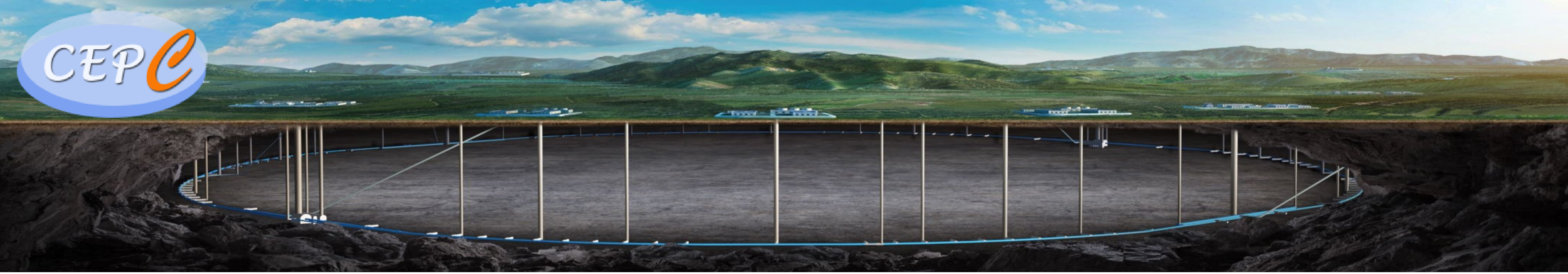

CEPC application potentials as an advanced photon source

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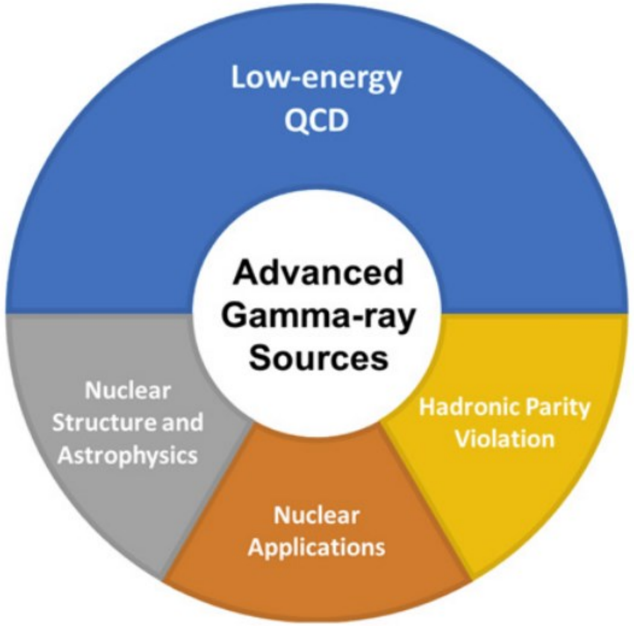
Content

- **CEPC serving as an ultra-high energy γ-ray synchrotron source**
  - Beam parameters
  - Radiation characters
  - Impact to the beam and mitigation measures
  - Conceptual design for the γ-ray extraction system
- **CEPC potential as an ultra high energy FEL facility**
  - Tentative schematic plan and beam parameters
  - Start-to-end simulation for the electron beams
  - FEL parameters optimization and selection
  - FEL simulations and indicators

CEPC as a gamma-ray SR facility

Gamma-ray SR facility: Laser Compton γ-ray sources



- medium-energy source with γ-ray beams in the range of 60 and 350 MeV
- Low-energy source, below 20 MeV

Project name/parameters	HIGS	LEPS/LEPS2	NewSUBARU	UVSOR-III	SLEGS	XGLS	ELI-NP
Location	Durham, US	Hyogo, Japan	Hyogo, Japan	Okazaki, Japan	Shanghai, China	Xi'an, China	Bucharest–Magurele, Romania
Accelerator technology	Storage ring	Storage ring	Storage ring	Storage ring	Storage ring	Linac	Storage ring
Laser technology	FEL	Solid state laser	Solid state/gas laser	Fiber/gas laser	CO_2 laser	Ti:sapphire laser	Solid state laser
Collision technology	Intra-cavity, head-on	External laser, head-on	External laser, head-on	External laser, head-on	External laser, cross-angle/head-on	External laser, head-on	Intra-cavity, head-on
Electron energy (MeV)	240–1200	8000	500–1500	750	3500	120–360	234–742
Laser wavelength (nm)	1060–190	266 and 355	532–10 600	1940 and 10 600	10 640	800	1030/515
Charge and temporal structure							
A. CW: Avg. current (mA), Q (nC)@reprate (MHz)	10–120, 1.8–22@5.58	100, 0.2–2@50–500	300, 0.6@500	300, 3@90	100–300, 0.28–0.87@347		1@71.4
B. Pulsed: f_{RF} (MHz), pulse: Q (nC)@reprate (Hz), pulse duration (full-width)						2856 (s-band), 0.5@10, 10 ps (micropulses)	
γ-beam energy (MeV)	1–100	1300–2900	1–40	1–5.4	0.4–20	0.2–3	1–19.5
Polarization	Lin, Cir	Lin, Cir	Lin, Cir	Lin, Cir	Lin, Cir	Lin, Cir	Lin
γ-beam energy resolution (FWHM)	0.8%–10% collimation	$< 15\%$ tagging	10% ($\phi = 3$ mm) collimation	2.9% ($\phi = 2$ mm) collimation	$< 5\%$ ($\phi = 2$ mm) collimation	1.2%–10% collimation	$< 0.5\%$ collimation
γ-beam temporal structure							
A. CW operation (MHz)	5.58 (typical)	50–500	500	90	347		71.4
B. Pulsed operation	0.5–1.5 ms (FW), 2–100 Hz, gain modulated		8 ns pulse, 10–100 kHz, Q-switched lasers			pulsed, 10 Hz	
On-target flux (avg, γ/s)	10^3–3×10^9	10^6–10^7	10^5–3×10^6 ($\phi = 3$ mm)	4×10^5 ($\phi = 2$ mm)	10^5–10^7 ($\phi = 2$ mm)	10^6–10^8	$\sim 10^8$
Total flux (avg, γ/s)	10^6–3×10^{10}	10^6–10^7	10^7–4×10^7	10^7	10^6–10^8	10^8–10^9	10^{11}
Operation status or projected operation date	Since 1996	Since 1999	Since 2005	Since 2015	Under construction, Operation in 2022	Under construction, Operation in 2023	Under construction, Operation in 2023
Reference	[268, 278]	[279]	[253]	[249]	[280, 281]	[282]	

Beam parameters

Beam parameters of CEPC

CEPC parameter	
Beam Energy (GeV)	120
Circumference (km)	100
Emittance (pm rad)	640/1.3 ($\varepsilon_x/\varepsilon_y$)
Beam Current (mA)	16.7

Beam parameters of HEPS @ Beijing

Main parameters	Unit	Value
Beam energy	GeV	
Circumference		.4
Emitta		< 60
	mA	200

Making CEPC a photon source for intensive ultra-high energy gamma-rays

Synchrotron ... ency
proportional ... and magnet field

$$\omega_c = \frac{3\gamma^3 c}{2\rho} \xrightarrow{\rho=\frac{m_e c\gamma}{eB}} \omega_c = \frac{3\gamma^2 eB}{2m_e}$$

- In a conventional SR facility, the beam energy stays lower than **10 GeV** level, resulting in a maximum photon energy in the level of **100 keV**.
- Due to the high beam energy, which is approximately **120 GeV**, the CEPC SR energy can reach the level of **100 MeV**

Radiation Spectrum

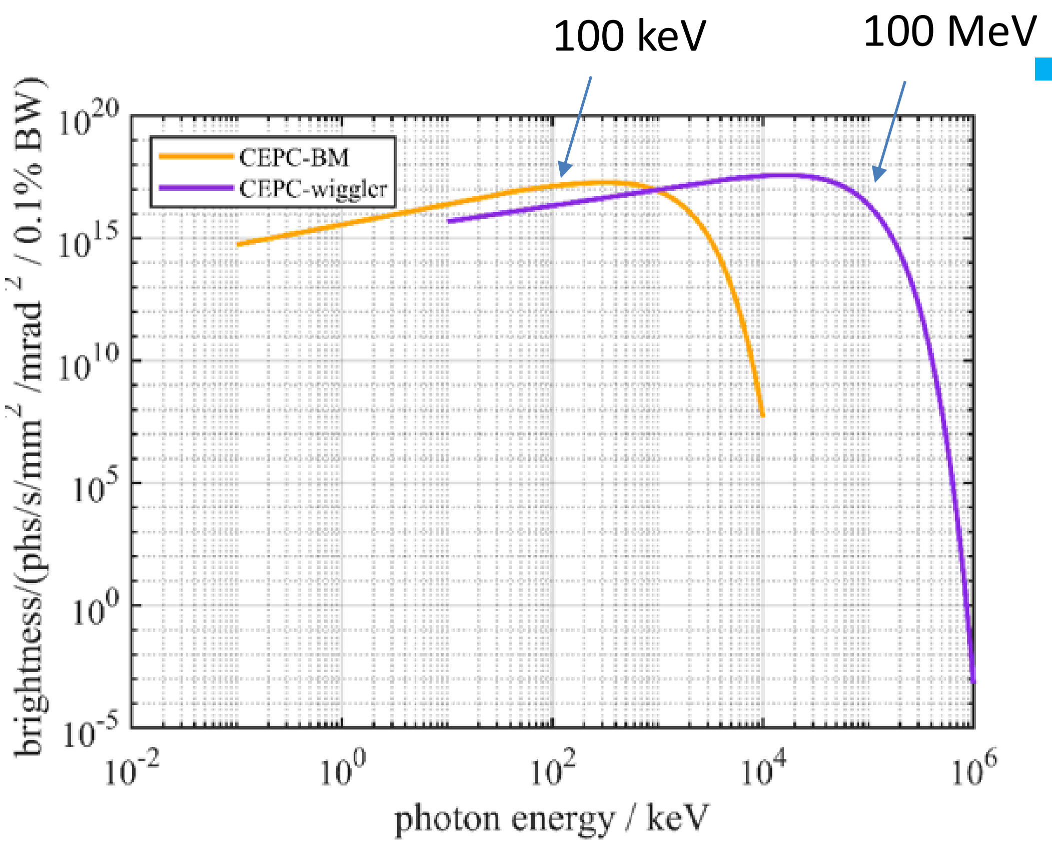
SR sources:

Wiggler parameter	
B (T)	2
Total length (m)	0.32
Magnetic period Length (m)	0.32
Period number	1
K value	59.7
Critical energy (MeV)	19.2
Bending magnet	
B (T)	0.04
Length (m)	20
Critical energy (keV)	383

Angular Density of Spectral Flux: [Ph/s/mr/0.1%bandwidth]

$$\frac{d\mathcal{F}}{d\varphi} = 2.46 \times 10^{13} E_e [GeV] I[A] G_1(\omega/\omega_c)$$

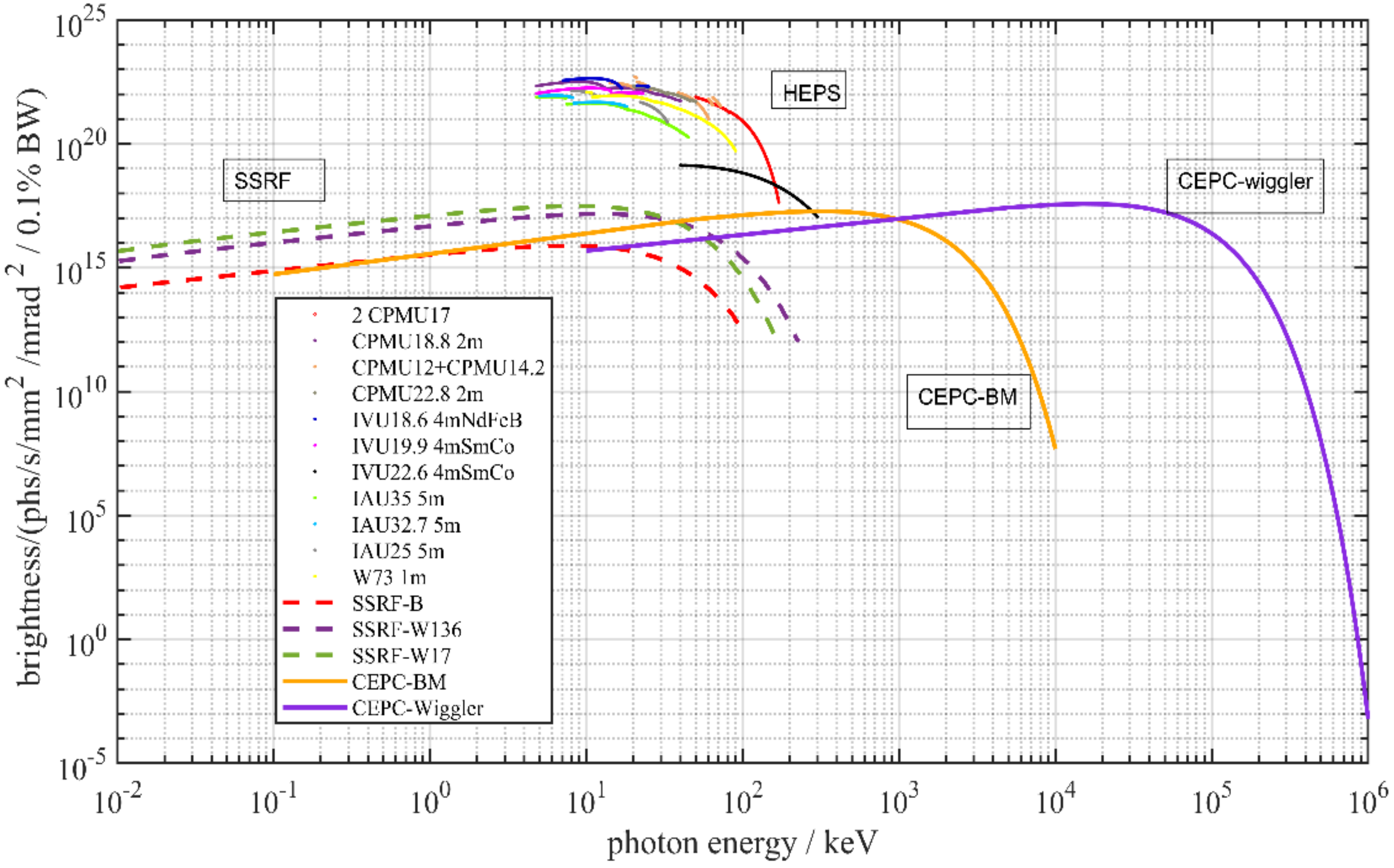
$$G_1(y) = y \int_y^{\infty} K_{5/3}(y')\, dy' \quad G_1(y) \approx \begin{cases} (\omega/\omega_c)^{1/3}, \omega \ll \omega_c \\ \exp\left(-\frac{\omega}{\omega_c}\right), \omega \gg \omega_c \end{cases}$$



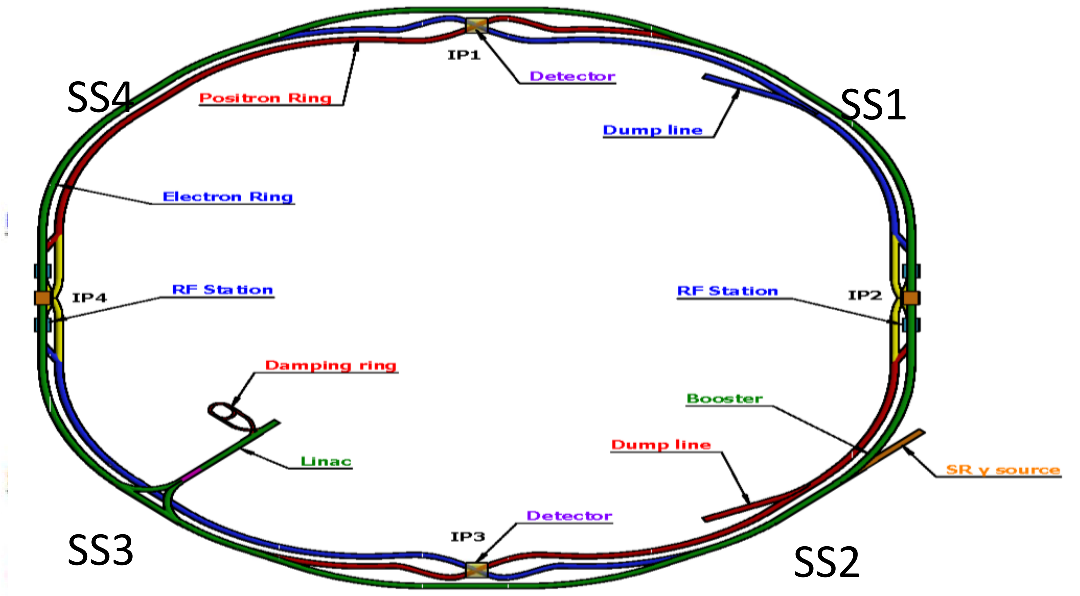
- Bending magnets generate intensive x-ray photon with energy around 100 keV
- Wiggler with 2T generates gamma-ray in the level of 100 MeV

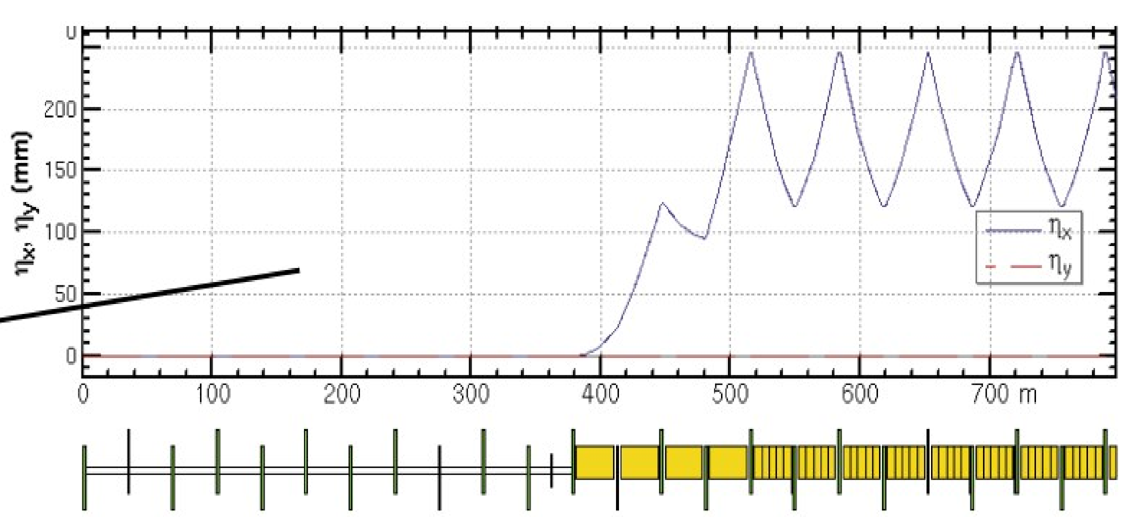
Comparison with other x-ray source

- Compare to the SSRF, HEPS in China, CEPC provides much wider energy range, higher intensity, and maximum photon energy



Beam line arrangement and impact to collider



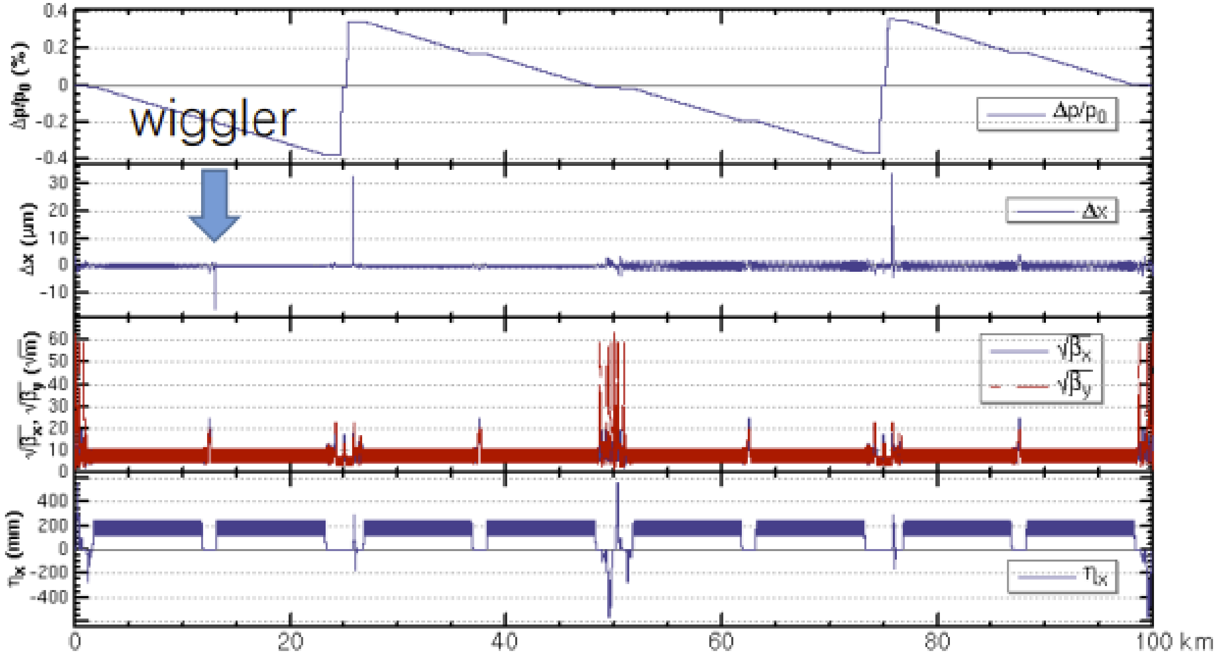


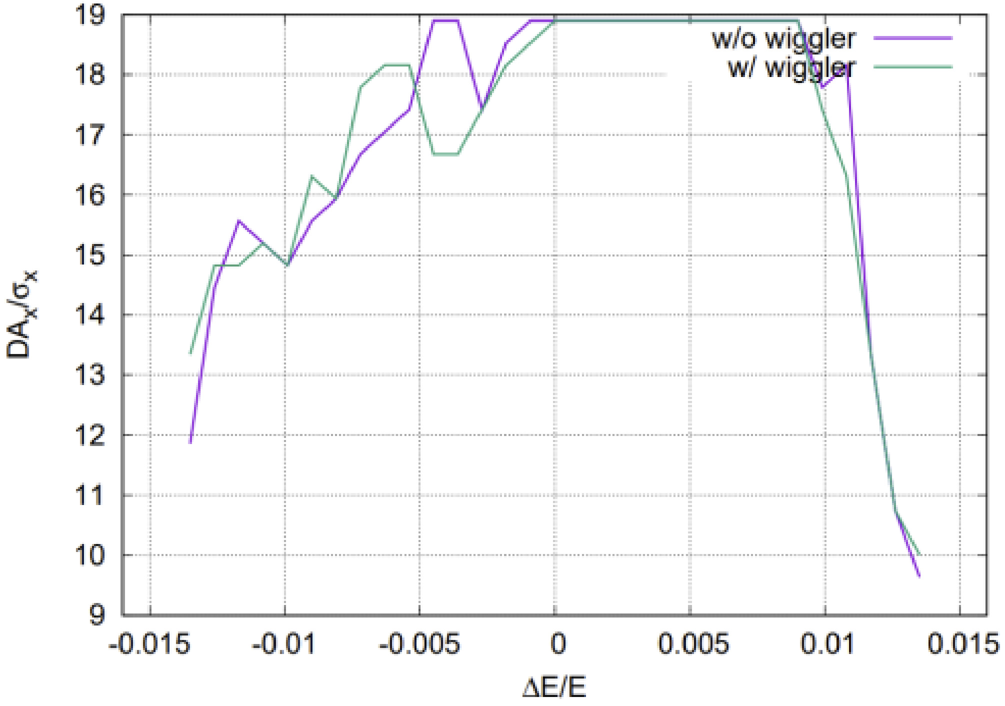
- Since the bending magnets are original ones used in CEPC, they introduce no additional impacts.
- The short wiggler is installed in the lattice at the down stream of the on-axis injection region. Switching on the wiggler increases additional 1.3% beam energy loss, which is acceptable according to specific simulations.

B [T]	Np	Length [m]	ΔU0/U0
2	1	0.32	1.3%

Mitigation measures to the SR effect

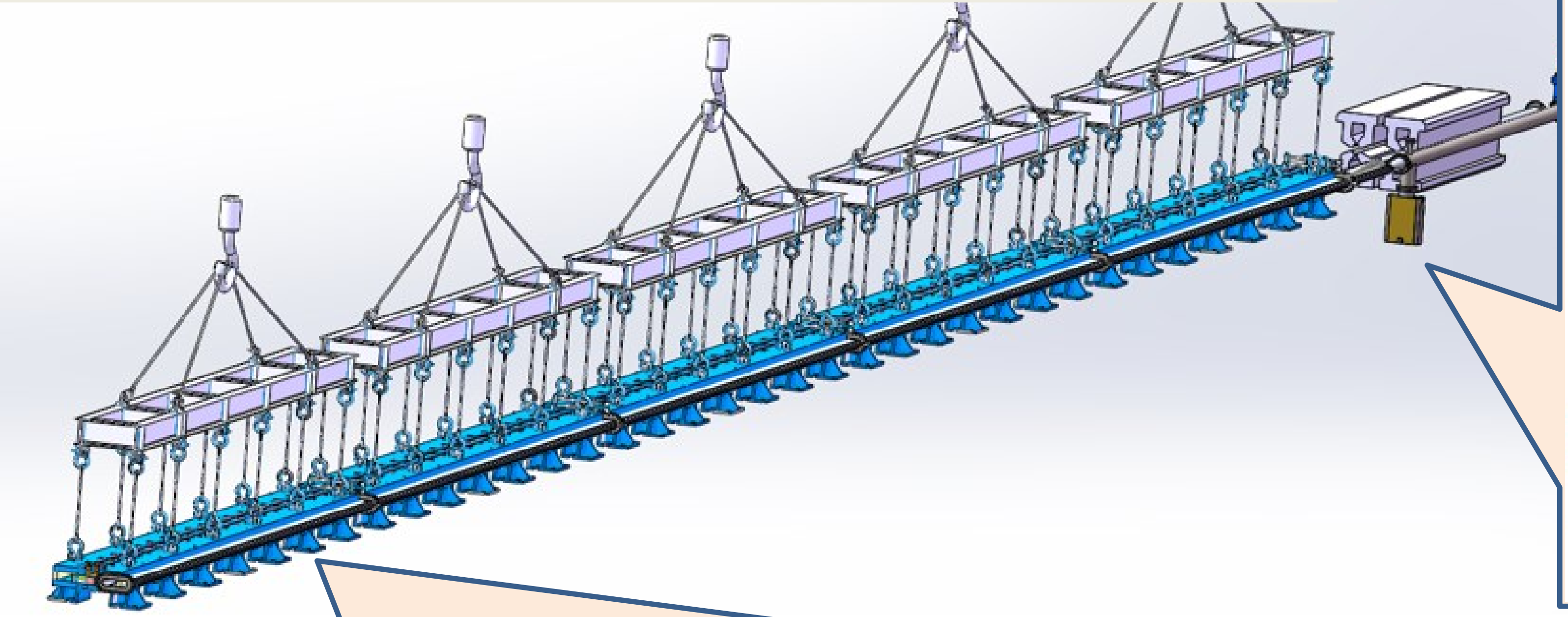
- The conventional measures to mitigate the beam energy loss due to SR is to **taper** the bending magnet field.
  - The closed orbit distortion is expected to be 15μm at wiggler by applying bending magnet tapering.
  - The dynamic aperture w/ and w/o wiggler are almost the same.

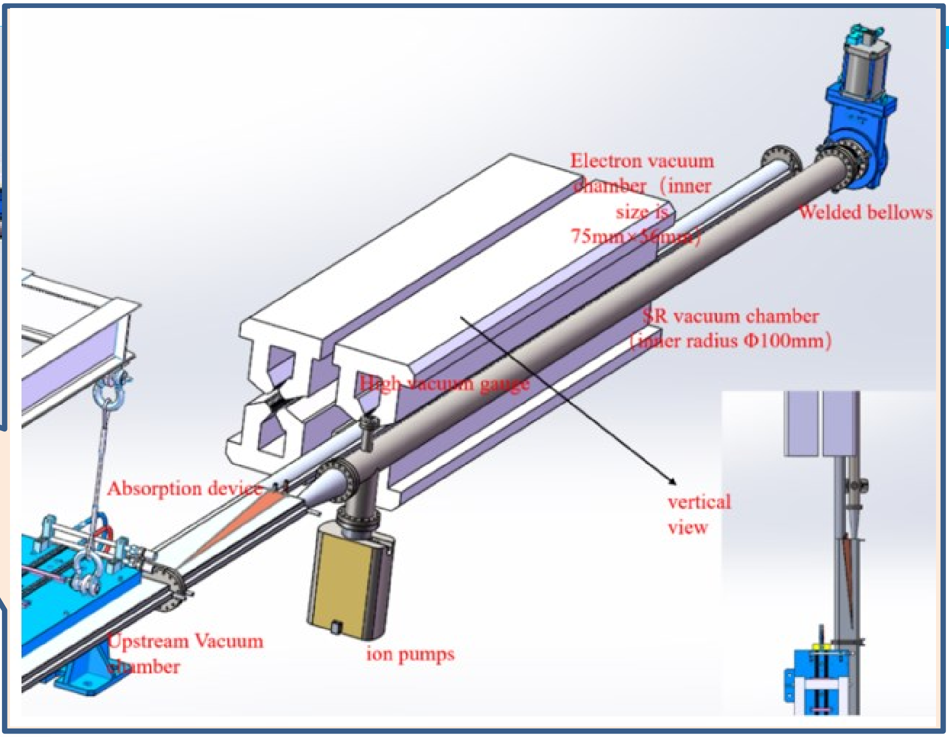


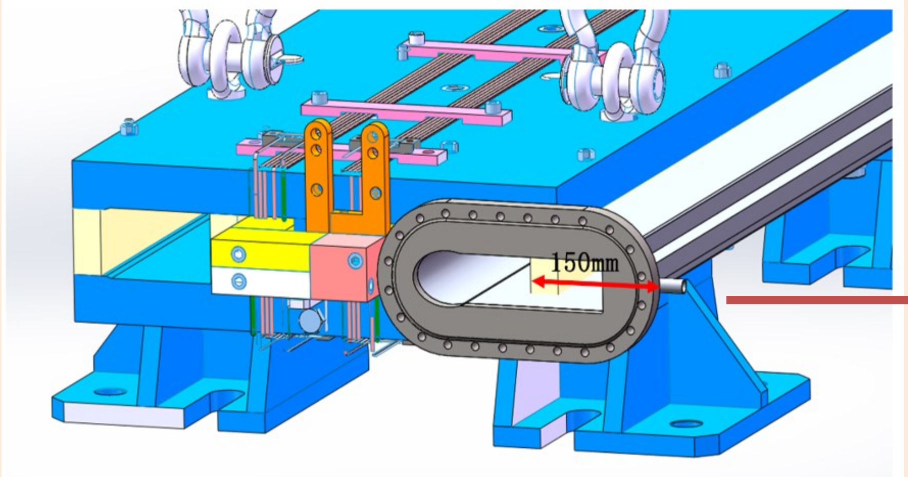


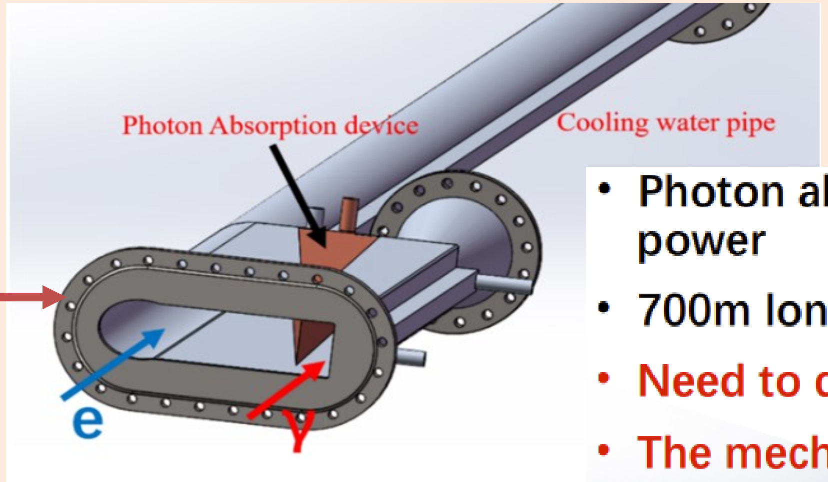
Conceptual design of the vacuum chambers

Dual-aperture dipole and extraction beam pipes







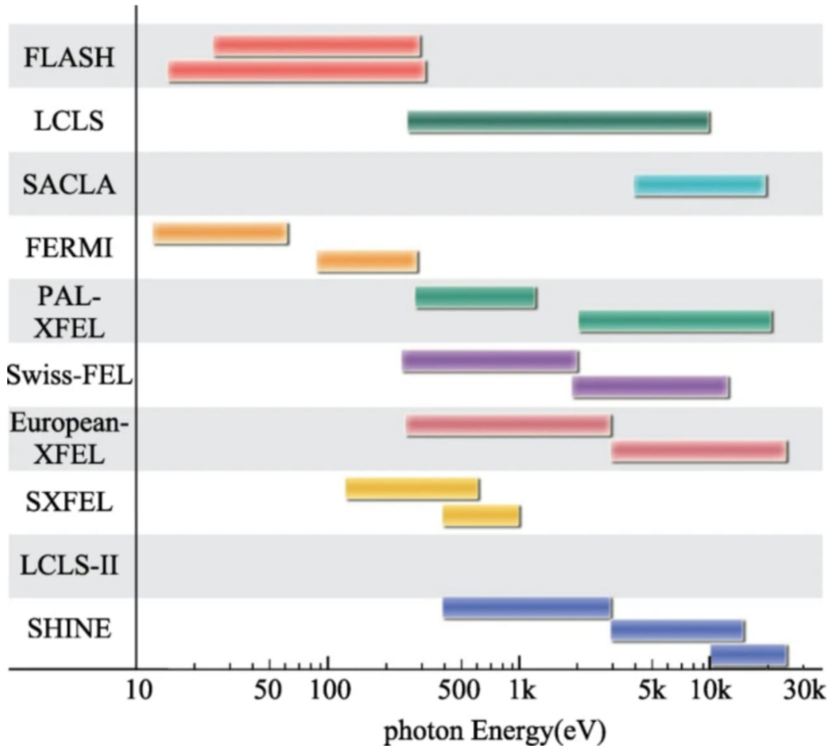


- Photon absorption device：800W radiation power
- 700m long of the line
- Need to do：
- The mechanical design of the total beamline

Conclusion to the application as gamma source

- Due to the ultra-high beam energy of over 100 GeV, CEPC presents an unique opportunity to generate 100 MeV level intensive gamma-rays using a 2 T wiggler
- Compare to other photon sources, CEPC may provide much higher photon energy with intensity
- Beam dynamic simulations indicate that the introduced beam energy loss is acceptable
- The original bending magnet can generate 100 keV level x-rays, covering a wide range of photon energies
- Conceptual design for the vacuum system were made
- There are wide-ranging applications waiting to be explored

CEPC as a high energy FEL facility



Survey of the hard x-ray FELs in the world

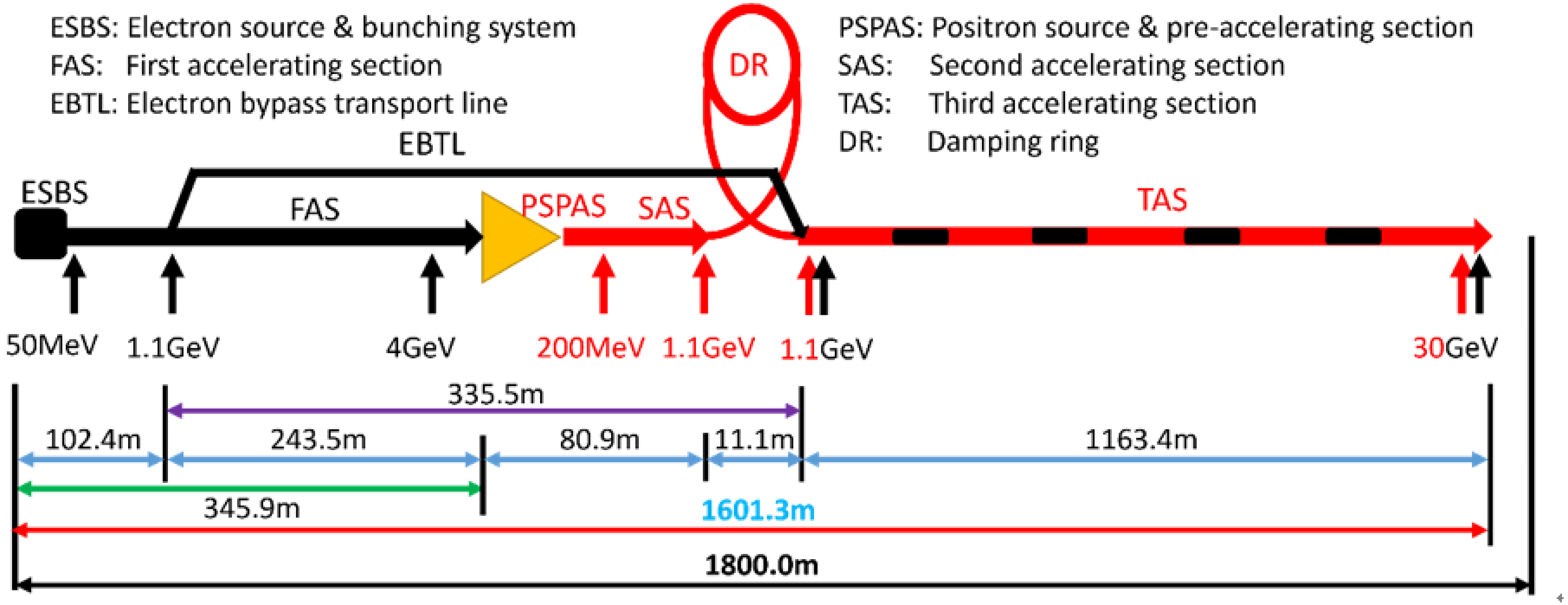
Hard XFEL Facilities	Beam Energy (GeV)	Photon Energy (keV)
European XFEL (Germany)	17.5	0.26- 25
LCLS (USA)	15	0.2-25
PAL-FEL (Korea)	10	0.25-15
SACLA (Japan)	8.5	4-20
SHINE (China, under construction)	8	0.4-25
Swiss FEL (Swiss land)	6	0.25-12

- Existing hard x-ray FELs use beam energy less than 20 GeV
- As the consequence, the maximum photon energy is lower than 25 keV
- In some specialized fields, the current indicators are difficult to meet the requirements. In the study of the dynamic properties of high-Z materials in materials science, there is a high demand for high-flux and high-photon-energy XFELs (photon energy of 50 keV and above).
- Ultra-high energy FELs in the level of 100 keV requires beam energy larger than 20 GeV

$$\lambda_r = \frac{\lambda_u}{2\gamma^2}(1 + \frac{K^2}{2})$$

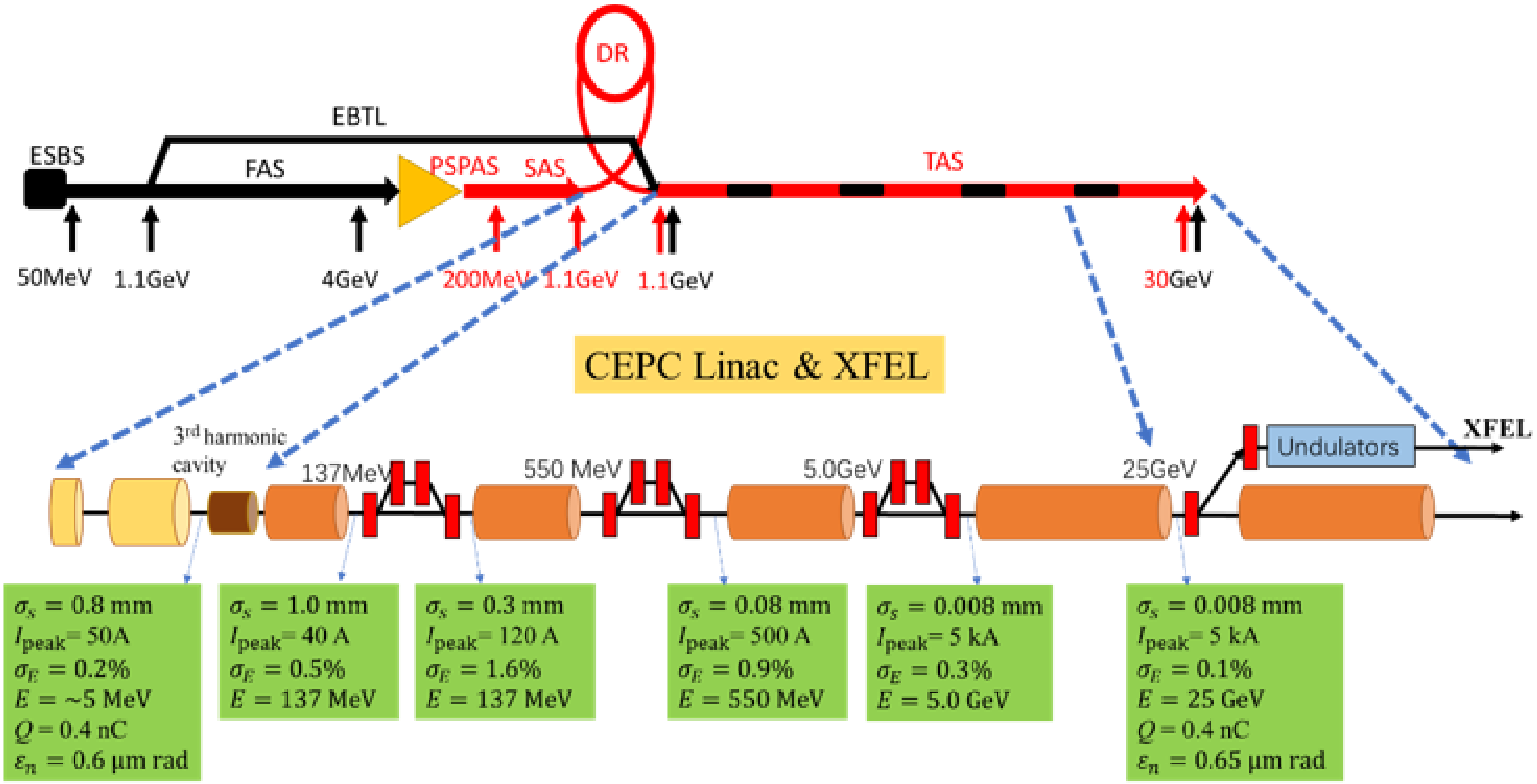
$$E = \frac{2hc\gamma^2}{\lambda_u(1 + \frac{K^2}{2})}$$

Linac Layout and Potential as a FEL Facility



- CEPC Linac is a 30 GeV normal conduction linear accelerator
- The C-band accelerator increase the beam energy from 1.1 GeV up to to 30 GeV
- It along can generate beam energy over 20 GeV, which is a very good candidate to drive a ultra-high energy x-ray FEL

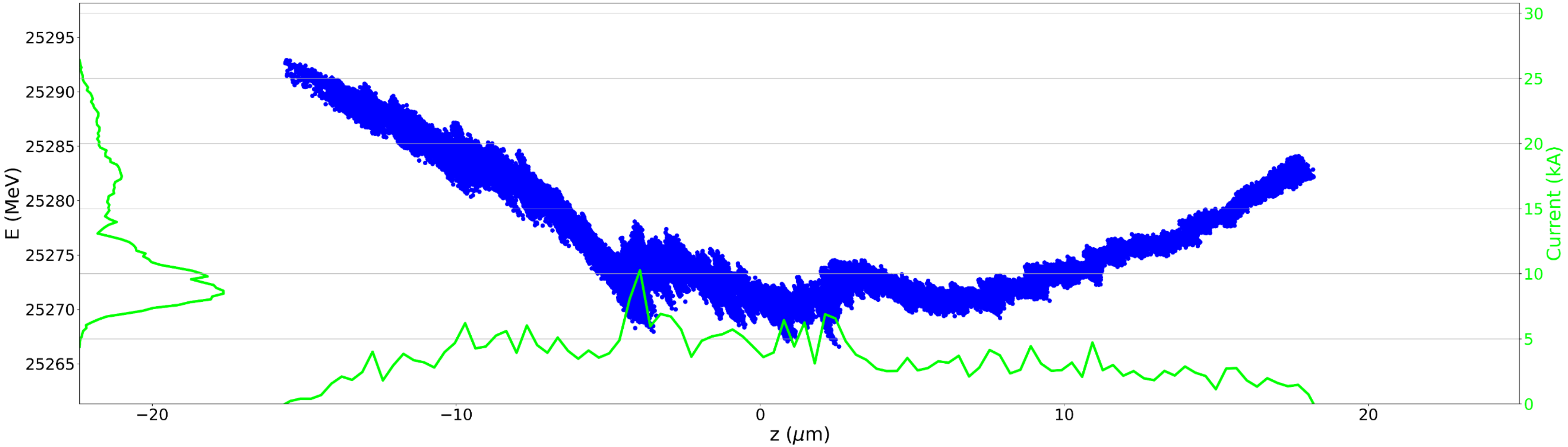
Schematic plan for the XFEL Facility



- Additional photon RF gun is needed, adjacent to the damping ring
- 3 chicanes are induced for bunch compression
- Beam energy of 25 GeV is sufficient
- An undulator line will be installed parallel to the linac

Start-to-end simulations of gun to Linac

Phase space at the accelerator end:

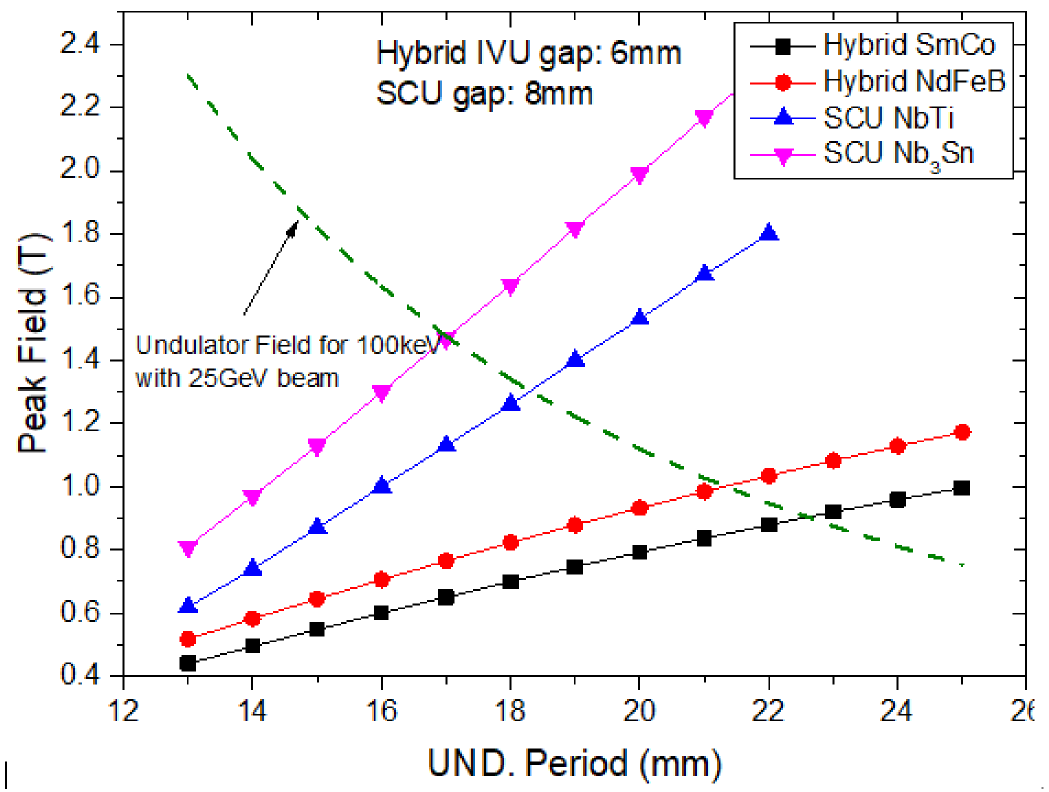


- Various effects, including CSR, wakefield, ect., have been accounted;
- 5kA peak current is available
- The energy spreads in the range of 25MeV, slice energy spread is 2MeV

Beam Parameters

	Value	Unit
Electron energy	25	GeV
Bunch charge	0.4	nC
Peak current	5	kA
Bunch length	8	µm
Normalized emittance(slice)	0.65	mm mrad
Energy spread (slice)	2.0	MeV
Max. Repetition rate	100	Hz

Undulator Parameter Selection



$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \qquad K = 0.934\lambda_u[cm]B[T]$$

	Value	Unit
Undulator Period	25	mm
Minimum Gap	6	mm
Maximum Field	1.2	T
Undulator parameter, K	2.8	-
Undulator type	IVU, hybrid	-
Magnet material	NbFeB	-
Polarization	Linear	

- The goal is to generate 100 keV FELs
- A certain tunability is need to the lower photon energy region
  - 48keV ~ 100keV
- Performance of different undulators are investigated

$$E(\text{keV}) = \frac{1.24}{\lambda_r(\text{nm})}$$

FEL Design Criteria

- 1-D Pierce Parameter: $(2\rho_{1D})^3 = \frac{\mu_0 e^2 n_0 K^2 [JJ]^2 \lambda_u{}^2}{16\pi^2 m\gamma^3}$
- One dimensional power gain length: $L_{g,1D} = \frac{\lambda_u}{4\sqrt{3}\pi\rho_{1D}}$
- Saturation length: $L_{sat} \approx 20 L_g$
- Saturation power: $P_{FEL} \approx \rho_{1D} P_e$
- Spectrum bandwidth: $2\rho_{1D}$
- Co-operating time: $t = \frac{1}{\omega\rho_{1D}}$
- 3-D Gain Length: $L_{g,3D} = L_{g,1D}(1+\delta)$

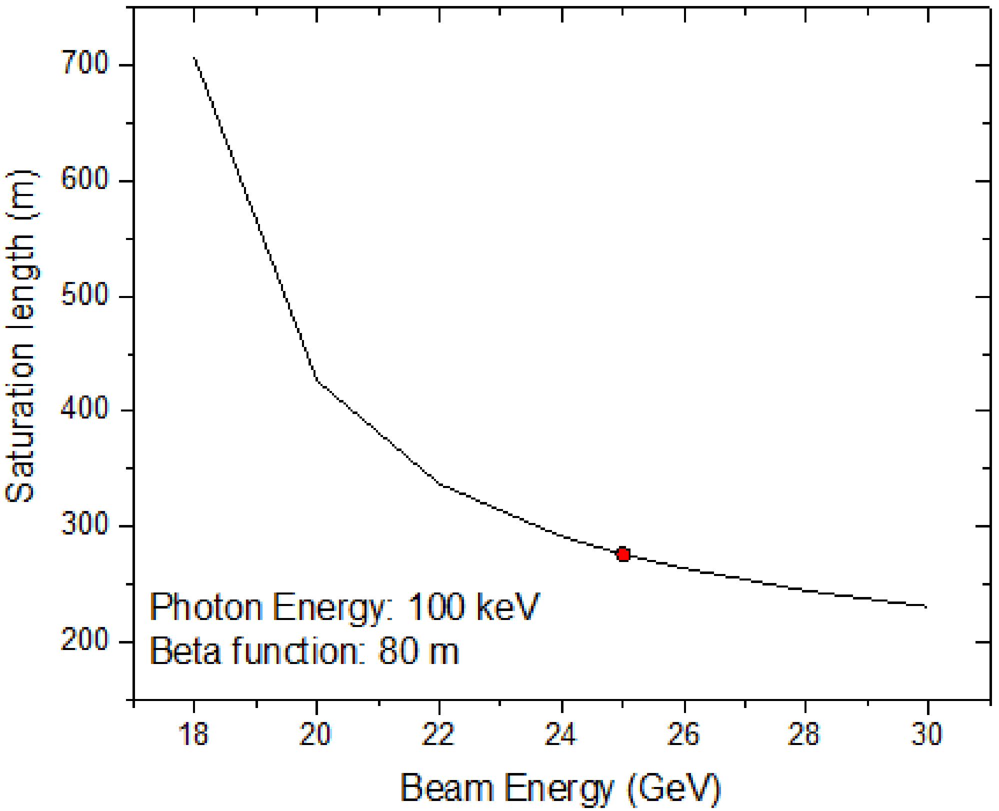
$$\delta = a_1\eta_d{}^{a_2} + a_3\eta_\varepsilon{}^{a_4} + a_5\eta_\gamma{}^{a_6} + a_7\eta_\varepsilon{}^{a_8}\eta_\gamma{}^{a_9} + a_{10}\eta_d{}^{a_{11}}\eta_\gamma{}^{a_{12}} + a_{13}\eta_d{}^{a_{14}}\eta_\varepsilon{}^{a_{15}} + a_{16}\eta_d{}^{a_{17}}\eta_\varepsilon{}^{a_{18}}\eta_\gamma{}^{a_{19}}$$

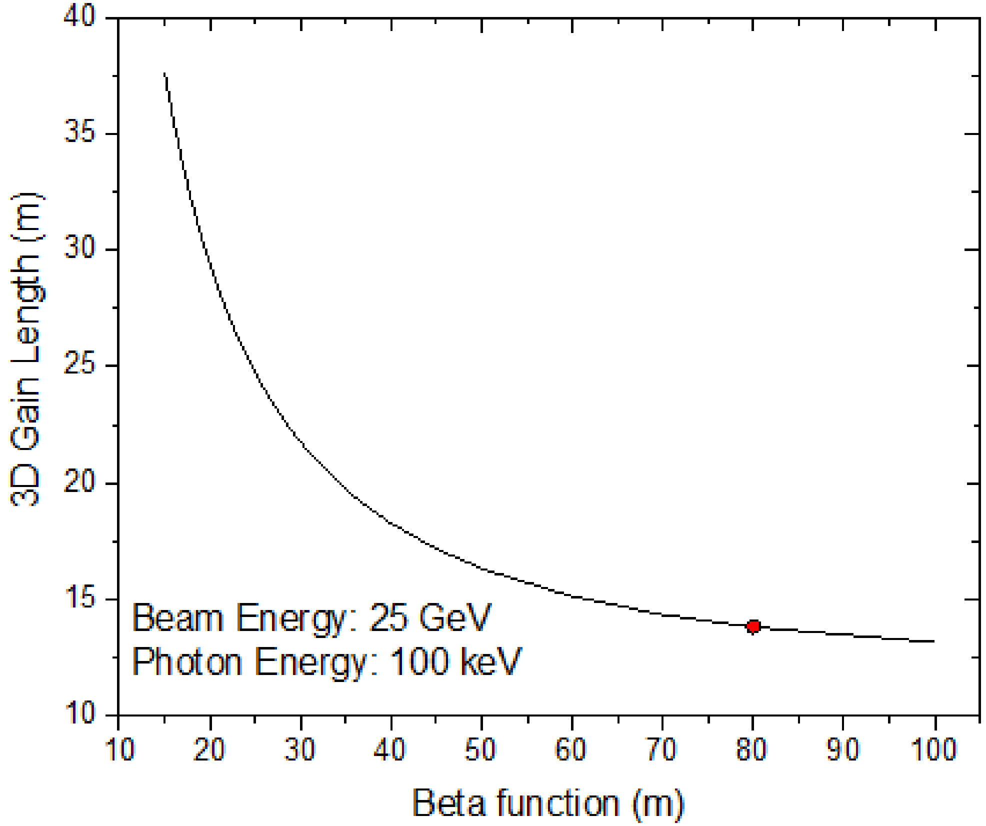
$$\eta_d = \frac{L_{g,1D}}{2k_r\sigma_x{}^2},\ \eta_\varepsilon = 2L_g\beta k_r\varepsilon,\ \eta_\gamma = 2L_g\lambda_u\sigma_\gamma$$

Ming Xie, NIM A, 445, 59 (2000)

Energy spread, beta-function and beam transverse size are accounted

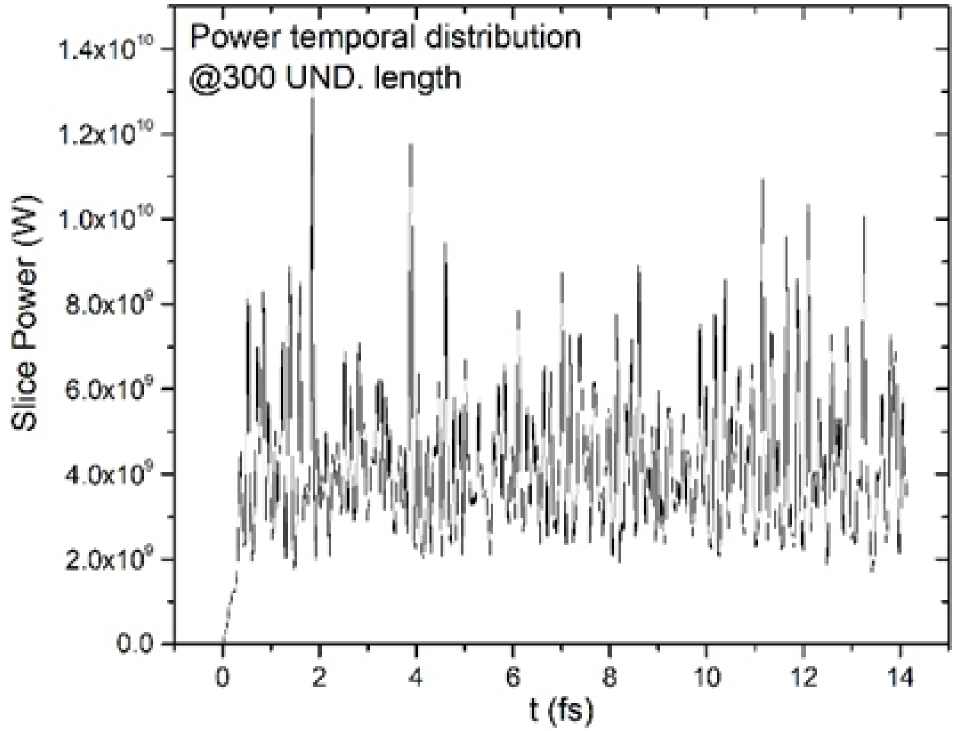
Beam Energy and β Function Investigation

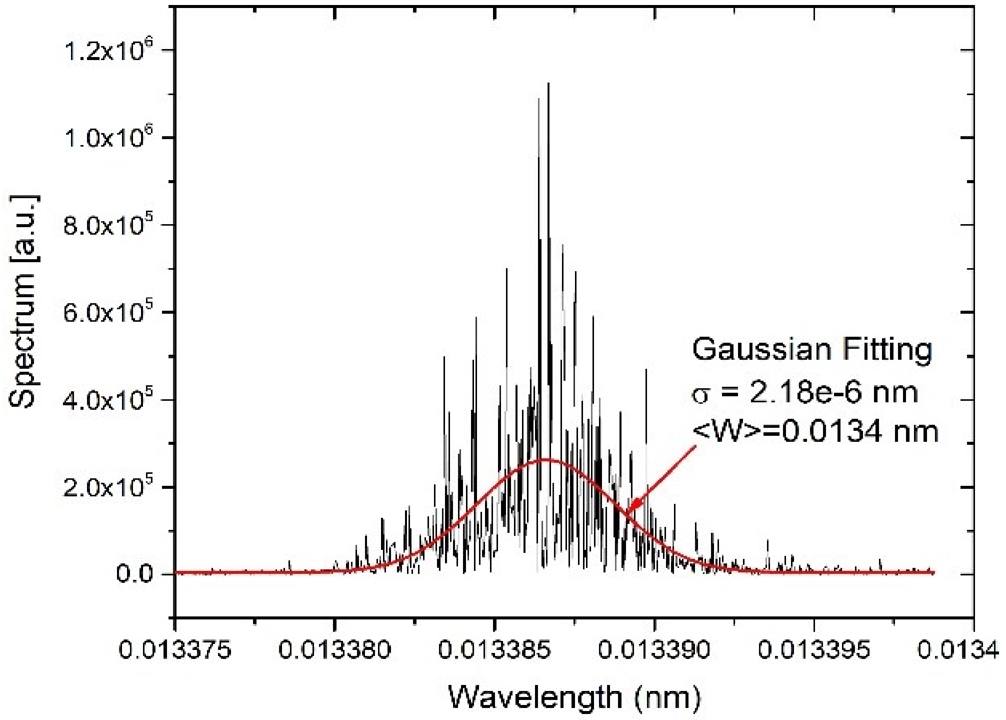




25 GeV beam energy and 80 m beta function is the optimum selection for a reasonable saturation length

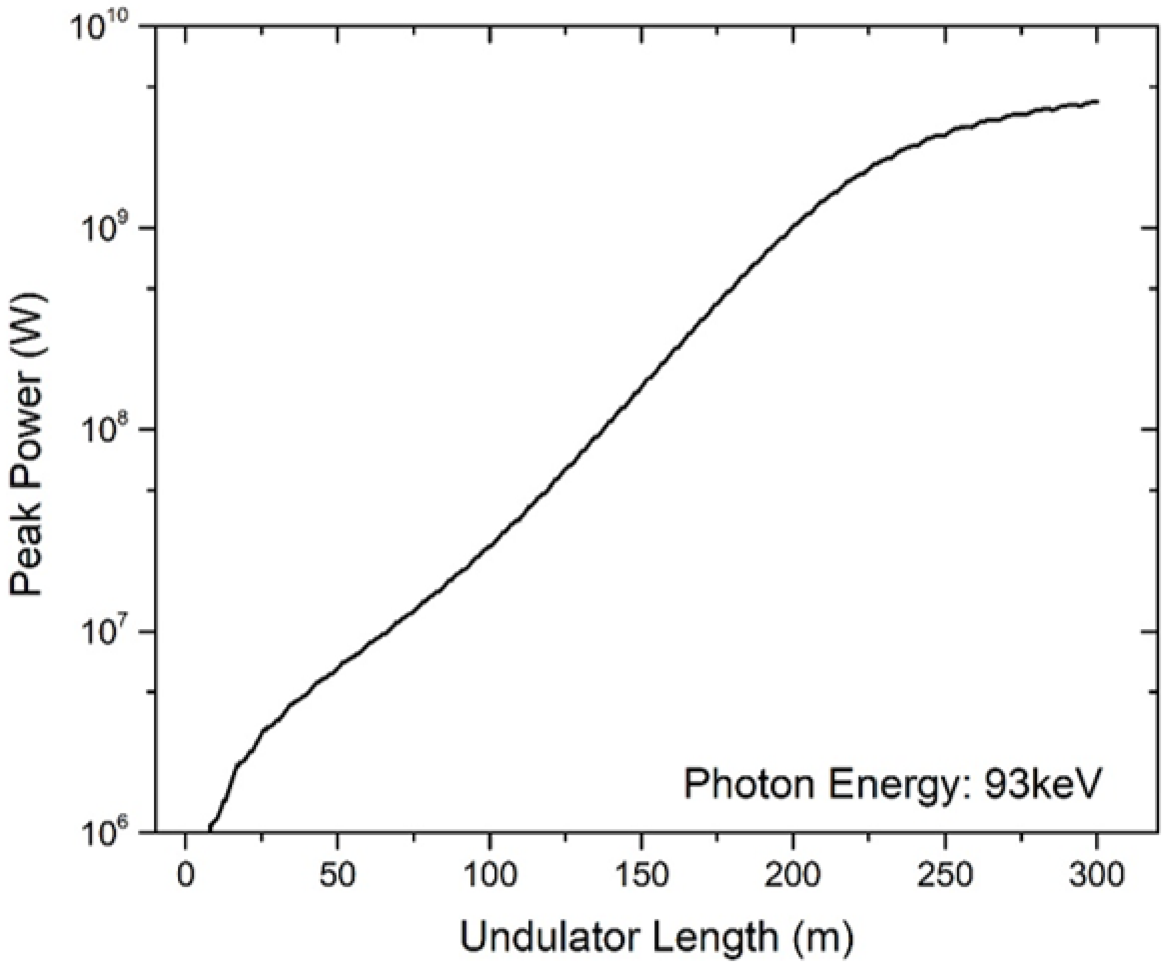
Saturation Spectrum in Time and Frequency Domain





- Homogeneity current of 5kA is supposed in the simulation
- The radiation wavelength is 0.0134 nm, corresponding to 93 keV
- The fitted sigma is 2.18e-6 nm, ($\frac{\Delta\omega}{\omega} \approx 3.26 \times 10^{-4}$), agree well with the band with evaluation using Pierce parameter (1.6 x 10^{-4})

Radiation Gain Curve and FEL Characters

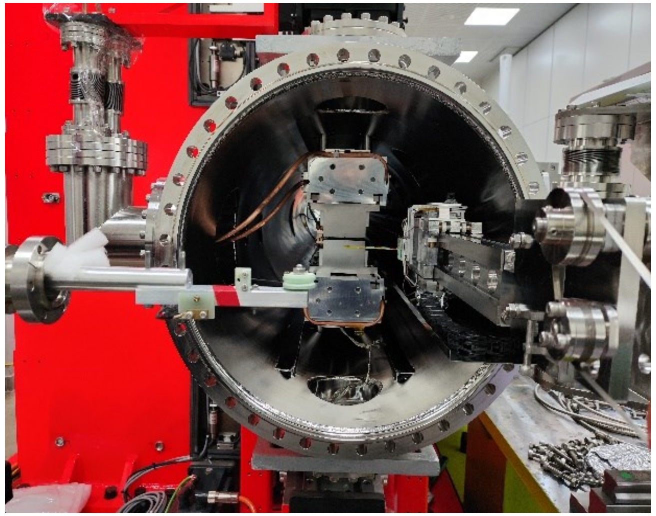


	Value	Unit
Beta function	80	m
1 D Pierce Parameter	1.6×10^{-4}	
3 D gain length	13.8	m
Saturation length	250	m
Bandwidth $\Delta\omega/\omega$	3.26×10^{-4}	
Photon energy	93	keV
Wavelength	0.0134	nm

Undulator system R&D

- Most of the technologies are conventional and mature
- IHEP holds full in-house experiences to most of the related technologies
- Undulator is the special technology, which is only used in photon sources
- IHEP develop undulators for HEPS, including the required in-vacuum UND

Undulator Tyep	Length [m]	Period [mm]	Performance Gap [mm]	Max. Peak Field [T]
CPMU	2	12.0	5.2-7.0	0.81
CPMU	2	14.2	5.2-9.9	1.00
CPMU	2	16.7	5.2-10.0	1.19
CPMU	2	18.8	5.2-13.1	1.35
CPMU	2	22.8	7.2-16.0	1.18
IVU (NdFeB)	4	18.8	5.2-13.1	1.35
IVU (SmCo)	4	19.9	5.2-14.0	0.97
IVU (SmCo)	4	22.6	5.2-15.2	1.10

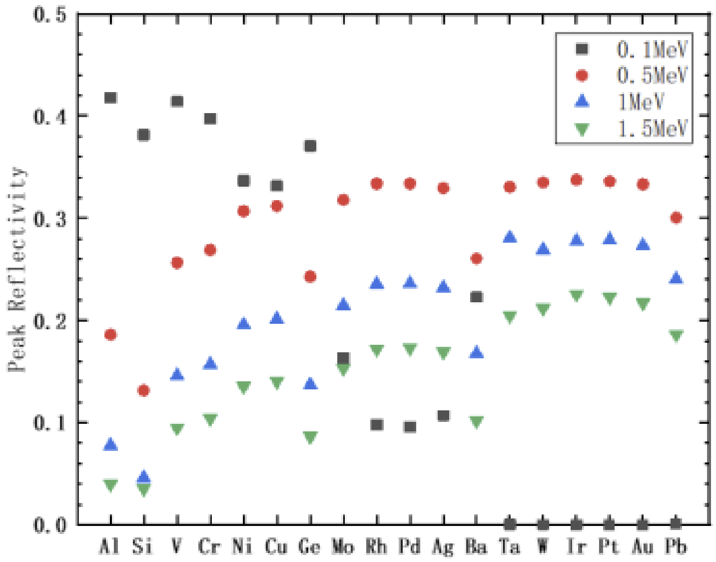


Conclusion to the application as a FEL facility

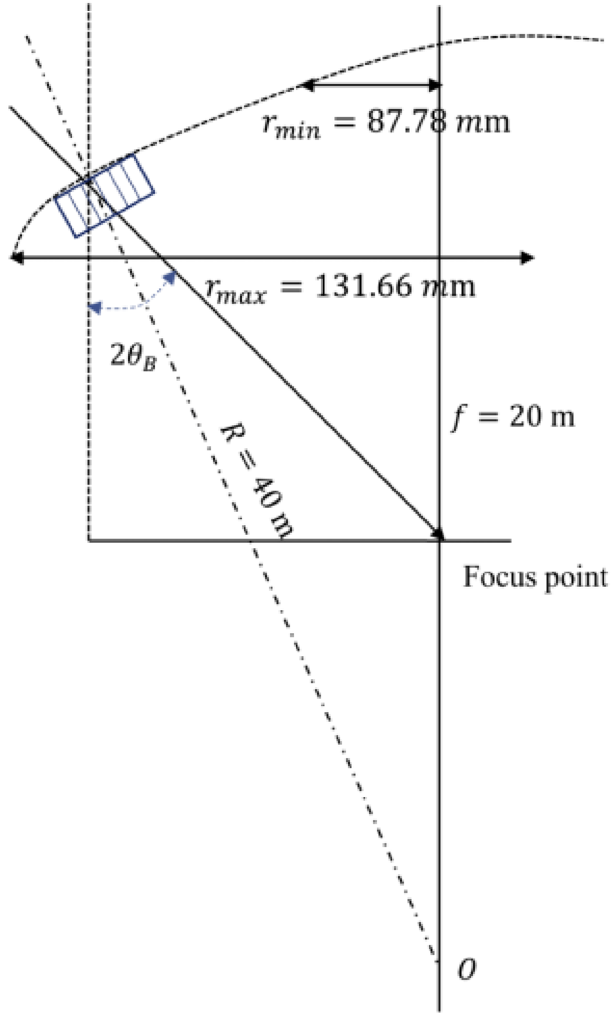
- CEPC exploits a 30 GeV Linac, which can drive an ultra-high x-ray FEL
- Additional photon RF gun is need for small emittance and energy spread
- 3 chicanes will be installed in Linac for the bunch compression, which results in 5kA peak current
- In-vacuum undulator will used to generate 100keV, with a centain wavelength tunability
- 100 keV SASE-FEL is simulated, corresponding to the analytical evaluation

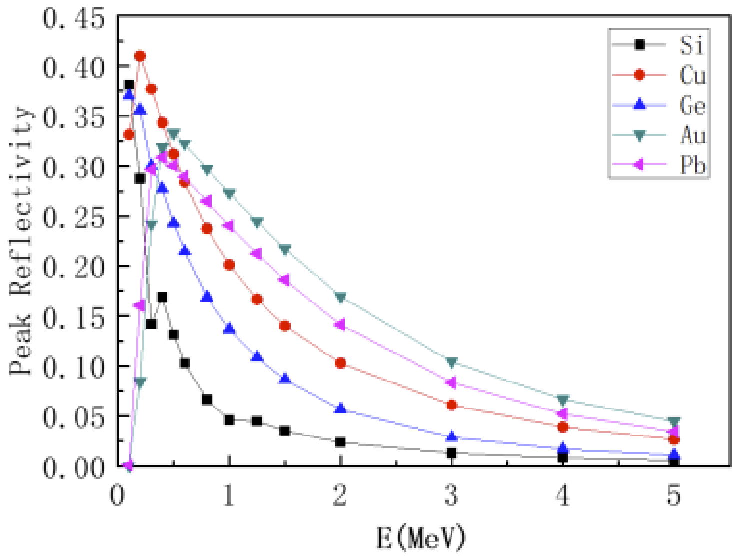
The End

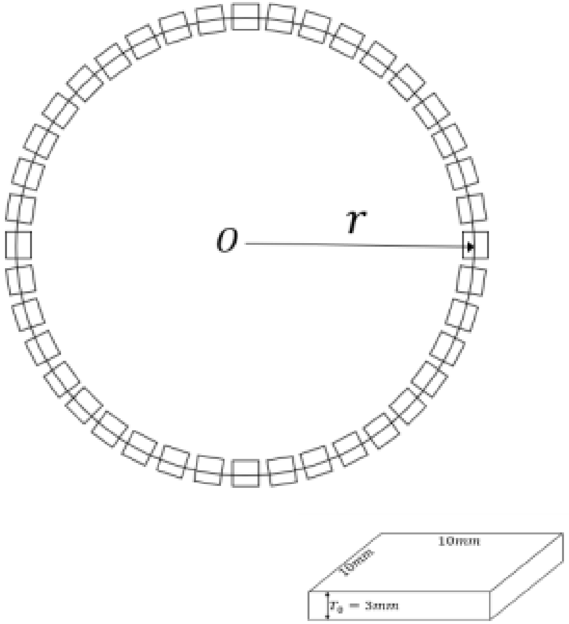
Gamma-ray focalization



- focusing of the synchrotron radiation beam: Laue lenses, Bragg diffraction, Au or Pb







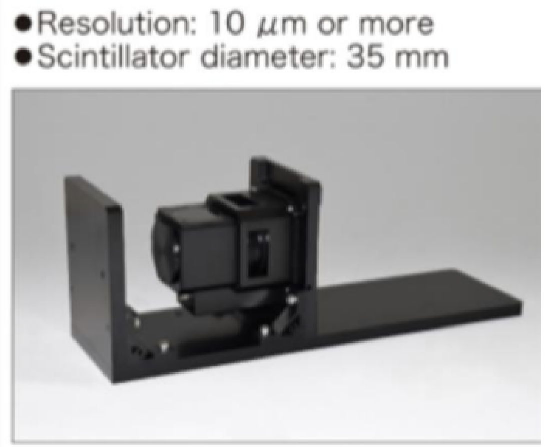
Gamma-Ray Detection

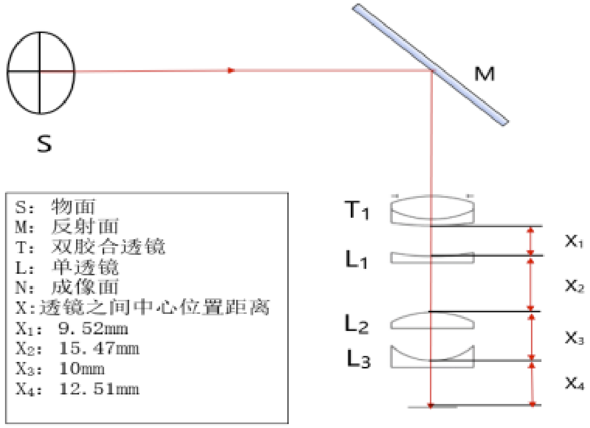
Gamma-ray camera: thin scintillator +focusing system+SPad

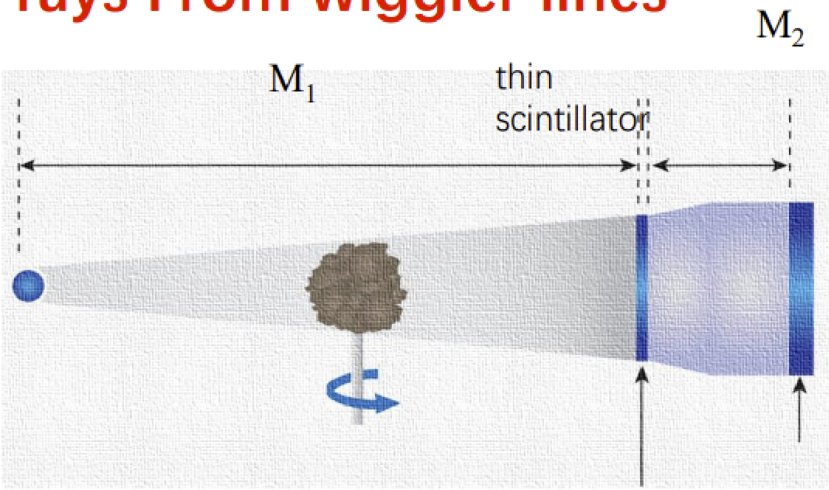
- The incident γ light passes through a thin scintillator and turns into visible light, which is imaged after lens focusing
- The focal plane uses a small-pixel SPAD （integrated SiPM)

X ray energy range: keV~MeV
Position resolution: 10 microns
Detector area: ~40mm

- Need to do：
- Flux and energy distribution of the gamma-rays From wiggler lines

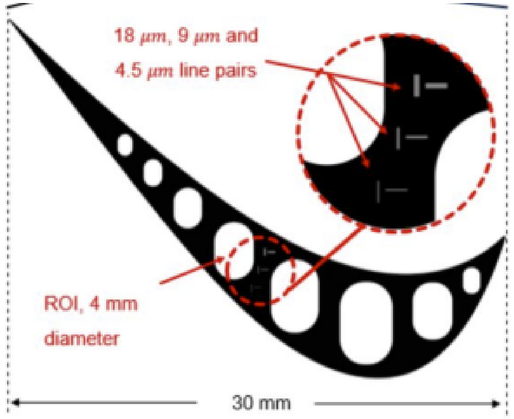


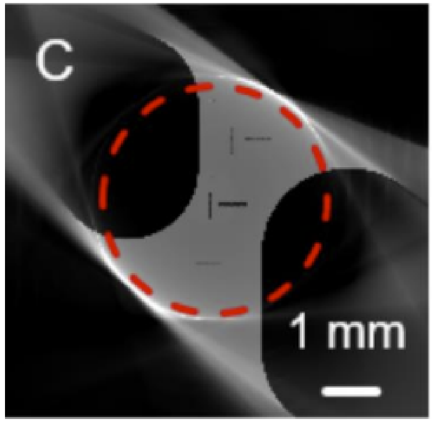


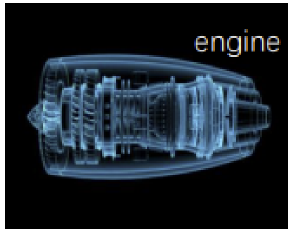


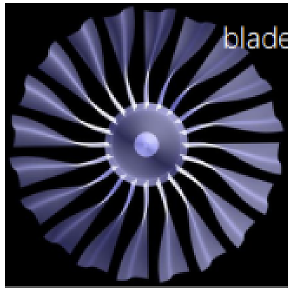
Possible Applications on Metals

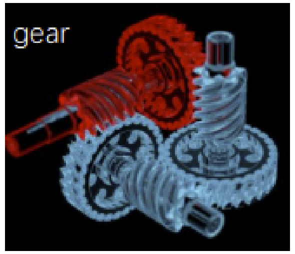
- ➢Processing of **heavy metal materials** in an in-situ environment
- ➢**Non-destructive** characterization of the **internal structure** of the workpiece under **casting, forging and service** conditions
- ➢**Internal welding problems, defect evolution, grain arrangement and failure analysis of materials**

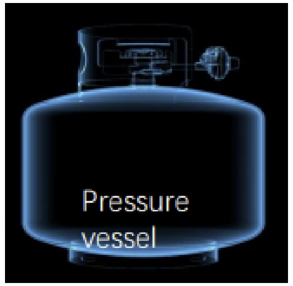












Dynamical diagnosis >1kHz+ large penetration depth+ clear imagination

$>10^{12}$photon/s

10^{9}photon----enough for a clear imagination

>1000Hz can satisfy:

Dynamical diagnosis of defect evolution/metal phase change process-droplet solidification/seawater corrosion mechanism

Possible Applications on Nucleon

Gamma assistant transmutation:

- The shortage of ADS idea is the transmutation by using neutrons in the sub-critical system, but meanwhile it produces actinides and long- lived fission products (LLFPs).

n+133Cs (stable) → 134Cs (2.06 y) → 135Cs (2.3 My) → 136Cs (13.16 d)

- **γ assistant transmutation is quite-valuable, and is an important supplement to neutron transmutation.**
- (γ,n), (γ,2n), Can increase the average number of fission neutrons!
- γ+135Cs → 134Cs、 133Cs; γ+ 133Cs → 132Cs、131Cs

Possible Applications on Medical

Radioisotope preparation for SPECT/CT & Flash RT

- $10^{14} p/s$ flux can produce: 10000Ci/y Mo99 compared with a linac 1mA per year

SPECT/CT is the first choice for early diagnosis of bone metastases from malignant tumors.

The judgment of the function of thyroid nodules and the differentiation of benign and malignant are of high diagnostic value.

Diagnosis of myocardial ischemia.

(1) $^{100}Mo + \gamma \rightarrow {}^{99}Mo + n$;

(2) $^{100}Mo + \gamma \rightarrow {}^{99m}Nb + p$, ^{99m}Nb $(T_{1/2} = 15s) \rightarrow {}^{99}Mo + \beta$;

(3) $^{100}Mo + \gamma \rightarrow {}^{99m}Nb + p$, ^{99m}Nb $(T_{1/2} = 12.6m) \rightarrow {}^{99}Mo + \beta$;

(4) $^{100}Mo + n \rightarrow {}^{99}Mo + 2n$