Fundamental physics with the Gamma Factory@CERN

EPIC conference, Geremeas, Sardinia

the 26th of September 2024

Mieczyslaw Witold Krasny

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

“*Gamma Factory*” studies

The Gamma Factory proposal for CERN †

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

Mieczyslaw Witold Krasny*

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

e-Print: 1511.07794 [hep-ex]

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

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

- *An appetiser: 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?* → *high energy atomic beams*
- *The science of* ***high energy (γ_L >> 1)*** *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 such a novel multidisciplinary project be developed ***and implemented*** *in a "High Energy Physics" laboratory such as CERN?*

2. Restoring a balance of the high-energy and high-intensity frontiers for particle-beams based science

- *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 >10^7 → 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^{16} neutrons/sec,*
- *radioactive ion beams →:10^{12} ions/sec*

3. Continuation of the CERN "extracted beams" research?

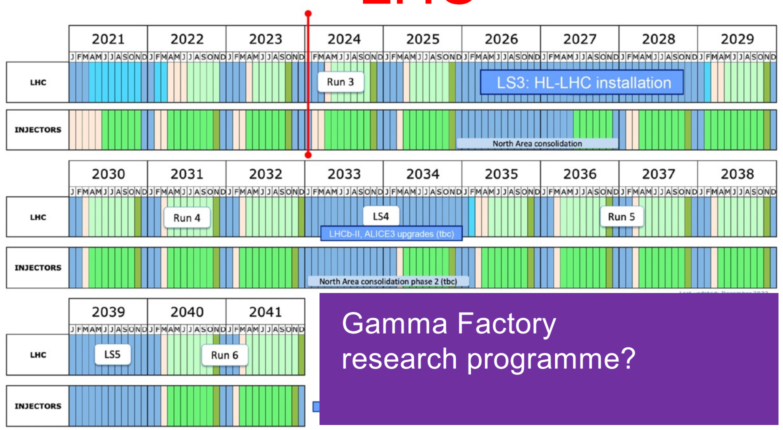
- *SPS has demonstrated operation with cycle intensity 2-4x10^{13} protons delivering 4x10^{19} protons/year for the SPS fixed target programme, (PSB can deliver 10^{20} protons/year for the ISOLDE programme)*

- *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*

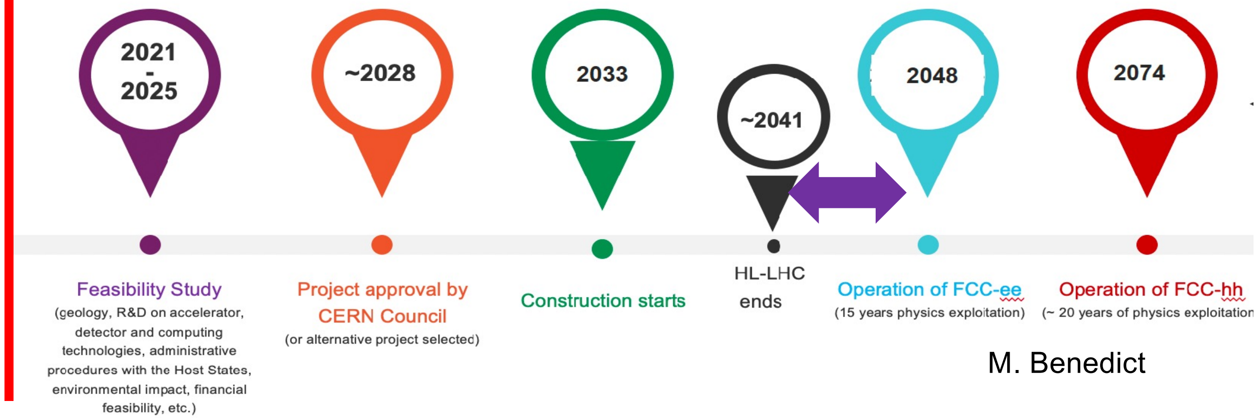
Gamma Factory could extract ~10^{25} γ/year for a fixed target programme (MHz repetition rate). Efficient extraction of the RF power in the form of particle beams!

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	

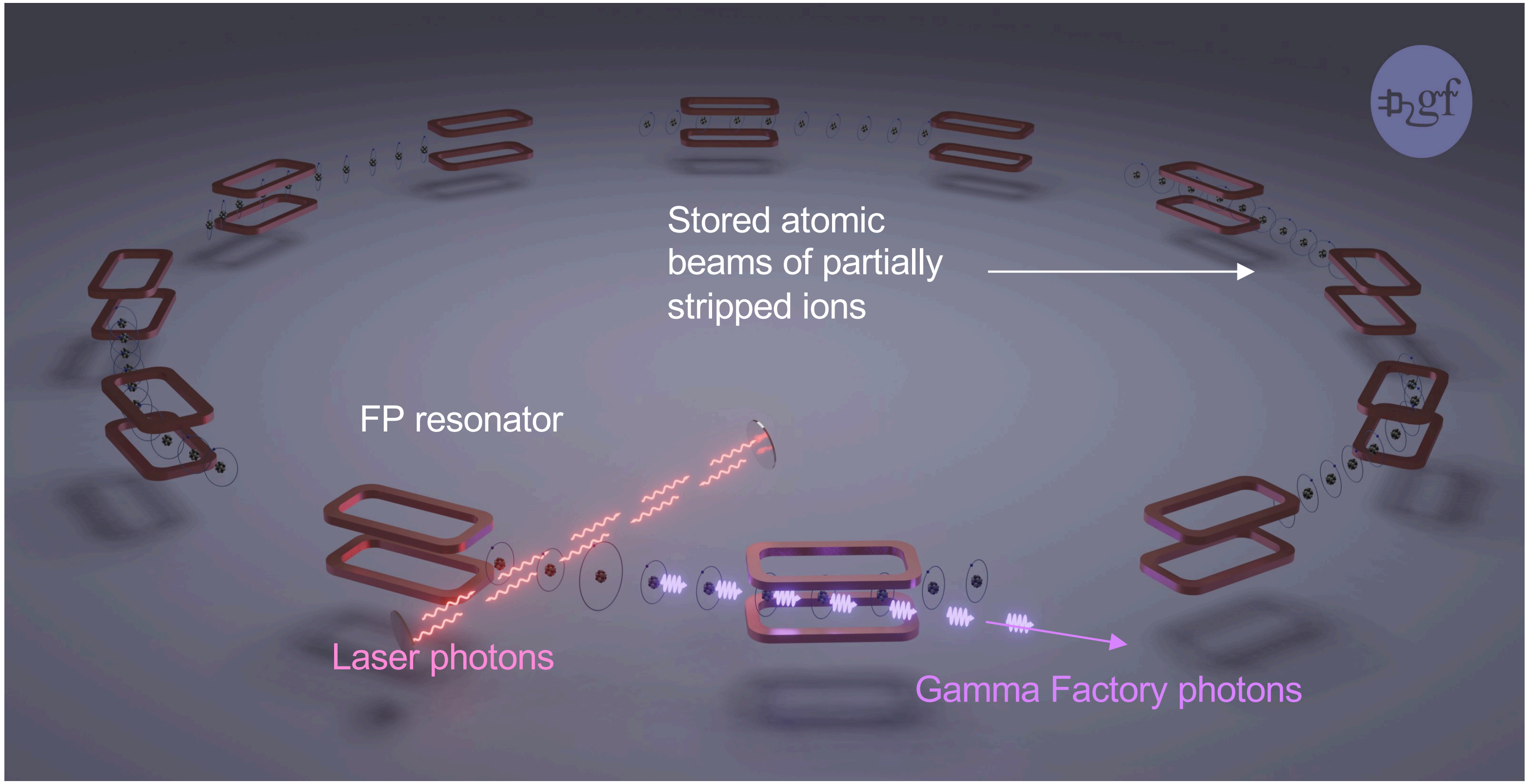
Gamma Factory beam-driven, sub-critical reactor (with the efficient transmutation of its waste) could potentially provide the necessary AC plug power needs for the growing CERN accelerator infrastructure.

6. Opening new research opportunities at CERN

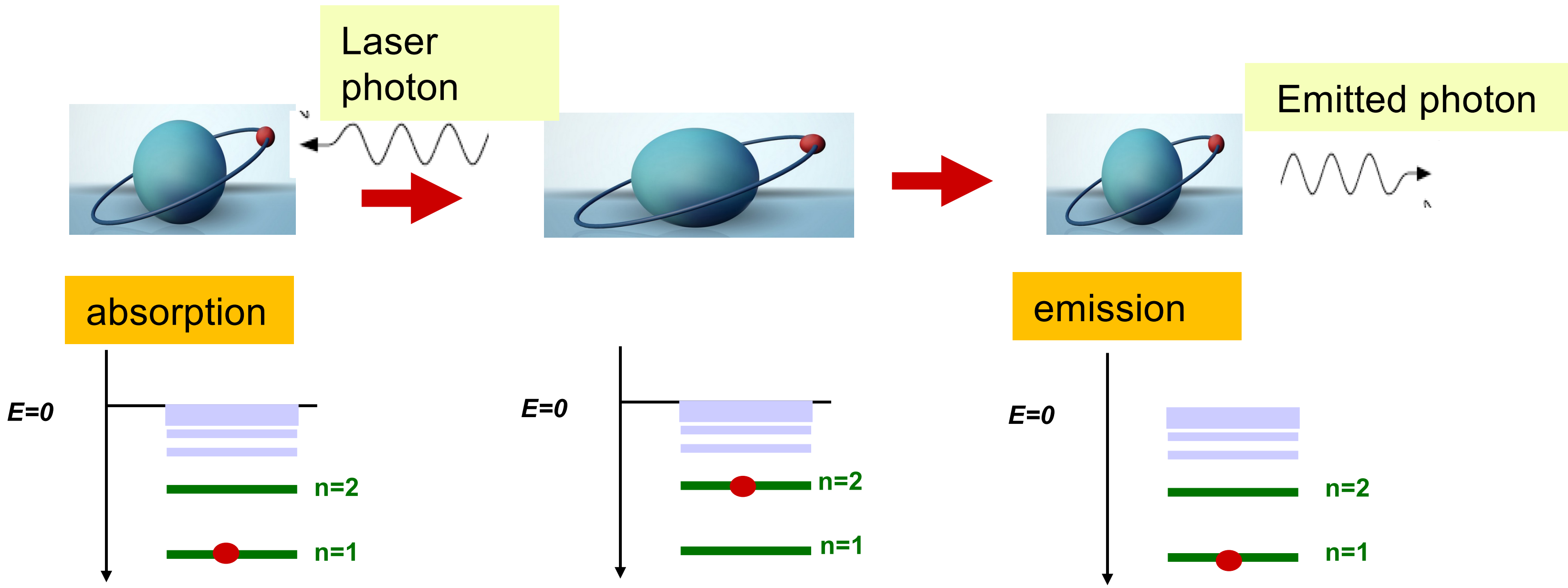
- ***particle physics*** *(precision QED and EW studies, vacuum birefringence, Higgs physics in $\gamma\gamma$ collision mode, rare muon decays, precision neutrino physics, QCD-confinement studies, …);*
- ***nuclear physics*** *(nuclear spectroscopy, cross-talk of nuclear and atomic processes, GDR, nuclear 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



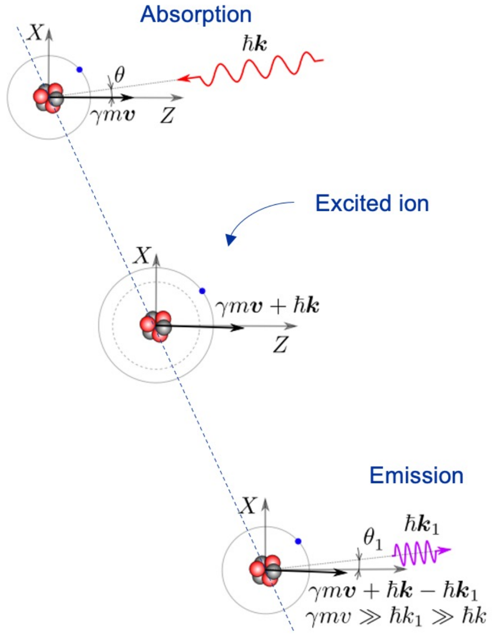
Resonant absorption and emissions of photons by **atoms**



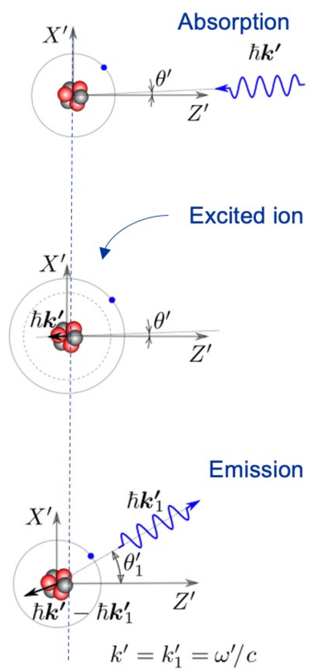
Photon acceleration -- Energy leap:

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

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

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

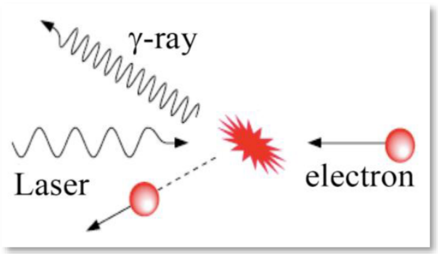
$$\nu^{max} \longrightarrow (4\,\gamma_L^{\,2})\;\nu_i$$

$\gamma_L = E/M$ - Lorentz factor for the ion beam -- **25-6500 for the CERN beams**

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:

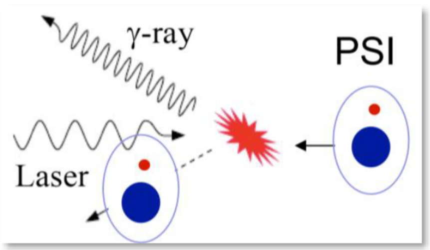
emission of 150 MeV photon:

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

(electron is lost!)

$\sigma \times 10^9$

Gamma Factory



Example: Pb, hydrogen-like ions,
stored in LHC γ_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

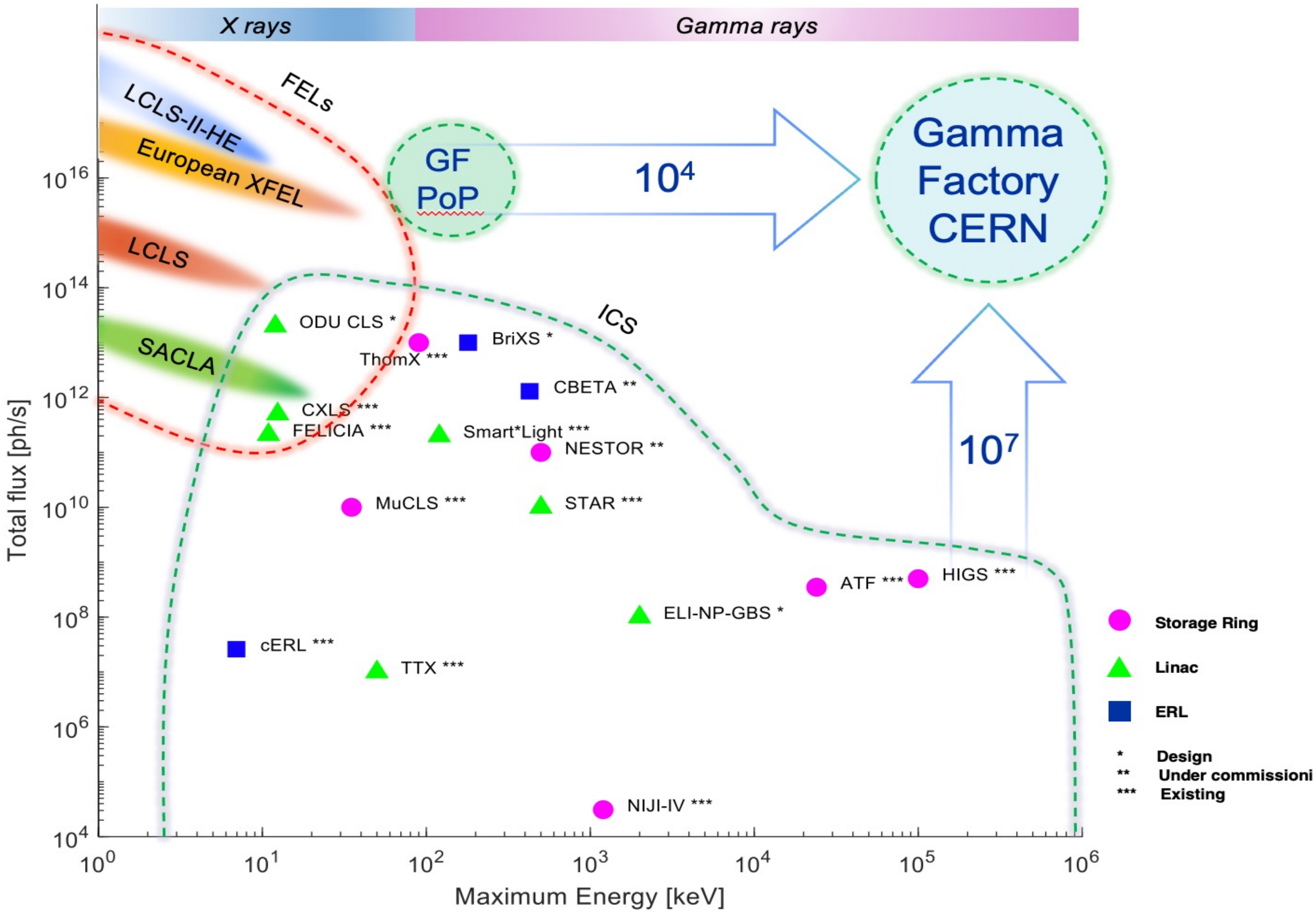
(LHC)

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 ***
Storage Ring
Linac
ERL
* Design
** Under commissioni
*** Existing
Total flux [ph/s]
Maximum Energy [keV]

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%***

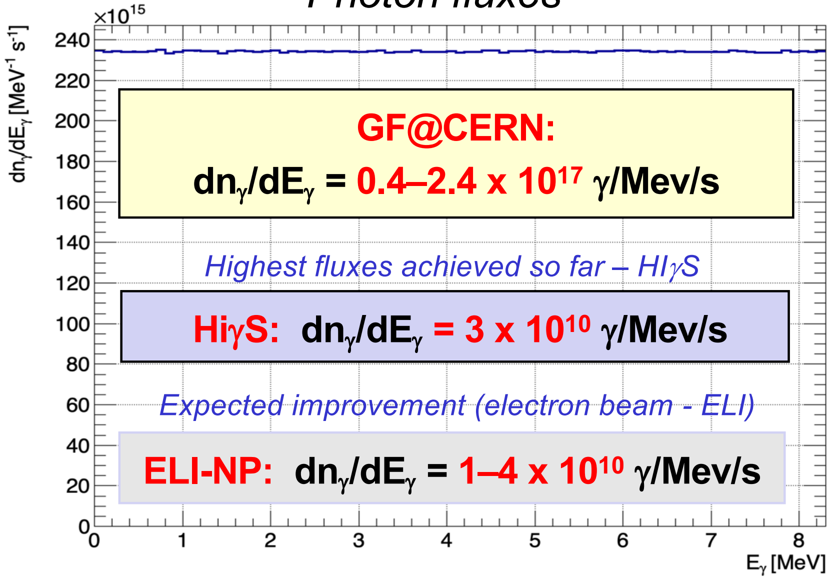
5. Unprecedented plug power efficiency (energy footprint):

- ***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

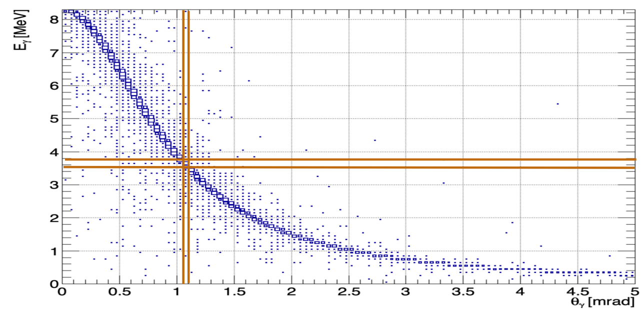


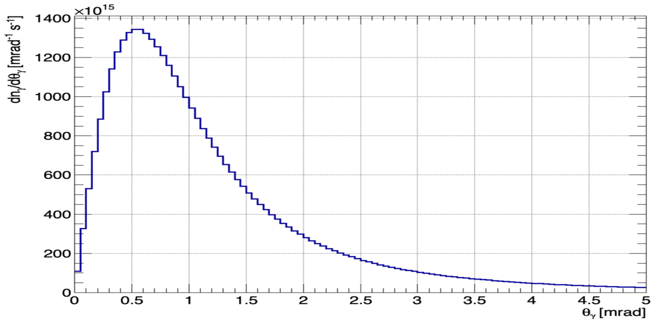
laser pulse parameters

- 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.

6. Highly-collimated monochromatic γ–beams:

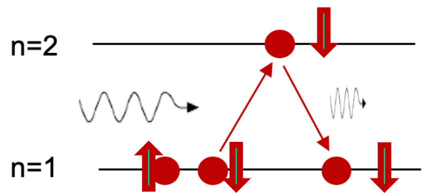
- *the beam power is concentrated in a narrow angular region (facilitates beam extraction),*
- *the $(E_\gamma, \Theta_\gamma)$ correlation can be used (collimation) to "monochromatize" the beam*





Polarised (and/or twisted) GF photon beams

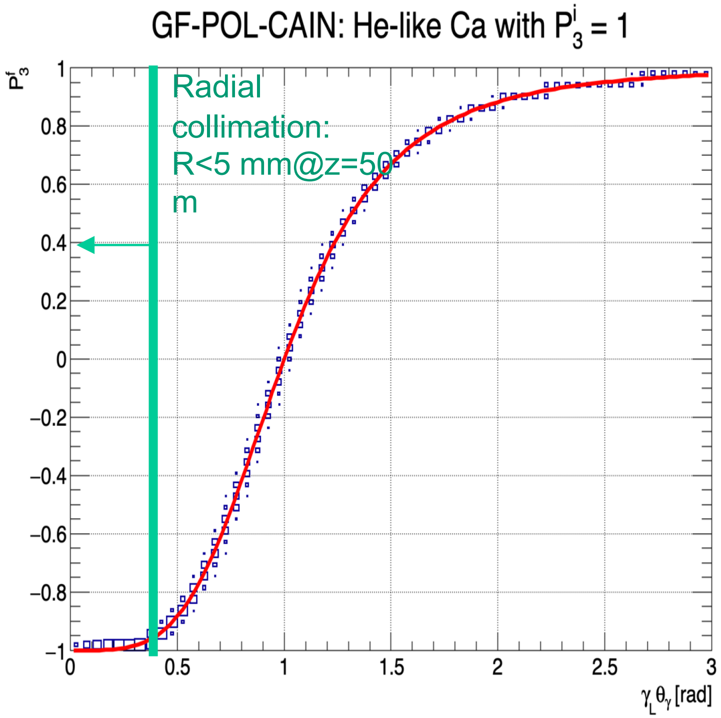
A trick: Pauli blocking

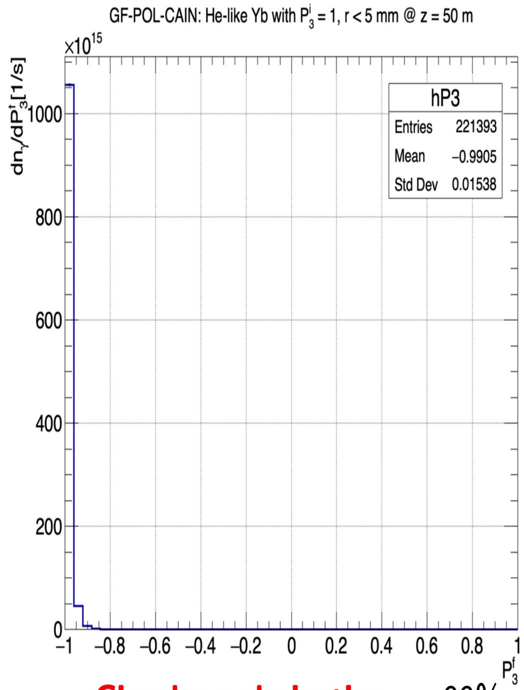


$$nS_0 \to n'P_1 \to nS_0$$

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

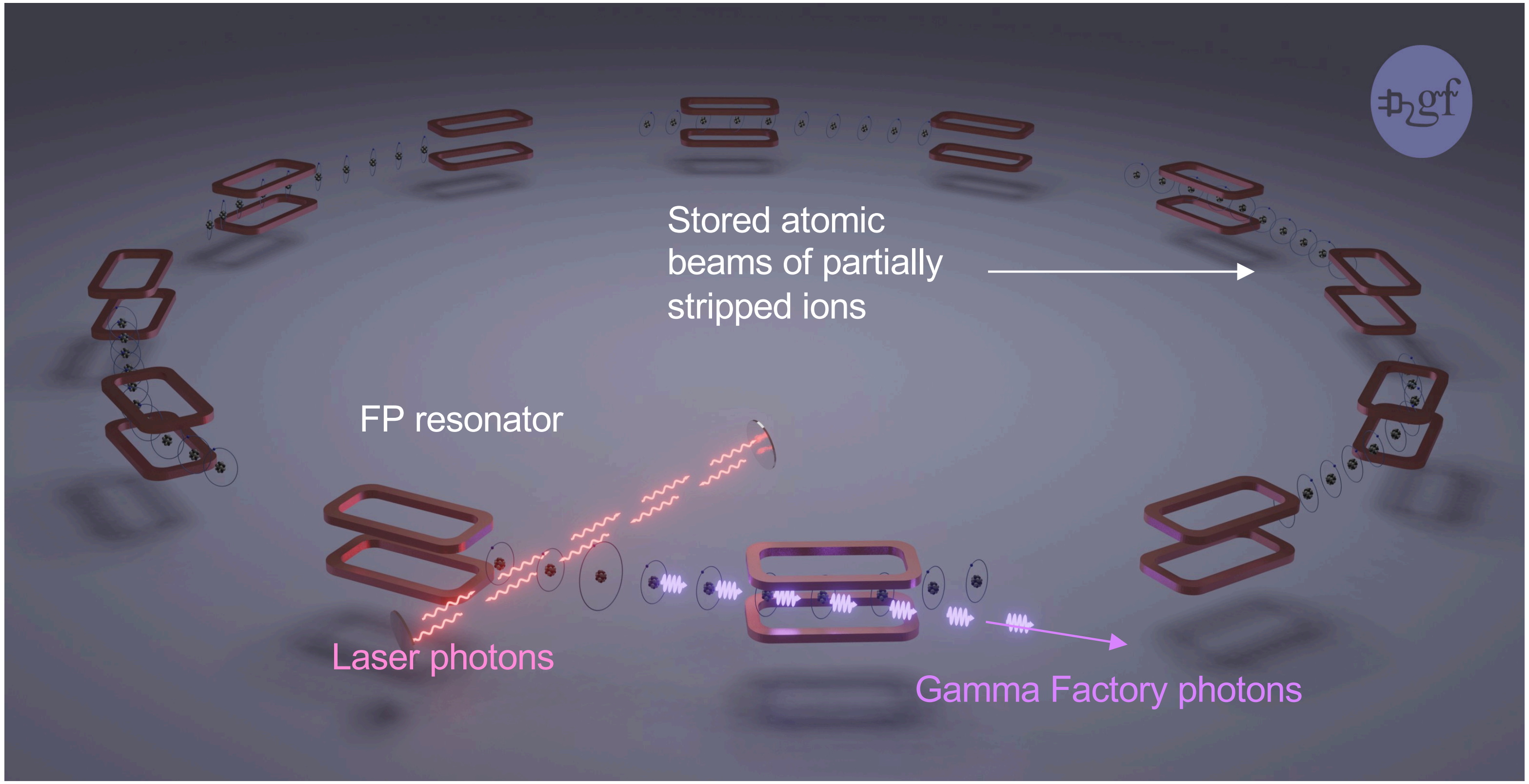




→ **Circular polarization** ≈ 99%

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

Gamma Factory – feasibility proof steps

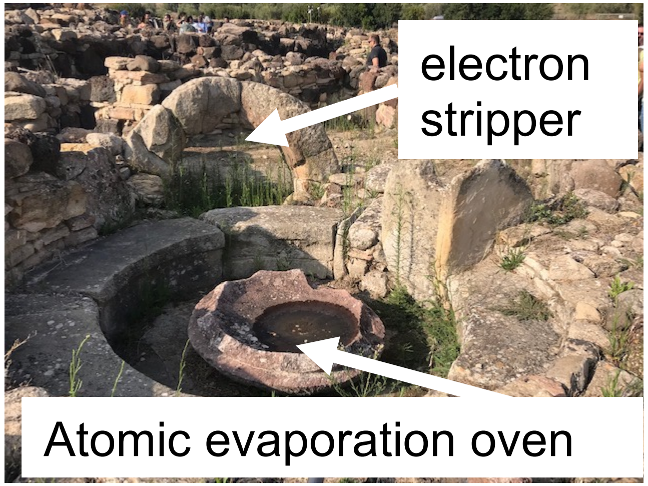


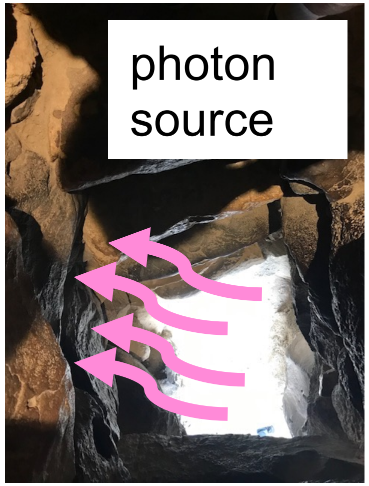
Novel technology:

Resonant scattering of laser photons on ultra-relativistic atomic beam


Choice of a site 1000 B.C.
Barumini?

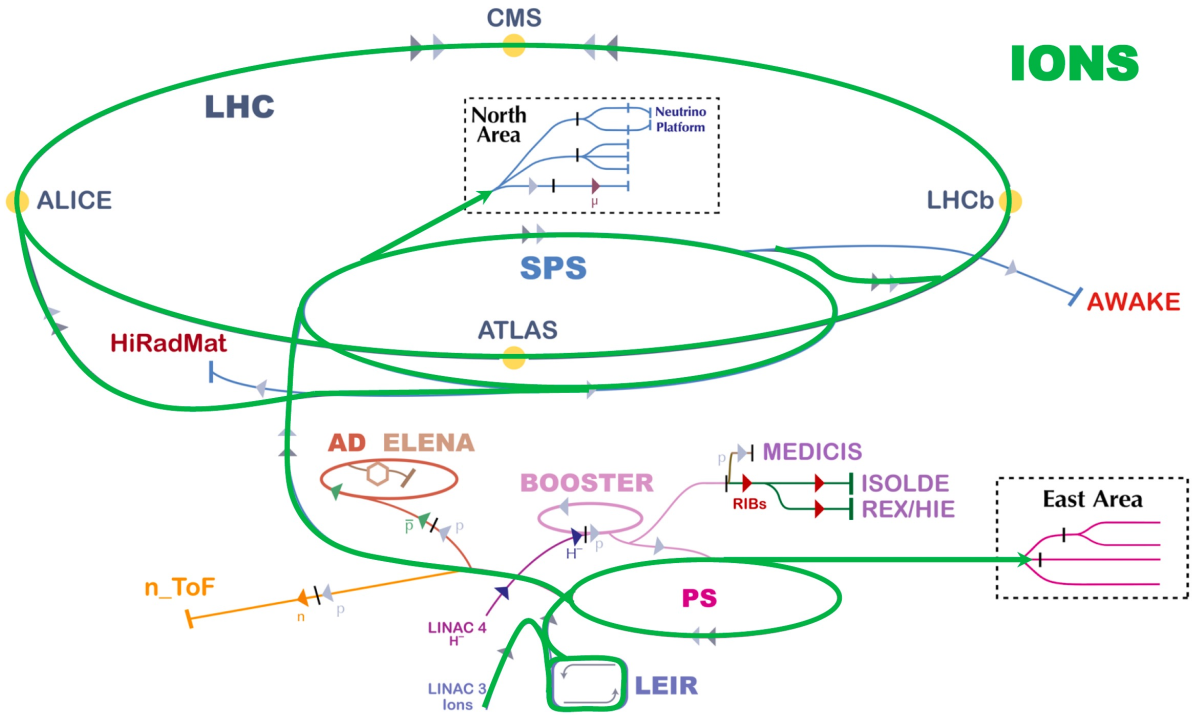

Beam storage ring


electron
stripper
Atomic evaporation oven


photon
source

Better choice (3000 years later): CERN as the GF project host:

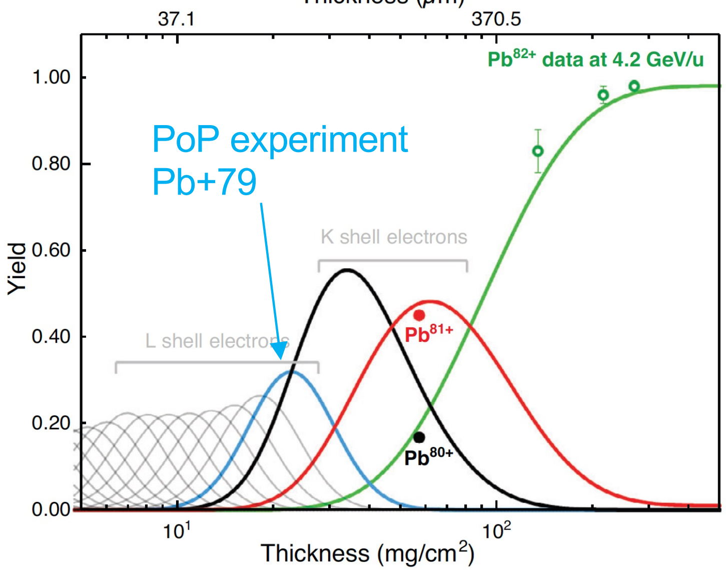
re-use of already existing accelerator infrastructure



Gamma Factory (additional) beam requirements:
- modification of the ion stripping scheme,
- storage of atomic beams in high-energy rings: SPS and LHC

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*

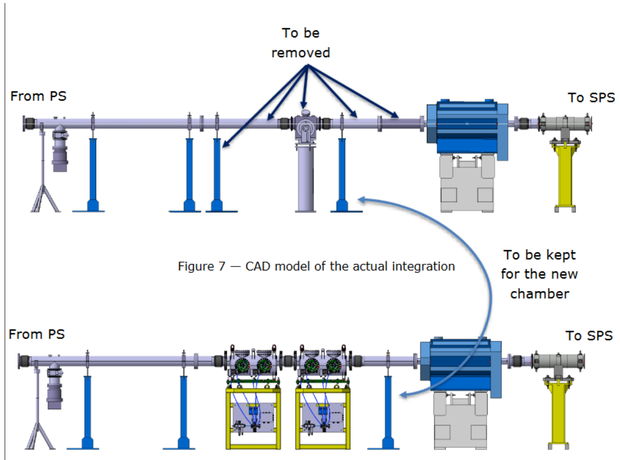
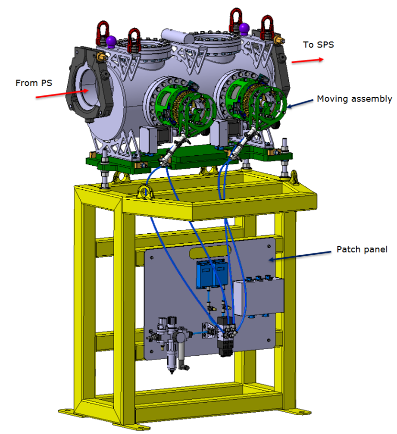
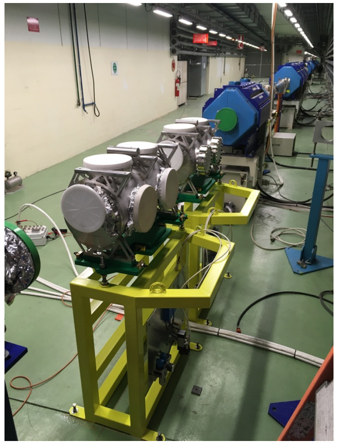


Figure 7 — CAD model of the actual integration

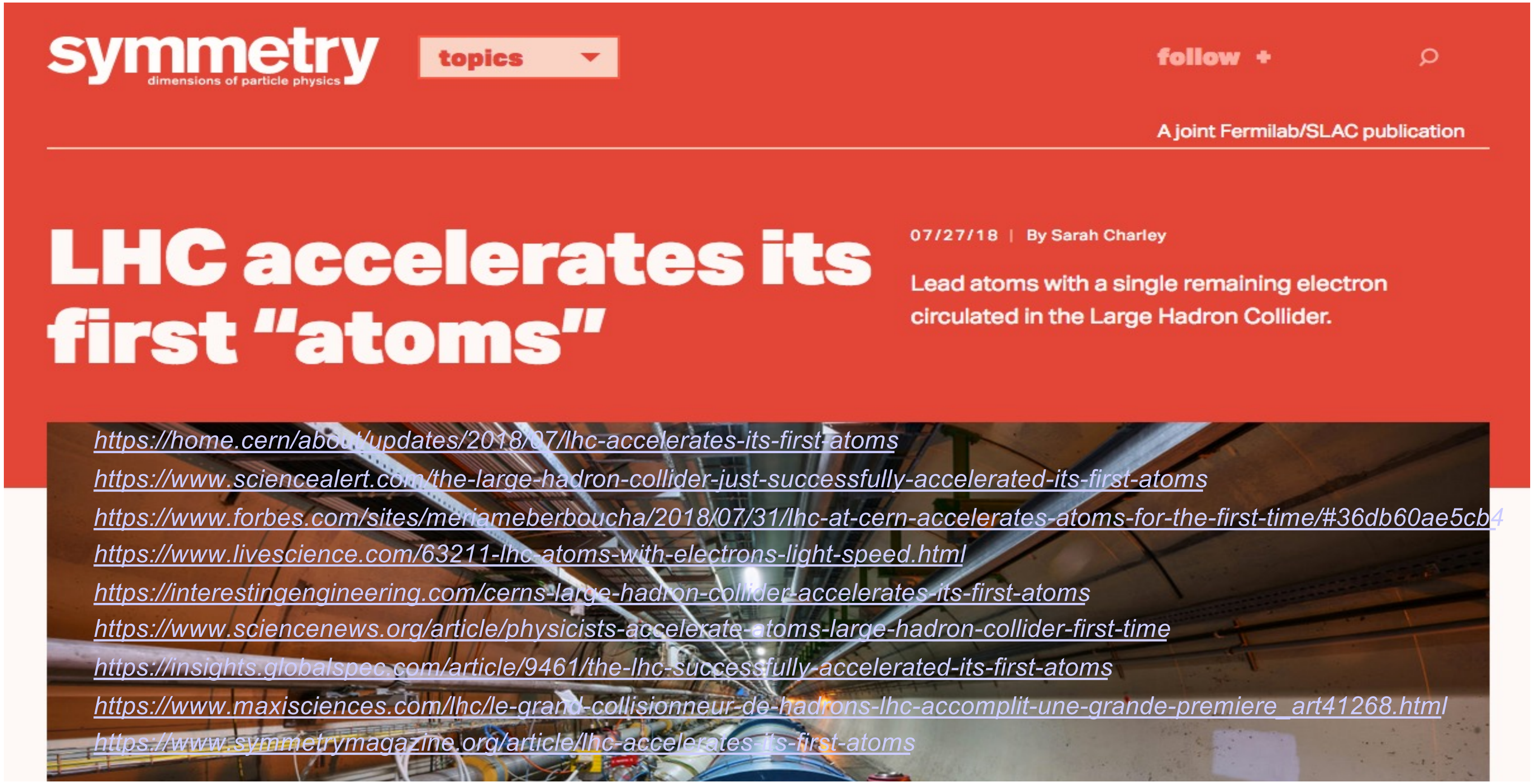
Figure 8 — CAD model of the new integration





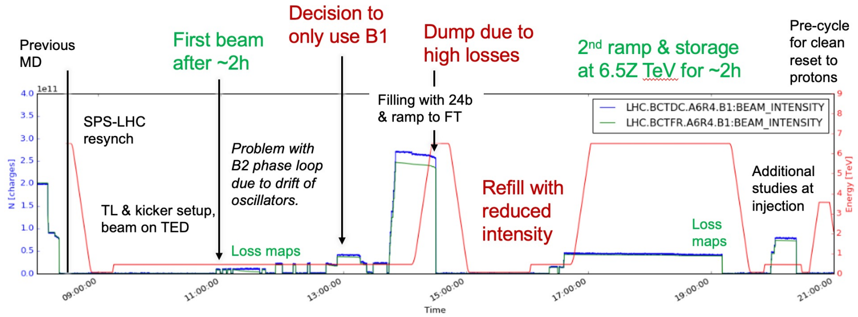
R. Alemany-Fernandez (BE.OP), E. Grenier-Boley and D. Baillard (SY.STI)

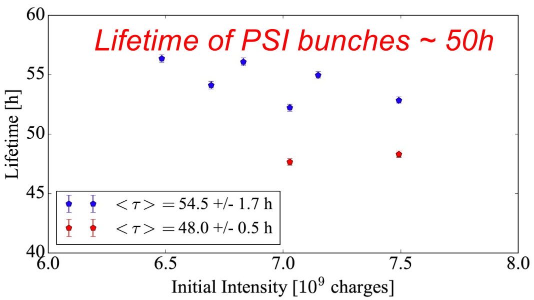
The two tanks of the new stripper system were installed during YETS 2021-2022 and YETS 2022-2023. Four stripper foil mechanisms are operating at ~Hz frequency.



- 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 2: Atomic beams stored in in the LHC






CERN-ACC-NOTE-2019-0012

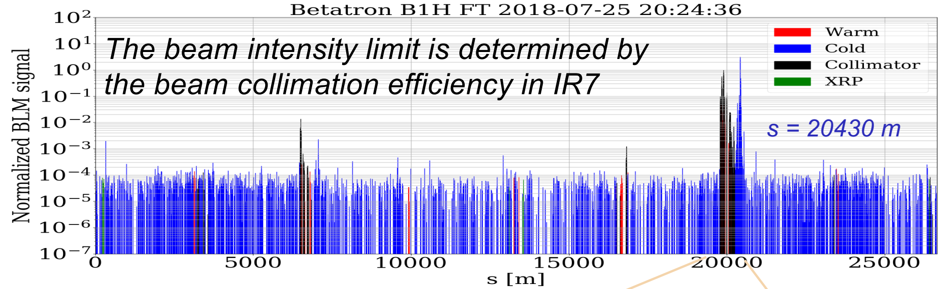
8 May 2019

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

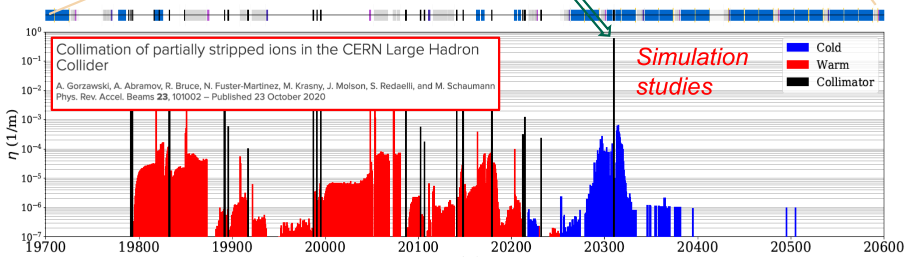
CERN, CH-1211 Geneva 23



IR7 zoom

<u>Mitigation strategies:</u>

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




PHYSICAL REVIEW ACCELERATORS AND BEAMS

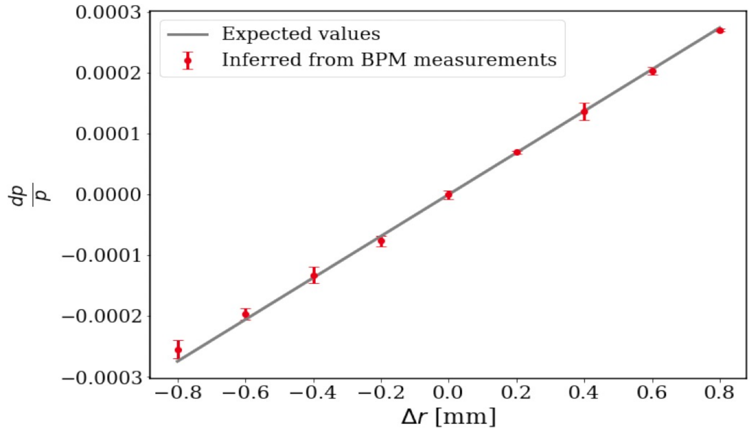
Highlights Recent Accepted Special Editions Authors Referees Sponsors Search

Editors' Suggestion Open Access

Collimation of partially stripped ions in the CERN Large Hadron Collider

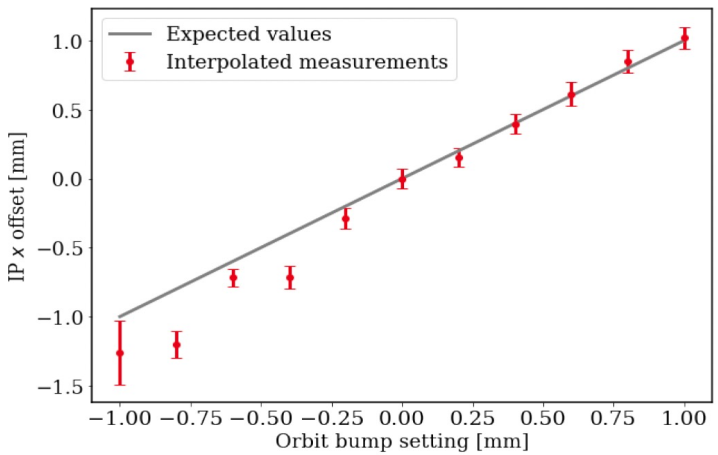
A. Gorzawski, A. Abramov, R. Bruce, N. Fuster-Martinez, M. Krasny, J. Molson, S. Redaelli, and M. Schaumann
Phys. Rev. Accel. Beams **23**, 101002 – Published 23 October 2020

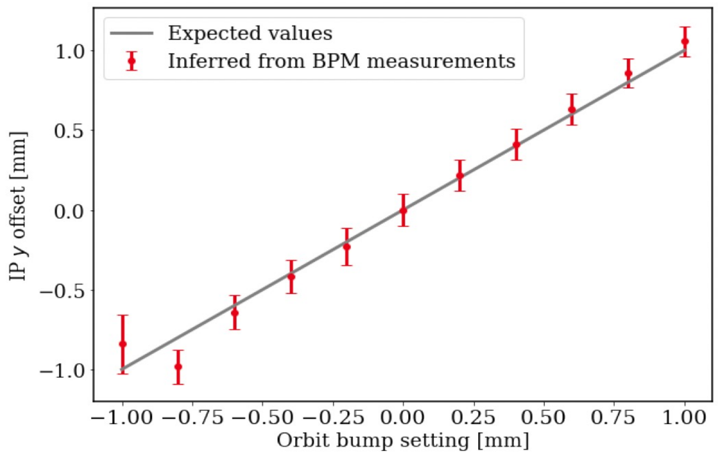
Step 3: Requisite precision of the momentum and beam position control at the collision point with laser photons



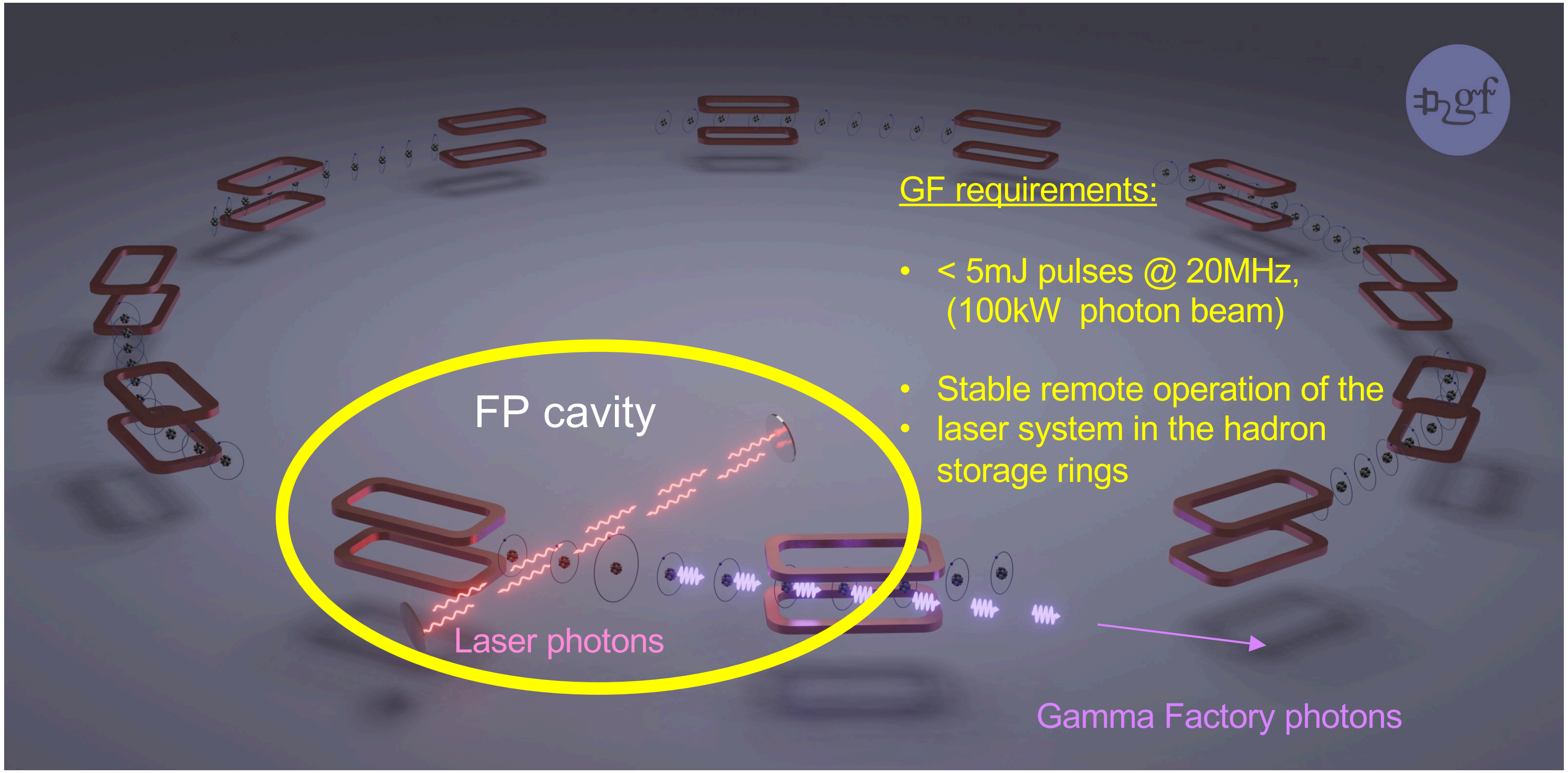
SPS MD5044 : machine stability characterisation
Gamma Factory SPS Proof-of-Principle Experime

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

Check for updates

+ Author & Article Information

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

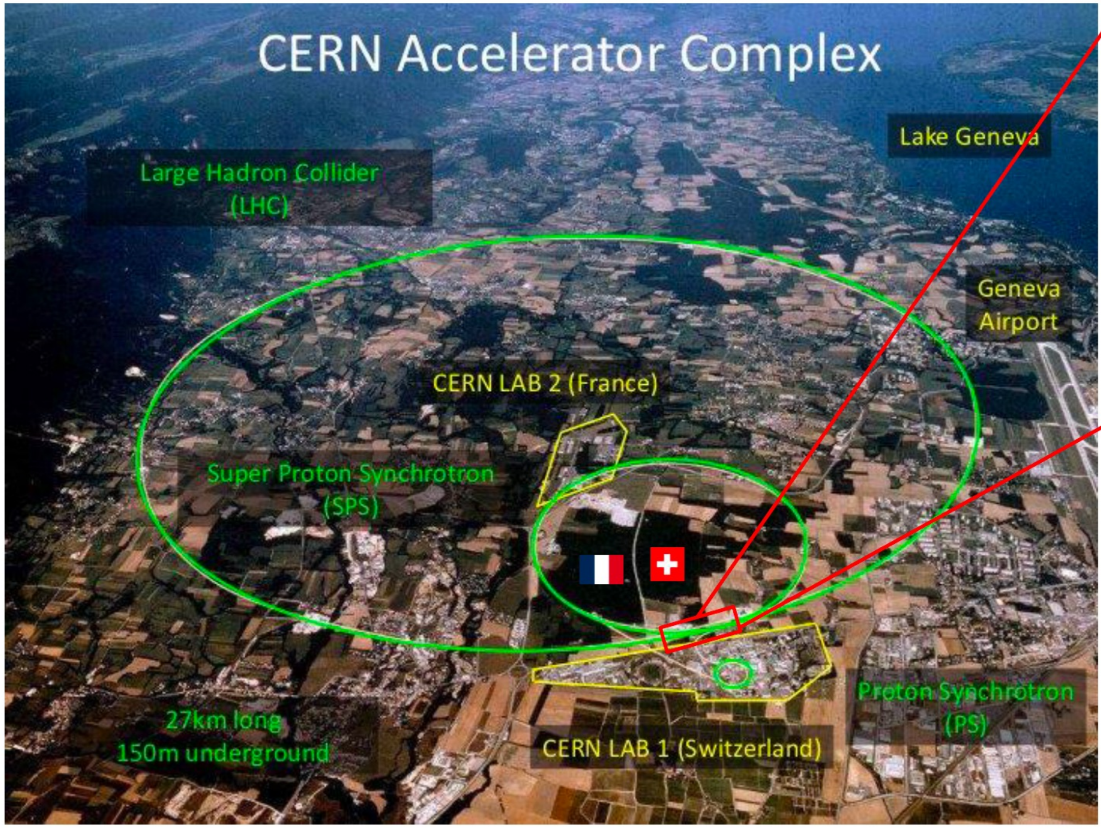
https://doi.org/10.1063/5.0213842 **Article history**

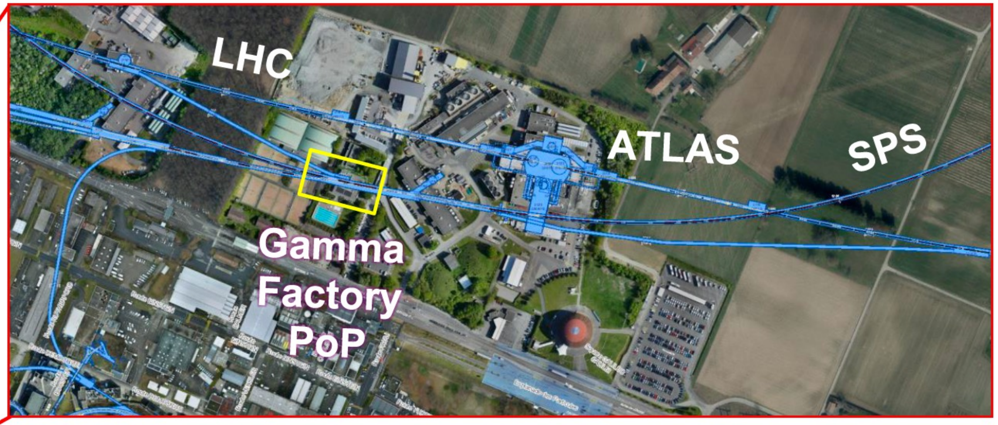
Stable 710kW enhancement Fabry-Perot cavity experiment

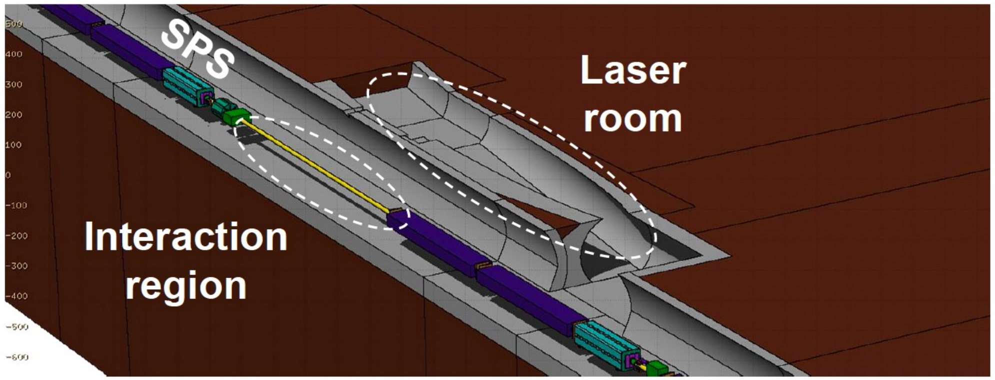
Aurélien Martens

On behalf of IJCLab ILE group

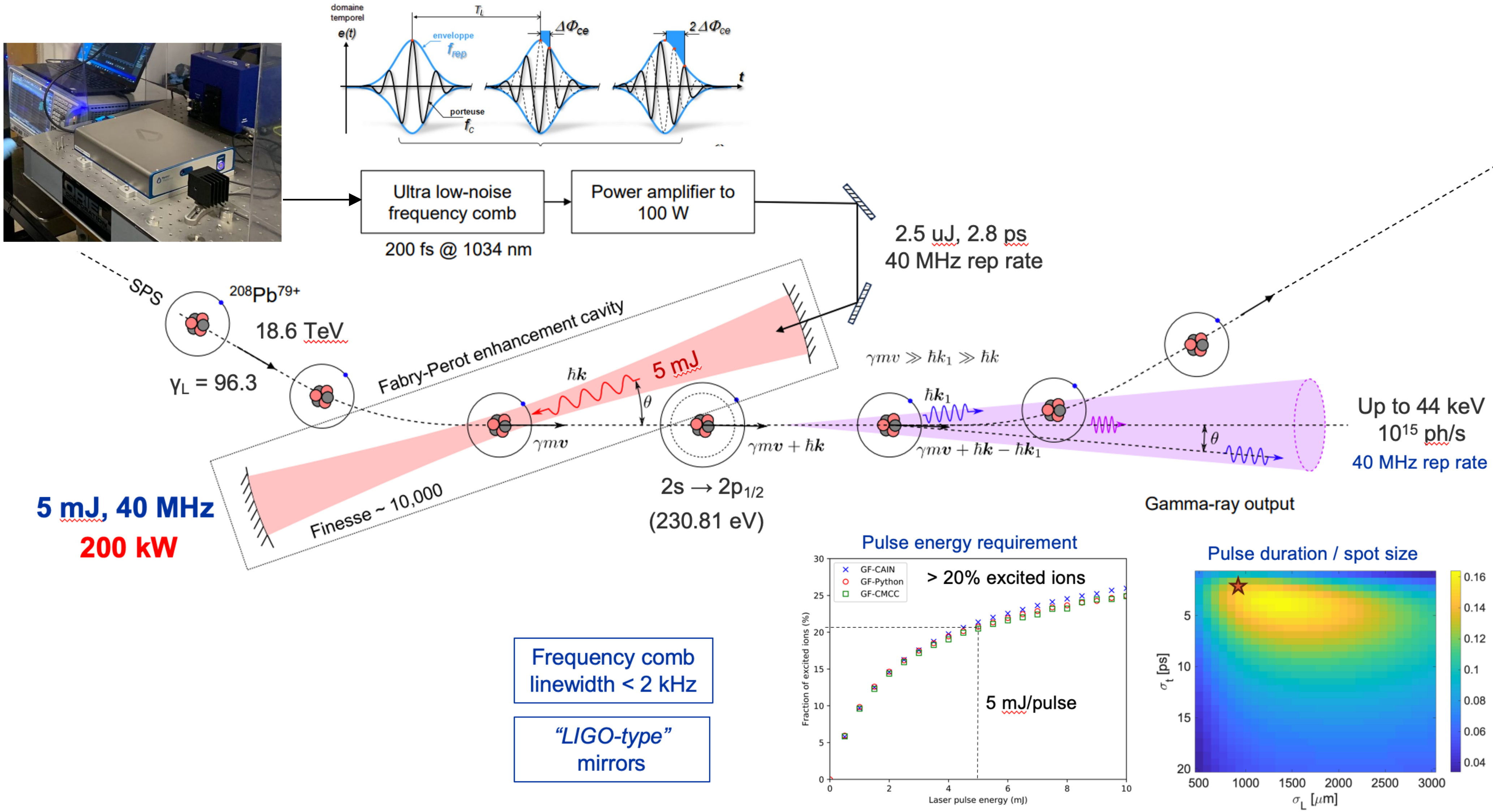
FINAL Step : Gamma Factory Proof-of-Principle experiment





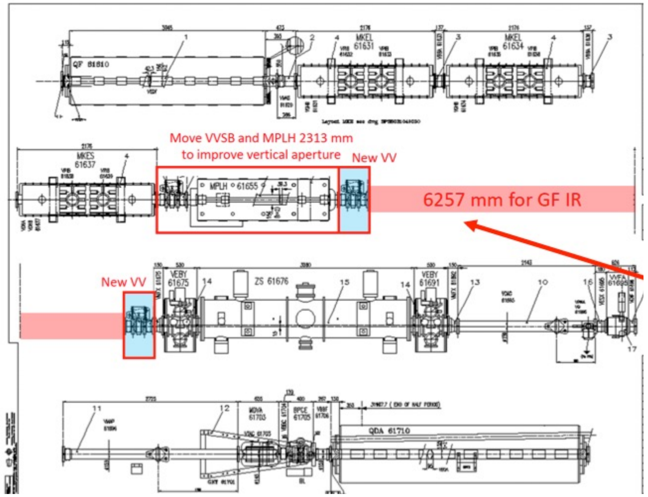


PLANNED INSTALLATION TIME – LS3


domaine temporel
e(t)
T_L
$\Delta\Phi_{ce}$
$2\Delta\Phi_{ce}$
enveloppe
f_{rep}
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
5 mJ
$\hbar k$
θ
$\gamma m v$
$\gamma m v + \hbar k$
$\gamma m v \gg \hbar k_1 \gg \hbar k$
$\hbar k_1$
$\gamma m v + \hbar k - \hbar k_1$
θ
Up to 44 keV
10^{15} ph/s
40 MHz rep rate
Gamma-ray output
Finesse ~ 10,000
$2s \rightarrow 2p_{1/2}$
(230.81 eV)
5 mJ, 40 MHz
200 kW
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]

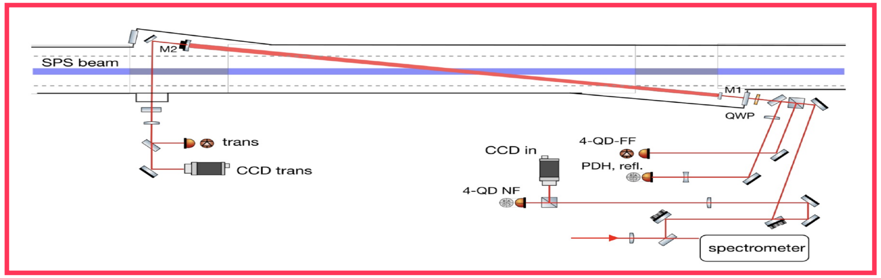
Gamma Factory Proof-of-Principle (PoP) SPS experiment

SPS LSS6 zone

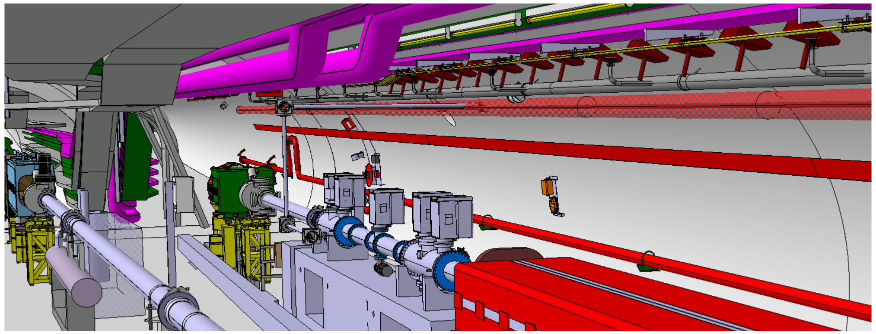


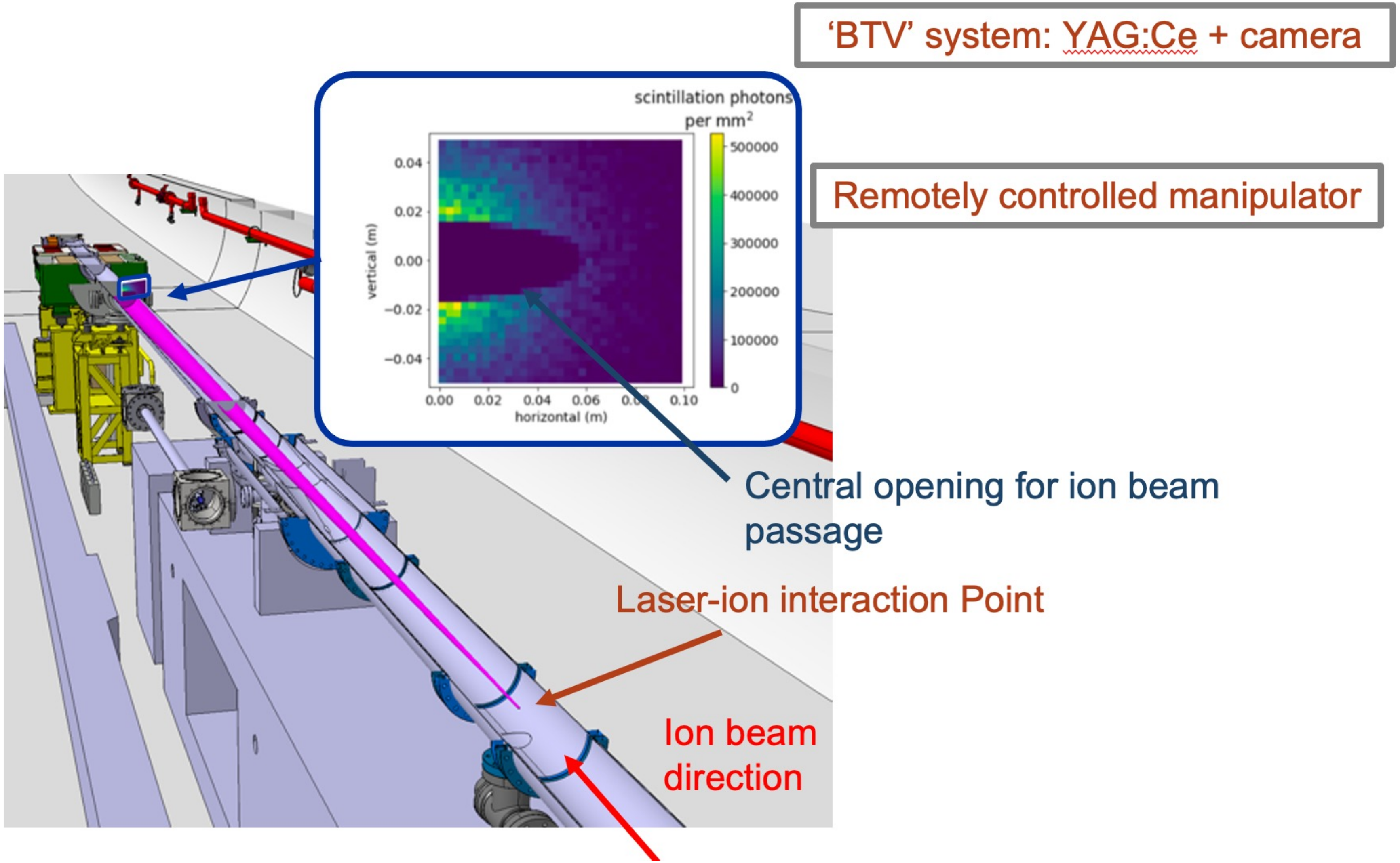
***F-P cavity length – 3.75 m** -- vertically tilted by 2..6 deg*

F-P cavity



F-P cavity – "in beam" position



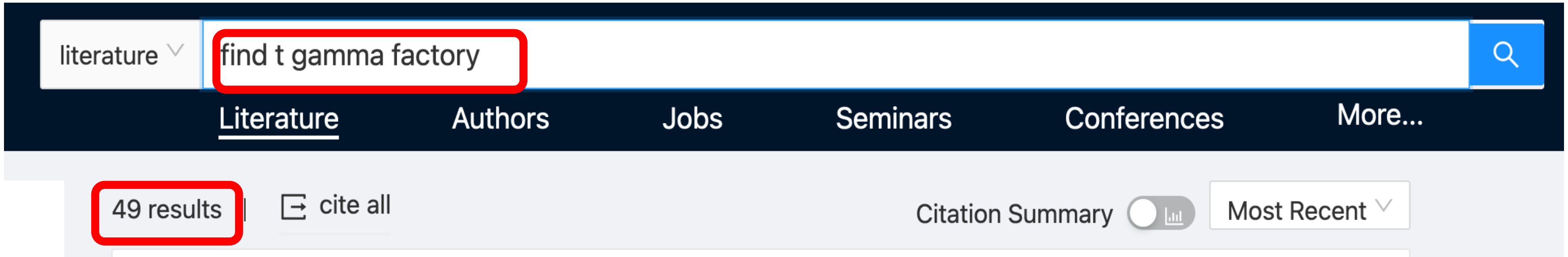


'BTV' system: YAG:Ce + camera
Remotely controlled manipulator
scintillation photons per mm^2
500000
400000
300000
200000
100000
0
0.04
0.02
0.00
−0.02
−0.04
vertical (m)
0.00
0.02
0.04
0.06
0.10
horizontal (m)
Central opening for ion beam passage
Laser-ion interaction Point
Ion beam direction

Scientific programme – selected examples

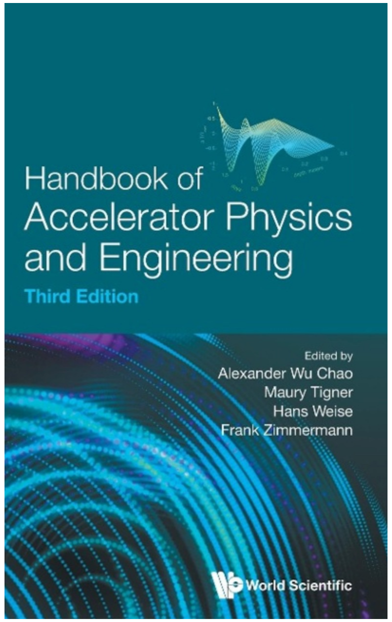
GF studies: published papers (INSPIRE) and books

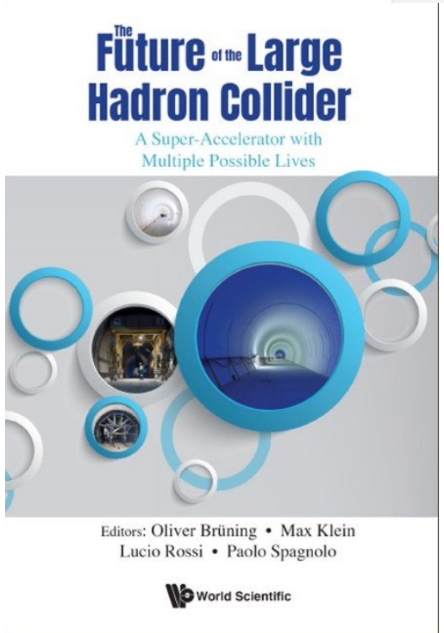
papers



books

Special issue of Annalen der Physik





New research opportunities

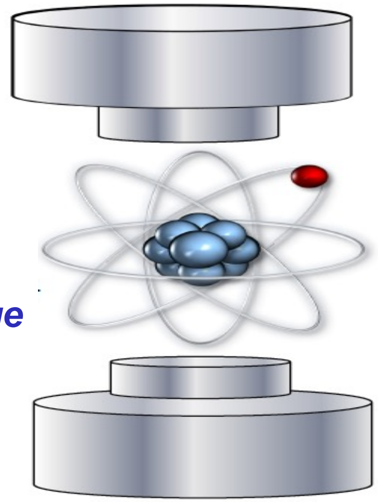
- ***particle physics*** *(precision QED and EW studies, vacuum birefringence, Higgs physics in $\gamma\gamma$ collision mode, rare muon decays, precision neutrino physics, QCD-confinement studies, …);*
- ***nuclear physics*** *(nuclear spectroscopy, cross-talk of nuclear and atomic processes, GDR, nuclear 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).*

GF experimental programme with atomic beams

Atomic Physics: highly-charged, “small-size” atoms

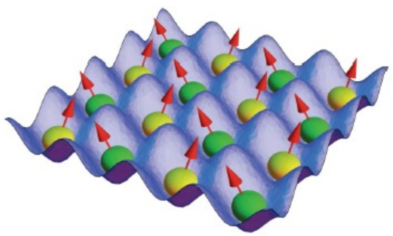
Atomic rest-frame

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



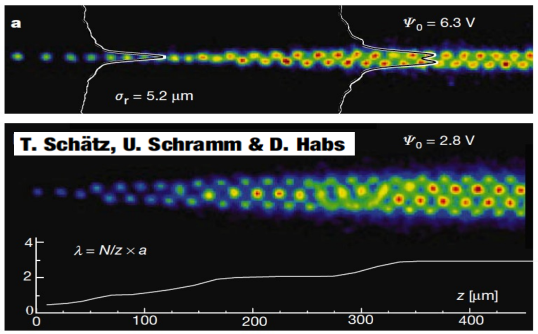
Opening new research opportunities in atomic physics:

- *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*



Crystalline beams?

letters to nature




annalen der physik

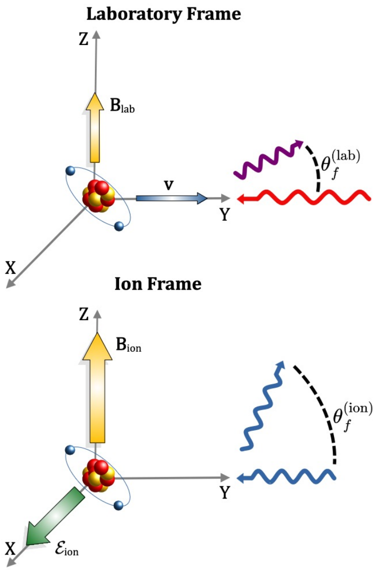
Feature Article | Open Access

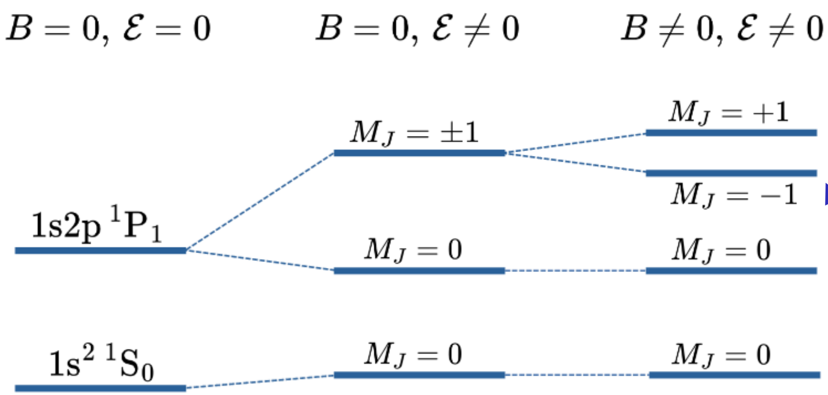
Atomic Physics Studies at the Gamma Factory at CERN

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

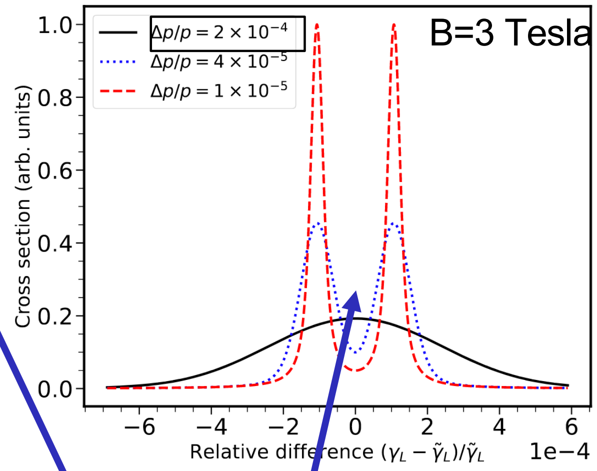
First published: 09 July 2020 | https://doi.org/10.1002/andp.202000204

Accelerator and Atomic physics interplay: very precise control of high energy beams (FP cavity in the dipole magnet)





Jan Richter, Preliminary



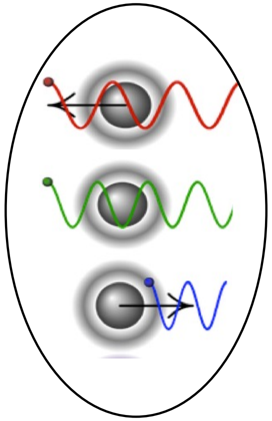
Observing Zeman splitting of the M_j = +/-1 sublevels of the excited He-like Ca atoms allows us to control the degree of cooling of the LHC beam

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

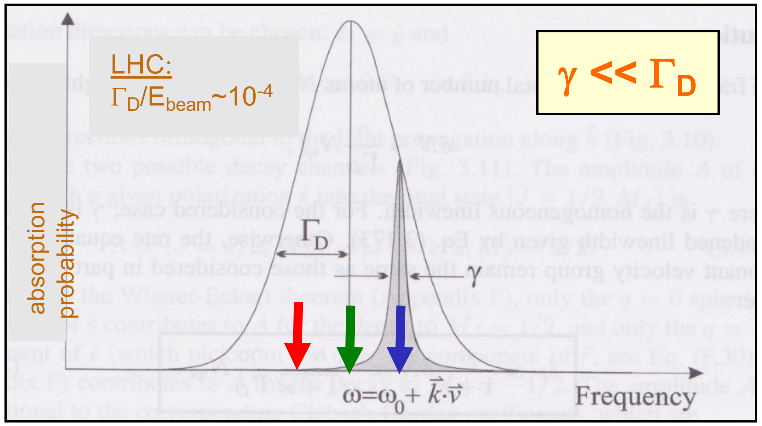
Jan Richter,[1,2,*] Mieczyslaw Witold Krasny,[3,4] Jan Gilles,[1,5] and Andrey Surzhykov[1,5]
[1] *Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany*
[2] *Institut für Theoretische Physik, Leibniz Universität Hannover, Appelstraße 2, 30167 Hannover, Germany*
[3] *LPNHE, 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*

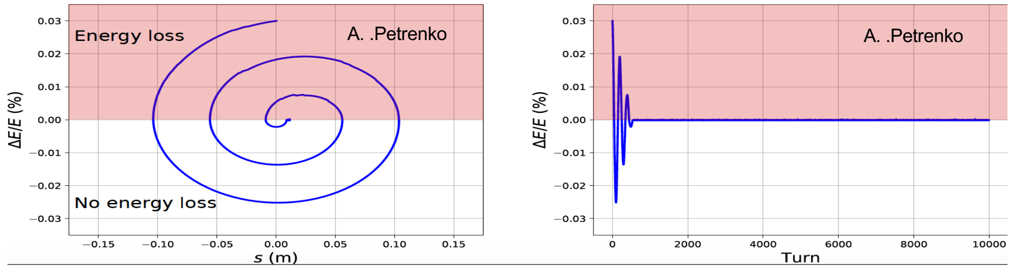
... to be published

Accelerator Physics: Gamma Factory "cold" atomic beams



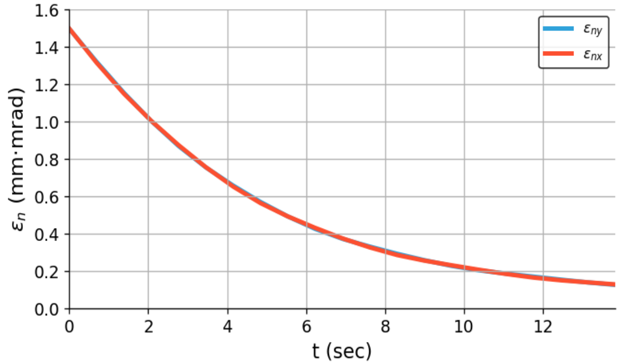
Bunch





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] nature reviews physics https://doi.org/10.1038/s42254-023-00682-0

Perspective

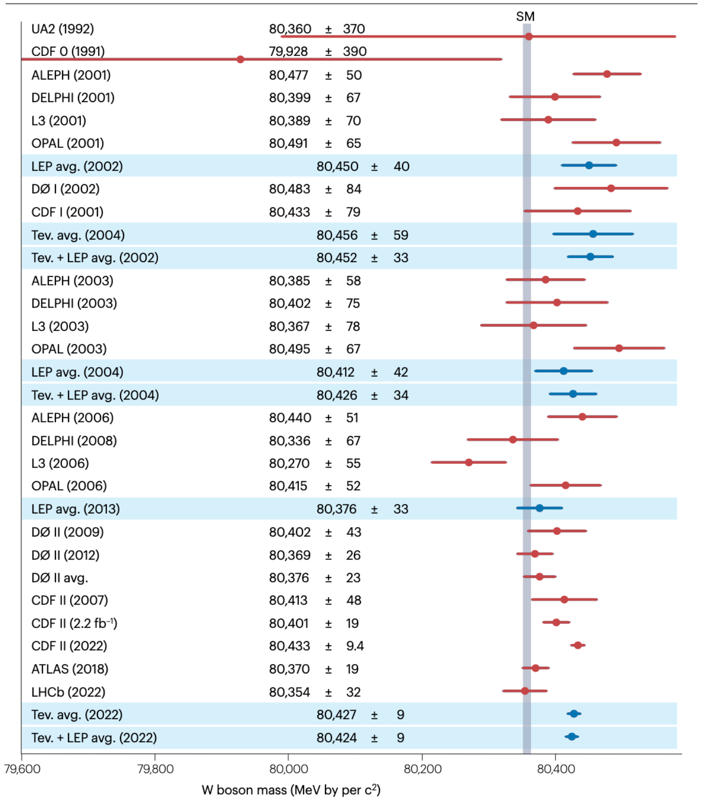
Check for updates

The precision measurement of the *W* boson mass and its impact on physics

Ashutosh V. Kotwal

Abstract

Sections

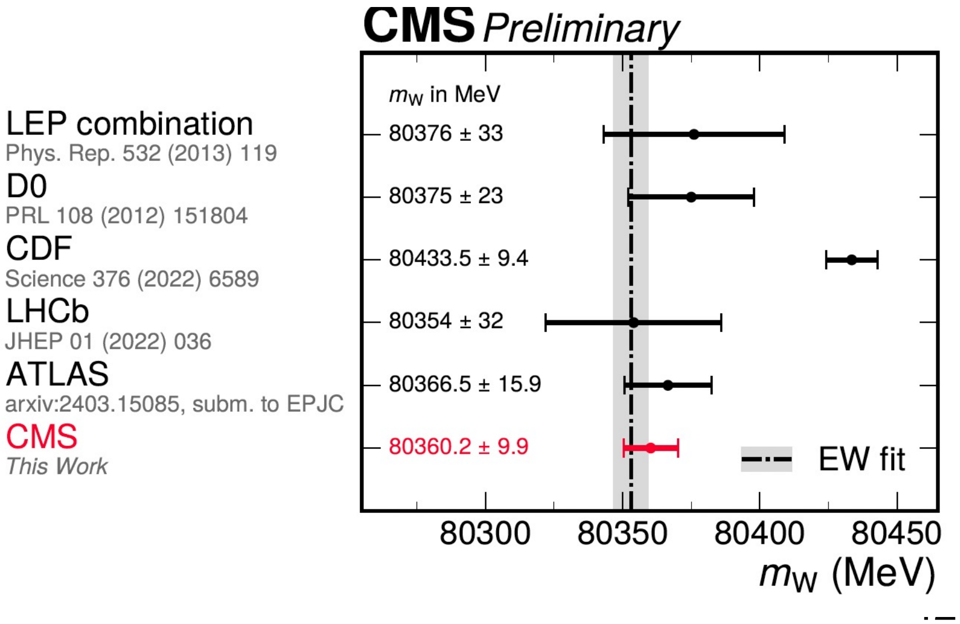


CMS Physics Analysis Summary

Contact: cms-pag-conveners-smp@cern.ch 2024/09/17

Measurement of the W boson mass in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration



Unconstrained PDF degrees of freedom for the pp collisions at the LHC energies

Assume for a while: $s(x)=\bar{s}(x)$, $c(x)=\bar{c}(x)$, $b(x)=\bar{b}(x)$ then:

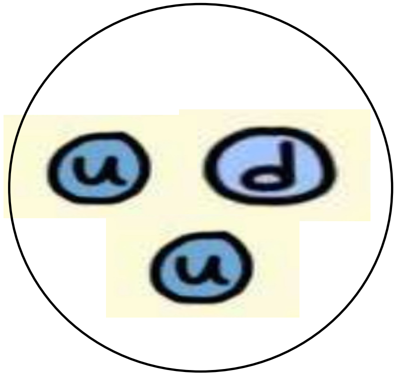
- 5 sea-quark flavours (u,d,s,c,b) + 2 valence quark flavours ($u^{(v)}$, $d^{(v)}$) 7 unknown PDFs:
- 4 constraints coming from the measurement of precision observables
- 7-4=3 degrees of freedom in the flavour-dependent pdf's remain unconstrained at the LHC (external input)

Important note:

At the Tevatron (lower energy) only the first quark family was relevant. In addition $\bar{p}p$ collisions.

This leaves only 2 (out of 7) flavour dependent pdf's. They are over-constrained.

Unbiased measurement of the EW processes at the LHC by using isoscalar ion rather than proton beams - WHY?



u and **d** quarks have different charges, weak isospin and vector and axial couplings.
For EW-physics: proton beams are equivalent to neutrino and electron beam mixed in not precisely known proportions.

In addition the relative distributions of the valence and sea u and d quarks determine the effective W/Z boson polarisation. Proton beams –> polarisation of W cannot be precisely controlled.

Isoscalar (A=2Z) ion beams

Profit from the flavour symmetry of strong interactions to to equalize the distributions of the u and d quarks: $u_{v,s}^{A=2Z,Z}(x, k_t, Q^2) = d_{v,s}^{A=2Z,Z}(x, k_t, Q^2)$

M.W. Krasny, F. Dydak, F. Fayette, W. Placzek, A. Siodmok, *Eur.Phys.J. C69 (2010) 379-397.*
F. Fayette, M.W. Krasny, W. Placzek, A. Siodmok, *Eur.Phys.J. C63 (2009) 33-56.*
M.W. Krasny, F. Fayette, W. Placzek, A. Siodmok, *Eur.Phys.J. C51 (2007) 607-617.*
M.W. Krasny, S. Jadach, W. Placzek, *Eur.Phys.J. C44 (2005) 333-350.*

Particle Physics: Gamma Factory path to HL-LHC:

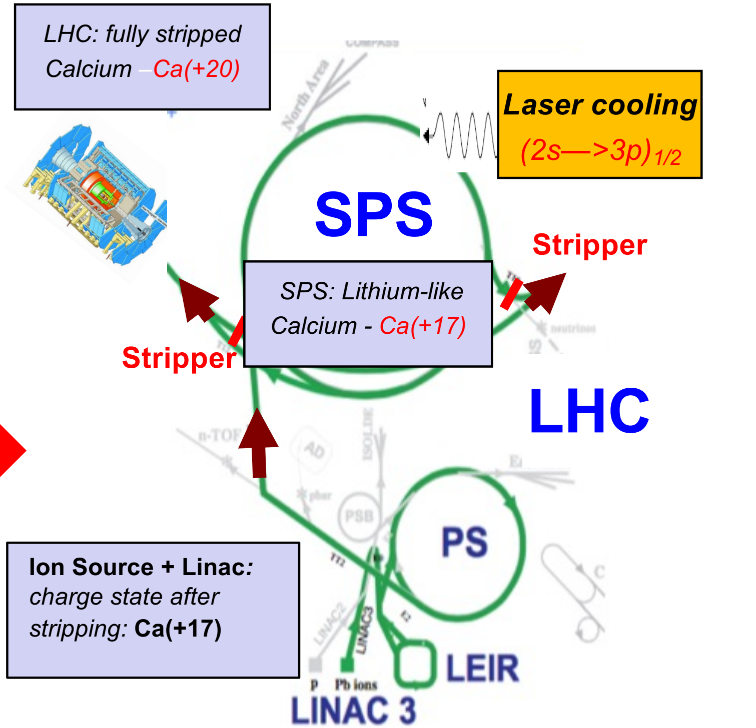
Studies of the implementation scheme with laser-cooled isoscalar Ca beams

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

***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

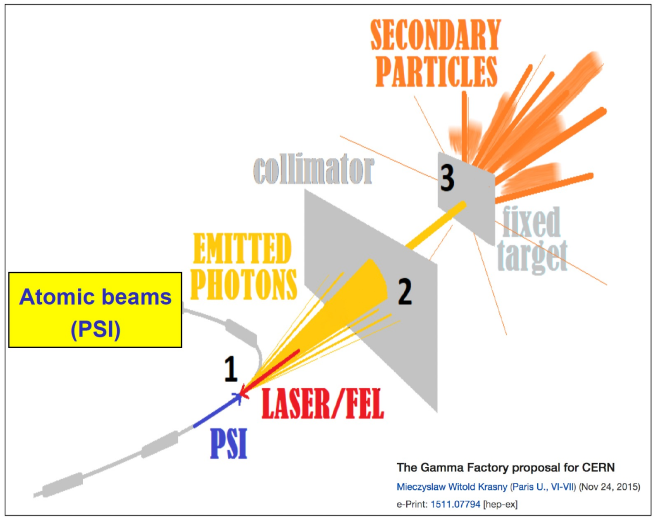
- *higher precision in measuring SM parameters in CaCa than in pp collisions*
- *Possible unique access to exclusive Higgs boson production in photon–photon collisions?*

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

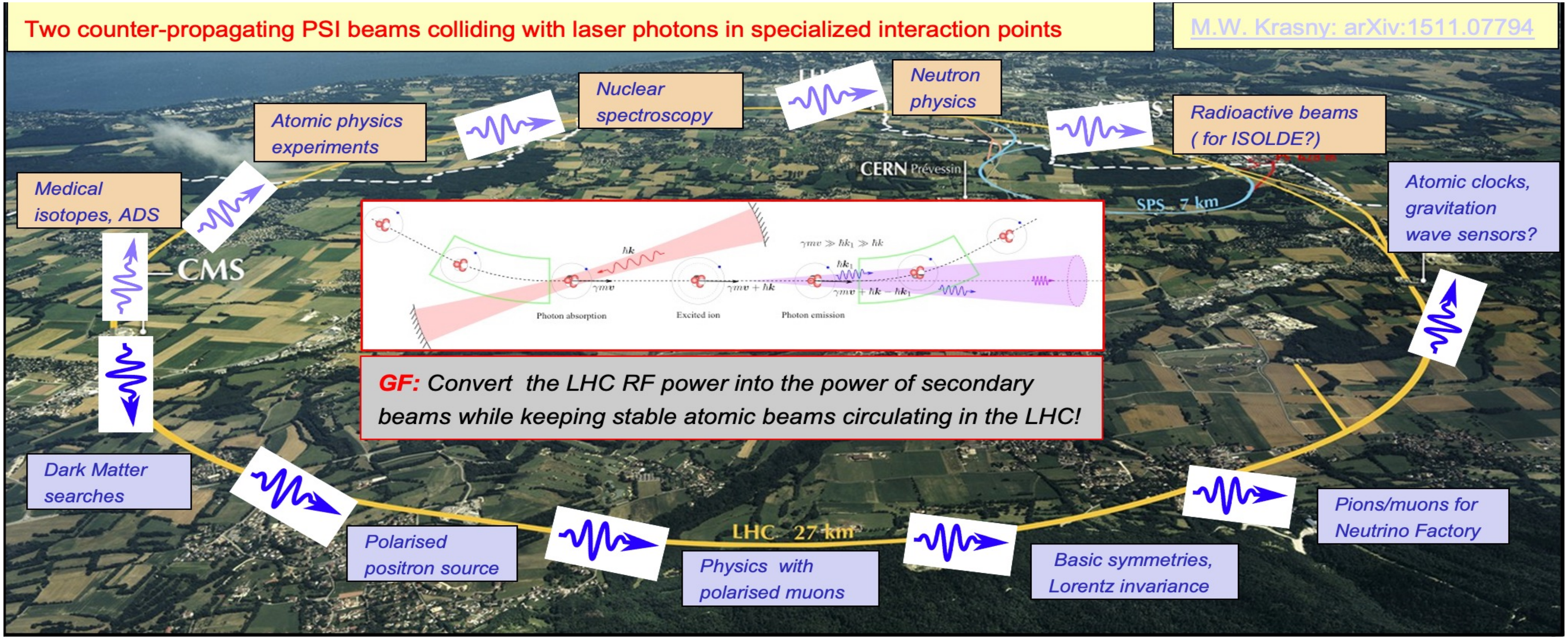
Review
High-luminosity Large Hadron Collider with laser-cooled isoscalar ion beams ☆

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

GF experimental programme with high intensity photon beams



… the GF-future of the LHC?



- ***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*

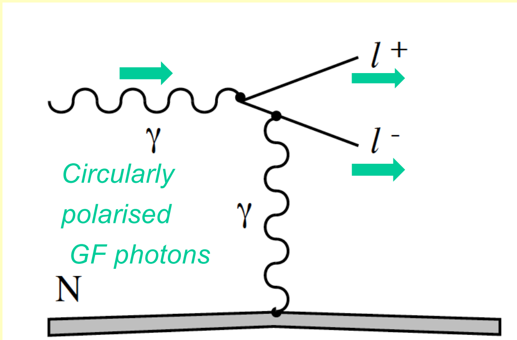
- ***Neutrons*** – *a comparable neutron flux with respect to the future neutron spallation sources e.g. at ESS – but quasi monoenergetic MeV neutrons*

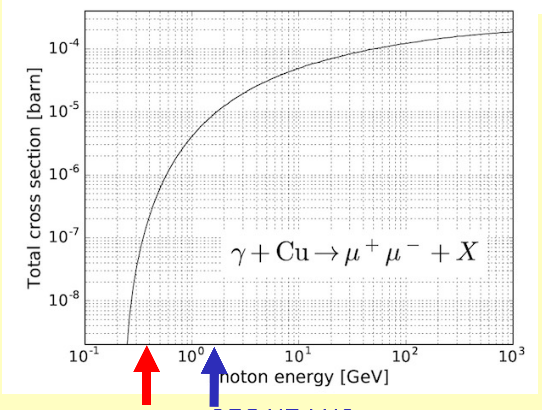
- ***Radioactive (neutron-rich) ions*** – *potential gain of up to a factor 10^4 in intensity with respect to e.g. ALTO*

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		$3 \cdot 10^4$	

Two ways of producing polarised muons by photons in GF



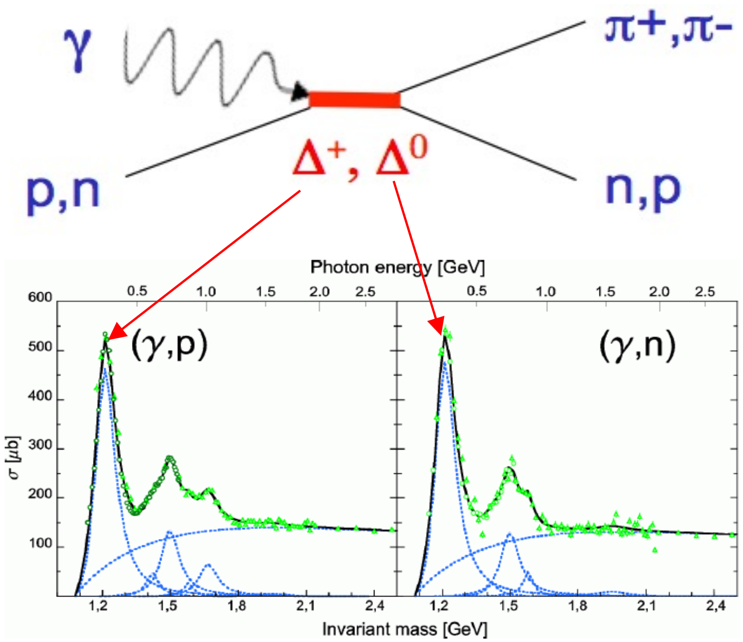


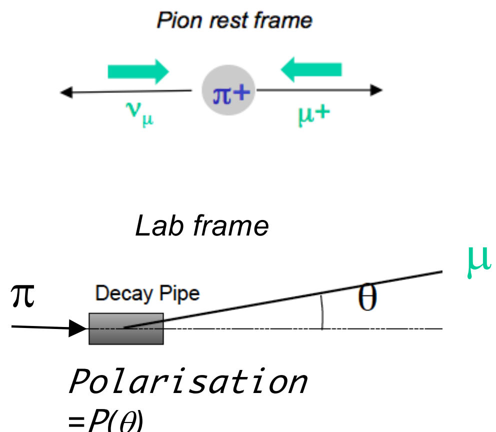
GF@LHC GF@HE-LHC

~ 10^{10} μ/s source for GF@LHC

(Mass threshold effect)

New concept





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

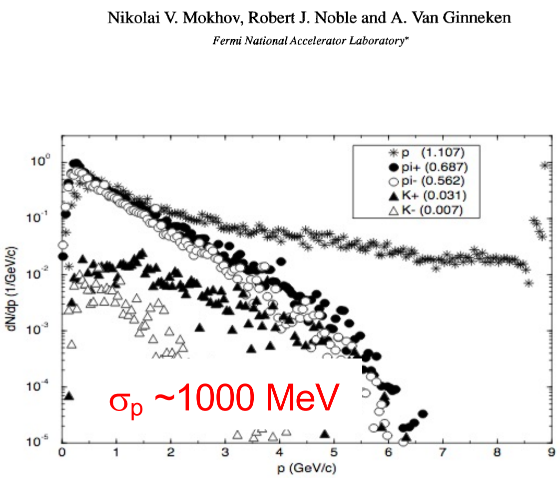
High intensity source: 2x10^{13} (10^14) μ^+ and μ^- per second for the 2X0 graphite (deuterium) target and 1 MW, 300 MeV photon beam!

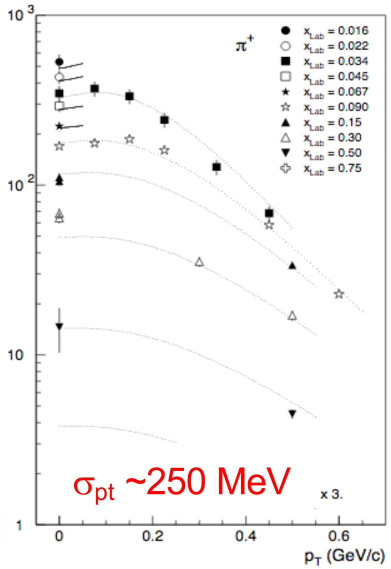
Pion spectral density

8 GeV proton beam

For λ_i = 2 **graphite** target:

~ 4.1 x 10^{14} π^+/s and ~ 2.6 x 10^{14} π^-/s for 1 MW p beam

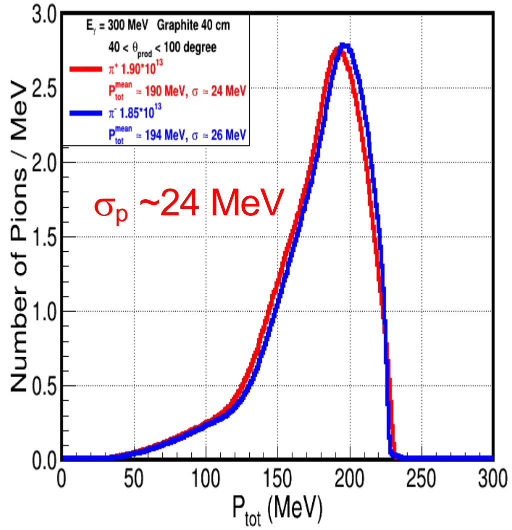


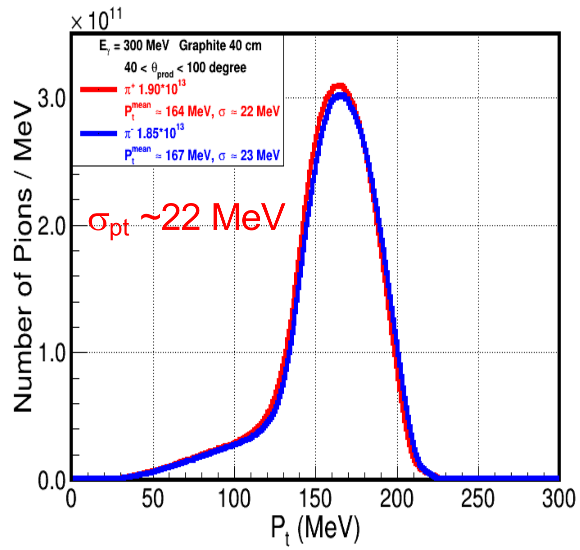


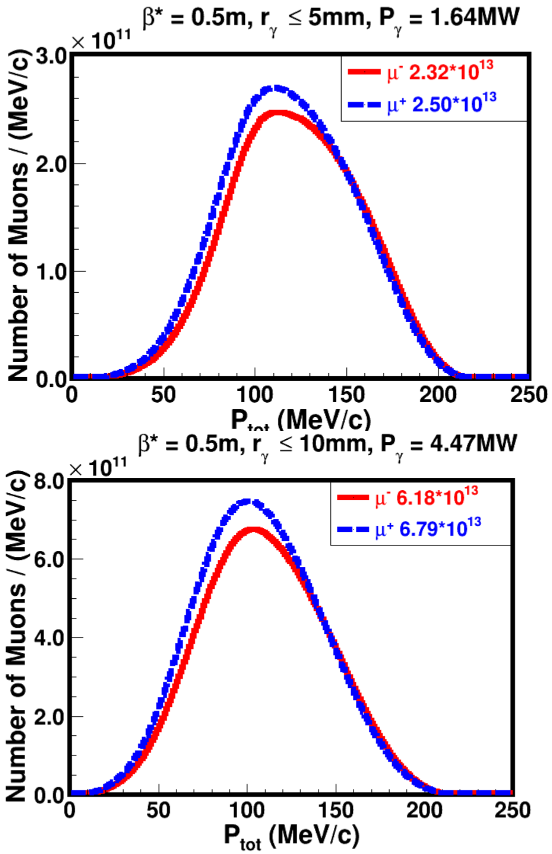
300 MeV GF γ-beam

For λ_i = 2 **graphite** target :

~ 3 x 10^{14} π^+ and π^- /s for 10 MW γ beam







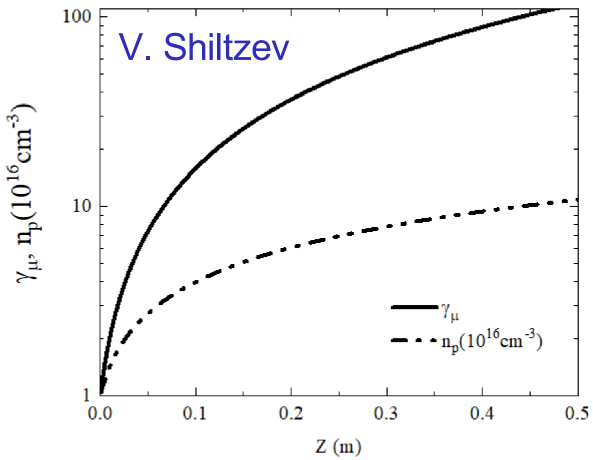
PHYSICAL REVIEW ACCELERATORS AND BEAMS **26,** 083401 (2023)

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*

Plasma Wakefield Accelerator-Based Low Emittance Muon Source

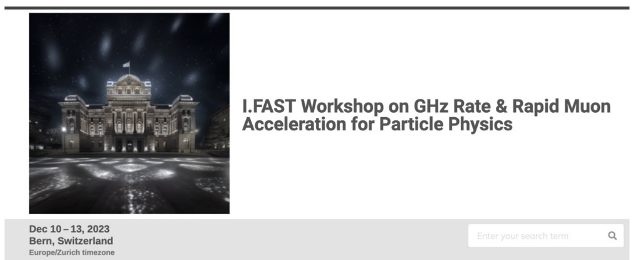
Tapered Plasma Density Rampup



$\gamma_p \approx (1+az)^{4/3}$

$n_p = n_0\ (1+az)^{2/3}$

Plasma density and muon energy in tapered PWA-based 10 GeV muon source with normalized acceptance of 25 µm - corresponding to



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

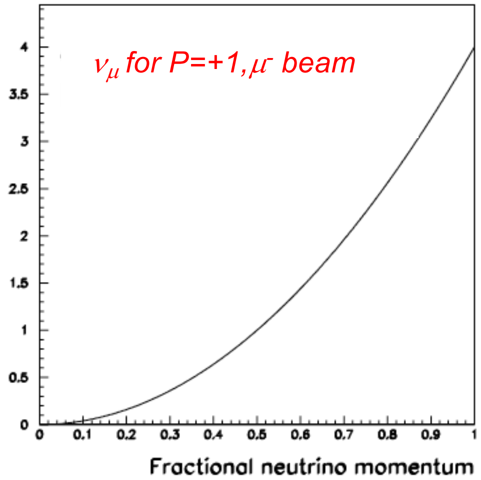
$$\frac{d^2N}{dx\,d\Omega} = \frac{1}{4\pi}\left[f_0(x) \mp \mathcal{P}_\mu f_1(x) \cos\theta\right]$$

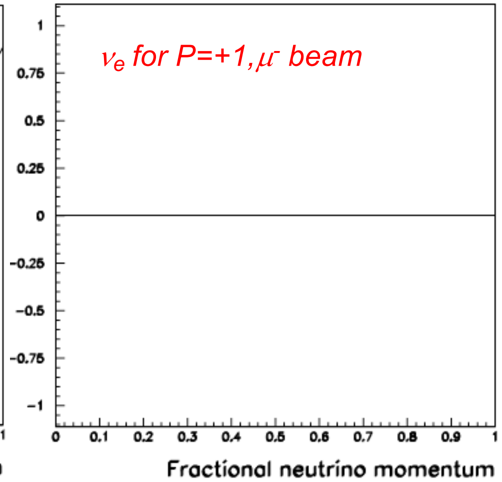
$x = 2E_\nu/m_\mu$

$\mathcal{P}_\mu$ 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	$12x^2(1-x)$	$12x^2(1-x)$

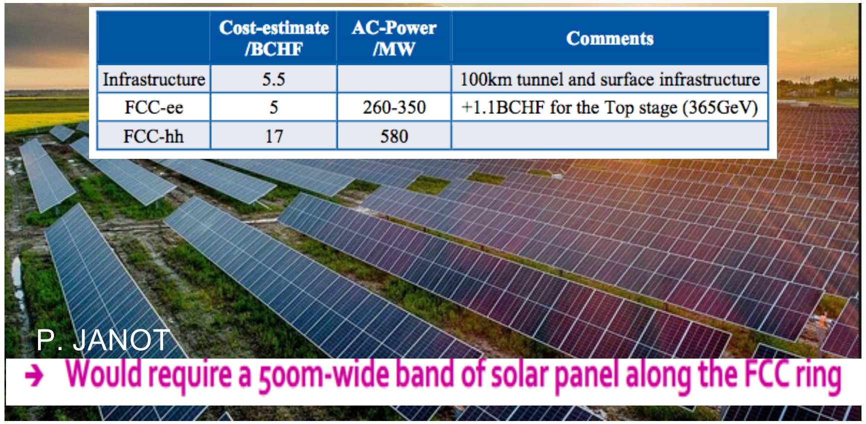




Conceptually optimal experiment to search for CP violation in the neutrino sector:

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^+.

Applied Physics: Photon-beam-driven energy source



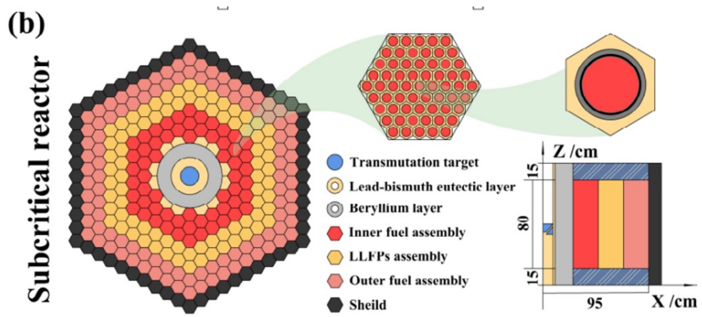
	Cost-estimate /BCHF	AC-Power /MW	Comments
Infrastructure	5.5		100km tunnel and surface infrastructure
FCC-ee	5	260-350	+1.1BCHF for the Top stage (365GeV)
FCC-hh	17	580	

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

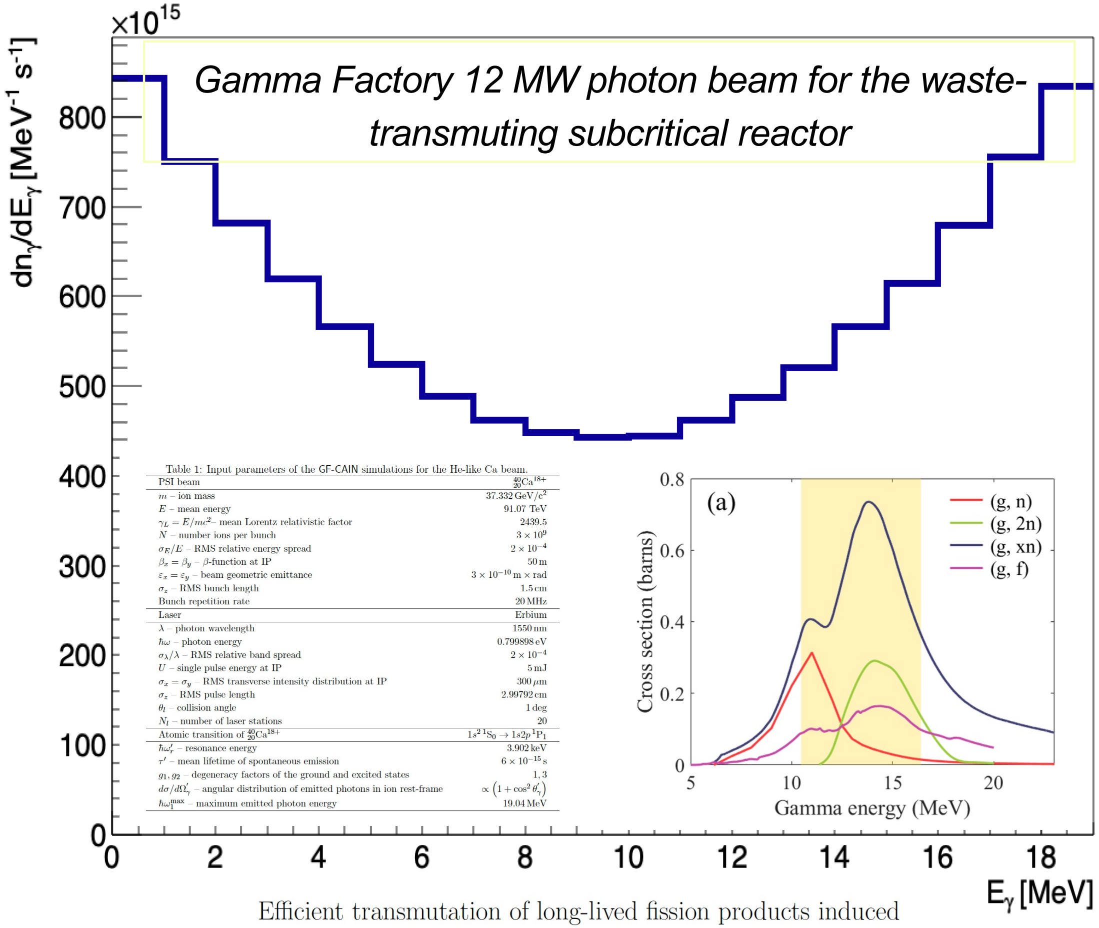


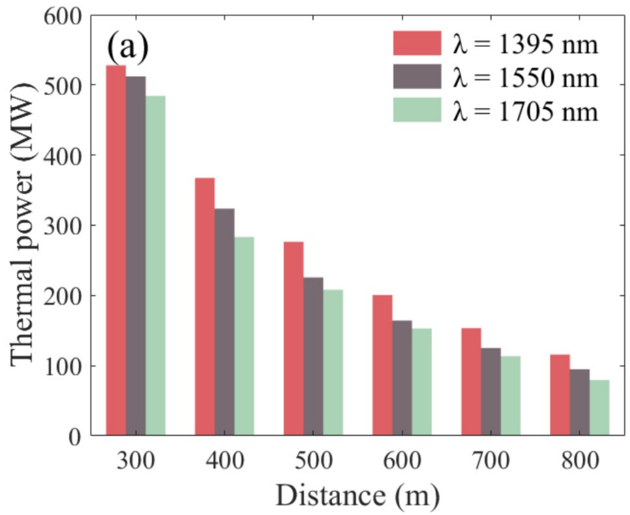
Table 1: Input parameters of the GF-CAIN simulations for the He-like Ca beam.

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

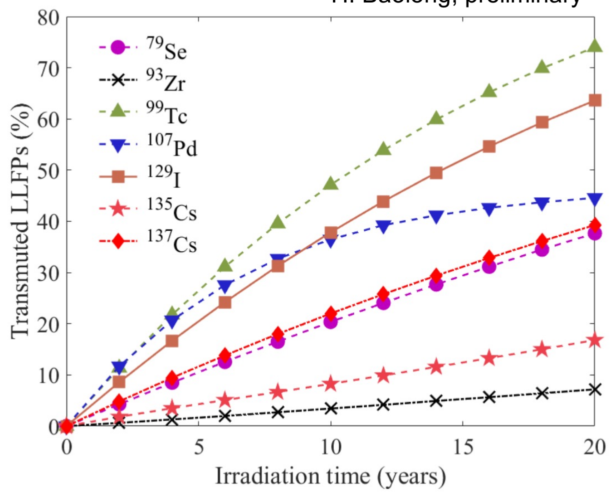
Efficient transmutation of long-lived fission products induced by Gamma Factory γ-ray beams

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

… to be published



H. Baolong, preliminary



Conclusions… and two possible subjects for discussion

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

- *The **next** CERN **high-energy frontier** project may take **long time** to be approved, built and become operational, … unlikely before 2048 (FCC-ee) or 2050+ (μ-collider)*

- *The **present** LHC **research programme** will certainly reach **earlier** (~2034?) its discovery **saturation** (little physics gain by a simple extending its pp/pA/AA running time)*

- *A strong **need** will certainly arise for a **novel** multidisciplinary programme which could **re-use** ("co-use") the **existing** CERN facilities (including LHC) in **ways** and at **levels** that were **not** necessarily **thought** of when the machines were **designed***

***The Gamma Factory** research programme could fulfil such a role. It can exploit **the existing world unique opportunities** offered by the CERN accelerator complex and CERN's scientific infrastructure **(not available elsewhere**) to conduct new, diverse, and vibrant research.*

1. Tool and Concept driven progress in science

"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

2. The future of our discipline

The existence of the Standard Model does not imply the existence of a standardized anticipation of the future. The only thing that deserves institutionalization is doubt. This problem of maintaining diversity of approach afflicts both experiment and theory, and if I have any concern about how the field is developing, it is about this point I worry the most.

James D. Bjorken (Bj)