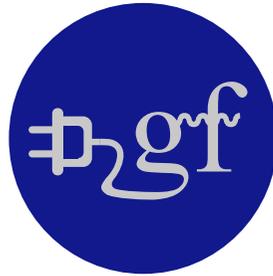


# The Gamma Factory proposal for CERN



*Photon-2017 Conference, May 2017*

Mieczysław Witold Krasny  
LPNHE, CNRS and University Paris Sorbonne

# The Gamma Factory in a nutshell

- *Accelerate and store 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, **by several (up to 7) orders of magnitude**, 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.*

## Its CERN framework

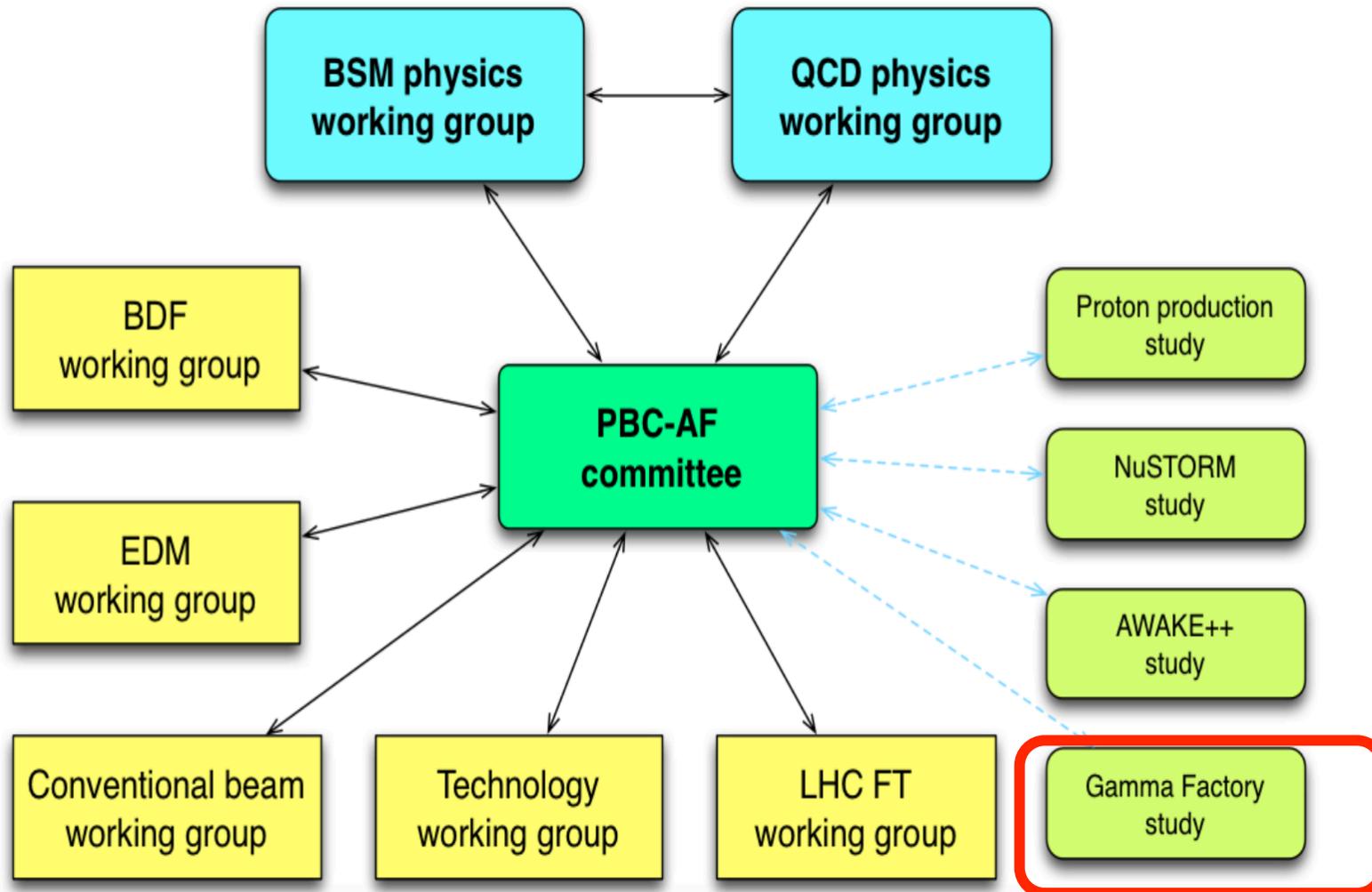
*The Gamma Factory initiative was proposed in ([arXiv:1511.07794](https://arxiv.org/abs/1511.07794) [hep-ex]) and recently endorsed by the CERN management by creating the Gamma Factory study group, embedded within the Physics Beyond Colliders studies framework:*

### **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.

# Its CERN framework



## The Gamma Factory group (as of today):

*E.G. Bessonov, Lebedev Physical Institute, Moscow, Russia; D. Budker<sup>†</sup>, Helmholtz Institute, Johannes Gutenberg University, Mainz, Germany; K. Cassou, I. Chaikovska, R. Chehab, K. Dupraz, A. Martens, F. Zomer, LAL Orsay, France; C. Curatolo, L. Serafini Department of Physics, INFN-Milan and University of Milan, Milan, Italy ; O. Dadoun, M. W. Krasny<sup>\*</sup>, LPNHE, University Paris VI et VII and CNRS-IN2P3, Paris, France; P. Czodrowski, J. Jowett, Reyes Alemany Fernandez, M. Kowalska, M. Lamont, D. Manglunki<sup>\*</sup>, A. Petrenko, F. Zimmermann, CERN, Geneva, Switzerland; W. Placzek, Jagellonian University, Krakow, Poland; Y. K. Wu, FEL Laboratory, Duke University, Durham, USA; M. S. Zolotorev<sup>†</sup>, Center for Beam Physics, LBNL, Berkeley, USA.*

\* PBC Gamma Factory group conveners

*This group is open to everyone willing to join this initiative!*

contact persons:

[Django.Manglunki@cern.ch](mailto:Django.Manglunki@cern.ch) and/or [Reyes.Alemany.Fernandez@cern.ch](mailto:Reyes.Alemany.Fernandez@cern.ch), and/or [krasny@lpnhe.in2p3.fr](mailto:krasny@lpnhe.in2p3.fr)

# 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–

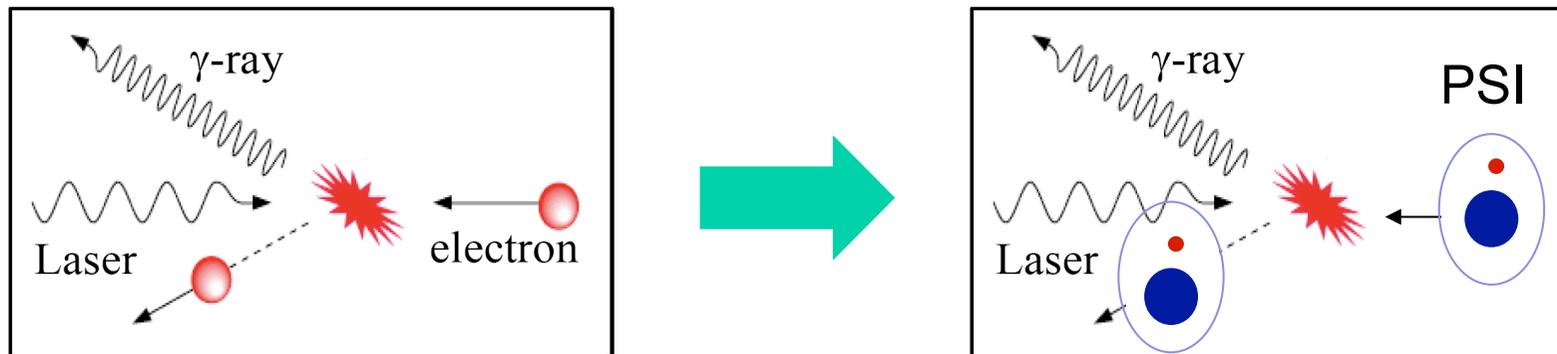
*The Gamma Factory goal: achieve comparable fluxes in the MeV domain as those in the KeV domain*

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

**An intensity jump by several orders of magnitude required !**

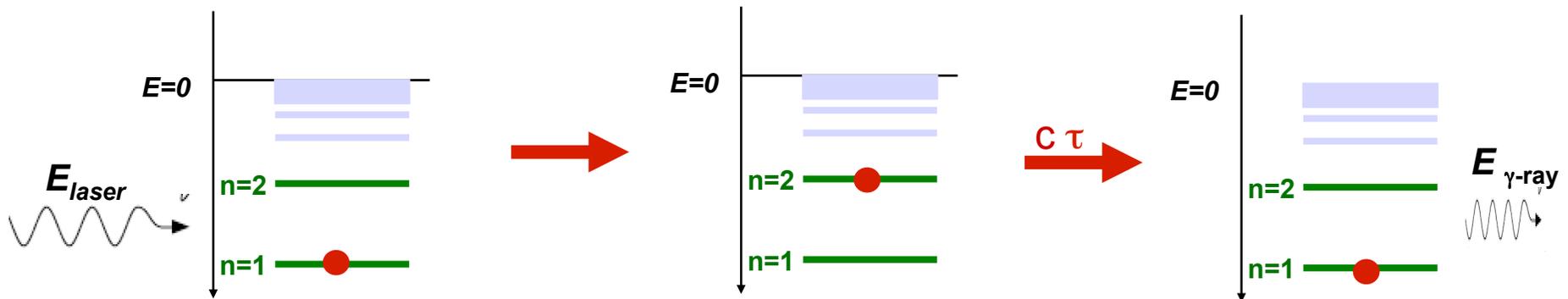
# The gamma ray source for Gamma Factory

The idea: replace an electron beam by a beam of Partially Stripped Ions (PSI)



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

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



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

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

Note:  $(E_{laser}/m_{beam}) \times 4\gamma_L \ll 1$

## Partially Stripped Ion beam as a light frequency converter

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

$\gamma_L = E/M$  - 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  $\gamma$ -ray energy at CERN in the **energy domain of 100 keV – 400 MeV.***

*Example (maximal energy):*

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

# The origin of the $\gamma$ -beam intensity leap

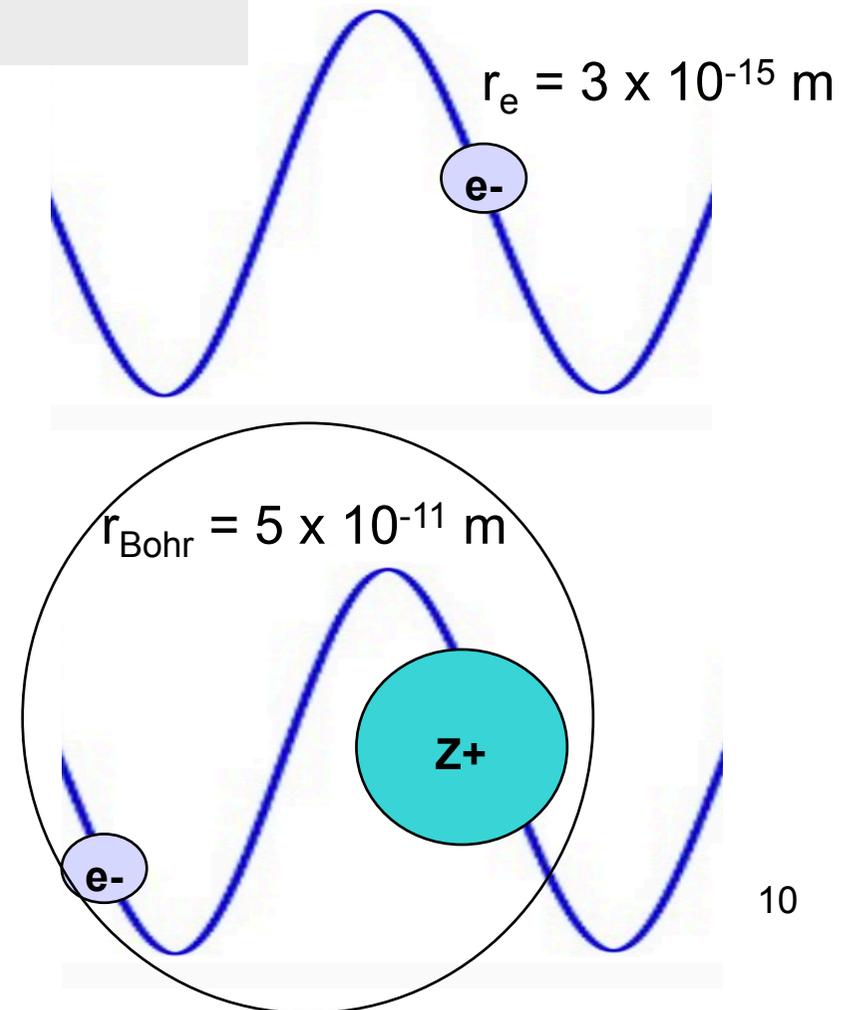
(matching the size of the target to the laser wavelength)

Ion beam rest frame

Lab reference frame laser  
light wavelength:  
 $\lambda_{\text{laser}} \sim 5 \times 10^{-7} \text{ m}$

$$\lambda_{\text{rest}} = \lambda_{\text{laser}} / 2 \gamma_L \sim O(10^{-10}) \text{ m}$$

for  $\gamma_L = 3000$



# The 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 absorption cross-section***

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

# 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:

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

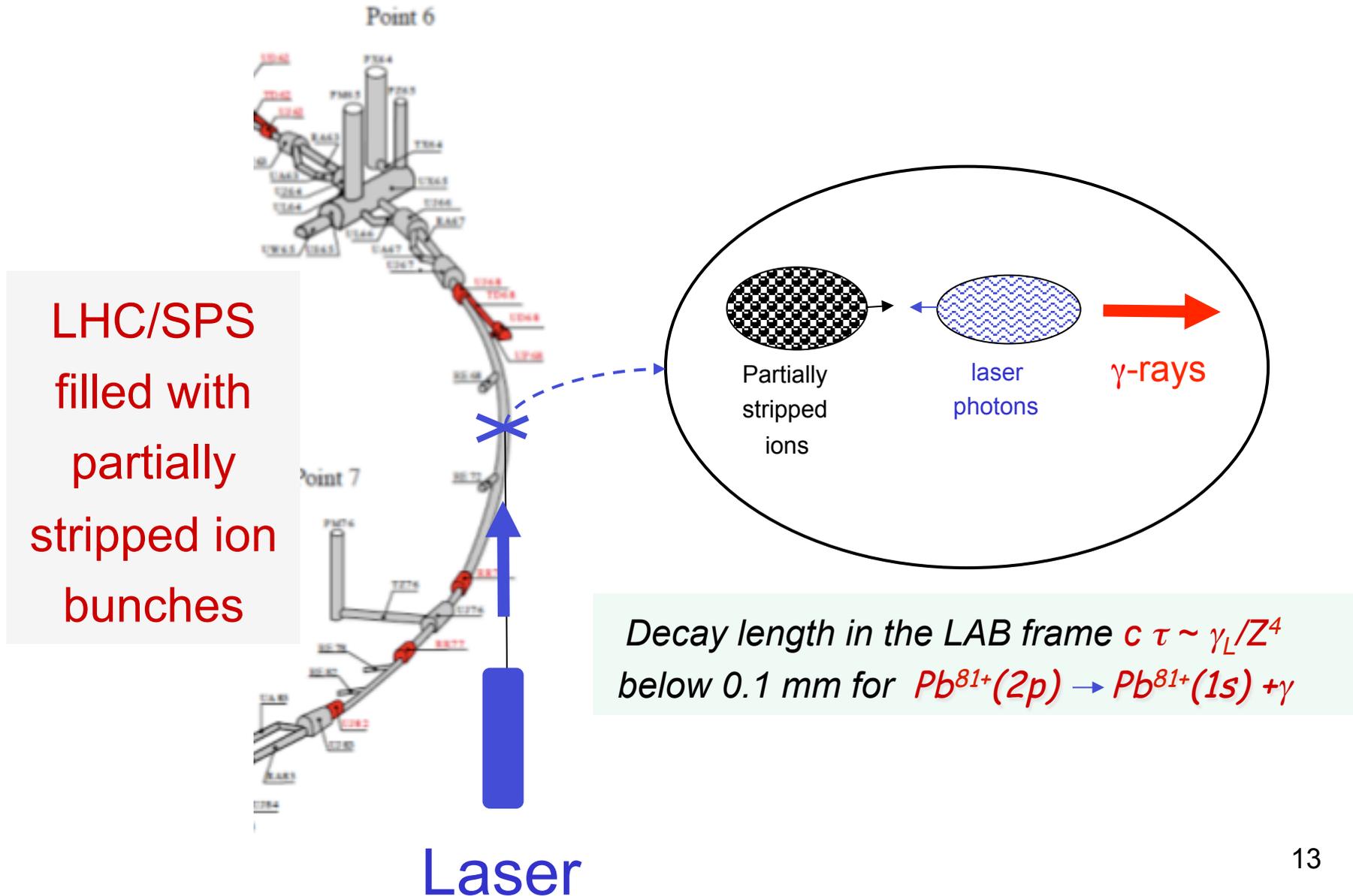
Electron fractional energy loss:  
emission of 150 MeV photon:

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

(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



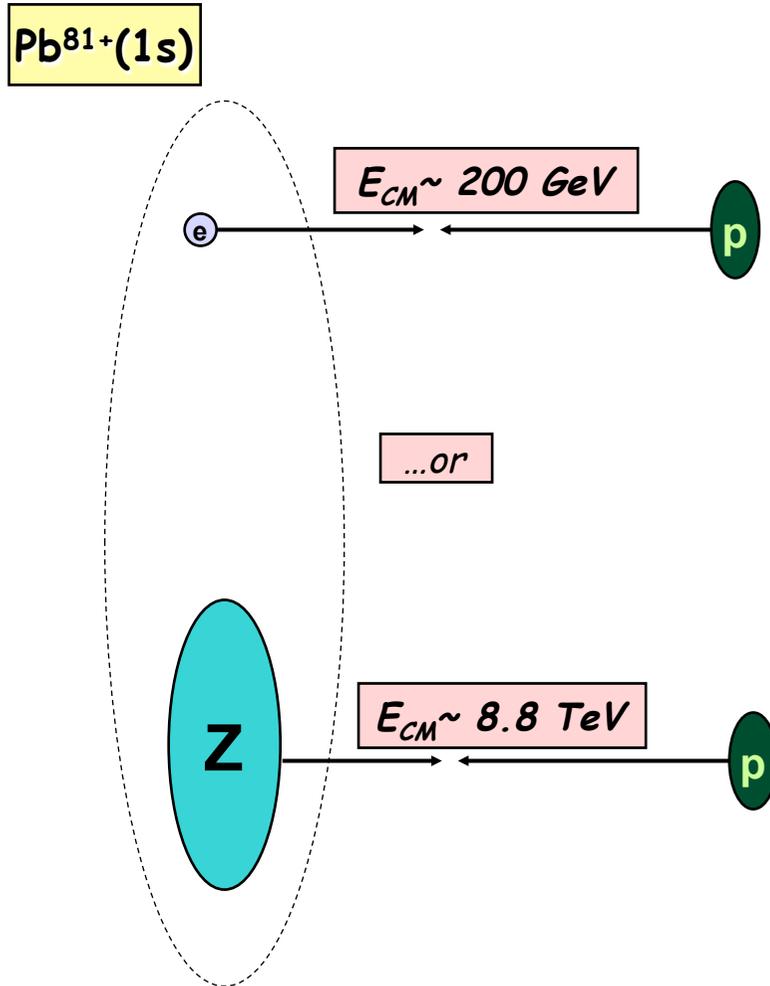


## The initial accelerator feasibility tests in 2017 and 2018

1. Test runs with the  $^{129}_{54}\text{Xe}(+39)$  (P-like) ions in the SPS (2017)
2. Preparation of the optimal stripping scenario to run the  $^{208}_{82}\text{Pb}(+80)$  (He-like) ions in the SPS and in the LHC for the year 2018 ) (2017)
3. Test runs with the  $^{208}_{82}\text{Pb}(+54)$  (Ni-like) and  $^{208}_{82}\text{Pb}(+80)$  (He-like) ions in the SPS (2018)
4. Test runs and a short physics run with  $^{208}_{82}\text{Pb}(+80)$  (He-like) ions in the LHC (2018)

LHC run as an electron-proton and photon-proton collider ?

# Cost-less electron-proton and $\gamma$ -proton collisions in the ATLAS, CMS, ALICE and LHCb interaction points



- average distance of the electron to the large Z nucleus  $d \sim 600 \text{ fm}$  (sizably higher than the range of strong interactions)

- partially stripped ion beams can be considered as independent electron and nuclear beams as long as the incoming proton scatters with the momentum transfer  $q \gg 300 \text{ KeV}$

- both beams have identical bunch structure (timing and bunch densities), the same  $\beta^*$ , the same beam emittance – the choice of collision type can be done exclusively by the trigger system (no read-out and event reconstruction adjustments necessary)

## ... and in parallel:

- *The design, LOI and a proposal of the Gamma Factory “proof-of-principle” experiment at the SPS (to be installed in the 2019-2020 shutdown), including the beam cooling tests?*
- *In depth studies of the feasibility and performance studies of the Gamma Factory research opportunities in all the applications domains (cannot be done without an expertise of the corresponding communities: everyone is invited to join the GF evaluation studies)*

# Beams and collision schemes

## primary beams:

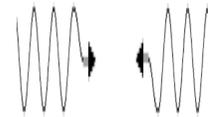
- partially stripped ions
- electron beam (for LHC)
- gamma rays

## secondary beam sources:



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

## collider schemes:



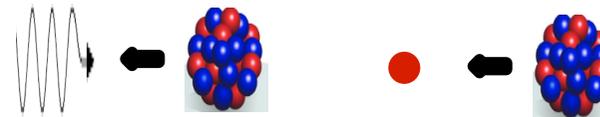
$\gamma$ - $\gamma$  collisions,

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



$\gamma$ - $\gamma_L$  collisions,

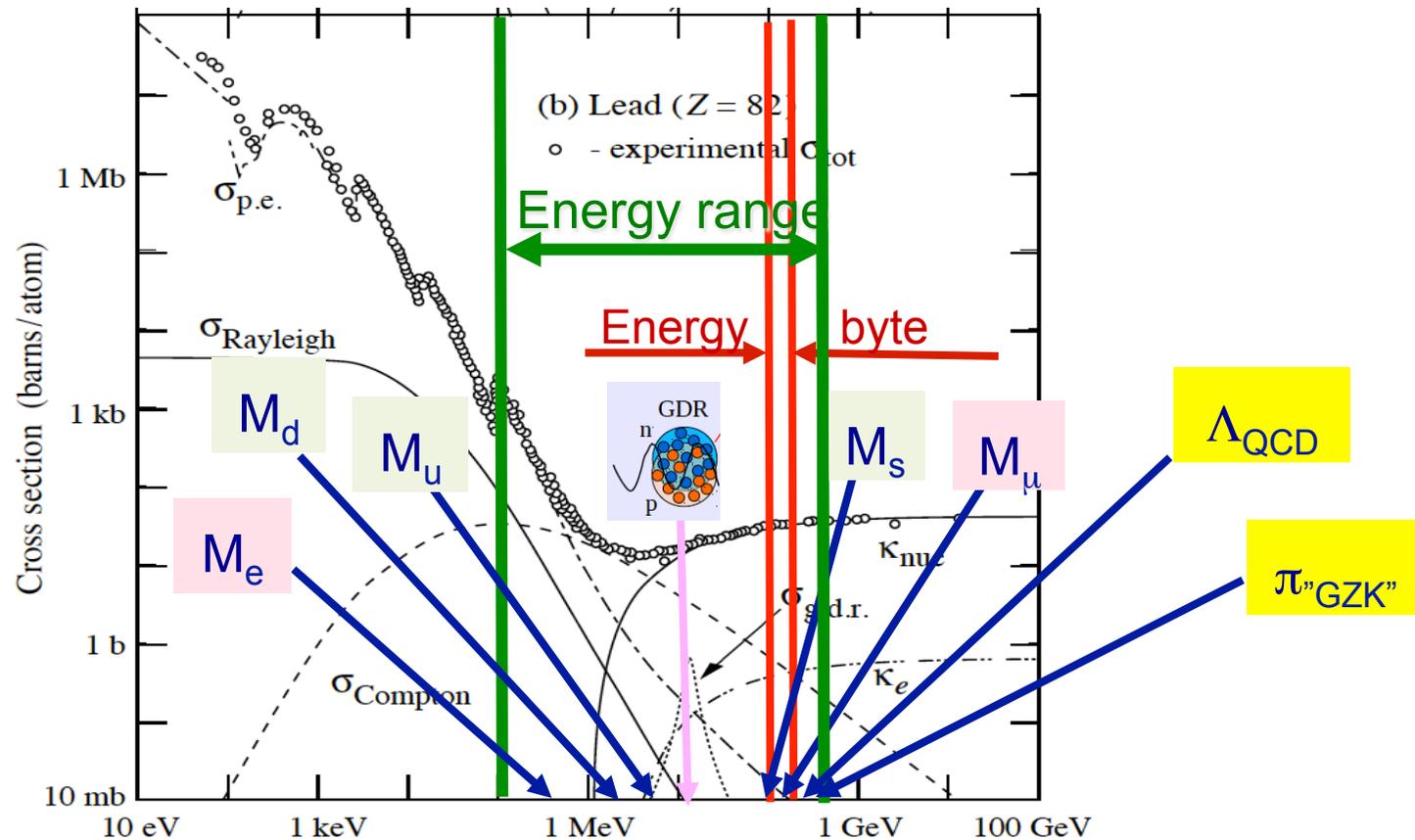
$$E_{\text{CM}} = 1 - 100 \text{ keV}$$



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

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

# Collisions of photons with matter



- $\sigma_{\text{p.e.}}$  = Atomic photoelectric effect (electron ejection, photon absorption)
- $\sigma_{\text{Rayleigh}}$  = Rayleigh (coherent) scattering—atom neither ionized nor excited
- $\sigma_{\text{Compton}}$  = Incoherent scattering (Compton scattering off an electron)
- $\kappa_{\text{nuc}}$  = Pair production, nuclear field
- $\kappa_e$  = 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.

- **particle physics** (*studies of the basic symmetries of the universe, dark matter searches, precision QED studies, rare muon decays, neutrino-factory physics, precision-support measurements for the LHC - DIS physics, muon collider physics*)
- **nuclear physics** (*confinement phenomena, link between the quark-gluon and nucleonic degrees of freedom, photo-fission research program*)
- **accelerator physics** (*beam cooling techniques, low emittance hadronic beams, plasma wake field acceleration, high intensity polarized positron and muon sources, secondary beams of radioactive ions and neutrons, neutrino-factory*)
- **atomic physics** (*electronic and muonic atoms*),
- **applied physics** (*accelerator driven energy sources , cold and warm fusion research, isotope production: e.g alpha-emitters for medical applications, ...*).

# Conclusions

*The goal of the Gamma Factory initiative is to open novel research opportunities in a very broad domain of basic and applied science.*

*The Gamma Factory research tools involve a high intensity gamma ray source, low emittance PSI beams, and high quality secondary beams of polarized positrons, muons, neutrinos, neutrons and radioactive ions.*

*These beams could be produced by the existing CERN accelerator infrastructure -- and thus requiring a “relatively” minor infrastructure investments.*

*The Gamma Factory studies are in their initial phase (the study group was created ~ 3 month ago). They will include both the accelerator feasibility tests and a detailed evaluation of the physics potential of the Gamma Factory by all communities which could be interested in using its tools in their future research.*

# Extra transparencies

# Initial estimates of the $\gamma$ - fluxes for the two concrete Gamma Factory scenarios

## Scenario 1 :

FEL: 104.4 nm,  $Pb^{80+}$  ion,  $\gamma_L=2887$ ,  $n=1 \rightarrow 2$ ,  $E_\gamma^{(max)} = 396$  MeV,  $N_\gamma^{max} \sim 6 \times 10^{15}$  [1/s]  
...for the present LHC RF system

## Scenario 2:

Erbium doped glass laser: 1540 nm,  $Ar^{16+}$  ion,  $\gamma_L=2068$ ,  $n=1 \rightarrow 2$ ,  $E_\gamma^{(max)} = 13.8$  MeV,  
 $N_\gamma^{max} \sim 3 \times 10^{17}$  [1/s] - a jump by 7 orders of magnitude w.r.t. Duke's Hi $\gamma$ s

## Comments:

1.  $N_{\gamma_{max}} = N_{bunch}^{ion} \times N_{bunches} \times f$  [1/s]  $\times$  RF [MV]  $\times$  Z /  $\langle E_\gamma$  [MeV]  $\rangle$ .
2. For scenario 2, where  $c\tau_{exited\ ion} = 1.2$  cm, the effect of the double photon absorption process, and the beam life-time remains to be calculated... if necessary it could be circumvented by using a pulsed laser beam

# Initial estimates of intensities of the secondary beam sources

- *Polarised electrons and positrons( up to  $10^{17}$  1/s):  
potential intensity jump by  $\sim 4$  orders of magnitude w.r.t. SLC*
- *Polarized muons and neutrinos ( up to  $10^{12}$  1/s and  $4 \times 10^{19}$  1/year)\*, potential jump by  $\sim 2$  orders of magnitude for ( $\mu^+$ ), higher for ( $\mu^-$ ) w.r.t. PSI, beams, unprecedented quality!*
- *Neutrons (GDR in heavy nuclei:  $\gamma + A \rightarrow A-1 + n$ ) (up to  $10^{15}$  1/s)  
comparable to those the future spallation sources but **mono-energetic***
- *radioactive ions (photo-fission:(  $\gamma + A \rightarrow A_1 + A_2 + \text{neutrons}$  ) ( up to  $10^{14}$  1/s)  
potential intensity jump by 3-4 orders of magnitude e.g. w.r.t. ALTO*

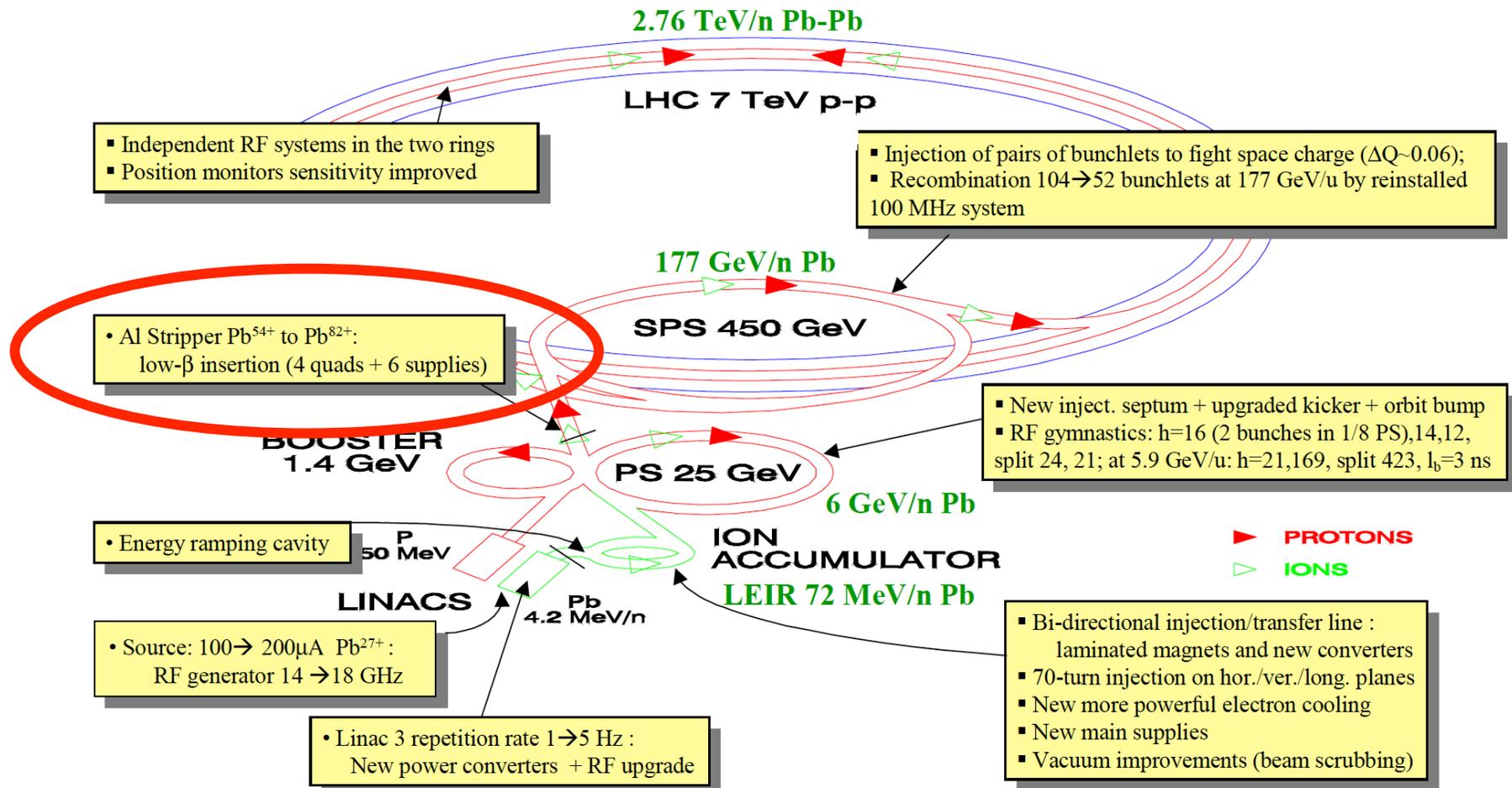
*\*) for the quoted flux of the muons/neutrinos the LHC circumferential voltage would need to be increased from the present value of RF=16 MV and/or the number of stored ions (bunch population and bunch frequency) would have to be increased by e.g. the factors of 2, 2 and 3. The power of the gamma-beam for the quoted fluxes would be of  $\sim 2.5$  MW.*

Table 1: Charge States and Typical Intensities

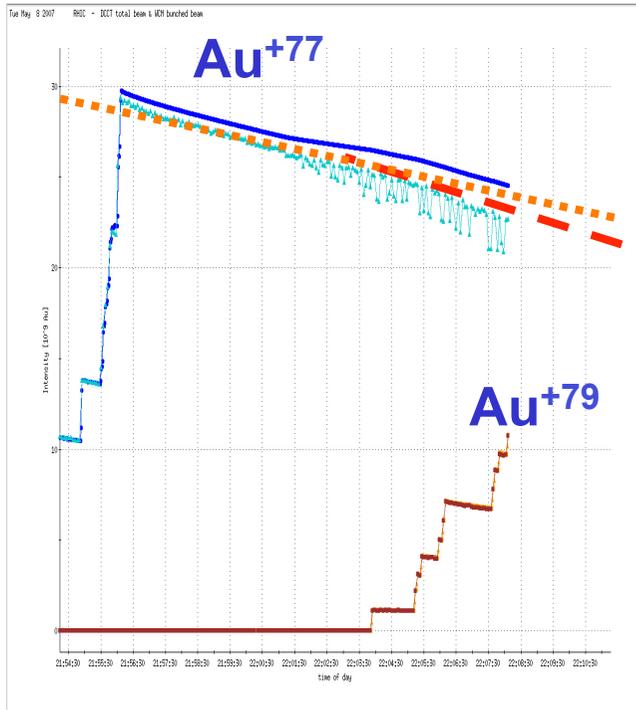
Species	Ar	Xe	Pb
Charge state in Linac3	Ar <sup>11+</sup>	Xe <sup>20+</sup>	Pb <sup>29+</sup>
Linac3 beam current after stripping [eμA]	50	27	25
Charge state <i>Q</i> in LEIR/PS	Ar <sup>11+</sup>	Xe <sup>39+</sup>	Pb <sup>54+</sup>
Ions/bunch in LEIR	3×10 <sup>9</sup>	4.3×10 <sup>8</sup>	2×10 <sup>8</sup>
Ions/bunch in PS	2×10 <sup>9</sup>	2.6×10 <sup>8</sup>	1.2×10 <sup>8</sup>
Charge state <i>Z</i> in SPS	Ar <sup>18+</sup>	Xe <sup>54+</sup>	Pb <sup>82+</sup>
Ions at injection in SPS	7×10 <sup>9</sup>	8.1×10 <sup>8</sup>	4×10 <sup>8</sup>
Ions at extraction in SPS	5×10 <sup>9</sup>	6×10 <sup>8</sup>	3×10 <sup>8</sup>

D. Manglunki et al.

CERN's Fixed Target Primary Ion Programme. IPAC'2016.



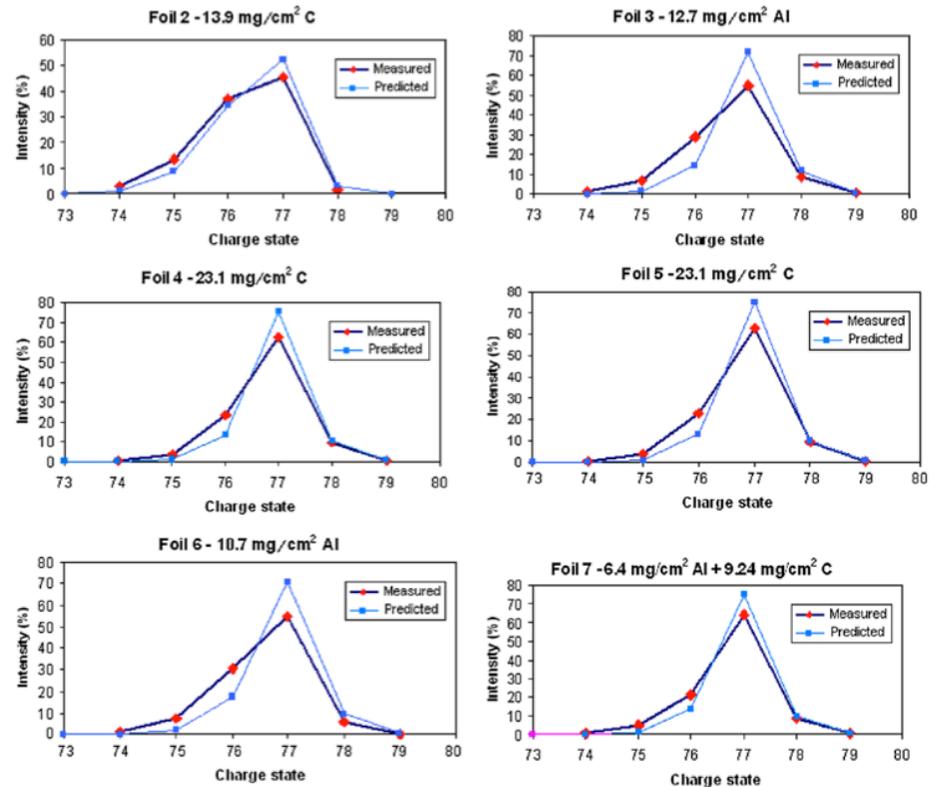
# Stripping, accelerating and storing of PSI - the BNL experience



*PSI beams were already accelerated and stored in AGS and in RHIC !*

P. THIEBERGER *et al.*

Phys. Rev. ST Accel. Beams **11**, 011001 (2008)



*Target type and thickness optimisation for the BNL Au<sup>77+</sup> beams (Helium-like Au ion)*