The Gamma Factory

GDR-InF workshop – the future of the intensity frontier?

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Introduction

November

2015

The Gamma Factory proposal for CERN †

Abstract

This year, 2015, marks the centenary of the publication of Einsteins Theory of General Relativity and it has been named the International Year of Light and light-based technologies by the UN General Assembly It is thus timely to discuss the possibility of broadening the present CERN research program by including a new component based on a novel concept of the light source which could pave a way towards a multipurpose Gamma Factory. The proposed light source could be realized at CERN by using the infrastructure of the existing accelerators. It could push the intensity limits of the presently operating light-sources by at least 7 orders of magnitude, reaching the flux of the order of 10^{17} photons/s, in the particularly interesting γ-ray energy domain of $1 \leq E_{photon} \leq 400$ MeV. This domain is out of reach for the FEL-based light sources. The energy-tuned, quasi-monochromatic gamma beams, together with the gamma-beams-driven secondary beams of polarized positrons, polarized muons, neutrons and radioactive ions would constitute the basic research tools of the proposed Gamma Factory. The Gamma Factory could open new research opportunities at CERN in a vast domain of uncharted fundamental physics and industrial application territories. It could strengthen the leading role of CERN in the high energy frontier research territory by providing the unprecedented-brilliance secondary beams of polarized muons for the TeV-energy-scale muon collider and for the polarized-muon-beam based neutrino factory.

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

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December 2017

The Gamma Factory group:

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GF group is embedded within the CERN Physics Beyond Colliders framework

It is open to everyone willing to join and contribute to this initiative!

The Gamma Factory in a nutshell

- *Accelerate and store at CERN high energy beams of Partially Stripped Ions and excite their atomic degrees of freedom, by laser photons to form high intensity primary beams of gamma rays and, in turn, secondary beams of polarised leptons, neutrinos, vector mesons, neutrons and radioactive ions.*

- *Provide a new, highly efficient scheme of transforming the accelerator RF power (selectively) to the above primary and secondary beams achieving a leap in their intensity and/or brightness, with respect to the existing facilities.*

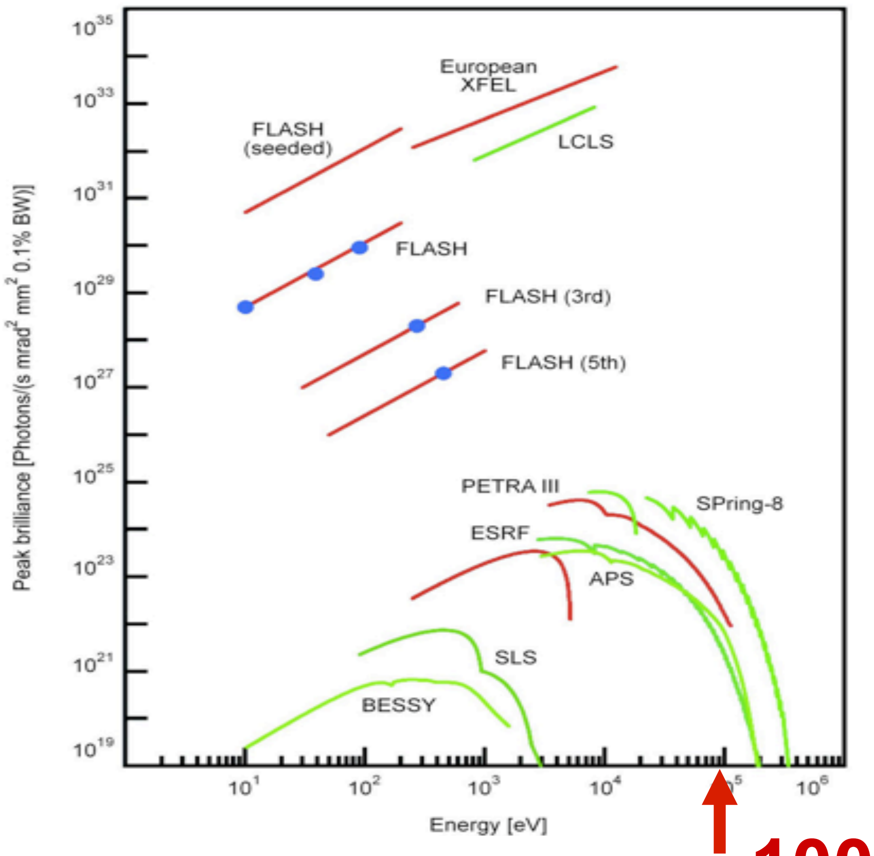
- *Use the primary and the secondary beams as principal tools of the Gamma Factory research programme.*

The Gamma Factory intensity/beam quality promise

- ***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*
- ***Neutrons*** – *up to a factor of 10^4 in number of neutrons per 1 kW of the driver beam power*
- ***Radioactive ions*** – *up p to a factor 10^4 gain in intensity w.r.t to ALTO*

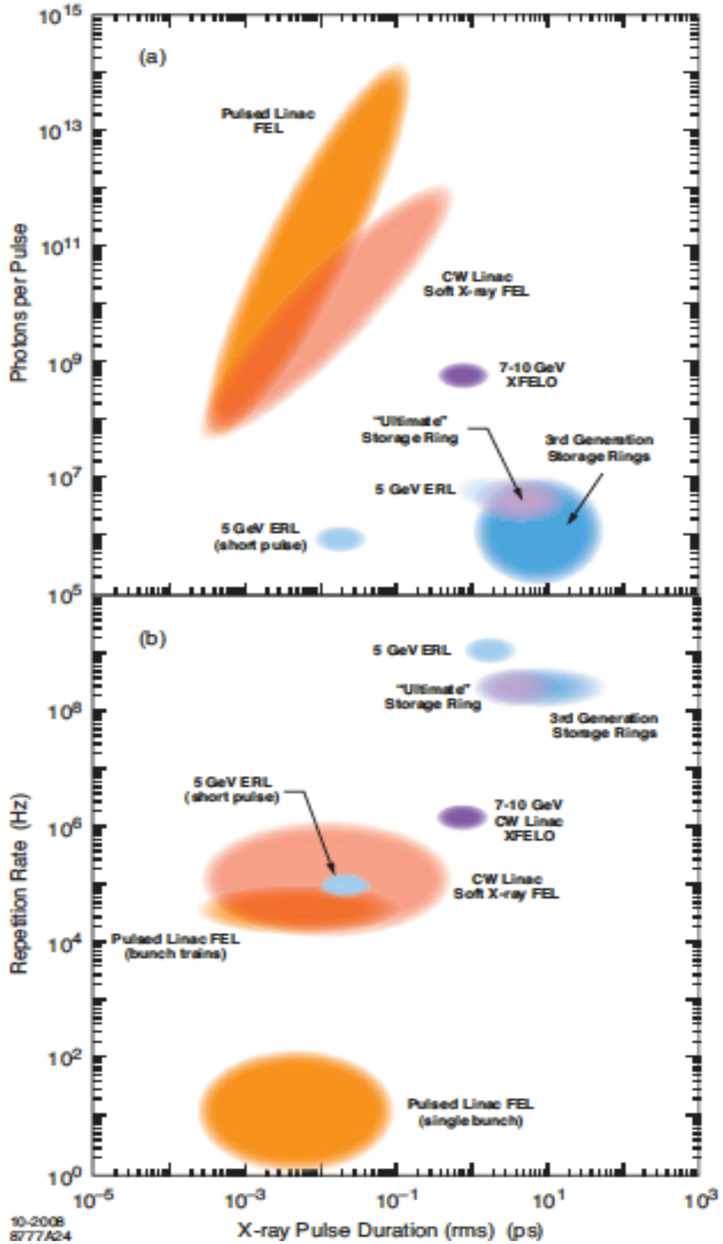
The γ-ray source as a backbone of the Gamma Factory

X-ray sources



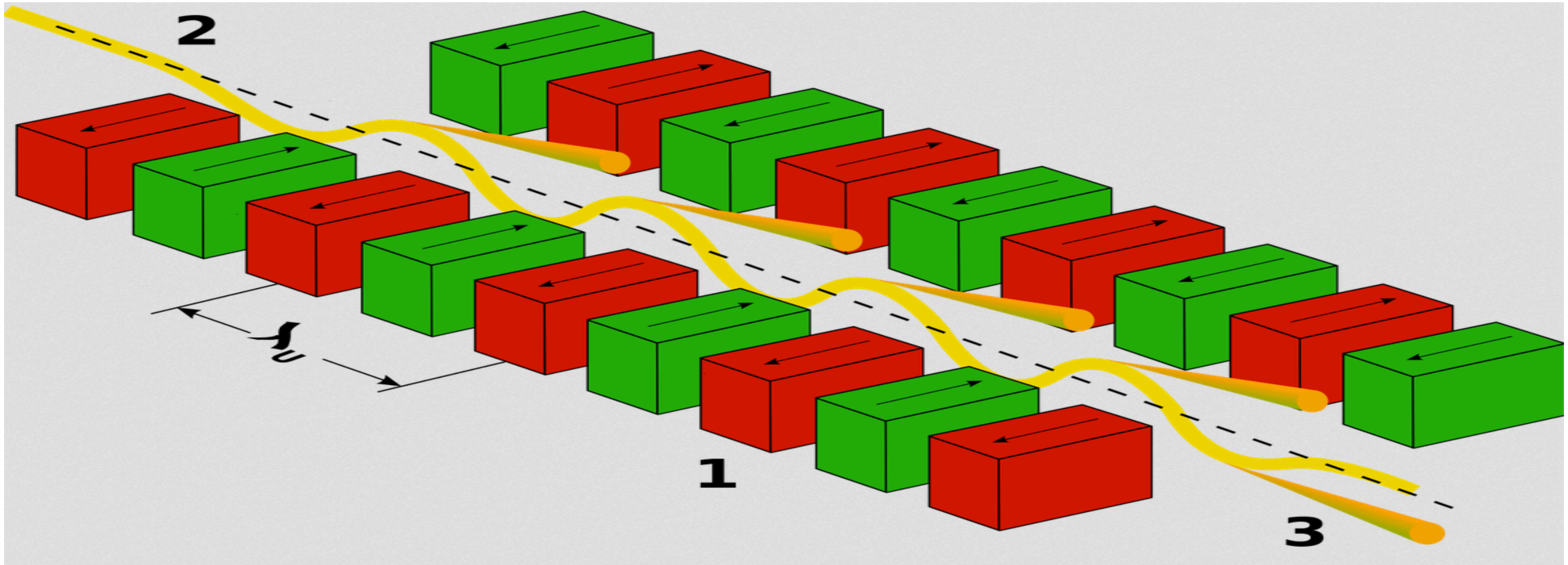
100 keV

Energies up to ~ 100 keV



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

FEL as a γ-ray source?

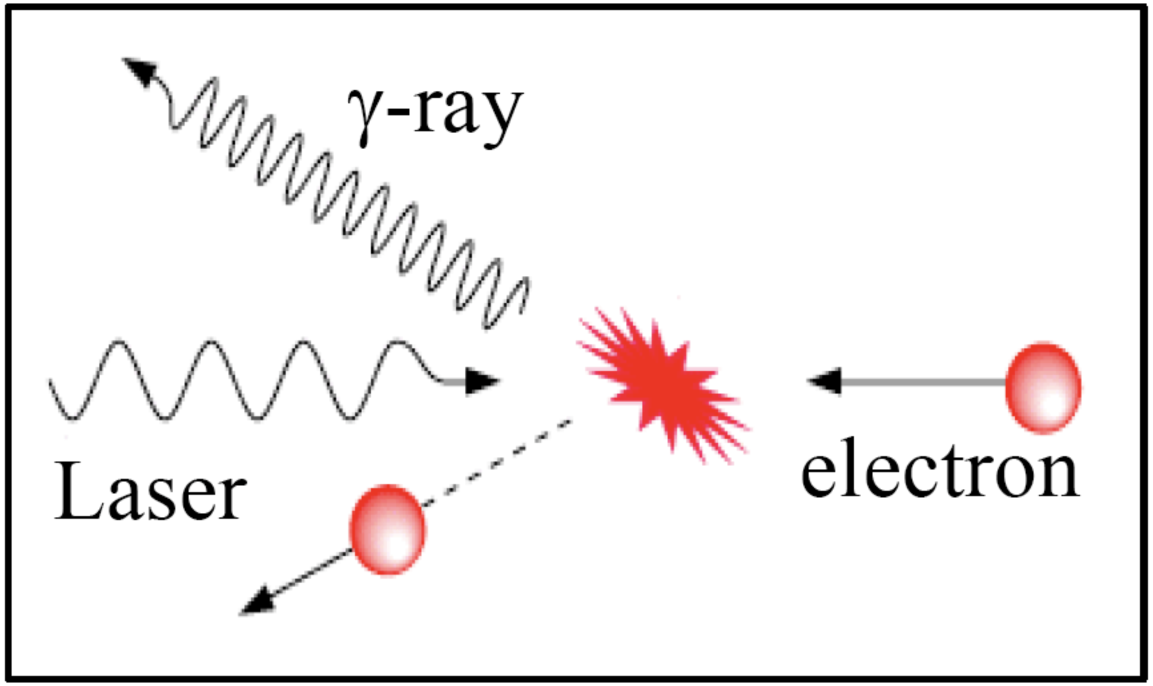


$$\lambda_r = \frac{\lambda_u}{2\gamma^2}(1 + K^2),$$

$$K = \frac{\gamma \lambda_u}{2\pi\rho} = \frac{eB_0\lambda_u}{\sqrt{8}\pi m_e c}$$

Need low emittance electron beams spanning the beam energy range of 1-10 TeV (assuming O(10 cm) period of magnetic field – not available in the foreseeable future)

Laser Compton Scattering as a γ-ray source



Parameters of the γ-ray sources around the world

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

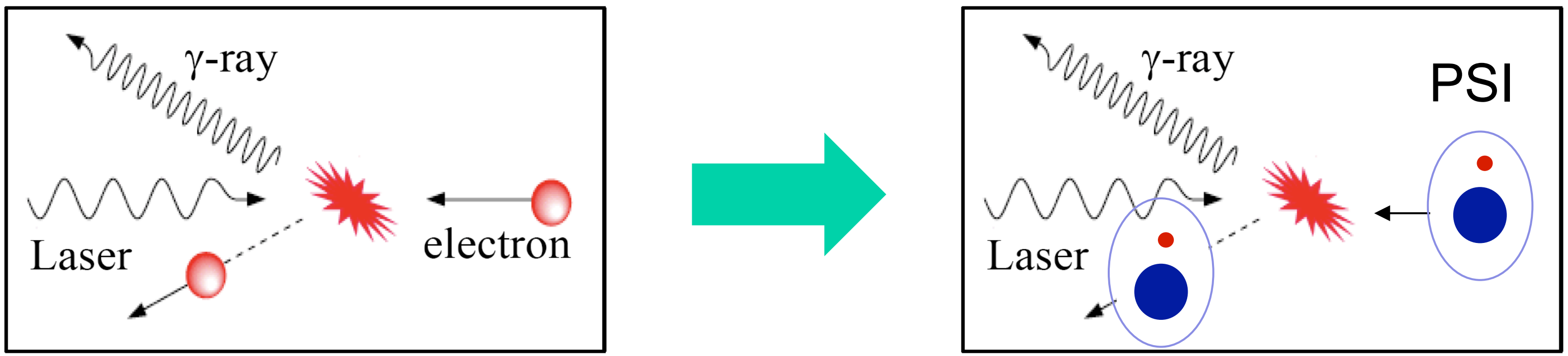
The Gamma Factory goal: achieve comparable fluxes in the MeV domain as those in the KeV domain

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

An intensity jump by several orders of magnitude required !

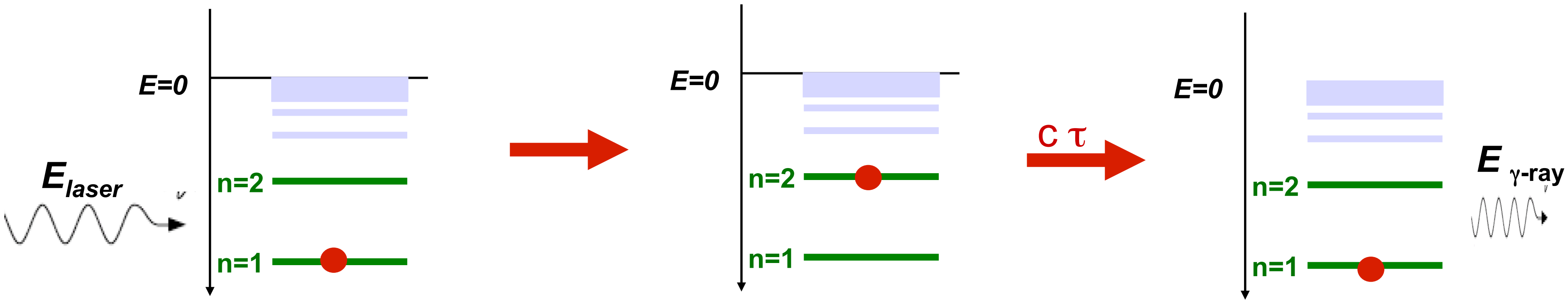
The gamma ray source for Gamma Factory

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



Scattering of photons on ultra-relativistic hydrogen-like, ions

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



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

Partially Stripped Ion (PSI) beam as a light frequency converter

$$\nu^{max} \longrightarrow (4\,\gamma_L^{\,2})\,\nu_i$$

γ_L =E/M - Lorentz factor for the ion beam

The tuning of the beam energy (SPS or LHC), the choice of the ion type, the number of left electrons and of the laser type allows to tune the γ-ray energy at CERN in the energy domain of 100 keV – 400 MeV.

Example (maximal energy):

LHC, Pb^{80+} *ion,* $\gamma_L = 2887$, n=1→2, λ_{laser} = 104.4 nm, E_γ (max) = 396 MeV

The magnitude of the γ-source intensity leap

Electrons:

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

r_e - classical electron radius

Partially Stripped Ions:

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

λ_{res} - photon wavelength in the ion rest frame

Electrons:

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

Partially Stripped Ions:

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

Numerical example: λ_{laser} = 1540 nm

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

~ 7 orders of magnitude increase of gamma fluxes

A leap in the gamma source efficiency

Example: Pb, hydrogen-like ions,
stored in LHC γ_L = 2887

Electrons:

E_{beam} = 1.5 GeV

Electron fractional energy loss:
emission of 150 MeV photon:
$E_\gamma/E_{beam} = 0.1$

(electron is lost!)

Partially stripped ions:

E_{beam} = 574 000 GeV

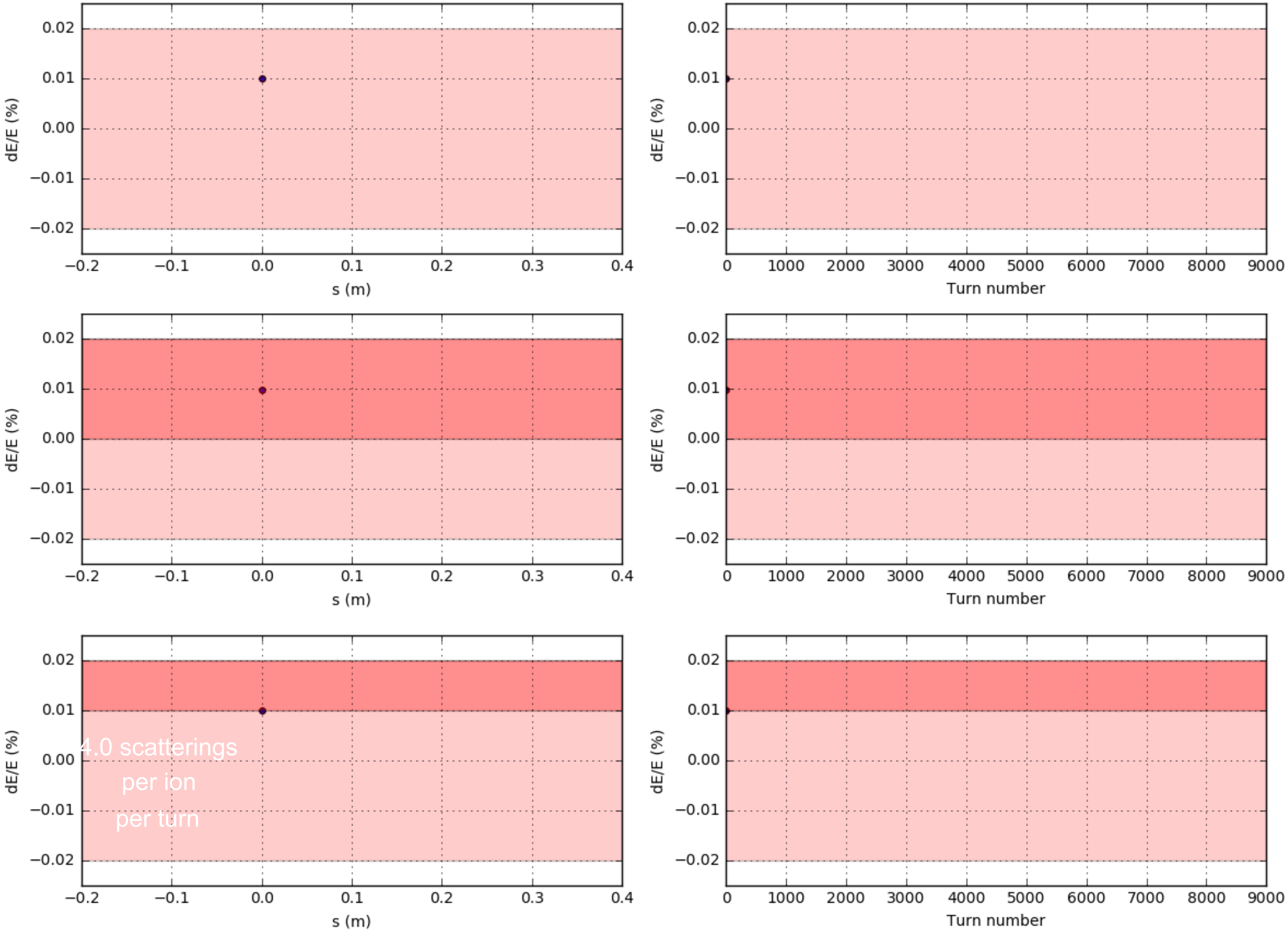
Electron fractional energy loss:
emission of 150 MeV photon:
$E_\gamma/E_{beam} = 2.6 \times 10^{-7}$

(ion undisturbed!)

…stable ion beams, even in the regime of multi photon emission per turn!

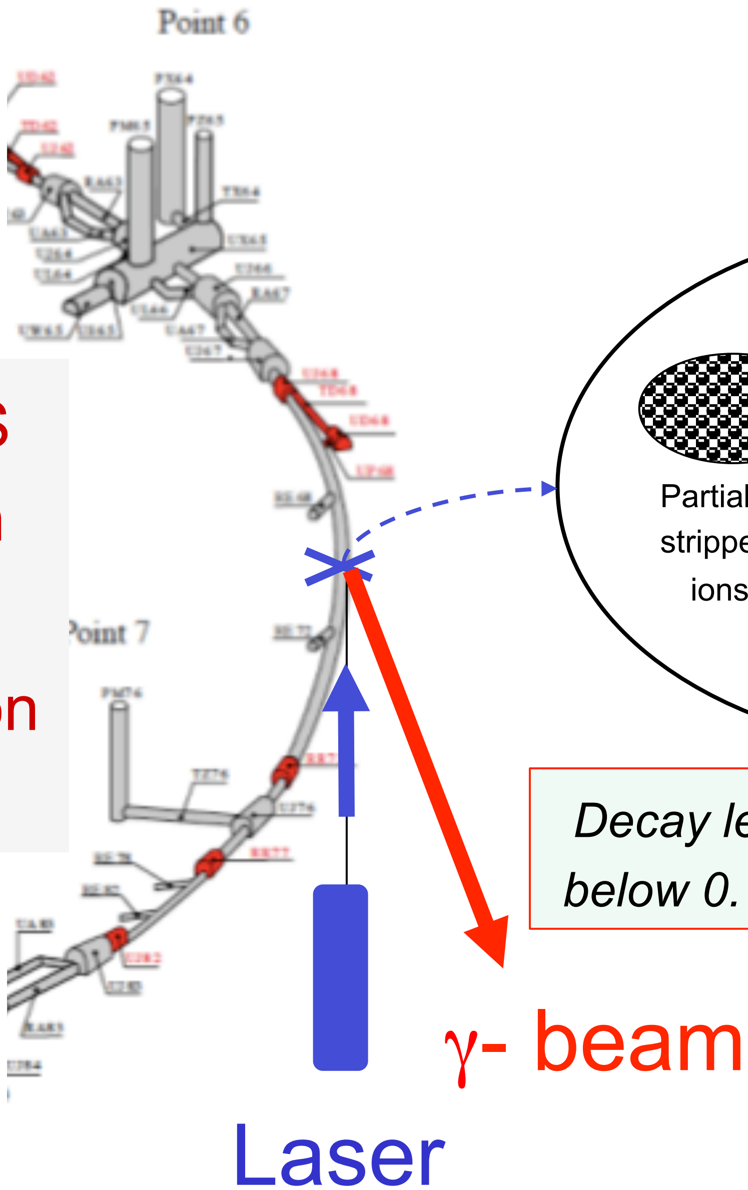
The source intensity is driven by the power of the storage ring RF cavities!

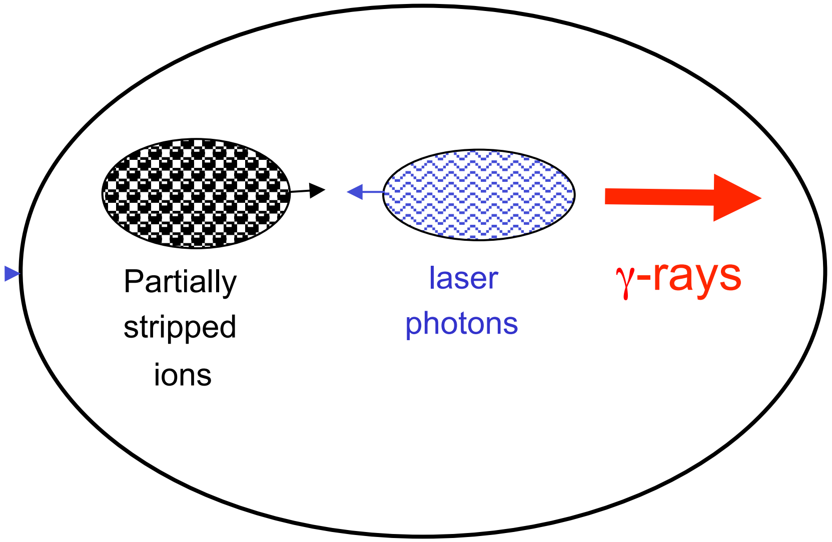
PSI beam stability and cooling simulations (A. Petrenko)



The γ-ray source scheme for CERN

LHC/SPS filled with partially stripped ion bunches





Decay length in the LAB frame $c\,\tau \sim \gamma_L/Z^4$
below 0.1 mm for $Pb^{81+}(2p) \rightarrow Pb^{81+}(1s) + \gamma$

The Gamma Factory research tools

Beams and collision schemes

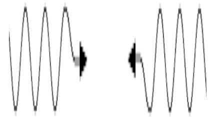
primary beams:

- **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_{CM} = 0.1 – 800 MeV

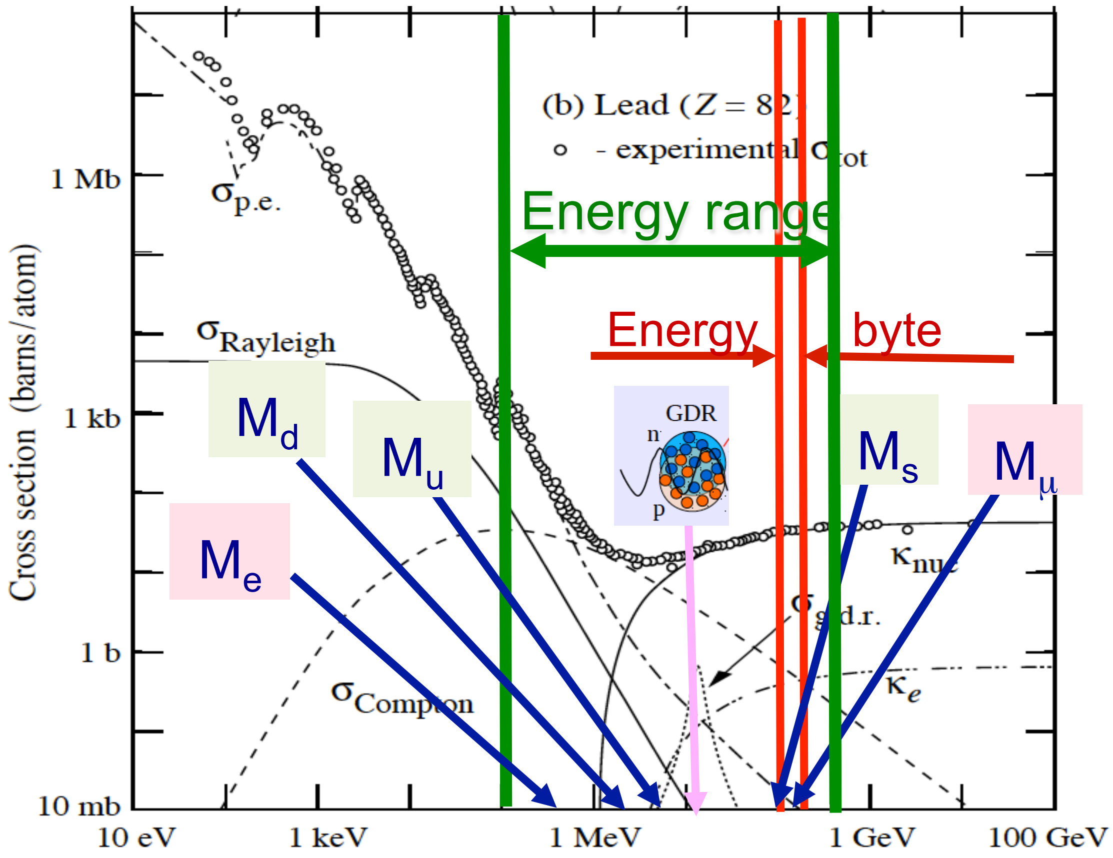
$\gamma-\gamma_L$ collisions,

E_{CM} = 1 – 100 keV

γ–p(A), ep(A) collisions,

E_{CM} = 4 – 200 GeV

Collisions of photons with matter



$\sigma_{\text{p.e.}}$ = Atomic photoelectric effect (electron ejection, photon absorption)

σ_{Rayleigh} = Rayleigh (coherent) scattering–atom neither ionized nor excited

σ_{Compton} = Incoherent scattering (Compton scattering off an electron)

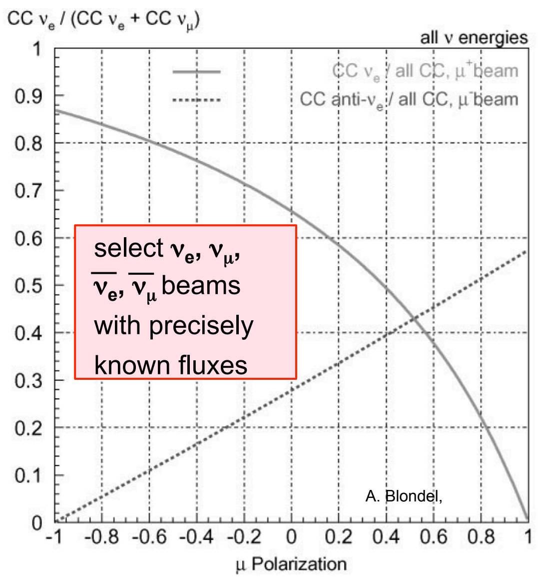
κ_{nuc} = Pair production, nuclear field

κ_e = Pair production, electron field

$\sigma_{\text{g.d.r.}}$ = Photonuclear interactions, most notably the Giant Dipole Resonance. In these interactions, the target nucleus is broken up.

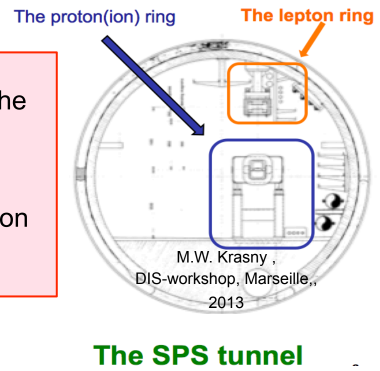
Promises of GF research tools - examples

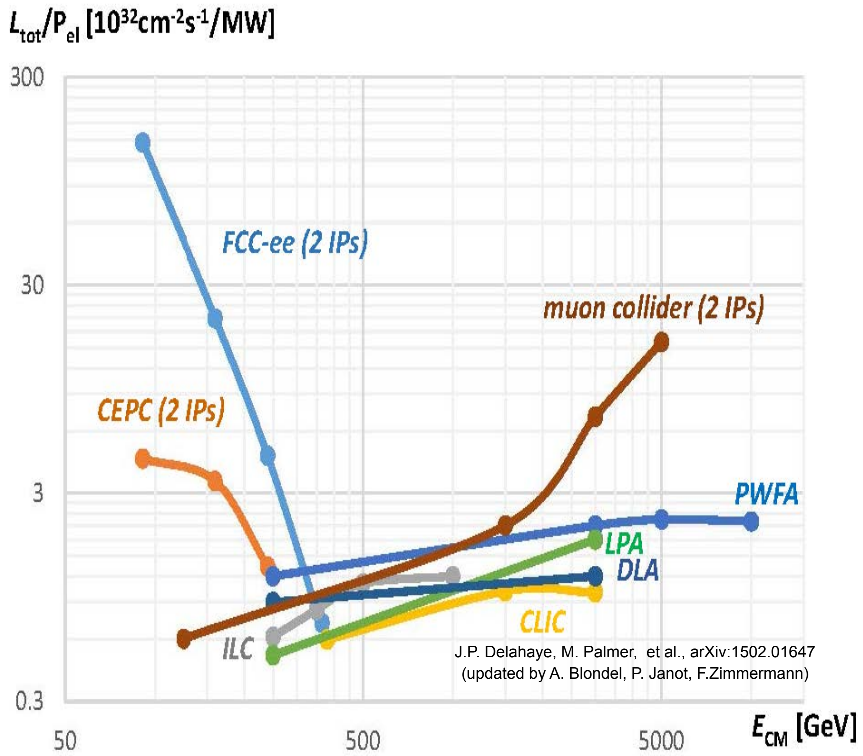
Low emittance, high intensity polarised positron and muon source for:
(1) ν-factory, (2) muon collider and (3) lepton-proton collider



select ν_e, ν_μ, $\overline{\nu}_e$, $\overline{\nu}_\mu$ beams with precisely known fluxes

Polarised e^+ and e^- for the "LHC precision support" DIS scattering program,
μ^+ and μ^- for the TeV region Lepton-Proton collider

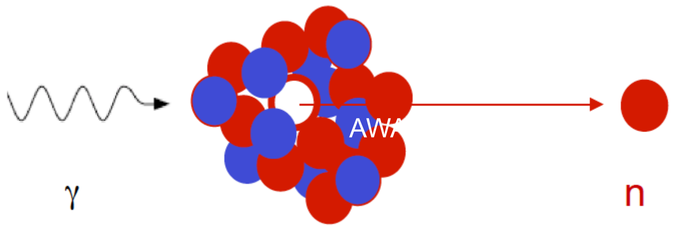




For the CM-energies above 2 TeV (10 fold increase w.r.t LEP) a muon collider appears to be the only way to achieve a requisite luminosity with reasonable wall power consumption

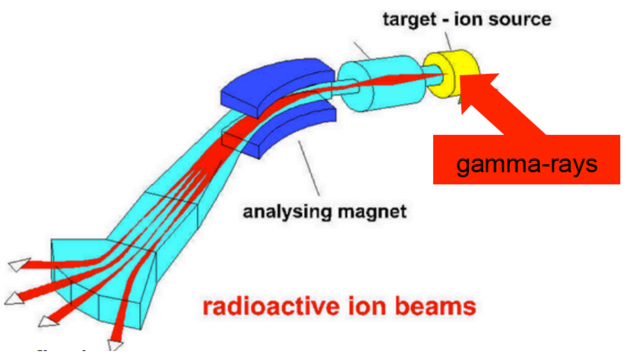
Promises of GF research tools - examples

Monochromatic neutron source



Resonant production (GDR) – maximises $N_{neutron}$/plug power

Radioactive ion source



Resonant production – maximises N_{ion}/plug power

Gamma Factory project milestones

1. *Produce high energy beams of highly ionised atoms (Partially Stripped Ions - PSI), accelerate them up LHC injection energy, inject and store them in the LHC ring(s).*

2. *Proof of Principle (PoP) experiment : collisions of the SPS PSI beams with the laser photons as a test-bed for the LHC gamma source.*

3. *Work out realistic schemes of producing the Gamma Factory secondary beams.*

4. *Quantitative evaluation of the Physics Reach of the Gamma Factory based research programme.*

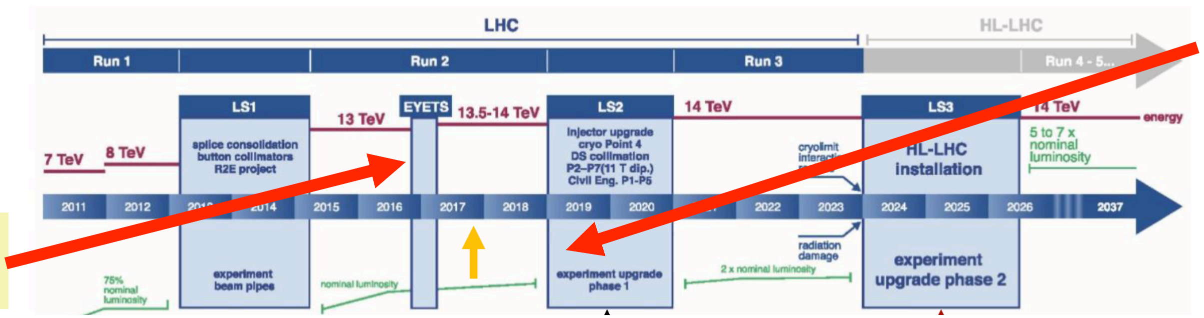
5. *TDR of the Gamma Factory project.*

Gamma Factory project-development constraints

1. *Do not disturb the canonical use of the accelerator complex*

2. *Respect the CERN accelerator running schedule*

Possible POP experiment installation



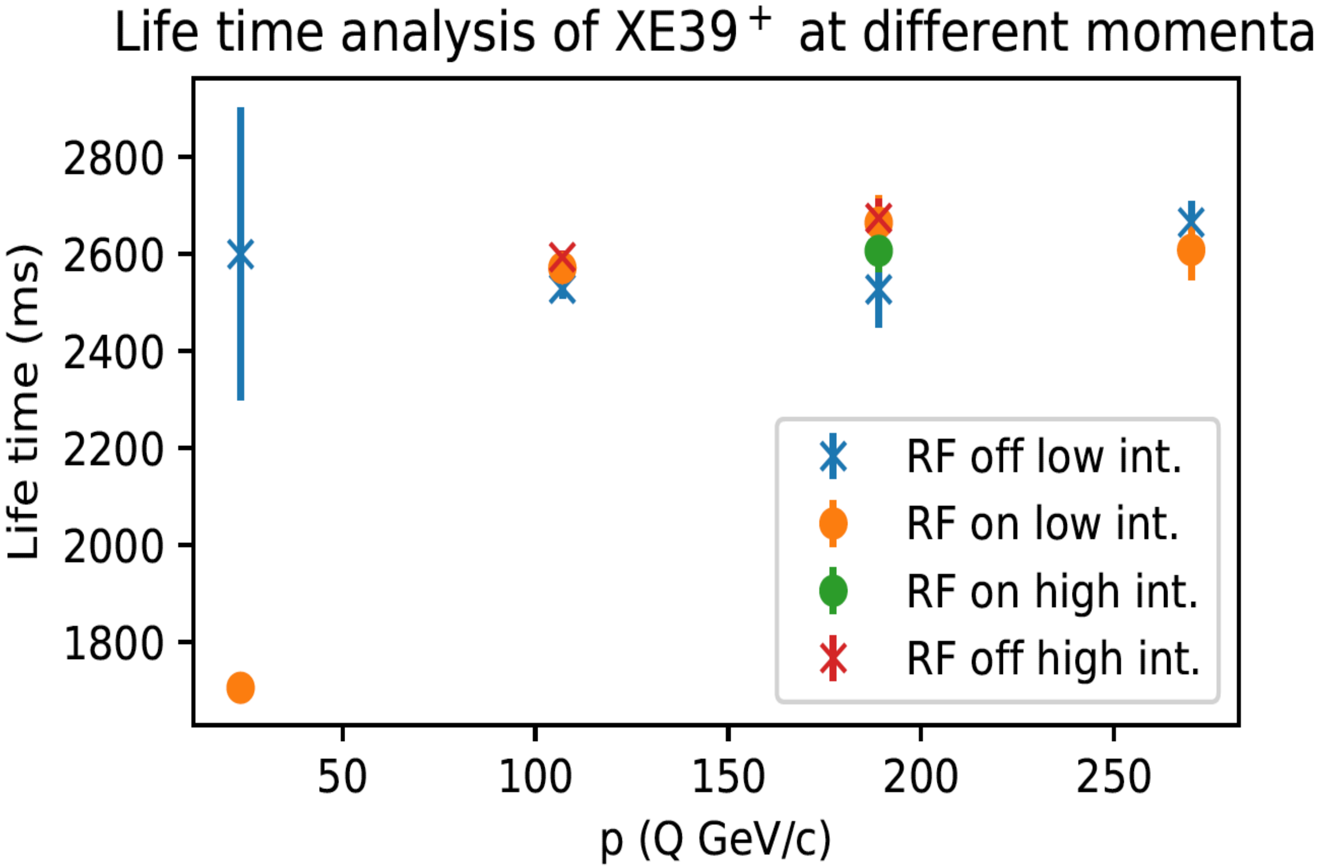
Strippers

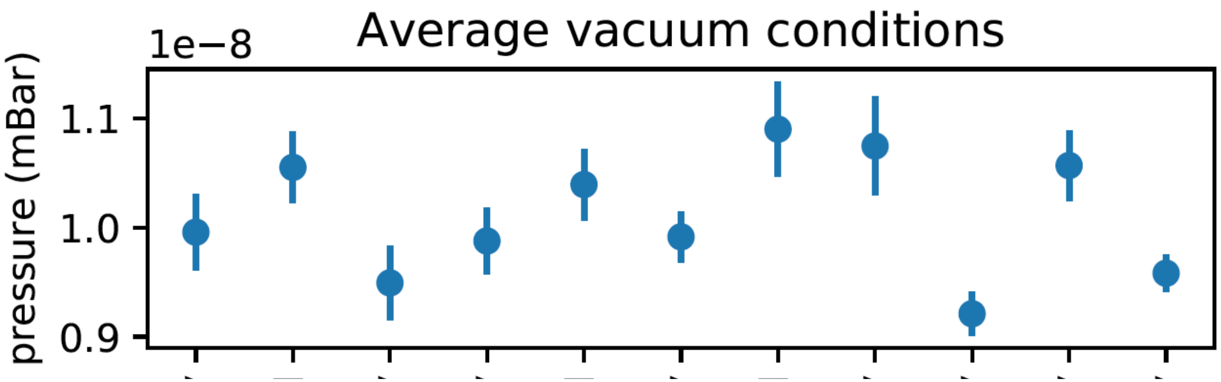
3. *Fit to the schedule of the PBC contribution to the European Strategy Process*

- Official launching of the process – September 2018;
- Collect inputs – end of 2018;
- Open meeting – mid May 2019;
- Drafting strategy update document – mid January 2020;
- Conclusion of the process – May 2020.

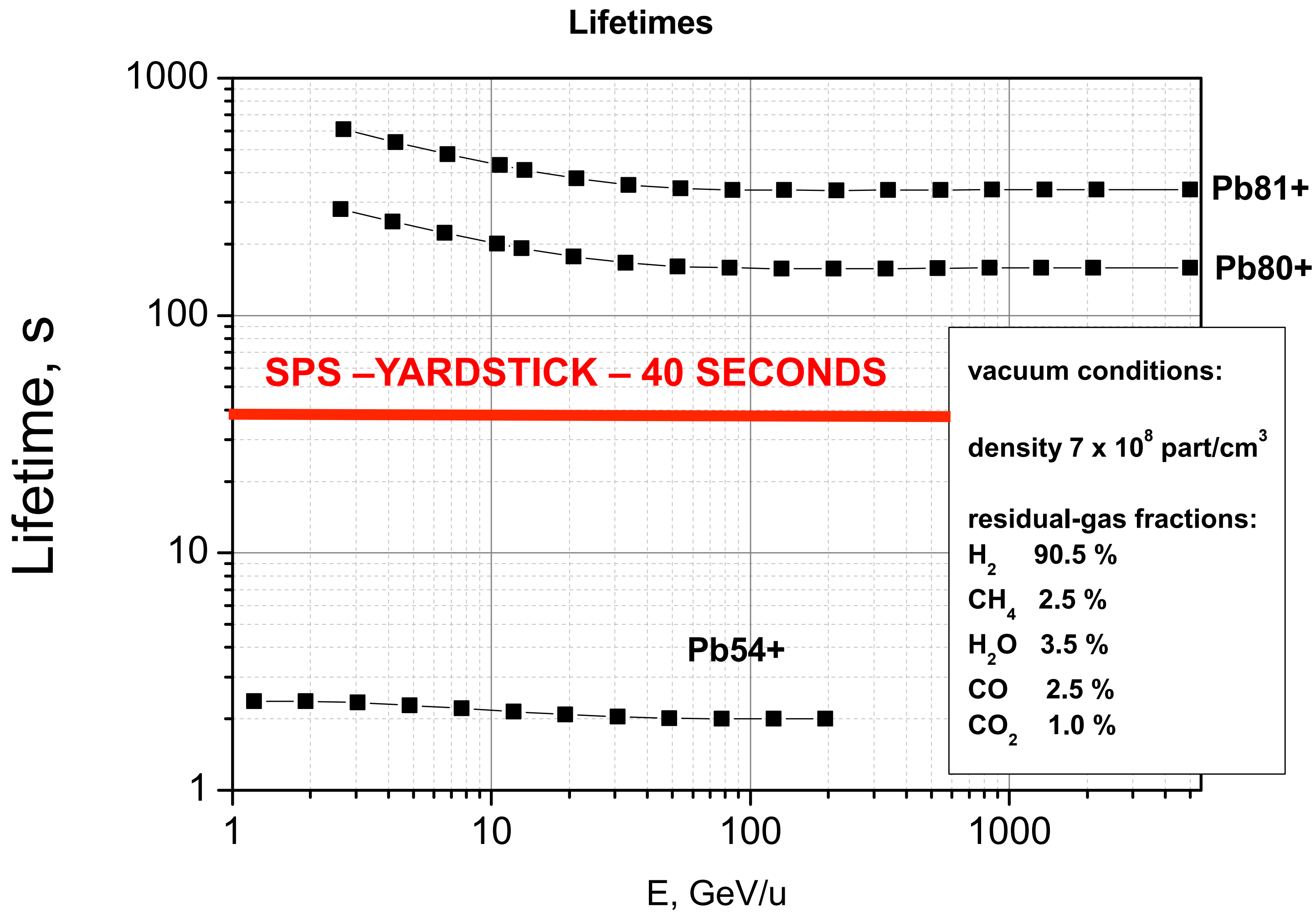
On-going studies

1. *Beam test (MD) studies with +39 Xe beam –* *(H. Bartosik, T. Bohl, S. Cettour, N. Biancacci,, **R.Alemany Fernandez**, S. Hirlander, V. Kain, M.W. Krasny, M. Lamont, D. Manglunki, G. Papotti, M. Schaumann, V.P. Shevelko, T. Soehlker)*
2. *Simulations of the optimal stripping schemes for the 2018 Pb runs* *(F.Kroeger, T. Stoehlker, G. Weber and M.W. Krasny)*
3. *Production and installation of the strippers for the +80 and +81 Pb runs in 2018* *(F. Roncarolo, S. Burger, S. Gilardoni and Reyes Alemany Fernandez)*
4. *Laser – PSI collisions - software development -- CAIN- based and stand-alone* *(W. Placzek, C Curatolo, A. Petrenko, I.Chaikowska, A. Apyan)*
5. *PSI beam stability studies and PSI beam cooling studies* *(A. Petrenko, E. Bessonov, P.S. Antsiferov,)*
6. *PoP experiment - conceptual development* *(F. Castelli, C.Curatolo, V. Petrillo, L. Serafini, K. Cassou, K. Dupraz, A. Martens, F. Zomer, B. Goddard, M.W. Krasny)*


Life time analysis of XE39$^+$ at different momenta
Life time (ms)
2800
2600
2400
2200
2000
1800
50
100
150
200
250
p (Q GeV/c)
RF off low int.
RF on low int.
RF on high int.
RF off high int.


Average vacuum conditions
1e−8
pressure (mBar)
1.1
1.0
0.9

Simulation results (Slava Shevelko)



LHC and the SPS rest gas molecules

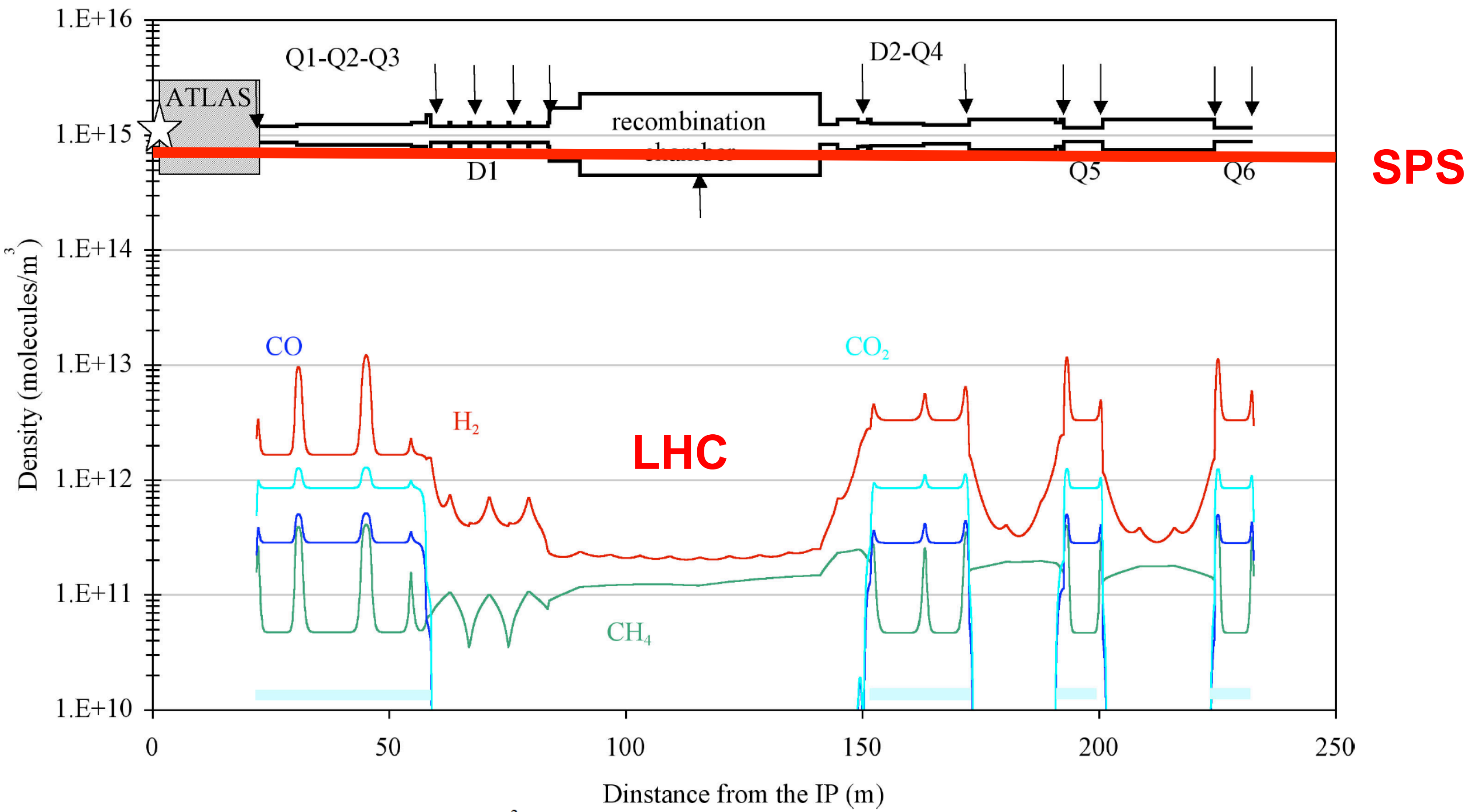


Figure 4: Residual gas density (molecules·m^{-3}) profile in the interaction regionIR1, for the “after machine conditioning” period, at nominal beam current and top energy.

Plans and goals for the year 2018

1. *MDs with +80, +81 and +54 Pb beams in SPS.*
2. *MDs with +80 and/or +81 Pb beam in the LHC.*
3. *Electron-proton collisions in the LHC experiment's IPs*
   (if of interest for the LHC experiments).
4. *A special SPS run with +80 Pb beam extracted to AWAKE zone (?)*

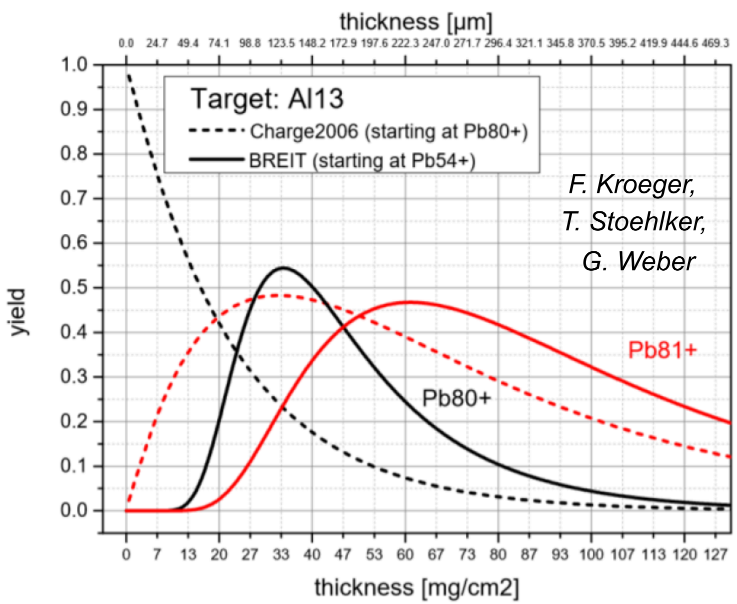
In parallel:

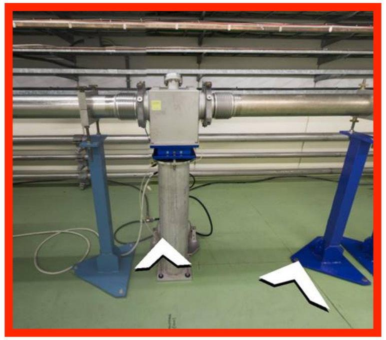
- *Proof of Principle (PoP) experiment design and a LOI to SPSC.*
  Two open options: (1) extracted beam, (2) beam circulating in the SPS.
- *Software development: Further development of the code for PSI beam dynamics and gamma beam production and collimation.*
- *Software development: A specialized code for production of the GF secondary beams.*
- *Elaboration of the Physics reach of the Gamma Factory proposal in each of its application domains.*

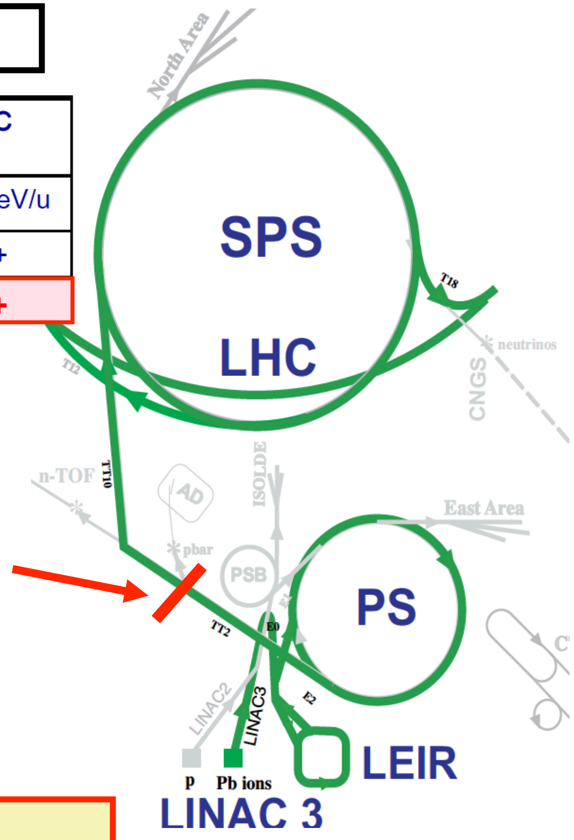
Preparing electron-striping schemes for the dedicated SPS and LHC MDs in 2018 with Pb+81 (hydrogen-like) ions

Present stripping scheme for the LHC beam of fully stripped Pb ions

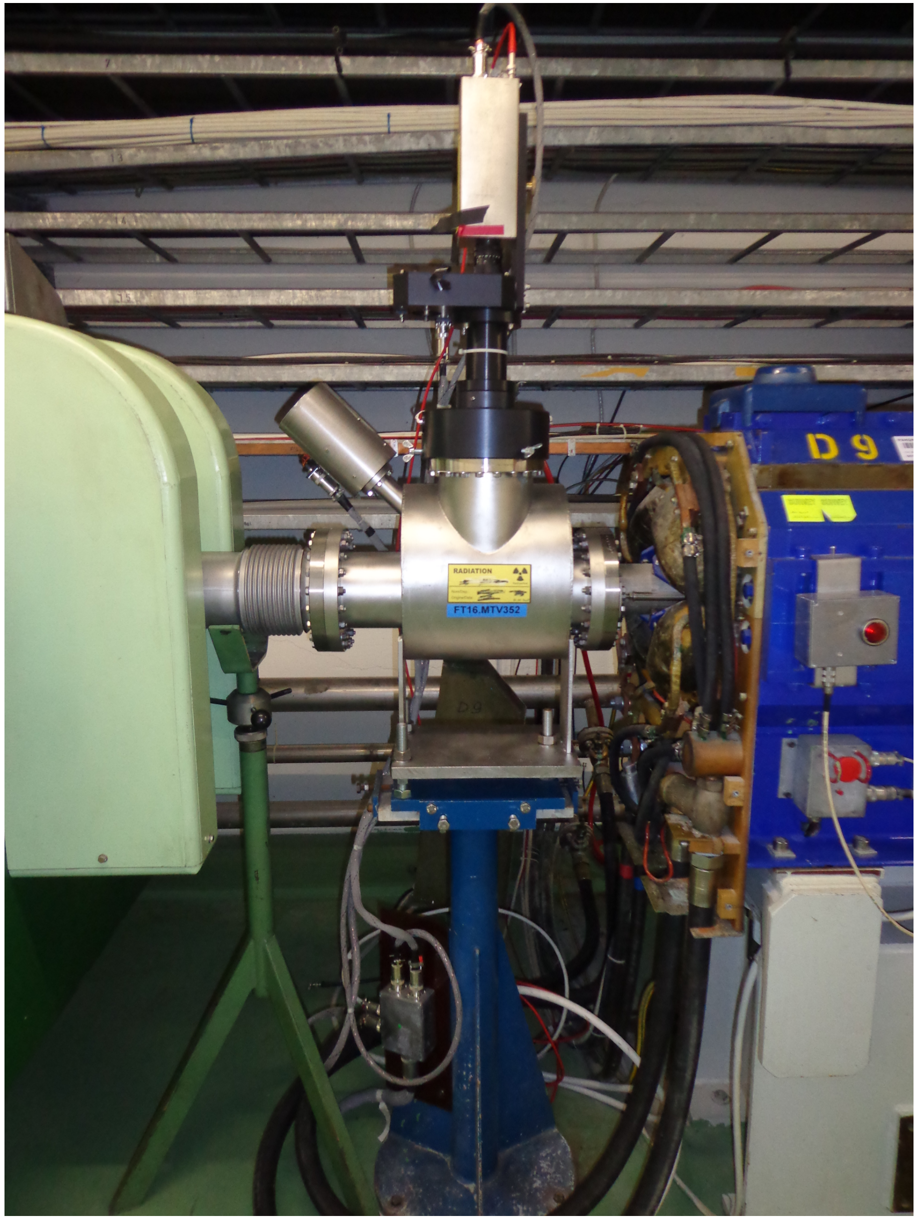
	ECR Source	Linac 3	LEIR	PS	SPS	LHC
Output energy	2.5 KeV/u	4.2 MeV/u	72.2 MeV/u	5.9 GeV/u	177 GeV/u	2.76 TeV/u
^{208}Pb charge state	29+	29+ → 54+	54+	54+ → 82+	82+	82+
				54+ → 81+	81+	81+



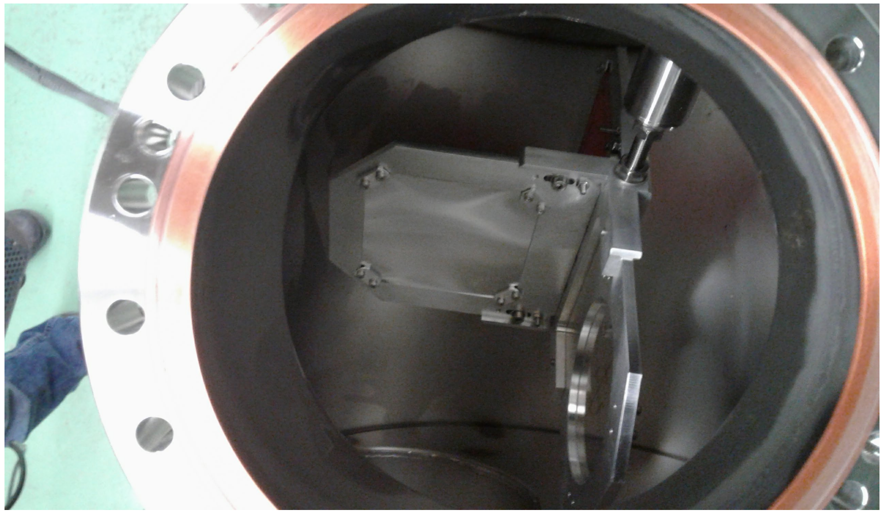




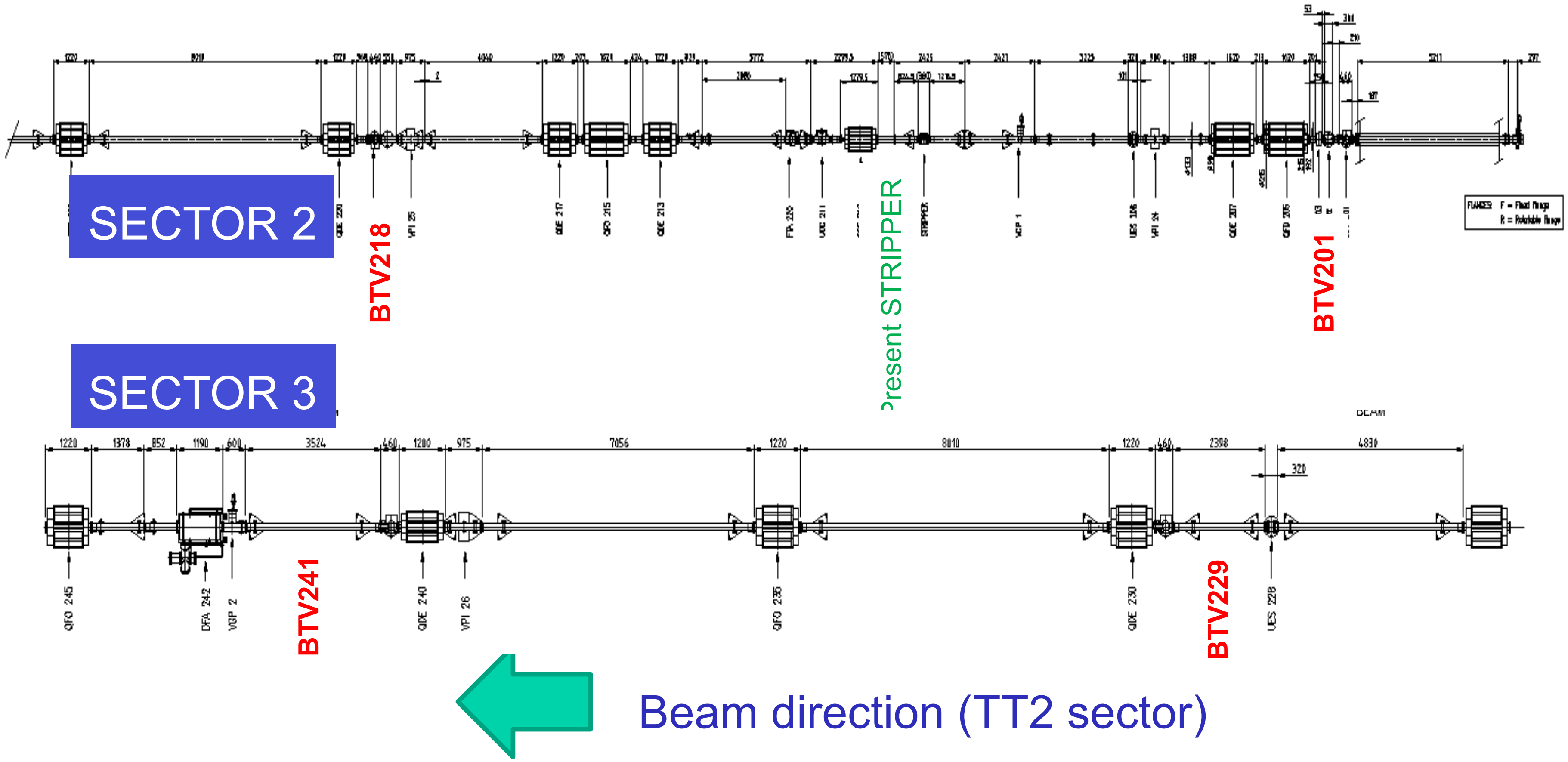
For PB+81 produce and install
A new GF-dedicated stripper



January 2018 – installation of the GF stripper in the TT2 transfer line

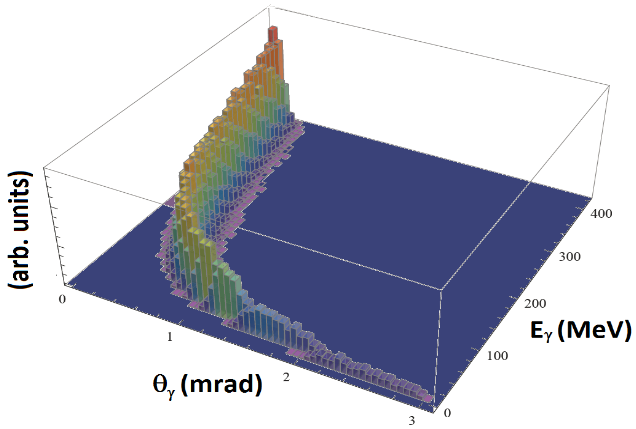


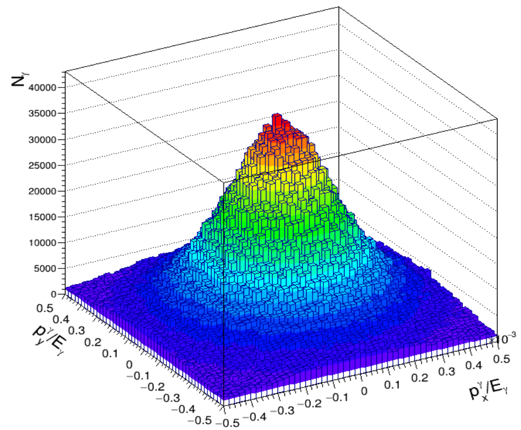
A back-up scheme for the hydrogen-like, +80 Pb beam

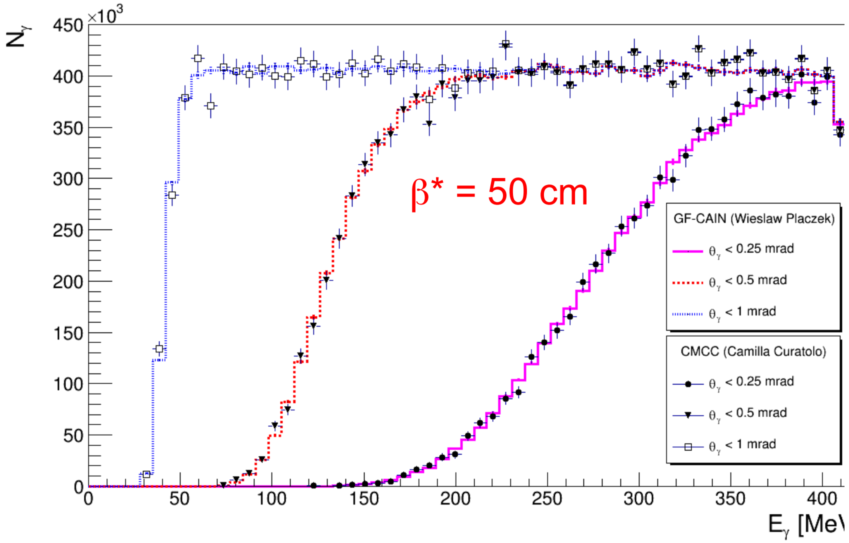


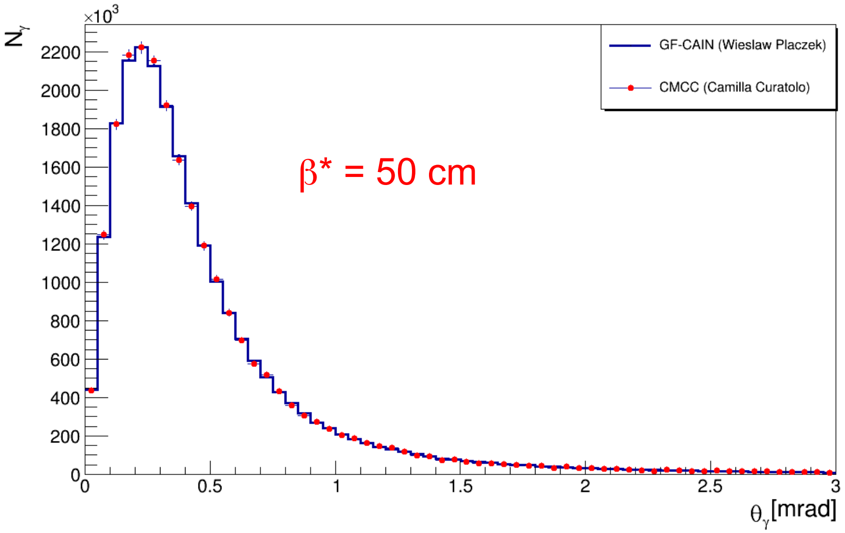
BTV229, **BTV241**, **BTV229** and **BTV241** instrumented with two types of screen: Al (10 μm) and Ti (12 μm) → we plan to use in 2018 a combination of these screens which maximises the +80 Pb beam intensity

Comparisons of two codes: Gamma ray production spectra for +81 Pb beam collisions with laser photons bunches at the top LHC energy: W.Placzek and C. Curatolo









Conclusions and a suggestion to the GDR-InF community

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

The Gamma Factory research programme, largely based on the existing CERN accelerator infrastructure -- and thus requiring a "relatively" minor infrastructure investments -- could fill the time-gap over which the new acceleration technology becomes available to re-address the high energy frontier of HEP.

The promise of technological leaps and the capacity to diversify the research program at CERN of the Gamma Factory is exciting but require further, in depths studies.

Such studies (both accelerator tests and requisite simulations) are already on the full swing -- in parallel to the canonical CERN research

The "urge of research diversification" is particularly amplified in the present phase of HEP research, as we neither have any solid theoretical guidance for a new physics "just around the corner, accessible by FCC or CLIC", nor a "reasonable cost" technology for a leap into very high energy " terra incognita".

The Gamma Factory study group is in its inflationary phase (expansion from a single person initiative to more than 40 members (representing 12 institutions in 8 countries) in less than two years, and growing). For its further expansion and consolidation a support and help coming from diverse communities is needed.

The target of help are the dedicated simulation studies which could translate the predicted leaps in the intensity of the GF beams into the physics gains in the wide spectrum of measurements at the high intensity frontier.

Fundamental Physics

- *Fundamental QED/EW measurements*
- *Precision EW-physics with high Z, H-like ions*
- *Anthropomorphic dark matter searches with gamma beams (ALPs, dark photons)*
- *Search of new physics in rare muon decays*
- *Towards a TeV scale muon collider*
- *Neutrino physics with pure muon, electron, neutrino and anti-neutrino beams*
- *Neutron dipole moment and neutron-antineutron oscillations*
- *Study of the confinement phenomena at the colour production threshold*
- *Study the CPT symmetries at the colour production threshold*
- *Physics with rare radioactive ions*
- *Physics of electron-proton and gamma-proton collisions at the LHC IPs*
- *DIS programme with polarised positrons and muons*

Applied Physics

- *Muon catalysed cold fusion*
- *Gamma-beam catalysed hot fusion*
- *Accelerator Driven Systems (ADS) and Energy Amplifiers (EA)*
- *Transmutation of nuclear waste*
- *Production of isotopes for Positron Emission Tomography (PET) and for the selective cancer-cell therapy with alpha emitters.*