A new paradigm for ultra-low emittance muon beam generation based on ERL

Electrons and **X**-rays to **M**uon **P**airs scheme

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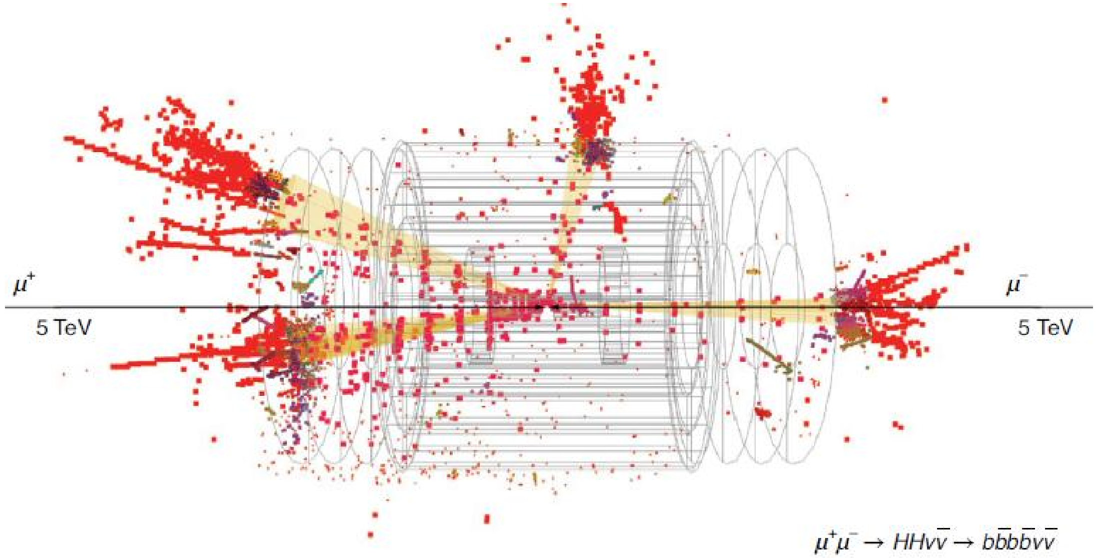
International Linear Accelerator Conference 2022
Sunday 28th August – Friday 2nd September 2022
The Arena Convention Centre, Liverpool

Presentation outlook



- Few words on Muon Colliders (MCs)
- Electrons and X-rays to Muon Pairs (EXMP): scheme & motivations
- Inverse Relativistic Kinematics for Muon Pair generation in electron-photon collision
- Simulation of Muon Beam Generation in EXMP
- Power Budget discussion
- A Proof-of-Principle experiment at DESY with XFEL electrons and a dedicated ICS

Muon Colliders

Muon beam collision @ TeV: incredible potential for HEP studies

- μ fundamental particles → clean collision and all energy available
- $M_\mu \sim 200\ M_e$, SR $\propto \gamma^4/\rho$ → higher acceleration and smaller footprint
- L/P grows linearly with energy while constant in Linacs: above 3 TeV only MC for leptons

MAP scheme:
$10^{12}\ \mu$/bunch
ε^n = 25 mm mrad
L ~ 10^{34} cm^{-2} s^{-1}

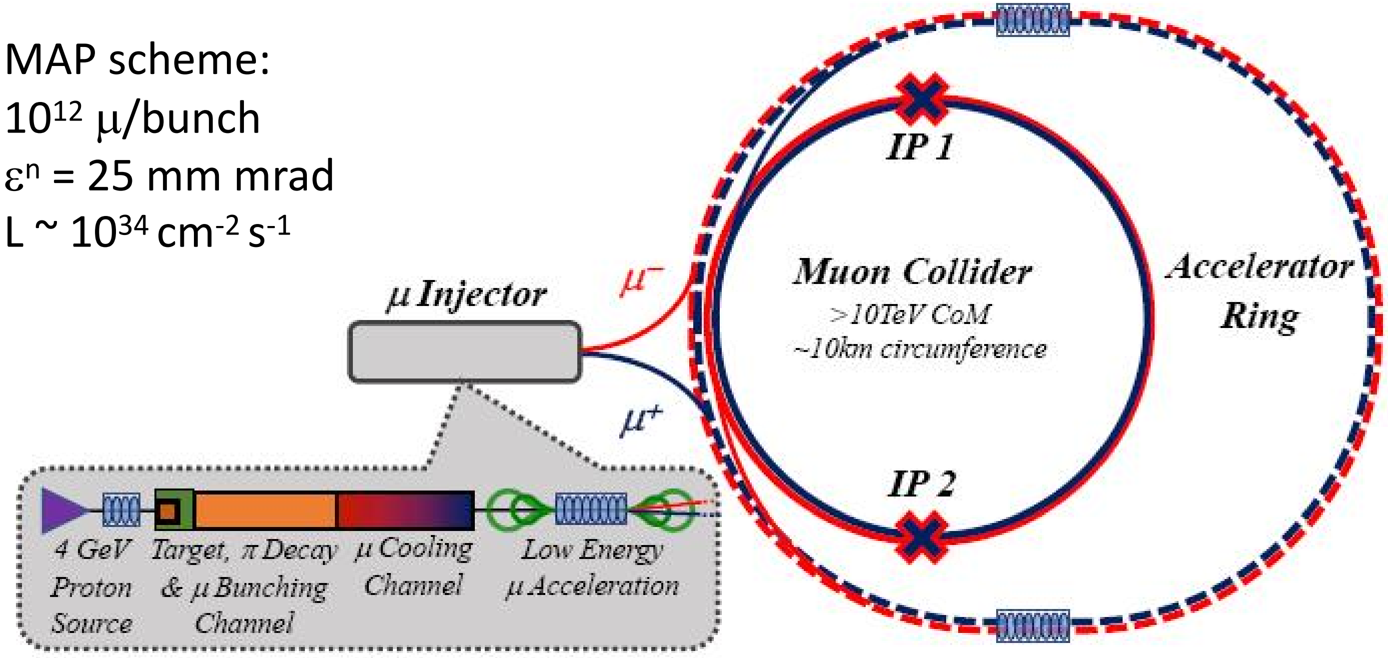
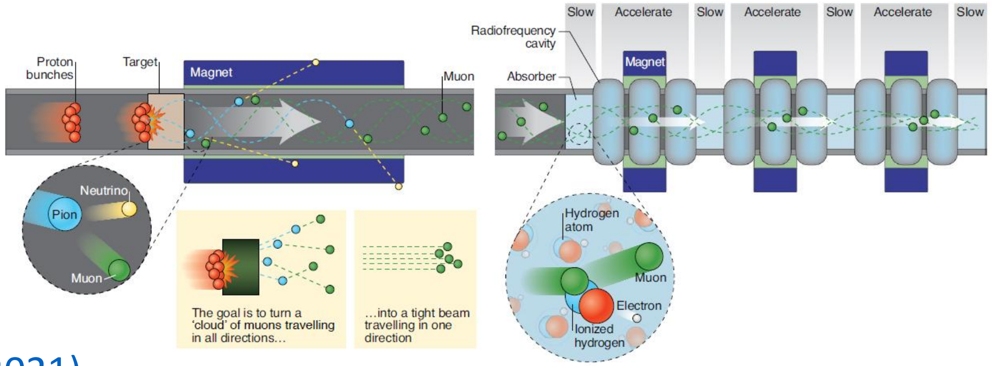


Fig. 5.1: A conceptual scheme for the muon collider.

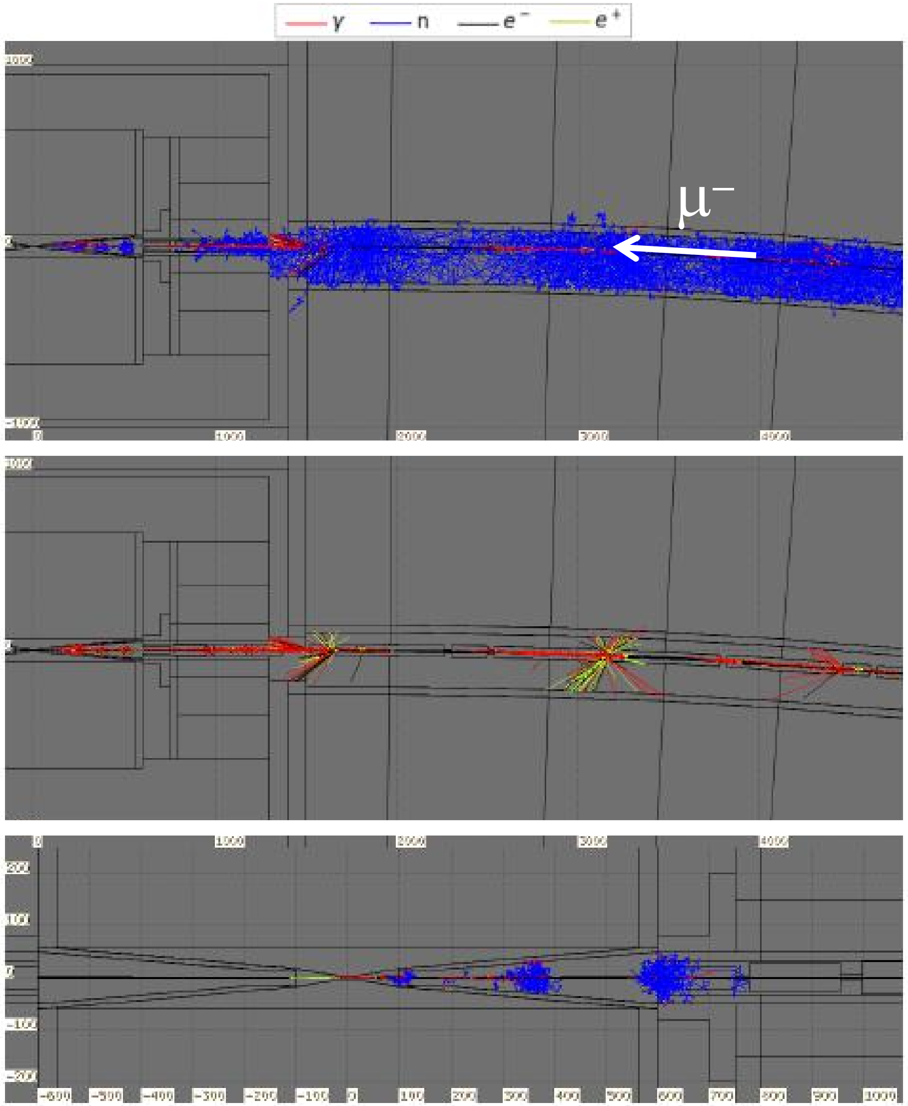
some technological challenges:
target handling
ionization cooling
fast acceleration

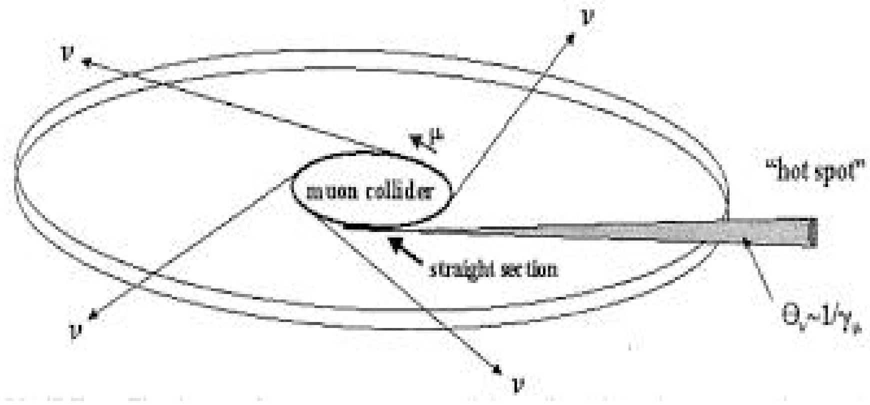


[Muon colliders to expand frontiers of particle physics. Nat. Phys. 17, 289–292 (2021)]

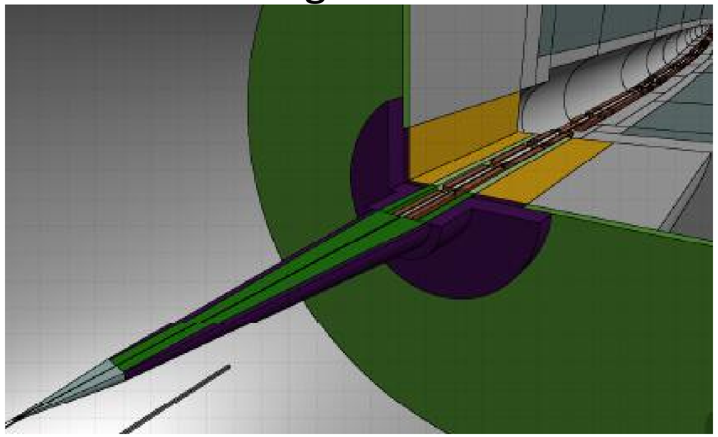
Muon Colliders

μ unstable particles with τ_0 = 2.2 μs,
decay in $\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$, $\mu^- \rightarrow e^- + \nu_e + \nu_\mu$ leads to two main issues:
Beam-Induced Background (BIB) & Neutrino radiation





conical shielding: nozzle

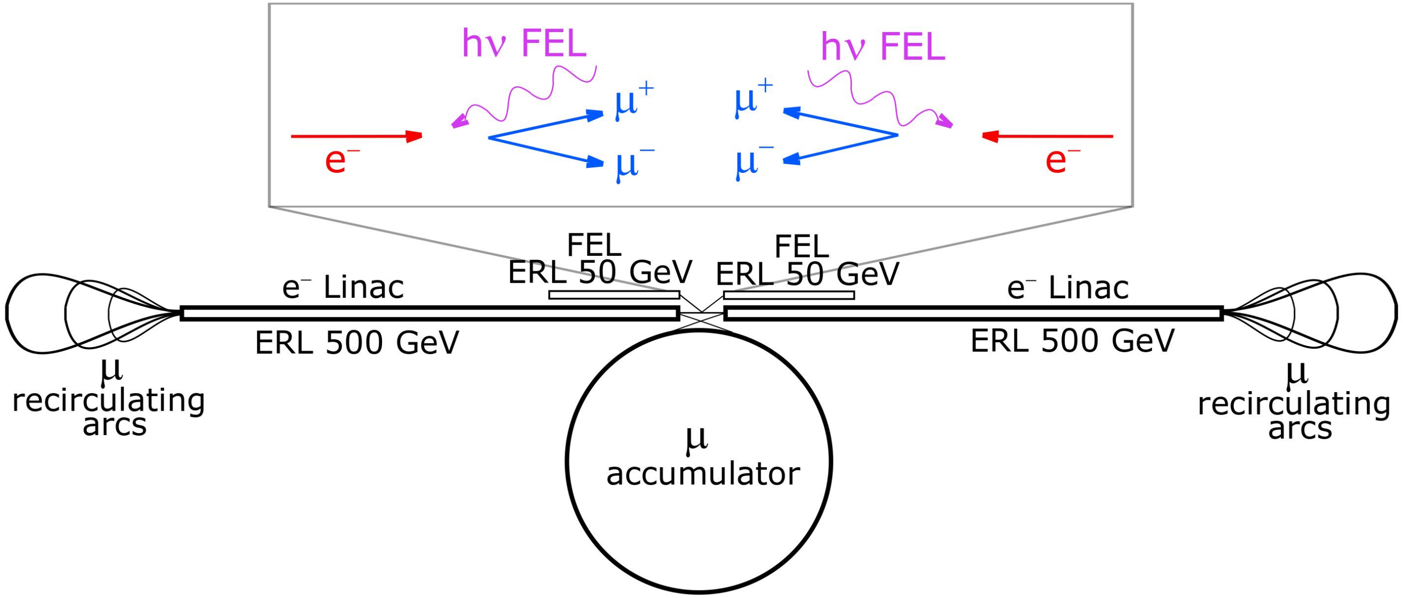


Mitigation through various methods for the MAP scheme: intense study ongoing
Alternative/complementar approach: less muons and lower emittance (L ∝ N²/ε)
ex: Low EMittance Muon Accelerator

Simulated Detector Performance at the Muon Collider, ArXiv (2022)

Electrons and X-rays to muon pairs (EXMP)

- electron beam injected in one of the main Linacs, accelerated to 500 GeV, collision with counterpropagating FEL radiation at 60 keV, injected in the opposite Linac and decelerated (Energy Recovery)
- produced muons injected in opposite main Linac with used electrons (out of phase) and fast accelerated to final energy using recirculating arcs



E_e=500 GeV, $h\nu$=60 keV

Strongly asymmetric collision: relativistic Doppler effect permits to have E_{CM} above MPP threshold

$$E_{CM} \simeq \sqrt{4E_e h\nu + M_e^2} = 346 \text{ MeV},\ h\nu' \simeq 2h\nu\gamma_e = 120 \text{ GeV}$$

Recoil parameter $X=4\gamma_e h\nu/M_e=4.6\cdot10^5$

[GeV muon beams with picometer-class emittance from electron-photon collisions, ArXiv (2021)]

[Electrons and X-rays to Muon Pairs (EXMP) Appl. Sci. (2022), 12(6), 3149]

Electron beams & FEL

Why using electrons to generate muons?

- Electron Beams achieve the highest beam brightness than any other charged particle beam (6D Brightness: short bunches, small emittance and energy spread → tight focus)

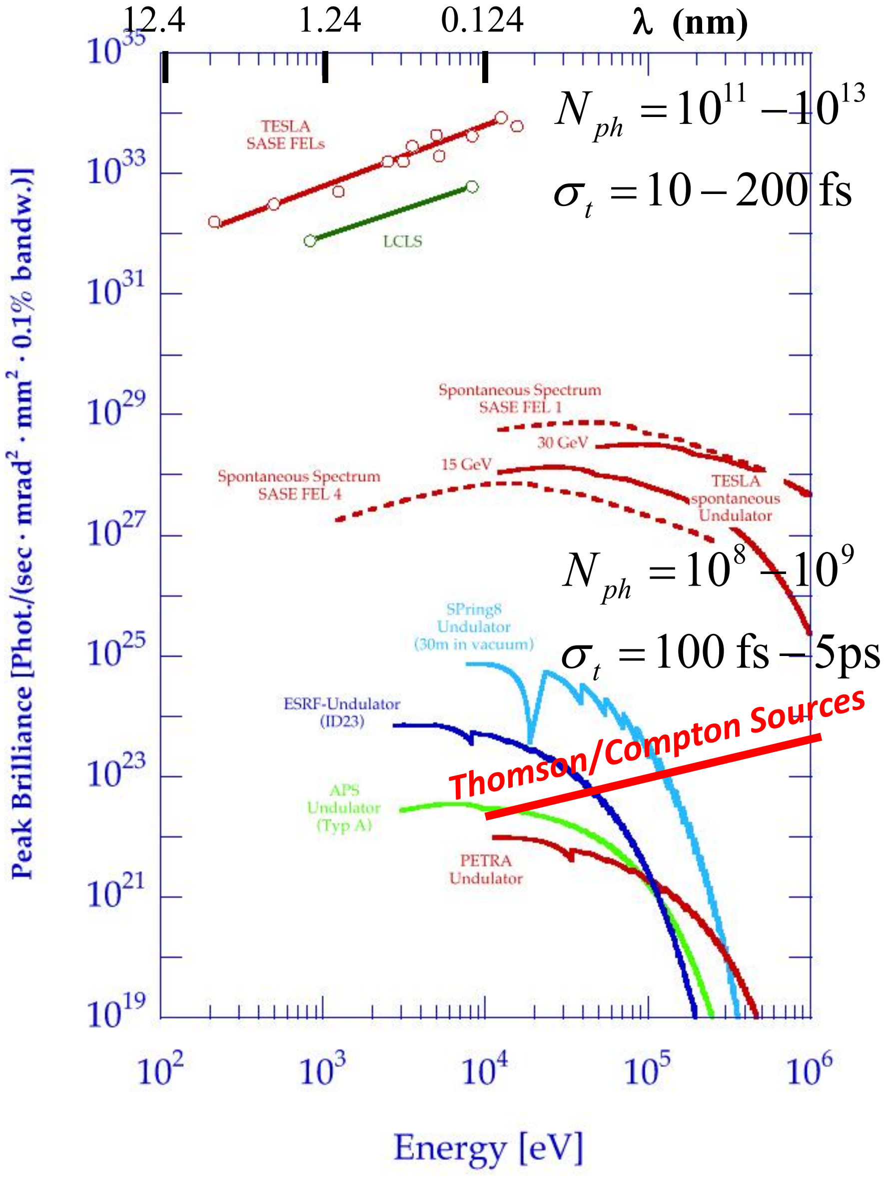
$$B_n \propto \frac{I_e}{\varepsilon_n^2 \frac{\Delta\gamma}{\gamma}} \quad ; \quad I_e = \frac{eN_e}{\sigma_t}$$

- We can recover the power stored in the electron beam via Energy Recovery Linacs (ERLs) for a large energy sustainability

Why using photons to generate muons?

- We have an outstanding photon machine: the Free Electron Laser (FEL)

$$B_{peak} \propto \frac{N_{ph}}{\lambda^2 \sigma_t \frac{\Delta E_X}{E_X}}$$



Parameters

FEL-graded CW electron beam – 800 MHZ (SC-RF Perle cavities) @ 200 mA

Parameters of Primary Beams			
Energy e-beam (GeV)	500.	FEL photon energy (keV)	60.
Bunch charge (pC)	250.	Photons per pulse (10^{12})	12.5
N_e (10^9)	1.6	Repetition rate (MHz)	800.
Repetition rate (MHz) CW	800.	$\varepsilon_{x,y}$ (pm·rad)	1.5
Average Current (mA)	2x200.	Focal spot size (rms, nm)	10.
Nominal beam power (GW)	2x100.	FEL beam power (MW)	2x100.
beam power recovery fraction	99.95 %	FEL-efficiency (tapering)	1%
beam power loss (MW)	2x50.	FEL e^- beam av. curr. (mA)	200.
Bunch length (psec)	0.2	FEL e- beam energy (GeV)	50.
$\varepsilon^n_{x,y}$ (mm mrad)	0.4	FEL e- beam power (GW)	2x10.
$\beta_{x,y}$ (mm)	0.23	e^- beam power recovery fraction (after FEL)	99.9%
$\sigma_{x,y}$ (nm)	10.	e^- beam power loss (MW)	2x10.
Total beam power loss (primary+FEL) (MW)			**320.**

electron-photon collision → no beam-beam, no beam disruption → round beam → no damping rings

β^*=0.23 mm → time jitter for synchronization system 0.6 psec

Peak Luminosity ($cm^{-2}s^{-1}$) = 2 x 1.25 · 10^{42}

In-vacuum MPP

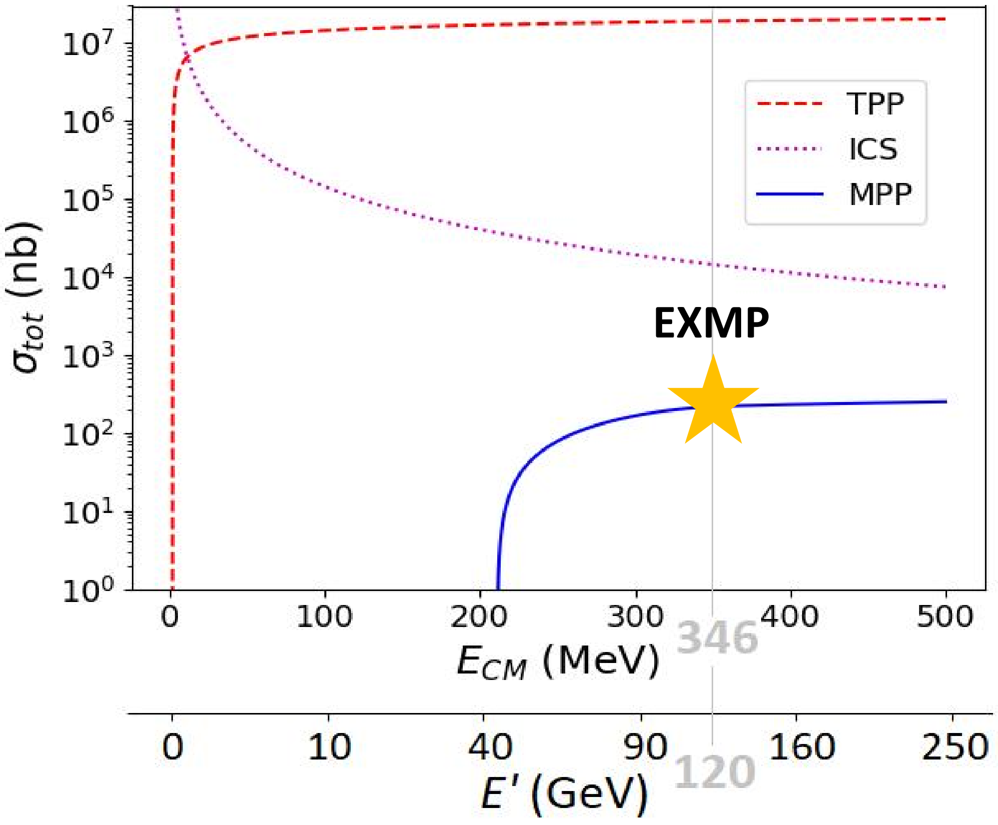
What are the positives of in-vacuum based muon beam generation?

- no target handling
- very low emittance → no cooling
- polarized muons

What are the drawbacks of in-vacuum based muon beam generation?

- Low MPP cross section
- Running a primary collider to generate a beam (not physics events) implies achieving outstanding luminosities: drop by 9-10 orders of magnitude from primary to secondary collider ($10^{4n} \rightarrow 10^{3n}$)
- Operational stability and reliability of the secondary collider (in our case muon collider) strongly depends on the performances of the primary collider

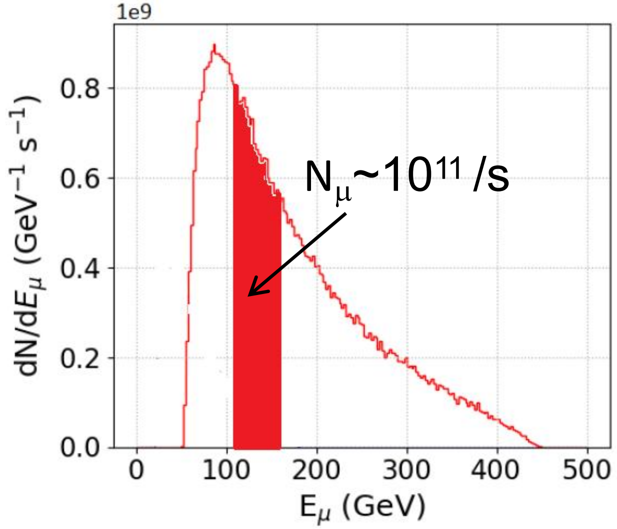
$$\sigma^{MPP} = \alpha r_\mu^2 \left(\frac{28}{9} ln\left(\frac{2\gamma h\nu}{M_\mu}\right) - \frac{218}{27}\right) - \sigma^{Borsellino}$$



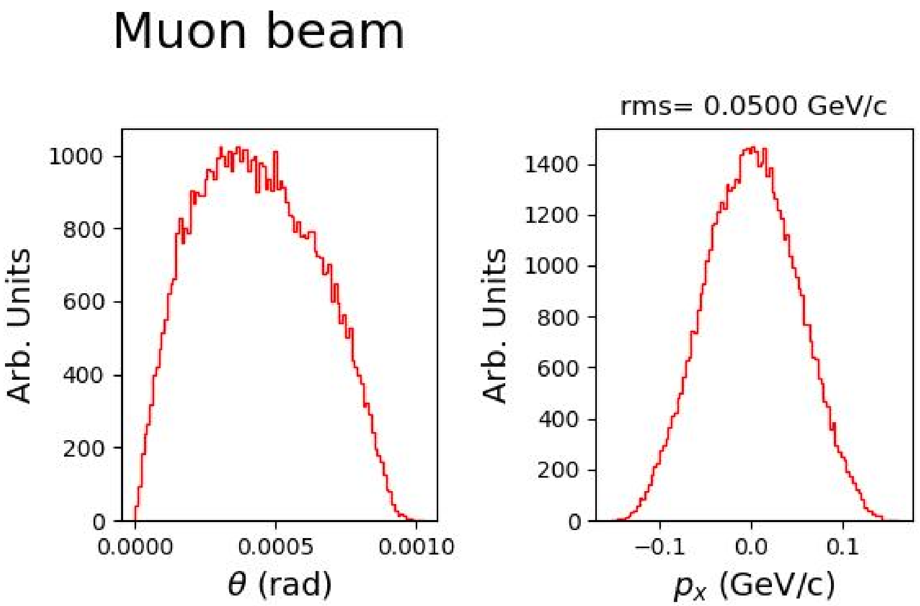
Simulated MPP

Event generator: Whizard + script for incoming beam features

E_e = 500 GeV σ_0 = 10 nm $\gamma_{CM} = 1450$ E_{cm} = 346 MeV

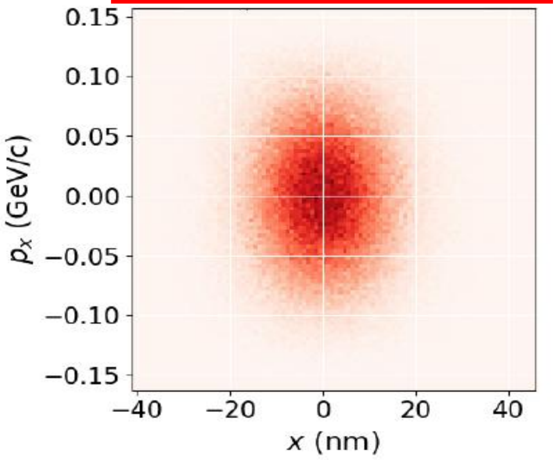


$E_{peak} \sim M_\mu \gamma_{CM} \sim 120\ GeV$



normalized rms transverse emittance @ source

$\boxed{\epsilon_x^n = 0.003\ \mu\mathrm{m\ rad}}$



Analytical formula agrees within 20-30%
Strong desensibilization on incoming electrons emittance since X very high

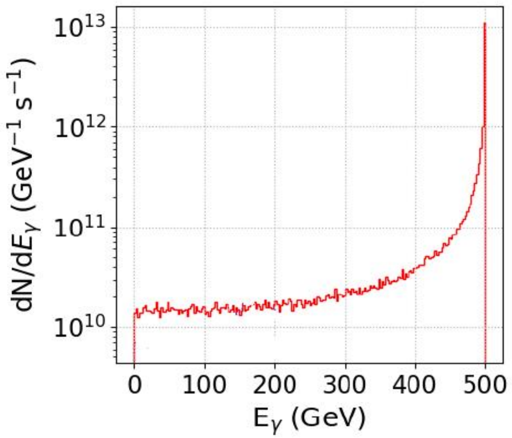
$$\epsilon_\mu^n \simeq \frac{2}{3}\sigma_0\left(\frac{M_e}{2M_\mu}\sqrt{X}-1\right)+\frac{\epsilon_e^n}{\sqrt{X}}$$

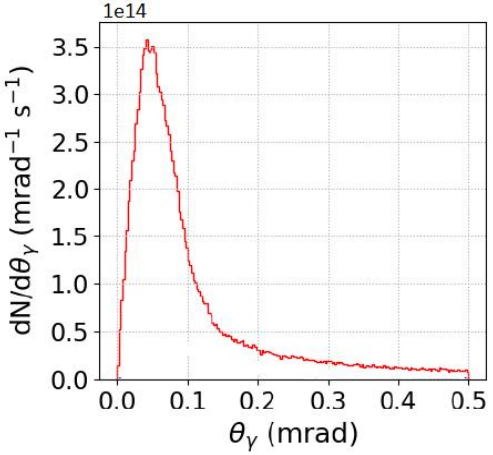
muon source	Rate μ/s	ε_{norm} μm	
MAP	10^{13}	25	after ionization cooling
LEMMA	10^{11}	40	after accumulation, no cooling

[Muon production and accumulation from positrons on target. PRAB 23, 051001 (2020)]

Simulated ICS and TPP

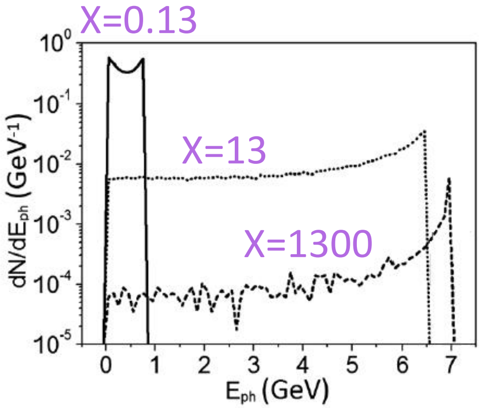
Gamma beam



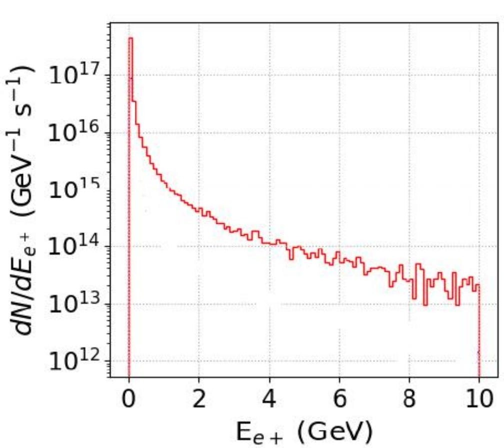


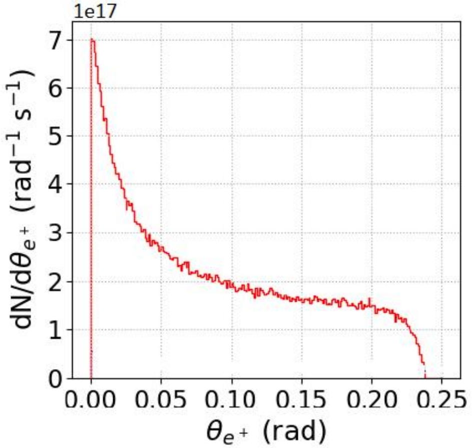
High recoil factor → photon beam peaked around incoming electron beam energy

Example of emitted photon spectra at different X



Positron beam





$\mathcal{N}_{e^\pm}$ (s^{-1})	$2 \times 2.4 \times 10^{16}$
$\mathcal{N}_{ICS}$ (s^{-1})	$2 \times 1.8 \times 10^{13}$
$\mathcal{N}_{\mu^\pm}$ (s^{-1})	$2 \times 2.7 \times 10^{11}$
$\epsilon^n_{x_\mu}$ (π nm rad)	3.3
$\mathcal{N}^{10\%}_{\mu^\pm}$	$2 \times 5.4 \times 10^{10}$

Far from TPP threshold → electron/positron produced at very low energy → no big impact on energy loss

Power budget

- Stored power into the colliding beams, electrons and FEL photons, at the collision point: 2x100 GW + 2x10 GW

- Total power loss: 320 MW dominated by ERL efficiency and FEL photons
  (50% of FEL photon beam power could be recovered through thermal recycling: net 220 MW power loss)

- Low power transferred from primary colliding electron/photon beams into the secondary beams:
  - muon pairs (10^{11} s^{-1} at an average energy of 100 GeV) ~ 8.6 kW
  - back-scattered Compton gammas ($4 \cdot 10^{13}$ s^{-1} at an average energy of 500 GeV) ~ 3.2 MW
  - e-/e+ pairs produced ($5 \cdot 10^{16}$ s^{-1} at an average energy of 2 GeV) ~ 10 MW

- Expected efficiency beam-to-plug not smaller than 20% (range 20-40%): AC power bill in 0.5 - 1 GW range

- With 200 GW of "circulating" beam power, energy recovery becomes absolutely mandatory: ERL is the key technique to go. ERLs are exiting their development era, mainly focused on radiation production (as drivers of FELs, ICS, and synchotron light), and they are now entering the future scenario of HEP

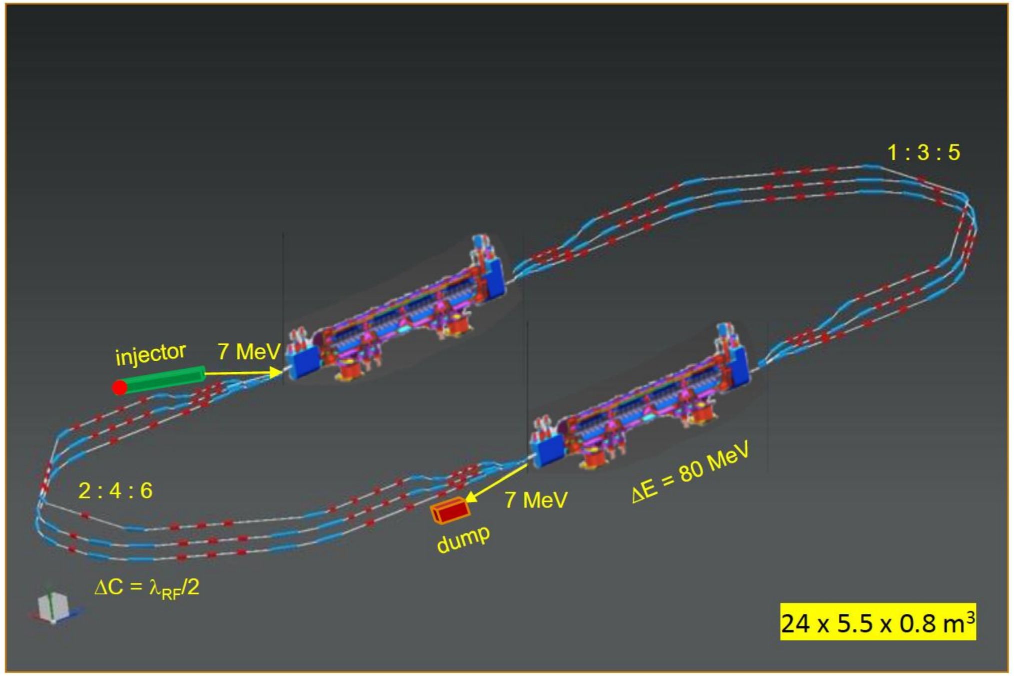
The Development of Energy-Recovery Linacs, ArXiv (2022)

ERL

ERL operation is possible only with Super-Conducting RF Cavities, for which $P_{RF} \sim P_{beam}$ (no significant dissipation of RF Power in Cavity walls) while room-temperature RF Linacs (copper cavities) dissipate most of the RF power into cavity walls $P_{RF} >> P_{beam}$

PERLE * (ERL R&D → Physics [NP, PP])

ALICE DC Photocathode, JLEIC Booster and SPL Cryomodule – in kind



CERN, Cornell, Daresbury, Jefferson Lab, Liverpool, Novosibirsk, IJCLab Orsay (Host) Collaboration, growing: Grenoble, GANIL +

* PERLE. Powerful energy recovery linac for experiments. Conceptual design report
Published in: *J.Phys.G* 45 (2018) 6, 065003 e-Print: 1705.08783 [physics.acc-ph]

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Paramater	Unit	Value
Frequency	MHz	801.58
Number of cells		5
active length l_{act}	mm	917.9
loss factor	V pC^{-1}	2.742
R/Q (linac convention)	Ω	523.9
$R/Q \cdot G$ per cell	Ω^2	28788
Cavity equator diameter	mm	327.95
Cavity iris diameter	mm	130
Beam tube inner diameter	mm	130
diameter ratio equator/iris		2.52
E_{peak}/E_{acc}		2.26
B_{peak}/E_{acc}	mT/(MV/m)	4.2
cell-to-cell coupling factor k_{cc}	%	3.21
TE_{11} cutoff frequency	GHz	1.35
TM_{01} cutoff frequency	GHz	1.77

Table 10.15: Parameter table of the 802 MHz prototype five-cell cavity.

LHeC Design Update 2007.14491 J.PhysG, 21

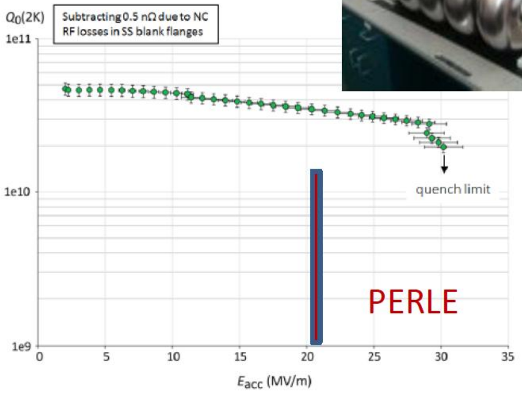
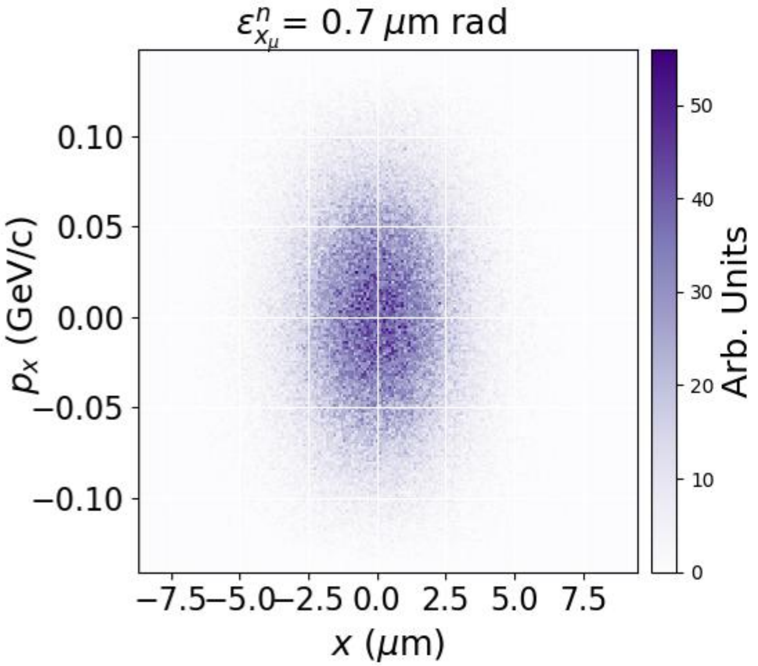


Figure 10.20: Vertical test result of the five-cell 802 MHz niobium cavity prototype.

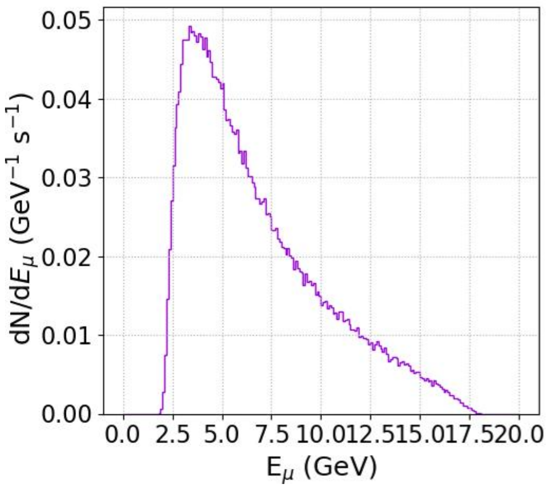
Proof-of-principle experiment

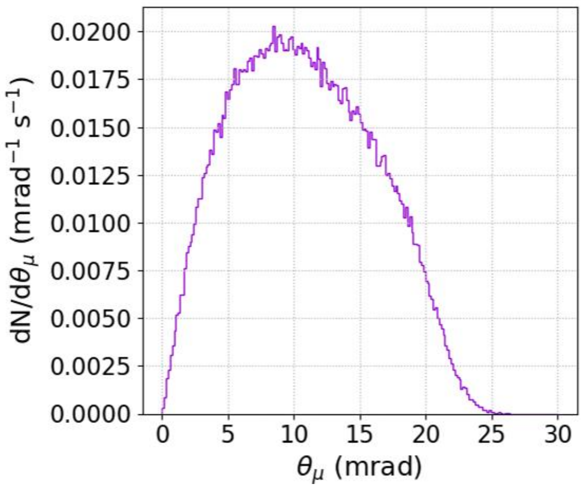
A PoP experiment at DESY with XFEL and a dedicated ICS



20 GeV XFEL electrons	1.5 MeV ICS photons
E_{CM}	346 MeV
Qe_-	800 pC
effective rep rate	32 kHz
primary collision spot-size	2 microns
ε^n	1 mm·mrad
N_{ICS} @ primary collision	5. 10^9
N μ^{+-}	0.3 (s^{-1})

- Muons peaked around 5 GeV
- Very good emittance, 0.7 mm·mrad
- Moderate amount of time to populate a phase space (few hours): flux ~ 1 μ/s





Conclusions

- We presented the straw-man design of a source for the generation of ultra-low emittance muon beams based on the collision of electron and photon beams
- Muon Pairs generated in-vacuum: no target, no cooling needed
- Ultra-tight focusing of primary electron beam, no beamstrahlung, no beam disruption, outstanding primary luminosity: 10^{42} cm^{-2}s^{-1}
- Primary electron beam recovered in energy (ERL) for sustainability
- Same Linac can accelerate electron beam and muon pairs!
- Polarized muon beams
- Mitigation of Beam-Induced Background and neutrino flux
- Open issue: stacking (collaboration needed) from CW muon beam with low bunch population to large bunch population in storage ring

BACKUP

MC

Target Parameter Scaling

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} cm^{-2}s^{-1}	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

Scaled from MAP parameters

Emittance is constant

$$\sigma_E \sigma_z = \text{const}$$

Collider ring acceptance is constant

$$\frac{\sigma_E}{E} = \text{const}$$

Bunch length decreases

$$\sigma_z \propto \frac{1}{\gamma}$$

Betafunction decreases

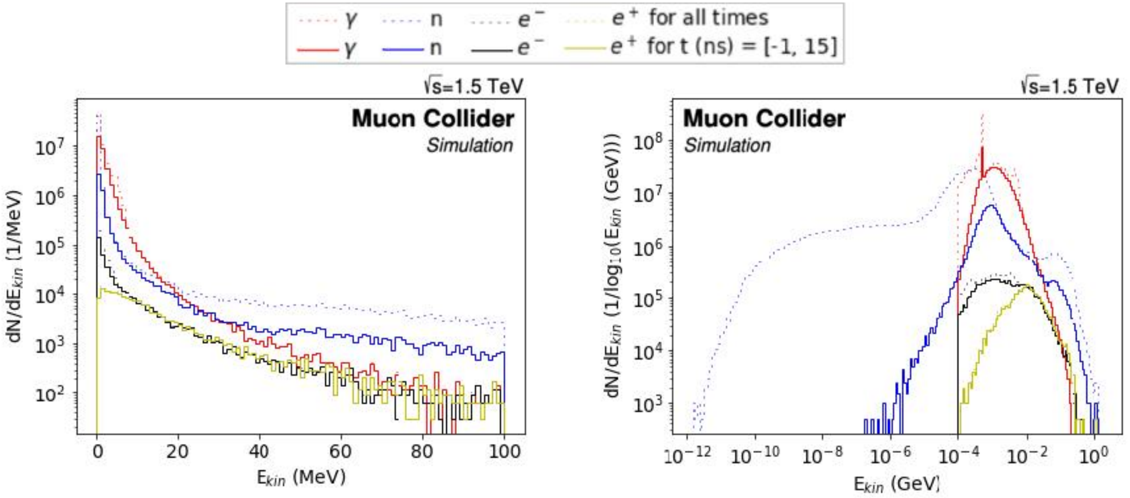
Target integrated luminosities

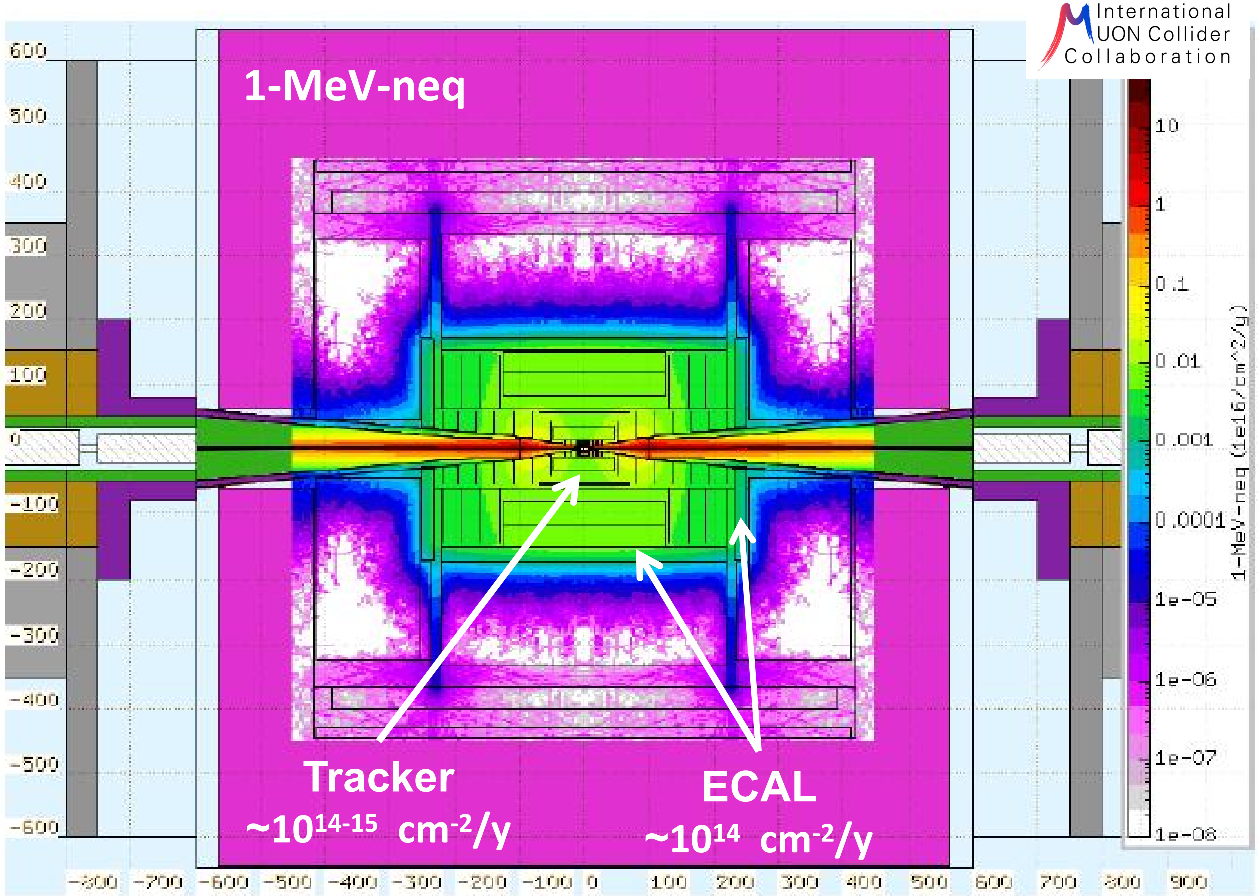
$\sqrt{s}$	$\int \mathcal{L} dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

Reasonably conservative
- each point in 5 years with tentative target parameters
- FCC-hh to operate for 25 years
- Aim to have two detectors
- But might need some operational margins

Note: focus on 3 and 10 TeV
Have to define staging strategy

Beam-Induced Background (BIB)





Simulations @ √s=1.5 TeV and comparison with MARS15 by MAP
JINST 16 P11009 (2021)

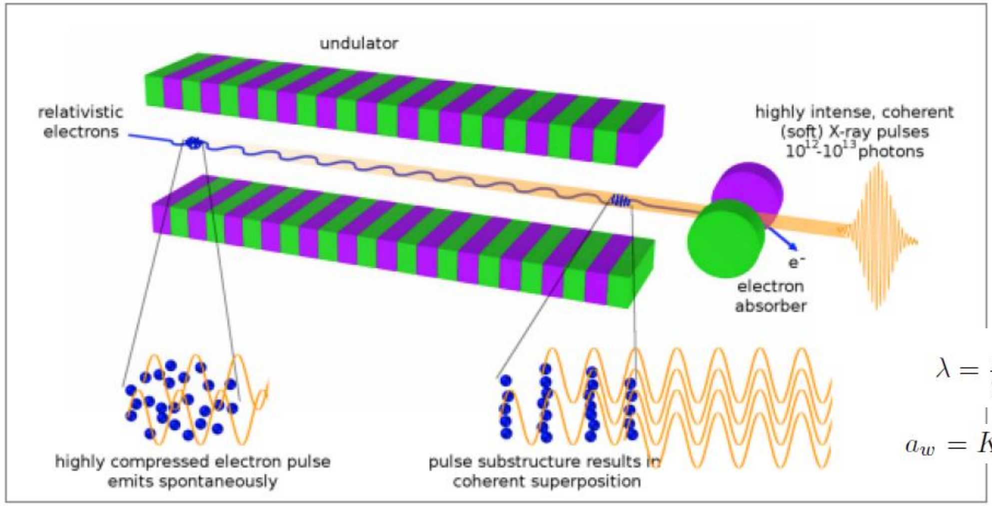
Radiation maps @ √s=1.5 TeV:
$2x10^{12}$ μ/bunch, C=2.5 km, 5 Hz injection rate, 200 days/y
Preliminar simulations @ √s=3 TeV: BIB same level √s=1.5 TeV (higher energy compensated by lower number)

TID $\sim 10^{-3}$ Grad/y on tracker and $\sim 10^{-4}$ Grad/y on ECAL

- Physics measurments with BIB ok, future optimization to enhance performances
- Radiation levels similar to HL-LHC
- Development of detector technologies to deal with BIB ongoing

project EU INFRADEV + Snowmass
Simulated Detector Performance at the Muon Collider
Promising Technologies and R&D Directions for the Future Muon Collider Detectors

FEL



$$\lambda = \frac{\lambda_w}{2\gamma^2}(1 + a_w^2)$$

$$a_w = K/\sqrt{2} = eB\lambda_w/(2\sqrt{2}\pi m_e c)$$

SCIENTIFIC REPORTS

OPEN

Nanofocusing of X-ray free-electron laser using wavefront-corrected multilayer focusing mirrors

Received: 27 July 2018
Accepted: 6 November 2018
Published online: 28 November 2018

S. Matsuyama[1], T. Inoue[1], J. Yamada[1], J. Kim[1,2], H. Yumoto[3], Y. Inubushi[3,4], T. Osaka[4], I. Inoue[4], T. Koyama[3], K. Tono[3,4], H. Ohashi[3], M. Yabashi[4], T. Ishikawa[4] & K. Yamauchi[1,5]

A method of fabricating multilayer focusing mirrors that can focus X-rays down to 10 nm or less was established in this study. The wavefront aberration induced by multilayer Kirkpatrick–Baez mirror optics was measured using a single grating interferometer at a photon energy of 9.1 keV at SPring-8 Angstrom Compact Free Electron Laser (SACLA), and the mirror shape was then directly corrected by employing a differential deposition method. The accuracies of these processes were carefully investigated, considering the accuracy required for diffraction-limited focusing. The wavefront produced by the corrected multilayer focusing mirrors was characterized again in the same manner, revealing that the root mean square of the wavefront aberration was improved from 2.7 (3.3) rad to 0.52 (0.82) rad in the vertical (horizontal) direction. A wave-optical simulator indicated that these wavefront-corrected multilayer focusing mirrors are capable of achieving sub-10-nm X-ray focusing.

ICS

PHYSICAL REVIEW ACCELERATORS AND BEAMS **20,** 080701 (2017)

Analytical description of photon beam phase spaces in inverse Compton scattering sources

C. Curatolo,[1,*] I. Drebot,[1] V. Petrillo,[1,2] and L. Serafini[1]
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[2]*Università degli Studi di Milano, via Celoria 16, 20133 Milano, Italy*
(Received 9 March 2017; published 3 August 2017)

4th order variational expansion over rms phase space distribution of e-hν colliding beams

acceptance angle $\Psi = \gamma_{CM}\theta_{max}$

relative energy spread

beam quality factor

laser wavelength

$$\frac{\Delta E_{ph}}{E_{ph}} \simeq \sqrt{\left[\frac{\Psi^2/\sqrt{12}}{1+\Psi^2} + \frac{\bar{P}^2}{1+\sqrt{12}\bar{P}^2}\right]^2 + \left[\left(\frac{2+X}{1+X}\right)\frac{\Delta\gamma}{\gamma}\right]^2 + \left(\frac{1}{1+X}\frac{\Delta E_L}{E_L}\right)^2 + \left(\frac{M^2\lambda_0}{2\pi w_0}\right)^4 + \left(\frac{a_0^2/3}{1+a_0^2/2}\right)^2}$$

$$\bar{P} = \gamma_{CM}\frac{\sqrt{2}\epsilon_x}{\sigma_x} = \frac{\sqrt{2}\epsilon_n}{\sigma_x\sqrt{1+X}}$$

laser bandwidth

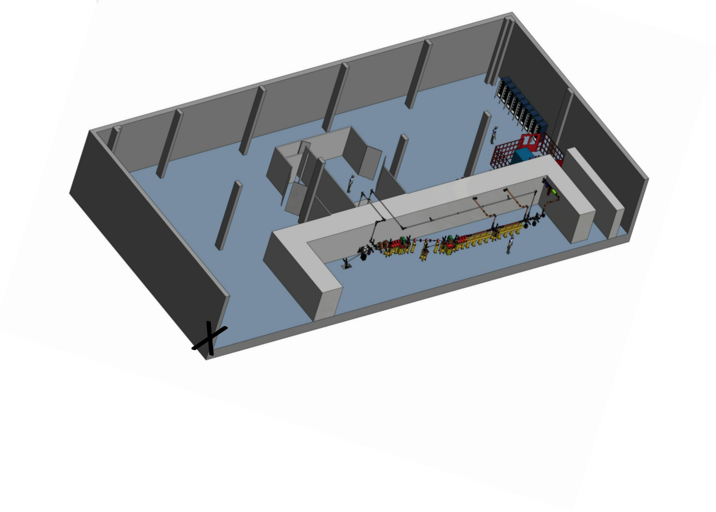
laser focal spot size

laser parameter

RECOIL PARAMETER X

- **Inverse Compton Scattering sources (like STAR, 200 keV photons) are operated with very small recoil factor X << 1. ICS for Nuclear Photonics (ELI-NP-GBS, 20 MeV photons) runs at X < 0.03.**
- **Hadron-Photon Collider works at small recoil factor X = 0.2**
- **EXMP is set to run at very large recoil factors, X > 10^5**

STAR



ELI-NP-GBS

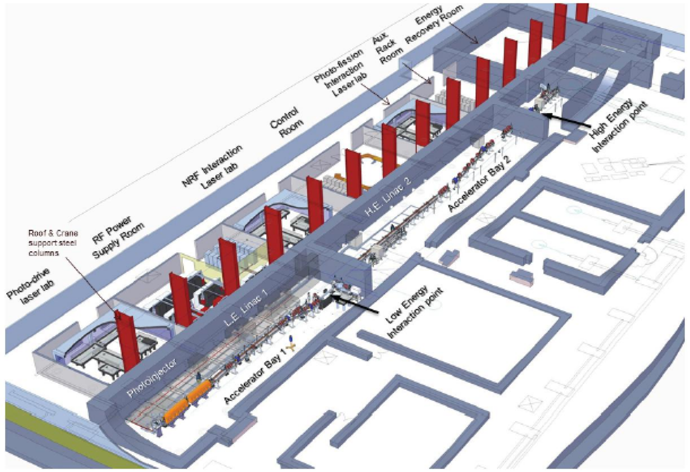


Fig. 197. Isometric 3D view of Building Layout of the Accelerator Hall & Experimental Areas

HPC

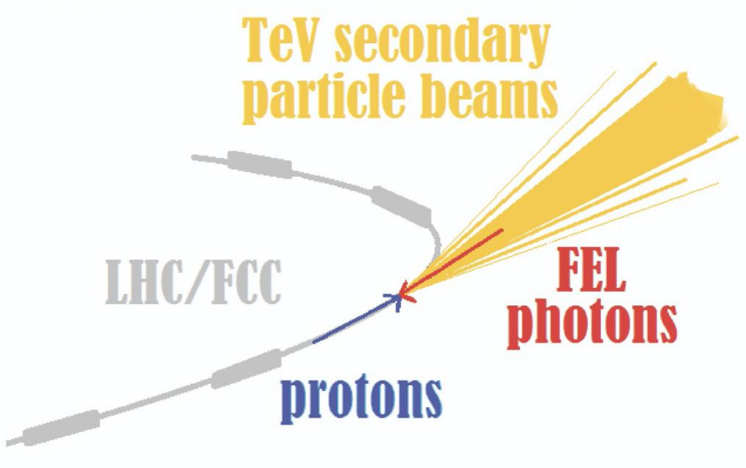


Table 1: Collider performances in various scenarios.

Proton source	E_{pr}	N_{pr}	spot size σ_0	Photon source	E_{ph}	N_{ph}
LHC	7 TeV	$2 \cdot 10^{11}$	7 μm	FEL	$10 - 20$ keV	10^{13}
FCC	50 TeV	10^{11}	1.6 μm	FEL	$1.43 - 12$ keV	10^{14}

Trespassing the Schwinger's Limit (E = 1.3·10^18 V/m) @ EXMP

The effective laser parameter is $a_0 = 4.3\,\frac{\lambda_0}{w_0}\sqrt{U(J)/\sigma_t(ps)}$ with λ_0 the wavelength, w_0 the focal spot size, U the energy, and σ_t the RMS pulse length of the laser. In the assumption that the FEL beam behaves as a single mode, TEM_{00} laser mode, we checked that non-linear effects due to field intensity of the FEL photon beam could be considered negligible, since a_0, defining the non linearity of the electron-e.m. field interaction, is quite small, definitely below 10^{-2}. However, since EXMP is operated in a very large recoil regime (being X in excess of 10^5), the combination $\chi = a_0 X$ comes out to be much larger than 1, nearly 3×10^3. This is linked to the fact that the FEL e.m. field of the focused FEL beam is in the range of 10^{15} V/m, which, in the electron rest frame, is transformed to 10^{21} V/m, almost 3 orders of magnitude larger than Schwinger's limit. Further studies are needed to investigate potentials of this high recoil regime with respect to amplification of the electron-photon interaction strength.

FEL 60 keV U = 0.125 J σ_t = 0.2 psec w_0 = 10 nm

a_0 = 4.3 λ $\sqrt{}(U/\sigma_t)$ /w_0=0.007, X=4.6 10^5 , χ = 3220

P = 0.94 U/(2 σ_t) =294 GW

I_p = 2 P / (π w_0^2) = 1.9 10^{27} W/m^2 = 1.9 10^{23} W/cm^2

E = $\sqrt{}(754\ I_p)$ = 1.2 10^{15} V/m

E' = E γ = 1.2 10^{21} V/m

ERLC

Superconducting twin linear collider with energy recovery (ERLC)

To solve the problem of parasitic collisions, Valery Telnov recently proposed the concept of a *twin* linear collider [308] with energy recovery and multiple use of beams, which can increase the luminosity by four orders of magnitude. What follows is a short version of this article.

In the twin linear collider, the beams are accelerated and then decelerated down to $E \approx 5\,\mathrm{GeV}$ in separate parallel linacs with coupled RF systems, see Fig. 5.10. The RF power is always divided equally among the linacs. RF energy is transferred to the beams both from an external RF source and from the beam being decelerated. The linacs can be either two separate SC linacs connected by RF couplers at the ends of multi-cell cavities (9-cell TESLA cavity) or one linac consisting of twin (dual) cavities with axes for two beams. Such cavities have been designed and tested for XFELs [309–312].

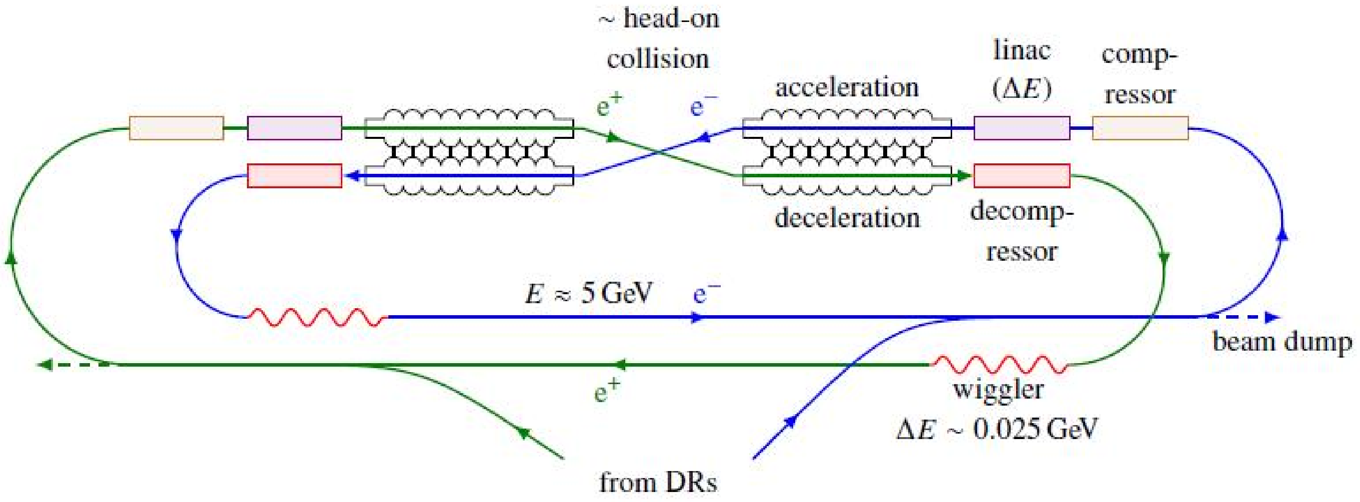


Figure 5.10. The layout of the SC twin linear collider.