FCC-ee booster as a Light Source

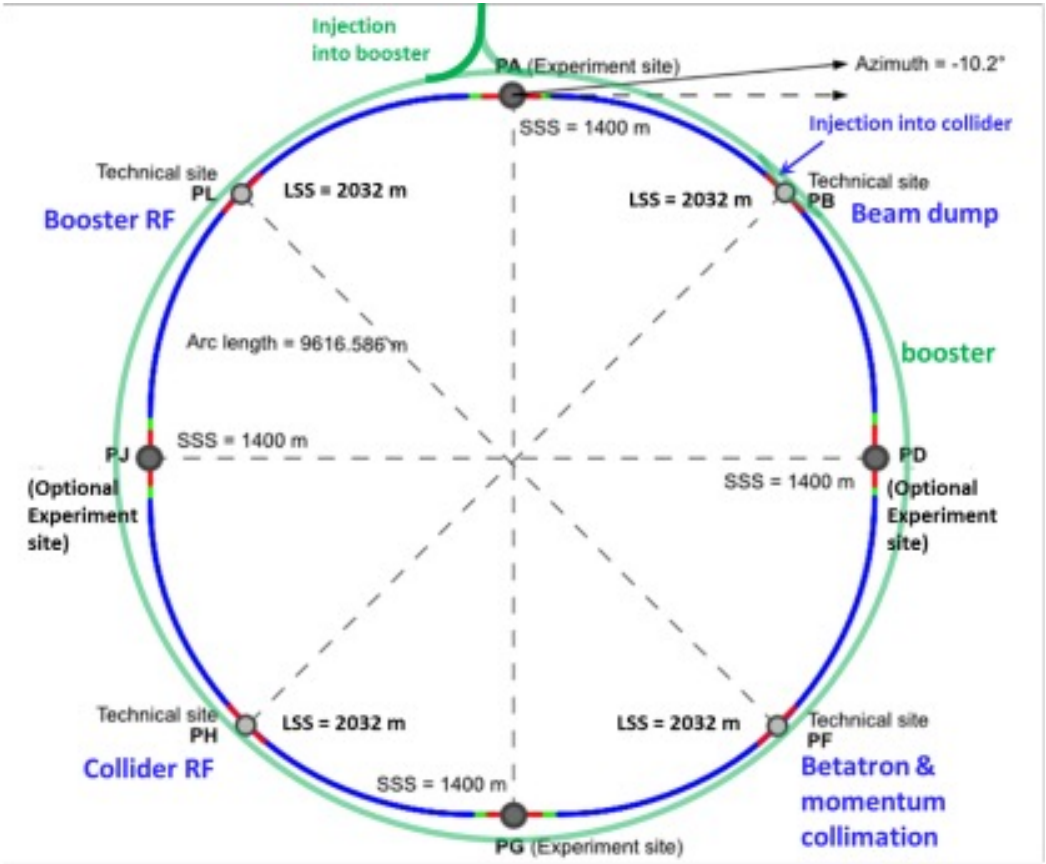
Sara Casalbuoni (European XFEL) and Frank Zimmermann (CERN)

Non collider science opportunities at FCC-ee | kickoff brainstorm
23 August 2024

Outline

- FCC-ee booster
- Diffraction limited storage rings
  - Small emittance ➡ high brilliance and high coherent flux
- Average and peak brilliance: FCC-ee booster versus PETRA IV and EuXFEL
- Conclusions

FCC-ee booster



Present parameters used for study of FCC-ee booster as photon source

	U_0 x 3	**U_0 x 94**
beam energy [GeV]	**20**	**20**
avg. beam current [mA]	**6**	**6**
number of bunches	1120	1120
rms bunch length [mm]	7.9	9.5
rms relative energy spread [10^{-3}]	1.8	2.2
beta at wiggler /undulator [m]	1.6	1.6
wiggler field [T]	1	1
wiggler period [mm]	40	40
magnetic gap [mm]	10	10
tot. length wiggler [m]	6.4	264
hor. emittance [pm rad]	**15**	**0.5**
vert. emittance [pm rad]	**<1.5**	**<0.05**

circumference = 90.7 km

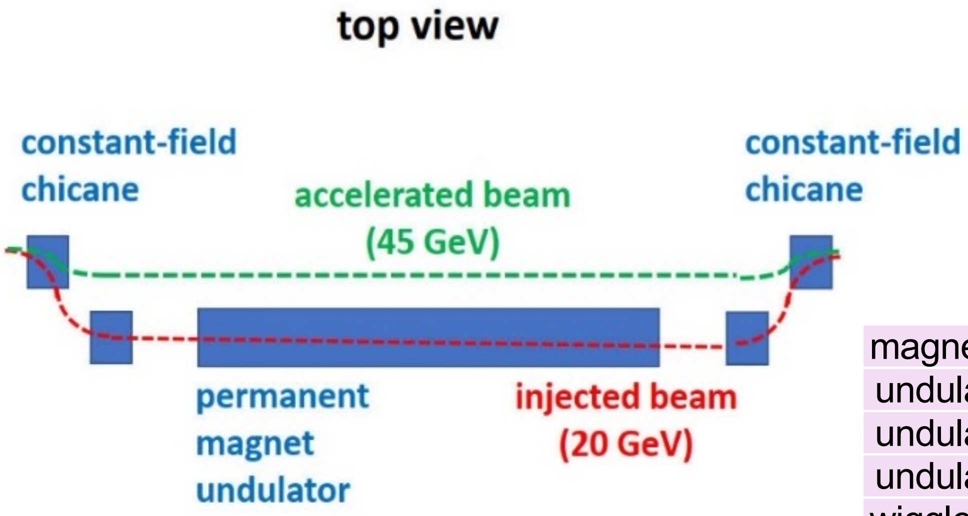
without wigglers

U_0 = energy loss / turn = 1.33 MeV

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

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

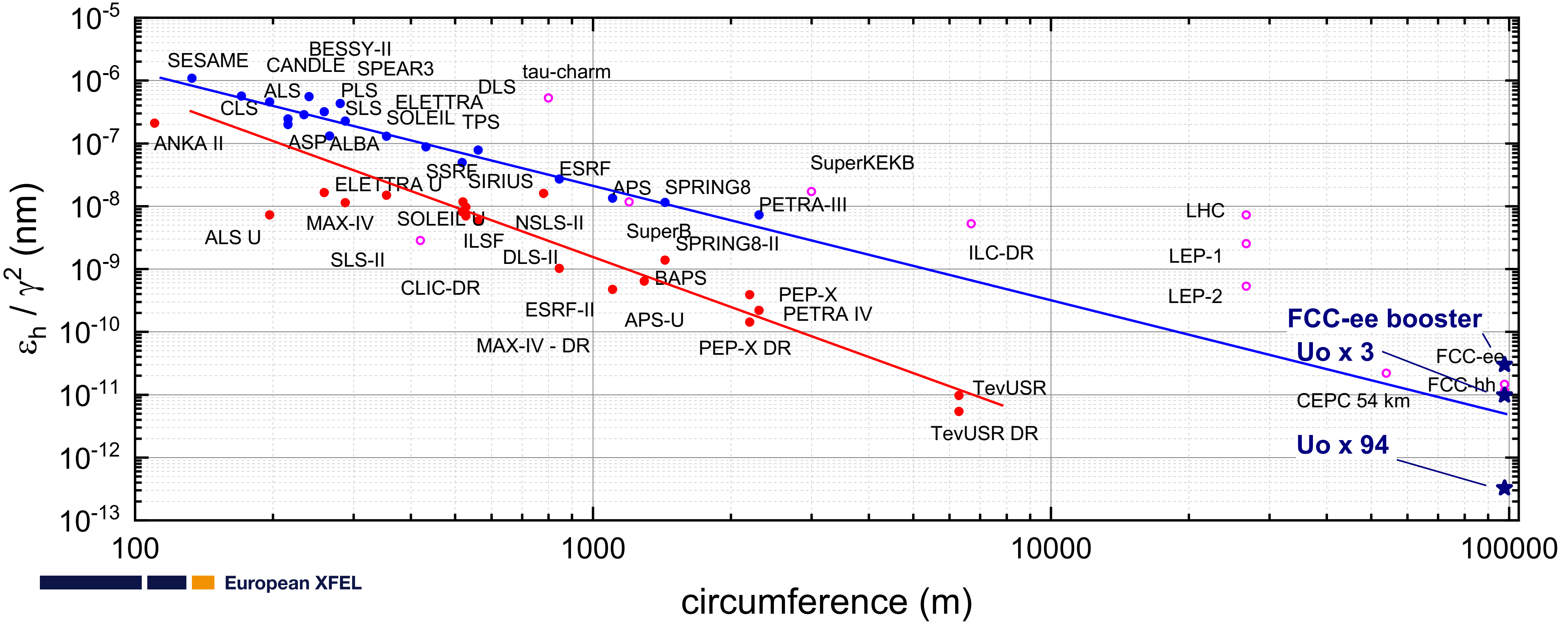
magnetic gap [mm]	10	
undulator field [T]	0.71-0.32	
undulator period [mm]	28	
undulator unit length [m]	5	
wiggler field [T]	1	
wiggler period [mm]	40	
	U_0 x 3	U_0 x 94
wiggler unit length [m]	6.4	5

U28

U40

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



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 Å ($< 120\ eV$) $\Rightarrow \varepsilon_x \approx 0.8$ nm rad (ESRF, APS, PETRA III)

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

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

> 0.1 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

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

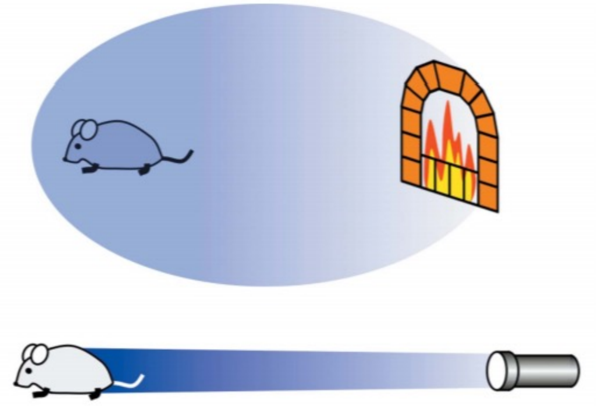
σ = rms beam size
σ' = rms beam divergence

Source dimension and divergence

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

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

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



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

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

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

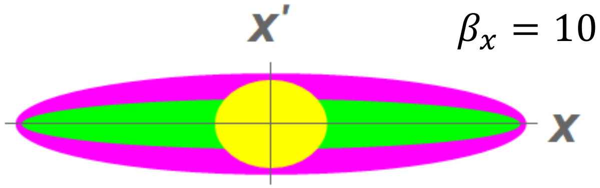
- For $\varepsilon_{x,y} \approx \varepsilon_{ph}$ brilliance maximized when the electron and photon beam phase spaces are matched

$$\beta_{x,y} = \frac{\sigma_{ph}}{\sigma'_{ph}} = L/\pi \qquad Brilliance = \frac{Flux}{4\pi^2(\varepsilon_x+\varepsilon_{ph})(\varepsilon_y+\varepsilon_{ph})} \approx \frac{Flux}{\lambda^2}$$

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

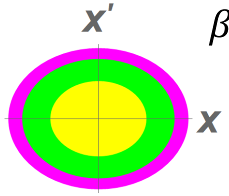
PETRAIV: undulator length $= L = 4\ m$ $\varepsilon_x = 20$ pm rad for 1 Å $\varepsilon_{ph} = 8$ pm rad

$\beta_x = 10$ 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

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

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

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

Without dispersion

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

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

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

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

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

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

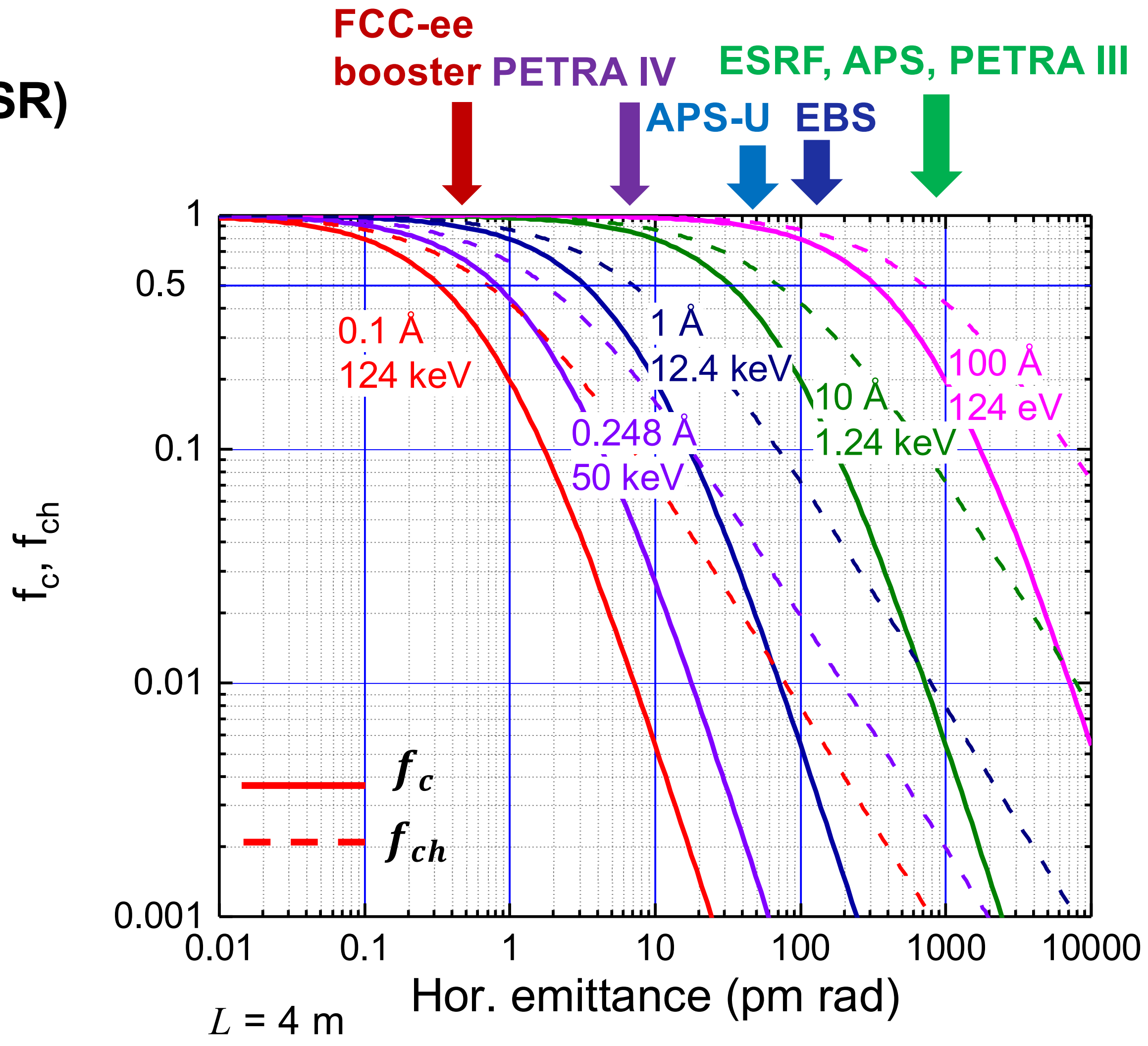
Fraction of X-rays transversally coherent

round beam, DLSR

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

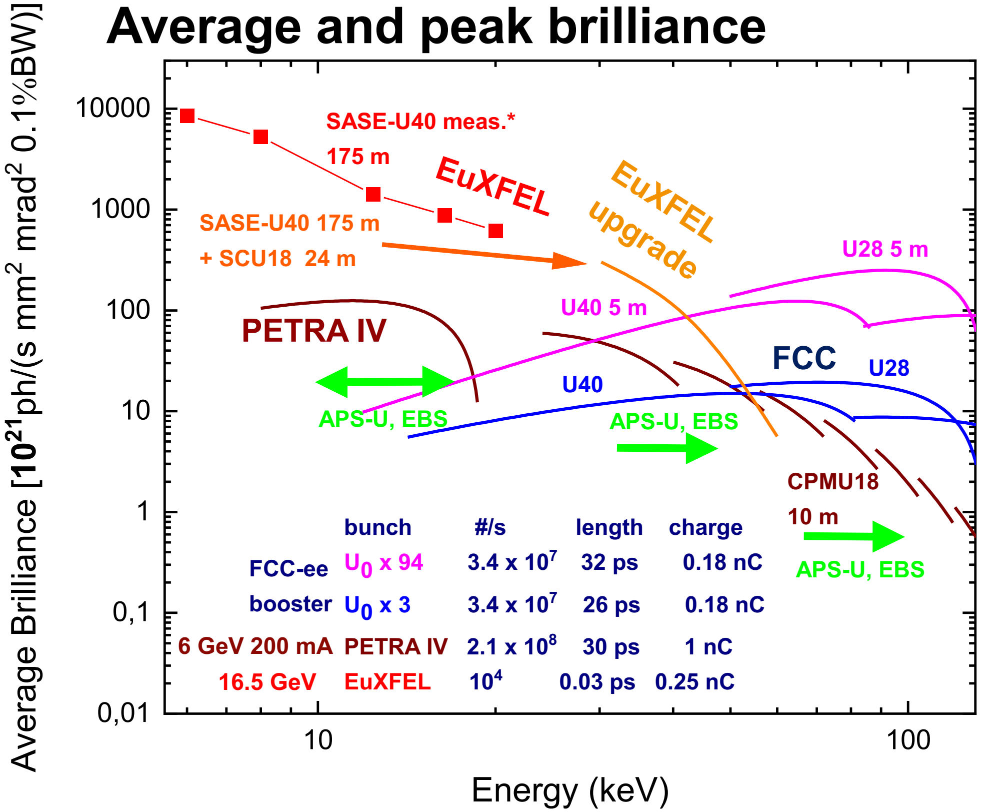
flat beam, FCC-ee booster

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

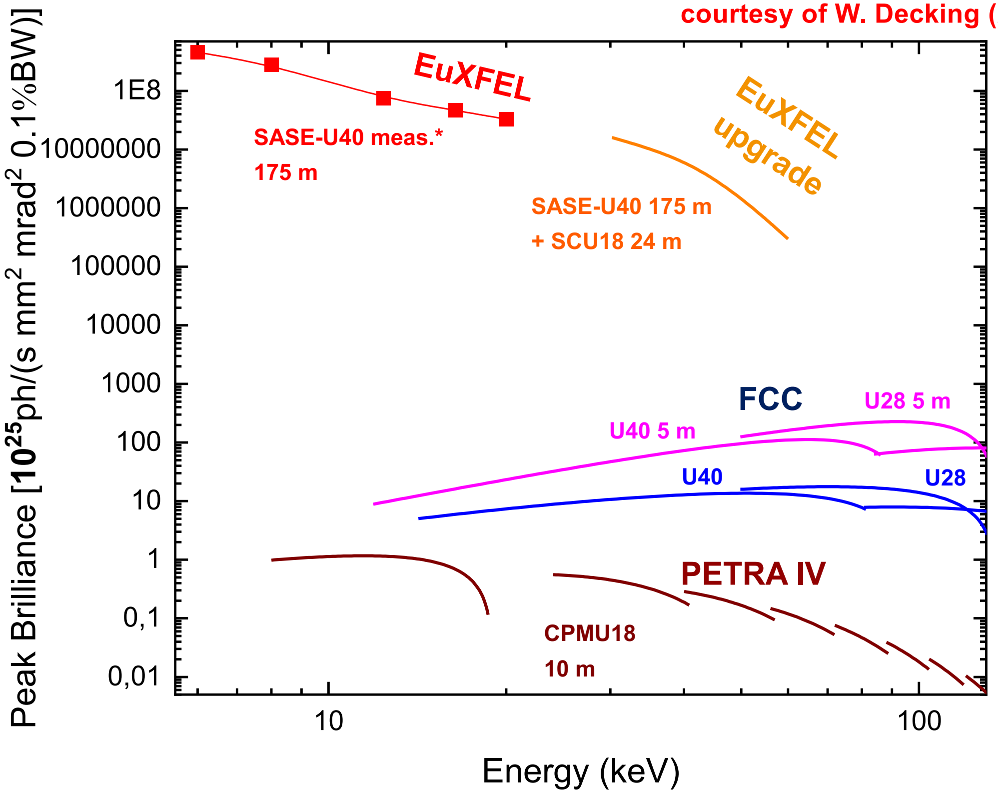


Average and peak brilliance

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



	bunch	#/s	length	charge
FCC-ee	U_0 x 94	3.4 x 10^7	32 ps	0.18 nC
booster	U_0 x 3	3.4 x 10^7	26 ps	0.18 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



■ high average brilliance ➡ flux hungry experiments

■ high peak brilliance ➡ time resolved experiments

Conclusions

- With respect to PETRA IV, planned diffraction limited storage ring with smallest emittance, the FCC-ee booster has the potential to produce
  - a fraction of coherent X-rays larger by one order of magnitude at 50-100 keV
  - an average brilliance larger by up to two orders of magnitude at 50-100 keV
  - a peak brilliance larger by up to four orders of magnitudes
- The compatibility of the use of the FCC-ee booster for the collider and requirements from possible users shall be further studied

Thank you for your attention !