Gamma Factory

New research opportunities for CERN

JENAS EoI, 16.07.2020

Kyaik-Tiyo, Myanmar(Burma)

JENAS Symposium 2022, Madrid 4.05.2022

Mieczyslaw Witold Krasny, Gamma Factory group

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

“*Gamma Factory*” proposal and 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.

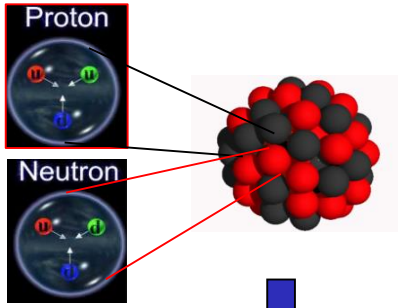
More info on the GF group activities:

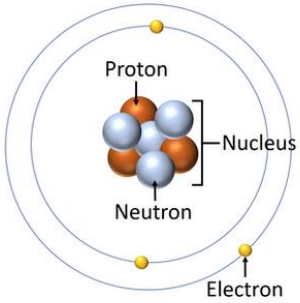
https://indico.cern.ch/category/10874

*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!*

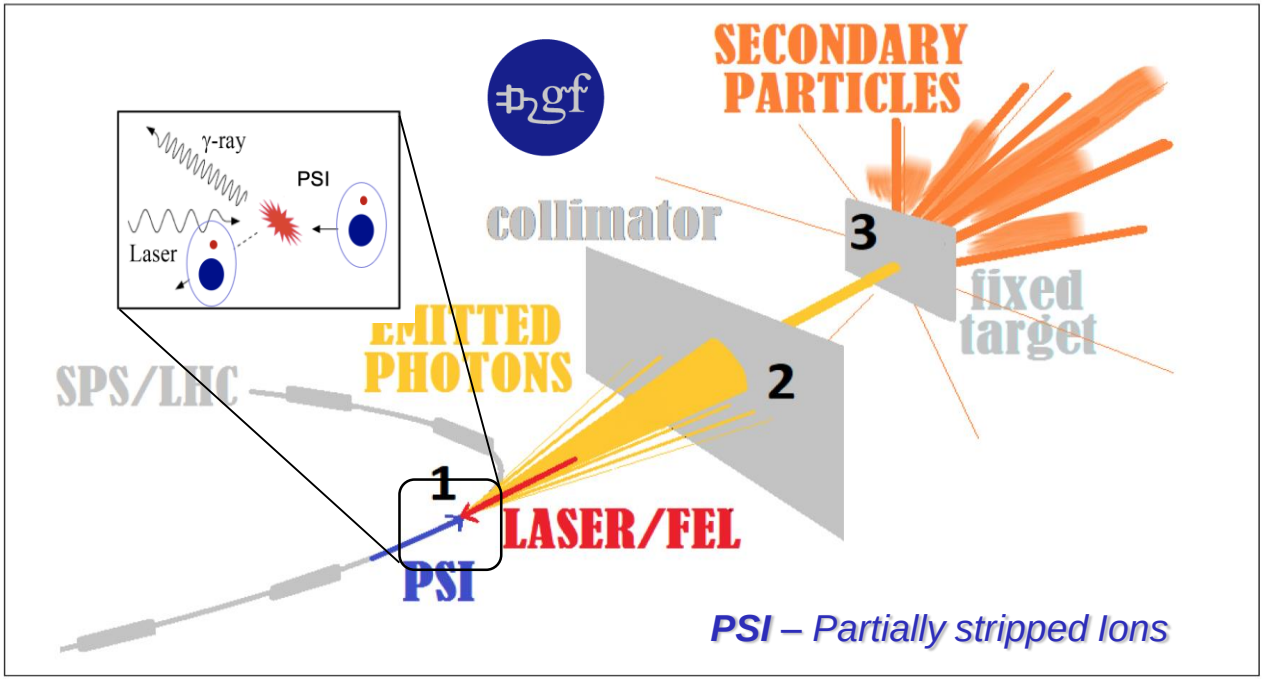
Gamma Factory: novel use of **existing** CERN's storage rings

LHC beams





- *Store **atomic beams of partially stripped ions** in the LHC*
- *Collide them with laser pulses **(circulating in Fabry-Pérot resonators)***



***PSI** – Partially stripped Ions*

Principal Gamma Factory research tools

1. *Atomic traps of highly charged, cold atoms*

2. *High intensity photon(γ)-beams*

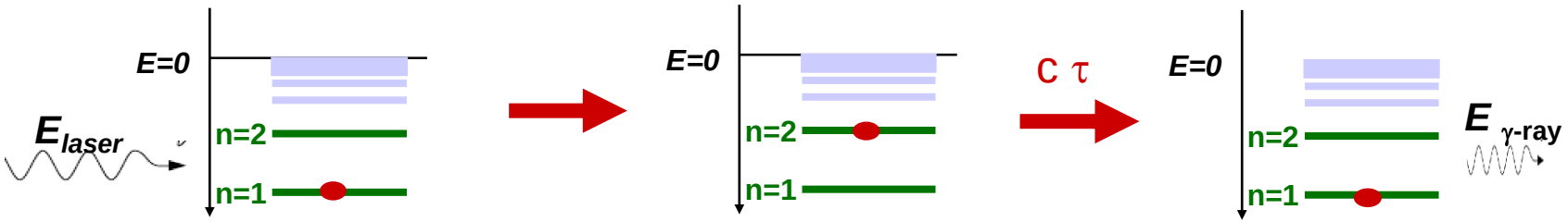
3. *Laser-light based cooling methods of high-energy hadronic beams*

4. *High-intensity beams of polarised electrons, polarised positrons, polarised muons, neutrinos, neutrons and radioactive ions*

5. *Electron beam for ep collisions in the LHC interaction points*

6. *Low emittance beams and electron source for plasma Wakefield acceleration*

Gamma Factory photon beam



Gigabarn cross section

High energy atomic beams play the role of **high-stability light-frequency converters**:

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

for photons emitted in the direction if incoming atoms, $\gamma_L = E/M$ is the Lorentz factor for the ion beam

GF photon beams

1. Point-like, small divergence

- $\Delta z \sim l_{PSI\text{-}bunch}$, $\Delta x, \Delta y \sim \sigma^{PSI}_{x}, {}^{PSI}_{y}$, $\Delta(\theta_x)$, $\Delta(\theta_y) \sim 1/\gamma_L < 1$ mrad

2. Huge jump in intensity:

- ***6–8 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%***

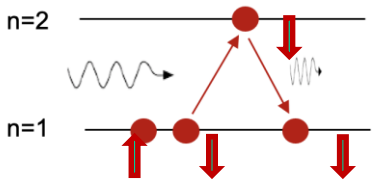
5. Unprecedented plug power efficiency (energy footprint):

- ***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)

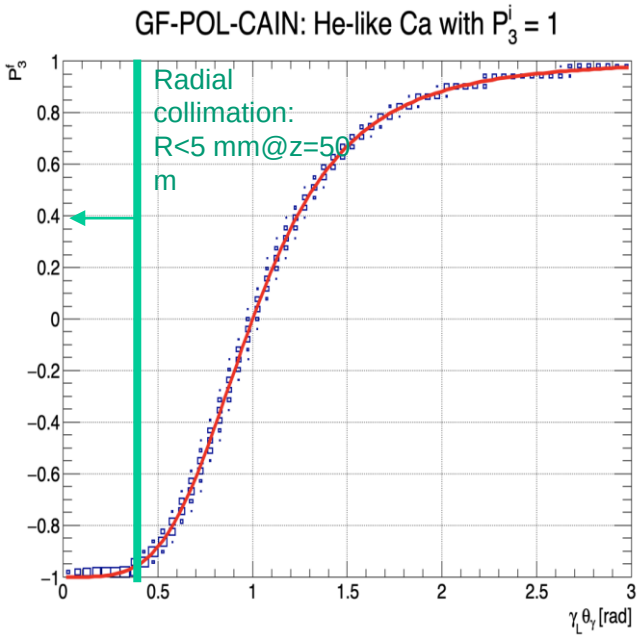
Polarised beams in GF – example: He-like, Calcium beam, Er:glass laser (1522 nm)

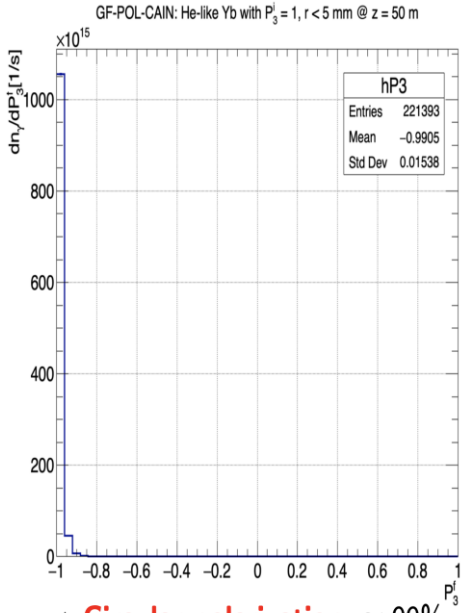
A trick: $1s^2\ 1S_0 \rightarrow 1s^1\ 2p^1\ {}^1P_1$ transition in He-like atoms



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

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



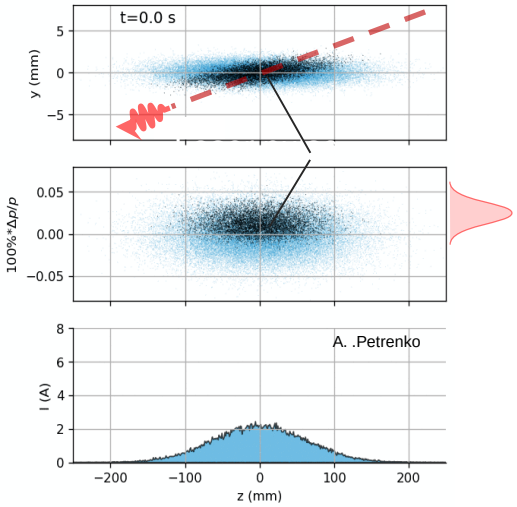


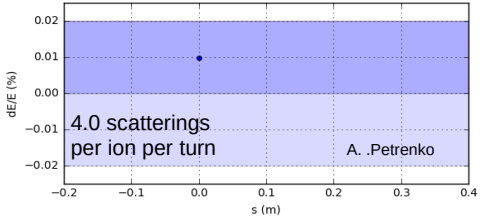
→ Circular polarization ≈ 99%

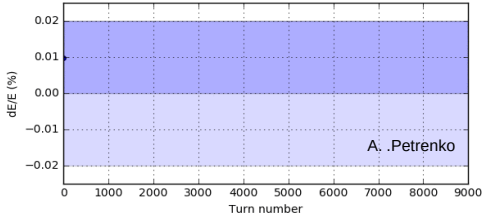
For more details see presentations at our recent, November 2021, Gamma Factory workshop: https://indico.cern.ch/event/1076086/

Laser cooling of high-energy hadronic beams

Beam cooling:
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.

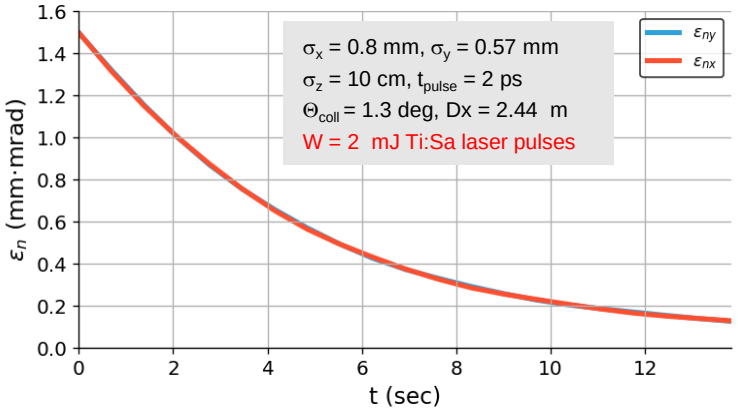






Opens a possibility of forming at CERN **high-energy** hadronic bunches of the required longitudinal and transverse emittances and population, (bunch merge + cooling) within a seconds-long time scale.

Prog.Part.Nucl.Phys. 114 (2020) 103792



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

Gamma Factory (complementary) path to HL-LHC:

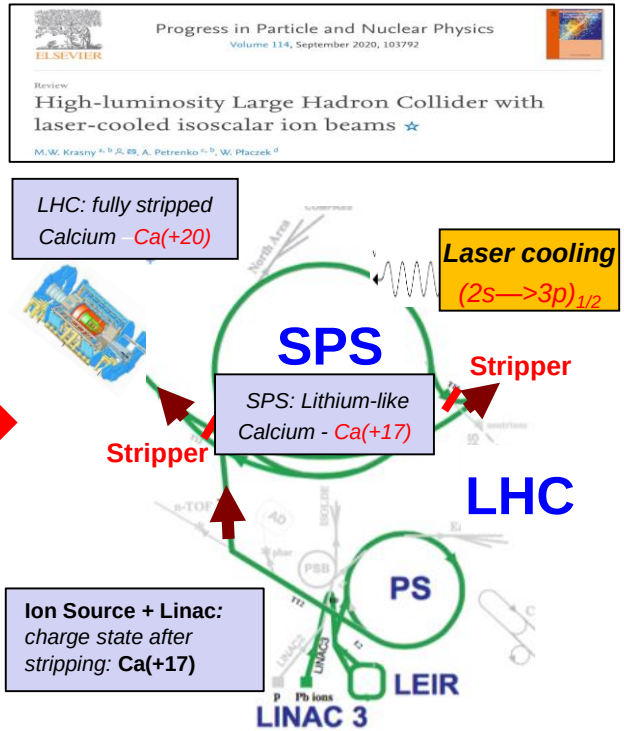
Studies of the implementation scheme with laser-cooled isoscalar Ca beams

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

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)

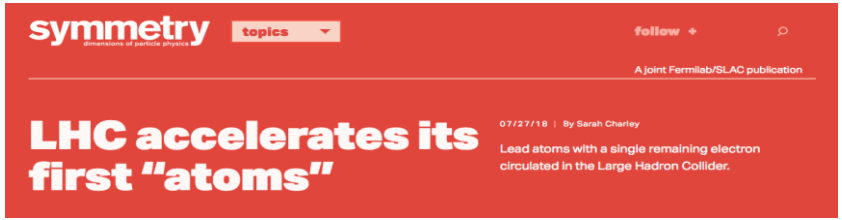
The merits of cold isoscalar beams

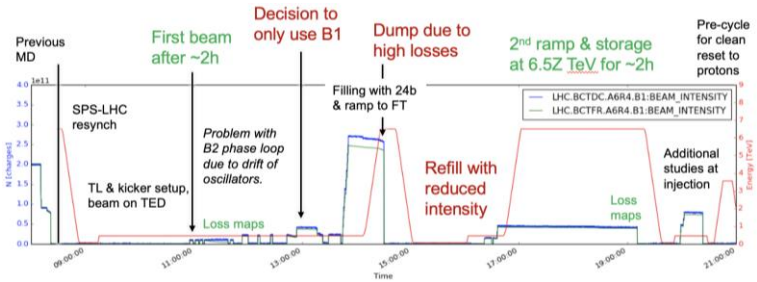
- *higher precision in measuring SM parameters (M_W, $\sin^2\theta_W$, …) in CaCa than in pp collisions,*
- *Possible unique access to exclusive Higgs boson production in photon–photon collisions,*
- *Lower pileup background at equivalent nucleon-nucleon (partonic) luminosity,*
- *New research opportunities 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)***

Technical Proof of Principle

Atomic beams in the LHC (Hydrogen-like Lead)





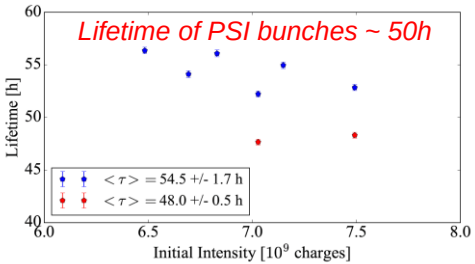
CERN-ACC-NOTE-2019-0012

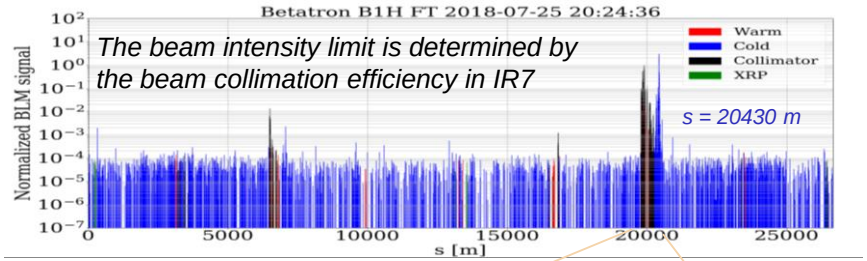
8 May 2019

Michaela.Schaumann@cern.ch

MD3284: Partially Stripped Ions in the LHC

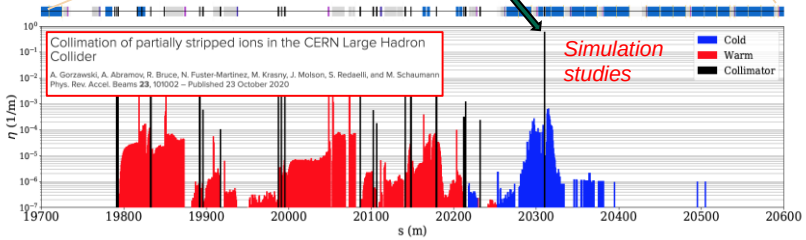
M. Schaumann, A. Abramov, R. Alemany Fernandez, T. Argyropoulos, H. Bartosik, N. Biancacci, T. Bohl, C. Bracco, R. Bruce, S. Burger, K. Cornelis, N. Fuster Martinez, B. Goddard, A. Gorzawski, R. Giachino, G.H. Hemelsoet, S. Hirlaender, M. Jebramcik, J.M. Jowett, V. Kain, M.W. Krasny, J. Molson, G. Papotti, M. Solfaroli Camillocci, H. Timko, D. Valuch, F. Velotti, J. Wenninger
CERN, CH-1211 Geneva 23





Mitigation strategies:

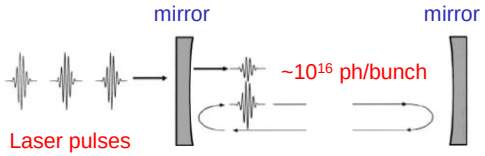
1. *Dispersion suppressor collimator (TCLD)*
2. *Crystal collimation*
3. *Laser collimation*

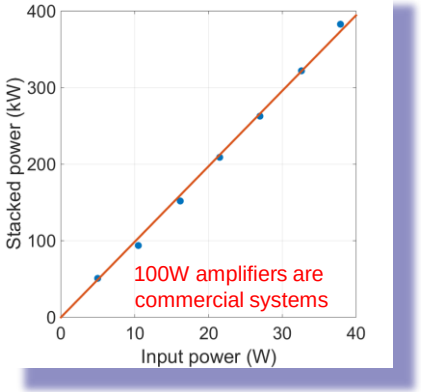


A dedicated LHC MD with crystal collimation of the PSI (H-like Pb) beam will be the next step…

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

Fabry-Pérot resonator

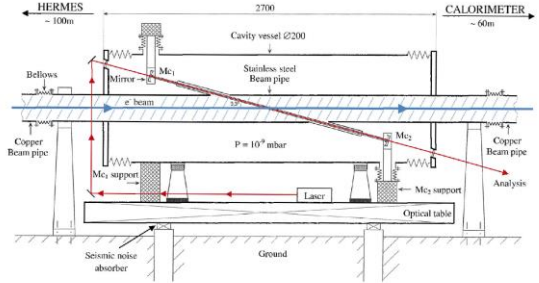




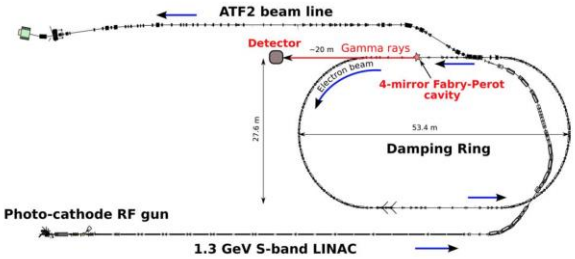
Amoudry L. et al., Applied Optics 59(2020)116

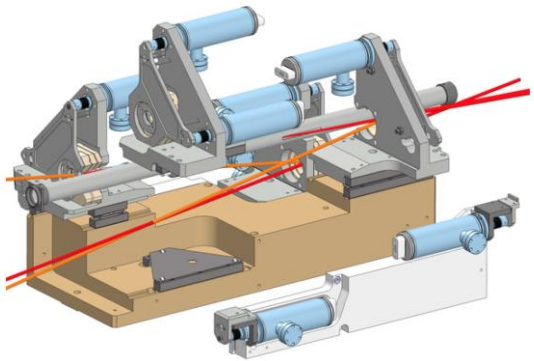
GF requirement:
< 5mJ pulses @ 40MHz,
(200kW photon beam)

HERA storage ring



KEK – ATF ring



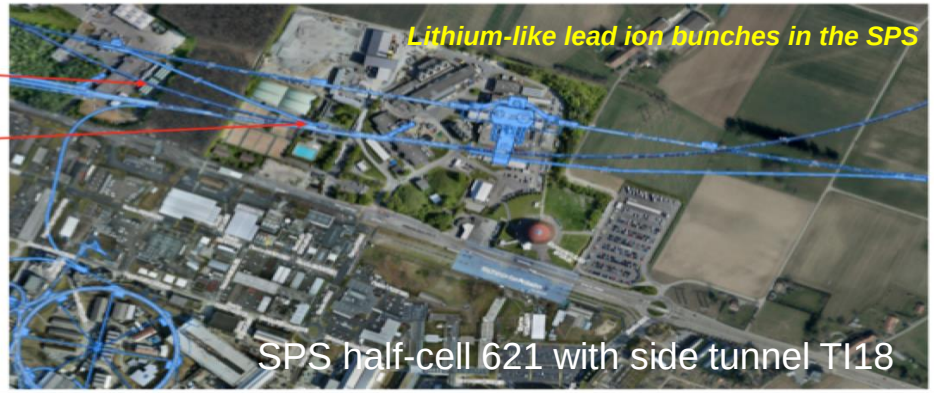


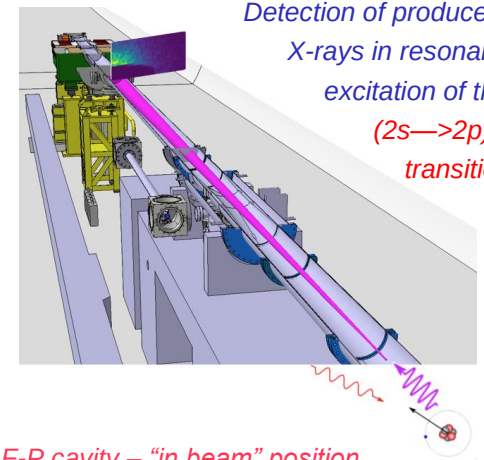
Towards the first integration of the FP resonator in the hadron storage ring →

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

SPS

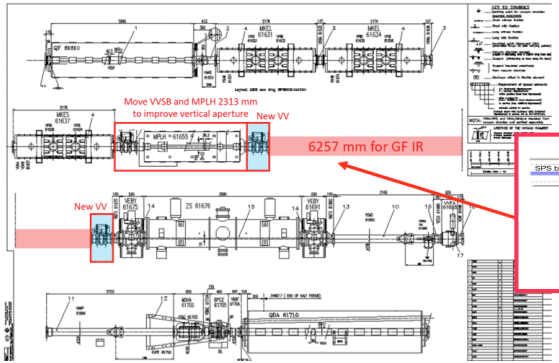
PoP location



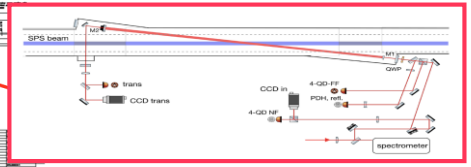


Detection of produced X-rays in resonant excitation of the $(2s \rightarrow 2p)_{1/2}$ transition

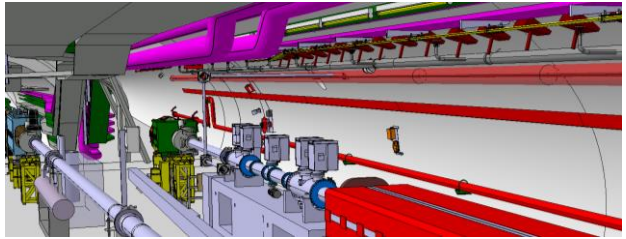
LSS6 zone



F-P cavity

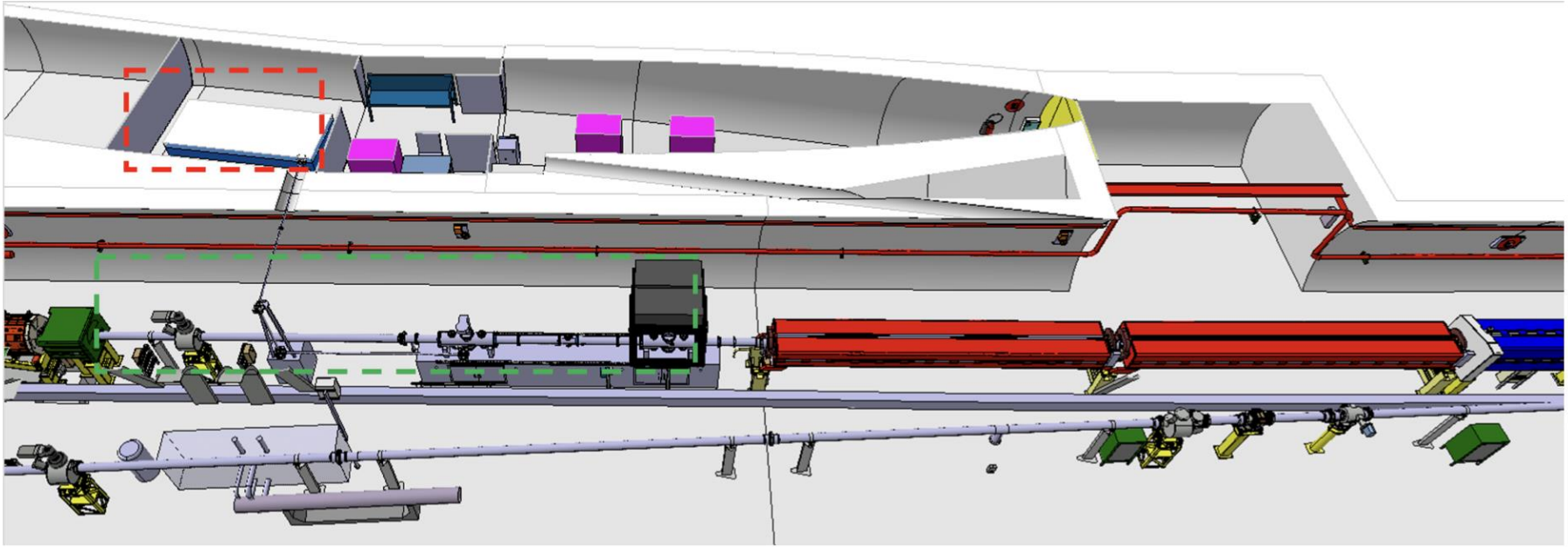


F-P cavity – "in beam" position



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

PoP experiment – location of laser room



The purpose of the GF SPS PoP experiment

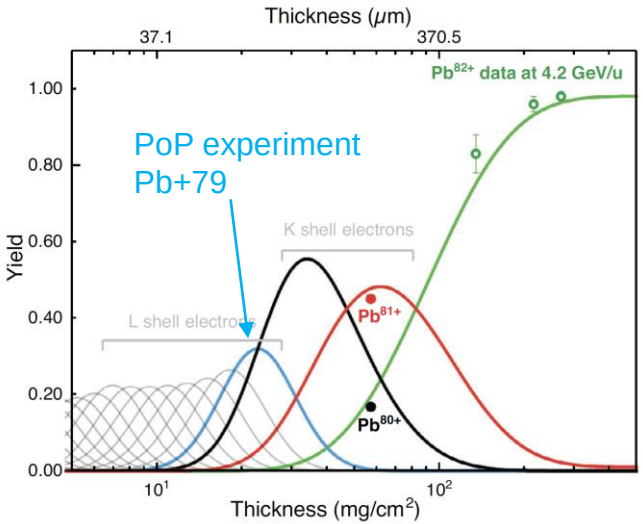
1. Demonstrate that an adequate laser system (5mJ@40MHz) can be (remotely) operated in the high radiation field of the SPS.
2. Demonstrate that very high rates of photons are produced : almost all PSI's are excited in single collision of the PSI bunch with the laser pulse
3. Demonstrate stable and repeatable operation
4. Confront data and simulations
5. Demonstrate ion beam cooling: longitudinal and then transverse
6. Atomic physics measurements

Estimated cost of the experiment 2.5 MCHF

Very recent technical developments:

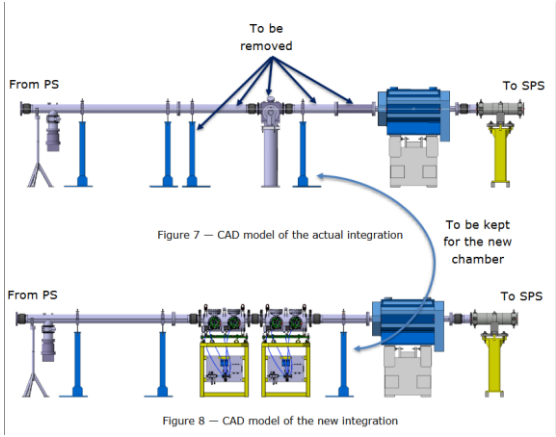
new TT2 stripper system

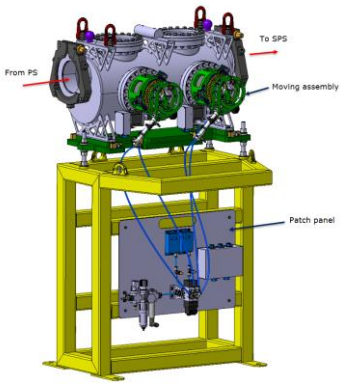
Stripping of Pb+54 ions in the TT2 PS-→ SPS transfer line



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)

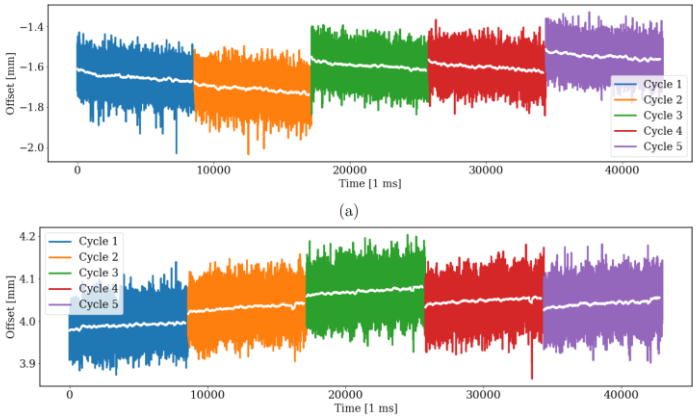
The two tanks of the new stripper system have been installed during YETS 2021-2022. The first of them is already one is equipped with two stripper foil mechanisms. The second will house additional two foil mechanism (installation in YETS 2022-20023)

Very recent technical developments: Beam orbit and beam momentum stability tests at the SPS

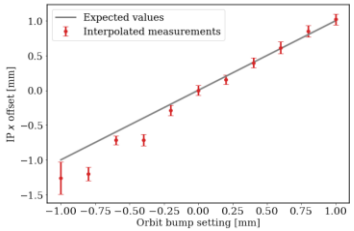
CERN-ACC-NOTE-2022-0014
CERN-PBC-Notes-2022-006
22 April 2022
rebecca.louise.ramjiawan@cern.ch

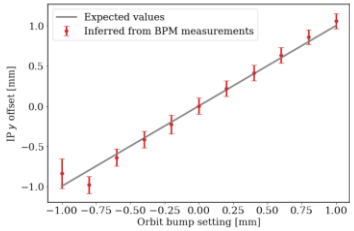
SPS MD5044 : machine stability characterisation of Gamma Factory SPS Proof-of-Principle Experiment

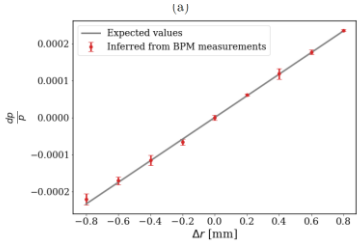
R. Ramjiawan, H. Bartosik, Y. Dutheil, W. Hofle, M. W. Krasny, A. Martens, Y. Papaphilippou, A. Petrenko, F. M. Velotti
CERN, CH-1211 Geneva, Switzerland



Control of the beam position and momentum in the PoP IP







Main result of the beam tests:

The beam position at the IP and beam momentum can be controlled with the requisite precision. The measured beam trajectory followed closely the predictions from simulations.

Very recent technical developments:

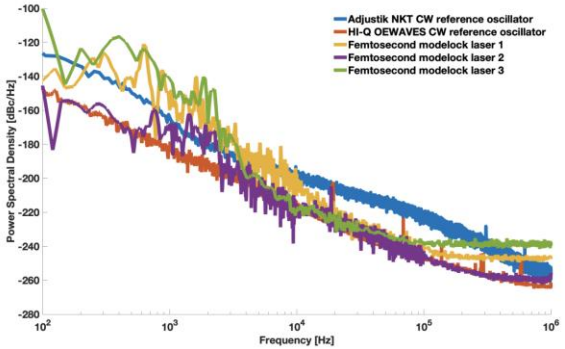
final design of the GF optical system

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

Aurélien Martens,* Kevin Cassou, Ronic Chiche, Kevin Dupraz, Daniele Nutarelli, Yann Peinaud, and Fabian Zomer
Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France

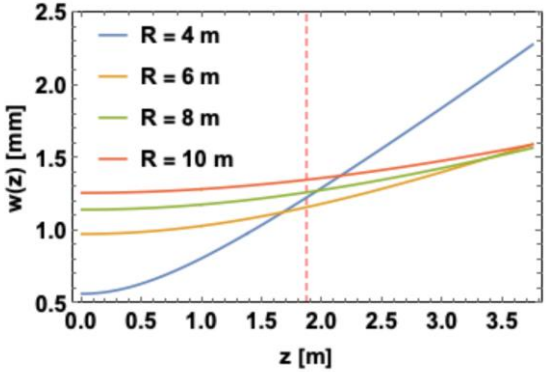
Yann Dutheil, Brennan Goddard, Mieczyslaw Witold Krasny, Thibaut Lefevre, and Francesco Maria Velotti
CERN, CH-1211, Geneva, Switzerland
(Dated: April 28, 2022) … submitted last week to Phys.Rev.

Choice of the laser oscillator – phase noise measurements

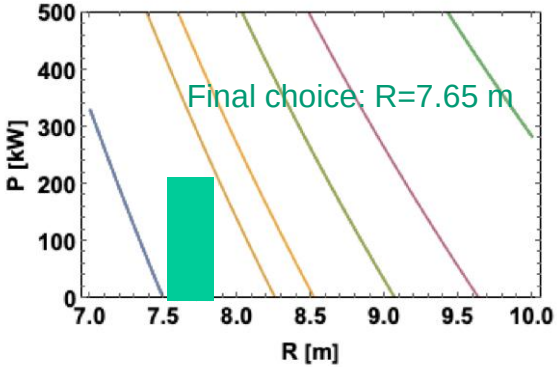


Laser 2 fulfils the requisite phase-stability criteria for the 40 Mhz, 10000 finesse FP cavity

Choice of the radius of the hemispherical mirrors



Dumping of non-gaussian modes in the FP cavity



GF-PoP experiment status

September 25, 2019

Gamma Factory

Proof-of-Principle Experiment

LETTER OF INTENT

CERN-SPSC-2019-031 / SPSC-I-253
25/09/2019

Gamma Factory Study Group

Contact persons:

M. W. Krasny, krasny@lpnhe.in2p3.fr, krasny@mail.cern.ch – **Gamma Factory team leader**

A. Martens, martens@lal.in2p3.fr – **Gamma Factory PoP experiment spokesperson**

Y. Dutheil, yann.dutheil@cern.ch – **Gamma Factory PoP study – CERN coordinator**

As received from the SPSC referees on Oct. 20th 2020

« The SPSC recognizes the Gamma Factory's potential to create a novel research tool, which may open the prospects for new research opportunities in a broad domain of basic and applied science at the LHC. »

We have recently finalised the final specification of the Laser and FP system for the GF-PoP experiment, made the requisite SPS beam-stability tests and finalised the technical specification of the stripper

In parallel, we are finalizing a detailed estimation of the CERN (Accelerator Sector), and participating labs, resources needed to construct the PoP experiment in the SPS tunnel with the plan to submit an EU funding request

We are in the process of signing the GF-PoP-MoU by collaborating institutes

Full experiment specifications have been finalised.
Target Installation time : LS3 ***-- what we (only) need is to find 2.5 MCHF to cover the cost of the experiment and to assure the requisite CERN FTE resources (experiment infrastructure)…***

Opening new possibilities

GF papers published since JENAS EoI submission (2020)

Probing Axion-Like-Particles at the CERN Gamma Factory

*Reuven Balkin, Mieczyslaw W. Krasny, Teng Ma, Benjamin R. Safdi, and Yotam Soreq**

Ann. Phys. (Berlin) **2022**, *534*, 2100222

Delta Baryon Photoproduction with Twisted Photons

Andrei Afanasev and Carl E. Carlson*

Ann. Phys. (Berlin) **2022**, *534*, 2100228

Double-Twisted Spectroscopy with Delocalized Atoms

Igor P. Ivanov

Ann. Phys. (Berlin) **2022**, *534*, 2100128

Vacuum Birefringence at the Gamma Factory

Felix Karbstein

Ann. Phys. (Berlin) **2022**, *534*, 2100137

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*

Ann. Phys. (Berlin) **2022**, *534*, 2100245

Access to the Kaon Radius with Kaonic Atoms

*Niklas Michel and Natalia S. Oreshkina**

Ann. Phys. (Berlin) **2022**, *534*, 2100150

Possible Polarization Measurements in Elastic Scattering at the Gamma Factory Utilizing a 2D Sensitive Strip Detector as Dedicated Compton Polarimeter

Wilko Middents, Günter Weber, Uwe Spillmann, Thomas Krings, Marco Vockert, Andrey Volotka, Andrey Surzhykov, and Thomas Stöhlker*

Ann. Phys. (Berlin) **2022**, *534*, 2100285

Radioactive Ion Beam Production at the Gamma Factory

Dragos Nichita, Dimiter L. Balabanski, Paul Constantin, Mieczyslaw W. Krasny, and Wieslaw Płaczek*

Ann. Phys. (Berlin) **2022**, *534*, 2100207

Electric Dipole Polarizability of Neutron Rich Nuclei

Jorge Piekarewicz

Ann. Phys. (Berlin) **2022**, *534*, 2100185

Resonant Scattering of Plane-Wave and Twisted Photons at the Gamma Factory

Valeriy G. Serbo, Andrey Surzhykov, and Andrey Volotka*

Ann. Phys. (Berlin) **2022**, *534*, 2100199

Local Lorentz Invariance Tests for Photons and Hadrons at the Gamma Factory

B. Wojtsekhowski and Dmitry Budker*

Ann. Phys. (Berlin) **2022**, *534*, 2100141

Optical Excitation of Ultra-Relativistic Partially Stripped Ions

*Jacek Bieroń, Mieczyslaw Witold Krasny, Wiesław Płaczek, and Szymon Pustelny**

Ann. Phys. (Berlin) **2022**, *534*, 2100250

Expanding Nuclear Physics Horizons with the Gamma Factory

Dmitry Budker, Julian C. Berengut, Victor V. Flambaum, Mikhail Gorchtein, Junlan Jin, Felix Karbstein, Mieczyslaw Witold Krasny, Yuri A. Litvinov, Adriana Pálffy, Vladimir Pascalutsa, Alexey Petrenko, Andrey Surzhykov, Peter G. Thirolf, Marc Vanderhaeghen, Hans A. Weidenmüller, and Vladimir Zelevinsky*

Ann. Phys. (Berlin) **2022**, *534*, 2100284

Parity-Violation Studies with Partially Stripped Ions

Jan Richter, Anna V. Maiorova, Anna V. Viatkina, Dmitry Budker, and Andrey Surzhykov**

Ann. Phys. (Berlin) **2022**, *534*, 2100561

Polarization of Photons Scattered by Ultra-Relativistic Ion Beams

Andrey Volotka, Dmitrii Samoilenko, Stephan Fritzsche, Valeriy G. Serbo, and Andrey Surzhykov*

Ann. Phys. (Berlin) **2022**, *534*, 2100252

ELSEVIER

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

Review

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

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

Gamma factory searches for extremely weakly interacting particles

Sreemanti Chakraborti, Jonathan L. Feng, James K. Koga, and Mauro Valli
Phys. Rev. D **104**, 055023 – Published 21 September 2021

Collimation of partially stripped ions in the CERN Large Hadron Collider

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

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,…);*
- ***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,…);*
- ***atomic physics*** *(APV in highly charged atoms, electronic and muonic atoms, pionic atoms);*
- ***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…);*
- ***atomic physics*** *(highly charged atoms, electronic and muonic atoms, pionic and kaonic atoms);*
- ***applied physics*** *(accelerator driven energy sources, fusion research, medical isotopes' and isomers' production).*

Visions for the future requirements for physics research

Mieczyslaw Witold Krasny

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

https://indico.cern.ch/event/1133593/timetable/?print=1&view=standard

Four examples

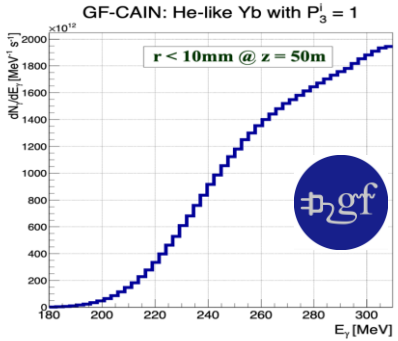
1. *particle physics*
2. *astrophysics*
3. *atomic physics*
4. *nuclear/applied physics*

Particle Physics: GF low-emittance, high-intensity muon source

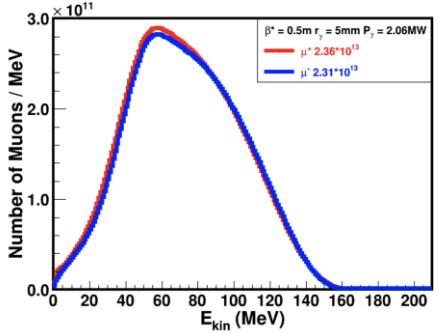
Existing and future muon sources

Laboratory/ Beam line	Energy/ Power	Present Surface μ^+ rate (Hz)	Future estimated μ^+/μ^- rate (Hz)
PSI (CH)	(590 MeV, 1.3 MW, DC)		
LEMS	"	$4 \cdot 10^8$	
$\pi E5$	"	$1.6 \cdot 10^8$	
HiMB	(590 MeV, 1 MW, DC)		$4 \cdot 10^{10}(\mu^+)$
J-PARC (JP)	(3 GeV, 1 MW, Pulsed) currently 210 KW		
MUSE D-line	"	$3 \cdot 10^7$	
MUSE U-line	"		$2 \cdot 10^8(\mu^+)$ (2012)
COMET	(8 GeV, 56 kW, Pulsed)		$10^{11}(\mu^-)$ (2019/20)
PRIME/PRISM	(8 GeV, 300 kW, Pulsed)		$10^{11-12}(\mu^-)$ (> 2020)
FNAL (USA)			
Mu2e	(8 GeV, 25 kW, Pulsed)		$5 \cdot 10^{10}(\mu^-)$ (2019/20)
Project X Mu2e	(3 GeV, 750 kW, Pulsed)		$2 \cdot 10^{12}(\mu^-)$ (> 2022)
TRIUMF (CA)	(500 MeV, 75 kW, DC)		
M20	"	$2 \cdot 10^6$	
KEK (JP)	(500 MeV, 2.5 kW, Pulsed)		
Dai Omega	"	$4 \cdot 10^5$	
RAL -ISIS (UK)	(800 MeV, 160 kW, Pulsed)		
RIKEN-RAL		$1.5 \cdot 10^6$	
RCNP Osaka Univ. (JP)	(400 MeV, 400 W, Pulsed)		
MUSIC	currently max 4W		$10^8(\mu^+)$ (2012) means > 10^{11} per MW
DUBNA (RU)	(660 MeV, 1.65 kW, Pulsed)		
Phasatron Ch:I-III		$3 \cdot 10^4$	

Gamma-Factory muon source



A.Apyan, M.W.Krasny, W. Placzek, to be published

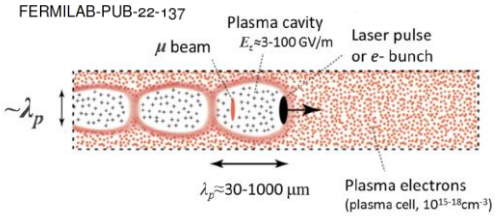


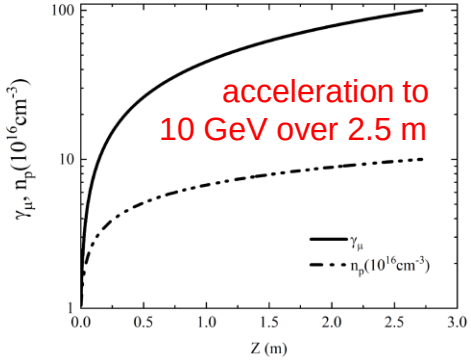
On Possibility of Low-emittance High-energy Muon Source Based on Plasma Wakefield Acceleration

Vladimir Shiltsev [a,1]

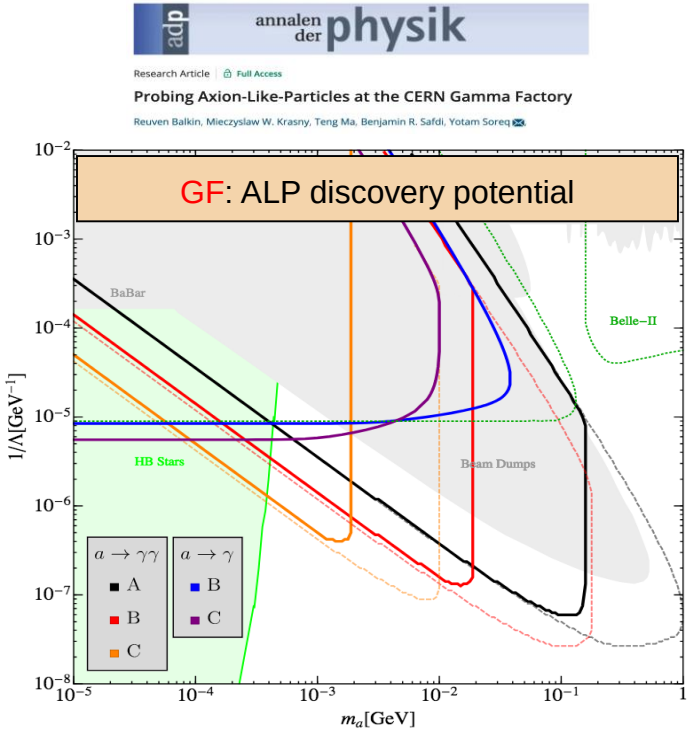
[a] Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

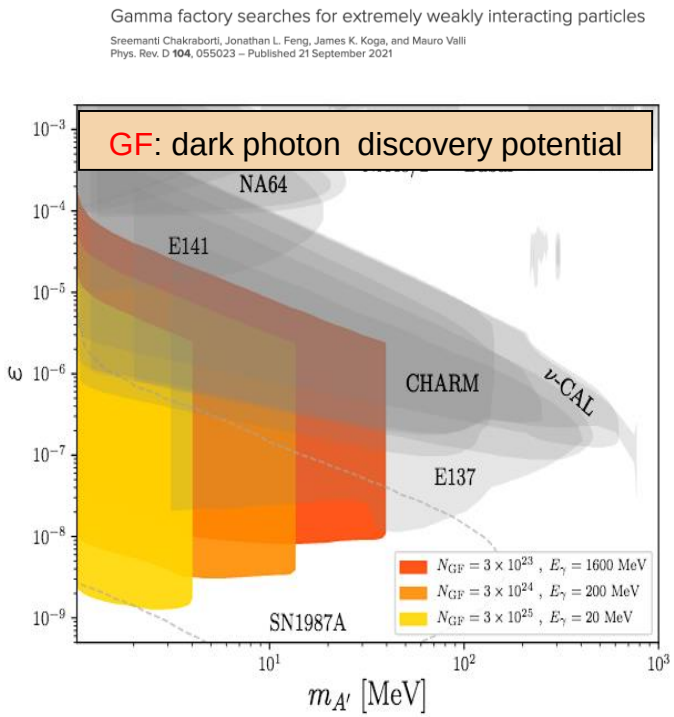
FERMILAB-PUB-22-137





Astrophysics: Dark matter searches

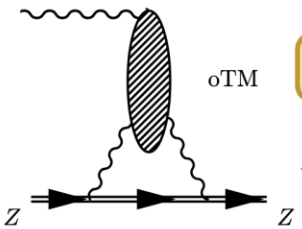




Significant discovery potential for Dark Matter particles with GF photon beams!

Atomic physics: muonium

2) "Low energy" TM production @ the GAMMA Factory



CROSS SECTION FOR oTM PRODUCTION FOR E>>m$_\mu$:

$$\sigma_{\gamma Z} = Z^2 \times 2.4 \cdot 10^{-39} \mathrm{cm}^2$$

Ginzburg, et al., Phys. Rev. C58, 3565 (1998)

Dimuons production in G4 now extended down to the muon pair production threshold on request of GF design group

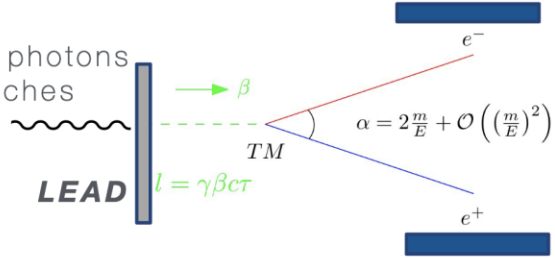
EPJ Web of Conferences **245**, 02009 (2020)

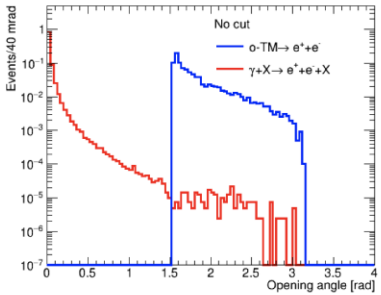
Production & detection of **TM** at GAMMA FACTORY:

See GF-TALK of Witek K.

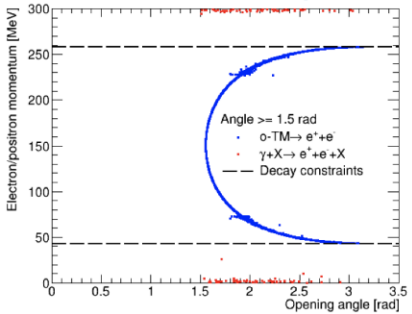
TRACKERS& DETECTORS

300 MeV 10^9 photons
n 500 ps bunches
at 20 MHz





10^{11} photons



Estimated **RATE** OF ~***O*(10$^{4\text{-}5}$) TM (1^{3}S$_1$)/day** and ~***O*(10$^{2\text{-}3}$) TM(2^{3}S$_1$)/day**

Nuclear/applied physics: GF photon-beam-driven energy source

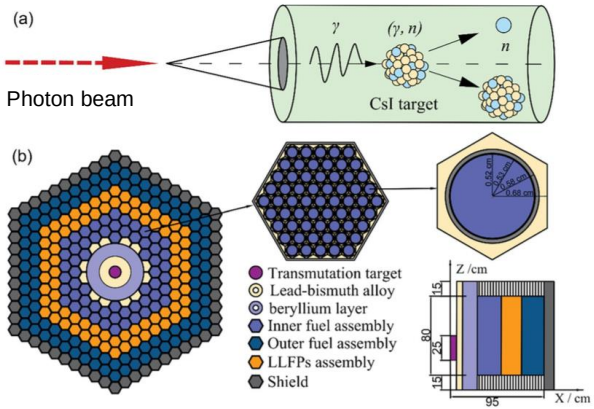
Nature:

Article | Open Access | Published: 09 February 2022

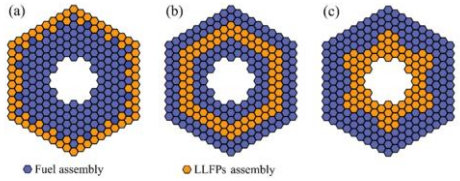
Transmutation of long-lived fission products in an advanced nuclear energy system

X. Y. Sun, W. Luo, H. Y. Lan, Y. M. Song, Q. Y. Gao, Z. C. Zhu, J. G. Chen & X. Z. Cai

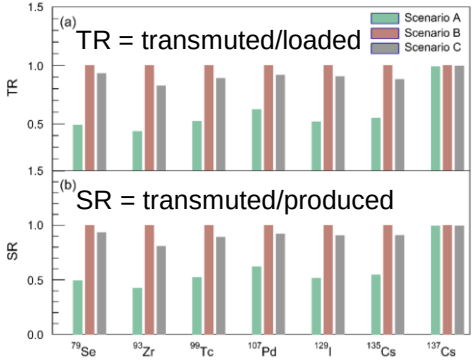
Scientific Reports **12**. Article number: 2240 (2022) | Cite this article



Main parameters	Data used in this study
Type of fuel	UO_2
Thermal power (MWt)	500
Electric power (MWe)	200
Core height (mm)	1100
Core diameter (mm)	1050
Number of fuel assemblies	60/102 (inner/outer)
Number of pins in each of fuel assembly	61
Pin diameter (mm)	5.8
Pellet diameter (mm)	5.2
^{235}U enrichment (%)	23.3
Number of LLFPs assemblies	78
Number of pins in each of LLFPs assembly	61
Number of shield assemblies	60



Physical quantity	Value
Effective multiplication factor (k_{eff})	0.979
Reactivity (ρ)	−0.019
Effective multiplication factor for prompt neutrons (k_p)	0.977
Eigenvalue (α)	−0.003
Effective delayed neutron fraction (β_{eff})	0.007
Neutron generation time (Λ) (μs)	0.523
Neutron worth of PNS (φ)	1.319
Sub-critical effective multiplication factor (k_s)	0.984



Can we produce rather than buy the plug-power necessary for the next generation of high-energy, high-current new accelerators locally, in situ, in our HEP research centers?

Conclusions

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

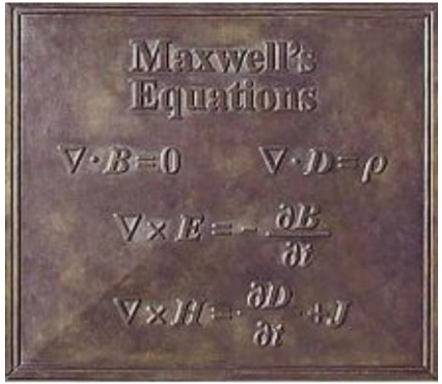
- *The **next** CERN **high-energy frontier** project (if ever constructed) may take **long time** to be approved, built and become operational, … unlikely before 2050-ties*

- *The **present** LHC **research programme** will certainly reach **earlier** (late 2030-ties?) its discovery **saturation** ($L_{int} \sim 0.5L_{goal}$) -- little physics gain by a simple extending its pp/pA/AA running time*

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

The Gamma Factory** research programme could fulfil such a role. It can exploit **the existing world unique opportunities** offered by the CERN accelerator complex and CERN's scientific infrastructure **(not available elsewhere)** to conduct new, diverse, and vibrant research in particle, nuclear, atomic, fundamental, applied physics, and astrophysics **with novel research tools

Concepts and tools



"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

A vision of the LHC operation mode in in the post-HL-LHC phase