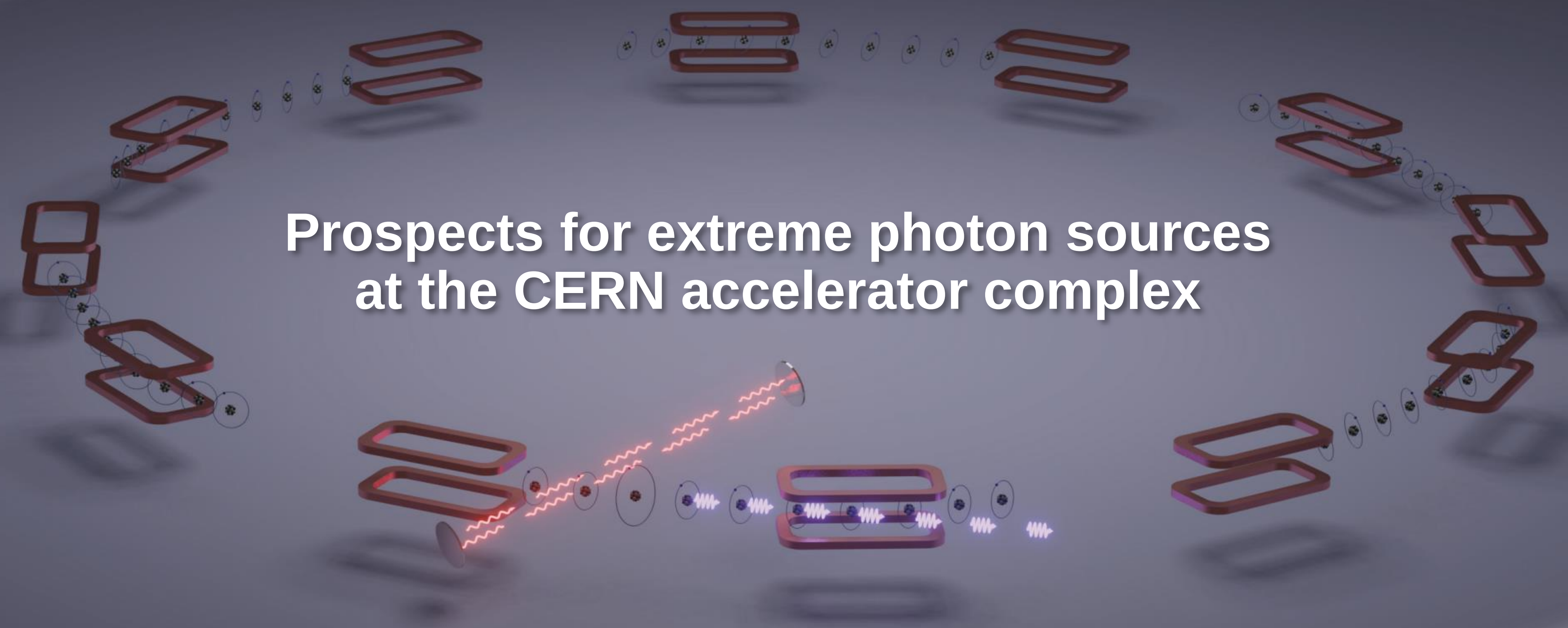
Prospects for extreme photon sources at the CERN accelerator complex



28th October 2024

E. Granados, *M.M. Calderon, B. A. Marsh, V. N. Fedosseev, M. W. Krasny, A. Latina, V. Musat, R. Corsini, A. Martens, F. Zomer, X. Lu, K. Cassou, R. Chiche, K. Dupraz, D. Nutarelli, E. Cormier, G. Santarelli, and Y. Dutheil*

… and many others

Outline

The CERN accelerator complex

- Brief history / introduction, key enabling technologies
- Interest in high-flux Gamma-ray sources: beam cooling, muon sources, dark matter research…

Gamma Factory

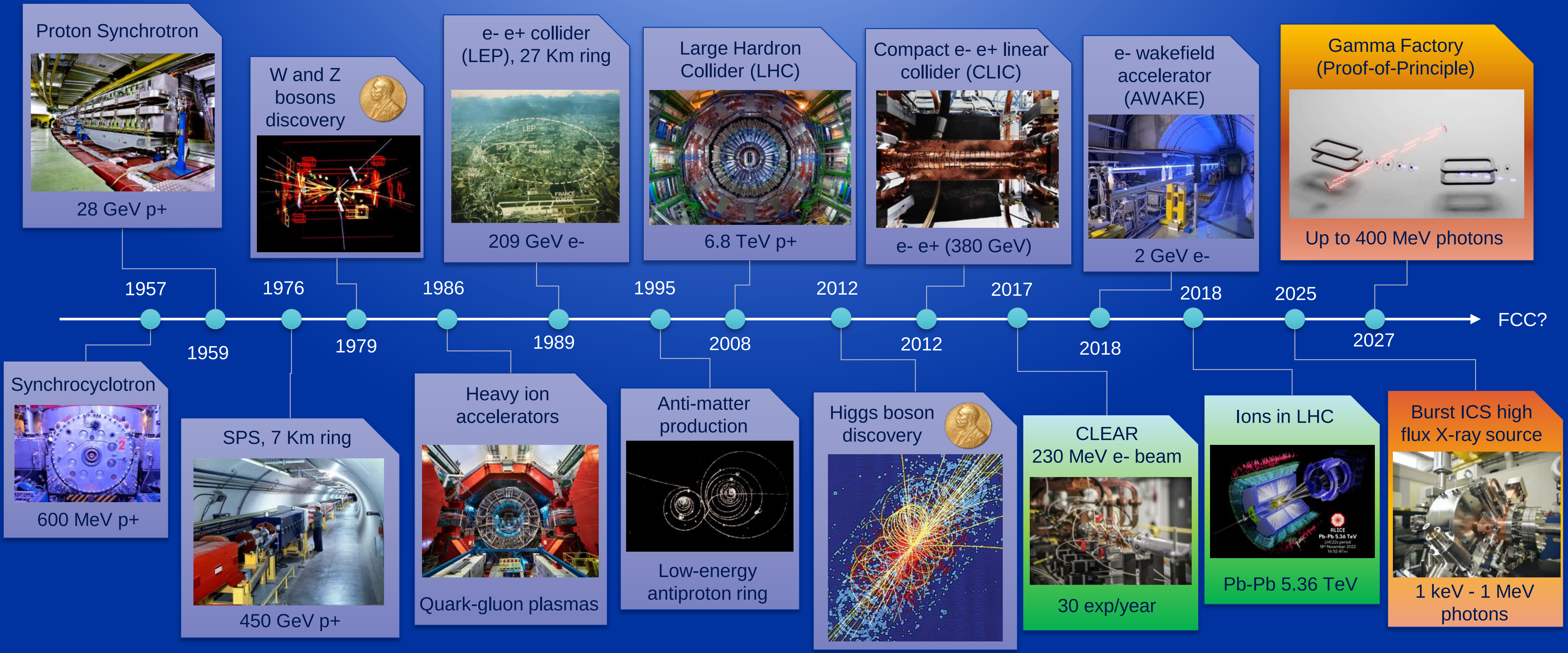
- Concept: exploiting the Doppler effect in ultra-relativistic partially stripped ion beams
- A 7 orders of magnitude Gamma-ray photon flux leap
- Roadmap – Proof of principle experiment in SPS, final experiment in the LHC
- Status: Lasers, experimental area, expected performance

Inverse Compton Scattering X-ray sources

- Inherited technology from e+/e- colliders: high charge X-band accelerators in burst-mode operation
- High energy electro-optic frequency combs for Fabry-Perot cavities

Conclusions

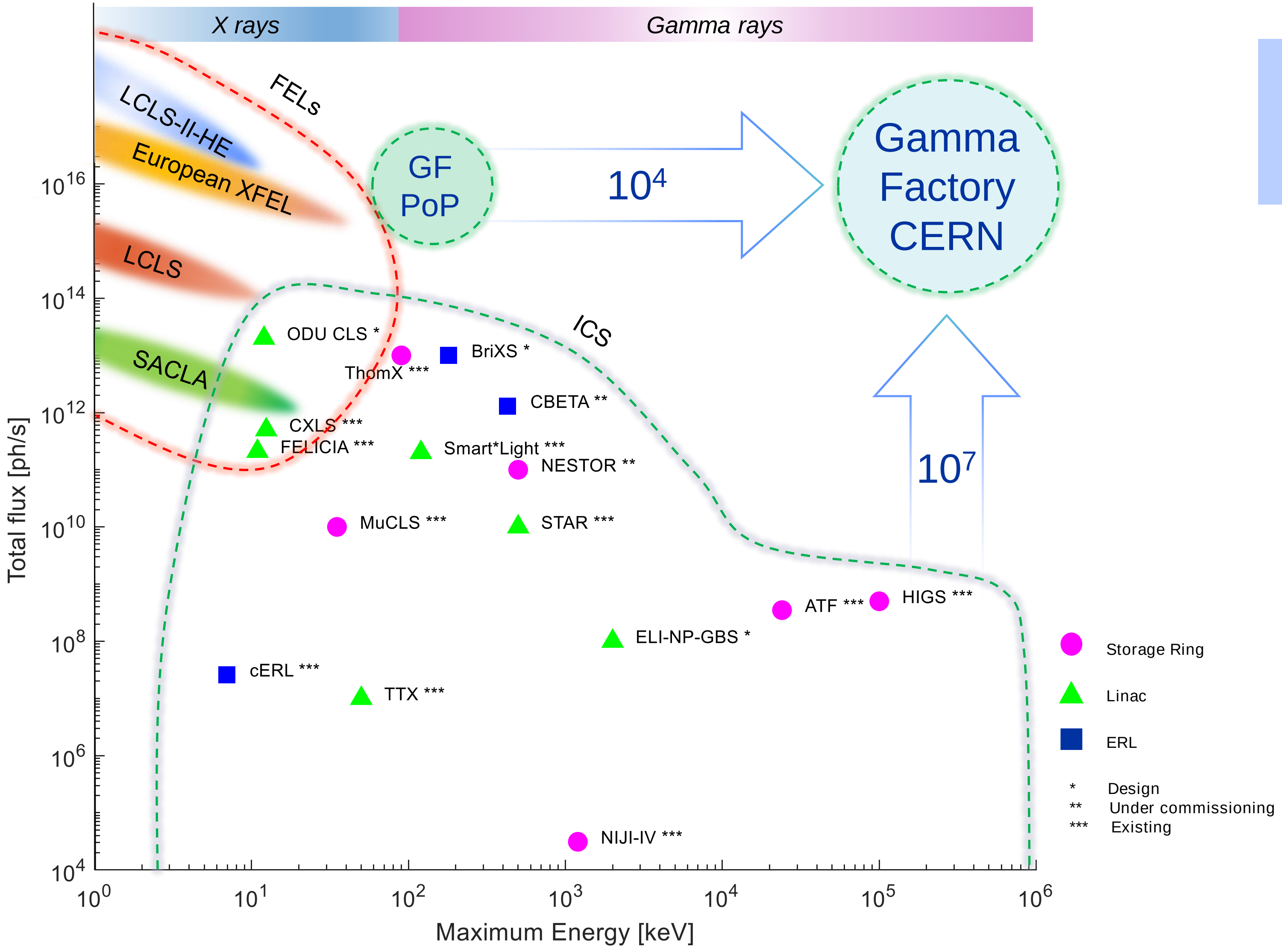
The CERN accelerator complex



The *CLIC development* of high average current ultrafast electron sources enables the production of **high-flux X-rays**

The demonstration of *heavy ions in LHC* enables the production of **extreme high-flux γ-rays**

Comparison to other X-ray and Gamma-ray sources



"Can one make a technological leap of 7 orders of magnitude to deliver similar fluxes to FELs in the Gamma-rays?"

Example:

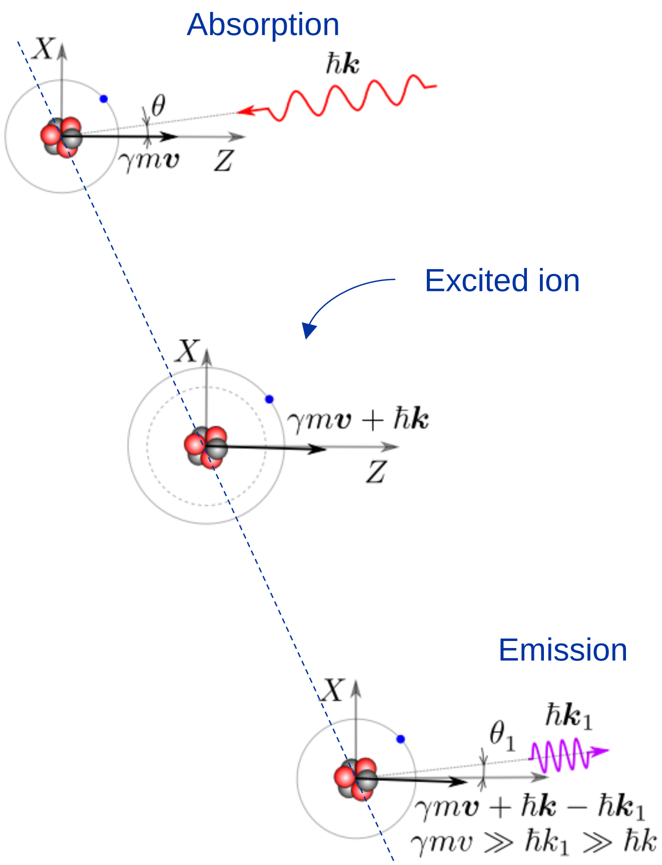
European XFEL	Gamma Factory
27,000 pulses/s	40 MHz
24 keV	400 MeV
10^{16} photons/s	10^{16} photons/s
1.4 mJ/pulse	16 mJ/pulse
38 W (J/s)	**640 kW (kJ/s)**

The Gamma Factory naturally requires **MW** power and **MJ** of stored beam energy

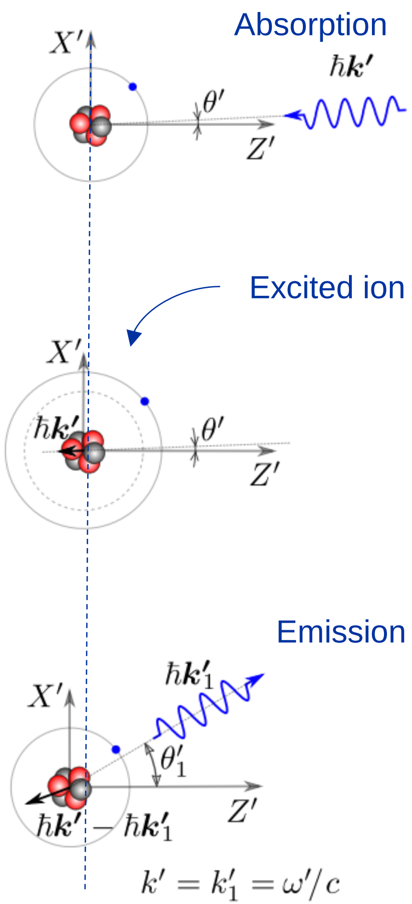
So far, the *only* facility currently providing such beam is the **LHC**

Basic idea: Use the Doppler effect with ultra-relativistic ions

In the lab frame



In the ion frame



Absorption

Lorentz transformation

$$\omega' \sin\theta' = \omega \sin\theta, \qquad \Delta\theta' \approx \frac{\Delta\theta}{2\gamma}$$

$$\omega' = (1+\beta\cos\theta)\gamma\omega \approx \left(1+\beta-\beta\frac{\theta^2}{2}\right)\gamma\omega \approx 2\gamma\omega.$$

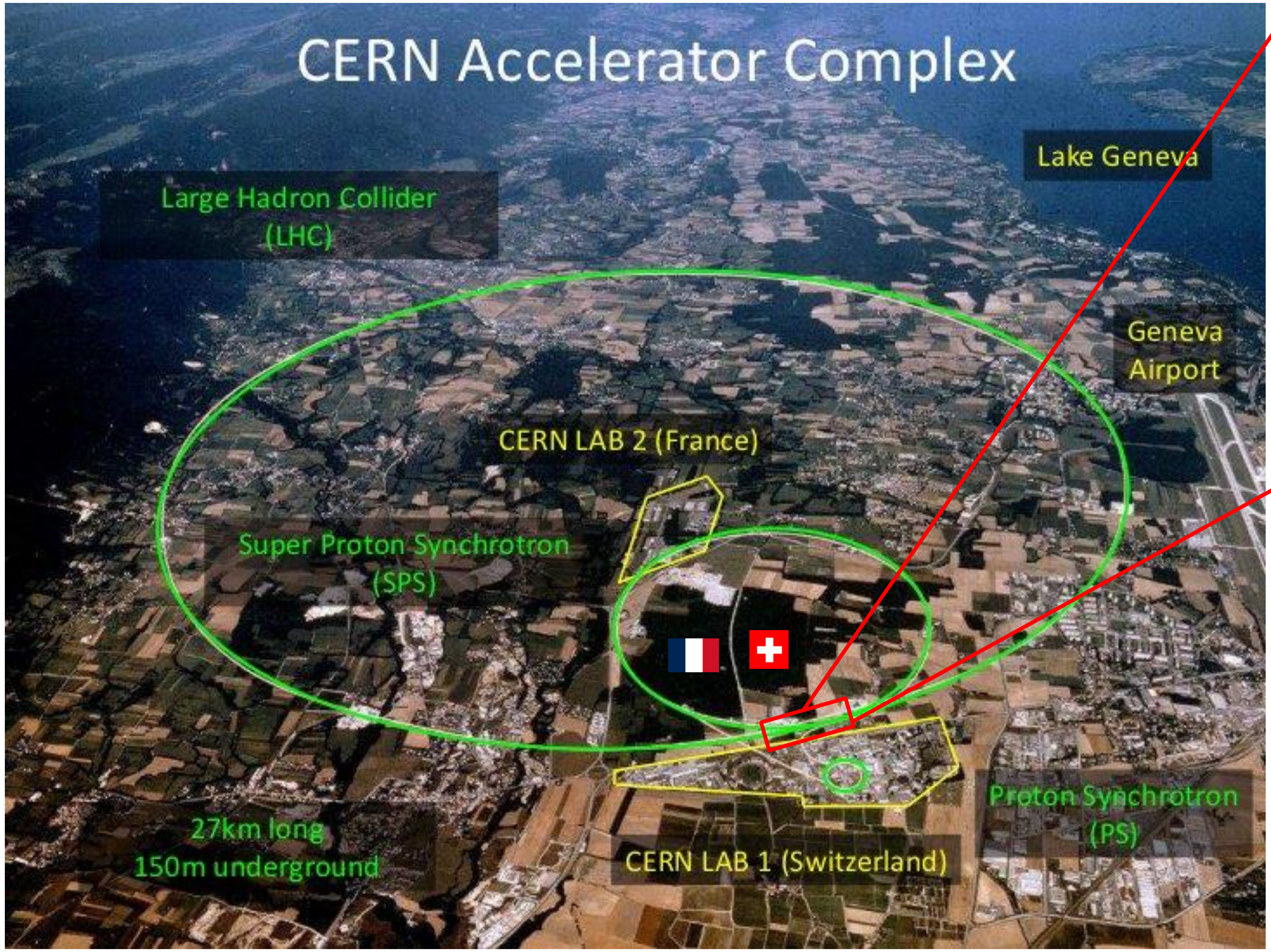
Emission

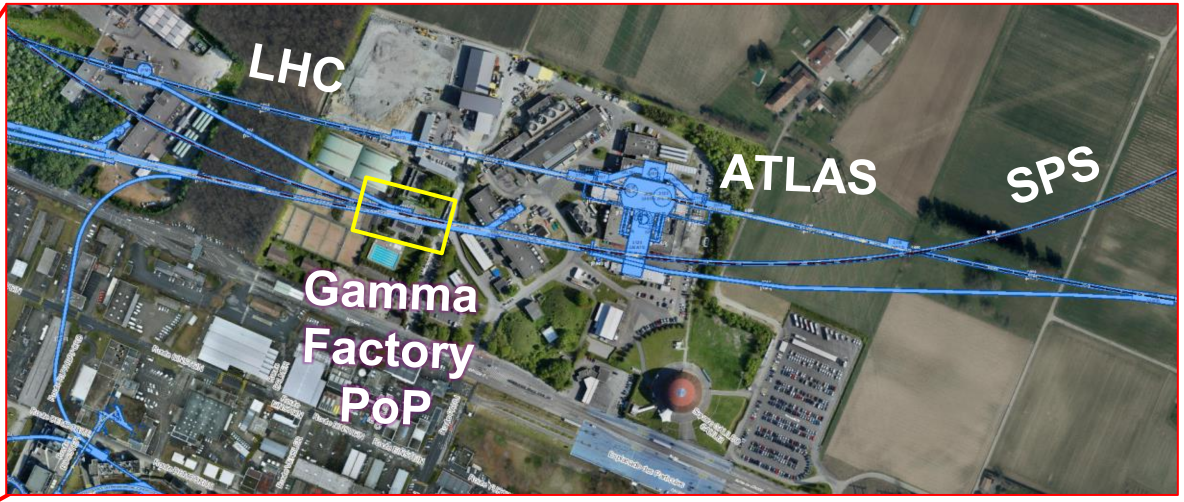
$$\omega_1 \sin\theta_1 = \omega' \sin\theta'_1 \;\Rightarrow\; \sin\theta_1 = \frac{\sin\theta'_1}{\gamma(1+\beta\cos\theta'_1)},$$

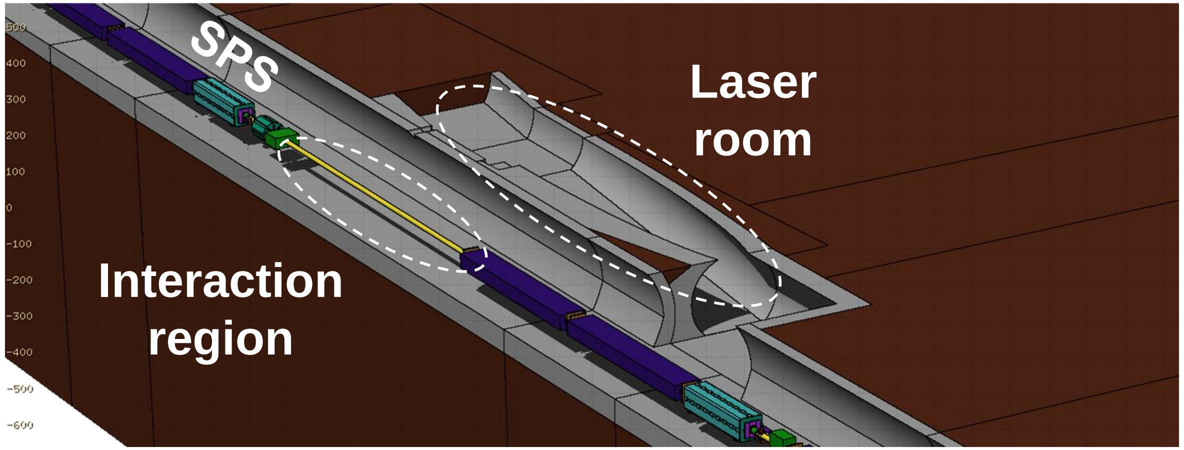
$$\omega_1 = \gamma(1+\beta\cos\theta'_1)\omega' \approx 2\gamma^2(1+\beta\cos\theta'_1)\omega.$$

$$\nu^{max} \longrightarrow (4\,\gamma_L^2)\,\nu_i$$

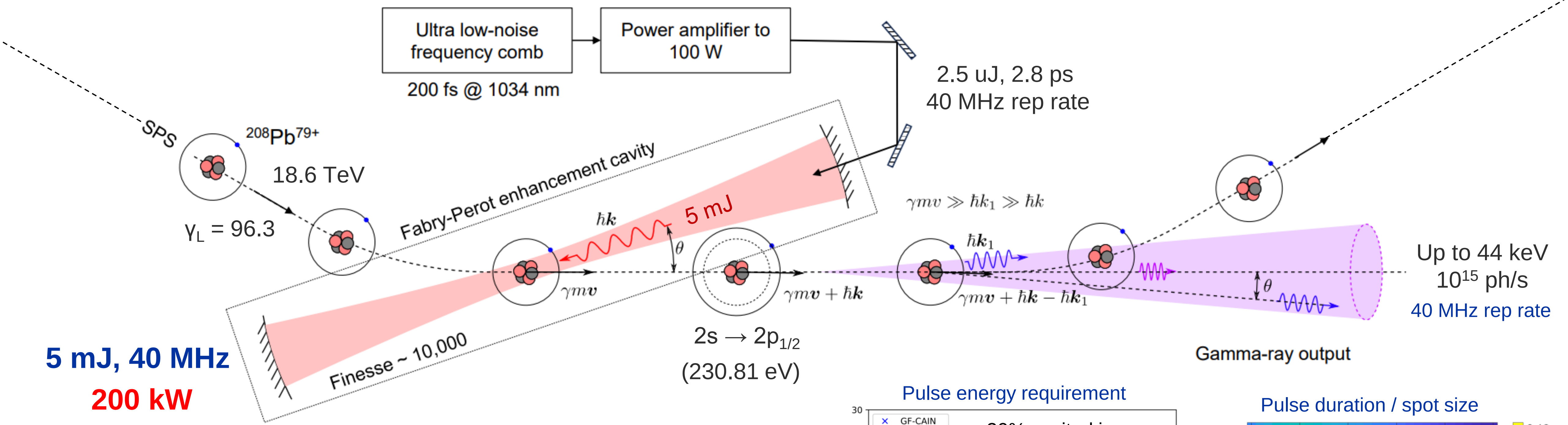
Proof of principle experiment location







Proof of principle experimental setup



5 mJ, 40 MHz

200 kW

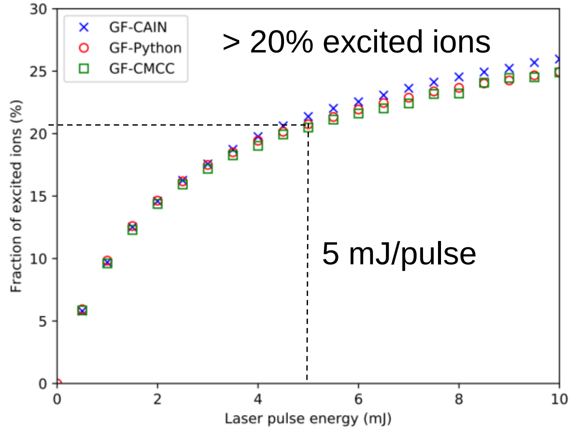
$$\mathcal{F} = 10{,}000 \approx 2\pi/\mathcal{L} \;\Rightarrow\; G \approx 4T_1/\mathcal{L}^2 \approx \textbf{5000}$$

$$\mathcal{L} = \underbrace{A_1 + A_2}_{\text{Absorption } 10^{-6}} + \underbrace{D_1 + D_2}_{\text{Diffraction } 10^{-5}} + \underbrace{T_1 + T_2}_{\text{Transmission } 10^{-4}}$$

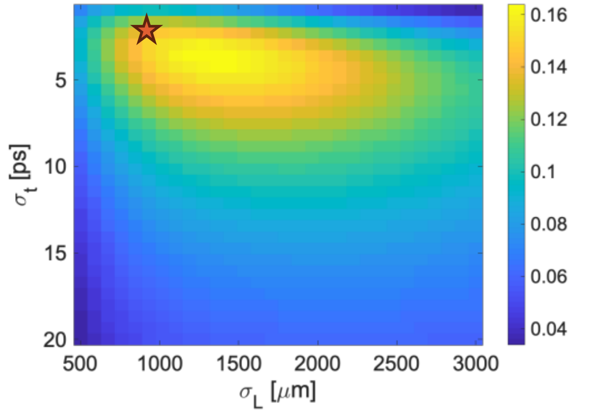
Frequency comb linewidth < 2 kHz

"LIGO-type" mirrors

Pulse energy requirement

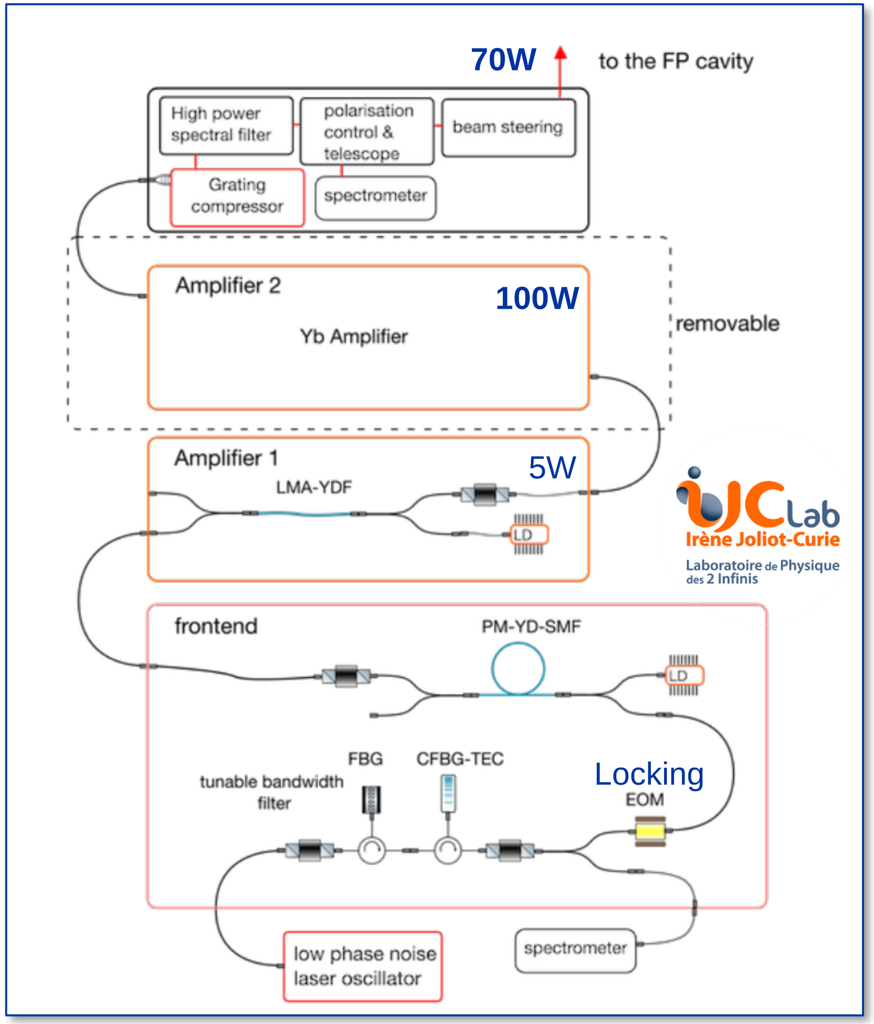


Pulse duration / spot size

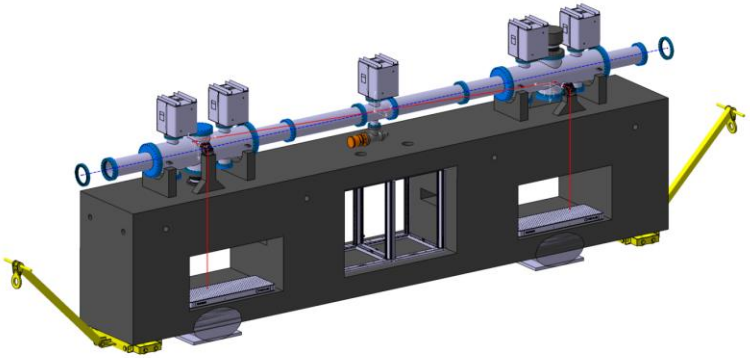


Laser systems and integration into SPS

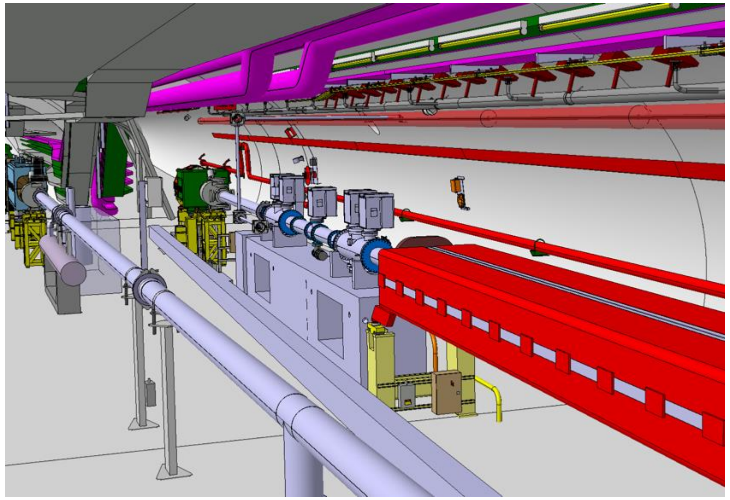
Laser system



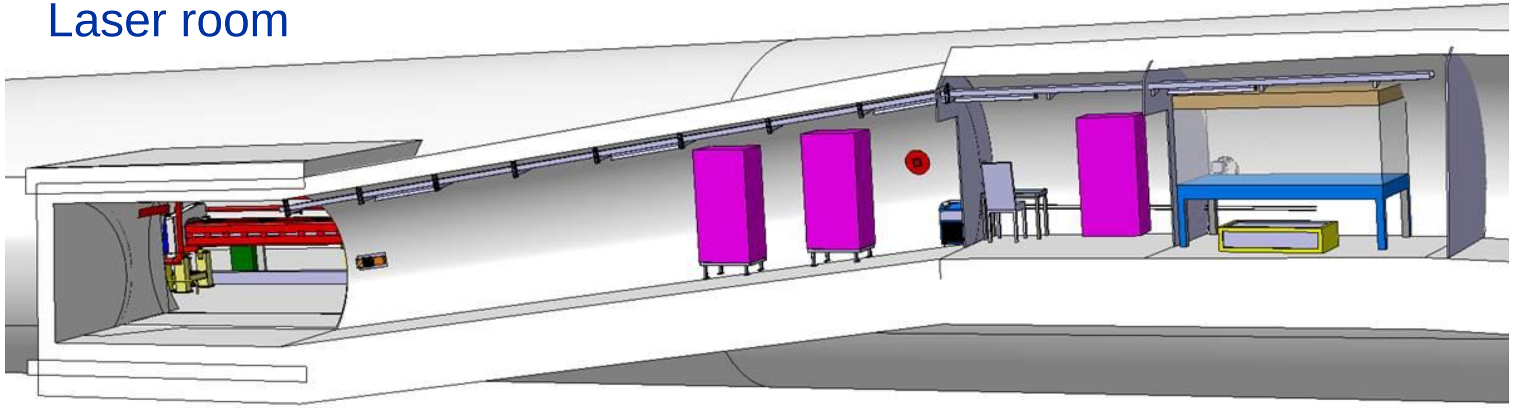
Fabry-Perot cavity assembly



Integration in SPS

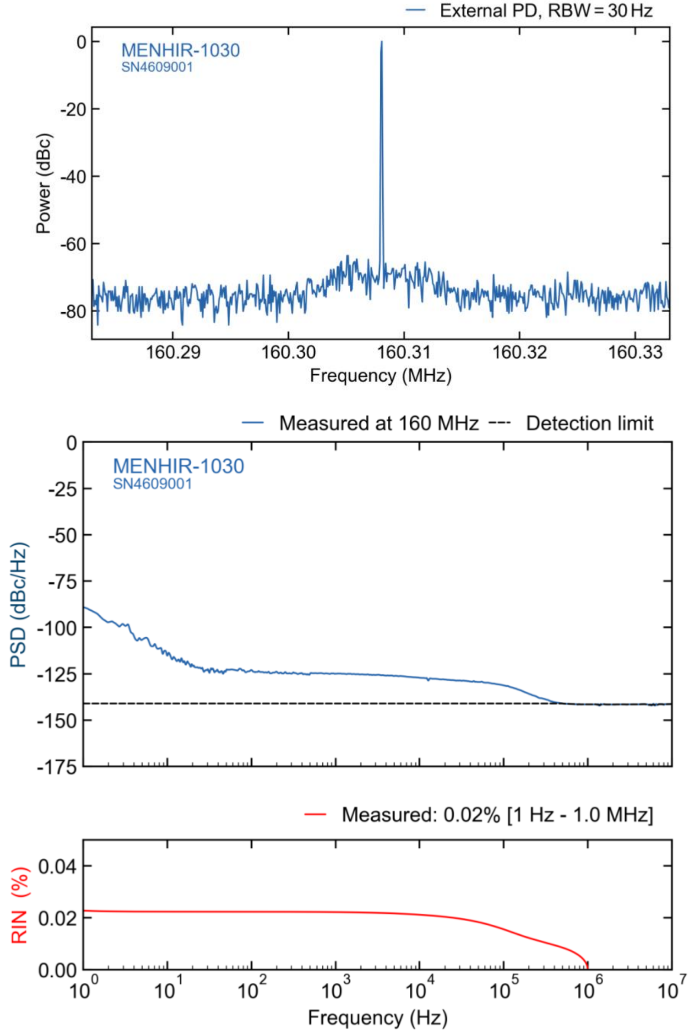


Laser room

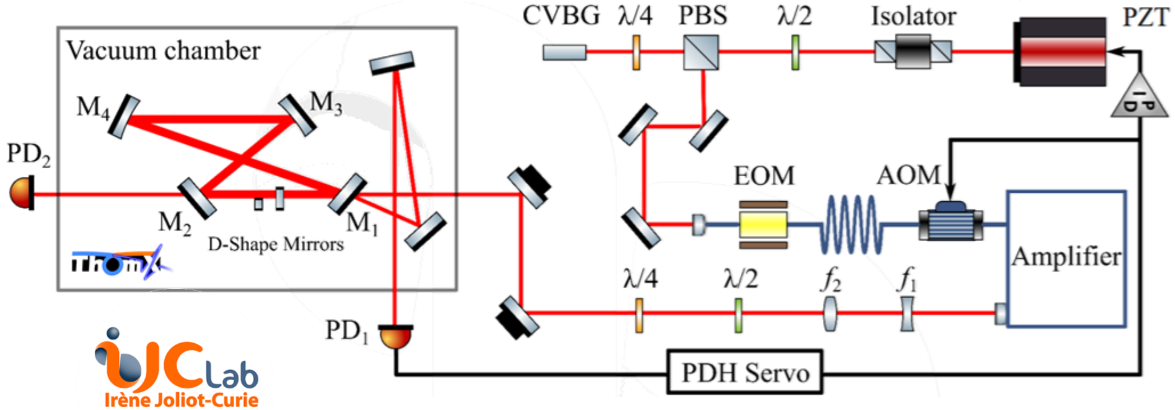


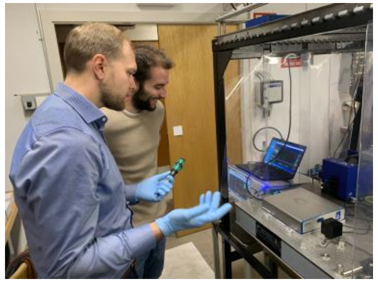
Laser front-end performance

Excellent phase-noise performance



Testing with ThomX FP cavity





	Demo	GF PoP
FSR	160 MHz	40 MHz
Cavity linewidth	10 kHz	4 kHz
Finesse	24,000	10,000
Gain	6,700	5,000
Coupling efficiency	70%	70%
Amplified power	70 W	50 W
Estimated power	**320 kW**	**180 kW**

Feb 2024

Next steps:

Tender amplifier to 100W

Installation at SPS in 2025-27

PoP experiments at SPS
2027-2032

‘Fresh’ from the press…

Applied Physics Letters ARTICLE pubs.aip.org/aip/apl

Stable 500 kW average power of infrared light in a finesse 35 000 enhancement cavity

Cite as: Appl. Phys. Lett. **124**, 251105 (2024); doi: 10.1063/5.0213842
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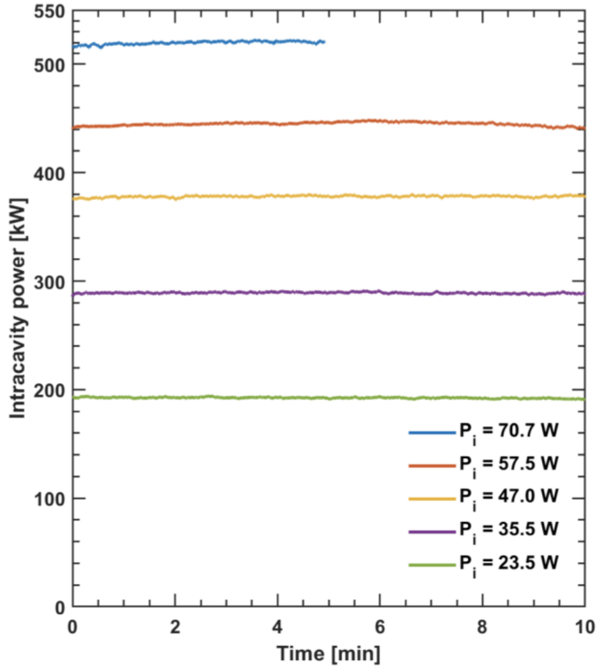
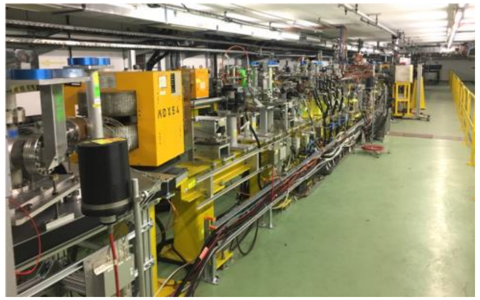
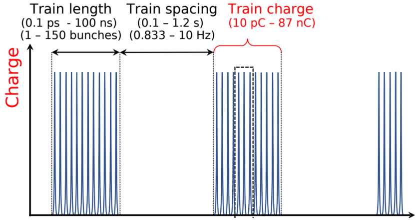


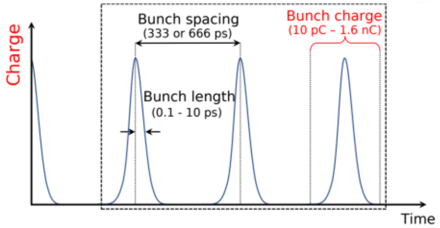
FIG. 3. Experimental measurements of intracavity power as a function of time for various values of injection power P_i.

Electron sources available at CERN

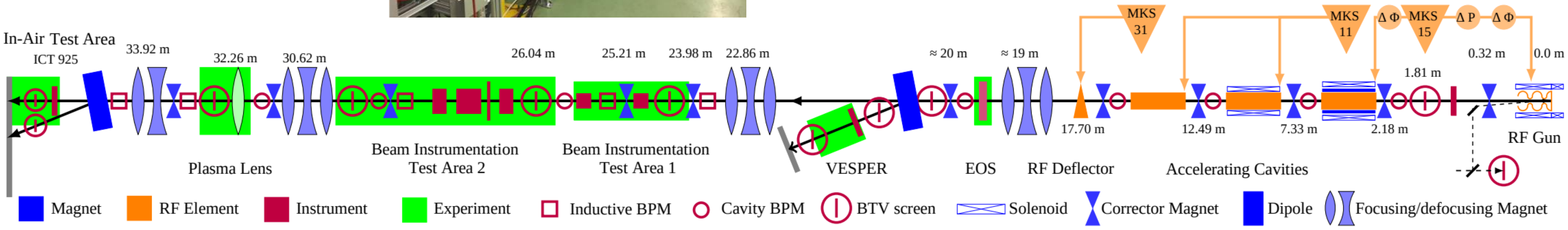
2017-2030





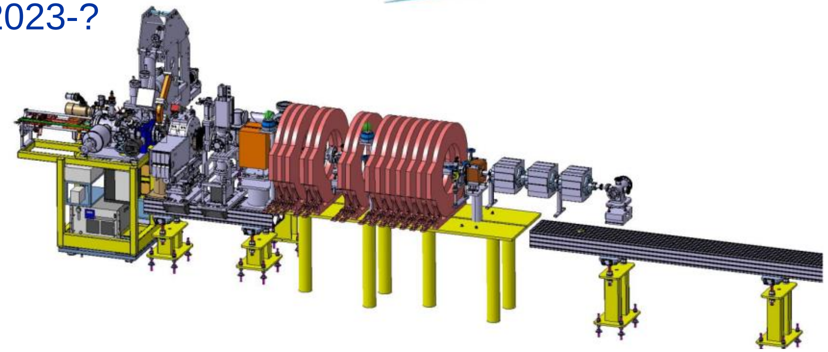


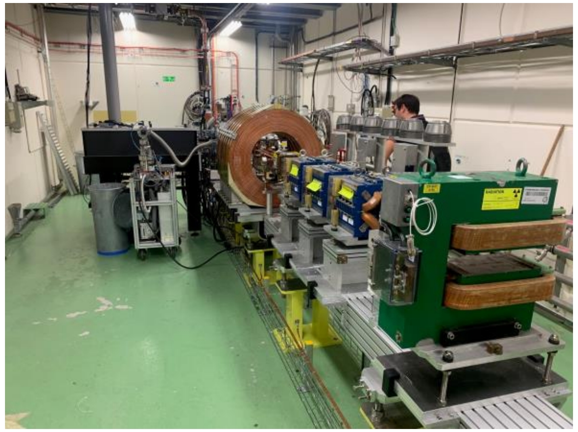
CLEAR
30 - 220 MeV
7 nC/bunch
1 - 150 bunches
1 - 10 Hz train rep rate
3 GHz
Cs_2Te photocathode



CTF-2

2023-?

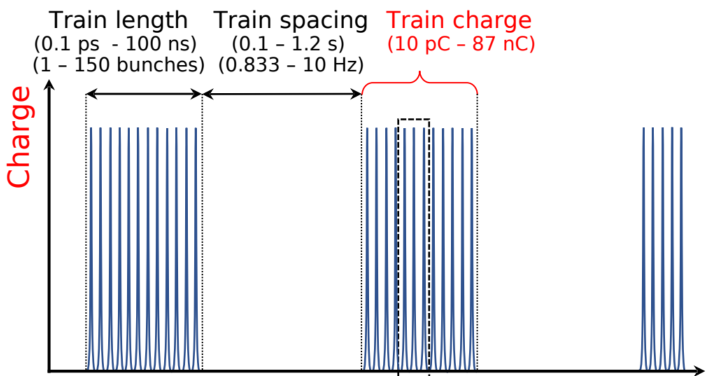




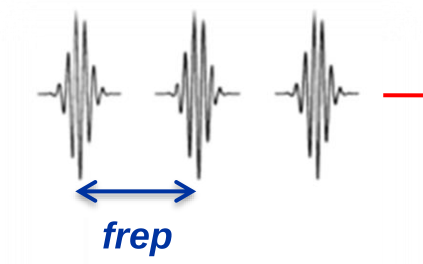
CTF2 / CLIC
6 - 150 MeV
1 - 2 nC/bunch
1- 10,000 bunches
1 - 5 Hz trains
12 GHz (X-band)

Burst-mode enhancement cavities

Injected electron bunches

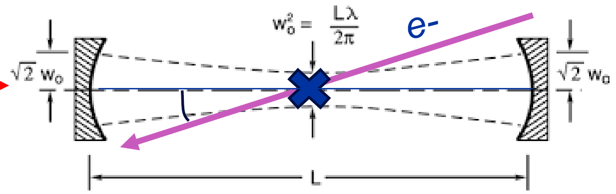


Injected laser pulses

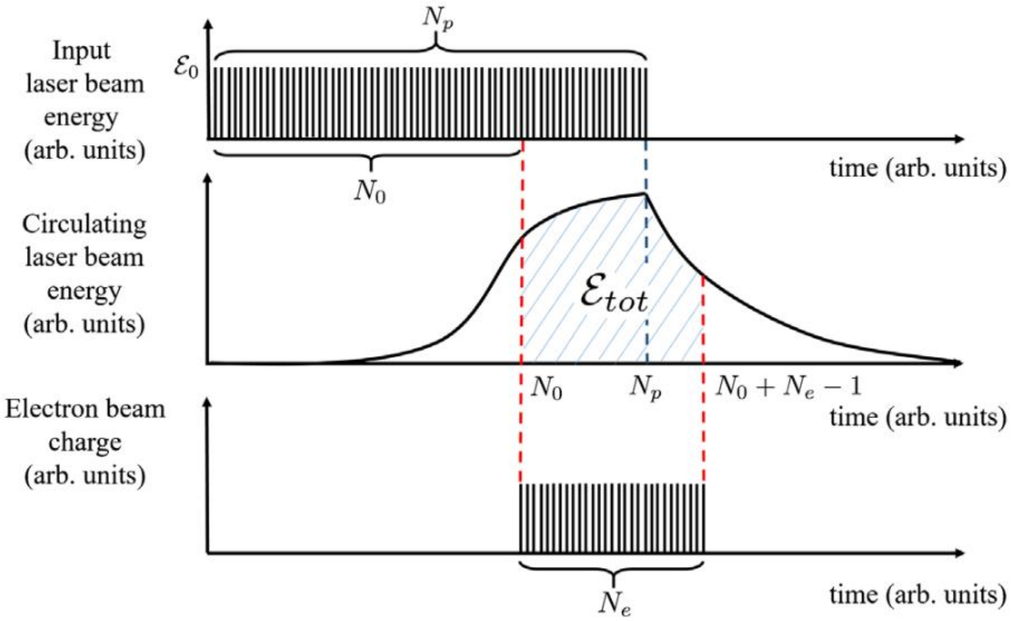


(Coupler) mirror

Spherical mirror



Burst-mode transient energy storage

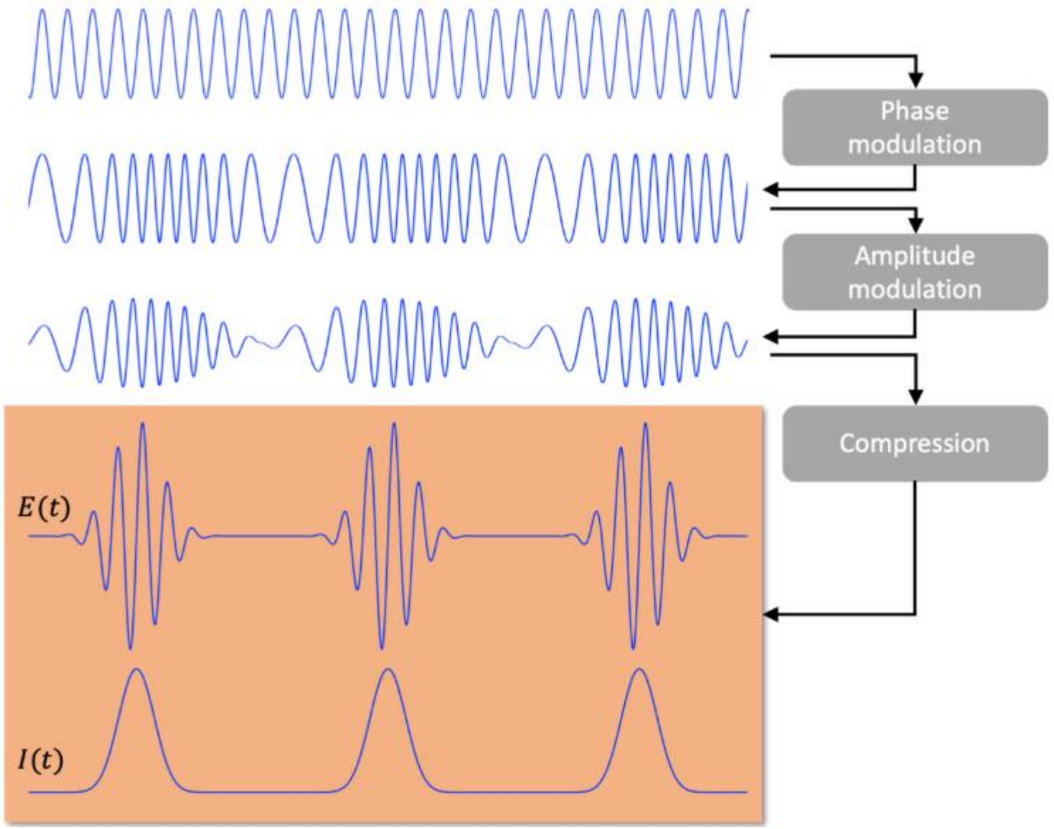


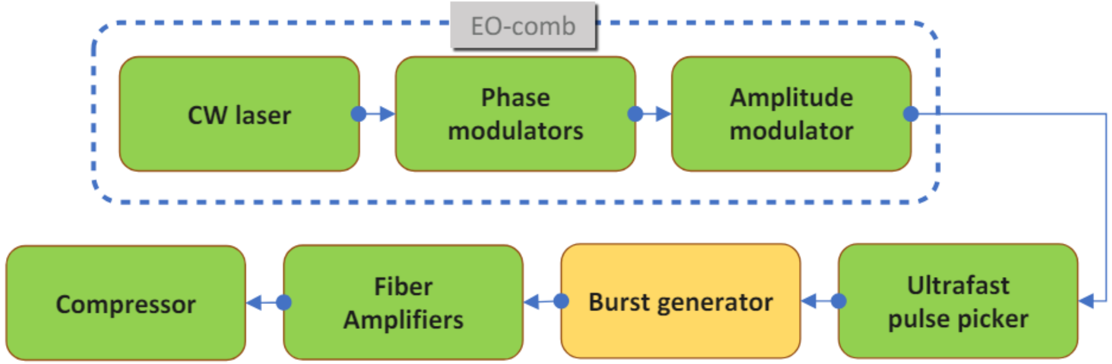
Phys. Rev. Accel. Beams **21**, 121601 (2018)

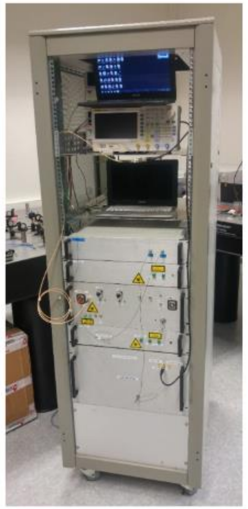
CTF2: 2×10^{10}**ph/s @ 890 eV**
CLEAR: **3** $\times$ 10^{10} **ph/s @ 740 keV**

"An Efficient Optimisation of a Burst Mode-Operated Fabry-Perot Cavity for Compton Light Sources", doi:10.18429/JACoW-FLS2023-TU1C1 (2023)

Electro-Optic GHz repetition rate frequency combs



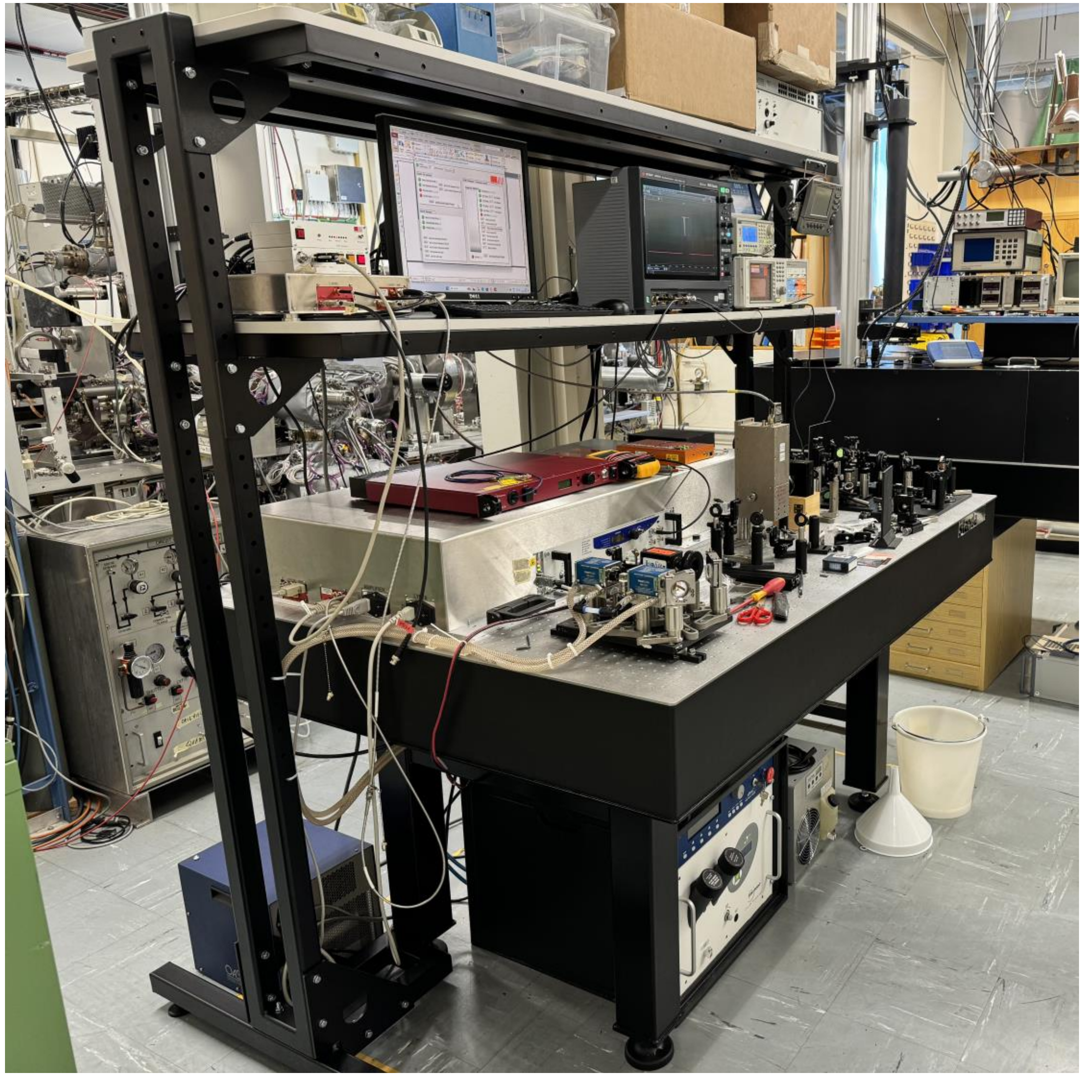


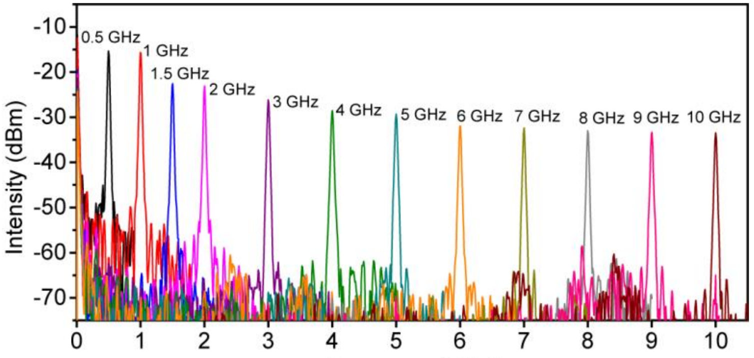


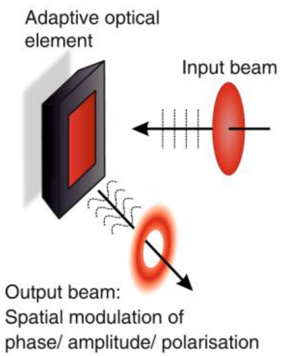
Gigapico Burst Mode:

Wavelength (Yb):	1030 nm
Average power:	40 W
Maximum burst energy:	1 mJ
Maximum pulse energy:	10 µJ
Pulse repetition rate :	0.25 GHz to 18 GHz
Burst repetition rate:	50 kHz to several MHz
Pulse duration:	800 fs to 2 ps
Number of pulses per burst:	10 to several 1000

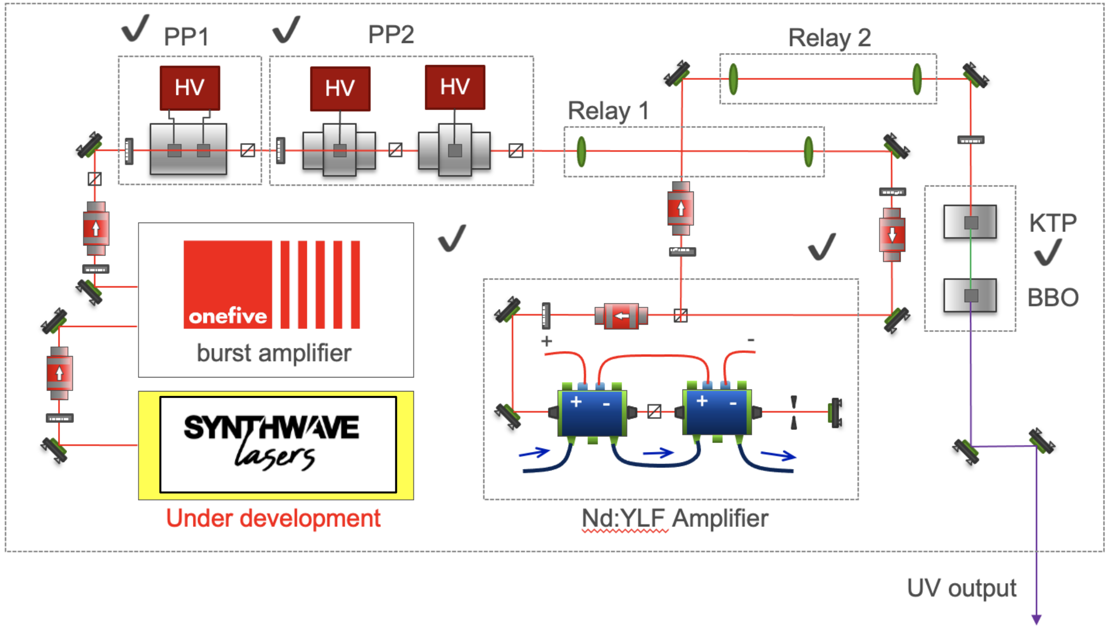
Electro-Optic GHz repetition rate frequency combs







FUTURE CIRCULAR COLLIDER



Conclusions

The CERN accelerator complex provides a variety of unique beams for high photon energy production

Gamma Factory

- Phase I – Proof of principle experiment starting 2027 to produce 44 keV photons at 10^{15} ph/s
- Phase II – in LHC up to 400 MeV photons at 10^{16} ph/s

Inverse Compton Scattering X-ray sources

- High energy electro-optic frequency combs at multi-GHz repetition rate development underway
- Currently 2 electron beam user facilities operative with lasers and diagnostics for X-ray experiments
- Burst-mode high charge electron accelerators can yield 1 – 700 keV photons at 10^{10} ph/s

Acknowledgements

Gamma Factory Collaboration:

γgf

Physics Beyond Colliders

100+ physicists from 40 institutes in 15 countries

A. Abramov[1], A. Afanasev[37], S.E. Alden[1], R. Alemany Fernandez[2], P.S. Antsiferov[3], A. Apyan[4], G. Arduini[2], D. Balabanski[34], R. Balkin[32], H. Bartosik[2], J. Berengut[5], E.G. Bessonov[6], N. Biancacci[2], J. Bieroń[7], A. Bogacz[8], A. Bosco[1], T. Brydges[36], R. Bruce[2], D. Budker[9,10], M. Bussmann[38], P. Constantin[34], K. Cassou[11], F. Castelli[12], I. Chaikovska[11], C. Curatolo[13], C. Curceanu[35], P. Czodrowski[2], A. Derevianko[14], K. Dupraz[11], Y. Dutheil[2], K. Dzierżęga[7], V. Fedosseev[2], V. Flambaum[25], S. Fritzsche[17], N. Fuster Martinez[2], S.M. Gibson[1], B. Goddard[2], M. Gorshteyn[20], A. Gorzawski[15,2], M.E. Granados[2], R. Hajima[26], T. Hayakawa[26], S. Hirlander[2], J. Jin[33], J.M. Jowett[2], F. Karbstein[39], R. Kersevan[2], M. Kowalska[2], M.W. Krasny[16,2], F. Kroeger[17], D. Kuchler[2], M. Lamont[2], T. Lefevre[2], T. Ma[32], D. Manglunki[2], B. Marsh[2], A. Martens[12], C. Michel[40] S. Miyamoto[31] J. Molson[2], D. Nichita[34], D. Nutarelli[11], L.J. Nevay[1], V. Pascalutsa[28], Y. Papaphilippou[2], A. Petrenko[18,2], V. Petrillo[12], L. Pinard[40] W. Płaczek[7], R.L. Ramjiawan[2], S. Redaelli[2], Y. Peinaud[11], S. Pustelny[7], S. Rochester[19], M. Safronova[29,30], D. Samoilenko[17], M. Sapinski[20], M. Schaumann[2], R. Scrivens[2], L. Serafini[12], V.P. Shevelko[6], Y. Soreq[32], T. Stoehlker[17], A. Surzhykov[21], I. Tolstikhina[6], F. Velotti[2], A. Viatkina[9] A.V. Volotka[17], G. Weber[17], W. Weiqiang[27] D. Winters[20], Y.K. Wu[22], C. Yin-Vallgren[2], M. Zanetti[23,13], F. Zimmermann[2], M.S. Zolotorev[24] and F. Zomer[11]

Electron facilities at CERN:

clear AWAKE CLIC

Partners and collaborators:

Lasers & Optics

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

Institut d'Optique Graduate School ParisTech

université PARIS-SACLAY

Tsinghua University 1911

LP2N Laboratoire Photonique Numérique & Nanosciences

iP2i Les 2 Infinis Lyon

cnrs NUCLÉAIRE & PARTICULES

l'X École Polytechnique IP Paris

Electron sources

PAUL SCHERRER INSTITUT PSI

UKRI Science and Technology Facilities Council

SPARC LAB

INFN

cea

And many others…

Laser-particle interactions

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Jefferson Lab

UNIVERSITÉ PARIS 1 PANTHÉON SORBONNE

Duke UNIVERSITY

Berkeley UNIVERSITY OF CALIFORNIA

GSI

eli nuclear physics

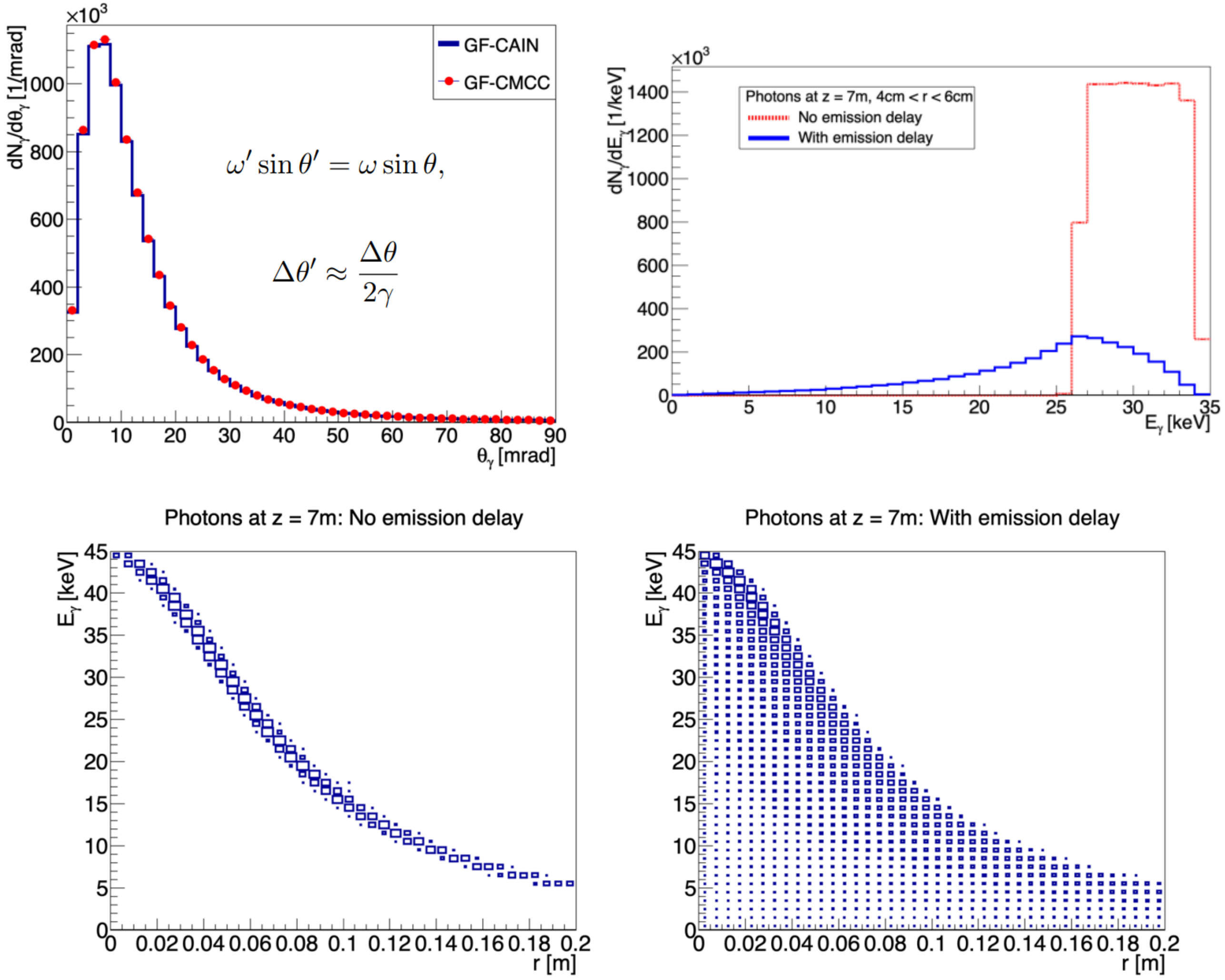
UNSW SYDNEY

BERKELEY LAB

調和ある多様性の創造 国立研究開発法人 QST 量子科学技術研究開発機構 National Institutes for Quantum Science and Technology home.cern

Expected performance

	Phase I	Phase II
	GF PoP	**Gamma Factory**
Ion beam	$^{208}Pb^{79+}$	$^{208}Pb^{81+}$
	18.652 TeV (SPS)	578.9 TeV (LHC)
	40 MHz	40 MHz
Produced photons	**44 keV**	**400 MeV**
	10^{15} photons/s	10^{16} photons/s
	0.2 uJ/pulse	16 mJ/pulse
	7 W (J/s)	**640 kW** (kJ/s)



J. Bieroń, M. W. Krasny, W. Płaczek, S. Pustelny, Optical Excitation of Ultra-Relativistic Partially Stripped Ions. *ANNALEN DER PHYSIK* 2022, 534, 2100250.