Introduction to the Gamma Factory

LISA conference, CERN

the 2nd of September 2024

Mieczyslaw Witold Krasny

LPNHE, CNRS and University Paris Sorbonne and CERN, BE-ABP

This talk is dedicated to Bruce

"New directions in science are launched by new tools much more often than by new concepts.

The effect of a concept-driven revolution is to explain old things in new ways.

The effect of a tool-driven revolution is to discover new things that have to be explained" - F. Dyson

"*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

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]

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!*

Outline of the talk

- *Rationale behind the Gamma Factory initiative*
- *Basic principles*
- *Feasibility proof*
- *Scientific programme – selected examples*
- *Outlook*

Rationale behind the Gamma Factory initiative

1. Curiosity

- *How to efficiently "accelerate" photons?*

- *The science of **high energy** atomic beams (production, storage, cooling, collision aspects) has, so far, not been developed. Atomic beams are very special -- they can be manipulated and controlled with unprecedented precision*

- *New quantum physics beam effects (beams of "Schrödinger cats")*

- *No simulation framework existed -- it had to be created and benchmarked*

- *New challenges for the laser technology*

- *Sociological curiosity:*

Can the particle, nuclear, atomic and accelerator and applied physics expertise be merged into a joint multidisciplinary project?

- *Political curiosity:*

Can a novel multidisciplinary project be developed ***and implemented*** *in a ”High Energy Physics” laboratory such as CERN?*

2. Balance of the high-energy and high-intensity frontiers

- *Main CERN mission: high energy frontier (detailed Higgs studies at the HL-LHC, FCC-ee)*

- *High intensity frontier (dark matter, neutrino mass puzzle(s), families, lepton universality, etc…*

Gamma Factory can significantly improve the present intensity limits of the:

- *γ-beams by a factor >10^6 → 10^{18} γ/sec,*
- *muon beams by a factor of 10^3, →7 x 10^{13} μ/sec,*
- *polarised positron beams by a factor of 10^3, →:10^{16} e+/sec,*
- *quasi-monochromatic MeV neutron beams of →:10^{17} neutrons/sec,*
- *radioactive ion beams →:10^{12} ions/sec*

3. Physics with LHC extracted beams?

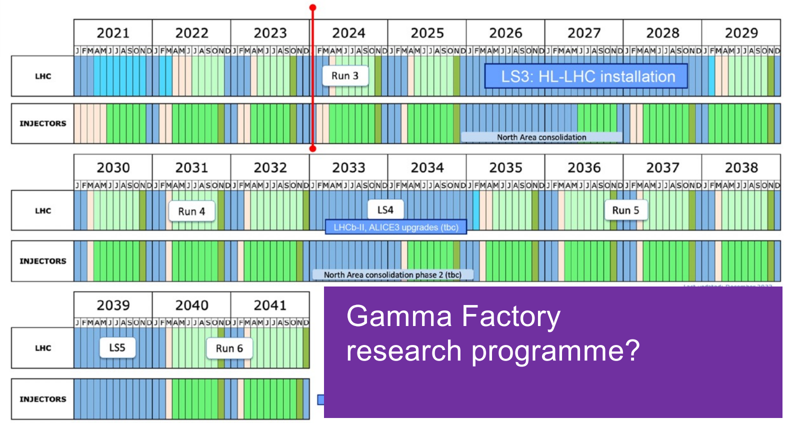
- *SPS has demonstrated operation with cycle intensity 2-4x10^{13} protons delivering 4x10^{19} protons/year for the SPS fixed target programme, (PSB can deliver 10^{20} protons/year for the ISOLDE programme)*

- *If LHC is used in the future as the source of extracted beams (3.5 10^{14} circulating protons with ~1 hour filling/ramping), then maximally 10^{18} (fast extraction) protons/year can be delivered for the LHC fixed target programme*

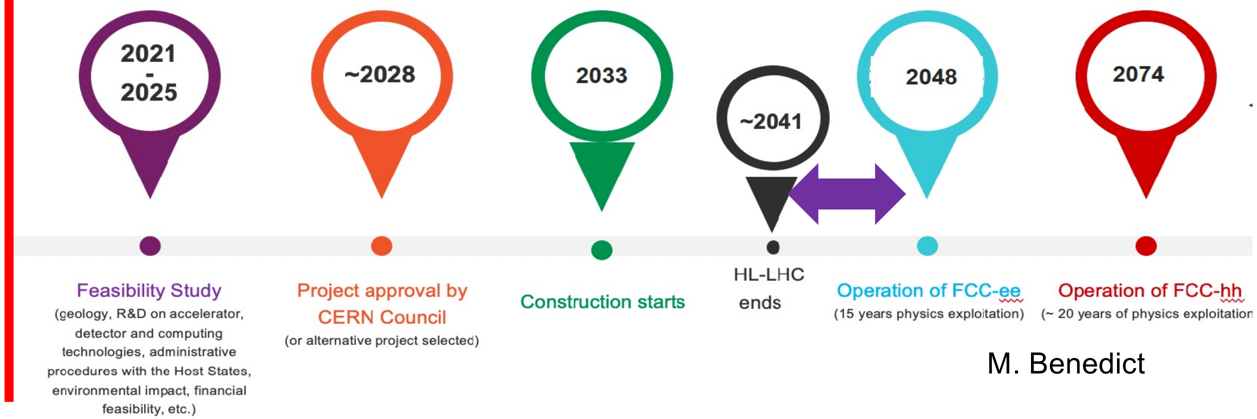
Gamma Factory could extract ~10^{25} γ/year for a fixed target programme (MHz repetition rate). Efficient extraction of the RF power in the form of particle beams!

4. Empty time slot for the Gamma Factory physics programme?

LHC



FCC



M. Benedict

- Gamma Factory can extend significantly the scope of the LHC-based physics programme (with new questions and new tools)
- … at a relatively low cost (~1% of the cost of the FCC-ee)

5. Energy consumption and sustainability

	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	

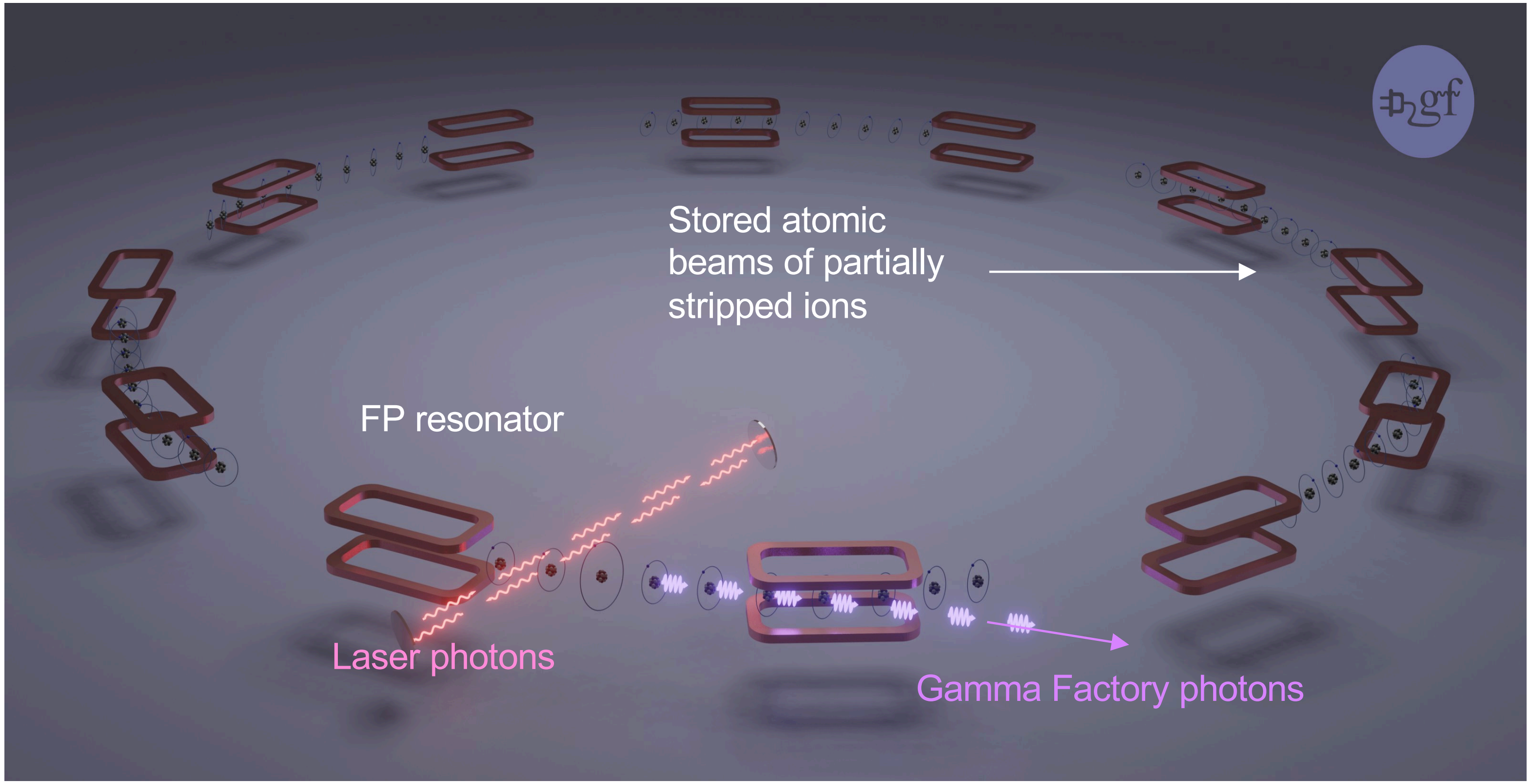
Gamma Factory beam-driven, sub-critical reactor (with the efficient transmutation of its waste) could potentially provide the necessary AC plug power needs for the growing CERN accelerator infrastructure.

6. Opening new research opportunities at CERN

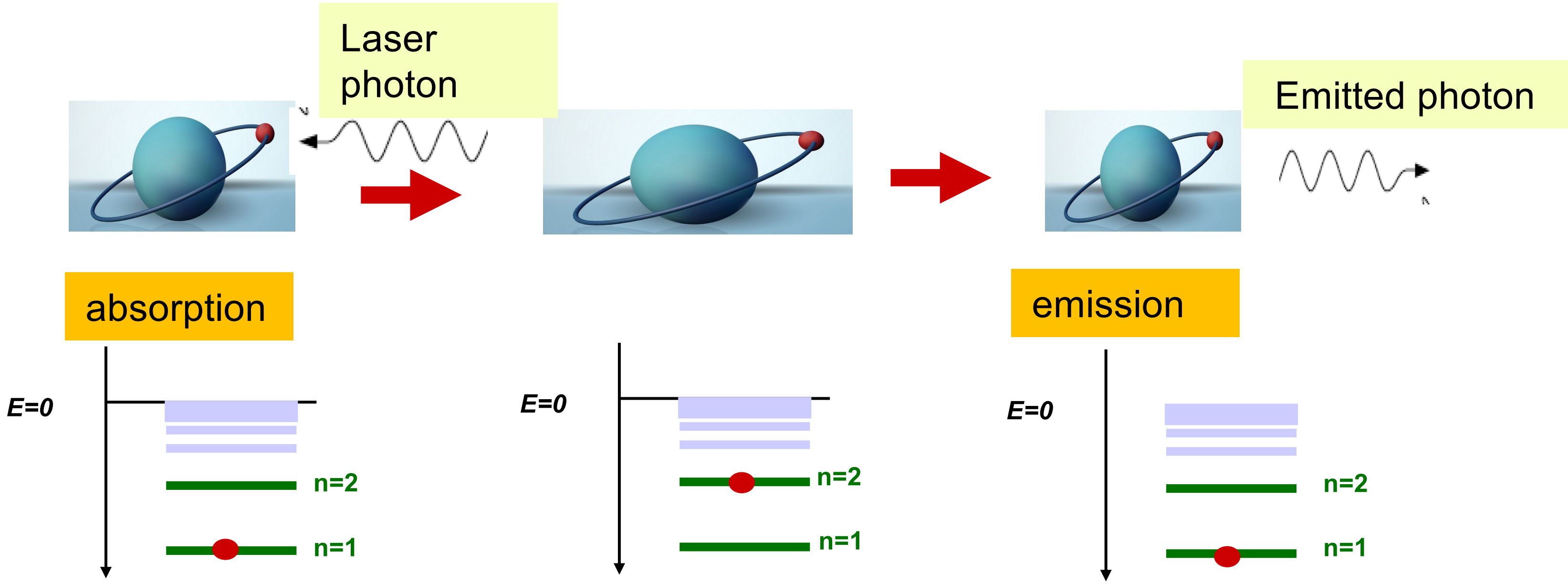
- ***particle physics*** *(precision QED and EW studies, vacuum birefringence, Higgs physics in $\gamma\gamma$ collision mode, rare muon decays, precision neutrino physics, QCD-confinement studies, …);*
- ***nuclear physics*** *(nuclear spectroscopy, cross-talk of nuclear and atomic processes, GDR, nuclear 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, high intensity polarised positron and muon sources, beams of radioactive ions and neutrons, very narrow band, and flavour-tagged neutrino beams, …);*
- ***applied physics*** *(accelerator driven energy sources, fusion research, medical isotopes and isomers precision lithography).*

Gamma Factory – basic principles

Gamma Factory photon source



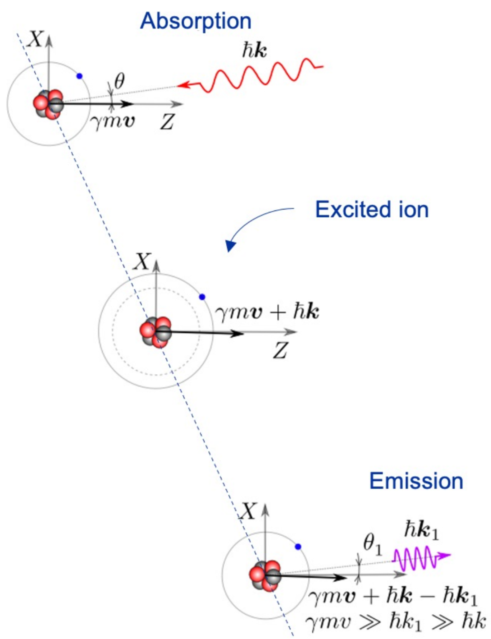
Resonant absorption and emissions of photons by **atoms**



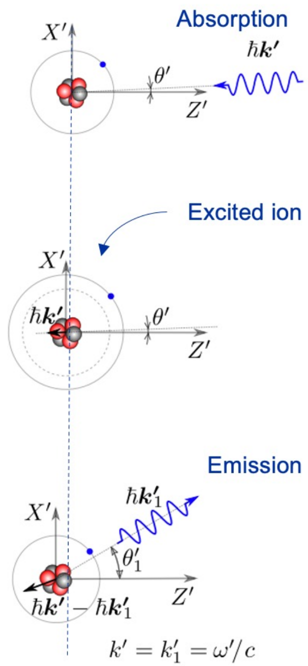
Photon acceleration -- Energy leap:

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

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

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

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

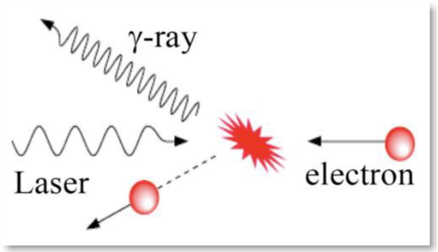
$$\nu^{max} \longrightarrow (4\,\gamma_L^2)\,\nu_i$$

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

Photon acceleration – Intensity and efficiency leap:

large cross-section for atomic collisions

Inverse Compton scattering



Cross-section

Electrons:

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

r_e - classical electron radius

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

Requirements

E_{beam} = 1.5 GeV

LINAC or LWFA

Electron fractional energy loss:

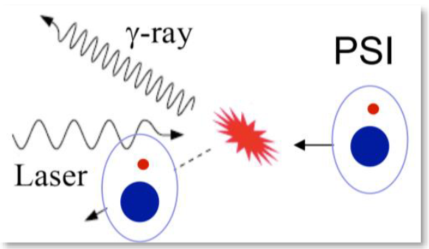
emission of 150 MeV photon:

$E_\gamma/E_{beam} = 0.1$

(electron is lost!)

⇩ $\sigma \times 10^9$

Gamma Factory



Example: Pb, hydrogen-like ions, *stored in LHC* $\gamma_L = 2887$

Partially Stripped Ions:

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

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

$\sigma_{res} = 5.9 \times 10^{-16}\ cm^2$

E_{beam} = 574 000 GeV

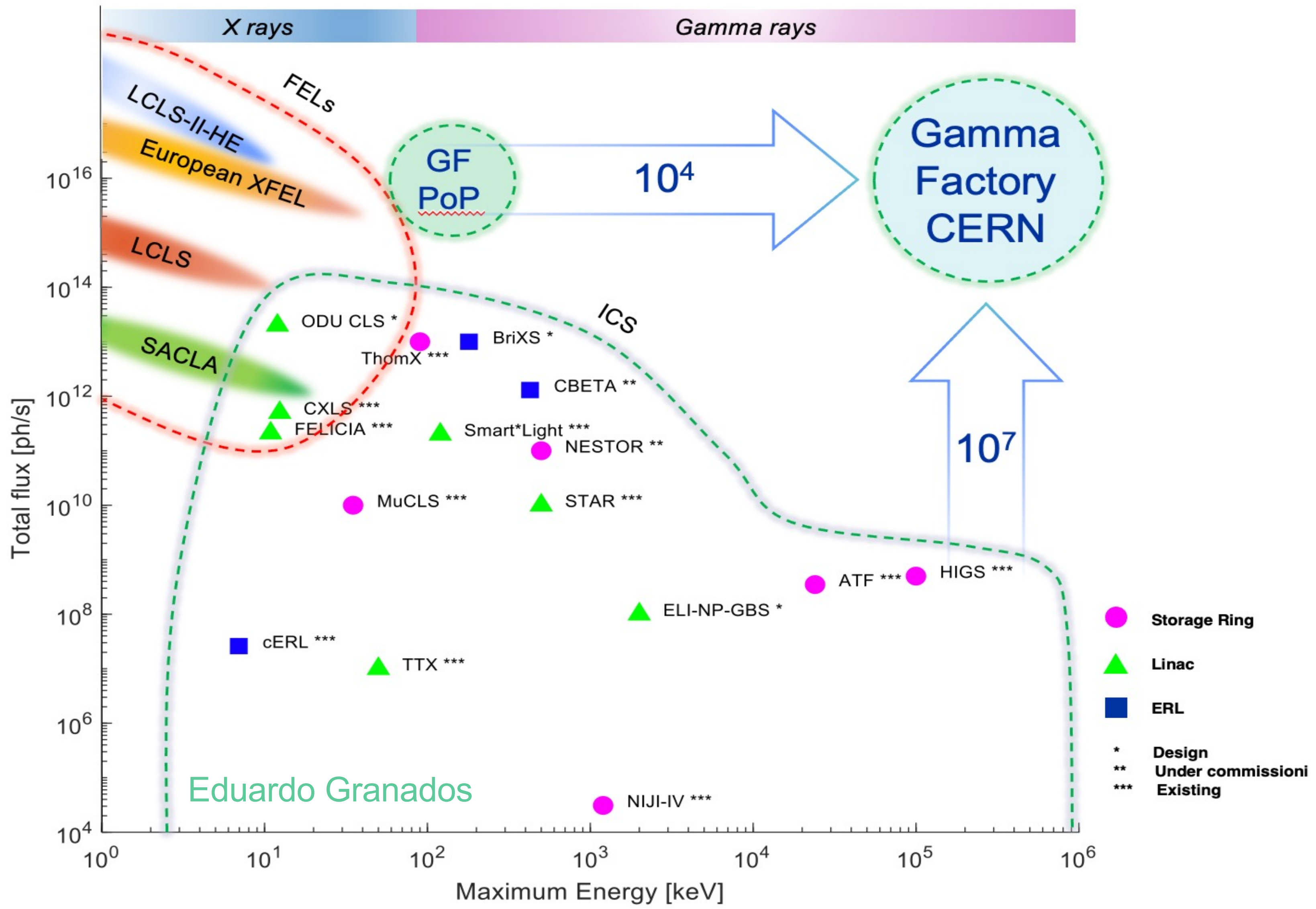
(LHC)

Electron fractional energy loss:

emission of 150 MeV photon:

$E_\gamma/E_{beam} = 2.6 \times 10^{-7}$

(ion undisturbed!)



X rays
Gamma rays
FELs
LCLS-II-HE
European XFEL
LCLS
SACLA
GF
PoP
10^4
Gamma
Factory
CERN
10^7
ICS
ODU CLS *
ThomX ***
BriXS *
CBETA **
CXLS ***
FELICIA ***
Smart*Light ***
NESTOR **
MuCLS ***
STAR ***
ATF ***
HIGS ***
ELI-NP-GBS *
cERL ***
TTX ***
NIJI-IV ***
Eduardo Granados
Storage Ring
Linac
ERL
* Design
** Under commissioni
*** Existing
Total flux [ph/s]
Maximum Energy [keV]
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
10^{16}
10^0
10^1
10^2
10^3
10^4
10^5
10^6

Extraordinary properties of the GF photon source

1. Point-like, small divergence

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

2. Huge jump in intensity:

- **More than 7 orders of magnitude** *with respect to existing (being constructed)* γ*-sources*

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%***

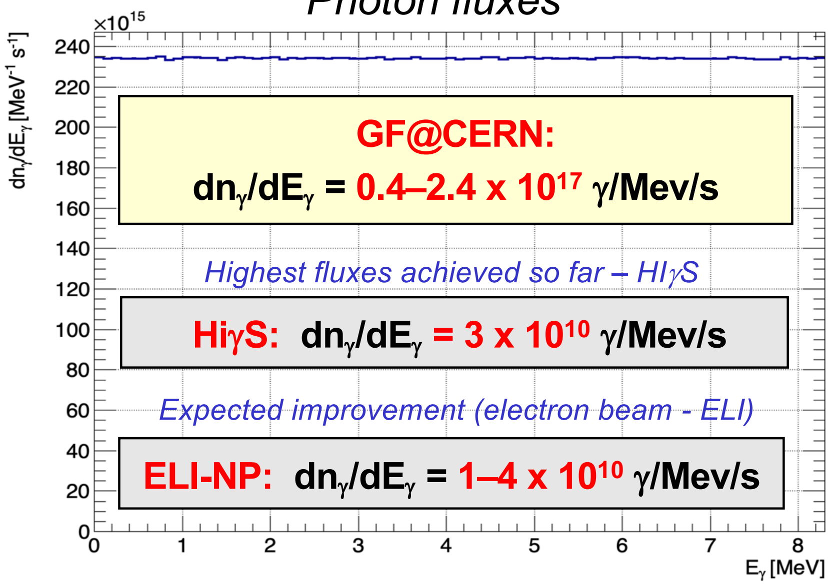
5. Unprecedented plug power efficiency (energy footprint):

- ***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, $(1s\text{->}2p)_{1/2}$ transition, TiSa laser, 20 MHz FP cavity

Photon fluxes

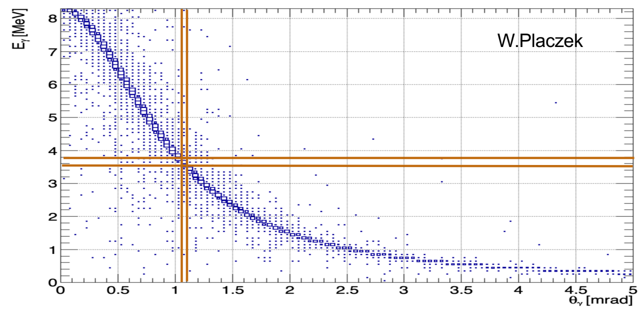


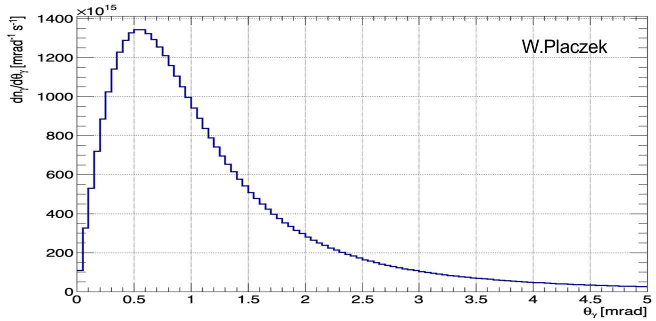
laser pulse parameters

- 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.

Highly-collimated monochromatic γ–beams:

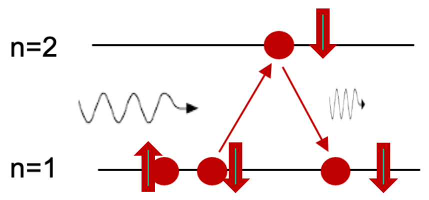
- *the beam power is concentrated in a narrow angular region (facilitates beam extraction),*
- *the $(E_\gamma, \Theta_\gamma)$ correlation can be used (collimation) to "monochromatize" the beam*





Polarised (and/or twisted) GF photon beams

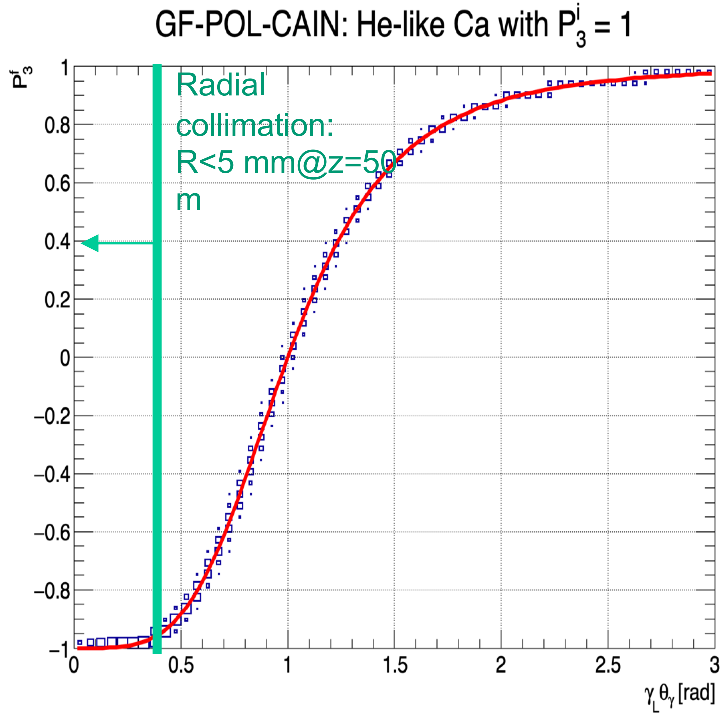
<u>A trick</u>: Pauli blocking

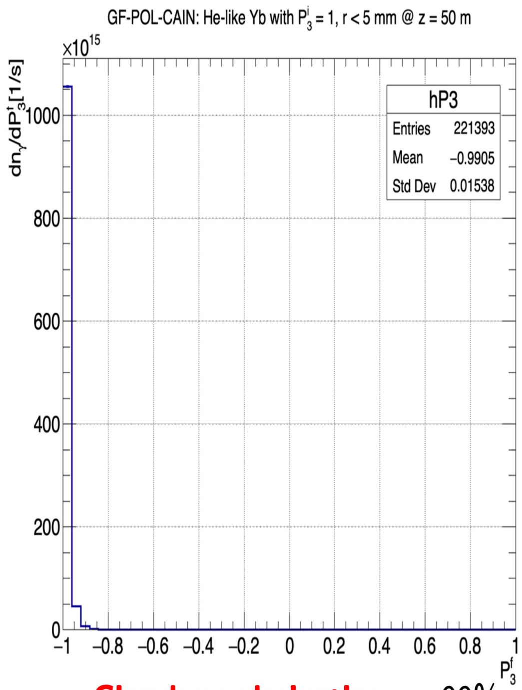


$$nS_0 \rightarrow n'P_1 \rightarrow nS_0$$

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

$1s^2$ $1S_0$ □ $1s^1$ $2p^1$ $^1P_1$ transition in He-like atoms

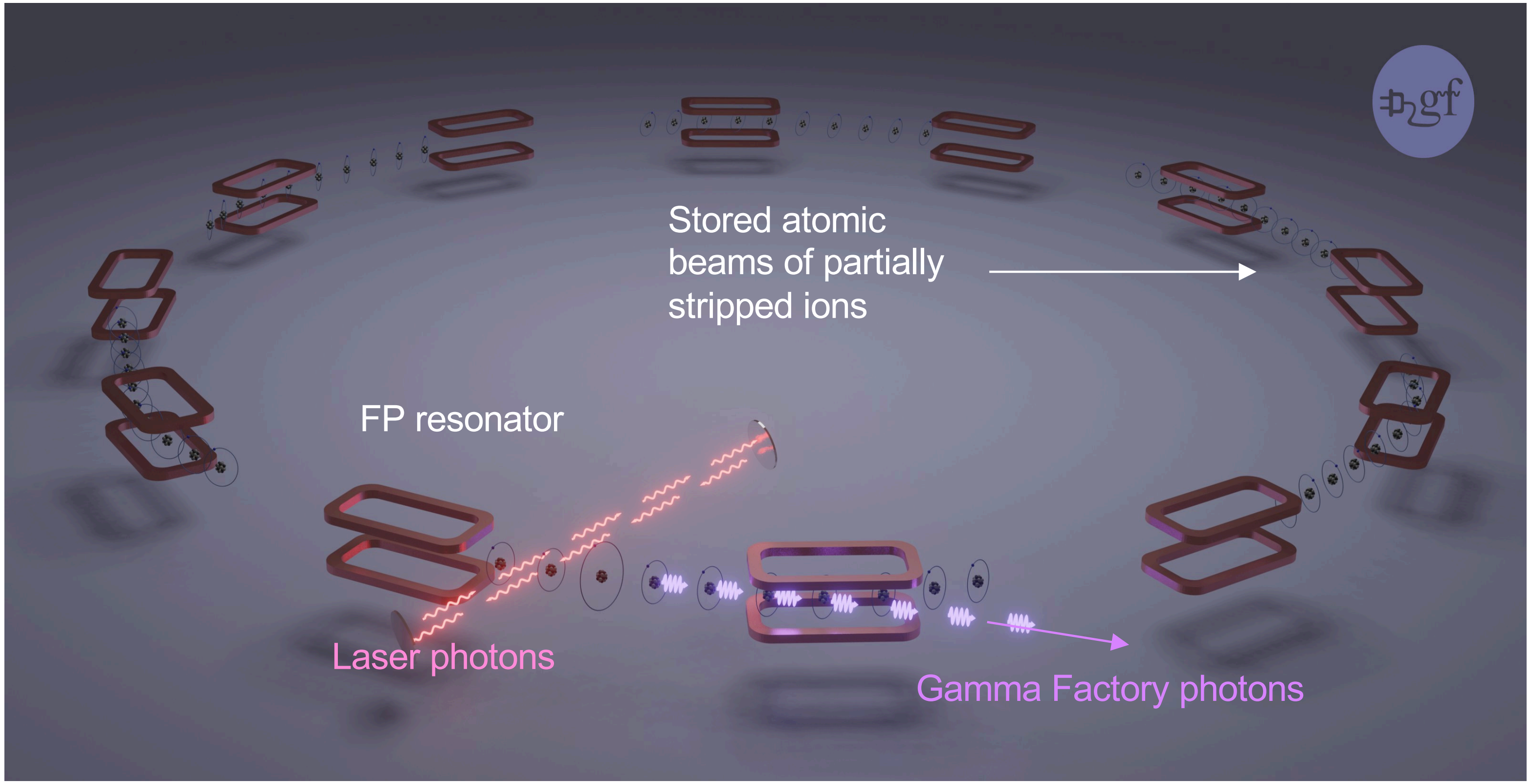




→ **Circular polarization** ≈ 99%

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

Gamma Factory – feasibility proof steps

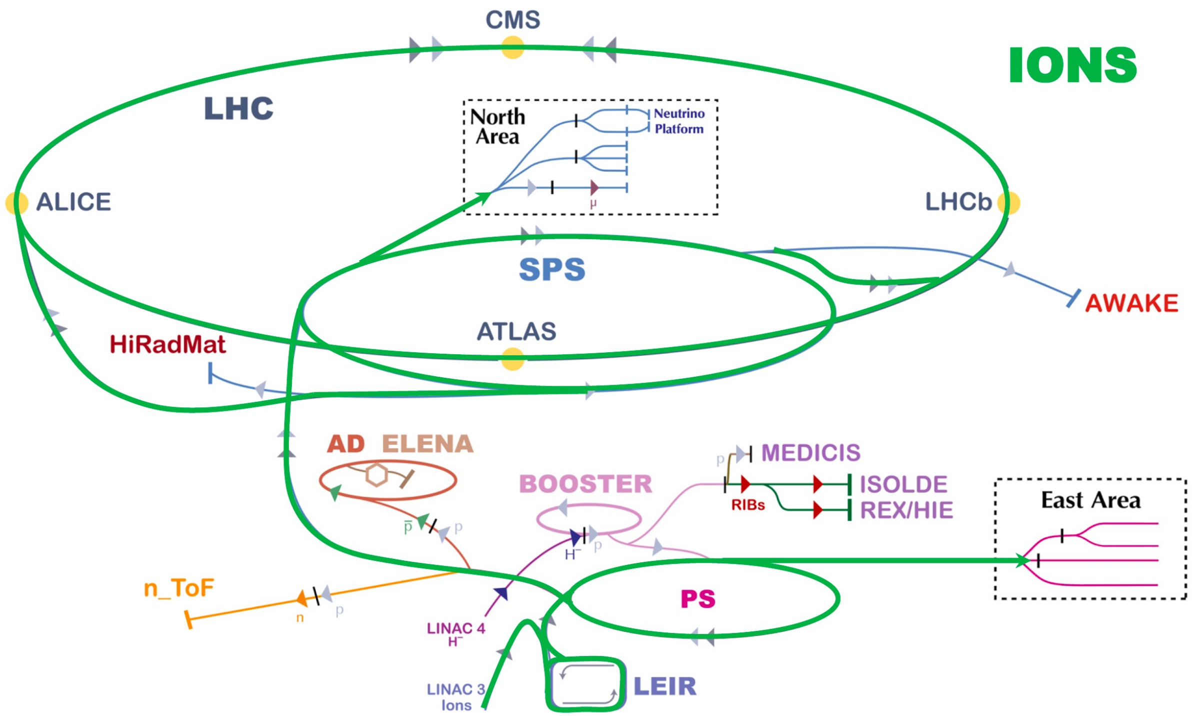


Novel technology:

Resonant scattering of laser photons on ultra-relativistic atomic beam

CERN as the GF project host:

re-use of already existing accelerator infrastructure

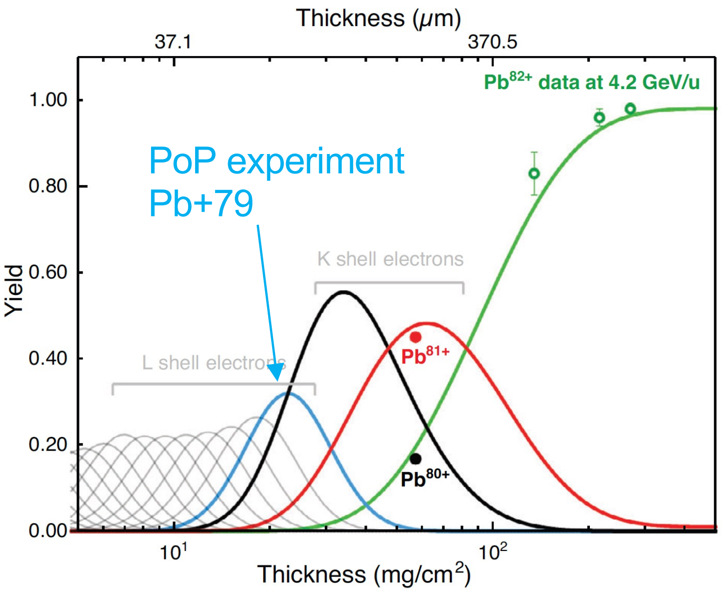


Gamma Factory (additional) beam requirements:

- modification of the ion stripping scheme,
- storage of atomic beams

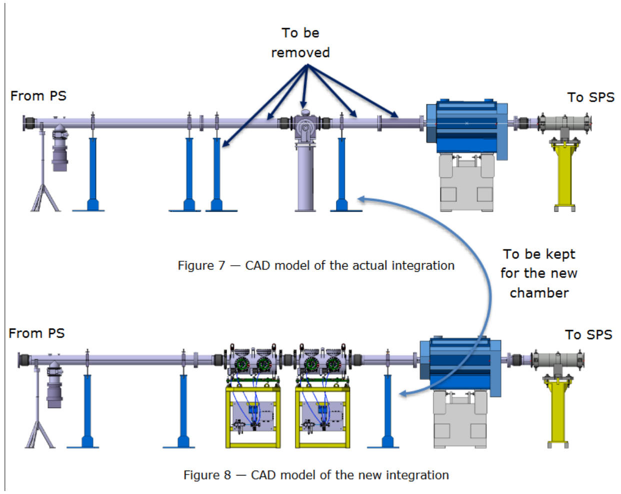
Step 1 : Requisite TT2 stripper system installed

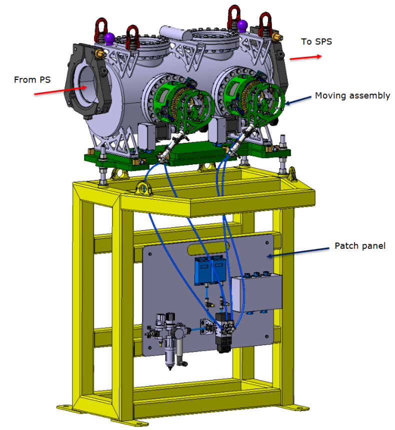
Stripping of Pb+54 ions in the TT2 PS-□ SPS transfer line



Charge-State Distributions of Highly Charged Lead Ions at Relativistic Collision Energies

Felix M. Kröger, Günter Weber, Simon Hirlaender, Reyes Alemany-Fernandez, Mieczyslaw W. Krasny, Thomas Stöhlker, Inga Yu. Tolstikhina, and Viacheslav P. Shevelko*

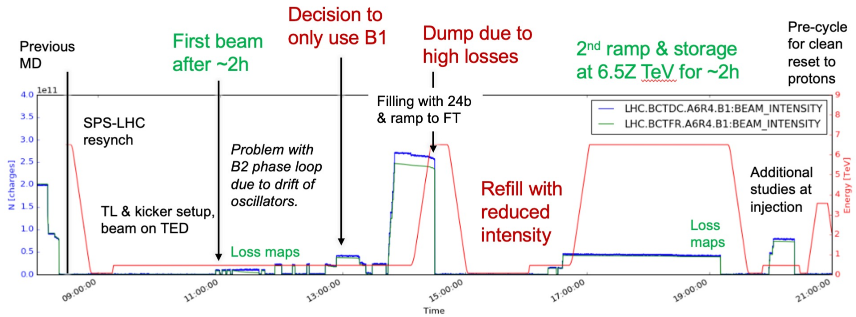


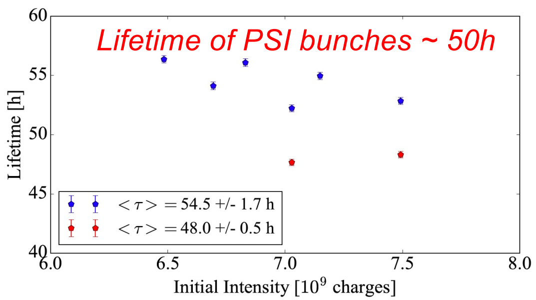


R. Alemany-Fernandez (BE.OP), E. Grenier-Boley and D. Baillard (SY.STI)

The two tanks of the new stripper system were installed during YETS 2021-2022 and YETS 2022-2023. Four stripper foil mechanisms are operating at ~Hz frequency.

Step 2: Atomic beams stored in in the LHC






CERN-ACC-NOTE-2019-0012

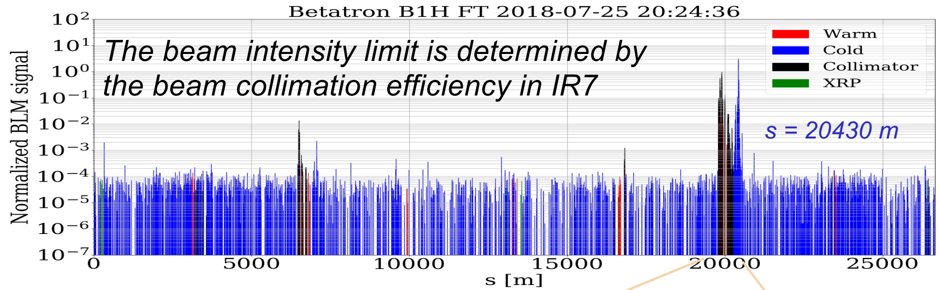
8 May 2019

Michaela.Schaumann@cern.ch

MD3284: Partially Stripped Ions in the LHC

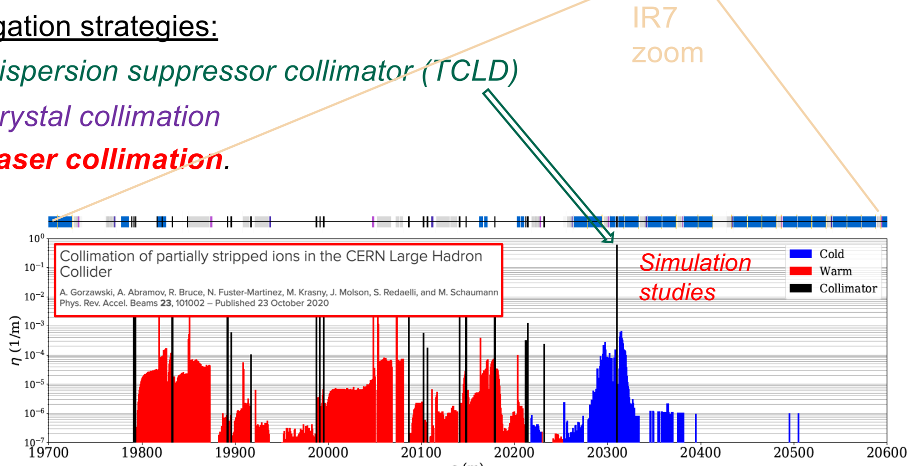
M. Schaumann, A. Abramov, R. Alemany Fernandez, T. Argyropoulos, H. Bartosik, N. Biancacci, T. Bohl, C. Bracco, R. Bruce, S. Burger, K. Cornelis, N. Fuster Martinez, B. Goddard, A. Gorzawski, R. Giachino, G.H. Hemelsoet, S. Hirlaender, M. Jebramcik, J.M. Jowett, V. Kain, M.W. Krasny, J. Molson, G. Papotti, 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***.

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Collimation of partially stripped ions in the CERN Large Hadron Collider

A. Gorzawski, A. Abramov, R. Bruce, N. Fuster-Martinez, M. Krasny, J. Molson, S. Redaelli, and M. Schaumann

Phys. Rev. Accel. Beams **23**, 101002 – Published 23 October 2020

symmetry
dimensions of particle physics

topics

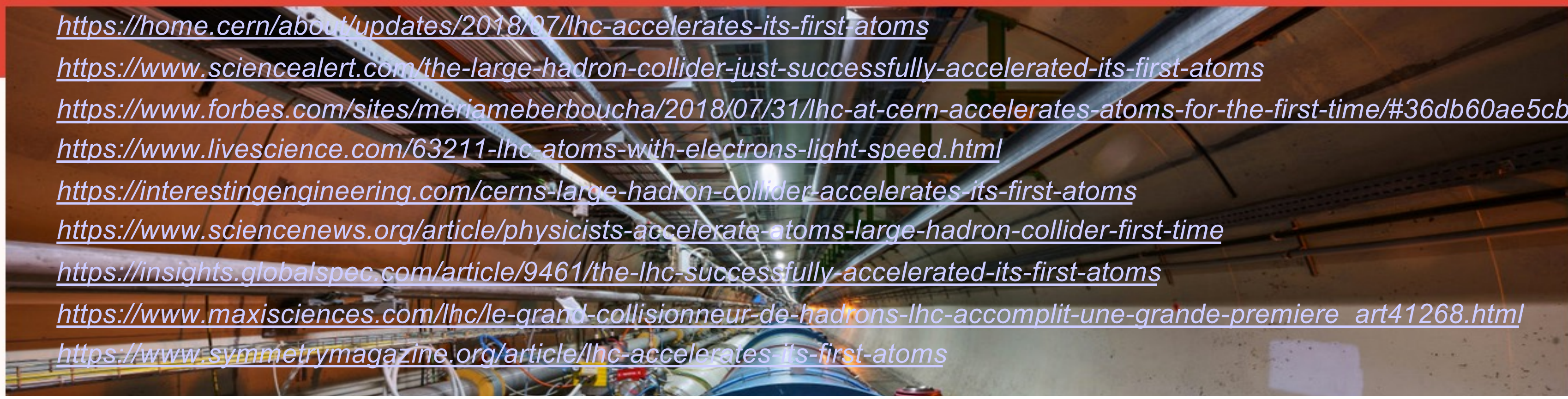
follow +

A joint Fermilab/SLAC publication

LHC accelerates its first "atoms"

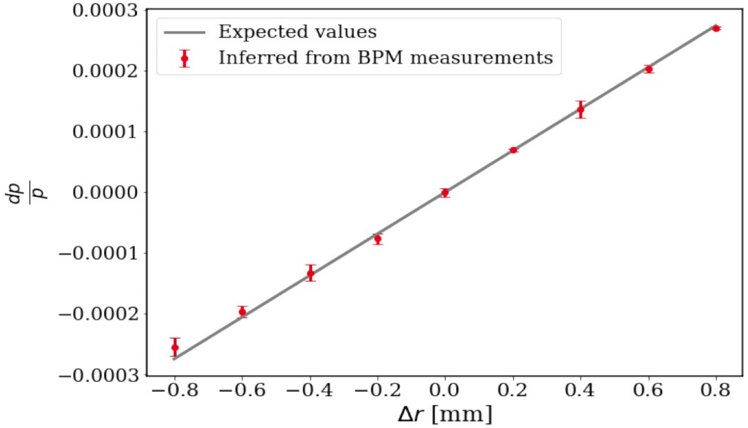
07/27/18 | By Sarah Charley

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



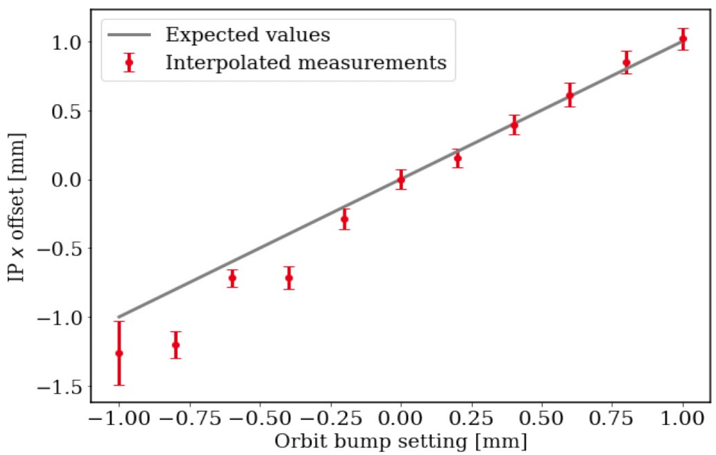
https://home.cern/about/updates/2018/07/lhc-accelerates-its-first-atoms
https://www.sciencealert.com/the-large-hadron-collider-just-successfully-accelerated-its-first-atoms
https://www.forbes.com/sites/meriameberboucha/2018/07/31/lhc-at-cern-accelerates-atoms-for-the-first-time/#36db60ae5cb4
https://www.livescience.com/63211-lhc-atoms-with-electrons-light-speed.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

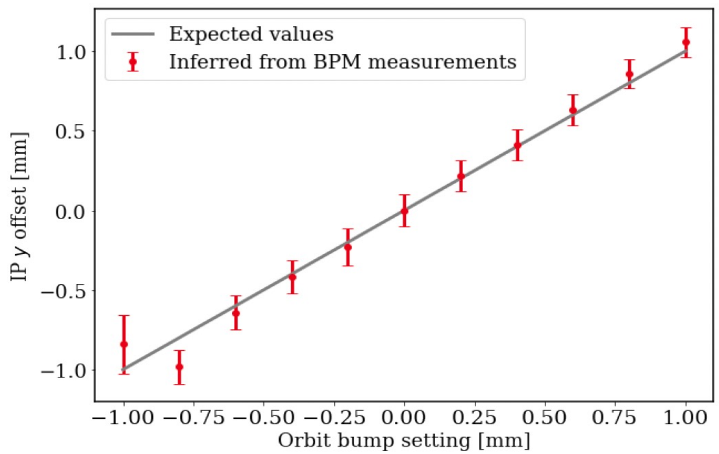
Step 3: Requisite precision of the momentum and beam position control at the collision point with laser photons



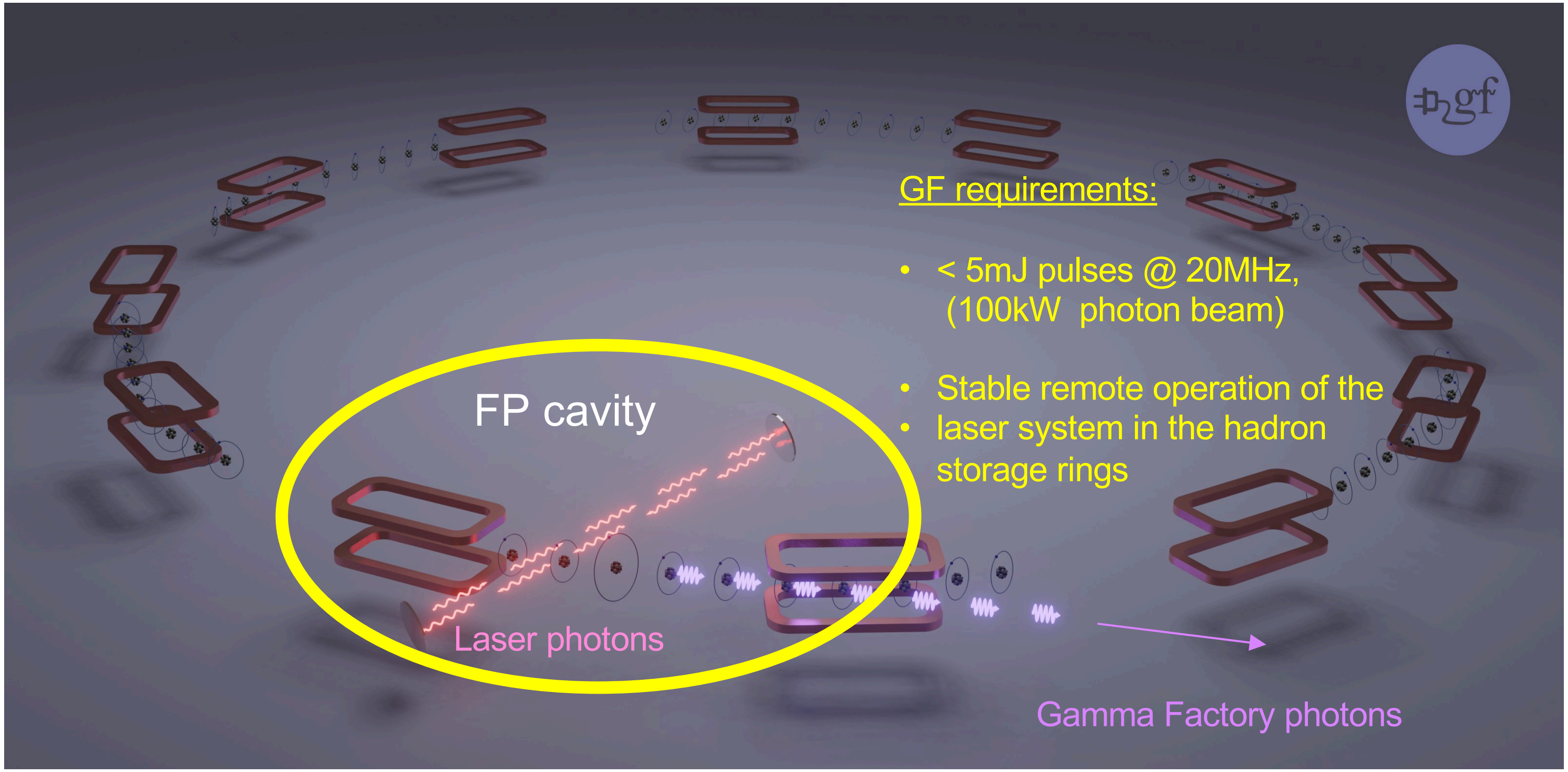
SPS MD5044 : machine stability characterisation
Gamma Factory SPS Proof-of-Principle Experime

R. Ramjiawan, G. Arduini, H. Bartosik, Y. Dutheil, W. Hofle, M. W
Krasny, A. Martens, Y. Papaphilippou, A. Petrenko, F. M. Velotti,
CERN, CH-1211 Geneva, Switzerland





Laser photons



Step 4: World record of the stored laser photon beam power – satisfying the full GF research programme

RESEARCH ARTICLE | JUNE 20 2024

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

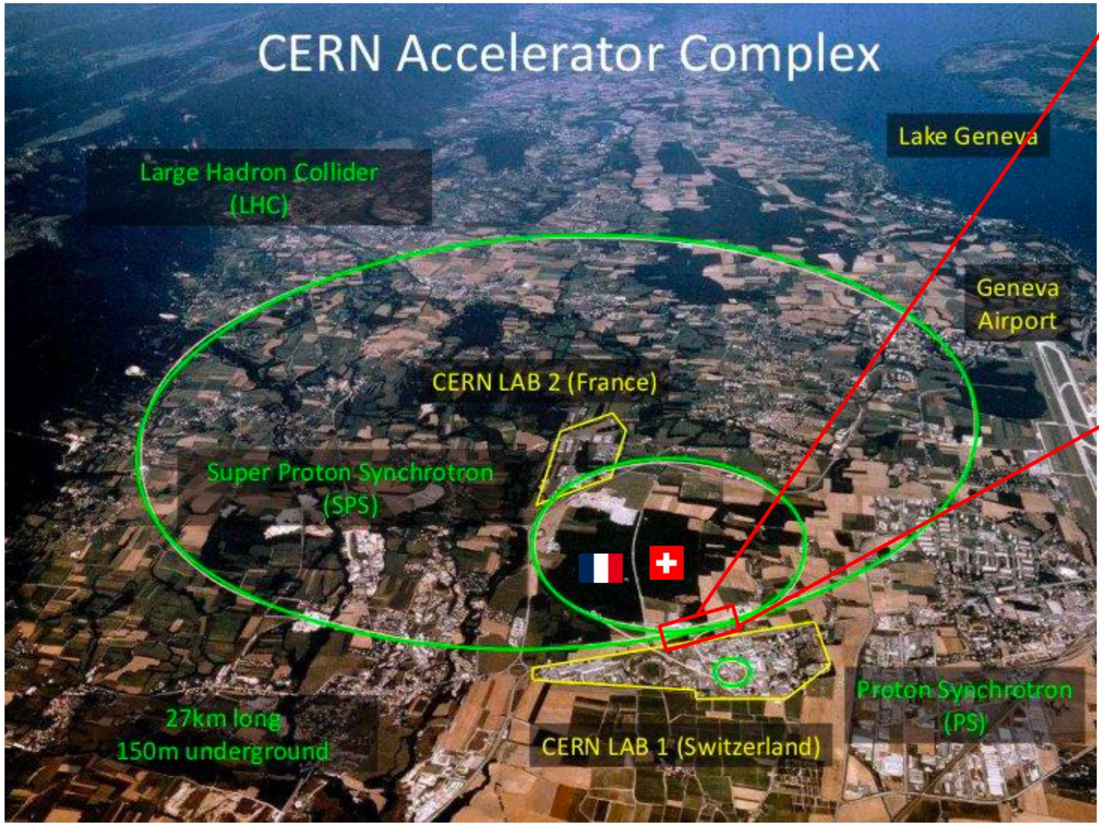
X.-Y. Lu; R. Chiche; K. Dupraz; F. Johora; A. Martens; D. Nutarelli; Y. Peinaud; V. Soskov; A. Stocchi; F. Zomer; C. Michel; L. Pinard; E. Cormier; J. Lhermite; X. Liu; Q.-L. Tian; L.-X. Yan; W.-H. Huang; C.-X. Tang; V. Fedosseev; E. Granados; B. Marsh

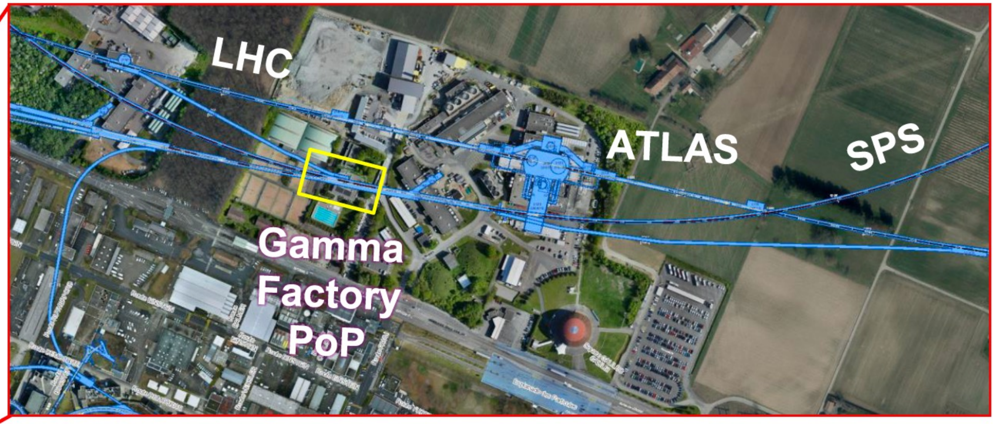
+ Author & Article Information

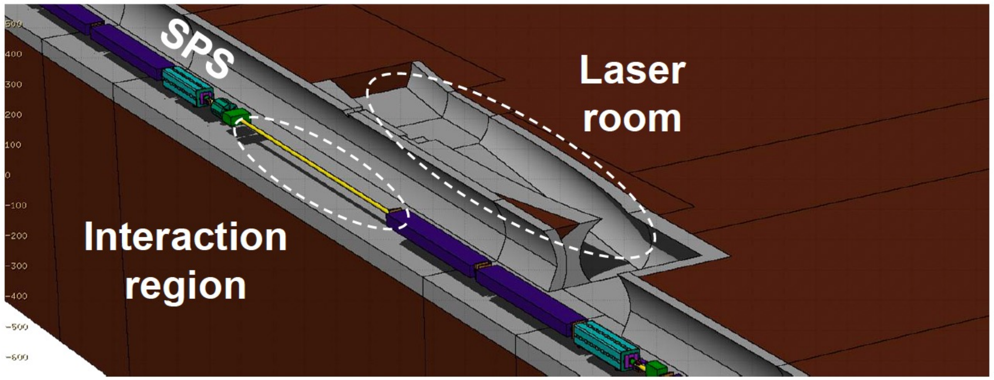
Appl. Phys. Lett. 124, 251105 (2024)

https://doi.org/10.1063/5.0213842 **Article history**

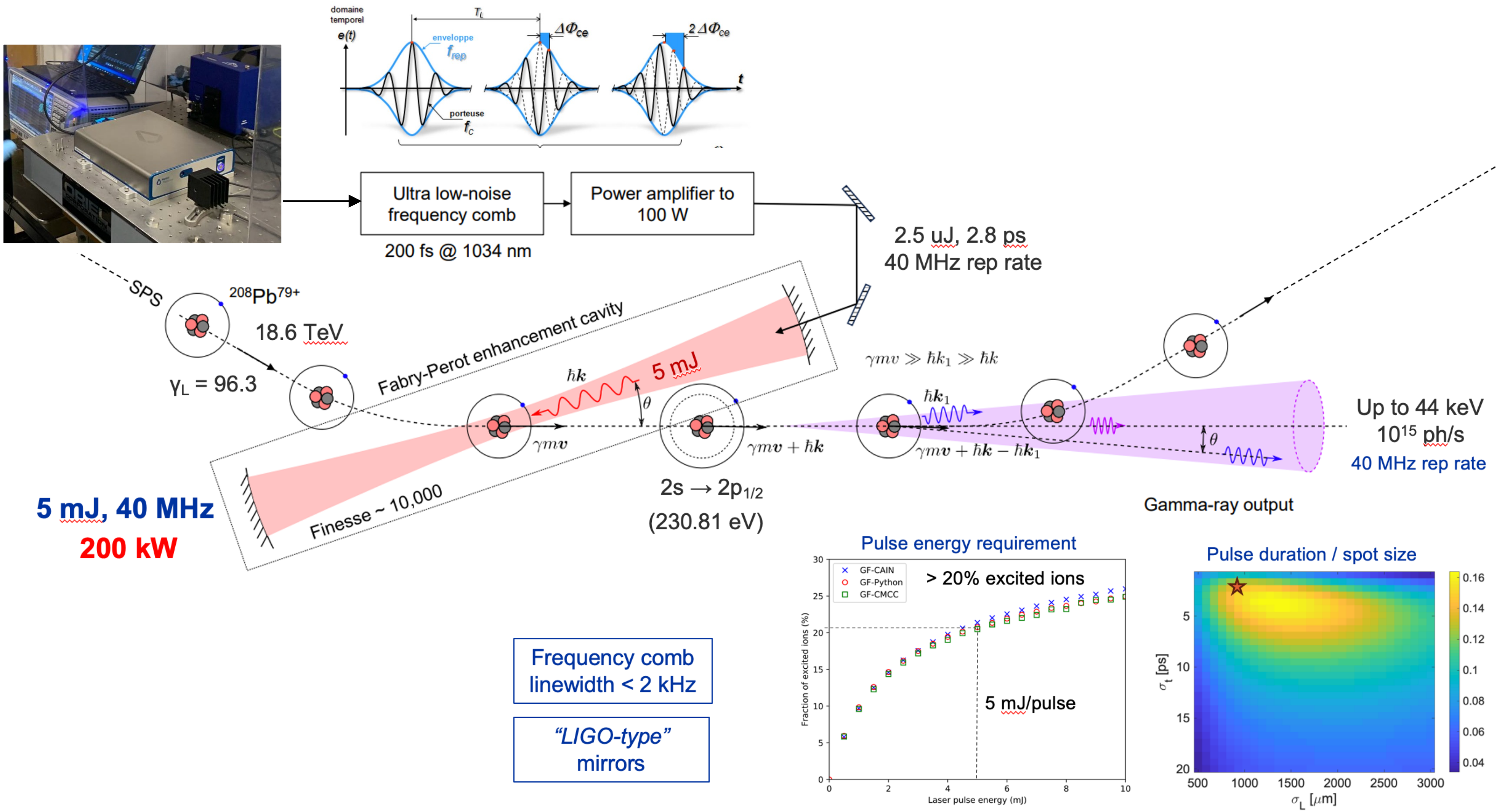
FINAL Step : Gamma Factory Proof-of-Principle experiment





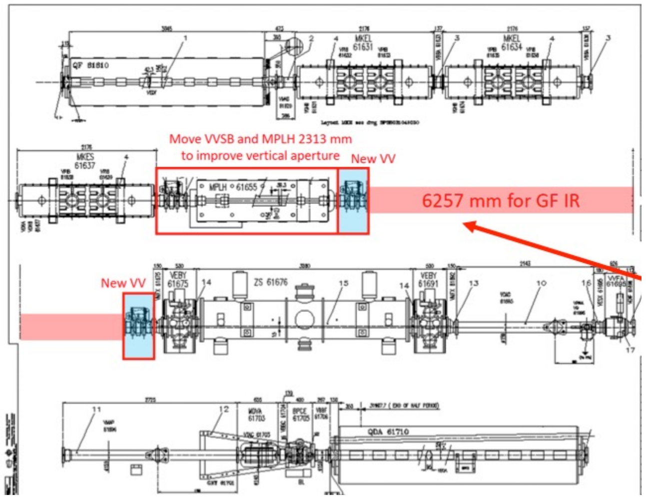


PLANNED INSTALLATION TIME – LS3


domaine temporel
e(t)
enveloppe
f_{rep}
T_L
$\Delta\Phi_{ce}$
$2\Delta\Phi_{ce}$
porteuse
f_c
t
Ultra low-noise frequency comb
Power amplifier to 100 W
200 fs @ 1034 nm
2.5 uJ, 2.8 ps
40 MHz rep rate
SPS
$^{208}Pb^{79+}$
18.6 TeV
γ_L = 96.3
Fabry-Perot enhancement cavity
$\hbar k$
5 mJ
θ
$\gamma m v$
$\gamma m v + \hbar k$
$2s \rightarrow 2p_{1/2}$
(230.81 eV)
Finesse ~ 10,000
5 mJ, 40 MHz
200 kW
$\gamma m v \gg \hbar k_1 \gg \hbar k$
$\hbar k_1$
$\gamma m v + \hbar k - \hbar k_1$
Up to 44 keV
10^{15} ph/s
40 MHz rep rate
Gamma-ray output
Frequency comb linewidth < 2 kHz
"LIGO-type" mirrors
Pulse energy requirement
GF-CAIN
GF-Python
GF-CMCC
> 20% excited ions
5 mJ/pulse
Fraction of excited ions (%)
Laser pulse energy (mJ)
Pulse duration / spot size
σ_t [ps]
σ_L [μm]

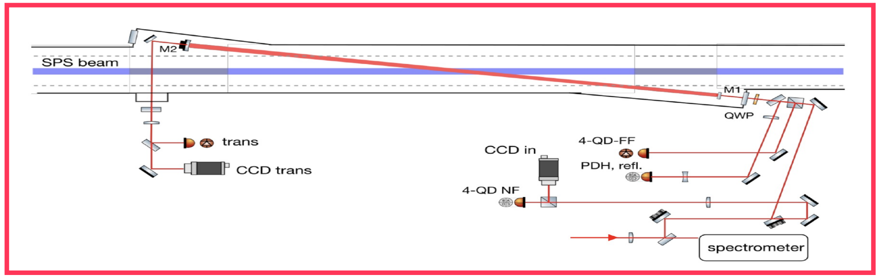
Gamma Factory Proof-of-Principle (PoP) SPS experiment

SPS LSS6 zone

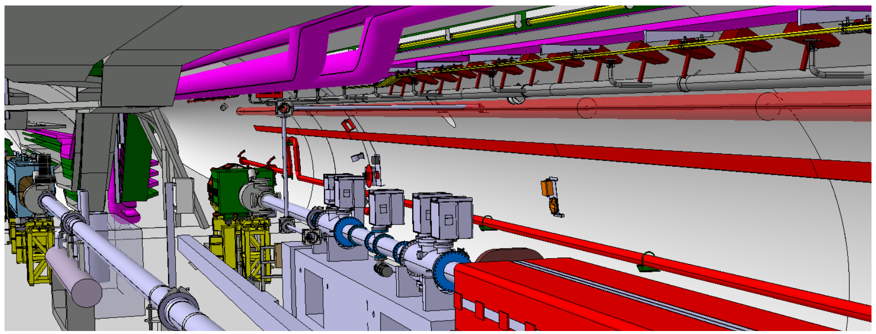


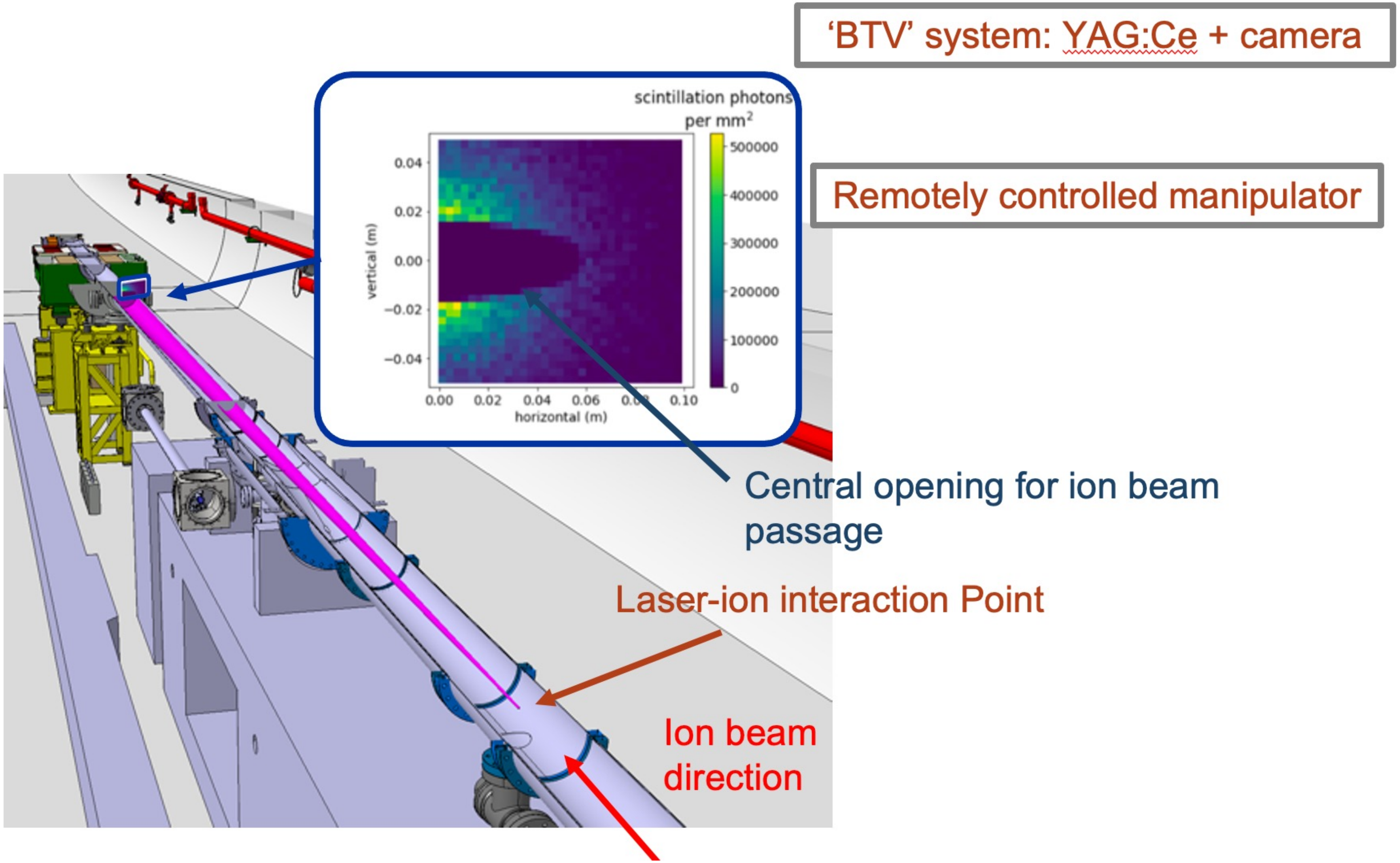
***F-P cavity length – 3.75 m** -- vertically tilted by 2..6 deg*

F-P cavity



F-P cavity – "in beam" position



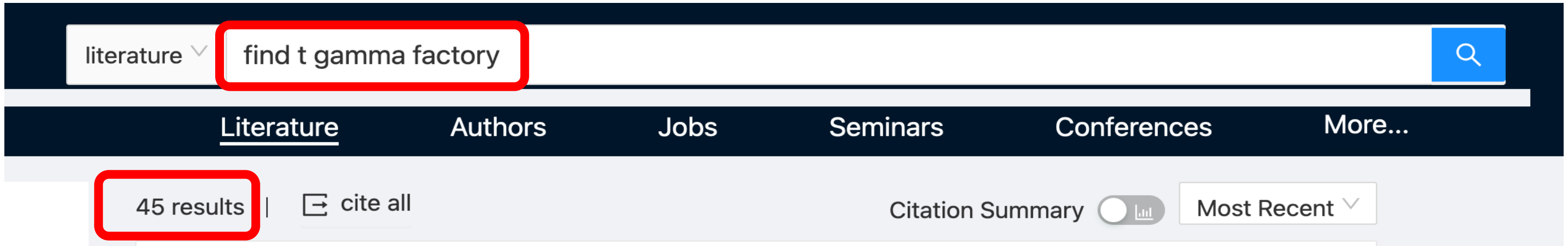


'BTV' system: YAG:Ce + camera
Remotely controlled manipulator
scintillation photons per mm^2
500000
400000
300000
200000
100000
0
0.04
0.02
0.00
−0.02
−0.04
vertical (m)
0.00
0.02
0.04
0.06
0.08
0.10
horizontal (m)
Central opening for ion beam passage
Laser-ion interaction Point
Ion beam direction

Scientific programme – selected examples

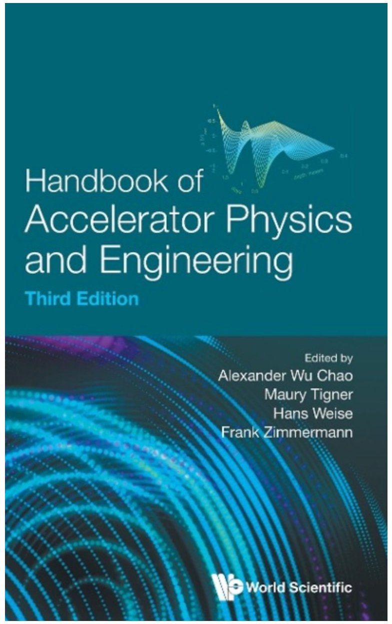
GF studies: published papers (INSPIRE) and books

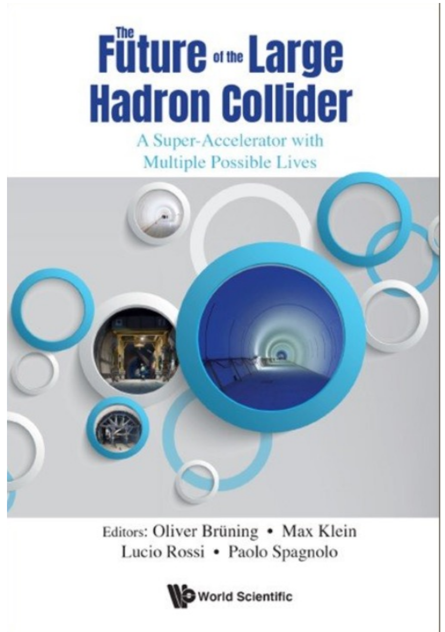
papers



books

Special issue of Annalen der Physik



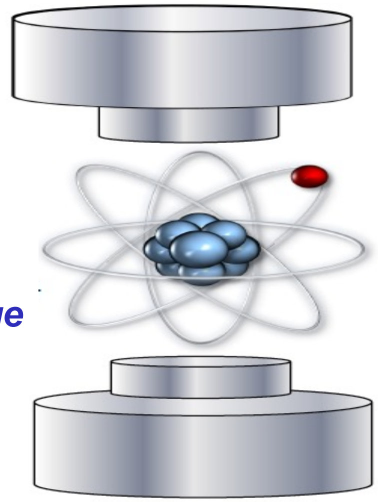


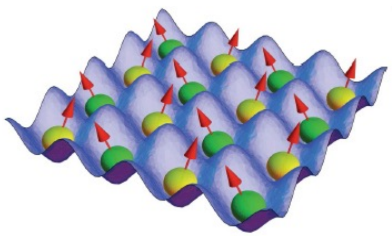
GF experimental programme with atomic beams

Spectroscopy of highly-charged, "small-size" atoms

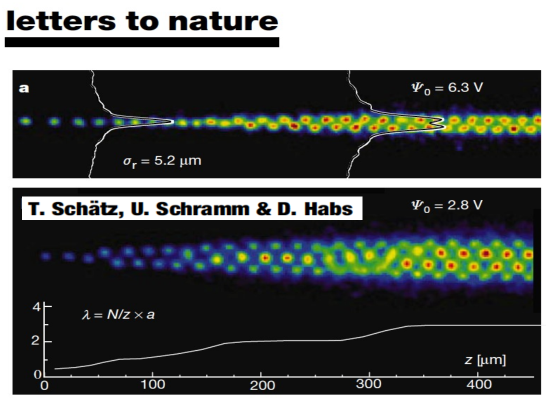
Atomic rest-frame

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





Crystalline beams?



Opening new research opportunities in atomic physics:

- *Highly-charged atoms – very strong (~10^{16} V/cm) electric field (QED-vacuum effects)*
- *Small size atoms (electroweak effects, $\sin^2\theta_W$, …*
- *Hydrogen-like and Helium-like atomic structure (calculation precision and simplicity)*
- *Atomic degrees of freedom of trapped highly-charged atoms can be resonantly excited by lasers*


adp annalen der physik

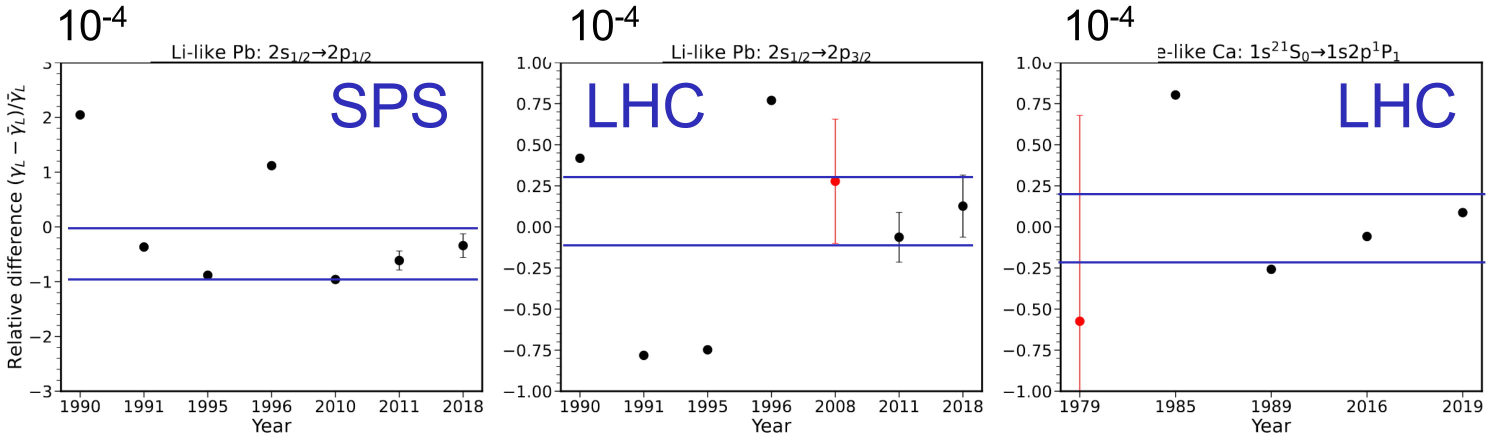
Feature Article | Open Access

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

First published: 09 July 2020 | https://doi.org/10.1002/andp.202000204

Gamma Factory offers an unprecedented precision of the absolute energy (γ_L) calibration of the SPS and LHC beams

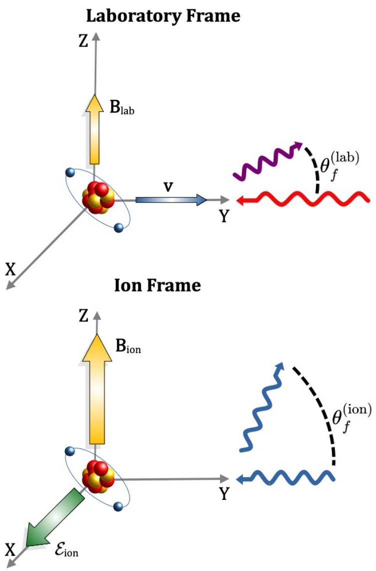


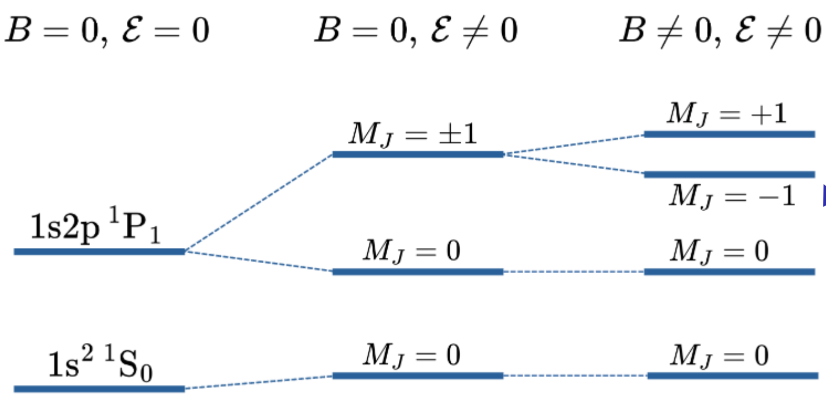
Jan Richter, Preliminary

- Present calibration uncertainty (LHC) – 10^{-3}
- Gamma Factory < 2×10^{-4}

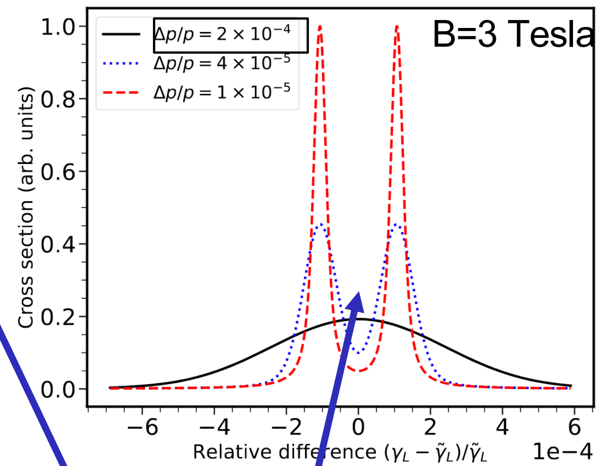
(limited only by the precision of the calculation of the transition energies in H-like, He-like and Li-like atoms)

… and very precise control of their momentum spread (FP cavity in the dipole magnet)





Jan Richter, Preliminary



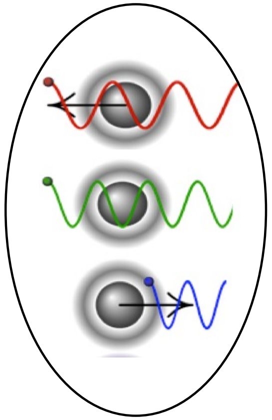
Controlling the Resonant Scattering Process of Photons on Relativistic Ion Beams Using Strong External Electromagnetic Fields

Jan Richter,[1,2,*] Mieczyslaw Witold Krasny,[3,4] Jan Gilles,[1,5] and Andrey Surzhykov[1,5]
[1]*Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany*
[2]*Institut für Theoretische Physik, Leibniz Universität Hannover, Appelstraße 2, 30167 Hannover, Germany*
[3]*LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Tour 33, RdC, 4, pl. Jussieu, 75005 Paris, France*
[4]*CERN, BE-ABP, 1211 Geneva 23, Switzerland*
[5]*Institut für Mathematische Physik, Technische Universität Braunschweig, Mendelssohnstrasse 3, D-38106 Braunschweig, Germany*

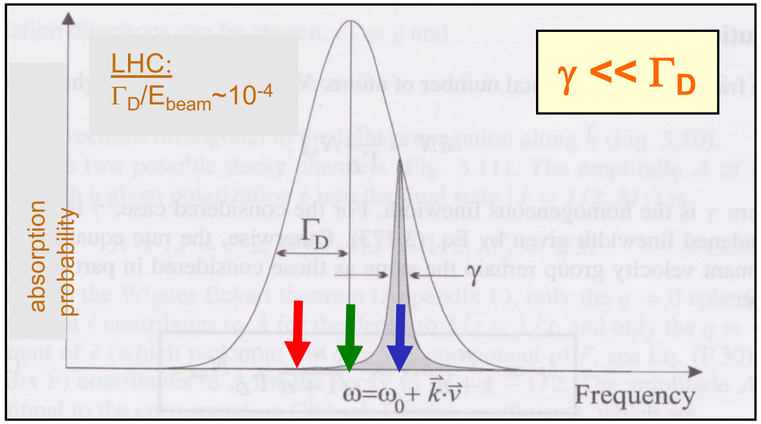
… to be published

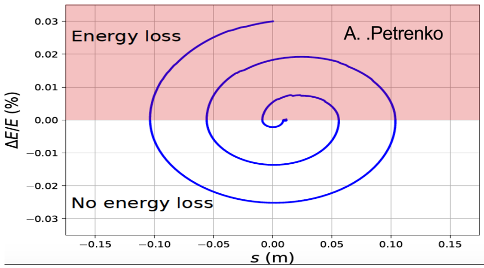
Observing Zeman splitting of the M_j = +/-1 sublevels of the excited He-like Ca atoms allows us to control the degree of cooling of the LHC beam

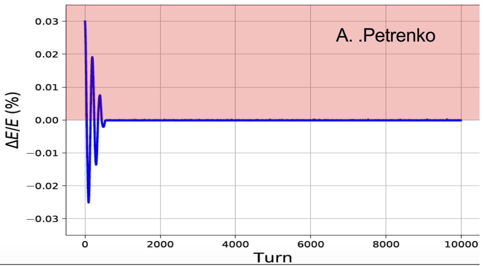
Gamma Factory "cold" atomic beams



Bunch

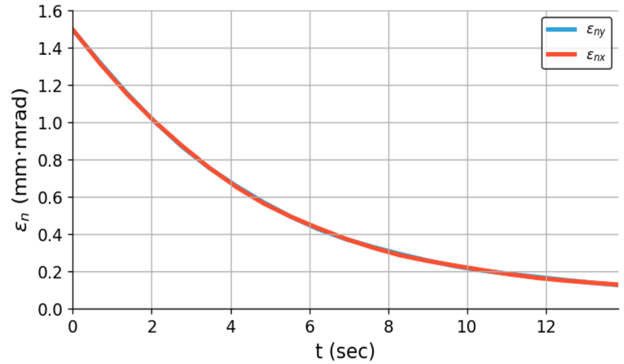






Beam cooling speed: *the laser wavelength band is chosen such that only the ions moving in the laser pulse direction (in the bunch rest frame) can resonantly absorb photons.*

Opens a possibility of forming at CERN hadronic beams of the required longitudinal and transverse emittances within a seconds-long time scale



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

High-luminosity Large Hadron Collider with laser-cooled isoscalar ion beams

M.W. Krasny (Paris U., VI-VII and CERN), A. Petrenko (CERN and Novosibirsk, IYF), W. Płaczek (Jagiellonian U.) (Mar 25, 2020)

Published in: *Prog.Part.Nucl.Phys.* 114 (2020) 103792 • e-Print: 2003.11407 [physics.acc-ph]

Gamma Factory (complementary) path to HL-LHC:

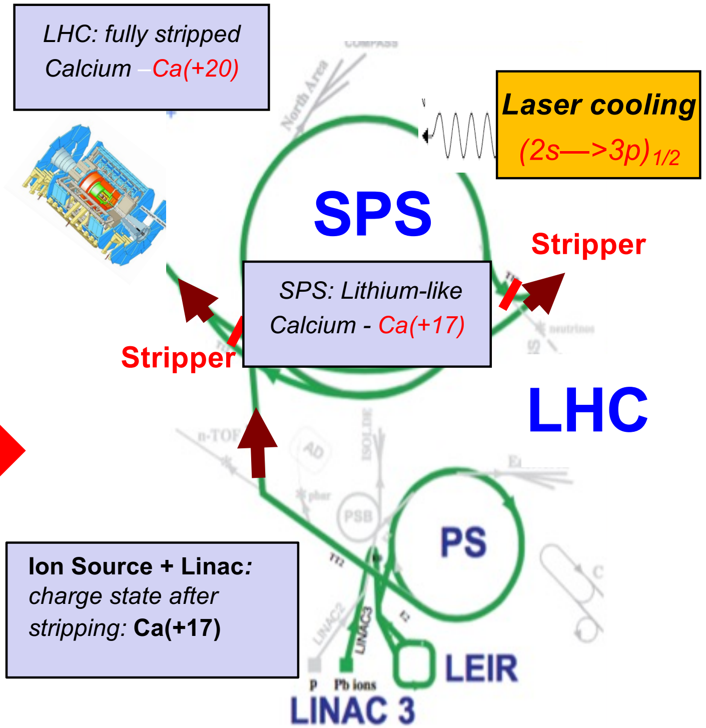
Studies of the implementation scheme with laser-cooled isoscalar Ca beams

$$\mathscr{L} = f \frac{n_1 n_2}{4\pi \sqrt{\epsilon_x \, \beta_x^* \, \epsilon_y \, \beta_y^*}}$$

Two complementary *ways to* ***increase*** *collider* ***luminosity*** *for fixed n_1,n_2,and f :*

- **reduce** β_x^* and β_y^*
- **reduce** ε_x and ε_y

HL-LHC – *β^* reduction by a factor of 3.7 (new inner triplet)*



Reduction of the transverse x,y, emittances by a factor of 5 can be achieved in 9 seconds (top SPS energy)

The merits of cold isoscalar beams

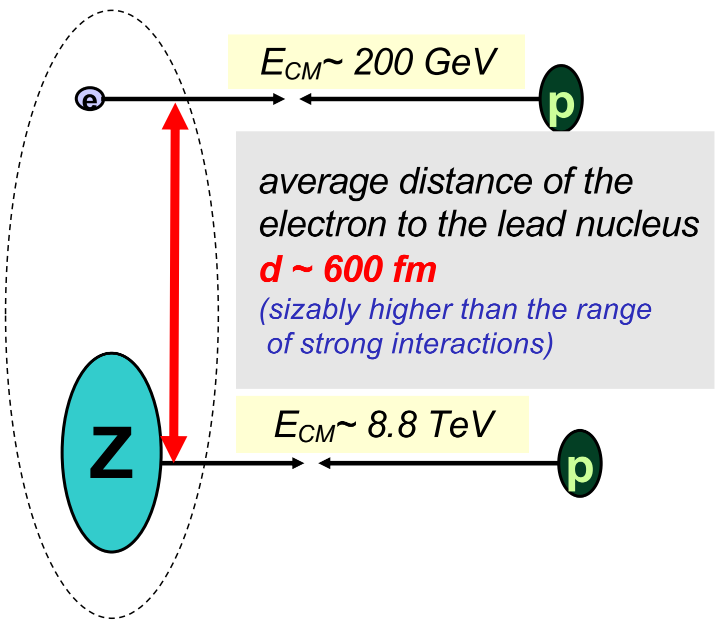
- *higher precision in measuring SM parameters in CaCa than in pp collisions*
- *Possible unique access to exclusive Higgs boson production in photon–photon collisions?*
- *Lower pileup background at equivalent nucleon-nucleon (partonic) luminosity.*
- *New research opportunities for the EW symmetry breaking sector.*

If necessary: *add optical stochastic cooling time for the Ca beam at the LHC top energy t_{cool} ~1.5 hours* ***(V. Lebedev)***

ep collisions at LHC

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

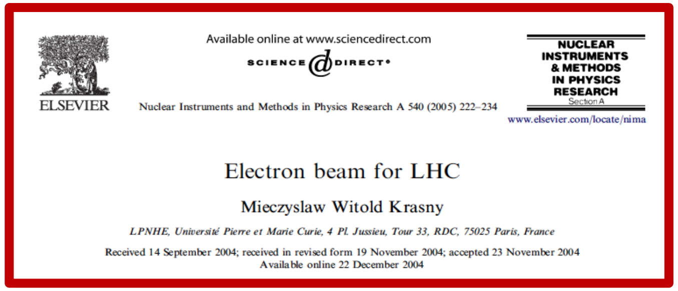
Hydrogen-like lead



*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:



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Electron beam for LHC

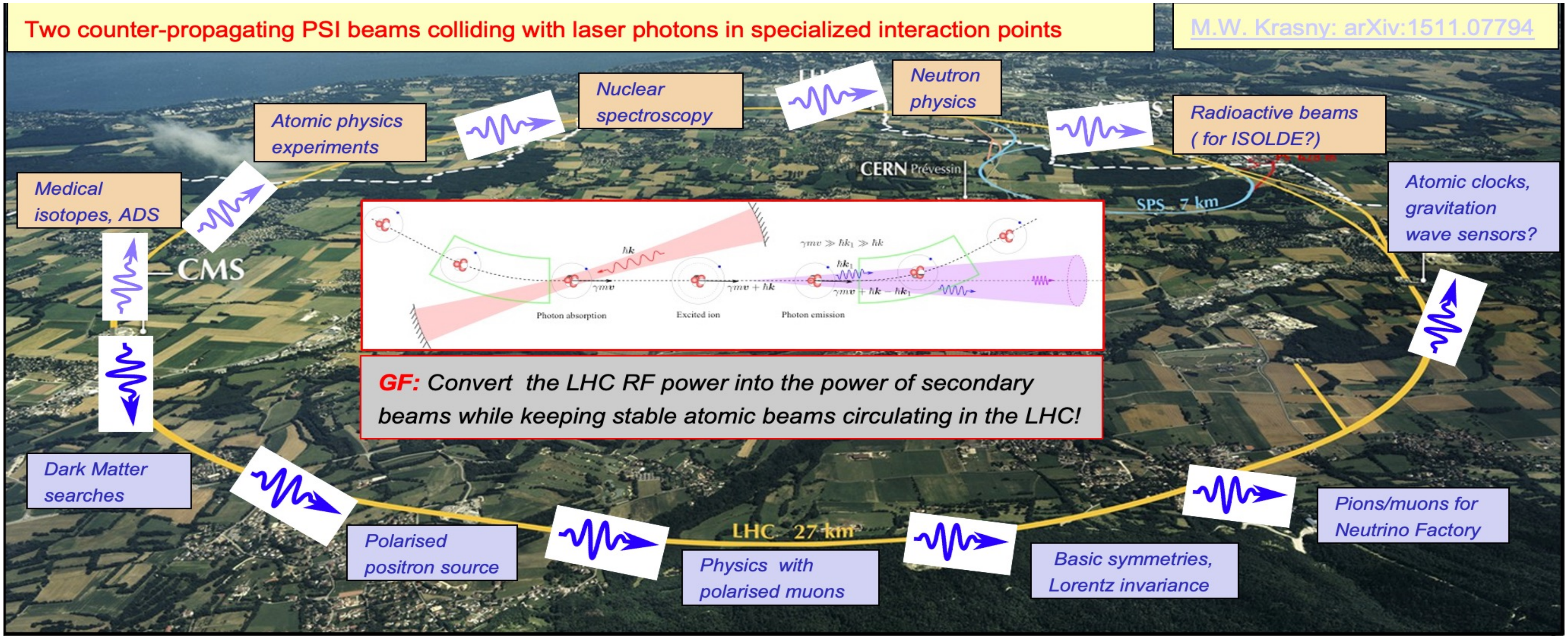
Mieczyslaw Witold Krasny

LPNHE, Université Pierre et Marie Curie, 4 Pl. Jussieu, Tour 33, RDC, 75025 Paris, France

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

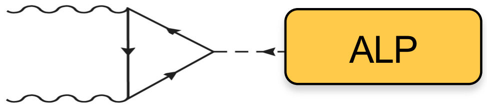
GF experimental programme with high intensity photon beams

… the GF-future of the LHC?

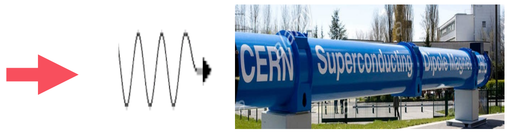


DM searches and studies (if discovered), ALP example

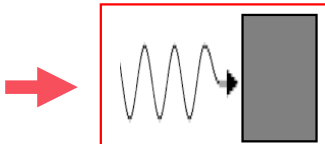
Collision schemes for ALP production:



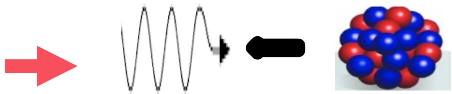
Search phase



γ_{GF} – **B field**
$m_{ALP} < 1$ keV



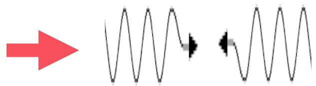
γ_{GF} – A **collisions** (beam dump)
$m_{ALP} \sim 1$ keV – 10 MeV



γ_{GF} – A **collisions** (LHC)
$m_{ALP} \sim 10$ MeV – 10 GeV

"Production" phase

$\gamma_{GF} - \gamma_{Laser}$ **collisions**
$m_{ALP} \sim 1$–100 keV



$\gamma_{GF} - \gamma_{GF}$ **collisions** (LHC)
$m_{ALP} \sim 100$ keV – 800 MeV

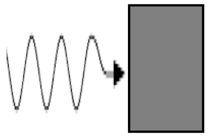
Concurrent, rich QED programme (e.g. vacuum birefringence studies)

Three principal advantages of the Gamma Factory photon beams:

- ***Large fluxes**: ~10^{25} photons on target over year (SHIP – 10^{20} protons on target)*
- ***Multiple ALP production schemes** covering a vast region of ALP masses **(sub eV – GeV)***
- ***Once** ALP candidate **seen** → a unique possibility to **tune** the GF beam **energy** to the **resonance**.*

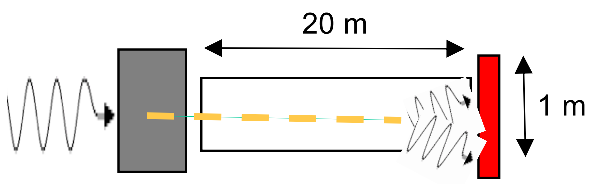
DM searches and studies (ALP example)

Search phase
Example: beam-dump mode

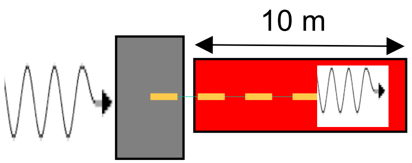


γ_{GF}–A *collisions*
1.6, 0.2, 0.02 GeV
beams (A,B,C)

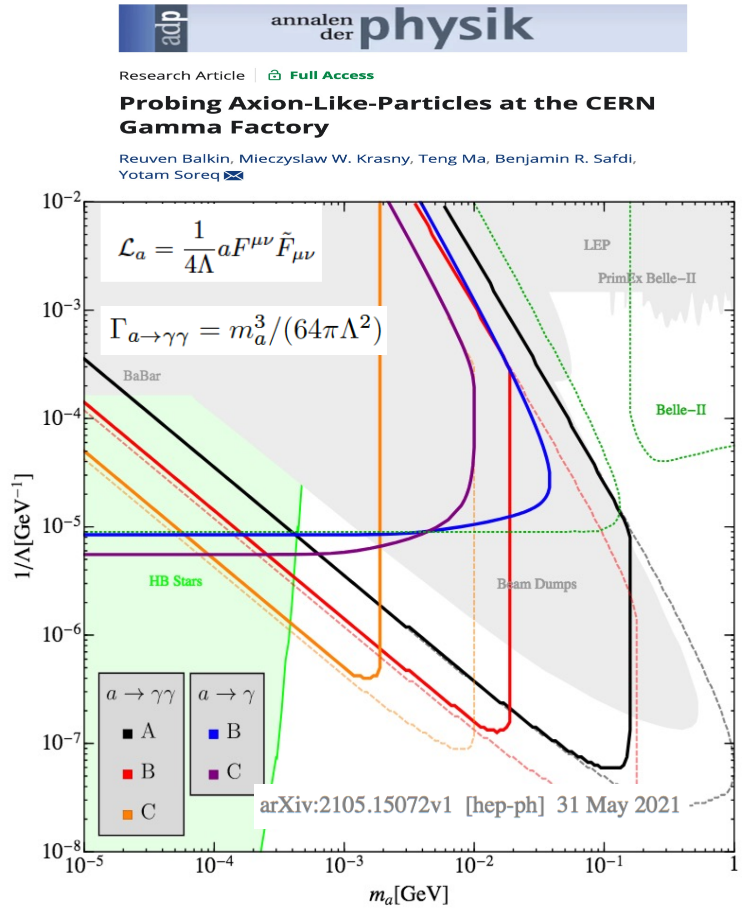
Two appearance modes:



- *decay: a □$\gamma\gamma$ (A,B,C)*



- *reconversion: aN □γN (B,C)*



DM searches and studies (dark photon example)

PHYSICAL REVIEW D
covering particles, fields, gravitation, and cosmology

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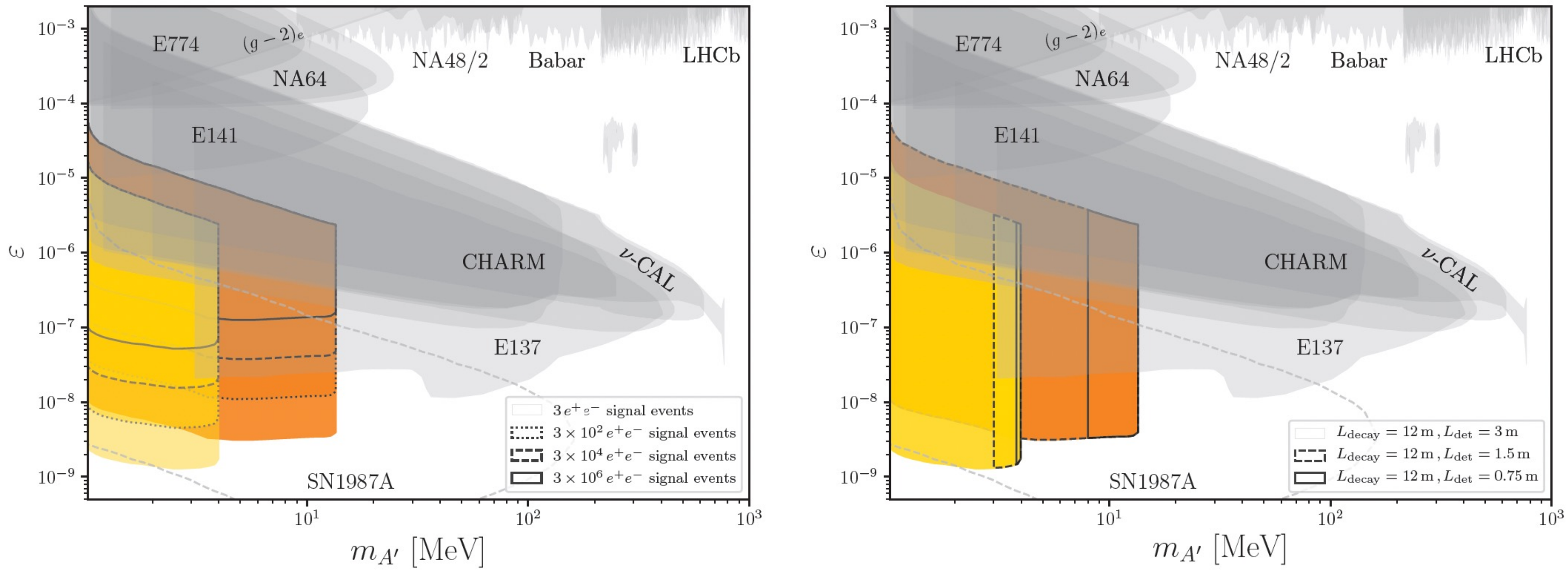
Gamma factory searches for extremely weakly interacting particles

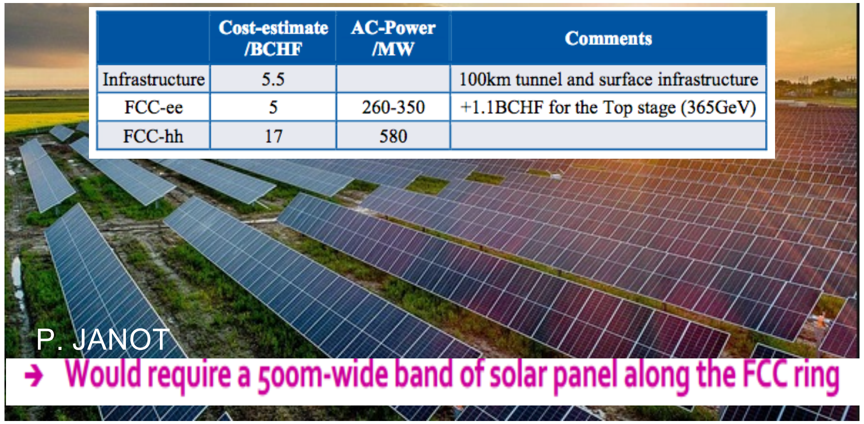
Sreemanti Chakraborti, Jonathan L. Feng, James K. Koga, and Mauro Valli

Phys. Rev. D **104**, 055023 – Published 21 September 2021



Photon-beam-driven energy source

Best use of the CERN expertise to produce rather than buy the plug-power:



	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	

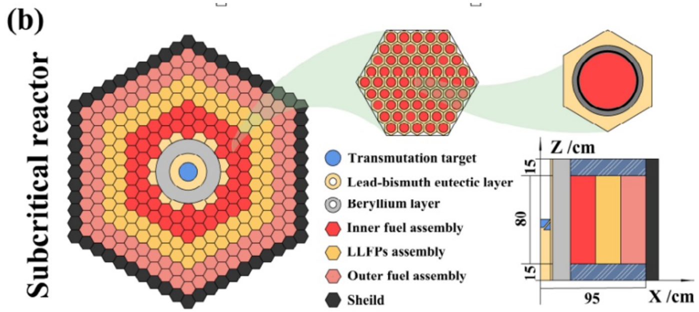
➔ Would require a 500m-wide band of solar panel along the FCC ring

➔ Would require 500 such turbines (one every 200m) along the FCC ring

GF- Photon-beam-driven energy source (ADS)

Satisfying three conditions;

- 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 **Accelerate Solving Energy Crisis: From Fission to Fusion**
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

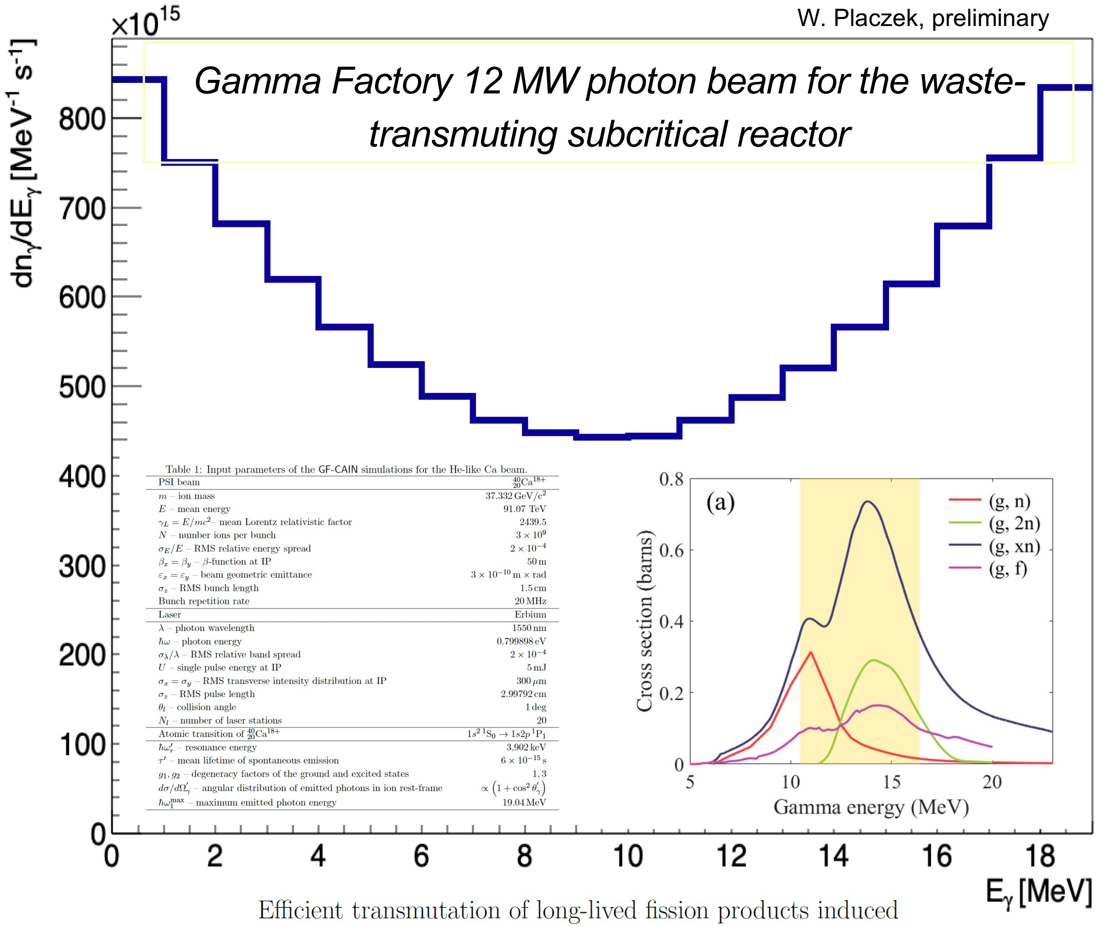


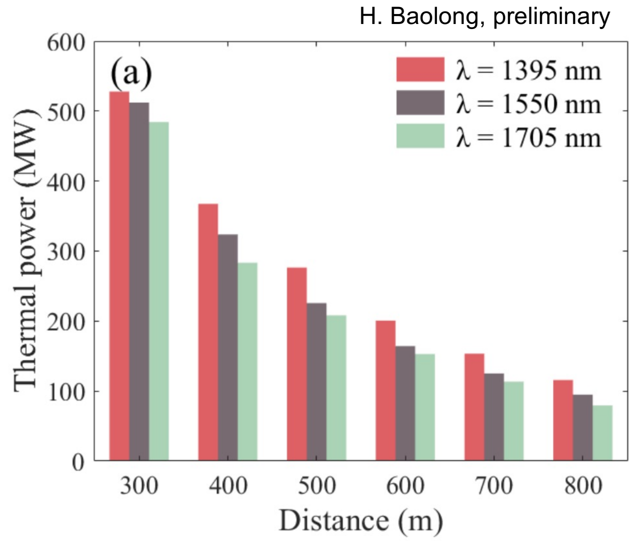
Table 1: Input parameters of the GF-CAIN simulations for the He-like Ca beam.

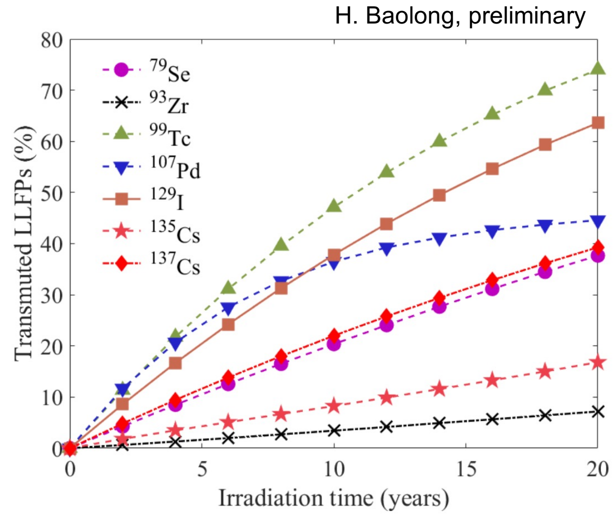
PSI beam	$^{40}_{20}Ca^{18+}$
m – ion mass	37.332 GeV/c^2
E – mean energy	91.07 TeV
$\gamma_L = E/mc^2$ – mean Lorentz relativistic factor	2439.5
N – number ions per bunch	3×10^9
σ_E/E – RMS relative energy spread	2×10^{-4}
$\beta_x = \beta_y$ – β-function at IP	50 m
$\varepsilon_x = \varepsilon_y$ – beam geometric emittance	3×10^{-10} m × rad
σ_z – RMS bunch length	1.5 cm
Bunch repetition rate	20 MHz
Laser	Erbium
λ – photon wavelength	1550 nm
$\hbar\omega$ – photon energy	0.799898 eV
σ_λ/λ – RMS relative band spread	2×10^{-4}
U – single pulse energy at IP	5 mJ
$\sigma_x = \sigma_y$ – RMS transverse intensity distribution at IP	300 μm
σ_z – RMS pulse length	2.99792 cm
θ_l – collision angle	1 deg
N_l – number of laser stations	20
Atomic transition of $^{40}_{20}Ca^{18+}$	$1s^2\,{}^1S_0 \to 1s2p\,{}^1P_1$
$\hbar\omega'_r$ – resonance energy	3.902 keV
τ' – mean lifetime of spontaneous emission	6×10^{-15} s
g_1, g_2 – degeneracy factors of the ground and excited states	1, 3
$d\sigma/d\Omega'_\gamma$ – angular distribution of emitted photons in ion rest-frame	$\propto \left(1 + \cos^2\theta'_\gamma\right)$
$\hbar\omega_1^{max}$ – maximum emitted photon energy	19.04 MeV

Efficient transmutation of long-lived fission products induced by Gamma Factory γ-ray beams

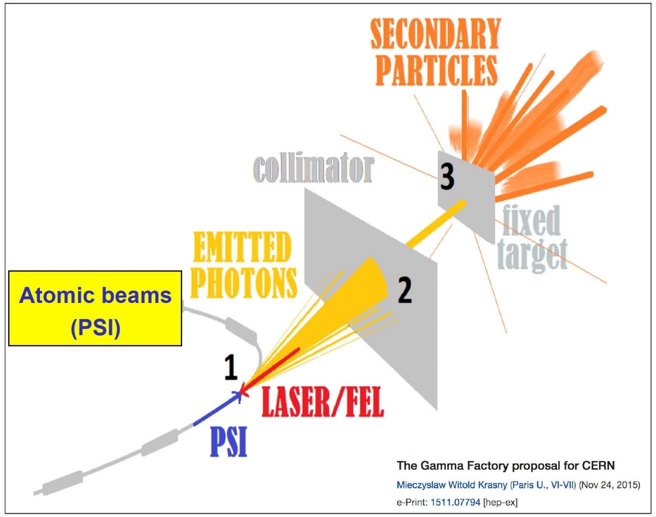
Baolong Hu[1,2], Wiesław Płaczek[3], Wen Luo[1,2*], Mieczyslaw Witold Krasny[4,5*], Xinxiang Li[1], Yun Yuan[1], Zhichao Zhu[1], Xiaoming Shi[1], Kaijun Luo[1]

… to be published





GF experimental programme with secondary beams



- ***Polarised positrons*** – *potential gain of up to a factor of 10^4 in intensity with respect to the KEK positron source, satisfying both the LEMMA muon–collider and the LHeC requirements*

- ***Muons*** – *potential gain by a factor of 10^3 in intensity with respect to the PSI muon source, charge symmetry ($N\mu^+ \sim N\mu^-$), polarisation control*

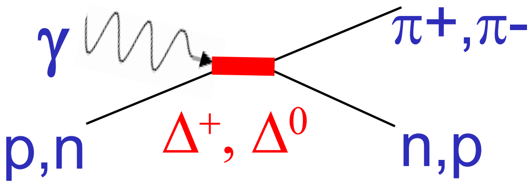
- ***Neutrinos*** – *fluxes comparable to NuMAX but: (1) Very Narrow Band Beam, driven by the small spectral density pion beam and (2) unique possibility of creating flavour- and CP-tuned beams driven by the beams of polarised muons*

- ***Neutrons*** – *a comparable neutron flux with respect to the future neutron spallation sources e.g. at ESS – but quasi monoenergetic MeV neutrons*

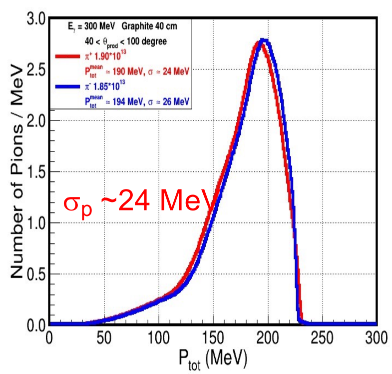
- ***Radioactive (neutron-rich) ions*** – *potential gain of up to a factor 10^4 in intensity with respect to e.g. ALTO*

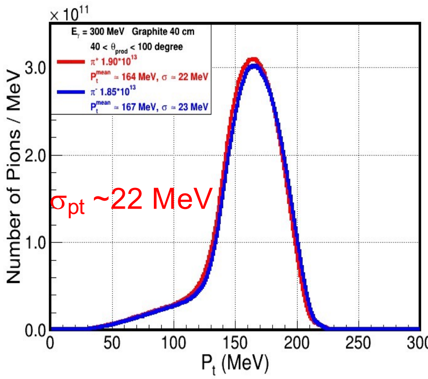
Novel paradigm for high brightness **μ and ν sources**:

resonant photo-excitation of Δ resonances



Exclusive process:
unprecedented spectral density of produced pions





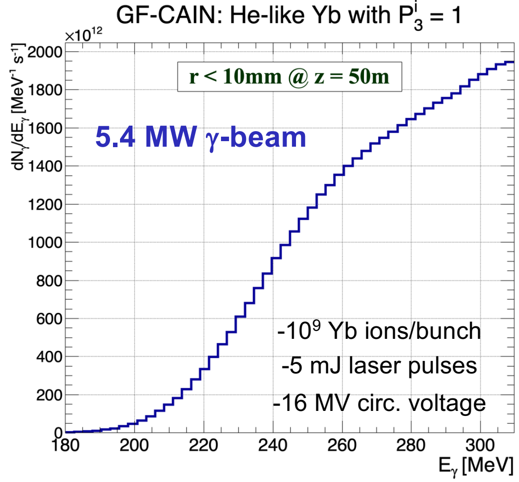
Muons	$r_\gamma \le$ 5mm	$r_\gamma \le$ 10mm
μ^-	2.32×10^{13} s^{-1}	6.18×10^{13} s^{-1}
μ^+	2.50×10^{13} s^{-1}	6.79×10^{13} s^{-1}

GF photon beam

For 1X0 **graphite** target
2-7 x 10^{13} μ^+ and μ^-/s,
for 2-6 MW γ beam

Expected intensity jump with respect to HiMB@PSI prospects >2025 – **1.2 x 10^{11}** μ+/s

GF, He-like
Yb-driven γ-beam



PHYSICAL REVIEW ACCELERATORS AND BEAMS **26,** 083401 (2023)

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

Armen Apyan,[1,*] Mieczyslaw Witold Krasny,[2,3] and Wiesław Płaczek[4]

[1]*A. Alikhanyan National Laboratory (AANL), 2 Alikhanian Brothers St., 0036 Yerevan, Armenia*
[2]*LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Tour 33, RdC, 4, pl. Jussieu, 75005 Paris, France*
[3]*CERN, BE-ABP, 1211 Geneva 23, Switzerland*
[4]*Institute of Applied Computer Science and Mark Kac Center for Complex Systems Research, Jagiellonian University, ul. Łojasiewicza 11, 30-348 Krakow, Poland*

The potential use of the Gamma Factory muon source:

- *Muonium studies*
- *Lepton universality*
- *Rare muon decays*
- *Neutrino factory*
- *Muon-catalysed nuclear fusion*
- *Atomic physics studies of muonium atoms*
- *Electroweak studies with muon atoms*
- *Measuring nuclear radius and neutron skin*
- *Muon collider??? –*

Conclusions and outlook

- *Gamma Factory can create, at CERN, a variety of novel research tools, which could open novel research opportunities in a very broad domain of basic and applied science*

- *The Gamma Factory research programme can be largely based on the existing CERN accelerator infrastructure – it requires "relatively" minor infrastructure investments*

- *Its "quest for diversity of research subjects and communities" is of particular importance in the present phase of accelerator-based research, as we neither have any solid theoretical guidance for a new physics "just around the corner", accessible by FCC, ILC, or CLIC, nor an established "reasonable cost" technology for a leap into very high energy " terra incognita"*

- *Gamma Factory project needs to make the last step in R&D studies and demonstrate its feasibility by the SPS GF-Proof-of-Principle experiment prior to reaching advanced phase of the HL-LHC programme – the CERN management and wide scientific community support for this project is a "sine qua non" condition for its further development*