The Gamma Factory project for CERN

New research opportunities

LPNHE, 18.07.2022

Kyaik-Tiyo, Myanmar(Burma)

Mieczyslaw Witold Krasny, Gamma Factory group leader

LPNHE and CERN, BE-ABP

Instead od introduction:

A lesson from the past – the EIC project path

(project initiated at LPNHE and developed in the 90-ties)

The fist steps towards the EIC project (1994-1998):

Hamburg, 11.07.1996.

Memorandum

To: B. Wiik, A. Wagner, DESY

From: M.W. Krasny, LPNHE - Paris

- to build an "A-tunable" ion injector system and collide at HERA electrons with nuclei. The ePb collisions would have the world record center-of-mass energy (if realized before RHIC becomes operational) and, apart from several merits which I tried to explain in my summary talk of the HERA workshop, would provide the largest effective luminosity for photon-photon interactions in the intermediate W range. It is worth noticing that several physicists became interested in the nuclear option for HERA after introducing to the program of the Paris HERA workshop, back in 1995, a parallel session on nuclei and that this physics received some attention during the DESY workshop this year.
- to design a dedicated experiment for HERA for the "low Q^2" ($Q^2 \leq 100\ GeV^2$) domain optimized both for the ep and eA interactions. Let me note, as an example, that neither the upgraded H1 experiment nor the ZEUS experiment will be able to measure structure functions, in particular σ_L/σ_T, with the precision comparable to that of SLAC experiments of 70-ties, despite the energies and angles of the scattered electrons are, in this Q^2 range, similar. Such a detector would have to measure the energies and angles of particles produced over the large domain of η, covering in particular the proton (nucleus) fragmentation region, which still remains a "terra incognita". It should use large β rather than small β optics because the physics advocated here requires modest luminosities and high detection quality of particles emitted at small angles. I failed, back in 1991, to persuade the spokesman of the HERMES experiment that the first component of such an experiment could be the HERMES electron spectrometer used in the colliding beam mode.

DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY

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

Der Vorsitzende des Direktoriums

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

August 19, 1996

Dear Dr. Krasny,

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

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

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

With my best wishes

Björn H. Wiik

Björn H. Wiik

Professor Bjorn Wiik, Director
DESY
Notkestrasse 85
D-22607 Hamburg
Germany

1997 – a support letter from the QCD "fathers"

Dear Bjorn:

We write to you concerning the future physics program at HERA. The two-volume report "Future Physics at HERA" has given a remarkably thorough presentation of the possibilities that lie ahead. In surveying that report we have been struck by the fact that one particular proposal, having nuclear beams in HERA, builds on the most impressive results of the present HERA program and extends the range and scope of these experiments in a very significant way...

...We urge you to give the most careful consideration to the electron-ion option, and do hope that it may become a reality.

With our best regards,

James Bjorken	Stanley Brodsky	Alfred Mueller	Larry McLerran
SLAC	SLAC	Columbia Univ.	Theoretical

1999 – the end of a dream of the European QCD Facility at DESY

- *B. Wiik's unfortunate accident --*
  TESLA project loses its momentum and is finally abandoned

- *GSI works towards a local FAIR PROJECT (low energy),*
  ELFE (e.g French) groups join the CEBAF program

- *The electron-ion concept moves to US (thanks to a strong commitment*
  to this project by Peter Paul – the BNL director)

  A consequence: closing the HEP accelerator program at DESY couple of
  years later

2001: Peter Paul – BNL director--
brings the eRHIC/EIC project to BNL

Date: Tue, 11 Sep 2001 16:41:16 -0400
From: "Paul, Peter" <ppaul@bnl.gov>
To: "'krasny@lpnhep.in2p3.fr'" <krasny@lpnhep.in2p3.fr>
Subject: eRHIC

[The following text is in the "iso-8859-1" character set.]
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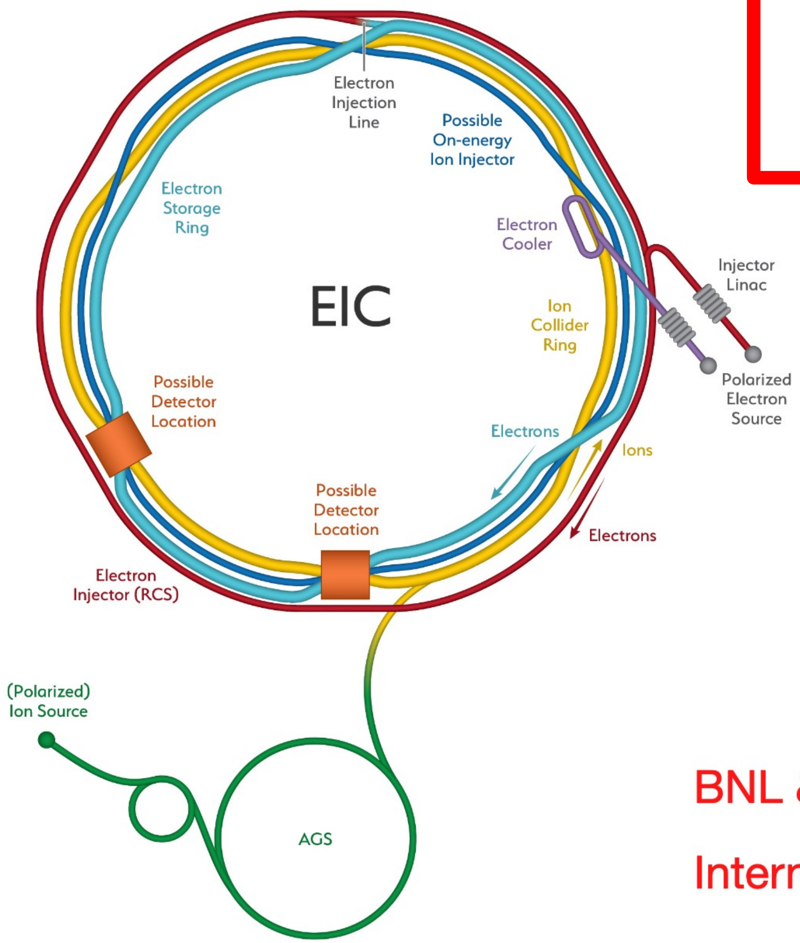
[characters may be displayed incorrectly.]

Dear Witek: thanks for your letter of Sept. 6 and the slide copies that are included.
I thank you for all the help that you have provided so far in regards to eRHIC.
The project is indeed moving forward politically, although it is behind at least one very large project in nuclear physics. A group is now working to finalize a really good white paper on it. This is being done mostly by people from BNL and BATES-MIT. Bernd Surrow from DESY-Zeus will be joining BNL in October and will add strength to our team. Taking you up on our offer to help, I would like to ask you to review the paper when we have it completed, especially where we write about the detectors. However, this may take at least another month.
We are all very busy here at this time since the RHIC spin program is starting. After that the effort on the White paper will increase again. I will stay in touch with you as you move to CERN. Please give me your new e-mail address there.
Best wishes,
Peter P.

→EIC had to wait until the FRIB construction was finalised…

U.S.-based Electron-Ion Collider



EIC will be constructed at Brookhaven National Laboratory

EIC is well on its path towards realization (CD-1 in June 2021)

Now in the detector design and collaboration formation phase

Start of operation expected ~2031

BNL & TJNAF (Jefferson Lab) partnership

International facility, large EU involvement

“*Gamma Factory*” proposal (2015) 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

A. Abramov[1], A. Afanasev[37], S.E. Alden[1], R. Alemany Fernandez[2], P.S. Antsiferov[3], A. Apyan[4], G. Arduini[2], D. Balabanski[34], R. Balkin[32], H. Bartosik[2], J. Berengut[5], E.G. Bessonov[6], N. Biancacci[2], J. Bieroń[7], A. Bogacz[8], A. Bosco[1], T. Brydges[36], R. Bruce[2], D. Budker[9,10], M. Bussmann[38], P. Constantin[34], K. Cassou[11], F. Castelli[12], I. Chaikovska[11], C. Curatolo[13], C. Curceanu[35], P. Czodrowski[2], A. Derevianko[14], K. Dupraz[11], Y. Dutheil[2], K. Dzierżęga[7], V. Fedosseev[2], V. Flambaum[25], S. Fritzsche[17], N. Fuster Martinez[2], S.M. Gibson[1], B. Goddard[2], M. Gorshteyn[20], A. Gorzawski[15,2], M.E. Granados[2], R. Hajima[26], T. Hayakawa[26], S. Hirlander[2], J. Jin[33], J.M. Jowett[2], F. Karbstein[39], R. Kersevan[2], M. Kowalska[2], M.W. Krasny[16,2], F. Kroeger[17], D. Kuchler[2], M. Lamont[2], T. Lefevre[2], T. Ma[32], D. Manglunki[2], B. Marsh[2], A. Martens[12], C. Michel[40] S. Miyamoto[31] J. Molson[2], D. Nichita[34], D. Nutarelli[11], L.J. Nevay[1], V. Pascalutsa[28], Y. Papaphilippou[2], A. Petrenko[18,2], V. Petrillo[12], L. Pinard[40] W. Płaczek[7], R.L. Ramjiawan[2], S. Redaelli[2], Y. Peinaud[11], S. Pustelny[7], S. Rochester[19], M. Safronova[29,30], D. Samoilenko[17], M. Sapinski[20], M. Schaumann[2], R. Scrivens[2], L. Serafini[12], V.P. Shevelko[6], Y. Soreq[32], T. Stoehlker[17], A. Surzhykov[21], I. Tolstikhina[6], F. Velotti[2], A. Viatkina[9] A.V. Volotka[17], G. Weber[17], W. Weiqiang[27] D. Winters[20], Y.K. Wu[22], C. Yin-Vallgren[2], M. Zanetti[23,13], F. Zimmermann[2], M.S. Zolotorev[24] and F. Zomer[11]

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

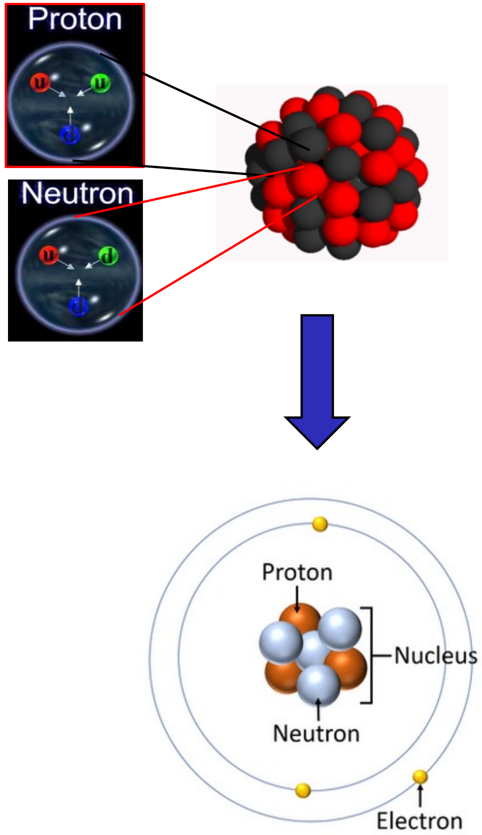
More info on the GF group activities:

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

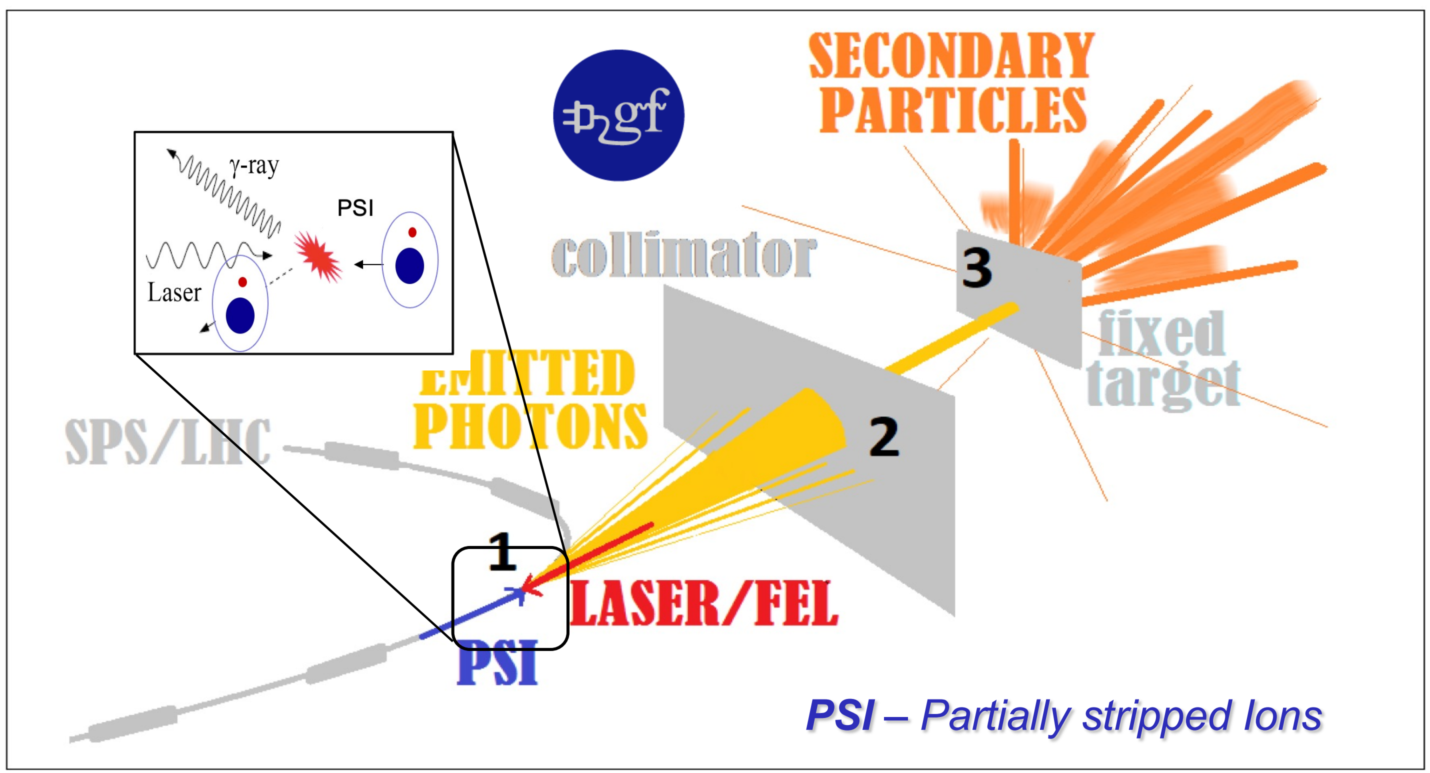
*We acknowledge the crucial role of the CERN **PBC** framework in bringing our accelerator tests, GF-PoP experiment design, software development and physics studies to their present stage!*

Gamma Factory: novel use of <u>**existing**</u> CERN's storage rings

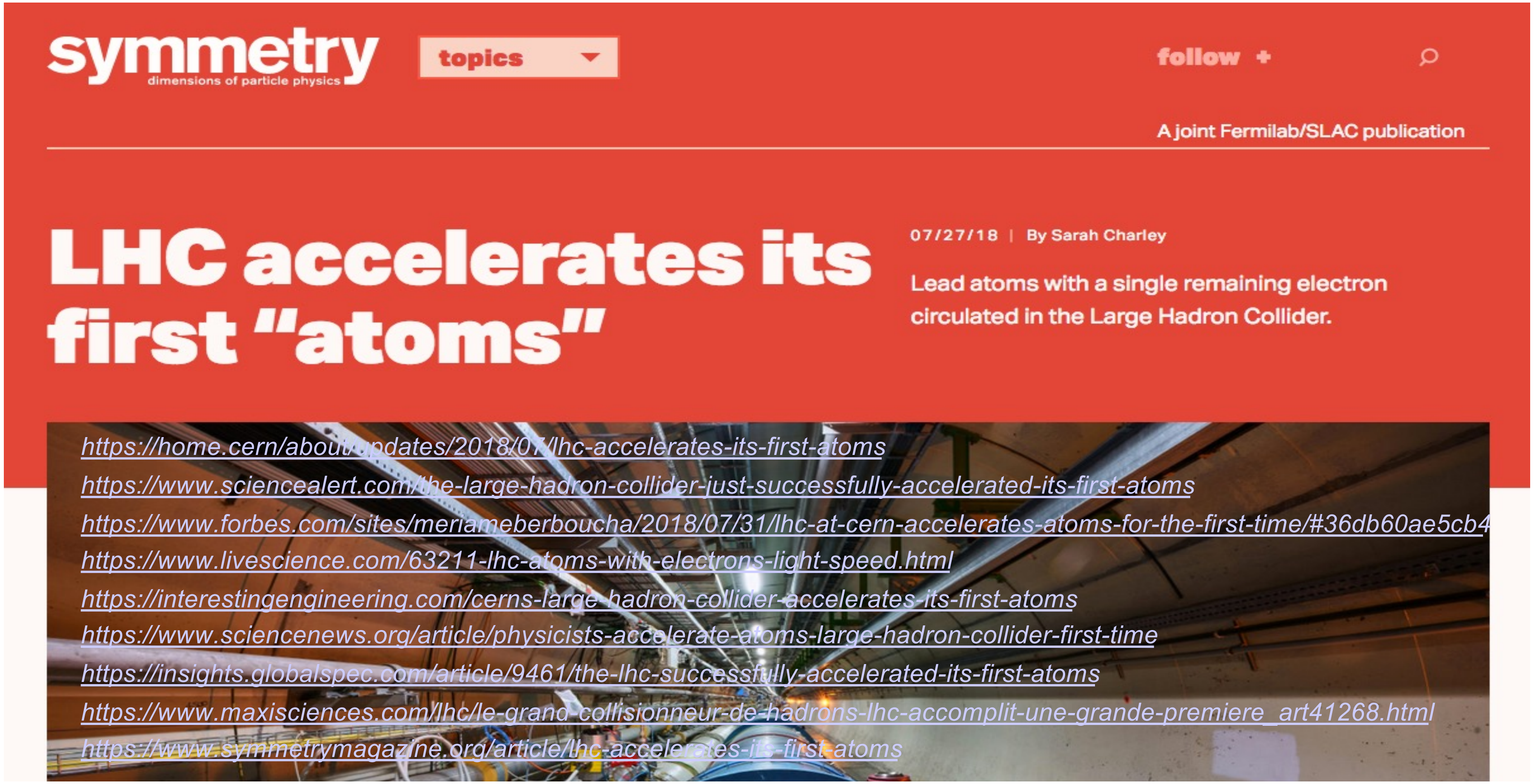
LHC beams



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



July 2018: Birth of Atomic Physics research at CERN



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

Principal Gamma Factory research tools

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

2. *High intensity photon(γ)-beams*

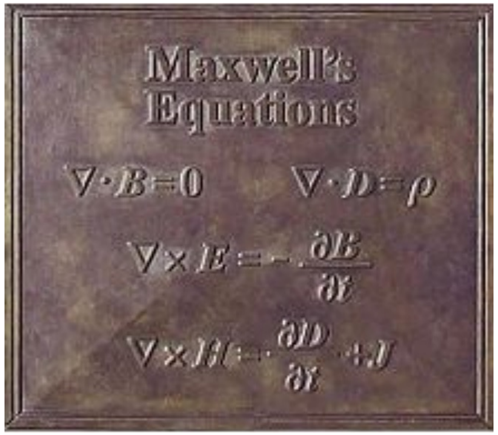
3. *Laser-light based cooling methods of high-energy hadronic beams*

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*

Concepts and tools



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

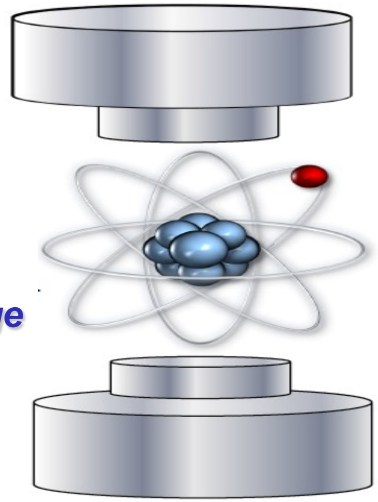
The effect of a concept-driven revolution is to explain old things in new ways.

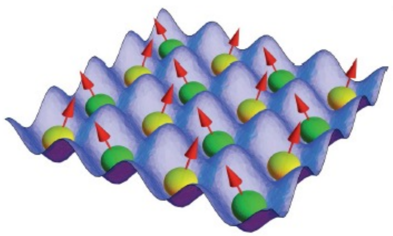
The effect of a tool-driven revolution is to discover new things that have to be explained" - F. Dyson

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

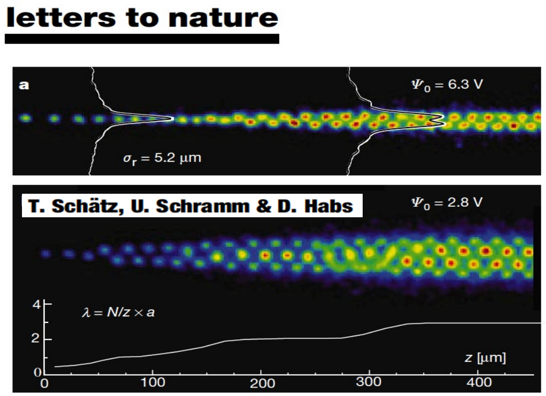
Atomic rest-frame

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

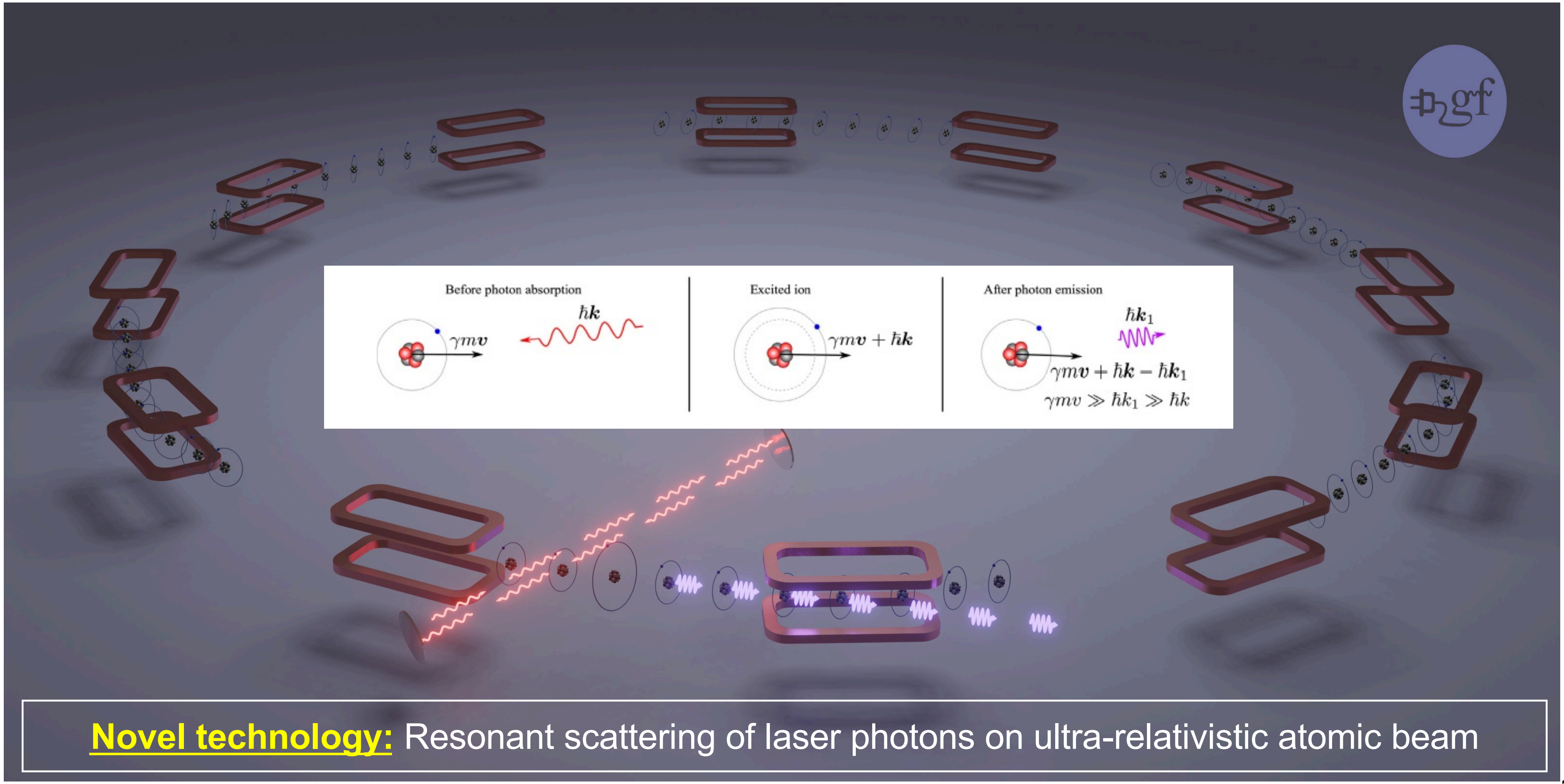
Feature Article | Open Access

Atomic Physics Studies at the Gamma Factory at CERN

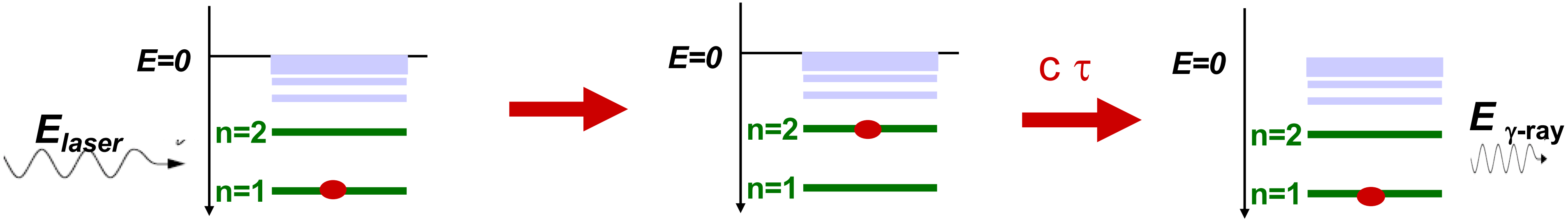
Dmitry Budker, José R. Crespo López-Urrutia, Andrei Derevianko, Victor V. Flambaum, Mieczyslaw Witold Krasny, Alexey Petrenko, Szymon Pustelny, Andrey Surzhykov, Vladimir A. Yerokhin, Max Zolotorev ... See fewer authors

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

2.Gamma Factory γ-source



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 beam

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%***

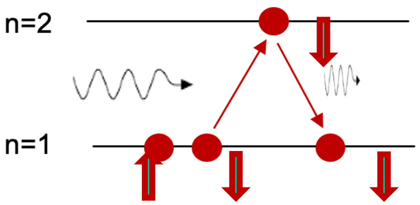
5. Unprecedented plug power efficiency (energy footprint):

- ***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)

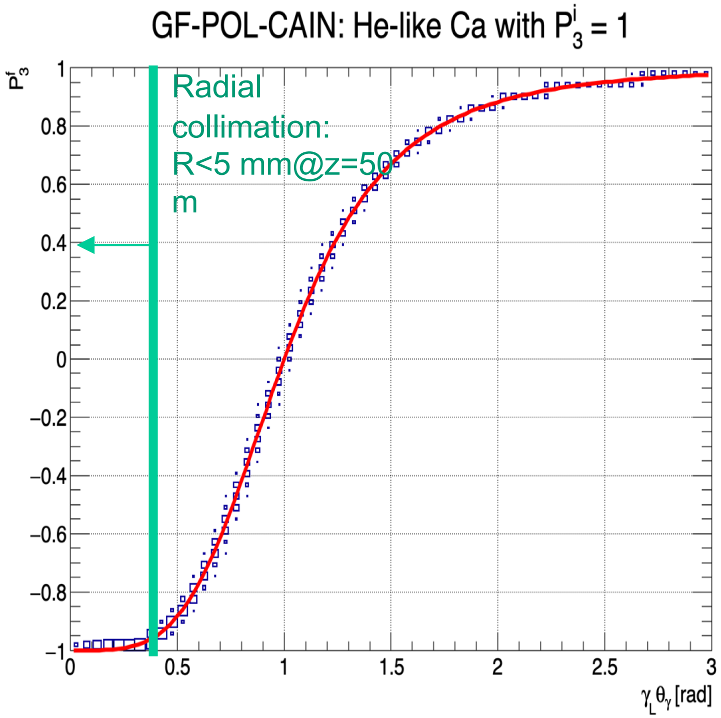
Polarised beams in GF – example: He-like, Calcium beam, Er:glass laser (1522 nm)

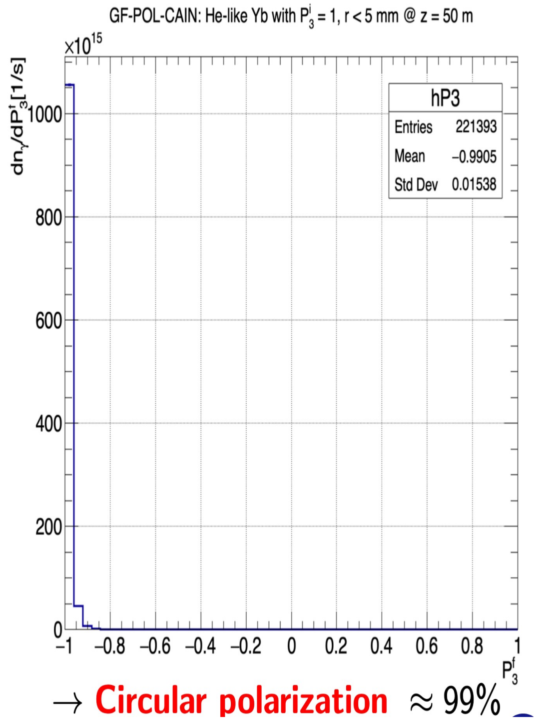
A trick: $1s^2\ ^1S_0 \rightarrow 1s^1 2p^1\ ^1P_1$ transition in He-like atoms



$$nS_0 \to n'P_1 \to nS_0$$

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

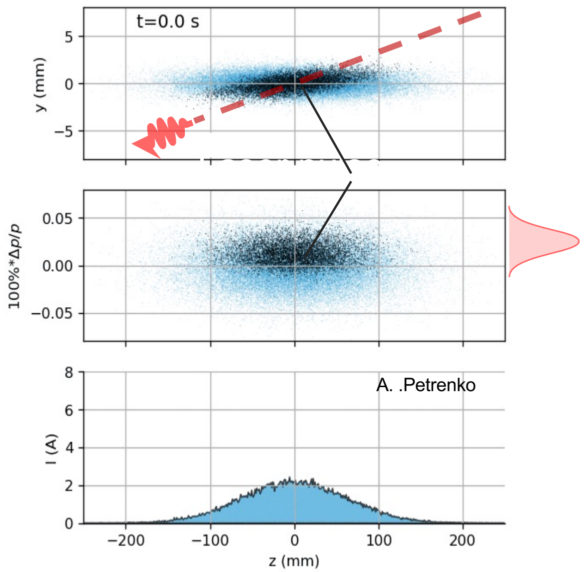


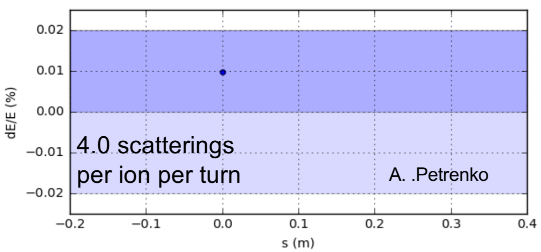


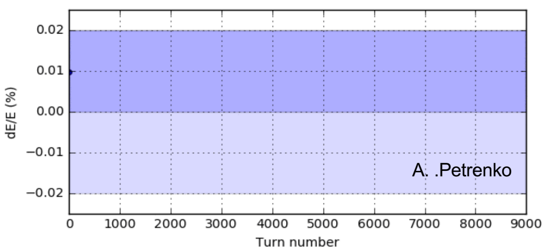
For more details see presentations at our recent, November 2021, Gamma Factory workshop: https://indico.cern.ch/event/1076086/

3. 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.

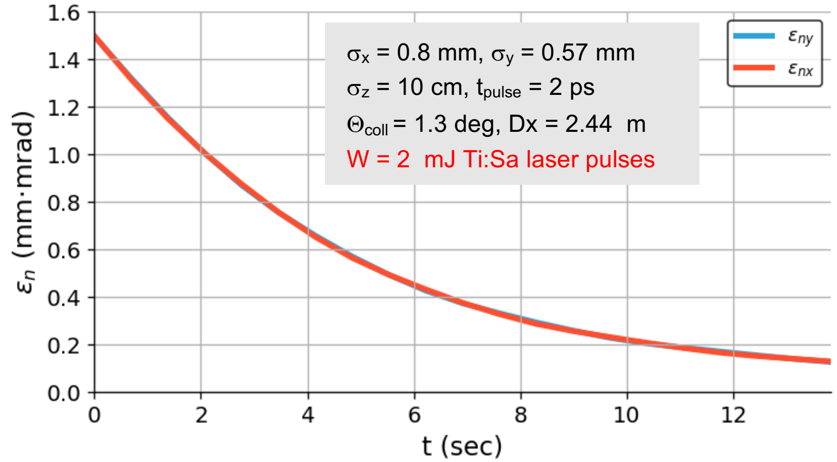






Opens a possibility of forming at CERN **high-energy** hadronic bunches of the required longitudinal and transverse emittances and population, (bunch merge + cooling) within a seconds-long time scale.

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:

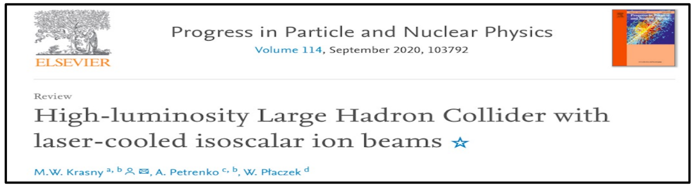
Studies of the implementation scheme with laser-cooled isoscalar Ca beams

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

***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*

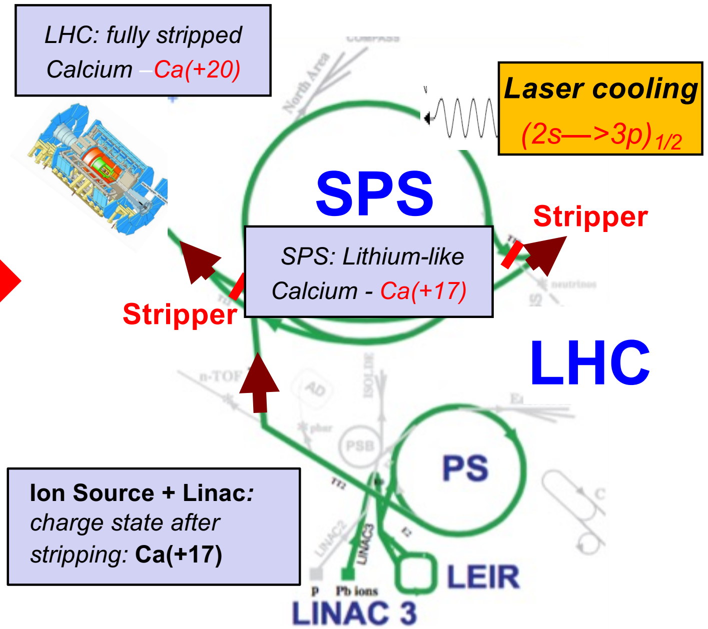
***HL-LHC** – β* reduction by a factor of 3.7 (new inner triplet)*



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

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

M.W. Krasny, A. Petrenko, W. Płaczek



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

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

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.*

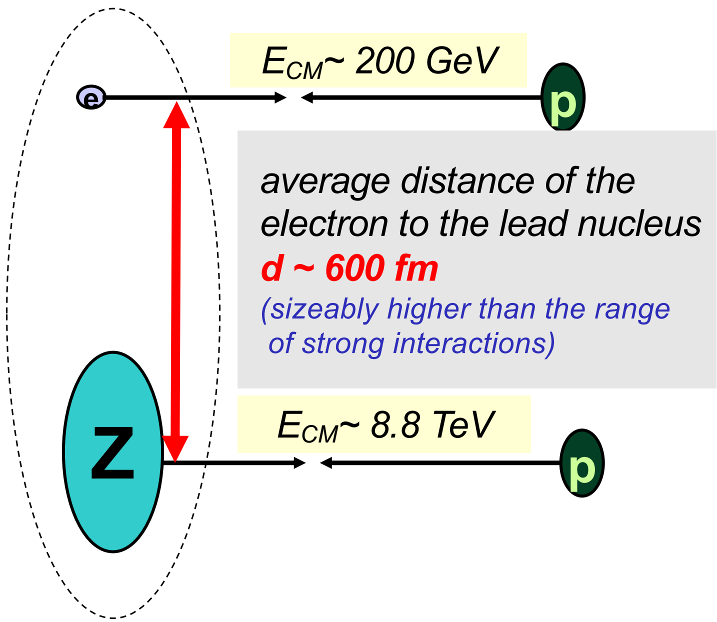
4.Tertiary beams' sources – Intensity/quality targets

- ***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 and the LHeC requirements*
- ***Pions*** – *potential, gain by a factor of 10^3, gain in the spectral density ($dN_\pi /dEdp_T dP$ [MeV^{-2} x MW] with respect to proton-beam-driven sources at KEK and FNAL (P is the driver beam power)*
- ***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, no necessity of the muon beam cooling?*
- ***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*** – *potential gain of up to a factor of 10^4 in intensity of primary MeV-energy neutrons per 1 MW of the driver beam power*
- ***Radioactive ions*** – *potential gain of up to a factor 10^4 in intensity w.r.t. e.g. ALTO*

5.Electron beam for ep collisions at LHC

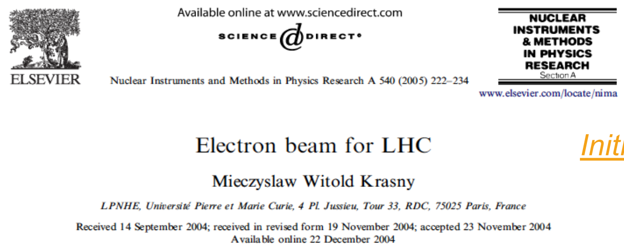
(in the ATLAS, CMS, ALICE and LHCb interaction points)

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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Electron beam for LHC

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

Initial studies:

Very recent important 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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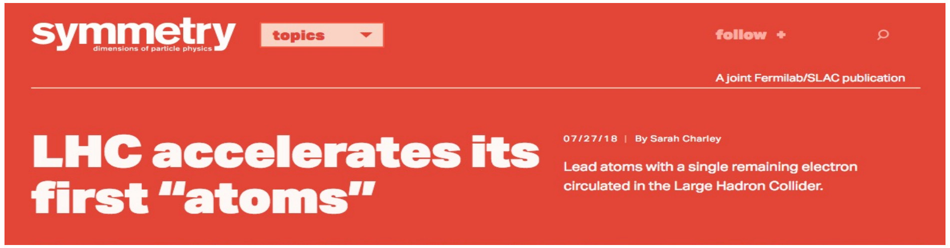
(Received 3 August 2020; accepted 5 October 2020; published 23 October 2020)

Technical Proof of Principle

Atomic beams in the LHC (Hydrogen-like Lead)


symmetry
dimensions of particle physics
topics
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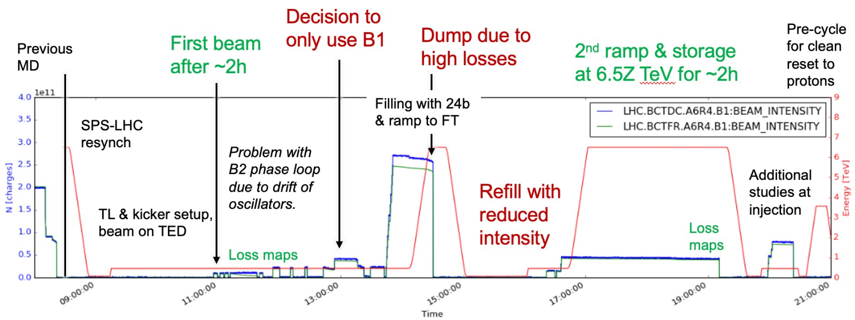
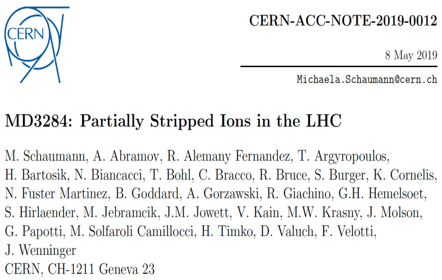
A joint Fermilab/SLAC publication
LHC accelerates its first "atoms"
07/27/18 | By Sarah Charley
Lead atoms with a single remaining electron circulated in the Large Hadron Collider.




CERN

CERN-ACC-NOTE-2019-0012

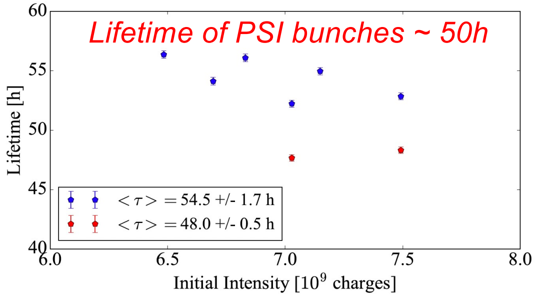
8 May 2019

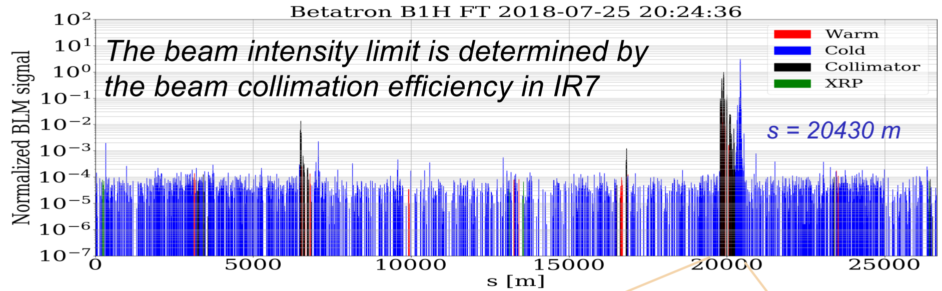
Michaela.Schaumann@cern.ch

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

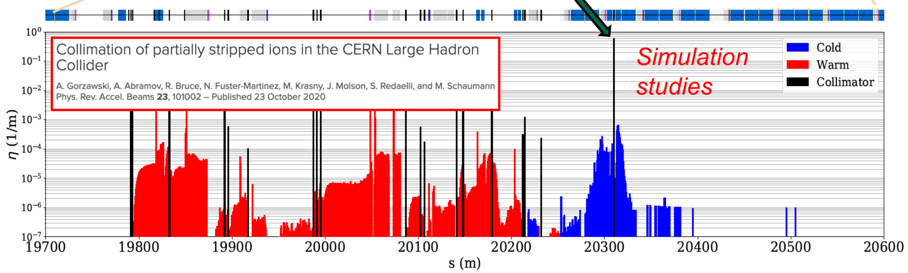
CERN, CH-1211 Geneva 23





Mitigation strategies:

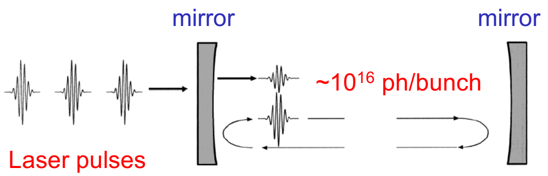
1. *Dispersion suppressor collimator (TCLD)*
2. *Crystal collimation*
3. *Laser collimation*

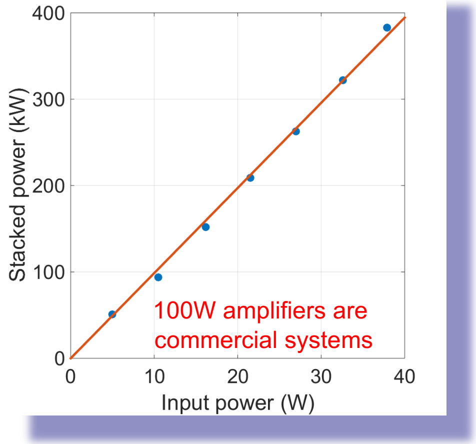


A dedicated LHC MD with crystal collimation of the PSI (H-like Pb) beam will be the next step…

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

Fabry-Pérot resonator

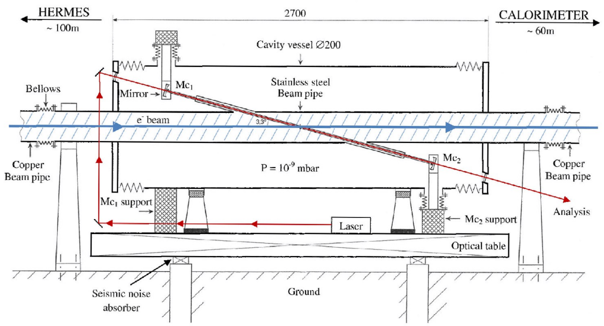




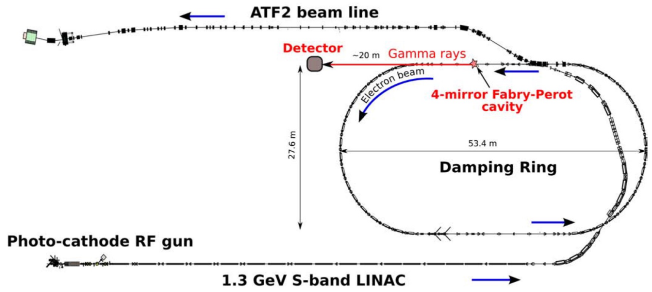
Amoudry L. et al., Applied Optics 59(2020)116

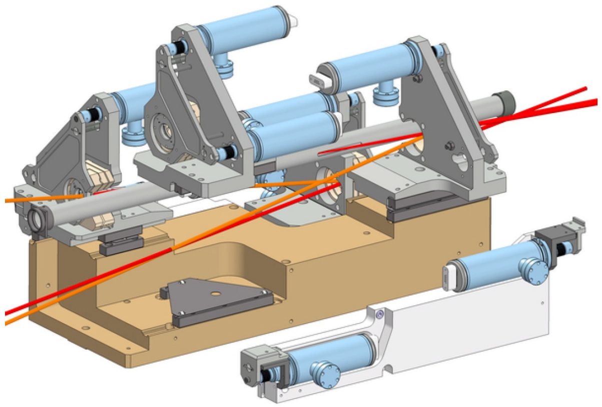
GF requirement:
< 5mJ pulses @ 40MHz,
(200kW photon beam)

HERA storage ring



KEK – ATF ring



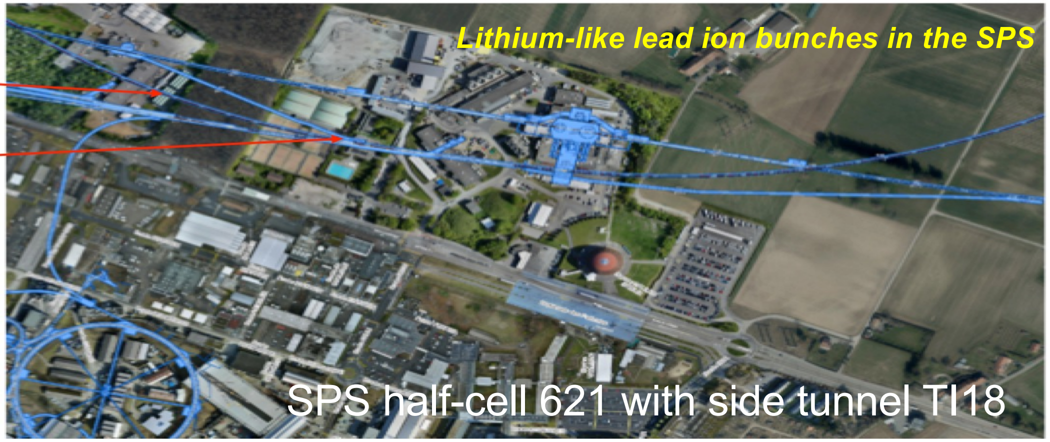


Towards the first integration of the FP resonator in the hadron storage ring →

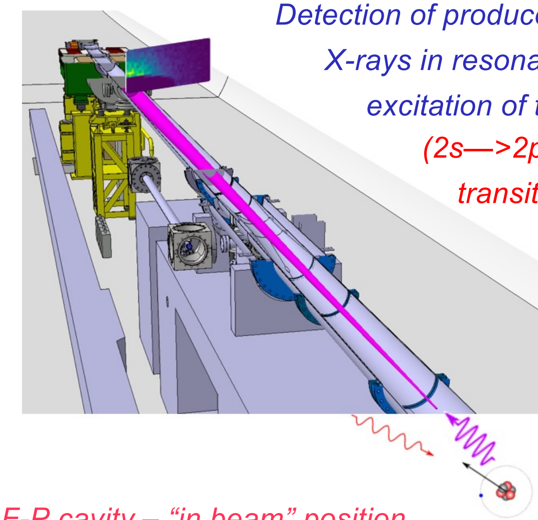
Gamma Factory Proof-of-Principle (PoP) SPS experiment

SPS

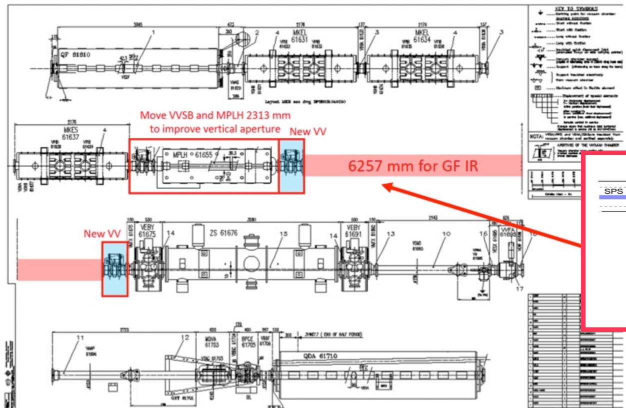
PoP location



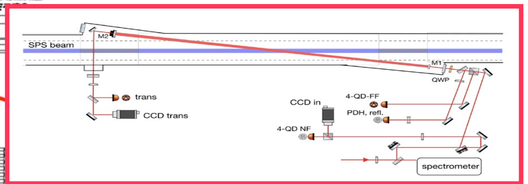
Detection of produced X-rays in resonant excitation of the $(2s \rightarrow 2p)_{1/2}$ transition



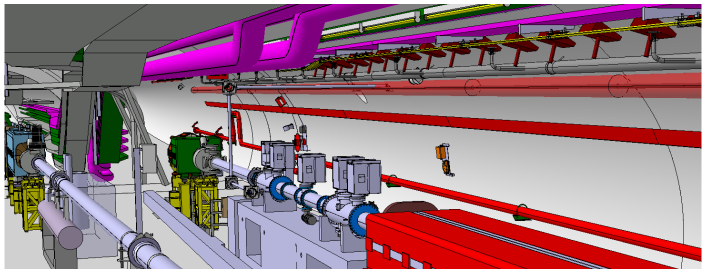
LSS6 zone



F-P cavity

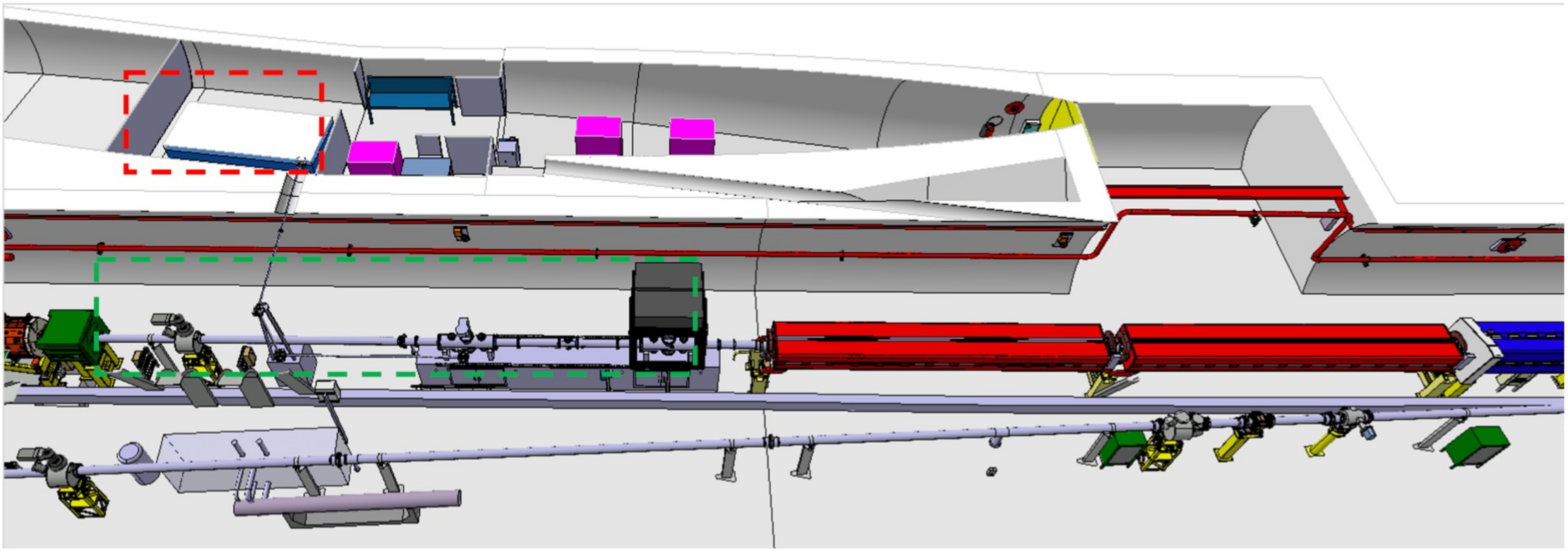


F-P cavity – "in beam" position



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

PoP experiment – location of laser room



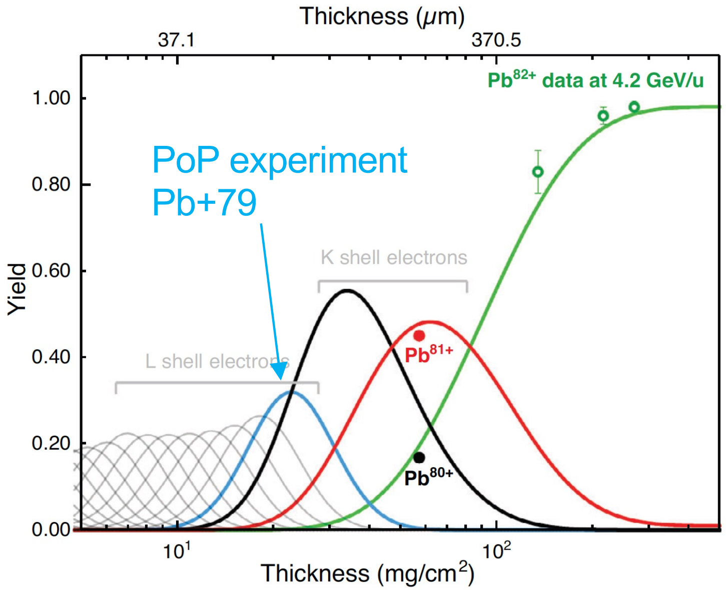
The purpose of the GF SPS PoP experiment

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*

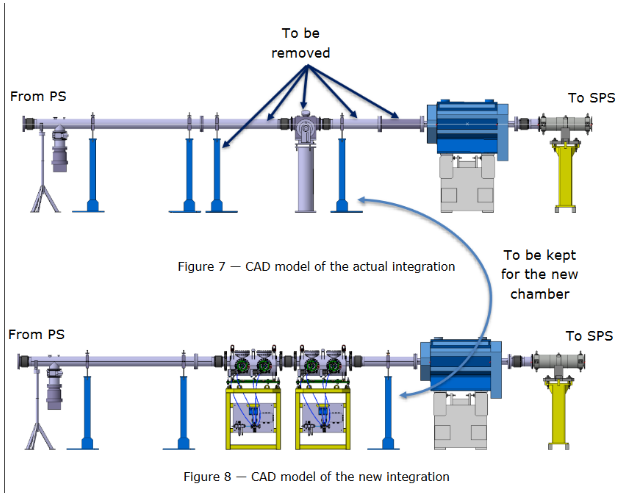
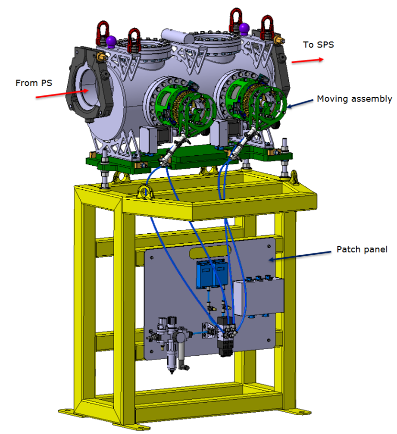
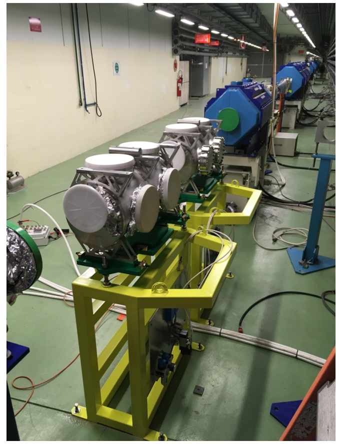


Figure 7 — CAD model of the actual integration

Figure 8 — CAD model of the new integration





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

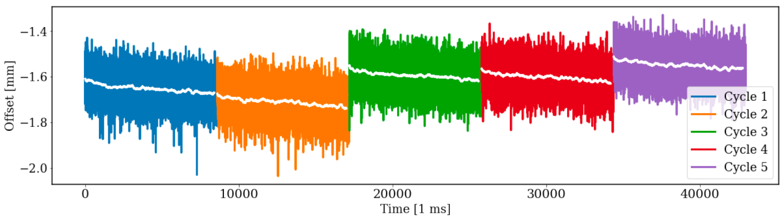
CERN-PBC-Notes-2022-006

22 April 2022

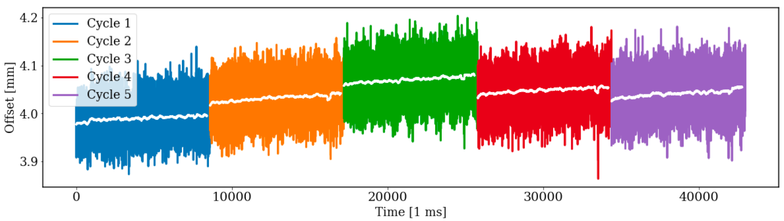
rebecca.louise.ramjiawan@cern.ch

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

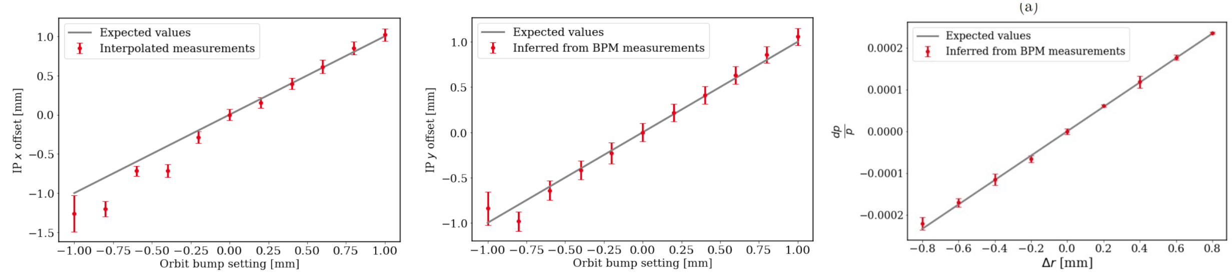


(a)



Control of the beam position and momentum in the PoP IP

(a)



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

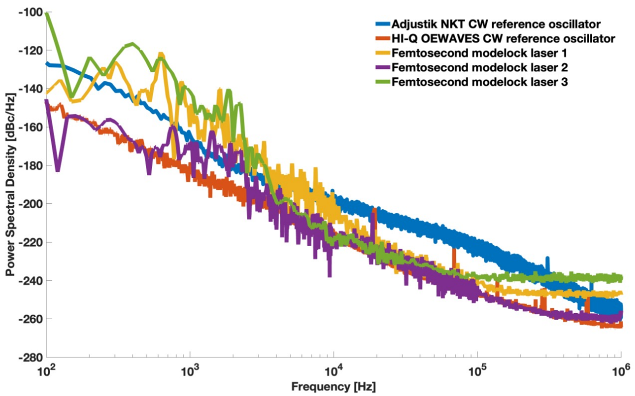
Design of the optical system for the gamma factory proof of principle experiment at the CERN Super Proton Synchrotron

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

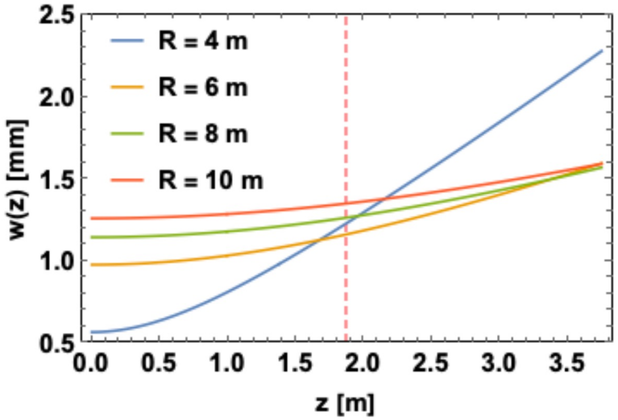
(Dated: April 28, 2022) … submitted last week to Phys.Rev.

Choice of the laser oscillator – phase noise measurements

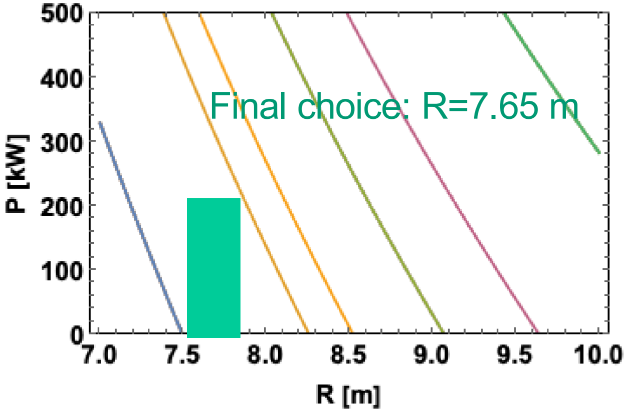


Laser 2 fulfils the requisite phase-stability criteria for the 40 Mhz, 10000 finesse FP cavity

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 over the last year

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 ☆

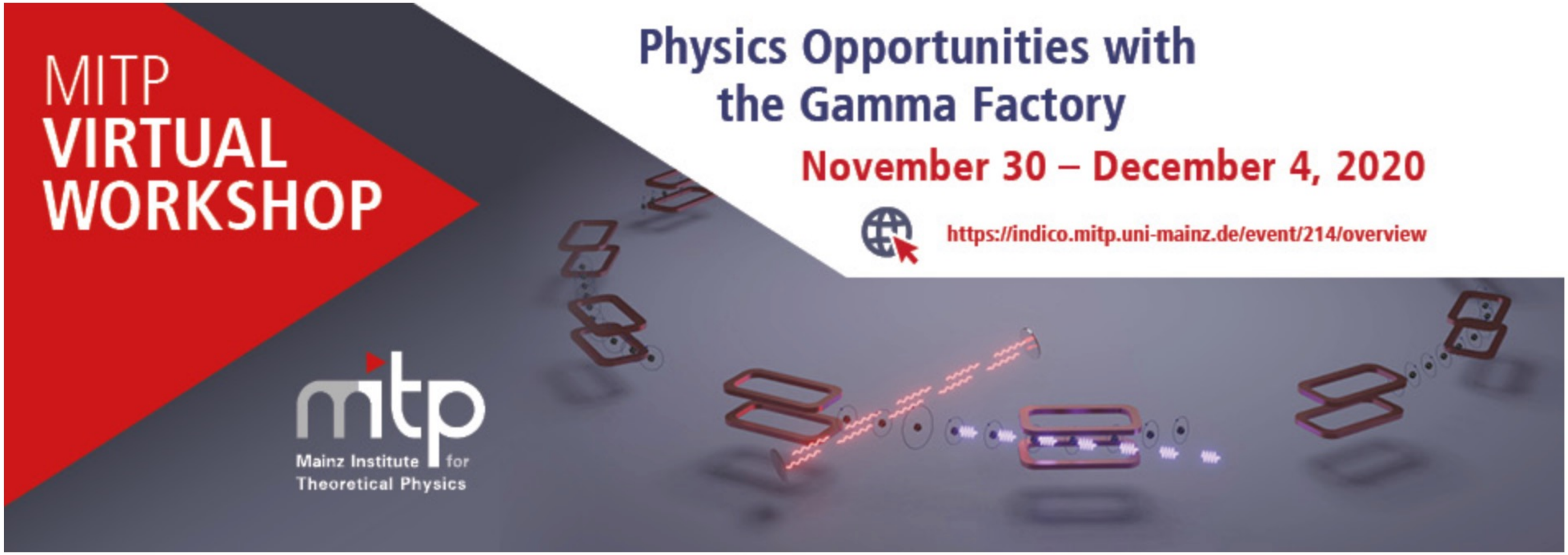
M.W. Krasny [a, b], A. Petrenko [c, b], W. Płaczek [d]

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



Physics Opportunities with the Gamma Factory

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

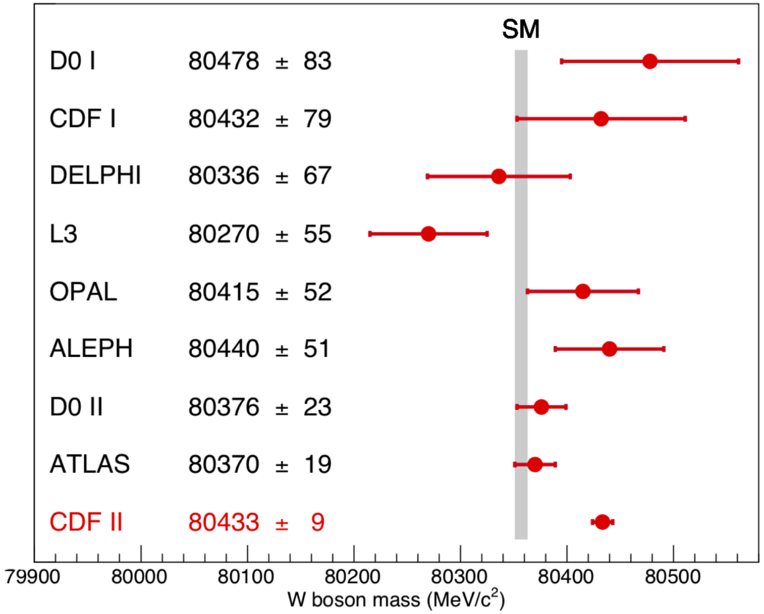
Examples of potential applications domains of the *Gamma Factory* research tools

- ***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).*

Four examples

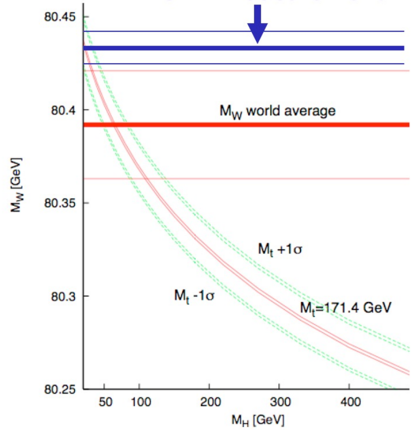
1. *Particle physics*
2. *Astrophysics*
3. *Atomic physics*
4. *Accelerator physics*
5. *Applied physics*

1.Particle Physics : precision EW measurements

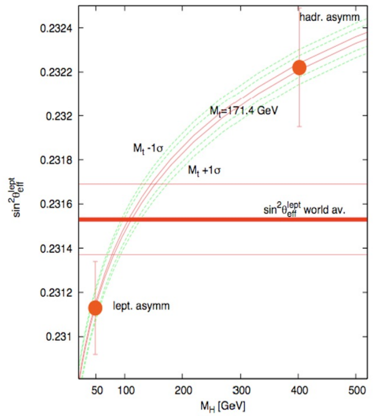


Precision goals (2009)

April 2022:
CDF measurement



precision target (2009) ~ 10 MeV
(reached by CDF -2022)



precision target (2009) ~ 0.0001
(not yet reached)

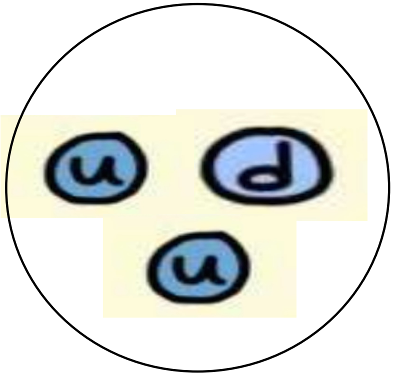
Can LHC experiments improve Tevatron precision of the SM parameters measurements?
… yes, provided that proton beams are replaced by isoscalar ion beams

The merits of the GF-cooled isoscalar beams

1. ***The impact of the modelling uncertainties of partonic emittances*** *(longitudinal and transverse) on the achievable measurement precision can be drastically reduced* ***and controlled the LHC data alone*** *(no precision brick-walls coming from the LHC-external data, PDFs, and PS models). Significantly* ***higher systematic precision*** *in measuring the* ***EW parameters*** *by using* ***isoscalar ion beams*** *rather than proton beams (as in the earlier fixed target experiments).*

2. ***Lower pileup background*** *at the equivalent (high) nucleon-nucleon luminosity.*

Significantly higher precision can be achieved in measuring the EW processes by using isoscalar ion rather than proton beams - WHY?



u and **d** quarks have different charges, weak isospin and vector and axial couplings.
For EW-physics: proton beams are equivalent to neutrino and electron beam mixed in not precisely known proportions.

In addition the relative distributions of the valence and sea u and d quarks determine the effective W/Z boson polarisation. Proton beams –> polarisation cannot be precisely controlled.

Isoscalar (A=2Z) ion beams

Profit from the flavour symmetry of strong interactions to to equalize the distributions of the u and d quarks: $\boxed{u_{v,s}^{A=2Z,Z}(x,k_t,Q^2) = d_{v,s}^{A=2Z,Z}(x,k_t,Q^2)}$

M.W. Krasny, F. Dydak, F. Fayette, W. Placzek, A. Siodmok, *Eur.Phys.J. C69 (2010) 379-397.*
F. Fayette, M.W. Krasny, W. Placzek, A. Siodmok, *Eur.Phys.J. C63 (2009) 33-56.*
M.W. Krasny, F. Fayette, W. Placzek, A. Siodmok, *Eur.Phys.J. C51 (2007) 607-617.*
M.W. Krasny, S. Jadach, W. Placzek, *Eur.Phys.J. C44 (2005) 333-350.*

Expected biases in the measured values of M_W [MeV] – isoscalar beams

Systematic ξ	Expected precision [%]	ΔM [MeV]
"$\epsilon^+ - \epsilon^-$"	0.5	< 5
"u_v / d_v"	0.2	< 5
"$c - s$" $\mathcal{L}_{int} = 10 fb^{-1}$	2	20
"$c - s$" $\mathcal{L}_{int} = 100 fb^{-1}$	0.7	7
"b"	20	7*

Expected biases in the measured values of M_{W+} - M_{W-} [MeV] – isoscalar beams

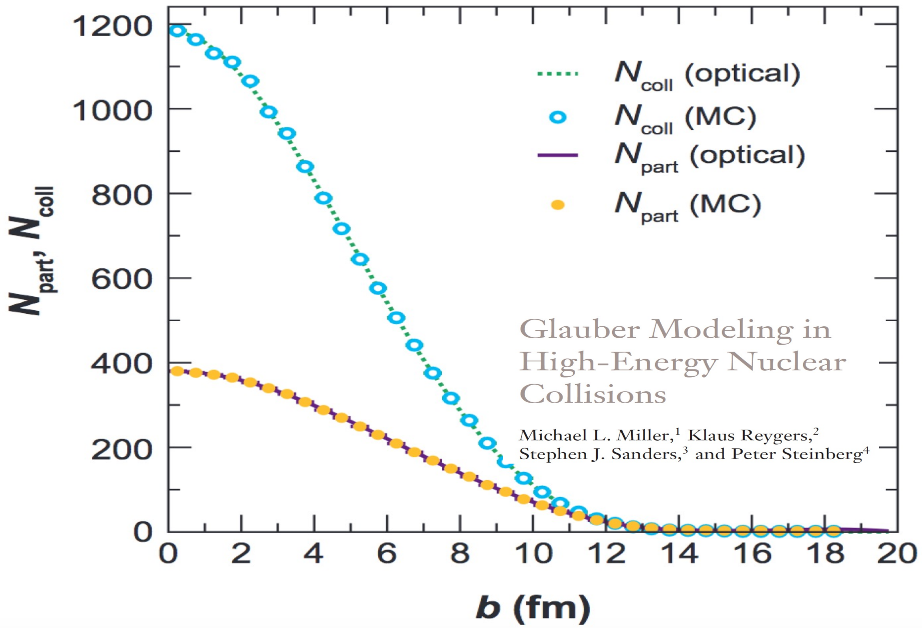
	Systematic ξ	pp - $\lvert\eta_l\rvert < 2.5$	pp - $\lvert\eta_l\rvert < 0.3$	pp - $\lvert y_W\rvert < 0.3$	dd - $\lvert\eta_l\rvert < 2.5$
$u^{(v)}, d^{(v)(*)}$	$u^{(v)}_{max} = 1.05\, u^{(v)}$ $d^{(v)}_{min} = d^{(v)} - .05\, u^{(v)}$	114.5	74.4	-38.1	2.4
	$u^{(v)}_{min} = 0.95\, u^{(v)}$ $d^{(v)}_{max} = d^{(v)} + .05\, u^{(v)}$	-138.5	-83.8	59.8	2.9
	$u^{(v)}_{max} = 1.02\, u^{(v)}$ $d^{(v)}_{min} = 0.92\, d^{(v)}$	85.2	51.2	-34.7	4.1
	$u^{(v)}_{min} = 0.98\, u^{(v)}$ $d^{(v)}_{max} = 1.08\, d^{(v)}$	-85.9	-53.2	47.2	-0.1

* …biases reflecting the uncertainties in the b-quark distributions reduced in a dedicated measurement in the restricted $2.0 < |\eta_l| < 2.5$ region

Lower pileup background at the equivalent (and high) partonic luminosity

$$\nu_{AA} = \nu_{pp} \times \frac{\sigma_{AA}}{\sigma_{pp}} \times A^{-2}$$

Example: Au-Au collisions



N_{pileup} (pp) ~ N_{coll}, N_{pileup} (AA) ~ $N_{part}/2$

(stripping-off of soft partons and the nucleus surface)

Reduction of the average number of beam particle collisions per bunch crossing, at the same partonic luminosity by a factor of 40, 136, 650 and 1260 for OO, CaCa, XeXe and PbPb collisions (opens a possibility of studying exclusive processes).

Reduction of the multiplicity of the soft, pileup particles (opens a possibility to run the LHC detectors (trackers) at higher partonic luminosity w.r.t. HL(pp)-LHC).

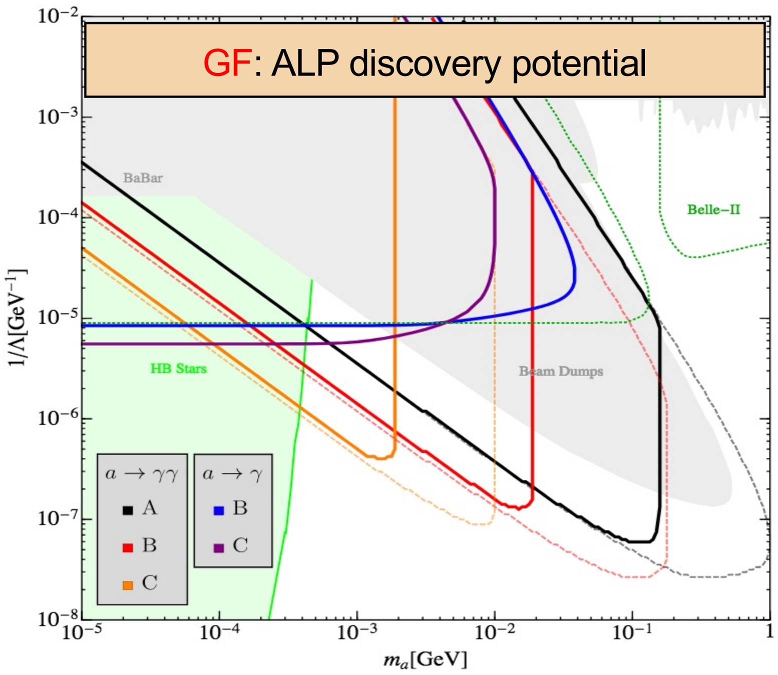
2. **Astrophysics**: ALPs and dark photon searches

annalen der physik

Research Article | Full Access

Probing Axion-Like-Particles at the CERN Gamma Factory

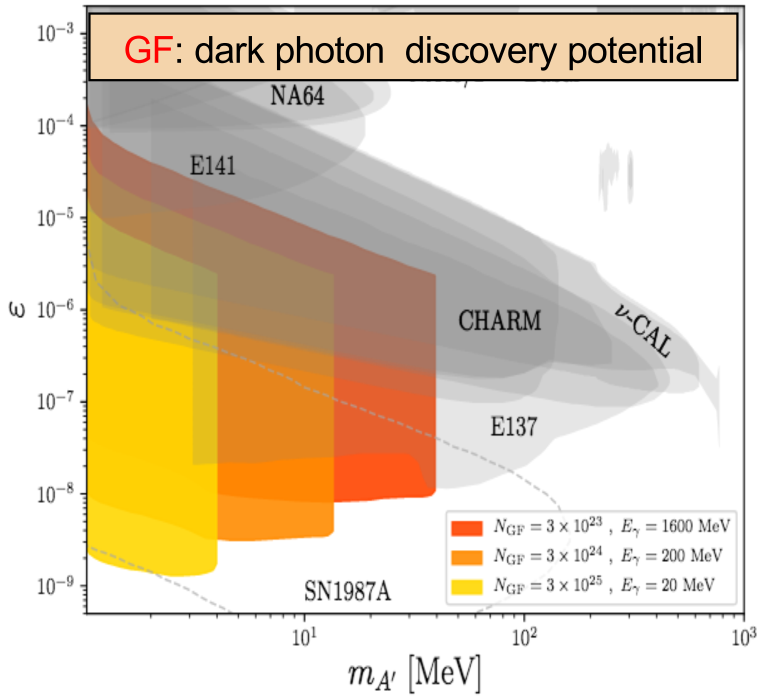
Reuven Balkin, Mieczyslaw W. Krasny, Teng Ma, Benjamin R. Safdi, Yotam Soreq



Gamma factory searches for extremely weakly interacting particles

Sreemanti Chakraborti, Jonathan L. Feng, James K. Koga, and Mauro Valli

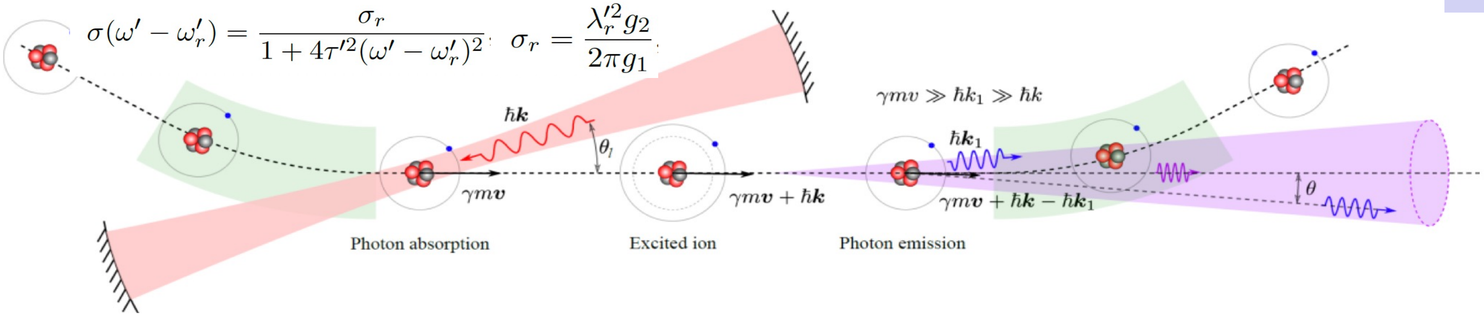
Phys. Rev. D **104**, 055023 – Published 21 September 2021



Unique discovery potential for light Dark Matter particles with GF photon beams!

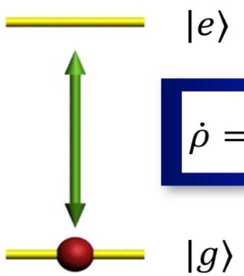
3. Atomic physics: quantum interference phenomena

Probabilistic framework



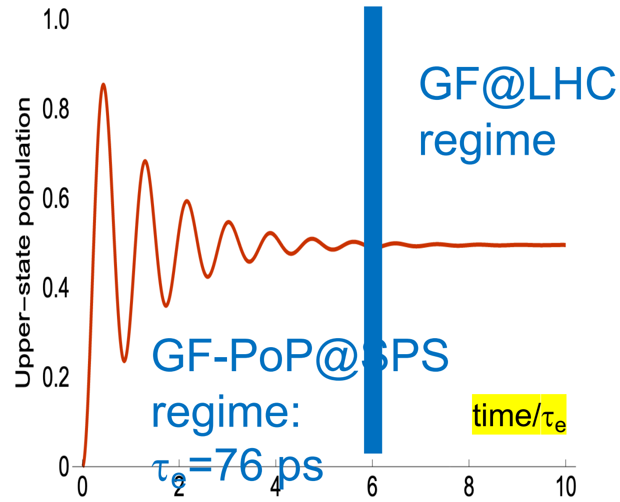
Probabilistic framework sufficient

Quantum-Mechanical framework



$$\boxed{\dot{\rho} = -\frac{i}{\hbar}[H,\rho] + \Gamma(\rho)}$$

$$\begin{aligned}
\dot{\rho}_{eg} &= \left(i\Delta\omega - \frac{\gamma_e}{2}\right)\rho_{eg} + \frac{i\Omega_R}{2}(\rho_{gg} - \rho_{ee}),\\
\dot{\rho}_{ge} &= -\left(i\Delta\omega + \frac{\gamma_e}{2}\right)\rho_{ge} - \frac{i\Omega_R}{2}(\rho_{gg} - \rho_{ee}),\\
\dot{\rho}_{ee} &= \frac{i\Omega_R}{2}(\rho_{ge} - \rho_{eg}) - \gamma_e\rho_{ee},
\end{aligned}$$



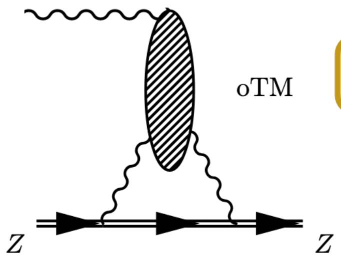
Quantum interference important

$\Omega_R = \frac{dE_0}{\hbar}$ Rabi frequency (coupling strength)

$\gamma_e = \frac{1}{\tau_e}$ excited-state relaxation constant (natural width of the excited state)

Atomic physics: muonium

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



CROSS SECTION FOR oTM PRODUCTION FOR E>>m_μ:

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

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

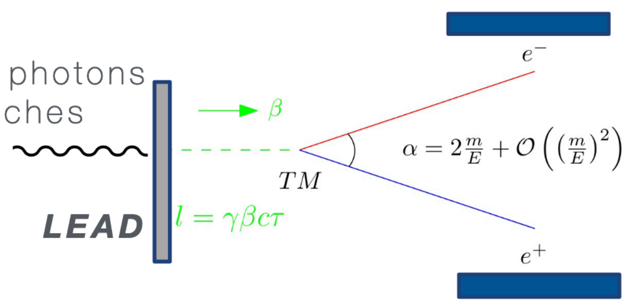
EPJ Web of Conferences **245**, 02009 (2020)

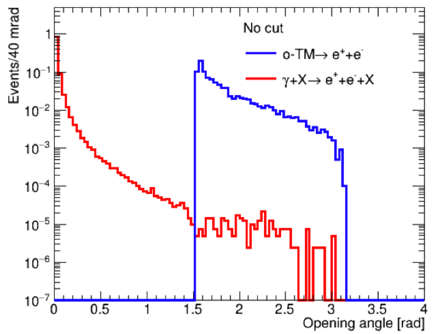
Production & detection of **TM** at GAMMA FACTORY:

See GF-TALK of Witek K.

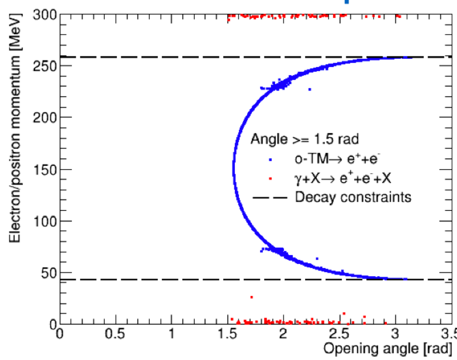
TRACKERS& DETECTORS

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





10^{11} photons



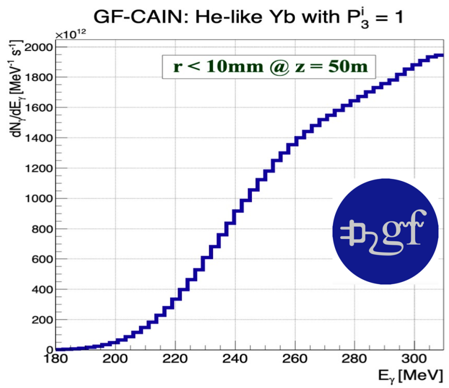
Estimated **RATE** OF ~$\mathcal{O}(10^{4\text{-}5})$ **TM (1^3S_1)/day** and ~$\mathcal{O}(10^{2\text{-}3})$ **TM(2^3S_1)/day**

4. Accelerator physics: GF, low-emittance, high-intensity muon source

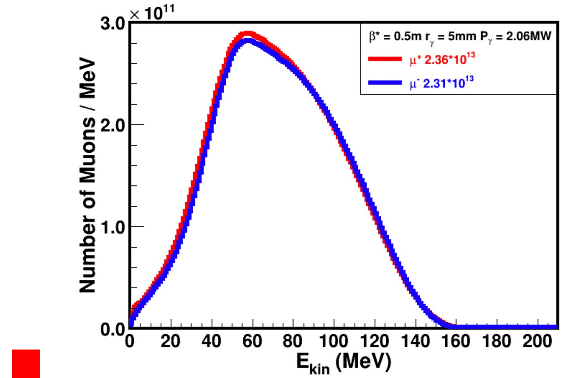
Existing and future muon sources

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

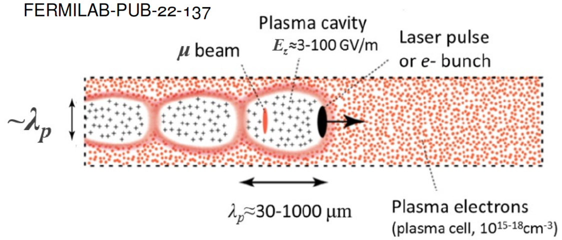


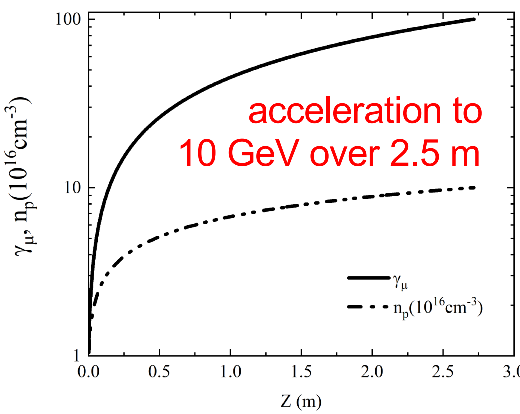
On Possibility of Low-emittance High-energy Muon Source Based on Plasma Wakefield Acceleration

Vladimir Shiltsev [a,1]

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

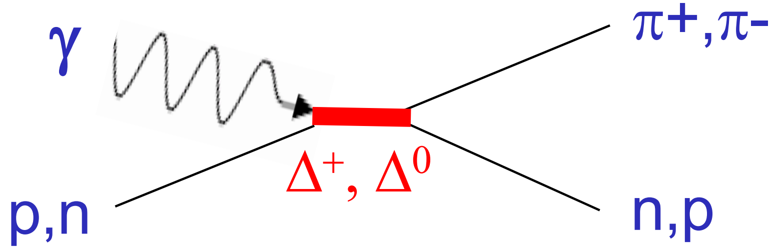
FERMILAB-PUB-22-137





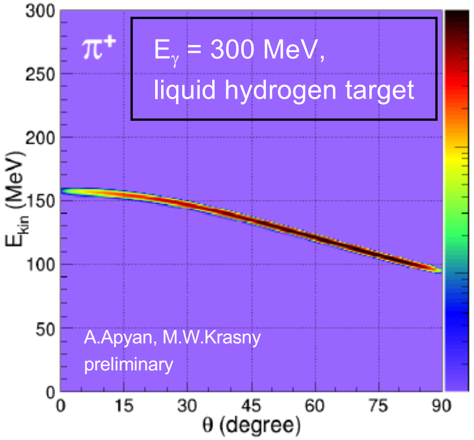
Novel paradigm: μ and ν sources based on exclusive pion production in photo-excitation of Δ resonances with the Gamma Factory photon beam

$$\gamma + p \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$$
$$\gamma + n \rightarrow \Delta^{0} \rightarrow p + \pi^{-}$$

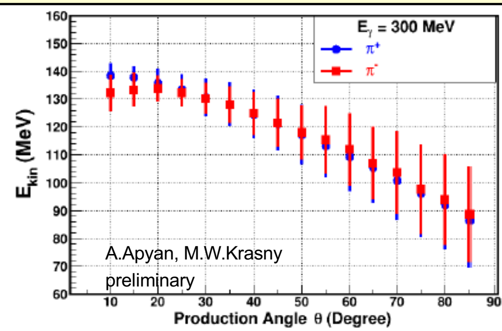


Exclusive process:

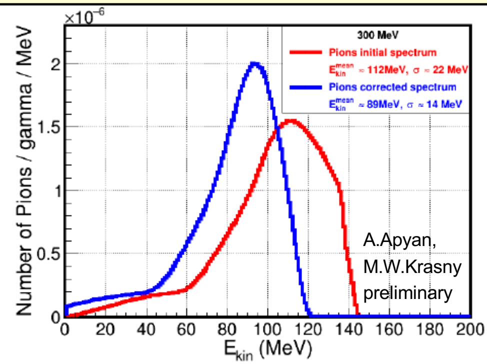
- *Pion energy and transverse momentum* ***no*** *longer random*
- ***Fully*** *specified by* ***one*** *parameter: the pion* ***emission angle***, θ



Symmetry of π^{+} and π^{-} production for **isoscalar target** (e.g. graphite) *(the cost: Fermi smearing - error bars)*



Further "Monochromatisation" of the pion kinetic energy by a suitable choice of the target radius

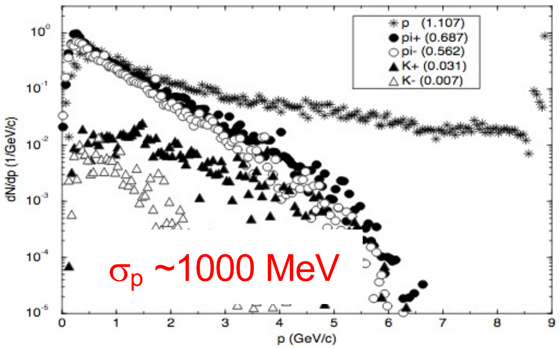


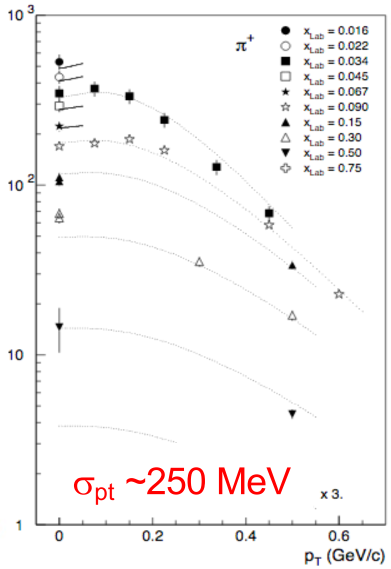
Pion production rate and spectra: proton versus GF γ–beams

8 GeV proton beam

For λ_i = 2 **graphite** target:
~ 4.1 x 10^{14} π^+/s and ~ 2.6 x 10^{14} π^-/s for 1 MW p beam

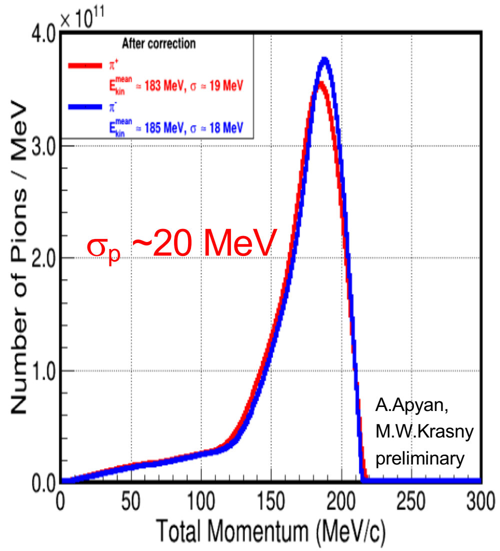
1 MW photon beam deposits ~ 6 times less energy in the λ_i = 2 graphite target! …in addition ~20% muons lost in the cooling channel

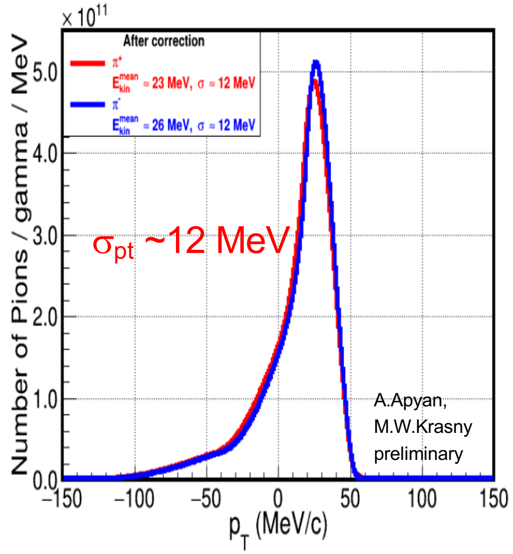




300 MeV GF γ-beam

For λ_i = 2 **graphite** target :
~ 2 x 10^{13} π^+ and π^-/s for 1 MW γ beam (2 x 10^{16} γ/s)





$\varepsilon_{T(x,y)}$ ~$(\sigma_T\sigma_{pt})/mc^2$
ε_L ~$(\sigma_z\sigma_p)/mc^2$

Expected **reduction** of the **transverse pion-beam emittance** (x,y) by a factor of > **10** and **longitudinal emittance** by a factor of > **20**. If preserved while forming μ-beam (under study), no cooling necessary!

Mark Palmer *for the Muon Accelerator Program (MAP)*

Cooling

Proposed scheme:

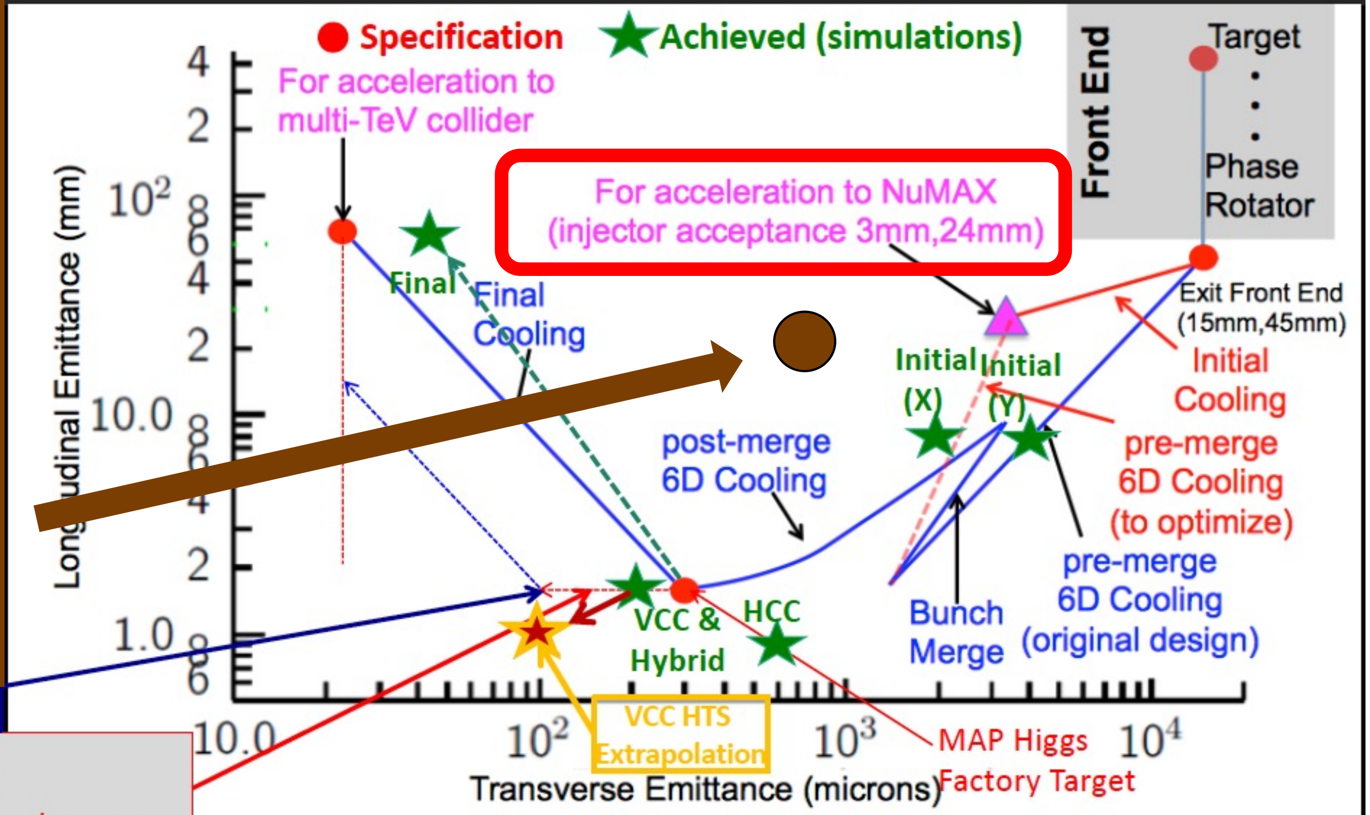
*Expected **pion source** beam emittance:*

$\varepsilon_T \sim \sigma_T \sigma_{pT}/mc \sim 0.8$ mm

$\varepsilon_L \sim \sigma_{||} \sigma_p/mc \sim 20$ mm

1 MW gamma beam, 20 cm long graphite target, $N\pi$= 1.3x10^13 of each sign

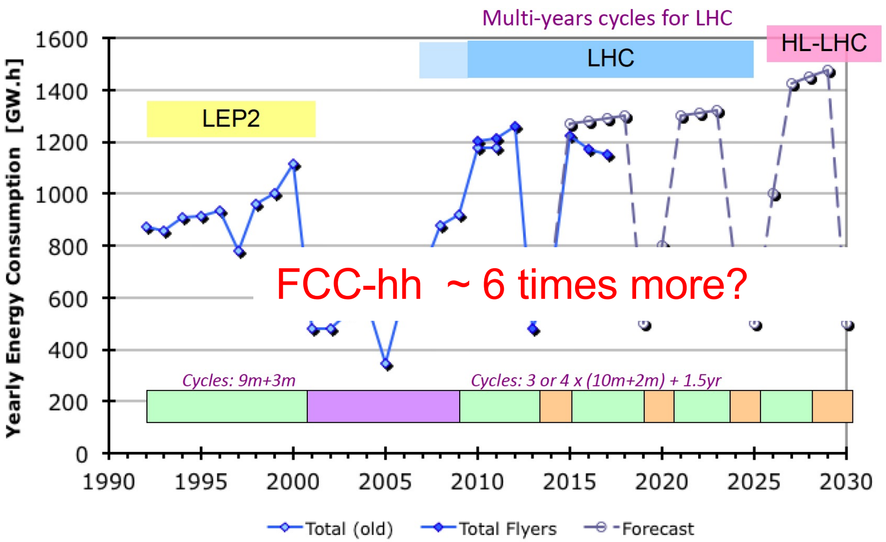
Remaining challenge: design a pion/muon collection scheme in which the emittance is preserved (…or worsen by not more than a factor of ~4) (under study)

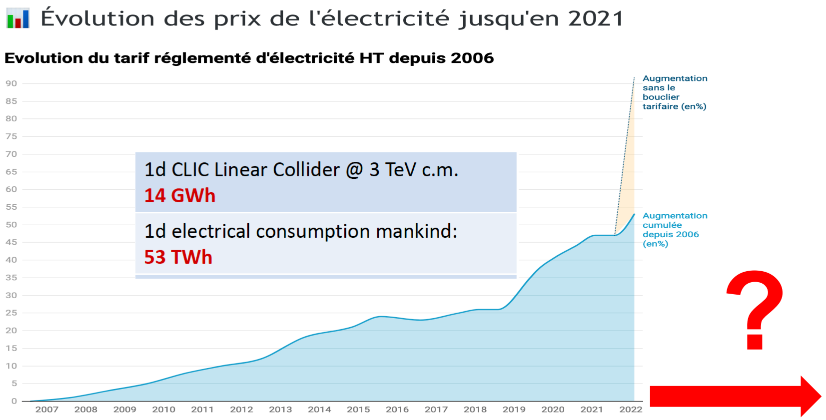


Rubbia's Proposal

Advanced techniques ⇨
Improved HF Luminosity
Simplified Final Cooling requirements

5. Applied physics: GF photon-beam-driven energy source





Prix kWh (before Russian invasion of Ukraine):

- France (professionels) -- 0.144 euro
- CERN deal - ~0.06 euro

Electricity cost LHC(FCC-hh);

- French prices -- ~216 (1300?) x 10^6 euro/year
- CERN deal - ~90 (630?) x 10^6 euro/year

In my view, we should try to produce, rather than buy the plug-power -- necessary for the next generation of high-energy, accelerators -- locally, in our HEP research centers… … becoming now a sine qua non condition for sustainable research at the high energy frontier…

Towards the Gamma-Factory-beam-driven energy source

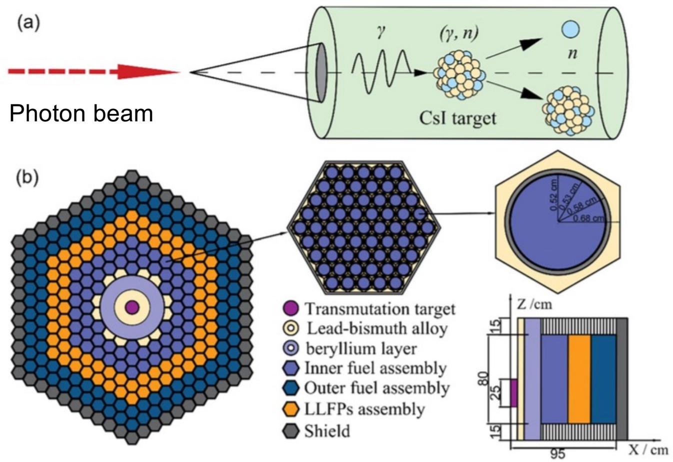
Nature:

Article | Open Access | Published: 09 February 2022

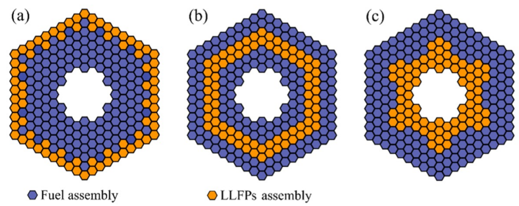
Transmutation of long-lived fission products in an advanced nuclear energy system

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

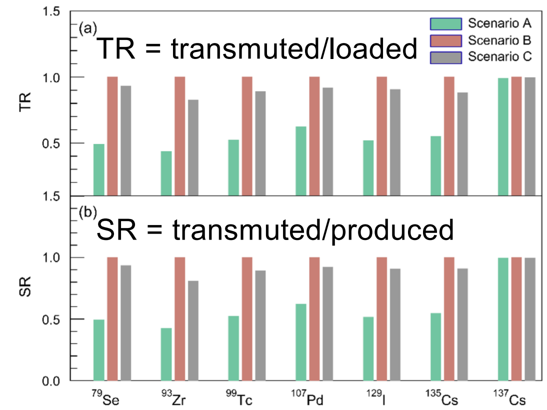
Scientific Reports 12, Article number: 2240 (2022) | Cite this article



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



Dedicated study group crated….studies ongoing….

Energy footprint of the Gamma Factory beams : Comparison of the DESY-XFEL and the CERN GF photon sources

DESY-XFEL

- Wall-pug power – 19 MW
- Driver beam power consumption – 600 kW
- Photon beam power 600 W
- **beam power efficiency ~ 0.1 %**
- **overall plug-power consumption efficiency ~ 0.003 %**
  (thanks to Andrea Latina for these numbers)

CERN-GF

- wall-pug power – 200 MW (total CERN)
- wall-pug power – 125 MW (LHC)
- beam lifetime 10 h
- **driver beam power consumption = photon beam power**
  (power to ramp the beam to requite energy negligible)
- **beam power efficiency ~ 99 %**
- **overall energy spending efficiency ~1%**
  (for 2 MW GF photon beams)

CERN **GF photon source** energy footprint is expected to be smaller, by a factor of 300, than the **DESY-XFEL** photon source…

…for the fixed power of the produced photon beam…

Moreover, It has a potential to provide the electrical power for the future ~300 MW accalarator project (FCC, CLIC, muon collider)

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** ($L_{int} \sim 0.5 L_{goal}$) -- 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. The GF tools may turn out to be indispensable for addressing the high energy frontier research.

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