Gamma Factory's ***high intensity particle beams and their potential impact on the future accelerator-technology-driven research.***

EPS conference Marseille

the 10th of July 2024

Mieczyslaw Witold Krasny (Gamma Factory)

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

"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

"Gamma Factory"

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

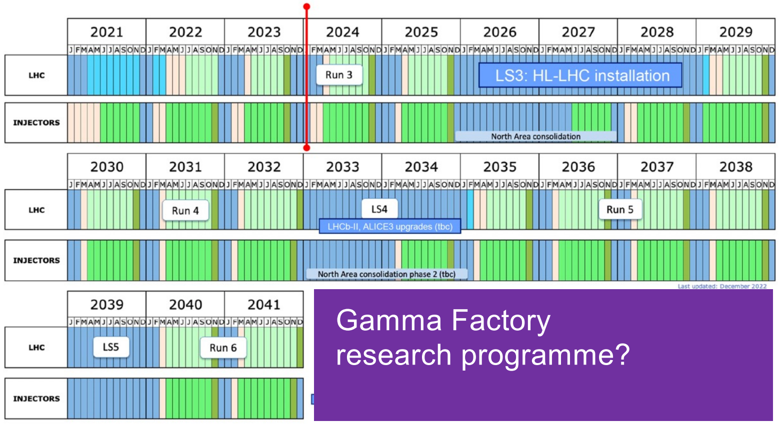
*We acknowledge the crucial role of the CERN **PBC** "framework" in bringing our accelerator tests, GF-PoP experiment preparation and software development to their present stage!*

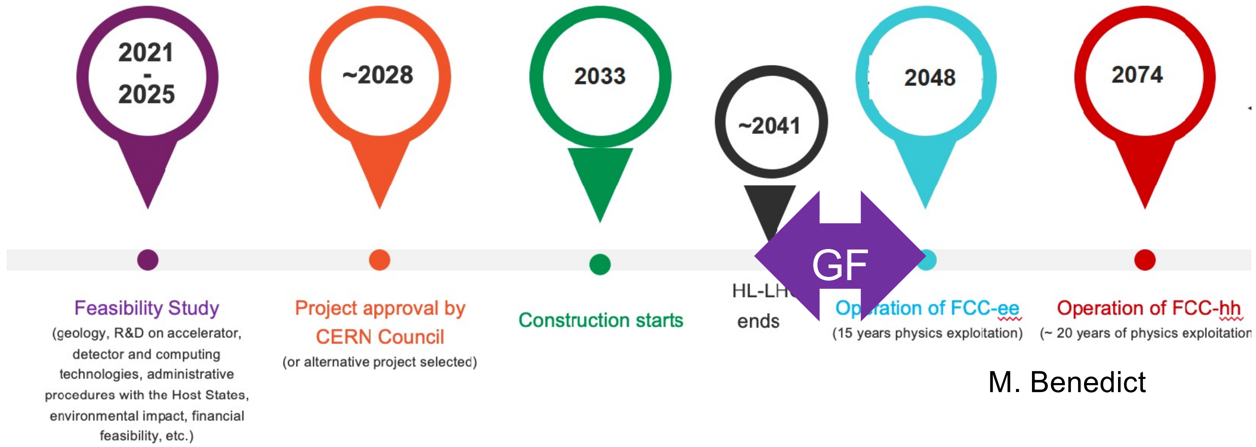
Outline of the talk

- *Rationale behind the Gamma Factory initiative*
- *Basic principles*
- *Gamma Factory beams*
- *Feasibility studies*
- *Proof-of-Principle experiment at the SPS*

Rationale behind the Gamma Factory initiative

Gamma Factory – novel research tools and a significant extension of the CERN research programme **using the existing CERN accelerator infrastructure**





- *Maximal LHC pp-luminosity and maximal intensity of the PS, PS-Booster and SPS extracted beams will be reached by the LS4 time. New paradigms/concepts of **using the existing CERN accelerator infrastructure** will be badly needed.*

- ***Gamma Factory** broad research programme can fill the gap between the end of the HL-LHC programme and the beginning of the next high-energy-frontier collider operation … at a relatively low cost (O(MCHF)) with the novel-type, unprecedented-intensity particle beams produced with high plug-power efficiency.*

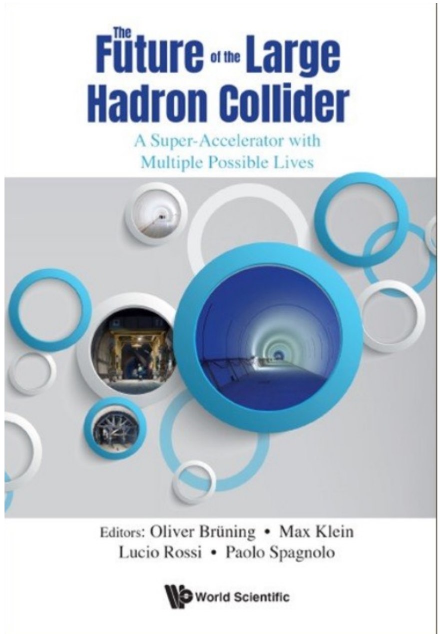
Gamma Factory: "A multidisciplinary research programme"

- ***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, $^{16}O(\gamma,\alpha)^{12}C$ 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 studies: published papers and books (Inspire)

papers

books



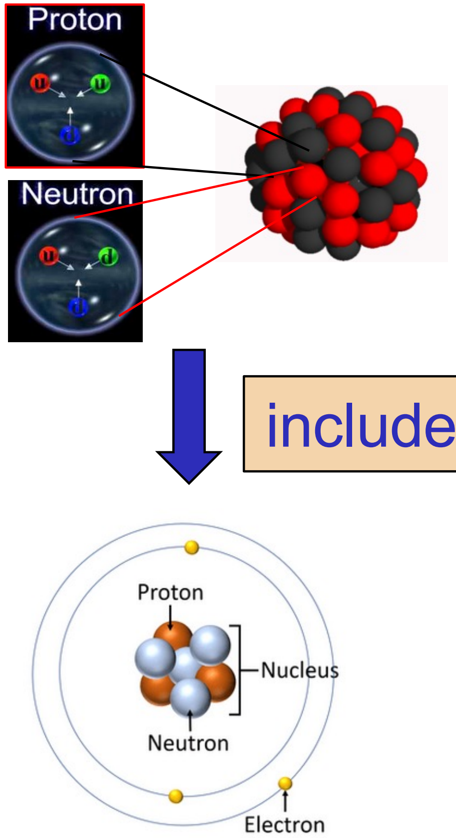
Gamma Factory: "Novel research tools made from light"

1. *Atomic traps of highly-charged atoms (connecting domains of atomic, nuclear and particle physics)*
2. *High intensity polarised photon(γ)-beams – (intensity leap by~7 orders of magnitude)*
3. *Novel, high intensity sources of polarised electrons, polarised positrons, polarised muons, (potentially) CP and flavour-tagged neutrinos, neutrons and radioactive ions (intensity/brightness leap >3 orders of magnitude)*
4. *Laser cooling methods of high-energy hadronic beams (unprecedented precision of controlling particle beams and reaching highest partonic luminosities at high energy hadronic colliders)*
5. *New type of the photon-beam--driven energy source (covering the plug-power consumption of CERN)*
6. *Electron beam for ep collisions in the LHC interaction points (unique partonic emittance diagnostic tool for high energy hadron colliders*
7. *…*

Basic principles

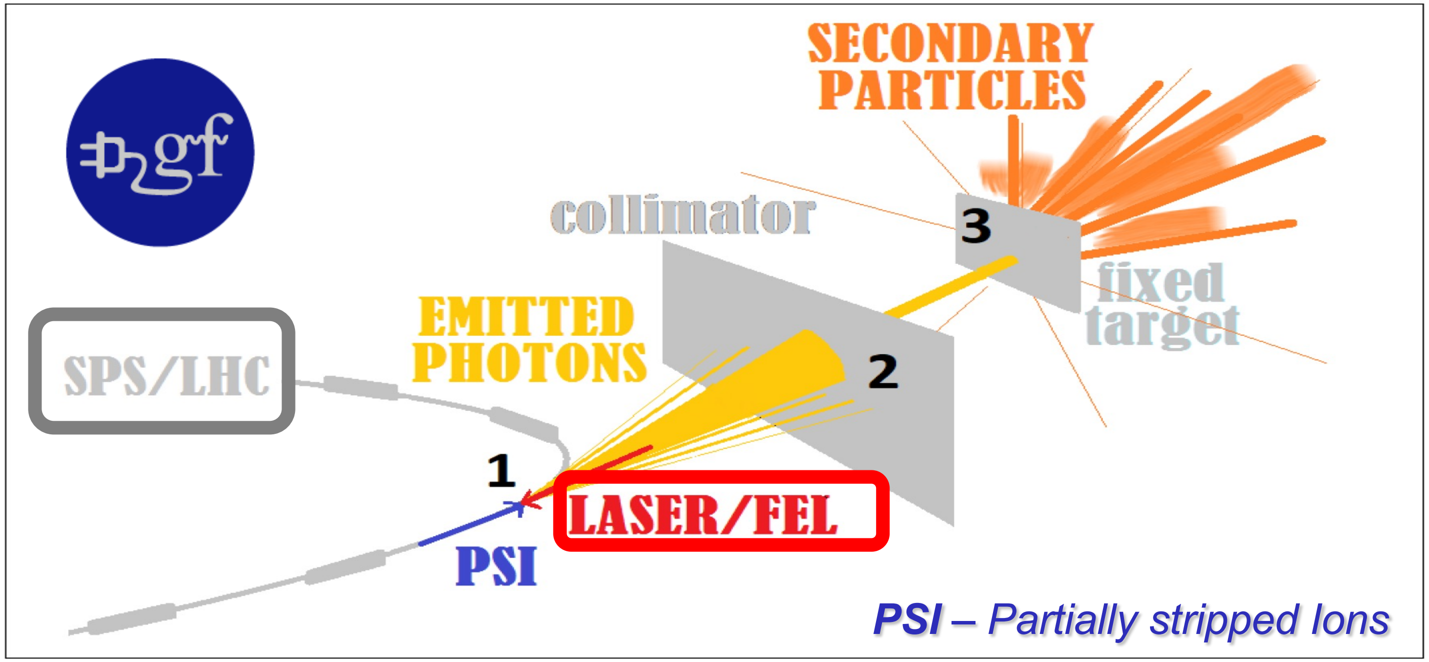
Gamma Factory requirements

LHC beams



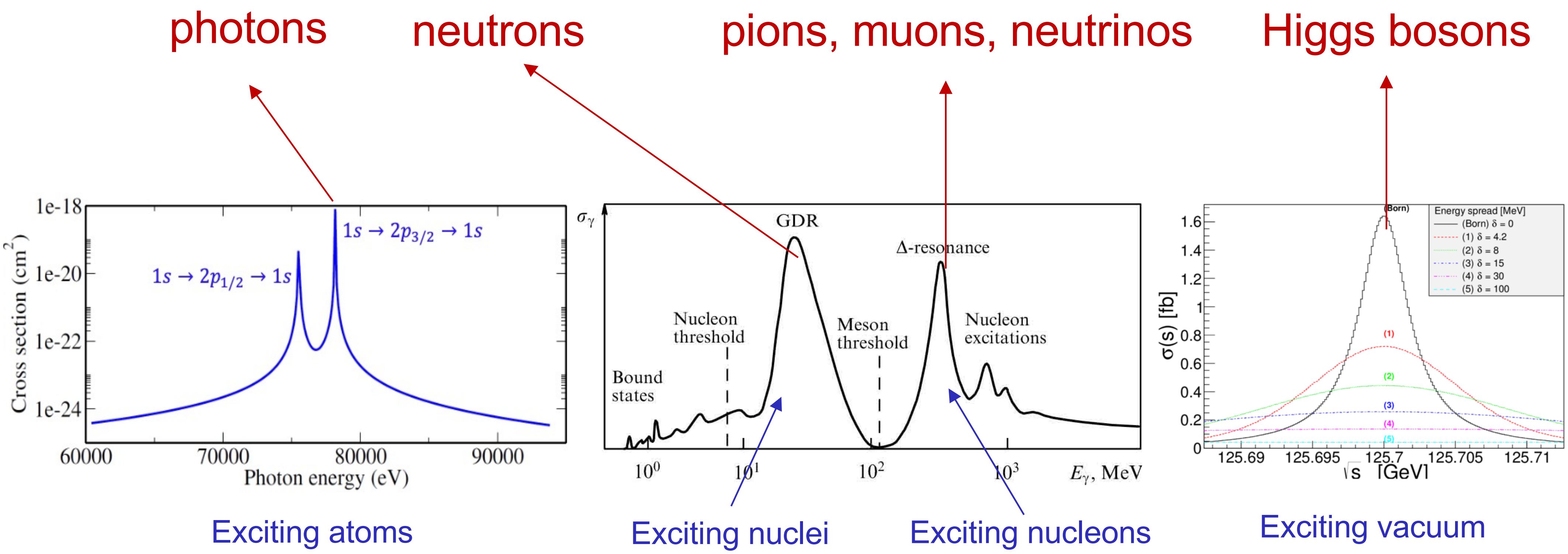
include

- *Include **atomic beams of partially stripped ions** in the LHC menu*
- *Collide them with laser pulses to produce beams of polarized photons polarized electrons, positrons, muons, neutrons, radioactive ions*



***PSI** – Partially stripped Ions*

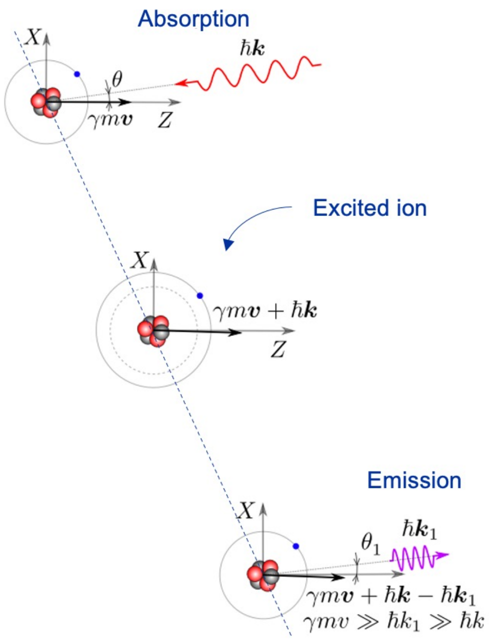
Gamma Factory: exploiting the resonant photon collisions



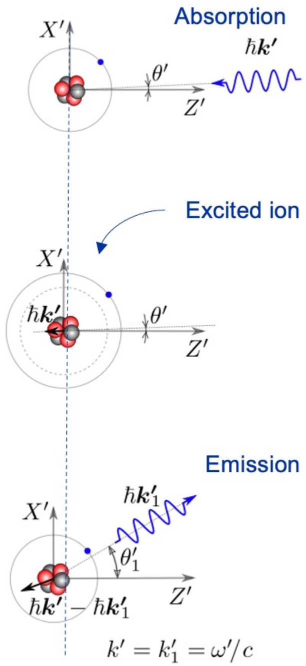
<u>“Photon acceleration”:</u>

High energy atomic beams play the role o 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

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

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

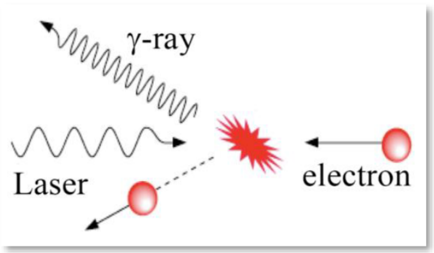
$$\nu^{max} \longrightarrow (4\,\gamma_L^{\,2})\;\nu_i$$

γ_L = E/M - Lorentz factor for the ion beam

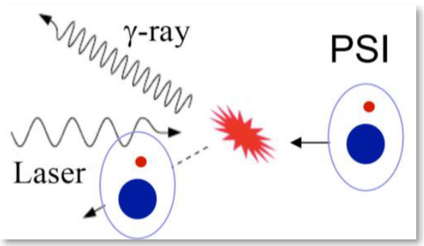
(100 - 3000 for CERN beams!)

Photon acceleration – Intensity and efficiency leap:

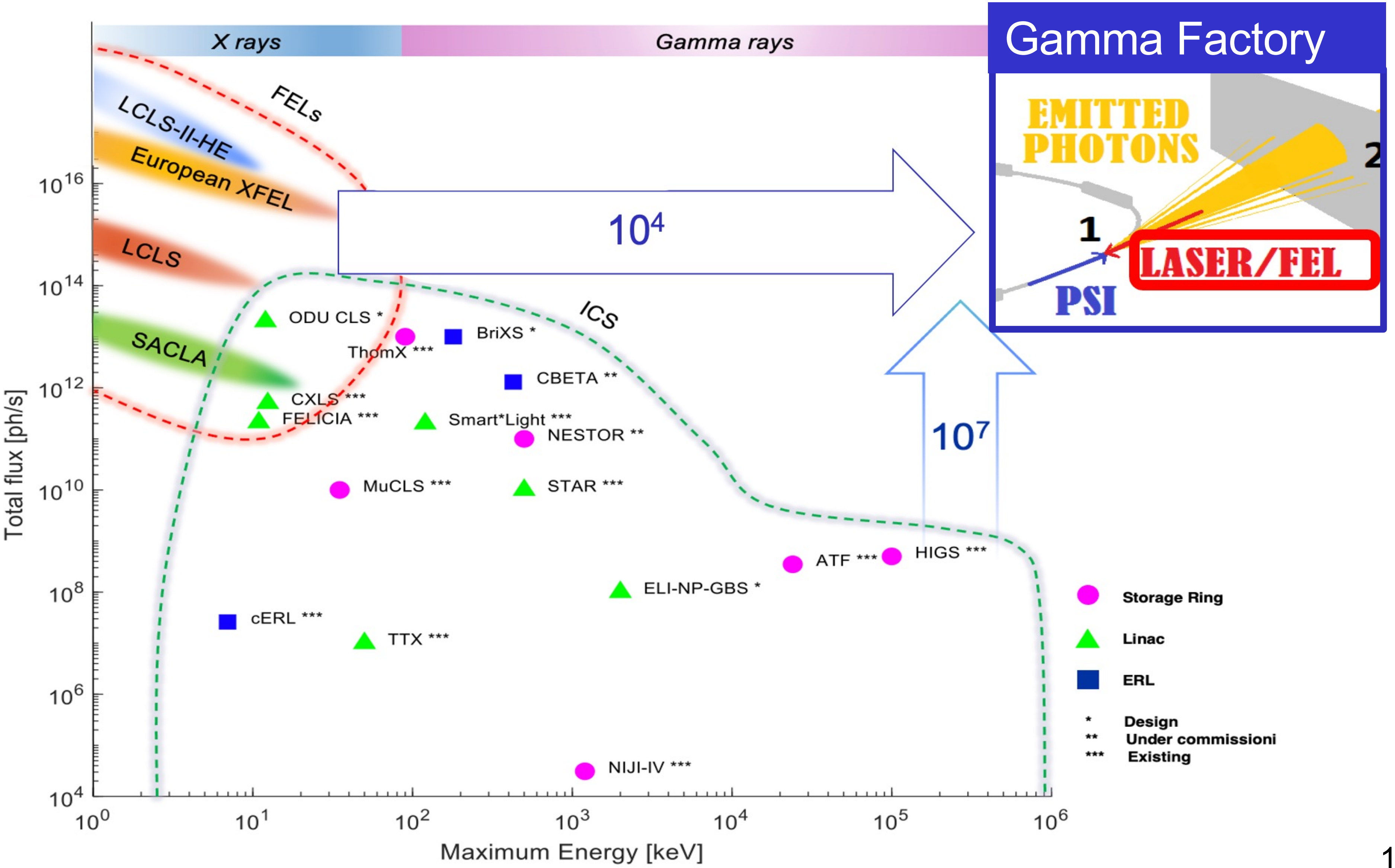
large cross-section for atomic collisions

Inverse Compton scattering	*cross-section*	*efficiency*
	Electrons: $\sigma_e = 8\pi/3 \times r_e^2$; r_e - classical electron radius ; $\sigma_e = 6.6 \times 10^{-25}\,cm^2$	$E_{beam} = 1.5$ 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		
	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!)

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


Gamma Factory
EMITTED PHOTONS
2
1
LASER/FEL
PSI
X rays
Gamma rays
FELs
LCLS-II-HE
European XFEL
LCLS
SACLA
ICS
10^4
10^7
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]
10^{16}
10^{14}
10^{12}
10^{10}
10^8
10^6
10^4
10^0
10^1
10^2
10^3
10^4
10^5
10^6

Extraordinary properties of the GF photon source

1. Point-like, small divergence

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

2. Huge jump in intensity:

- **More than 7 orders of magnitude** *w.r.t. 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 (Pauli blocking):

- 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)

Gamma Factory beams

Gamma Factory proposes to create and store in the LHC novel type of beams of:

- *Hydrogen-like and Helium-like ions (unpolarised and polarised),*
- *Low emittance, cold (isoscalar) ions (high precision EW studies, Higgs studies)*
- *Nuclear isomers, …e.g. ^{229m}Th (nuclear clock)*
- *Electrons, circulating in the LHC and colliding with the LHC proton beams (PIE collider).*

… and control/manipulate them with unprecedented precision using lasers

Gamma Factory can improve the present intensity limits of the:

- *Polarised γ-beams by a factor >10^7, → 10^{18} γ/sec*
- *Muon beams by a factor of 10^3, → 7 x 10^{13} μ^+,μ^-/sec*
- *Polarised positron beams by a factor of 10^3. → 10^{16} e+/sec*

Gamma Factory can also deliver :

- *monochromatic neutron beams, → 10^{17} n/sec*
- *radioactive ion beams. → 10^{12} extracted r.i./sec,*

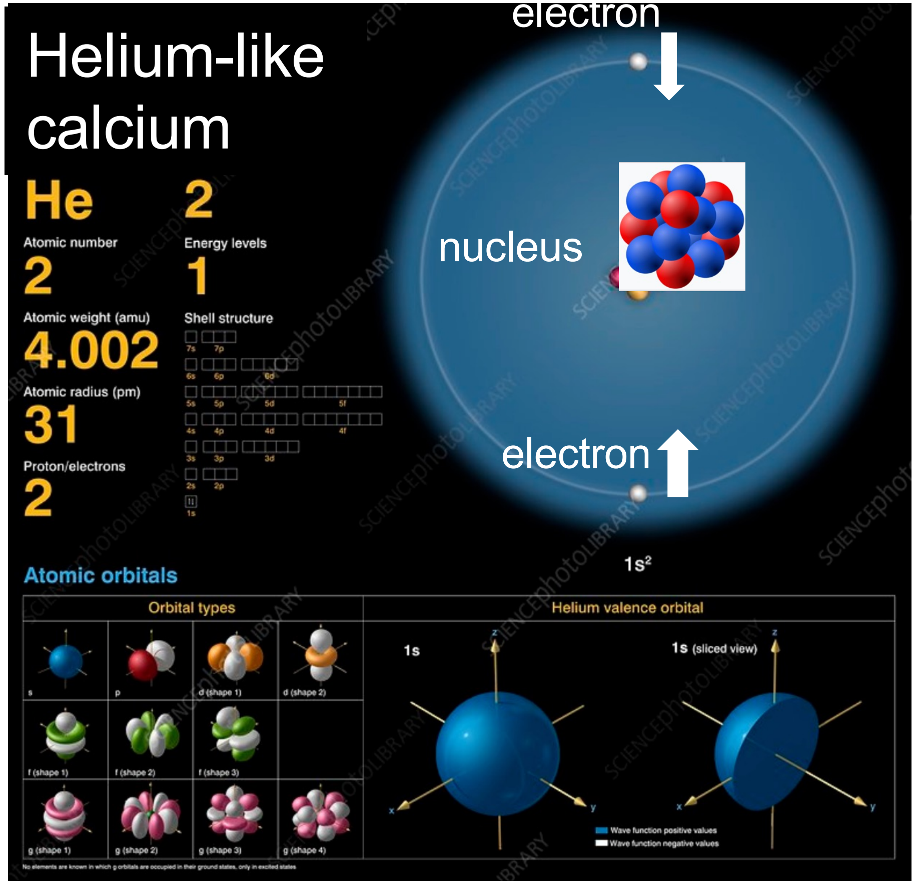
… complementary to those delivered by the presently operating and future facilities

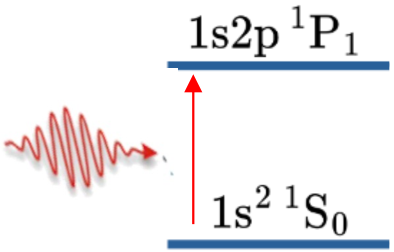
examples →

Novel type of beam particles with internal degrees of freedom -

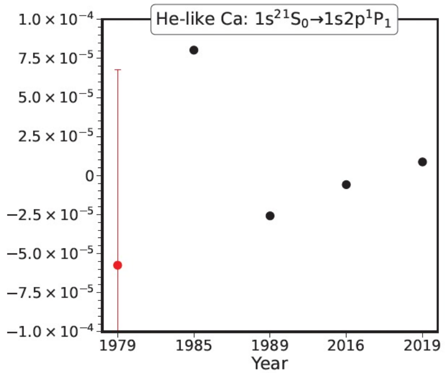
LHC beam energy calibration can be improved by a factor of >100

Helium-like calcium





Atomic transition energy precision



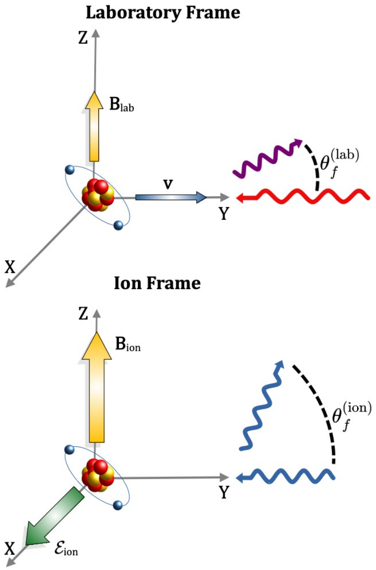
Tuning γ_L to the atomic transition resonance:

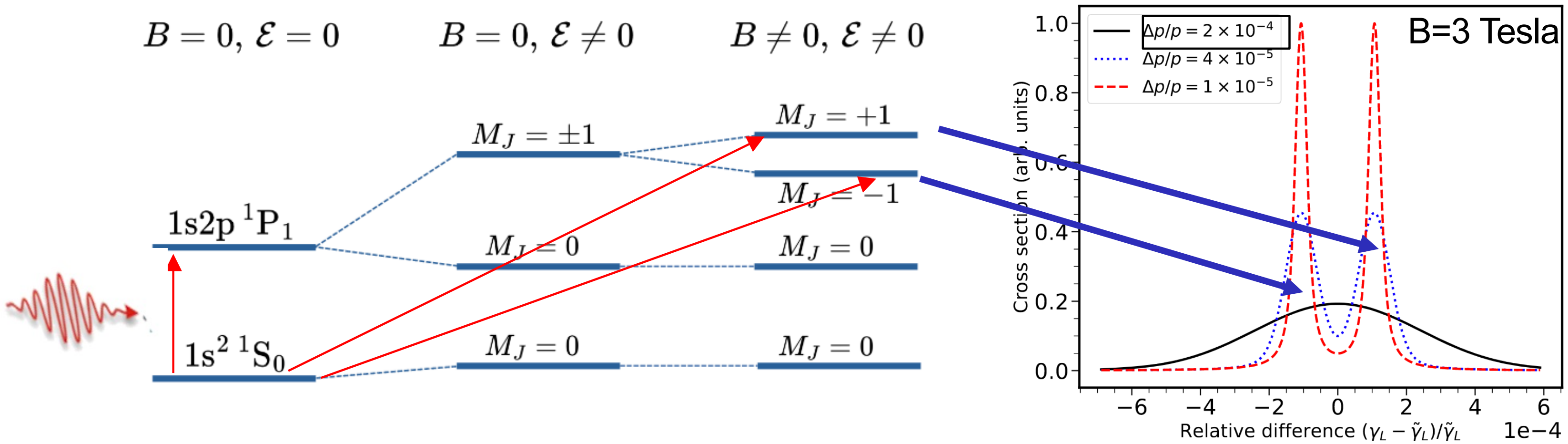
$$\omega_{\rm ion} = (1+\beta\cos\Theta)\gamma_L\omega_{\rm lab}$$

- $\omega_{\rm ion}$: Atomic transition energy
- Θ: collision angle
- γ_L: Lorentz factor of the beam
- $\omega_{\rm lab}$: Laser photon energy

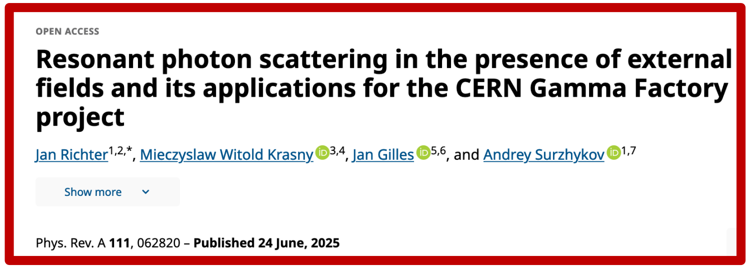
Novel type of beam particles with internal degrees of freedom Ultra-precise control of the stability and the emittance of the LHC beams

Collisions in a dipole magnet





Observing Zeman splitting of the M_j = +/-1 sublevels of the excited He-like Ca atoms allows us to control the LHC beam energy fluctuations to better than ~10^{-7} relative precision at ~10 kHz frequency (better than LEP) → a path to the gravitational wave detection in the high-energy storage rings? In addition, we can polarise ions using polarised laser photons!


OPEN ACCESS

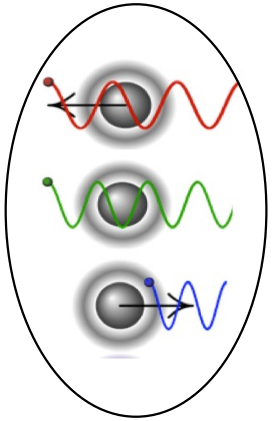
Resonant photon scattering in the presence of external fields and its applications for the CERN Gamma Factory project

Jan Richter[1,2,*], Mieczyslaw Witold Krasny[3,4], Jan Gilles[5,6], and Andrey Surzhykov[1,7]

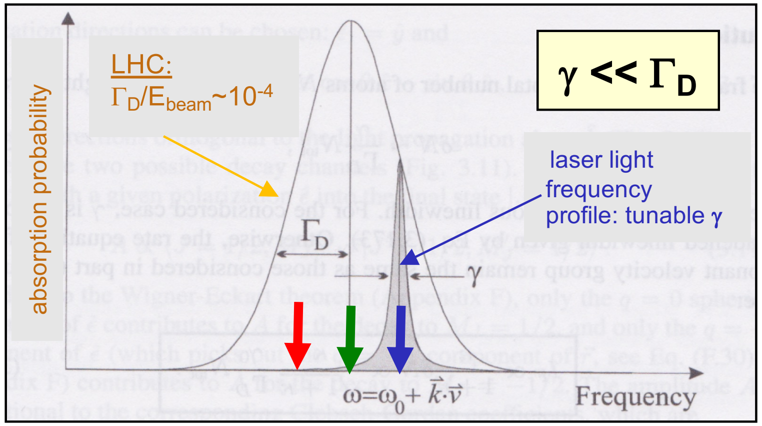
Show more

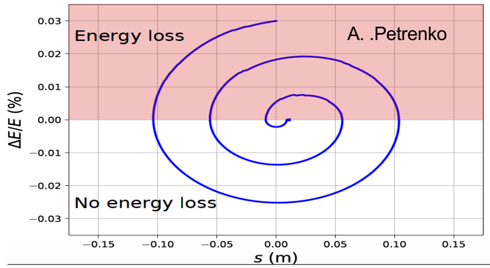
Phys. Rev. A **111**, 062820 – **Published 24 June, 2025**

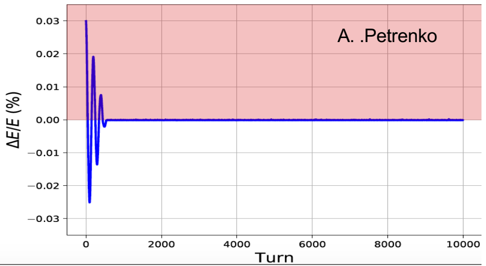
Gamma Factory's "cold" ion beams



Bunch

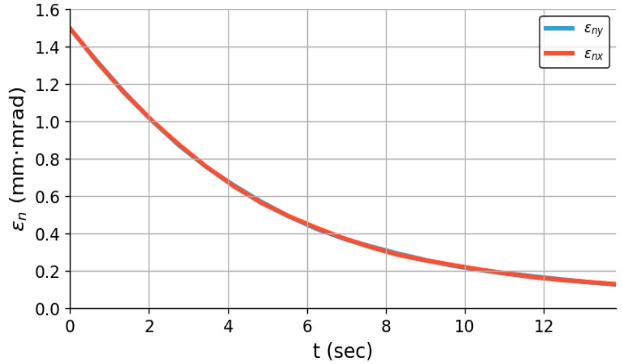






Beam cooling speed: *the laser wavelength band is chosen such that only the ions moving in the laser pulse direction (in the bunch rest frame) can resonantly absorb photons.*

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



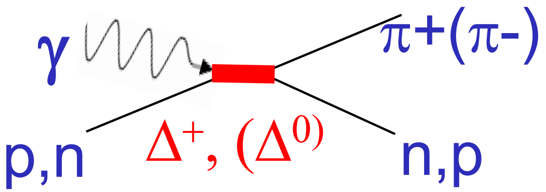
Simulation of laser cooling of the lithium-like Ca(+17) bunches in the SPS: transverse emittance evolution.

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

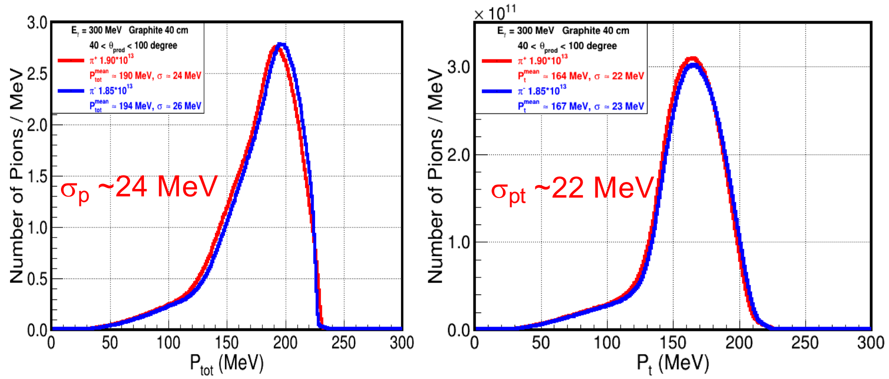
M.W. Krasny (Paris U., VI-VII and CERN), A. Petrenko (CERN and Novosibirsk, IYF), W. Płaczek (Jagiellonian U.) (Mar 25, 2020)

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

Gamma Factory muon and positron source



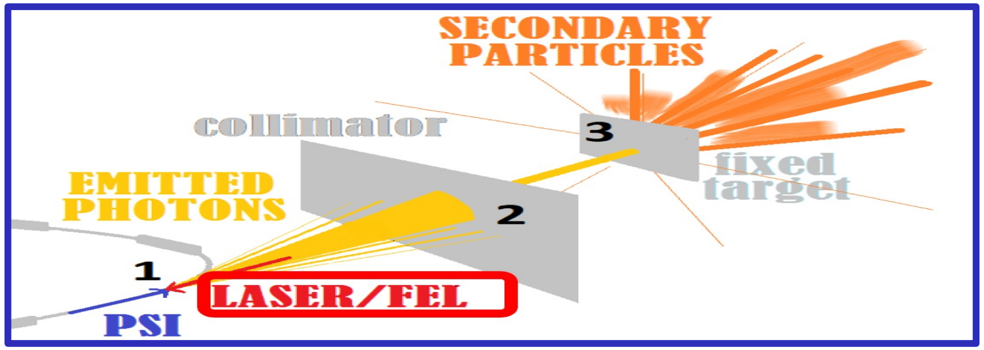
Exclusive process:
unprecedented spectral density of produced pions



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*

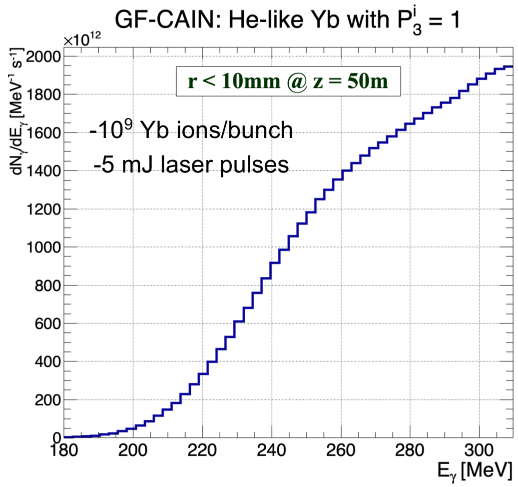


GF photon beam

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

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

γ-beam spectrum



The merit of quasi-monochromatic pion source:
muon **longitudinal** polarisation

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

- *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*

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

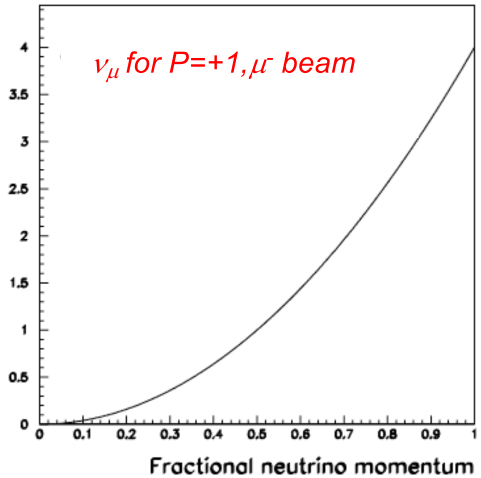
$$\frac{d^2N}{dx d\Omega} = \frac{1}{4\pi}[f_0(x) \mp \mathcal{P}_\mu f_1(x) \cos\theta]$$

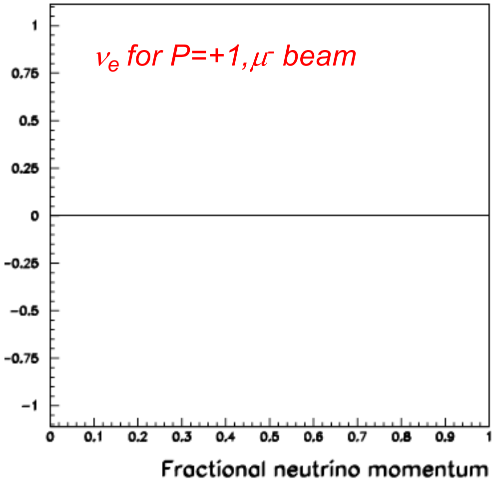
$x = 2E_\nu/m_\mu$

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

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

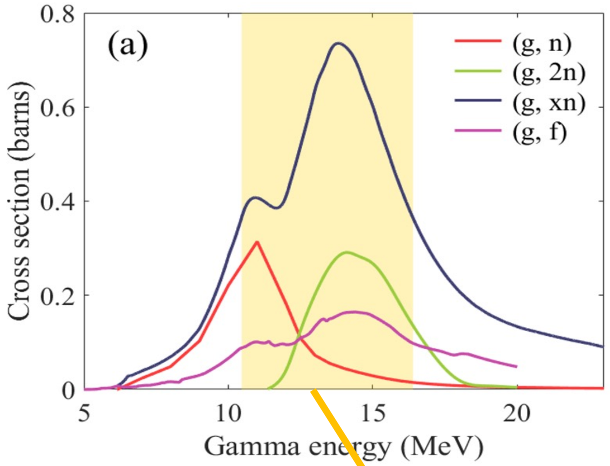
	$f_0(x)$	$f_1(x)$
ν_μ, e	$2x^2(3-2x)$	$2x^2(1-2x)$
ν_e	$12x^2(1-x)$	$12x^2(1-x)$





Gamm Factory, γ-beam driven high intensity neutron source:

resonant photo-excitation of the Giant Dipole Resonance



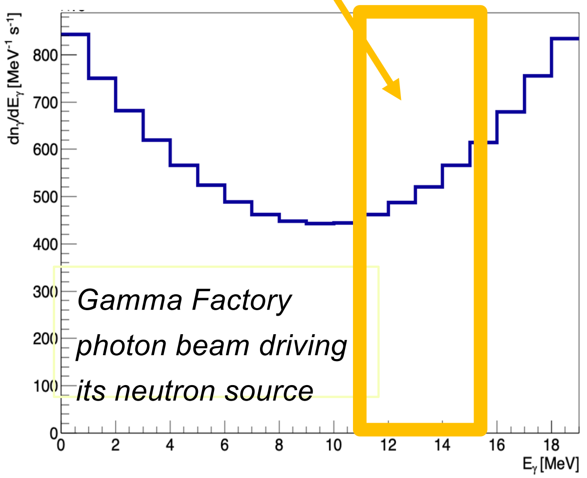


Table 1: Input parameters of the GF-CAIN simulations for the He-like Ca beam.

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 $^{40}_{20}Ca^{18+}$	$1s^2\,{}^1S_0 \rightarrow 1s2p\,{}^1P_1$
$\hbar\omega'_r$ – 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

nature > scientific reports > articles > article

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Efficient transmutation of long-lived fission products in a Gamma Factory beam driven advanced nuclear energy system

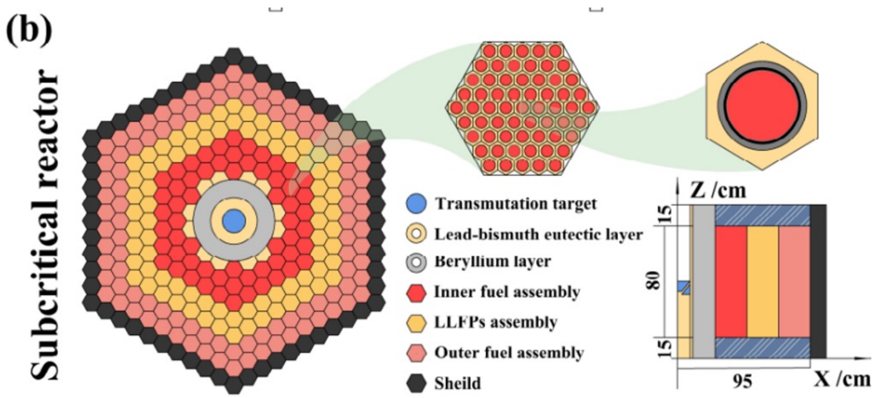
Baolong Hu, Mieczyslaw Witold Krasny, Wiesław Płaczek, Yun Yuan, Xiaoming Shi, Kaijun Luo & Wen Luo

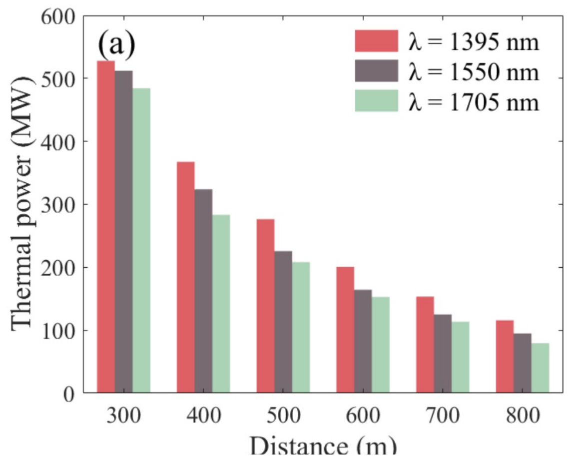
Scientific Reports 15, Article number: 12562 (2025) | Cite this article

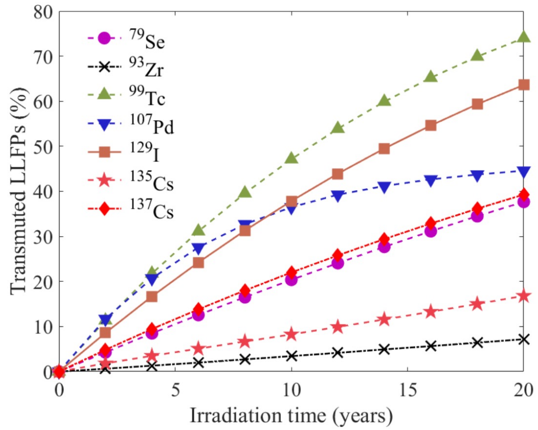
Gamma Factory photon-beam-driven energy source

Satisfying three conditions;

- requisite power for the present and future CERN scientific programme
- operation safety **(a subcritical reactor)**
- efficient transmutation of the nuclear waste







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Efficient transmutation of long-lived fission products in a Gamma Factory beam driven advanced nuclear energy system

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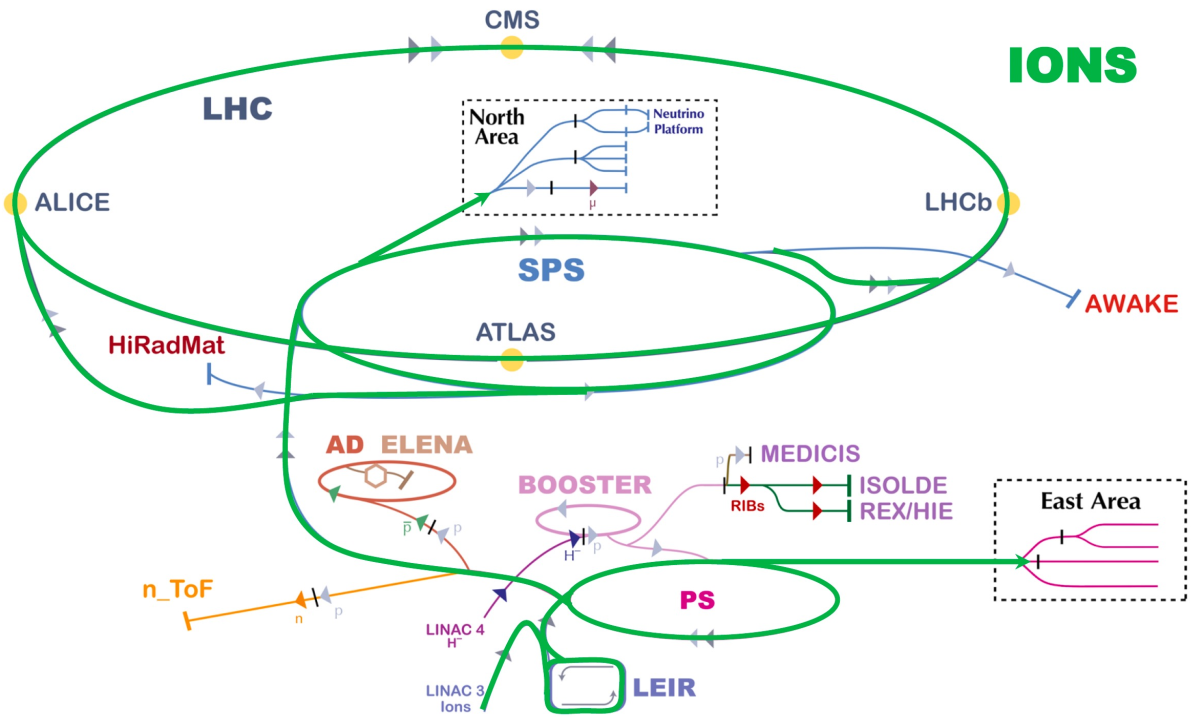
Feasibility studies

Re-use of the already existing CERN accelerator infrastructure

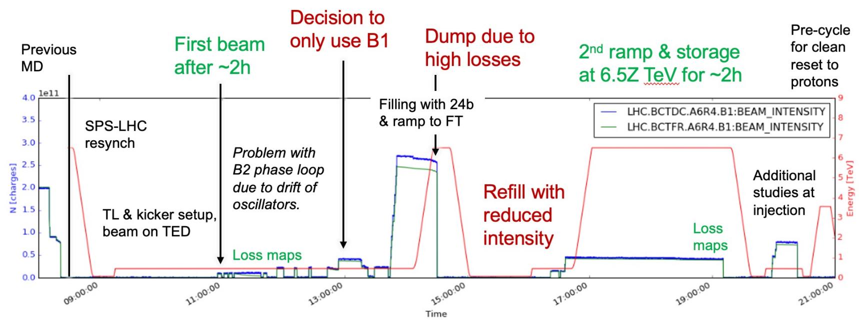


<u>Gamma Factory requirements:</u>

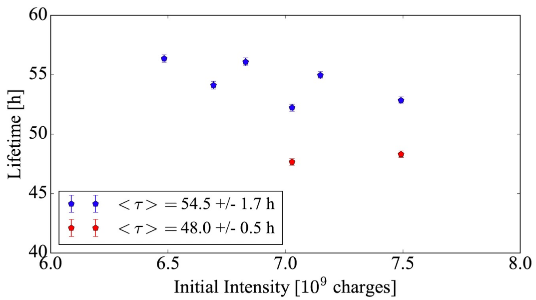
- modification of the ion stripping scheme,
- storage of atomic beams

Atomic beams stored in in the SPS and LHC

Lifetime of H-like Pb ions in the LHC



Lifetime of PSI bunches ~ 50h




CERN-ACC-NOTE-2019-0012

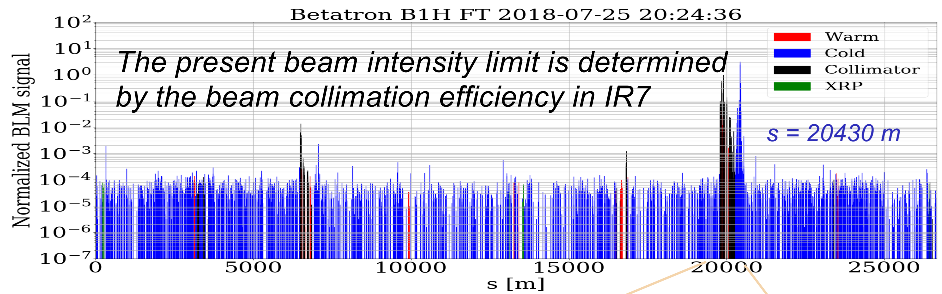
8 May 2019

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

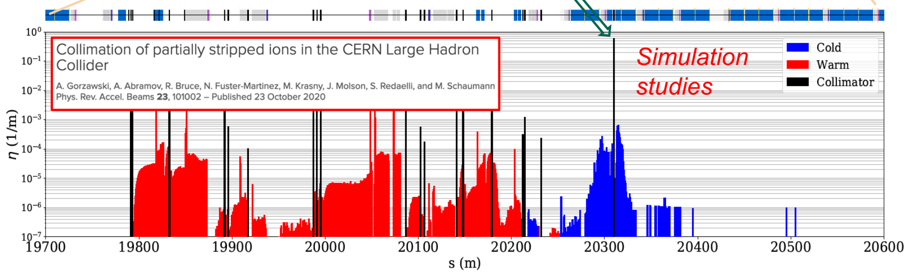


The present beam intensity limit is determined by the beam collimation efficiency in IR7

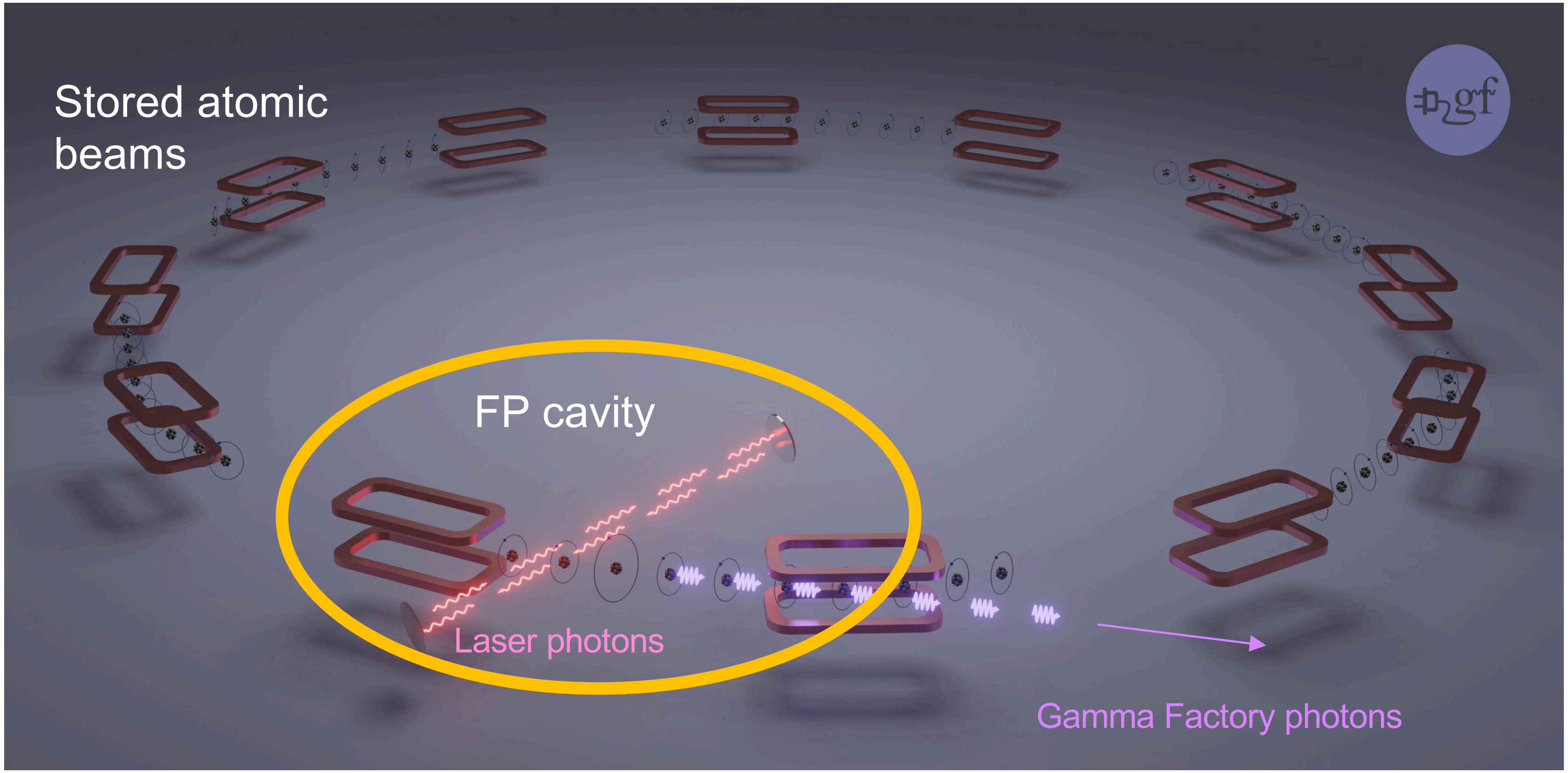
IR7 zoom

Mitigation strategies:

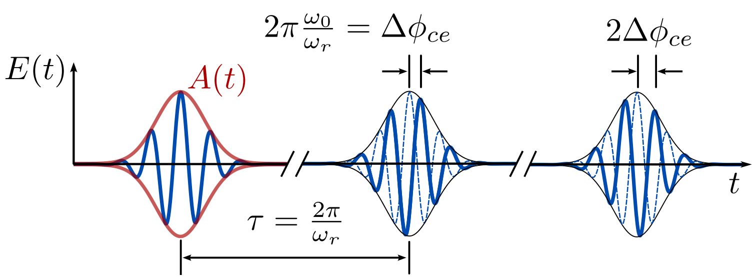
1. *Dispersion suppressor collimator (TCLD)*
2. *Crystal collimation*
3. ***Laser collimation***.



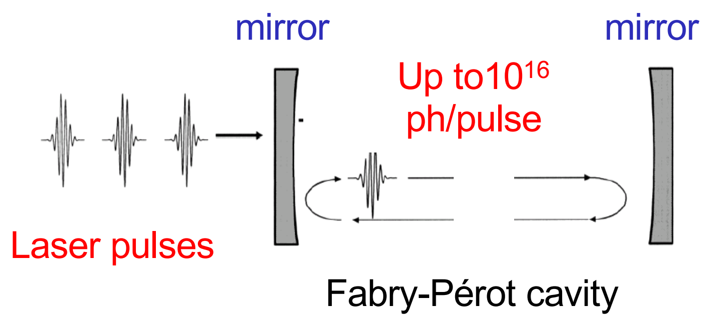
Laser + FP cavity system

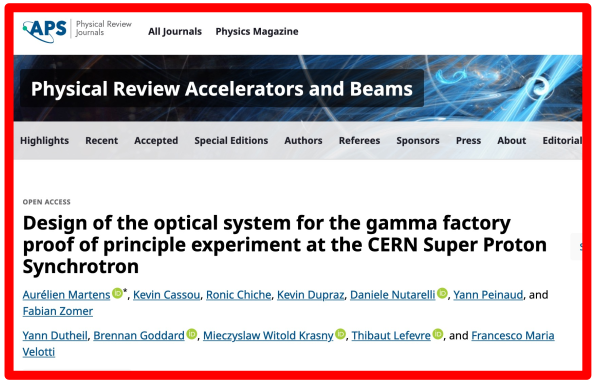


Towards the first integration of the Fabry-Pérot (FP) cavity in the hadron storage ring



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




APS Physical Review Journals | All Journals | Physics Magazine

Physical Review Accelerators and Beams

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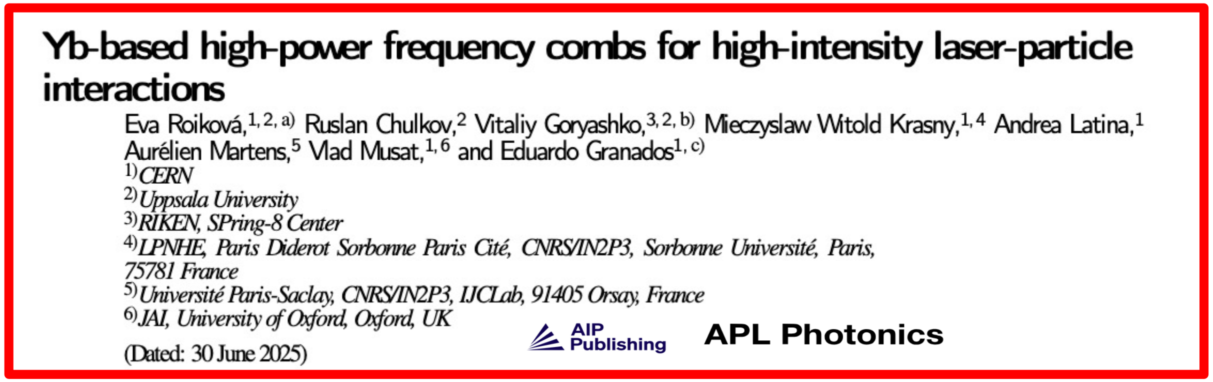
OPEN ACCESS

Design of the optical system for the gamma factory proof of principle experiment at the CERN Super Proton Synchrotron

Aurélien Martens*, Kevin Cassou, Ronic Chiche, Kevin Dupraz, Daniele Nutarelli, Yann Peinaud, and Fabian Zomer

Yann Dutheil, Brennan Goddard, Mieczyslaw Witold Krasny, Thibaut Lefevre, and Francesco Maria Velotti


Yb-based high-power frequency combs for high-intensity laser-particle interactions

Eva Roiková,[1,2,a)] Ruslan Chulkov,[2] Vitaliy Goryashko,[3,2,b)] Mieczyslaw Witold Krasny,[1,4] Andrea Latina,[1] Aurélien Martens,[5] Vlad Musat,[1,6] and Eduardo Granados[1,c)]

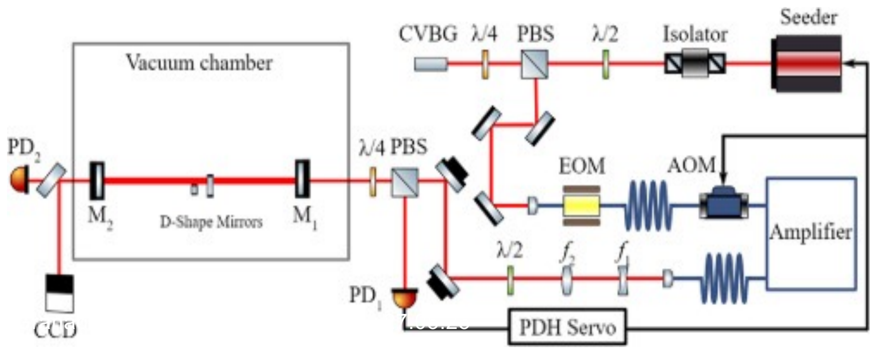
[1)] *CERN*
[2)] *Uppsala University*
[3)] *RIKEN, SPring-8 Center*
[4)] *LPNHE, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Sorbonne Université, Paris, 75781 France*
[5)] *Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France*
[6)] *JAI, University of Oxford, Oxford, UK*

(Dated: 30 June 2025)

AIP Publishing **APL Photonics**

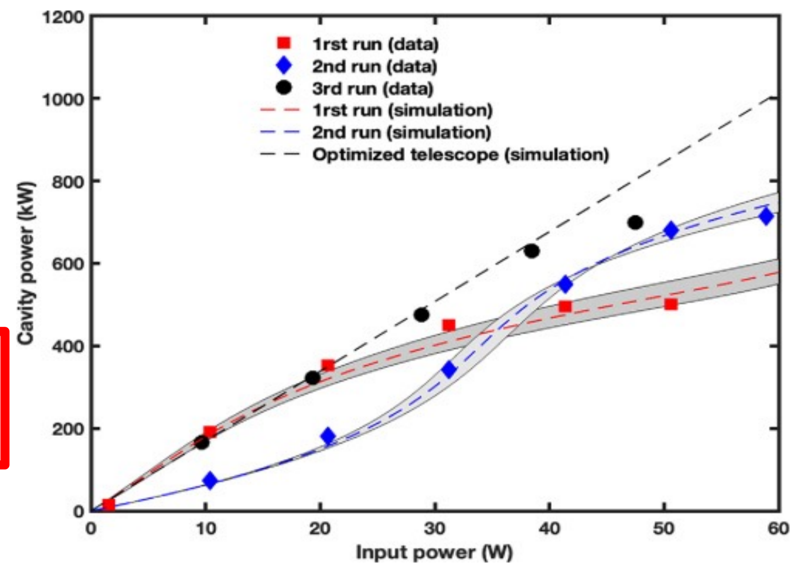
Optical Cavity tests at IJCLab

2 mirror cavity test



"710 kW stable average power in a 45,000 finesse two-mirror optical cavity," *Opt. Lett. 49, 6884-6887 (2024)*

World record in the stored power of photon pulses !



What have we achieved?

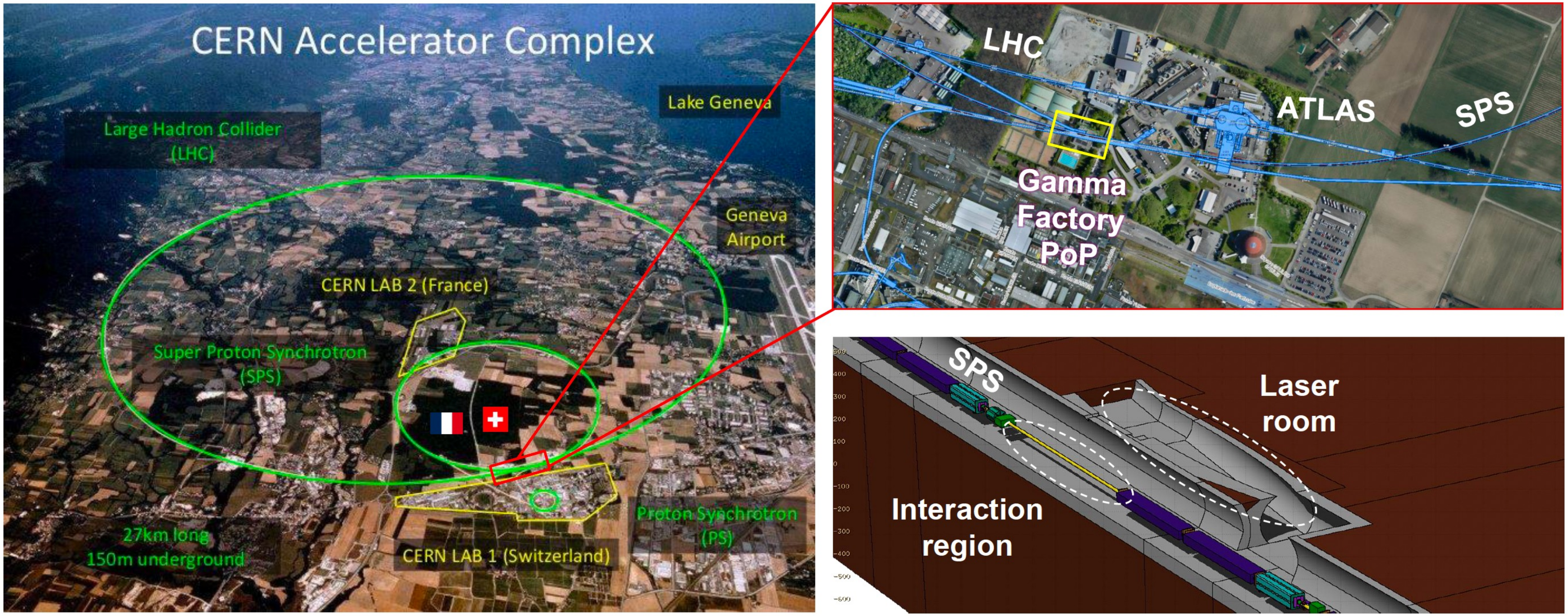
- *Demonstration of efficient production, storage and operation of the atomic beams n the SPS and LHC*
- *Demonstration of the stable, high power, laser photon beam storage in the Fabry-Perot cavity (world record of 700 kW stored, average power)*
- *Demonstration of the requisite precision of the beam steering in the collision point of laser pulses with atomic beam bunches*
- *Creation and benchmarking of the requisite software to simulate the production of the atomic beams, GF-photon beams and tertiary beams*

What remains to be demonstrated?

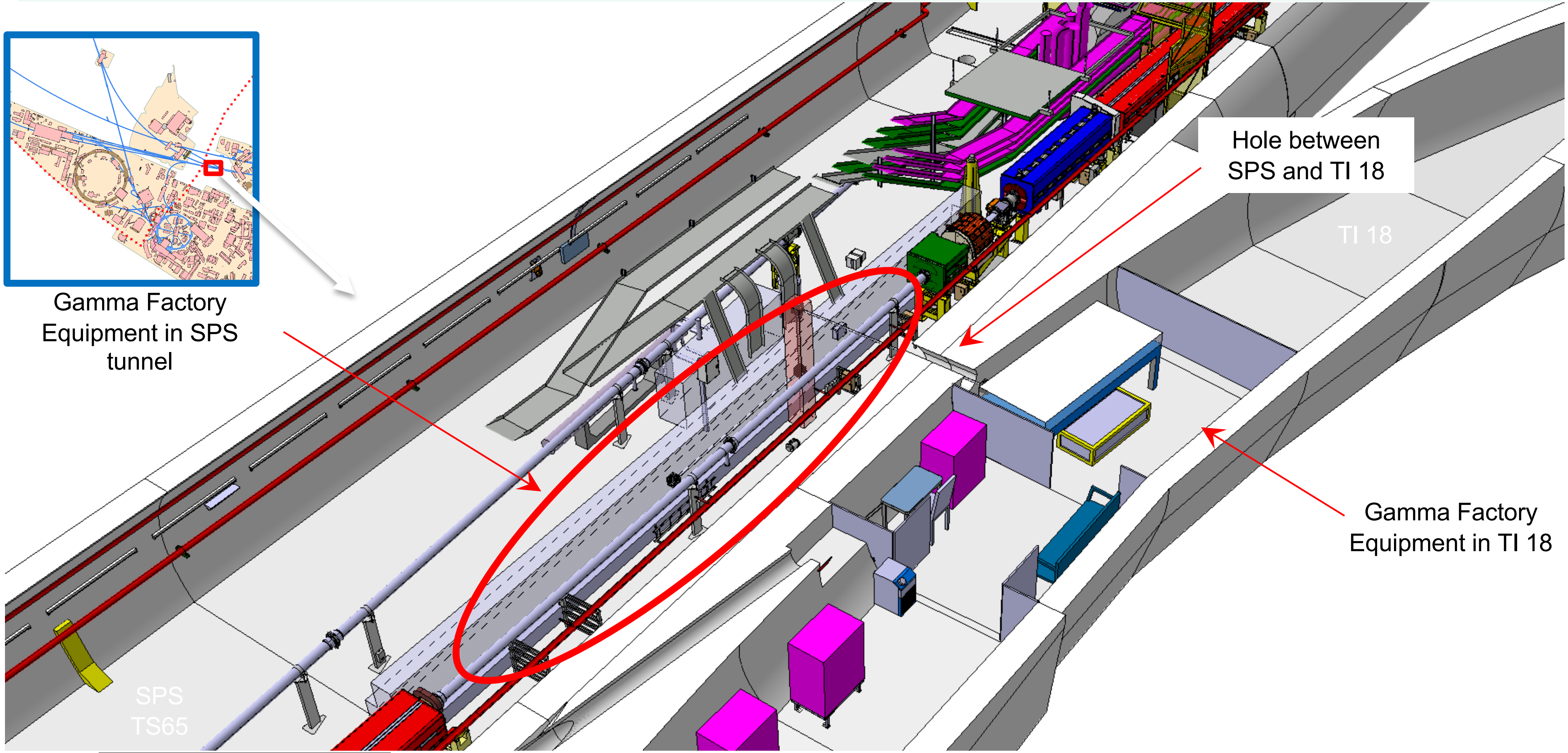
Proof of the stable remote operation of the laser + FP system incorporated to hadronic rings
→ The Gamma Factory Proof-of-Principle (PoP) experiment

Proof-of-Principle experiment at the SPS

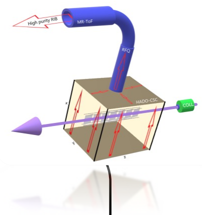
Gamma Factory Proof-of-Principle experiment location



Gamma Factory Proof-of-principle experiment

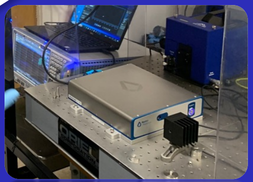


Status of the Gamma Factory PoP experiment



PROCURED

Laser system



- Laser oscillator procured, accepted, tested…
- Successful demonstration paired to enhancement cavity (>700 kW!)
- Tender for 100 W amplifier completed, will be sent to IJCLab (addendum #2 to MoU) in 2025.

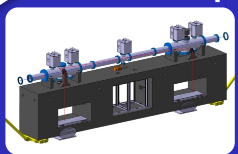
INSTALLED

Laser beamline

- Measurement of SPS vibrations with interferometer.
- Simulations of laser coupling and structure resonances completed
- Beamline support was designed, constructed, installed at SPS

STARTED

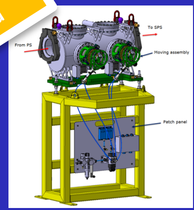
Fabry Perot cavity



- Working with EN-MME on a design update.
- Test at IJCLab were performed at a higher repetition rate, need to perform at 40 MHz
- Mock-up construction at CERN + testing is currently being considered.

Completed

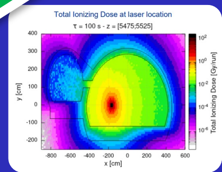
PSI beam studies



- Design and implementation of the of the electron stripper
- Successful SPS tests with Xe and Pb PSI beams
- Successful LHC tests with H-like Pb beam
- Successful beam control studies

COMPLETED

Radiation studies



- Installation of BATMONs (waiting for readout).
- FLUKA simulations have been carried out
- To be determined: the suitable electronics that can be used for the control systems (with R2E).

COMPLETED

TI-18 tunnel (laser lab)

- Opening and inspection was carried out at the end of 2023
- 3D scan completed
- Cabling requests were completed + PLAN already in the schedule for LS3. Resources not committed.

Conclusions and outlook

Conclusions

- *Gamma Factory can create, at CERN, a variety of novel beams, which can open novel research opportunities in a very broad domain of basic and applied science (not limited to high energy physics) … (documented in ~40 published papers)*

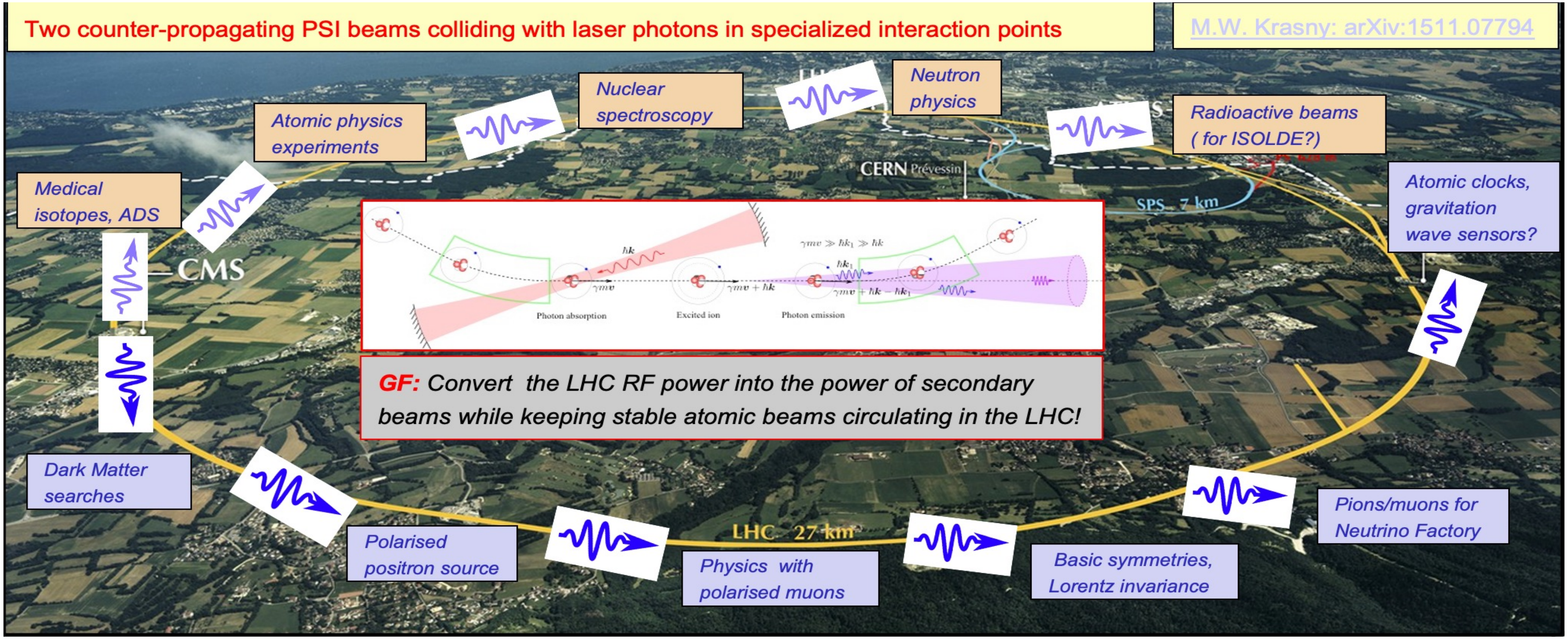
- *The Gamma Factory research programme plans to reuse the existing CERN accelerator infrastructure in a novel way– it requires minor infrastructure investments*

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

- *Gamma Factory project needs to make the last step in its feasibility studies -- execution of the SPS GF-Proof-of-Principle experiment… the question if the present CERN community would accept novel research methods and new research communities -- co-using its accelerator infrastructure -- remains open …*

Gamma Factory research programme with the extracted beams

-- a very significant extension of the present CERN research programme

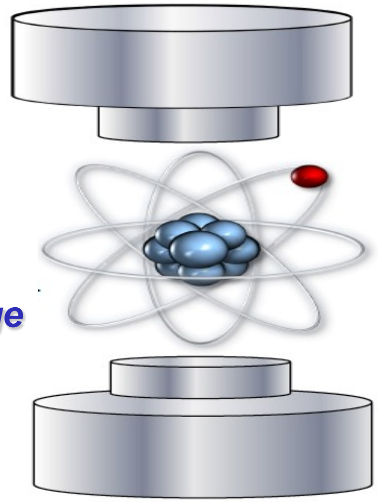


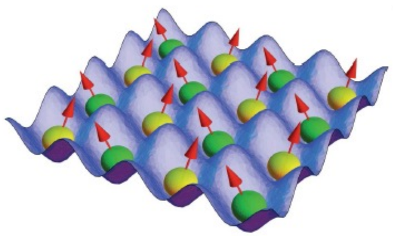
Supplementary slides

Experimental programme with "small-size" atoms

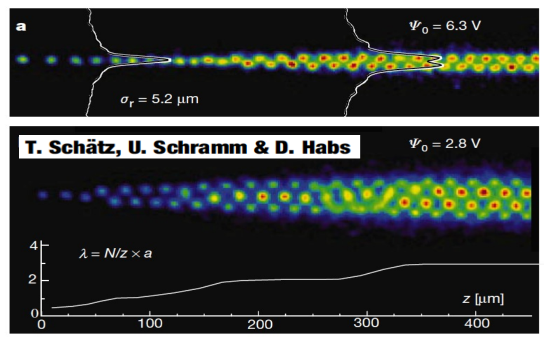
Atomic rest-frame

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





Crystalline beams?



Opening new research opportunities in atomic physics:

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


adp annalen der physik

Feature Article | Open Access

Atomic Physics Studies at the Gamma Factory at CERN

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

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

Gamma Factory (complementary) path to HL-LHC:

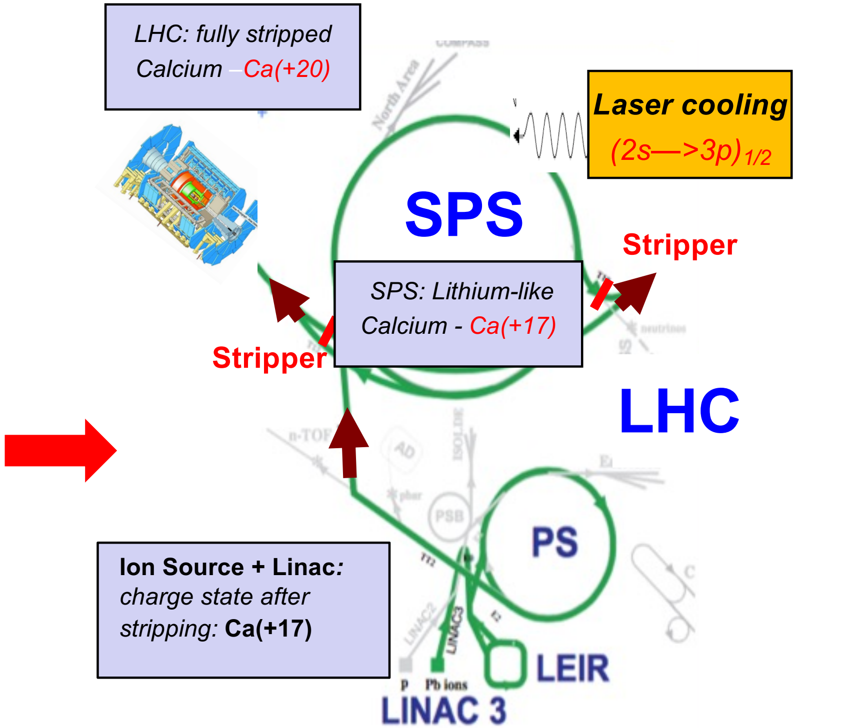
Studies of the implementation scheme with laser-cooled isoscalar Ca beams

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

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

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

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



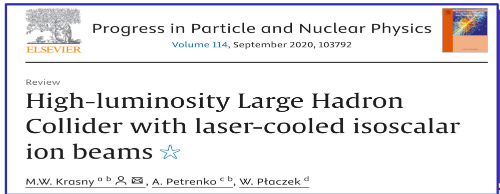
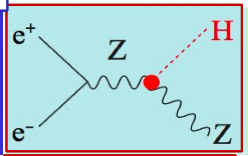
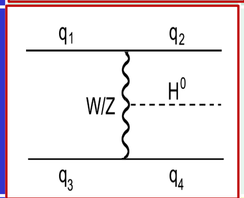
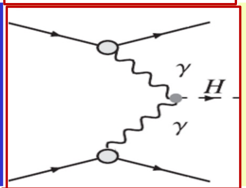
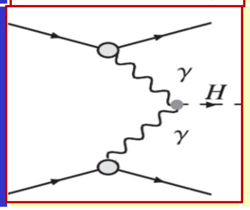
Reduction of the transverse x,y, emittances by a factor of 5 can be achieved in 9 seconds (top SPS energy)

The merits of cold isoscalar beams

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

*Optical stochastic cooling time for the Ca beam at the LHC tinjection energy t_{cool} ~1.5 hours **(V. Lebedev)***

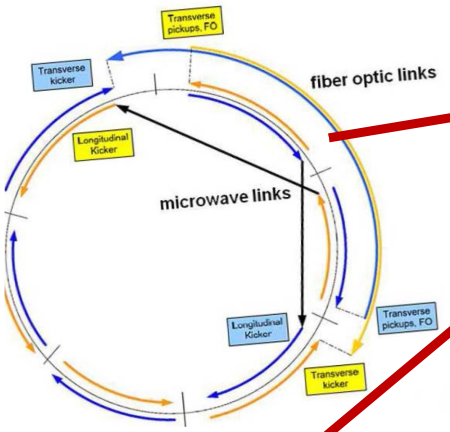
*Higgs physics reach: FCC-ee, LHeC and HL(AA)LHC**

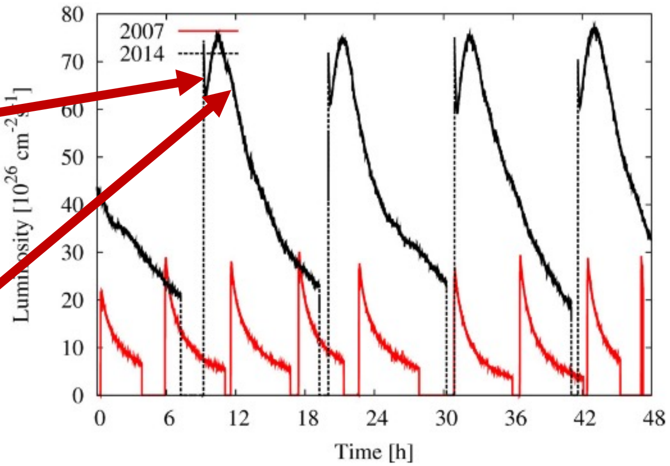
 ELSEVIER Progress in Particle and Nuclear Physics Volume 114, September 2020, 103792 Review High-luminosity Large Hadron Collider with laser-cooled isoscalar ion beams M.W. Krasny, A. Petrenko, W. Płaczek	**Diagram**	**σ_{prod} [pb]**	**Higgs/year**	**Collider**	**Experiment**	**Backg.**
FCC-ee semi-inclusive (HZ)		200	200000 (1000fb^{-1})	To be constructed	To be constructed	tiny
LHeC inclusive		0.033	33 (100fb^{-1})	To be constructed	To be constructed	large
HL(AA)LHC* Exclusive $\gamma\gamma$		550	260 (0.47fb^{-1})	existing	4 exp. existing	small (no nuclear remnants)
HL-HE-(AA)LHC* Exclusive $\gamma\gamma$		2600	1220 (0.47fb^{-1})	New LHC dipoles	4 exp existing	small (no nuclear remnants)

*) HL(AA)LHC: (1) BNL-like performance of the ion injectors, (2)GF beam cooling at the SPS,
(3) BNL-like performance of stochastic cooling at the LHC injection (presented table: CaCa collisions)

Gamma Factory path to HL(AA)-LHC:

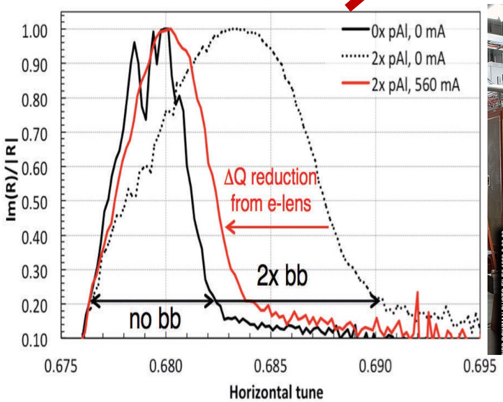
BNL performance – ion beams and their collisions at RHIC



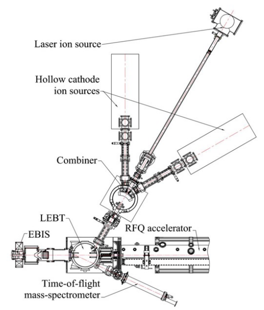


parameter	unit	design 2000†	achieved 2016	upgrade ≥2022
circumference C	km		— 3.834 —	
beam energy E	GeV/n		— 100 —	
bunch intensity N_b	10^9	1.0	2.0	2.5
no of bunches k_b	...	60	111	111
stored beam energy	MJ/beam	0.12	0.70	0.88
rms emittance ϵ_n	μm		— 2.5 —	
rms bunch length σ_s	m		— 0.3 —	
beam-beam ξ/IP	10^{-3}	2.3	3.1	3.8
lattice β^*	m	2.0	0.7	0.6
luminosity $\mathcal{L}_{peak}$	10^{26}cm^{-2}s^{-1}	8	130	200
luminosity $\mathcal{L}_{avg}$	10^{26}cm^{-2}s^{-1}	2	83	160

† Column gives the design values. 2000 is the first year of operation.



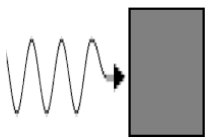
Schematic of ion optics for external ion injection



Principal difference between BNL and CERN:
-- N_{Au}/bunch (BNL-RHIC) = 2.5 x 10^9
-- N_{Pb}/bunch(CERN-SPS/LHC) = 1.6 x10^8
(approximate BNL scaling N_A x A =N_{nucl} ~N_p)

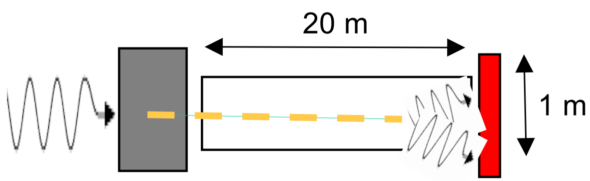
DM searches and studies (ALP example)

Search phase
Example: beam-dump mode

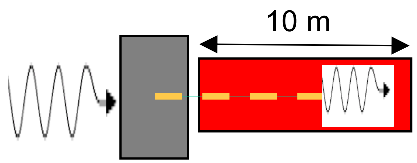


γ_{GF}–A *collisions*
1.6, 0.2, 0.02 GeV
beams (A,B,C)

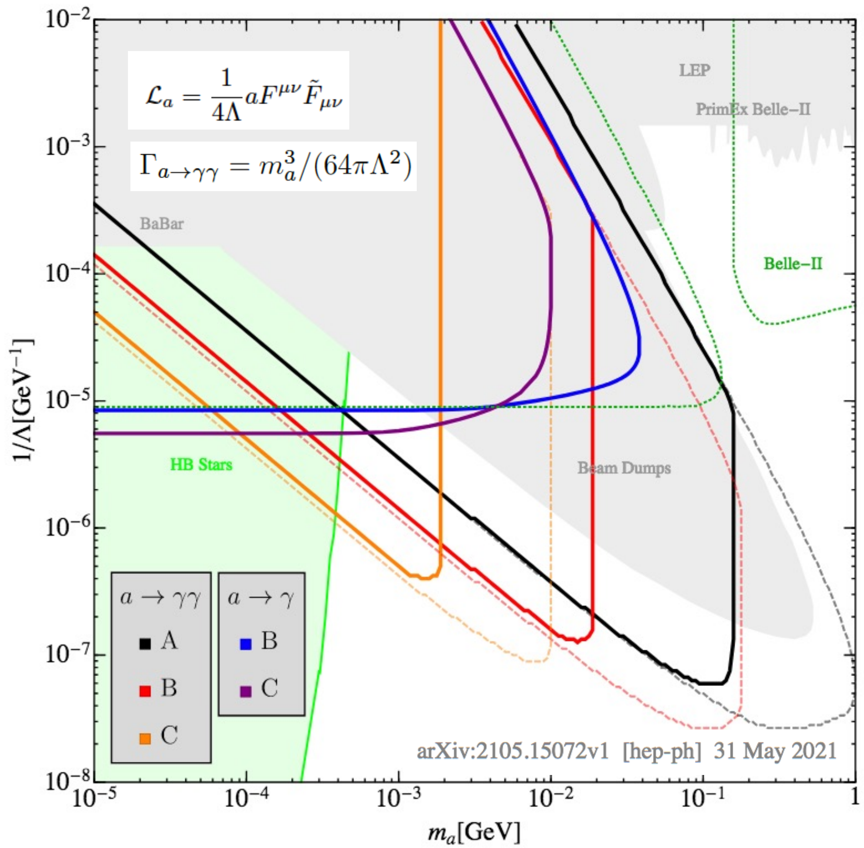
Two appearance modes:



- *decay: a →$\gamma\gamma$ (A,B,C)*

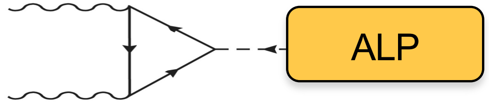


- *reconversion: aN →γN (B,C)*



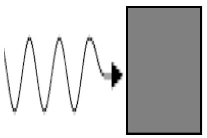
DM searches and studies (if discovered), ALP example

Collision schemes for ALP production:

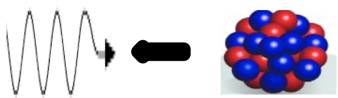


Search phase

$\gamma_{GF} - B$ **field**
$m_{ALP} < 1$ keV



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



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

"Production" phase

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

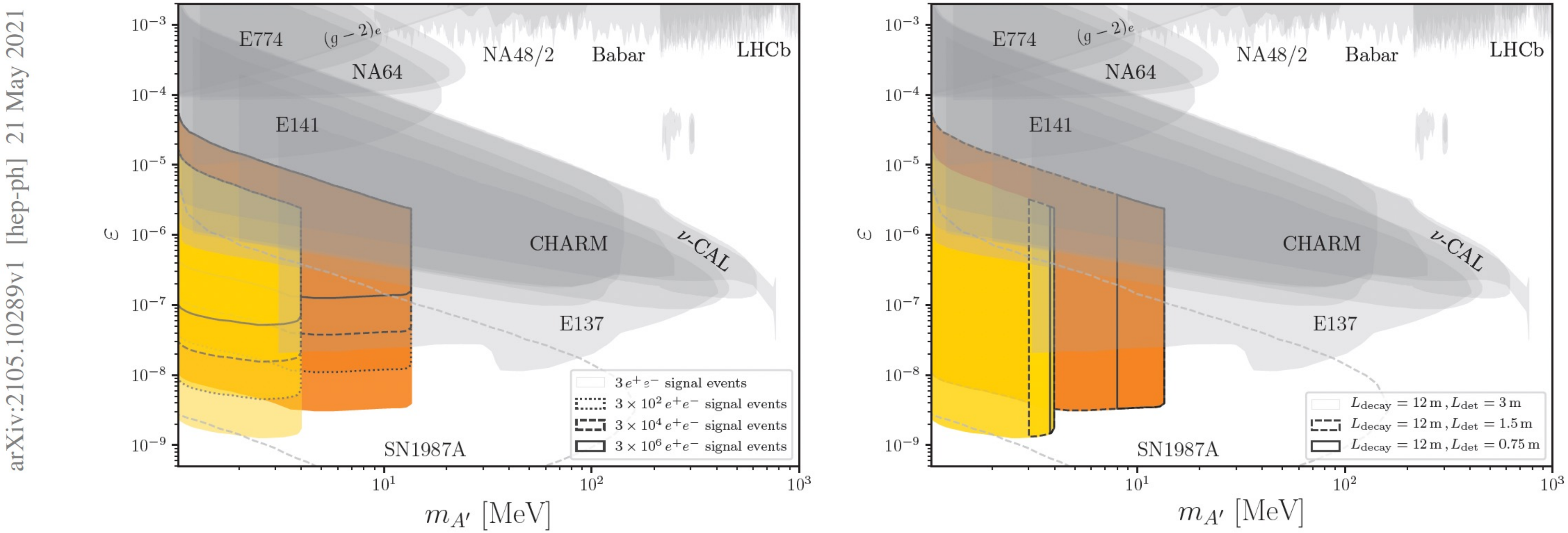
$\gamma_{GF} - \gamma_{GF}$ **collisions** (LHC)
$m_{ALP} \sim 100$ keV – 800 MeV

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

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

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

DM searches and studies (dark photon example)



Gamma Factory nuclear clocks: ^{229m}Th isomer beam

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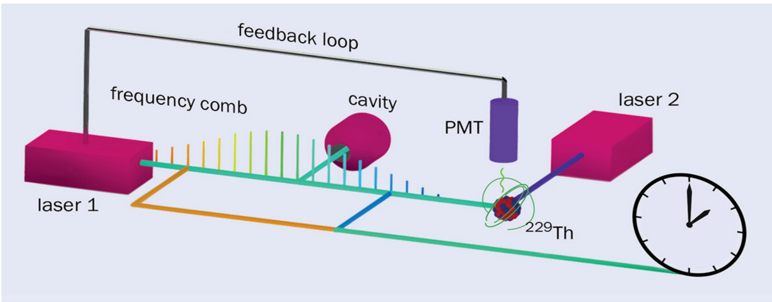
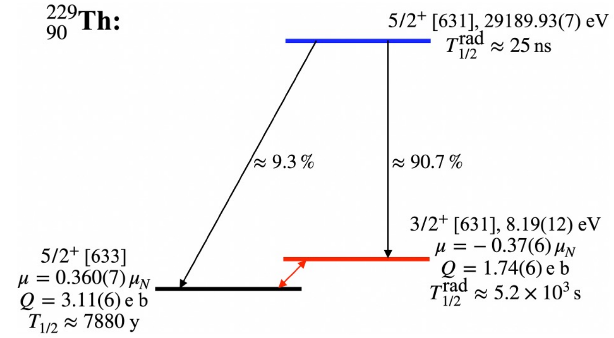
APPLICATIONS | FEATURE

From atomic to nuclear clocks





OPEN ACCESS

Excitation and probing of low-energy nuclear states at high-energy storage rings

Junlan Jin[1,2,*], Hendrik Bekker[3,4], Tobias Kirschbaum[5], Yuri A. Litvinov[6], Adriana Pálffy[5], Jonas Sommerfeldt[7,8], Andrey Surzhykov[7,8], Peter G. Thirolf[9], and Dmitry Budker[3,4,10,†]

Show more

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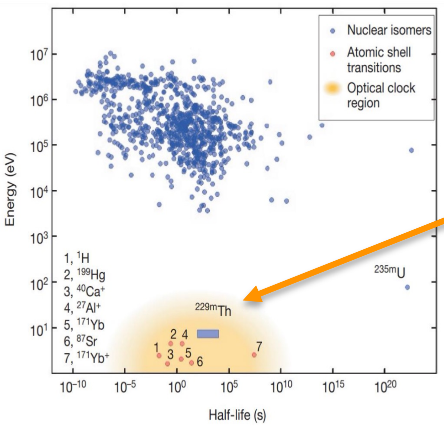
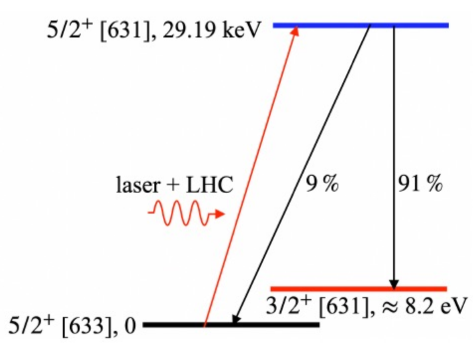
DOI: https://doi.org/10.1103/PhysRevResearch.5.023134

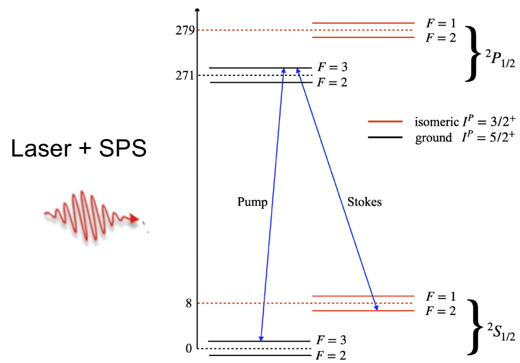


Two “GF” ways of producing ^{229m}Th isomer with high efficiency

1. Excitation in bare Th nuclei



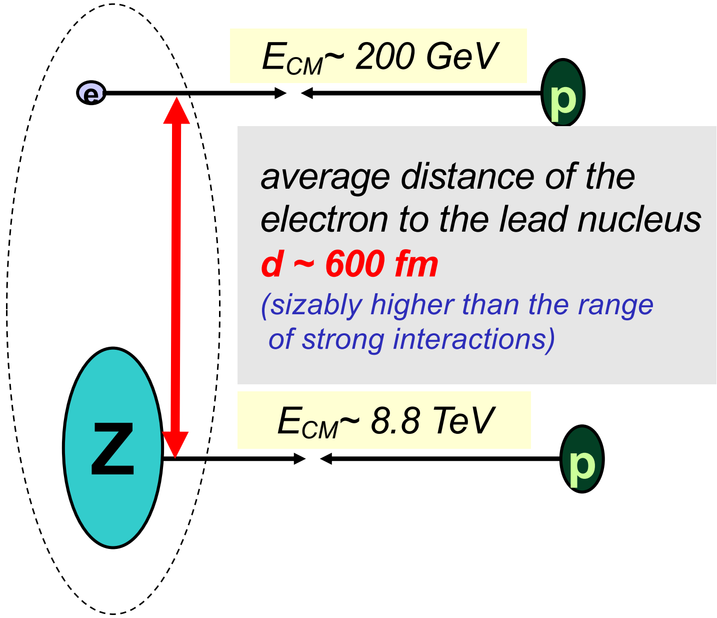
2. Excitation in H- or Li- like Th ions



Studies of ep collisions at LHC

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

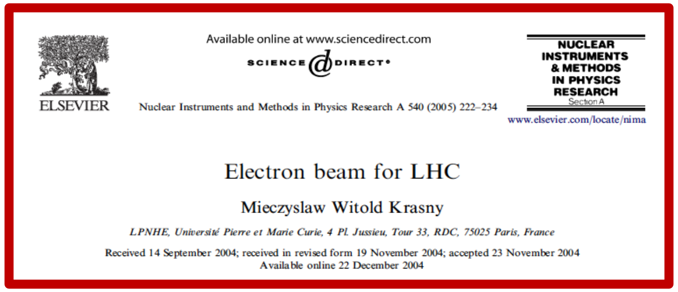
Hydrogen-like lead



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

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

Initial studies:



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Nuclear Instruments and Methods in Physics Research A 540 (2005) 222–234

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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Electron beam for LHC

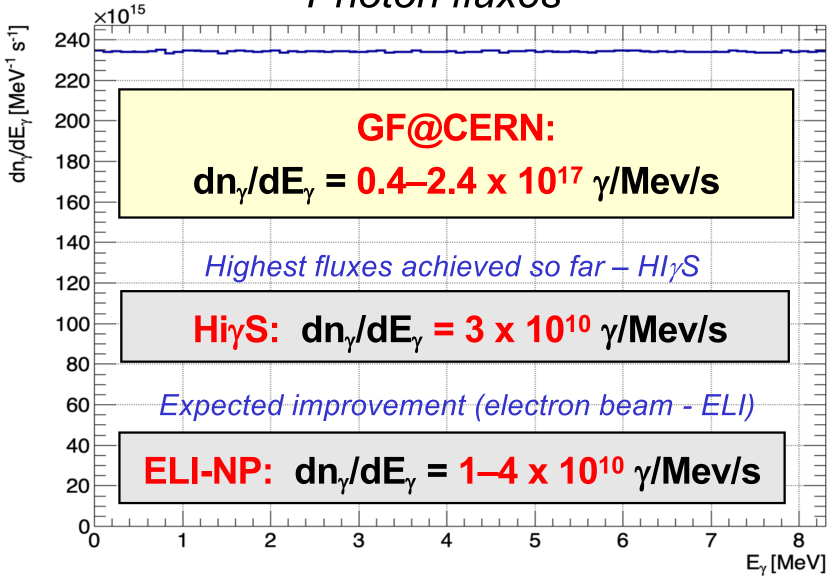
Mieczyslaw Witold Krasny

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

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

A concrete example: Nuclear physics application: H-like, Calcium beam (LHC), ($1s_{1/2} \rightarrow 2p_{1/2}$) transition, TiSa laser, 20 MHz FP cavity

Photon fluxes

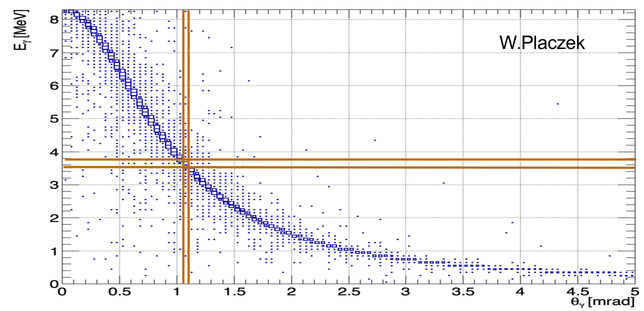


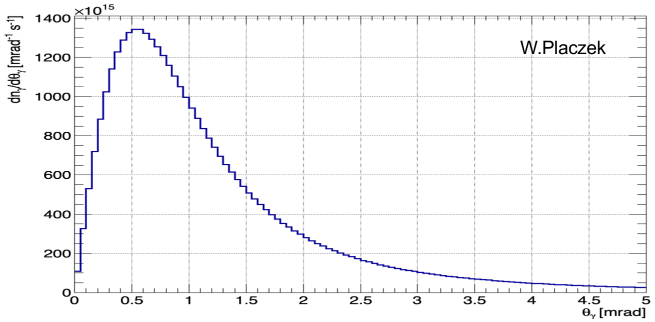
laser pulse parameters

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

Highly-collimated monochromatic γ–beams:

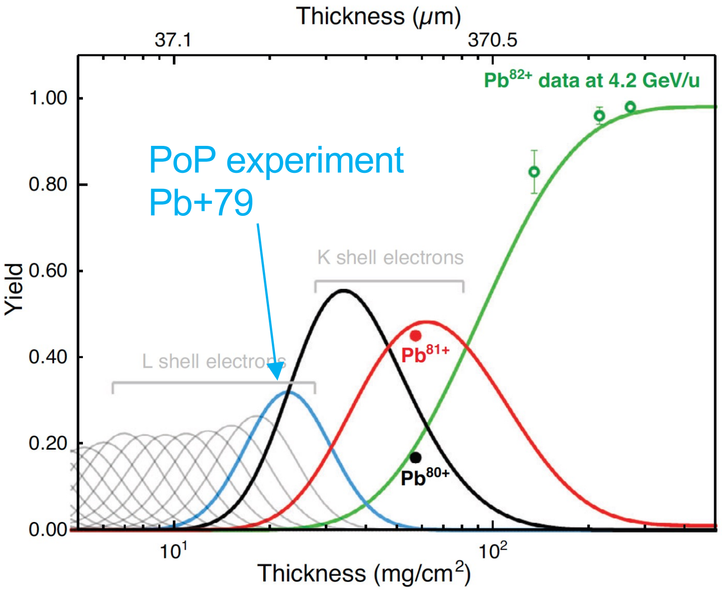
- *the beam power is concentrated in a narrow angular region (facilitates beam extraction),*
- *the (E_γ,Θ_γ) correlation can be used (collimation) to "monochromatize" the beam*





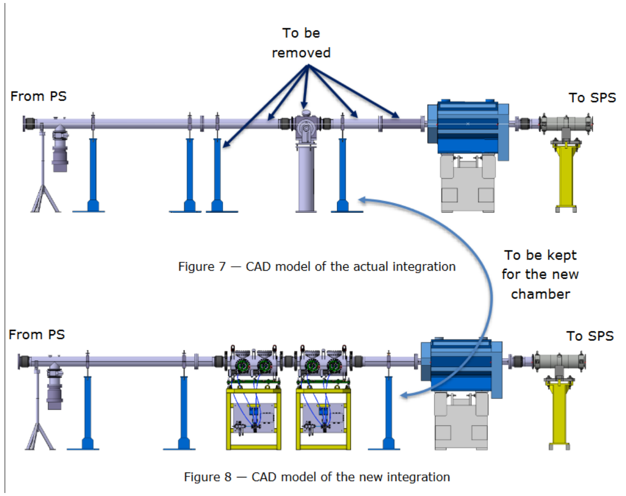
Requisite TT2 stripper system installed

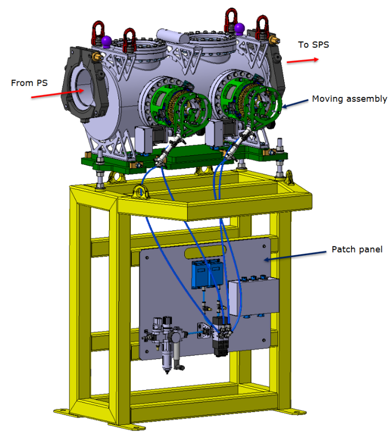
Example: Stripping of Pb+54 ions in the TT2 PS-→ SPS transfer line



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

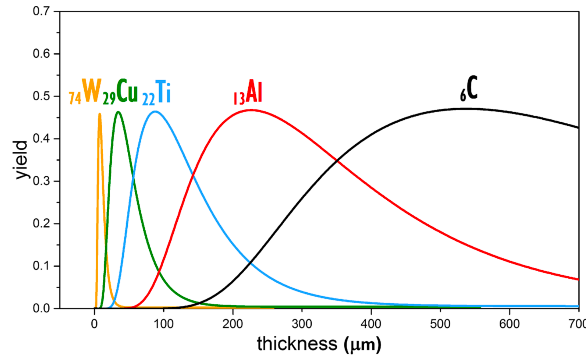
Felix M. Kröger, Günter Weber, Simon Hirlaender, Reyes Alemany-Fernandez, Mieczyslaw W. Krasny, Thomas Stöhlker, Inga Yu. Tolstikhina, and Viacheslav P. Shevelko*

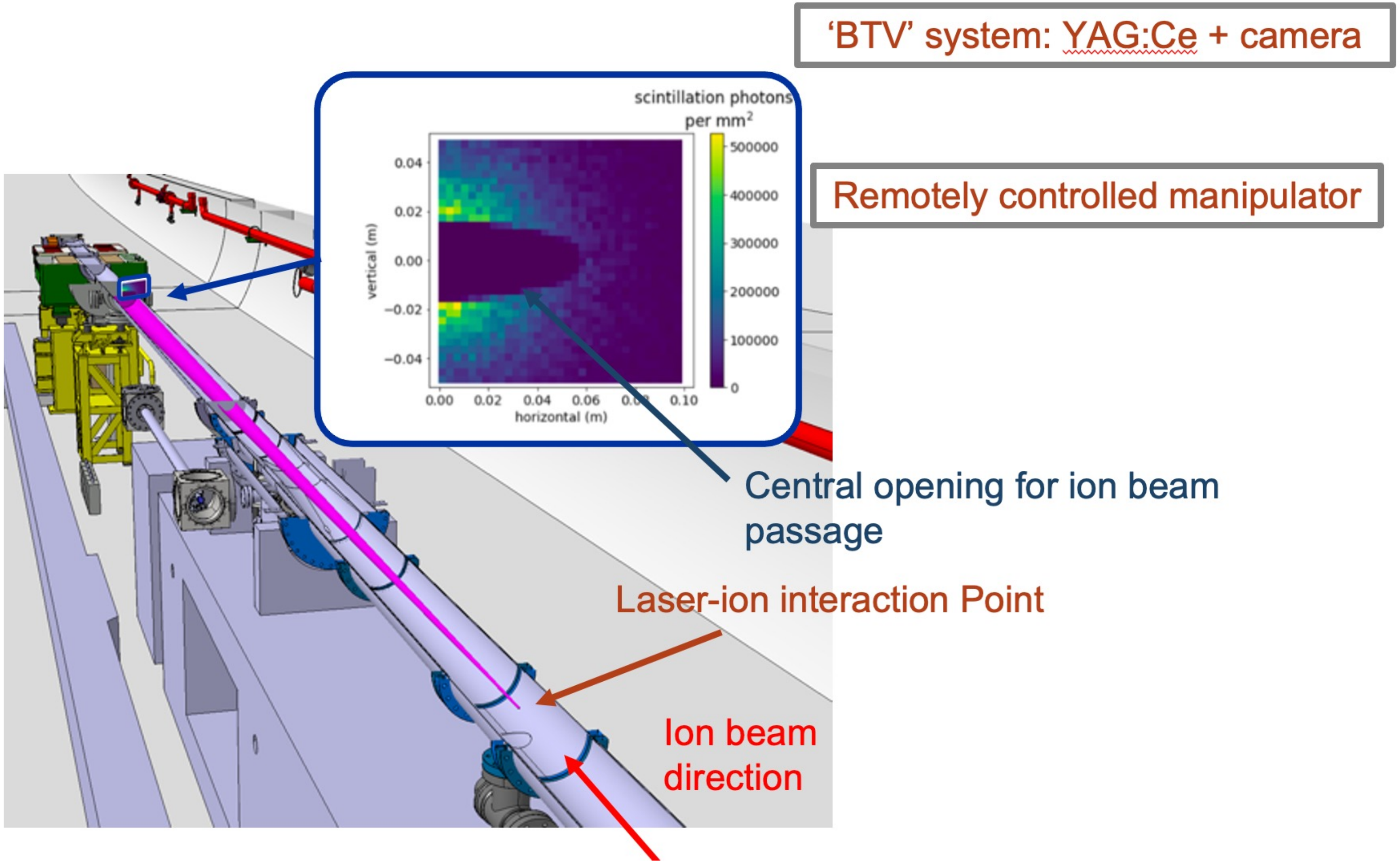


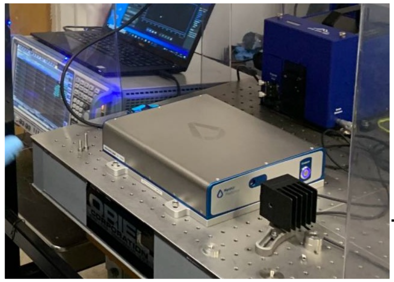


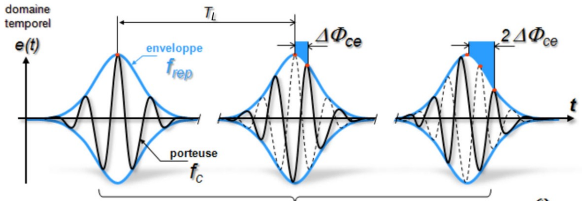
R. Alemany-Fernandez (BE.OP), E. Grenier-Boley and D. Baillard (SY.STI)

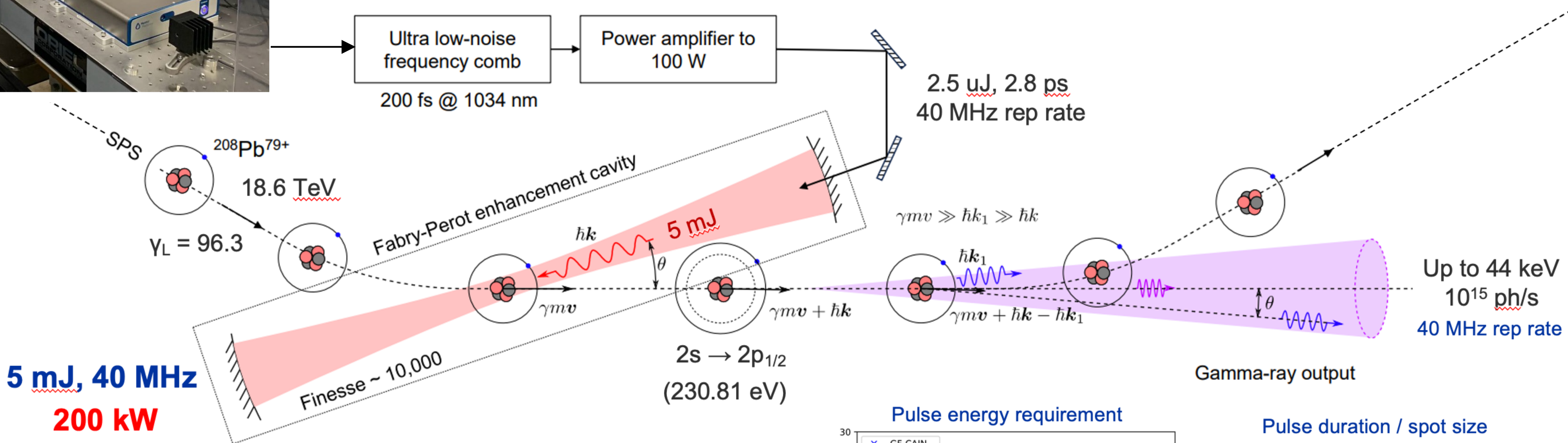
The two tanks of the new stripper system were installed during YETS 2021-2022 and YETS 2022-2023. Four stripper foil mechanisms are operating at ~Hz frequency.




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

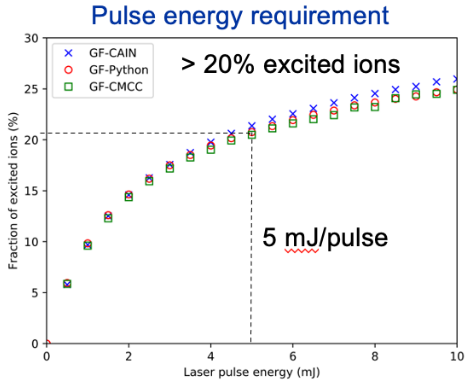


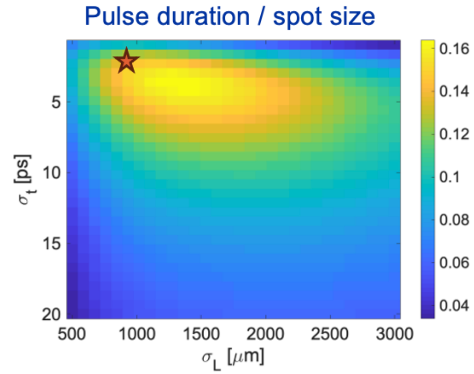




Frequency comb linewidth < 2 kHz

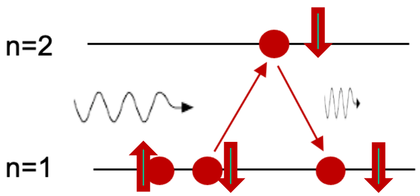
"LIGO-type" mirrors





Polarised (and/or twisted) GF photon beams

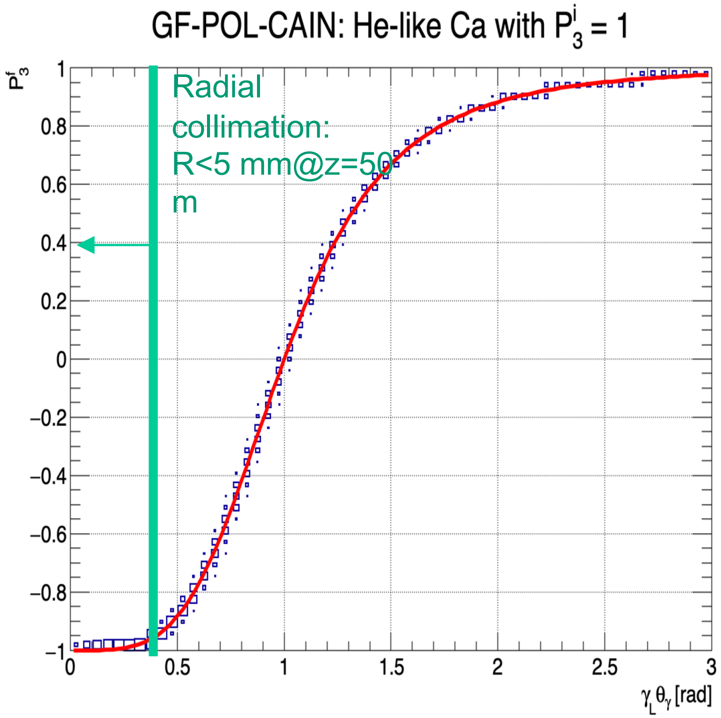
Novel concept: Pauli blocking

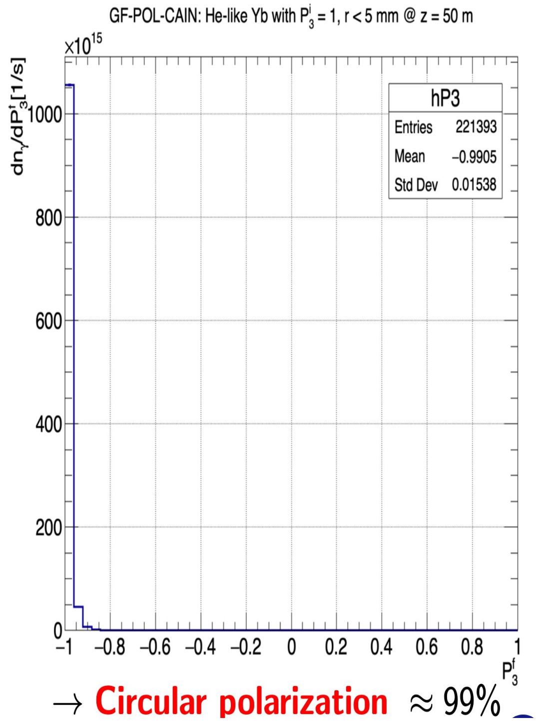


$$nS_0 \rightarrow n'P_1 \rightarrow nS_0$$

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

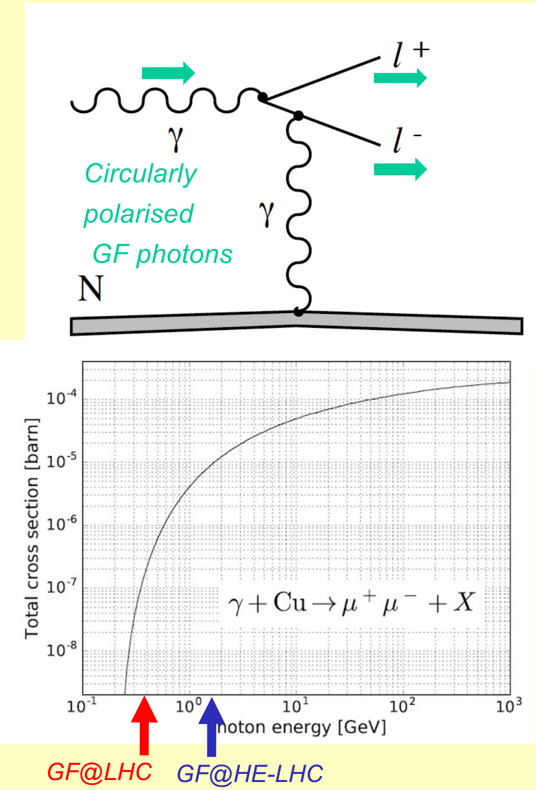
$1s^2\ ^1S_0 \rightarrow 1s^1\ 2p^1\ ^1P_1$ transition in He-like atoms





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

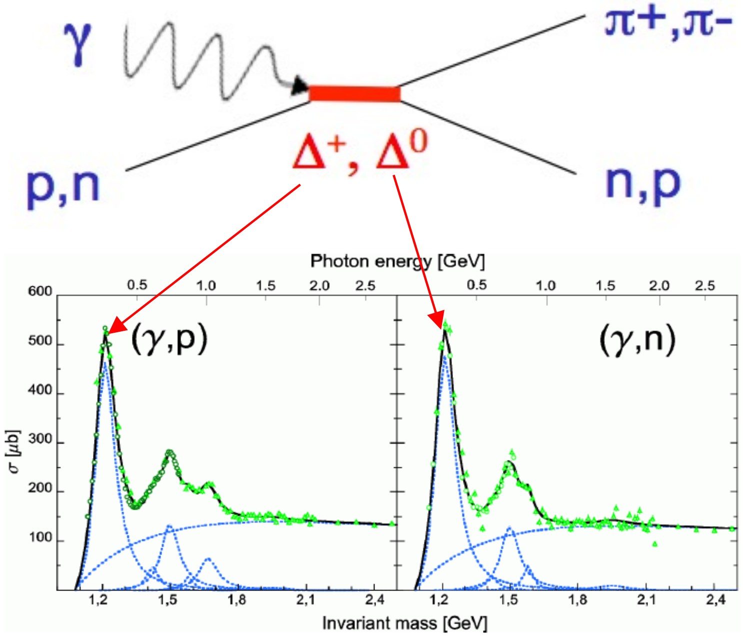
GF provides two ways of producing polarised muons

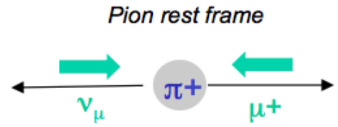


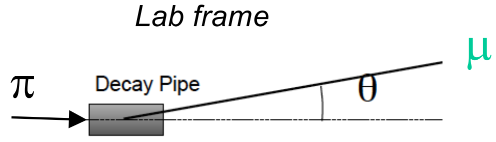
~ 10^{10} polarised μ/s source

(Mass threshold effect)

Novel concept







Polarisation
$=P(\theta)$

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