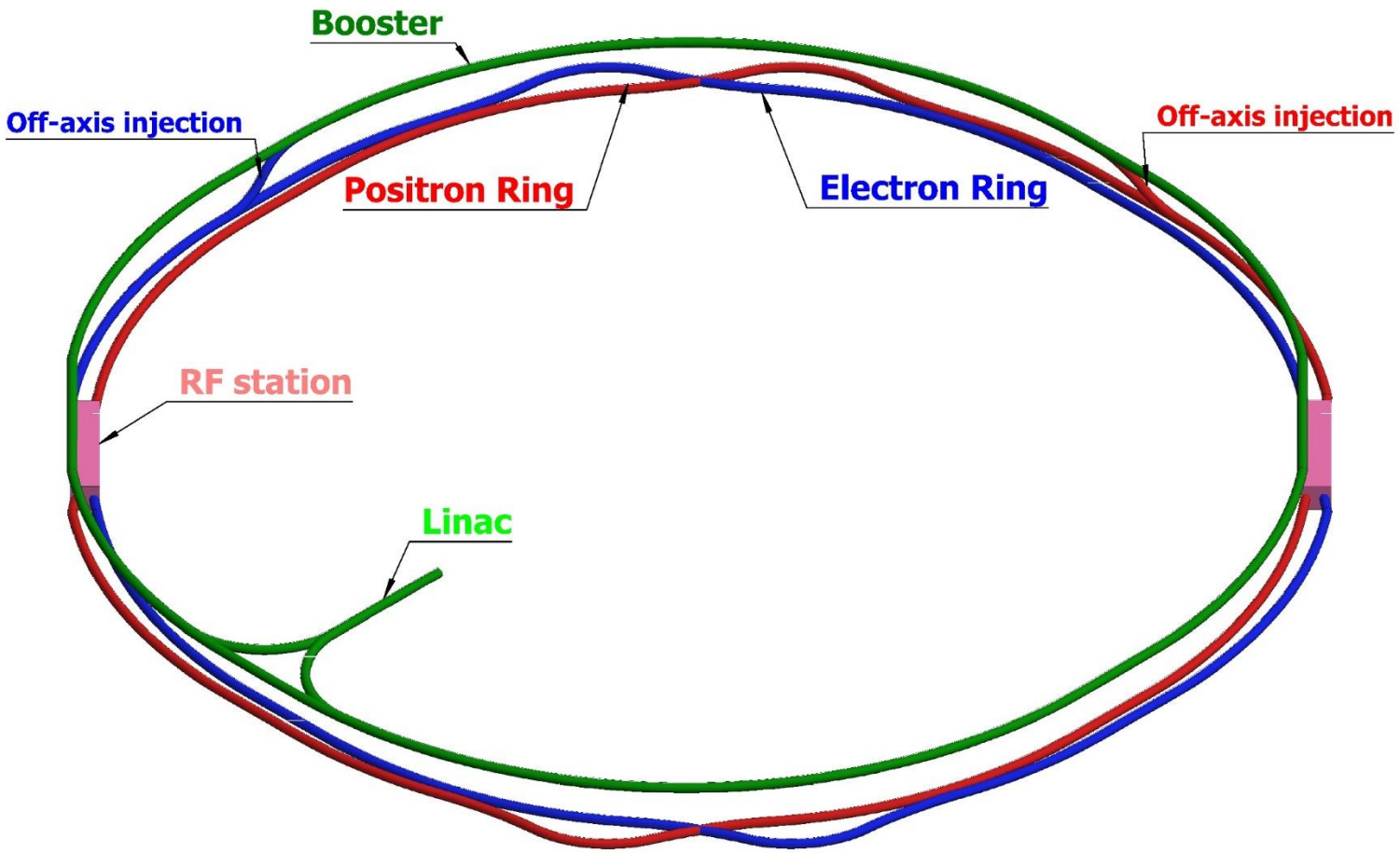
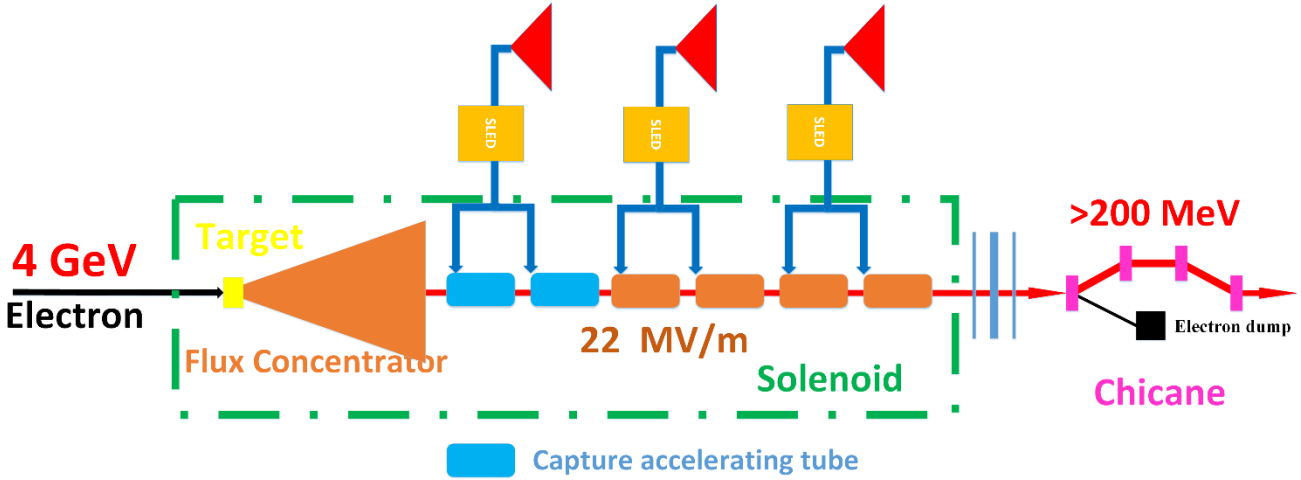
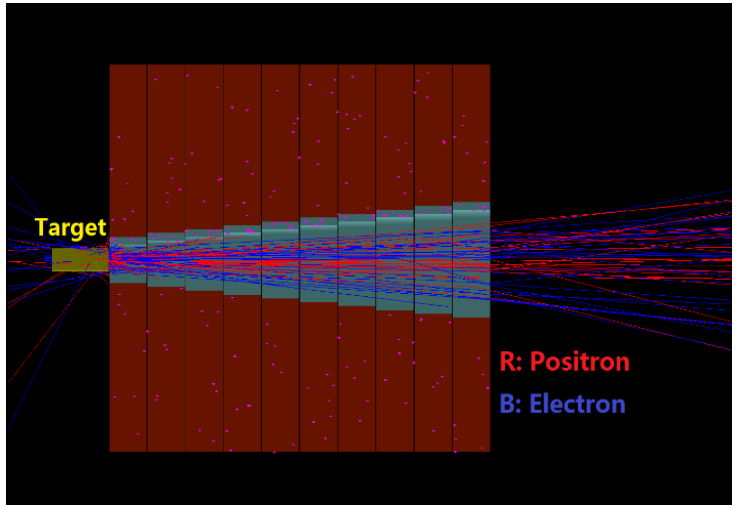


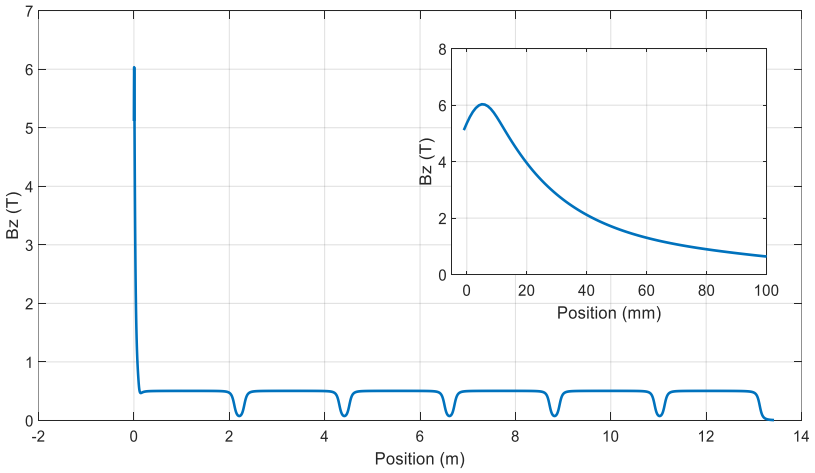
Positron source

Layout of PSPAS

- Layout of positron source
  - Target (Conventional)
    - W@15mm
    - Rms electron beam size:0.5mm
  - AMD (Adiabatic Matching Device)
    - Length: 100mm
    - Aperture: 8mm→26mm
  - Capture & Pre-accelerating structure
    - Length:2 m
    - **Aperture**: 25 mm
    - Gradient: 22 MV/m
  - Chicane
    - Wasted electron separation



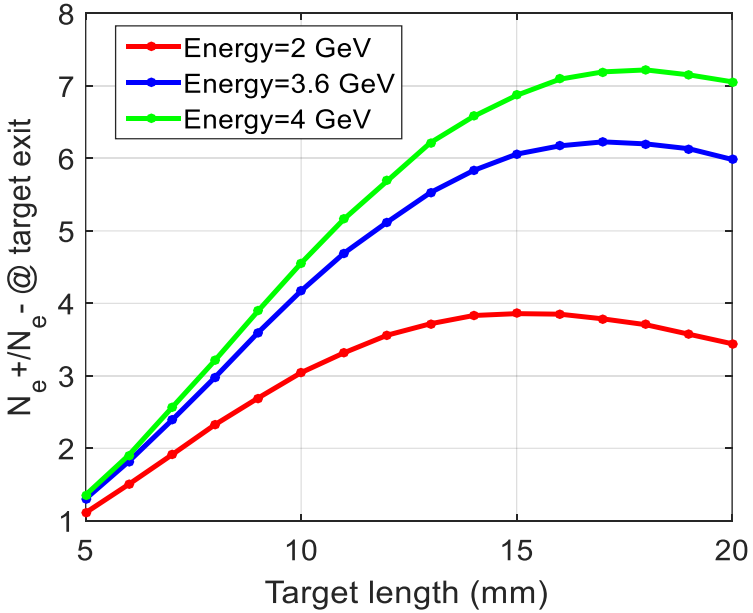


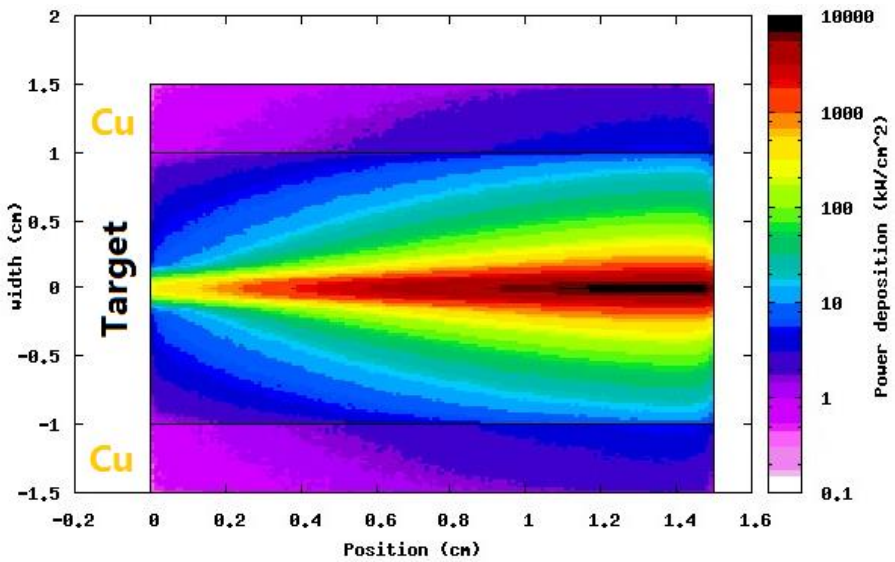


Positron source

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 source
  - Positron bunch charge > **3 nC**
  - Electron beam:
    - 4GeV
    - 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

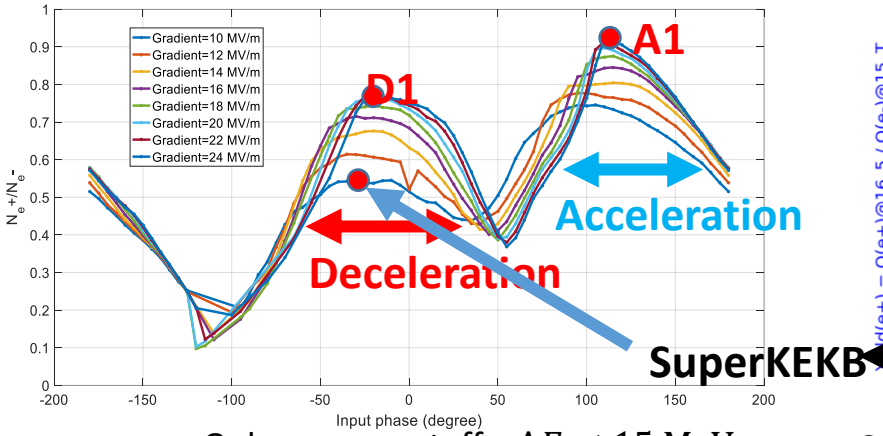




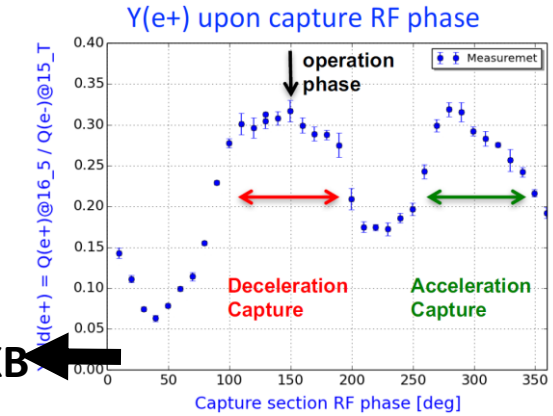
Positron source

Dynamic results of PSPAS

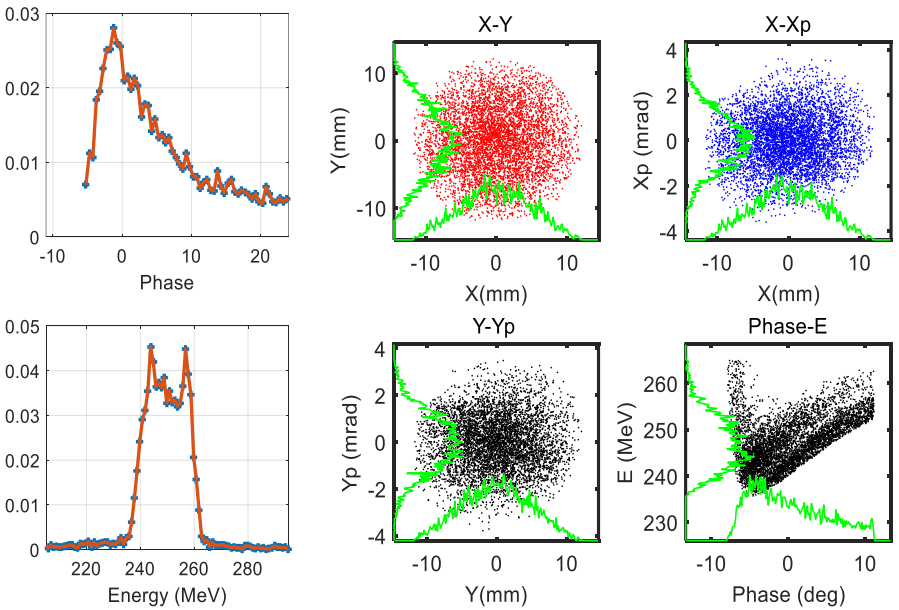
- Norm. RMS. Emittance
  - 2500 mm-mrad
- Energy: >200 MeV
- Positron yield
  - Ne+/Ne- > **0.55** @ [-6°, 14°, 235MeV, 265MeV]

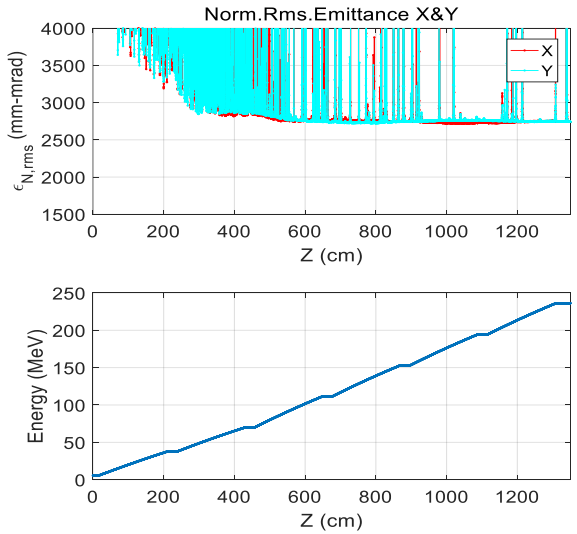


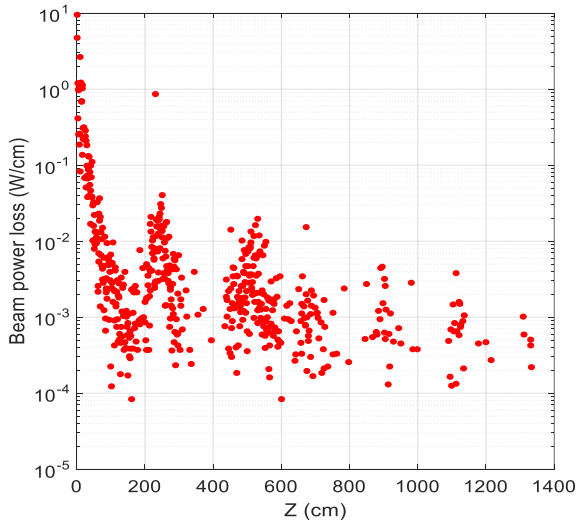
Only energy cutoff $\Delta E < 15$ MeV



SuperKEKB commissioning results







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		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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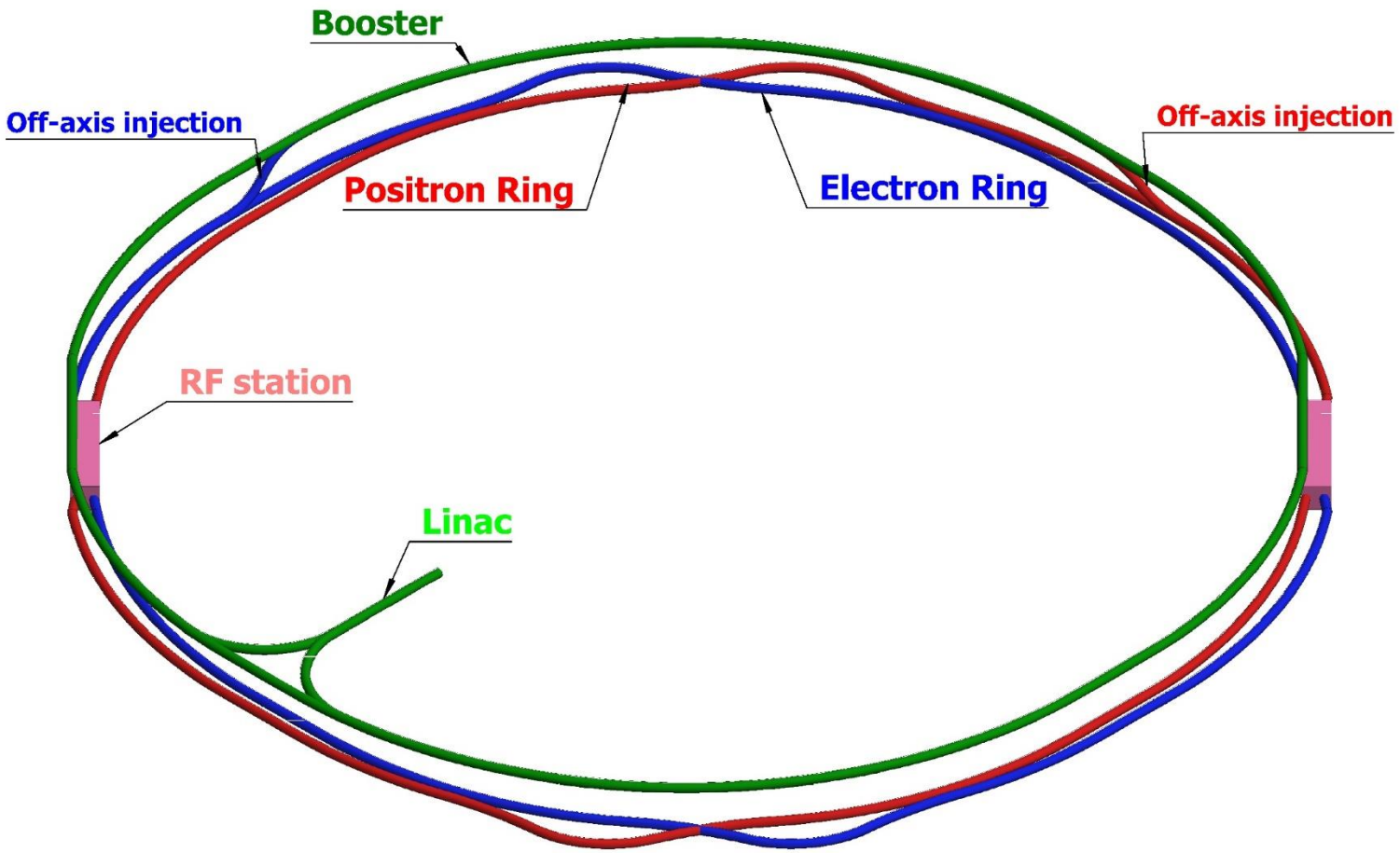
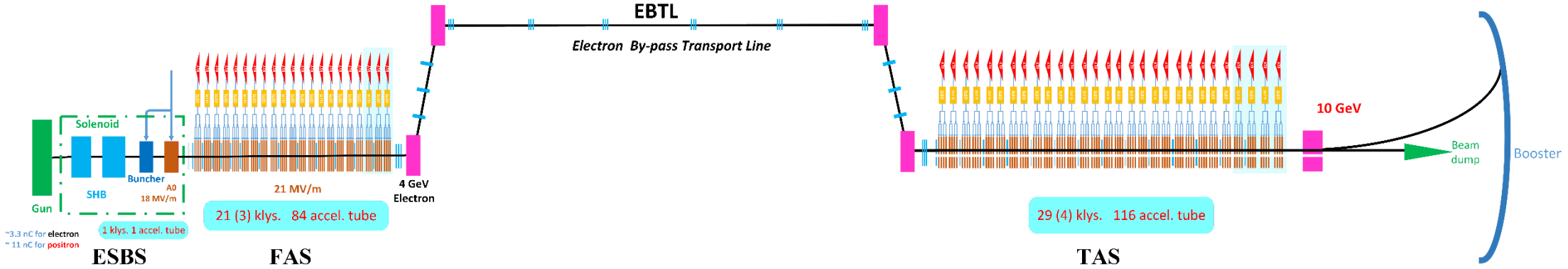
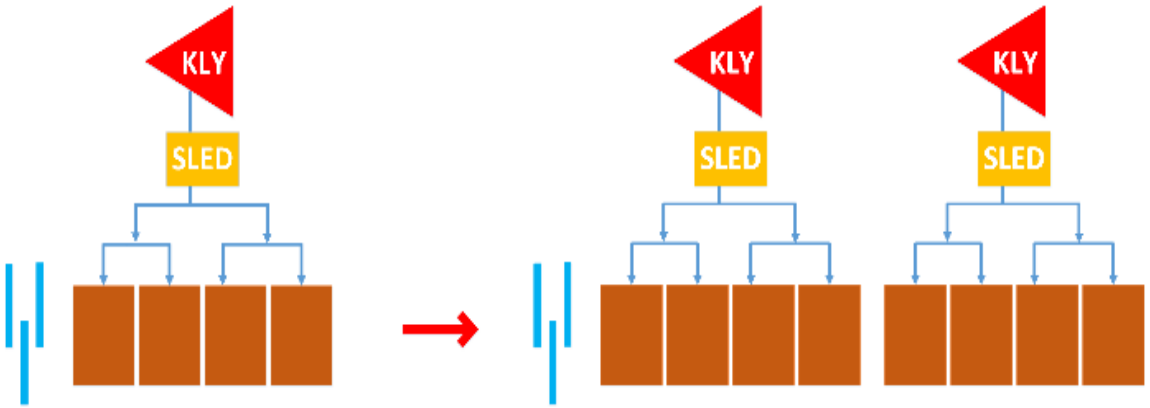


Linac design

Electron linac

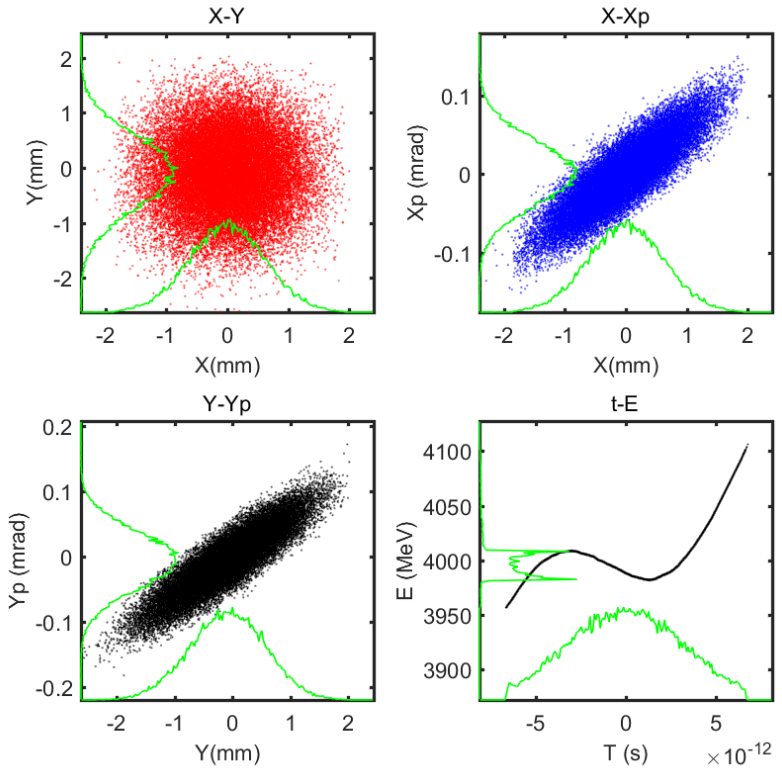


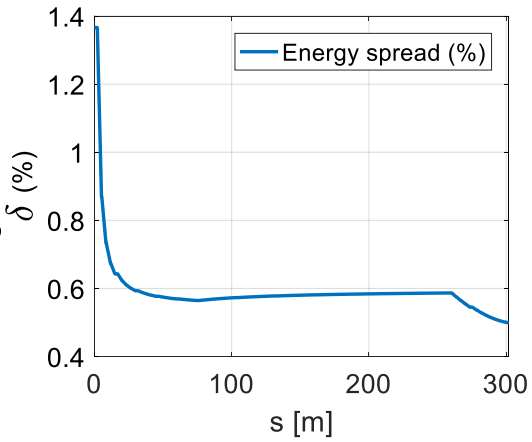
- Focusing structure: ***Triplet***
  - Long drift length for accelerating tubes
  - Beam size in Acc. tubes is small and easy control
  - Same beam envelopes at X/Y planes
  - *1 triplet+4 Acc. tubes→1 triplet+8 Acc. tubes*
- Operation mode :
  - High charge mode (positron production)
    - 4GeV & 10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

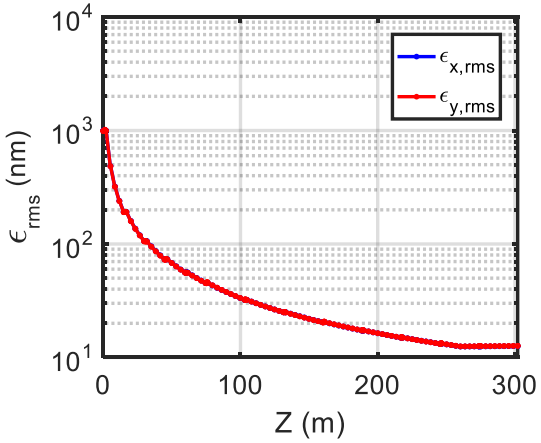


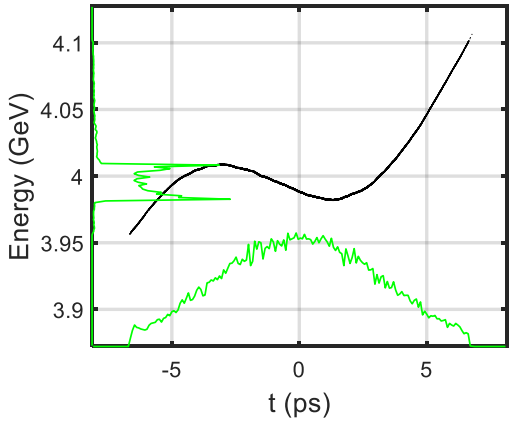
Linac design Electron linac→ *Positron production*

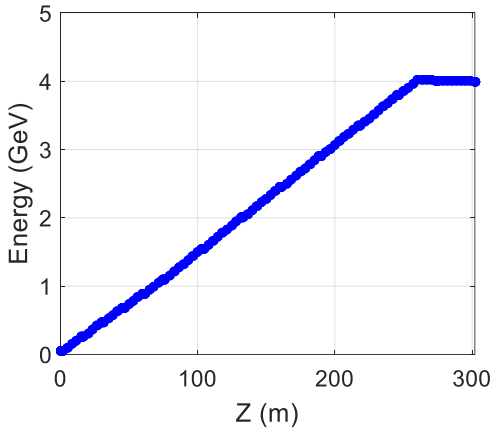
- High charge mode
  - 10 nC @ 4 GeV
  - Energy spread (rms): 0.5%
  - Emittance growth with errors

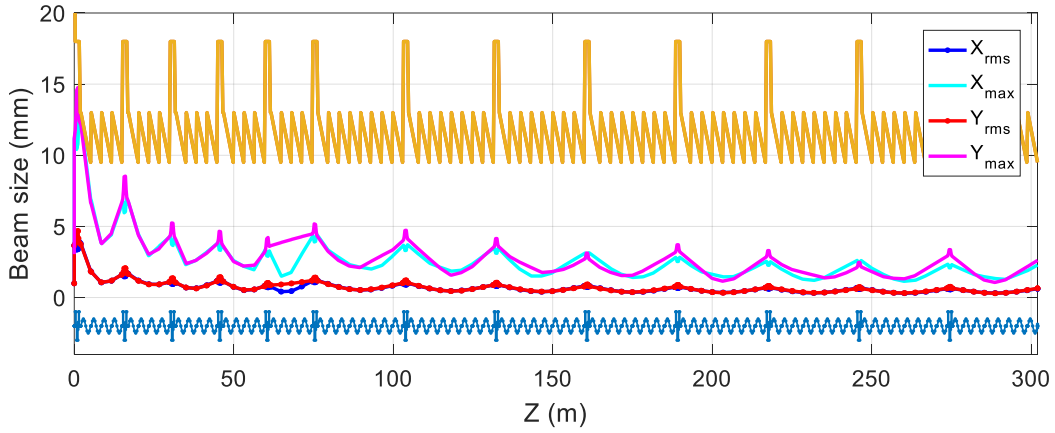






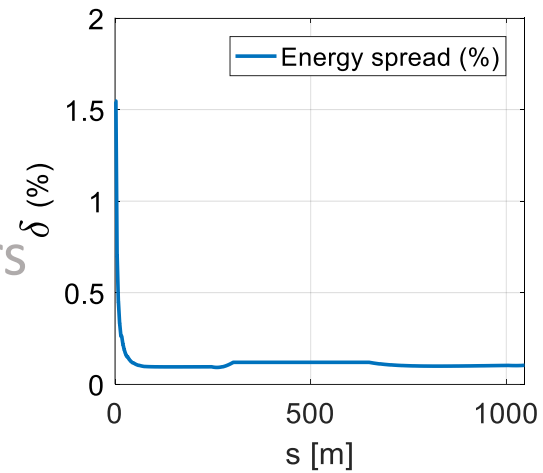


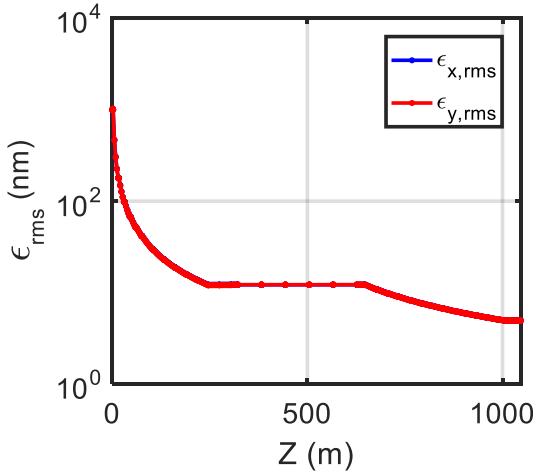


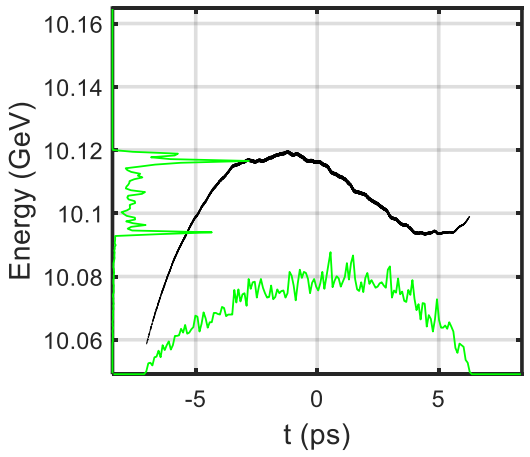


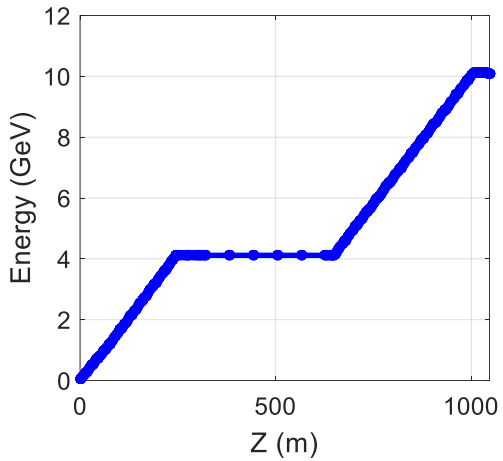
Linac design Electron linac→ *Electron injection*

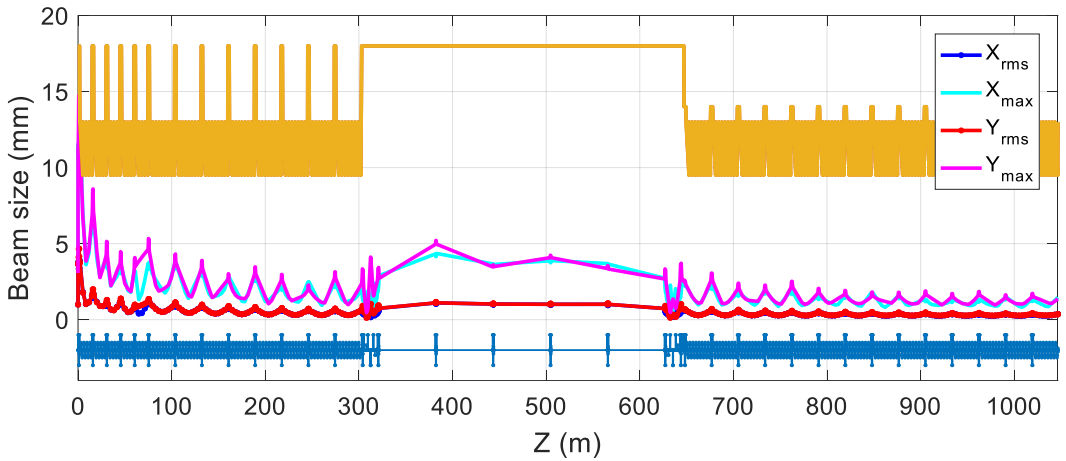
- High charge mode
  - 10 nC @ 4 GeV
  - Energy spread (rms): 0.5%
  - Emittance growth with errors
- Low charge mode
  - 3 nC @ 10 GeV
  - Energy spread (rms): 0.15%
  - Emittance (rms): 5 nm





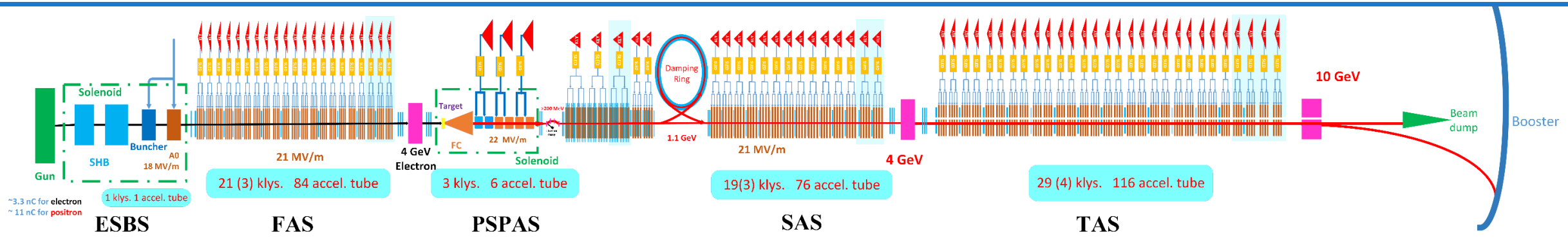




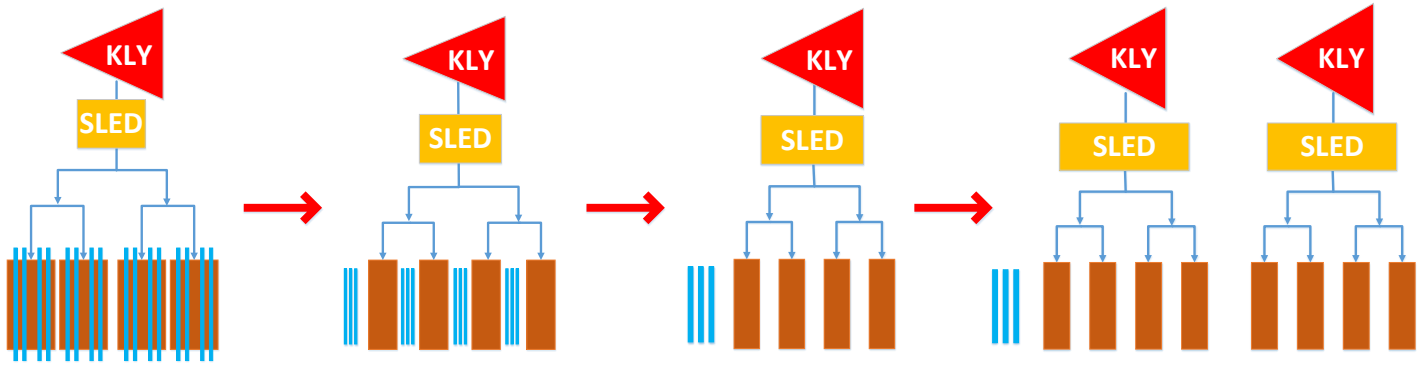


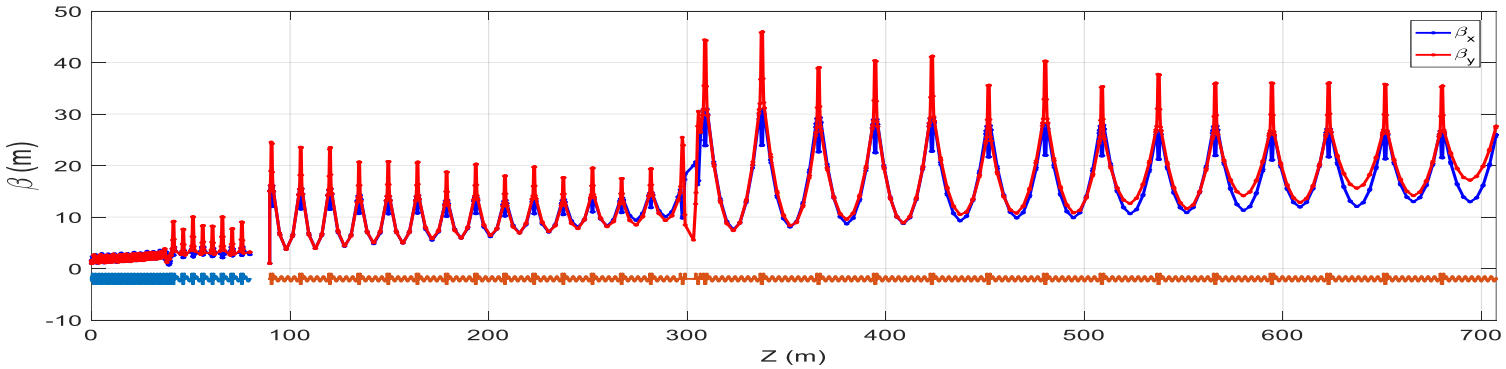
Linac design

Positron linac



- PSPAS→SAS (DR) +TAS
  - SAS: 200 MeV→4 GeV
  - Damping Ring @ 1.1 GeV
  - TAS: 4GeV→10 GeV
- Transverse focusing structure
  - FODO, nesting on Acc. tubes
  - Triplet

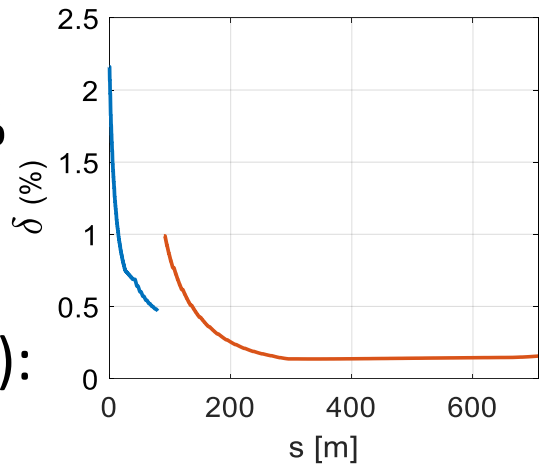


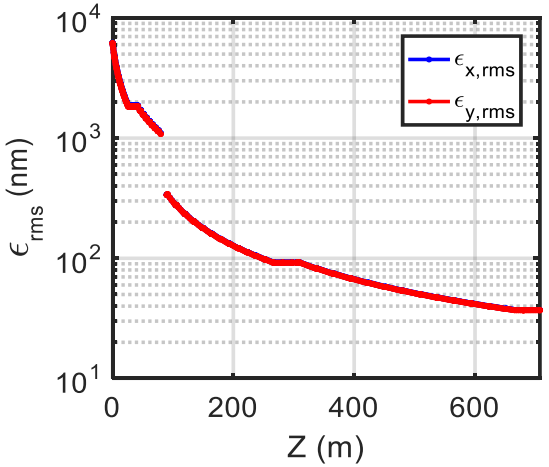


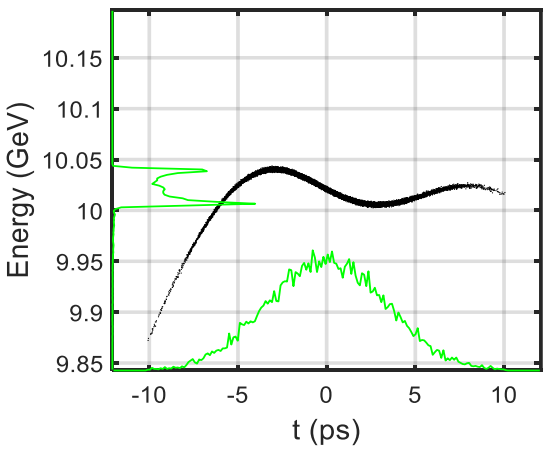
Linac design

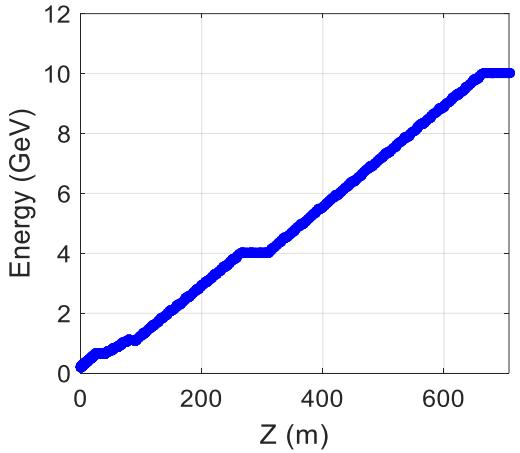
Positron linac

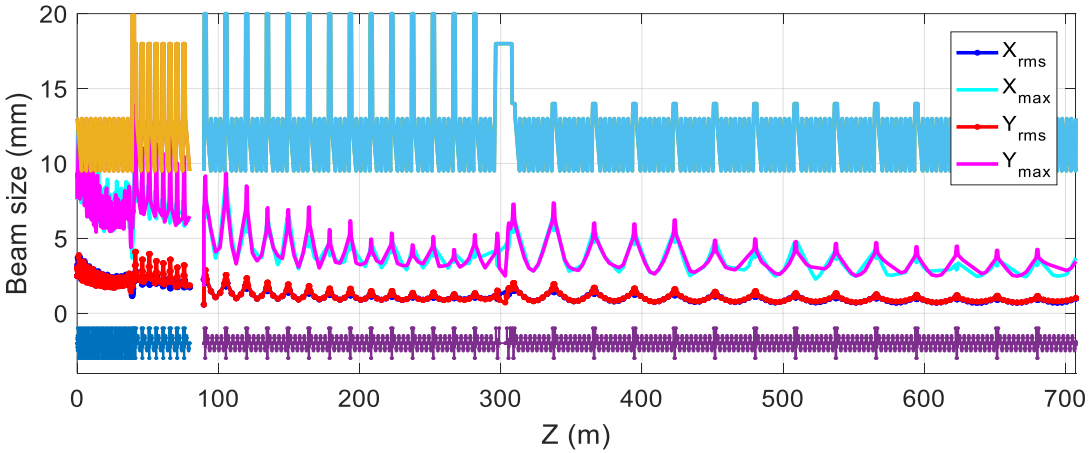
- Positron linac
  - 3 nC && 10 GeV
  - Energy spread (rms): 0.16%
  - Emittance with DR (rms): 40/24nm
  - Emittance without DR (rms): 120/120nm







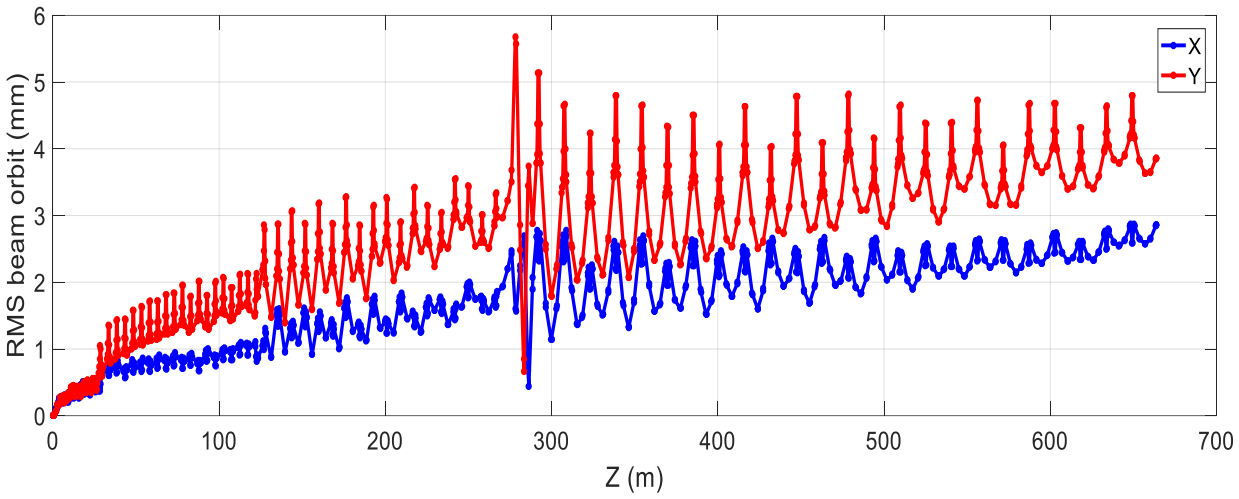




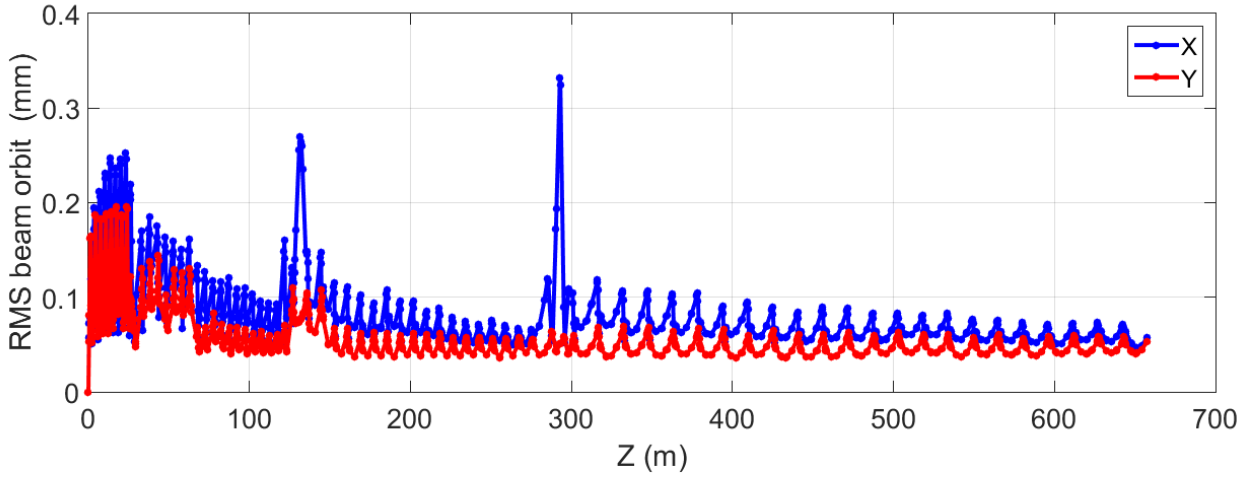
Linac design

Misalignment errors with correction

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



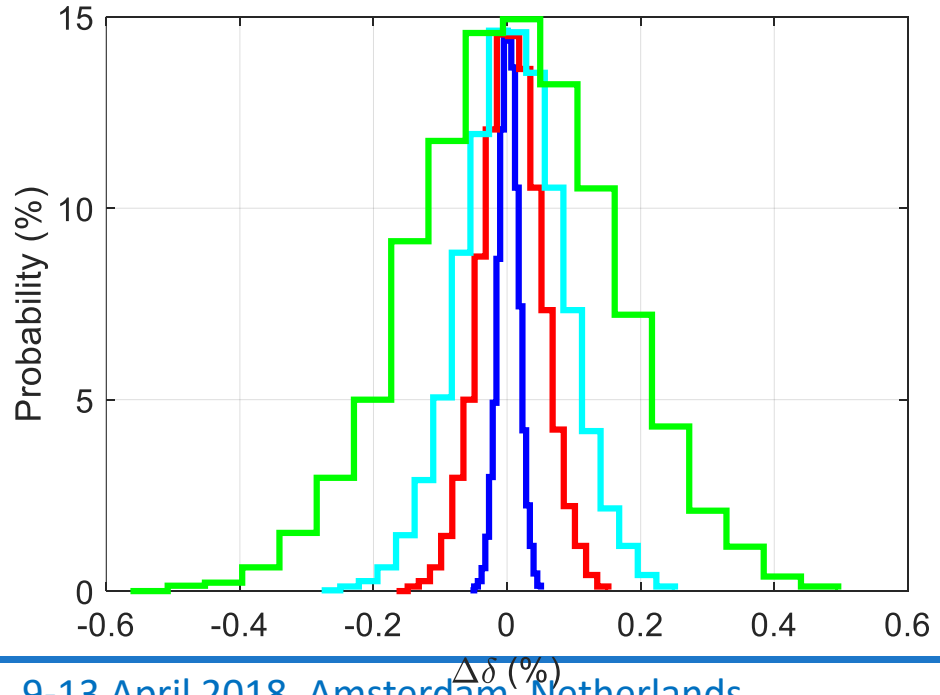
Error description	Unit	Value
Translational error	mm	0.1
Rotation error	mrad	0.2
Magnetic element field error	%	0.1
BPM uncertainty	mm	0.1



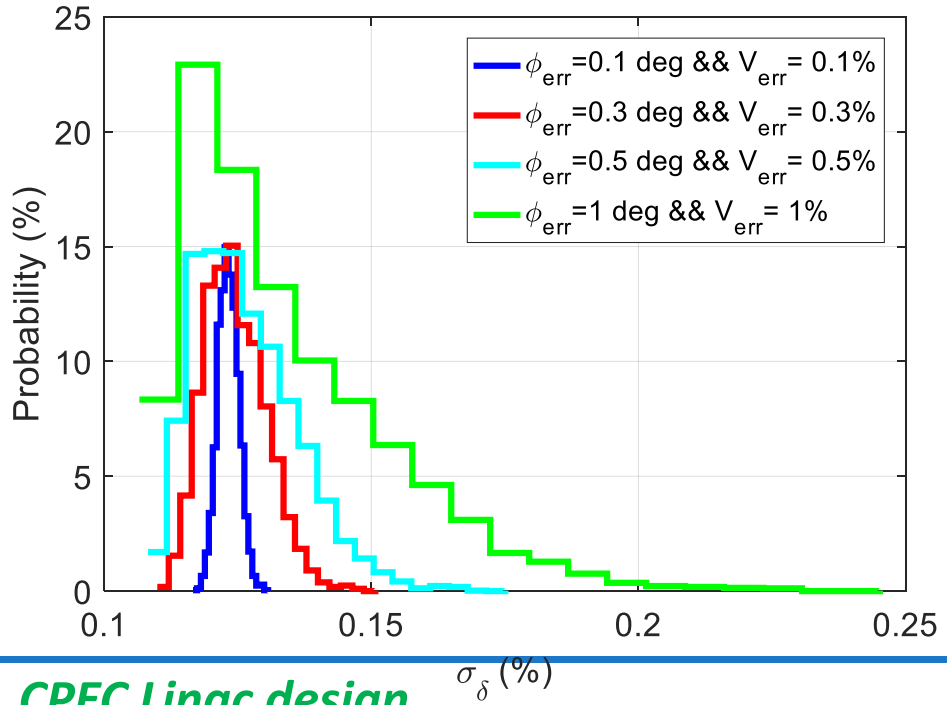
Linac design

Field errors

- 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)
  - Grad. errors: 0.5% (rms)
- Energy jitter: 0.2%

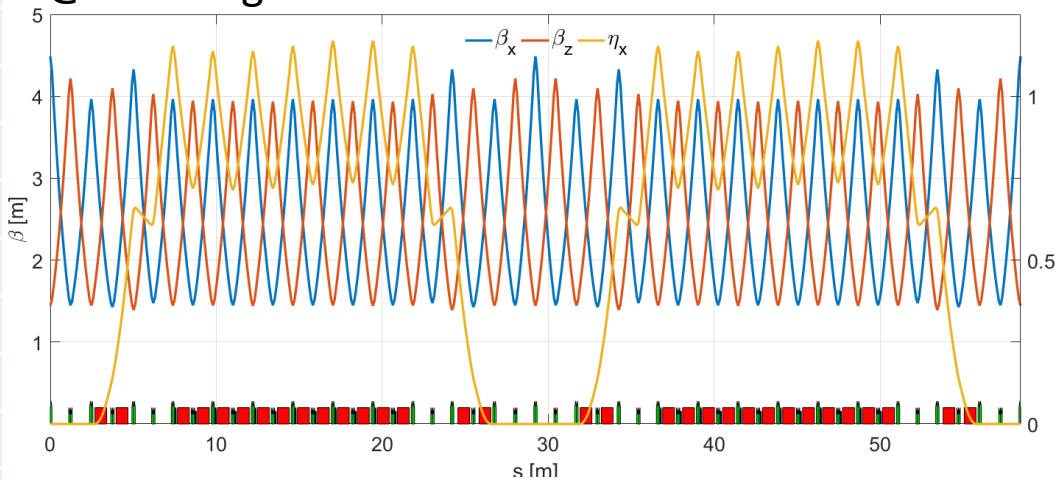


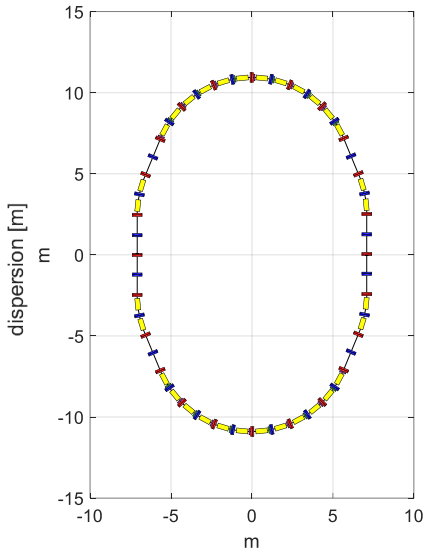
Linac design

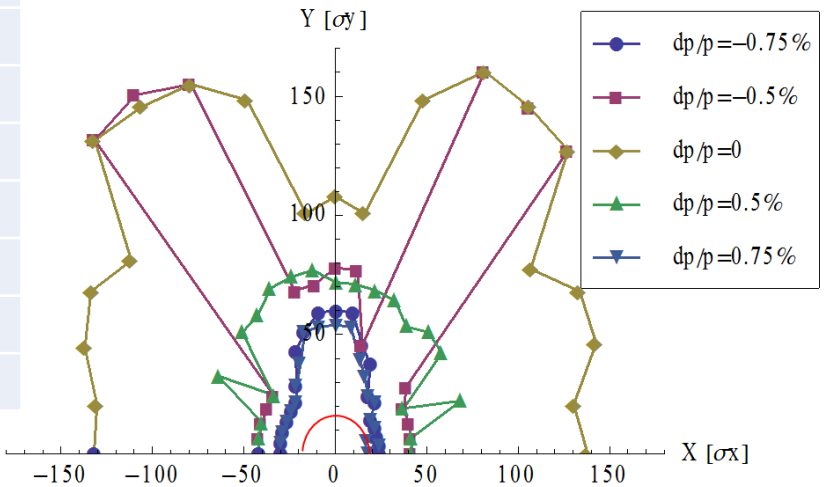
Damping Ring

DR V1.0	Unit	Value
Energy	GeV	1.1
Circumference	M	58.5
Repetition frequency	Hz	100
Bending radius	M	3.62
Dipole strength B_0	T	1.01
U_0	keV	35.8
Damping time x/y/z	ms	12/12/6
δ_0	%	0.05
ε_0	mm.mrad	287.4
Nature σ_z	mm	7 (23ps)
ε_{inj}	mm.mrad	2500
$\varepsilon_{ext\ x/y}$	mm.mrad	704/471
$\delta_{inj}/\delta_{ext}$	%	0.3/0.06
Energy acceptance by RF	%	1.0
f_{RF}	MHz	650
V_{RF}	MV	1.8

@ D. Wang







- Emittance not critical
- One bunch in DR(200ns)
  - 10 ms→20ms
  - Two bunch: yes
- **IBS**
  - Emittance growth
- **CSR (Coherent synchrotron radiation)**
  - CSR Instability

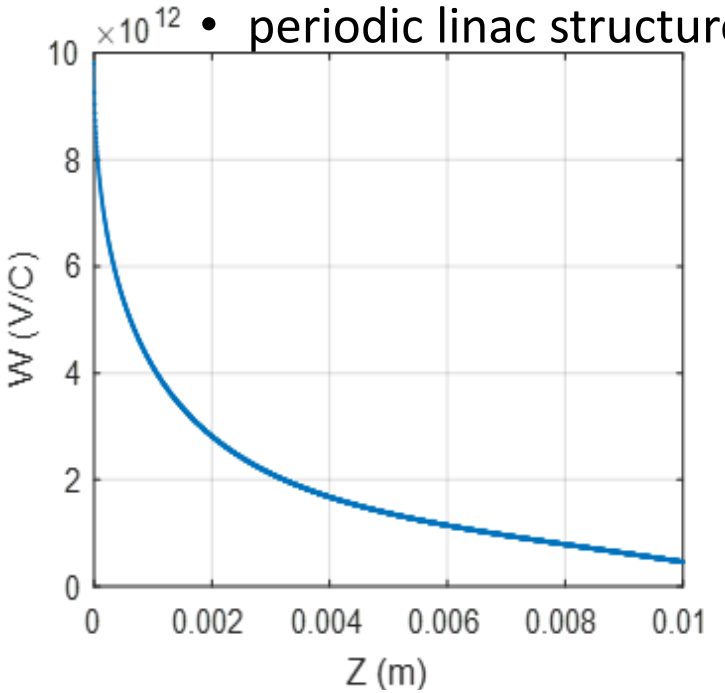
Summary

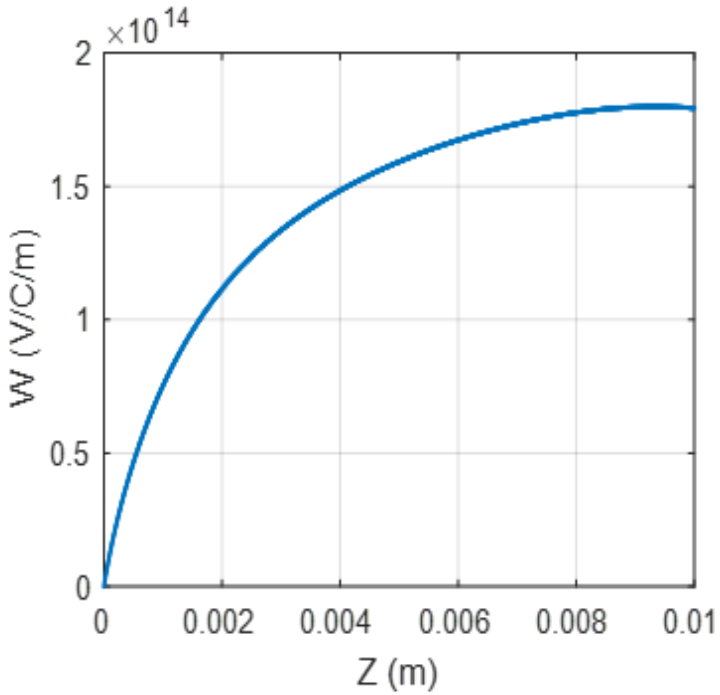
- The CEPC linac works with 100 Hz repetition, 10 GeV and one-bunch-per-pulse;
- The linac can provide positron beam and electron beam with 3nC bunch charge, which is larger than the requirements;
- One preliminary damping ring is proposed;
- By now seems it’s no problem in linac design and further works are on the way.

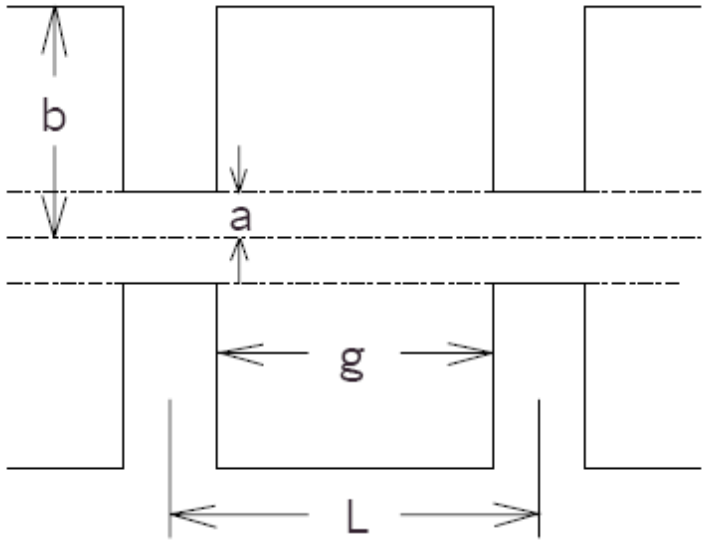
Linac design

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

Injection

Mode	Higgs		W		Z	
Injection Mode	Top-up	Full	Top-up	Full	Top-up	Full
Bunch number	242		1524		6000	
Bunch Charge (nC)	0.72	1	0.576	0.87	0.384	0.55
Beam Current (mA)	0.5227	0.726	2.63	4	6.91	10
Current threshold	1 mA		4 mA		10 mA	
Number of Cycles	1		1		2	
Current decay	3%	4.17%	3%	4.55%	3%	4.3%
Ramping Cycle (sec) (Up + Down）	10		6.6		3.8	
Filling time (sec) （e+， e-)	25.84		45.68		275.2	
Injection period (sec)	73.1		131		438	
Full Injection time	600 s		900 s		2.2 Hour (从230mA） 对撞	

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