NON COLLIDER SCIENCE OPPORTUNITIES AT FCC-ee

Frank Zimmermann

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

Past studies

brainstorming in July 2020

- Michael Benedikt, Sara Casalbuoni (EU-XFEL), Michael Doser, Frank Zimmermann

1. Photon science

1.1 FCC-LS : The world's most powerful light source for very hard X-rays

1.2 FCC-CBS: 3-5 orders of magnitude more flux and higher photon energy than ELI-NP

2. Other applications

2.1 Positron source for material research

2.2 Testbed for LEMMA muon collider

2.3 Plasma acceleration of positrons

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

2.5 Positronium-based GeV photon source – a speculative proposal

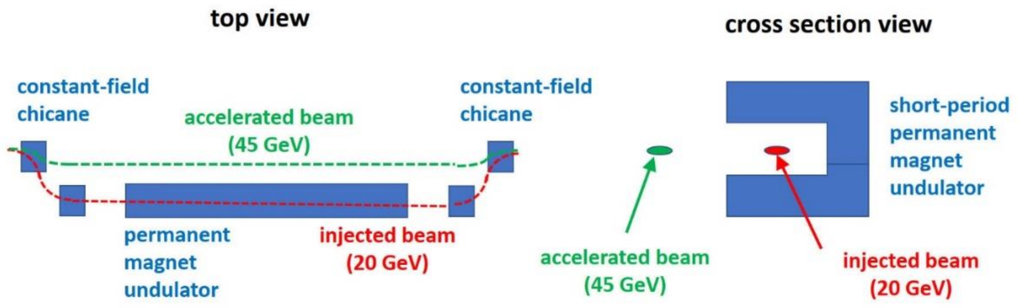
Documented in M. Benedikt, F. Zimmermann, M. Doser, S. Casalbuoni, 10.5281/zenodo.7675663

Photon Science: FCC-LS – motivation

The large FCC-ee rings are outstanding: **high beam current** (1.5 A in the collider, ~10 mA average current in the full-energy booster, to be compared with 30 μA at the European XFEL, a difference by many orders of magnitude), and an **extremely low emittance**.

Photon energies from an undulator or wiggler increase as γ^2. Radiation remains coherent for photon wavelengths $\lambda > 4\pi\varepsilon$. For constant cell-length the horizontal emittance ε in a storage ring scales as γ^2/ρ^3. With the extremely large radius ρ of the FCC, we can achieve **such a small emittance that high brilliance and coherent radiation could be reached also at high photon energies, inaccessible with the present and planned light sources**. The FCC-ee booster at injection energy offers the lowest emittance. The **emittance can be further lowered by introducing wigglers / undulators,** which could be the same a for photon science.

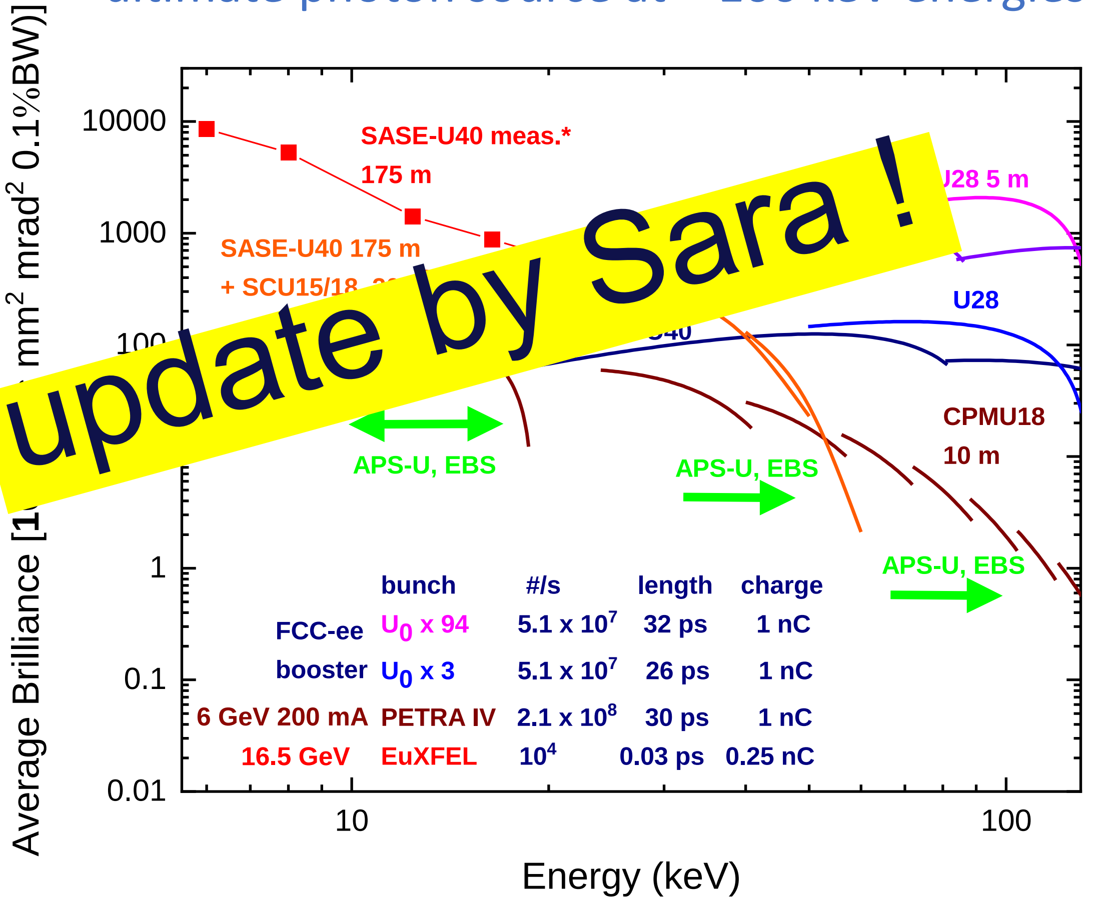
Photon Science: FCC-LS - Powerful light source for very hard X-rays



Sketch of permanent-magnet undulator and fixed-field chicane for the FCC-ee booster

The peak and average brilliance can be roughly 1000 times higher than at the proposed future storage ring light source PETRA IV in the very hard X ray regime, and coherent wavelengths down by a factor 100, opening up new areas of science.

ultimate photon source at ~100 keV energies



FCC-ee booster at injection with 28 (40) mm period undulator (wiggler) offers highest average brilliance at E_γ>30 keV

Photon Science: FCC-LS – Parameter comparison

Parameters for the FCC-ee booster as light source (FCC-LS), compared with the European XFEL [1,2] and the proposed PETRA IV facility [3]. At present, the European XFEL cannot reach photon energies above 30 keV.

	w/o wiggler	U_0 x3	U_0 x94	XFEL	PETRA IV
beam energy [GeV]	20	20	20	17.5	6
average beam current [mA]	50	50	50	0.03	200
bunch population [10^{10}]	2	2	2		
RF voltage [MV]	60	65	190		
beta at wiggler /undulator [m]	1.6	1.6	1.6		
wiggler field [T]		1	1		
wiggler period [cm]	-	4	4		
wiggler unit length [m]	-	6.4	5		
undulator field [T]		0.71-0.32	0.71-0.32	[illegible]	0.3-1.1
undulator period [cm]		2.8	2.8	[illegible]	1.8
undulator unit length [m]		5	5	[illegible]	10
magnetic gap	10	10	[illegible]	[illegible]	6
energy loss / turn [MeV]	1.33	4	[illegible]	[illegible]	4
SR power at 0.15 A [MW]	0.2	[illegible]	[illegible]	[illegible]	
total length of wiggler [m]	**-**	[illegible]	[illegible]	[illegible]	
horizontal emittance [nm]	[illegible]	[illegible]	[illegible]	**0.04 (slice)**	**0.02**
vertical emittance [pm]	[illegible]	[illegible]	[illegible]	**40 (slice)**	**4**
wiggler photon energy 1st [illegible]	[illegible]	[illegible]	**10-50**	-	
undulator photon energy [illegible]	[illegible]	[illegible]	50-100	9.1-30.7	7-16.8
coherence limit [Å]	[illegible] (2.1 keV)	**1.9** (6.5 keV)	**0.06** (200 keV)	**5** (2.5 keV)	**1.5** (8.3 keV)
peak brilliance [ph/s/0.1%b[illegible]]					
@ 12 keV					
@25 keV		$4.2x10^{22}$	$2x10^{25}$	$5x10^{33}$	$3x10^{24}$
@50 keV		$1.1x10^{23}$	$7.9x10^{25}$	$4 x10^{33}$	$1.4x10^{24}$
@100 keV		**$1.0x10^{26}$**	**$3x10^{26}$**	**N/A**	**$3.8 x10^{23}$**
		$1.1 x10^{26}$	**$5.2x10^{26}$**	**N/A**	**$3x10^{22}$**
average brilliance [ph/s/0.1%bw/mm²/mrad²]					
simulations for the FCC-ee injector with SPECTRA [4]					
@ 12 keV					
@25 keV		$4.2x10^{22}$	$8.2x10^{22}$	$1.6x10^{25}$	$8x10^{22}$
@50 keV		$1.1x10^{23}$	$3.2x10^{23}$	$2.5x10^{24}$	$3.8x10^{22}$
@100 keV		**$2.2x10^{23}$**	**$1.2x10^{24}$**	**N/A**	**$1 x10^{22}$**
		$2.5x10^{23}$	**$2.1x10^{24}$**	**N/A**	**$8x10^{20}$**

update by Sara !

FCC-CBS: 1000-100000x more flux & higher energy than ELI-NP

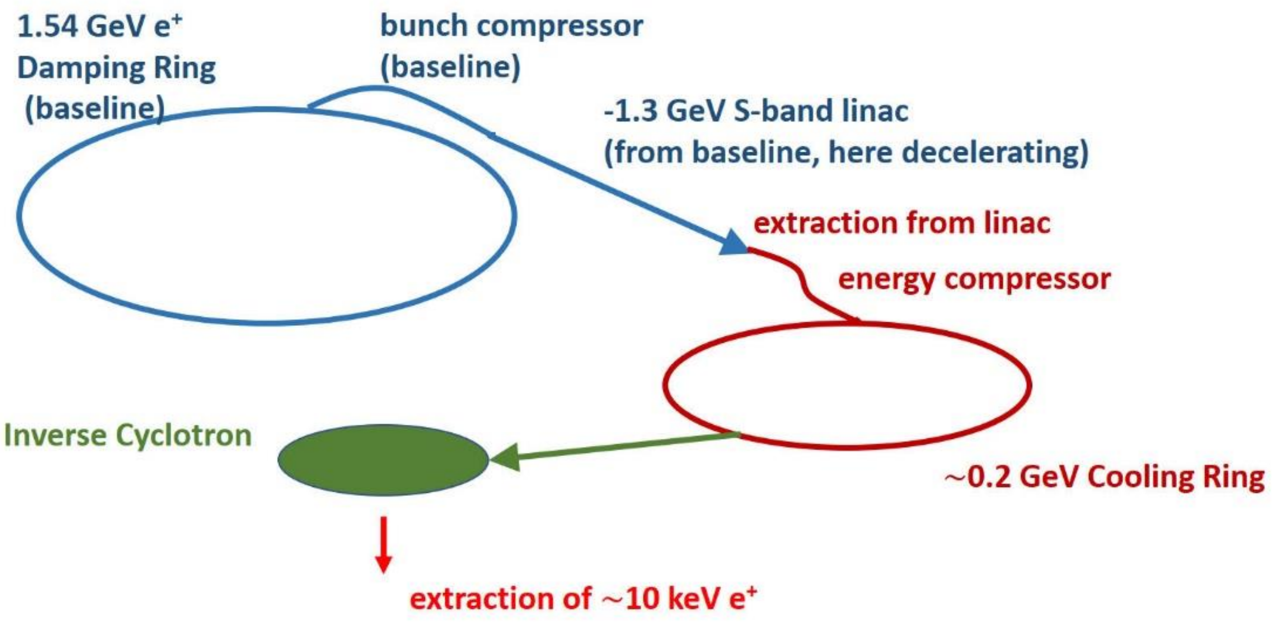
Comparison of ELI-NP and FCC-ee Compton Backscattering Source (FCC-ee-CBS), assuming Yb:YAG laser (2.3 eV)

	ELI-NP	FCC-ee-CBS-20	FCC-ee-CBS-45	FCC-ee-CBS-120
beam energy [GeV]	**0.72**	**20**	**45.6**	**120**
average beam current [A]	**0.8×10^{-6}**	**0.15**	**0.15**	**0.05**
beam size at laser CP [mm]	~0.5	~0.5	~0.5	~0.5
Compton *x* parameter	0.25	7	16	42
max photon energy [GeV]	**0.02**	**17.5**	**43**	**117**
photon flux [1/s]	**10^{9}**	**$\sim 10^{13}$**	**$\sim 10^{13}$**	**$\sim 10^{13}$**

The photon energies are 1000 times higher, the photon flux exceed ELI-NP's by about a factor 10,000. To achieve this rate the laser beam recirculator system of ELI-NP would need to be modified or, possibly, be replaced by an optical cavity, suitable for cw operation.

Positron source for material research

The availability of one of the world's most powerful positron sources, delivering high-flux positrons a of a few 10^{12} e+/second, in an energy range from a few 100 MeV to 20 GeV, could offer numerous other applications.

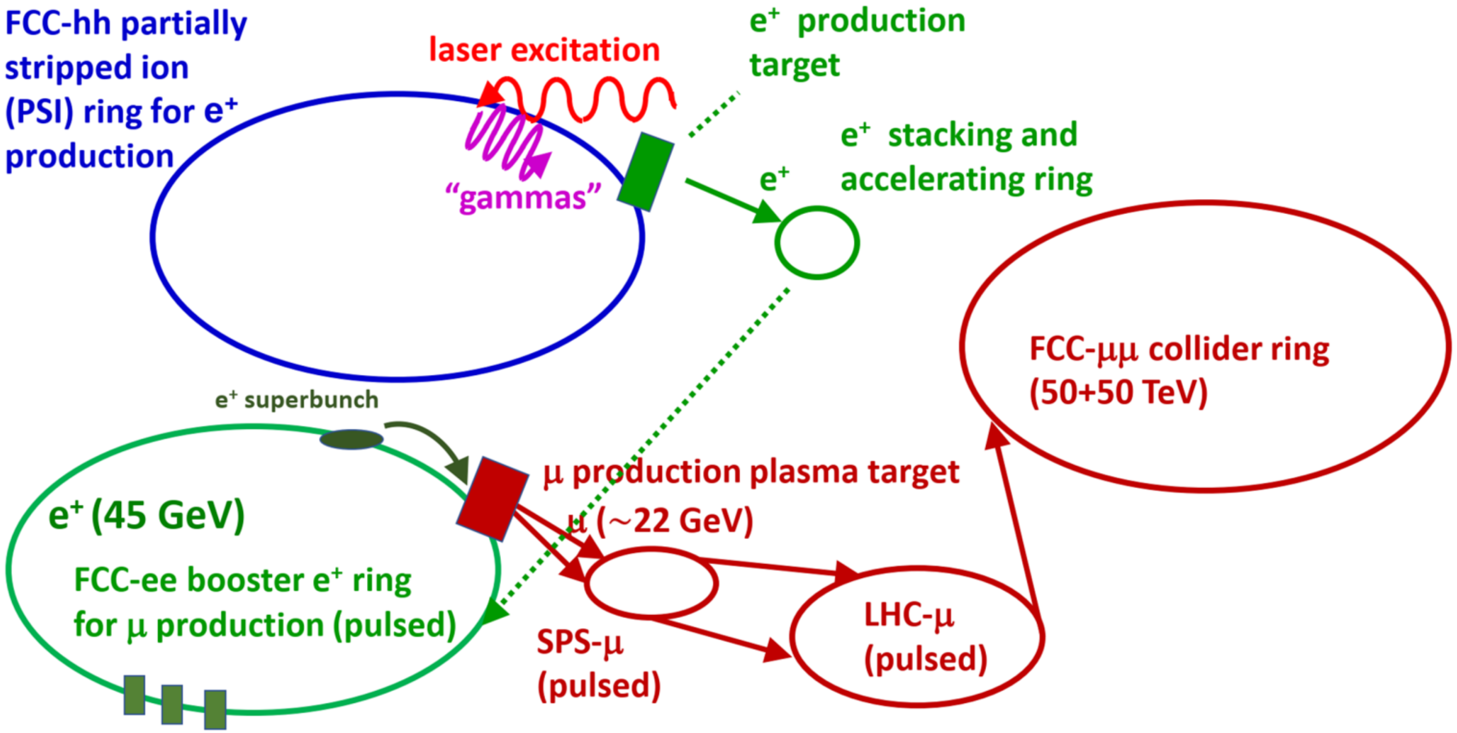


Layout of high-intensity cold positron source fed from the FCC-ee e^+ damping ring, passing through the bunch compressor and part of the baseline S-band linac. After extraction from the linac, and energy-spread compression. low-energy cooling ring and a small (1 metre) inverse cyclotron are added to provide a high-flux low-energy low-emittance positron beam.

e.g. C. Hugenschmidt, Positrons in Surface Physics, https://arxiv.org/pdf/1611.04430

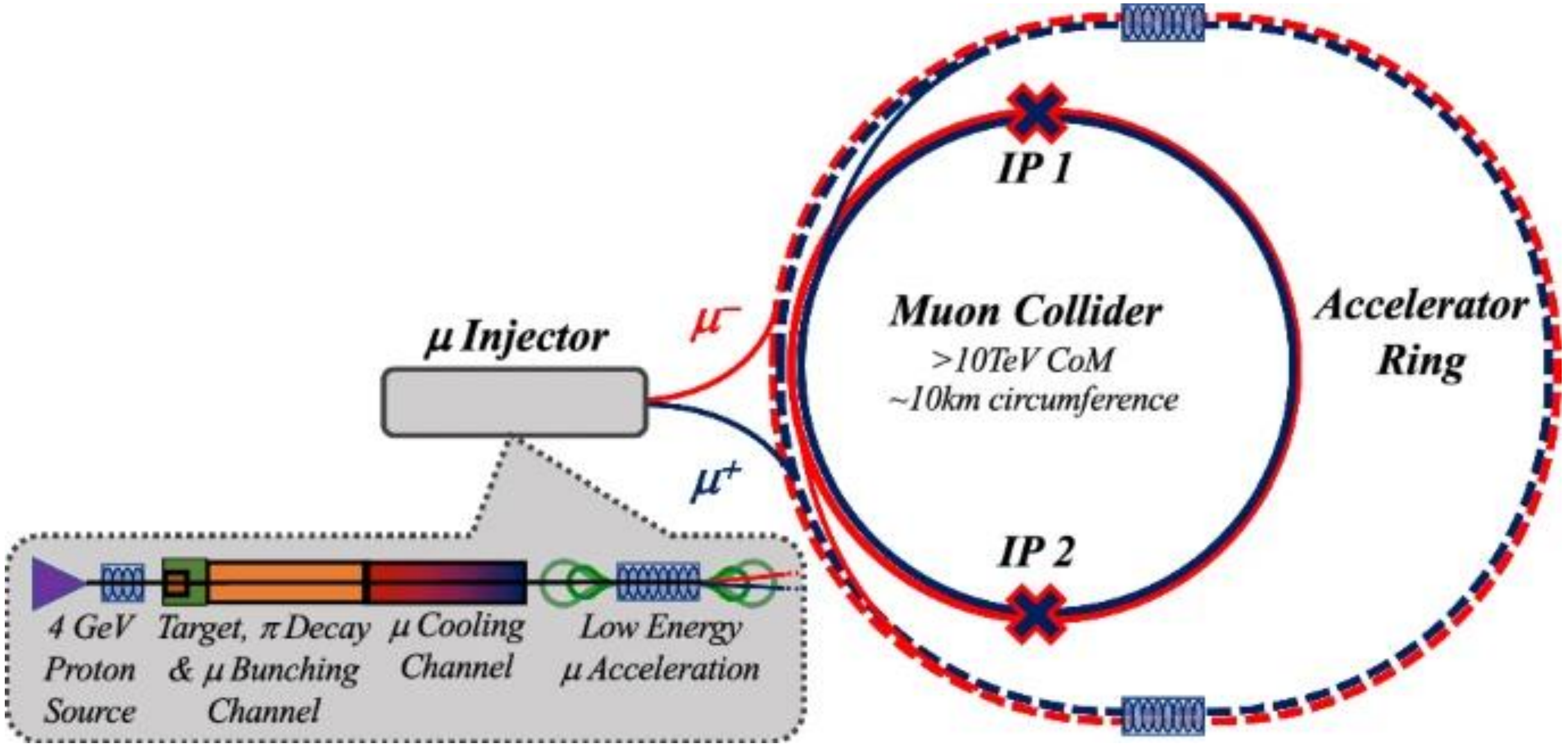
Testbed for LEMMA muon collider

FCC-ee would allow many important proof-of-principle tests for the LEMMM based muon collider. For example, 45 GeV positrons extracted from the booster would be by far the best conceivable platform for carrying out demonstration experiments and beam tests for the LEMMA low-emittance muon-beam production scheme. Various targets and accumulation schemes could be studied. The emittance of the generated muons could be characterized.



Farmer et al., *Muon Collider based on Gamma Factory, FCC-ee and Plasma Target*, IPAC'22

FCC as muon accelerator ring to feed muon collider in LHC tunnel



FCC-ee tunnel hosts muon accelerator ring

LHC tunnel hosts
~30 TeV CoM muon collider

C. Accettura et al.
EPJC, vol 83, 864 (2023)

Plasma acceleration of positrons

Plasma acceleration of positron is not yet a fully solved problem. The positrons from the FCC injector complex could be used for acceleration-tests in AWAKE-like experiments or for tests with positrons for other novel acceleration schemes, e.g. acceleration of positrons in crystals.

e.g.

Gevy J. Cao, et al., Phys. Rev. Accel. Beams 27, 034801 (2024)

Non-perturbative QED Experiments – boiling the QED vacuum

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 [5], or, via laser Compton backscattering off bunches in the booster. These high-energy photons are then collided with low energy photons from a laser and pairs of electrons and positrons are created via the Schwinger process. The intensity of the laser is varied, e.g., between 5×10^{18} W/cm^2 and 1×10^{20} W/cm^2 (parameters from LUXE) and the rate of electron/positron pairs is measured as function of this intensity, The rate should be proportional to E^2 e $(-E_S/E)$ where E is the electric field of the laser.

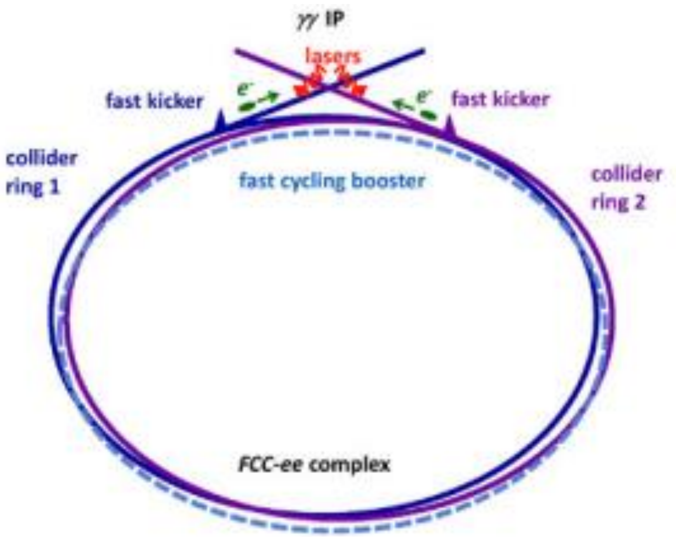
Comparison of FCC-ee QED explorer configurations and the European XFEL's LUXE proposal.

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

Positronium-based GeV photon source – a speculative proposal

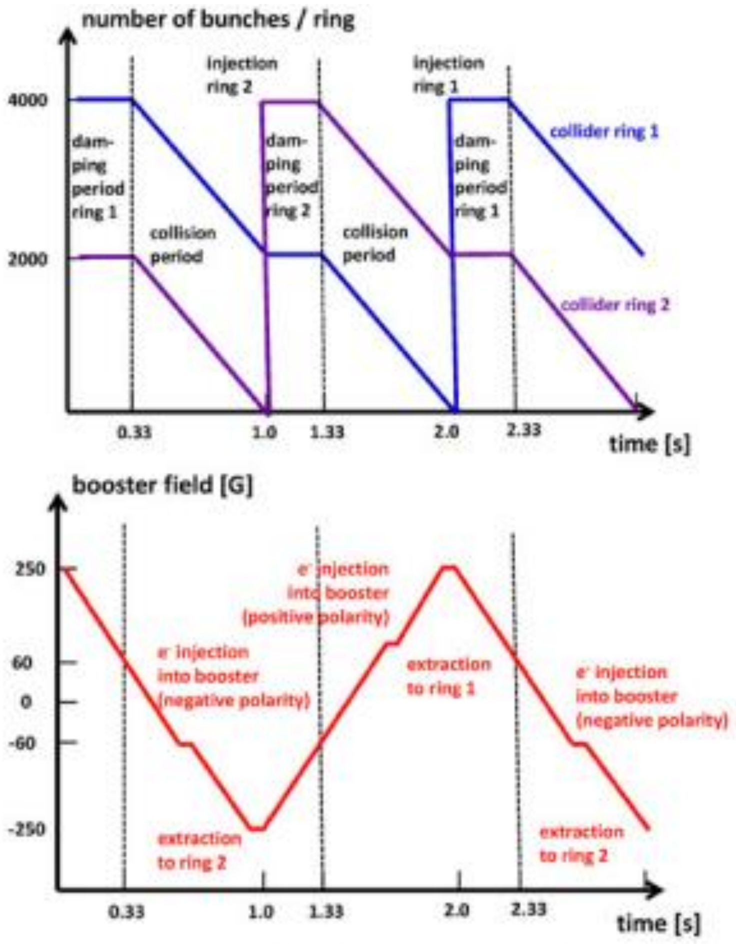
Aligning positron and electrons in a joint long straight section at ~1 GeV energy ($\gamma \sim 2000$), would potentially allow formation and decay of positronium in flight, yielding a narrow-line GeV photon source. This concept requires some basic soundness checks: configuration, cross sections, luminosity, decay time, last not least the expected/achievable rate.

$\gamma\gamma$ collider based on FCC-ee



Schematic $\gamma\gamma$ collider based on filling the two FCC-ee collider rings with e^- bunches and extracting one bunch per beam and per turn into a dedicated $\gamma\gamma$ line.

R. Aleksan, A. Apyan, Y. Papaphilippou, F. Zimmermann, IPAC2015



Cycle pattern for two collider rings (top) and for the booster (bottom).

Table 1: Tentative Parameters for FCC-ee Based $\gamma\gamma$ Higgs Factory Compared with those of SAPPHIRE

	symbol	SAPPHIRE	FCC-ee
average el. power	P	100 MW	100 MW
beam energy	E	80 GeV	85 GeV
b. polarization	P_e	0.80	0.80
bunch popul.	N_b	10^{10}	7.7×10^{10}
laser rep rate	f_{rep}	200 kHz	3 kHz
av. collision rate	f_{coll}	200 kHz	2 kHz
laser pulse energy		5 J	5 J
laser power		1000 kW	15 kW
laser wave length	λ	350 nm	350 nm
Rayleigh length	z_R	0.3 mm	0.3 mm
rms laser spot CP	$\sigma_{\gamma,x,y}$	4 µm	4 µm
laser pulse length	σ_λ	0.25 mm	0.15 mm
# bunches / beam	n_b	-	4000
collider period		-	2 s
bunch length	σ_z	30 µm	350 µm
E damping time	τ_E	-	67 ms
energy spread	σ_δ	?	7×10^{-4}
RF frequency	f_{rf}	800 MHz	800 MHz
RF voltage	V_{rf}	2×10 GV	6 GV
$\gamma\gamma$ crossing angle	θ_c	≥20 mrad	≥20 mrad
nor.hor./vert. emit	$\gamma\varepsilon_{x,y}$	5, 0.5 µm	69, 0.06 µm
geom. h./v. emit.	$\varepsilon_{x,y}$	32, 3 pm	440, 0.4 pm
hor. IP beta funct.	β_x^*	5 mm	1 mm
vert. IP beta funct.	β_y^*	0.1 mm	0.1 mm
hor. rms spot size	σ_x^*	400 nm	700 nm
vert. rms spot size	σ_y^*	18 nm	6 nm
hor. rms CP spot	σ_x^{CP}	410 nm	1000 nm
vert. rms CP spot	σ_y^{CP}	180 nm	60 nm
distance IP – CP		~1 mm	1 mm
e^-e^- geometric luminosity	L_{ee}	2.2×10^{34} $cm^{-2}s^{-1}$	1.3×10^{34} $cm^{-2}s^{-1}$
$\gamma\gamma$ luminosity >125 GeV	$L_{\gamma\gamma}$	6×10^{32} $cm^{-2}s^{-1}$	8×10^{32} $cm^{-2}s^{-1}$

References

1. M. Altarelli et al. (Eds.), XFEL: The European X-Ray Free-Electron Laser.Technical Design Report, Preprint DESY 2006-097, DESY, Hamburg, 2006 (see also http://xfel.desy.de).
2. E.A. Schneidmiller and M.V. Yurkov,*"Photon Beam Properties at the European XFEL"*, DESY-11-152; TESLA-FEL 2011-01
3. C. G. Schroer et al., PETRA IV Conceptual Design Report, https://bib-pubdb1.desy.de/record/426140/files/DESY-PETRAIV-Conceptual-Design-Report.pdf
4. T. Tanaka and H. Kitamura, *"SPECTRA: a synchrotron radiation calculation code"*, Journal of Synchrotron Radiation 8, 1221 (2001)
5. F. Burkart et al., "*LUXE — A QED Experiment at the European XFEL*," 10th Int. Particle Accelerator Conf. IPAC2019, Melbourne, Australia JACoW Publishing ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-TUPRB008
6. C. Hugenschmidt, *Positrons in Surface Physics* (2016), https://arxiv.org/pdf/1611.04430
7. M. Benedikt, S. Casalbuoni, M. Doser, F. Zimmermann, *First thoughts on the synergetic use of the FCC-ee collider and its injector complex for photon science and other applications*, 10.5281/zenodo.7675663.
8. S. Casalbuoni and F. Zimmermann, *FCC-ee booster as ultimate storage ring photon source*, FCC Week 2021
9. R. Aleksan, A. Apyan, Y. Papaphilippou, F. Zimmermann, *Scenarios for Circular Gamma-Gamma Higgs Factories*, Proc. IPAC2015, Richmond (2015) 2156

Possible work plan

need to update all to new parameters (booster intensity, DR energy)

on FCC side focus on light source and Compton source applications, perhaps also e+ for material research

PBC looking after QED vacuum boiling & also positronium scheme? Other science applications?