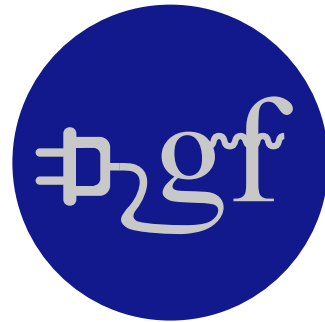


# The CERN Gamma Factory Initiative



*IPAC2018, Vancouver, May 2018*

Mieczyslaw Witold Krasny, CERN BE-ABP division,  
LPNHE, CNRS-IN2P3 and University Paris Sorbonne  
representing Gamma Factory study group

# Introduction

# The Gamma Factory proposal in a nutshell

1. Accelerate and store high energy beams of highly ionised atoms and excite their *atomic degrees of freedom*, by laser photons to produce primary beams of gamma rays and, in turn, secondary beams of polarised leptons, neutrinos, vector mesons, neutrons and radioactive ions.
2. Provide a new, efficient scheme of transforming the accelerator RF power (selectively) to the above primary and secondary beams to achieve a *leap, by several orders of magnitude, in their intensity and/or brightness*, with respect to the existing facilities.
3. Use the primary and the secondary beams as principal tools of the Gamma Factory research programme.

## Its context

- *The next CERN high-energy frontier project may take a long time to be approved, financed and built.*
- *It is very likely that the present high-energy CERN research programme will reach earlier its discovery saturation (no physics gain by extending the running time).*
- *In such a case, a strong need will arise for a novel programme which could re-use its existing facilities in ways and at levels that were not necessarily thought of when the machines were designed*
- ***Gamma Factory*** *is an initiative going in this direction.*
- *It requires extensive experimental and simulation studies and R&D to prove its feasibility, and to be considered as a realistic proposal !*

## Its CERN-based framework

*The Gamma Factory initiative ([arXiv:1511.07794 \[hep-ex\]](https://arxiv.org/abs/1511.07794)) was recently endorsed by the CERN management by creating (February 2017) the Gamma Factory study group, embedded within the Physics Beyond Colliders studies framework:*

### **Mandate of the "Physics Beyond Colliders" Study Group**

Conveners: J. Jaeckel, M. Lamont, C. Vallee

CERN Management wishes to launch an exploratory study aimed at exploiting the full scientific potential of its accelerator complex and other scientific infrastructure through projects complementary to the LHC and HL-LHC and to possible future colliders (HE-LHC, CLIC, FCC). These projects would target fundamental physics questions that are similar in spirit to those addressed by high-energy colliders, but that require different types of beams and experiments.

# The Gamma Factory group members

*P.S. Antsiferov, Institute of Spectroscopy, Russian Academy of Science, Moscow, Russia; A. Apyan, A.I. Alikhanyan National Science Laboratory, Yerevan, Armenia; E.G. Bessonov, V.P. Shevelko, P.N. Lebedev Physical Institute, Moscow, Russia; D. Budker, Helmholtz Institute, Johannes Gutenberg University, Mainz, Germany; K. Cassou, I. Chaikovska, R. Chehab, K. Dupraz, A. Martens, F. Zomer, LAL Orsay, France; F. Castelli, C. Curatolo, V. Petrillo, L. Serafini Department of Physics, INFN-Milan and University of Milan, Milan, Italy ; O. Dadoun, M. W. Krasny\*, LPNHE, University Paris VI et VII and CNRS-IN2P3, Paris, France; H. Bartosik, N. Biancacci, P. Czodrowski, B. Goddard, J. Jowett, Reyes Alemany Fernandez\*, S. Hirlander, R. Kersevan, M. Kowalska, M. Lamont, D. Manglunki, A. Petrenko, M. Schaumann, C. Yin-Vallgren, F. Zimmermann, CERN, Geneva, Switzerland; K. J. Bieron, K. Dzierzega, S. Pustelny, W. Placzek, Jagellonian University, Krakow, Poland; F. Kroeger, T. Stohlker, G. Weber, HI Jena, IOQ FSU Jena, and GSI Darmstadt, Germany; Y. K. Wu, FEL Laboratory, Duke University, Durham, USA; M. S. Zolotarev, Center for Beam Physics, LBNL, Berkeley, USA.*

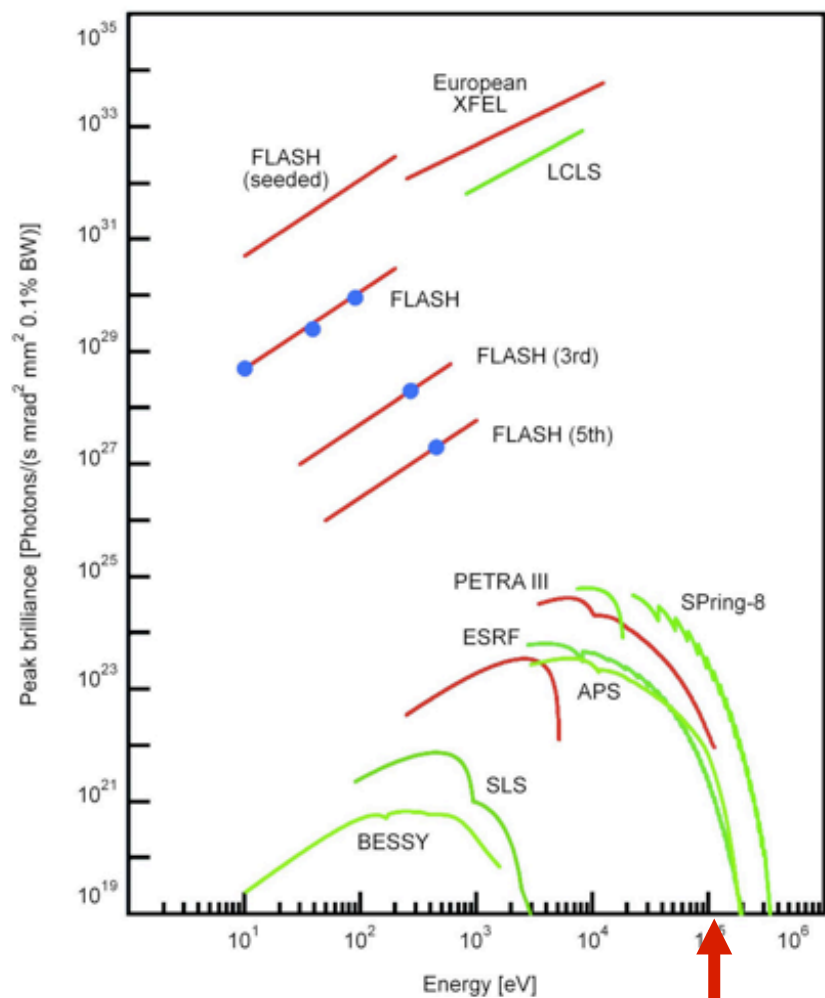
IPAC2018 contributions

*GF study group is open to everyone willing to join this initiative!*

# Gamma Source



# X-ray sources



atomic  
structures



How about the quanta capable of resolving the nuclear structure and allowing to convert light into matter ( $\gamma$ -ray domain)?

100 KeV

# Parameters of the $\gamma$ -ray sources around the world

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

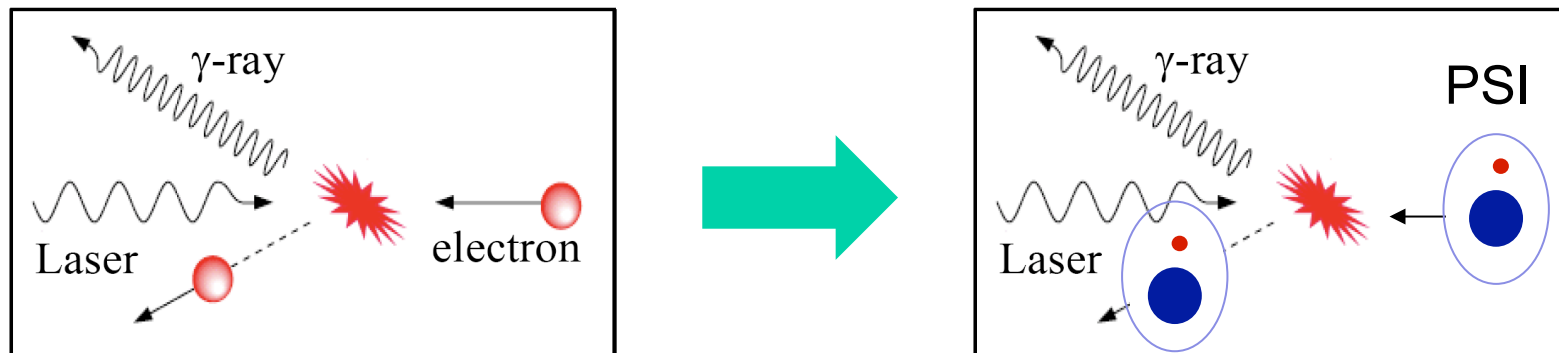
*The Gamma Factory goal: achieve comparable fluxes in the MeV domain as those in the KeV domain – e.g. those of the DESY XFEL:*

*(DESY FEL: photons/pulse --  $10^{11}$ – $10^{13}$ , pulses/second –10–5000  $\rightarrow$   **$10^{12}$  –  $10^{17}$  photons/s**)*

**An intensity jump of up to 3-8 orders of magnitude required !**

# The gamma ray source for Gamma Factory

The idea: replace an electron beam by a beam of highly ionised atoms (Partially Stripped Ions - **PSI**)



K.A. ISPIRIAN, A.T. MARGARIAN, N.G. BASOV,  
A.N. ORAEVSKI, B.N. CHICHKOV  
E.G. BESSONOV, K-J. KIIM, M.W. KRASNY...

# The expected magnitude of the $\gamma$ -source intensity leap

## Electrons:

$$\sigma_e = 8\pi/3 \times r_e^2$$

$r_e$  - classical electron radius

## Partially Stripped Ions:

$$\sigma_{\text{res}} = \lambda_{\text{res}}^2 / 2\pi$$

$\lambda_{\text{res}}$  - photon wavelength in the ion rest frame

## Electrons:

$$\sigma_e = 6.6 \times 10^{-25} \text{ cm}^2$$

## Partially Stripped Ions:

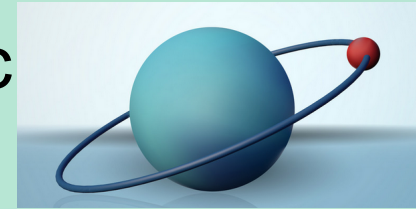
$$\sigma_{\text{res}} = 5.9 \times 10^{-16} \text{ cm}^2$$

Numerical example:  $\lambda_{\text{laser}} = 1540 \text{ nm}$

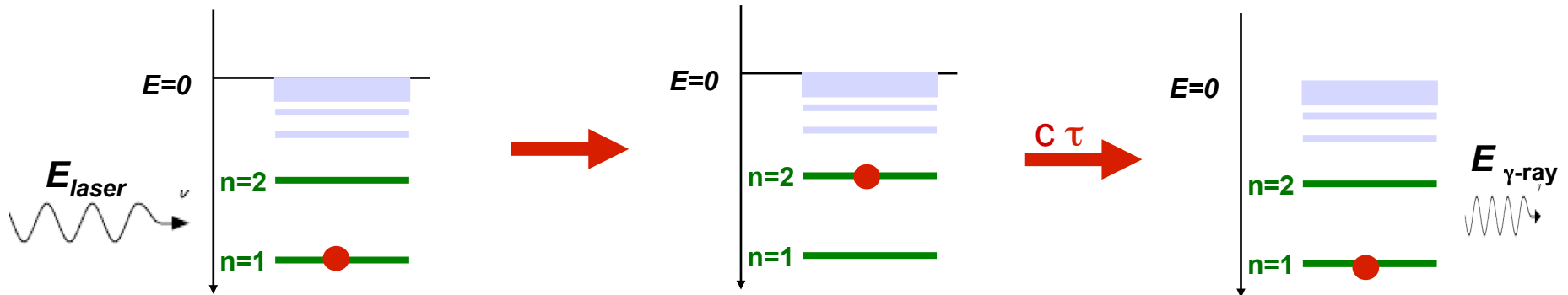
**~ 9 orders of magnitude difference in the cross-section**

**~ 7 orders of magnitude increase of gamma fluxes**

# Scattering of photons on ultra-relativistic hydrogen-like, Rydberg atoms



$$-E_n = 1\text{Ry } Z^2/n^2$$



$$E_{laser} = 1\text{Ry } (Z^2 - Z^2/n^2)/2\gamma_L$$

$$E_{\gamma\text{-ray}} = E_{laser} \times 4\gamma_L^2 / (1 + (\gamma_L \theta)^2)$$

$\gamma_L = E/M$  - Lorentz factor of the PSI beam

## Partially Stripped Ion beam as a light frequency converter

$$\nu_{\text{max}} \longrightarrow (4 \gamma_L^2) \nu_i$$

*Tuning of the beam energy, the choice of the ion type, the number of left electrons and of the laser type allows to tune the  $\gamma$ -ray energy, at CERN, in the **energy domain of 100 keV – 400 MeV.***

*Example (maximal energy):*

*LHC, Pb<sup>80+</sup> ion,  $\gamma_L = 2887$ ,  $n=1 \rightarrow 2$ ,  $\lambda = 104.4$  nm,  $E_\gamma$  (max) = 396 MeV*

# A leap in the gamma source efficiency

## Electrons:

$$E_{\text{beam}} = 1.5 \text{ GeV}$$

Electron fractional energy loss:  
emission of 150 MeV photon:

$$E_{\gamma}/E_{\text{beam}} = 0.1$$

(electron is lost!)

Example: Pb, hydrogen-like ions,  
stored in LHC  $\gamma_L = 2887$

## Partially stripped ions:

$$E_{\text{beam}} = 574\,000 \text{ GeV}$$

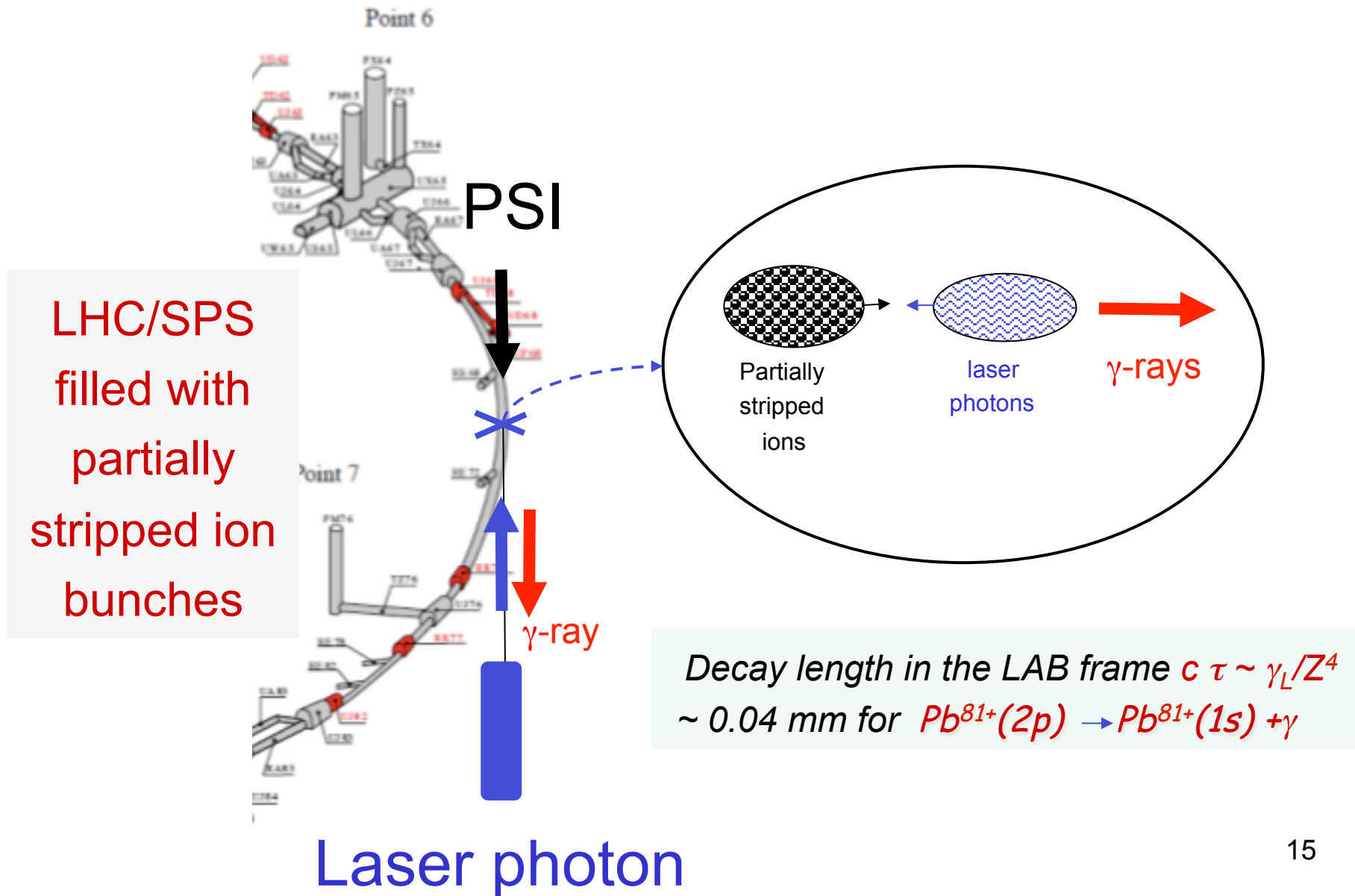
Electron fractional energy loss:  
emission of 150 MeV photon:

$$E_{\gamma}/E_{\text{beam}} = 2.6 \times 10^{-7}$$

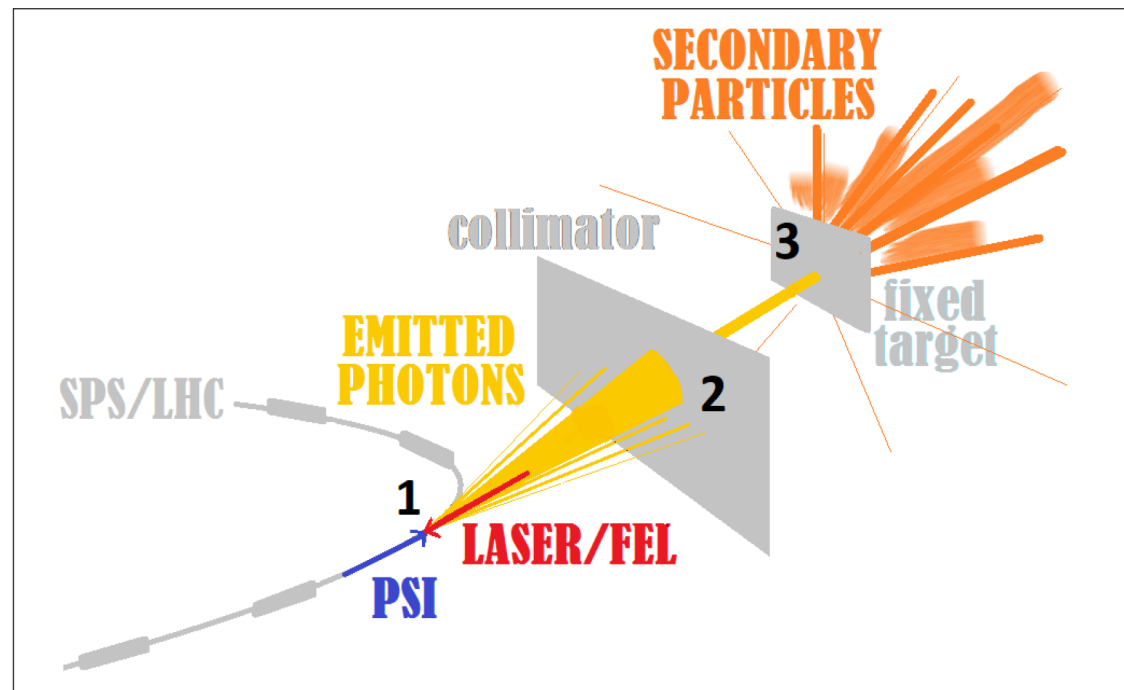
(ion undisturbed!)

...stable ion beams, even in the regime of multi photon emission per turn!  
The source intensity is driven by the power of the storage ring RF cavities!

# The $\gamma$ -ray source scheme for CERN



# Gamma Factory



# Beams and collision schemes

## primary beams:

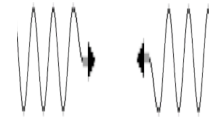
- partially stripped ions
- electron beam (for LHC)
- gamma rays

## secondary beam sources:



- polarised electrons,
- polarised positrons
- polarised muons
- neutrinos
- neutrons
- vector mesons
- radioactive nuclei

## collider schemes:



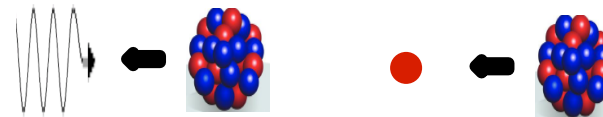
$\gamma$ - $\gamma$  collisions,

$$E_{\text{CM}} = 0.1 - 800 \text{ MeV}$$



$\gamma$ - $\gamma_L$  collisions,

$$E_{\text{CM}} = 1 - 100 \text{ keV}$$



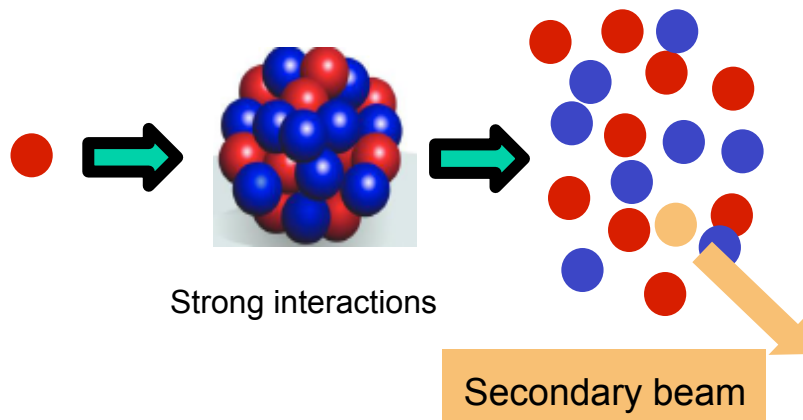
$\gamma$ -p(A), ep(A) collisions,

$$E_{\text{CM}} = 4 - 200 \text{ GeV}$$

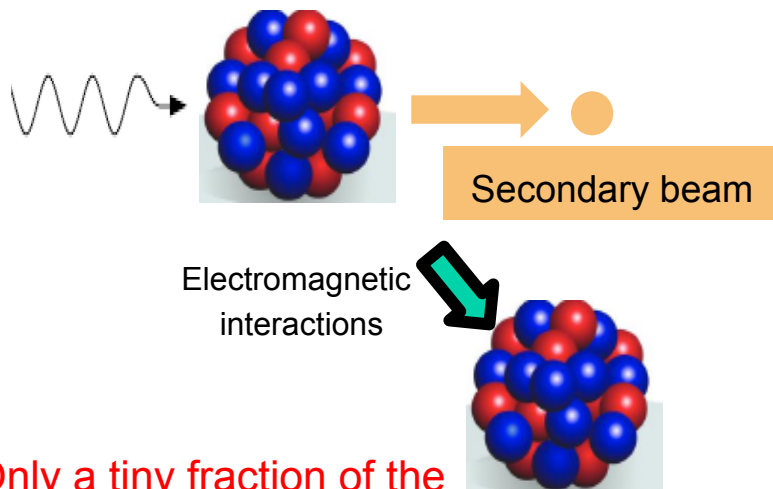
# Gamma Factory secondary beams

(from “mining” paradigm to “production-by-demand” paradigm)

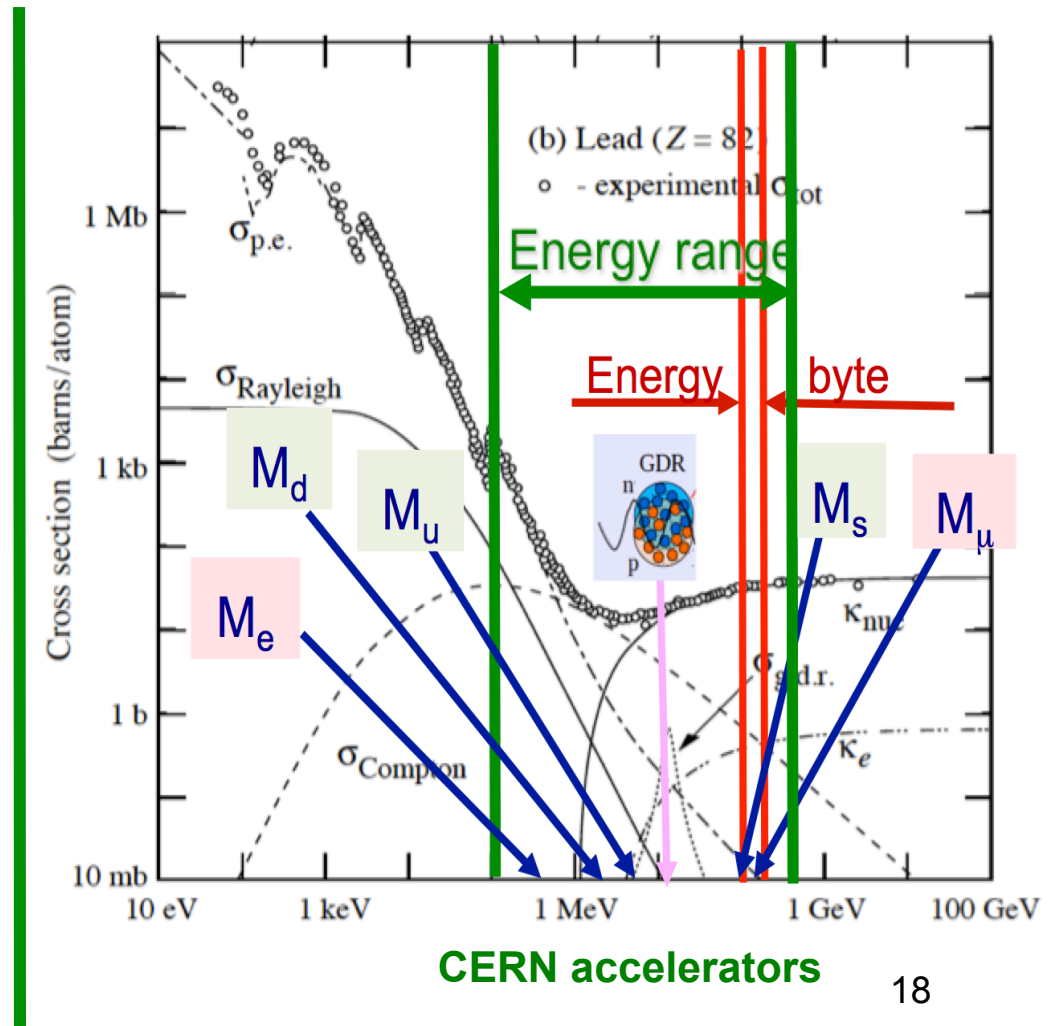
## “mining” paradigm:



## “production” paradigm:



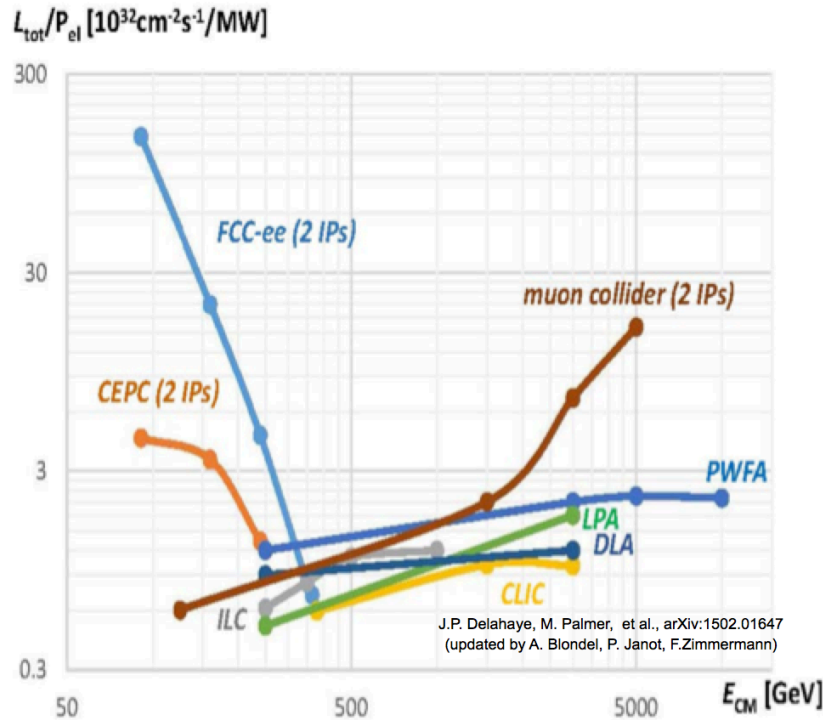
Only a tiny fraction of the primary beam energy is wasted!



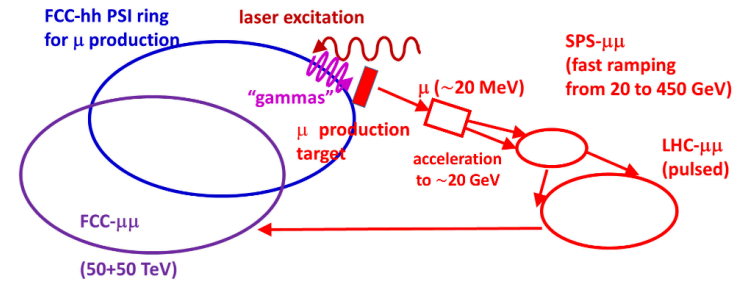
# The Gamma Factory beam intensity targets

- Highly ionised atoms – new at relativistic energies
- Photons – up to a factor of  $10^7$  gain in intensity w.r.t the present gamma sources
- Polarised positrons – up to a factor of  $10^4$  gain in intensity w.r.t KEK positron source
- Polarised muons - up to a factor  $10^3$  gain in intensity w.r.t to PSI muon source – (low emittance beams → muon collider, high purity neutrino beams)
- Neutrons – up to a factor of  $10^4$  in flux of primary neutrons per 1 kW of the driver beam power
- Radioactive ions – up to a factor  $10^4$  gain in intensity w.r.t to e.g. ALTO

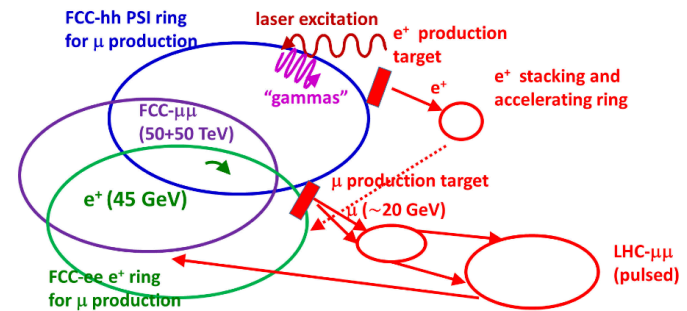
# Example: Variants of 100 TeV muon colliders based on the FCC and Gamma Factory concepts



For the CM-energies above 2 TeV (10 fold increase w.r.t LEP) a muon collider appears to be the only way to achieve a requisite luminosity with reasonable wall power consumption



100 TeV  $\mu$  collider FCC- $\mu\mu$  with FCC-hh PSI  $e^+$  & FCC-ee  $\mu^\pm$  production

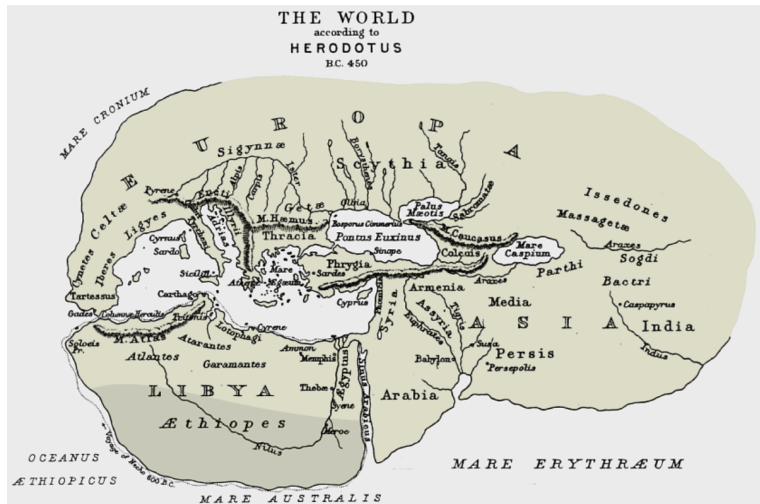


## LHC/FCC-BASED MUON COLLIDERS\*

F. Zimmermann<sup>†</sup>, CERN, Geneva, Switzerland

# The way forward

(from the GF initiative to the GF project)

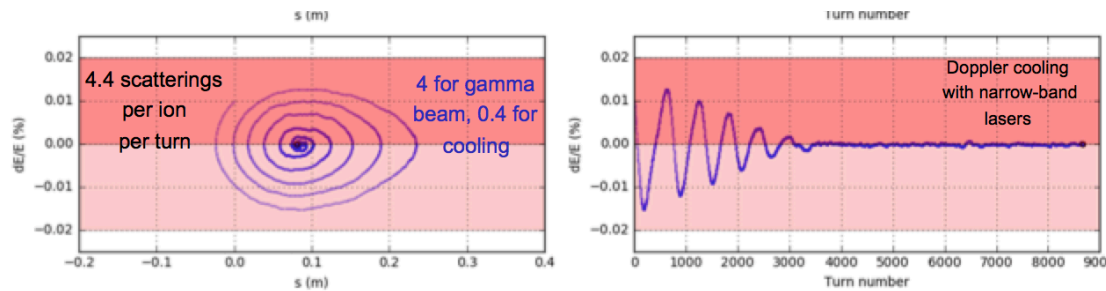


# The Gamma Factory feasibility proof milestones

1. *Understanding of production, acceleration and storage of the PSI beams in the CERN accelerator complex (choice of ions, ion stripping schemes, beam transfers, understanding the PSI beam dynamics, understanding of the PSI beam particles losses beam tests with Xe and Pb ions in 2017 and 2018 – SPS and LHC (S. Hirlander, IPAC2018)*
2. *Development of the simulation tools for collisions of photon and ion bunches (C Curatolo, IPAC2018)*
3. *Study of the concrete GF implementation scenarios (SPS and LHC): choice of ions, choice of lasers and collision geometry,.*
4. *POP experiment in the SPS ring including PSI beam cooling demonstration.*
5. *Evaluation of the physics highlights of the Gamma Factory research programme.*
6. *Gamma Factory project TDR.*

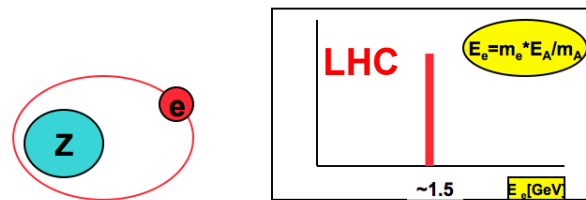
# Potential impact of the Gamma Factory R&D on the on-going CERN programme (examples)

- Doppler beam cooling technology (*PWA, HL-(AA)-LHC*)



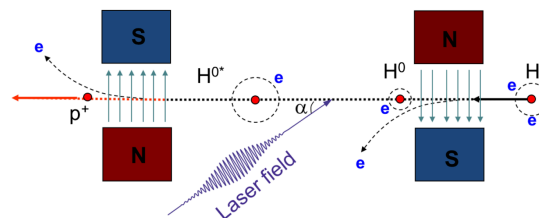
SPS simulations: A. Petrenko

- “No cost”, monochromatic electron beam (*AWAKE, LHC exp.*)



See: Nucl.Instrum.Meth. A540 (2005) 222-234

- $H^-$  injection scheme to circular machines



recent progress: PRL 118, 074801 (2017)

# Conclusions

*In the present phase of the accelerator-based HEP research – in which we no longer have any theoretical guidance for a new physics “just around the corner, accessible by ILC, FCC or CLIC”, nor a “reasonable cost” technology for a leap into very high energy “terra incognita” – the high-risk, high gain, initiatives become particularly important.*

*The target goal of the Gamma Factory initiative presented in this talk is to create, at CERN, a variety of novel research tools, which could potentially open new research opportunities in a very broad domain of basic and applied science.*

*Following the phase of its conceptual development the Gamma Factory initiative enters the phase of its experimental tests and simulation studies aiming to prove its feasibility (first step: dedicated GF SPS and LHC test runs with partially stripped ions in 2017 and 2018) – stay tuned.*