Gamma Factory

Corfu 2024 workshop on Future accelerators
the 25th of May 2024

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

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

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

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

"*Gamma Factory*" studies

The Gamma Factory proposal for CERN †

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

Mieczyslaw Witold Krasny*

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

e-Print: 1511.07794 [hep-ex]

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

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Gamma Factory studies are anchored and supported by the CERN Physics Beyond Colliders (PBC) framework.

More info on all the GF group activities:

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

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

Outline of the talk

- *Rationale behind the Gamma Factory initiative*
- *Basic principles and feasibility studies*
- *Scientific programme – selected examples*
- *Proof-of-Principle experiment at the SPS*
- *Outlook*

Rationale behind the Gamma Factory initiative

1. Curiosity

- *How to efficiently “accelerate” photons?*
- *The science of high energy* ***atomic beams*** *(production, storage, cooling, collision aspects) has so far, not been developed. Atomic beams are very special -- they can be controlled with unprecedented precision -- a path to the ultimate-luminosity hadronic colliders?*
- *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 physics expertise be merged into a joint multidisciplinary project?

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

- *High energy frontier (detailed Higgs studies at the FCC-ee, etc…)*

- *High intensity frontier (dark Matter, neutrino mass puzzle(s), families, lepton universality, etc… FCC-ee potential – ~10^5 Z/sec, 10 W/sec, …)*

Gamma Factory can improve the present intensity limits of the:

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

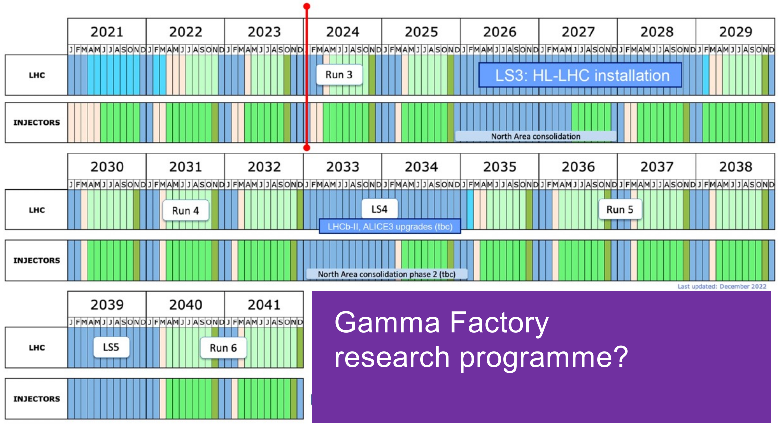
3. LHC extracted beams

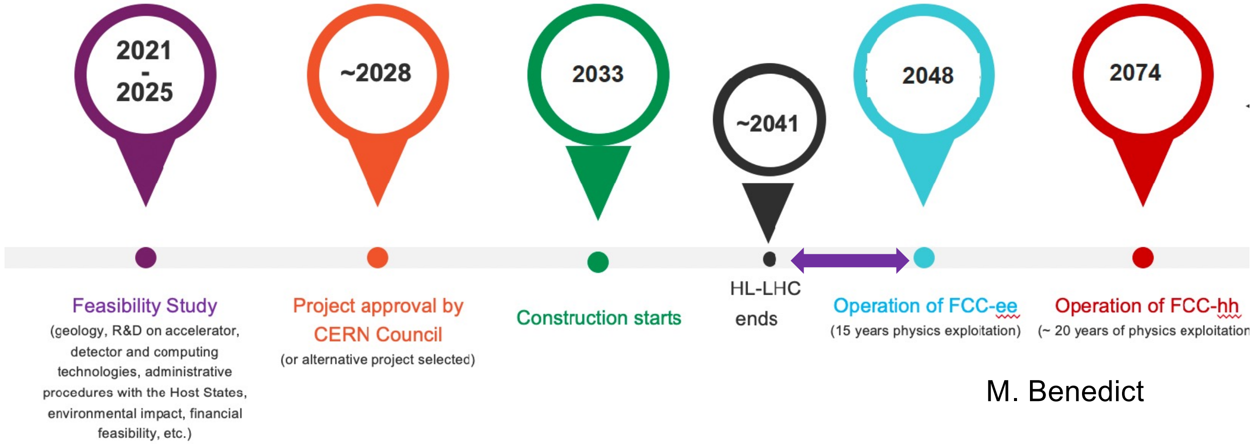
- *SPS has demonstrated operation with cycle intensity 2-4x10^{13} protons delivering 4x10^{19} protons/year for the SPS fixed target programme, (PSB can deliver 10^{20} protons/year for the ISOLDE programme)*

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

Gamma Factory could extract ~10^25 γ/year for a fixed target programme With ~100% efficiency

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





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

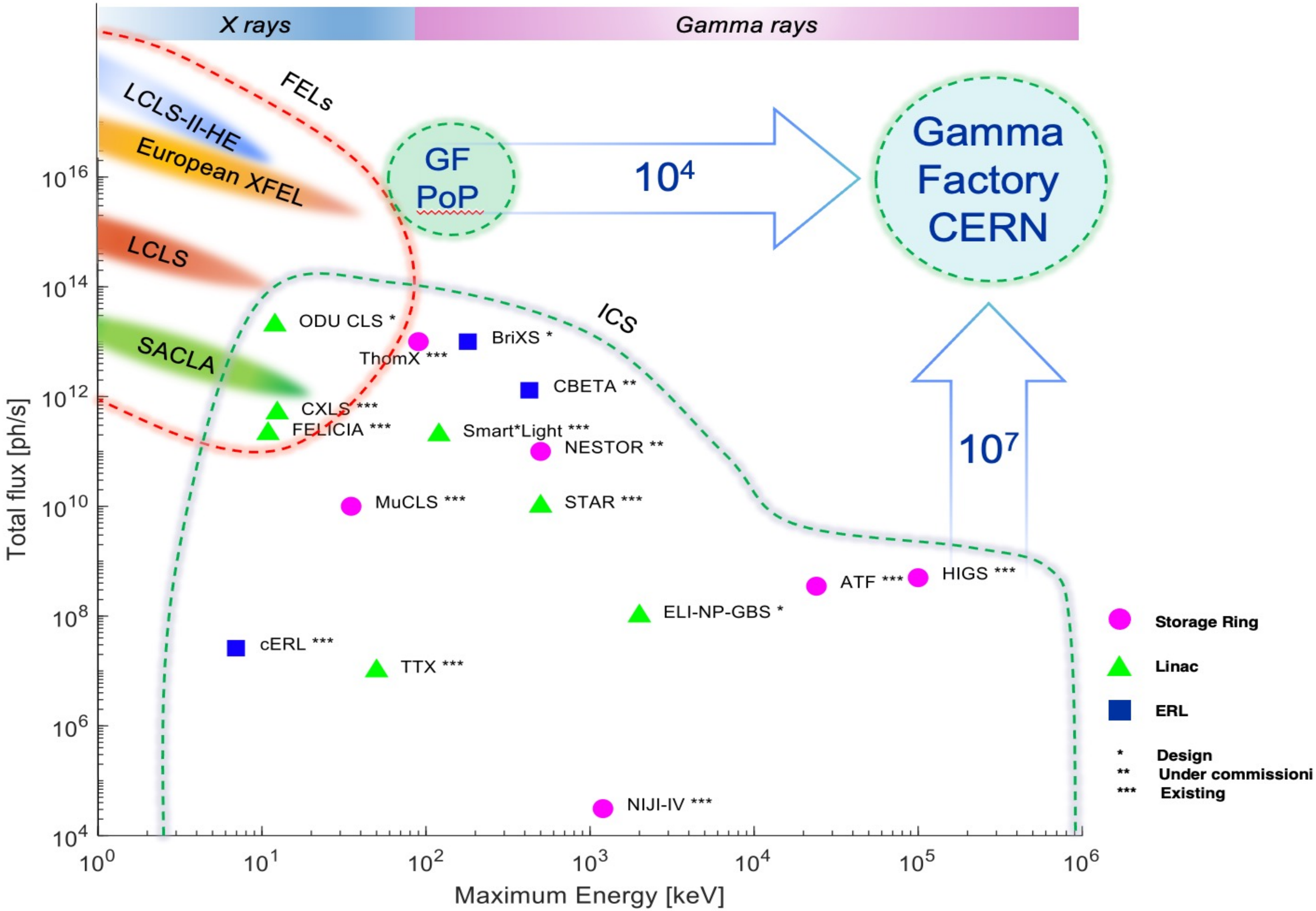
	Cost-estimate /BCHF	AC-Power /MW	Comments
Infrastructure	5.5		100km tunnel and surface infrastructure
FCC-ee	5	260-350	+1.1BCHF for the Top stage (365GeV)
FCC-hh	17	580	

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

6. Opening new research opportunities at CERN

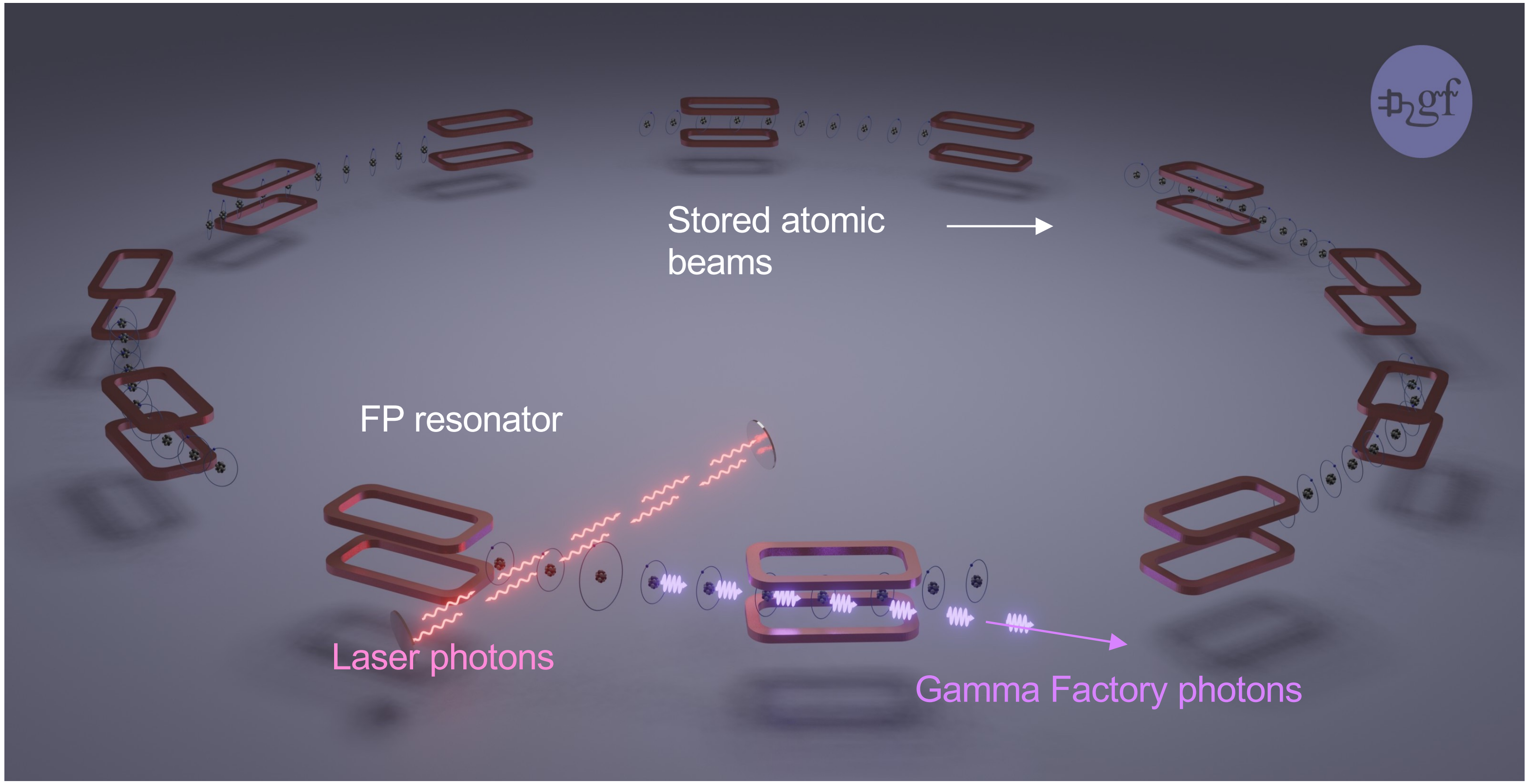
- ***particle physics*** *(precision QED and EW studies, vacuum birefringence, Higgs physics in $\gamma\gamma$ collision mode, rare muon decays, precision neutrino physics, QCD-confinement studies, …);*
- ***nuclear physics*** *(nuclear spectroscopy, cross-talk of nuclear and atomic processes, GDR, nuclear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



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]

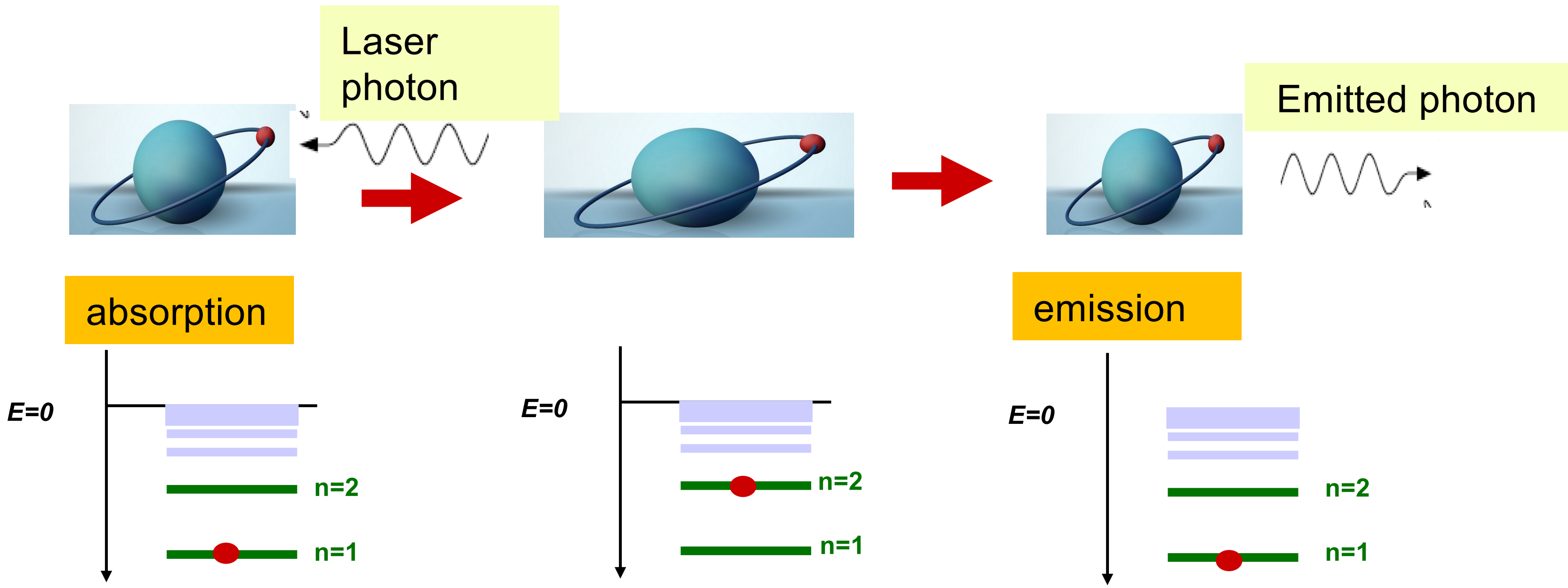
Gamma Factory photon source



Novel technology:

Resonant scattering of laser photons on ultra-relativistic atomic beam

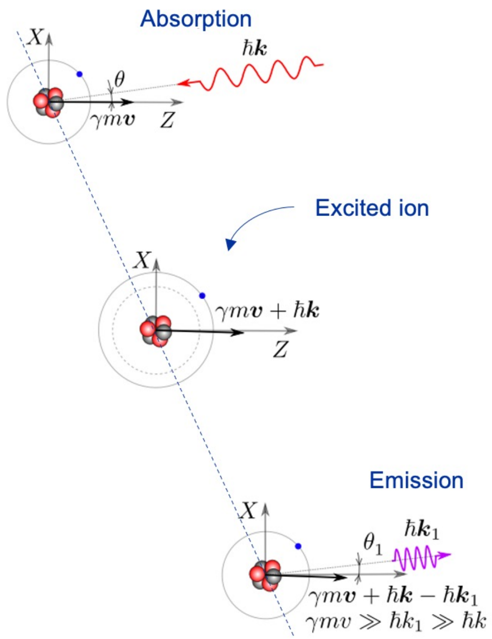
Resonant absorption and emissions of photons by **atoms**



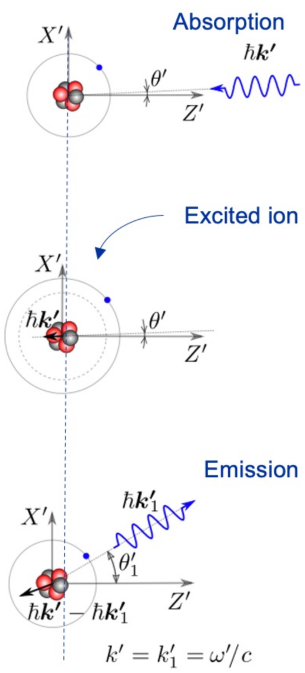
Photon acceleration -- Energy leap:

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

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

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

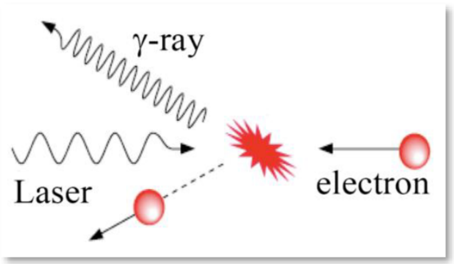
$$\nu^{max} \longrightarrow (4\,\gamma_L^{\,2})\,\nu_i$$

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

Photon acceleration – Intensity and efficiency leap:

large cross-section for atomic collisions

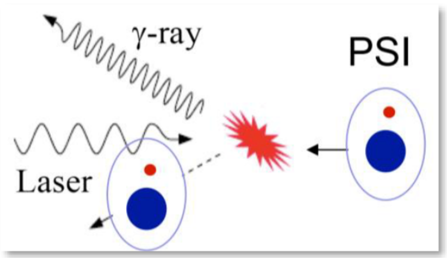
Inverse Compton scattering



Cross-section	Requirements
Electrons:	E_{beam} = 1.5 GeV
$\sigma_e = 8\pi/3 \times r_e^2$	LINAC or LWFA
r_e - classical electron radius	Electron fractional energy loss: emission of 150 MeV photon: $E_\gamma/E_{beam} = 0.1$
$\sigma_e = 6.6 \times 10^{-25}$ cm^2	(electron is lost!)

$\sigma \times 10^9$

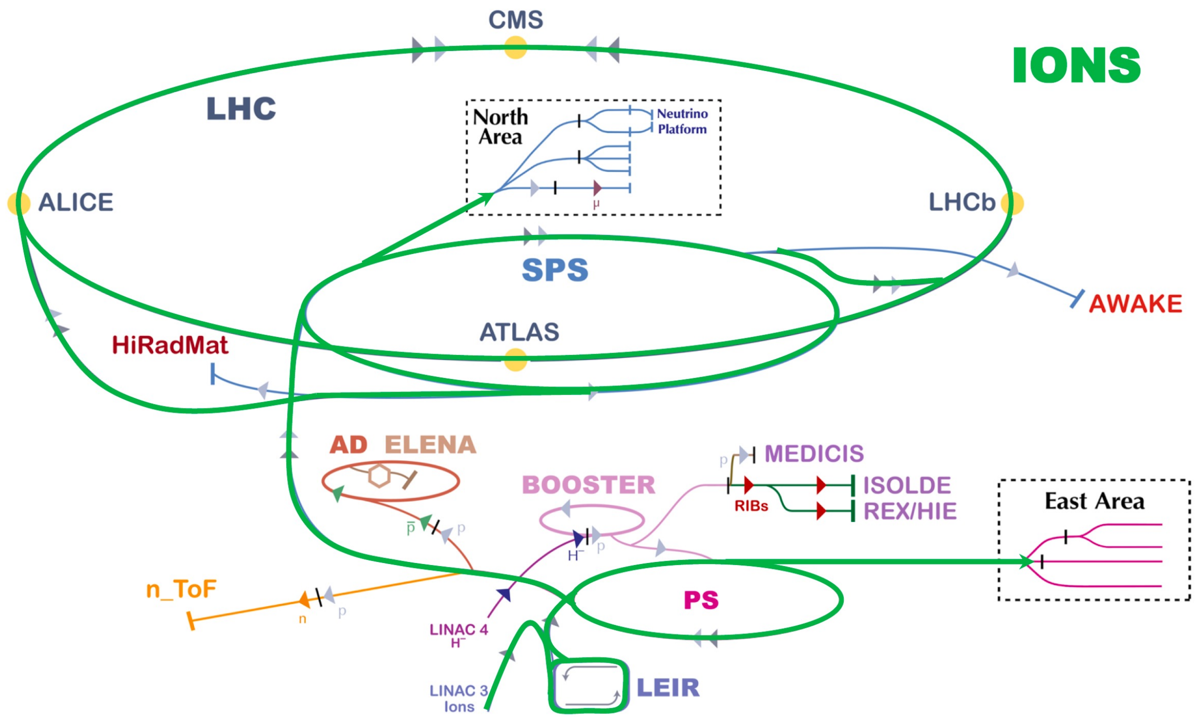
Gamma Factory



Cross-section	Requirements
Partially Stripped Ions:	E_{beam} = 574 000 GeV
$\sigma_{res} = \lambda_{res}^2/2\pi$	(LHC)
λ_{res} - photon wavelength in the ion rest frame	Electron fractional energy loss: emission of 150 MeV photon: $E_\gamma/E_{beam} = 2.6 \times 10^{-7}$
$\sigma_{res} = 5.9 \times 10^{-16}$ cm^2	(ion undisturbed!)

Example: Pb, hydrogen-like ions, *stored in LHC* γ_L = 2887

Re-use of already existing accelerator infrastructure – CERN

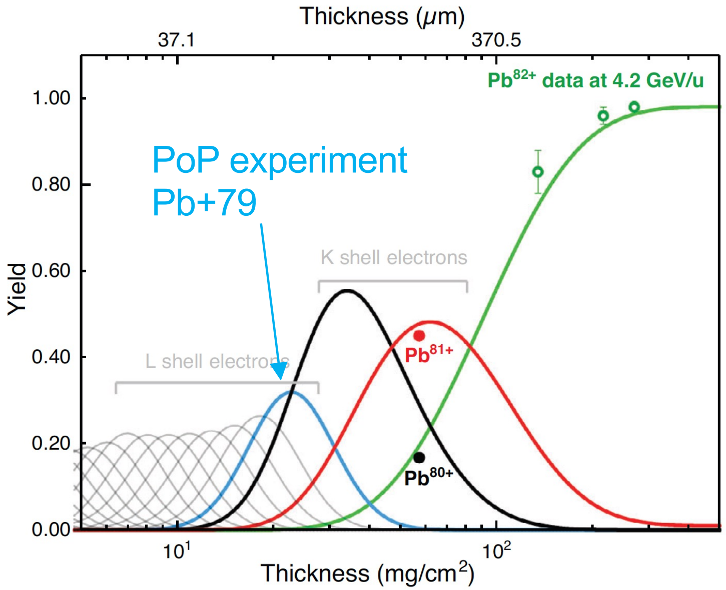


Gamma Factory (additional) beam requirements:

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

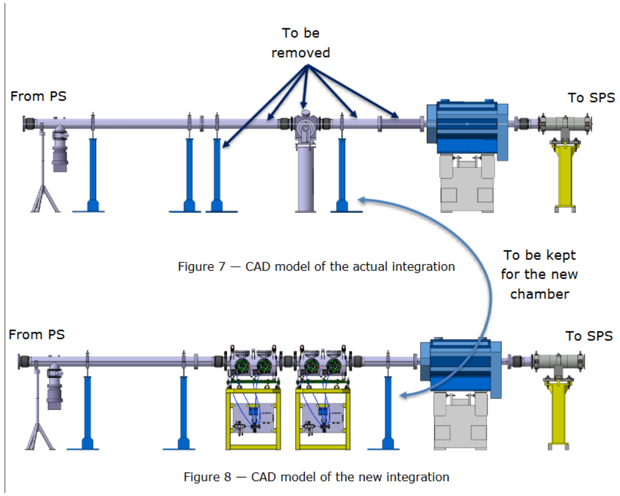
Achievements : Requisite TT2 stripper system installed

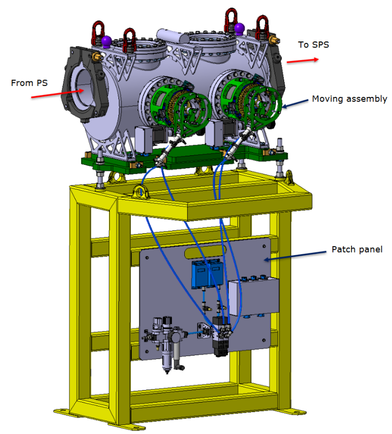
Stripping of Pb+54 ions in the TT2 PS-→ SPS transfer line

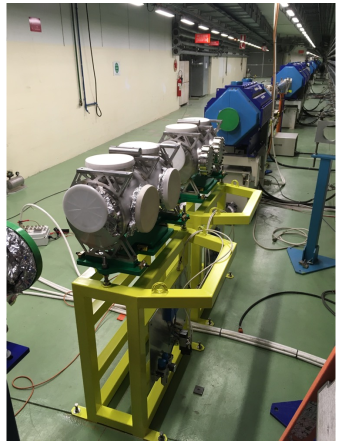


Charge-State Distributions of Highly Charged Lead Ions at Relativistic Collision Energies

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







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

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

symmetry
dimensions of particle physics

topics

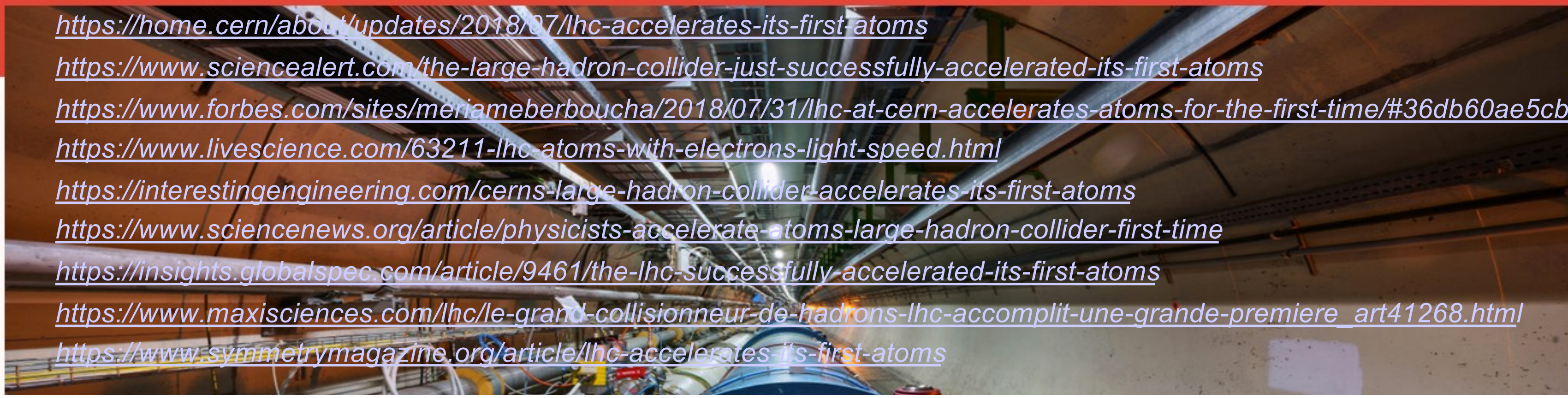
follow +

A joint Fermilab/SLAC publication

LHC accelerates its first "atoms"

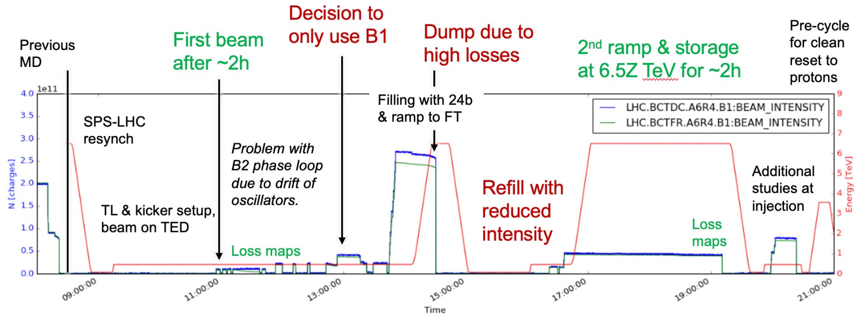
07/27/18 | By Sarah Charley

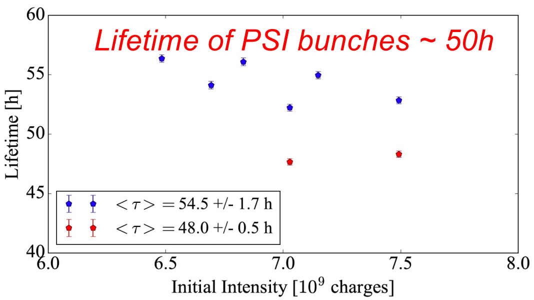
Lead atoms with a single remaining electron circulated in the Large Hadron Collider.



https://home.cern/about/updates/2018/07/lhc-accelerates-its-first-atoms
https://www.sciencealert.com/the-large-hadron-collider-just-successfully-accelerated-its-first-atoms
https://www.forbes.com/sites/meriameberboucha/2018/07/31/lhc-at-cern-accelerates-atoms-for-the-first-time/#36db60ae5cb4
https://www.livescience.com/63211-lhc-atoms-with-electrons-light-speed.html
https://interestingengineering.com/cerns-large-hadron-collider-accelerates-its-first-atoms
https://www.sciencenews.org/article/physicists-accelerate-atoms-large-hadron-collider-first-time
https://insights.globalspec.com/article/9461/the-lhc-successfully-accelerated-its-first-atoms
https://www.maxisciences.com/lhc/le-grand-collisionneur-de-hadrons-lhc-accomplit-une-grande-premiere_art41268.html
https://www.symmetrymagazine.org/article/lhc-accelerates-its-first-atoms

Achievements: Atomic beams stored in in the LHC





CERN-ACC-NOTE-2019-0012

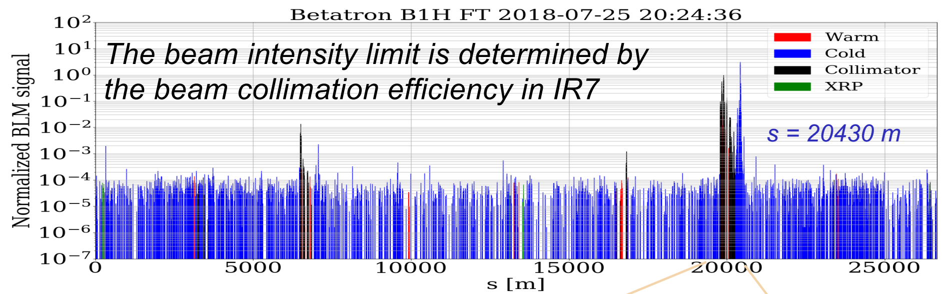
8 May 2019

Michaela.Schaumann@cern.ch

MD3284: Partially Stripped Ions in the LHC

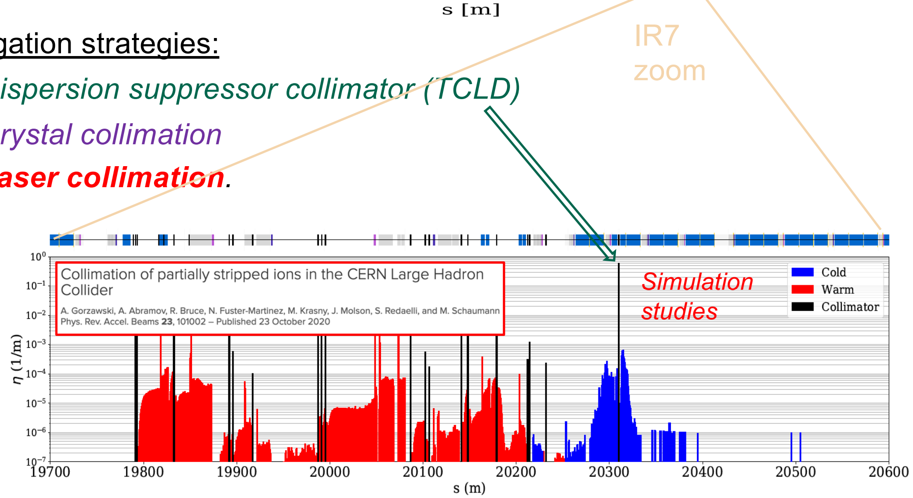
M. Schaumann, A. Abramov, R. Alemany Fernandez, T. Argyropoulos, H. Bartosik, N. Biancacci, T. Bohl, C. Bracco, R. Bruce, S. Burger, K. Cornelis, N. Fuster Martinez, B. Goddard, A. Gorzawski, R. Giachino, G.H. Hemelsoet, S. Hirlaender, M. Jebramcik, J.M. Jowett, V. Kain, M.W. Krasny, J. Molson, G. Papotti,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

CERN, CH-1211 Geneva 23

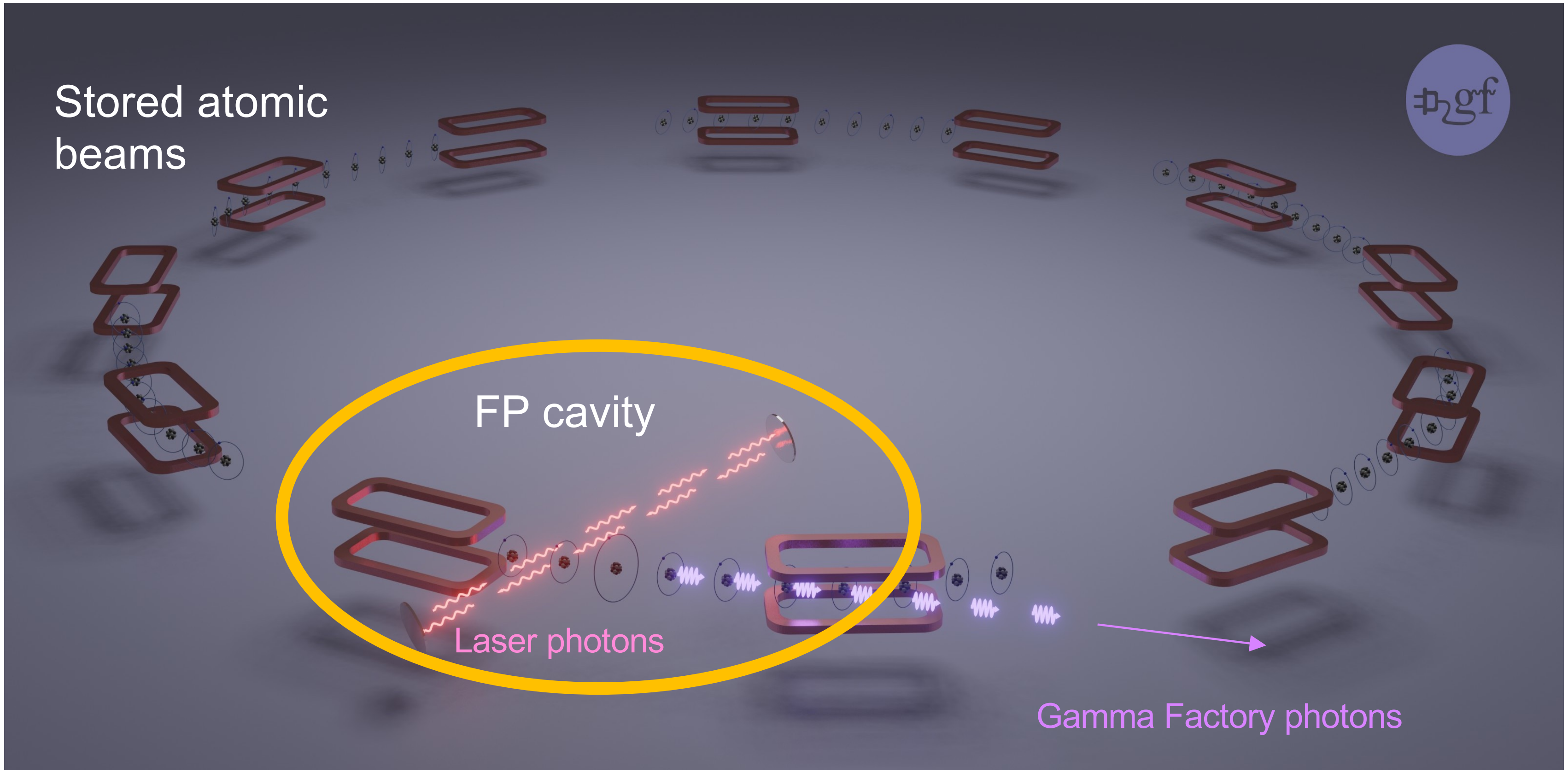


Mitigation strategies:

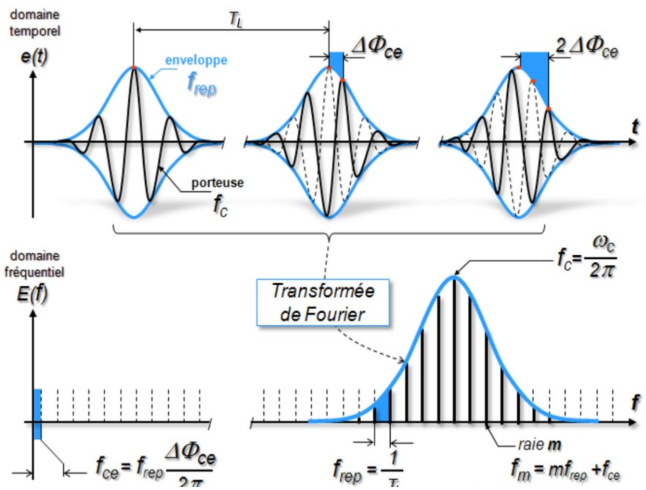
1. *Dispersion suppressor collimator (TCLD)*
2. *Crystal collimation*
3. ***Laser collimation***.

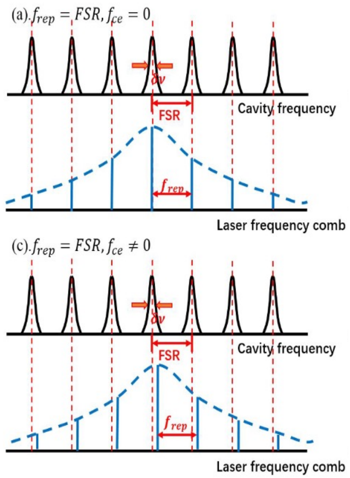


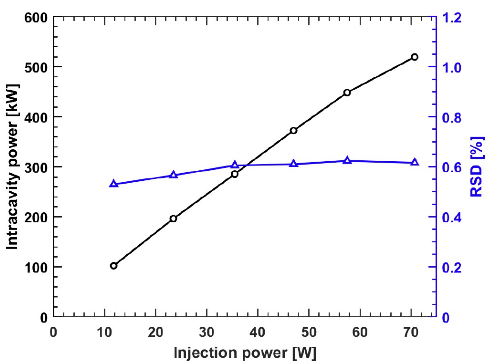
Laser photons

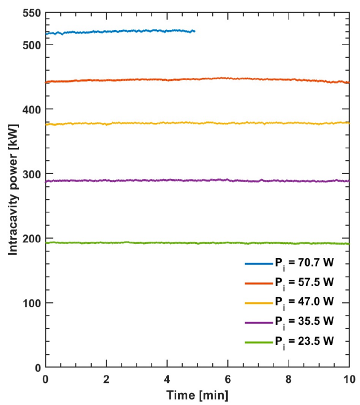


Towards the first integration of the Fabry-Pérot (FP) cavity in the hadron storage ring

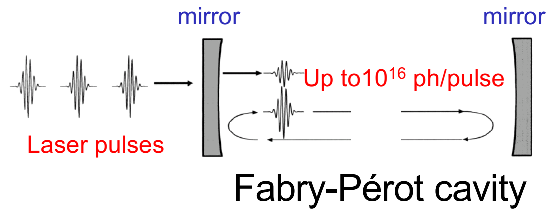








GF at SPS and LHC rings



GF requirements:

- < 5mJ pulses @ 20MHz, (100kW photon beam)
- Stable remote operation of the laser system in the hadron storage rings (to be demonstrated in the GF proof-of-Principle experiment)

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

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

X.-Y. Lu,[1, a)] R. Chiche,[1] K. Dupraz,[1] F. Johora,[1] A. Martens,[1] D. Nutarelli,[1] Y. Peinaud,[1] V. Soskov,[1] A. Stocchi,[1] F. Zomer,[1] C. Michel,[2] L. Pinard,[2] E. Cormier,[3] J. Lhermite,[4] X. Liu,[5] Q.-L. Tian,[5] L.-X. Yan,[5] W.-H. Huang,[5] C.-X. Tang,[5] V. Fedosseev,[6] E. Granados,[6] and B. Marsh[6]

[1)] *Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France*

[2)] *Laboratoire des Matériaux Avancés - IP2I, CNRS, Université de Lyon, Université Claude Bernard Lyon 1, F-69622 Villeurbanne, France*

[3)] *Laboratoire Photonique Numérique et Nanosciences (LP2N), UMR 5298, CNRS-IOGS-Université Bordeaux, 33400 Talence, France*

[4)] *Université de Bordeaux- CNRS-CEA, Centre Lasers Intenses et Applications (CELIA), 351 cours de la Libération F- 33405 Talence, France*

[5)] *Department of Engineering Physics, Tsinghua University, Beijing 100084, China*

[6)] *CERN, CH-1211, Geneva, Switzerland*

(*Electronic mail: aurelien.martens@ijclab.in2p3.fr.)

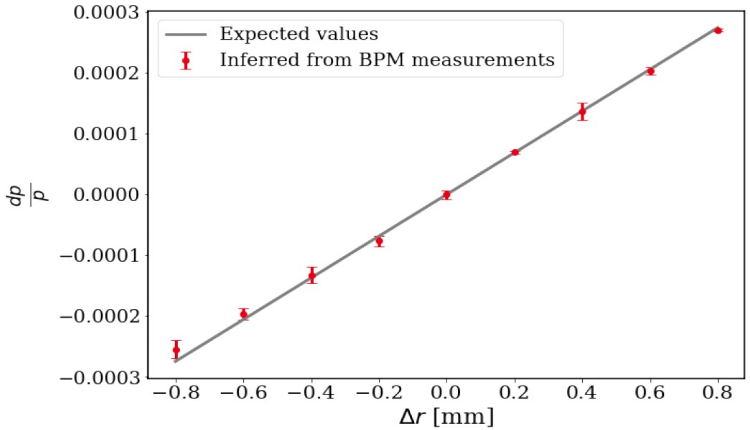
(Dated: 23 April 2024)

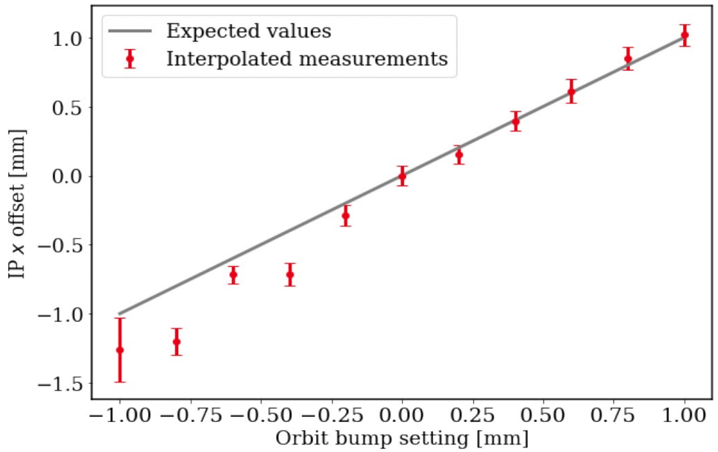
Paper has just been submitted to *Applied Physics Letters*

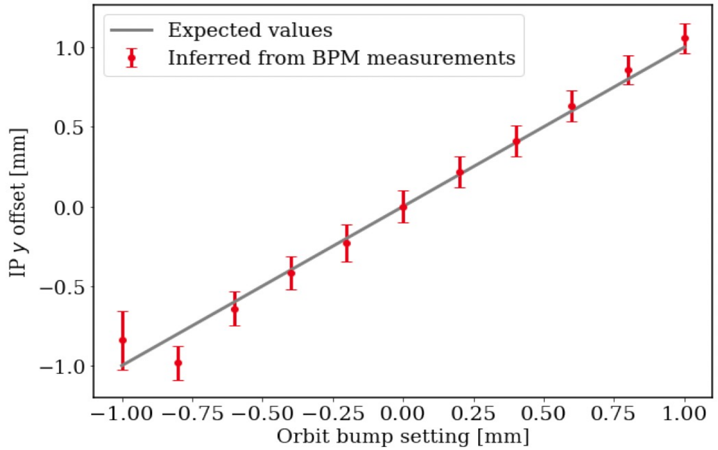
Achievements: Requisite precision of the momentum and beam position control at the collision point with laser photons

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

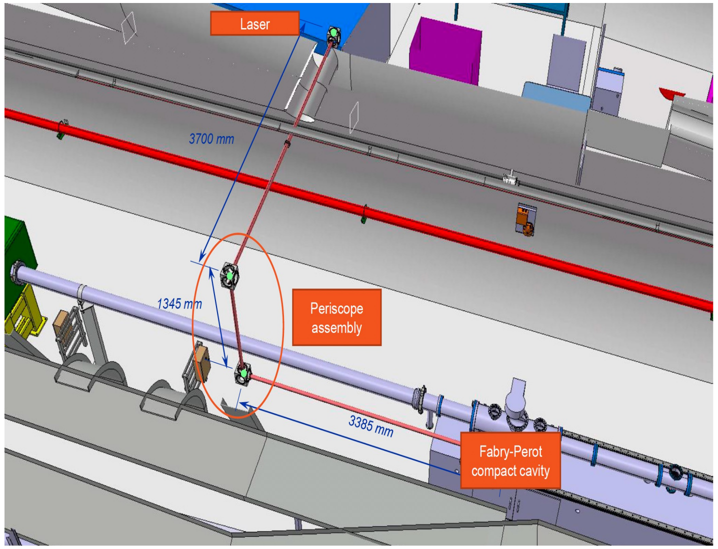
R. Ramjiawan, G. Arduini, H. Bartosik, Y. Dutheil, W. Hofle, M. W. Krasny, A. Martens, Y. Papaphilippou, A. Petrenko, F. M. Velotti,
CERN, CH-1211 Geneva, Switzerland

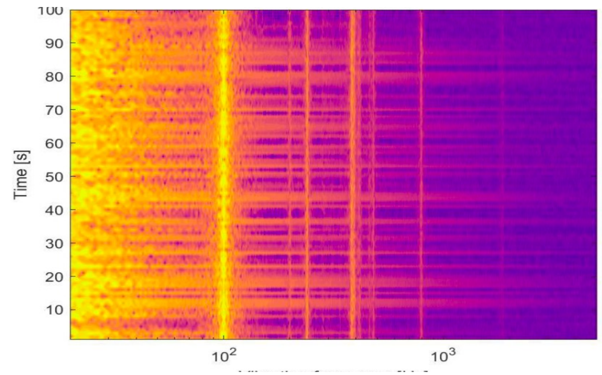


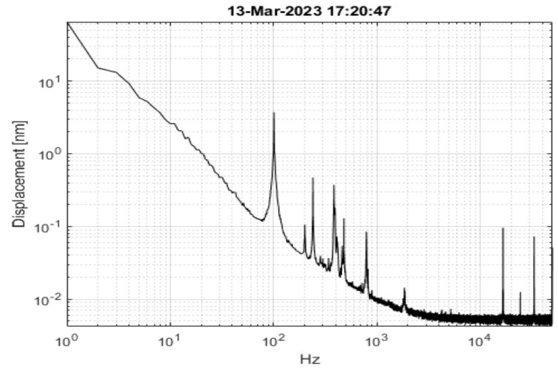


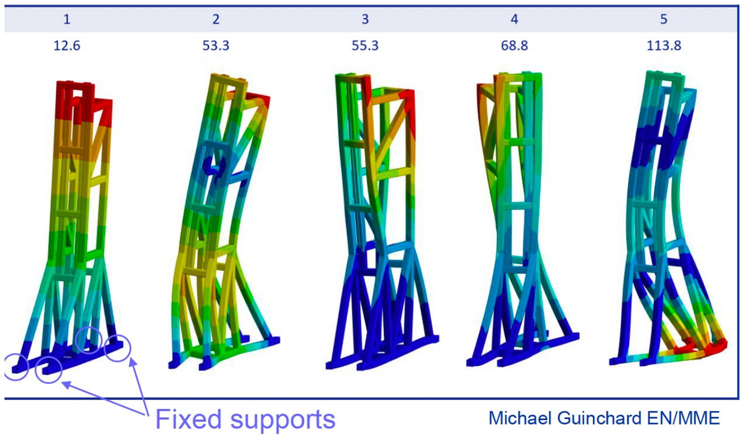


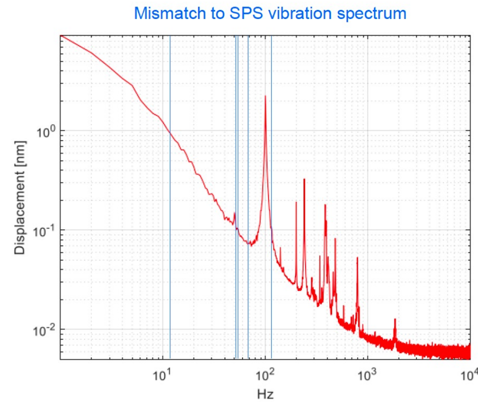
Achievements: Measurement of vibration modes of the laser photon transport line (and their mitigation)



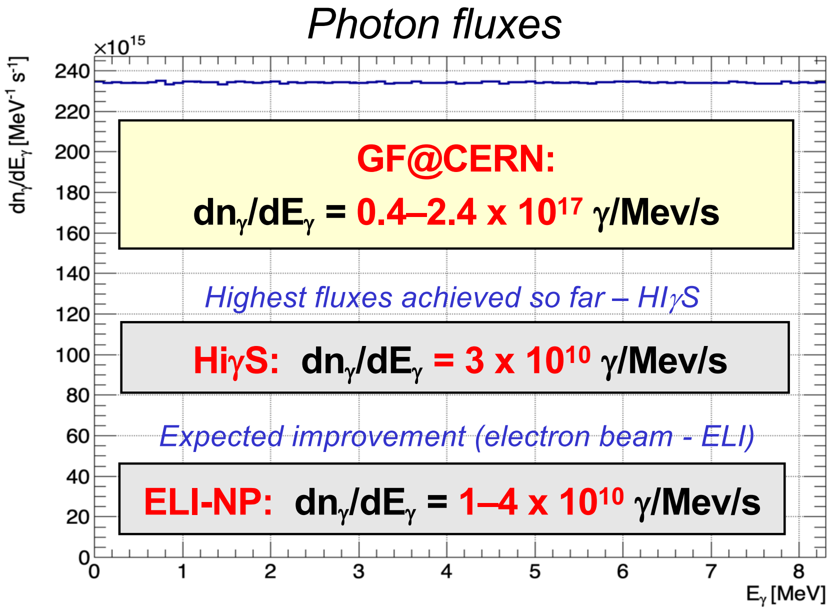








A concrete example: Nuclear physics application: He-like, LHC Calcium beam, $(1s \rightarrow 2p)_{1/2}$ transition, TiSa laser, 20 MHz FP cavity

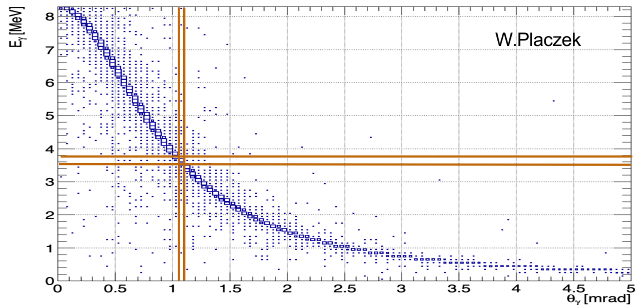


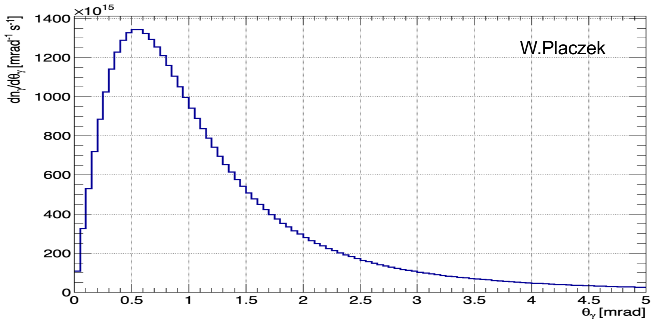
laser pulse parameters

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

Highly-collimated monochromatic γ–beams:

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

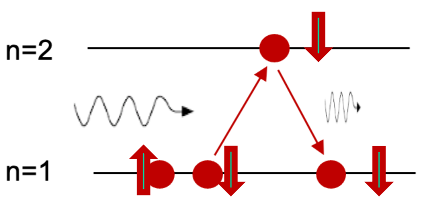




Polarised (and/or twisted) GF photon beams

… for Gudrid

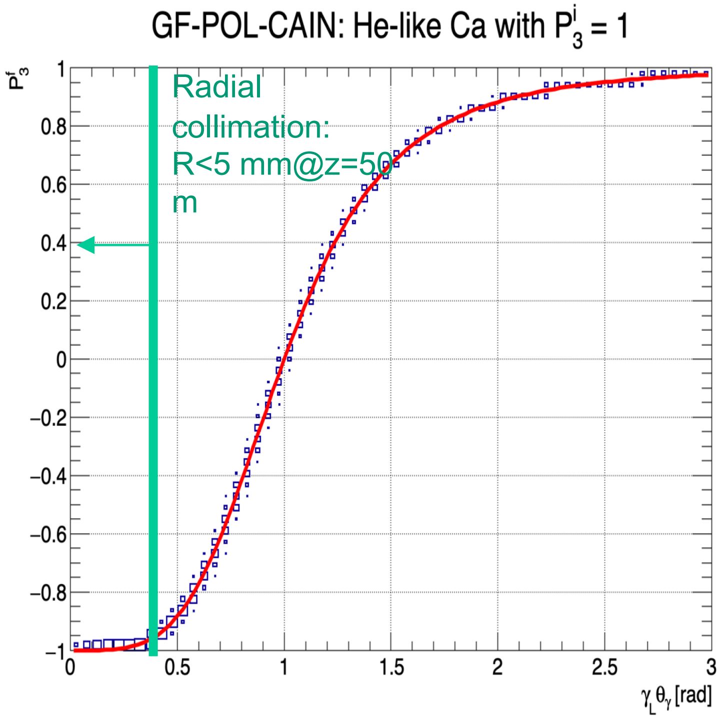
<u>A trick</u>: Pauli blocking

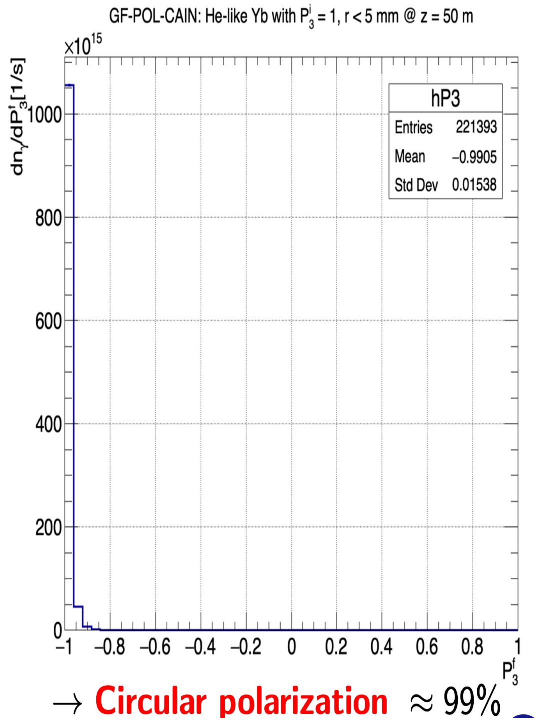


$nS_0 \rightarrow n'P_1 \rightarrow nS_0$

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

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





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

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:

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

5. Unprecedented plug power efficiency (energy footprint):

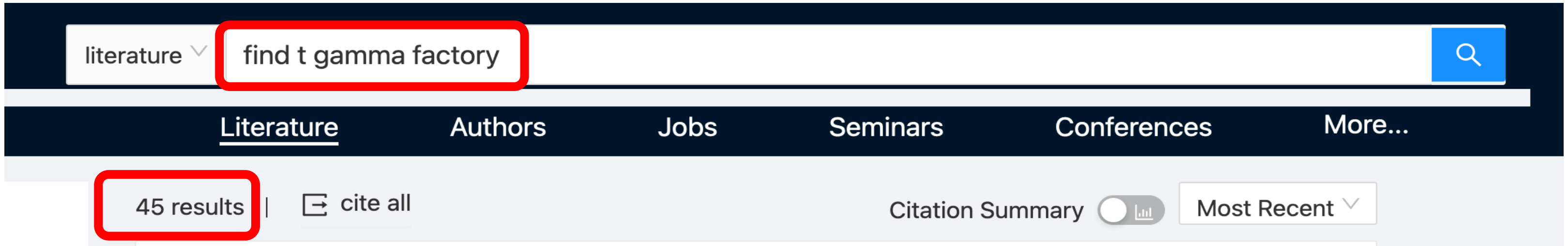
- ***LHC RF power can be converted to the photon beam power.*** *Wall-plug power efficiency of the* ***GF photon source is*** *by a factor of* ***~300 better than that of the DESY-XFEL!***

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

Scientific programme – selected examples

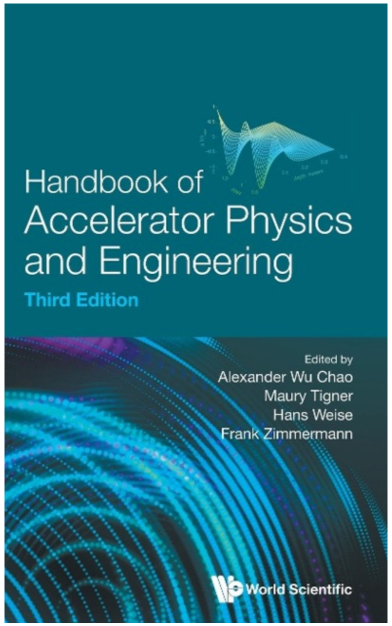
<u>GF studies:</u> published papers (INSPIRE) and books

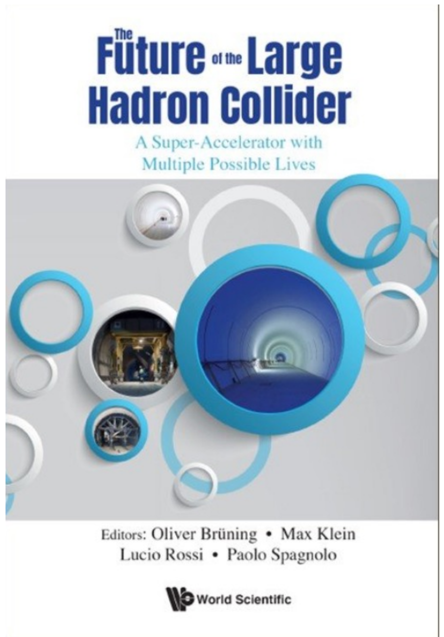
papers



books

Special issue of Annalen der Physik

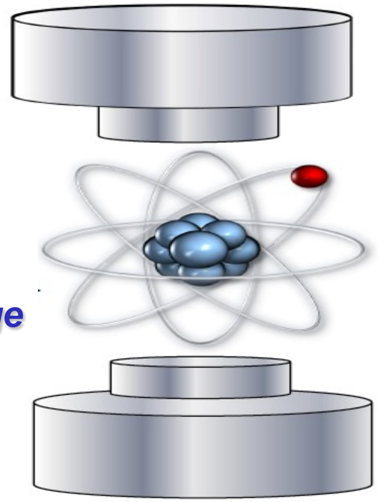


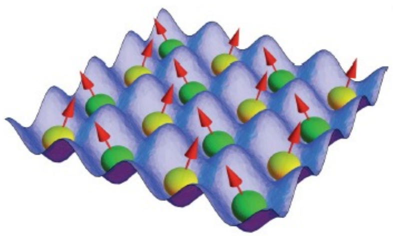


1. Experimental programme with “small-size” atoms

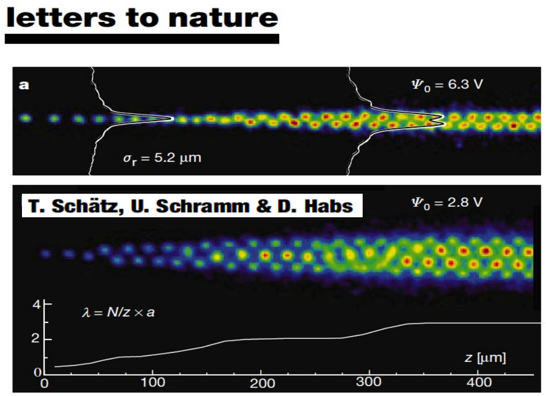
Atomic rest-frame

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





Crystalline beams?



<u>Opening new research opportunities in atomic physics</u>:

- *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

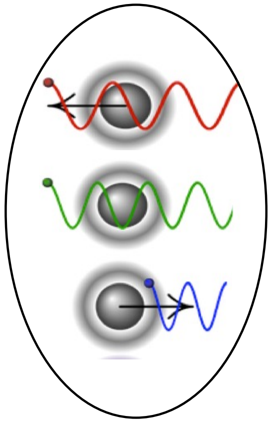
Feature Article | Open Access

Atomic Physics Studies at the Gamma Factory at CERN

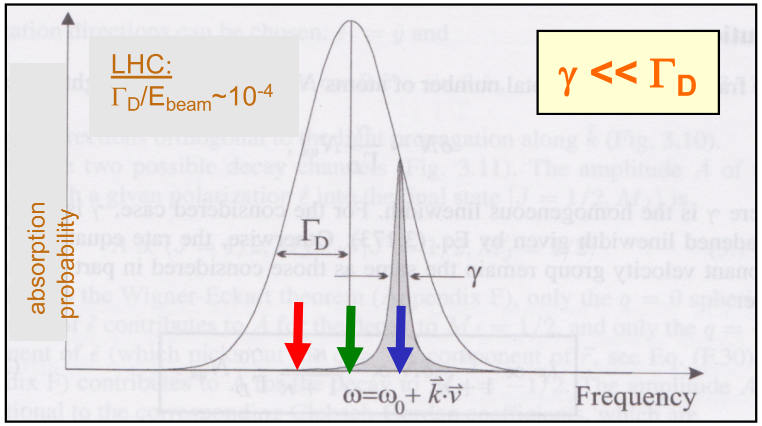
Dmitry Budker, José R. Crespo López-Urrutia, Andrei Derevianko, Victor V. Flambaum, Mieczyslaw Witold Krasny, Alexey Petrenko, Szymon Pustelny, Andrey Surzhykov, Vladimir A. Yerokhin, Max Zolotorev ... See fewer authors

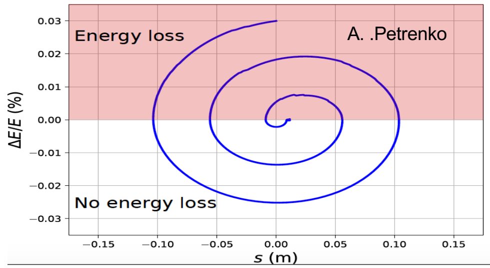
First published: 09 July 2020 | https://doi.org/10.1002/andp.202000204

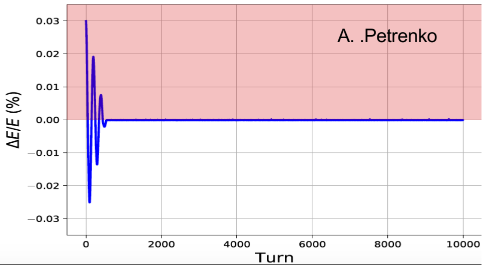
2. Experimental programme with “cold” ion beams



Bunch

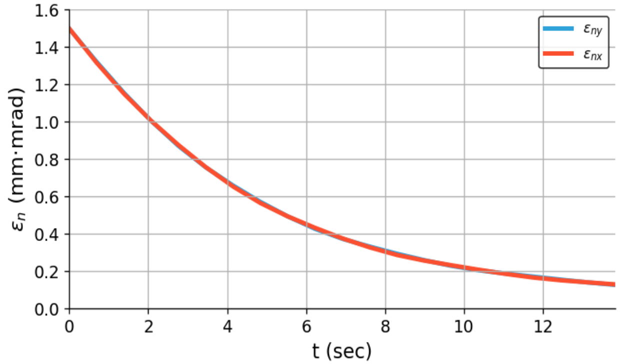






Beam cooling speed: *the laser wavelength band is chosen such that only the ions moving in the laser pulse direction (in the bunch rest frame) can resonantly absorb photons.*

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 (complementary) path to HL-LHC:

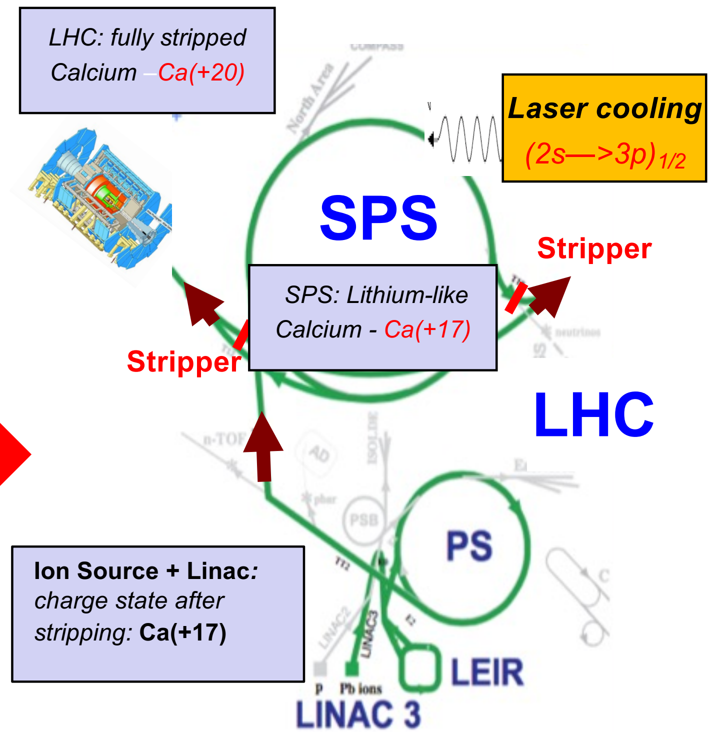
Studies of the implementation scheme with laser-cooled isoscalar Ca beams

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

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

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

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



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

The merits of cold isoscalar beams

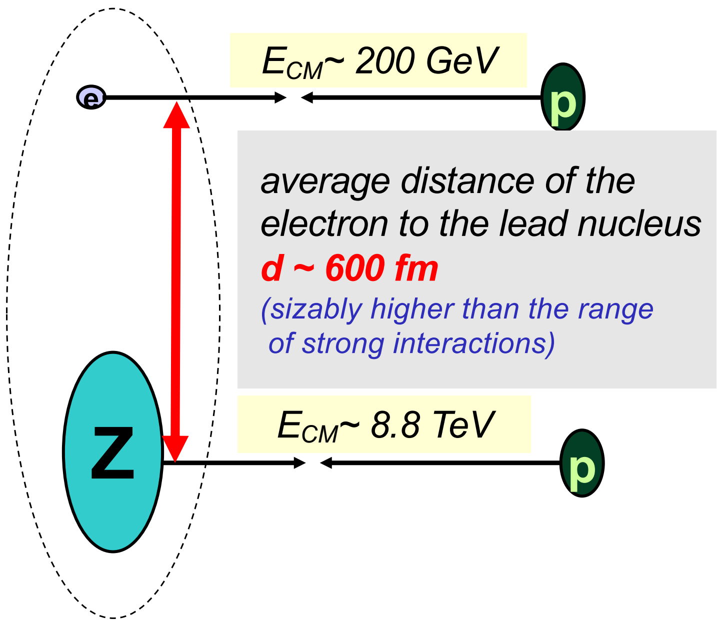
- *higher precision in measuring SM parameters in CaCa than in pp collisions*
- *Possible unique access to exclusive Higgs boson production in photon–photon collisions?*
- *Lower pileup background at equivalent nucleon-nucleon (partonic) luminosity.*
- *New research opportunities for the EW symmetry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

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

3. Studies of ep collisions at LHC

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

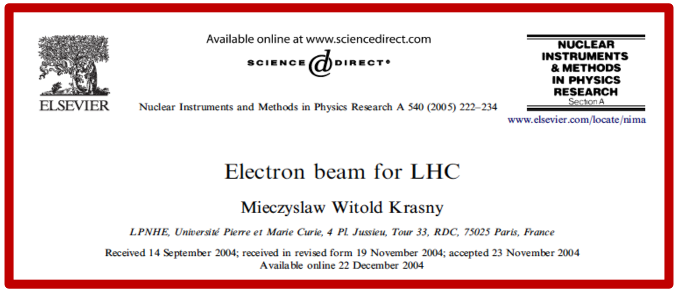
Hydrogen-like lead



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
www.elsevier.com/locate/nima

Electron beam for LHC

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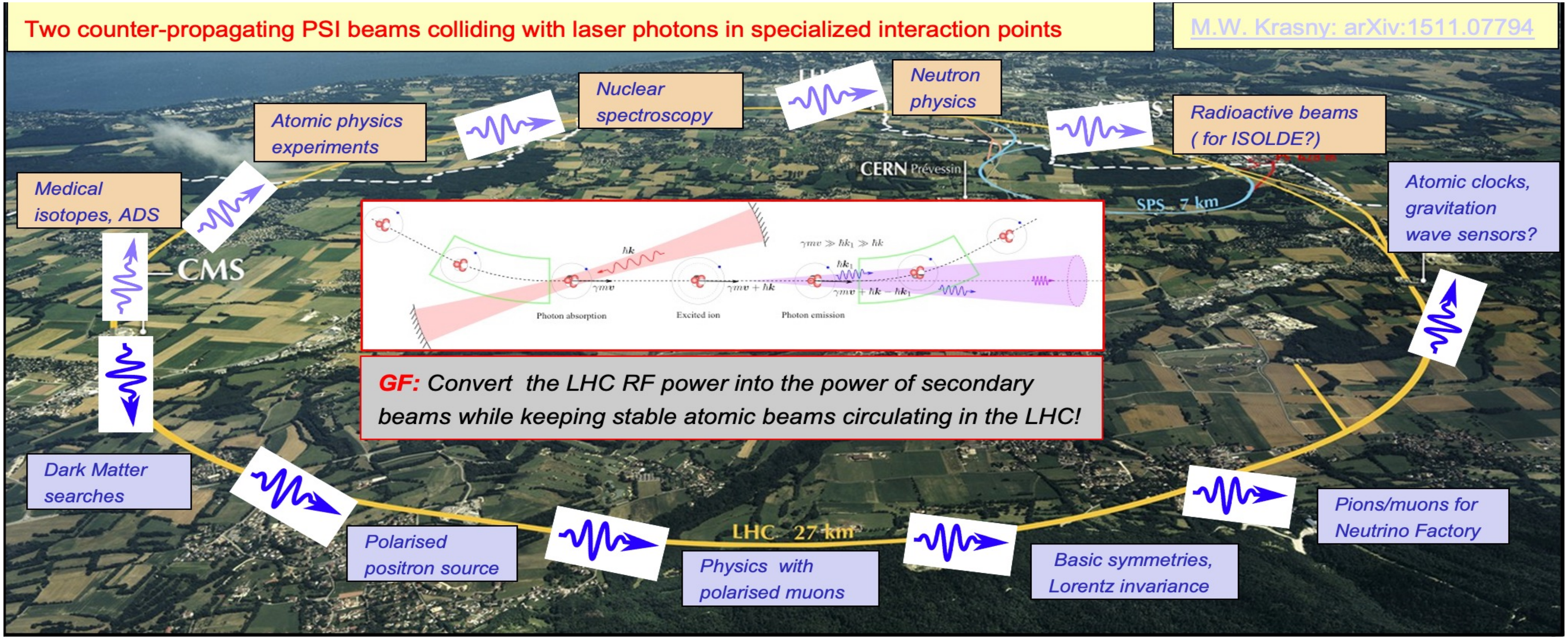
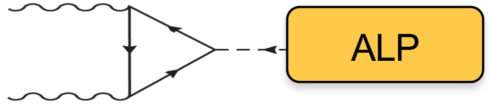
Received 14 September 2004; received in revised form 19 November 2004; accepted 23 November 2004
Available online 22 December 2004

4. Gamma Factory research programme with extracted beams



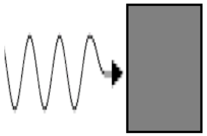
4.1 DM searches and studies (if discovered), ALP example

Collision schemes for ALP production:

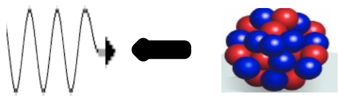


Search phase

γ_{GF} – **B field**
m_{ALP} < 1 keV



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



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

"Production" phase

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

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

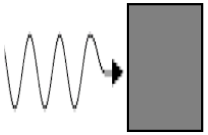
Concurrent, rich QED programme (e.g. vacuum birefringence studies)

***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**.*

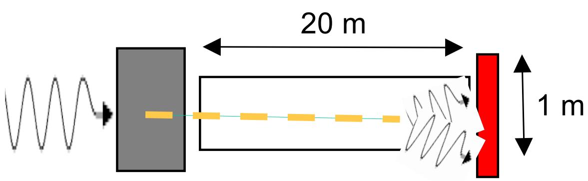
4.1 DM searches and studies (ALP example)

Search phase
Example: beam-dump mode

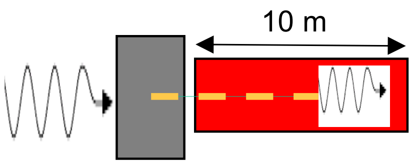


γ_{GF}–A collisions
1.6, 0.2, 0.02 GeV beams (A,B,C)

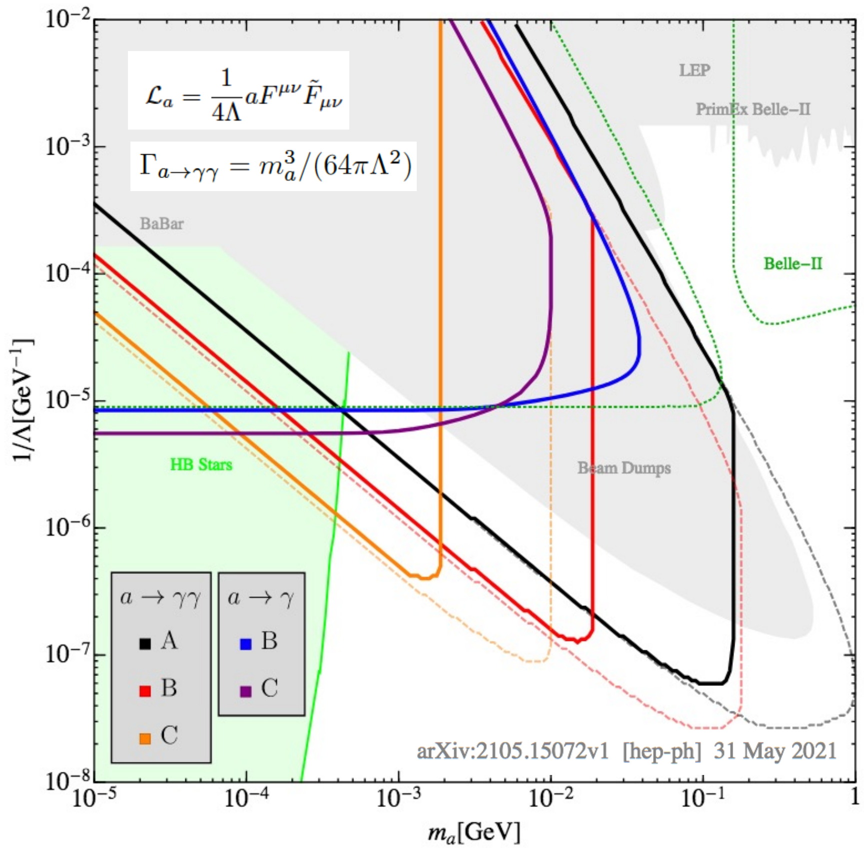
Two appearance modes:



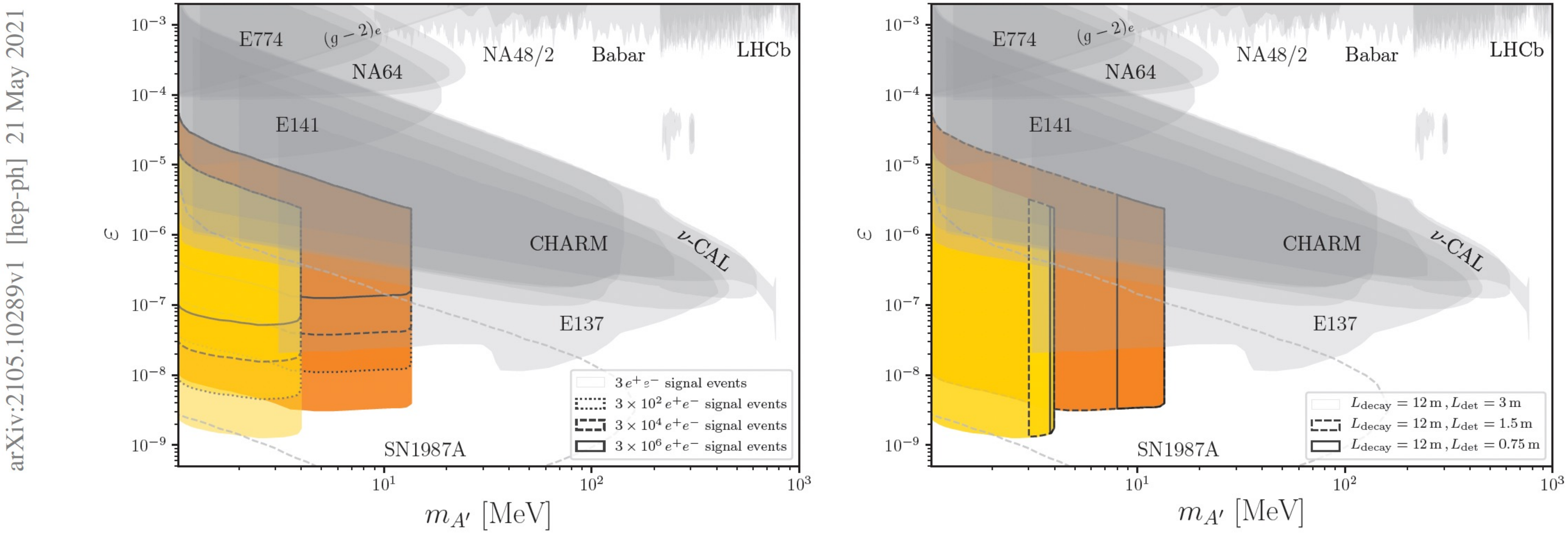
- *decay: a → $\gamma\gamma$ (A,B,C)*



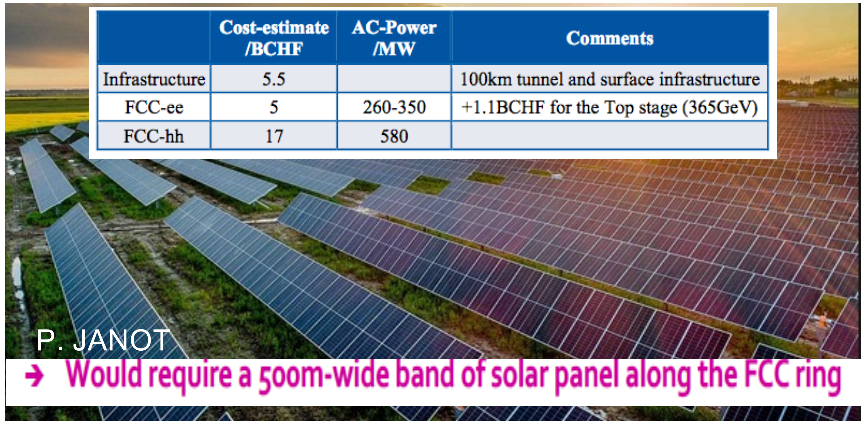
- *reconversion: aN → γN (B,C)*



4.1 DM searches and studies (dark photon example)



4.2 Photon-beam-driven energy source studies



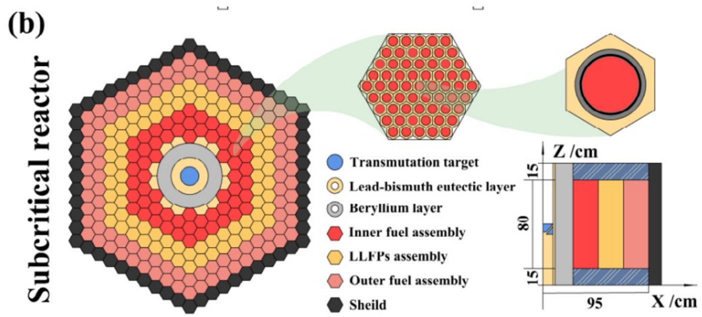
	Cost-estimate /BCHF	AC-Power /MW	Comments
Infrastructure	5.5		100km tunnel and surface infrastructure
FCC-ee	5	260-350	+1.1BCHF for the Top stage (365GeV)
FCC-hh	17	580	

<u>Best use of the CERN expertise to produce rather than buy the plug-power</u>:

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

<u>Satisfying three conditions;</u>

- 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

Gamma Factory 12 MW photon beam for the subcritical reactor

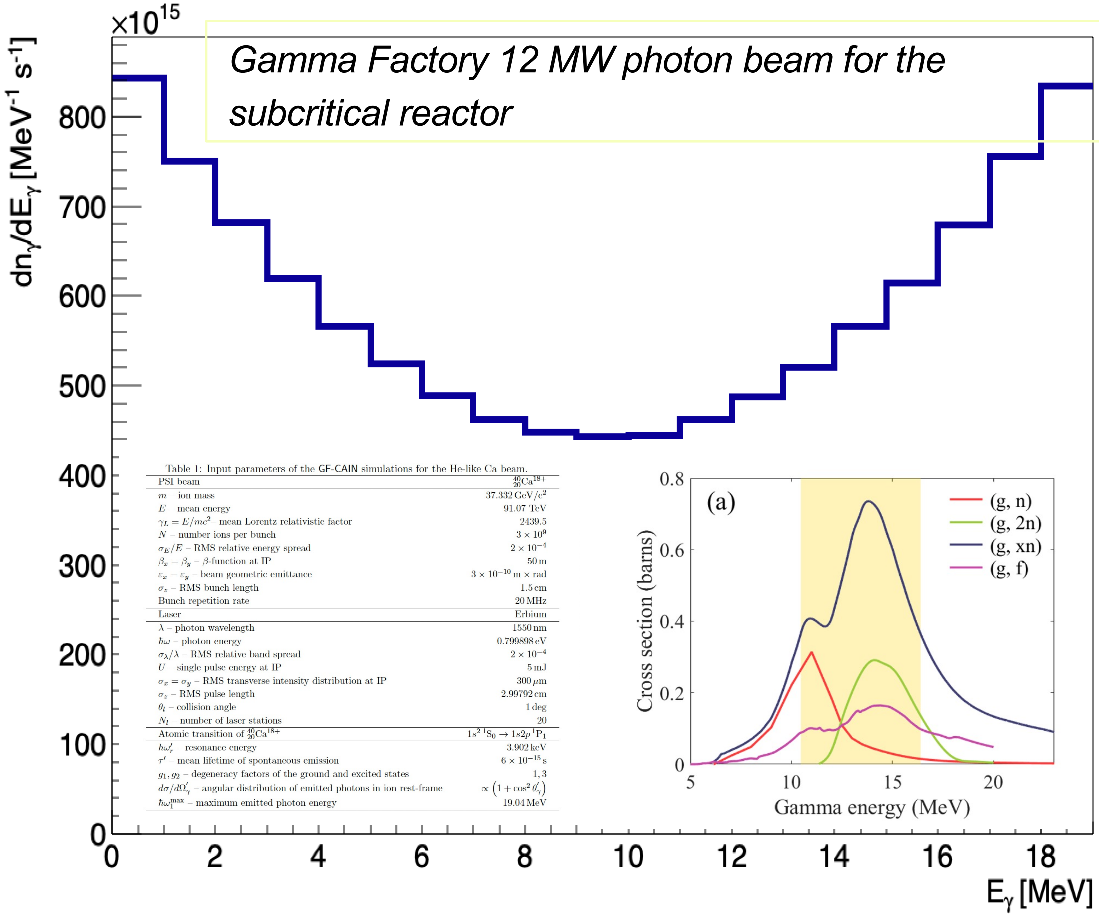
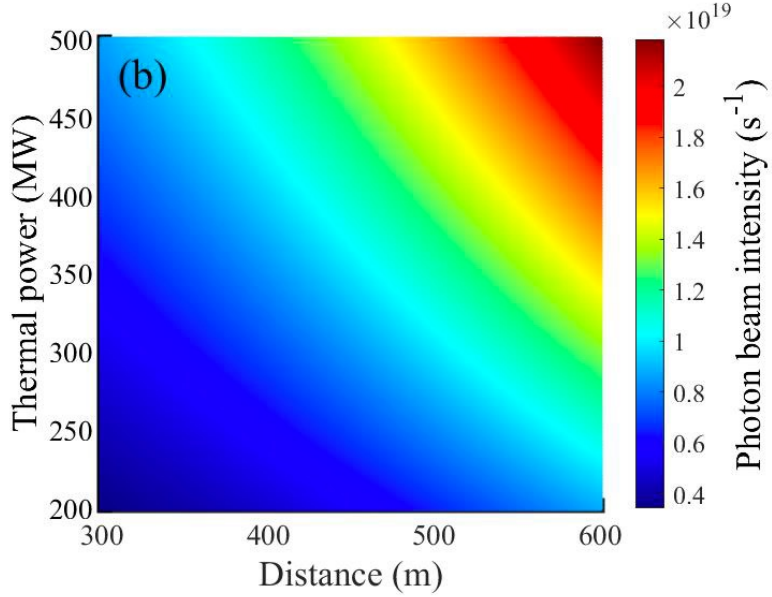
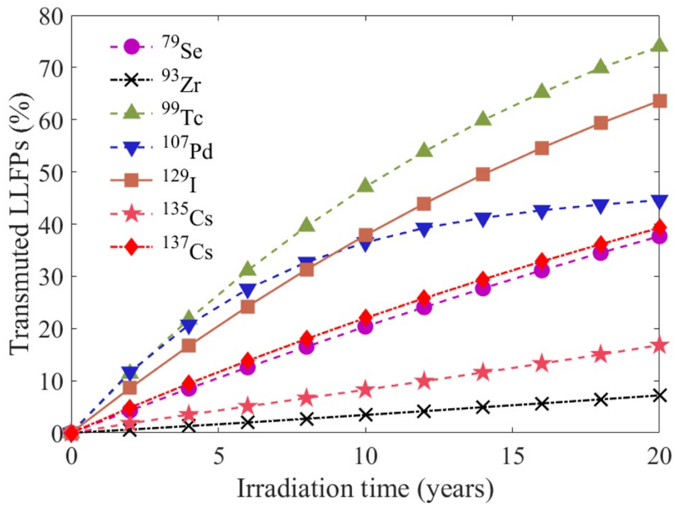


Table 1: Input parameters of the GF-CAIN simulations for the He-like Ca beam.

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





Efficient transmutation of long-live fission products induced by Gamma Factory gamma-ray beams

B. L. Hu[1,2], W. P laczek[2,3], W. Luo[1,2*], M. W. Krasny[4,5*], X. X. Li [1,2], Y. Yuan [1,2], Z. C. Zhu[1,2], X. M. Shi[1,2], K. J. Luo[1,2]

… in preparation

5. Research programme with tertiary beams'

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

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

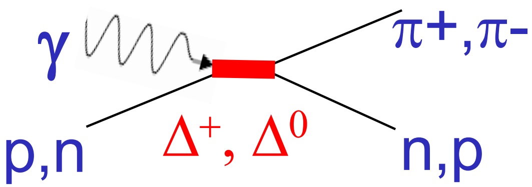
- ***Neutrinos*** *– fluxes comparable to NuMAX but: (1) Very Narrow Band Beam, driven by the small spectral density pion beam and (2) unique possibility of creating flavour- and CP-tuned beams driven by the beams of polarised muons*

- ***Neutrons*** *– a comparable neutron flux w.r.t the future neutron spallation sources e.g. at ESS – but quasi monoenergetic neutrons*

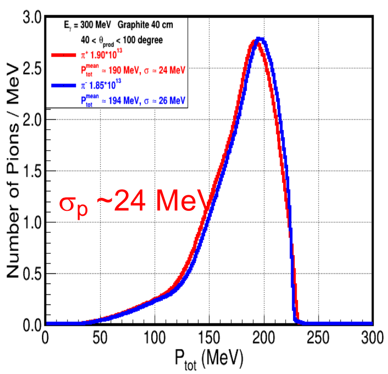
- ***Radioactive (neutron-rich) ions*** *– potential gain of up to a factor 10^4 in intensity w.r.t. e.g. ALTO*

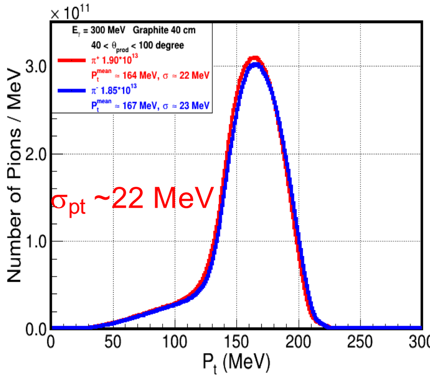
Novel paradigm for high brightness **μ and ν sources**:

resonant photo-excitation of Δ resonances



Exclusive process: *unprecedented spectral density of produced pions*





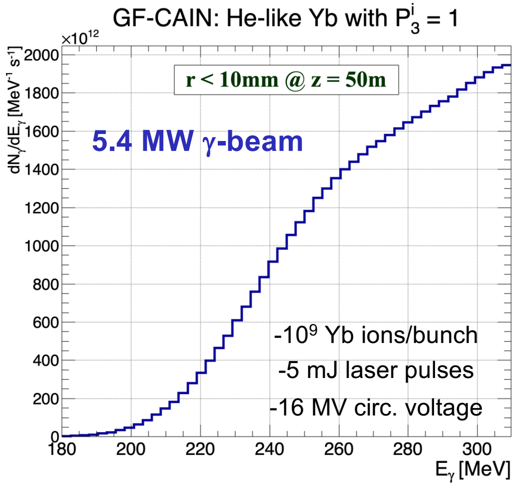
Muons	$r_\gamma \leq 5$mm	$r_\gamma \leq 10$mm
μ^-	2.32×10^{13} s^{-1}	6.18×10^{13} s^{-1}
μ^+	2.50×10^{13} s^{-1}	6.79×10^{13} s^{-1}

GF photon beam

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

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

GF, He-like Yb-driven γ-beam



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

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

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

The potential use of the Gamma Factory muon source:

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

Gamma Factory Proof-of-Principle experiment at the SPS

The remaining Gamma Factory R&D step – the PoP experiment

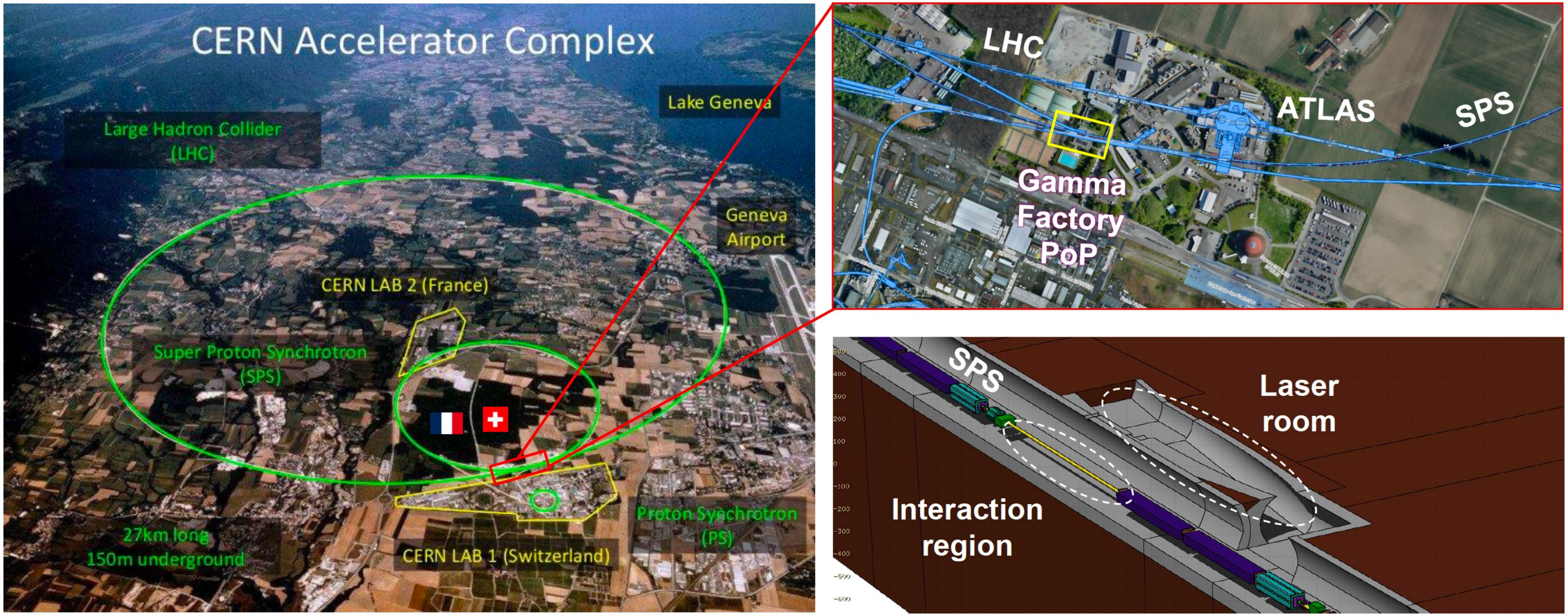
What has been achieved?

- *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 500 kW stored 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 done?

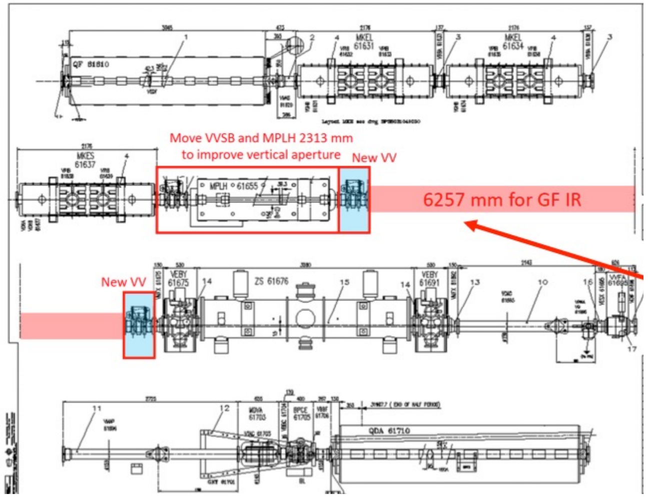
Proof of the stable remote operation of the laser + FP system incorporated to hadronic rings
→ Gamma Factory PoP experiment

Gamma Factory Proof-of-Principle experiment location



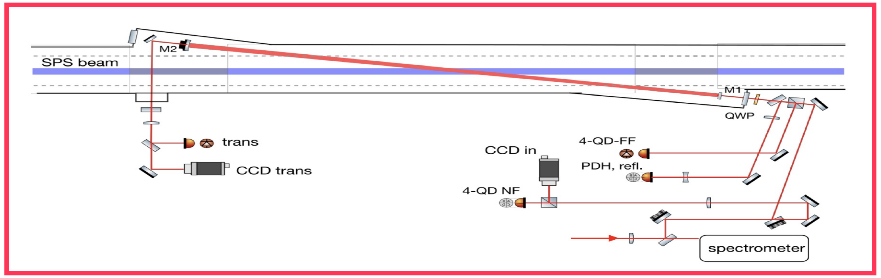
Gamma Factory Proof-of-Principle (PoP) SPS experiment

SPS LSS6 zone

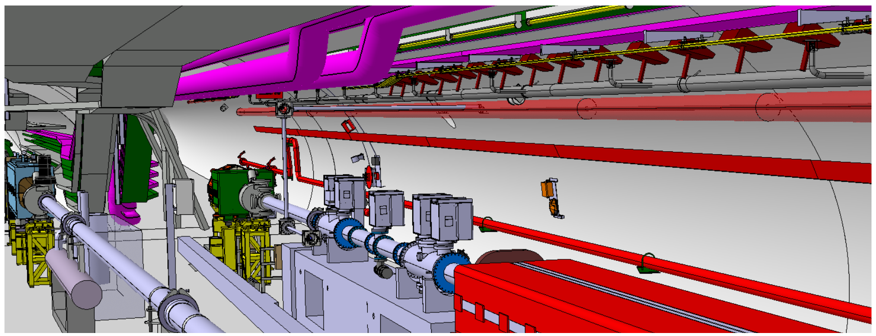


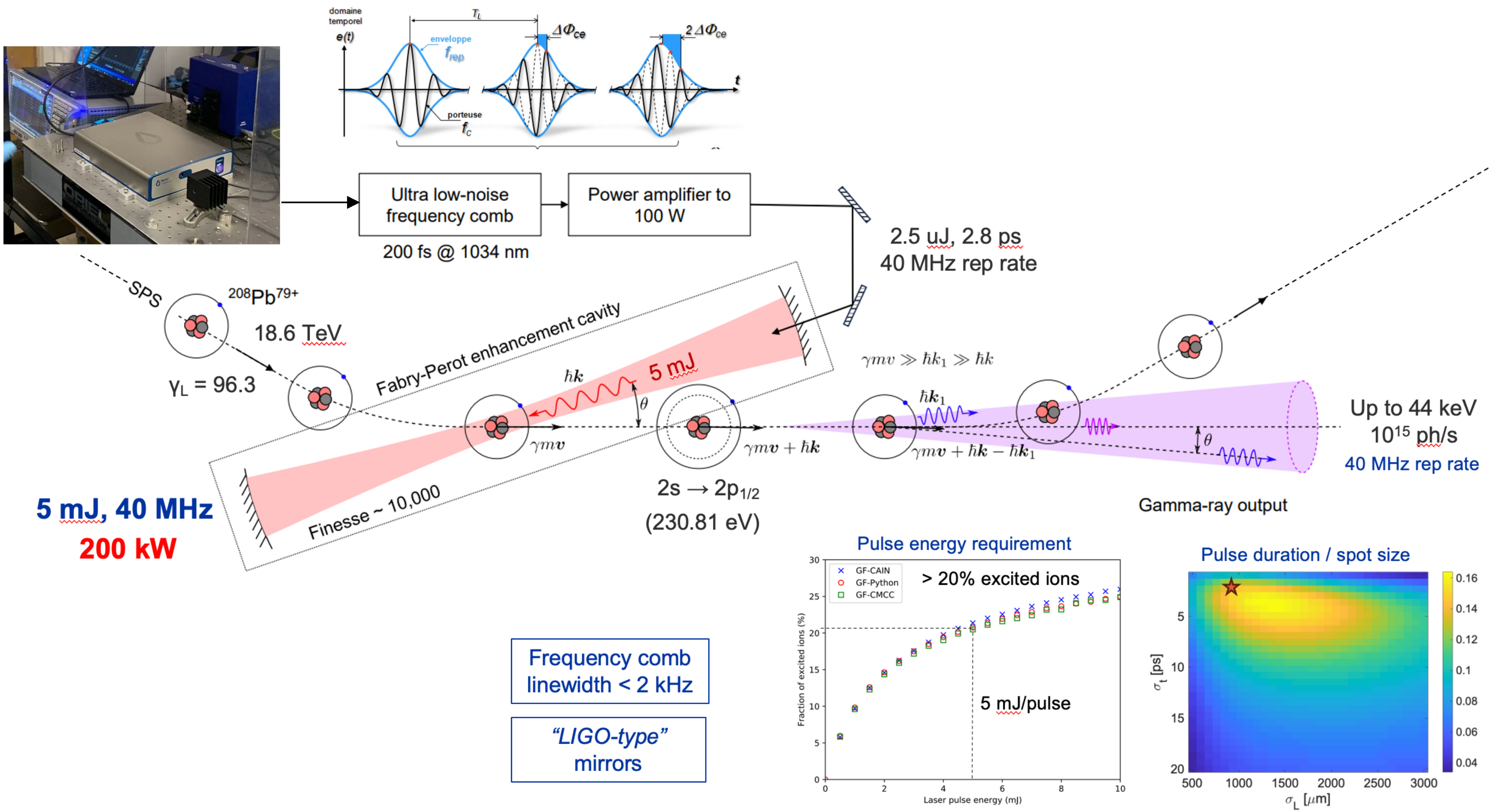
***F-P cavity length – 3.75 m** -- vertically tilted by 2..6 deg*

F-P cavity

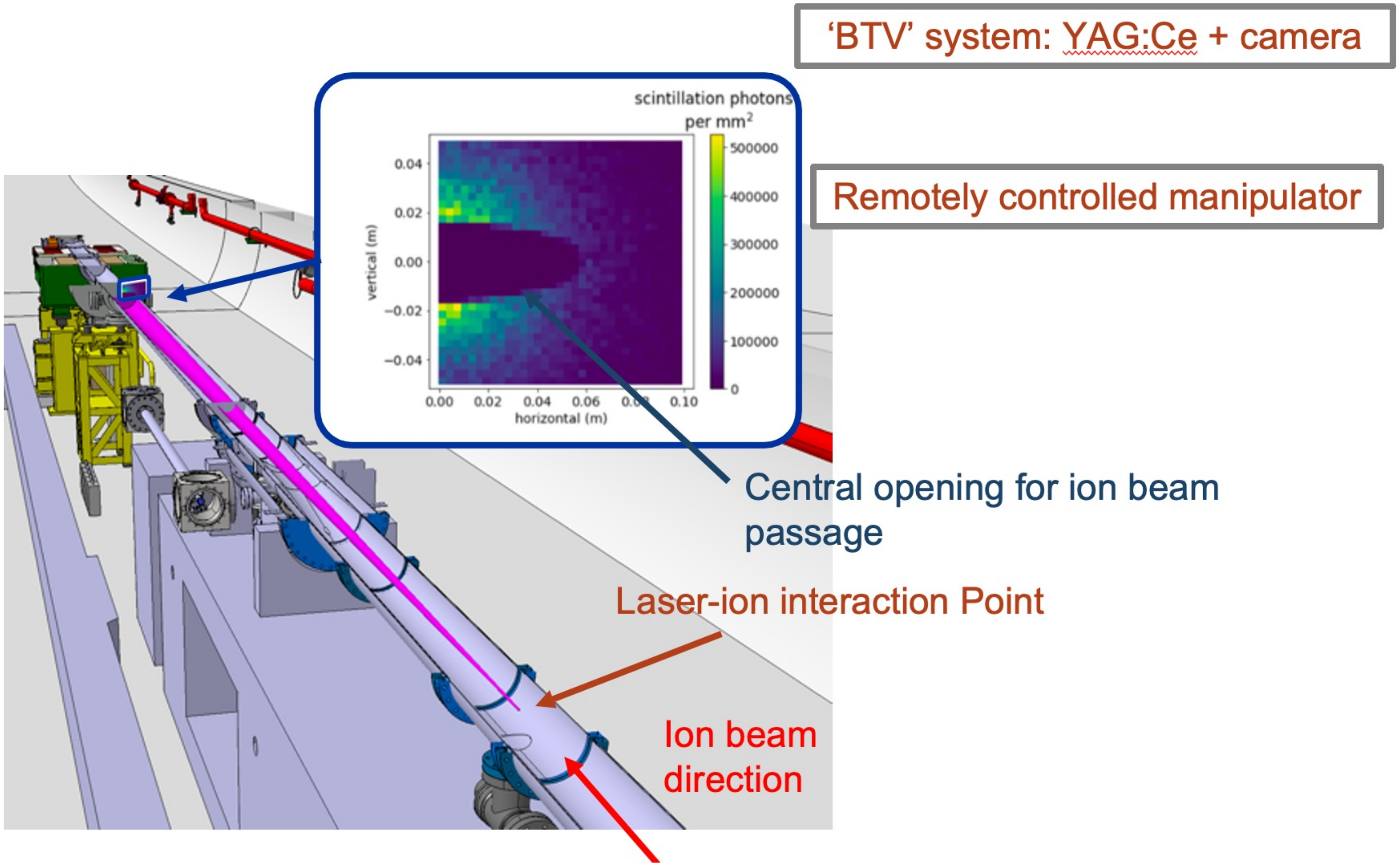


F-P cavity – "in beam" position





domaine temporel
e(t)
enveloppe
frep
porteuse
fc
TL
ΔΦce
2ΔΦce
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
208Pb79+
18.6 TeV
γL = 96.3
Fabry-Perot enhancement cavity
ħk
5 mJ
θ
γmv
γmv + ħk
γmv ≫ ħk1 ≫ ħk
ħk1
γmv + ħk − ħk1
Up to 44 keV
1015 ph/s
40 MHz rep rate
Gamma-ray output
5 mJ, 40 MHz
200 kW
Finesse ~ 10,000
2s → 2p1/2
(230.81 eV)
Frequency comb linewidth < 2 kHz
"LIGO-type" mirrors
Pulse energy requirement
> 20% excited ions
GF-CAIN
GF-Python
GF-CMCC
5 mJ/pulse
Fraction of excited ions (%)
Laser pulse energy (mJ)
Pulse duration / spot size
σt [ps]
σL [μm]



‘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

GF Proof-of-Principle (PoP) experiment -- next steps

- *Ultra low-phase noise laser and amplification chain procurement and commissioning*
- *Laser photon beam transport system -- vibration tests, controls and diagnostic at IP (an experiment using a reference Fabry-Perot cavity and a single-frequency CW laser*
- *Final design of the F-P cavity (beam impedance)*
- *Conversion of the TL18 area to a laser lab during LS3*
- *Installation of the F-P cavity in the SPS tunnel*
- *Installation of the BTV system and its associated cameras*
- *Initial phase of the of the GF PoP experiment: demonstrate full remote end-to-end operation of laser beams and Fabry-Perot cavity*
- *Advanced phase of the GF-PoP experiment: demonstrate beam cooling, atomic physics studies*

Conclusions and outlook

Conclusions

- *Gamma Factory can create, at CERN, a variety of novel research tools, which could open novel research opportunities in a very broad domain of basic and applied science*
- *The Gamma Factory research programme can be largely based on the existing CERN accelerator infrastructure – it requires "relatively" minor infrastructure investments*
- *Its "quest for diversity of research subjects and communities" is of particular importance in the present phase of accelerator-based research, as we neither have any solid theoretical guidance for a new physics "just around the corner", accessible by FCC, ILC, or CLIC, nor an established "reasonable cost" technology for a leap into very high energy " terra incognita"*
- *Gamma Factory project needs to make the last step in R&D studies and demonstrate its feasibility by the SPS GF-Proof-of-Principle experiment prior to reaching advanced phase of the HL-LHC programme – the CERN management and wide scientific community support for this project is a "sine qua non" condition for its further development*

A lesson from DESY:
1995 – HERA needs substantial upgrade

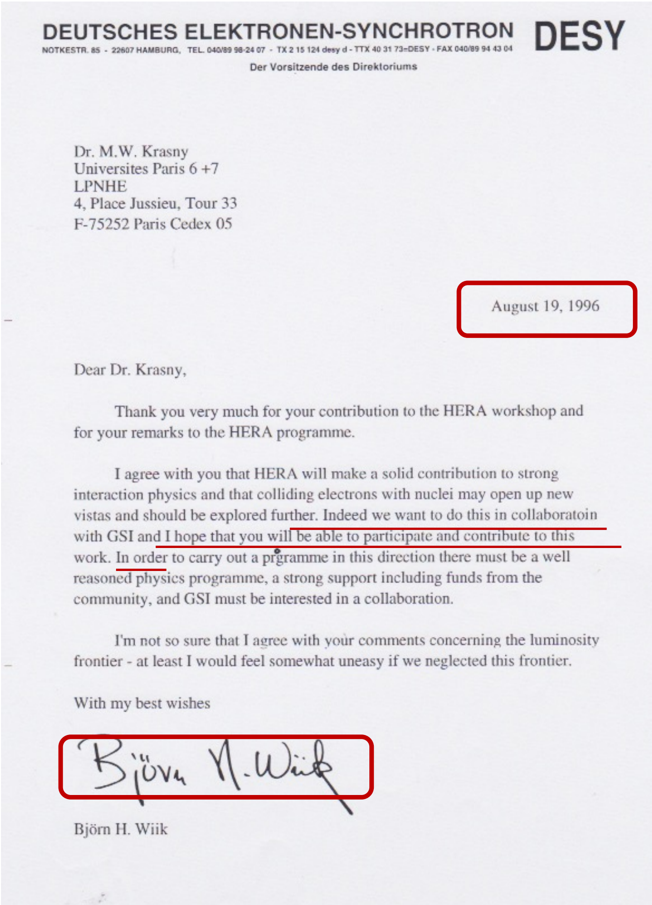
- *The DESY research programme must include a development of high intensity sources of both isoscalar ions (including deuterium) and the highest Z ions, and their low emittance pre-injector(s)*

- *One of its detectors for must have a full 4π acceptance (allowing to detect all the fragments of the nucleus)*

- *The "HERA leg" of this programme requires a factor of O(100) increase of the collider luminosity :*
  - *-- statistics: F_2^c, F_2^b, F_L, EW, multidimensional studies*
  - *-- systematics: drastic reduction of syst. errors (e.g. x and Q2 scans at fixed theta as a unction of (E_n E_e)*

- *RHIC expected to start in 2000 and the LHC in 2006 –> the DESY QCD program -- capable to provide a vital input for the interpretation of the RHIC and the LHC data -- must start before (or soon after) RHIC and LHC became operational*

A lesson from DESY (the need for the plan B,C,…)



DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY
NOTKESTR. 85 - 22607 HAMBURG, TEL. 040/89 98-24 07 - TX 2 15 124 desy d - TTX 40 31 73=DESY - FAX 040/89 94 43 04
Der Vorsitzende des Direktoriums

Dr. M.W. Krasny
Universites Paris 6 +7
LPNHE
4, Place Jussieu, Tour 33
F-75252 Paris Cedex 05

August 19, 1996

Dear Dr. Krasny,

Thank you very much for your contribution to the HERA workshop and for your remarks to the HERA programme.

I agree with you that HERA will make a solid contribution to strong interaction physics and that colliding electrons with nuclei may open up new vistas and should be explored further. Indeed we want to do this in collaboratoin with GSI and I hope that you will be able to participate and contribute to this work. In order to carry out a prgramme in this direction there must be a well reasoned physics programme, a strong support including funds from the community, and GSI must be interested in a collaboration.

I'm not so sure that I agree with your comments concerning the luminosity frontier - at least I would feel somewhat uneasy if we neglected this frontier.

With my best wishes

Björn H. Wiik

Björn H. Wiik

DESY director

Bjorn Wiik plan B: strong (even if hidden) support for the joint DESY/GSI QCD-Lab project (if TESLA project is not approved)

- *B. Wiik's unfortunate accident (TESLA abandoned)*
- *GSI started working towards a local FAIR PROJECT (low energy, QCD nonperturbative regime), European ELFE groups joined the CEBAF program*
- *The electron-ion collider concept exported to US (thanks to a strong commitment to this project by Peter Paul – the BNL director → **at the moment the leading financed (2.5x10^9 $) accelerator project in the US)***
- *End of the HEP era at DESY*