High energy photons from the FCC-ee complex

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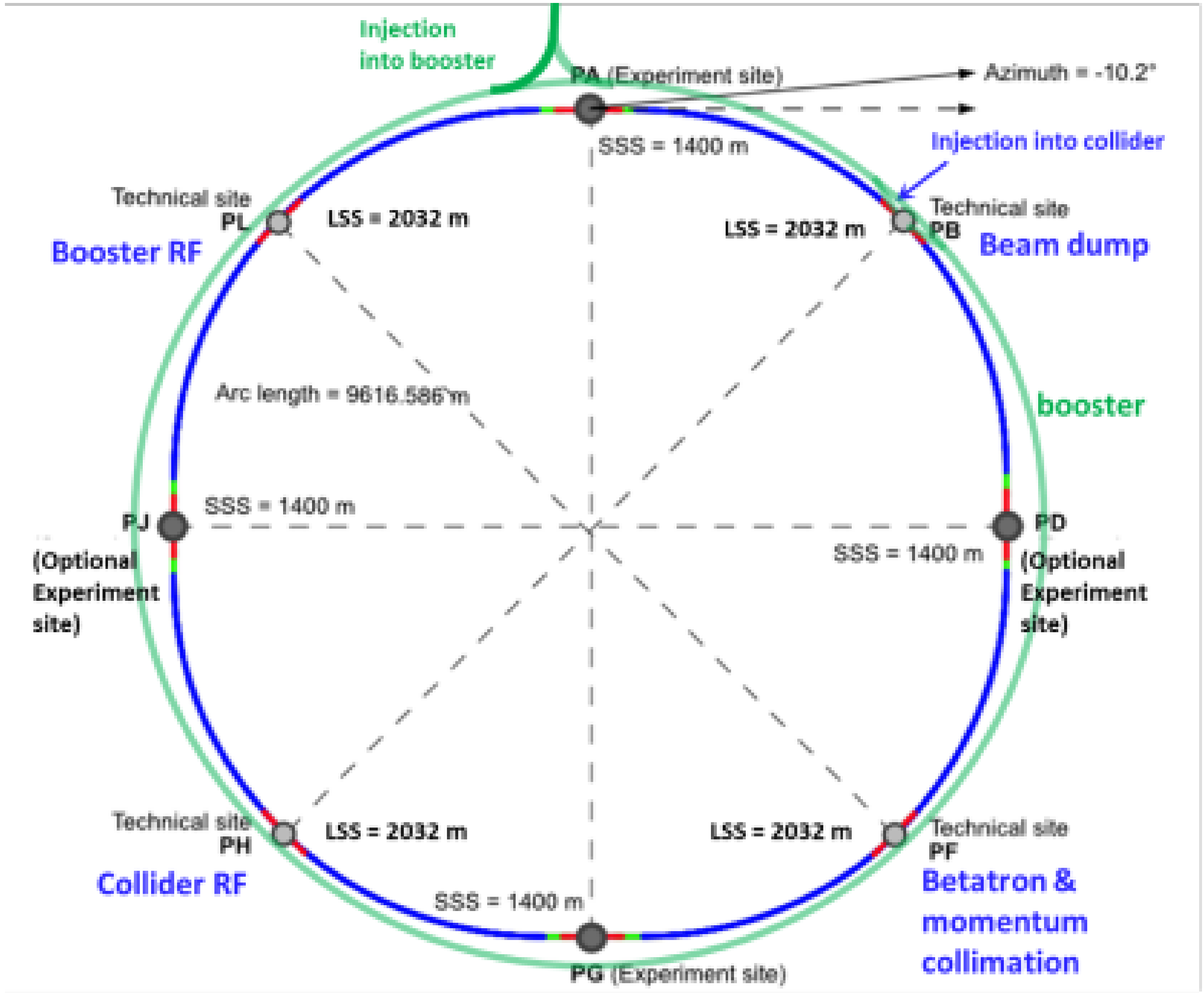
Other Science Opportunities at the FCC-ee
28 November 2024

Outline

- FCC-ee booster: parameters used for operating it as a photon source
- Diffraction limited storage rings
  - Small emittance → high brilliance and high coherent flux
- Average and peak brilliance: FCC-ee booster versus PETRA IV and EuXFEL
- FCC-ee booster for gamma rays for nuclear physics
- FCC-ee linac operating as an XFEL
- Conclusions
- Outlook

FCC-ee booster



circumference = 90.7 km

Parameters used for study of FCC-ee booster as photon source*

	3xU_0	94xU_0	U_0
beam energy [GeV]	**20**	**20**	**45.6**
avg. beam current [mA]	**6**	**6**	**15**
Avg. number of bunches	500	500	1120
rms bunch length [mm]	4	9.5	4.4
rms relative energy spread [10^{-3}]	0.4	2.2	0.4
beta at wiggler /undulator [m]	1.6	1.6	1.6
wiggler field [T]	1	1	1
wiggler period [mm]	40	40	40
magnetic gap [mm]	10	10	10
tot. length wiggler [m]	6.4	264	5
hor. emittance [pm rad]	**15**	**0.5**	**100**
vert. emittance [pm rad]	**1.5**	**0.05**	**0.2**
Time for users (s) over a cycle of 4 s	**2.5**	**2.5**	**0.4**

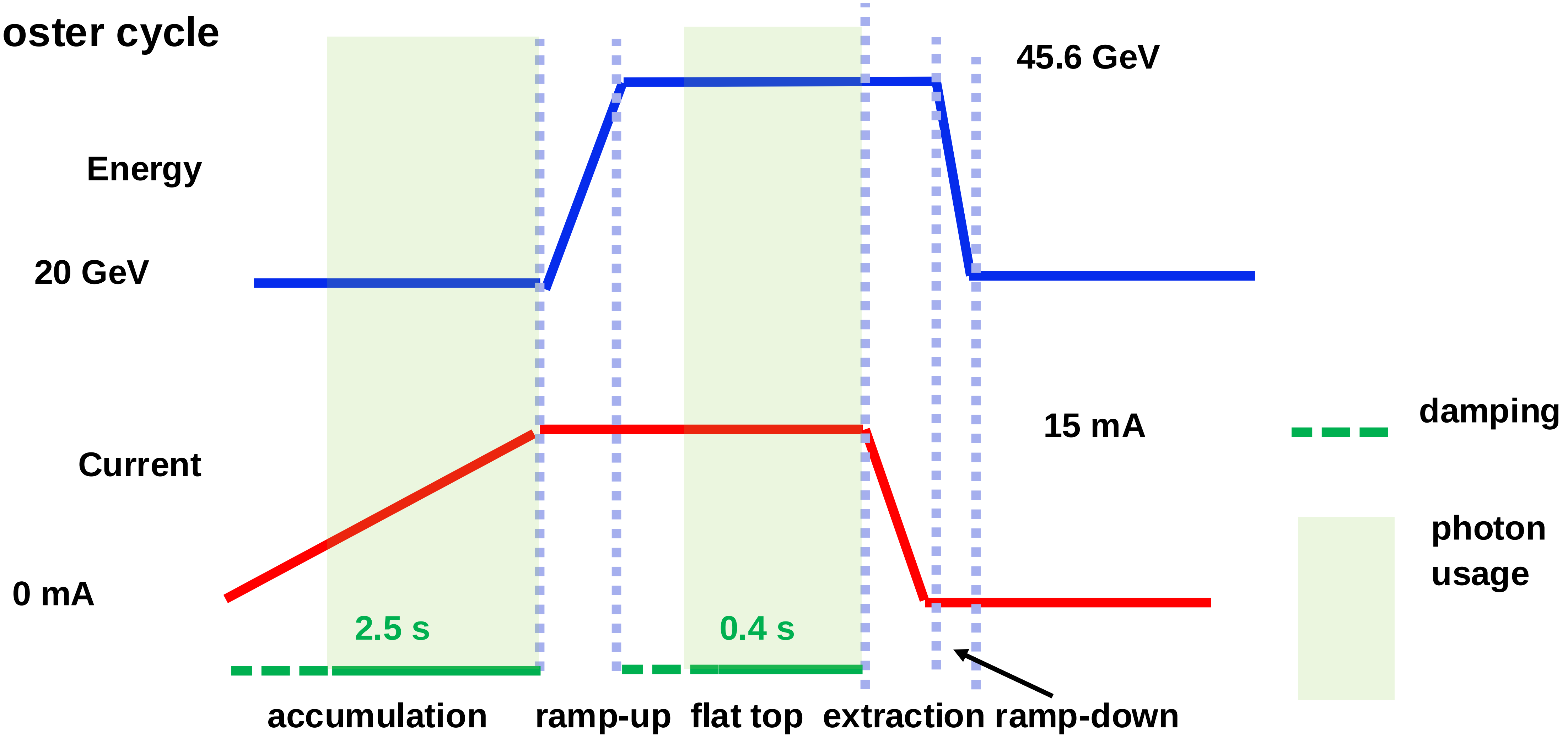
*Courtesy of F. Zimmermann

without wigglers

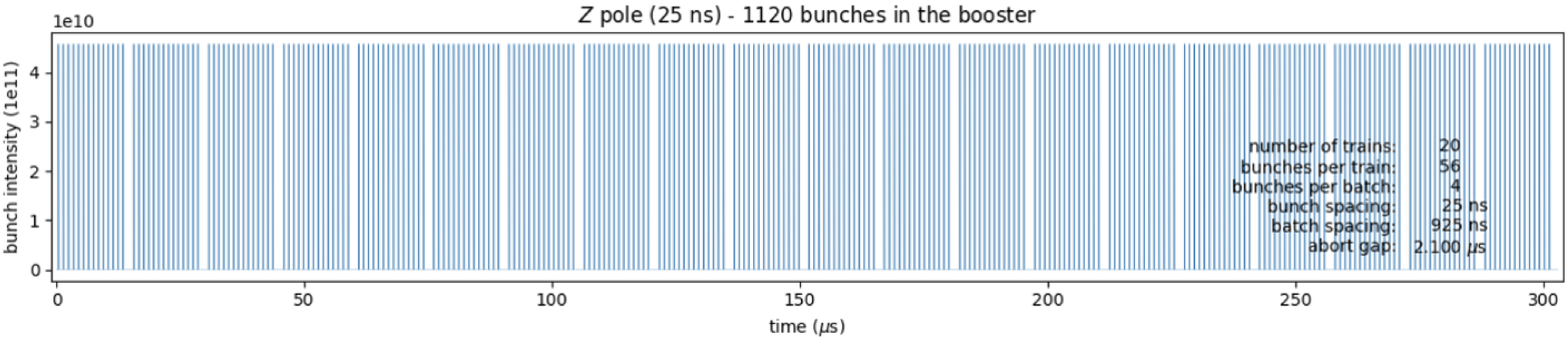
U_0 = energy loss / turn = 1.33 MeV

hor. em. = 46 pm rad; vert. em. < 5 pm rad

Booster cycle



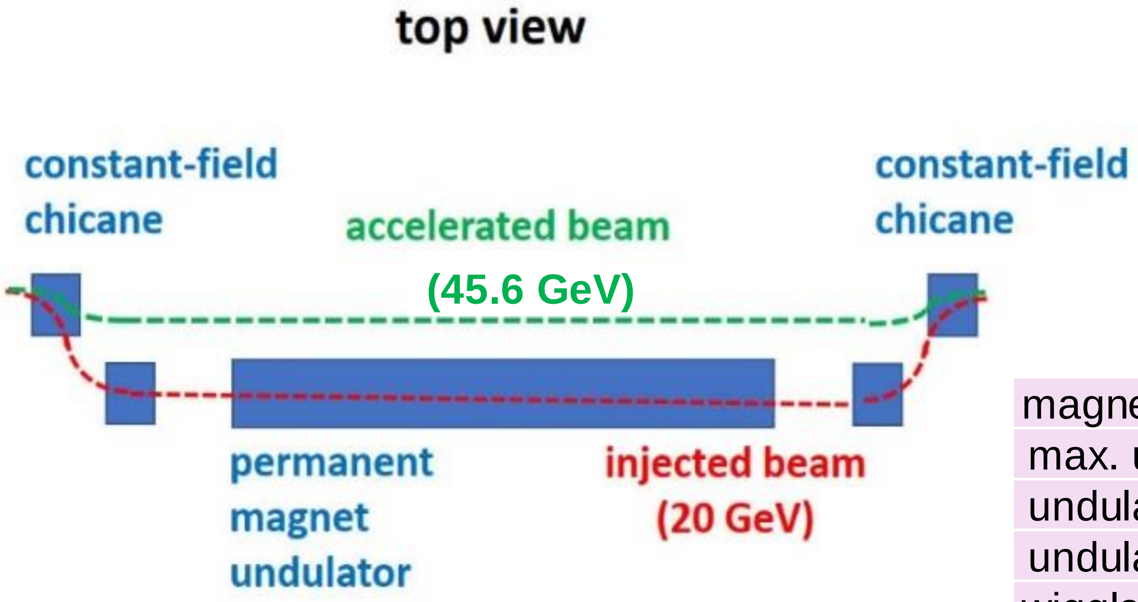
Filling pattern



Full-energy booster design, A. Chance et al. 2024

FCC-ee booster operated as photon source

- Fixed-field chicane: the beam automatically moves out of the wiggler during acceleration



- **U_0 x 3 : 1 U40 6.4 m → ε_x = 15 pm rad**
- **U_0 x 94 : 53 U40 5 m → ε_x = 0.5 pm rad**

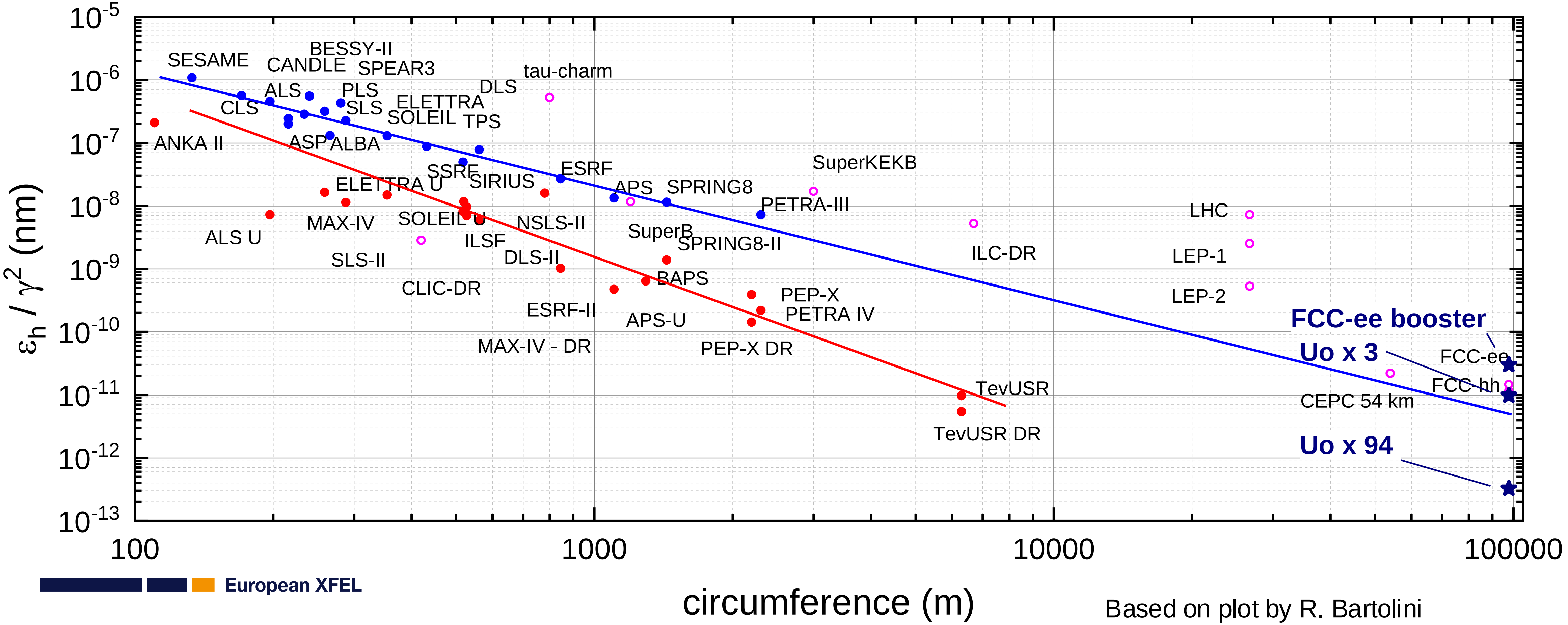
Permanent magnet technology

magnetic gap [mm]	10		
max. undulator field [T]	0.71		
undulator period [mm]	28		**U28**
undulator unit length [m]	5		
wiggler field [T]	1		
wiggler period [mm]	40		**U40**
	U_0 x 3	U_0 x 94	
wiggler unit length [m]	6.4	5	

- To be studied: what happens during the ramp?

Horizontal emittance versus circumference

- Storage ring photon sources upgrades to decrease the horizontal emittance
- FCC-ee booster small emittance as a result of large circumference + damping wigglers/undulators



Based on plot by R. Bartolini

Diffraction limited storage ring (DLSR)

- A ring with horizontal emittance ε_x ($\varepsilon_y < \varepsilon_x$) is diffraction limited at all photon wavelengths λ emitted by undulators for which

$$\varepsilon_{x,y} \leq \varepsilon_{ph} \approx \frac{\lambda}{4\pi}$$

Electron beam emittance

$$\varepsilon_{x,y} = \sigma_{x,y}\sigma'_{x,y}$$

Photon beam emittance

$$\varepsilon_{ph} = \sigma_{ph}\sigma'_{ph}$$

σ = rms beam size

σ' = rms beam divergence

diffraction limited at photon wavelengths

>100 $\mathrm{Å}$ ($< 120\ eV$) $\Rightarrow \varepsilon_x \approx$ 0.8 nm rad (ESRF, APS, PETRA III)

>10 $\mathrm{Å}$ ($< 1.2\ keV$) $\Rightarrow \varepsilon_x \approx$ 80 pm rad (APS-U, EBS)

>1 $\mathrm{Å}$ ($< 12\ keV$) $\Rightarrow \varepsilon_x \approx$ 8 pm rad (PETRA IV)

> 0.1 $\mathrm{Å}$ ($< 120\ keV$) $\Rightarrow \varepsilon_x \approx$ 0.8 pm rad (FCC-ee booster + U_0 x 94)

- **Small emittance → high brilliance and high coherent flux**

Diffraction limited storage ring (DLSR)

- High brilliance

$$Brilliance = \frac{Flux}{4\pi^2 \Sigma_x \Sigma_y \Sigma'_x \Sigma'_y}$$

σ = rms beam size

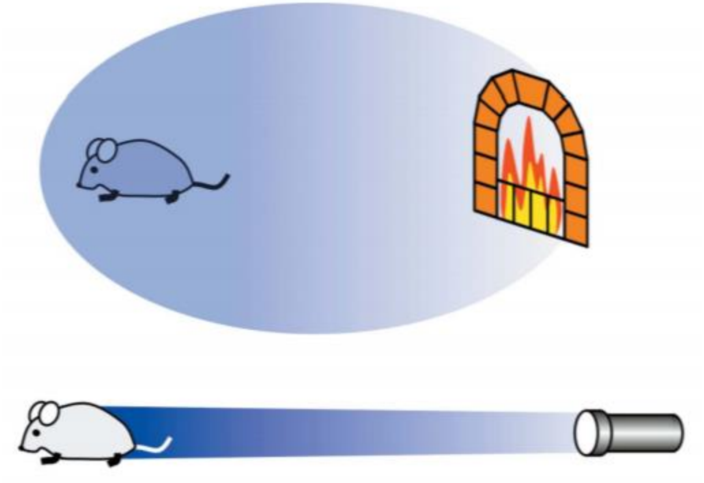
σ' = rms beam divergence

Source dimension and divergence

Without dispersion $\Sigma_{x,y} = \sqrt{\sigma^2_{x,y} + \sigma^2_{ph}}$ $\Sigma'_{x,y} = \sqrt{\sigma'^2_{x,y} + \sigma'^2_{ph}}$

$$\sigma_{x,y} = \sqrt{\varepsilon_{x,y}\,\beta_{x,y}}$$

$$\sigma'_{x,y} = \sqrt{\varepsilon_{x,y}/\beta_{x,y}}$$



Y. Hwu & G. Margaritondo, JSR 28-3, 1014 (2021)

Different approximations of single electron undulator emission to gaussian beam

	σ_{ph}	σ'_{ph}	ε_{ph}	$\beta_{ph} = \sigma_{ph}/\sigma'_{ph}$
Kim (NIM 1986)	$\sqrt{\lambda/L}$	$\sqrt{\lambda L}/4\pi$	$\lambda/4\pi$	$L/4\pi$
Kim (PAC87)	$\sqrt{\lambda/2L}$	$\sqrt{2\lambda L}/4\pi$	$\lambda/4\pi$	$L/2\pi$
Ellaume (2003)	$\sqrt{\lambda/2L}$	$\sqrt{2\lambda L}/2\pi$	$\lambda/2\pi$	L/π
Lindberg & Kim (2015)	$\boldsymbol{\sqrt{\lambda/4L}}$	$\boldsymbol{\sqrt{\lambda L}/2\pi}$	$\boldsymbol{\lambda/4\pi}$	$\boldsymbol{L/\pi}$

Diffraction limited storage ring (DLSR)

- Maximum brilliance for $\varepsilon_{x,y} \ll \varepsilon_{ph}$

$$Brilliance = \frac{Flux}{4\pi^2 \Sigma_x \Sigma_y \Sigma'_x \Sigma'_y} \approx \frac{Flux}{4\pi^2 \varepsilon_{ph}^2} = \frac{4\ Flux}{\lambda^2}$$

Without dispersion

$$\sigma_{x,y} = \sqrt{\varepsilon_{x,y}\, \beta_{x,y}}$$

$$\sigma'_{x,y} = \sqrt{\varepsilon_{x,y}/\beta_{x,y}}$$

- For $\varepsilon_{x,y} \approx \varepsilon_{ph}$ brilliance maximized when the electron and photon beam phase spaces are matched

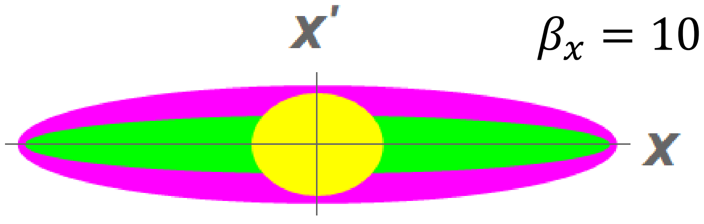
$$\beta_{x,y} = \frac{\sigma_{ph}}{\sigma'_{ph}} = L/\pi$$

$$Brilliance = \frac{Flux}{4\pi^2 (\varepsilon_x + \varepsilon_{ph})(\varepsilon_y + \varepsilon_{ph})} \approx \frac{Flux}{\lambda^2}$$

σ_{ph}	σ'_{ph}	ε_{ph}	$\beta_{ph} = \sigma_{ph}/\sigma'_{ph}$
$\sqrt{\lambda/4L}$	$\sqrt{\lambda L}/2\pi$	$\lambda/4\pi$	L/π

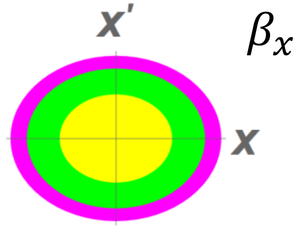
PETRAIV: undulator length $= L = 4\ m$ $\varepsilon_x = 20$ pm rad for 1 Å $\varepsilon_{ph} = 8$ pm rad

$\beta_x = 10$ m



Not matched

$\beta_x = L/\pi = 1.27$ m



Matched

Photon phase space
Electron phase space
Total phase space

Diffraction limited storage ring (DLSR)

σ = rms beam size
σ' = rms beam divergence

- High transverse coherence

$$Coherent\ Flux = f_c \cdot Flux$$

Fraction of X-rays transversally coherent

$$f_c = \frac{\varepsilon_{ph}}{\Sigma_x \Sigma'_x} \cdot \frac{\varepsilon_{ph}}{\Sigma_y \Sigma'_y} \xrightarrow{\varepsilon_{x,y} \to 0} 1$$

Assuming

$\varepsilon_x = \varepsilon_y = \varepsilon$ round beam

$$\beta_{x,y} = L/\pi$$

$$f_c = \frac{\left(\lambda/_{4\pi}\right)^2}{\left(\varepsilon \cdot \frac{L}{\pi} + \frac{\lambda L}{4\pi^2}\right)\left(\varepsilon \cdot \frac{\pi}{L} + \frac{\lambda}{4L}\right)}$$

Without dispersion

$$\sigma_{x,y} = \sqrt{\varepsilon_{x,y}\, \beta_{x,y}}$$

$$\sigma'_{x,y} = \sqrt{\varepsilon_{x,y}/\beta_{x,y}}$$

$$\Sigma_{x,y} = \sqrt{\sigma_{x,y}^2 + \sigma_{ph}^2}$$

$$\Sigma'_{x,y} = \sqrt{\sigma'^2_{x,y} + \sigma'^2_{ph}}$$

σ'_{ph}	σ_{ph}	ε_{ph}	$\beta_{ph} = \sigma_{ph}/\sigma'_{ph}$
$\sqrt{\lambda/4L}$	$\sqrt{\lambda L}/2\pi$	$\lambda/4\pi$	L/π

Diffraction limited storage ring (DLSR)

- High transverse coherence

$$Coherent\ Flux = f_c \cdot Flux$$

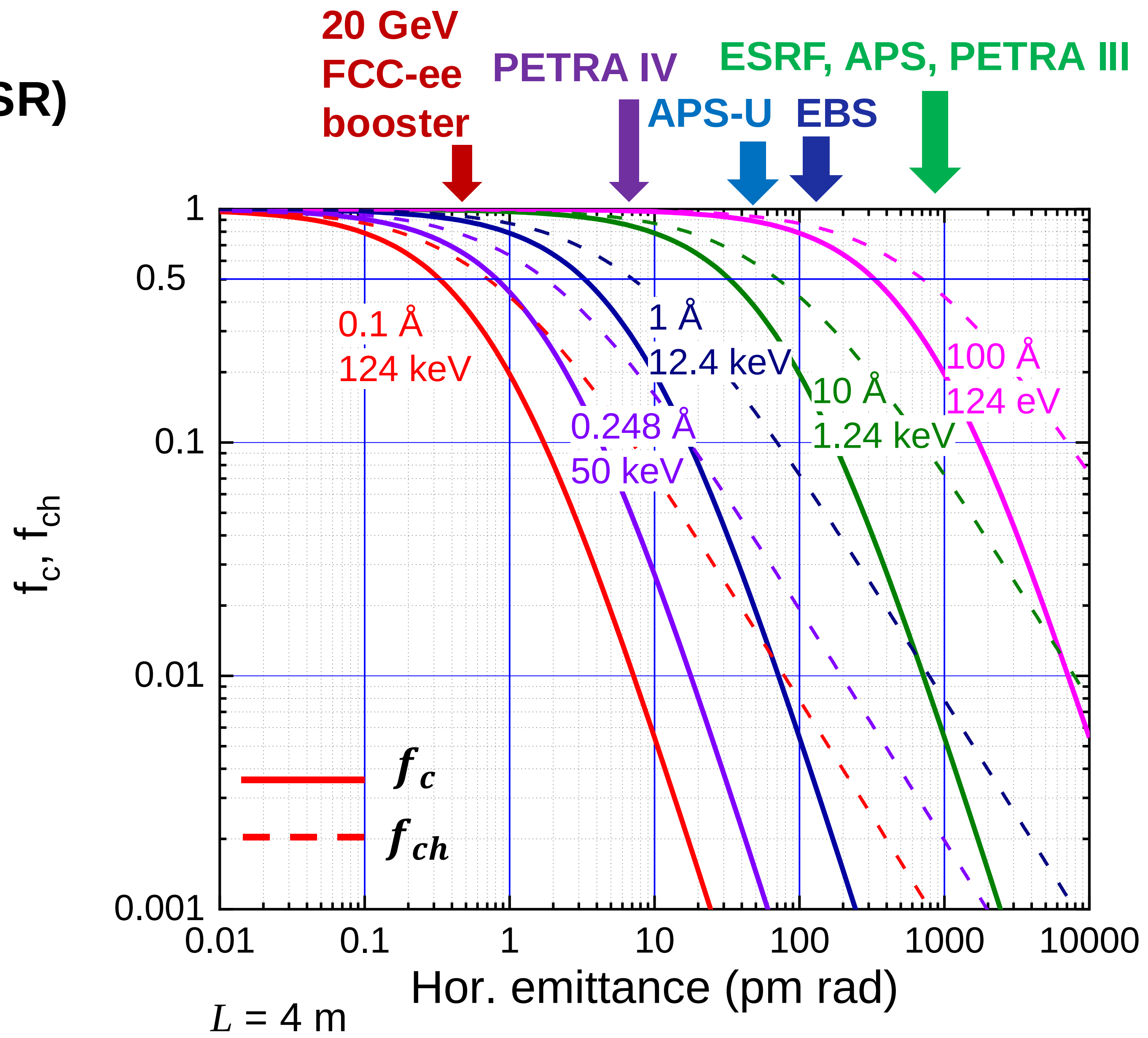
Fraction of X-rays transversally coherent

round beam, DLSR

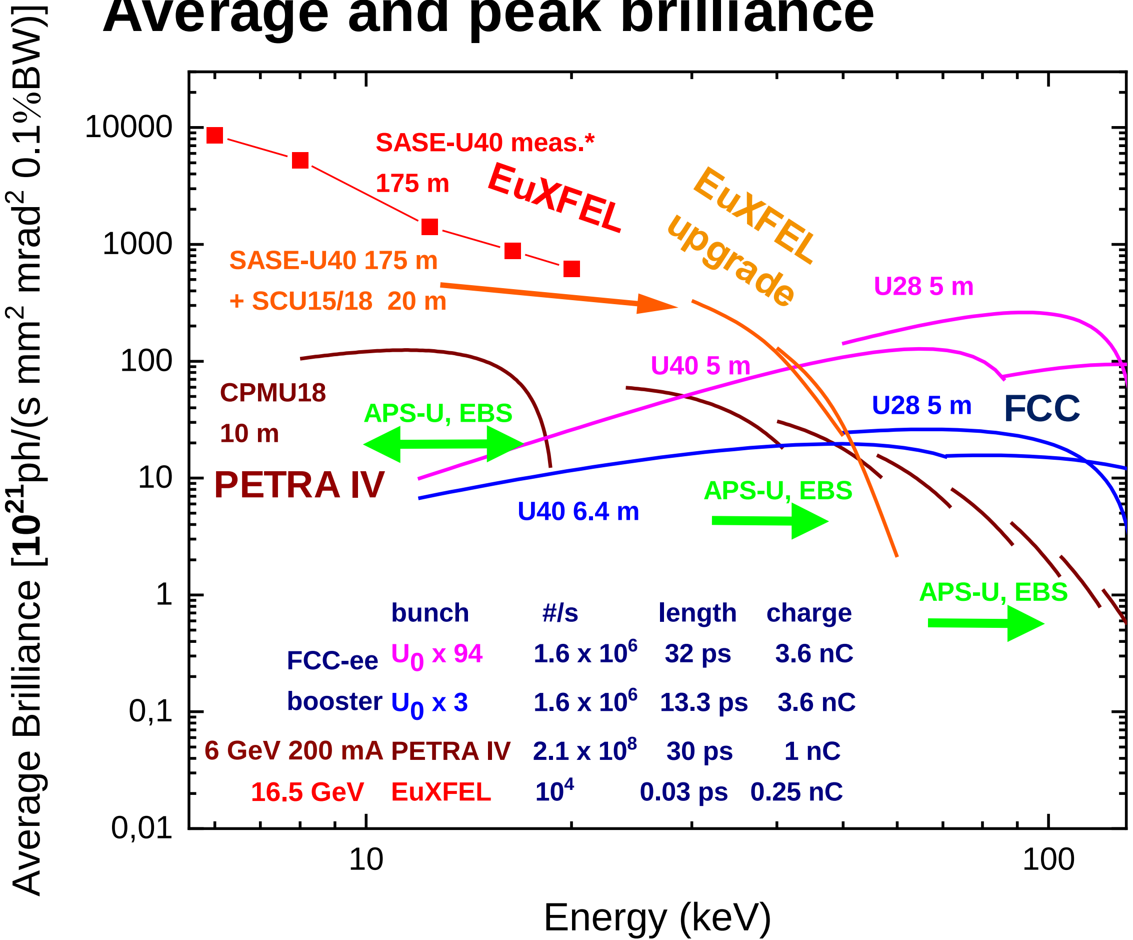
$$f_c = \frac{\left(\lambda/_{4\pi}\right)^2}{\left(\varepsilon\cdot\frac{L}{\pi}+\frac{\lambda L}{4\pi^2}\right)\left(\varepsilon\cdot\frac{\pi}{L}+\frac{\lambda}{4L}\right)}$$

flat beam, FCC-ee booster

$$f_c = f_{ch} = \frac{\left(\lambda/_{4\pi}\right)}{\sqrt{\varepsilon_x\cdot\frac{L}{\pi}+\frac{\lambda L}{4\pi^2}}\sqrt{\varepsilon_x\cdot\frac{\pi}{L}+\frac{\lambda}{4L}}}$$

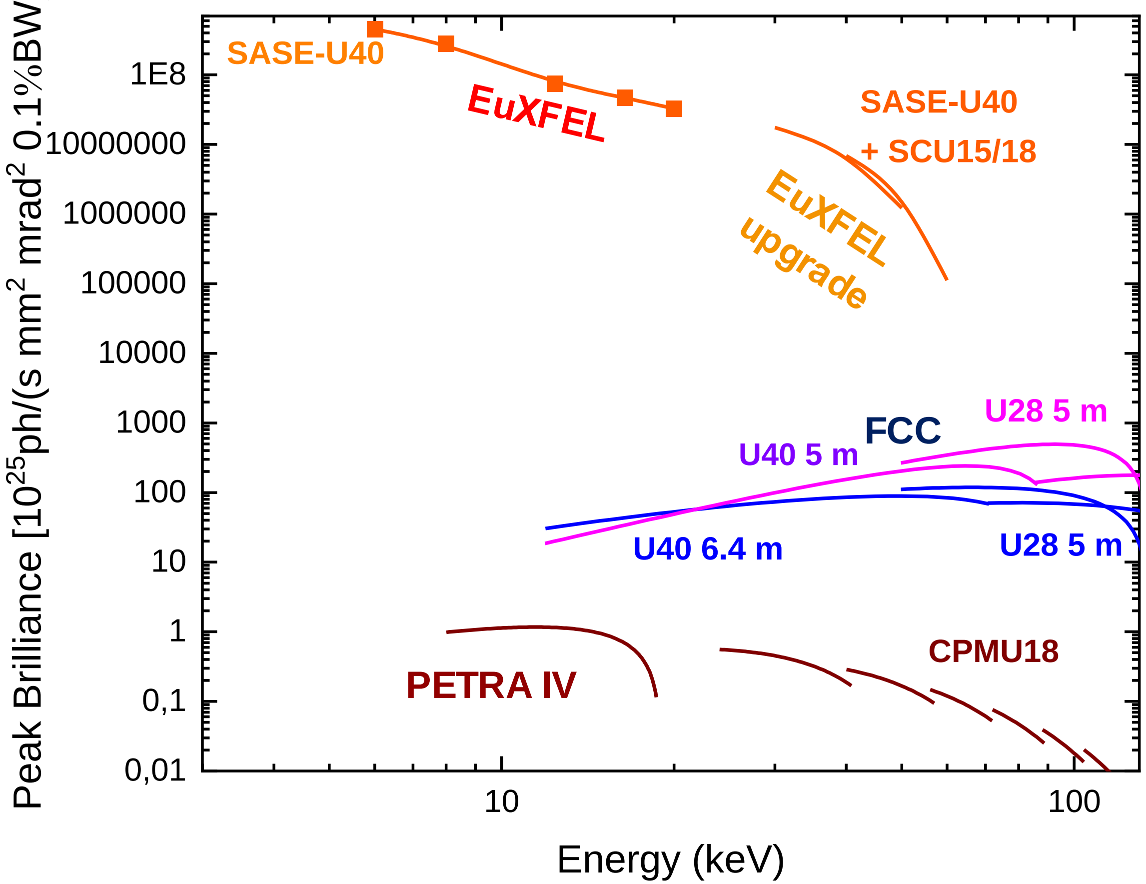


Average and peak brilliance



	bunch	#/s	length	charge
FCC-ee	U_0 x 94	1.6 x 10^6	32 ps	3.6 nC
booster	U_0 x 3	1.6 x 10^6	13.3 ps	3.6 nC
6 GeV 200 mA	PETRA IV	2.1 x 10^8	30 ps	1 nC
16.5 GeV	EuXFEL	10^4	0.03 ps	0.25 nC

- unpublished
from energy/pulse
courtesy of W. Decking (2021)



- high average brilliance → flux hungry experiments
- high peak brilliance → time resolved experiments

Simulations performed with SPECTRA
T.Tanaka, JSR (2021). 28, 1267-1272

European XFEL

Scientific opportunities for hard X-ray lasing (40-100 keV)

In general: ***Non-reproducible processes that live on time-scales of microseconds to femtoseconds and happen in difficult to access sample environments.***

Two examples are (for more see workshop *Scientific opportunities with very hard x-ray FEL radiation, European XFEL Jan 18-20 2023*):

- High energy density (HED) science: Extreme conditions can be produced only for short times and once per setup (e.g. shock-compressed diamond anvil cell, pulsed magnetic fields). These set-ups are so complex that detectors have to be placed far away and see only a limited solid angle. Hard X-rays can penetrate the sample environments and compress the Q-space in scattering experiments.

- In-situ microscopy on technological processes, e.g. welding or battery research: On the best storage rings, these experiments are current flux-limited to a time resolution of seconds. With very hard X-ray lasing in burst-mode this can be pushed to microseconds and faster.

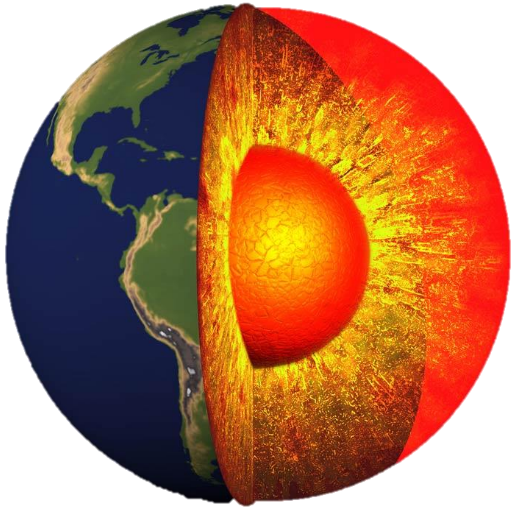


Image source: Science, doi: 10.1126/article.30069

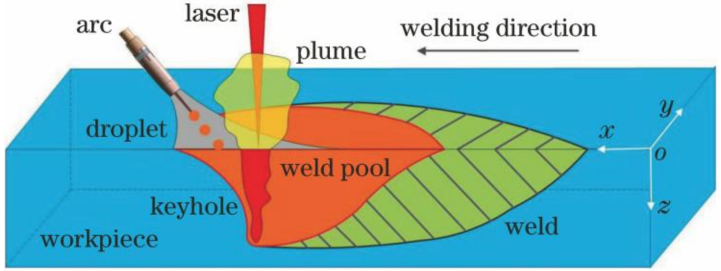
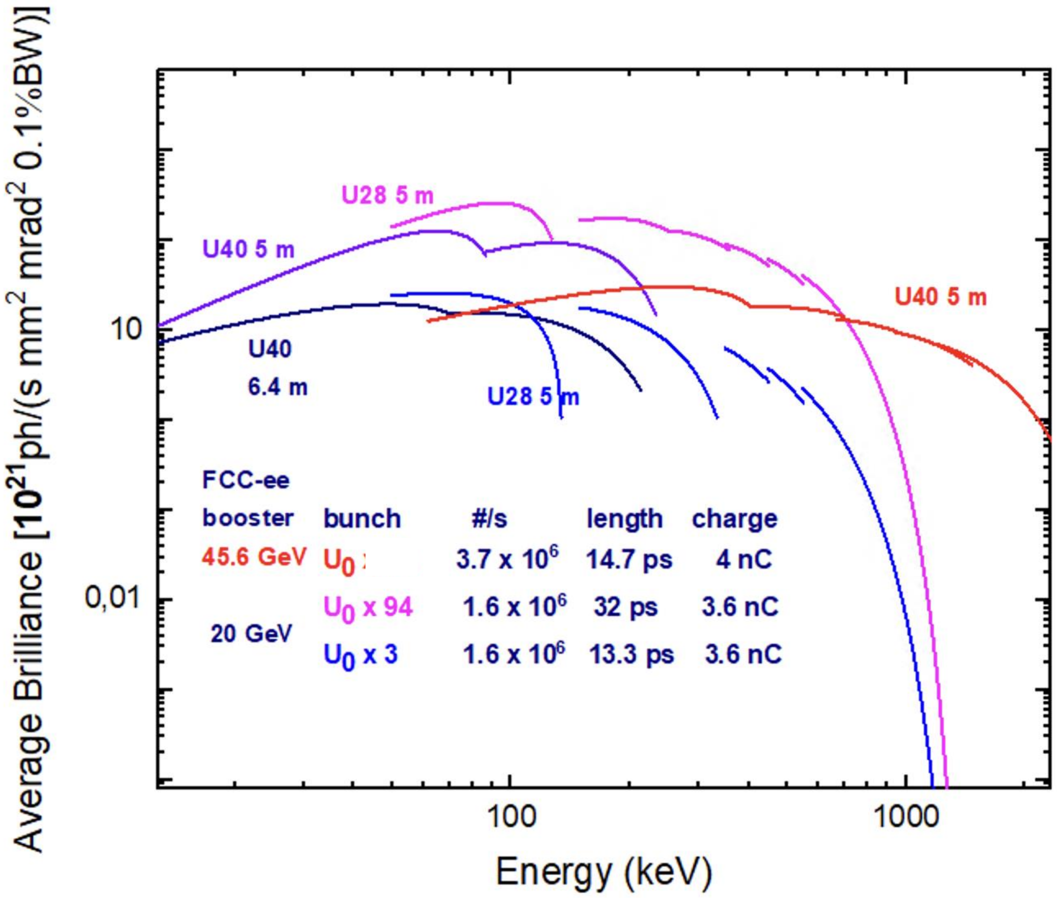


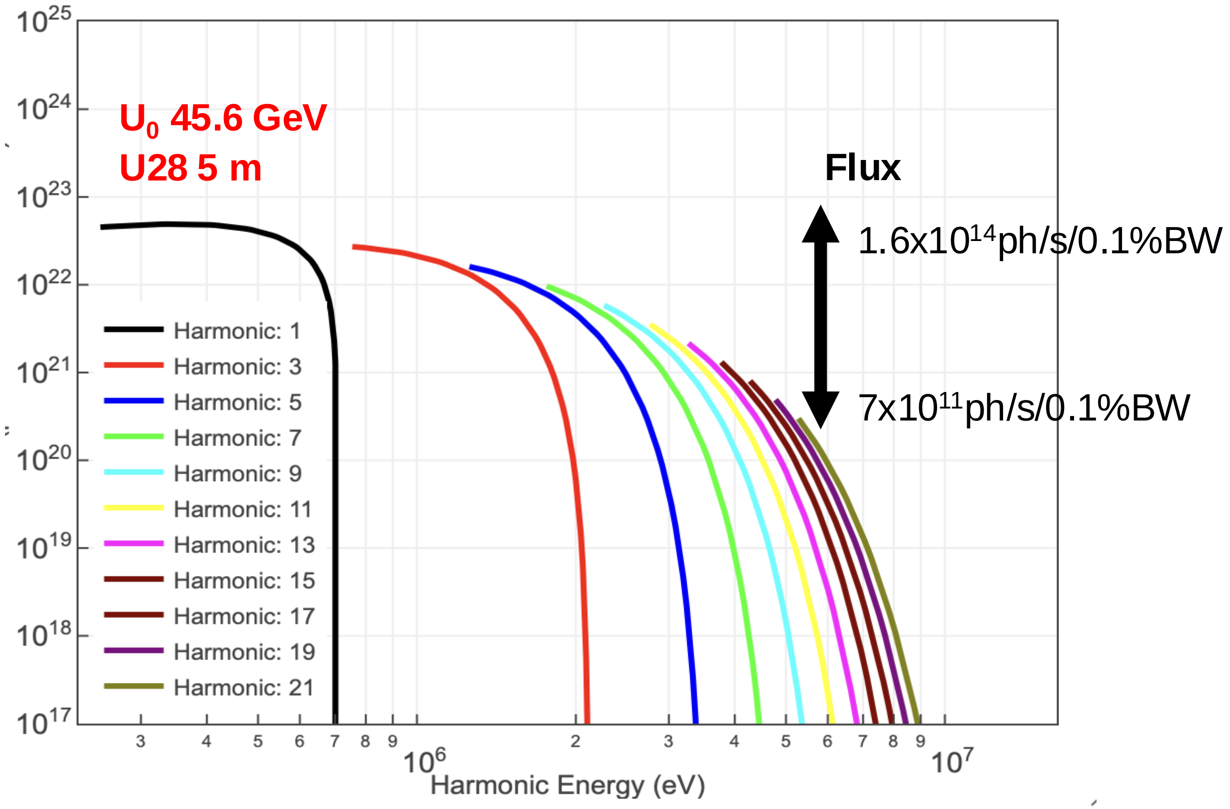
Image source: Chinese Journal of Lasers, Volume. 46, Issue 9, 902003(2019)

Courtesy of Harald Sinn

Above 100 keV up to few MeV



FCC-ee booster	bunch	#/s	length	charge
45.6 GeV	U_0	3.7×10^6	14.7 ps	4 nC
20 GeV	$U_0 \times 94$	1.6×10^6	32 ps	3.6 nC
	$U_0 \times 3$	1.6×10^6	13.3 ps	3.6 nC



U_0 45.6 GeV
U28 5 m

Flux

1.6×10^{14}ph/s/0.1%BW

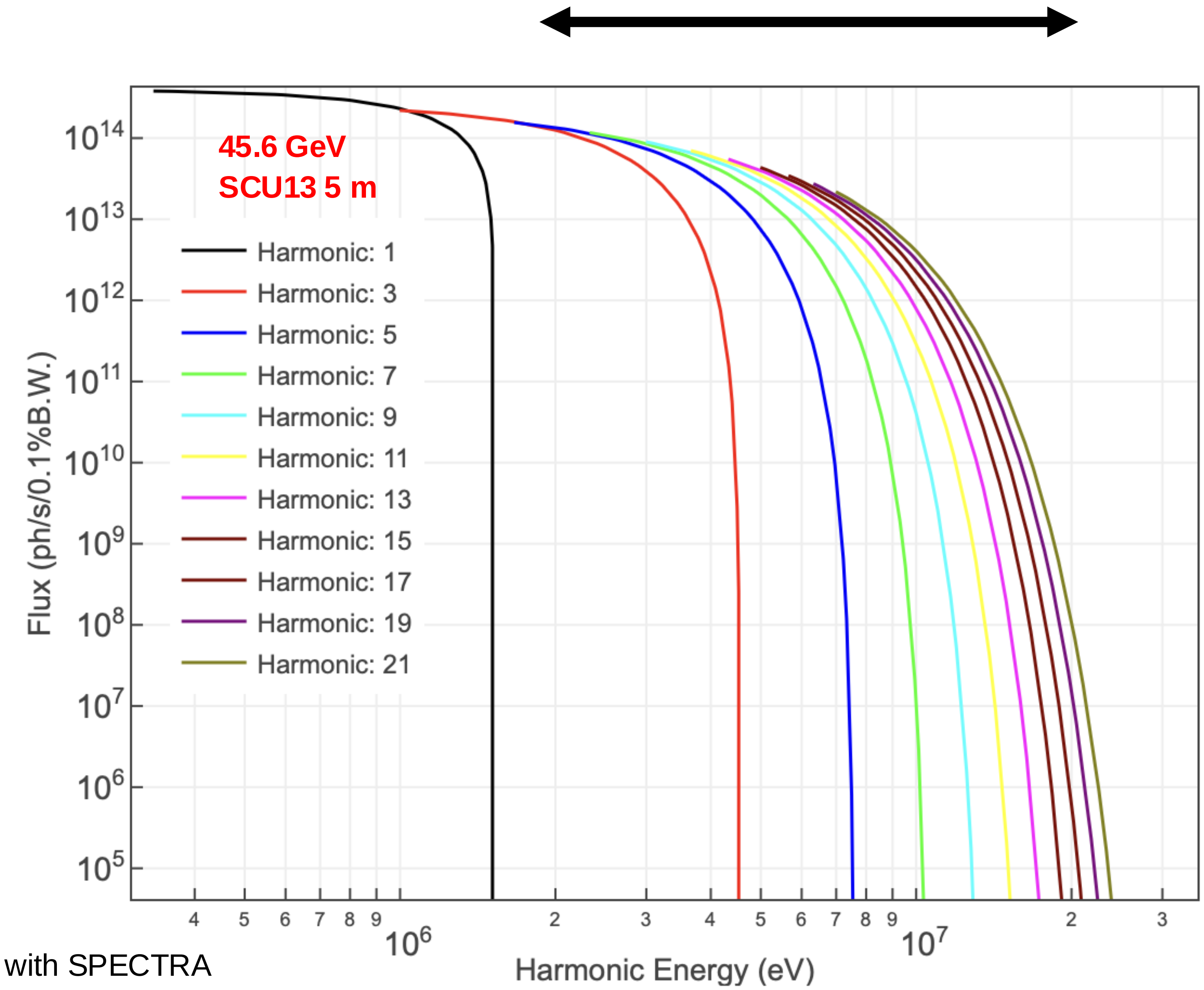
7×10^{11}ph/s/0.1%BW

Simulations performed with SPECTRA
T.Tanaka, JSR (2021). 28, 1267-1272

Eγ < 20 MeV

- **Applications**
  - **Nuclear structure and astrophysics**
  - **Nuclear applications**
  - **Hadronic parity violation**

International workshop on next generation gamma-ray sou
C R Howell et al 2022 J. Phys. G: Nucl. Part. Phys. 49 01



Undulator
High Temperature Superconducting
HTS@4K

Vacuum gap (mm)	**5**
λ_U(mm)	**13**
B_{max} (T)	**2.2**

European XFEL

Simulations performed with SPECTRA
T.Tanaka, JSR (2021). 28, 1267-1272

60 MeV <Eγ < 350 MeV

- Low energy QCD

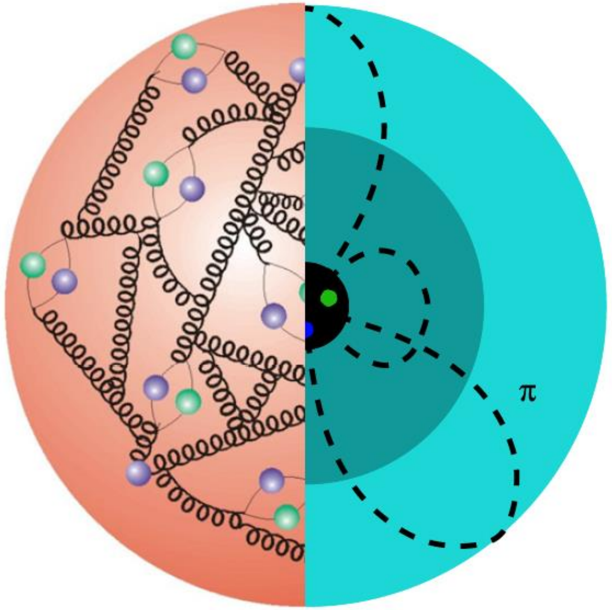


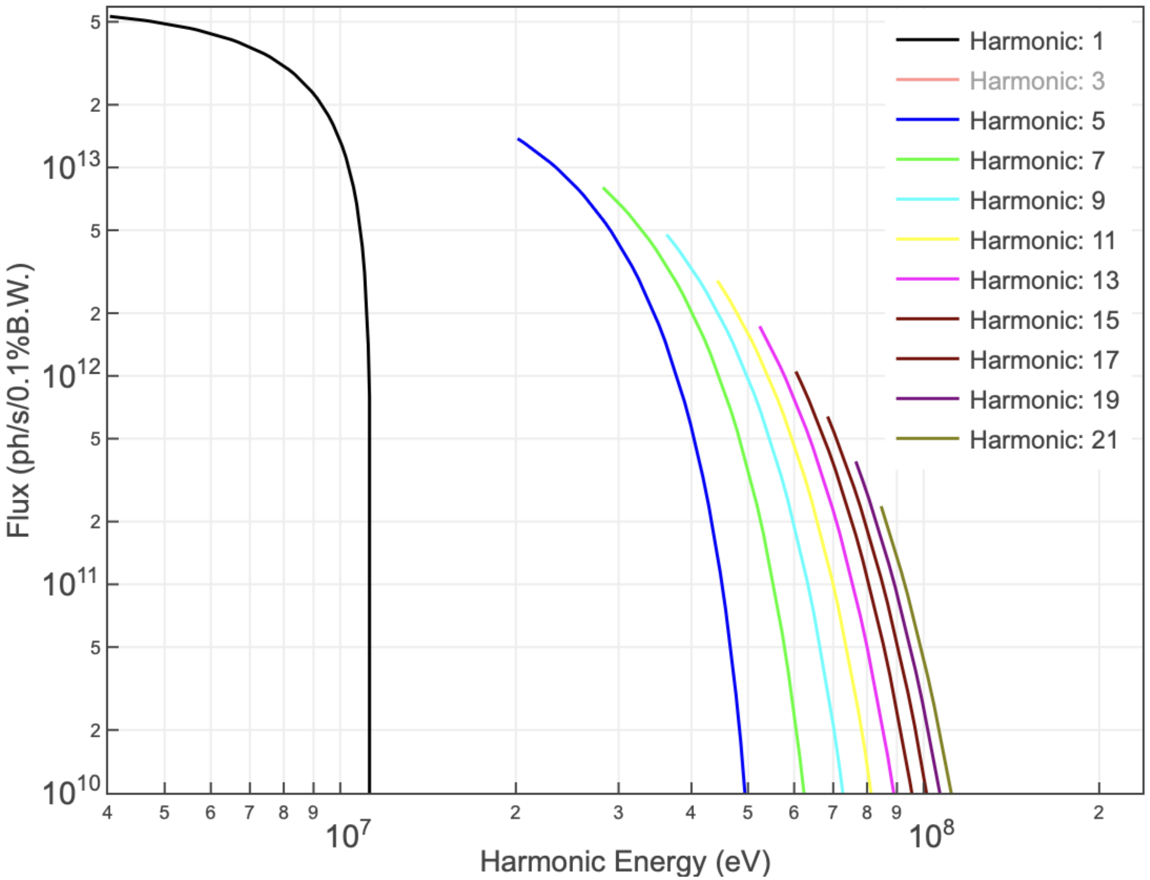
Figure 18. The appropriate degrees of freedom with which to describe nucleon structure depend on the distance scale at which it is probed: quarks and gluons at high energies (left); or nucleons, their pion clouds and nucleonic excitations at low energies (right).

International workshop on next generation gamma-ray source
C R Howell et al 2022 J. Phys. G: Nucl. Part. Phys. 49 010502

In the collider up to 100 MeV

	U_0
beam energy [GeV]	**182.5**
avg. beam current [mA]	**4.9**
Avg. number of bunches	56
rms bunch length [mm]	2.3
rms relative energy spread [10^{-3}]	2
beta at wiggler /undulator [m]	1.6
hor. emittance [pm rad]	**1400**
vert. emittance [pm rad]	**2.8**

🟧 U28 permanent magnet undulator

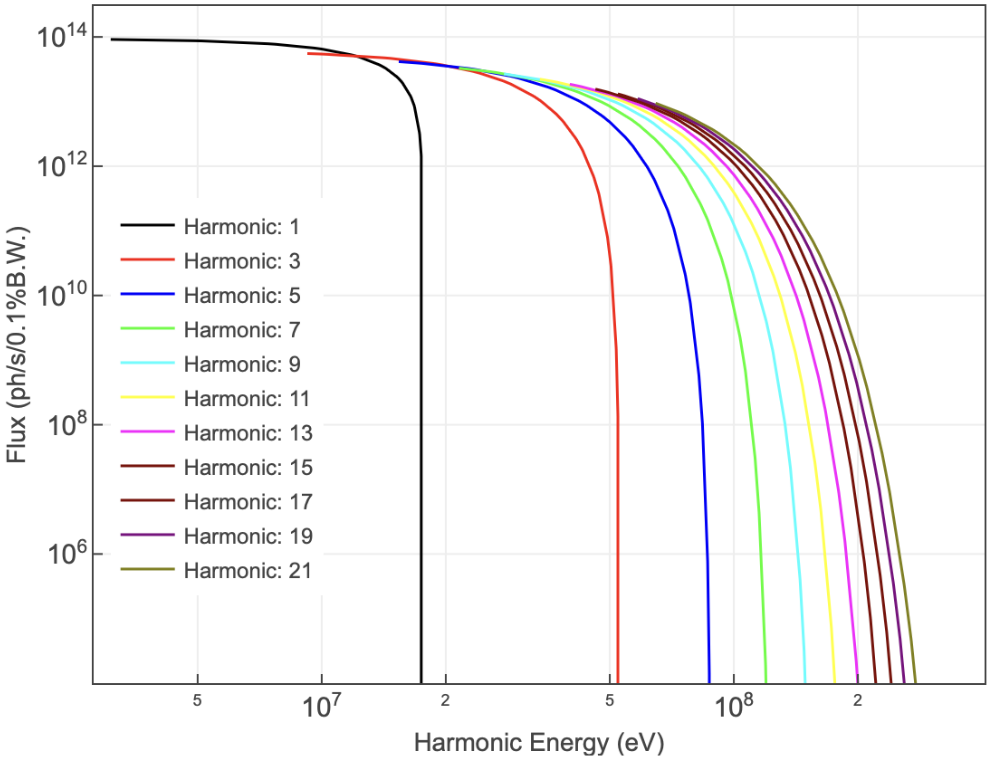


Simulations performed with SPECTRA
T.Tanaka, JSR (2021). 28, 1267-1272

In the collider with SCUs up to 300 MeV

NbTi@4K

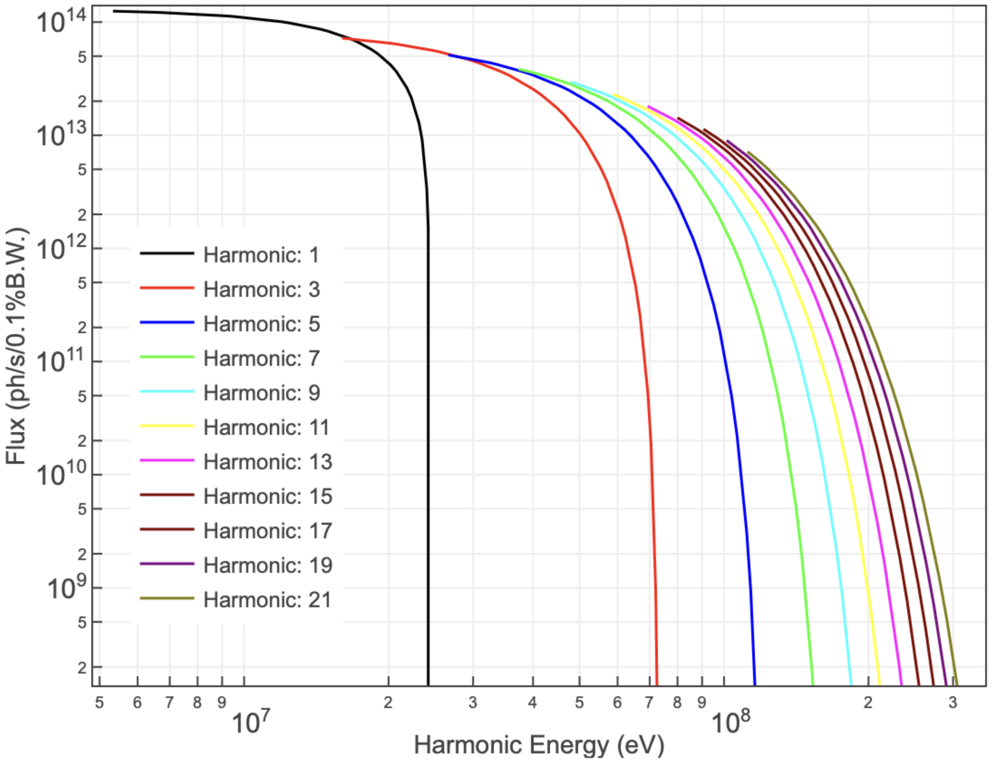
Vacuum gap (mm)	**5**
λ_U(mm)	**18**
B_{max} (T)	**1.83**



HTS@4K

Vacuum gap (mm)	**5**
λ_U(mm)	**13**
B_{max} (T)	**2.2**

Simulations performed with SPECTRA
T.Tanaka, JSR (2021). 28, 1267-1272



XFEL from linac

- Possible parameters after photocathode electron RF gun + damping ring inserting bunch comprressors at positions to be studied
- Doubling the number of klystrons in the high energy linac it’s possible to increase the electron beam energy to 25 GeV
- No show stoppers but more detailed simulations including collective effects are necessary

Electron beam parameters*

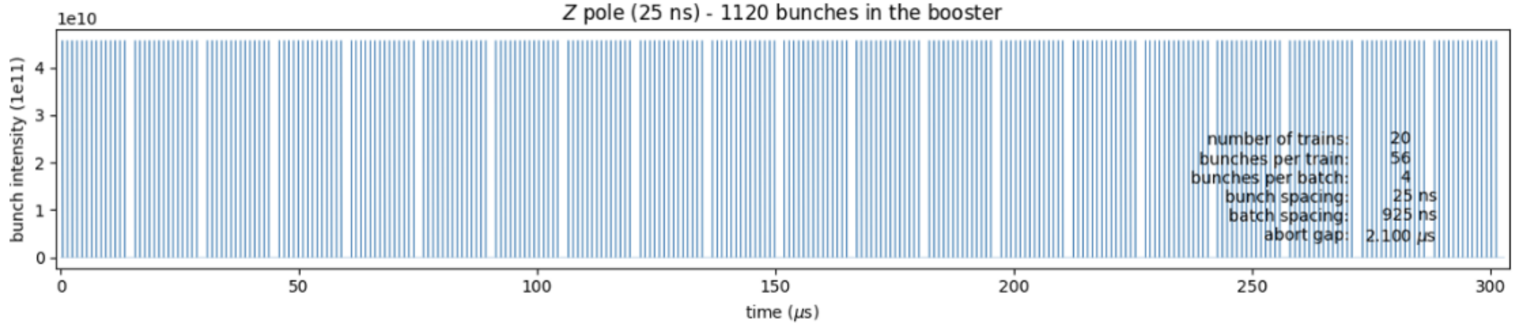
Energy (GeV)	**25**
Bunch length (µm)	**15**
Slice emittance x,y (µm rad)	**0.4**
Bunch charge (pC)	**250**
Slice energy spread	**0.2‰**
Beta_x,y (m)	**30**

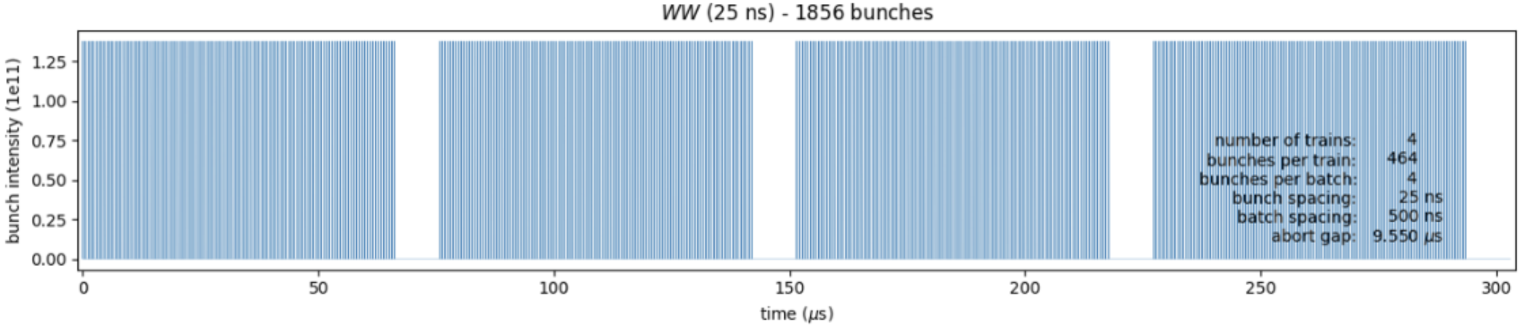
*Courtesy of P. Craievich (PSI)

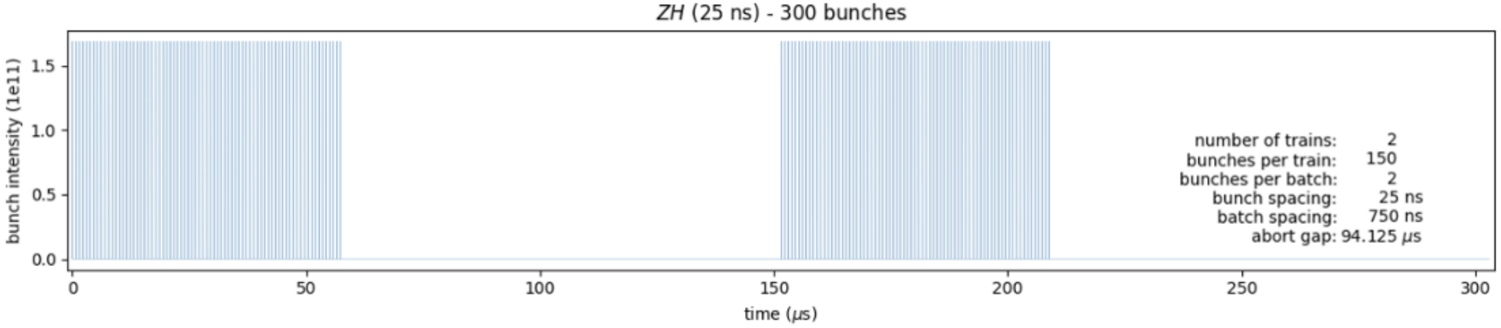
Booster filling patterns

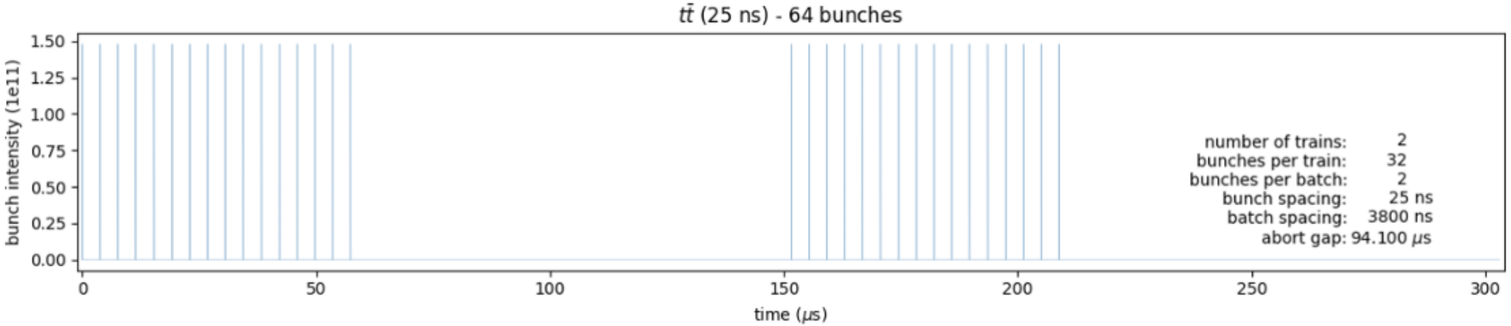
- During injector commissioning: exploratory studies
- Injector can be used as XFEL with WW, ZH and ttbar modes
- Only few bunches can be used in the Z mode for an XFEL (not possible during accumulation at 100 Hz)

To be studied if the abort gap would allow for additional bunches for the XFEL









Plots are courtesy of H. Bartosik

XFEL from linac

Electron beam

Energy (GeV)	**25**
Bunch length (µm)	**15**
Emittance x,y (µm rad)	**0.4**
Bunch charge (pC)	**250**
Energy spread	**0.2‰**
Beta_x,y (m)	**30**

4 bunches separate by 25 ns
at 100 Hz when booster is not in
accumulation mode

Superconducting Undulator

NbTi@4K

Vacuum gap (mm)	**5**
λ_U(mm)	**18**
B_{max} (T)	**1.83**

L_{sat}(m)	**85 m**
$Energy_{min}$ (keV)	**60**
Pulse energy (mJ)	**0.95**

HTS@4K

Vacuum gap (mm)	**5**
λ_U(mm)	**13**
B_{max} (T)	**2.2**

L_{sat}(m)	**100**
$Energy_{min}$ (keV)	**100**
Pulse energy (mJ)	**0.4**

- To be studied if possible to increase up to trains 100 ns long with > 4 bunches

European XFEL

Calculations with Ming Xie'snFEL formula in SIMPLEX,
T. Tanaa J Synchrotron Radiations 2015, 22(5) 1319-26

Conclusions

- With respect to PETRA IV, planned diffraction limited storage ring with smallest emittance, the FCC-ee booster has the potential to produce at 50-100 keV
  - a fraction of coherent X-rays larger by one order of magnitude
  - an average brilliance larger by up to two orders of magnitude
  - a peak brilliance larger by up to four orders of magnitudes

Conclusions

- Use the booster at collision energy or the collider to produce photons up to 20 MeV for
  - Nuclear structure and astrophysics
  - Nuclear applications
  - Hadronic parity violation

and from 60 to 300 MeV for low energy QCD

- The injector with superconducting undulators could be used as XFEL for producing hard to very hard X-rays with pulse energy ~mJ. This would be possible mainly for WW, ZH and ttbar modes

Outlook

To be further studied the compatibility of:

- the use of the FCC-ee booster for the collider and requirements from possible users
- the parameters of the FCC-ee injector used as a linac-based XFEL

Thank you for your attention !