FCC-ee booster as ultimate storage ring photon source

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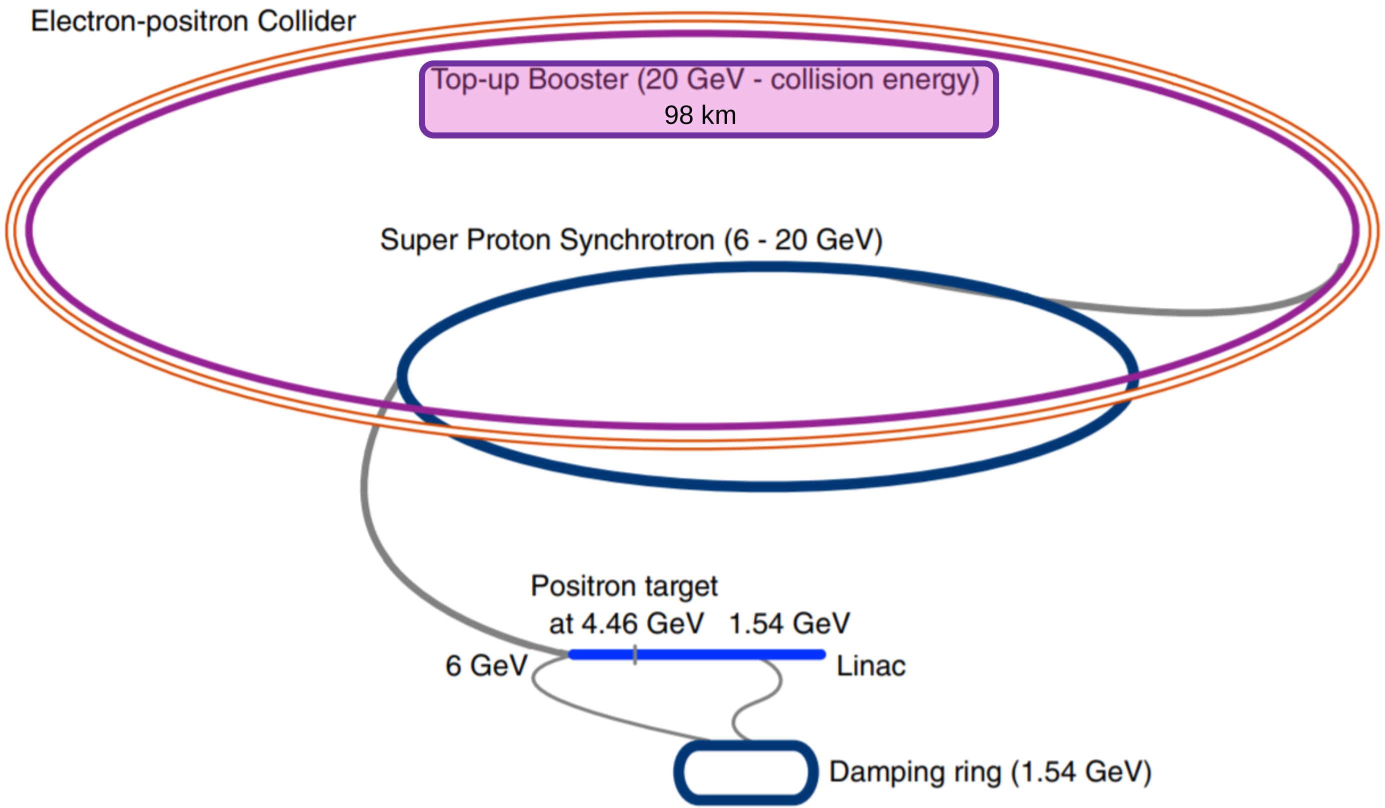
Outline

- FCC-ee booster
- Diffraction limited storage rings
  - Small emittance → high brilliance and high coherent flux
- Superconducting undulator afterburner at EuXFEL
- Average and peak brilliance: FCC-ee booster versus PETRA IV and EuXFEL
- Conclusions

FCC-ee booster



Abada, A., Abbrescia, M., AbdusSalam, S.S. *et al.* FCC-ee: The Lepton Collider. *Eur. Phys. J. Spec. Top.* 228, 261–623 (2019). https://doi.org/10.1140/epjst/e2019-900045-4

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]	**50**	**50**
bunch population [10^{10}]	2	2
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**

without wigglers

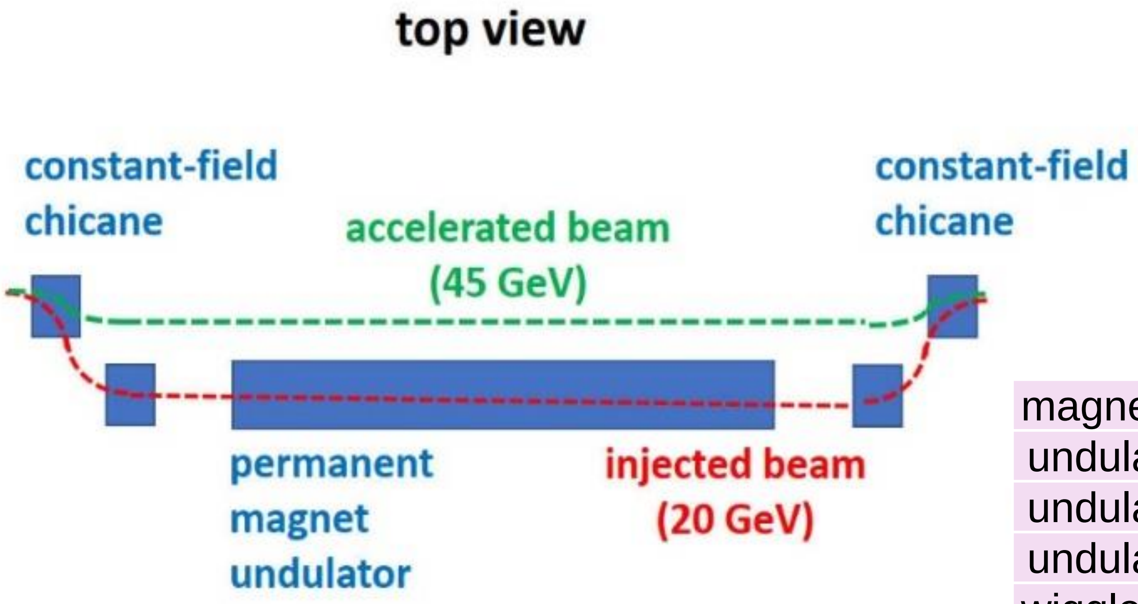
U_0 = energy loss / turn = 1.33 MeV

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

Different injection and operation modes are still open to considerations

FCC-ee booster operated as photon source

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



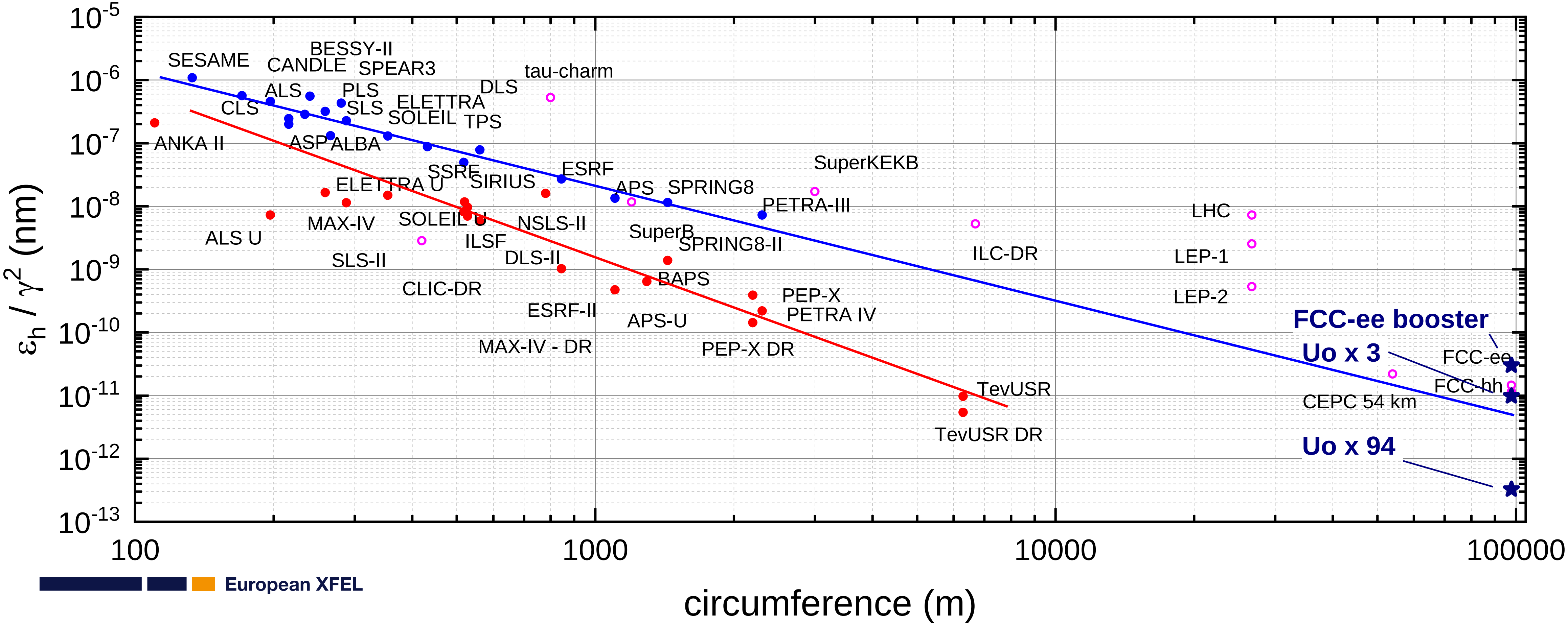
- **U_0 x 3 : 1 U40 6.4 m → ε_x = 15 pm rad**
- **U_0 x 94 : 53 U40 5 m → ε_x = 0.5 pm rad**

Permanent magnet technology

magnetic gap [mm]	10		
undulator field [T]	0.71-0.32		
undulator period [mm]	28		**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	

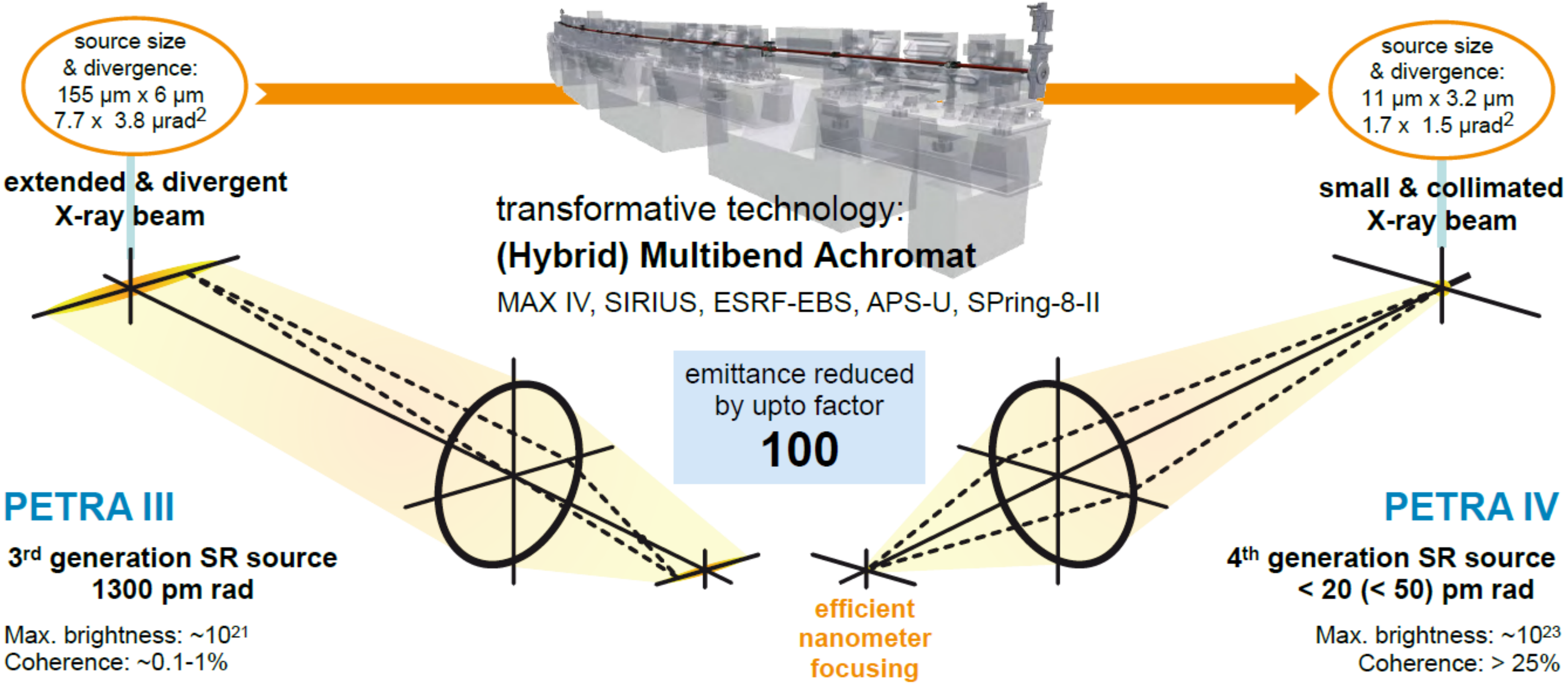
Horizontal emittance versus circumference

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



Ultimate 3-D microscope

- The electron beam cross section of is very small and well collimated, **the X-ray beam can be nanofocused almost free of loss up to an X-ray energy of 10 keV**



source size
& divergence:
155 μm x 6 μm
7.7 x 3.8 μrad^2

extended & divergent X-ray beam

transformative technology:
(Hybrid) Multibend Achromat
MAX IV, SIRIUS, ESRF-EBS, APS-U, SPring-8-II

source size
& divergence:
11 μm x 3.2 μm
1.7 x 1.5 μrad^2

small & collimated X-ray beam

emittance reduced by upto factor
100

PETRA III

3rd generation SR source
1300 pm rad

Max. brightness: $\sim 10^{21}$
Coherence: ~0.1-1%

efficient nanometer focusing

PETRA IV

4th generation SR source
< 20 (< 50) pm rad

Max. brightness: $\sim 10^{23}$
Coherence: > 25%

Upgrade of PETRA III to the Ultimate 3D X-ray Microscope
Conceptual Design Report
https://bib-pubdb1.desy.de/record/426140/files/DESY-PETRAIV-Conceptual-Design-Report.pdf

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

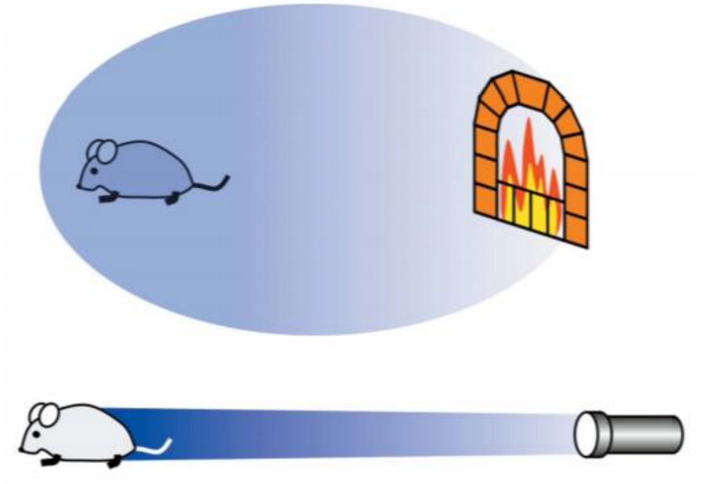
Source dimension and divergence

Without dispersion

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

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

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



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

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

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

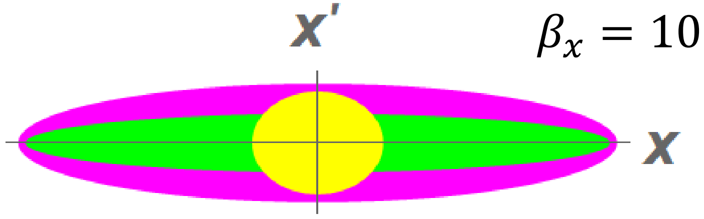
- For $\varepsilon_{x,y} \approx \varepsilon_{ph}$ brilliance maximized when the electron and photon beam phase spaces are matched

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

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

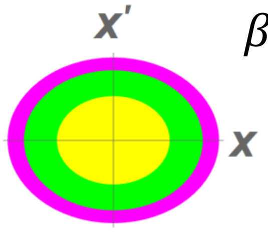
σ_{ph}	σ'_{ph}	ε_{ph}	$\beta_{ph} = \sigma_{ph}/\sigma'_{ph}$
$\sqrt{\lambda/4L}$	$\sqrt{\lambda L}/2\pi$	$\lambda/4\pi$	L/π

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

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

Without dispersion

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

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

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

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

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

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

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

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

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

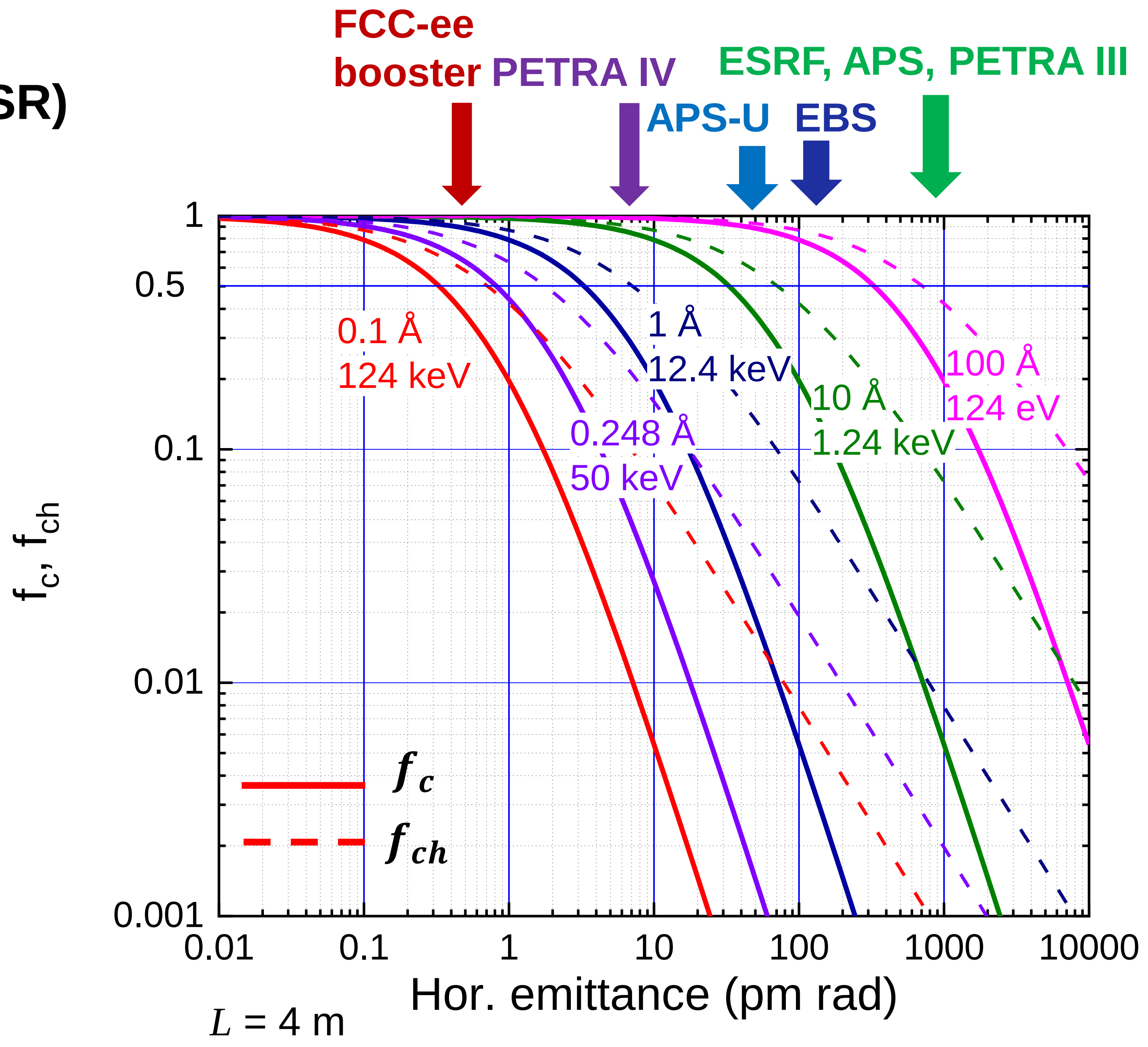
Fraction of X-rays transversally coherent

round beam, DLSR

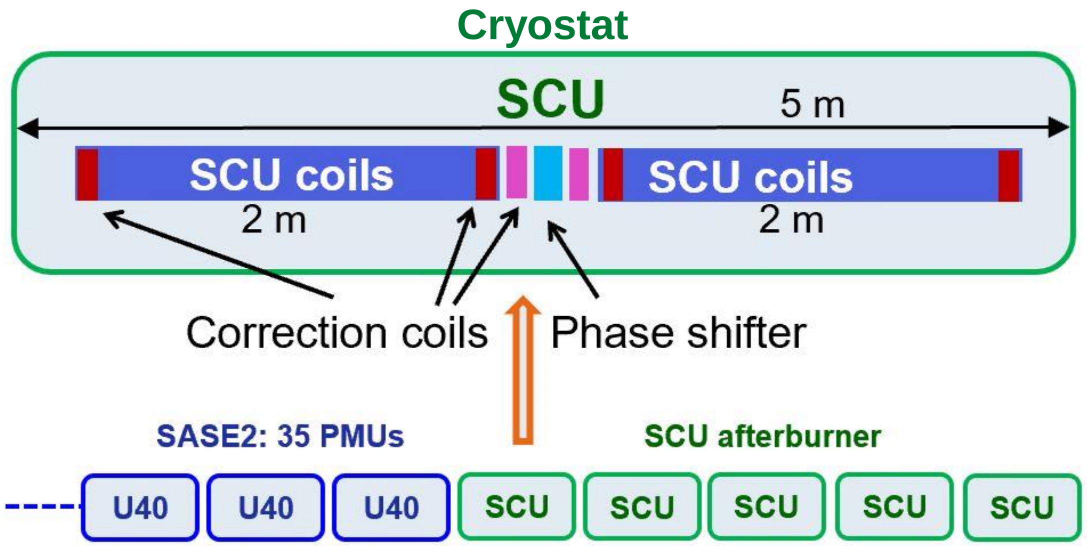
$$f_c = \frac{\left(\lambda/_{4\pi}\right)^2}{\left(\varepsilon \cdot \frac{L}{\pi} + \frac{\lambda L}{4\pi^2}\right)\left(\varepsilon \cdot \frac{\pi}{L} + \frac{\lambda}{4L}\right)}$$

flat beam, FCC-ee booster

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



SCU afterburner

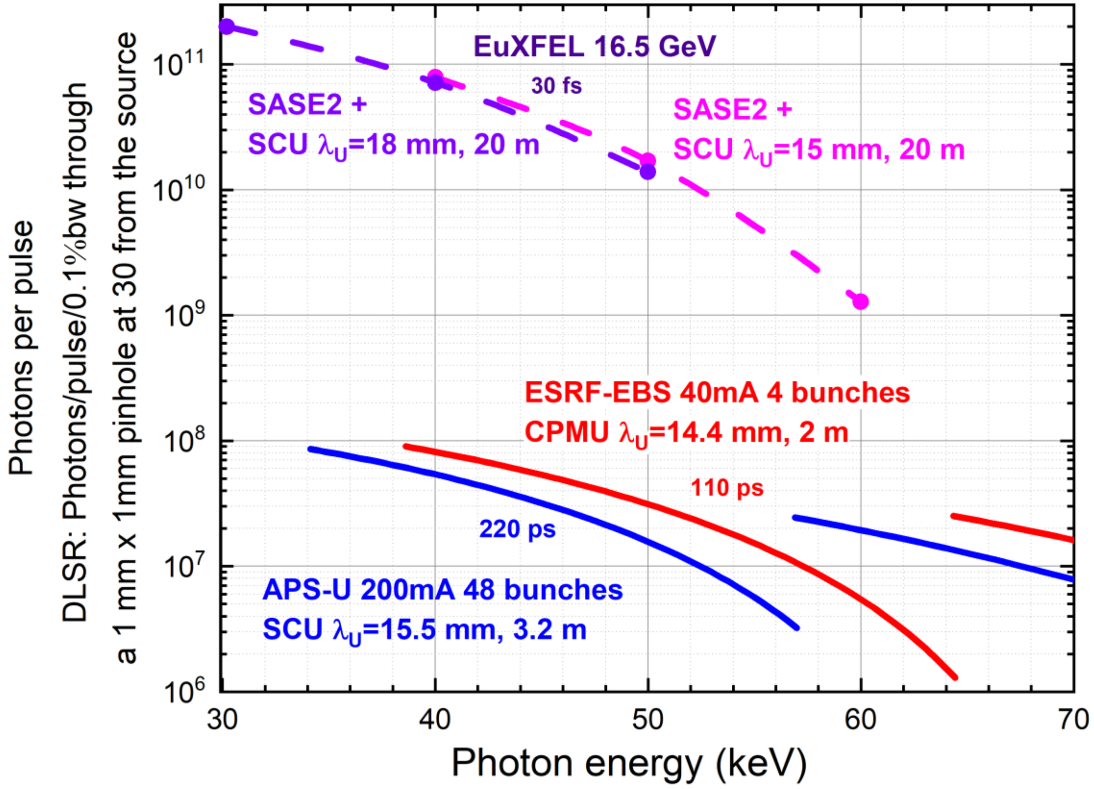


- The degree of transverse coherence of the flux produced by the SCU afterburner at EuXFEL is about an order of magnitude larger than the one obtainable at the diffraction limited storage rings (DLSR)

S.Casalbuoni et al., WEPAB132, IPAC21

Normalized emittance	0.4 mm mrad
Initial energy spread	3 MeV
Current	5 kA

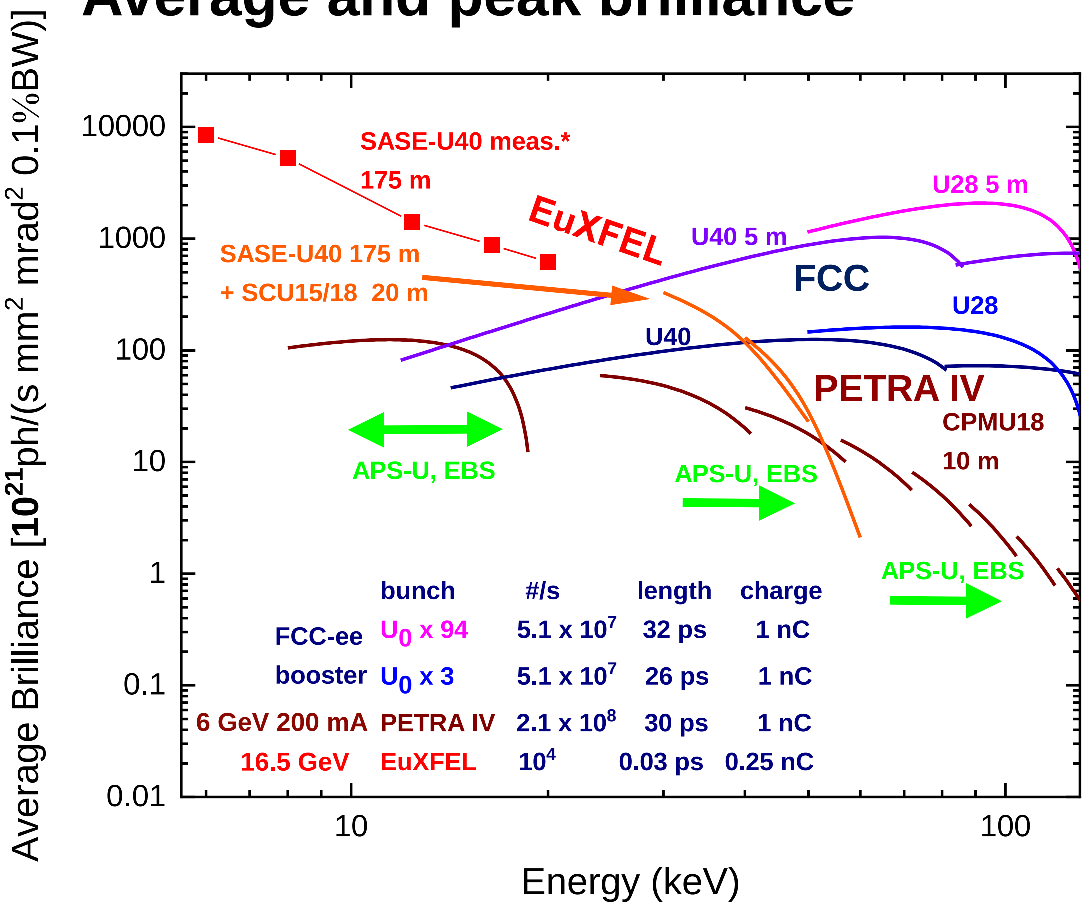
The simulations do not consider wakefields, synchrotron radiation losses and tapering



- The SCUs further amplify on their fundamental, the output of the fundamental of the PMUs

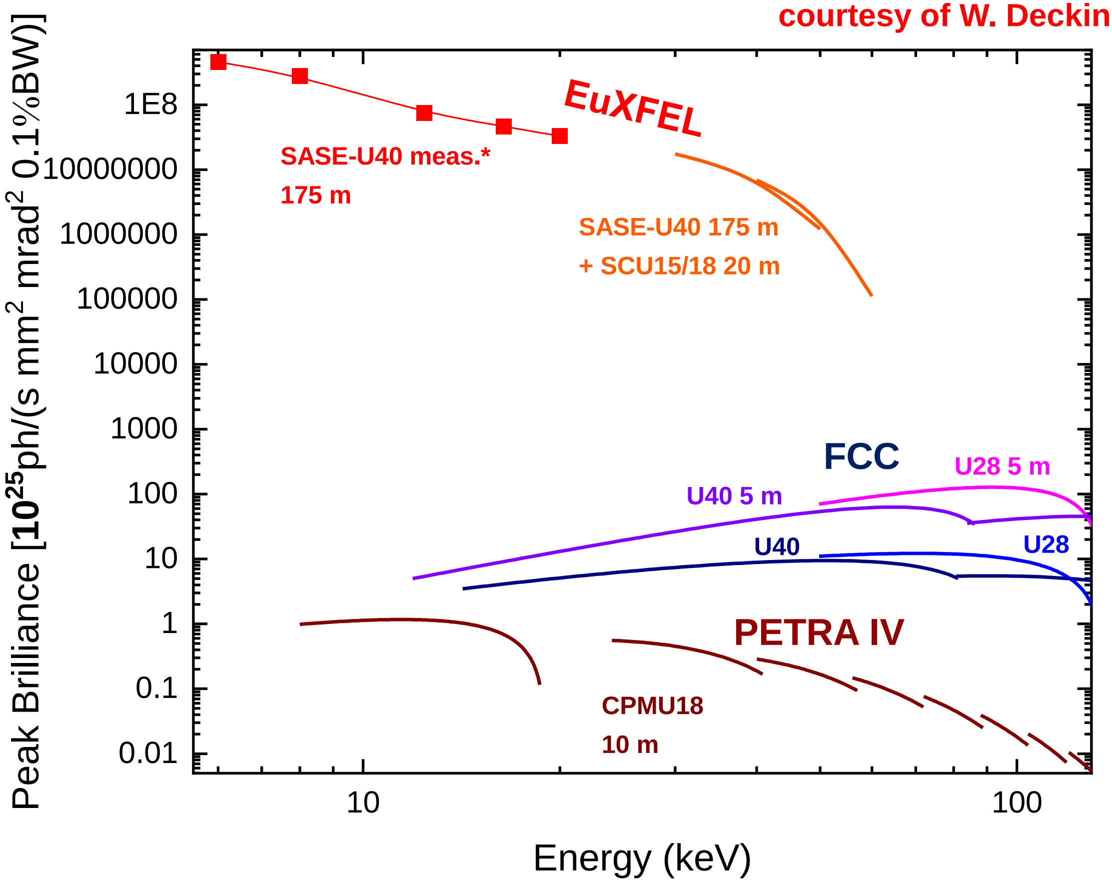
- At higher photon energies the SCU afterburner will still be tuned on Its fundamental. Schemes for amplifying and/or using the bunching of the higher harmonics produced by the SASE PMUs are under study

Average and peak brilliance



	bunch	#/s	length	charge
FCC-ee	U_0 x 94	5.1 x 10^7	32 ps	1 nC
booster	U_0 x 3	5.1 x 10^7	26 ps	1 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**



- FCC-ee booster highest average brilliance > 30 keV → flux hungry experiments
- EuXFEL with SCU afterburner complementary with highest 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
  - an average brilliance larger by up to three order of magnitudes at 100 keV
  - a fraction of coherent X-rays larger by one order of magnitude at 50-100 keV
- 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 !

Synergetic use of the FCC-ee collider and its injector complex for other applications

Non-perturbative QED Experiments – proving the boiling of the QED vacuum

	LUXE*	FCC-ee linac	FCC-ee booster
Beam energy [GeV]	14 (17)	20	20 or 45.6
Conversion	bremsstrahlung	bremsstrahlung	Laser back Compton
Bunch charge [nC]	0.25 (1)	3	3 (only fraction converted to g)
Number of bunches	1	2 or 4	up to 16,000
Repetition rate [Hz]	1 (10)	200	3,000
Rms spot size [mm]	5	3 (1 cm β)	30

The FCC-ee injector complex can generate high rates of high-energy photons either by sending bunches from the linac against a target via bremsstrahlung, as in the proposed LUXE experiment*, or, via laser Compton backscattering off bunches in the booster. These high-energy photons are then collided with low energy photons from an intense laser 10^{14} V/m. Above the Schwinger limit (non-perturbative QED) electron and positrons pairs are created via the Breit-Wheeler process

$$\mathcal{E}_{\mathrm{cr}} = m_e^2 c^3/(e\hbar) = 1.32 \cdot 10^{18}\ \mathrm{V/m}.$$

$$\gamma + n\gamma_L \rightarrow e^+ e^-$$

Pair production rate

$$\Gamma_{\mathrm{BW}} \propto \left(\frac{\mathcal{E}_{\mathrm{L}}}{\mathcal{E}_{\mathrm{cr}}}\right)^2 \exp\left[-\frac{8}{3}\frac{1}{\gamma_e(1+\cos\theta)}\frac{\mathcal{E}_{\mathrm{cr}}}{\mathcal{E}_{\mathrm{L}}}\right]$$

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* H. Abramowicz et al., CDR LUXE, https://arxiv.org/pdf/2102.02032.pdf

Synergetic use of the FCC-ee collider and its injector complex for other applications

- **Compton Backscattering Source for nuclear physics studies**

	ELI-NP	FCC-ee-CBS-20	FCC-ee-CBS-45
beam energy [GeV]	0.72	20	45.6
average beam current [A]	0.8x10^{-6}	0.15	0.15
beam size at laser CP [mm]	~0.5	~0.5	~0.5
max photon energy [GeV]	0.02	14	73
photon flux [1/s]	10^9	~10^{14}	~10^{14}

- **Positron source for material research and positron plasma acceleration studies**