Gamma Factory
– a tool-driven revolution?

IFJ-PAN-Krakow, the 30st of March 2023

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

Outline of the talk

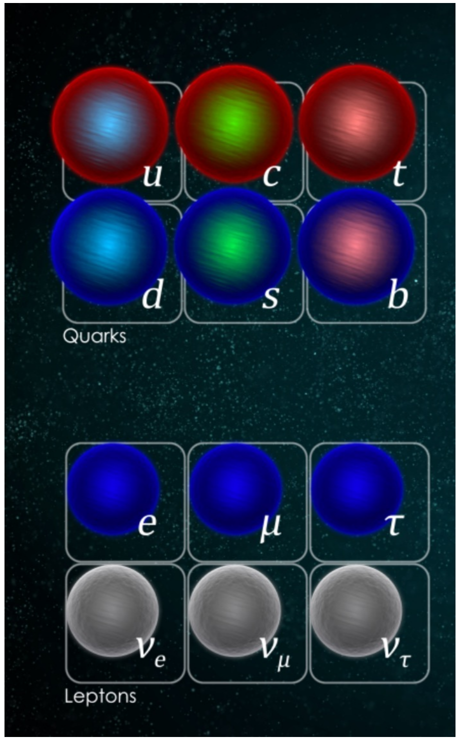
- *Scientific context*
- *Photons*
- *Gamma Factory photon source*
- *Novel research tools made out of light*
- *New research opportunities*
- *Gamma Factory project status*

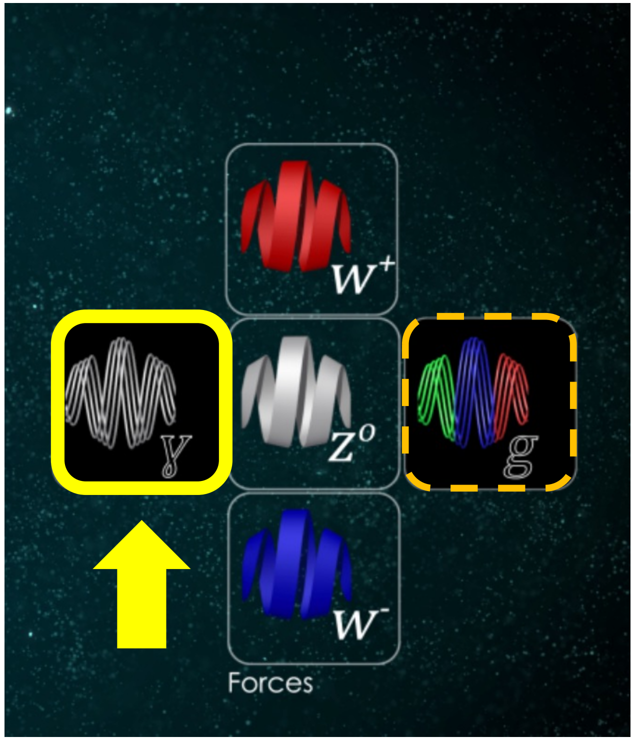
Scientific context

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****!*

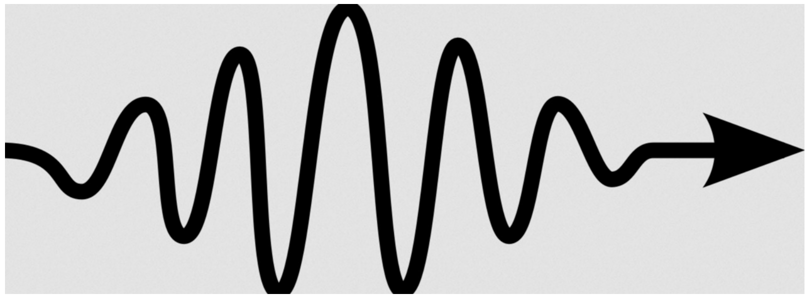
- ***At this moment*** *of particular* ***importance*** *for our discipline, since we* ***neither*** *have any* ***hints*** *for a* ***new physics*** *which is accessible by the* ***present*** *technologies at a* ***reasonable*** *cost,* ***nor*** *a* ***certainty*** *that Particle Physics will* ***survive, 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.

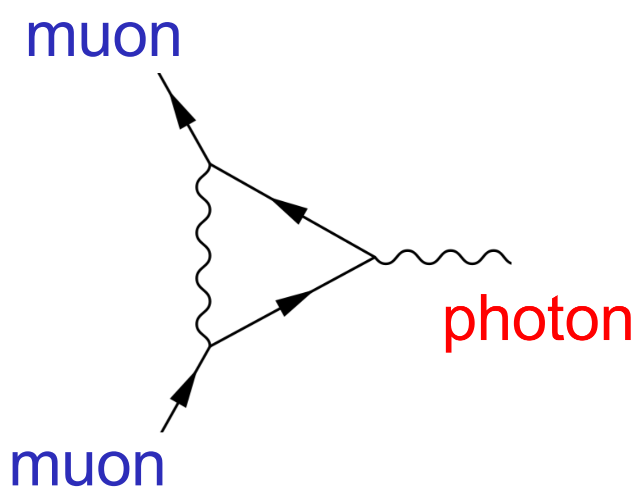
The effect of a tool-driven revolution is to discover new things that have to be explained" - F. Dyson

Photons



Photons as research tools:

extraordinary precision of Quantum Electrodynamics



g – measured magnetic moment of the muon

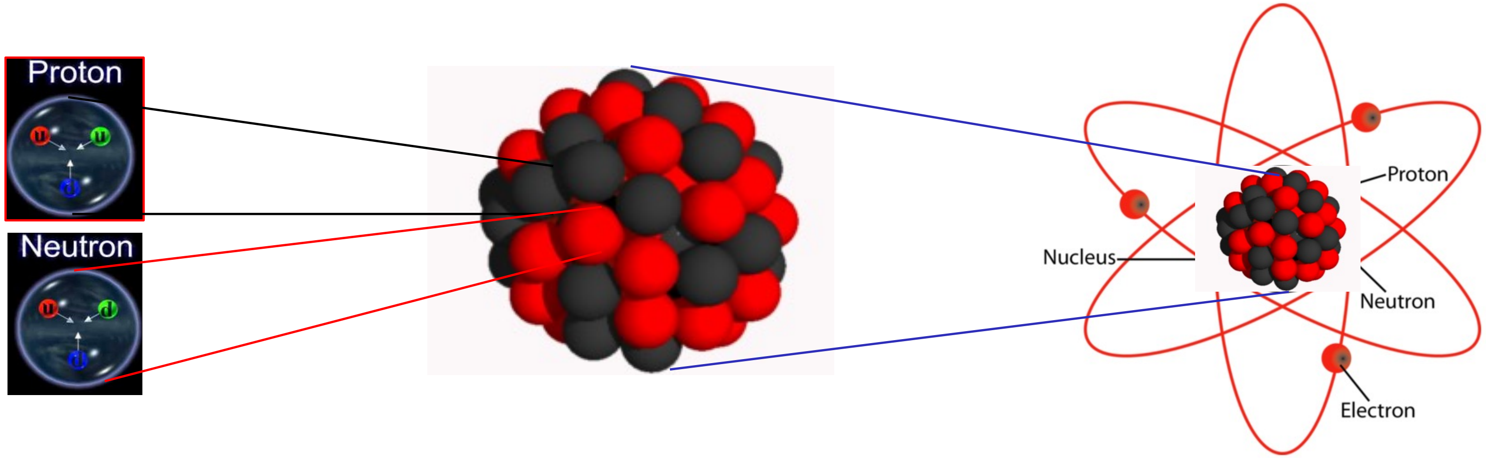
Dirac equation: g =2

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

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

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

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

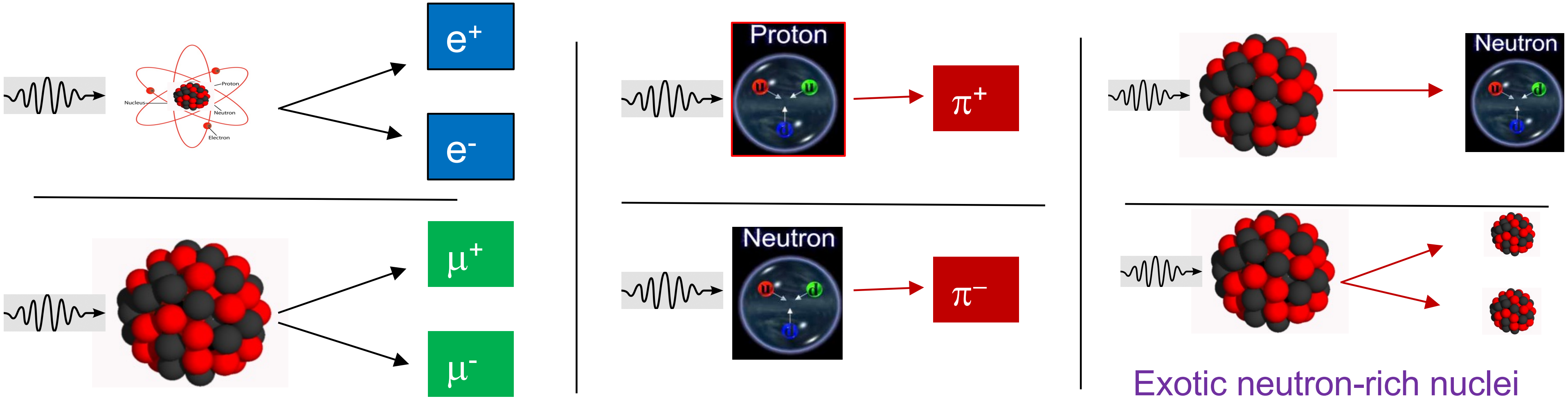


γ-rays

X-rays

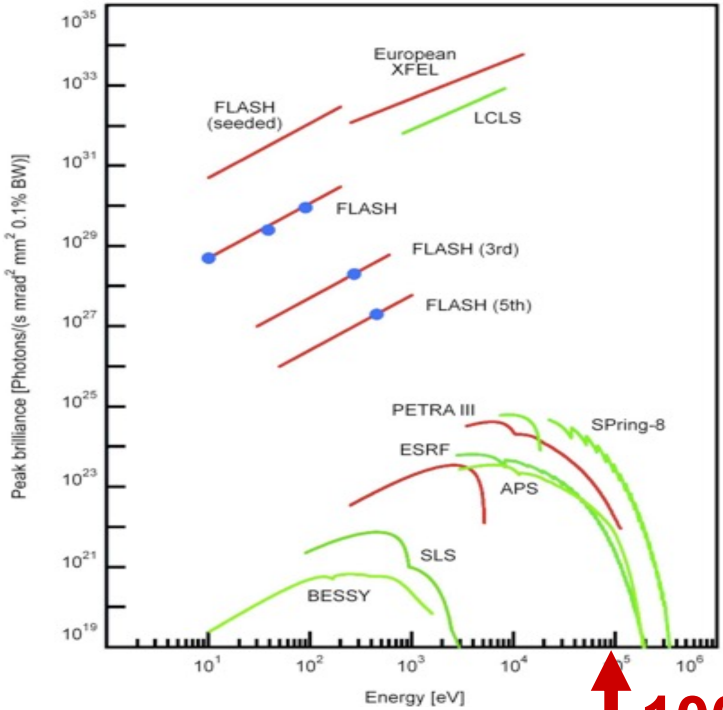
Photons of energy in the range of sub-eV to hundreds of MeV (wavelengths comparable to the size of objects)

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



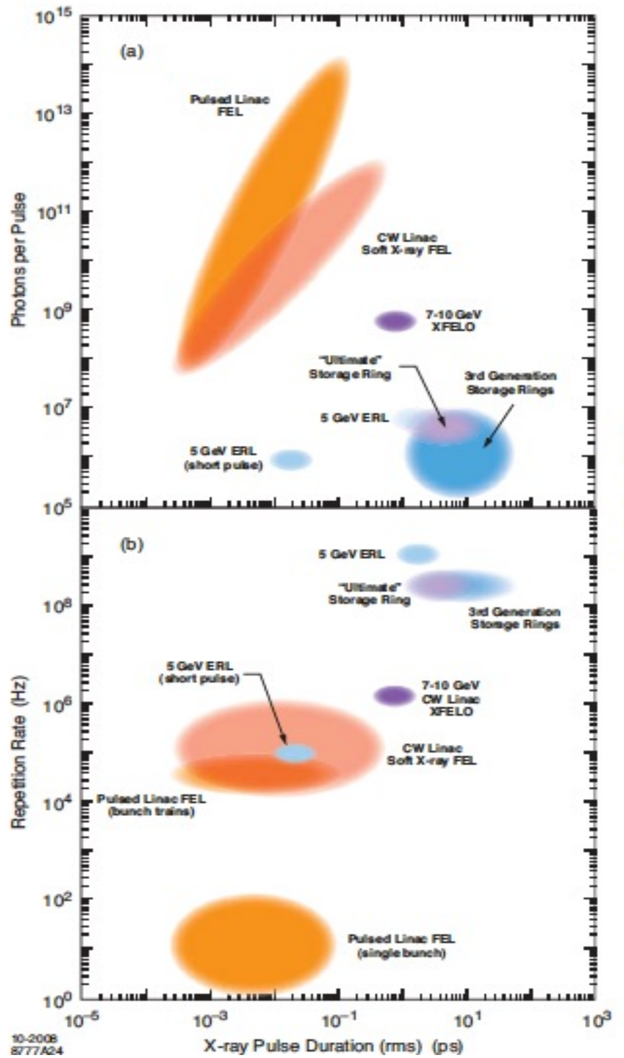
Require photons of the energy langer than ~1 MeV (γ-rays)

Photon sources (X-rays)



100 keV

Energies up to ~ 100 keV



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

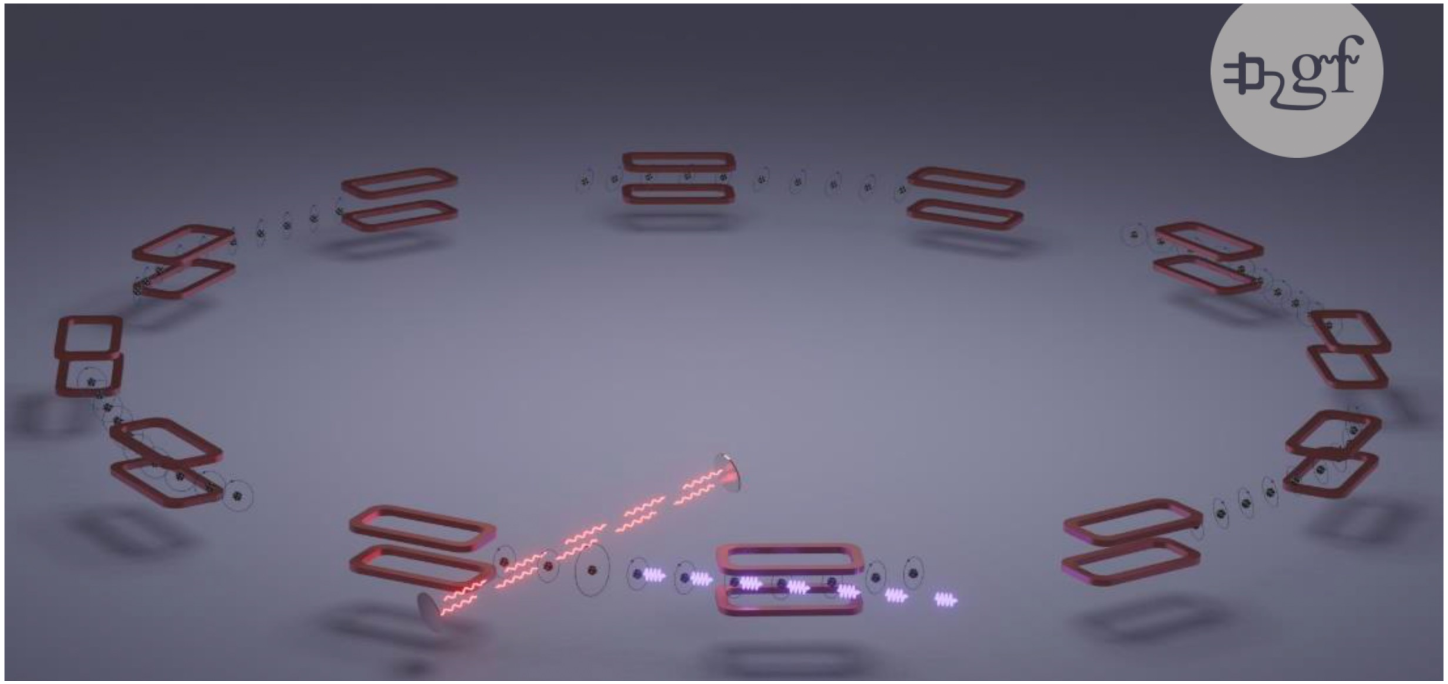
Photon sources (γ-rays)

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–

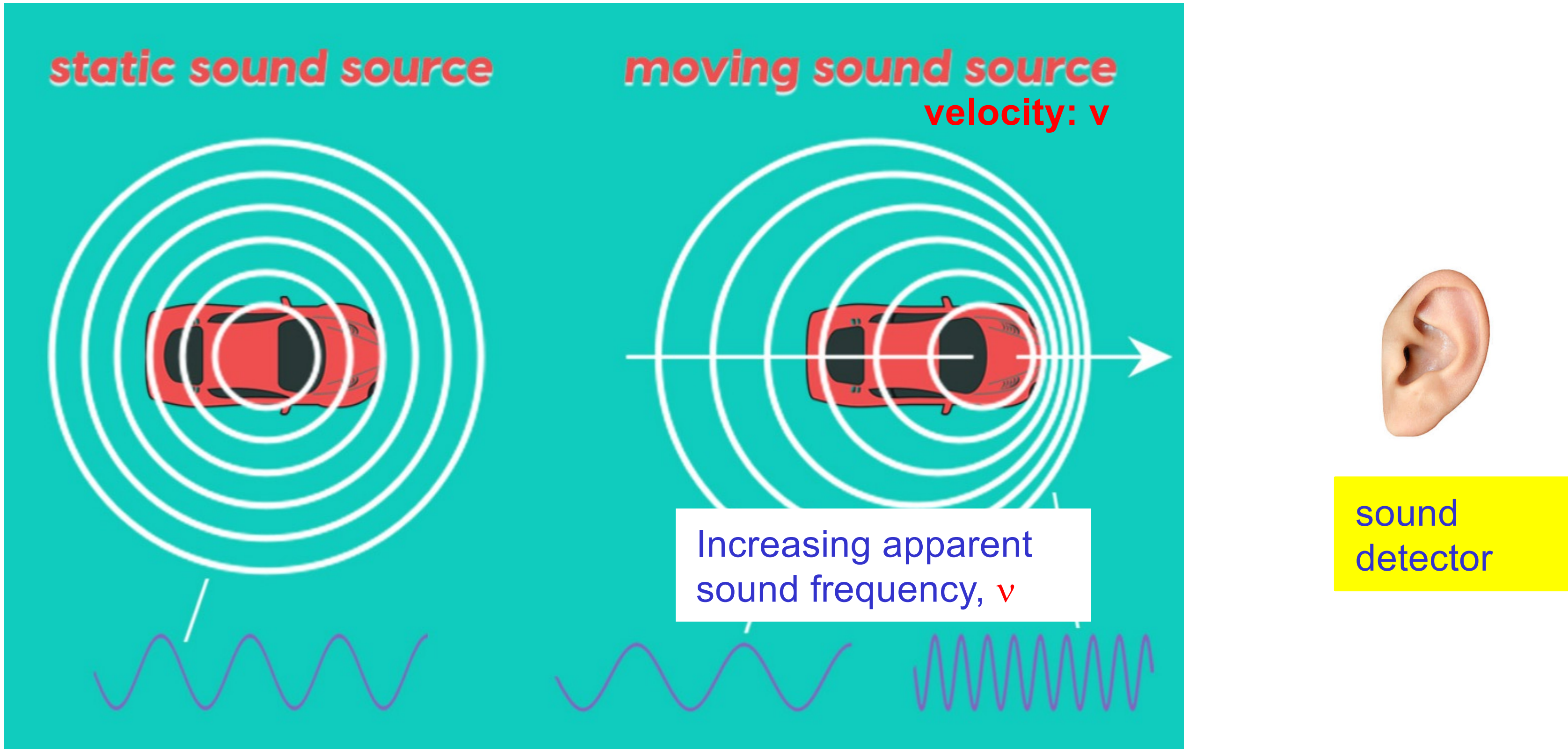
Intensities up to ~ **10^9 photons /s**

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?

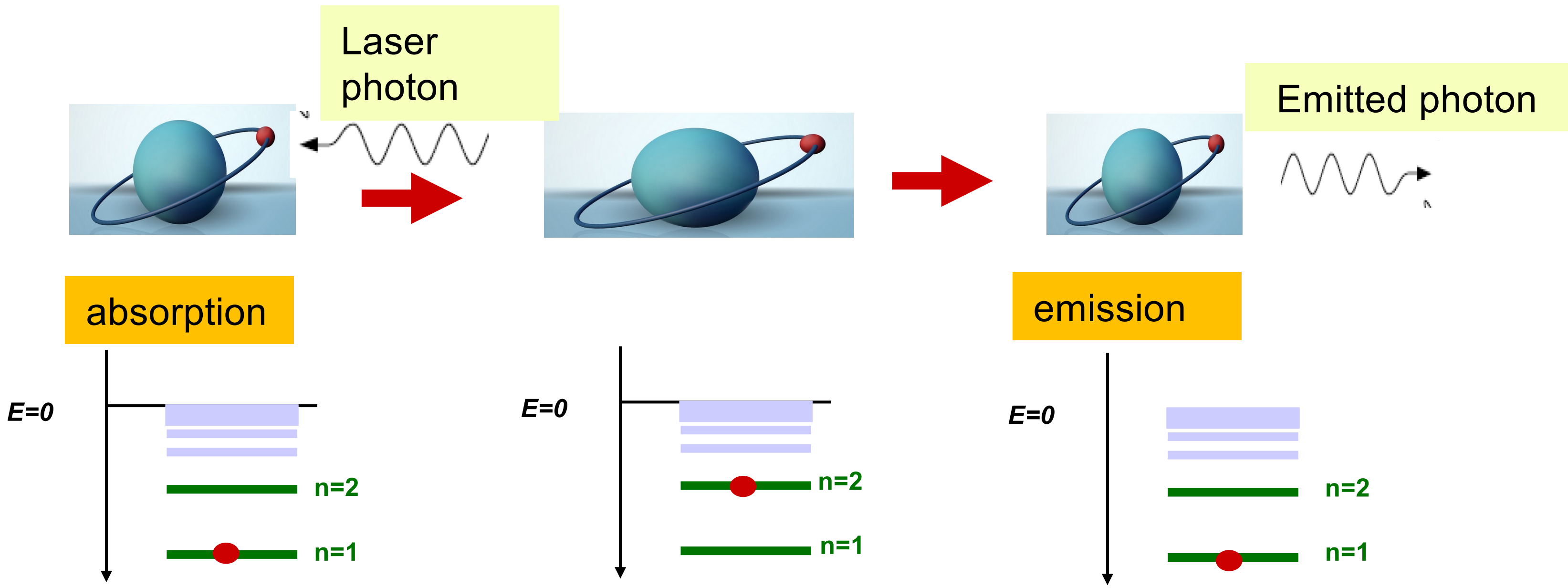
Gamma Factory photon source



The basic idea: Use Doppler effect

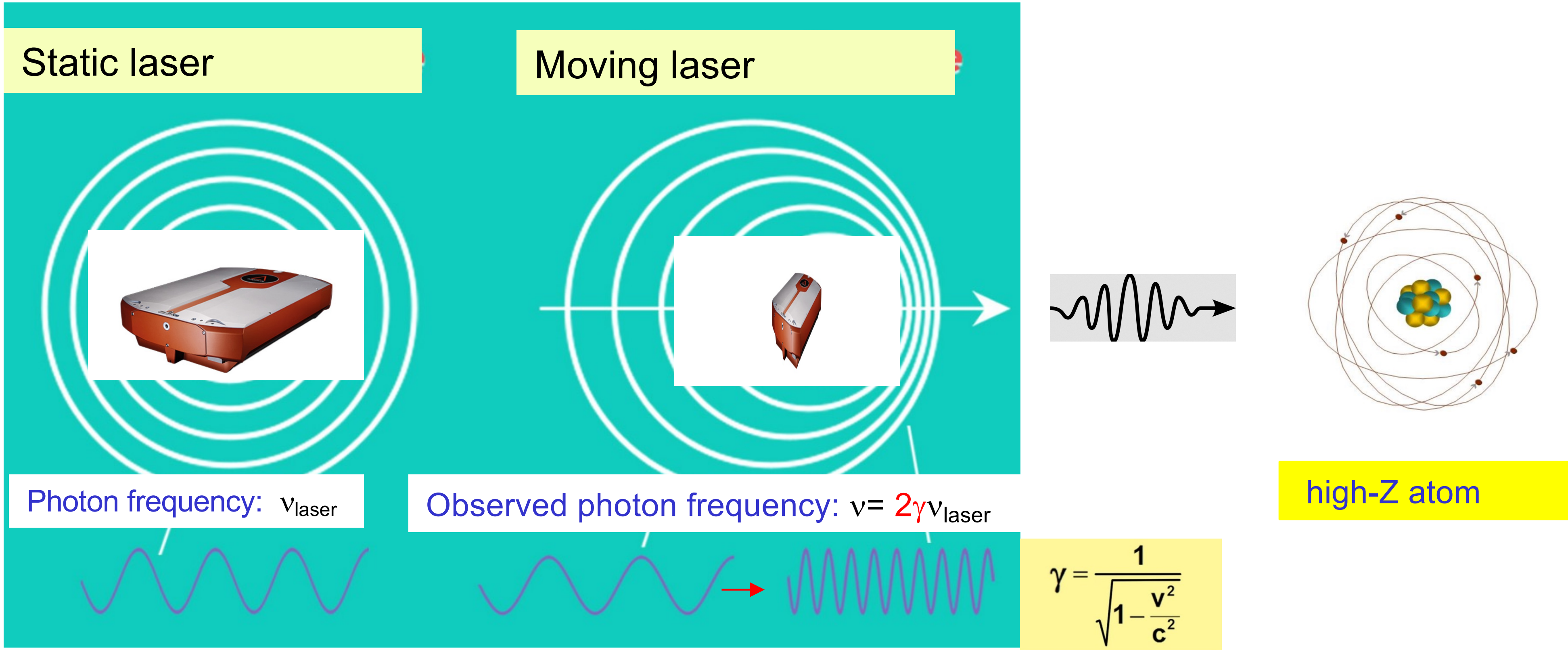


Absorption and emissions of photons by **atoms**

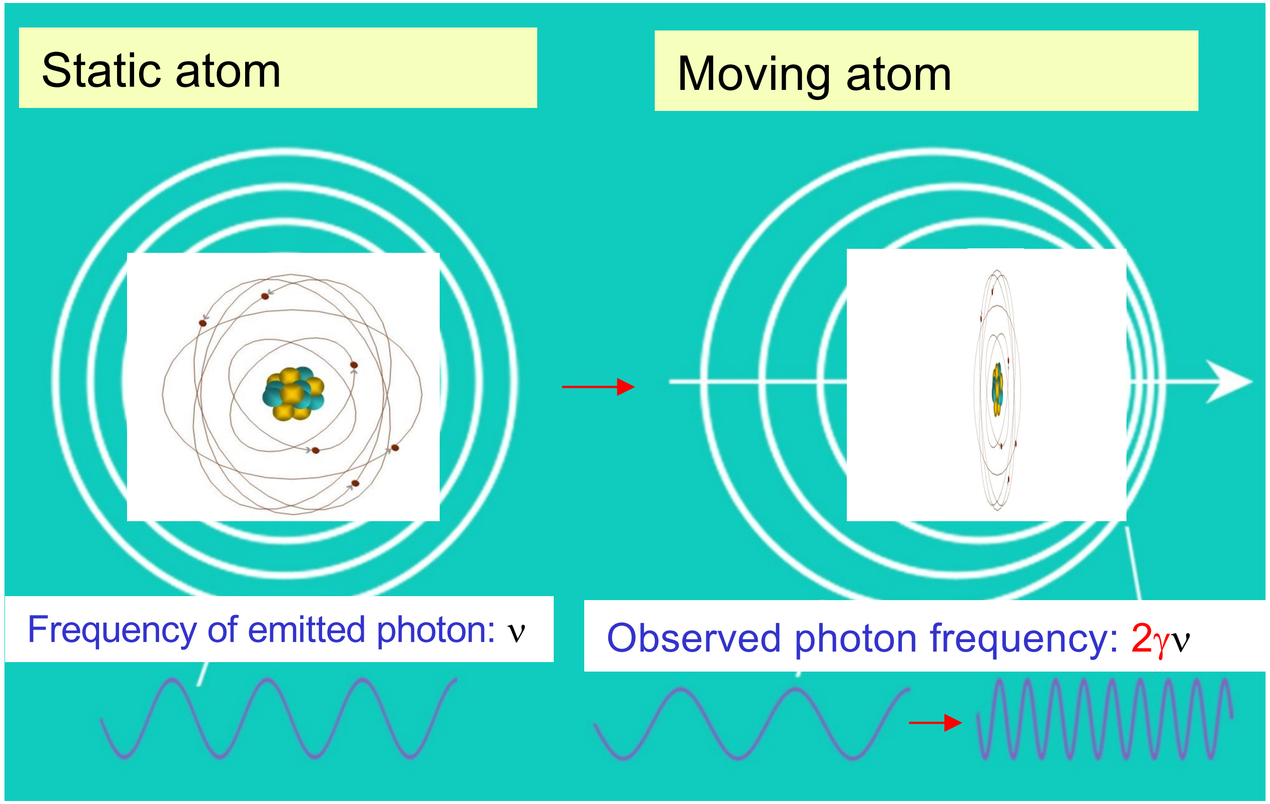


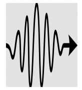
Let's accelerate an atom to a relativistic velocity: v ~ c

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



Emission phase …back to the laboratory frame





Photon detector

Gamma Factory photon source: energy leap

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

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

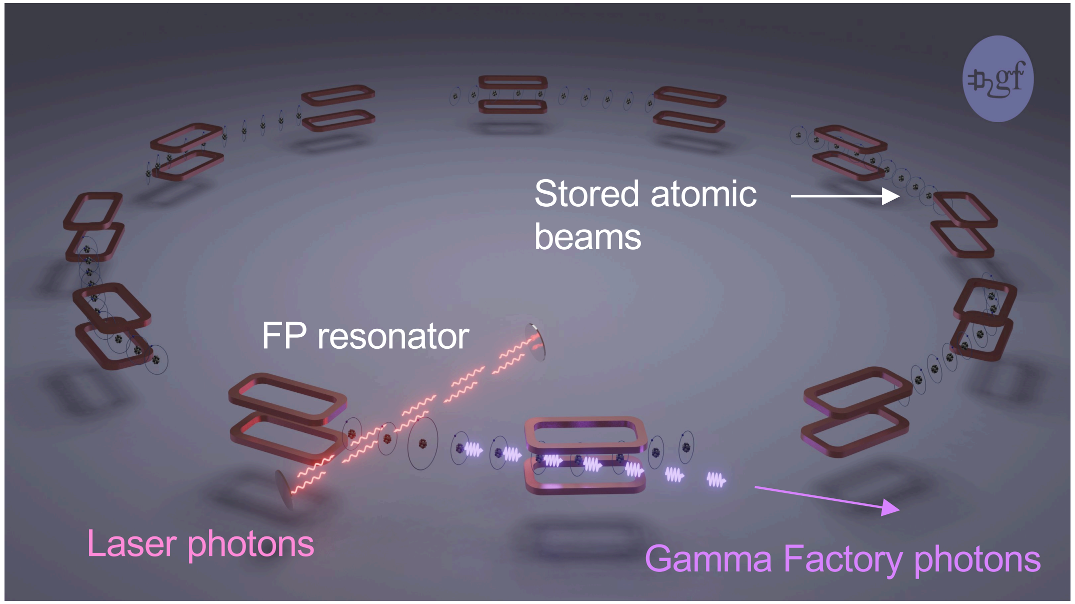
…for the photon emitted in the direction of the moving atom

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

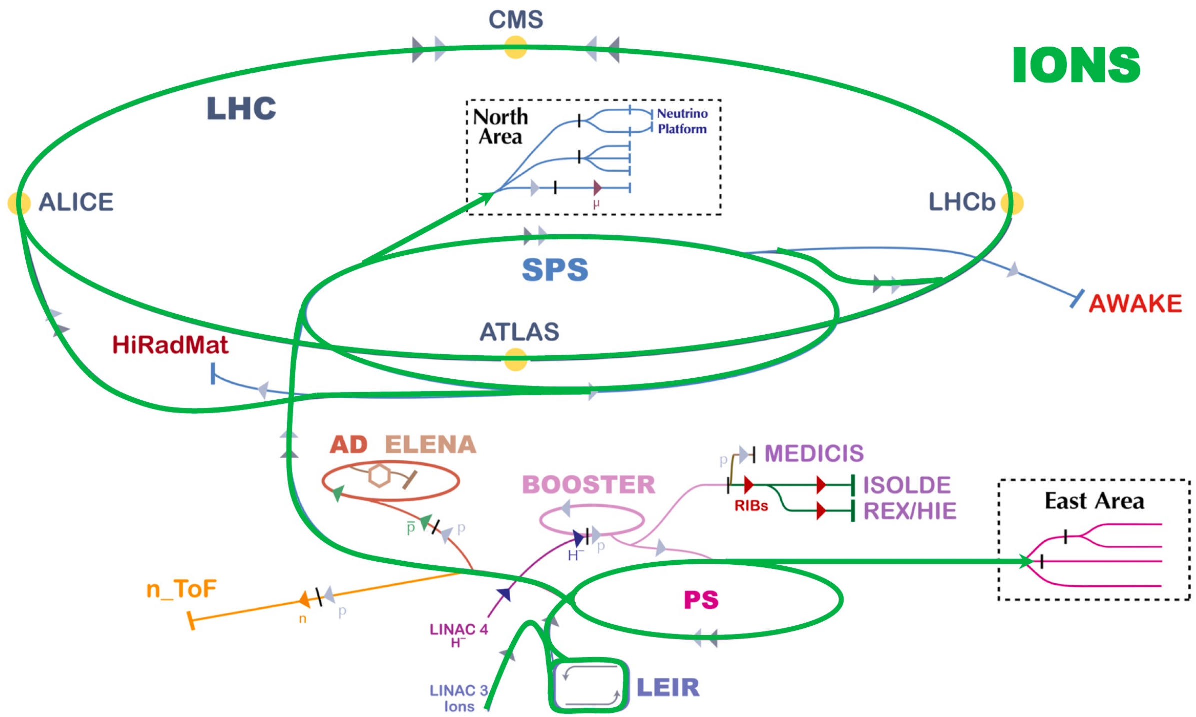
Requirements: *Accelerated bunches of ~10^8-10^9 partially stripped atoms, delivered with ~20 MHz frequency, ~5 mJ laser photon pulses stacked in 20 MHz, Fabry-Perot resonator*



Novel technology:

Resonant scattering of laser photons on ultra-relativistic atomic beam

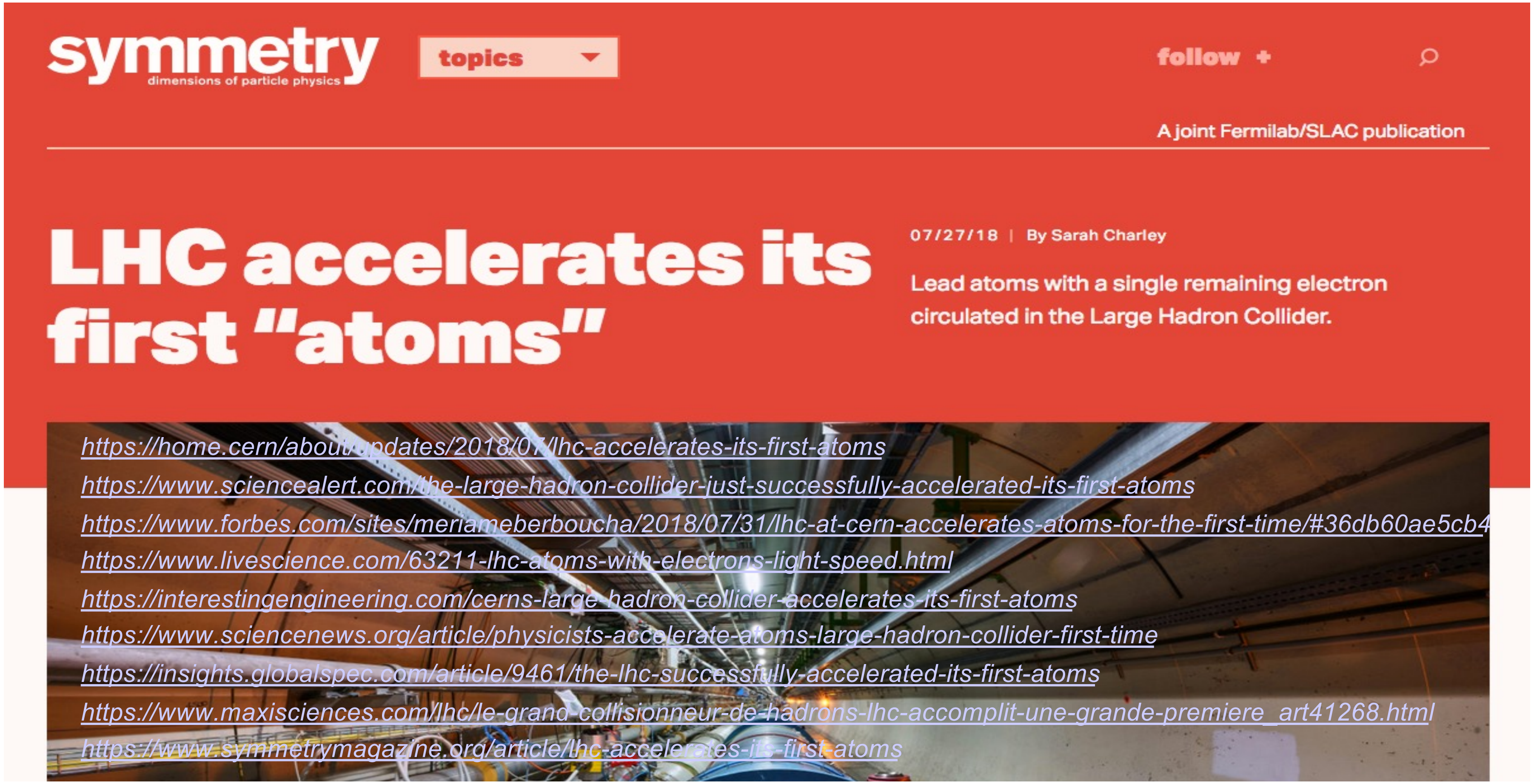
Sustainability: Re-use of already existing accelerator infrastructure – CERN



Gamma Factory (additional) requirements:

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

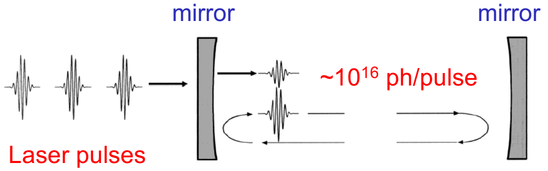
Decisive beam tests

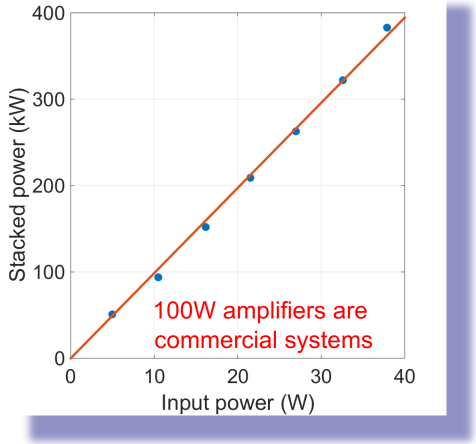


https://home.cern/about/updates/2018/07/lhc-accelerates-its-first-atoms
https://www.sciencealert.com/the-large-hadron-collider-just-successfully-accelerated-its-first-atoms
https://www.forbes.com/sites/meriameberboucha/2018/07/31/lhc-at-cern-accelerates-atoms-for-the-first-time/#36db60ae5cb4
https://www.livescience.com/63211-lhc-atoms-with-electrons-light-speed.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

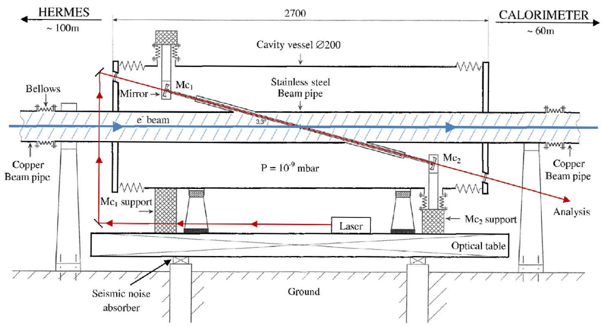




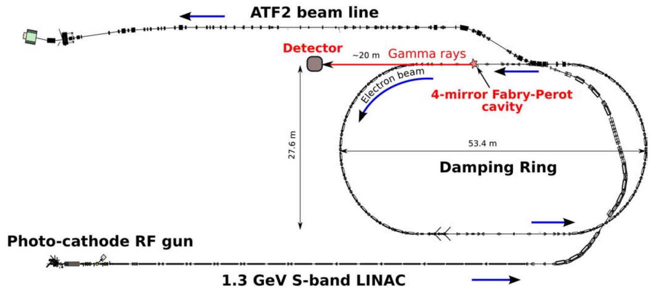
Amoudry L. et al., Applied Optics 59(2020)116

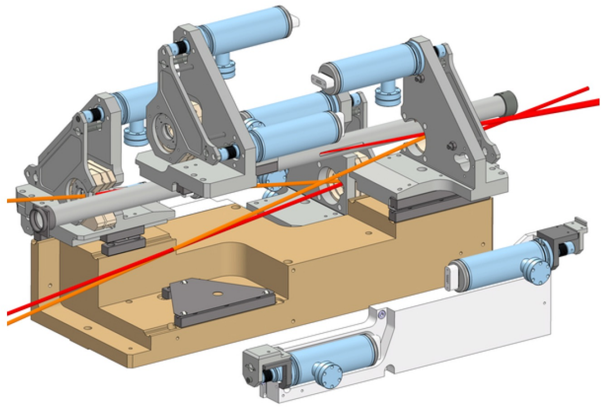
GF requirement:
< 5mJ pulses @ 20MHz,
(100kW photon beam)

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 resonant 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

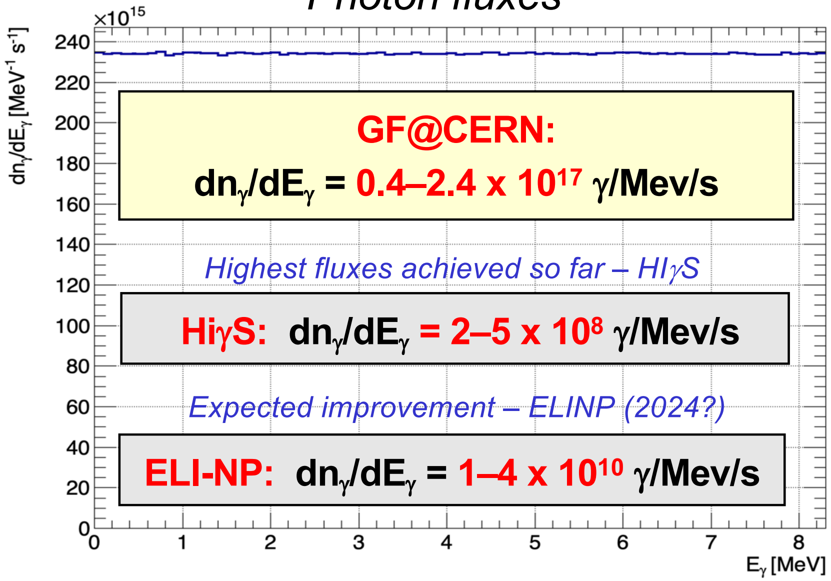
N_A = 6,023·10^{23}

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

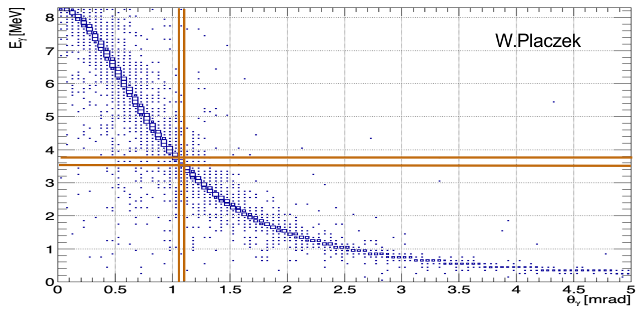


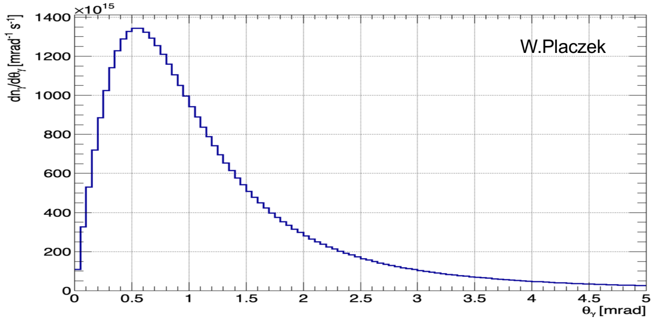
laser pulse parameters

- 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%**

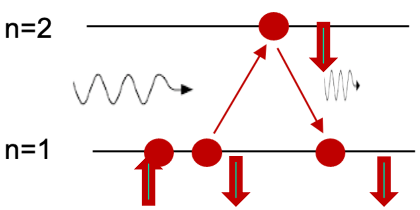
5. Unprecedented plug power efficiency (energy footprint):

- ***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)

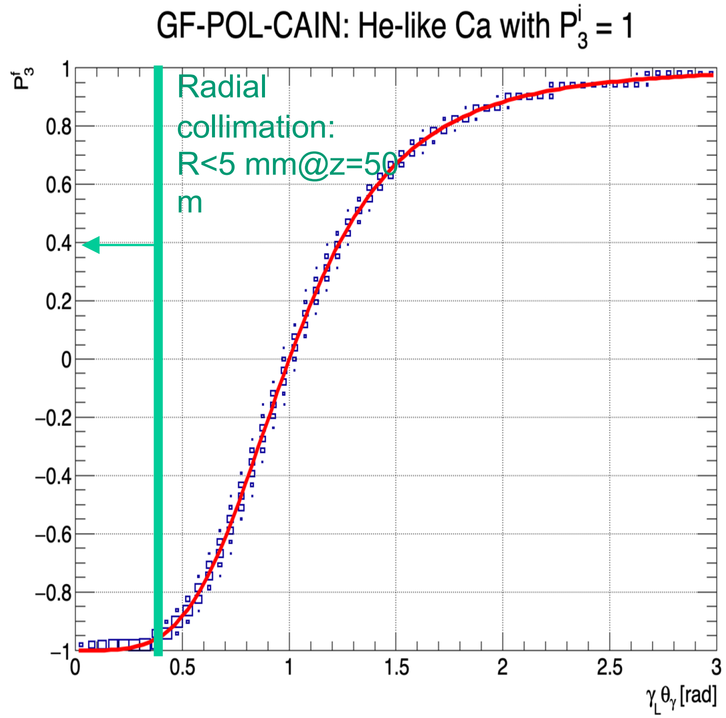
Polarised beams in GF – example: He-like, Calcium beam, Er:glass laser (1522 nm)

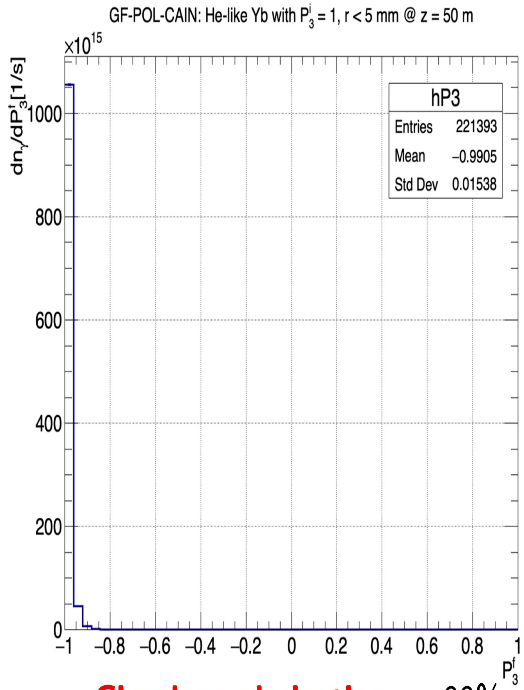
A trick: $1s^2\ {}^1S_0 \rightarrow 1s^1 2p^1\ {}^1P_1$ transition in He-like atoms



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

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

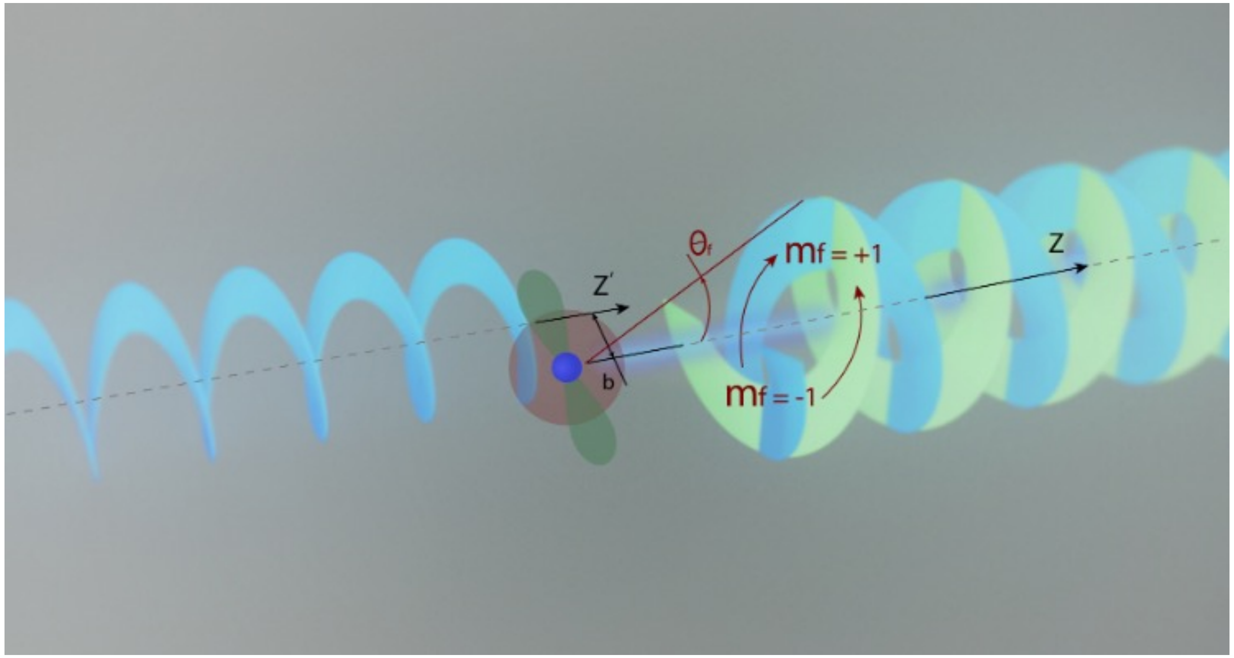




$\rightarrow$ **Circular polarization** $\approx 99\%$

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

Gamma Factory twisted photons



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

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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".*

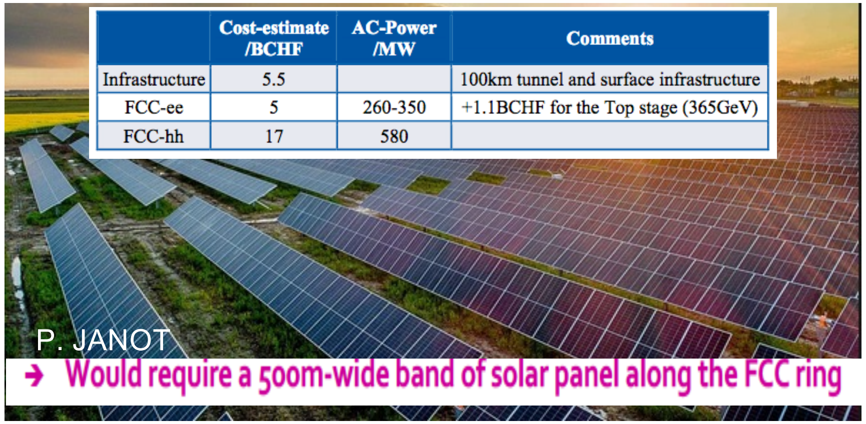
Novel research tools made from light




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



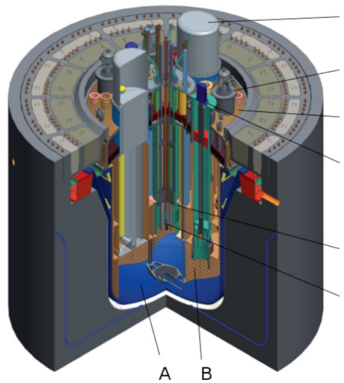
	Cost-estimate /BCHF	AC-Power /MW	Comments
Infrastructure	5.5		100km tunnel and surface infrastructure
FCC-ee	5	260-350	+1.1BCHF for the Top stage (365GeV)
FCC-hh	17	580	

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

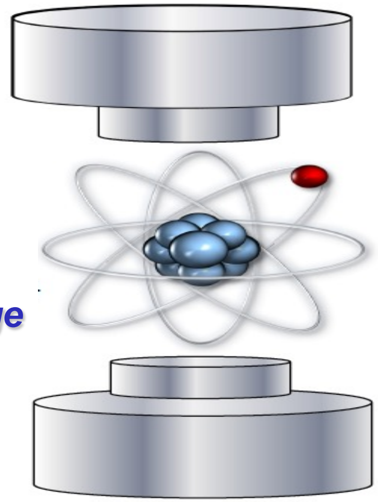
Minneapolis, Minnesota (Apr 15-18)

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

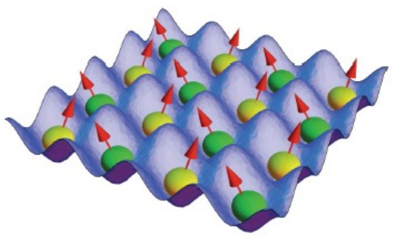
Atomic rest-frame

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

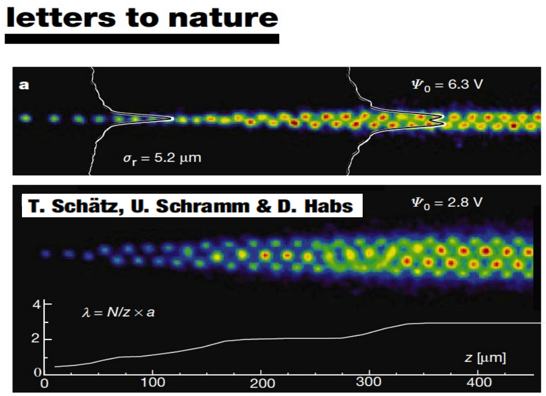


Opening new research opportunities in atomic physics:

- *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*



Crystalline beams?




annalen der physik

Feature Article | Open Access

Atomic Physics Studies at the Gamma Factory at CERN

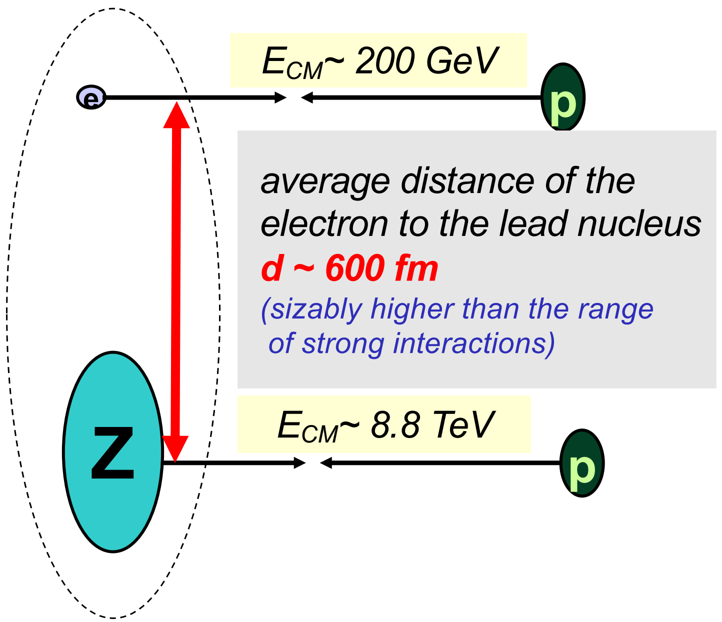
Dmitry Budker, José R. Crespo López-Urrutia, Andrei Derevianko, Victor V. Flambaum, Mieczyslaw Witold Krasny, Alexey Petrenko, Szymon Pustelny, Andrey Surzhykov, Vladimir A. Yerokhin, Max Zolotorev ... See fewer authors

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!*

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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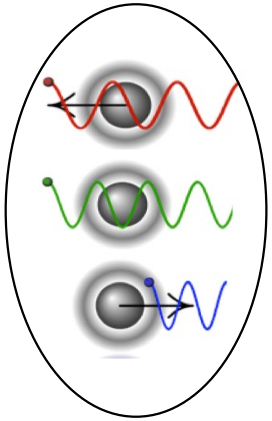
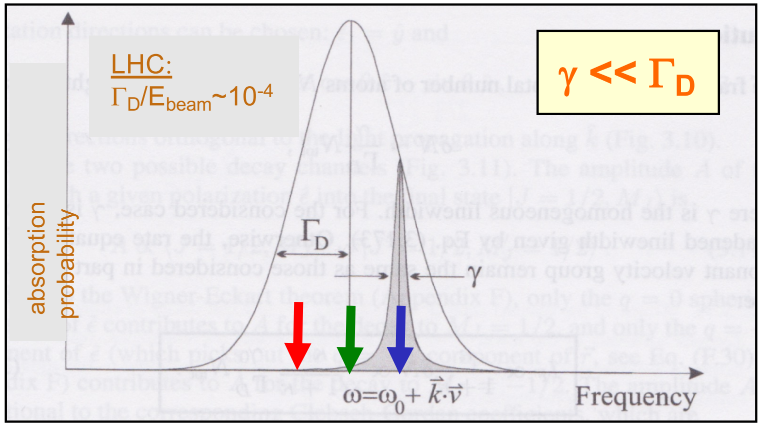
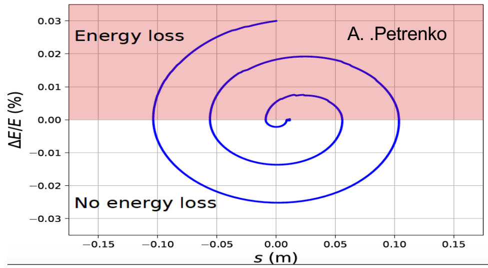
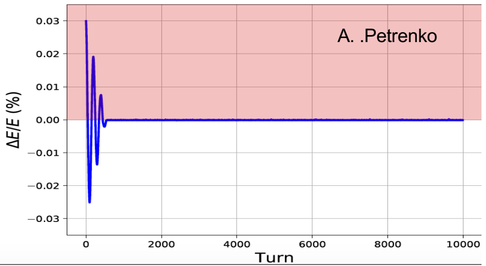
4. Laser cooling of high energy atomic beams



Bunch

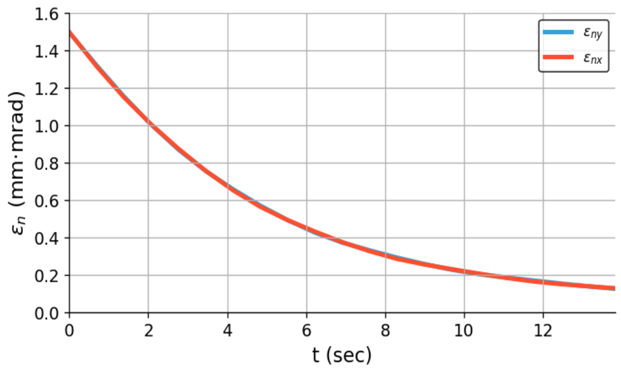






Beam cooling speed: *the laser wavelength band is chosen such that only the ions moving in the laser pulse direction (in the bunch rest frame) can resonantly absorb photons.*

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

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.

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!*

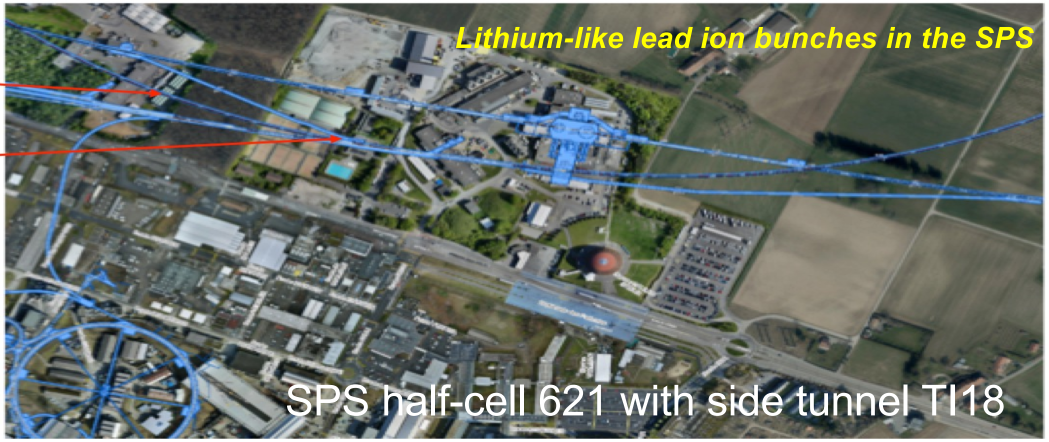
Gamma Factory milestones – where we are?

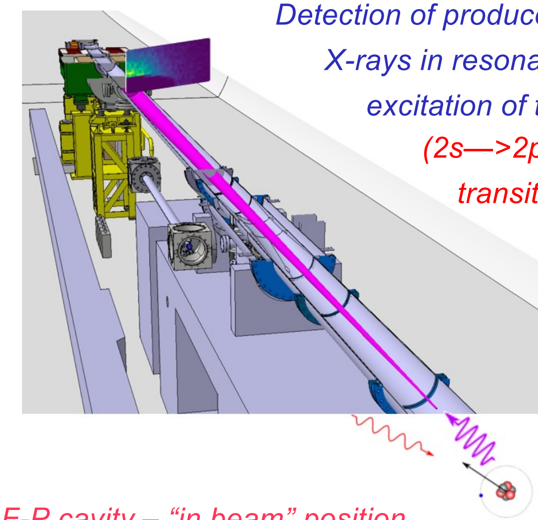
1. *Successful demonstration of efficient production, acceleration and storage of "atomic beams" in the CERN accelerator complex.* → *Done…*
2. *Development "ab nihilo" the requisite Gamma Factory software tools.* → *Done…*
3. *Building up the physics cases for the LHC-based GF research programme and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

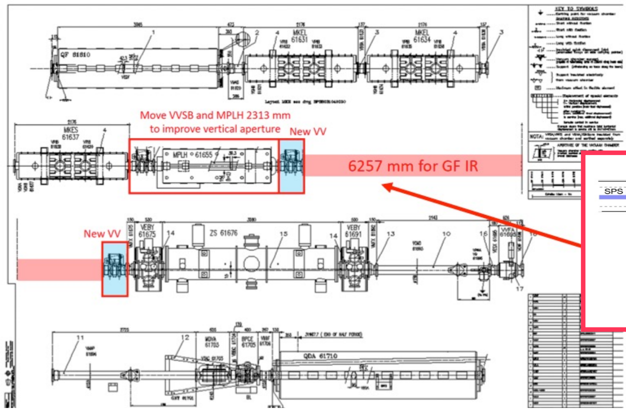
1. *Extrapolation of the PoP experiment results to the LHC case and precise assessment of the performance figures of the GF programme.*
2. *Elaboration of the TDR for the LHC-based GF research programme.*

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

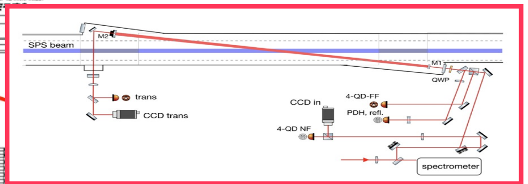




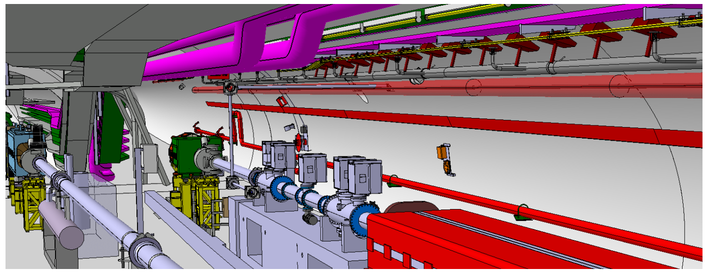
LSS6 zone



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

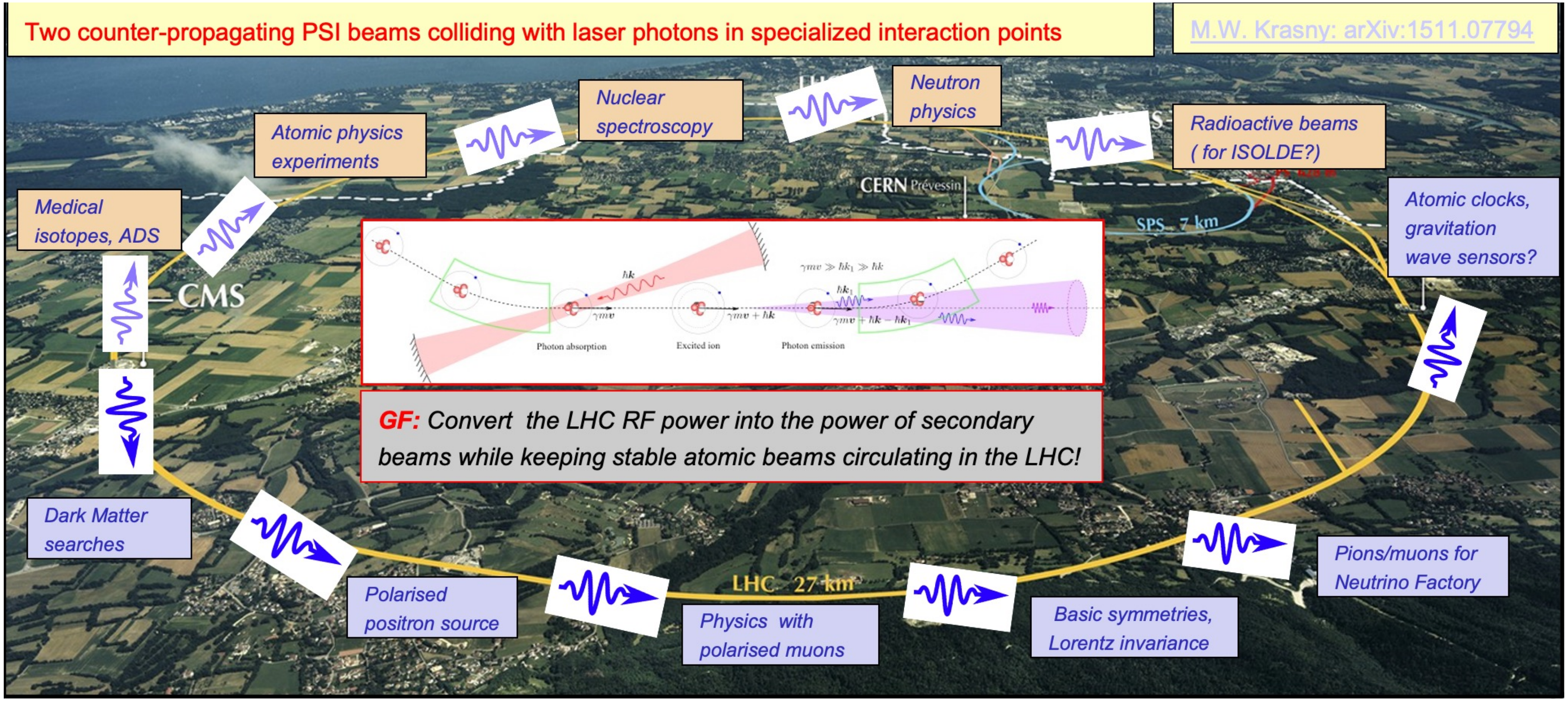
- *Gamma Factory can create, at CERN, a variety of novel research tools, which could open novel research opportunities in a very broad domain of basic and applied science*

- *The Gamma Factory research programme can be largely based on the existing CERN accelerator infrastructure – it requires "relatively" minor infrastructure investments*

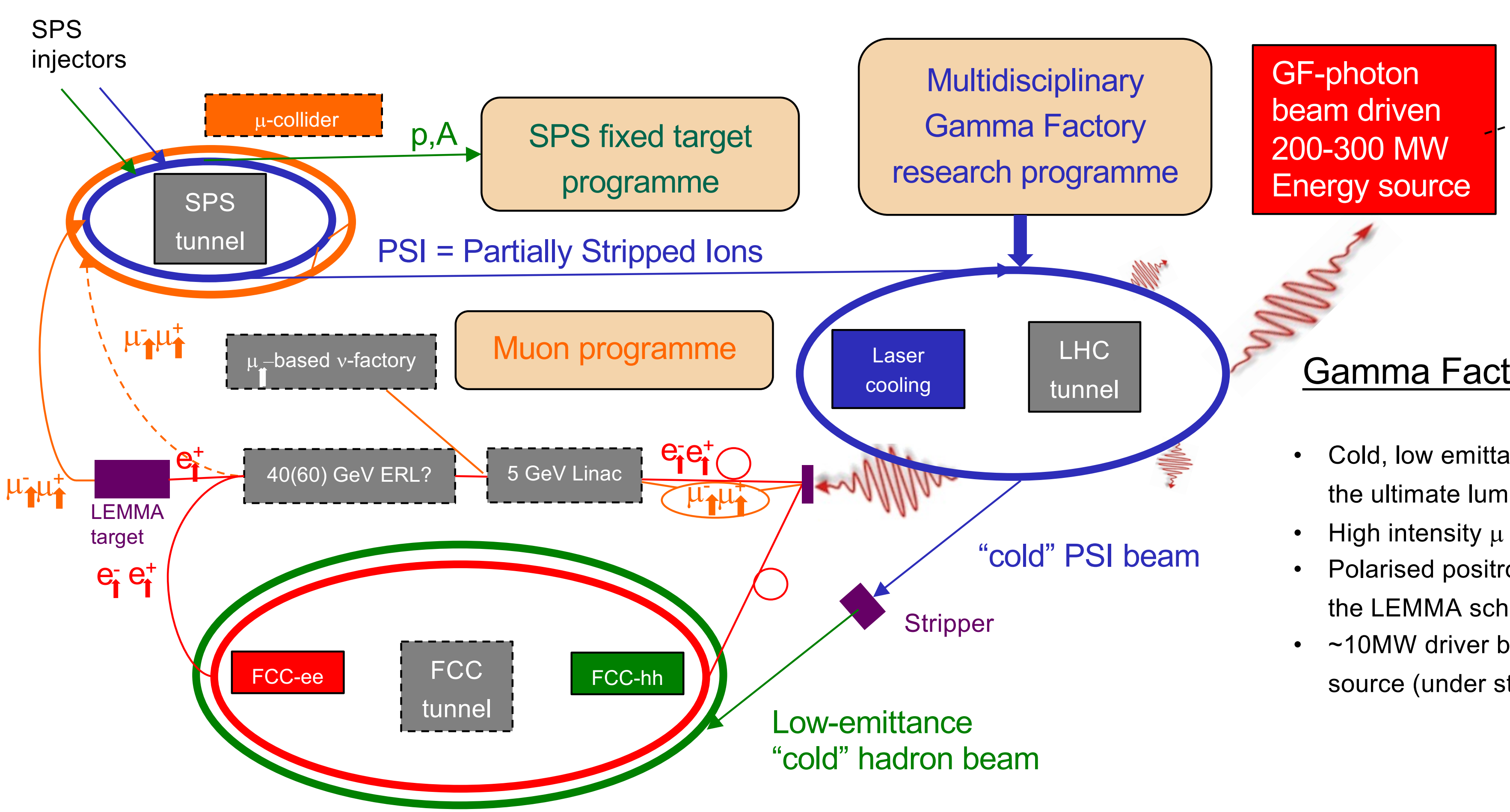
- *Its "quest for diversity of research subjects and communities" is of particular importance in the present phase of accelerator-based research, as we neither have any solid theoretical guidance for a new physics "just around the corner", accessible by FCC, ILC, or CLIC, nor an established "reasonable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



Potential GF role in the incremental, sustainable and multi-disciplinary development of the research infrastructure at CERN



Gamma Factory could provide:

- Cold, low emittance, hadronic beam for the ultimate luminosity hadron collider
- High intensity μ source ($>10^{13}$ μ/s)
- Polarised positron source ($>10^{16}$ e^+/s) for the LEMMA scheme muon collider
- ~10MW driver beam for the ADS energy source (under study)