Gamma Factory

multidisciplinary research tools based on LHC

WIESŁAW PŁACZEK

Jagiellonian University in Krakow

Poland

Representing the Gamma Factory Study Group

Polish Particle and Nuclear Theory Summit (2PiNTS)

Institute of Nuclear Physics, Polish Academy of Sciences,
Krakow, Poland, 22–24 November 2023

Gamma Factory studies

The Gamma Factory proposal for CERN †

† An Executive Summary of the proposal addressed to the CERN management.

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e-Print: 1511.07794 [hep-ex]

~100 physicists from ~40 institutions have contributed so far to the Gamma Factory studies

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Gamma Factory studies are **anchored and supported** by the CERN **Physics Beyond Colliders (PBC)** framework.

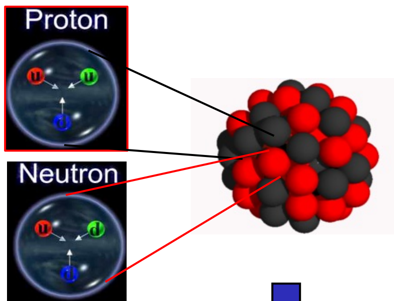
More info on all the GF group activities:
https://indico.cern.ch/category/10874

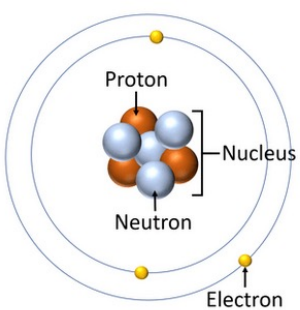
*We acknowledge the crucial role of the CERN **PBC** framework in bringing our accelerator tests, GF-PoP experiment design, software development and physics studies to their present stage!*

Principles

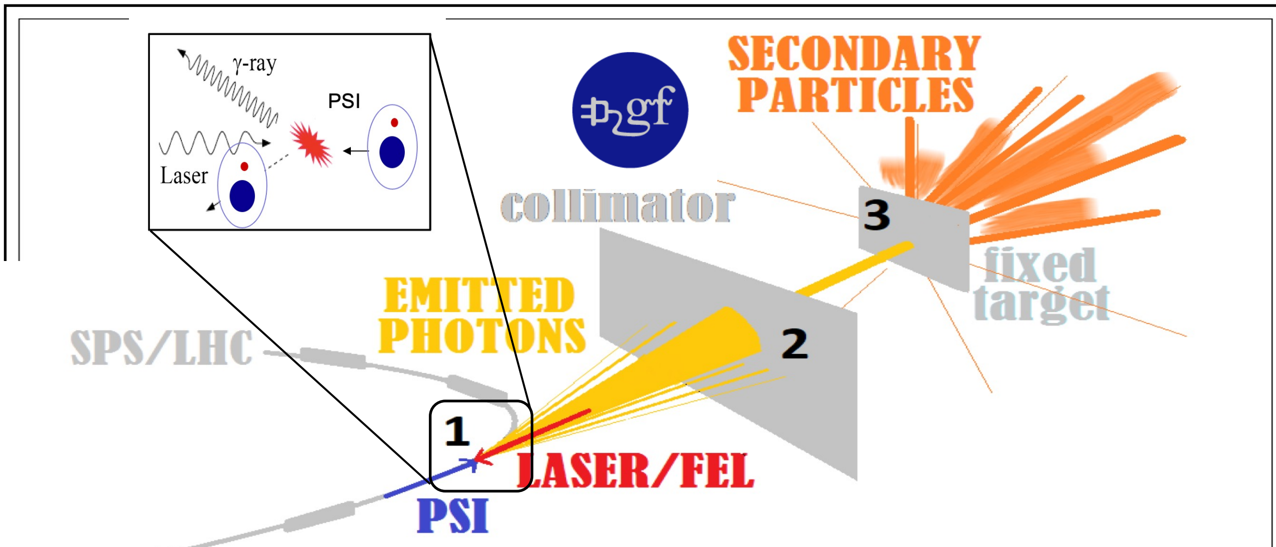
Gamma Factory beams

LHC beams



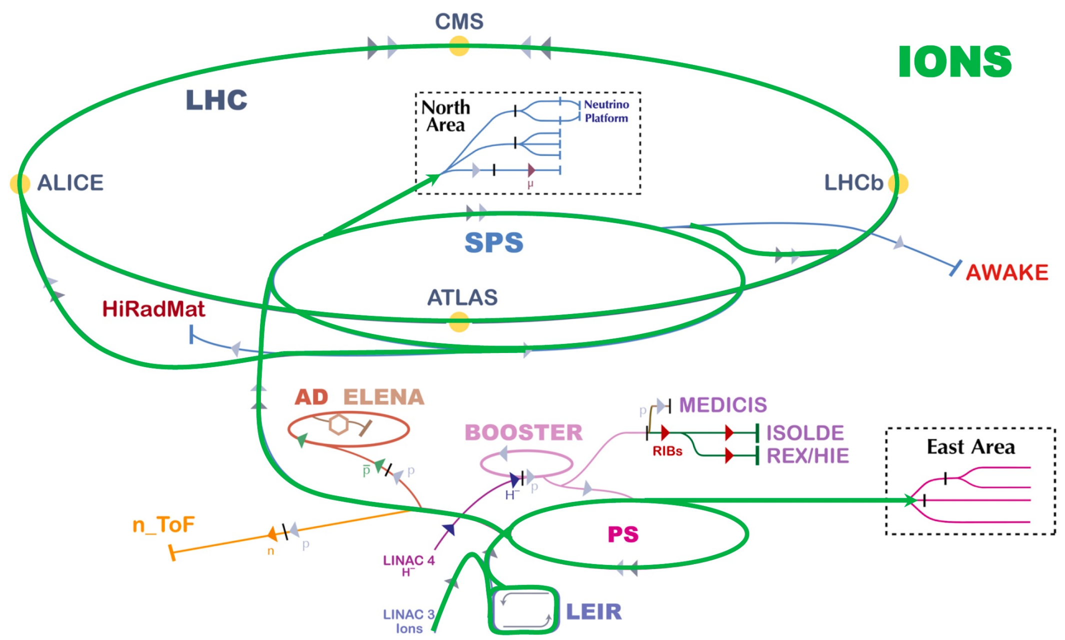


- Include **atomic beams of partially stripped ions** in the LHC menu.
- Collide them with laser pulses (circulating in Fabry-Pérot resonators) to **produce beams of polarised photons** and secondary beams of polarised electrons/positrons/muons, neutrons and radioactive ions.



PSI – atomic beams of **Partially Stripped Ions**

CERN accelerator infrastructure

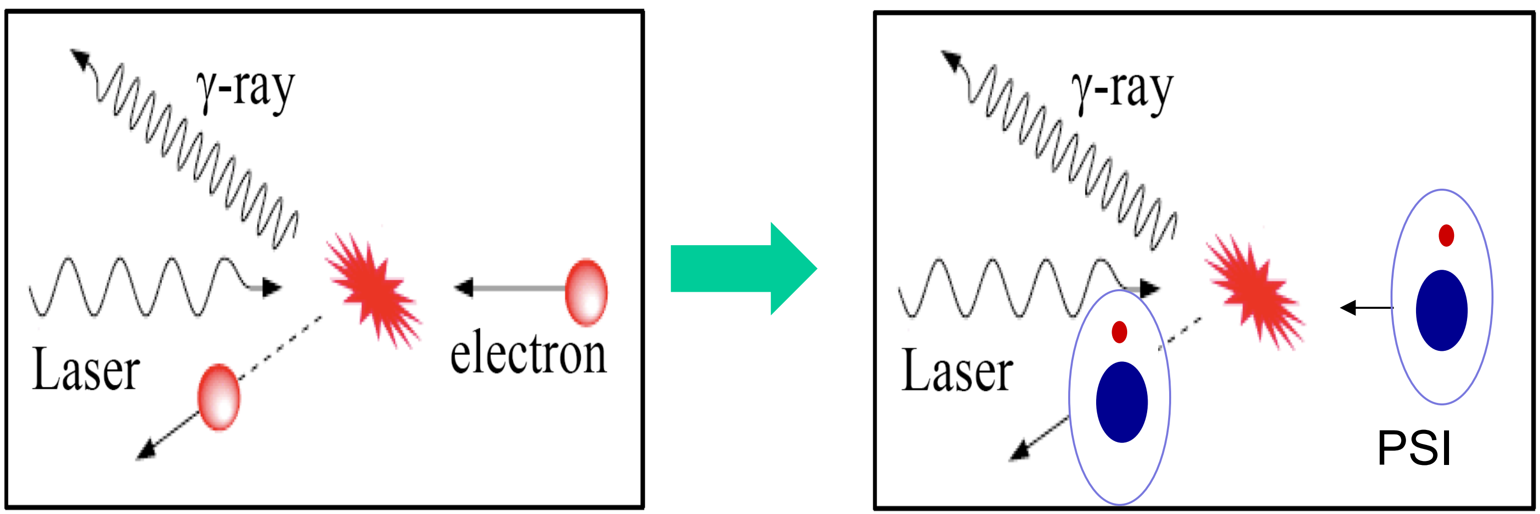


Gamma Factory (additional) requirements:

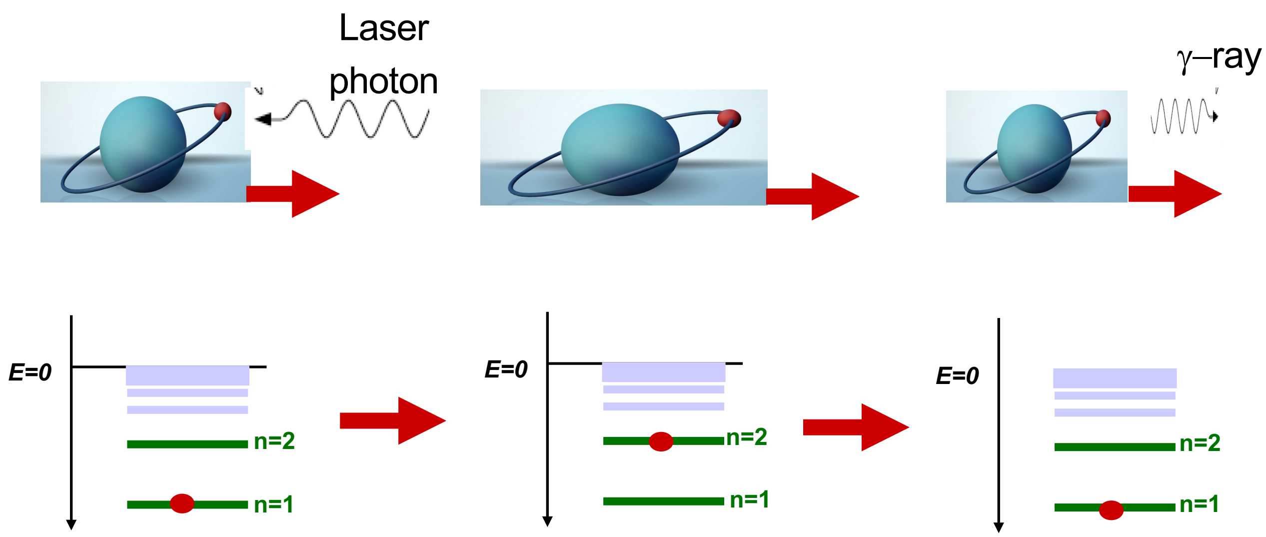
- modification of the ion stripping scheme
- storage of atomic beams in the LHC

The idea:

Replace an **electron** beam (Inverse Compton Scattering) by a beam of **Partially Stripped Ions (PSI)**



High energy atomic beams play a role of **passive light-frequency converters**:



$$\nu^{max} \longrightarrow (4\gamma_L^2)\ \nu_{Laser}$$

$\gamma_L = E/M$ – relativistic Lorentz factor of a PSI beam

(~100 at SPS, ~3000 at LHC)

Performance of electron-beam and PSI-beam driven photon sources: **cross sections and beam rigidity**

Electrons:

$$\sigma_{max} = (8\pi/3)\, r_e^2$$

r_e – classical electron radius

$$\sigma_e = 6.65 \times 10^{-25}\ \mathrm{cm}^2$$

Partially Stripped Ions (PSIs):

$$\sigma_{peak} = \lambda_{res}^2 / 2\pi$$

λ_{res} – photon wavelength in the ion rest frame

$$\sigma_{peak} = 1.7 \times 10^{-15}\ \mathrm{cm}^2$$

Numerical example: λ_{laser} = 1034 nm, γ_L^{PSI} = 1000

PSI beams:

Highly efficient (~100%) conversion of the RF power into the power of the photon beam!

(PSI looses only a tiny fraction, < 10^{-6}, of its energy in the process of photon emission)

Extraordinary properties GF photon source

1. Point-like, small divergence:

- $\Delta z \sim l_{PSI\text{-}bunch} < 7$ cm; Δx, $\Delta y \sim \sigma^{PSI}{}_x$, $\sigma^{PSI}{}_y < 50\ \mu m$; $\Delta(\theta_x)$, $\Delta(\theta_y) \sim 1/\gamma_L < 1$ mrad

2. Huge jump in intensity:

- ***More than 7 orders of magnitude*** *w.r.t. existing (being constructed) γ-sources: up to* $\mathbf{10^{18}}$ ***γ/s***

3. Very wide range of tuneable energy photon beam:

- ***10 keV – 400 MeV –*** *extending by a factor of* ***~1000*** *the energy range of FEL photon sources*

4. Tuneable polarisation:

- ***Polarisation transmission*** *from laser photons to γ-beams of* ***up to 99%***

5. Unprecedented plug power efficiency (energy footprint):

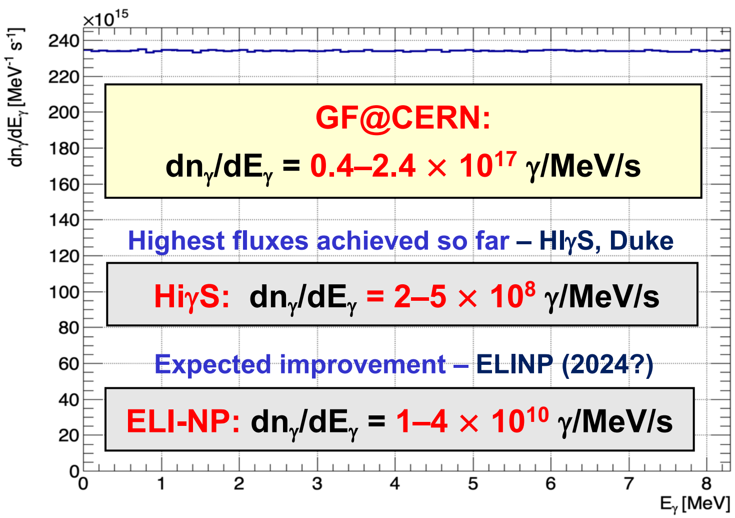
- ***LHC RF power can be converted to the photon beam power.*** *Wall-plug power efficiency of the* ***GF photon source is*** *by a factor of* ***~300 better*** *than that of* ***DESY-XFEL****!*

  (assuming power consumption: 200 MW – CERN, 19 MW – DESY)

A concrete example: Nuclear physics application

He-like, LHC Calcium beam, $(1s \rightarrow 2p)_{1/2}$ transition, Ti:Sa laser

Photon fluxes

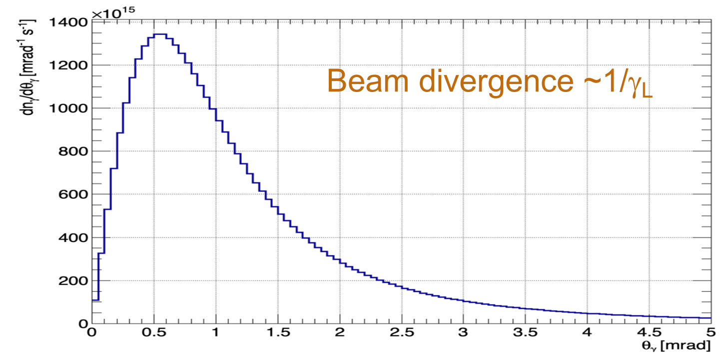


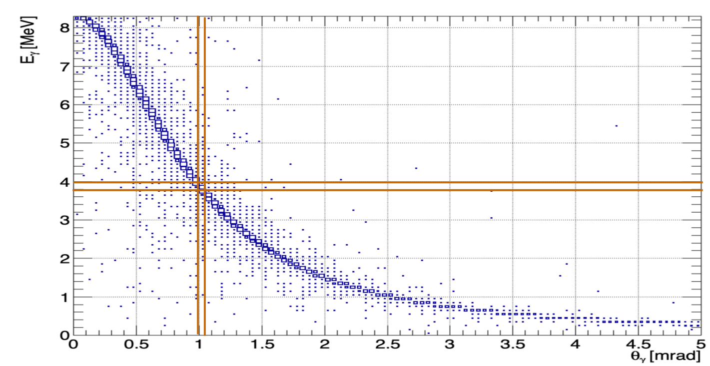
laser pulse parameters

- Gaussian spatial and time profiles,
- photon energy: E_photon = 1.8338 eV
- photon pulse energy spread: sigma_{omega}/omega = 2 x 10^{-4},
- photon wavelength: lambda = 676 nm,
- pulse energy: W_{l} = 5 mJ,
- peak power density 1.12 x 10^13 W/m^2
- r.m.s. transverse beam size at focus: sigma_{x} = \sigma_{y } = 150 um (micrometers),
- Rayleigh length: R_{L,x} = R_{L,y} = 7.5 cm,
- r.m.s. pulse length: l_{l} = 15 cm.

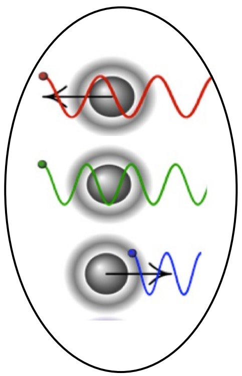
6. Highly-collimated monochromatic γ–beams:

- *beam* ***power*** *is concentrated in a* ***narrow*** *angular region (facilitates beam extraction)*
- *(E_γ, Θ_γ) correlation can be used (collimation) to* ***"monochromatise"*** *the beam*

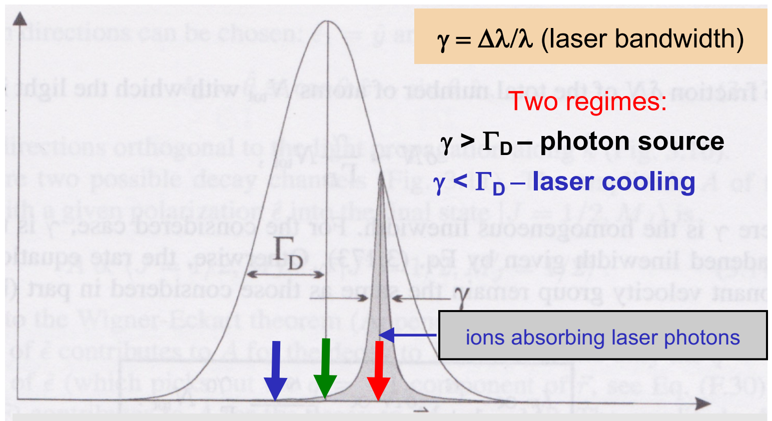




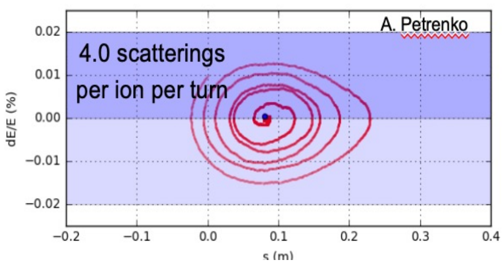
Laser cooling of atomic beams

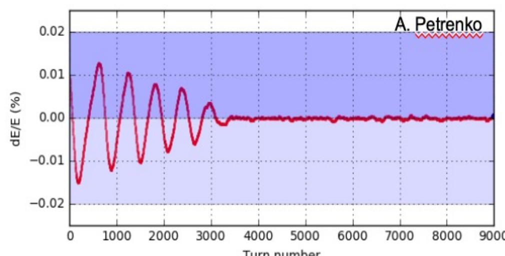


Bunch



Ion momentum profile, $\Delta p/p$ ($\Gamma_D \sim 10^{-4}$ at the LHC)



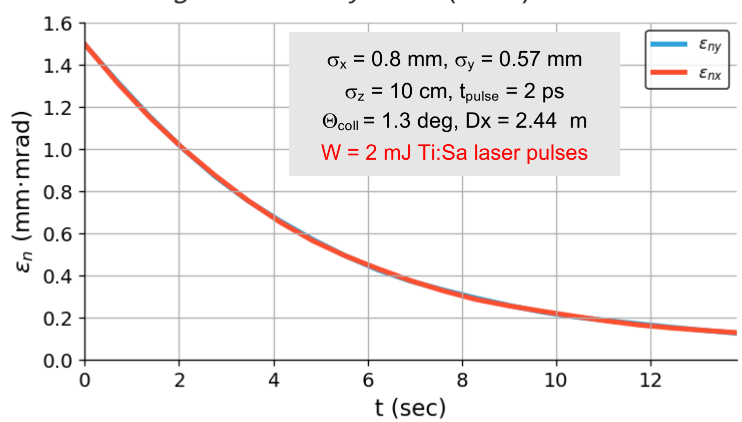


Beam cooling

*The **laser wavelength band** is chosen such that only the **ions** moving in the **laser-pulse direction** (in the bunch-rest frame) can **resonantly absorb** photons.*

Opens a possibility of forming at CERN **high-energy** hadronic bunches of the **required** longitudinal and transverse **emittances** and **population** (bunch merge + cooling) within a **seconds-long** time scale.

Prog.Part.Nucl.Phys. 114 (2020) 103792

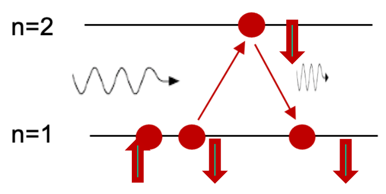


Simulation of laser cooling of the lithium-like Ca^{17+} bunches in the SPS: **transverse emittance evolution.**

Polarised beams in GF – example:

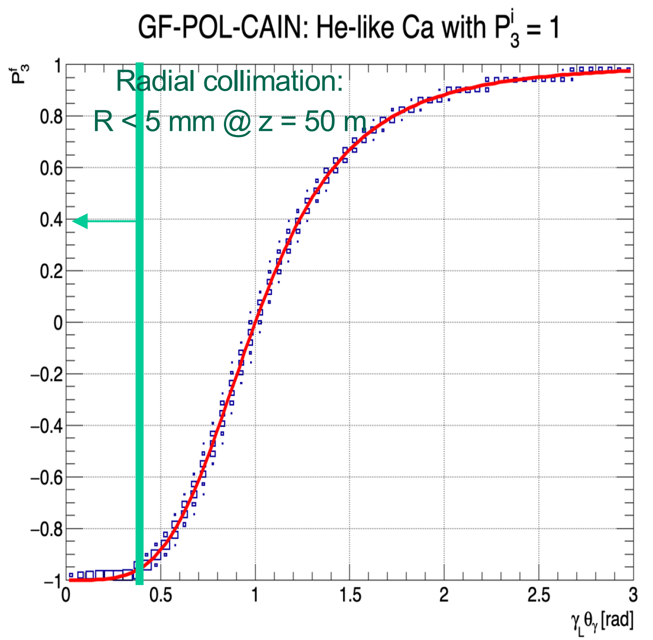
He-like Calcium beam, Er:glass laser (1522 nm)

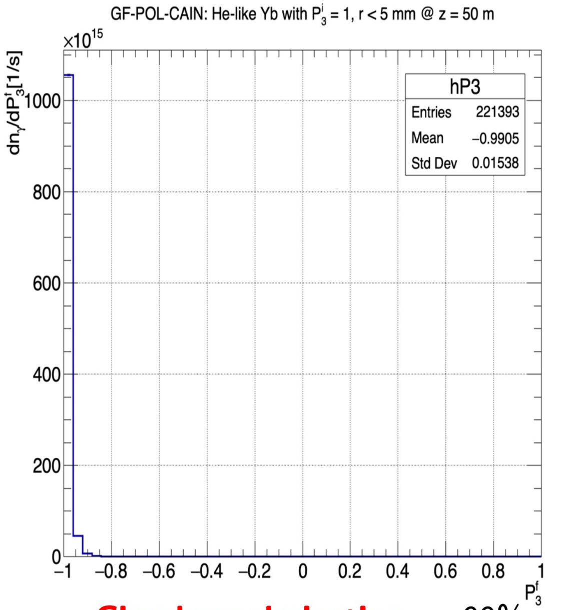
A trick: $1s^2\ ^1S_0 \rightarrow 1s^1 2p^1\ ^1P_1$ transition in He-like atoms



$$nS_0 \rightarrow n'P_1 \rightarrow nS_0$$

Closed transition in Helium-like atoms (n=1, n' =2) preserve initial polarisation of the laser light





→ **Circular polarization** ≈ 99%

- For more details see presentations at Gamma Factory workshop: https://indico.cern.ch/event/1076086/

Tertiary beams' sources – intensity/quality targets

- **Polarised positrons** – potential gain of up to a factor of 10^4 in intensity w.r.t. the KEK positron source, satisfying both the LEMMA (for muon collider) and the LHeC requirements;
  → Phys. Rev. Accel. Beams **26**, 083401 (2023).

- **Pions** – potential, gain by a factor of 10^3, gain in the spectral density ($d^2N/dpdp_T$) with respect to proton-beam-driven sources at KEK and FNAL → PRAB **26**, 083401 (2023).

- **Muons** – potential gain by a factor of 10^3 in intensity w.r.t. the PSI (Villigen, Switzerland) muon source, charge symmetry ($N\mu^+ \sim N\mu^-$), polarisation control → PRAB **26**, 083401 (2023).

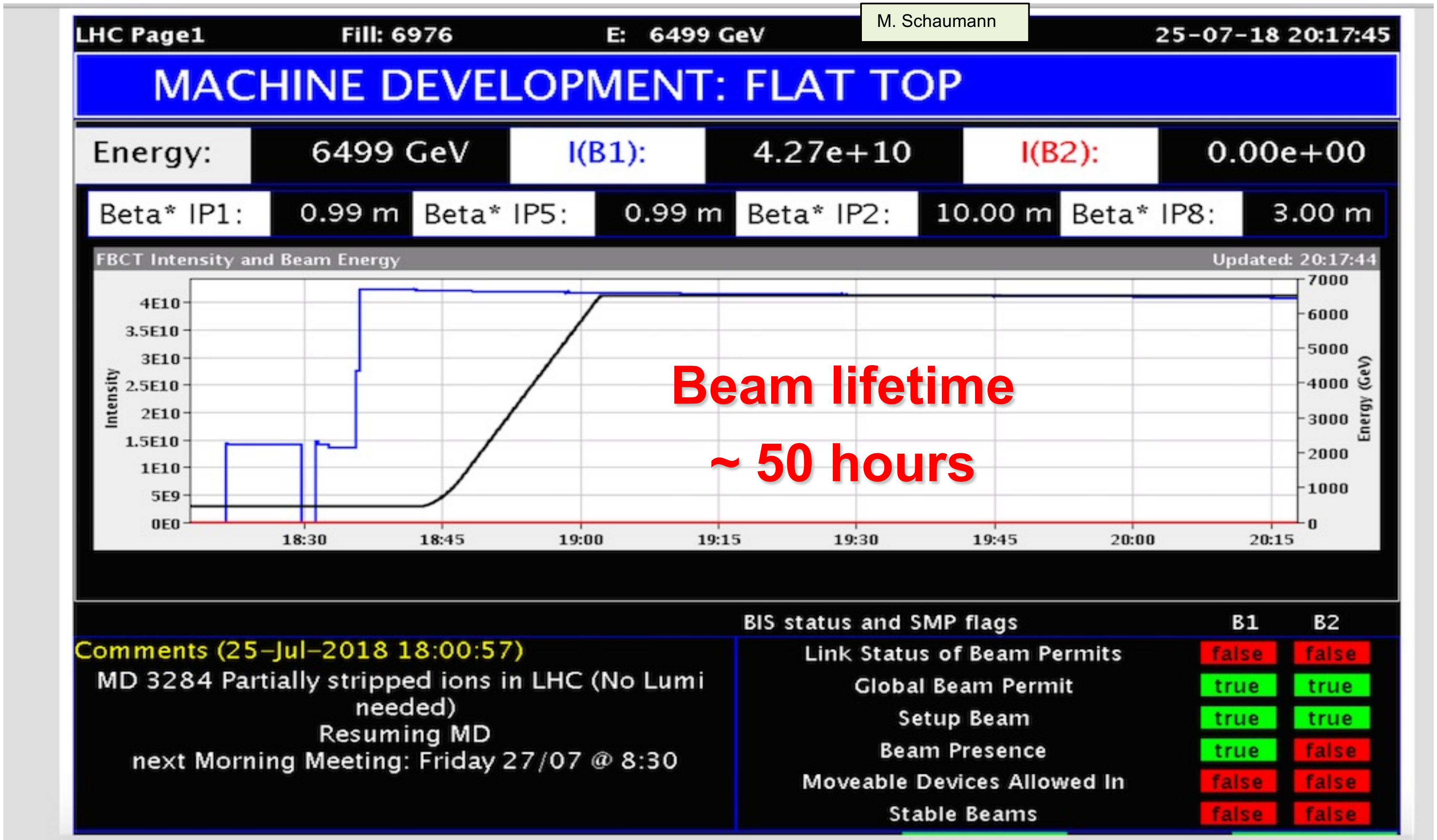
- **Neutrinos** – fluxes comparable to the proposed NuMAX (FNAL) but: (1) Very Narrow-Band Beam, driven by the small spectral density pion beam and (2) unique possibility of creating flavour and CP-tuned beams driven by the beams of polarised muons.

- **Neutrons** – potential gain of up to a factor of 10^4 in intensity of primary MeV-energy neutrons per 1 MW of the driver beam power.

- **Radioactive ions** – potential gain of up to a factor of 10^4 in intensity w.r.t. e.g. ALTO (Orsay).

Challenges

25 July 2018: successful production, injection, ramp and storage of the **hydrogen-like lead beam in LHC!**



- **Intensity/bunch (~ 7 x 10^9), 6 bunches circulating.**

July 2018: Birth of Atomic Physics research at CERN

symmetry
dimensions of particle physics

topics

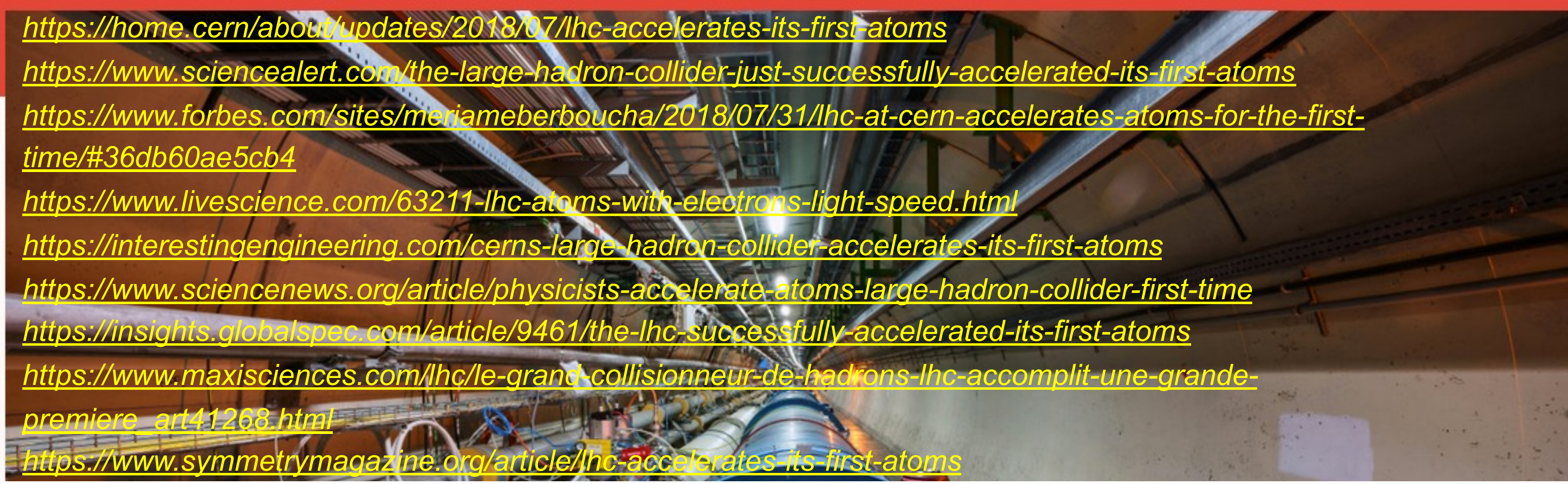
follow +

A joint Fermilab/SLAC publication

LHC accelerates its first "atoms"

07/27/18 | By Sarah Charley

Lead atoms with a single remaining electron circulated in the Large Hadron Collider.

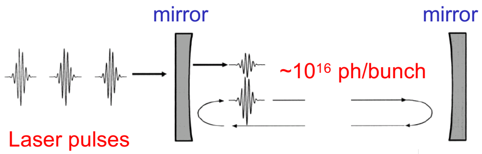


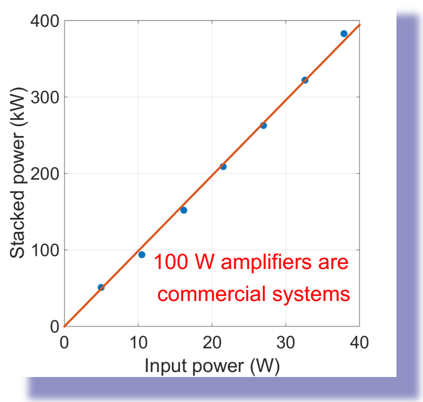
https://home.cern/about/updates/2018/07/lhc-accelerates-its-first-atoms
https://www.sciencealert.com/the-large-hadron-collider-just-successfully-accelerated-its-first-atoms
https://www.forbes.com/sites/meriameberboucha/2018/07/31/lhc-at-cern-accelerates-atoms-for-the-first-time/#36db60ae5cb4
https://www.livescience.com/63211-lhc-atoms-with-electrons-light-speed.html
https://interestingengineering.com/cerns-large-hadron-collider-accelerates-its-first-atoms
https://www.sciencenews.org/article/physicists-accelerate-atoms-large-hadron-collider-first-time
https://insights.globalspec.com/article/9461/the-lhc-successfully-accelerated-its-first-atoms
https://www.maxisciences.com/lhc/le-grand-collisionneur-de-hadrons-lhc-accomplit-une-grande-premiere_art41268.html
https://www.symmetrymagazine.org/article/lhc-accelerates-its-first-atoms

IFJ PAN LHC po raz pierwszy przyspiesza „atomy": https://www.ifj.edu.pl/aktualnosci/2018/18-07-31/

Fabry-Pérot (FP) resonators
and their integration in the electron storage rings

Fabry-Pérot resonator

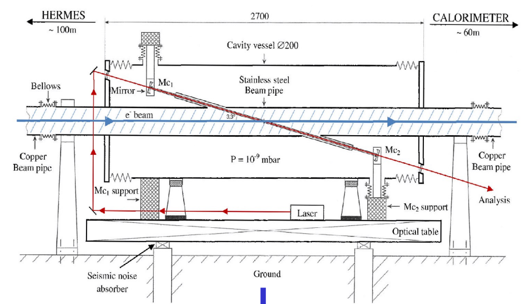




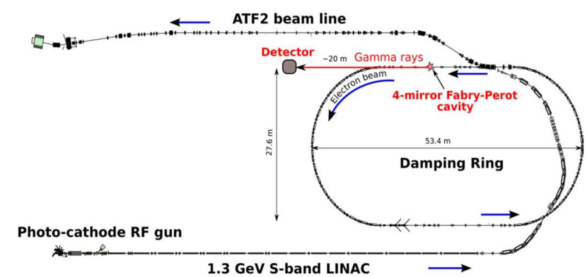
Amoudry L. et al., Applied Optics 59(2020)116

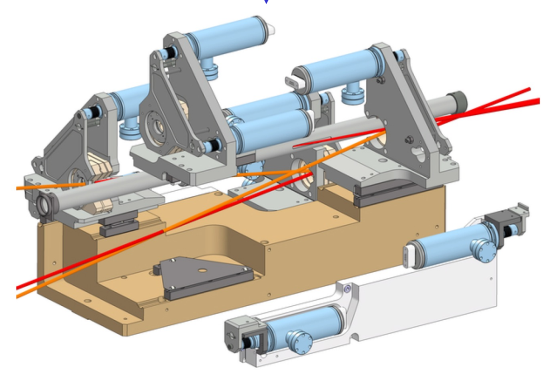
GF requirement:
~ 5 mJ pulses @ 40 MHz,
(200 kW photon beam)

HERA storage ring



KEK – ATF ring





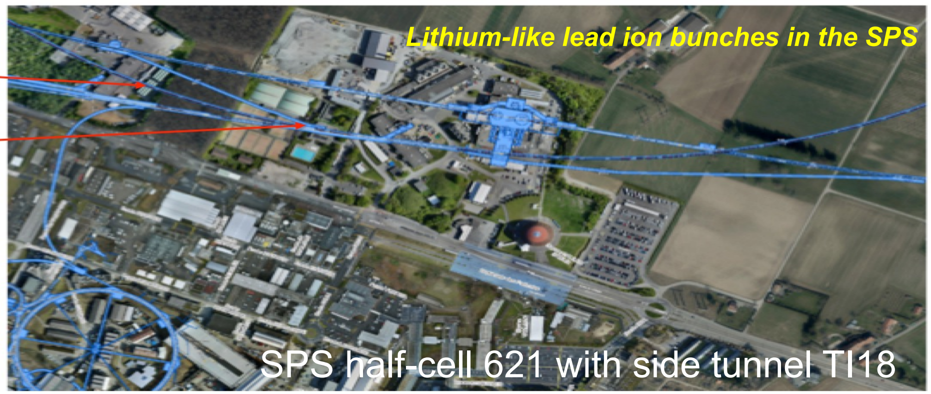
Towards the first integration of the FP resonator in the hadron storage ring →

Proof of Principle

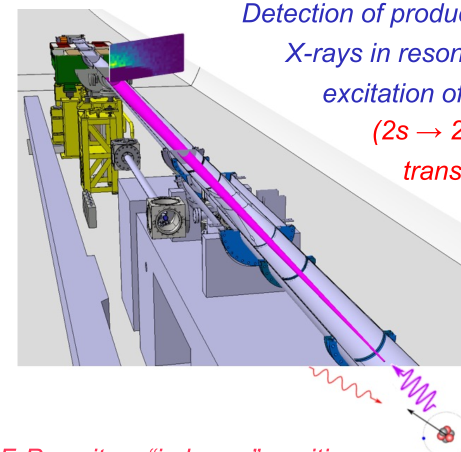
Gamma Factory Proof-of-Principle (PoP) SPS experiment

SPS

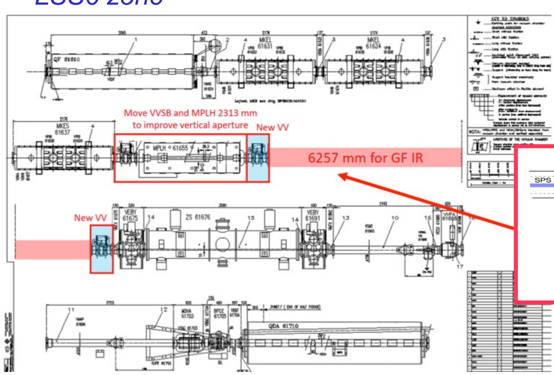
PoP location



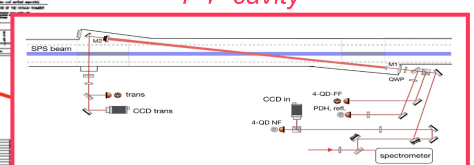
Detection of produced X-rays in resonant excitation of the $(2s \rightarrow 2p)_{1/2}$ transition



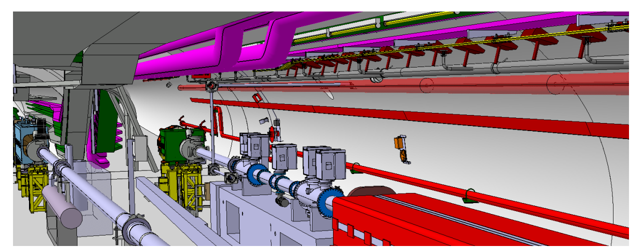
LSS6 zone



F-P cavity



F-P cavity – "in beam" position



F-P cavity length: 3.75 m *– vertically tilted by 2.6 deg*

Purpose of GF SPS PoP experiment

1. Demonstrate that an adequate laser system (5 mJ @ 40 MHz) can be (remotely) operated in the high-radiation field of the SPS.
2. Demonstrate that very high rates of photons are produced: almost all ions are excited in a single collision of a PSI bunch with a laser pulse.
3. Demonstrate stable and repeatable operation.
4. Confront data and simulations.
5. Demonstrate ion beam cooling: longitudinal, and then transverse.
6. New atomic physics measurements.

➢ *Estimated cost of the experiment: 2.5 MCHF*

PoP experiment status

September 25, 2019

Gamma Factory

Proof-of-Principle Experiment

LETTER OF INTENT

CERN-SPSC-2019-031 / SPSC-I-253
25/09/2019

Gamma Factory Study Group

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A. Martens, martens@lal.in2p3.fr – **Gamma Factory PoP experiment spokesperson**

Y. Dutheil, yann.dutheil@cern.ch – **Gamma Factory PoP study – CERN coordinator**

- **As received from the SPSC referees on Oct. 20th, 2020:**

«The SPSC recognizes the Gamma Factory's potential to create a novel research tool, which may open the prospects for new research opportunities in a broad domain of basic and applied science at the LHC.»

«The SPSC recognizes the GF-PoP experiment as a path finder in the GF R&D process. The SPSC … looks forward to further details of how the GF proto-collaboration intends to deliver this programme.»

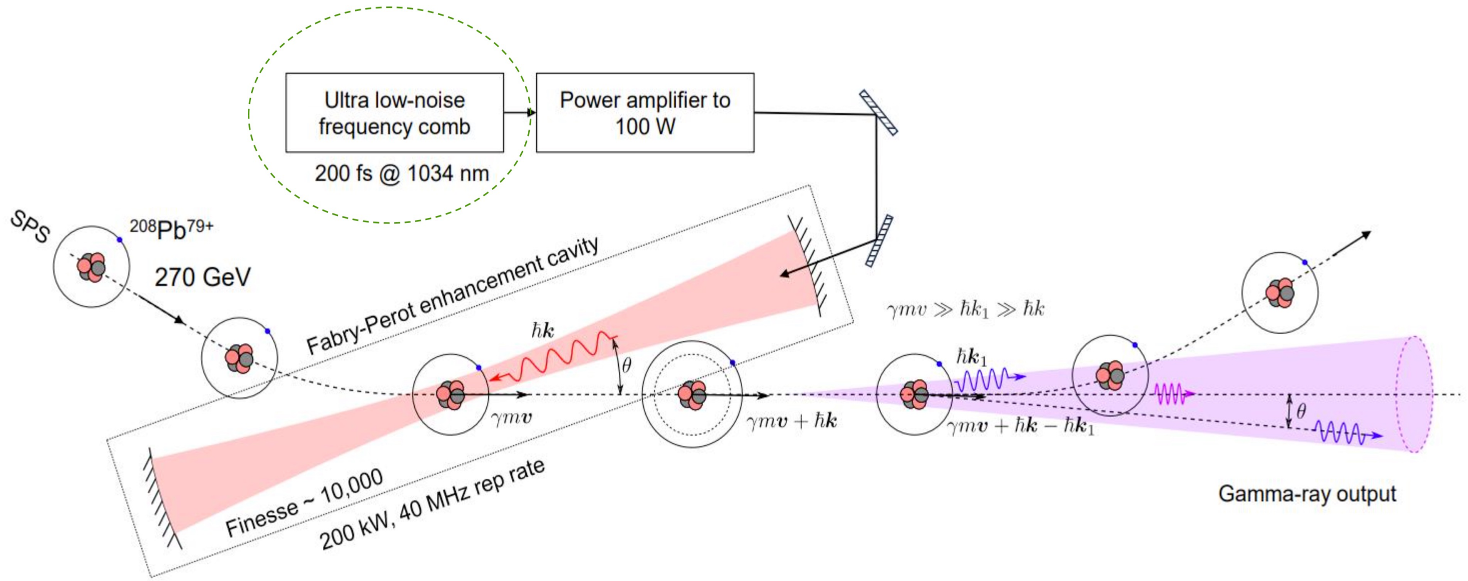
→ *We are in the process of signing the GF-PoP MoU by collaborating institutes.*

→ *In parallel, we are finalising a detailed estimation of the CERN (BE, SY and EN departments) and participating labs resources needed to construct and operate the PoP experiment in the SPS tunnel.*

→ *Target installation time:* ***LS3*** *(2026–2027).*

Recent news

Gamma Factory PoP laser system



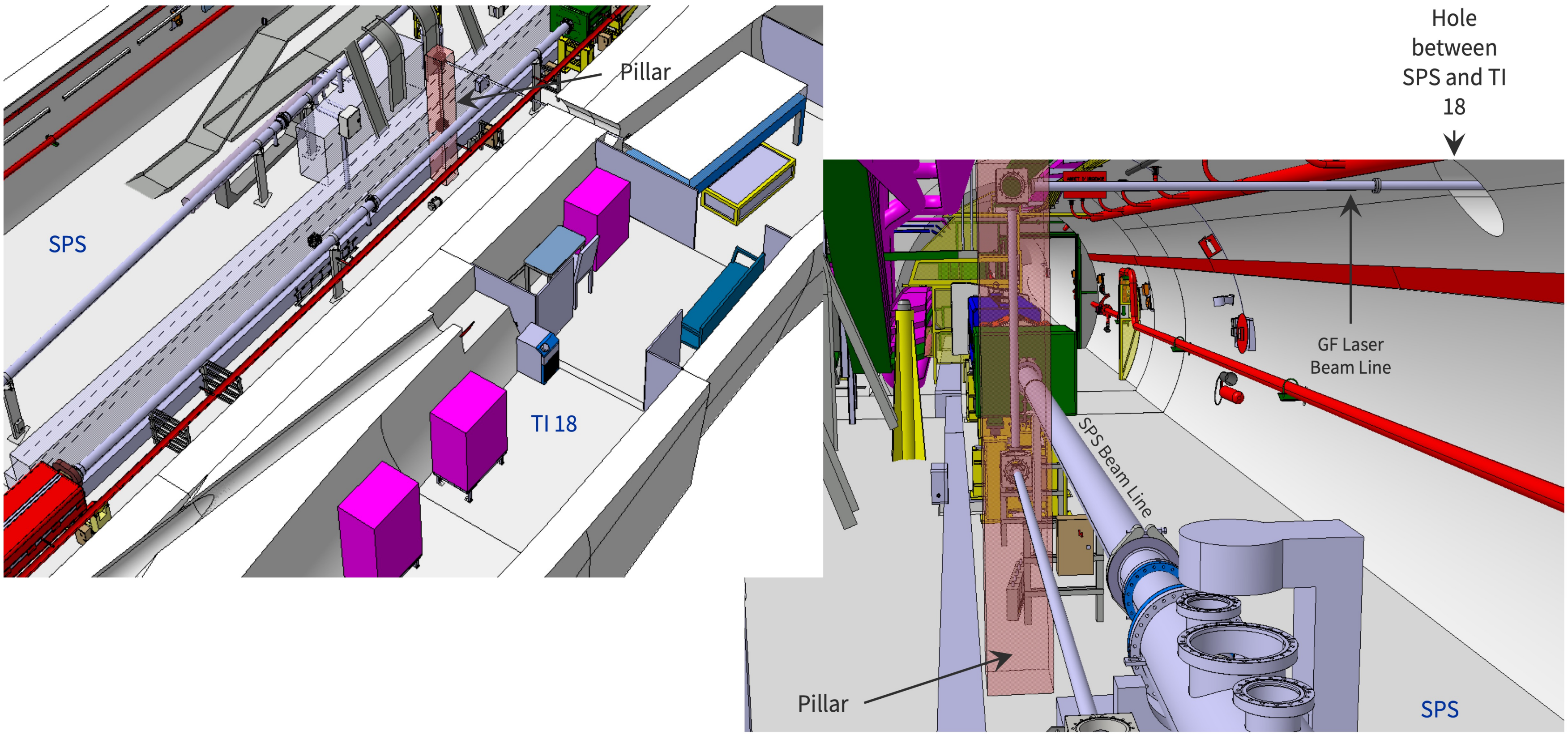
- Menhir Photonics was selected as the supplier, delivery was performed on 2nd November 2023.
- The oscillator has been shipped to IJCLab for testing with FP cavity.
- Started specification of power amplifier to 100 W.

E. Granados, GF PoP meeting, 14 Nov. 2023

Plans for YETS 2023-2024

SPS – Gamma Factory – Pillar Installation

Gamma Factory Area :



Possibilities

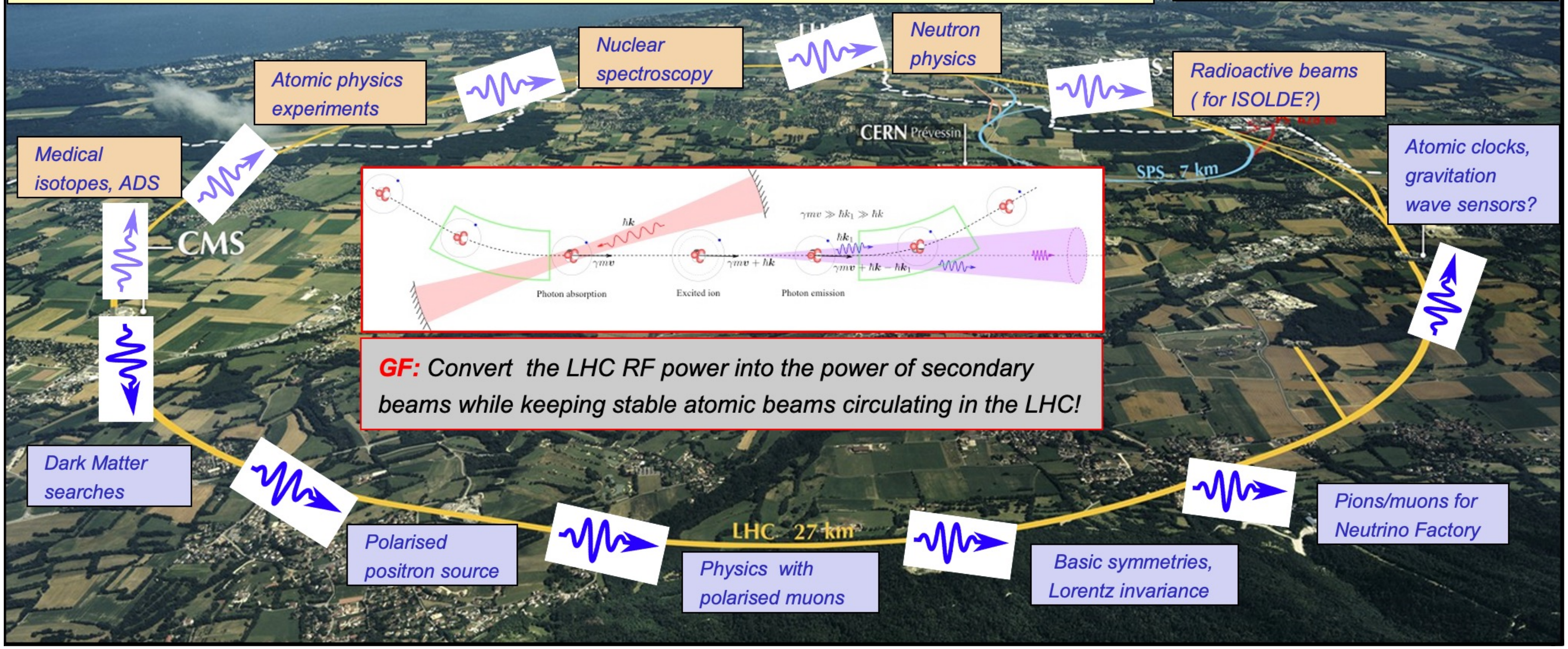
Examples of potential applications domains of the *Gamma Factory* research tools

- ***Particle physics:*** *precision QED and EW studies, vacuum birefringence, Higgs physics in $\gamma\gamma$ collision mode with laser-cooled ion beams, rare muon decays, precision neutrino physics, QCD-confinement studies, …*
- ***Nuclear physics:*** *nuclear spectroscopy, cross-talk of nuclear and atomic processes, GDR, nuclear photo-physics, photo-fission research, gamma polarimetry, physics of rare radioactive nuclides,…*
- ***Atomic physics:*** *highly charged atoms, electronic, muonic, pionic and kaonic atoms, …*
- ***Astrophysics:*** *dark matter searches, gravitational waves detection, gravitational effects of cold particle beams, $^{16}O(\gamma,\alpha)^{12}C$ reaction and S-factors …*
- ***Fundamental physics:*** *studies of the basic symmetries of the universe, atomic interferometry, …*
- ***Accelerator physics:*** *beam cooling techniques, low-emittance hadronic beams, plasma wake field acceleration, high-intensity polarised positron and muon sources, beams of radioactive ions and neutrons, very narrow band and flavour-tagged neutrino beams, neutron sources, …;*
- ***Applied physics:*** *accelerator driven energy sources, nuclear fusion research, medical isotope and isomer production, …*

"A dream" vision of the LHC operation in post-HL-LHC phase (in ~20 years?)

Two counter-propagating PSI beams colliding with laser photons in specialized interaction points

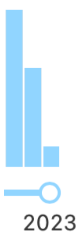
M.W. Krasny: arXiv:1511.07794



GF studies: recently published papers

literature | find t Gamma Factory

Literature | Authors | Jobs | Seminars | Conferences



46 results | cite all

Gamma Factory

Mieczyslaw Witold Krasny (LPNHE, Paris and CERN) (2023)

pdf DOI cite claim

Gamma Factory high-intensity muon and positron source: Exploratory studies

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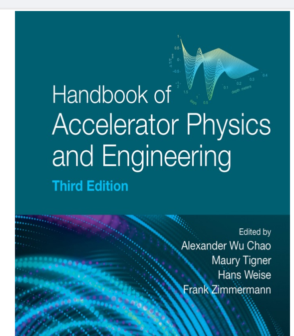
Special Issue: Physics Opportunities with the Gamma Factory

March 2022

Issue Edited by: **Dmitry Budker, Mikhail Gorchtein, Mieczyslaw Witold Krasny, Adriana Pálffy, Andrey Surzhykov**



Conclusions

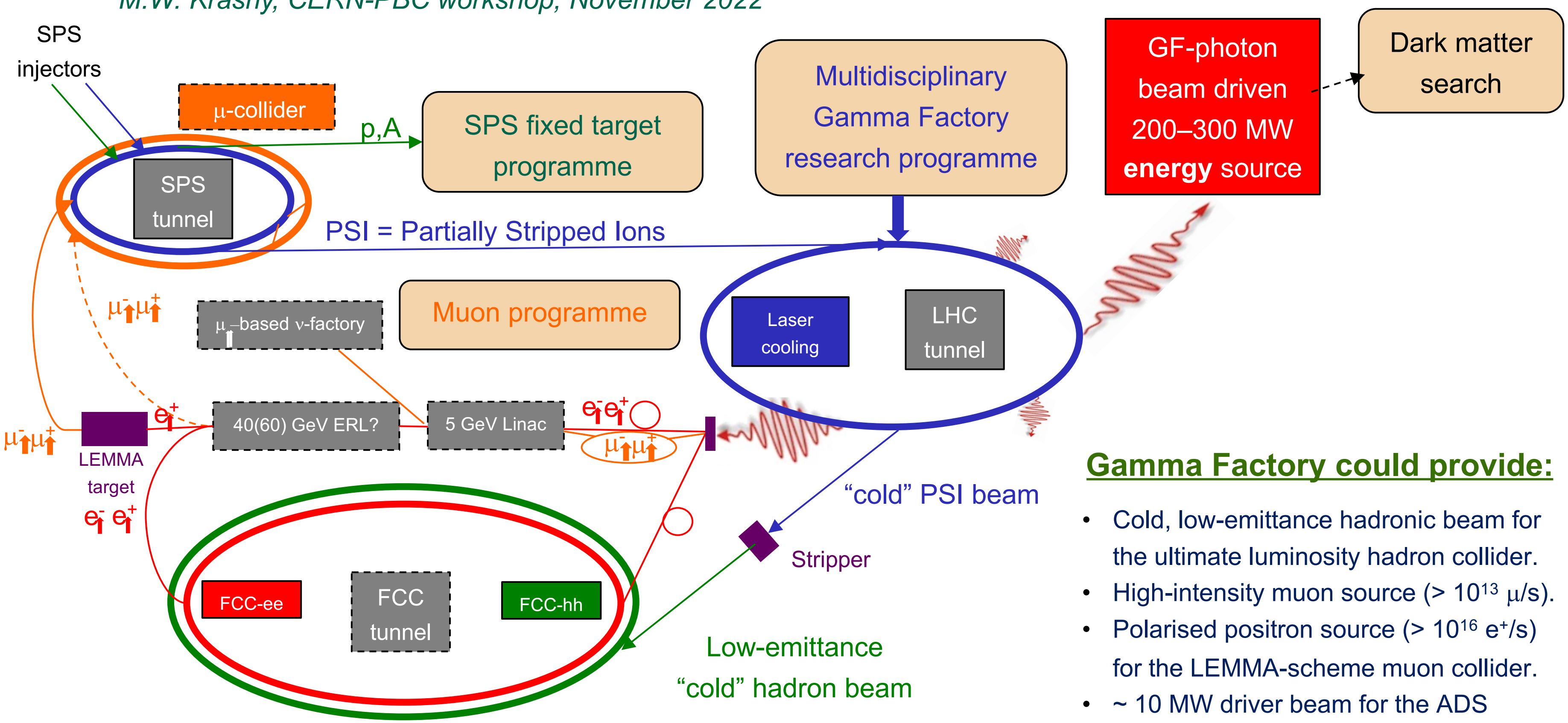
A potential place of the Gamma Factory (GF) in the future CERN research programme

- *The **next** CERN **high-energy frontier** project may take **long time** to be approved, built and become operational (if ever), … unlikely before 2050?.*
- *The **present LHC research programme** will probably reach **earlier** (late 2030's?) its discovery **saturation** (little physics gain by simple extending its pp/pA/AA running time).*
- *A strong **need** will certainly arise for a **novel** multidisciplinary programme which could **re-use** ("co-use") the **existing** CERN facilities (including LHC) in **ways** and at **levels** that were **not** necessarily **thought** of when the machines were **designed**.*

The Gamma Factory research programme (2035-????) could fulfil such a role. It can exploit **the existing world unique opportunities** offered by the CERN accelerator complex and CERN's scientific infrastructure (**not available elsewhere**) to conduct new, diverse and vibrant research in particle, nuclear, atomic, fundamental and applied physics **with novel research tools and methods**.

Potential **Gamma Factory** role in the incremental, sustainable and multi-disciplinary development of the research infrastructure at **CERN**

M.W. Krasny, CERN-PBC workshop, November 2022

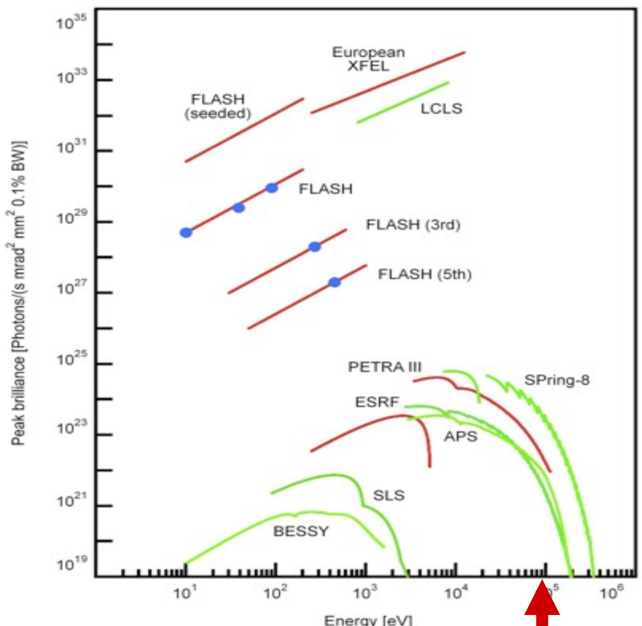


Gamma Factory could provide:

- Cold, low-emittance hadronic beam for the ultimate luminosity hadron collider.
- High-intensity muon source (> 10^{13} μ/s).
- Polarised positron source (> 10^{16} e^+/s) for the LEMMA-scheme muon collider.
- ~ 10 MW driver beam for the ADS energy source (under study).

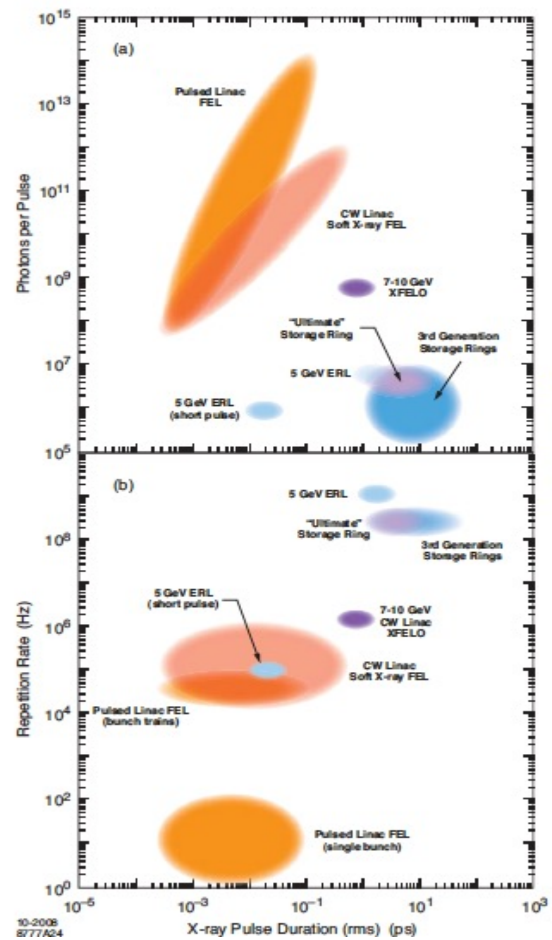
BACKUP SLIDES

Photon sources: X-rays



100 keV

Energies up to ~ **100 keV**



Intensities up to ~ 10^{16} **photons/s**

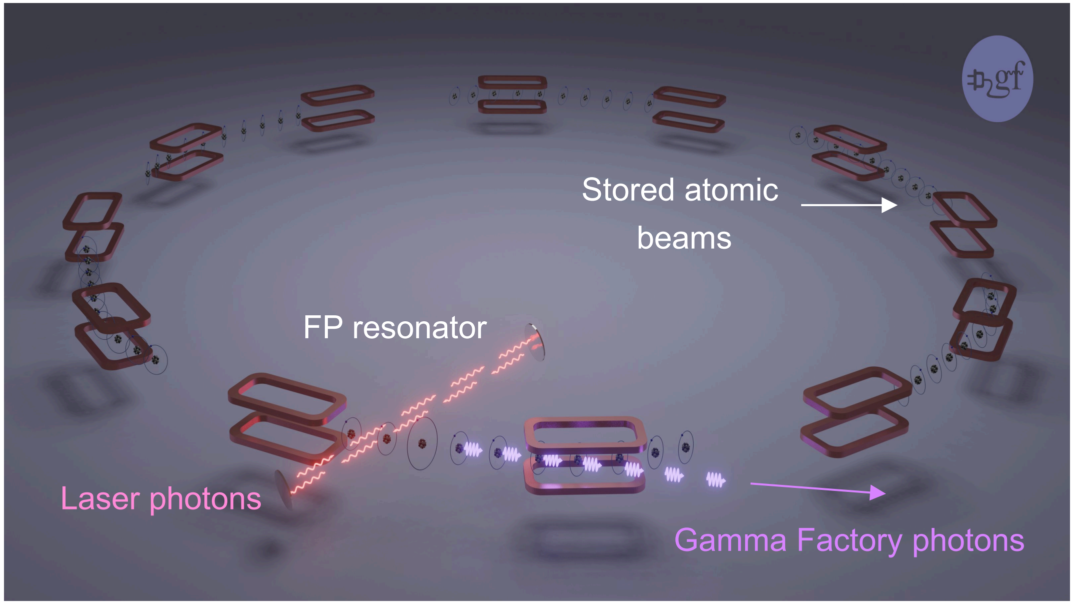
Photon sources: γ-rays

Project name	LADON[a]	LEGS	ROKK-1M[b]	GRAAL	LEPS	HIγS[c]
Location	Frascati Italy	Brookhaven US	Novosibirsk Russia	Grenoble France	Harima Japan	Durham US
Storage ring	Adone	NSLS	VEPP-4M	ESRF	SPring-8	Duke-SR
Electron energy (GeV)	1.5	2.5–2.8	1.4–6.0	6	8	0.24–1.2
Laser energy (eV)	2.45	2.41–4.68	1.17–4.68	2.41–3.53	2.41–4.68	1.17–6.53
γ-beam energy (MeV)	5–80	110–450	100–1600	550–1500	1500–2400	1–100 (158)[d]
Energy selection	Internal tagging	External tagging	(Int or Ext?) tagging	Internal tagging	Internal tagging	Collimation
γ-energy resolution (FWHM)						
ΔE (MeV)	2–4	5	10–20	16	30	0.008–8.5
$\frac{\Delta E}{E}$ (%)	5	1.1	1–3	1.1	1.25	0.8–10
E-beam current (A)	0.1	0.2	0.1	0.2	0.1–0.2	0.01–0.1
Max on-target flux (γ/s)	5×10^5	5×10^6	10^6	3×10^6	5×10^6	10^4–5×10^8
Max total flux (γ/s)						10^6–3×10^9[e]
Years of operation	1978–1993	1987–2006	1993–	1995–	1998–	1996–

Intensities up to ~ **10^9 photons/s**

Gamma Factory photon source: intensity leap

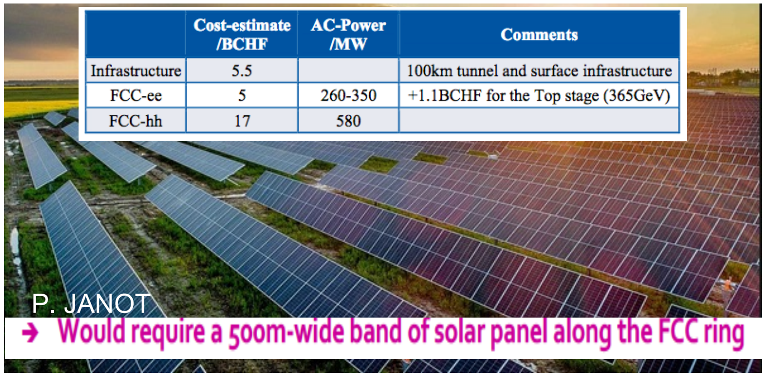
Requirements: *Accelerated bunches of ~10^8–10^9 partially stripped atoms, delivered with ~20 MHz frequency, ~5 mJ laser photon pulses stacked in 20 MHz, Fabry-Perot resonator*



Novel technology:

Resonant scattering of laser photons on ultra-relativistic atomic beam

High intensity (MW) photon beams



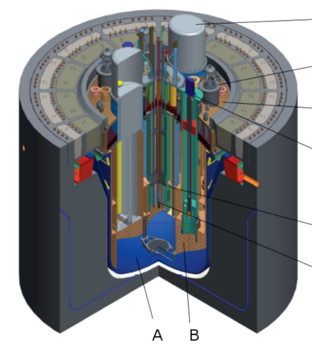
	Cost-estimate /BCHF	AC-Power /MW	Comments
Infrastructure	5.5		100km tunnel and surface infrastructure
FCC-ee	5	260-350	+1.1BCHF for the Top stage (365GeV)
FCC-hh	17	580	

<u>Best use of the CERN expertise to produce rather than buy the plug-power</u>:

GF photon-beam-driven energy source (ADS)

<u>Satisfying three conditions;</u>

- requisite power for the present and future CERN scientific programme
- operation safety **(a subcritical reactor)**
- efficient transmutation of the nuclear waste (**very important societal impact if demonstrated at CERN – given its reputation)**



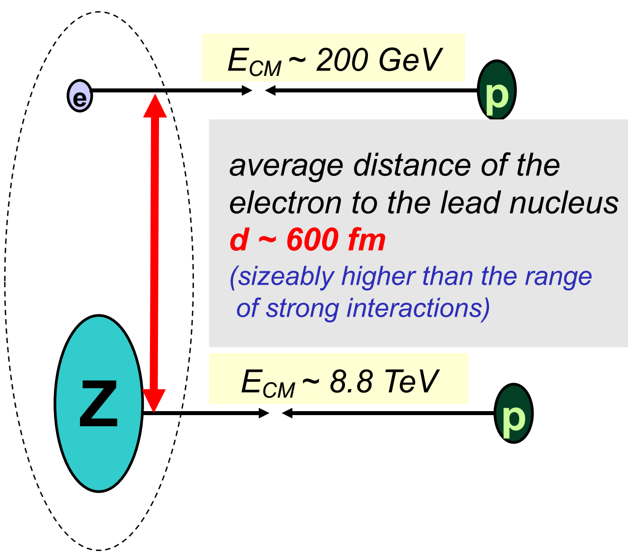
APS April Meeting 2023
Minneapolis, Minnesota (Apr 15-18)

M06 Invited <u>Accelerate Solving Energy Crisis: From Fission to Fusion</u>
Room: MG Salon F - 3rd Floor **Sponsor**: DPB FIP **Chair**: Christine Darve, European Spallation Source
Invited Speakers: Hamid Ait Abderrahmane, Mieczyslaw Witold Krasny, Ahmed Diallo, Alireza Haghighat

Electron beam for ep collisions at LHC

(in the ATLAS, CMS, ALICE and LHCb interaction points)

Hydrogen-like lead



Atomic beams can be considered as ***independent electron and nuclear beams*** *as long as the incoming proton scatters with the momentum transfer q >> 300 KeV!*

Opens the possibility of collecting by each of the LHC detectors over one day of the ***Pb^{81+}–p*** *operation the effective ep-collision luminosity comparable to the HERA integrated luminosity in the first year of its operation (1992) – in-situ diagnostic of the emittance of partonic beams at the LHC!*

Initial studies:

Available online at www.sciencedirect.com
SCIENCE DIRECT®
Nuclear Instruments and Methods in Physics Research A 540 (2005) 222–234
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
www.elsevier.com/locate/nima

Electron beam for LHC

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Received 14 September 2004; received in revised form 19 November 2004; accepted 23 November 2004
Available online 22 December 2004

Recent development:

PHYSICAL REVIEW ACCELERATORS AND BEAMS **23,** 101002 (2020)

Editors' Suggestion

Collimation of partially stripped ions in the CERN Large Hadron Collider

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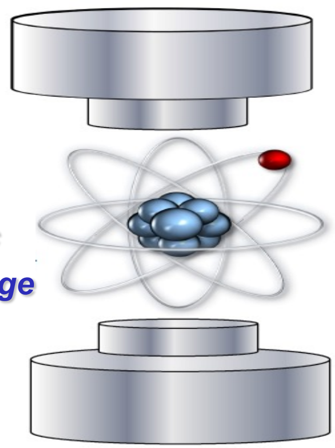
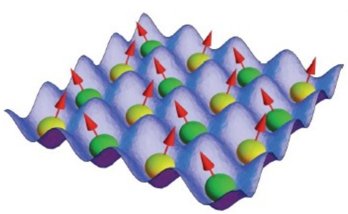
Atomic traps of highly-charged "small-size" atoms

<u>Atomic rest-frame</u>

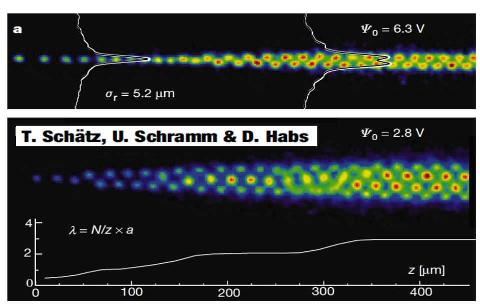
Trapped stationary atoms exposed to pulsed magnetic and electric fields of the storage ring





Crystalline beams?

letters to nature



<u>Opening new research opportunities in atomic physics</u>:

- *Highly-charged atoms – very strong (~10^{16} V/cm) electric field (QED-vacuum effects)*
- *Small size atoms (electroweak effects)*
- *Hydrogen-like and helium-like atomic structure (calculation precision and simplicity)*
- *Atomic degrees of freedom of trapped highly-charged ions can be resonantly excited by lasers*

adp annalen der physik

Feature Article | Open Access

Atomic Physics Studies at the Gamma Factory at CERN

Dmitry Budker, José R. Crespo López-Urrutia, Andrei Derevianko, Victor V. Flambaum, Mieczyslaw Witold Krasny, Alexey Petrenko, Szymon Pustelny, Andrey Surzhykov, Vladimir A. Yerokhin, Max Zolotorev ... See fewer authors

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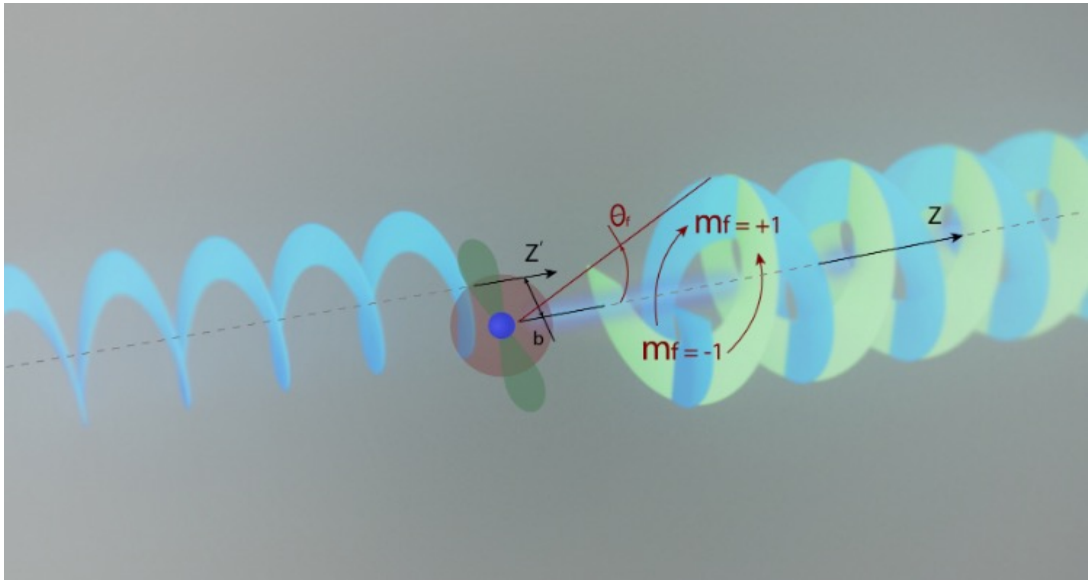
Gamma Factory twisted photons



Resonant scattering of plane-wave and twisted photons at the Gamma Factory

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