Gamma Factory

— a tool-driven revolution?

FIP Webinar, 23rd of March 2023

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

Outline of the talk

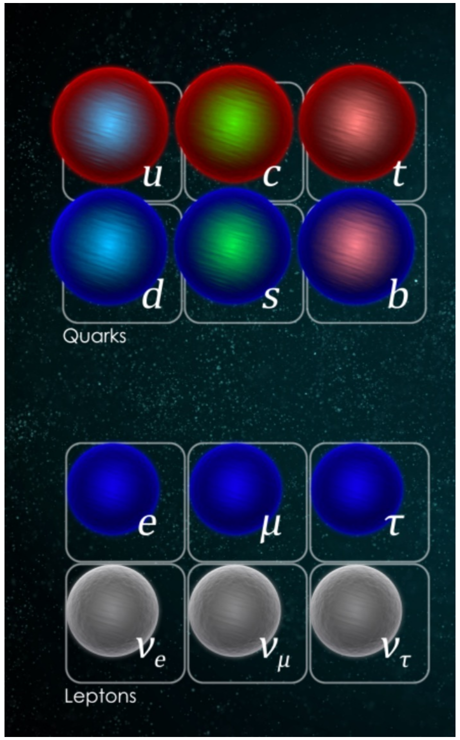
- *Scientific context*
- *Photons*
- *Gamma Factory photon source*
- *Novel research tools made out of light*
- *New research opportunities*
- *Gamma Factory project status*

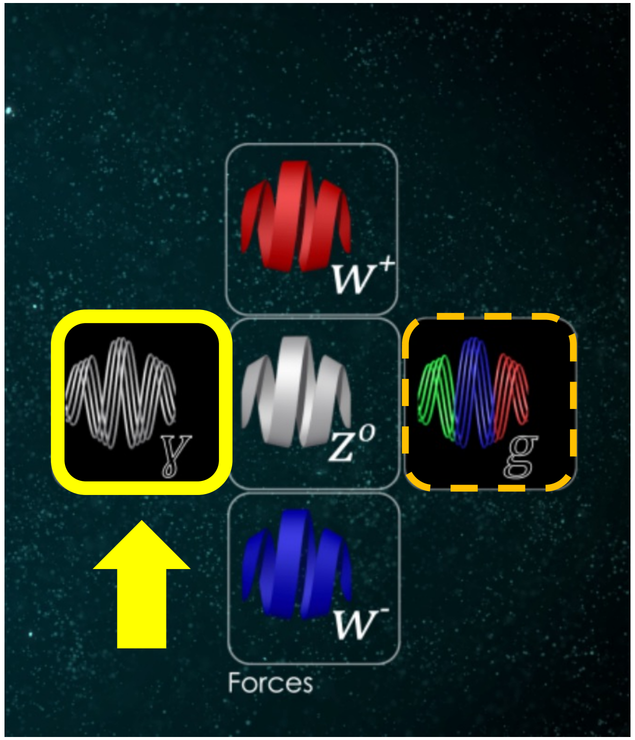
Scientific context

The World Ahead 2023

Future-gazing analysis, predictions and speculation

The success story of accelerator-based science: understanding of the elementary blocks of matter and their interactions





What should be our next steps?

Revisiting three paths of progress in accelerator technology driven fundamental science

1. ***Increasing*** *(incrementally)* ***precision*** *of the canonical measurements to* ***test*** *well-established* ***theories*** *and* ***models*** *in new higher energy regime (FCC, ILC, CLIC,…)*

2. ***Verifying*** *predictions of* ***new*** *theoretical* ***models/concepts*** *(40 years of the super-symmetry searches ended up in disillusion – at present no guidance from the theory, neither for the energy scale of new phenomena, nor for coupling strength of new particles to the SM particles).*

3. ***Technological leaps****, creating* ***new, accelerator-technology-driven, research tools*** *… or* ***increasing*** *the* ***precision*** *of the established ones by* ***several orders of magnitude****!*

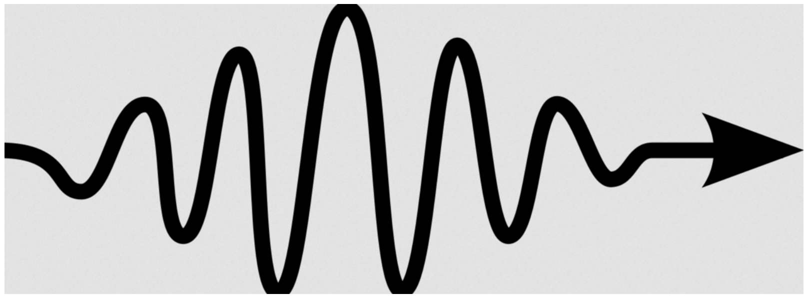
- ***At this moment*** *of particular* ***importance*** *for our discipline, since we* ***neither*** *have any* ***hints*** *for a* ***new physics*** *which is accessible by the* ***present*** *technologies at a* ***reasonable*** *cost,* ***nor*** *a* ***certainty*** *that Particle Physics will* ***survive, in its present form,*** *by addressing* ***"old questions"*** *with the new,* ***incremental-energy-increase,*** *accelerators!*

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

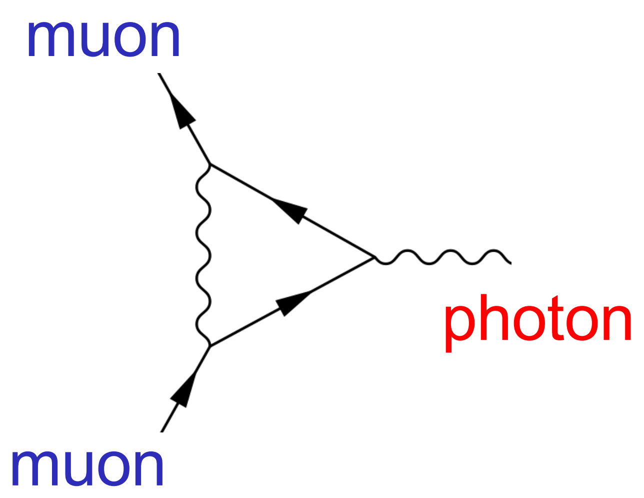
The effect of a concept-driven revolution is to explain old things in new ways.

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

Photons



Photons as research tools:
extraordinary precision of Quantum Electrodynamics



g – measured magnetic moment of the muon

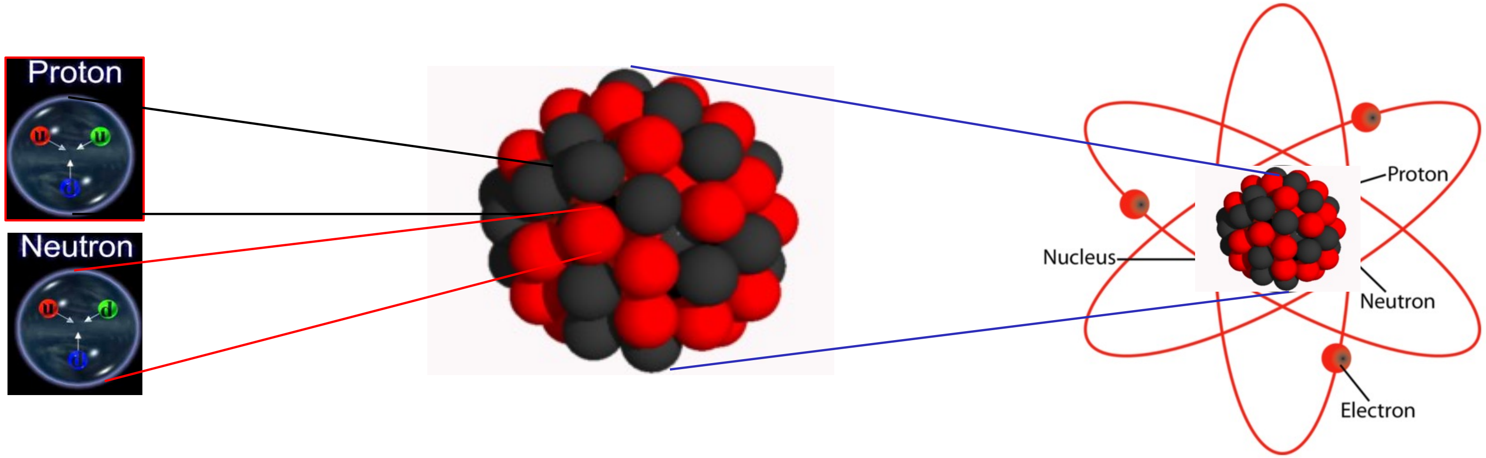
Dirac equation: g =2

$$a = \frac{g-2}{2}$$

$$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{hadron}}$$
$$= 0.001\,165\,918\,04(51)$$

$$a_\mu = 0.001\,165\,920\,61(41)$$

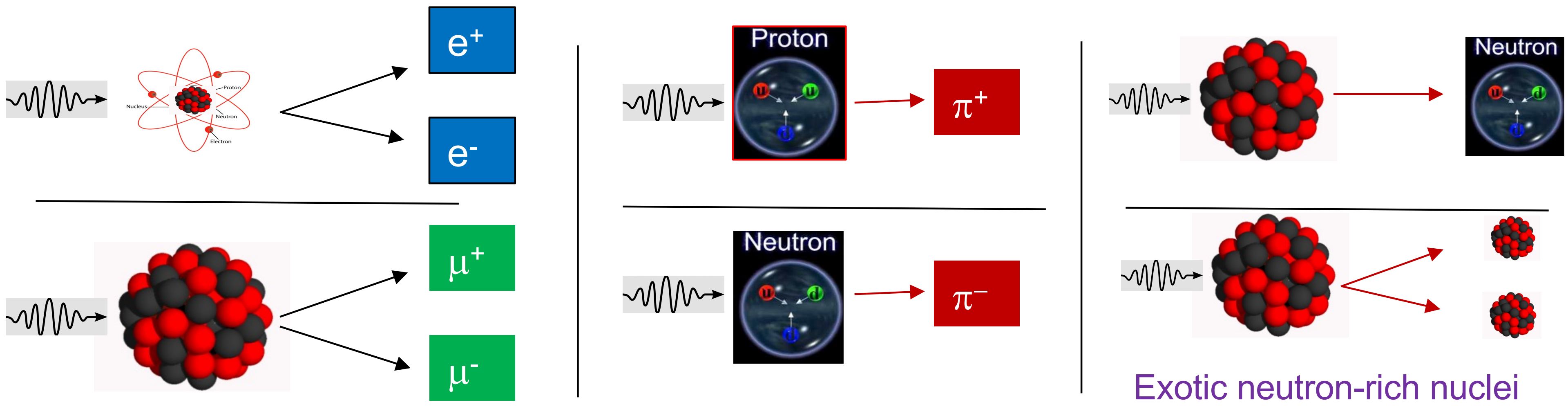
Photons – high precision tools to study the structure of molecules, atoms, nuclei and nucleons



γ-rays ← X-rays ←

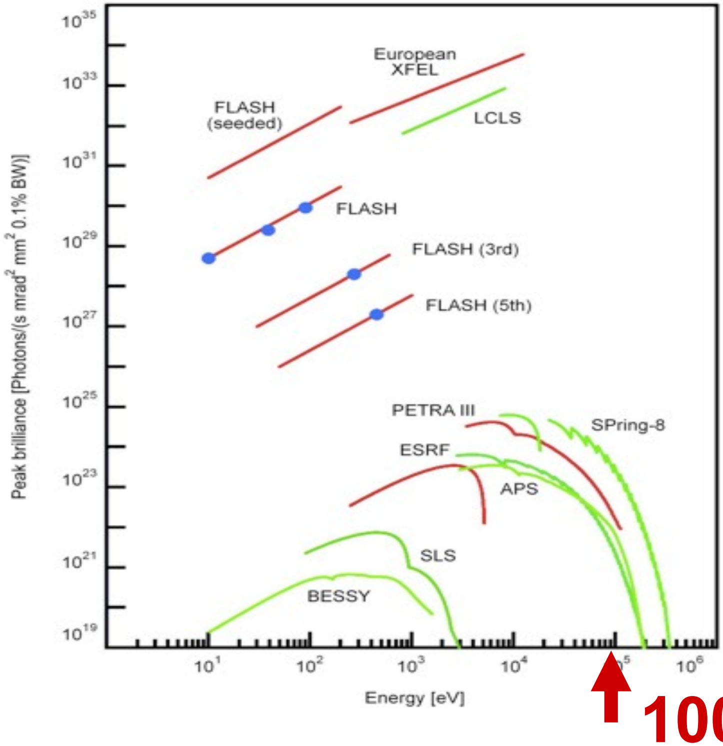
Photons of energy in the range of sub-eV to hundreds of MeV
(wavelengths comparable to the size of objects)

Photon – a tool to produce elementary particles of matter and antimatter (with identical characteristics) and exotic composite objects



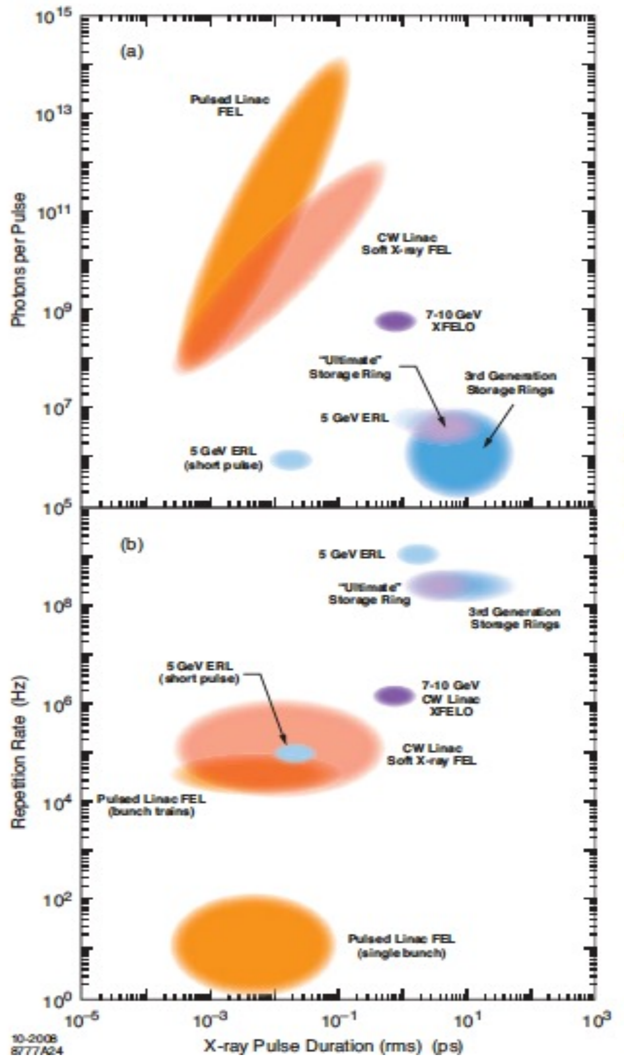
Require photons of the energy langer than ~1 MeV (γ-rays)

Photon sources (X-rays)



100 keV

Energies up to ~ 100 keV



Intensities up to ~ **10^{16} photons/s**

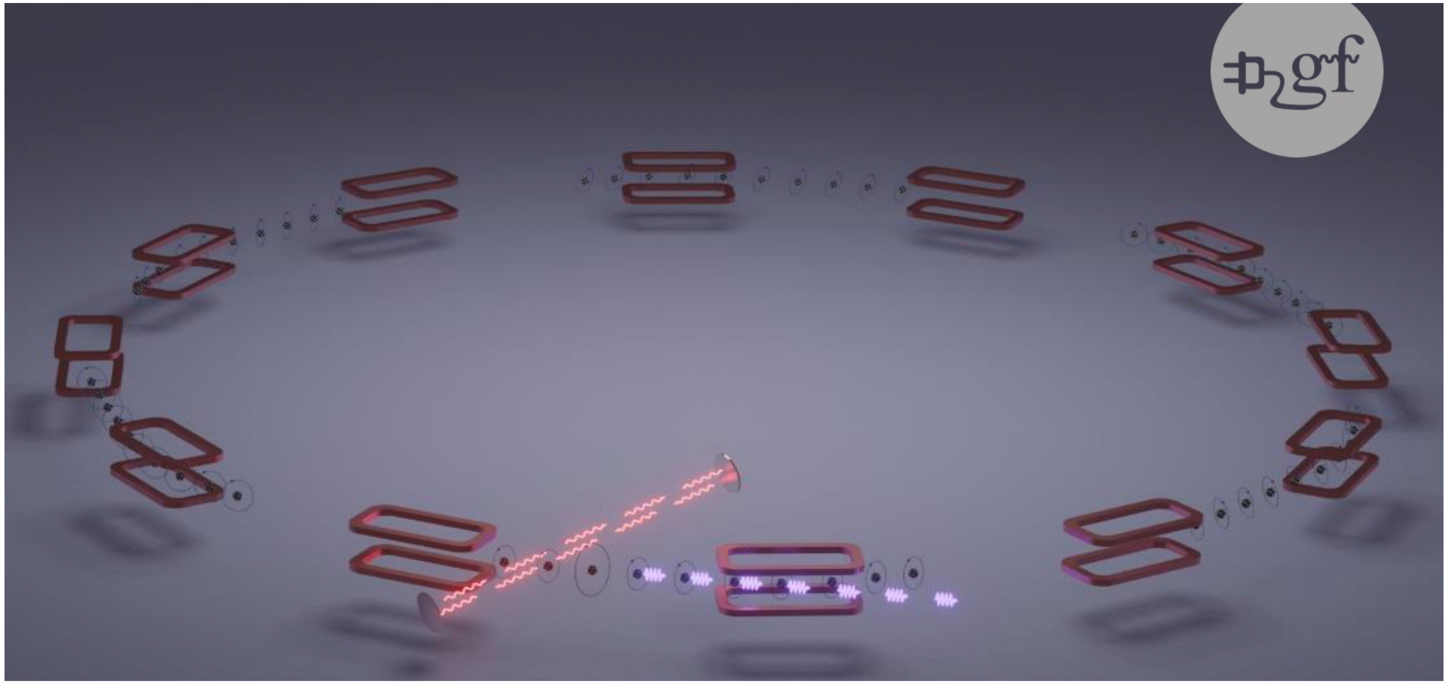
Photon sources (γ-rays)

Project name	LADON[a]	LEGS	ROKK-1M[b]	GRAAL	LEPS	HIγS[c]
Location	Frascati Italy	Brookhaven US	Novosibirsk Russia	Grenoble France	Harima Japan	Durham US
Storage ring	Adone	NSLS	VEPP-4M	ESRF	SPring-8	Duke-SR
Electron energy (GeV)	1.5	2.5–2.8	1.4–6.0	6	8	0.24–1.2
Laser energy (eV)	2.45	2.41–4.68	1.17–4.68	2.41–3.53	2.41–4.68	1.17–6.53
γ-beam energy (MeV)	5–80	110–450	100–1600	550–1500	1500–2400	1–100 (158)[d]
Energy selection	Internal tagging	External tagging	(Int or Ext?) tagging	Internal tagging	Internal tagging	Collimation
γ-energy resolution (FWHM)						
ΔE (MeV)	2–4	5	10–20	16	30	0.008–8.5
$\frac{\Delta E}{E}$ (%)	5	1.1	1–3	1.1	1.25	0.8–10
E-beam current (A)	0.1	0.2	0.1	0.2	0.1–0.2	0.01–0.1
Max on-target flux (γ/s)	5×10^5	5×10^6	10^6	3×10^6	5×10^6	10^4–5×10^8
Max total flux (γ/s)						10^6–3×10^9[e]
Years of operation	1978–1993	1987–2006	1993–	1995–	1998–	1996–

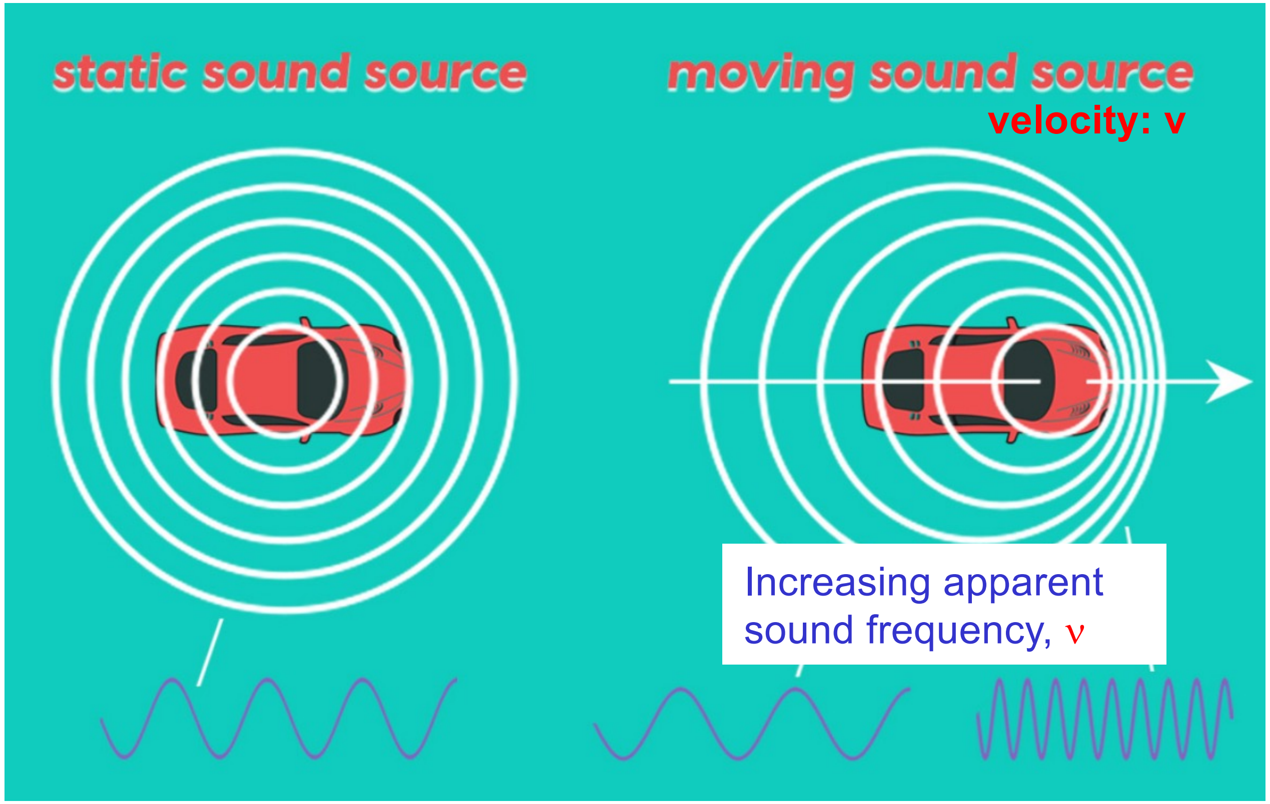
Intensities up to ~ **10^9 photons /s**

Can one make a technological leap (of > 7 orders of magnitude) and deliver comparable, of higher, fluxes of γ-rays, than the present X-ray sources?

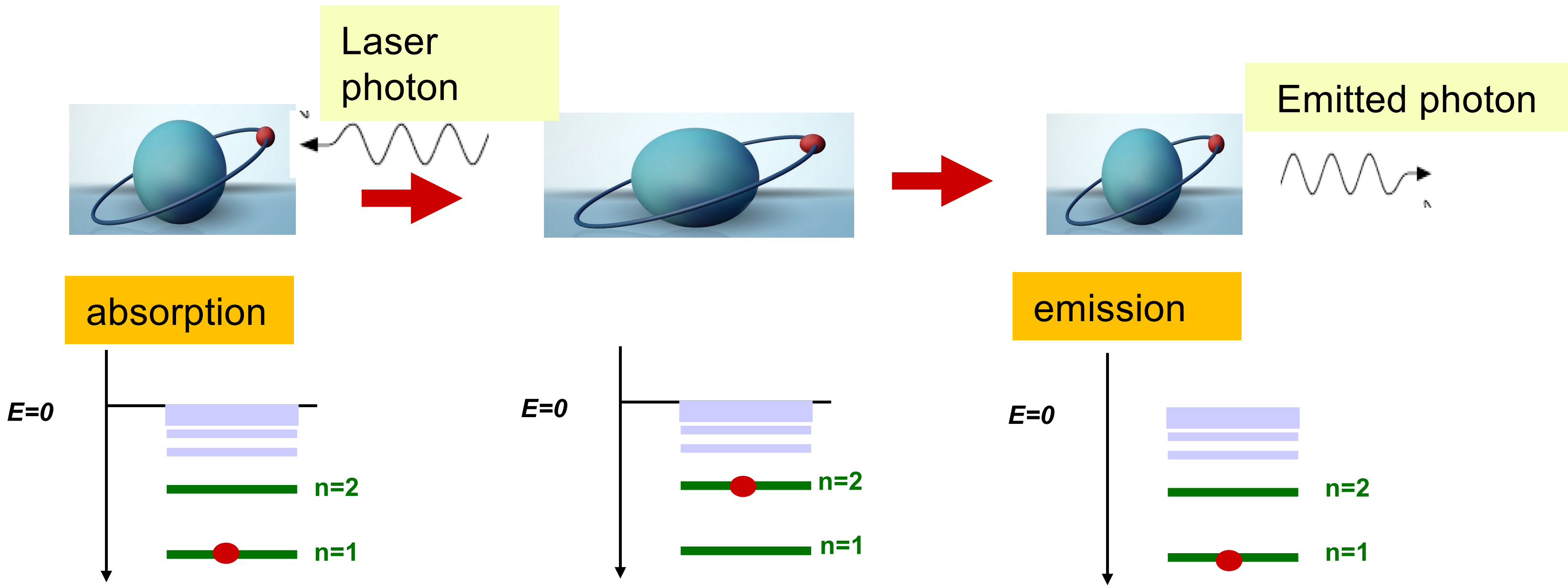
Gamma Factory photon source



The basic idea: Use Doppler effect

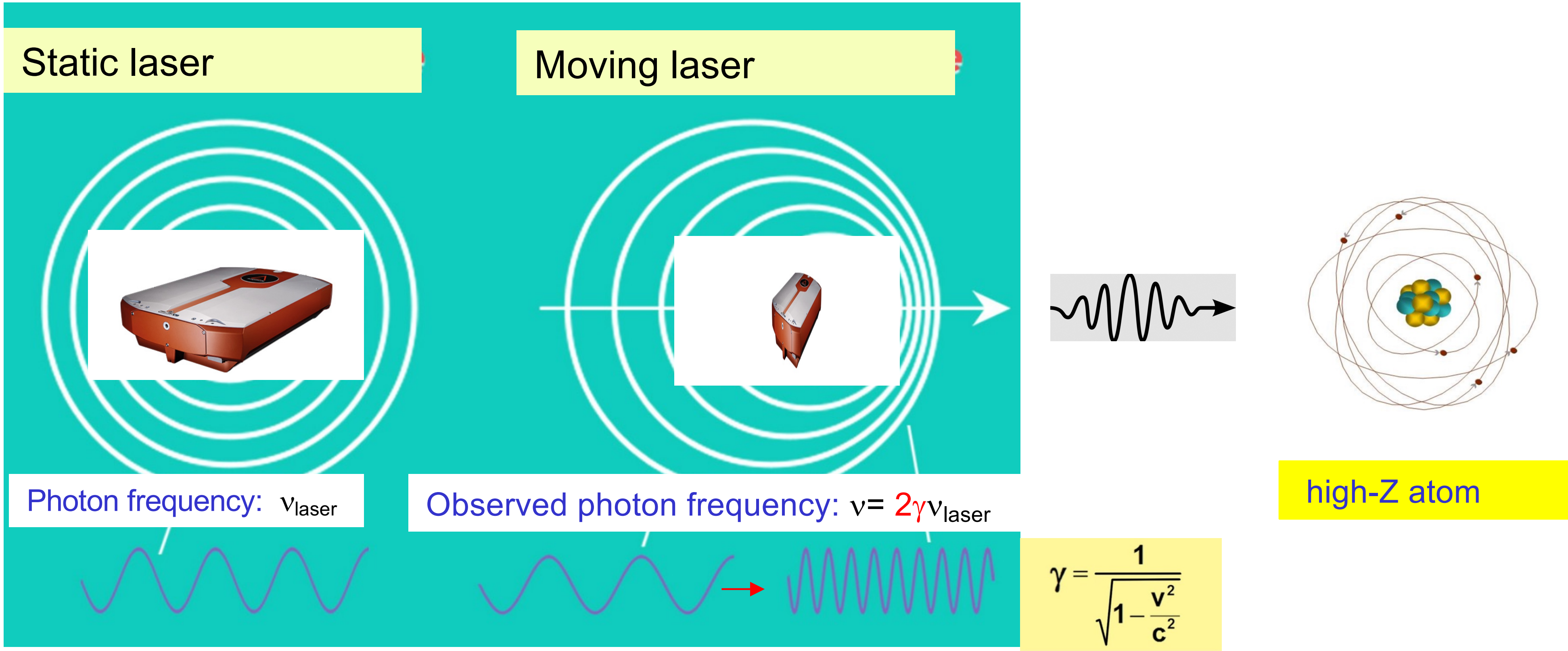


Absorption and emissions of photons by **atoms**

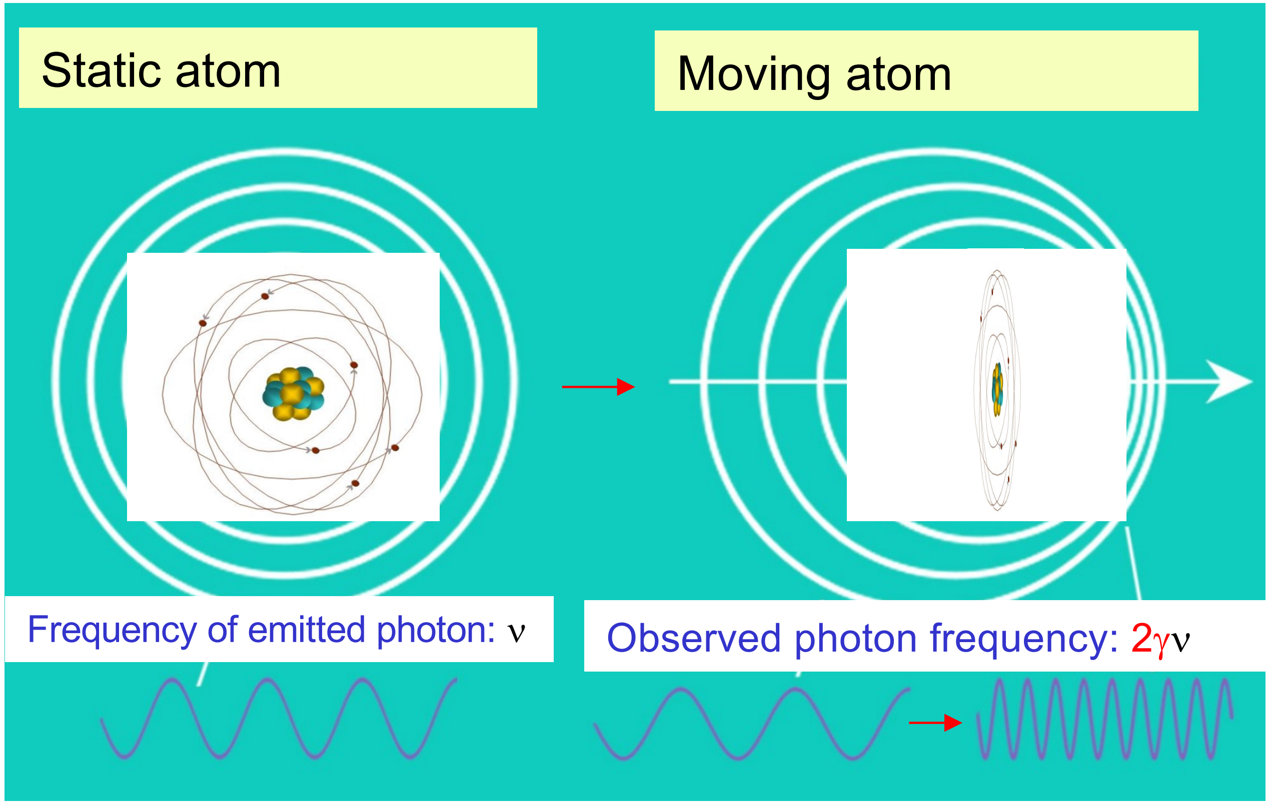


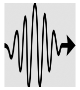
Let's accelerate an atom to a relativistic velocity: v ~ c

Doppler effect in the atom's rest frame – absorption phase (Lorentz transformation)



Emission phase ...back to the laboratory frame





Gamma Factory photon source: energy leap

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

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

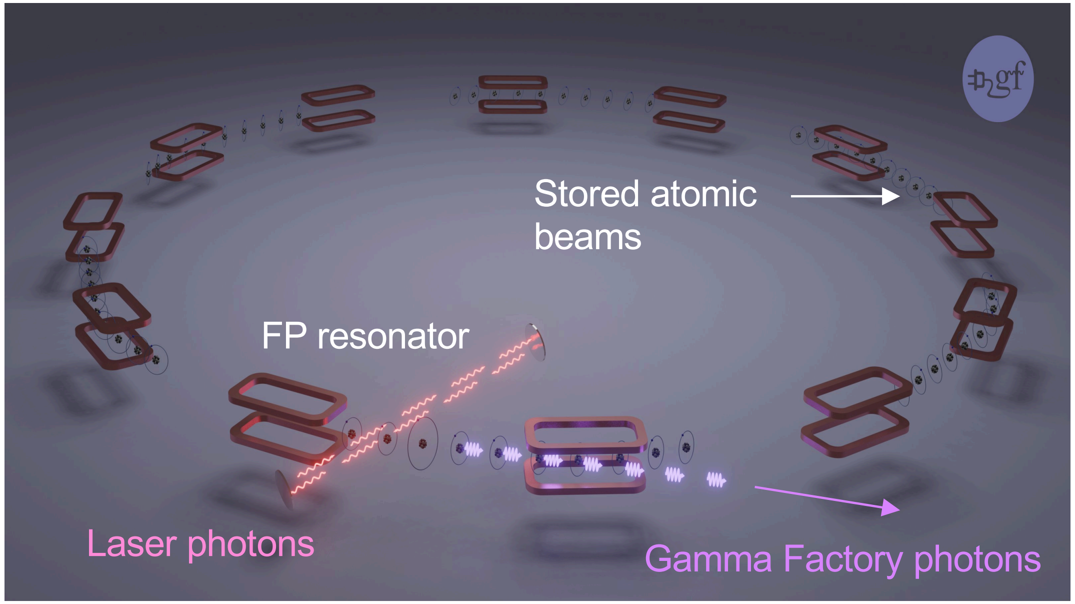
…for the photon emitted in the direction of the moving atom

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

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

Gamma Factory photon source: intensity leap

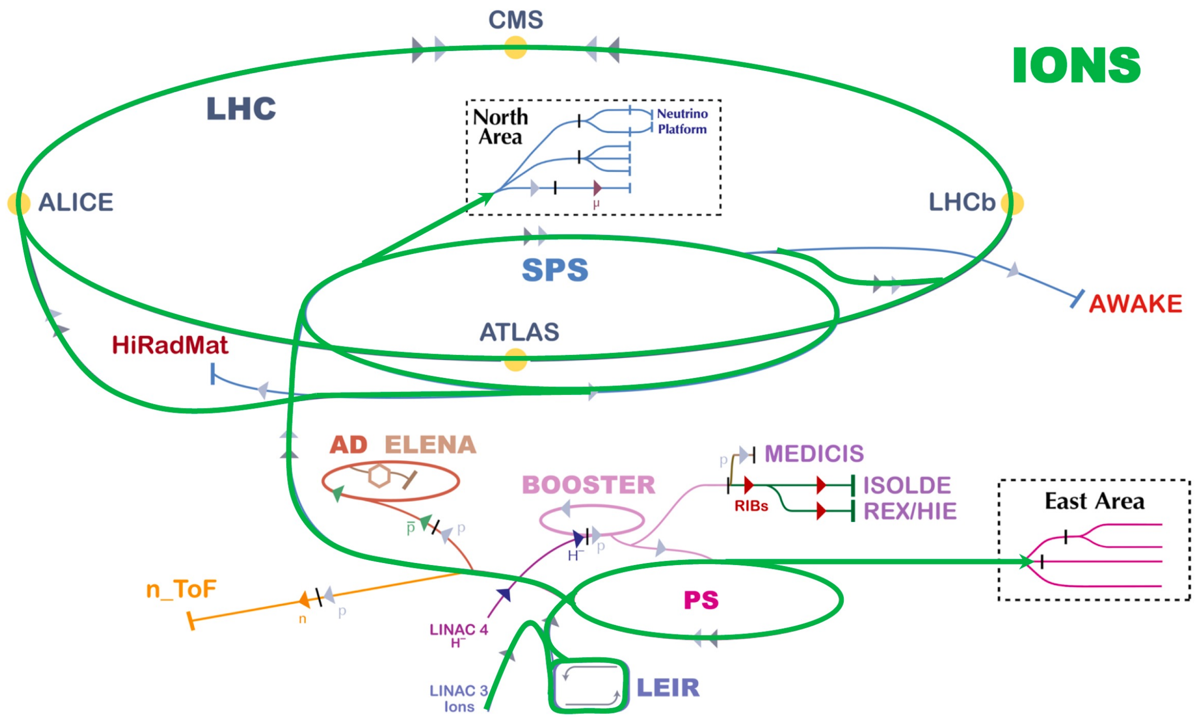
Requirements: *Accelerated bunches of ~10^8-10^9 partially stripped atoms, delivered with ~20 MHz frequency, ~5 mJ laser photon pulses stacked in 20 MHz, Fabry-Perot resonator*



Novel technology:

Resonant scattering of laser photons on ultra-relativistic atomic beam

Sustainability: Re-use of already existing accelerator infrastructure – CERN



Gamma Factory (additional) requirements:

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

Decisive beam tests

symmetry
dimensions of particle physics

topics

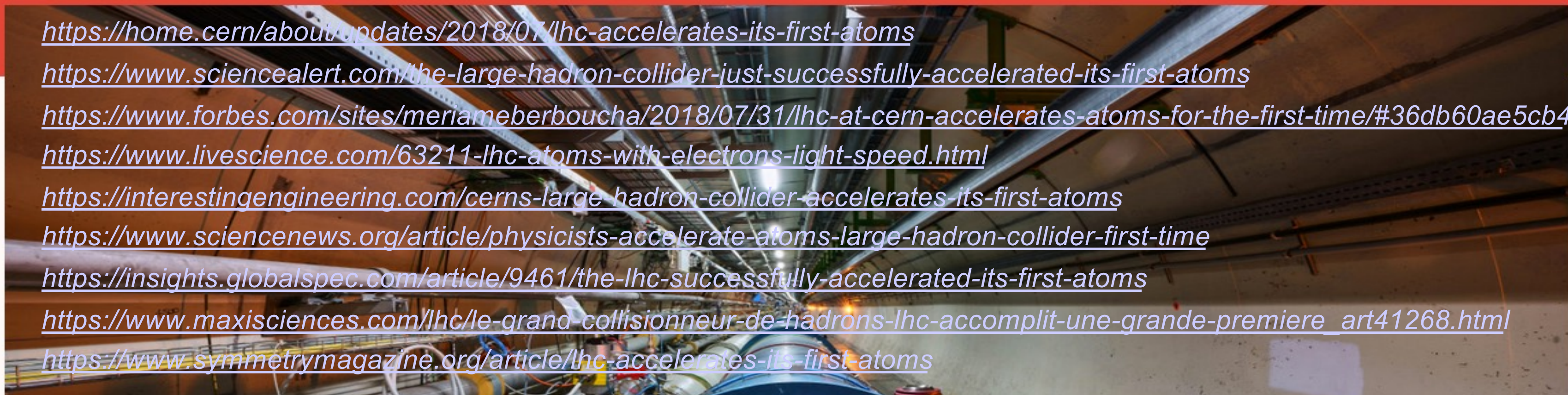
follow +

A joint Fermilab/SLAC publication

LHC accelerates its first "atoms"

07/27/18 | By Sarah Charley

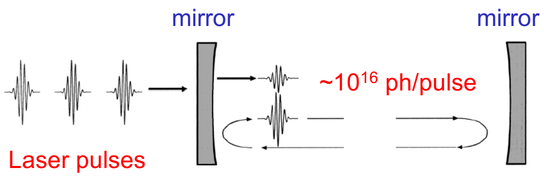
Lead atoms with a single remaining electron circulated in the Large Hadron Collider.

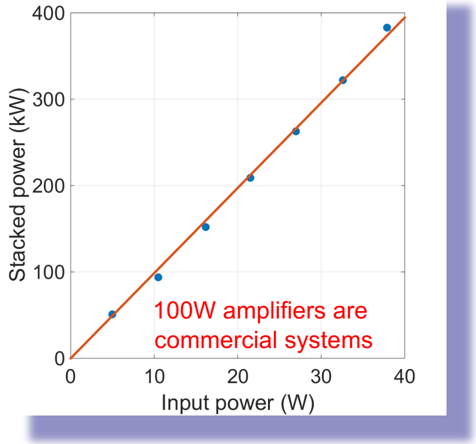


https://home.cern/about/updates/2018/07/lhc-accelerates-its-first-atoms
https://www.sciencealert.com/the-large-hadron-collider-just-successfully-accelerated-its-first-atoms
https://www.forbes.com/sites/meriameberboucha/2018/07/31/lhc-at-cern-accelerates-atoms-for-the-first-time/#36db60ae5cb4
https://www.livescience.com/63211-lhc-atoms-with-electrons-light-speed.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

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

Fabry-Pérot resonator

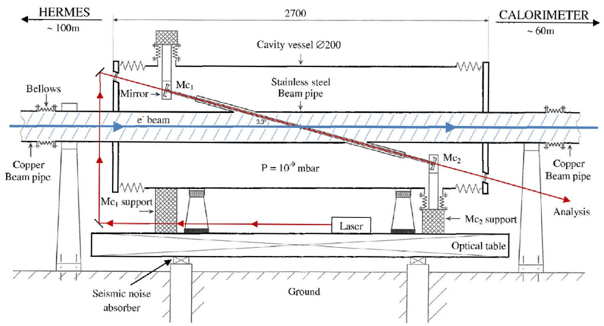




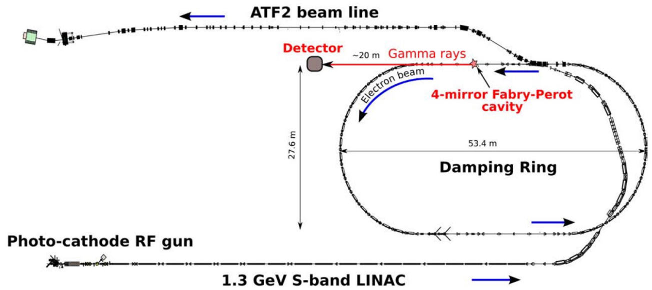
Amoudry L. et al., Applied Optics 59(2020)116

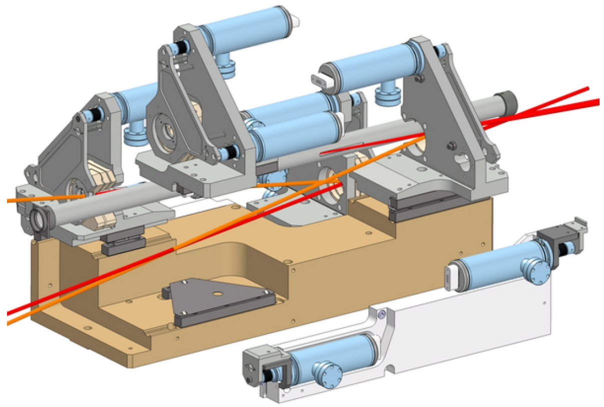
GF requirement:
< 5mJ pulses @ 20MHz,
(100kW photon beam)

HERA storage ring



KEK – ATF ring





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

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

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

An intensity jump by >7 orders of magnitude wrt existing sources

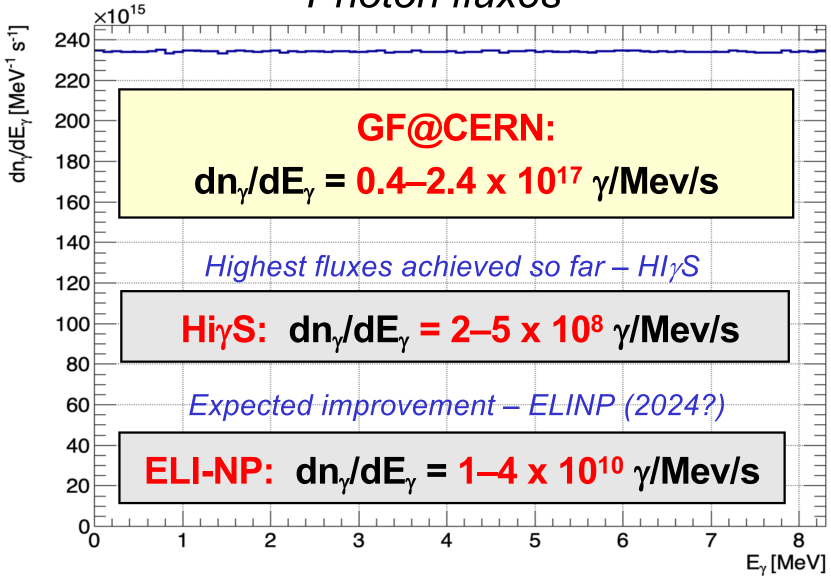
N_A = $6{,}023 \cdot 10^{23}$

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

Open new technological possibilities (e.g. new beam-driven energy sources)

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

Photon fluxes

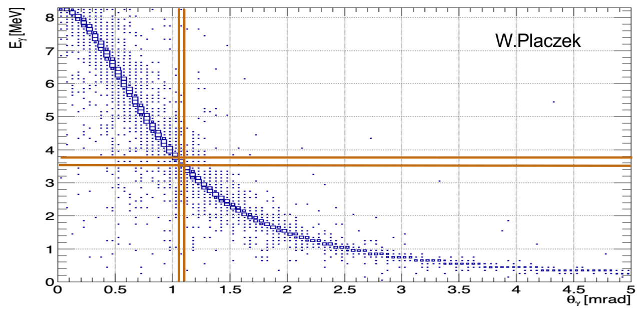


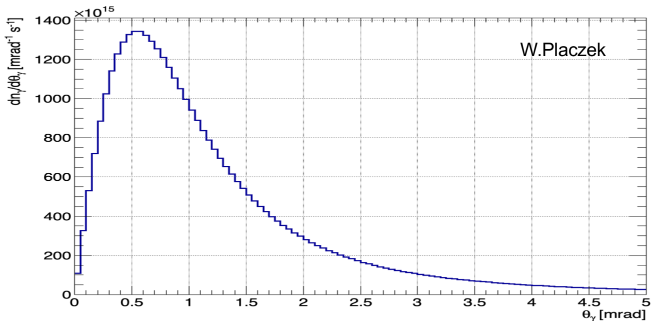
laser pulse parameters

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

Highly-collimated monochromatic γ–beams:

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





Extraordinary properties of the GF photon source

1. Point-like, small divergence

- $\Delta z \sim l_{PSI\text{-}bunch} < 7$ 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%**

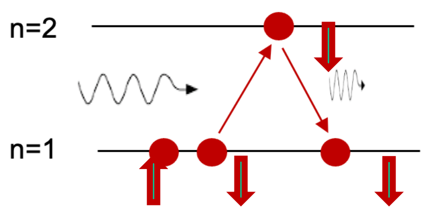
5. Unprecedented plug power efficiency (energy footprint):

- **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)

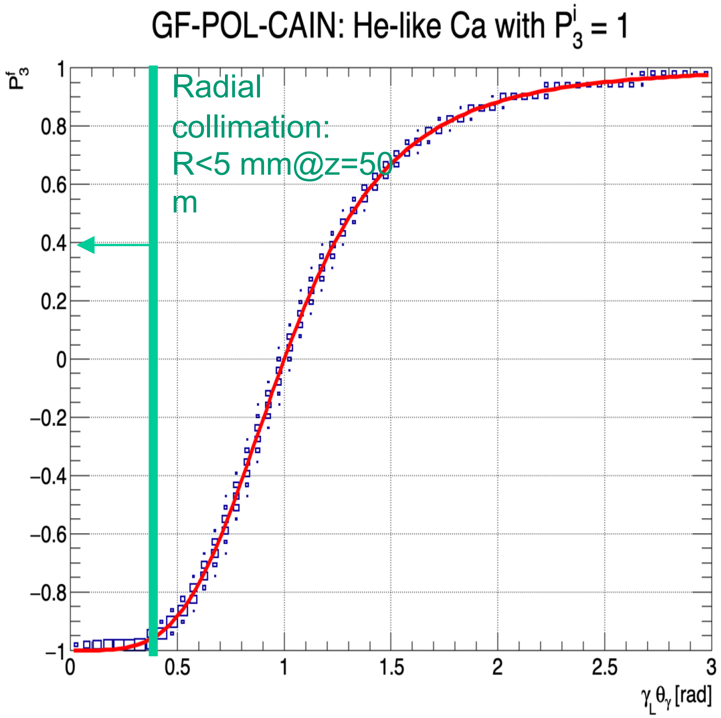
Polarised beams in GF – example: He-like, Calcium beam, Er:glass laser (1522 nm)

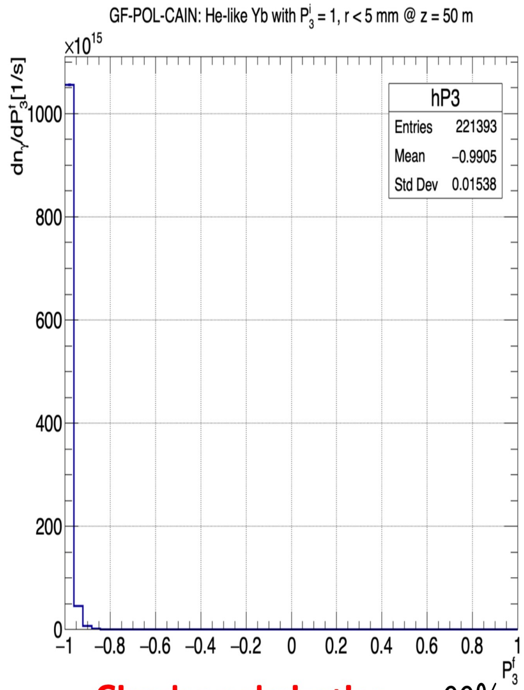
A trick: $1s^2\ {}^1S_0 \rightarrow 1s^1 2p^1\ {}^1P_1$ transition in He-like atoms



$$nS_0 \longrightarrow n'P_1 \longrightarrow nS_0$$

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

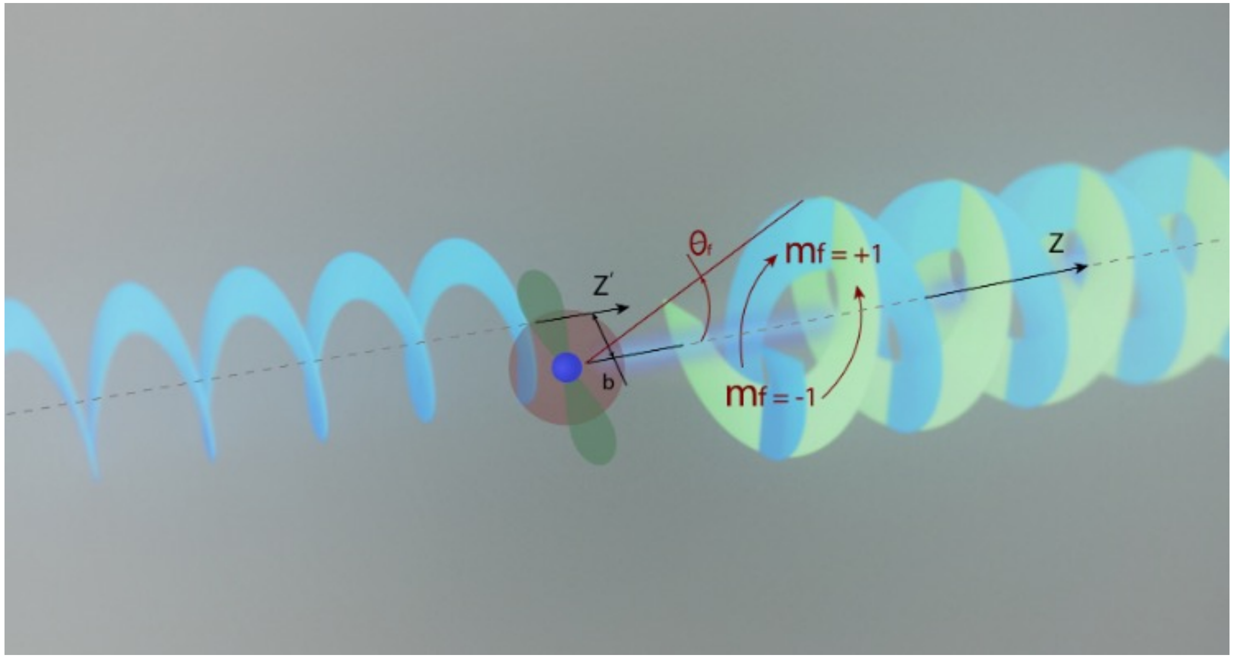




$\rightarrow$ **Circular polarization** $\approx 99\%$

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

Gamma Factory twisted photons



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

Valeriy G. Serbo
Novosibirsk State University, RUS–630090, Novosibirsk, Russia and
Sobolev Institute of Mathematics, RUS–630090, Novosibirsk, Russia

Andrey Surzhykov
Physikalisch–Technische Bundesanstalt, D–38116 Braunschweig, Germany
Institut für Mathematische Physik, Technische Universität Braunschweig, D–38106 Braunschweig, Germany and
Laboratory for Emerging Nanometrology Braunschweig, D-38106 Braunschweig, Germany

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

Gamma Factory in a nutshell

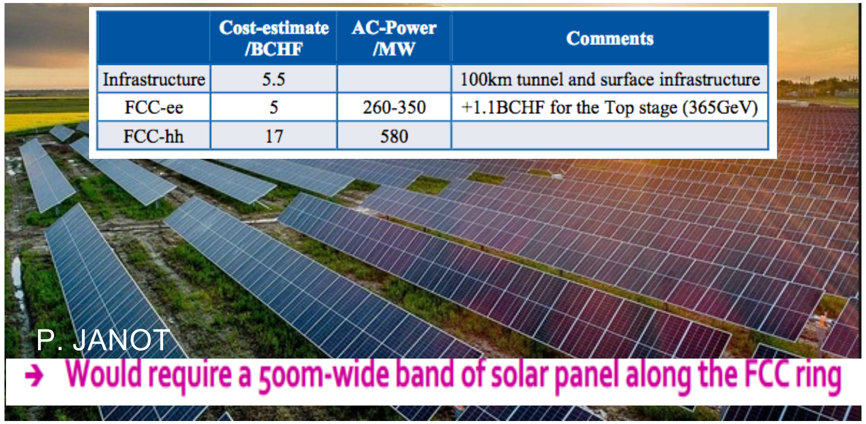
- *The infrastructure and the operation mode of the CERN accelerators allowing to:*
    - *produce, accelerate, cool and store beams of highly ionised atoms,*
    - *excite their atomic degrees of freedom by laser photons to form high intensity secondary beams of gamma rays,*
    - *produce plug-power-efficient diverse tertiary beams.*
- *The research programme in a broad domain of science enabled by the "Gamma Factory tools".*

Novel research tools made from light

Gamma Factory novel tools – 5 examples

1. *Unprecedented intensity photon(γ)-beams.*
2. *Atomic traps of highly charged atoms.*
3. *Electron beam for ep collisions in the LHC interaction points.*
4. *Laser-light based cooling methods of high-energy hadronic beams.*
5. *High-intensity sources of polarised electrons, polarised positrons, polarised muons, neutrinos, neutrons and radioactive ions.*

1. High intensity (MW) photon beams



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

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

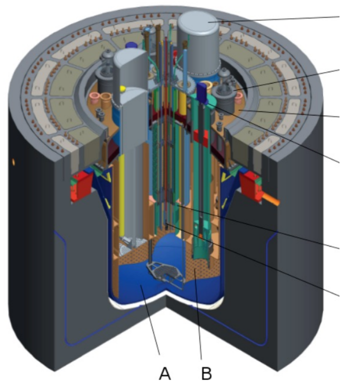
→ Would require 500 such turbines (one every 200m) along the FCC ring

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

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

Satisfying three conditions;

- requisite power for the present and future CERN scientific programme
- operation safety **(a subcritical reactor)**
- efficient transmutation of the nuclear waste (**very important societal impact if demonstrated at CERN –given its reputation**)



APS April Meeting 2023

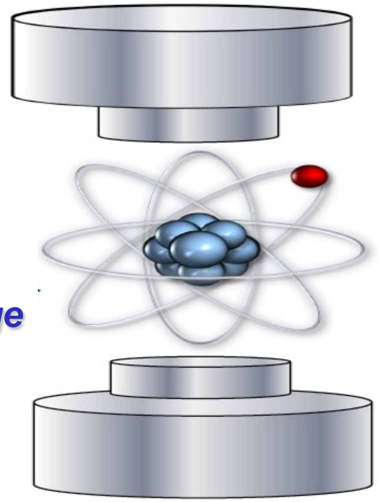
Minneapolis, Minnesota (Apr 15-18)

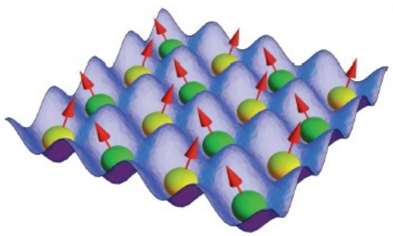
M06 Invited **Accelerate Solving Energy Crisis: From Fission to Fusion**
Room: MG Salon F - 3rd Floor **Sponsor**: DPB FIP **Chair**: Christine Darve, European Spallation Source
Invited Speakers: Hamid Ait Abderrahmane, Mieczyslaw Witold Krasny, Ahmed Diallo, Alireza Haghighat

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

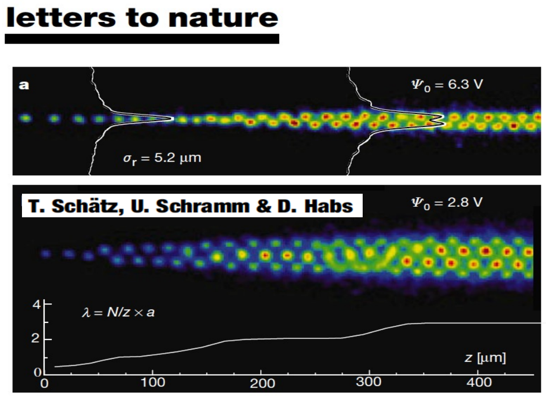
Atomic rest-frame

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





Crystalline beams?



Opening new research opportunities in atomic physics:

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

adp annalen der physik

Feature Article | Open Access

Atomic Physics Studies at the Gamma Factory at CERN

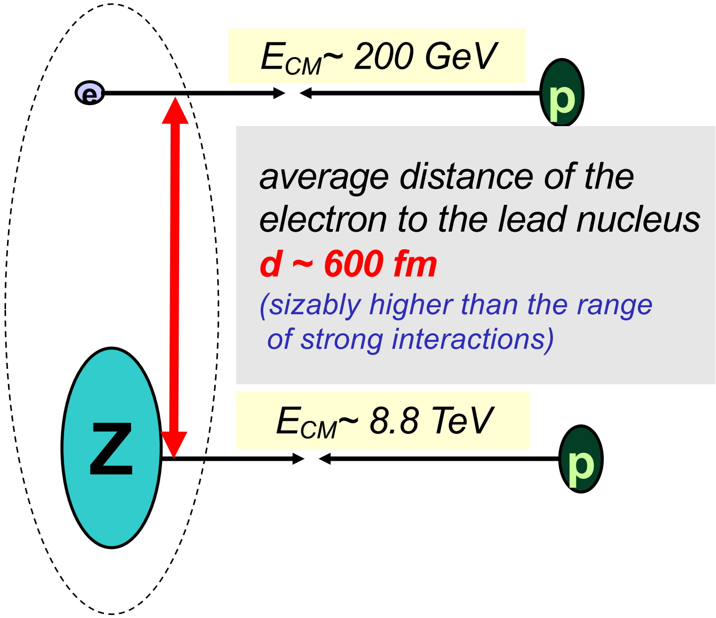
Dmitry Budker, José R. Crespo López-Urrutia, Andrei Derevianko, Victor V. Flambaum, Mieczyslaw Witold Krasny, Alexey Petrenko, Szymon Pustelny, Andrey Surzhykov, Vladimir A. Yerokhin, Max Zolotorev ... See fewer authors

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

3. Electron beam for ep collisions at LHC

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

Hydrogen-like lead



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

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

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Available online at www.sciencedirect.com

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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

Initial studies:

Mieczyslaw Witold Krasny

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

Received 14 September 2004; received in revised form 19 November 2004; accepted 23 November 2004

Available online 22 December 2004

Recent development:

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

Editors' Suggestion

Collimation of partially stripped ions in the CERN Large Hadron Collider

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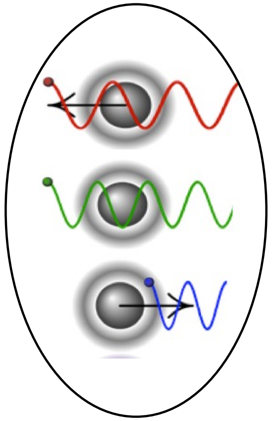
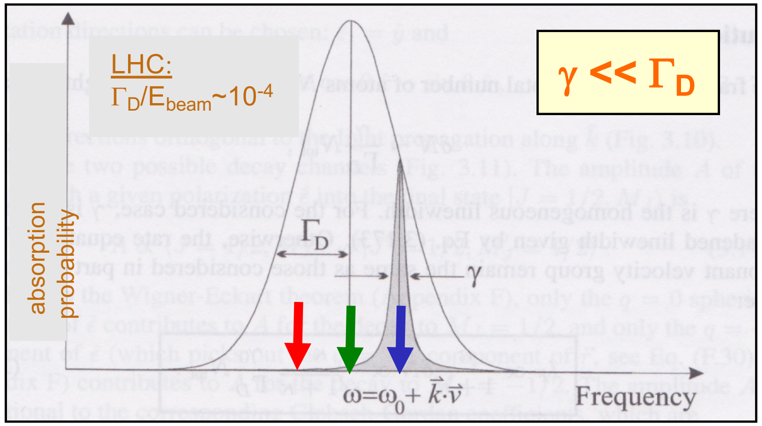
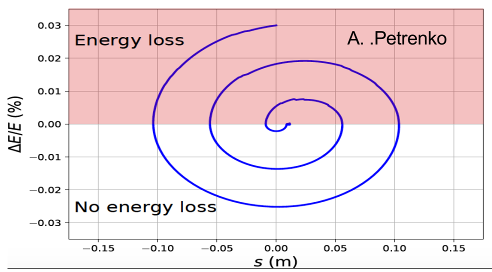
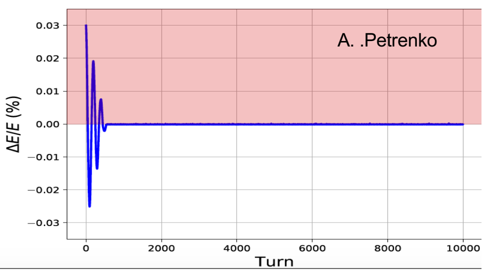
4. Laser cooling of high energy atomic beams



Bunch

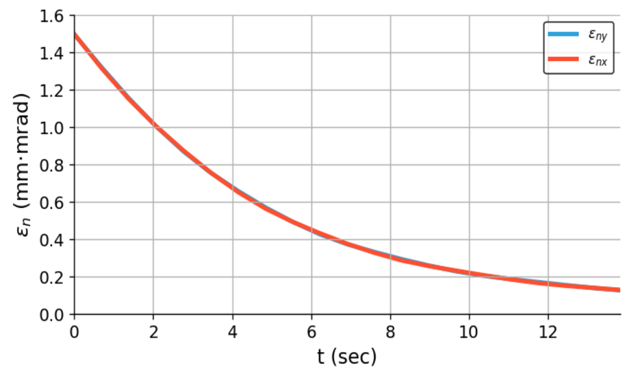






Beam cooling speed: *the laser wavelength band is chosen such that only the ions moving in the laser pulse direction (in the bunch rest frame) can resonantly absorb photons.*

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



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

High-luminosity Large Hadron Collider with laser-cooled isoscalar ion beams
M.W. Krasny (Paris U., VI-VII and CERN), A. Petrenko (CERN and Novosibirsk, IYF), W. Płaczek (Jagiellonian U.) (Mar 25, 2020)
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5.Tertiary beams' sources – Intensity/quality targets

- ***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*

New research opportunities

Examples of potential applications domains of the *Gamma Factory* research tools

- **particle physics** *(precision QED and EW studies, vacuum birefringence, Higgs physics in $\gamma\gamma$ collision mode, rare muon decays, precision neutrino physics, QCD-confinement studies, …);*
- **nuclear physics** *(nuclear spectroscopy, cross-talk of nuclear and atomic processes, GDR, nuclear photo-physics, photo-fission research, gamma polarimetry, physics of rare radioactive nuclides,…);*
- **atomic physics** *(highly charged atoms, electronic and muonic atoms, pionic and kaonic atoms);*
- **astrophysics** *(dark matter searches, gravitational waves detection, gravitational effects of cold particle beams, $^{16}O(\gamma,\alpha)^{12}C$ reaction and S-factors…);*
- **fundamental physics** *(studies of the basic symmetries of the universe, atomic interferometry,…);*
- **accelerator physics** *(beam cooling techniques, low emittance hadronic beams, plasma wake field acceleration, high intensity polarised positron and muon sources, beams of radioactive ions and neutrons, very narrow band, and flavour-tagged neutrino beams, neutron sources…);*
- **applied physics** *(accelerator driven energy sources, fusion research, medical isotopes' and isomers' production).*

GF studies: recently published papers (INSPIRE)

Special issue of "Annalen der Physik" -- devoted to the GF physics highlights -- published in March 2022.

Gamma Factory status

"*Gamma Factory*" studies

The Gamma Factory proposal for CERN [†]

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

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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!*

Gamma Factory milestones – where we are?

1. *Successful demonstration of efficient production, acceleration and storage of "atomic beams" in the CERN accelerator complex.*
2. *Development "ab nihilo" the requisite Gamma Factory software tools.*
3. *Building up the physics cases for the LHC-based GF research programme and attracting wide scientific communities to evaluate and use (in the future) the GF tools in their respective research.*
4. ***Successful execution of the GF Proof-of-Principle (PoP) experiment in the SPS tunnel.***

Done…

Done…

Work ongoing…

LoI submitted to the SPSC on the 25th of September 2019 → Target installation time – LS3 (2026-2027). We are still missing ~1.5 MCHF to construct the PoP experiment.

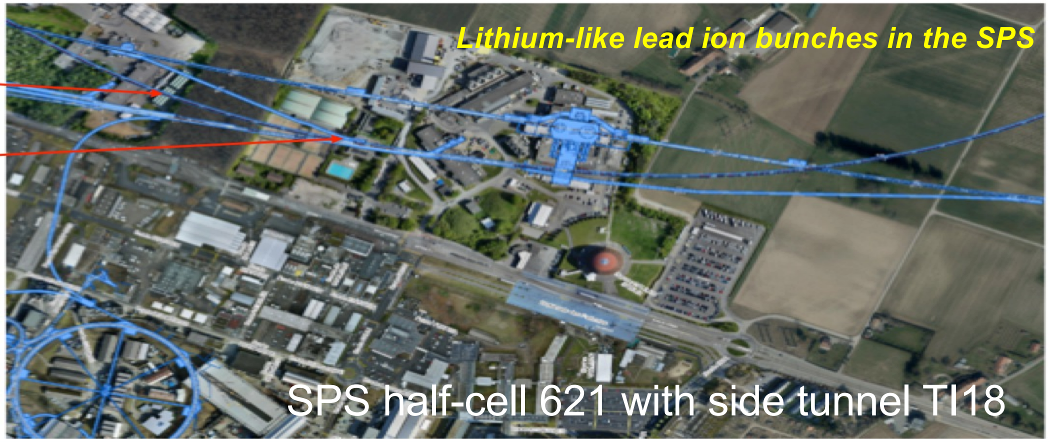
future

1. *Extrapolation of the PoP experiment results to the LHC case and precise assessment of the performance figures of the GF programme.*
2. *Elaboration of the TDR for the LHC-based GF research programme.*

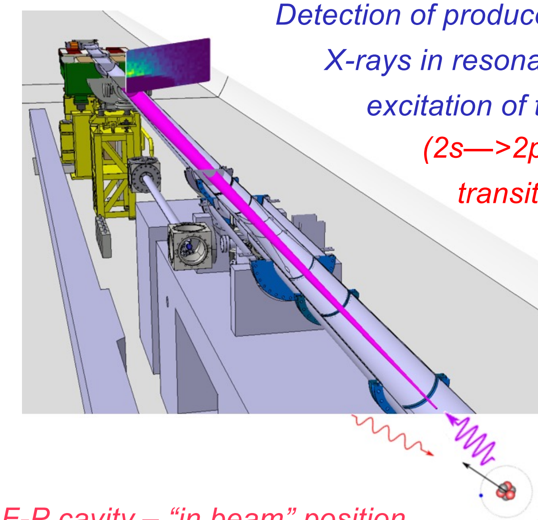
Gamma Factory Proof-of-Principle (PoP) SPS experiment

SPS

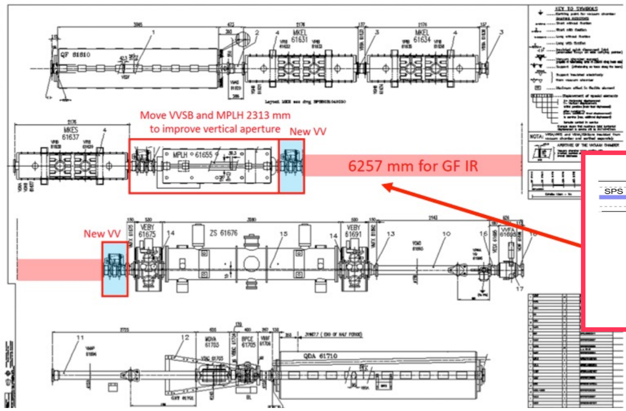
PoP location



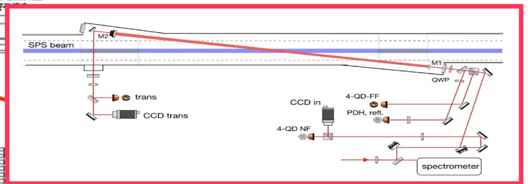
Detection of produced X-rays in resonant excitation of the $(2s \rightarrow 2p)_{1/2}$ transition



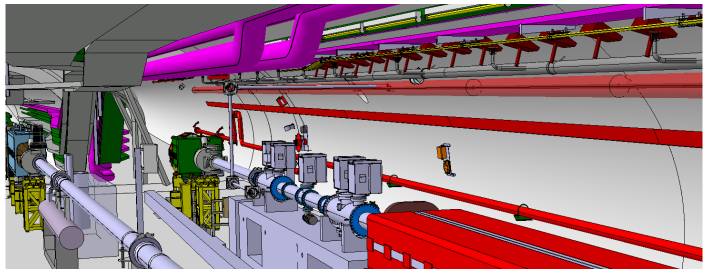
LSS6 zone



F-P cavity



F-P cavity – "in beam" position



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

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

- *The **next** CERN **high-energy frontier** project may take **long time** to be approved, built and become operational, (if ever?) … unlikely before 2045 (FCC-ee) or 2050+ (μ-collider).*

- *The **present** LHC **research programme** will certainly reach **earlier** (~2032?) its discovery **saturation** (little physics gain by a simple extending its pp/pA/AA running time).*

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

__The Gamma Factory__ research programme (2035-????) could fulfil such a role. It can exploit __the existing world unique opportunities__ offered by the CERN accelerator complex and CERN's scientific infrastructure __(not available elsewhere__) to conduct new, diverse, and vibrant research with new tools.

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 finalise its 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 and wide scientific community support for this project is a "sine qua non" condition for its further development*

"I have a dream" vision of the LHC operation in in the post-HL-LHC phase (in ~20 years?)