



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

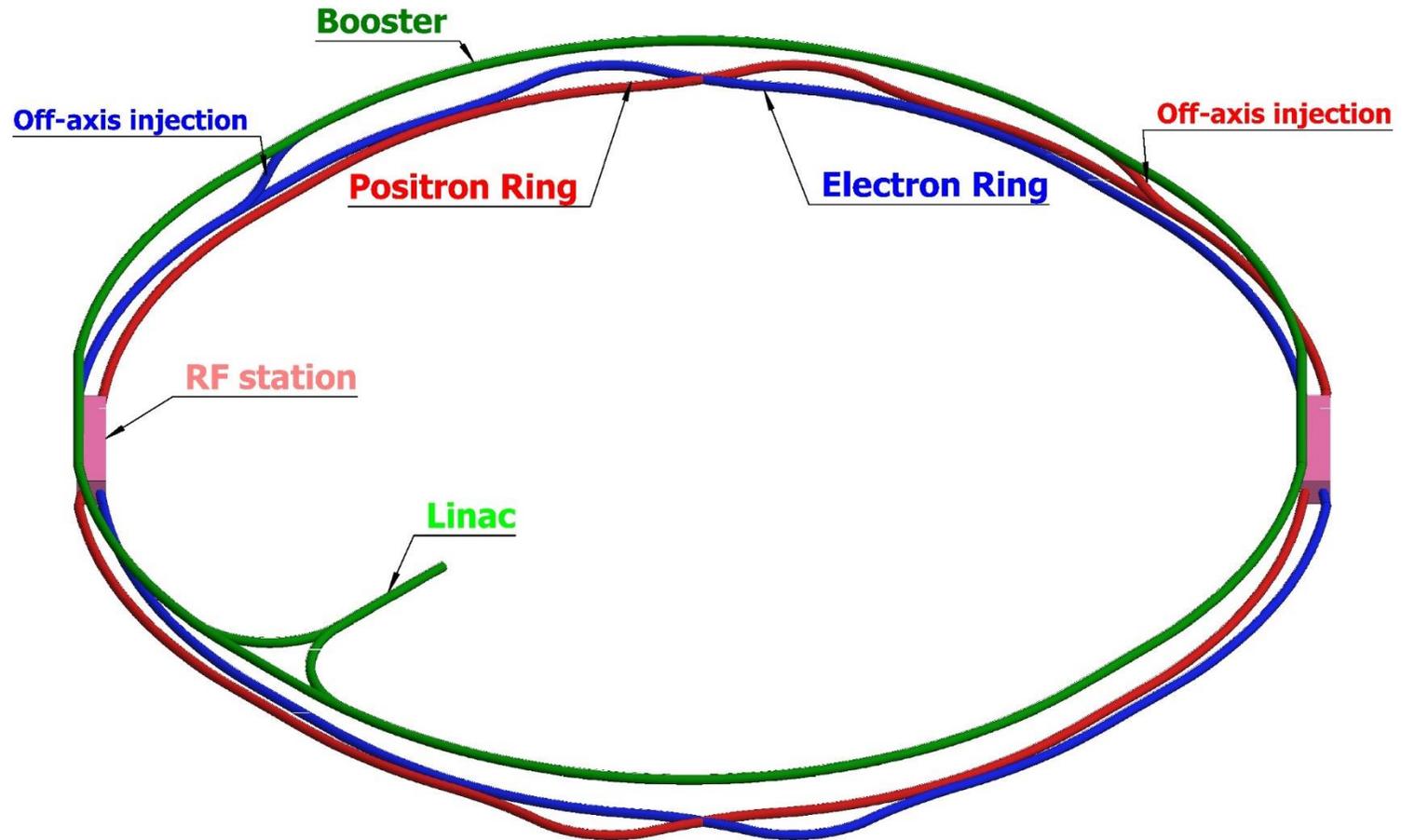
11 April, 2018

Cai Meng, Guoxi Pei, Jingru Zhang, Xiaoping Li,

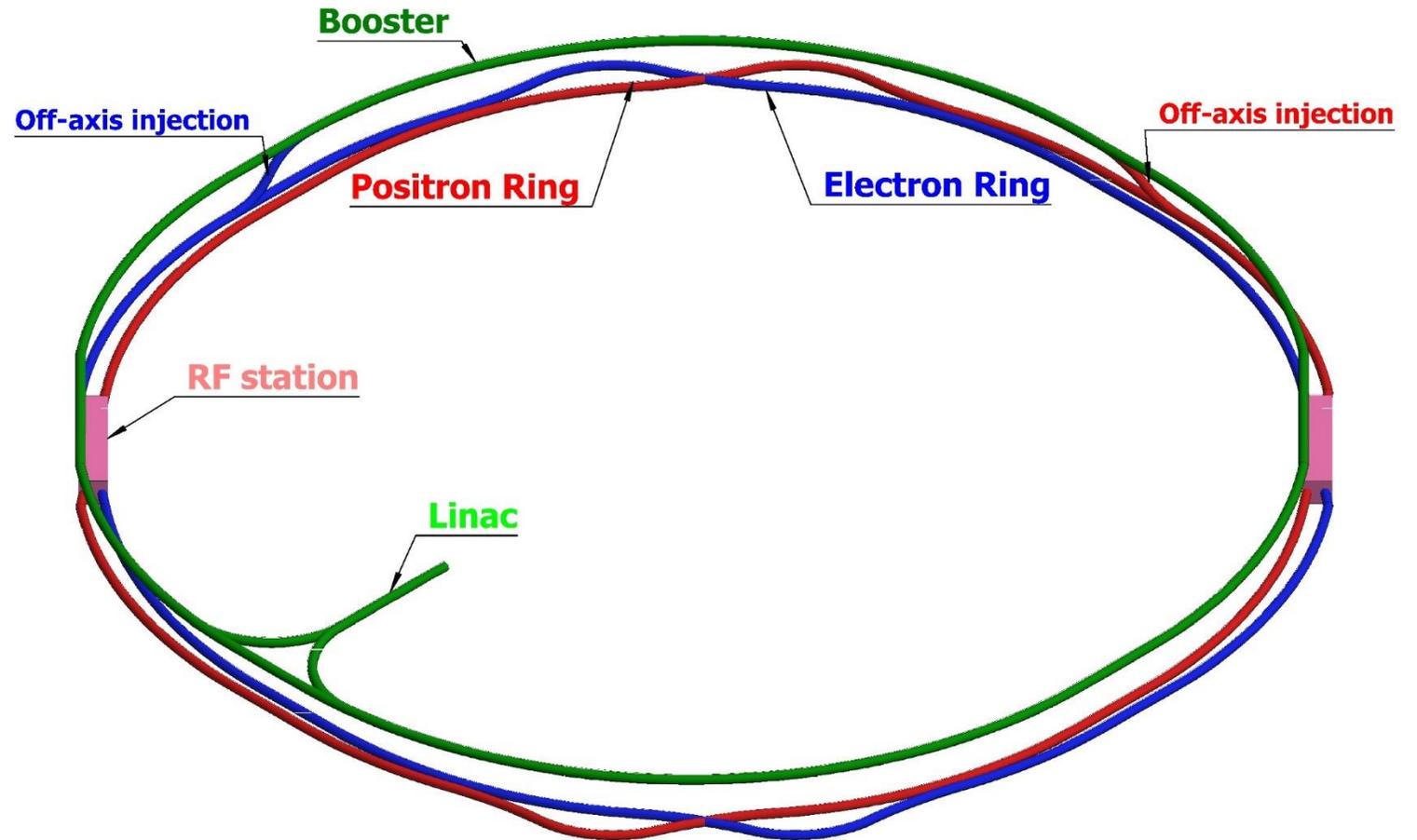
Dou Wang, Jie Gao, Shilun Pei, Yunlong Chi

Institute of High Energy Physics, CAS, Beijing

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



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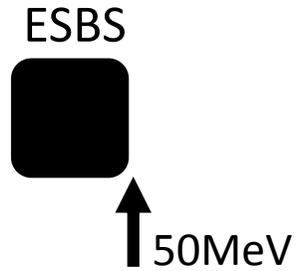


- Linac design goal and principles
 - **Simplicity**
 - Layout
 - S-band accelerating structure (2856.75MHz)
 - 2856.75MHz = 3.25MHz × 879, Linac
 - 650 MHz = 3.25MHz × 200, Booster
 - 1300 MHz = 3.25MHz × 400, Collider
 - **High Availability and Reliability**
 - ~ 15% backups for Klystrons and accelerating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

- 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

Positron Linac



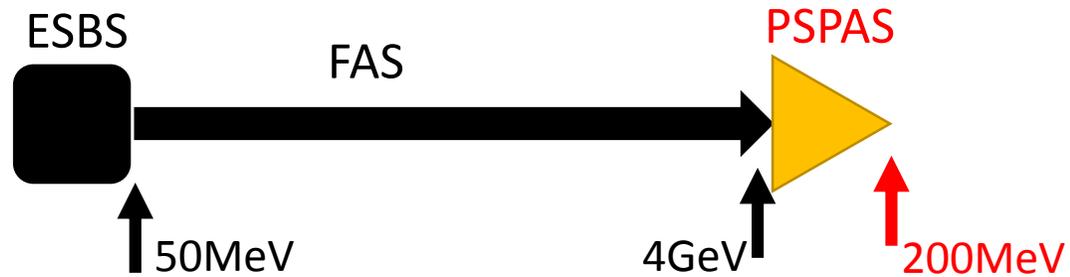
- ESBS (*Electron Source and Bunching System*)
 - 50 MeV & 11nC for positron production

Positron Linac



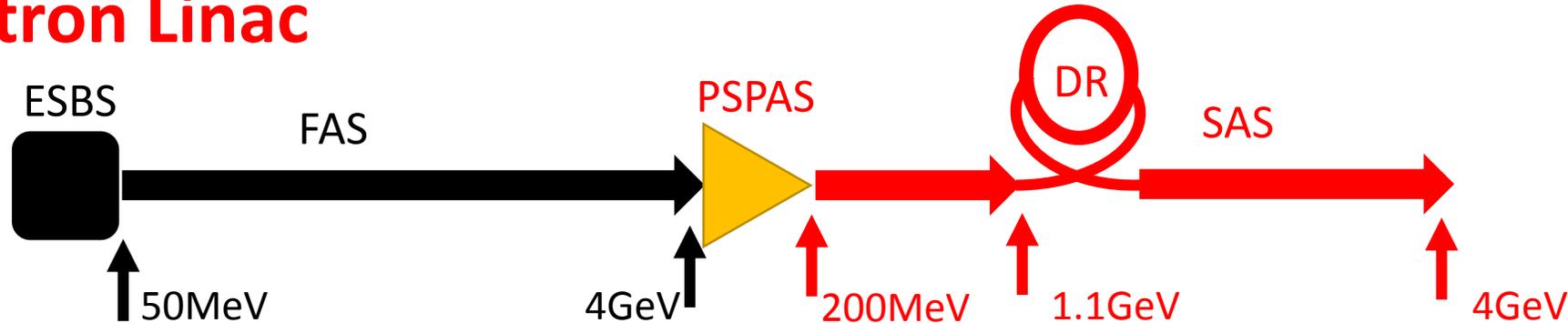
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 - Electron beam to 4 GeV & 10nC for positron production

Positron Linac



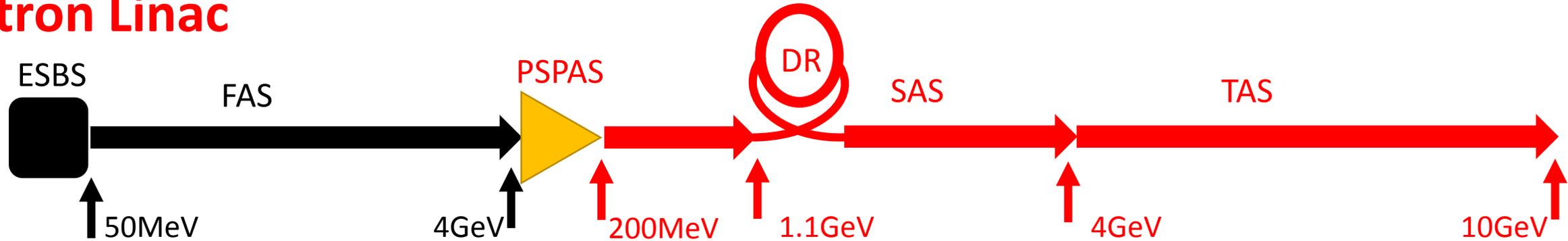
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 - 50 MeV & 11 nC for positron production
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- PSPAS (*Positron Source and Pre-Accelerating Section*)
 - Positron beam larger than 200 MeV & larger than 3 nC

Positron Linac



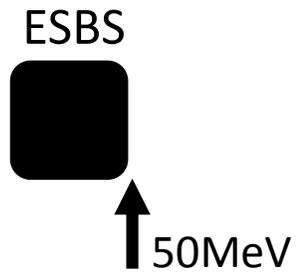
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 - Positron beam larger than 200 MeV & larger than 3 nC
- DR (*Damping Ring*)
 - Positron beam 1.1GeV/60m
- SAS (*the Second Accelerating Section*)
 - Positron beam to 4 GeV & 3 nC

Positron Linac



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 - Positron beam 1.1 GeV/60m
- TAS (*the Third Accelerating Section*)
 - Positron beam to 10 GeV & 3 nC

Electron Linac



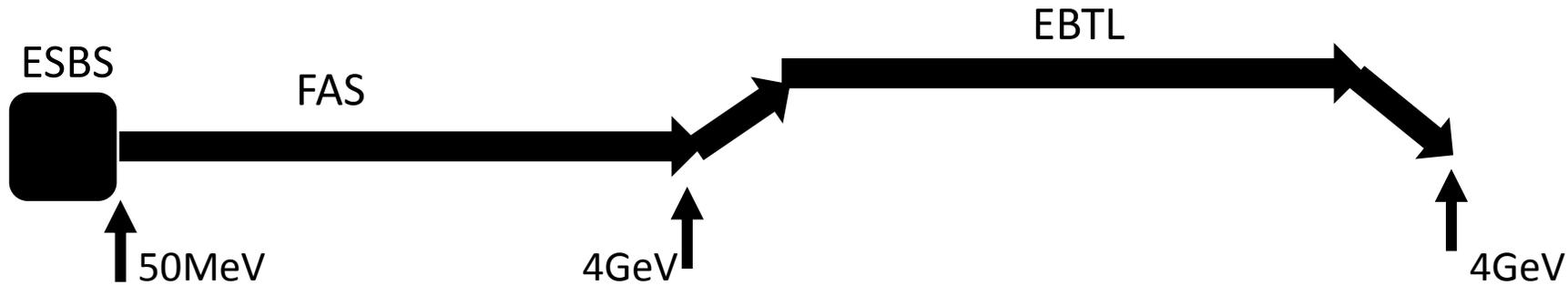
- ESBS (*Electron Source and Bunching System*)
 - 50 MeV & 3.3 nC

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

Electron Linac

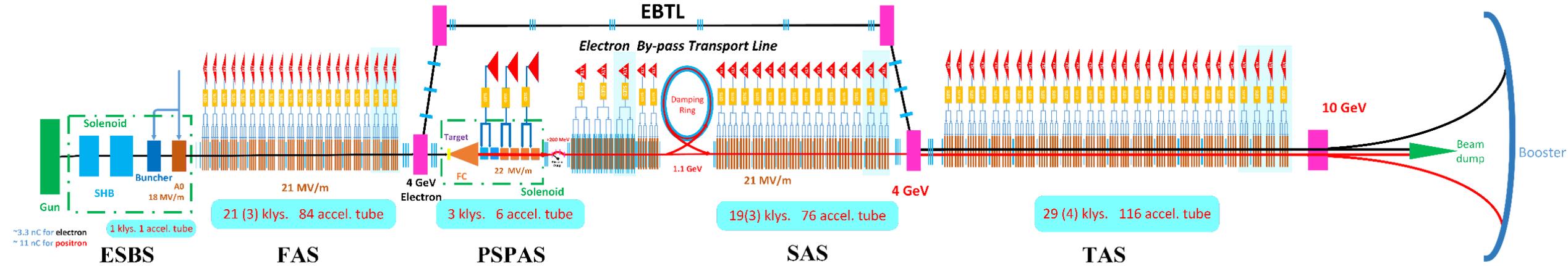


- ESBS (*Electron Source and Bunching System*)
 - 50 MeV && 3.3 nC
- FAS (*the First Accelerating Section*)
 - Electron beam to 4 GeV && 3 nC
- EBTL (*Electron Bypass Transport Line*)
 - Electron beam @ 4 GeV && 3 nC

Electron Linac

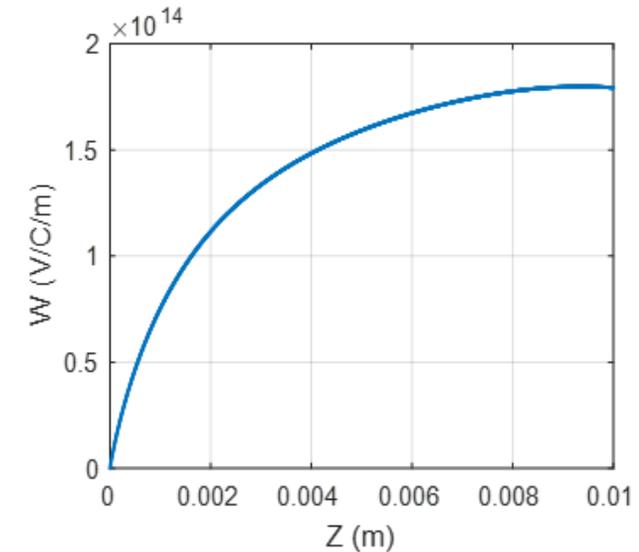
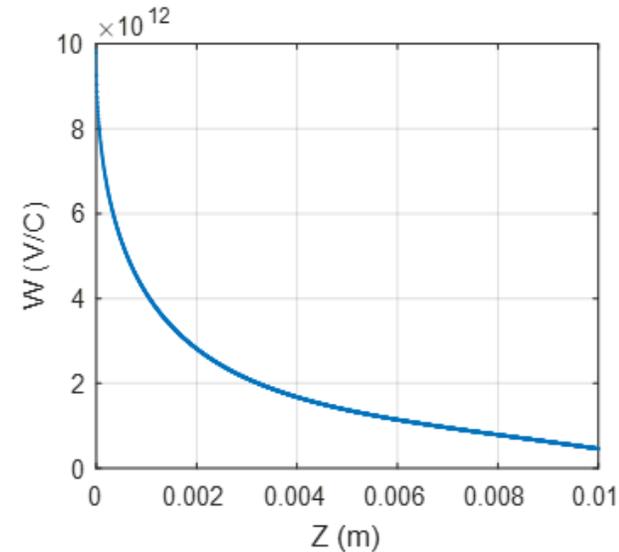


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 - Electron beam to 10 GeV && 3 nC



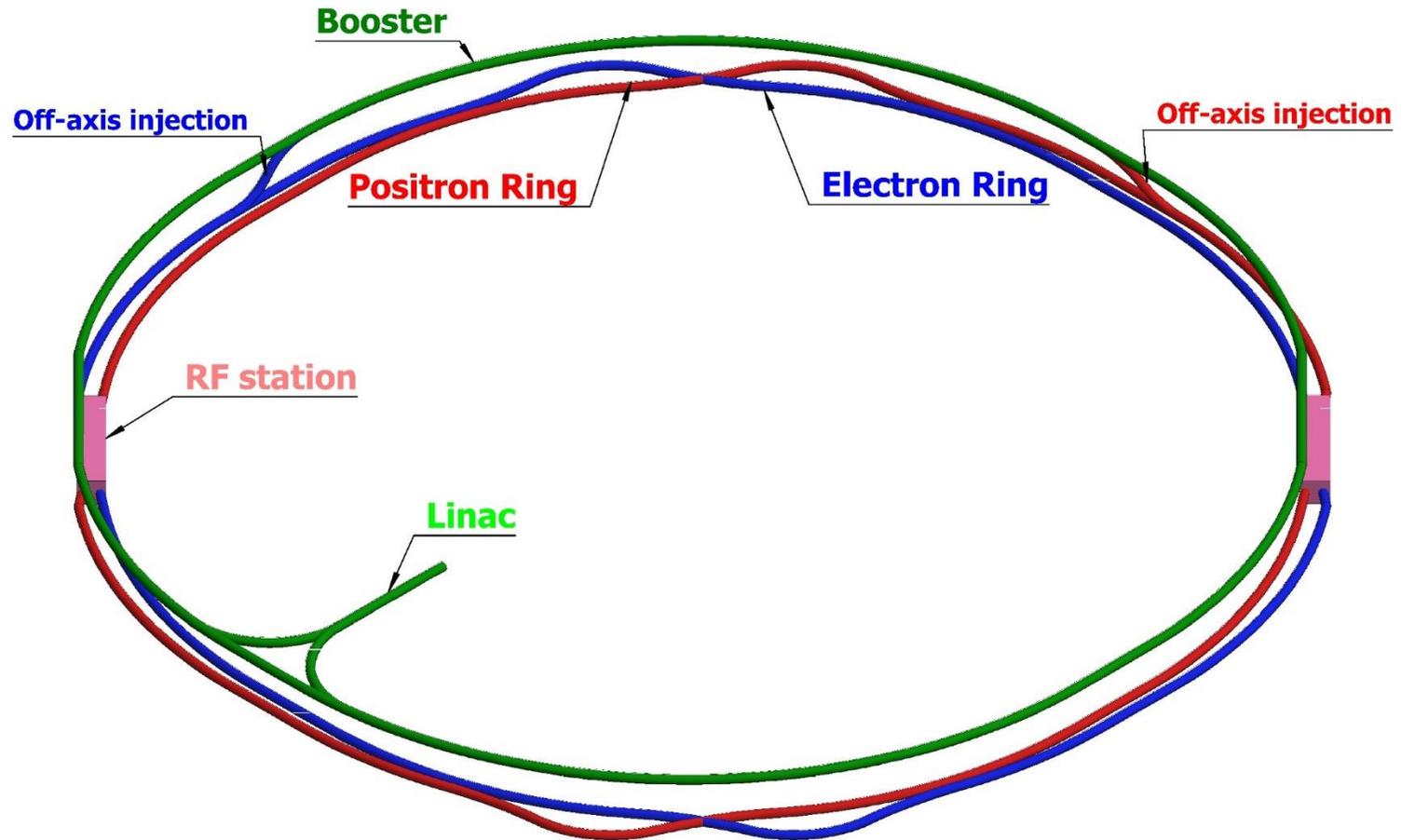
Accelerating structure

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

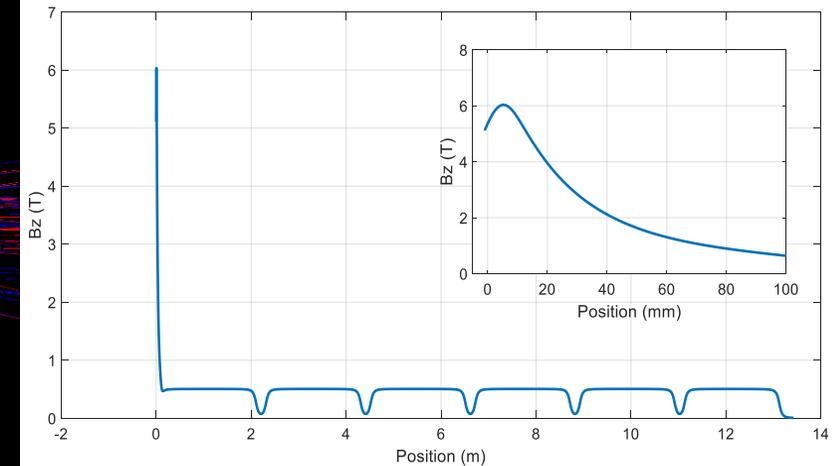
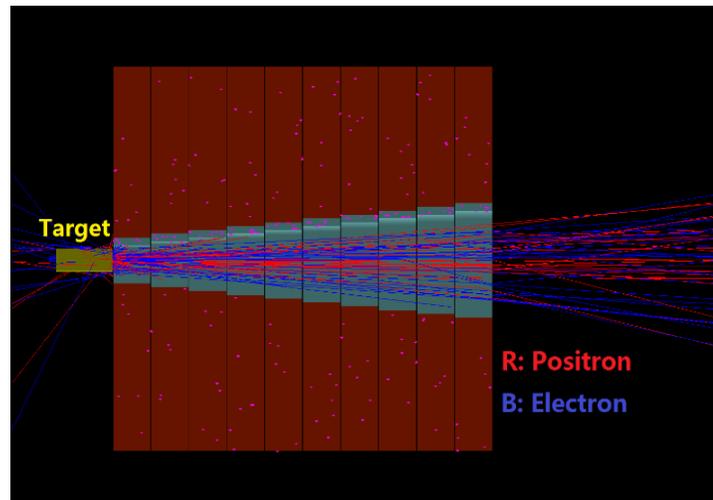
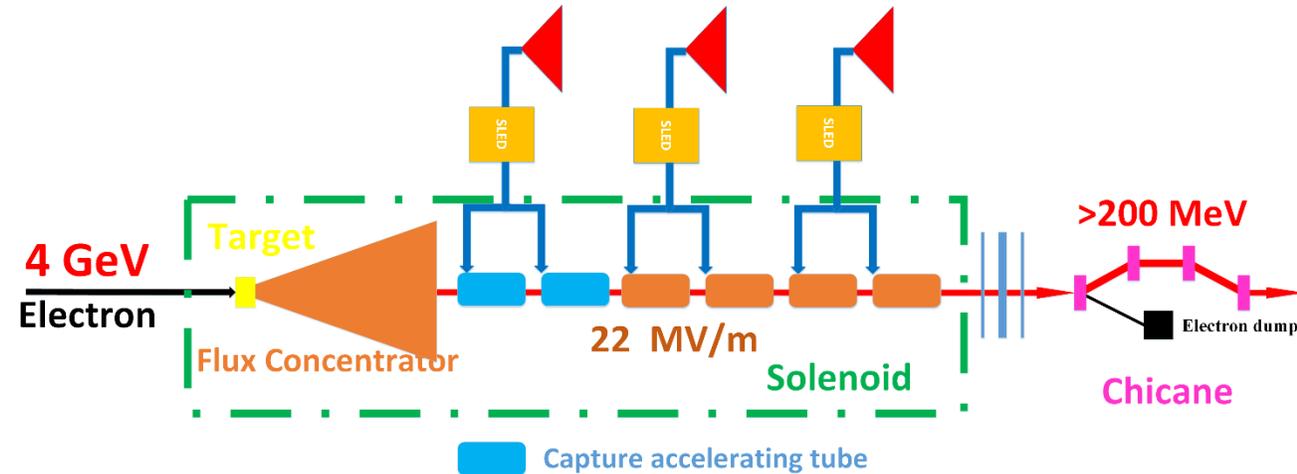


K. Yokoya and K. Bane, The longitudinal high-frequency impedance of a periodic accelerating structure, Proceedings of the 1999 PAC, New York, 1999.

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- 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



- SuperKEKB positron linac commissioning (3.3 GeV)

- 2014, $N(e+)/N(e-) \sim 20\%$
- 2015, $N(e+)/N(e-) \sim 30\%$ [designed 50%]

- CEPC positron source

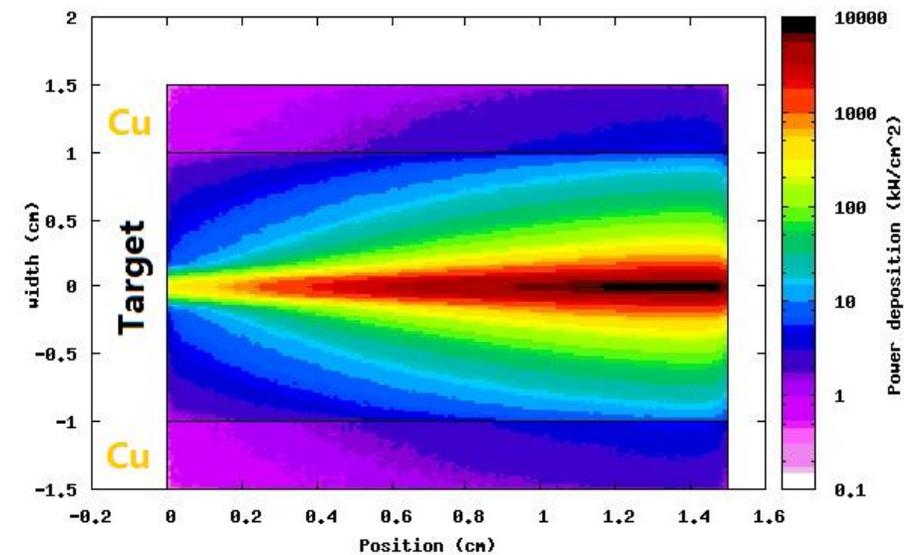
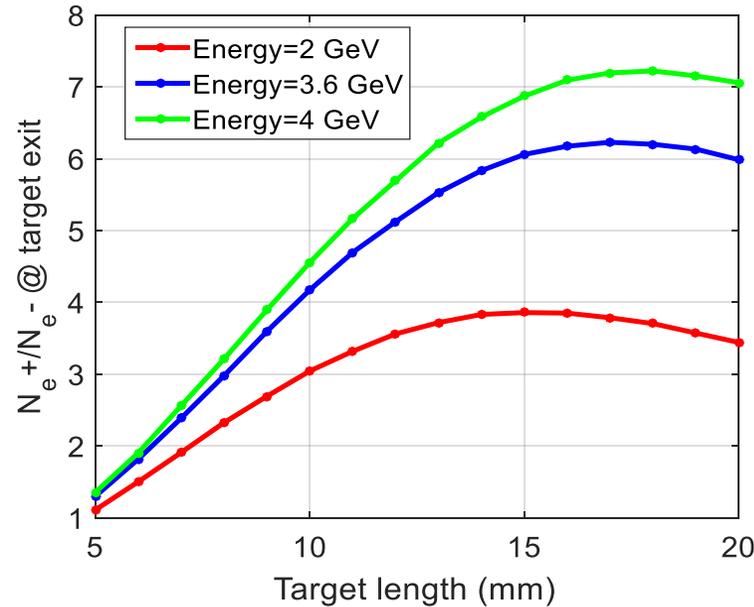
- Positron bunch charge > **3 nC**
- Electron beam:
 - 4 GeV
 - 10 nC/bunch (maybe lower)
- Electron beam: 4 kW

- Energy deposition

- 0.784 GeV/e- @ FLUKA
- 784 W \rightarrow water cooling

- Target

- tungsten
- 15 mm
- Beam size: 0.5 mm



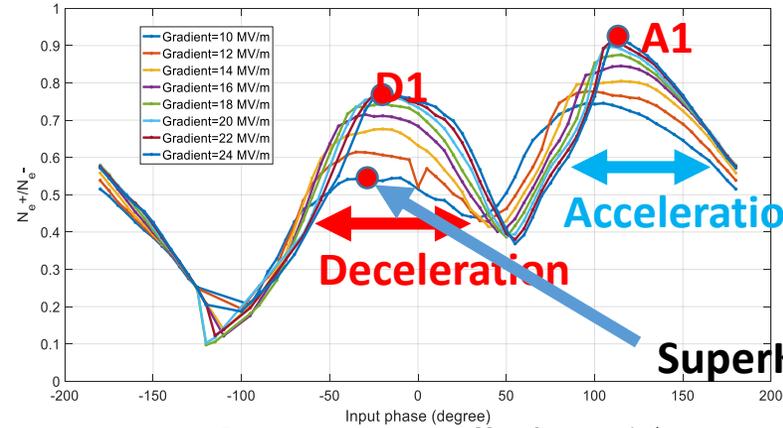
Positron source

Dynamic results of PSPAS

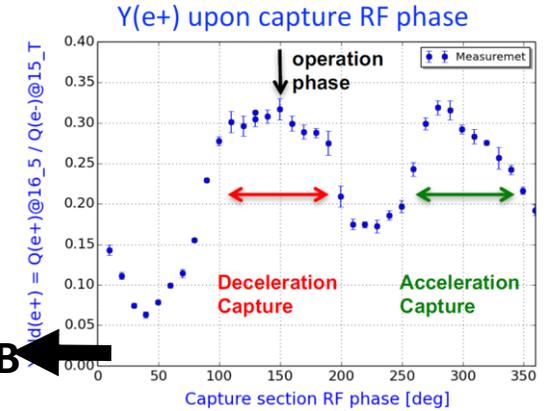


- Norm. RMS. Emittance
 - 2500 mm-mrad
- Energy: >200 MeV
- Positron yield

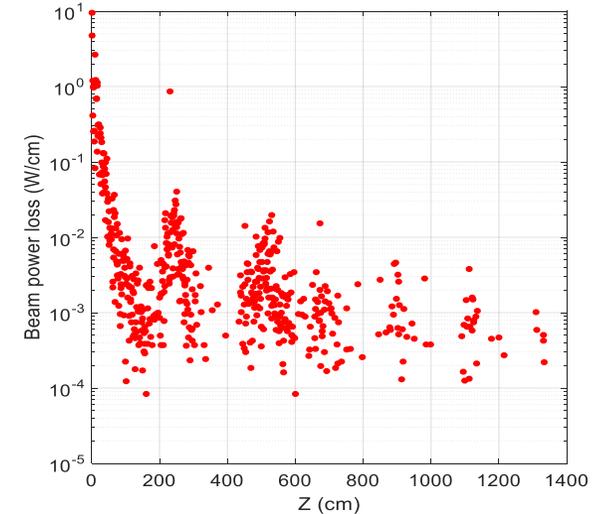
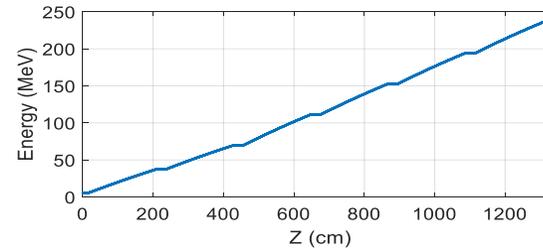
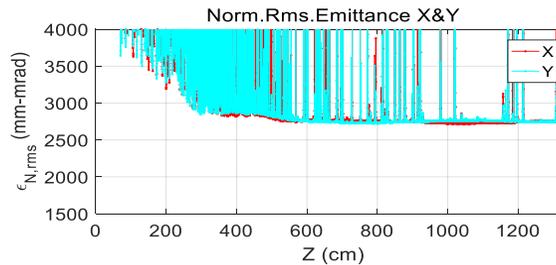
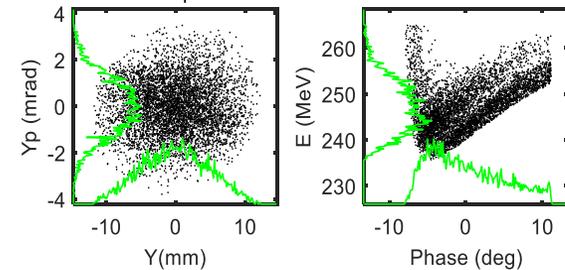
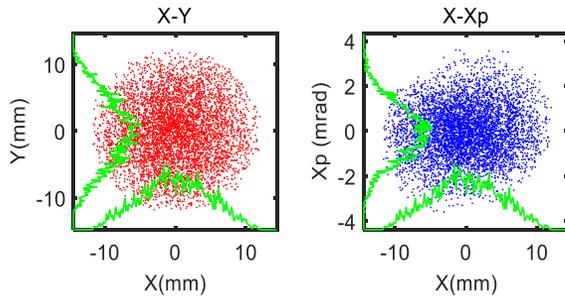
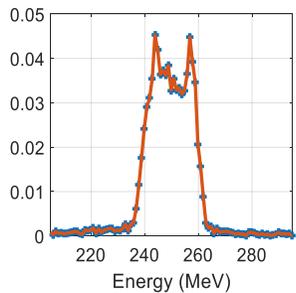
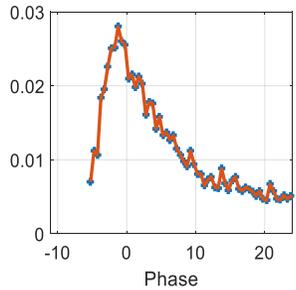
• $N_{e^+}/N_{e^-} > 0.55$ @ $[-6^\circ, 14^\circ, 235\text{MeV}, 265\text{MeV}]$



Only energy cutoff $\Delta E < 15$ MeV



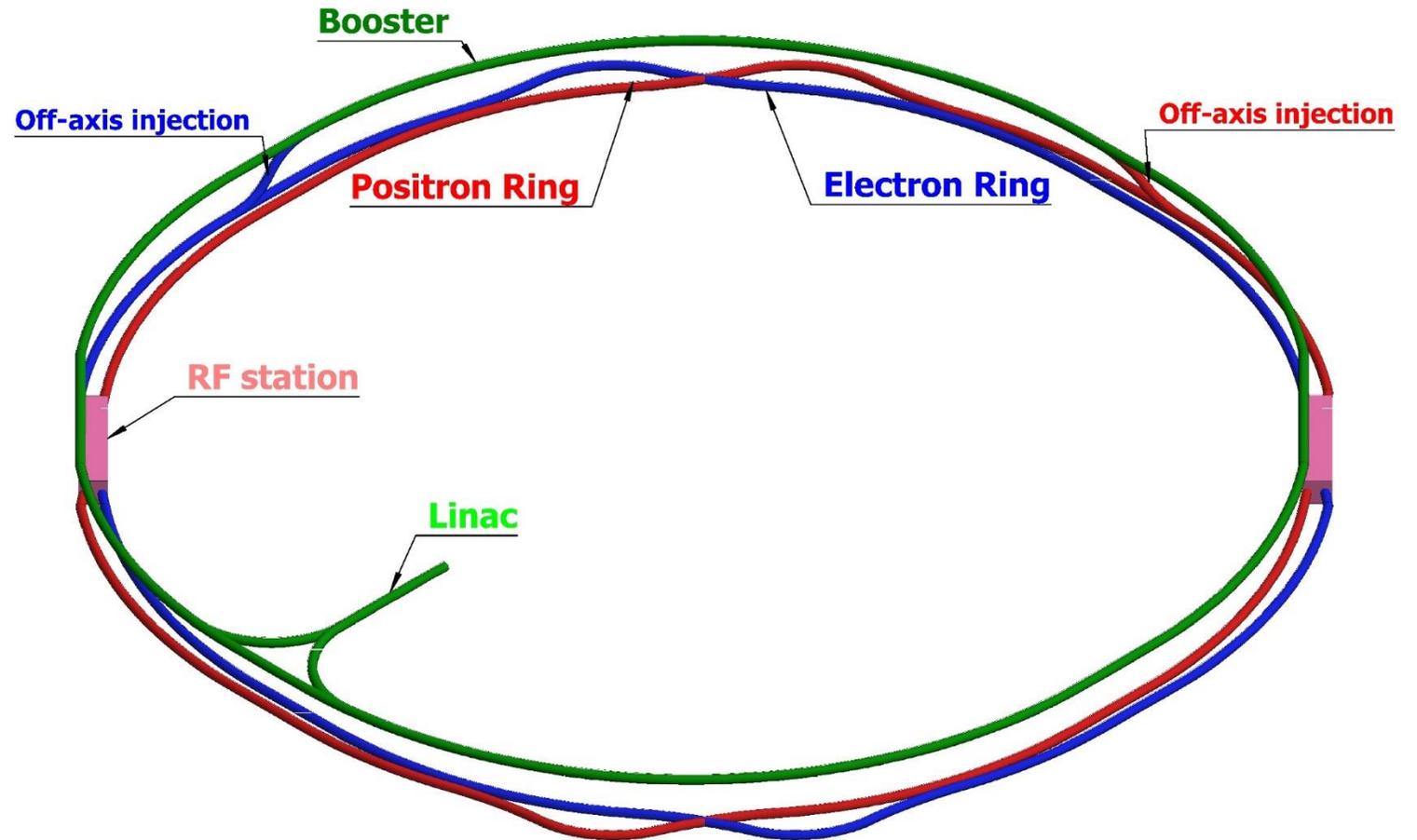
SuperKEKB commissioning results

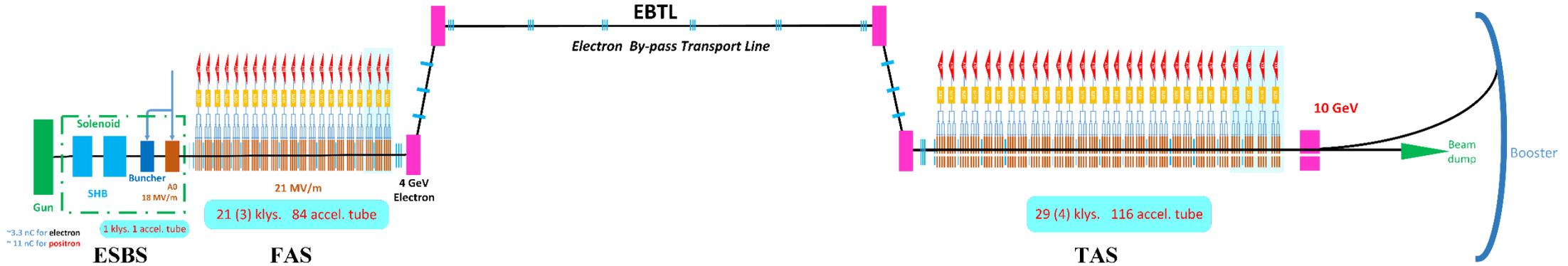


	SLC	LEP (LIL)	KEKB/SUPER KEBK	FCC-ee (conv.)	CEPC
Incident e- beam energy	33 GeV	200 MeV	3.3/3.3 GeV	4.46 GeV	4 GeV
e-/bunch [10^{10}]	3-5	0.5 - 30 (20 ns pulse)	6.25/6.25	5.53	6.25
Bunch/pulse	1	1	2/2	2	1
Rep. rate	120 Hz	100 Hz	50 Hz/50 Hz	200 Hz	100Hz
Incident Beam power	~20 kW	1 kW (max)	3.3 kW	15 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	$\lambda/4$ 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-

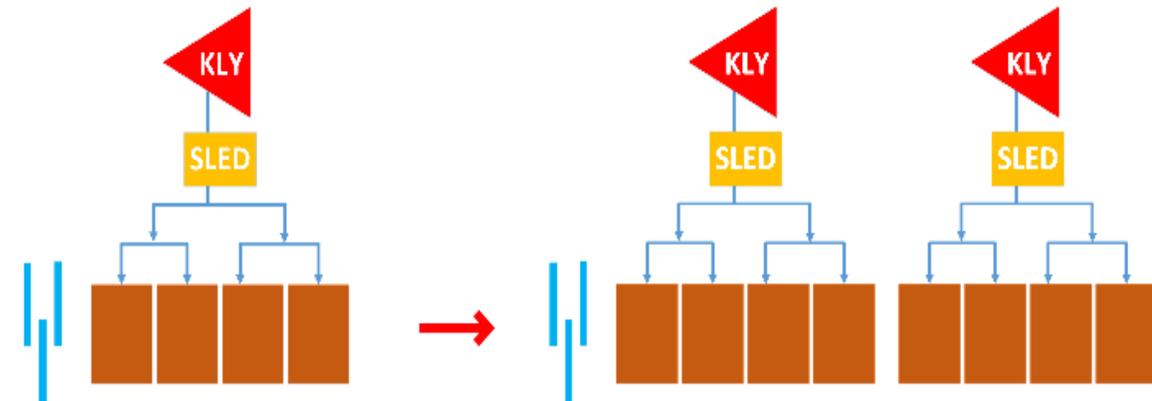
Tungsten radiation length X_0 is 0.35 cm.

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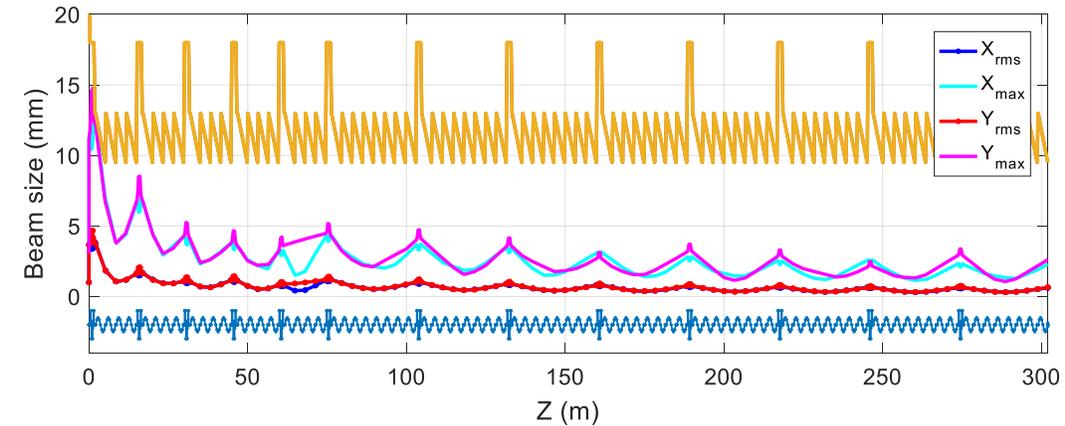
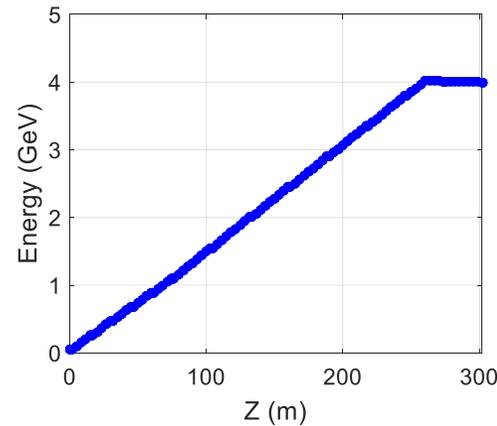
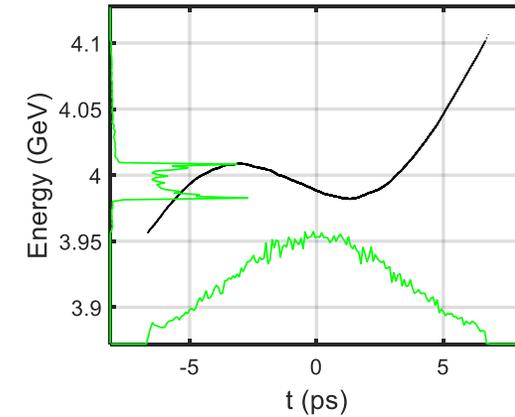
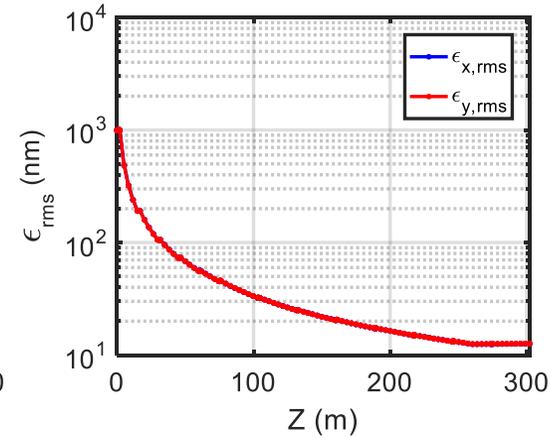
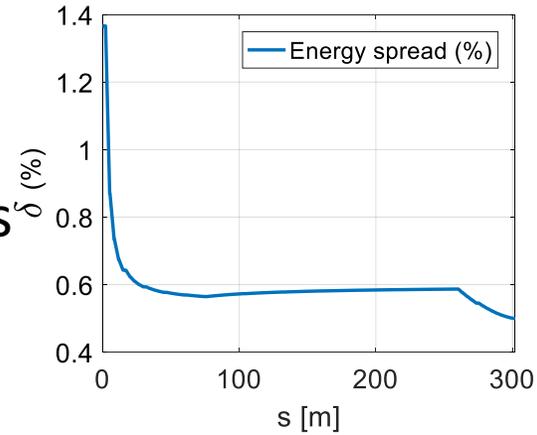
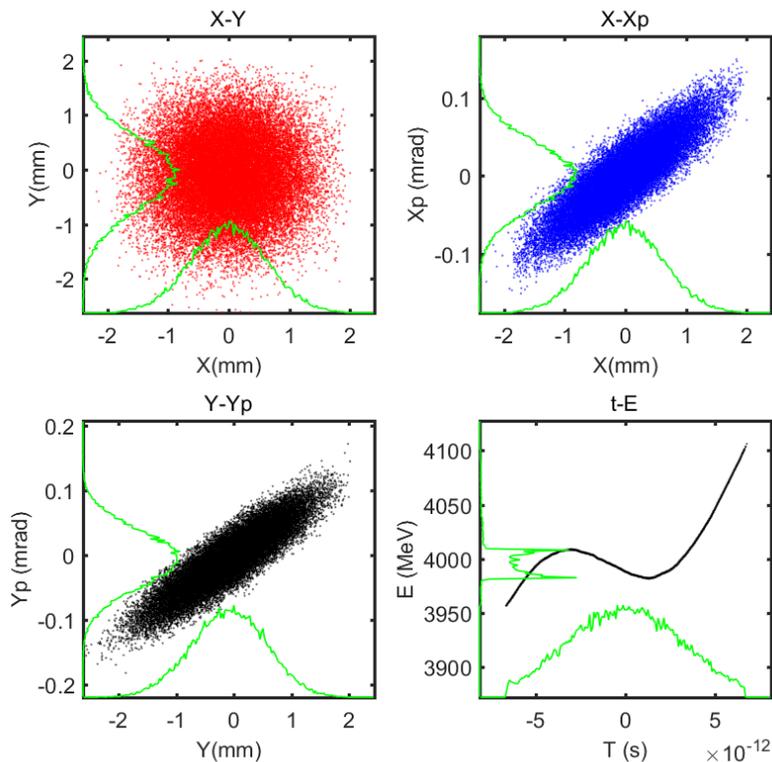


- Focusing structure: **Triplet**
 - Long drift length for accelerating tubes
 - Beam size in Acc. tubes is small and easy control
 - Same beam envelopes at X/Y planes
 - *1 triplet+4 Acc. tubes* → *1 triplet+8 Acc. tubes*
- Operation mode :
 - High charge mode (positron production)
 - 4GeV & 10 nC
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



- High charge mode

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

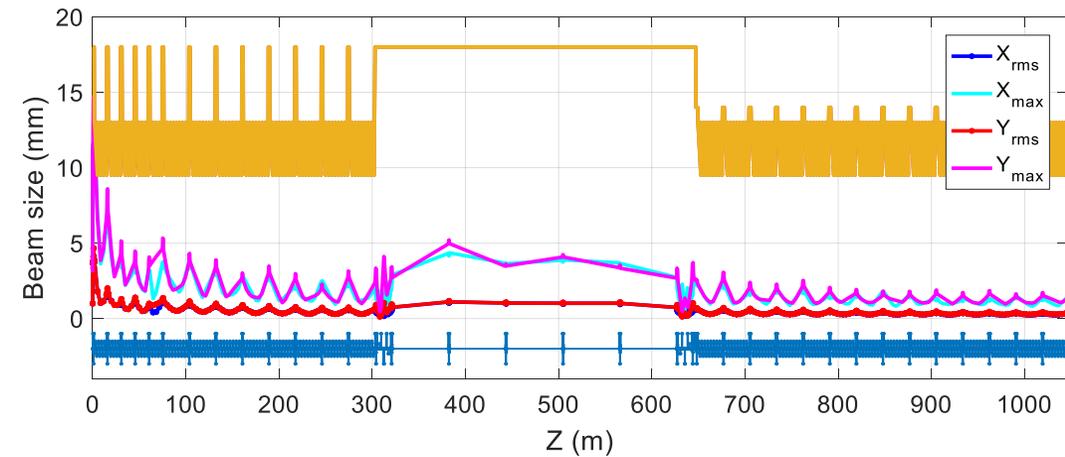
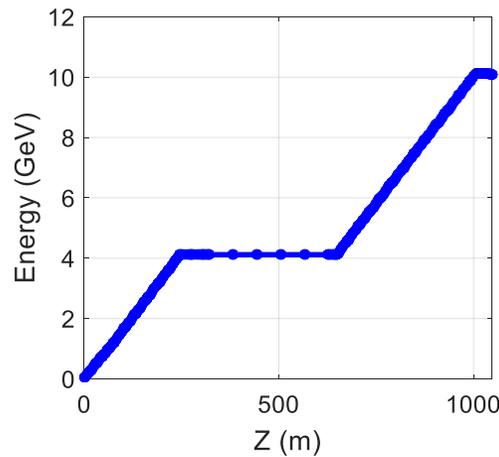
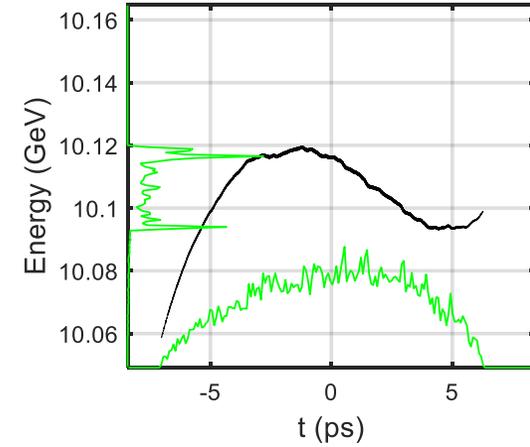
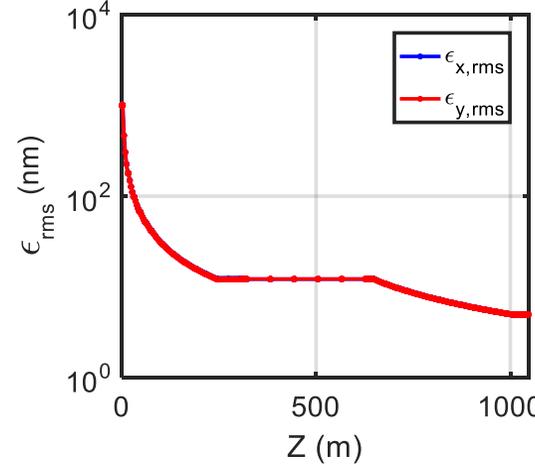
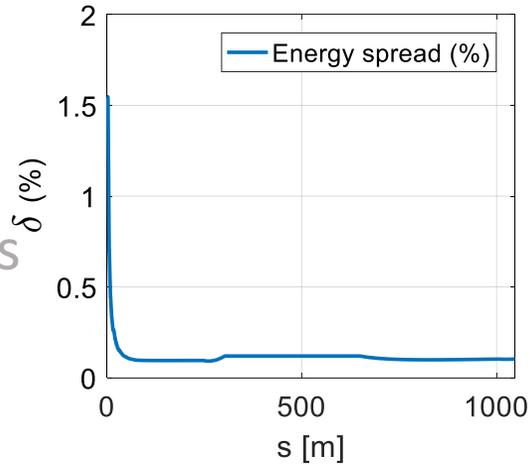


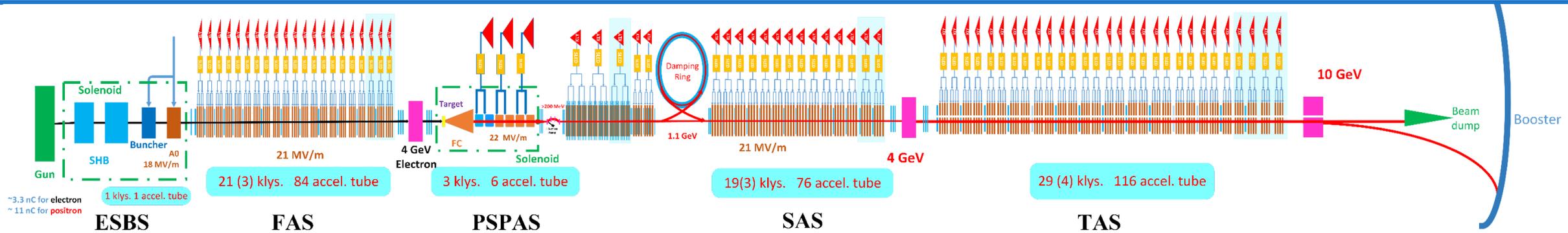
Linac design

Electron linac → *Electron injection*

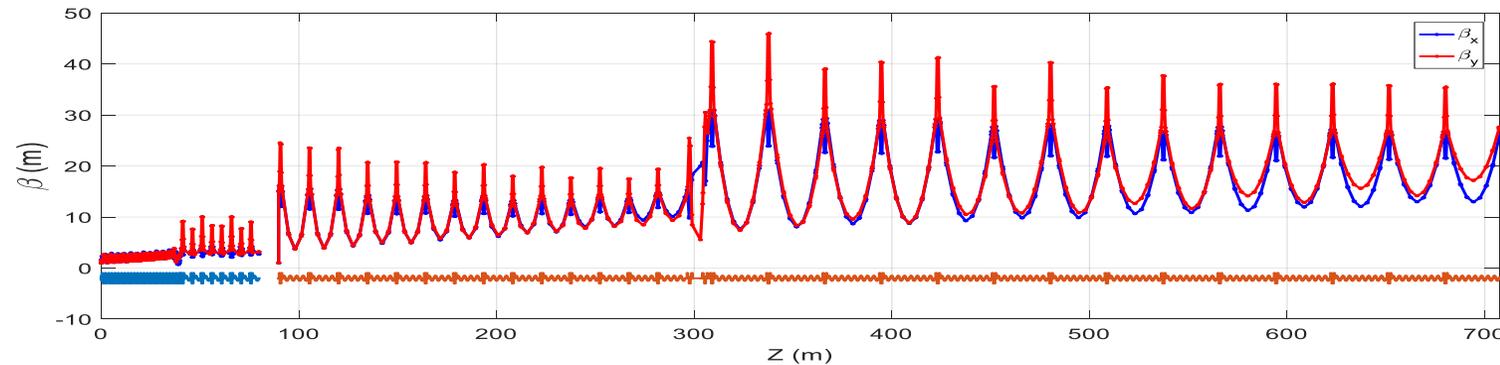
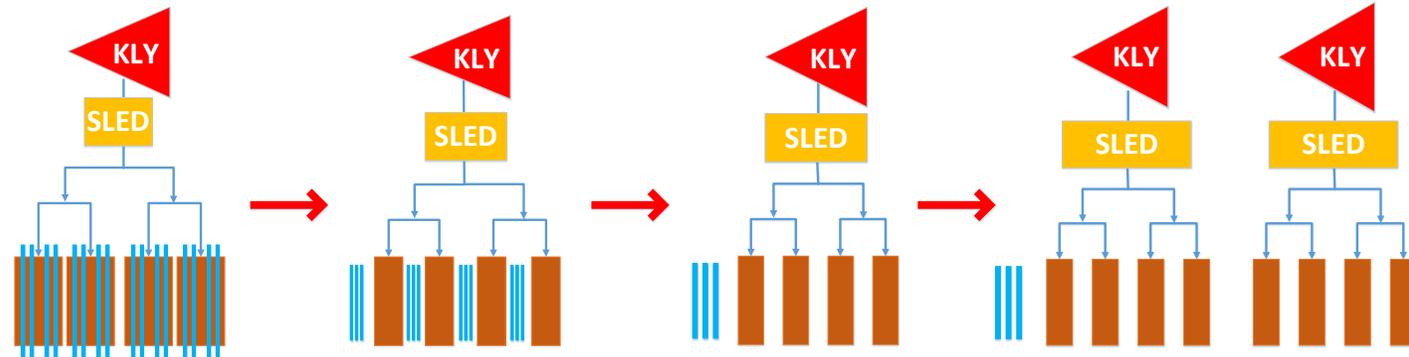


- High charge mode
 - 10 nC @ 4 GeV
 - Energy spread (rms): 0.5%
 - Emittance growth with errors
- Low charge mode
 - 3 nC @ 10 GeV
 - Energy spread (rms): 0.15%
 - Emittance (rms): 5 nm



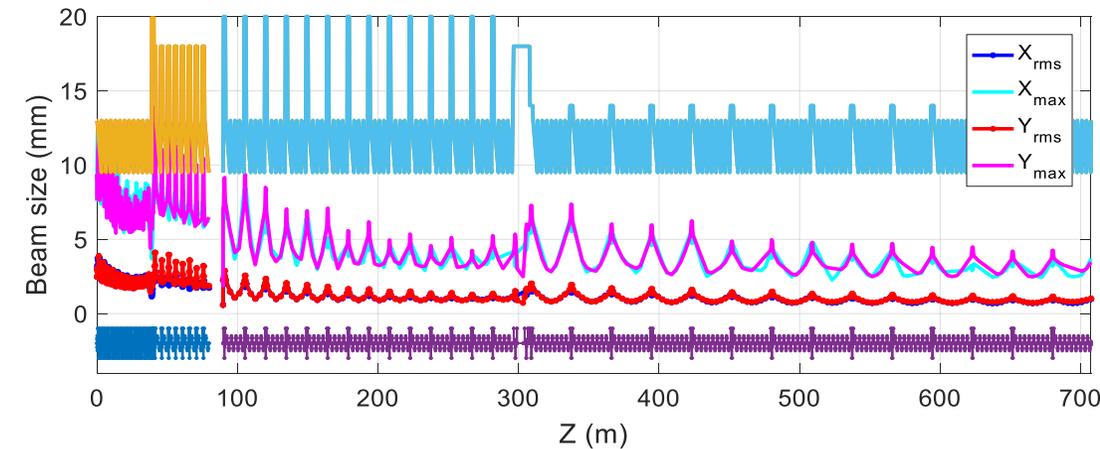
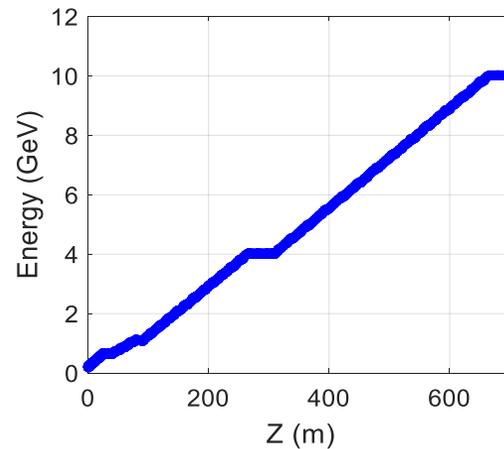
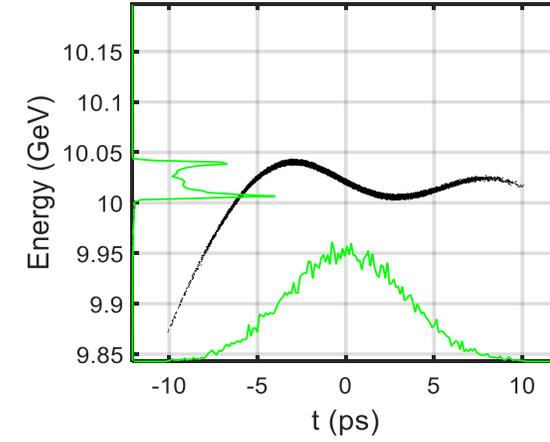
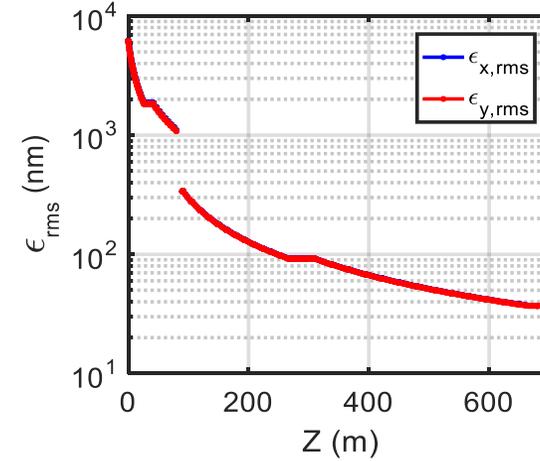
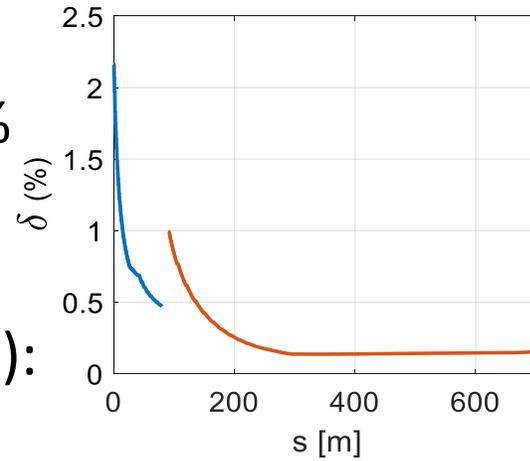


- PSPAS \rightarrow SAS (DR) + TAS
 - SAS: 200 MeV \rightarrow 4 GeV
 - Damping Ring @ 1.1 GeV
 - TAS: 4 GeV \rightarrow 10 GeV
- Transverse focusing structure
 - FODO, nesting on Acc. tubes
 - Triplet

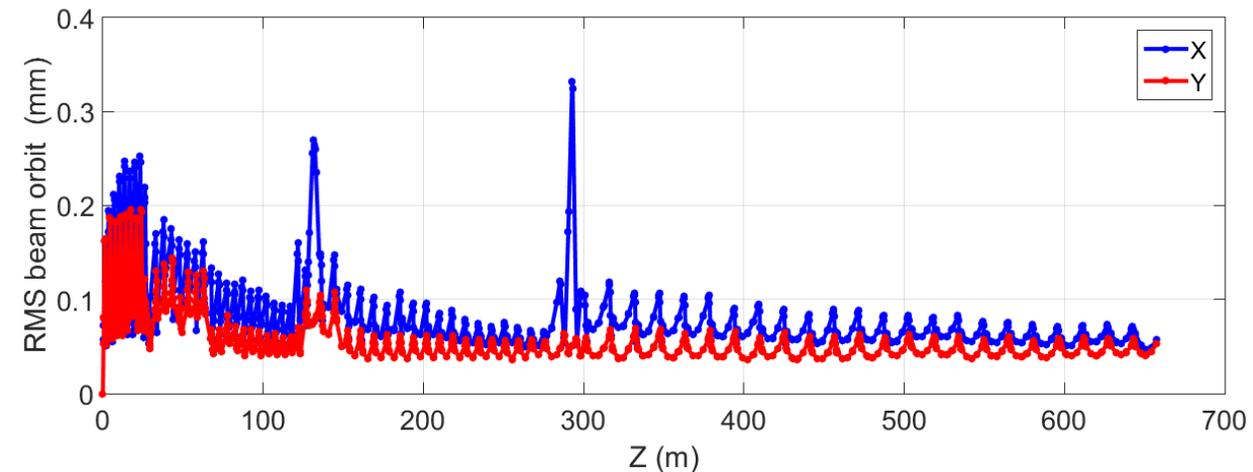
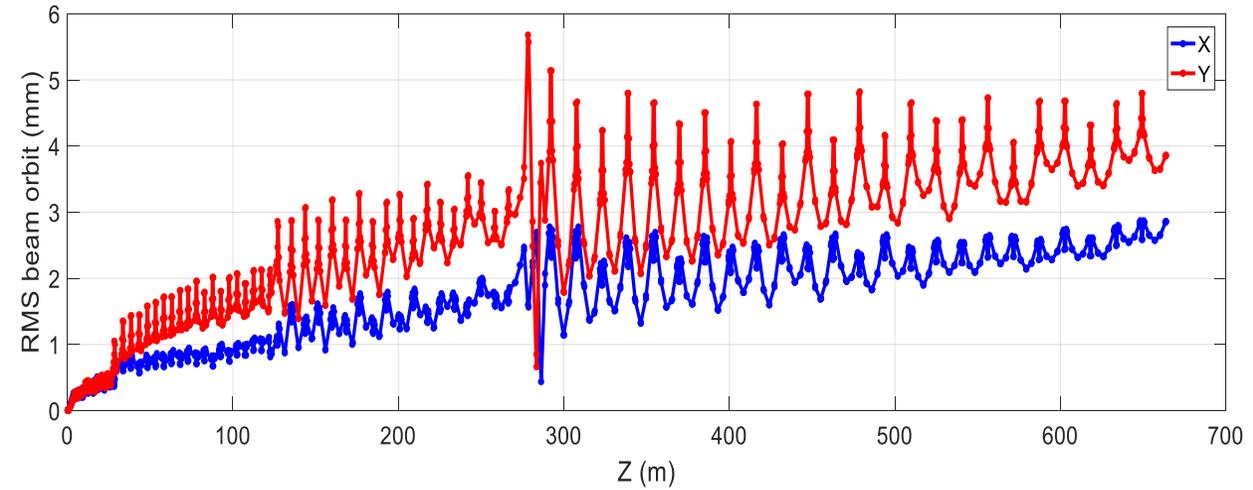


- Positron linac

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



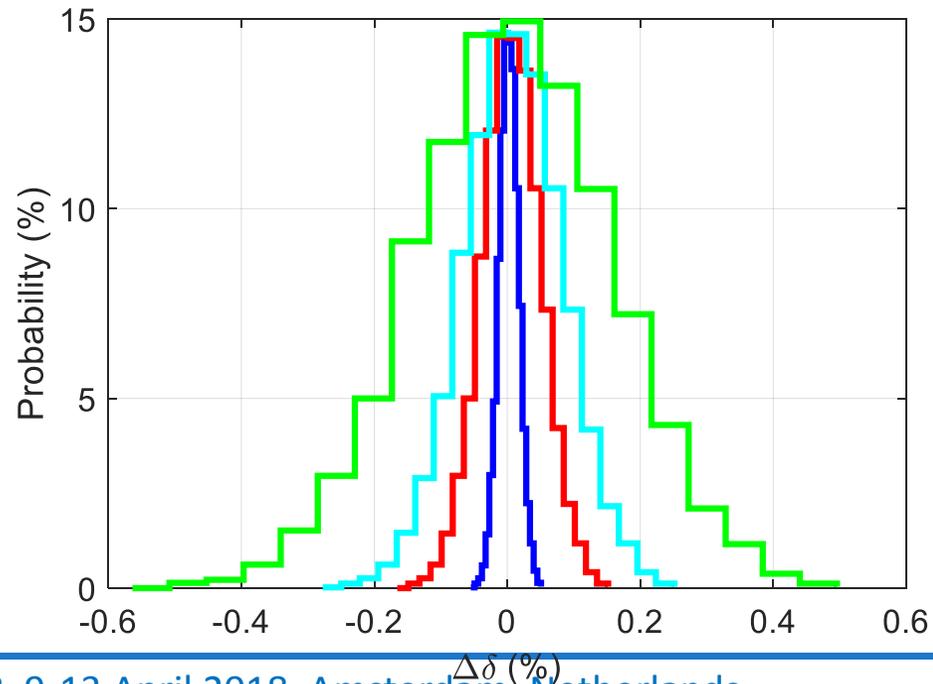
- Positron linac
 - One-to-one correction scheme
 - Errors: Gaussian distribution, 3σ truncated
- Beam orbit
 - RMS value < 0.3 mm
 - Rms value < 0.1 mm (high energy part)



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

- Simulation condition

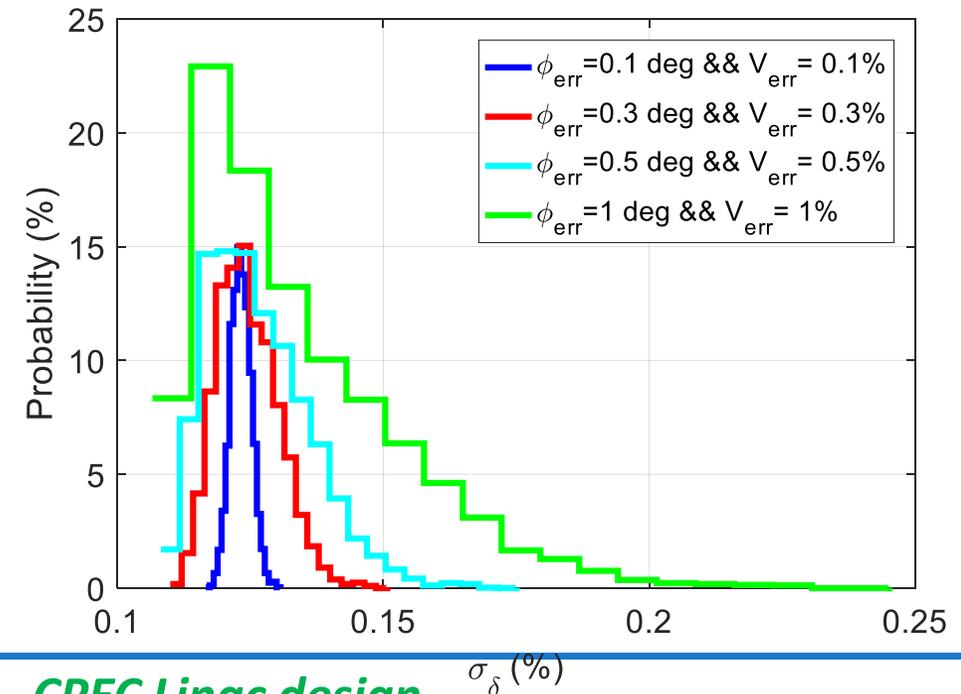
- 5000 seeds
- Accelerating tubes
 - phase errors and amp errors
 - 4 in 1 KLY, 4 accelerating tubes in one group
- 3σ -Gaussian



- Energy spread $< 0.2\%$

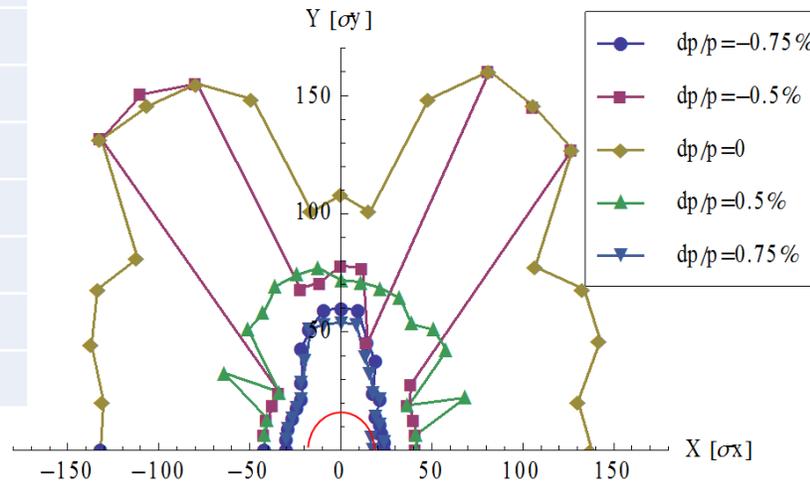
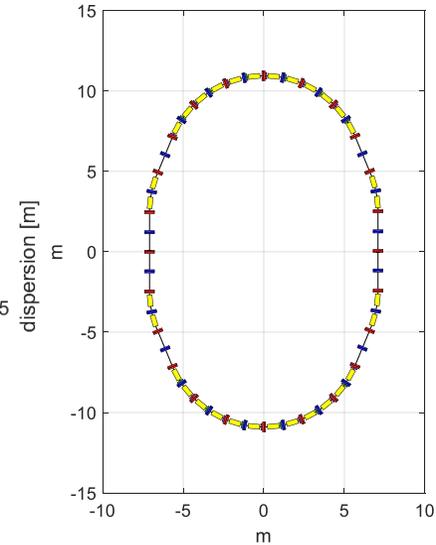
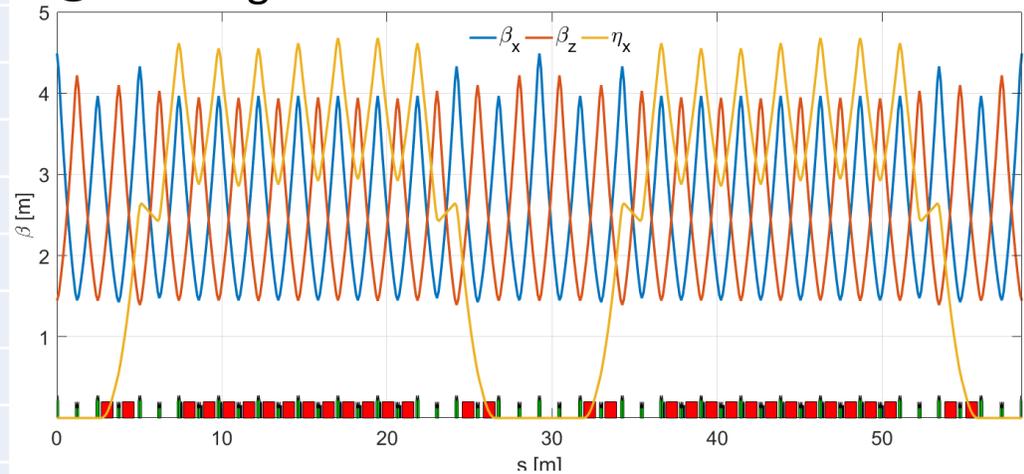
- Phase errors: 0.5 degree (rms)
- Grad. errors: 0.5% (rms)

- Energy jitter: 0.2%



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
$\epsilon_{ext\ x/y}$	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

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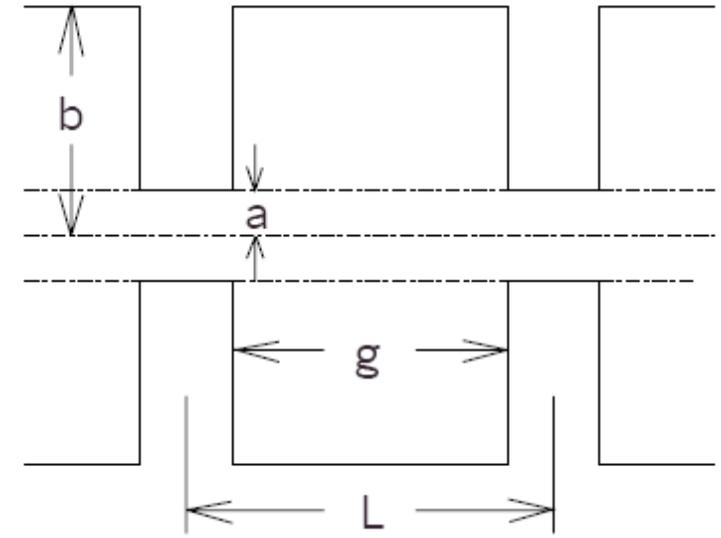
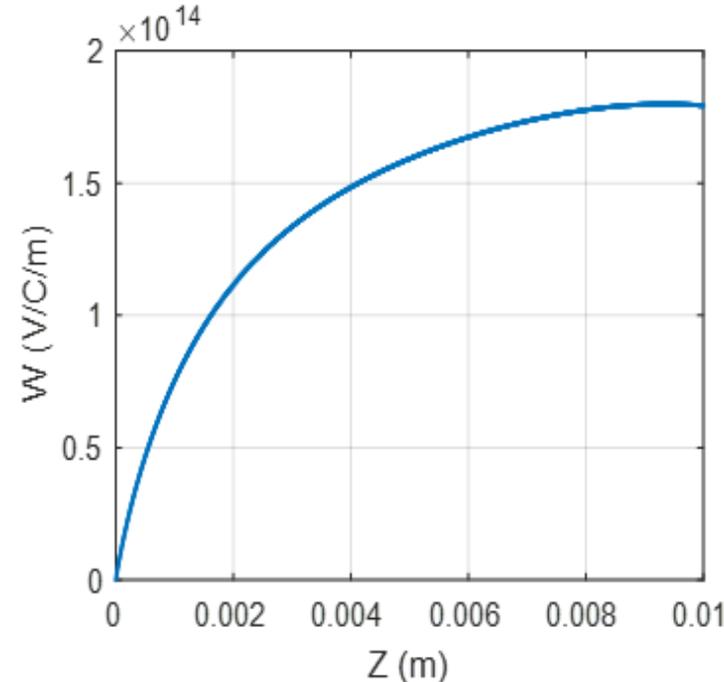
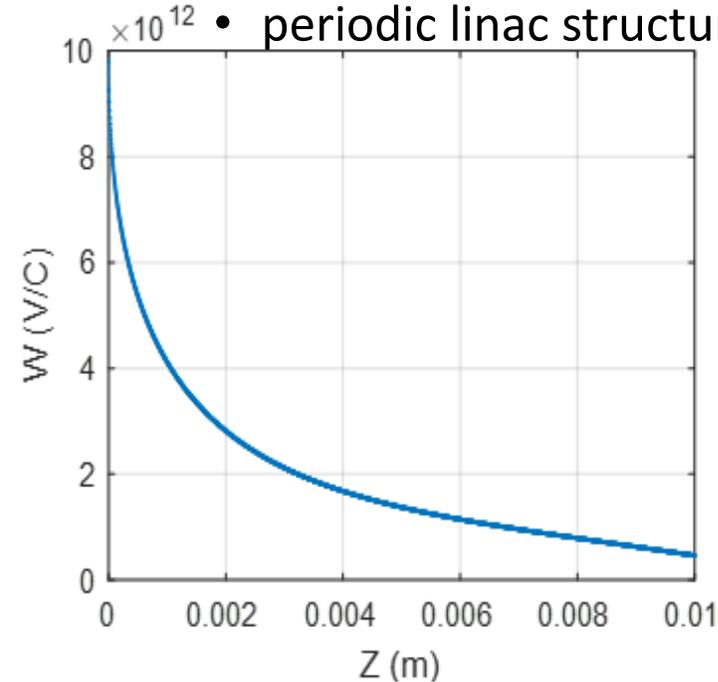


- Emittance not critical
- One bunch in DR(200ns)
 - 10 ms \rightarrow 20ms
 - Two bunch: yes
- **IBS**
 - Emittance growth
- **CSR (Coherent synchrotron radiation)**
 - CSR Instability

- 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.

- k. Yokoya and K. bane's Wakefield model

- periodic linac structure



The short-range wake is obtained by Inverse Fourier transforming:

$$W_L(s) = \frac{Z_0 c}{\pi} \exp\left(\frac{\pi s}{4s_{00}}\right) \operatorname{erfc}\left(\sqrt{\frac{\pi s}{4s_{00}}}\right)$$

with $s_{00} = \frac{g}{8} \left(\frac{a}{(1 - 0.465\sqrt{g/p} - 0.07g/p)p} \right)^2$ for $s > 0$ and $W_L(s) = 0$ for $s < 0$.

For short s (1) can be rewritten in the following simpler way:

$$W_L(s) \approx \frac{Z_0 c}{\pi a^2} \exp\left(-\sqrt{\frac{s}{s_{00}}}\right)$$

$$W_x(s) = \frac{4Z_0 c s_{00}}{\pi a^4} \left[1 - \left(1 + \sqrt{\frac{s}{s_{00}}} \right) \exp\left(-\sqrt{\frac{s}{s_{00}}}\right) \right]$$

$$S_{00} = 0.169 \frac{a^{1.79} g^{0.38}}{L^{1.17}}$$

$$W_L(s) = \frac{cZ_0}{\pi a^2} \left[1 + W_{L1}\sqrt{\zeta} + W_{L2}\zeta + W_{L3}\zeta\sqrt{\zeta} \right]$$

$$W_T(s) = \frac{cZ_0}{\pi a^4} s \left[2 + W_{T1}\sqrt{\zeta} + W_{T2}\zeta + W_{T3}\zeta\sqrt{\zeta} \right]$$

$$\begin{aligned} W_{L1} &= -1.614r^{0.122}, & W_{L2} &= +1.012r^{0.169}, & W_{L3} &= -0.231r^{0.111} \\ W_{T1} &= -2.781r^{0.217}, & W_{T2} &= +1.637r^{0.511}, & W_{T3} &= -0.364r^{0.793} \end{aligned}$$

$$\zeta = \frac{Ls}{a^2} \quad r = \frac{a/\lambda}{0.15}$$

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	

- 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

