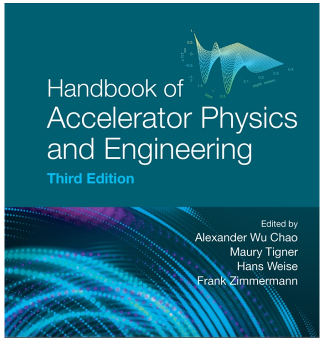
Gamma-Factory@CERN

status and perspectives



CNFS Workshop, Stony Brook/BNL, April 2023

Mieczyslaw Witold Krasny
Gamma Factory group
LPNHE, CNRS and University Paris Sorbonne and CERN, BE-ABP

“*Gamma Factory*” studies

The Gamma Factory proposal for CERN †

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

Mieczyslaw Witold Krasny*

LPNHE, Universités Paris VI et VII and CNRS–IN2P3, Paris, France

e-Print: 1511.07794 [hep-ex]

~100 physicists form 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:

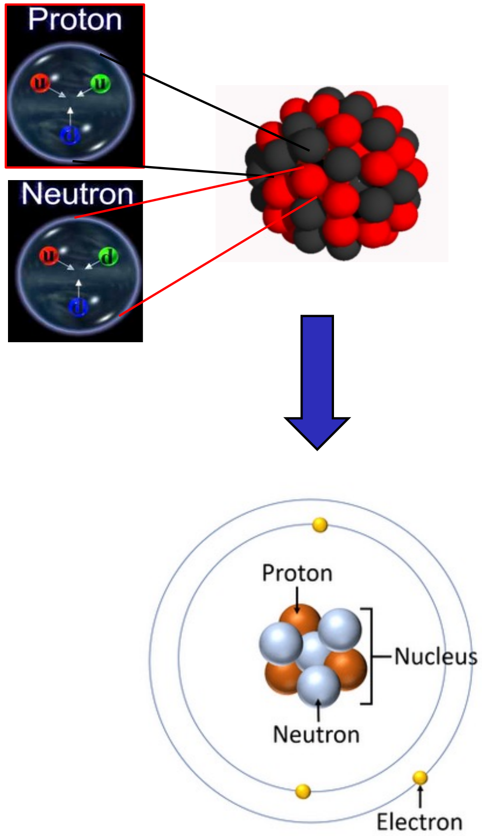
https://indico.cern.ch/category/10874

*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!*

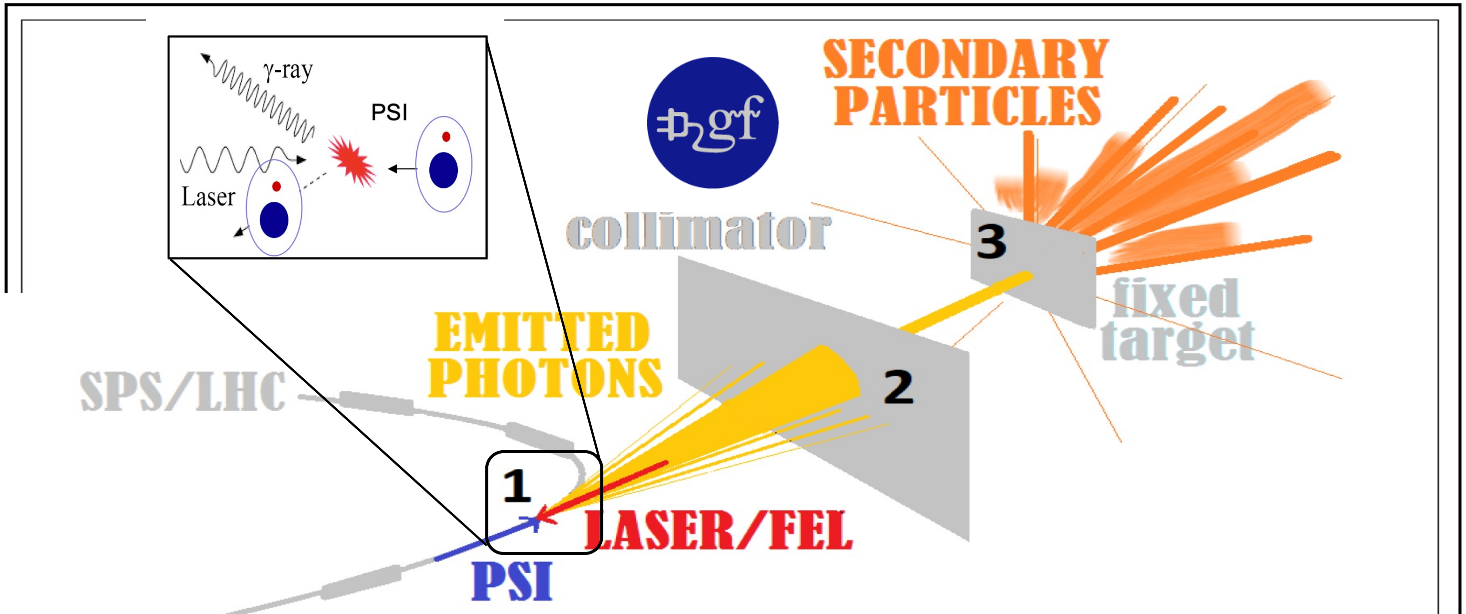
Principles

Gamma Factory beams

LHC beams

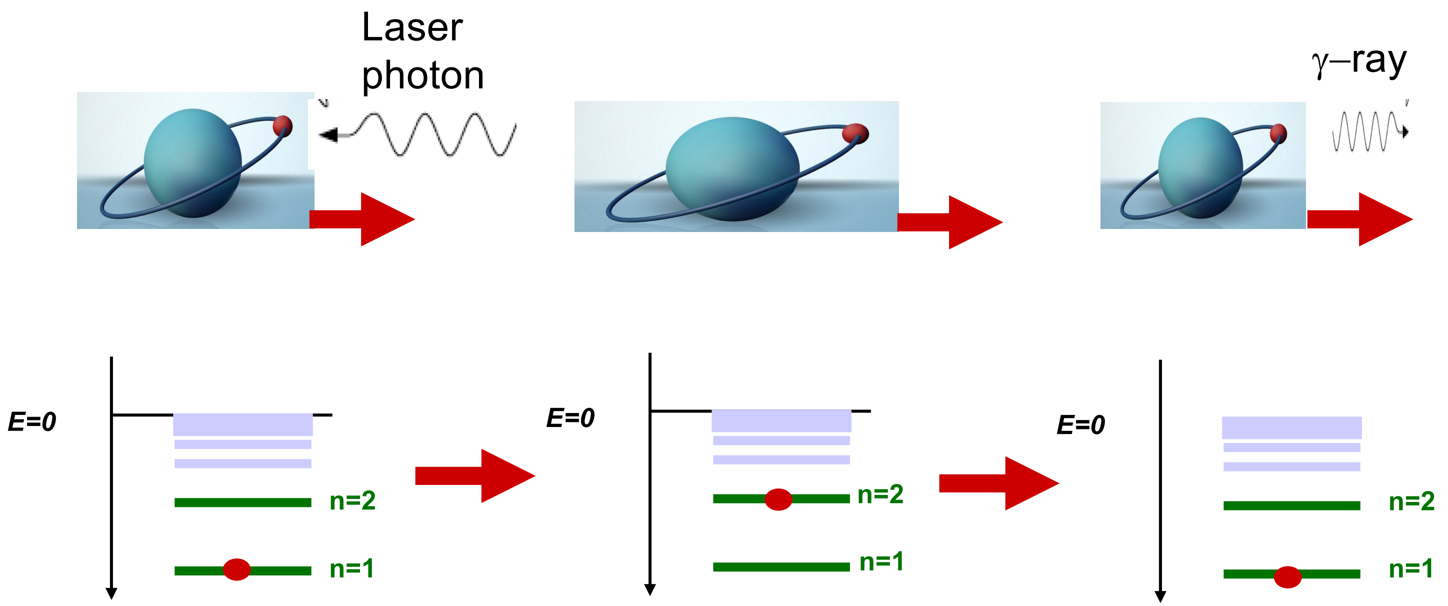


- *Include **atomic beams of partially stripped ions** in the LHC menu*
- *Collide them with laser pulses (circulating in Fabry-Pérot resonators) to **produce beams of polarized photons** and secondary beams of polarized electrons, positrons, muons, neutrons and radioactive ions*



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

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



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

$\gamma_L = E/M$ - Lorentz factor for the ion beam

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

Electrons:

$\sigma_e = 8\pi/3 \times \mathbf{r_e^2}$

$\mathbf{r_e}$ - classical electron radius

Partially Stripped Ions (PSIs):

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

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

Electrons:

$\sigma_e = 6.6 \times 10^{-25}\ \mathrm{cm}^2$

PSIs:

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

Numerical example: λ_{laser} = 1034 nm, γ_L^{PSI} = 1000 γ_L^{PSI} = E/M - Lorentz factor for the ion beam

PSI beams:

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

Extraordinary properties of the GF photon source

1. Point-like, small divergence

- $\Delta z \sim l_{PSI\text{-}bunch}$, $\Delta x, \Delta y \sim \sigma^{PSI}_{x}$, ${}^{PSI}_{y}$, $\Delta(\theta_x)$, $\Delta(\theta_y) \sim 1/\gamma_L < 1$ mrad

2. Huge jump in intensity:

- **6–8 orders of magnitude** w.r.t. existing (being constructed) γ-sources **up tp 10^{18} photons/sec**

3.Very wide range of tuneable energy photon beam :

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

4. Tuneable polarisation:

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

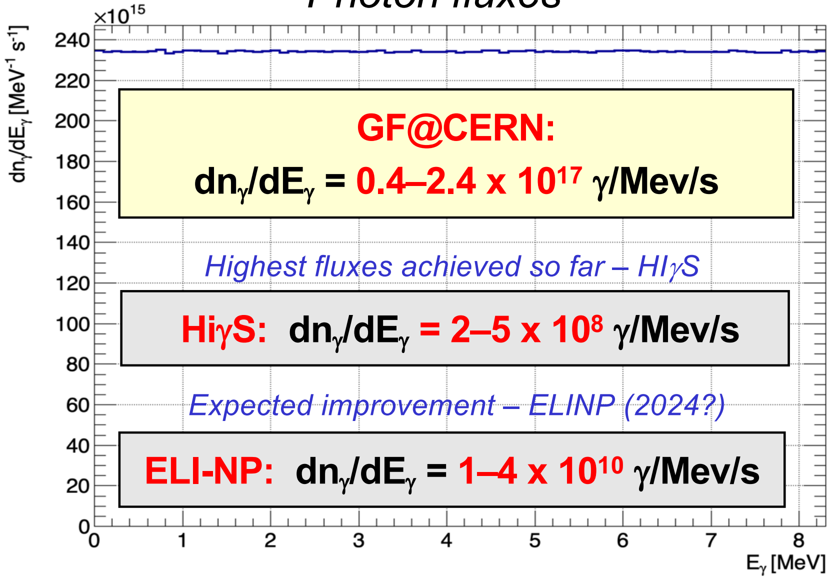
5. Unprecedented plug power efficiency (energy footprint):

- ***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 the DESY-XFEL!***

(assuming power consumption of 200 MW - CERN and 19 MW - DESY)

A concrete example: Nuclear physics application: He-like, LHC Calcium beam, $(1s \rightarrow 2p)_{1/2}$ transition, TiSa laser

Photon fluxes

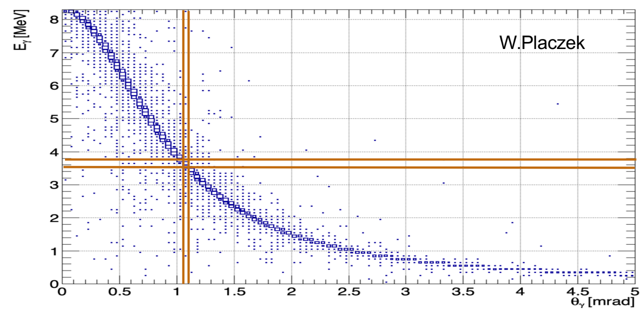


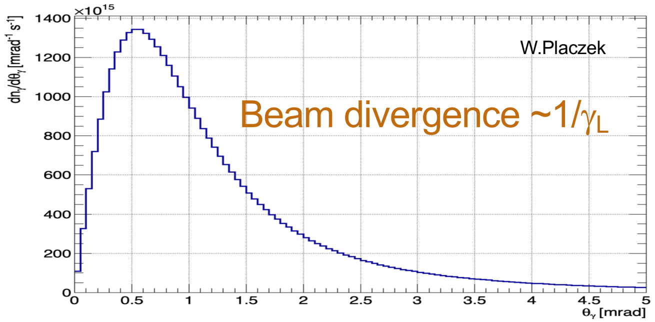
laser pulse parameters

- 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.

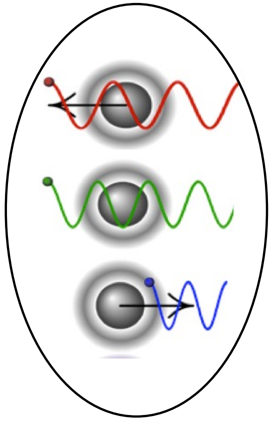
6. Highly-collimated monochromatic γ–beams:

- *the beam power is concentrated in a narrow angular region (facilitates beam extraction)*
- *the $(E_\gamma, \Theta_\gamma)$ correlation can be used (collimation) to "monochromatise" the beam*

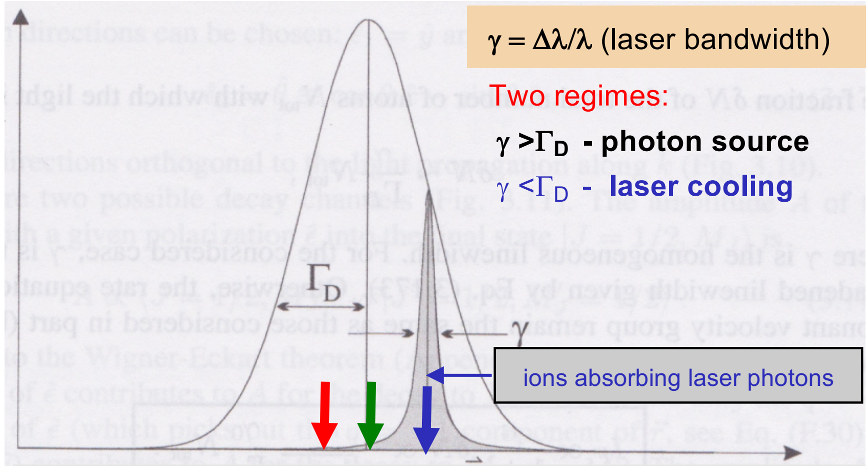




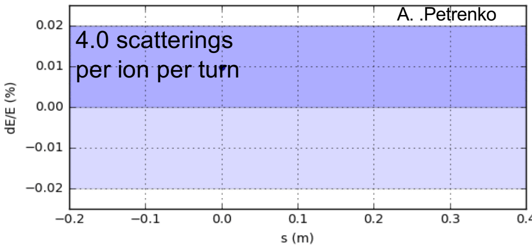
Laser cooling of atomic beams

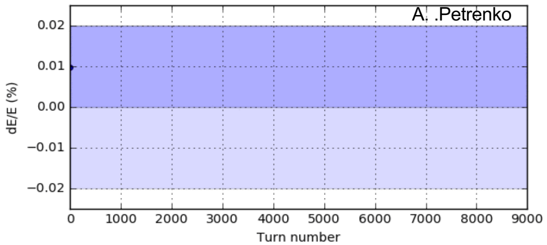


Bunch



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

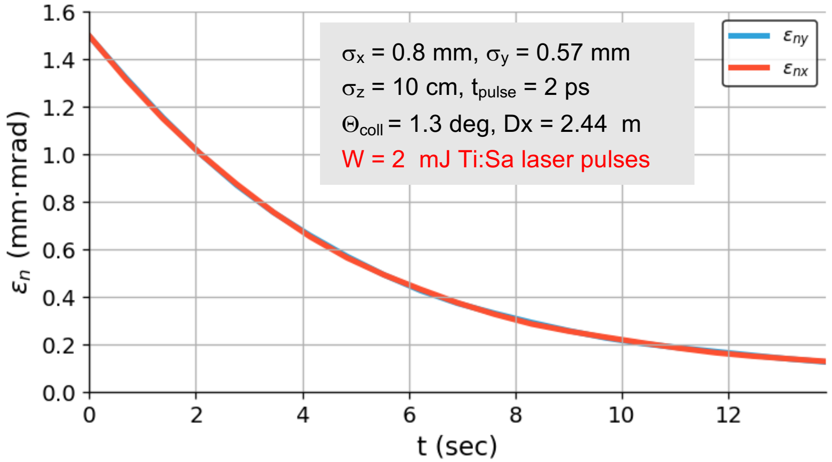




***Beam cooling**: the laser wavelength band is chosen such that only the ions moving in the laser pulse direction (in the bunch rest frame) can resonantly absorb photons.*

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.

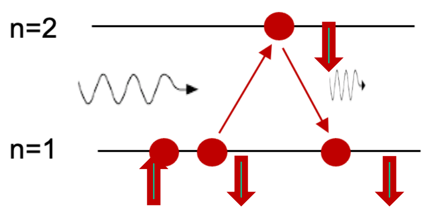
Prog.Part.Nucl.Phys. 114 (2020) 103792



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

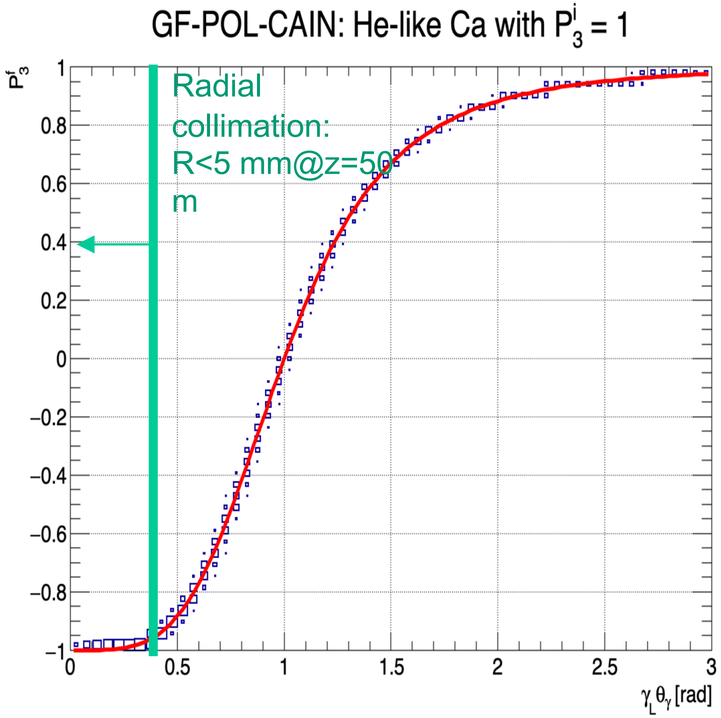
Polarised beams in GF – example: He-like, Calcium beam, Er:glass laser (1522 nm)

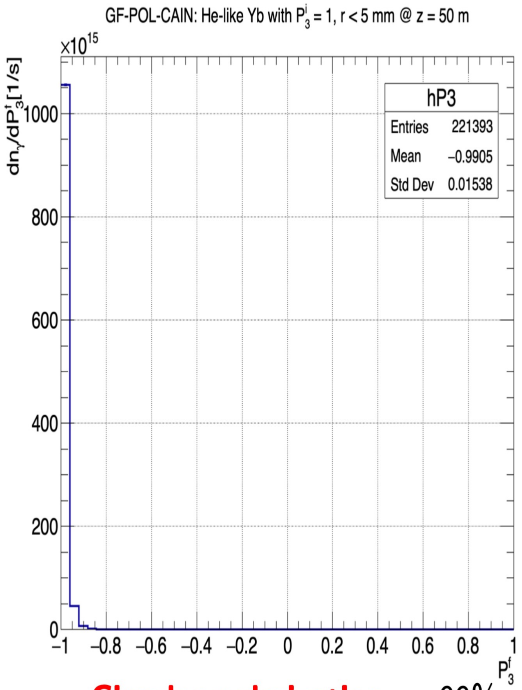
A trick: $1s^2\ ^1S_0 \rightarrow 1s^1 2p^1\ ^1P_1$ transition in He-like atoms



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

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





$\rightarrow$ **Circular polarization** $\approx 99\%$

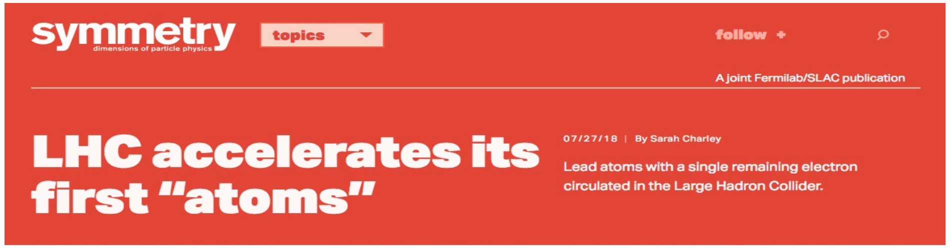
For more details see presentations at our recent, November 2021, Gamma Factory workshop: https://indico.cern.ch/event/1076086/

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 and the LHeC requirements*
- ***Pions*** – *potential, gain by a factor of 10^3, gain in the spectral density ($dN_\pi/dEdp_TdP$ [MeV^{-2} x MW] with respect to proton-beam-driven sources at KEK and FNAL (P is the driver beam power)*
- ***Muons*** – *potential gain by a factor of 10^3 in intensity w.r.t. the PSI muon source, charge symmetry ($N\mu^+ \sim N\mu^-$), polarisation control –* ***talk of Armen Apyan today***
- ***Neutrinos*** – *fluxes comparable to NuMAX 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 10^4 in intensity w.r.t. e.g. ALTO*

Challenges

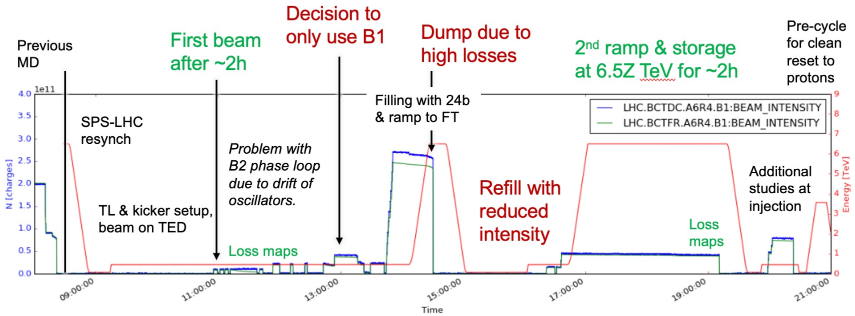
Atomic beams in the LHC (Hydrogen-like Lead)

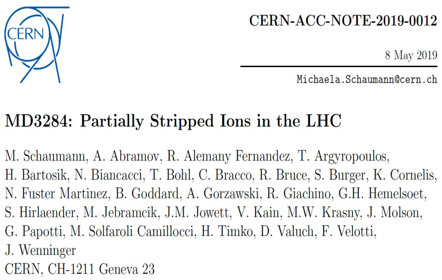

symmetry
dimensions of particle physics
topics
follow +
A joint Fermilab/SLAC publication

LHC accelerates its first "atoms"

07/27/18 | By Sarah Charley

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



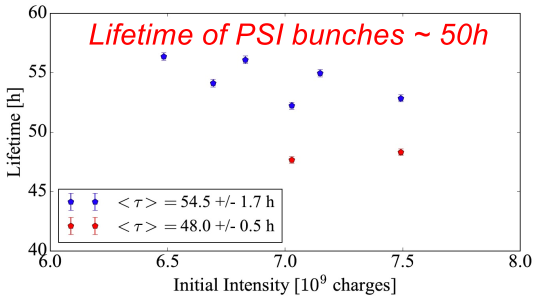

CERN-ACC-NOTE-2019-0012

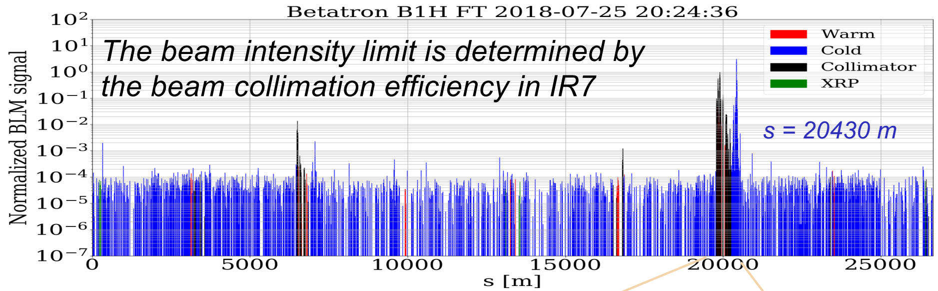
8 May 2019

Michaela.Schaumann@cern.ch

MD3284: Partially Stripped Ions in the LHC

M. Schaumann, A. Abramov, R. Alemany Fernandez, T. Argyropoulos, H. Bartosik, N. Biancacci, T. Bohl, C. Bracco, R. Bruce, S. Burger, K. Cornelis, N. Fuster Martinez, B. Goddard, A. Gorzawski, R. Giachino, G.H. Hemelsoet, S. Hirlaender, M. Jebramcik, J.M. Jowett, V. Kain, M.W. Krasny, J. Molson, G. Papotti, M. Solfaroli Camillocci, H. Timko, D. Valuch, F. Velotti, J. Wenninger
CERN, CH-1211 Geneva 23

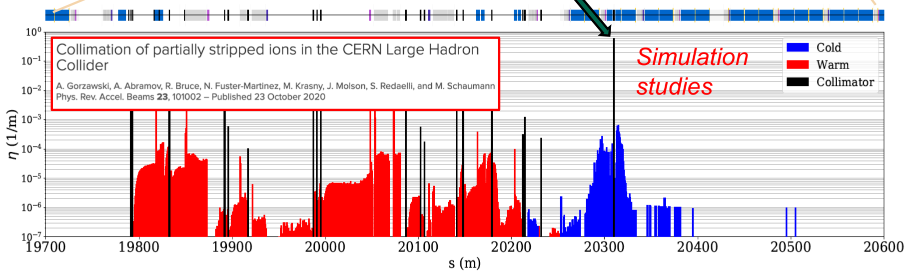




Mitigation strategies:

1. *Dispersion suppressor collimator (TCLD)*
2. *Crystal collimation*
3. *Laser collimation.*

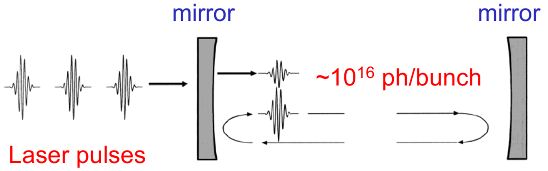
IR7 zoom

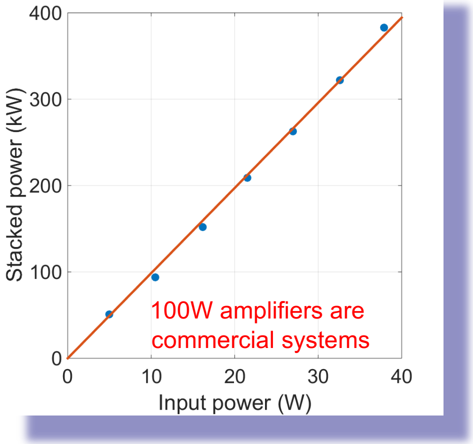


A dedicated LHC MD with crystal collimation of the PSI (H-like Pb) beam is a natural next step…

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

Fabry-Pérot resonator

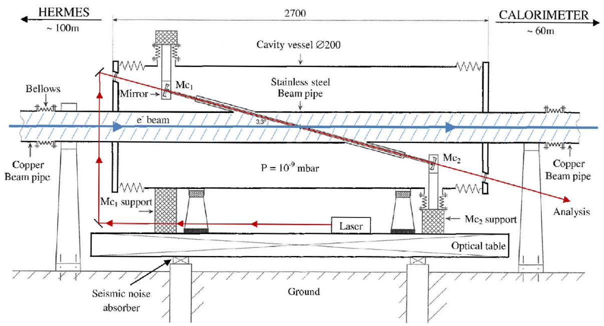




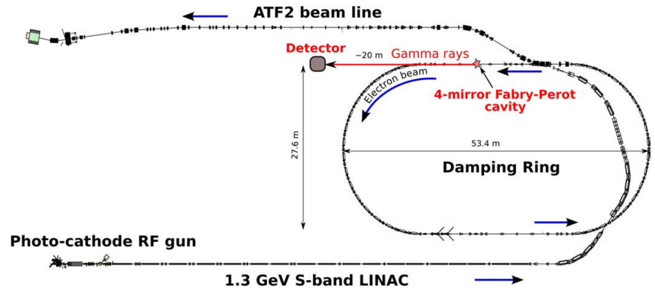
Amoudry L. et al., Applied Optics 59(2020)116

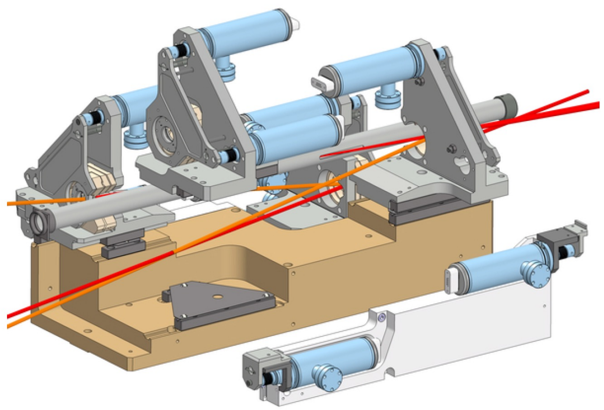
GF requirement:
< 5mJ pulses @ 40MHz,
(200kW photon beam)

HERA storage ring



KEK – ATF ring





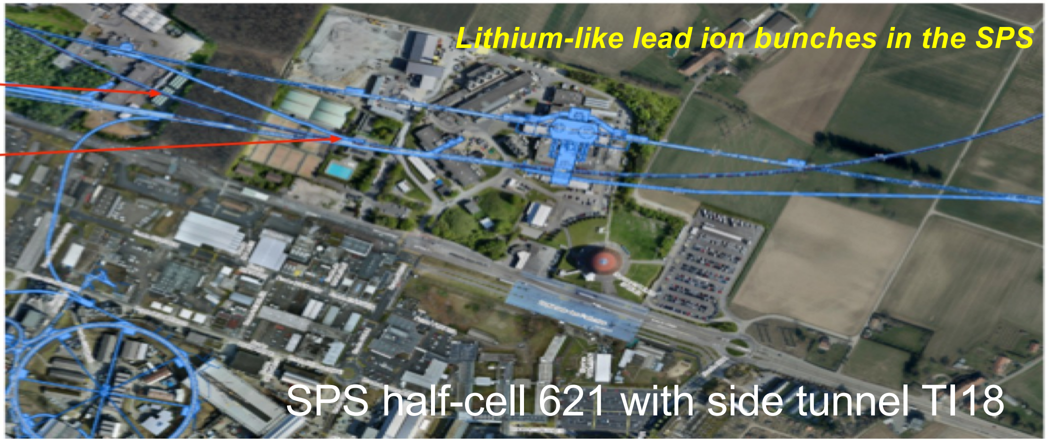
Towards the first integration of the FP resonator in the hadron storage ring →

Proof of Principle

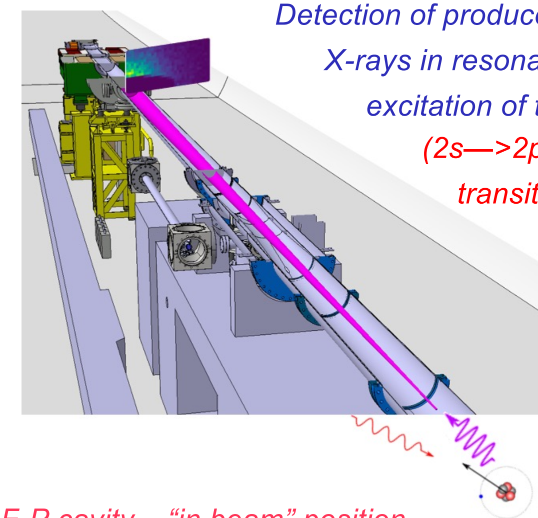
Gamma Factory Proof-of-Principle (PoP) SPS experiment

SPS

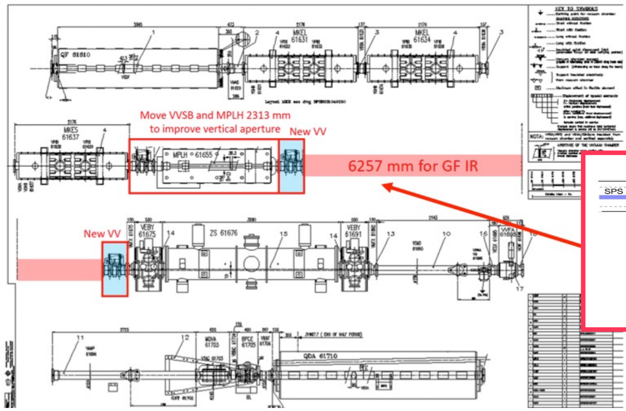
PoP location



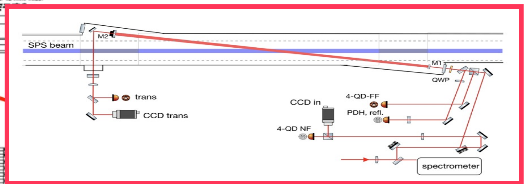
Detection of produced X-rays in resonant excitation of the (2s—>2p)$_{1/2}$ transition



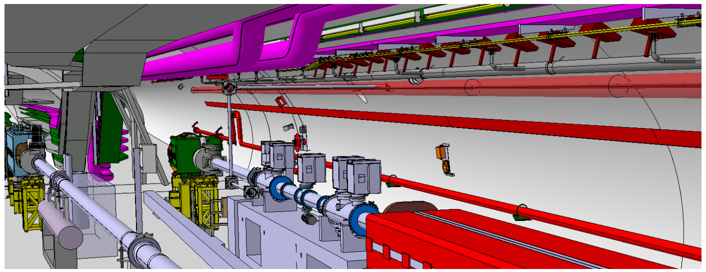
LSS6 zone



F-P cavity



F-P cavity – "in beam" position



***F-P cavity length – 3.75 m** -- vertically tilted by 2..6 deg*

The purpose of the GF SPS PoP experiment

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

Contact persons:

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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 finalizing 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***

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, 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 and muonic atoms, 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, fusion research, medical isotopes' and isomers' production).*

GF studies: recently published papers (INSPIRE)

Special issue of "Annalen der Physik" -- devoted to the GF physics highlights -- published in March 2022.

Conclusions

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

- *The **next** CERN **high-energy frontier** project (if ever constructed) may take **long time** to be approved, built and become operational, … unlikely before 2050-ties*

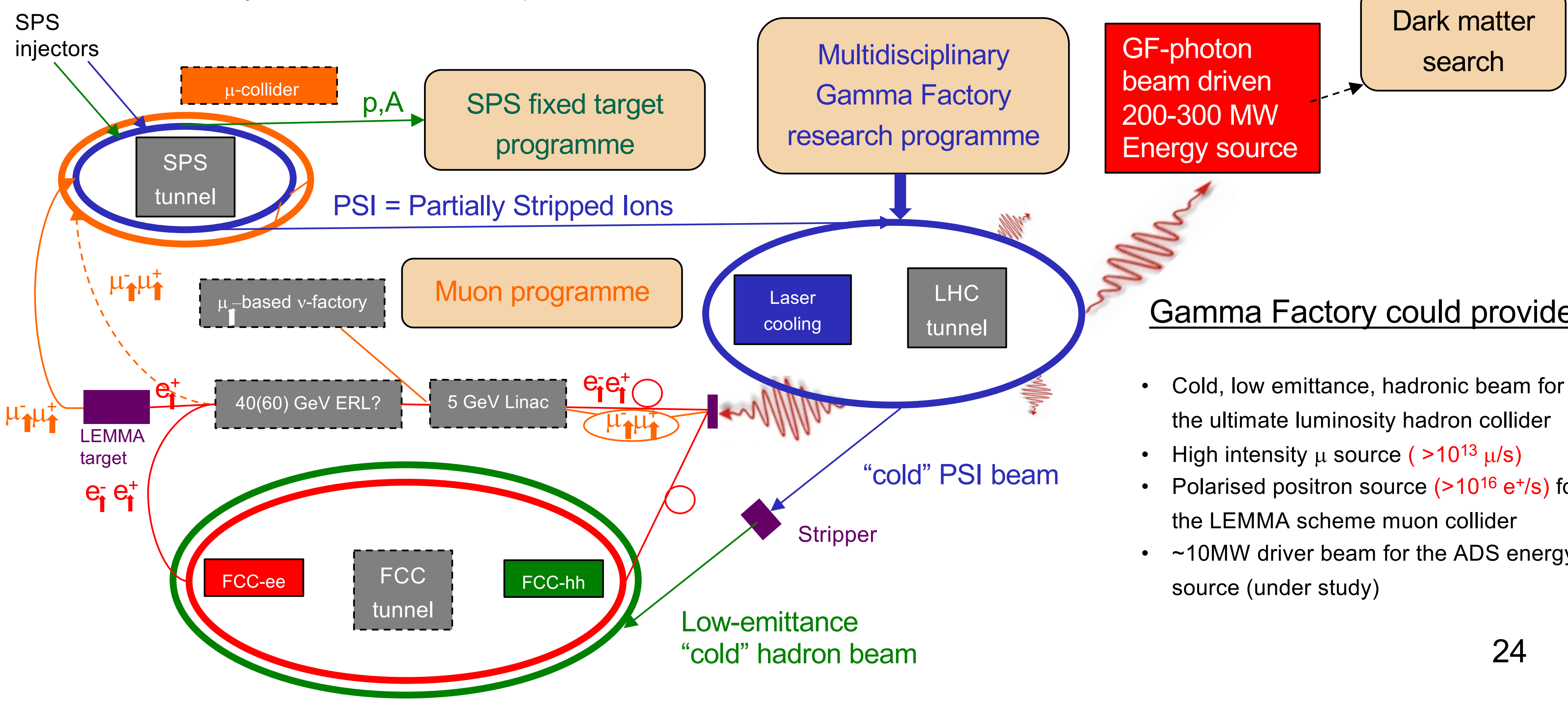
- *The **present** LHC **research programme** will certainly reach **earlier** (late 2030-ties?) its discovery **saturation** ($L_{int} \sim 0.5L_{goal}$) -- little physics gain by a simple extending its pp/pA/AA running time*

- *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 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 GF 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 μ source ($>10^{13}$ μ/s)
- Polarised positron source ($>10^{16}$ e^+/s) for the LEMMA scheme muon collider
- ~10MW driver beam for the ADS energy source (under study)