Gamma Factory

New research opportunities for CERN

Kyaik-Tiyo, Myanmar(Burma)

JLAB, April 2022

Mieczyslaw Witold Krasny, Gamma Factory group leader

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

Introduction

“*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.

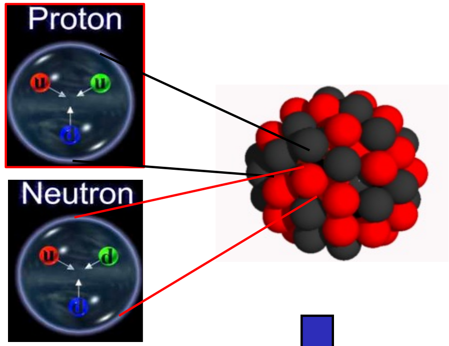
More info on all the GF group activities:

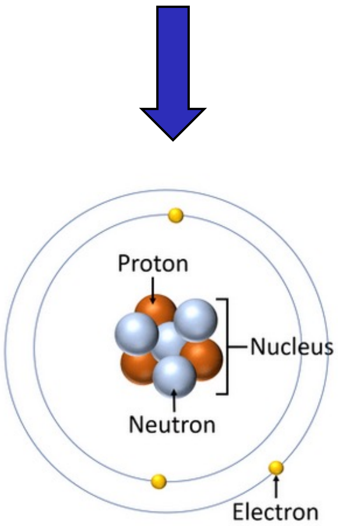
https://indico.cern.ch/category/10874

*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!*

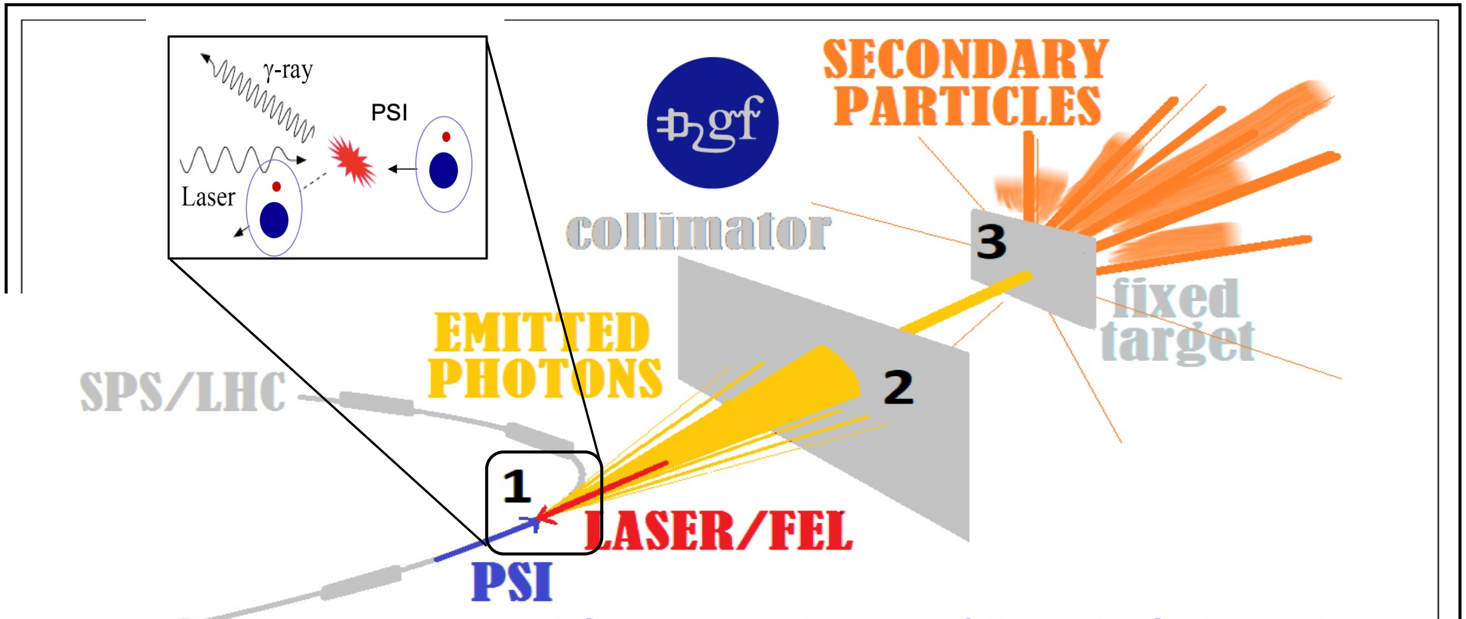
Gamma Factory beams

LHC beams



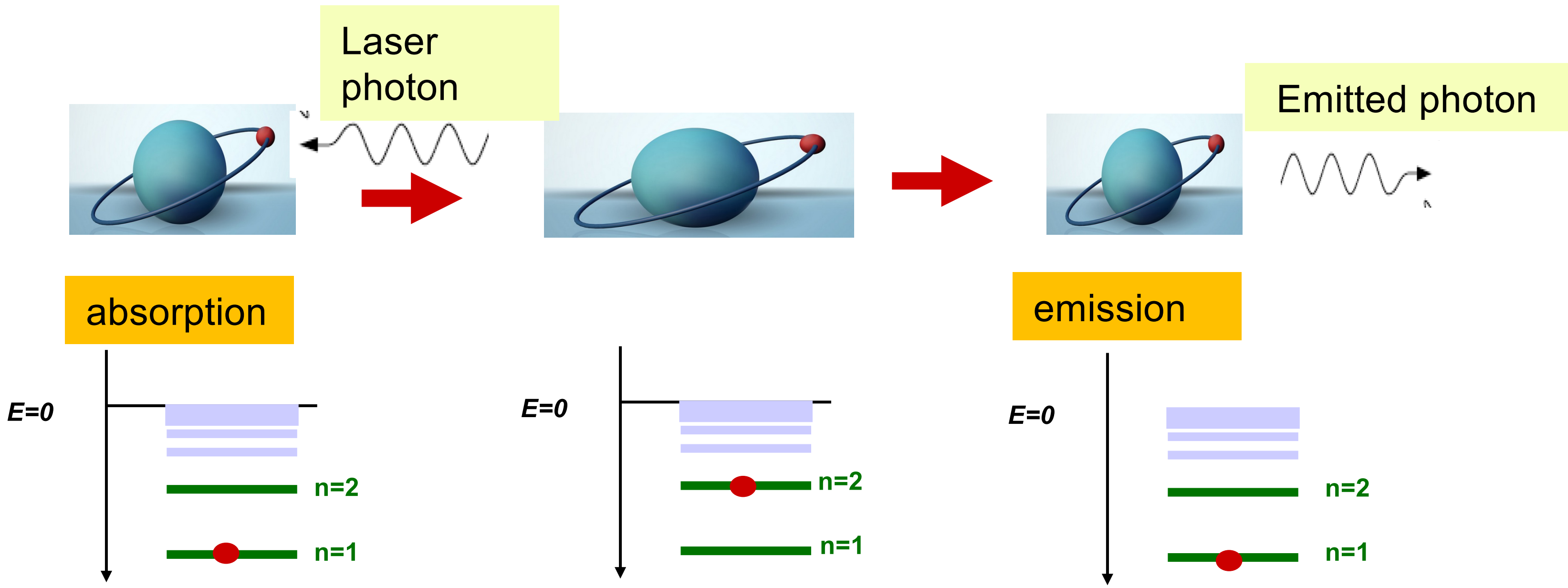


- *Include **atomic beams of partially stripped ions** in the LHC menu*
- *Collide them with laser pulses (circulating in Fabry-Pérot resonators) to **produce beams of polarized photons** and secondary beams of polarized electrons, positrons, muons, neutrons and radioactive ions*



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

Absorption and emissions of photons by **atoms**



Let's accelerate an atom to a relativistic velocity: v ~ c

Gamma Factory photon source: energy leap

Relativistic, high kinetic energy atoms play the role of **passive light-frequency converters**:

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

…for the photon emitted in the direction of the moving atom

Need γ larger than ~1000 to convert visible light photons into gamma rays

(presently only CERN can deliver atomic beams of Partially Stripped Ions (PSI) of such a high energy)

Gamma Factory photon source: intensity leap

Electrons:

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

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

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

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

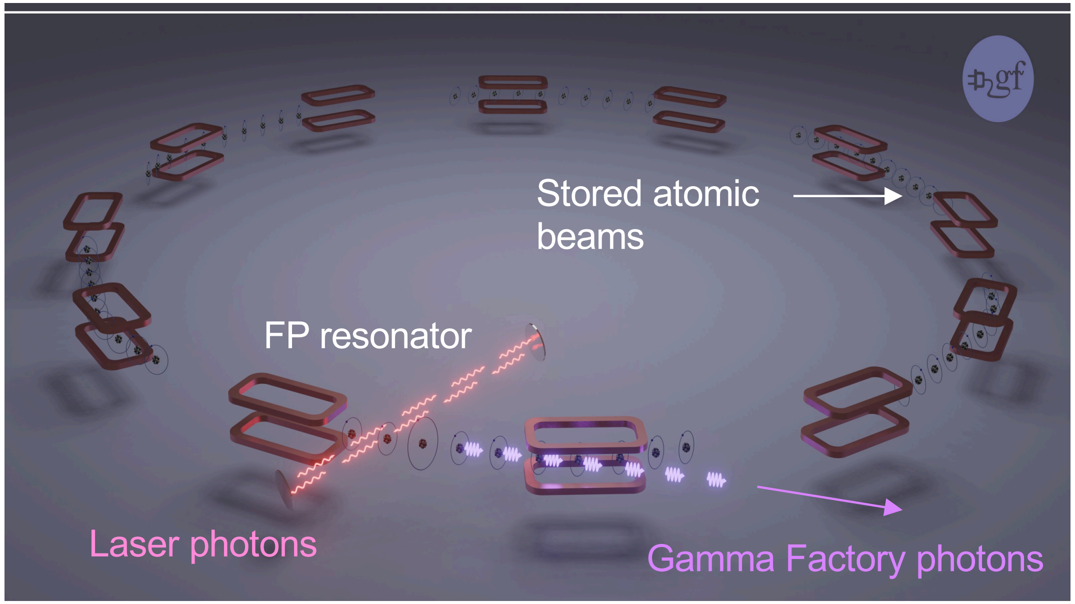
PSI beams:

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

Gamma Factory photon source: operation mode

Requirements for the MW power, GF photon source:

LHC-stored bunches of ~10^8-10^9 partially stripped atoms, ~20 MHz frequency, ~5 mJ laser photon pulses stacked in 20 MHz, Fabry-Perot resonator



The Gamma Factory can deliver fluxes of up to 10^{17} photons/second (upgradable) ... using the present CERN accelerator infrastructure, and commercially available lasers.

Giga barn cross section of the resonant photon absorption -- each ion can emit several photons while colliding with a photon pulse!

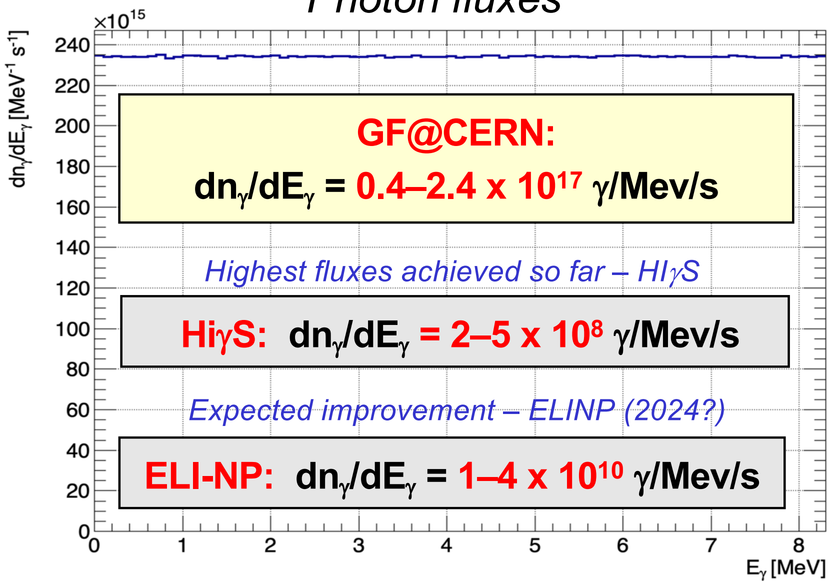
An intensity jump by >7 orders of magnitude

N_A = 6,023·10^{23}

Gamma Factory megawatt photon beams ~ 10^{23} γ/day

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

Photon fluxes

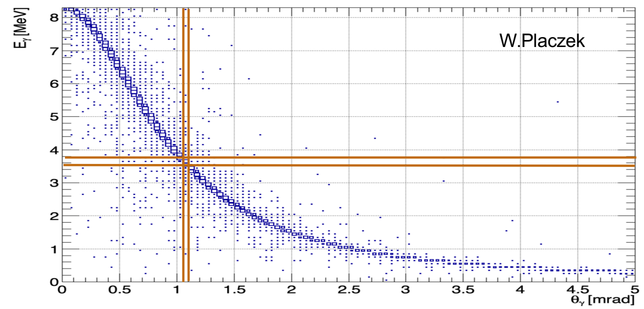


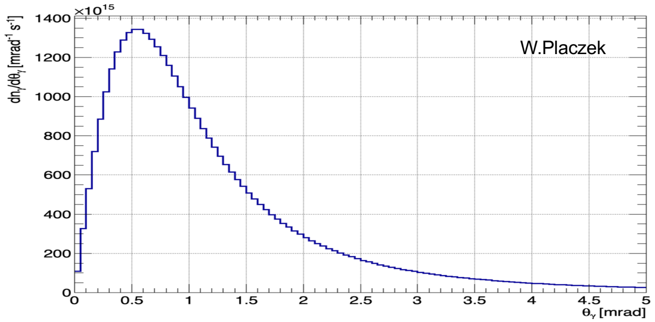
laser pulse parameters

- 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.

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*





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%**

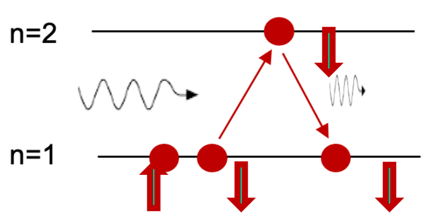
5. Unprecedented plug power efficiency (energy footprint):

- ***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)

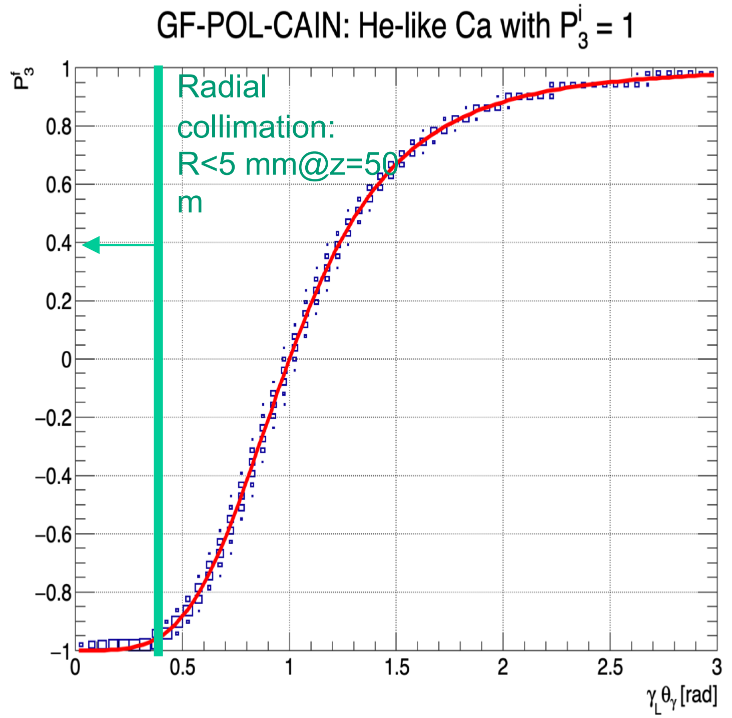
Polarised beams in GF – example: He-like, Calcium beam, Er:glass laser (1522 nm)

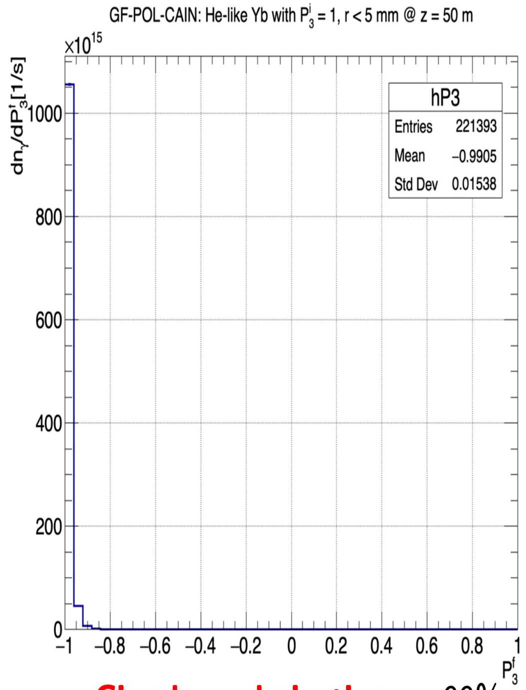
A trick: $1s^2\ {}^1S_0 \rightarrow 1s^1\ 2p^1\ {}^1P_1$ transition in He-like atoms



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

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

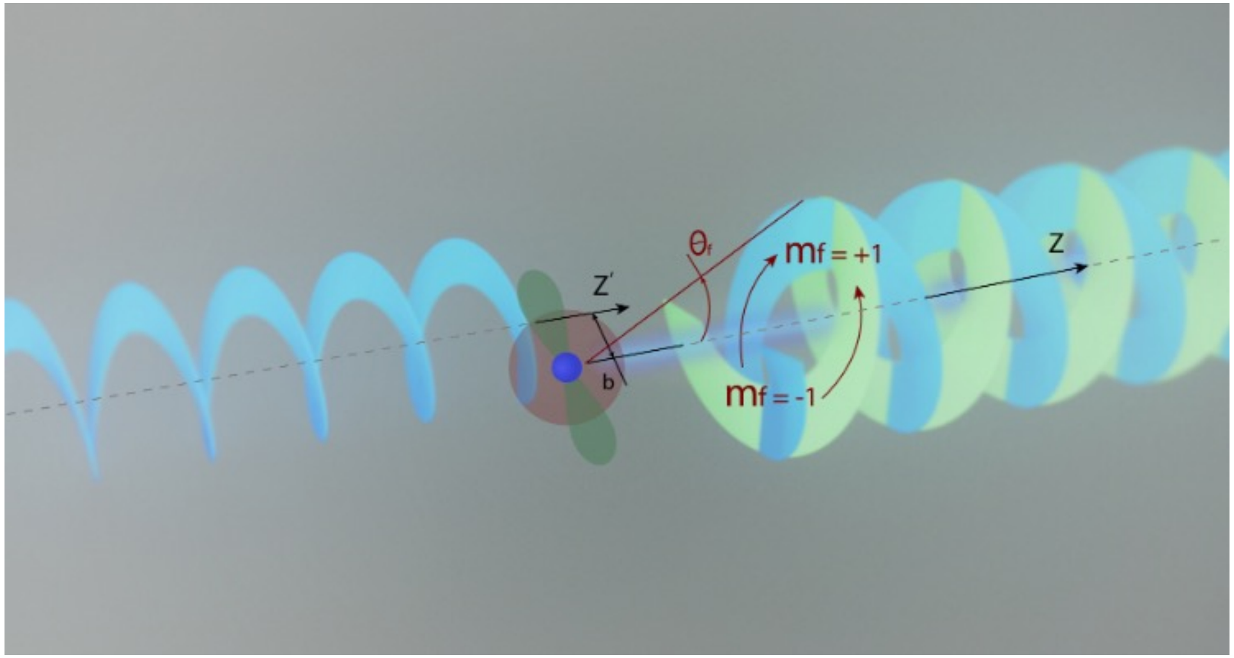




$\rightarrow$ **Circular polarization** $\approx 99\%$

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

Gamma Factory twisted photons



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

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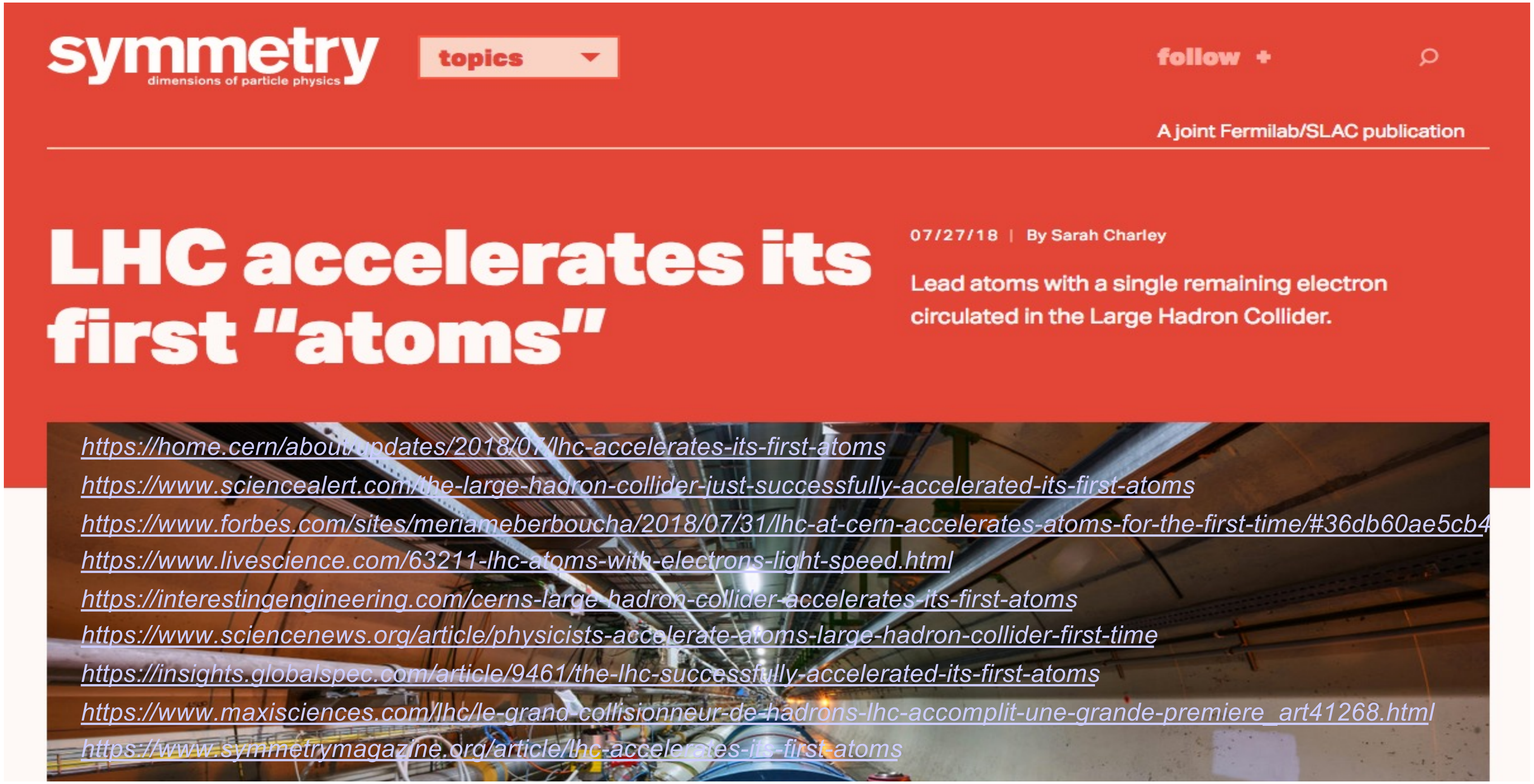
Laboratory for Emerging Nanometrology Braunschweig, D-38106 Braunschweig, Germany

Andrey Volotka
School of Physics and Engineering, ITMO University, RUS–199034, Saint-Petersburg, Russia

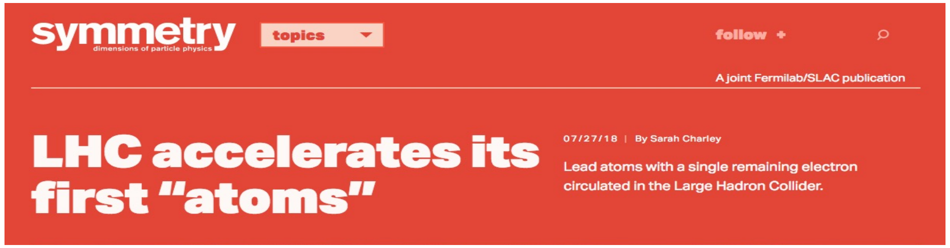
Proof of Principle

Decisive beam tests



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

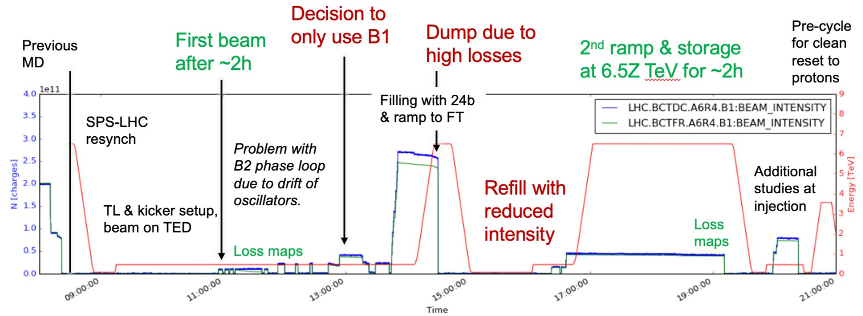
Atomic beams in the LHC (Hydrogen-like Lead)


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

CERN-ACC-NOTE-2019-0012

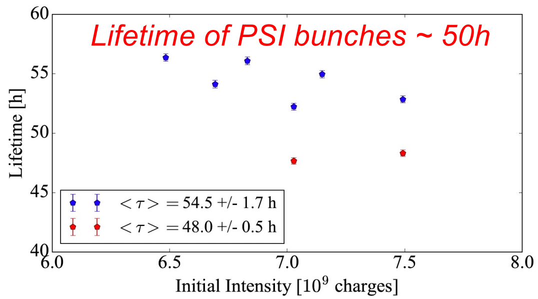
8 May 2019

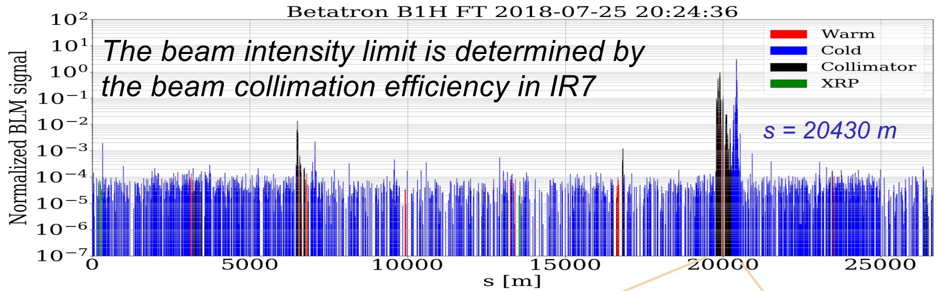
Michaela.Schaumann@cern.ch

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

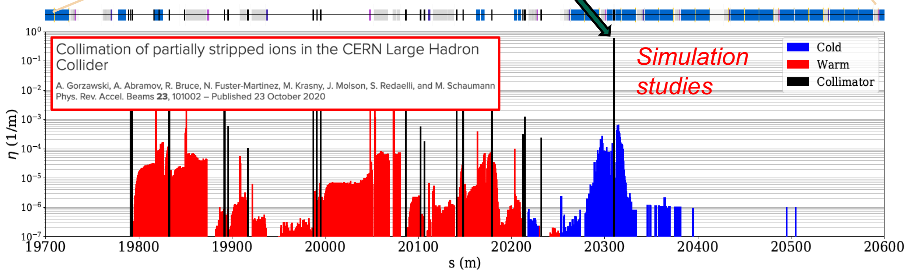
CERN, CH-1211 Geneva 23





Mitigation strategies:

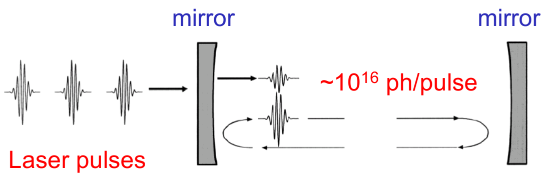
1. *Dispersion suppressor collimator (TCLD)*
2. *Crystal collimation*
3. *Laser collimation*

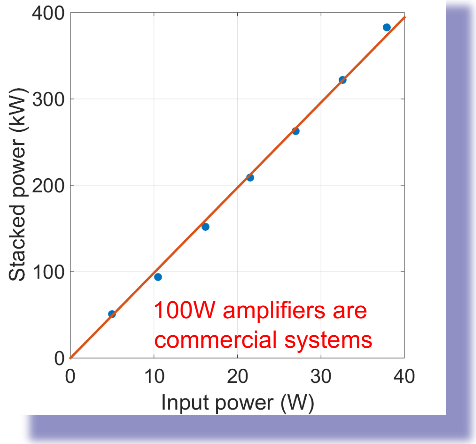


A dedicated LHC MD with crystal collimation of the PSI (H-like Pb) beam will be the next step…

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

Fabry-Pérot resonator

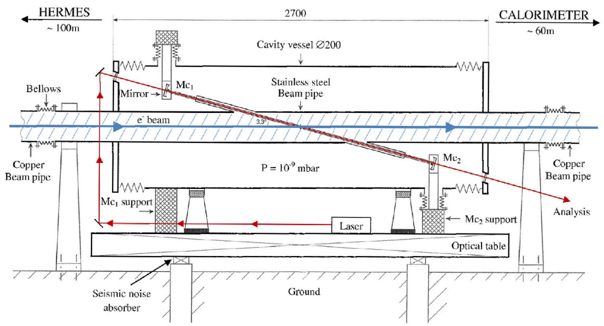




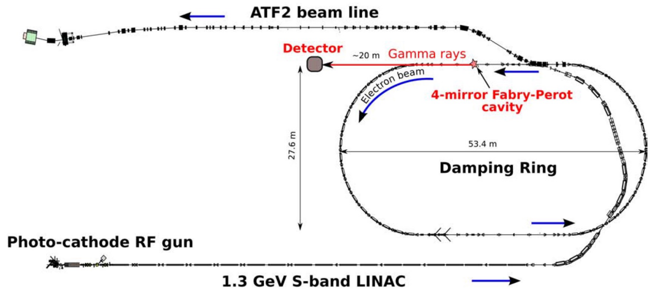
Amoudry L. et al., Applied Optics 59(2020)116

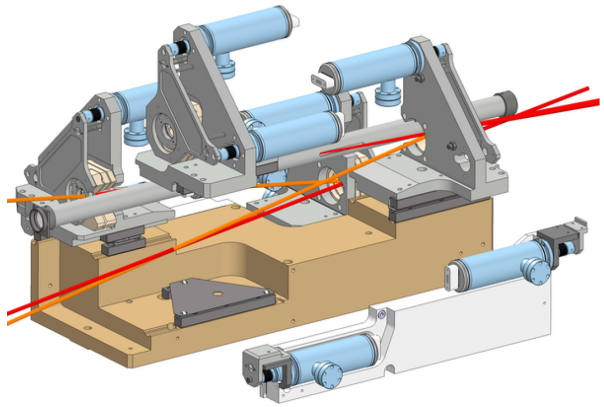
GF requirement:
< 5mJ pulses @ 20MHz,
(100kW photon beam)

HERA storage ring



KEK – ATF ring

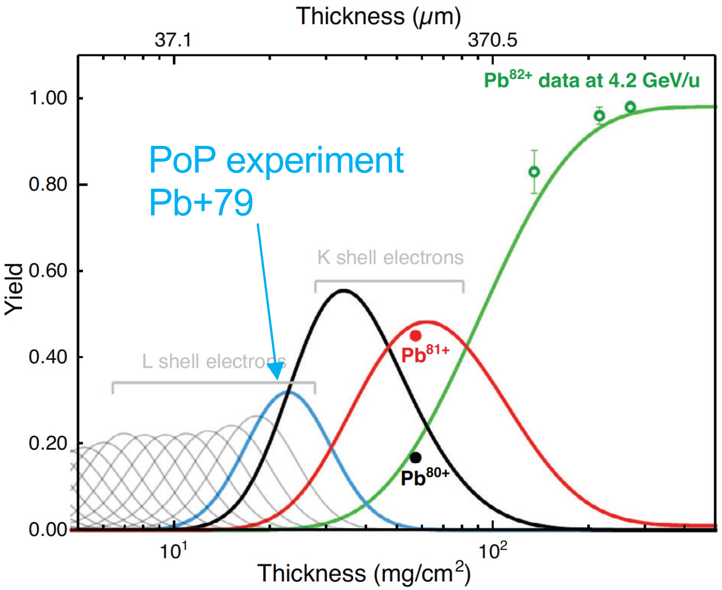




Towards the first integration of the FP resonator in the hadron storage ring →

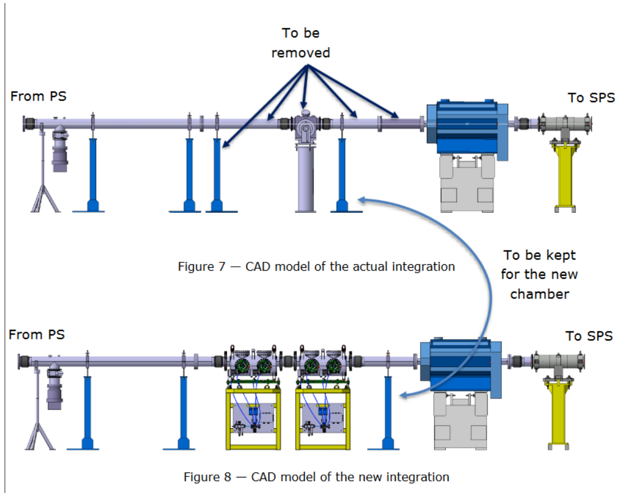
Recent technical development:
new TT2 stripper system

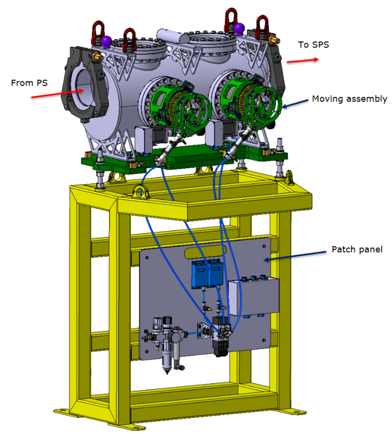
Stripping of Pb+54 ions in the TT2 PS-→ SPS transfer line

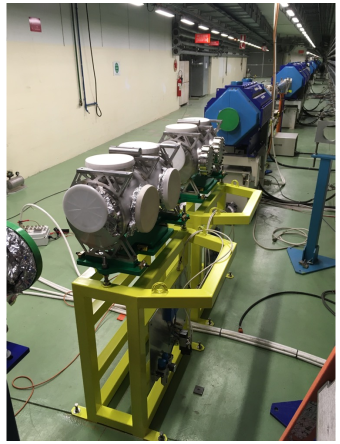


Charge-State Distributions of Highly Charged Lead Ions at Relativistic Collision Energies

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







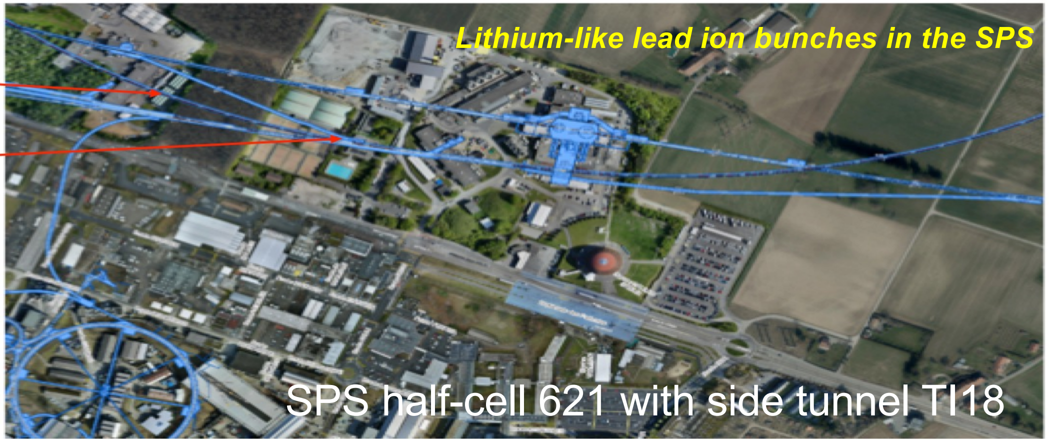
R. Alemany-Fernandez (BE.OP), E. Grenier-Boley and D. Baillard (SY.STI)

The two tanks of the new stripper system have been installed during YETS 2021-2022. The first of them is already one is equipped with two stripper foil mechanisms. The second will house additional two foil mechanism (installation in YETS 2022-20023)

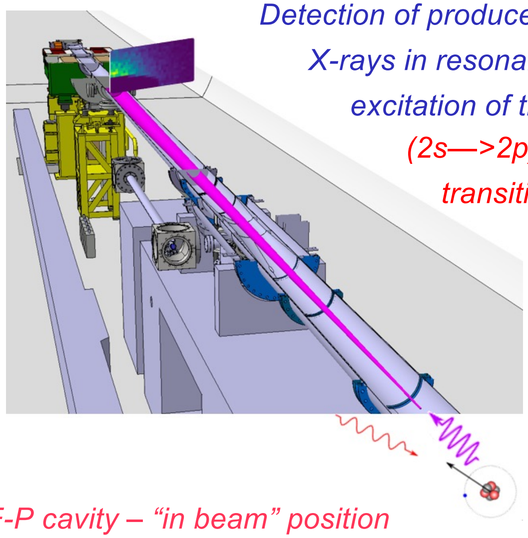
Gamma Factory Proof-of-Principle (PoP) SPS experiment

SPS

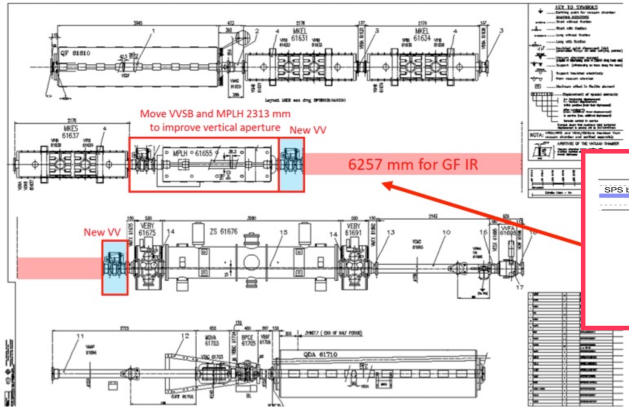
PoP location



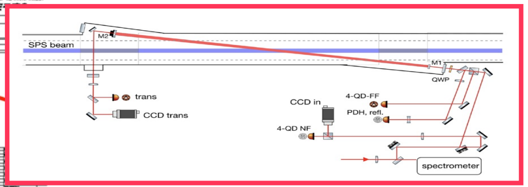
Detection of produced X-rays in resonant excitation of the (2s—>2p)$_{1/2}$ transition



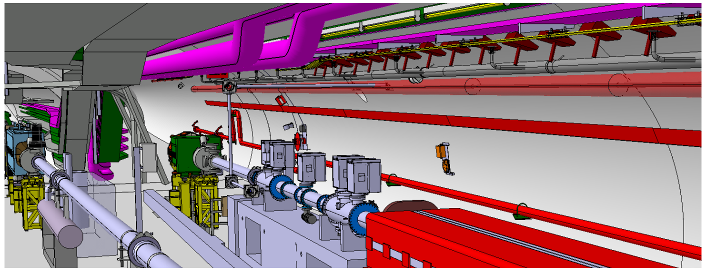
LSS6 zone



F-P cavity

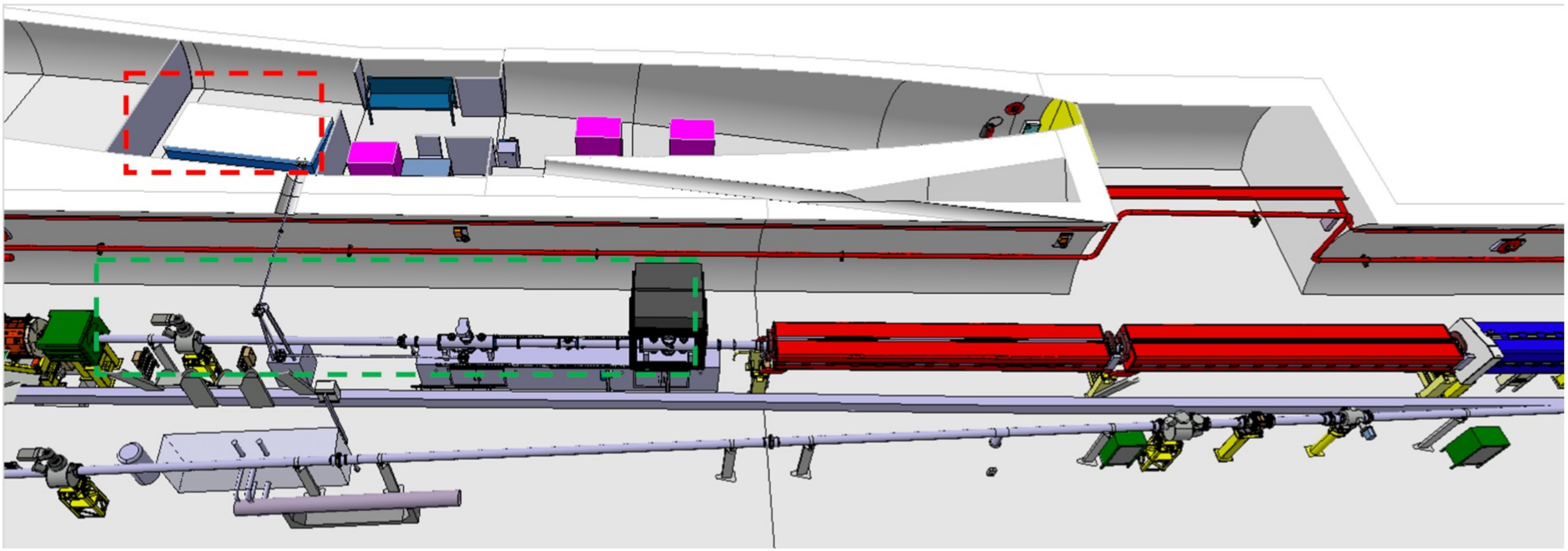


F-P cavity – "in beam" position



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

PoP experiment – location of laser room



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

GF-PoP experiment status


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

September 25, 2019

Gamma Factory

Proof-of-Principle Experiment

LETTER OF INTENT

Physics Beyond Colliders

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. »

→ *We have recently finalised the final specification of the Laser and FP system for the GF-PoP experiment, made the requisite SPS beam-stability tests and finalised the technical specification of the stripper* →

→ *In parallel, we are finalizing a detailed estimation of the CERN (Accelerator Sector), and participating labs, resources needed to construct the PoP experiment in the SPS tunnel with the plan to* submit an EU funding request

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

→ *Full experiment specifications have been finalised.*
Target Installation time : LS3 ***-- what we (only) need is to find 2.5 MCHF to cover the cost of the experiment and to assure the requisite CERN FTE resources (experiment infrastructure)…***

Gamma Factory research tools

Gamma Factory novel research tools – 5 examples

1. *Unprecedented intensity photon(γ)-beams.*

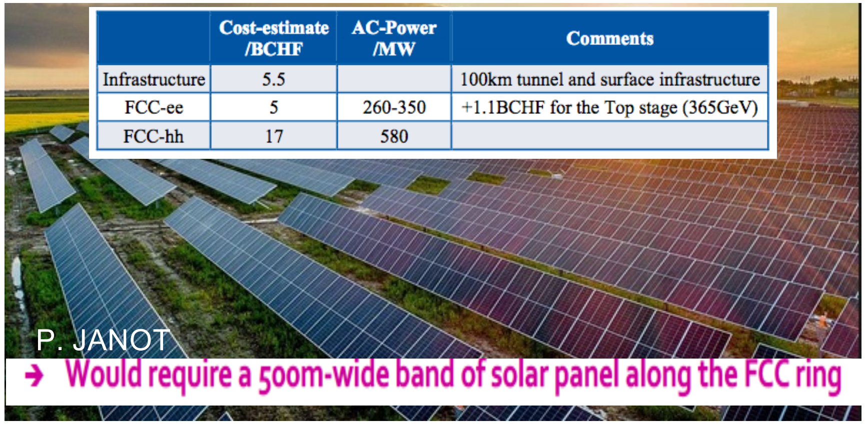
2. *Atomic traps of highly charged atoms.*

3. *Electron beam for ep collisions in the LHC interaction points.*

4. *Laser-light based cooling methods of high-energy hadronic beams.*

5. *High-intensity sources of polarised electrons, polarised positrons, polarised muons, neutrinos, neutrons and radioactive ions.*

1. High intensity (MW) photon beams



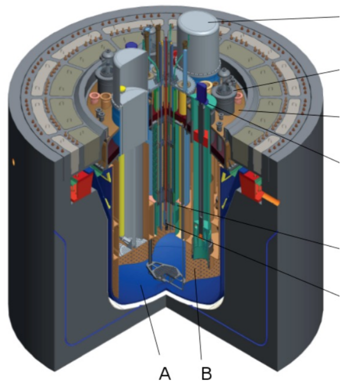
	Cost-estimate /BCHF	AC-Power /MW	Comments
Infrastructure	5.5		100km tunnel and surface infrastructure
FCC-ee	5	260-350	+1.1BCHF for the Top stage (365GeV)
FCC-hh	17	580	

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

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

GF photon-beam-driven energy source

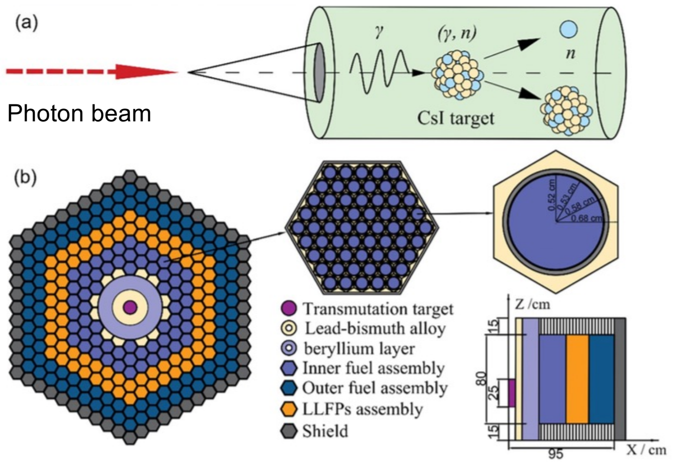
Nature:

Article | Open Access | Published: 09 February 2022

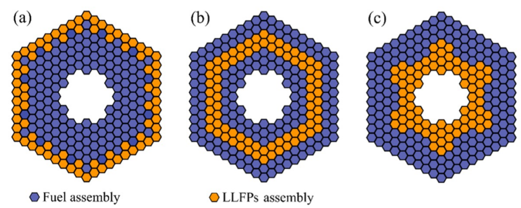
Transmutation of long-lived fission products in an advanced nuclear energy system

X. Y. Sun, W. Luo, H. Y. Lan, Y. M. Song, Q. Y. Gao, Z. C. Zhu, J. G. Chen & X. Z. Cai

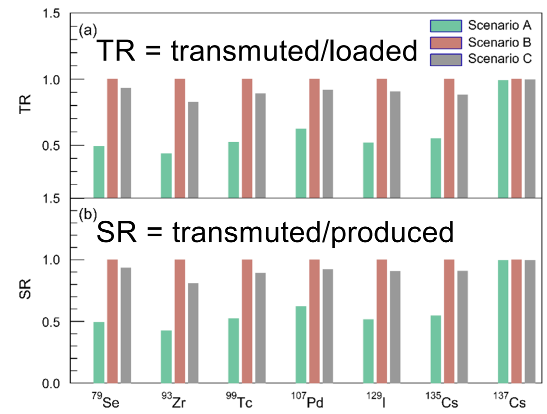
Scientific Reports **12**, Article number: 2240 (2022) | Cite this article



Main parameters	Data used in this study
Type of fuel	UO_2
Thermal power (MWt)	500
Electric power (MWe)	200
Core height (mm)	1100
Core diameter (mm)	1050
Number of fuel assemblies	60/102 (inner/outer)
Number of pins in each of fuel assembly	61
Pin diameter (mm)	5.8
Pellet diameter (mm)	5.2
^{235}U enrichment (%)	23.3
Number of LLFPs assemblies	78
Number of pins in each of LLFPs assembly	61
Number of shield assemblies	60

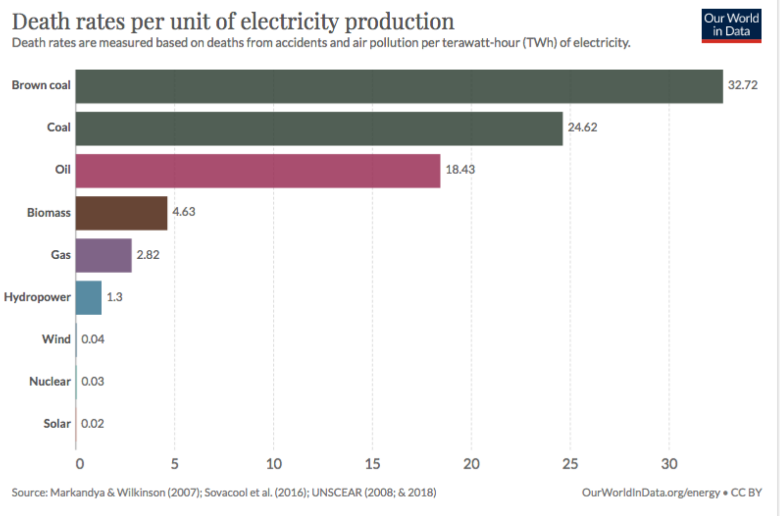


Physical quantity	Value
Effective multiplication factor (k_{eff})	0.979
Reactivity (ρ)	−0.019
Effective multiplication factor for prompt neutrons (k_p)	0.977
Eigenvalue (α)	−0.003
Effective delayed neutron fraction (β_{eff})	0.007
Neutron generation time (Λ) (μs)	0.523
Neutron worth of PNS (φ)	1.319
Sub-critical effective multiplication factor (k_s)	0.984



Potential merit of the GF-beam-driven sub-critical reactor.

Could provide the requisite plug-power for the present, and for the the future CERN's needs with one of the most safe (and clean!) sources of energy with resonant photo-transmutation of the long-lived nuclear waste isotopes!



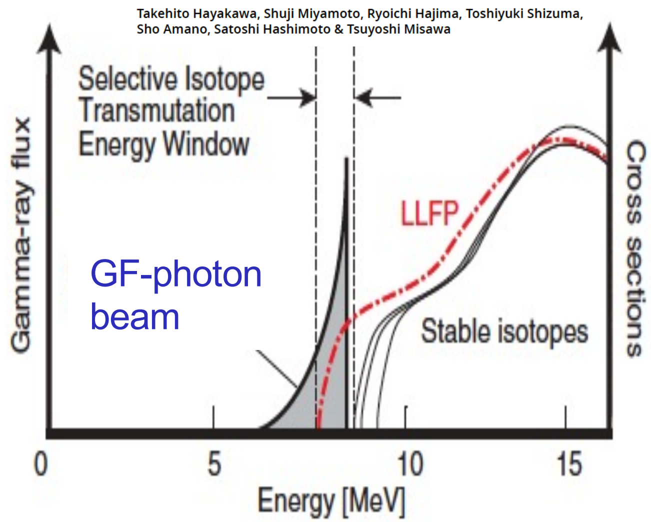
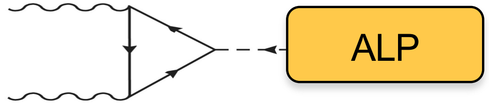


Table 1. Particle threshold energies and residual nuclei for even-Z elements including LLFPs.

Isotopes	$T_{1/2}$	E (MeV)	R.I.	$T_{1/2}$
^{90}Zr	-	8.355(p)	^{89}Y	-
^{91}Zr	-	7.195(n)	^{90}Zr	-
^{92}Zr	-	8.634(n)	^{91}Zr	-
^{93}Zr	1.61×10^6 y	6.734(n)	^{92}Zr	-
^{94}Zr	-	8.220(n)	^{94}Zr	1.61×10^6 y
^{96}Zr	-	7.854(n)	^{95}Zr	64 d
^{76}Se	-	9.508(p)	^{75}As	-
^{77}Se	-	7.418(n)	^{76}Se	-
^{78}Se	-	10.399(n)	^{77}Se	-
^{79}Se	2.95×10^5 y	6.914(n)	^{78}Se	-
^{80}Se	-	9.914(n)	^{79}Se	2.95×10^5 y
^{82}Se	-	9.276(n)	^{81}Se	18 m
^{104}Pd	-	8.658(p)	^{103}Ph	-
^{105}Pd	-	7.941(n)	^{104}Pd	-
^{106}Pd	-	9.347(p)	^{105}Rh	1.47 d
^{107}Pd	6.5×10^6 y	6.359(n)	^{106}Pd	-
^{108}Pd	-	9.221(n)	^{107}Pd	6.5×10^6 y
^{110}Pd	-	8.861(n)	^{109}Pd	13.7 h
^{117}Sn	-	6.945(n)	^{116}Sn	-
^{118}Sn	-	9.327(n)	^{117}Sn	-
^{119}Sn	-	6.485(n)	^{118}Sn	-
^{120}Sn	-	9.107(n)	^{119}Sn	-
^{122}Sn	-	8.814(n)	^{121}Sn	27 h
^{124}Sn	-	8.488(n)	^{123}Sn	40 m
^{126}Sn	2.3×10^5 y	8.193(n)	^{125}Sn	9.6 d
^{88}Sr	-	10.614(p)	^{87}Rb	-
^{90}Sr	28.8 y	7.806(n)	^{89}Sr	50.6 d
^{133}Cs	-	6.085(p)	^{132}Xe	-
		8.987(n)	^{132}Cs	6.5 d
^{135}Cs	2.3×10^6 y	6.751(p)	^{134}Xe	-
		8.762(n)	^{134}Cs	2.0 y
^{137}Cs	30 y	7.416(p)	^{136}Xe	-
		8.278(n)	^{136}Cs	13.2 d
^{127}I	-	6.206(p)	^{126}Te	-
@		9.143(n)	^{126}I	13.1 d
^{129}I	1.57×10^7 y	6.799(p)	^{128}Te	-
		8.833(n)	^{128}I	25 m
^{99}Tc	2.11×10^5 y	6.500(p)	^{98}Mo	-
		8.967(n)	^{98}Tc	4.2×10^6 y

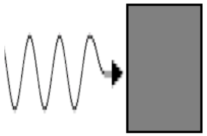
DM searches (and studies?): Axion-Like-Particles (ALP) example

Collision schemes for ALP production:

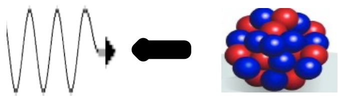


Search phase	**"Production" phase**

γ_{GF} – B field
m_{ALP} < 1 keV



γ_{GF} – A collisions (beam dump)
m_{ALP} ~ 1 keV – 10 MeV



γ_{GF} – A collisions (LHC)
m_{ALP} ~ 10 MeV – 10 GeV

γ_{GF} – γ_{Laser} collisions
m_{ALP} ~ 1–100 keV

γ_{GF} – γ_{GF} collisions (LHC)
m_{ALP} ~ 100 keV – 800 MeV

Concurrent, rich QED programme (e.g. $\gamma\gamma$ scattering)

***Three principal advantages of the Gamma Factory photon beams*:**

- ***Large fluxes***: *10^{24} 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**.*

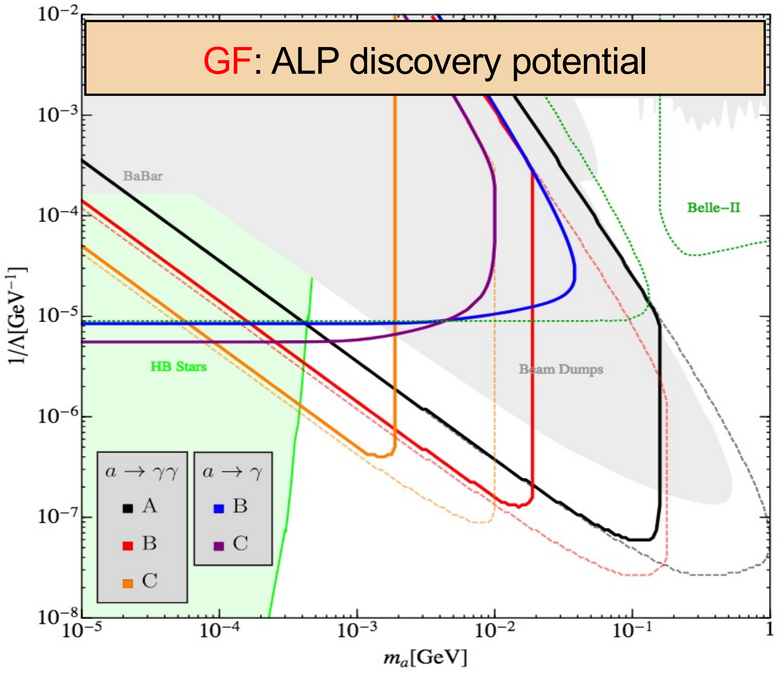
Dark matter searches

annalen der physik

Research Article | Full Access

Probing Axion-Like-Particles at the CERN Gamma Factory

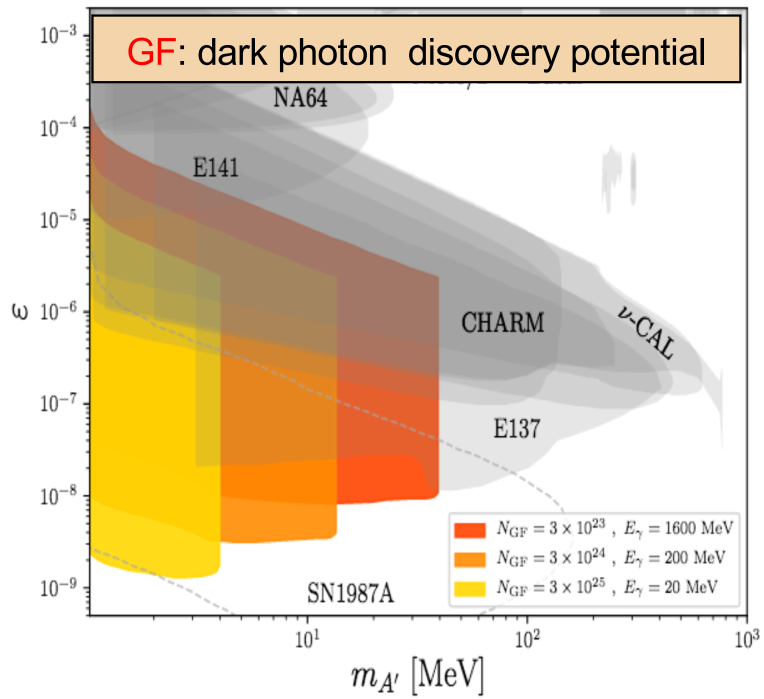
Reuven Balkin, Mieczyslaw W. Krasny, Teng Ma, Benjamin R. Safdi, Yotam Soreq



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

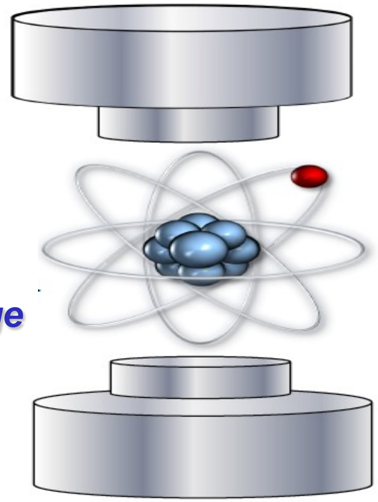


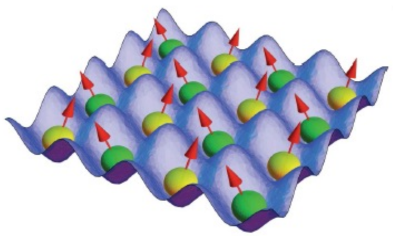
Significant discovery potential for Dark Matter particles with GF photon beams!

2. Atomic traps of highly-charged, “small-size” atoms

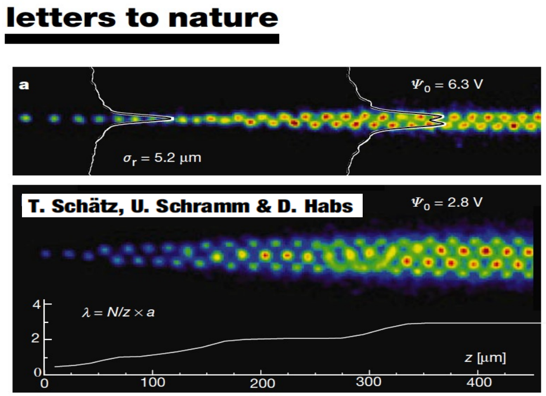
Atomic rest-frame

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)*
- *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

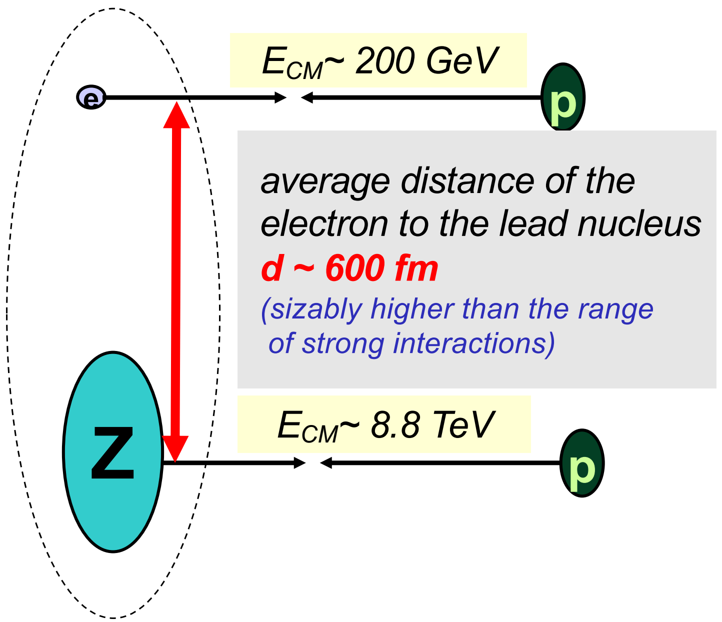
Dmitry Budker, José R. Crespo López-Urrutia, Andrei Derevianko, Victor V. Flambaum, Mieczyslaw Witold Krasny, Alexey Petrenko, Szymon Pustelny, Andrey Surzhykov, Vladimir A. Yerokhin, Max Zolotorev ... See fewer authors

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

3. 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:

ELSEVIER
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

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

Recent development:

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

Editors' Suggestion

Collimation of partially stripped ions in the CERN Large Hadron Collider

A. Gorzawski,[1,2,*] A. Abramov,[1,3,†] R. Bruce,[1] N. Fuster-Martinez,[1] M. Krasny,[1,4] J. Molson,[1] S. Redaelli,[1] and M. Schaumann[1]

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[2]University of Malta, Msida, MSD 2080 Malta
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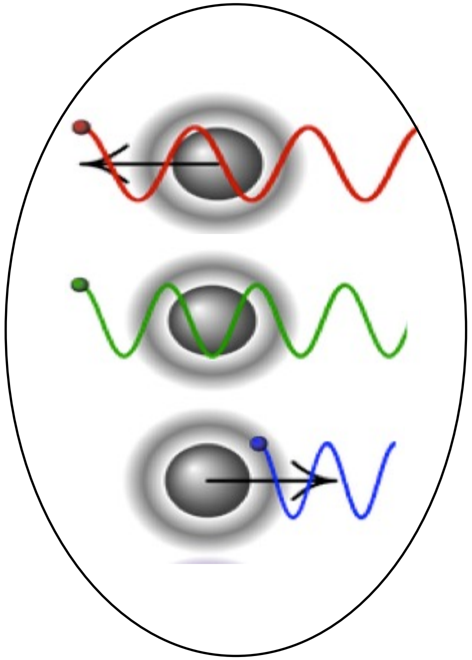
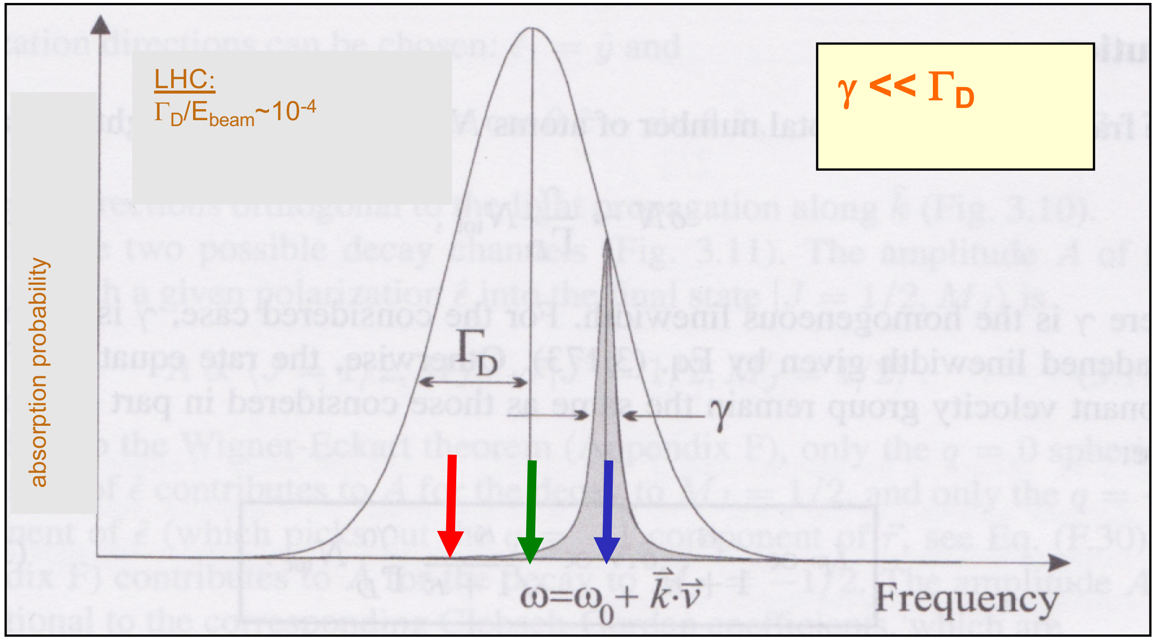
(Received 3 August 2020; accepted 5 October 2020; published 23 October 2020)

4. Laser cooling of high-energy hadronic beams

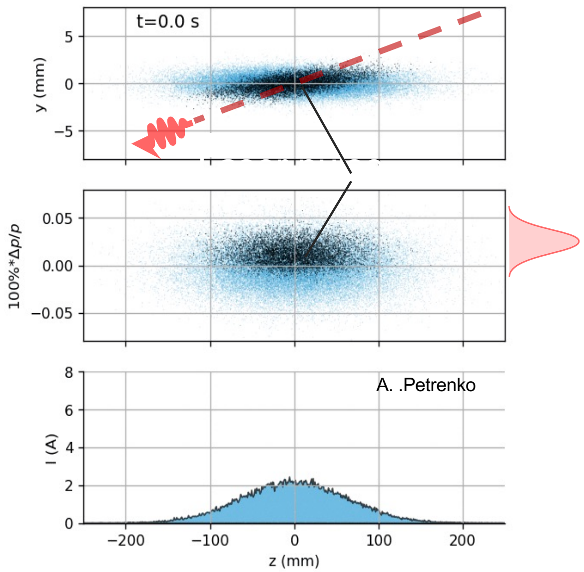


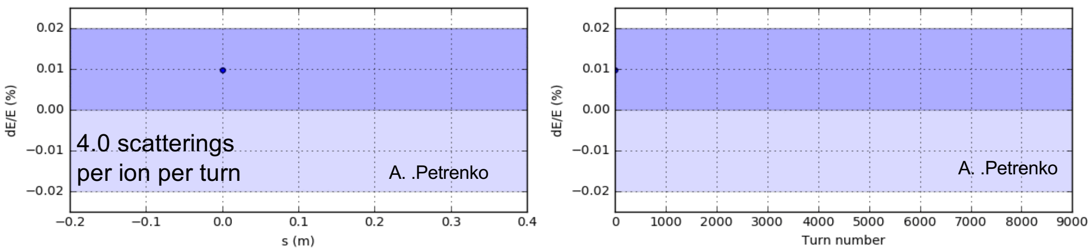
Bunch



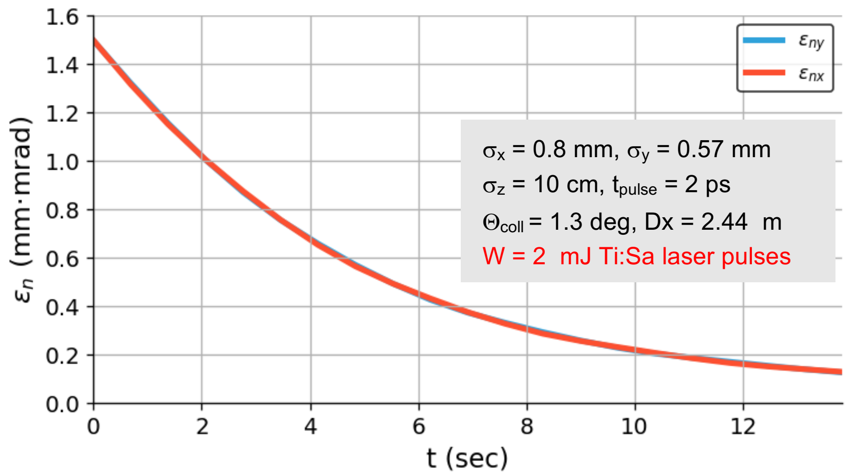
4. Laser cooling of high-energy hadronic beams

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.



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

Gamma Factory (complementary) path to HL-LHC:

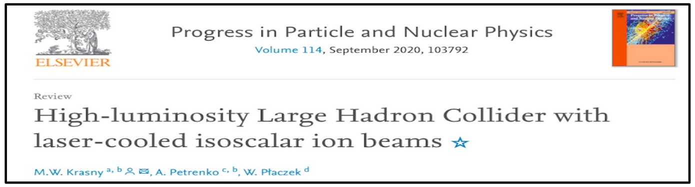
Studies of the implementation scheme with laser-cooled isoscalar Ca beams

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

***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*

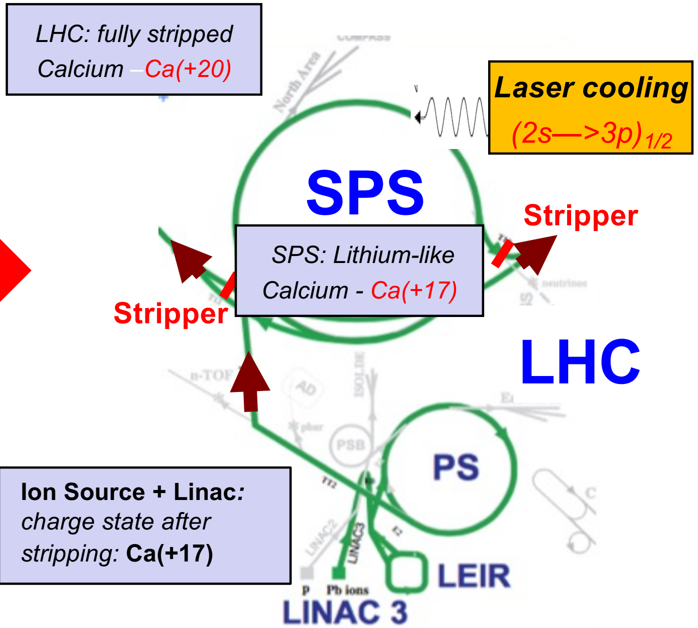
***HL-LHC** – β^* reduction by a factor of 3.7 (new inner triplet)*



Progress in Particle and Nuclear Physics
Volume 114, September 2020, 103792

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

M.W. Krasny [a, b], A. Petrenko [c, b], W. Płaczek [d]



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 (M_W, $\sin^2\theta_W$, …) 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)

5. Gamma Factory lepton sources

Presently operating positron sources

Facility	PEP-II	KEKB	DAFNE	BEPC	LIL	CESR	VEPP-5
Research center	SLAC	KEK	LNF	IHEP	CERN	Cornell	BINP
Repetition frequency, Hz	120	50	50	12.5	100	60	50
Primary beam energy, GeV	33	3.7	0.19	0.14	0.2	0.15	0.27
Number of electrons per bunch	5×10^{10}	6×10^{10}	1.2×10^{10}	5.4×10^{9}	3×10^{9}	3×10^{10}	2×10^{10}
Target	W-25Re	W	W-25Re	W	W	W	Ta
Matching device	AMD	QWT	AMD	AMD	QWT	QWT	AMD
Matching device field, T	6	2	5	2.6	0.83	0.9	10
Field in solenoid, T	0.5	0.4	0.5	0.35	0.36	0.24	0.5
Capture section RF frequency, MHz	S-band	S-band	S-band	S-band	S-band	S-band	S-band
Positron yield, 1/GeV	0.054	0.023	0.053	0.014	0.0295	0.013	0.1
Positron output, 1/s	8×10^{12}	2×10^{11}	2×10^{10}	2.5×10^{8}	2.2×10^{10}	6.6×10^{10}	10^{11}

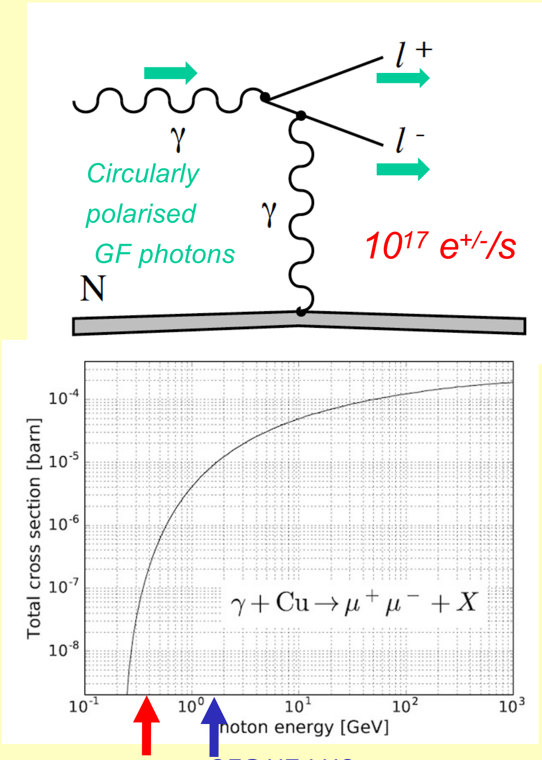
Polarised positrons/electrons sources required For CLIC, ILC and LHeC

	SLC	CLIC (380 GeV)	ILC (250 GeV)	LHeC (pulsed)	LHeC (ERL)	LEMMA	FCC-ee
e- beam energy(GeV)	45.6	380	250	140	60	45 (e+)	45.6
Norm. hor. emitt. (mm.mrad)	30	0.92	5	100	50	18	24.1
Norm. vert. emitt. (mm.mrad)	2	0.02	0.035	100	50	18	89
Bunches/macropulse	1	352	1312	10^5			2
Repetition Rate	120	50	5	10	CW		200 (Inj)
Bunches/second	120	17600	6560	10^6	20×10^6		16640
e+/second (10^{14})	0.08	1.1	1.3	18	440	100	0.06@Inj
Polarization	No	No/Yes	Yes	Yes	Yes	No	No

Existing and future muon sources

Laboratory/ Beam line	Energy/ Power	Present Surface μ^+ rate (Hz)	Future estimated μ^+/μ^- rate (Hz)
PSI (CH)	(590 MeV, 1.3 MW, DC)		
LEMS	"	$4 \cdot 10^8$	
$\pi E5$	"	$1.6 \cdot 10^8$	
HiMB	(590 MeV, 1 MW, DC)		$4 \cdot 10^{10} (\mu^+)$
J-PARC (JP)	(3 GeV, 1 MW, Pulsed) currently 210 KW		
MUSE D-line	"	$3 \cdot 10^7$	
MUSE U-line	"		$2 \cdot 10^8 (\mu^+)$ (2012)
COMET	(8 GeV, 56 kW, Pulsed)		$10^{11} (\mu^-)$ (2019/20)
PRIME/PRISM	(8 GeV, 300 kW, Pulsed)		$10^{11-12} (\mu^-)$ (> 2020)
FNAL (USA)			
Mu2e	(8 GeV, 25 kW, Pulsed)		$5 \cdot 10^{10} (\mu^-)$ (2019/20)
Project X Mu2e	(3 GeV, 750 kW, Pulsed)		$2 \cdot 10^{12} (\mu^-)$ (> 2022)
TRIUMF (CA)	(500 MeV, 75 kW, DC)		
M20	"	$2 \cdot 10^6$	
KEK (JP)	(500 MeV, 2.5 kW, Pulsed)		
Dai Omega	"	$4 \cdot 10^5$	
RAL -ISIS (UK)	(800 MeV, 160 kW, Pulsed)		
RIKEN-RAL		$1.5 \cdot 10^6$	
RCNP Osaka Univ. (JP)	(400 MeV, 400 W, Pulsed)		
MUSIC	currently max 4W		$10^8 (\mu^+)$ (2012) means $> 10^{11}$ per MW
DUBNA (RU)	(660 MeV, 1.65 kW, Pulsed)		
Phasatron Ch:I-III		$3 \cdot 10^4$	

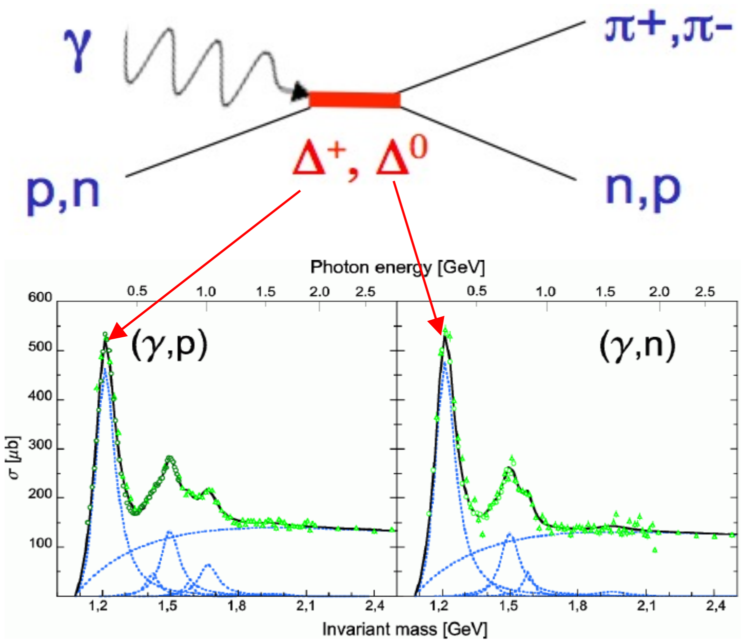
Gamma Factory - producing polarised leptons by photons

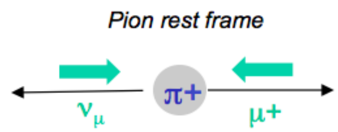


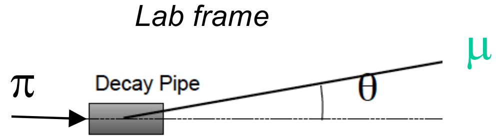
~ 10^{10} μ/s source for GF@LHC

(Mass threshold effect)

New concept







Polarisation =P(θ)

Requires quasi-monochromatic pion beam …and θ–dependent packing of muons into successive RF buckets to minimise the polarisation smearing!

High intensity source: 2×10^{13} (10^14) μ^+ and μ^- per second for the 2X0 graphite (deuterium) target and 1 MW, 300 MeV photon beam!

Quasi-monochromatic pion source:

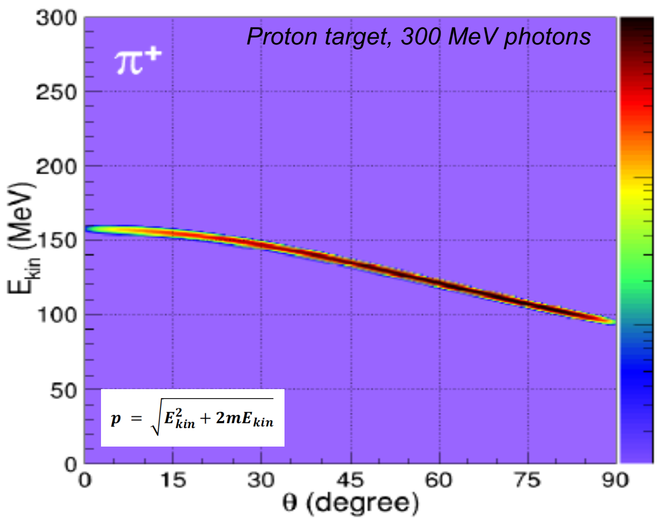
De-randomising pion spectra and restoring their charge symmetry

CM frame:

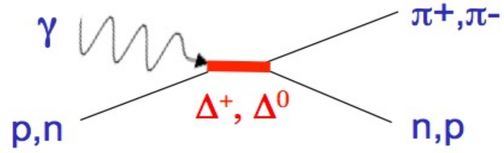
Monochromatic pions

Laboratory frame:

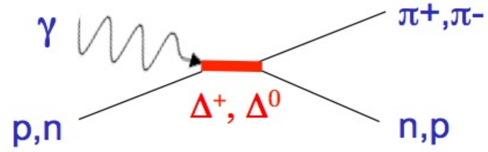
- *Pion energy and transverse momentum fully specified by one parameter: the pion emission angle, θ*



Unbound nucleon target



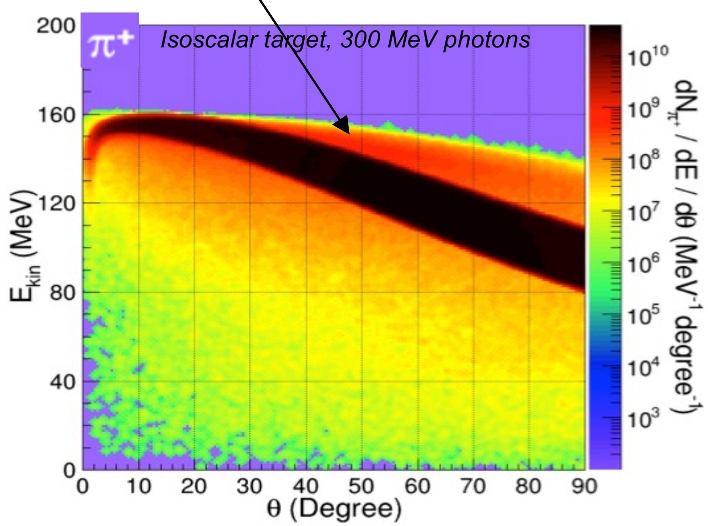
Nucleons bound in the nucleus



$Z=A/2$, ($N_p=N_n$)

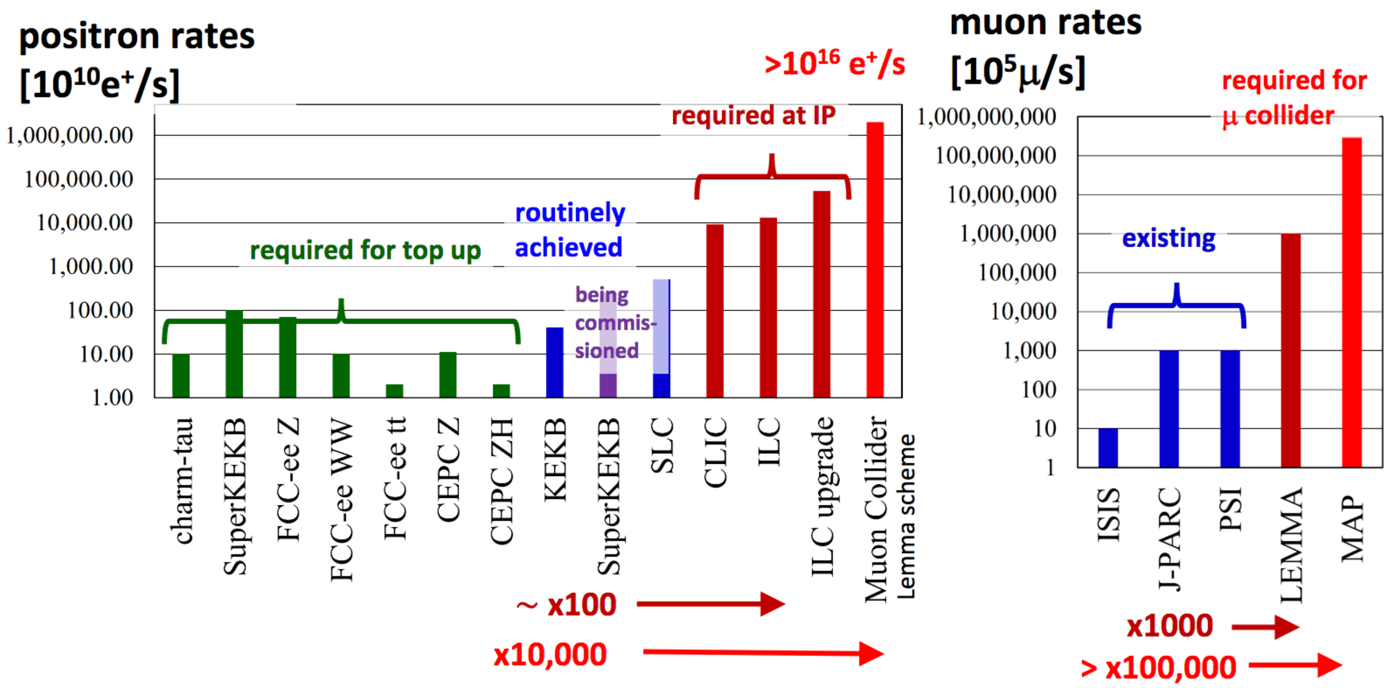
Isoscalar target choice: assures almost exact charge symmetry of π^+ and π^- production (below 2π production threshold)

(note the effect of the nucleon Fermi motion smearing – relative to hydrogen target)



GF – presently the only technology capable to deliver the requisite power polarised positron source for the CLIC, ILC and for the Lemma scheme muon collider

Frank Zimmermann – CERN seminar on challenges for future colliders



Gamma Factory: $N_{e+\uparrow} > 10^{16}$ 1/s, $N\mu+ = N\mu- > 10^{13}$ 1/s

The importance of muon (longitudinal) polarisation

Precise control of CP and flavour composition of the μ-beam driven neutrino source

$$\mu^{\pm} \rightarrow e^{\pm} + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$$

- *The GF source for isoscalar targets is “charge-symmetric”!*
- *Selection of $\nu_e\overline{\nu_\mu}$ or $\overline{\nu_e}\nu_\mu$ beam by changing the sign of collected pions*
- *Control of the relative $\overline{\nu_e}/\nu_\mu$ ($\nu_e/\overline{\nu_\mu}$) fluxes by changing muon polarisation*

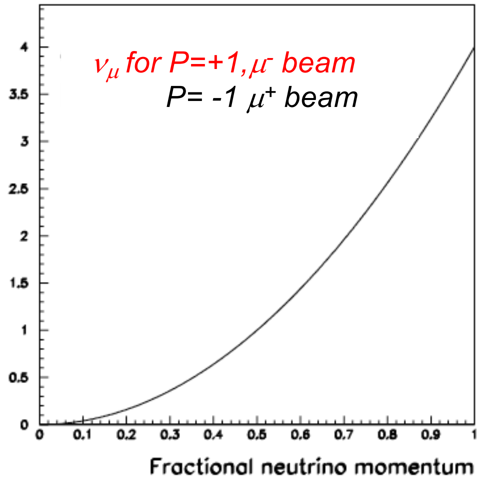
$$\frac{d^2N}{dx\,d\Omega} = \frac{1}{4\pi}[f_0(x) \mp \mathcal{P}_\mu f_1(x)\cos\theta]$$

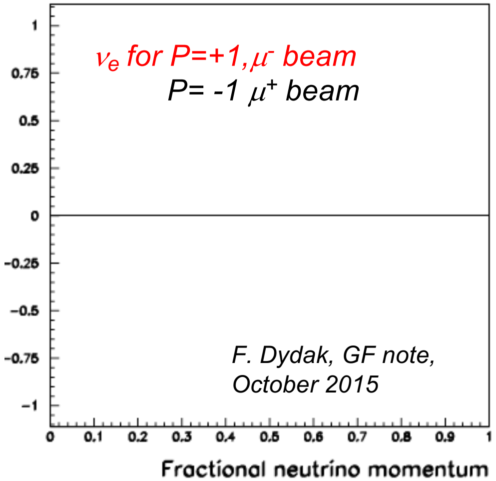
$x = 2E_\nu/m_\mu$

$\mathcal{P}_\mu$ is the muon polarization

θ is the angle between the neutrino momentum vector and the muon spin direction

	$f_0(x)$	$f_1(x)$
ν_μ, e	$2x^2(3-2x)$	$2x^2(1-2x)$
ν_e	$12x^2(1-x)$	$12x^2(1-x)$





Conceptually optimal experiment to search for CP violation in the neutrino sector:

The experiment would compare the oscillation probabilities of $\nu_\mu \rightarrow \nu_e$, with the ν_μ flux obtained from the decay under zero forward angle from fully polarized μ^-, and of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, with the $\bar{\nu}_\mu$ flux obtained from the decay under zero forward angle from fully polarized μ^+.

5. Radioactive ion beam production at the Gamma Factory

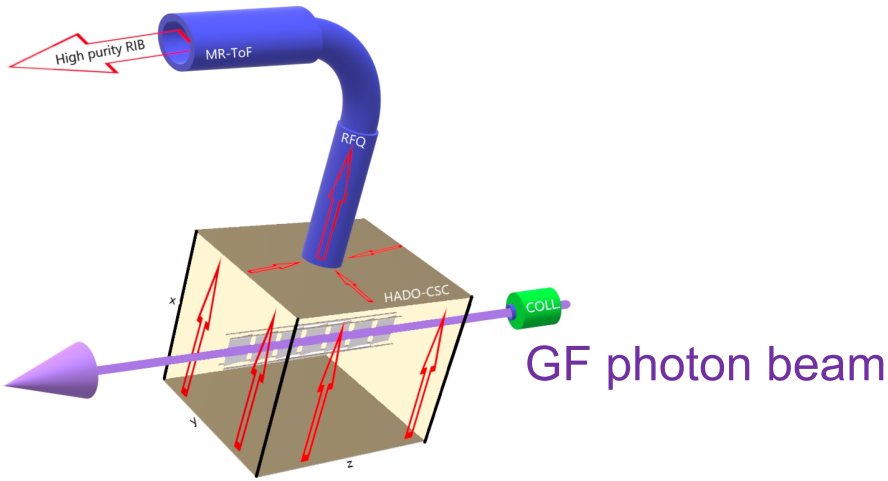
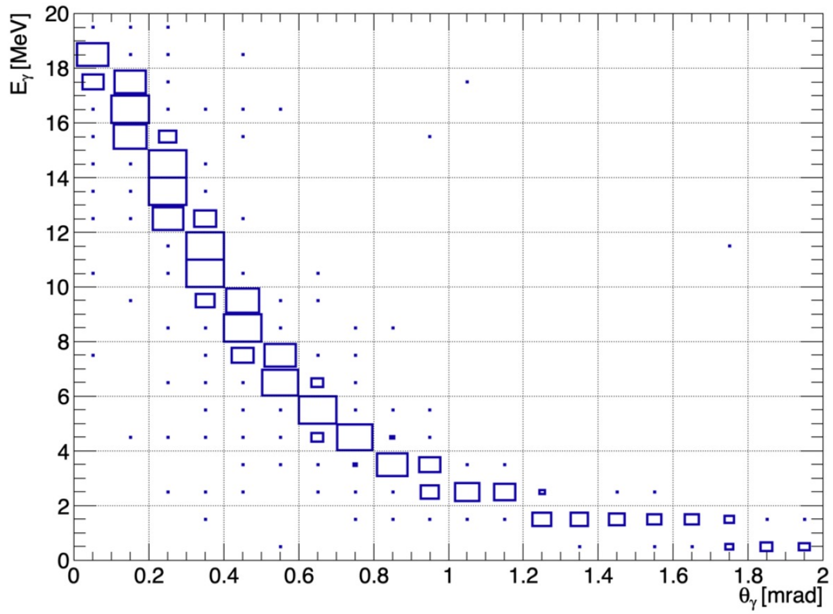
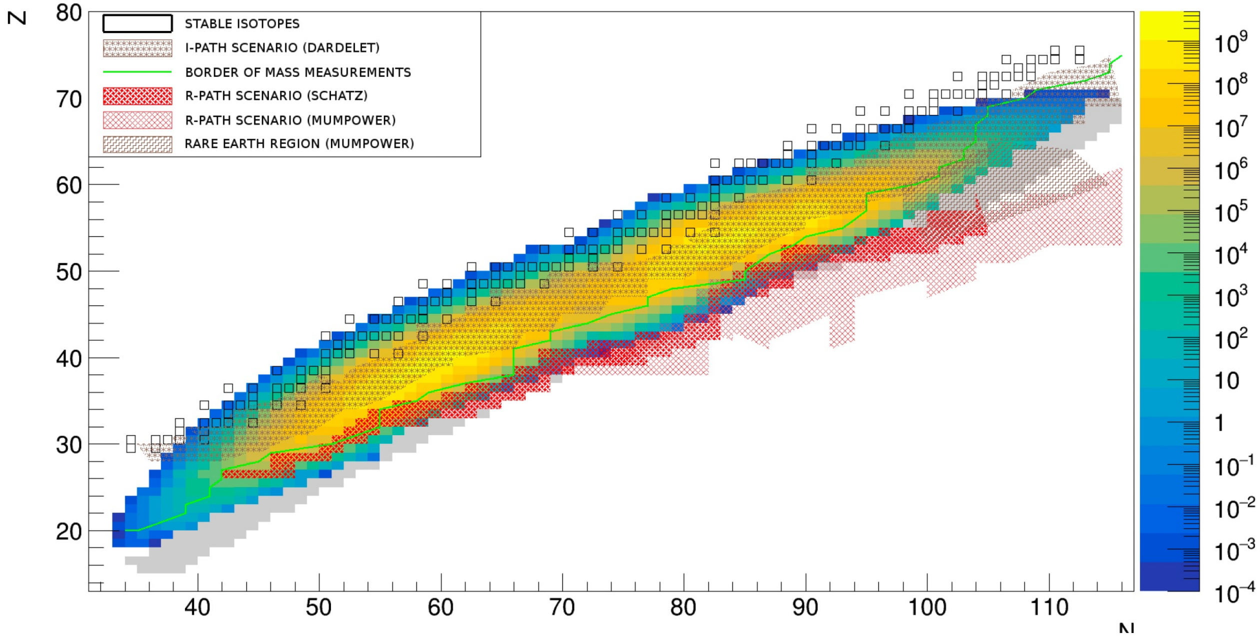


Figure 5.4: ELISOL generic setup scheme depicting the γ beam (purple) hitting many thin targets (light gray) placed inside the He filled HADO-CSC. The produced fission fragments are extracted using electric fields (red arrows), formed into a beam by a radio-frequency quadrupole (RFQ) and finally obtain a high-purity RIB using a multi-reflection time of flight (MR-ToF) mass spectrometer.



Radioactive ion beam production at the Gamma Factory



Radioactive Ion Beam Production at the Gamma Factory

Dragos Nichita (ELI-NP, Bucharest and U. Polytechnic Bucharest (main)), Dimiter L. Balabanski (ELI-NP, Bucharest and U. Polytechnic Bucharest (main)), Paul Constantin (ELI-NP, Bucharest), Mieczyslaw W. Krasny (Paris U., VI-VII and CERN), Wieslaw Placzek (Jagiellonian U.) (May 27, 2021)

Published in: *Annalen Phys.* 534 (2022) 3, 2100207 • e-Print: 2105.13058 [nucl-ex]

New physics opportunities

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).*

Visions for the future requirements for physics research

Mieczyslaw Witold Krasny

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

https://indico.cern.ch/event/1133593/timetable/?print=1&view=standard

Gamma Factory papers published over the last year

Probing Axion-Like-Particles at the CERN Gamma Factory

*Reuven Balkin, Mieczyslaw W. Krasny, Teng Ma, Benjamin R. Safdi, and Yotam Soreq**

Ann. Phys. (*Berlin*) **2022**, *534*, 2100222

Delta Baryon Photoproduction with Twisted Photons

Andrei Afanasev and Carl E. Carlson*

Ann. Phys. (*Berlin*) **2022**, *534*, 2100228

Double-Twisted Spectroscopy with Delocalized Atoms

Igor P. Ivanov

Ann. Phys. (*Berlin*) **2022**, *534*, 2100128

Vacuum Birefringence at the Gamma Factory

Felix Karbstein

Ann. Phys. (*Berlin*) **2022**, *534*, 2100137

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*

Ann. Phys. (*Berlin*) **2022**, *534*, 2100245

Access to the Kaon Radius with Kaonic Atoms

*Niklas Michel and Natalia S. Oreshkina**

Ann. Phys. (*Berlin*) **2022**, *534*, 2100150

Possible Polarization Measurements in Elastic Scattering at the Gamma Factory Utilizing a 2D Sensitive Strip Detector as Dedicated Compton Polarimeter

Wilko Middents, Günter Weber, Uwe Spillmann, Thomas Krings, Marco Vockert, Andrey Volotka, Andrey Surzhykov, and Thomas Stöhlker*

Ann. Phys. (*Berlin*) **2022**, *534*, 2100285

Radioactive Ion Beam Production at the Gamma Factory

Dragos Nichita, Dimiter L. Balabanski, Paul Constantin, Mieczyslaw W. Krasny, and Wieslaw Płaczek*

Ann. Phys. (*Berlin*) **2022**, *534*, 2100207

Electric Dipole Polarizability of Neutron Rich Nuclei

Jorge Piekarewicz

Ann. Phys. (*Berlin*) **2022**, *534*, 2100185

Resonant Scattering of Plane-Wave and Twisted Photons at the Gamma Factory

Valeriy G. Serbo, Andrey Surzhykov, and Andrey Volotka*

Ann. Phys. (*Berlin*) **2022**, *534*, 2100199

Local Lorentz Invariance Tests for Photons and Hadrons at the Gamma Factory

B. Wojtsekhowski and Dmitry Budker*

Ann. Phys. (*Berlin*) **2022**, *534*, 2100141

Optical Excitation of Ultra-Relativistic Partially Stripped Ions

*Jacek Bieroń, Mieczyslaw Witold Krasny, Wiesław Płaczek, and Szymon Pustelny**

Ann. Phys. (*Berlin*) **2022**, *534*, 2100250

Expanding Nuclear Physics Horizons with the Gamma Factory

Dmitry Budker, Julian C. Berengut, Victor V. Flambaum, Mikhail Gorchtein, Junlan Jin, Felix Karbstein, Mieczyslaw Witold Krasny, Yuri A. Litvinov, Adriana Pálffy, Vladimir Pascalutsa, Alexey Petrenko, Andrey Surzhykov, Peter G. Thirolf, Marc Vanderhaeghen, Hans A. Weidenmüller, and Vladimir Zelevinsky*

Ann. Phys. (*Berlin*) **2022**, *534*, 2100284

Parity-Violation Studies with Partially Stripped Ions

Jan Richter, Anna V. Maiorova, Anna V. Viatkina, Dmitry Budker, and Andrey Surzhykov**

Ann. Phys. (*Berlin*) **2022**, *534*, 2100561

Polarization of Photons Scattered by Ultra-Relativistic Ion Beams

Andrey Volotka, Dmitrii Samoilenko, Stephan Fritzsche, Valeriy G. Serbo, and Andrey Surzhykov*

Ann. Phys. (*Berlin*) **2022**, *534*, 2100252

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Progress in Particle and Nuclear Physics
Volume 114, September 2020, 103792

Review

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

M.W. Krasny [a, b], A. Petrenko [c, b], W. Płaczek [d]

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

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

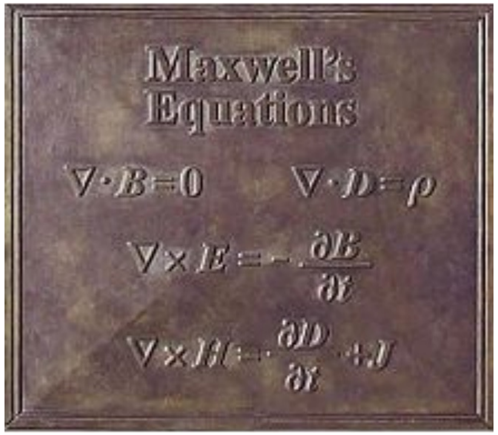
Conclusions

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,** by a broad scientific communities*

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, applied physics, and astrophysics **with novel research tools

Concepts and tools



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

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

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

A vision of the LHC operation mode in in the post-HL-LHC phase