Gamma Factory Proposal

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Introduction

The Gamma Factory proposal in a nutshell

1. *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.*

2. *Provide a new, highly efficient scheme of transforming the accelerator RF power (selectively) to the above primary and secondary beams trying to achieve a leap, by several orders of magnitude, in their intensity and/or brightness, with respect to the existing facilities.*

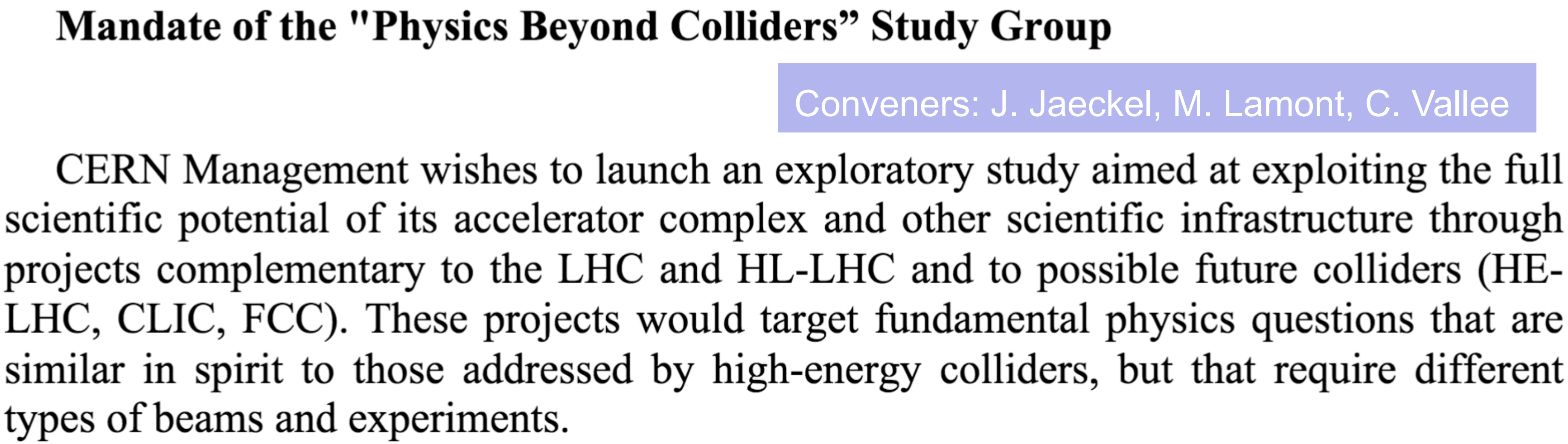
3. *Use the primary and the secondary beams as principal tools of the Gamma Factory research programme.*

Its context

- *The next high-energy frontier project for CERN may take a long time to be approved, financed and built.*
- *It is very likely that the high-energy CERN-LHC research program will reach earlier its discovery saturation (no physics gain by extending of the running time).*
- *In such a case, a strong need will arise for a novel research programme for CERN which could re-use its existing world-unique facilities and extend the CERN-based research to new territories.*
- *Gamma Factory is an initiative going in this direction.*
- *It requires extensive experimental and simulation studies to prove its feasibility, and to be considered as a realistic proposal for CERN.*

Its CERN-based framework

The Gamma Factory initiative (arXiv:1511.07794 [hep-ex]) 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 present Gamma Factory group members

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[⋆] PBC Gamma Factory group conveners

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

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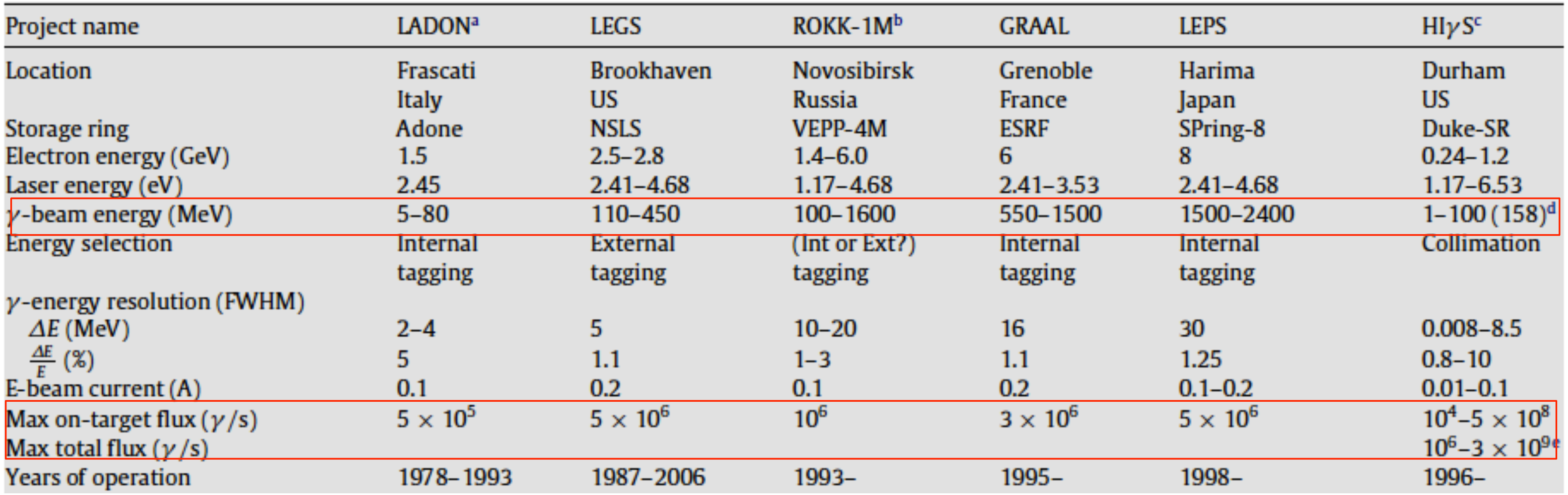
Gamma Source

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–

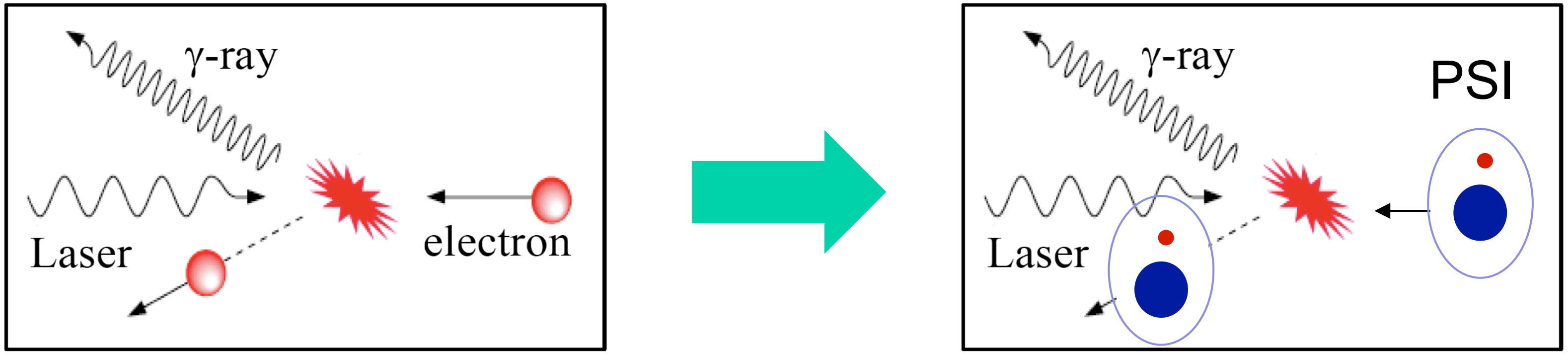
The Gamma Factory goal: achieve comparable fluxes in the MeV domain as those in the KeV domain – e.g. those of the DESY XFEL:

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

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

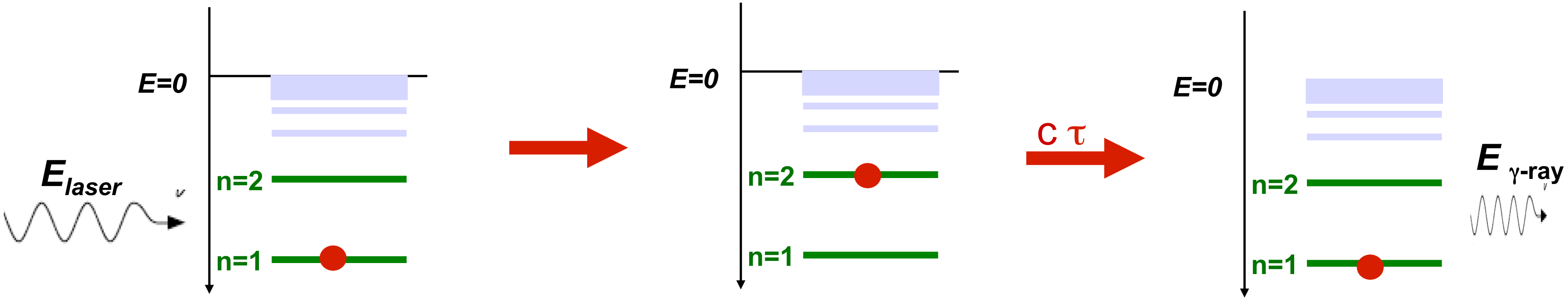
The gamma ray source for Gamma Factory

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



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

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



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

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

Partially Stripped Ion 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, 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,* $\gamma_L = 2887$, $n=1\rightarrow 2$, $\lambda_{laser} = 104.4$ nm, $E_\gamma\,(max) = 396$ MeV

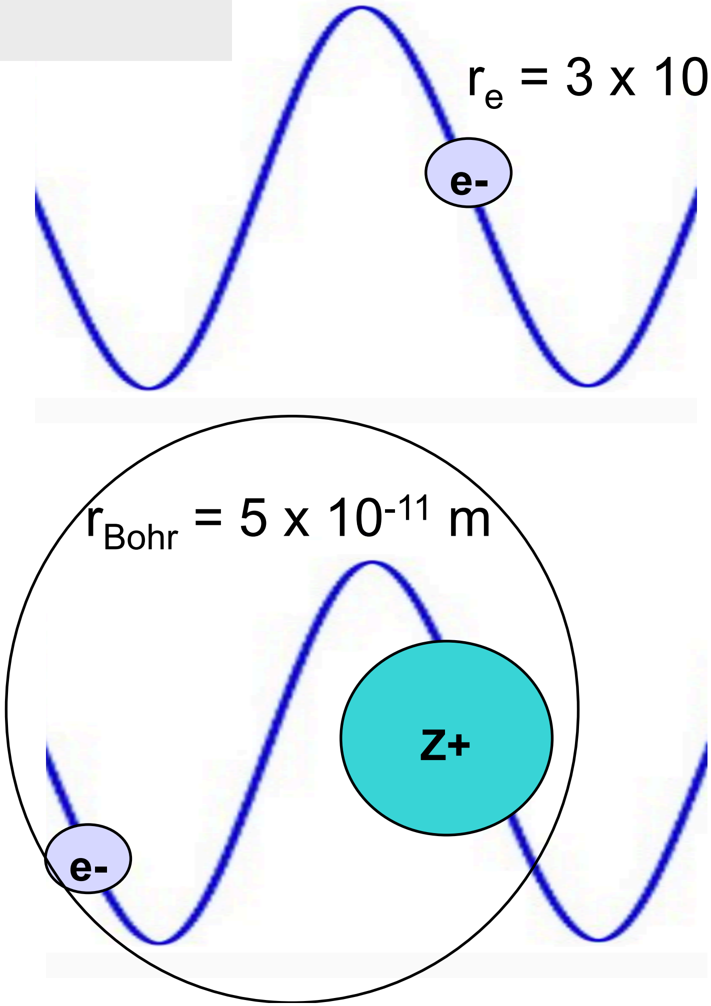
The origin of the γ-beam intensity leap

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

Ion beam rest frame

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

$\lambda_{rest} = \lambda_{laser}/2\,\gamma_{L} \sim O(10^{-10})$ m
for $\gamma_{L} = 3000$



The expected 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:

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

Partially Stripped Ions:

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

Numerical example: λ_{laser} = 1540 nm

~ 9 orders of magnitude difference in the 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 $\gamma_L = 2887$

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

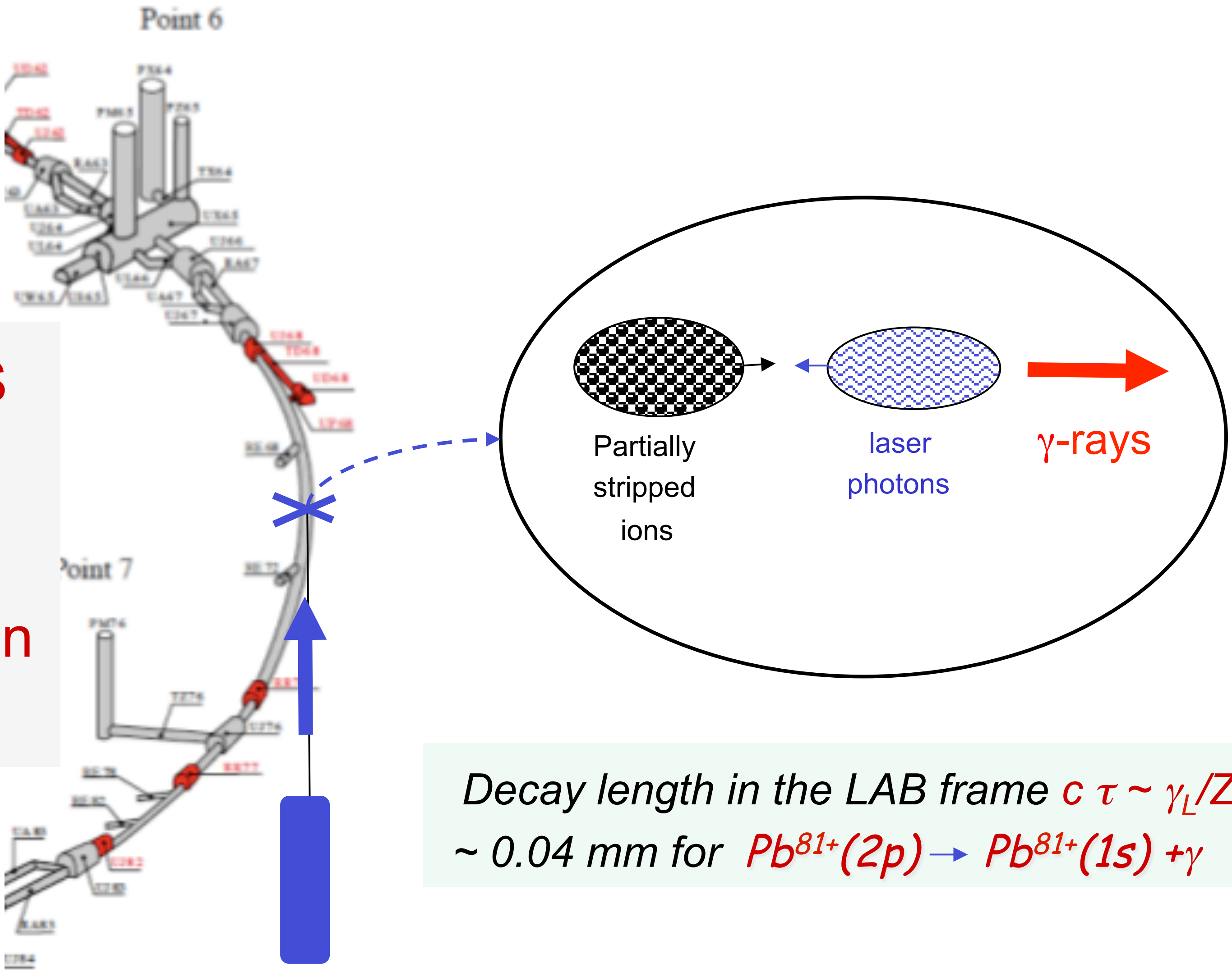
(ion undisturbed!)

…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!

The γ-ray source scheme for CERN

LHC/SPS filled with partially stripped ion bunches



Laser photons

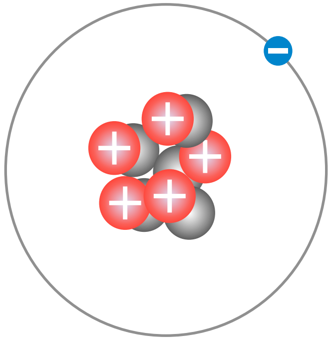
Decay length in the LAB frame $c\,\tau \sim \gamma_L/Z^4$

~ 0.04 *mm for* $Pb^{81+}(2p) \rightarrow Pb^{81+}(1s) + \gamma$

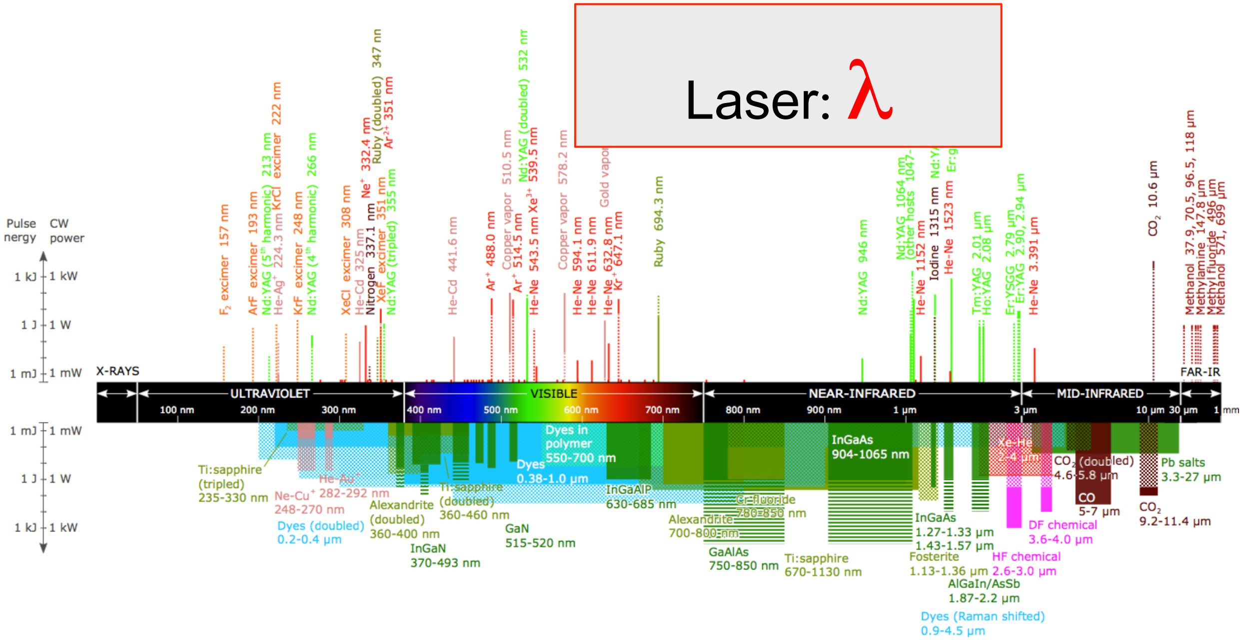
Choosing the gamma ray’s energy: $E_\gamma = f(Z_{nucl}, Z_{ion}, \gamma_L, \lambda)$

partially stripped ion:

Z_{nucl}, Z_{ion}

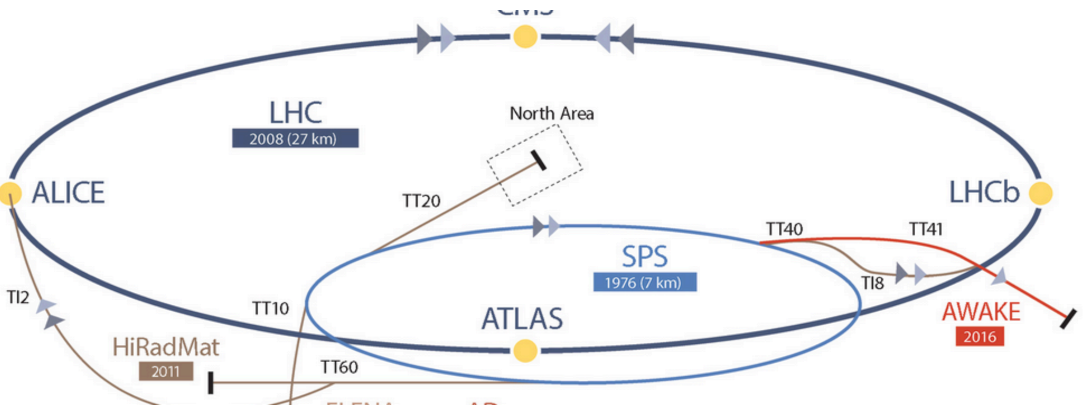


Laser: λ



ion storage ring and ion momentum:

γ_L



Initial estimates of the γ- fluxes for the two concrete gamma source scenarios

Scenario 1 :

*FEL: 104.4 nm, Pb^{80+} ion, γ_L=2887, n=1→2, $E_\gamma^{(max)}$ = 396 MeV, N^{max}_γ ~ **6 x 10^{15}**[1/s] …*
for the present LHC RF system

Scenario 2:

Erbium doped glass laser: 1540 nm, Ar^{16+} ion, γ_L=2068, n=1→2, $E_\gamma^{(max)}$ = 13.8 MeV,
***N^{max}_γ ~ 3 x 10^{17}** [1/s] - a potential jump by 7 orders of magnitude w.r.t. Duke's Hiγs*

Comments:

1. $N^{\gamma}_{max} = N^{ion}_{bunch} \times N_{bunches} \times f\,[1/s] \times RF\,[MV] \times Z / \langle E_\gamma\,[MeV]\rangle$.

2. For scenario 2, where $c\tau_{\text{exited ion}}$ = 1.2 cm, the effect of the double photon absorption process, and the beam life-time remains to be calculated… in principle it could be circumvented by using a pulsed laser beam

Gamma Factory

Beams and collision schemes

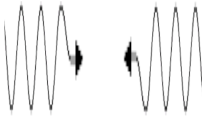
primary beams:

- **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:

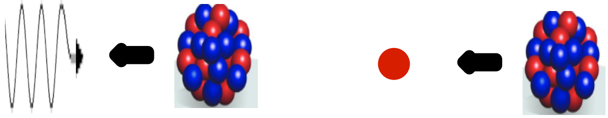


$\gamma-\gamma$ collisions,

E_{CM} = 0.1 – 800 MeV

$\gamma-\gamma_L$ collisions,

E_{CM} = 1 – 100 keV



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

E_{CM} = 4 – 200 GeV

Initial estimates of the intensity potential of the secondary beam sources

- *Polarised electrons and positrons(up to 10^{17} 1/s):*
  potential intensity jump by ~4 orders of magnitude w.r.t. SLC
- *Polarized muons and neutrinos (up to 10^{12} 1/s and 4×10^{19} 1/year)*, potential jump by ~2 orders of magnitude for (μ+), higher for (μ-) 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 of the future spallation sources but mono-energetic
- Radioactive ions *(photo-fission:($\gamma + A \rightarrow A_1 + A_2$ + 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 ~2.5 MW.*

- ***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, …).*

Initial feasibility studies

The initial task of the Gamma Factory study group: evaluation of the feasibility of the proposed scheme

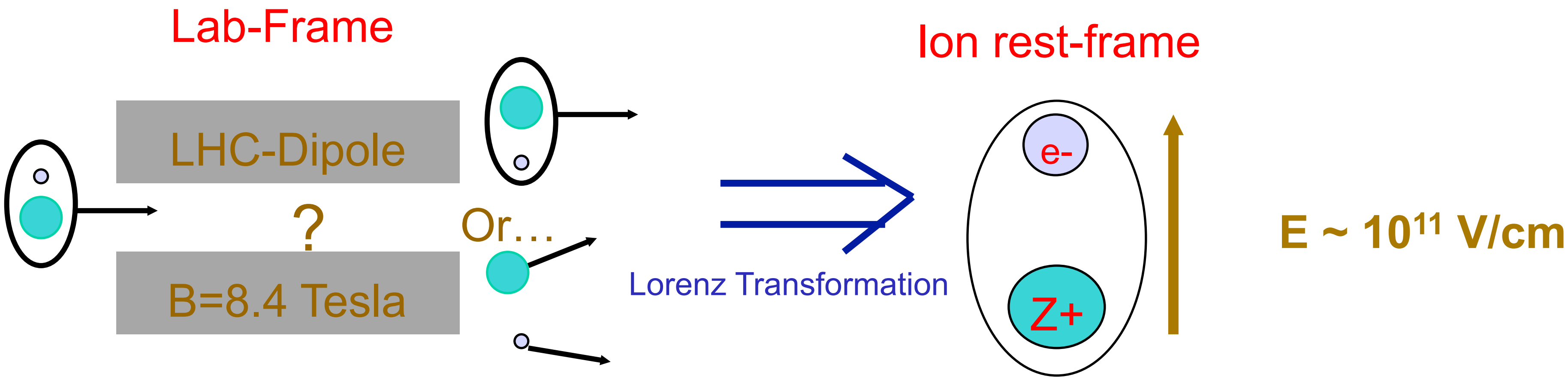
The main issue :

Stability of the partially stripped ion beams in the high energy storage rings (note: a loss of a single electron leads to a loss of the beam particle)

Selected aspects discussed in this presentation:

- *Stark effect*
- *Electron stripping by the residual gas*
- *Electron stripping by intra-beam scattering*
- *PSI ionisation by double laser-photon absorption*

Stark effect



Lab-Frame

LHC-Dipole

?

B=8.4 Tesla

Or…

Lorenz Transformation

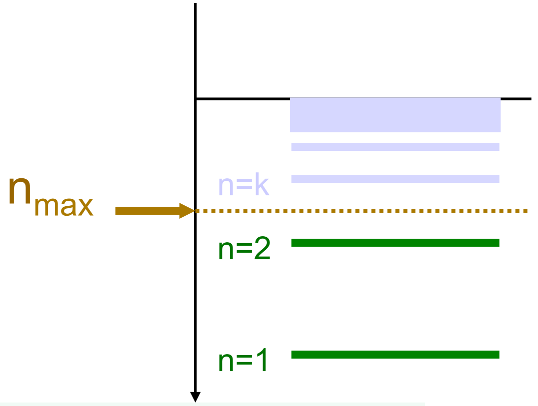
Ion rest-frame

e-

Z+

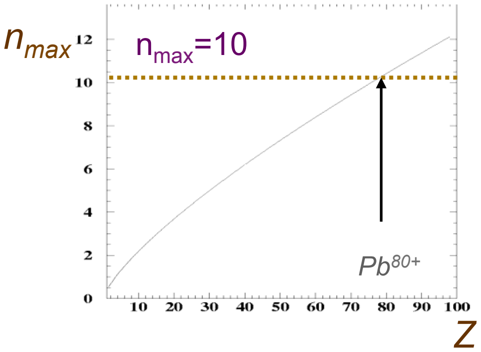
E ~ 10^{11} V/cm

Binding energy of Rydberg-like atoms



$E=1Ry\ Z^2/n^2$

Ionization of Rydberg-like atoms



Only the outer shell electrons of small Z Ions would be Stripped by the LHC dipole magnetic field!!!

$10^5 Z^2/n_{max}{}^2 > E/15620(n_{max}/Z)(n_{max})$

Bethe-Salpeter,:"Quantum mechanics Of One- and Two- Electron Atoms"

Electron stripping by residual gas

For an efficient Gamma Source the PSI beam must be stored in the LHC ring for at least couple of hours. Electron stripping in beam-gas collisions leads to a beam particle losses - a quantum jump in magnetic rigidity of the beam particles) and must be evaluated:

Ionization cross-sections- theory

Anholt and Becker, Phys.Rev.A36(1987)

Coulomb contribution:

$\sigma_{Coul} = s(Z_t, Z_p)\ (Z_t/Z_c)^2\ 10^4$ [barn/electron]

Transverse contribution:

$\sigma_{Tran} = t(Z_t, Z_p)\ (Z_t/Z_c)^2\ 10^4 \ln(\gamma^2)$ [barn/electron]

$s(Z_t,Z_p)$, $t(Z_t,Z_p)$ are slowly (logarithmically) varying functions of the electron carrier Z_c and target Z_t and γ is the Lorenz factor

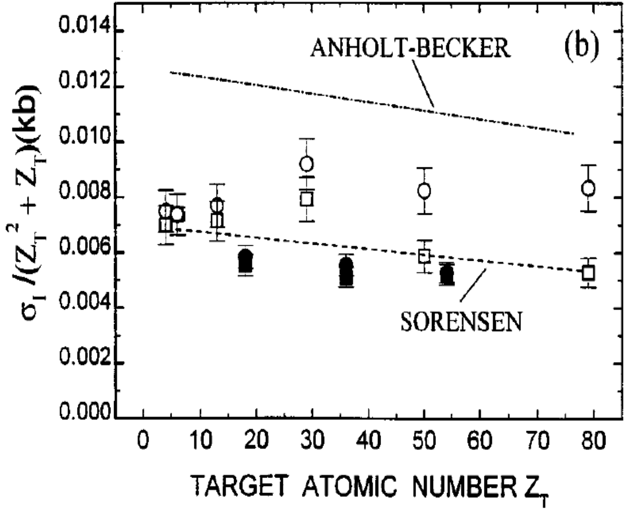
Note:

- *spin-flip contribution is neglected*
- *coherent bunch contribution is neglected*

Experimental cross-check

Krause et al., Phys.Rev.A63(2001)

Data: Pb^{81+}(1s) ions at 158GeV/A



Electron stripping by residual gas

Find a maximal allowed concentration of molecules to achieve 10-hour-long lifetime of the beam $Pb^{81+}(1s)$ ions in the LHC storage rings:

$$\tau^{-1} = \sigma \times \rho \times c$$

- *For the safe upper limit, compare the densities for the gas molecules in the interaction regions (better vacuum in the arcs) provided by by Rossi and Hilleret, LHC project rapport 674 (2003): (H2 – 1.3×10^{12}; CH4 – 1.9×10^{11}; … CO2 – 2.8×10^{11} mol/m^3) with the allowed concentration calculated using the Anhold-Becker theory.*

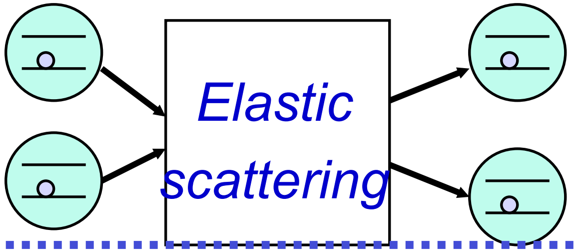
Result: *The Rossi and Hilleret densities are lower for all molecules with respect to the required ones – the safety factor varies between*

30 (H2 molecules) and 2 (CO2 molecules).

Note: The present LHC vacuum is better than the one predicted: scrubbing and no proton beam in the machine – no problem at the LHC! (SPS???)

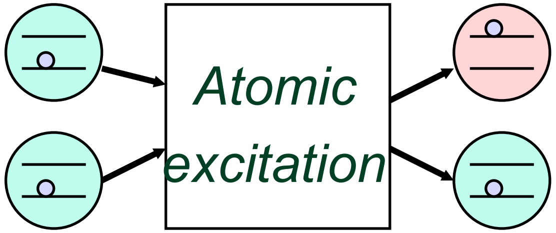
Electron stripping by intra-beam scattering

Intra-beam scattering at temperatures: $kT < E_1 - E_2$



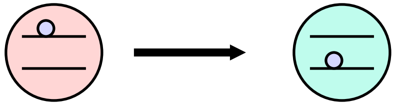
Elastic scattering

Intra-beam scattering at temperatures: $E_1 - E_{n\,max} < kT < E_1 - E_2$



Atomic excitation

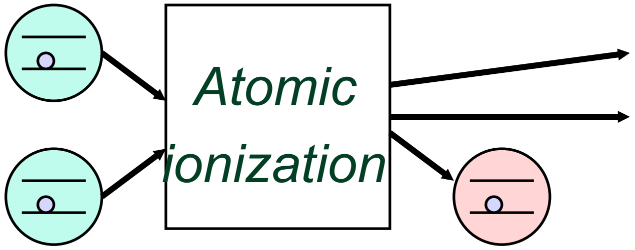
Followed by:



+ photon

$h\nu_k = E_1 - E_k$

Intra-beam scattering at temperatures: $kT > E_1$



Atomic ionization

Stripped ion

electron

Followed by a beam particle loss!

- M.Chanel, R.Giannini, P.Lefevre, R.Ley, D.Manglunki, D.Mohl
  "Measurement of H- Intra-Beam Stripping Cross-Section by Observing a Stored Beam in LEAR."
  Physics Letters B, Vol 192, nr 3-4, p475.

Electron stripping by intra-beam scattering

- Longitudinal temperature: $kT_{||} = m_{ion}c^2\beta^2(\sigma(p)/p)^2$
- Transverse temperature: $kT_{h,v} = m_{ion}c^2\beta^2(\varepsilon_N/<\sigma_{h,v}>)^2$

Where:

ε_N is the normalized emittance and $<\sigma_{h,v}>$ is the average horizontal (vertical) beam size

- Temperatures of the LHC bunches: **$kT_{||} \sim 2$ keV, $kT_{h,v} \sim 1$ MeV**

(at the LHC injection energy)

Kinetic energy of the transverse thermic motion larger than binding energy of the electron on the K-shell (~ 70 keV for $Pb^{81+}(1s)$)

Electron stripping by intra-beam scattering:

An order of magnitude estimation of the beam life-time

Mean free path of a partially stripped ion in the bunch (a crude approximation of non-interacting gas):

$$c\tau_{lab} = c\gamma/(\sigma\rho\Delta v)$$

Consider two cases: $\sigma_1 = \pi\,(10\, r_{PSI})^2$ *and* $\sigma_2 = \pi\, r_{PSI}^2$

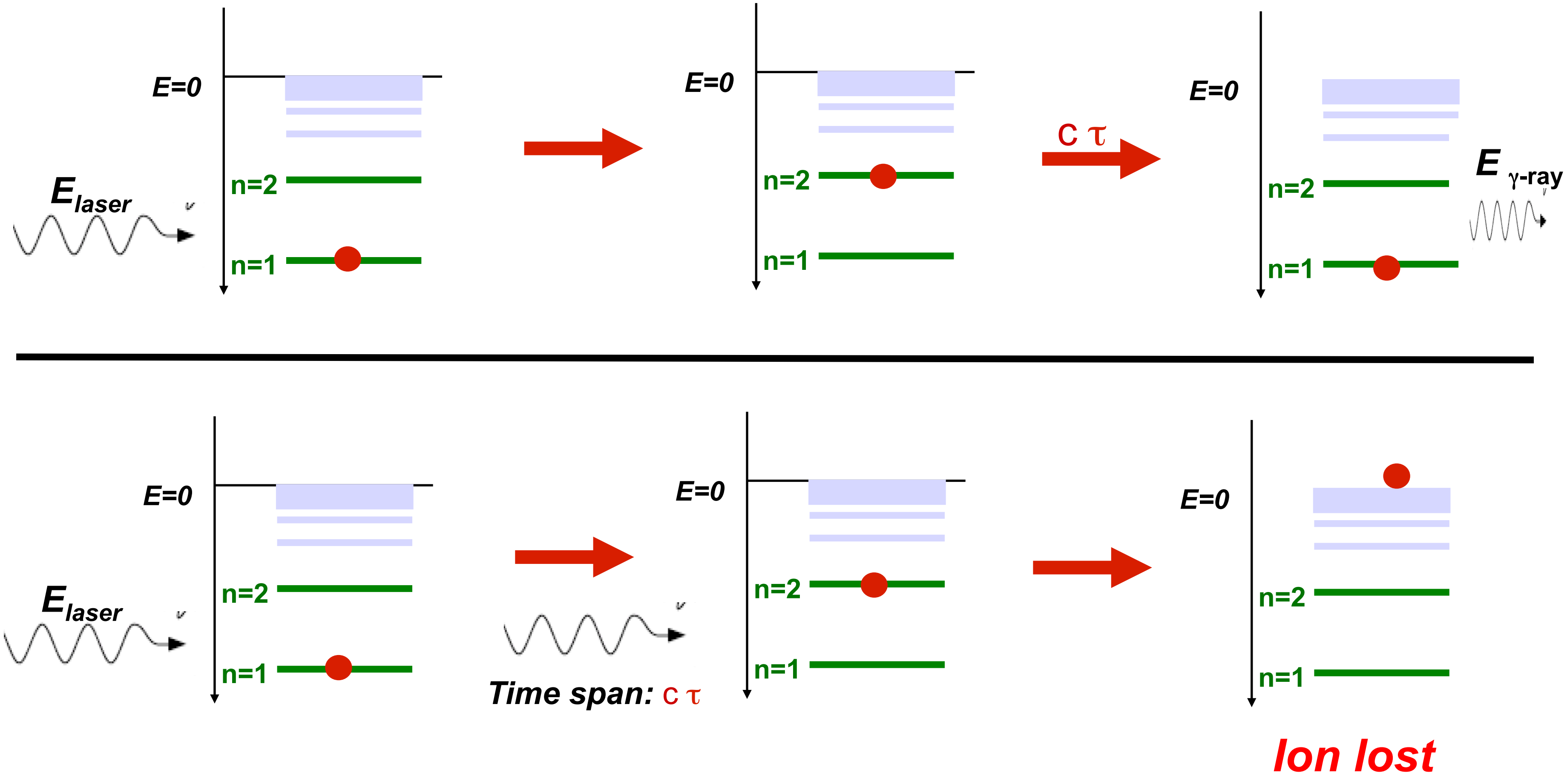
Δv – dispersion of velocity of ions (Maxwell distribution)

ρ – ion bunch density (bunch rest frame) averaged over the ring circumference (< β >)

$\underline{\tau \sim 1\text{ min} - 1.5\text{ hour}}$ …*at the LHC injection energy*

Intra-beam scattering may be a serious issue at the LHC for bunches of PSIs. If this would be the case: a remedy: laser cooling of the PSI beams at the SPS before injecting them to the LHC!

Ionisation by double photon absorption



Ionisation by double photon absorption

Example (Scenario 1) – gamma source driven by the ${}^{208}_{82}$Pb(+80) beam stored at the LHC in 547, l_{bunch} = 14 cm long bunches, each containing 1.4 x 10^8 ions and colliding (head-on) with a laser beam of the transverse and longitudinal bunch sizes matched to the sizes of the ion bunches, the mean free path of the ion before gamma emission: $c\gamma\tau_{PB^*}$=0.05 mm

Number of ions, N^{burn}, which will be lost ("burned out") while producing e.g. $N^{\gamma} = 10^{19}$ gammas → $N^{burn} \sim 2 \times 10^{10}$ (25% of the LHC fill)

$$N^{burn}/N^{\gamma} \sim N^{excited}/N^{ground\_state} \times c\gamma\tau_{PB}/l_{bunch} \times \sigma_{ionisation}/\sigma_{res} = 2\times10^{-9}$$

Important losses, in particular if the RF voltage of the LHC is increased for extreme Intensity of the gamma source (e.g. for the secondary muon beam)!

Remedies: sub-ps length laser pulses, longer ion bunches, non-zero collision angle, larger number of non stripped electrons …)

The initial accelerator feasibility tests 2017/2018

1. *Test runs with the $^{129}_{54}Xe(+39)$ (P-like) ions in the SPS (2017)*

2. *Preparation of the optimal stripping scenario to run the $^{208}_{82}Pb(+80)$ (He-like) ions in the SPS and in the LHC for the year 2018) (2017)*

3. *Test runs with the $^{208}_{82}Pb(+54)$ (Ni-like) and $^{208}_{82}Pb(+80)$ (He-like) ions in the SPS (2018)*

4. *Test runs and a short physics run with $^{208}_{82}Pb(+80)$ (He-like) ions in the LHC (2018)*

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

Conclusions

- *Gamma Factory has a potential to open novel research opportunities in a very broad domain of basic and applied science.*

- *The list of its 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.*

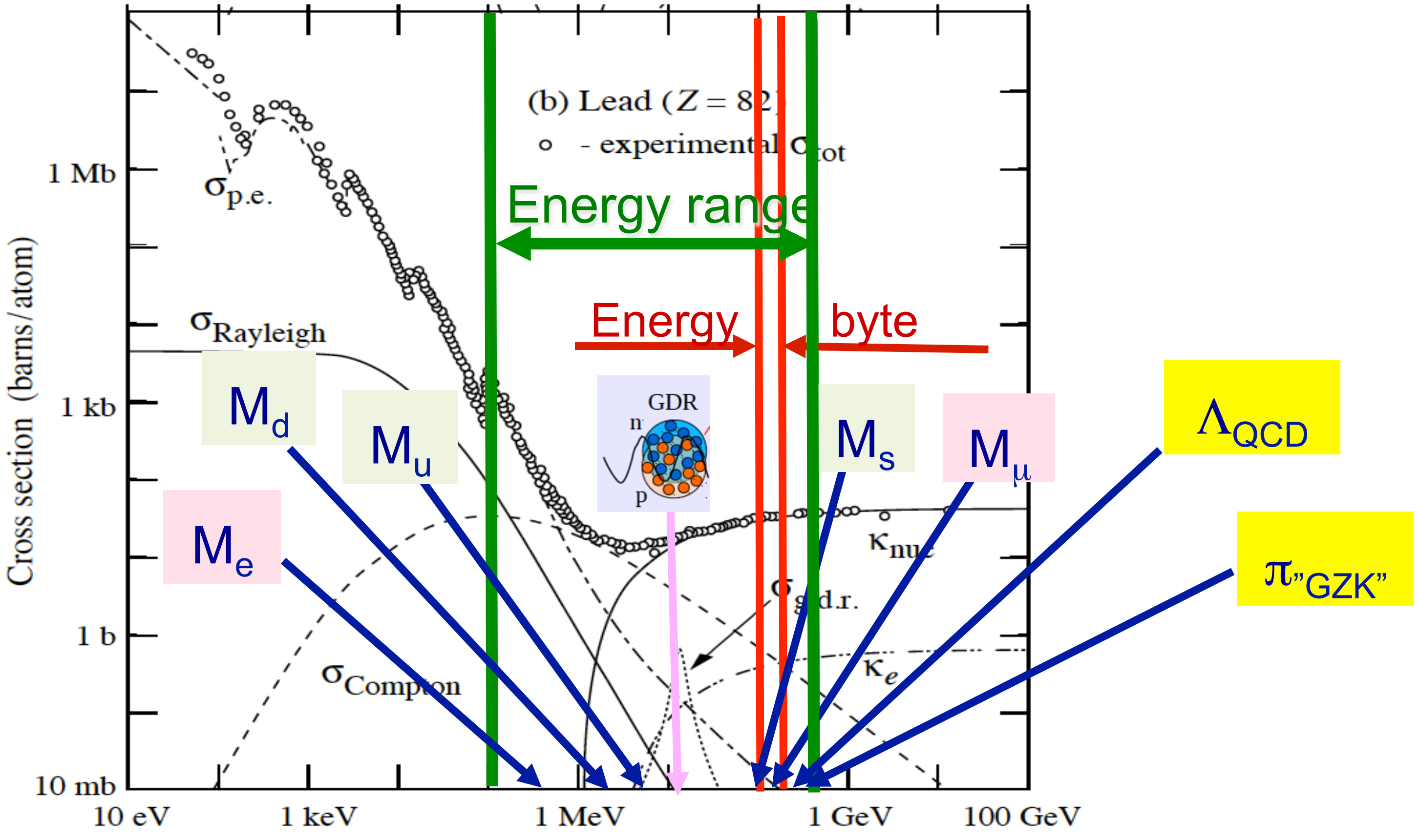
- *These beams could be produced by the existing CERN accelerator infrastructure -- and thus requiring a "relatively" minor infrastructure investments.*

- *The Gamma Factory concept must be validated by the dedicated accelerator test runs and by dedicated realistic simulation collisions of the laser photons with partially stripped ion bunches*

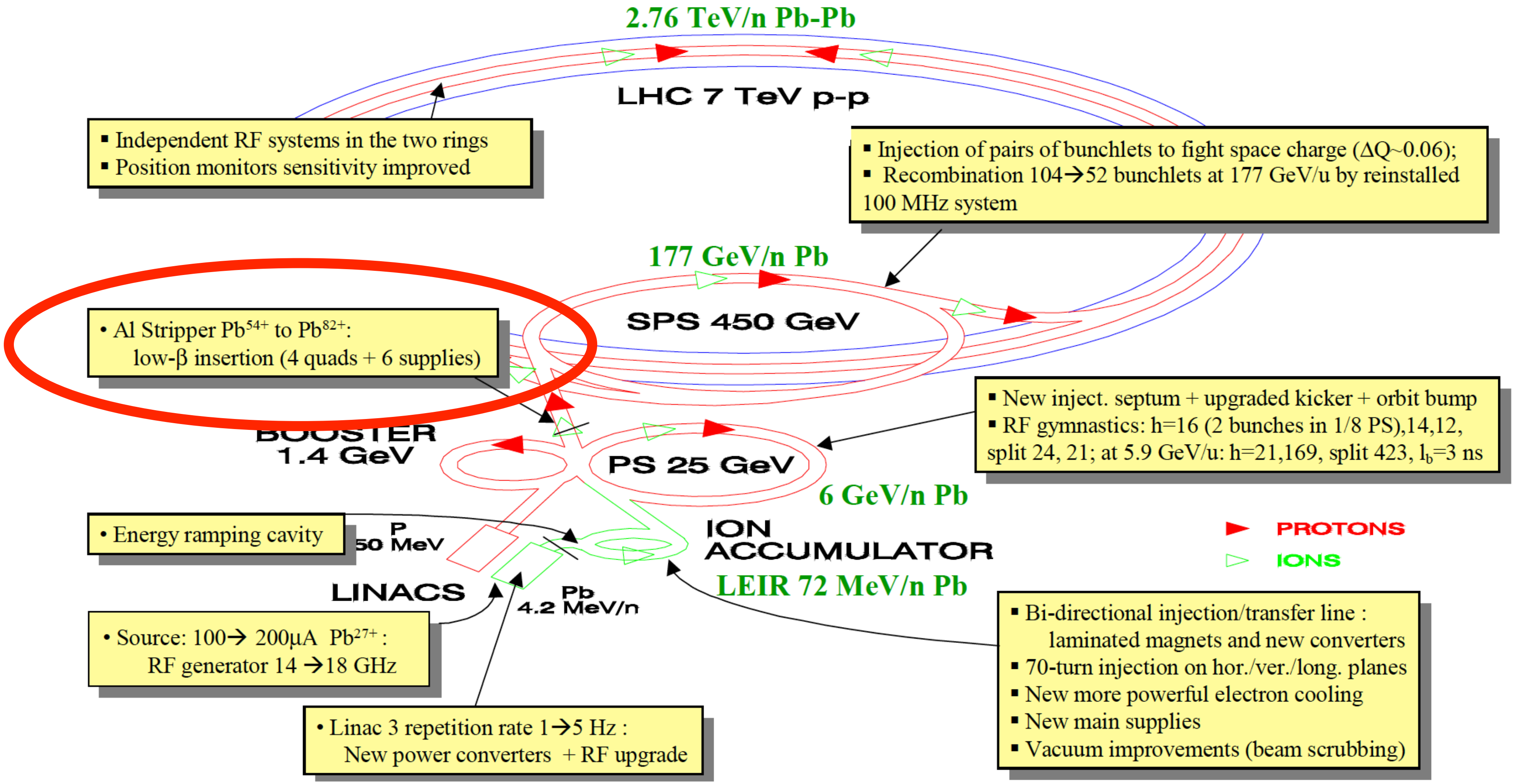
- *These studies are just starting. They need an expertise of the accelerator and laser physics communities. Everyone is invited to contribute.*

Extra transparencies

Collisions of photons with matter



$\sigma_{p.e.}$ = Atomic photoelectric effect (electron ejection, photon absorption)
$\sigma_{Rayleigh}$ = Rayleigh (coherent) scattering–atom neither ionized nor excited
$\sigma_{Compton}$ = Incoherent scattering (Compton scattering off an electron)
κ_{nuc} = Pair production, nuclear field
κ_e = Pair production, electron field
$\sigma_{g.d.r.}$ = Photonuclear interactions, most notably the Giant Dipole Resonance
In these interactions, the target nucleus is broken up.



- Independent RF systems in the two rings
- Position monitors sensitivity improved

- Injection of pairs of bunchlets to fight space charge (ΔQ~0.06);
- Recombination 104→52 bunchlets at 177 GeV/u by reinstalled 100 MHz system

- Al Stripper Pb^{54+} to Pb^{82+}:
  low-β insertion (4 quads + 6 supplies)

- New inject. septum + upgraded kicker + orbit bump
- RF gymnastics: h=16 (2 bunches in 1/8 PS),14,12, split 24, 21; at 5.9 GeV/u: h=21,169, split 423, l$_b$=3 ns

- Energy ramping cavity

- Source: 100→ 200μA Pb^{27+}:
  RF generator 14 →18 GHz

- Linac 3 repetition rate 1→5 Hz :
  New power converters + RF upgrade

- Bi-directional injection/transfer line :
  laminated magnets and new converters
- 70-turn injection on hor./ver./long. planes
- New more powerful electron cooling
- New main supplies
- Vacuum improvements (beam scrubbing)

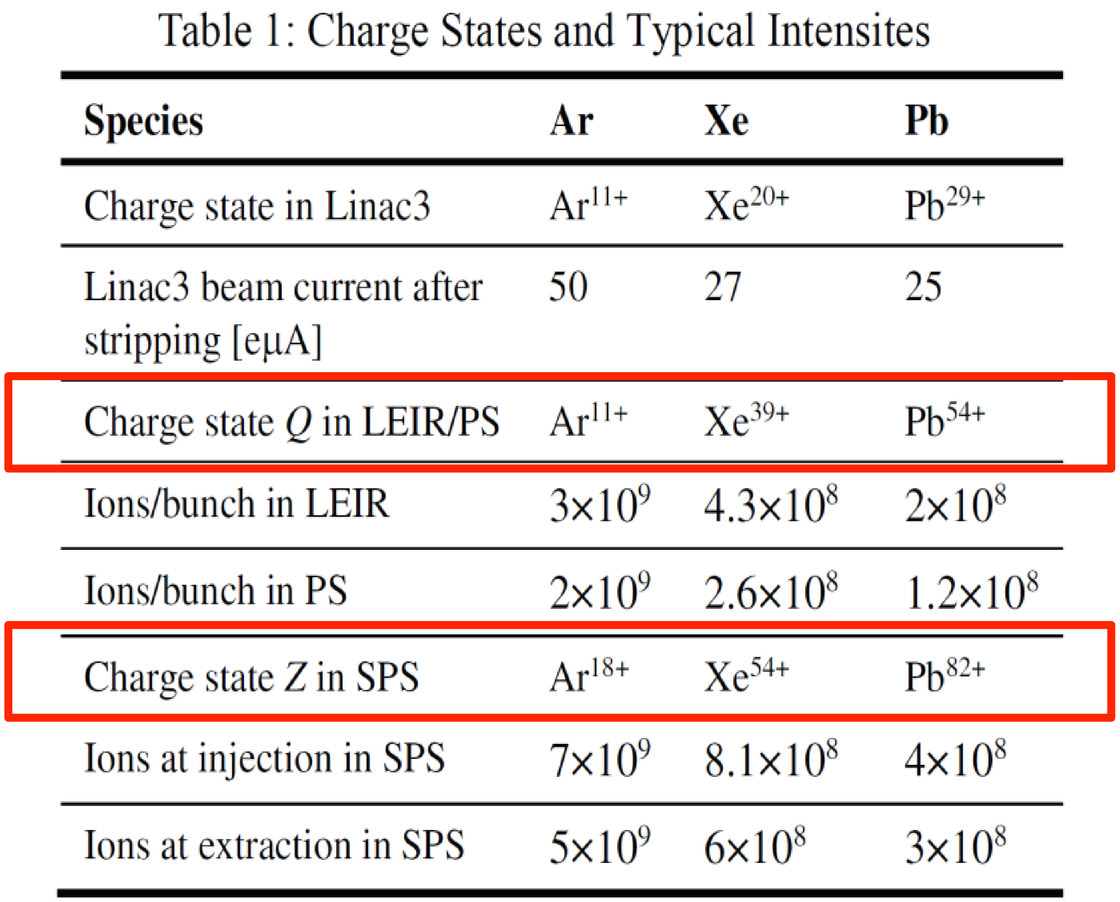
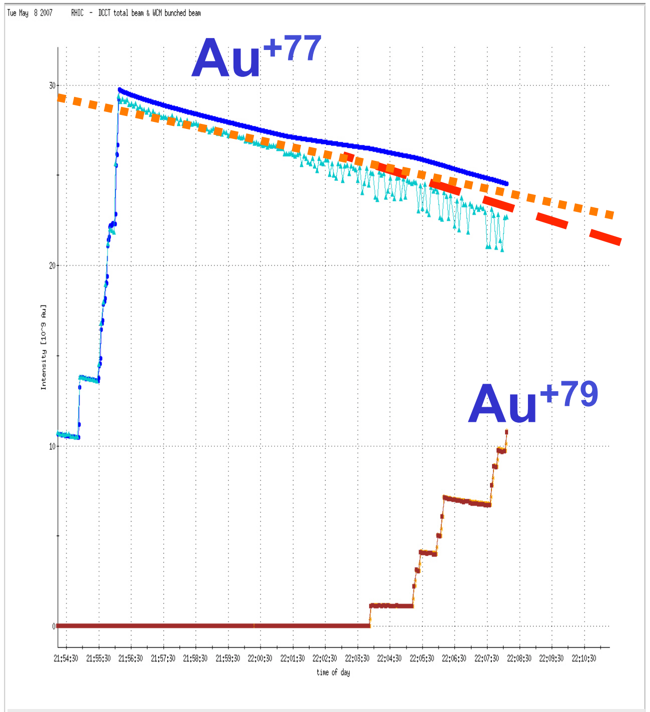


Table 1: Charge States and Typical Intensites

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

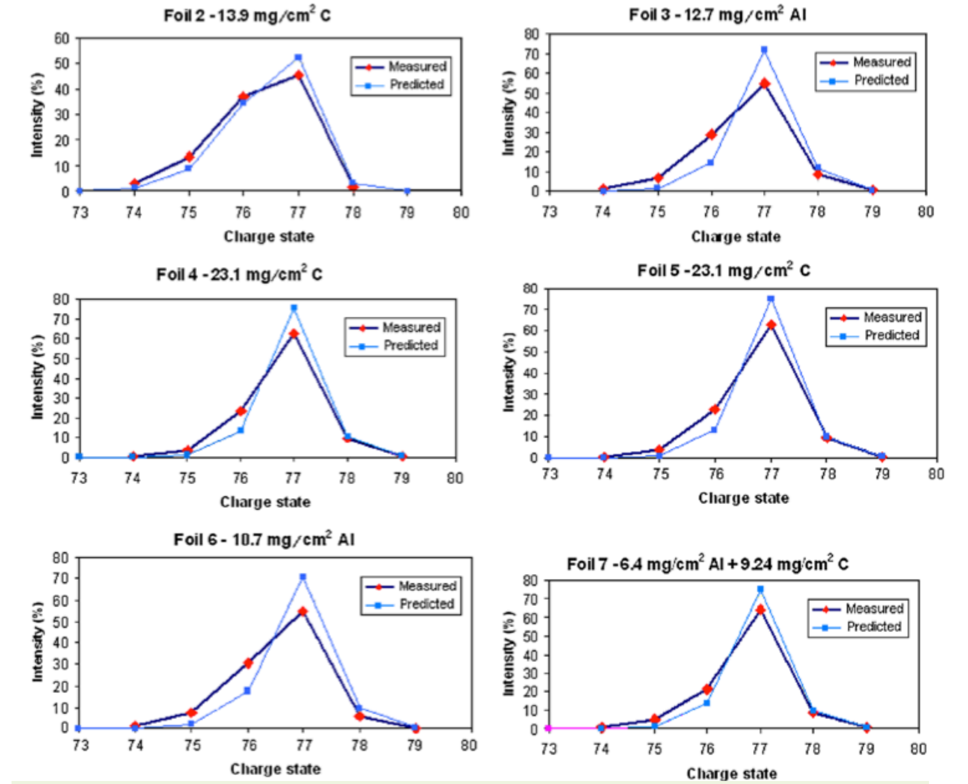
D. Manglunki et al.
CERN's Fixed Target Primary Ion Programme. IPAC’2016.

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^{77+} beams (Helium-like Au ion)

Stripping efficiencies (GLOBAL and CHARGE codes)

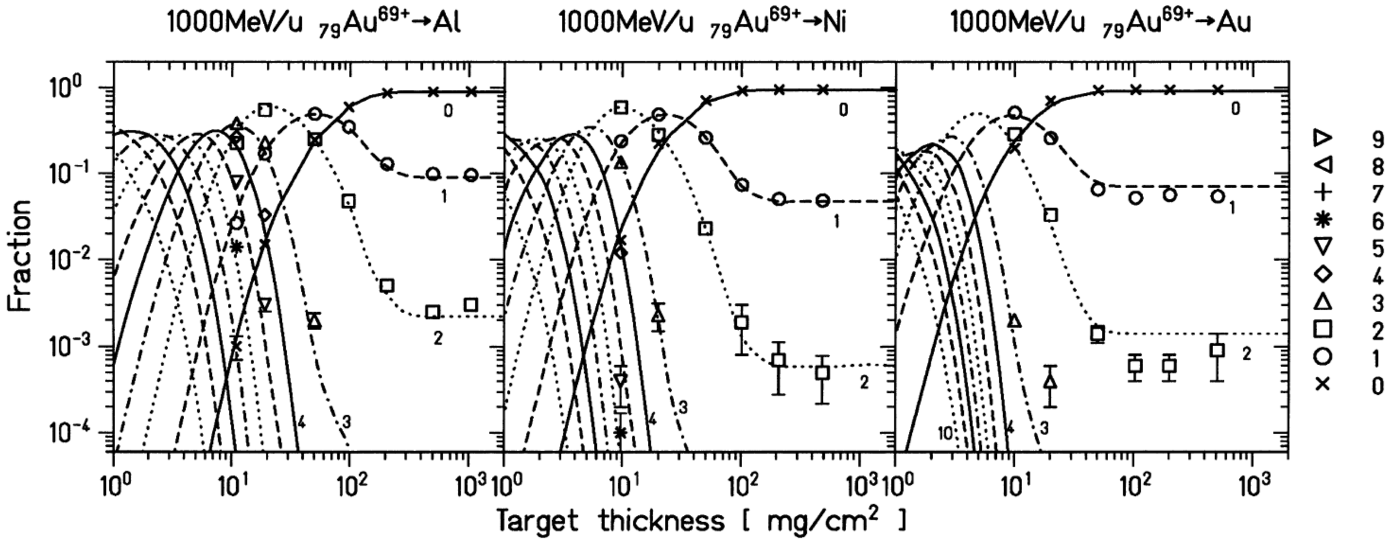
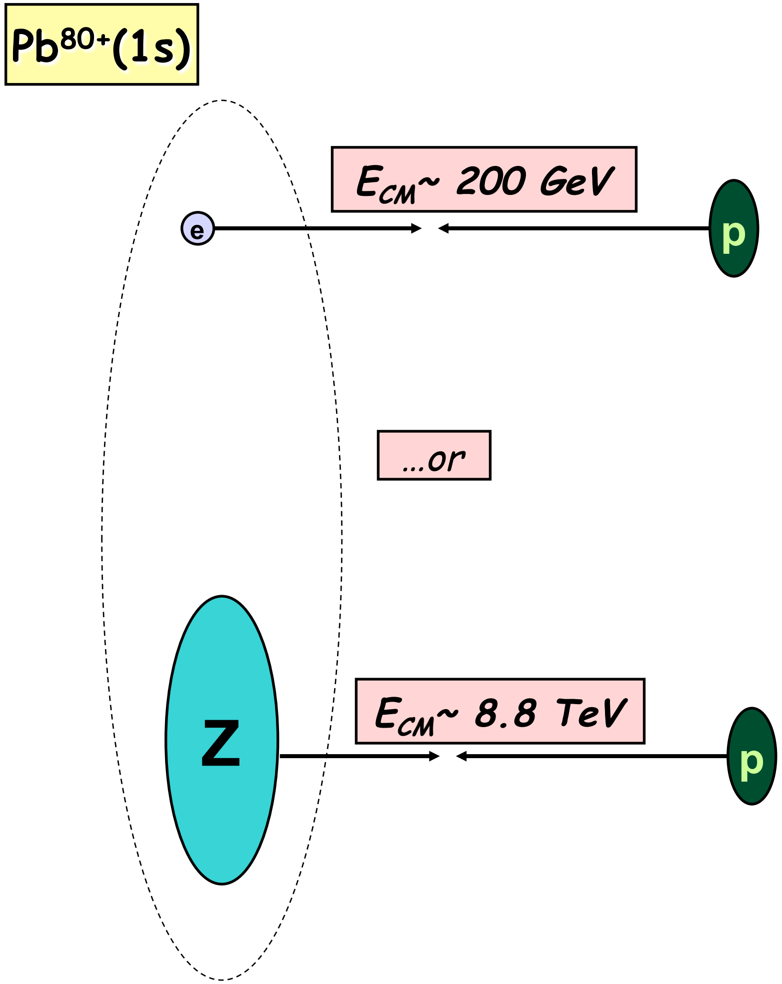


Fig. 8. Charge-state evolution of 1000-MeV/u Ne-like Au ions impinging on Al, Ni, and Au targets. Due to the much larger cross sections in high-Z materials, charge-state equilibrium in Au targets is reached much earlier than in Al and Ni [22]. The curves are the results of GLOBAL. The symbols used for the experimental data denote the electron number n attached to the projectile and are used from now on throughout the paper with the same meaning.

C. Scheidenberger et al. / Nucl. Instr. and Meth. in Phys. Res. B 142 (1998) 441–462

Cost-less electron-proton and γ-proton collisions in the ATLAS, CMS, ALICE and LHCb interaction points



- *average distance of the electron to the large Z nucleus d ~ 600 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 >> 300 KeV*

- *both beams have identical bunch structure (timing and bunch densities), the same β^*, 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)*

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

PIE@LHC: Pb^{80+} example*

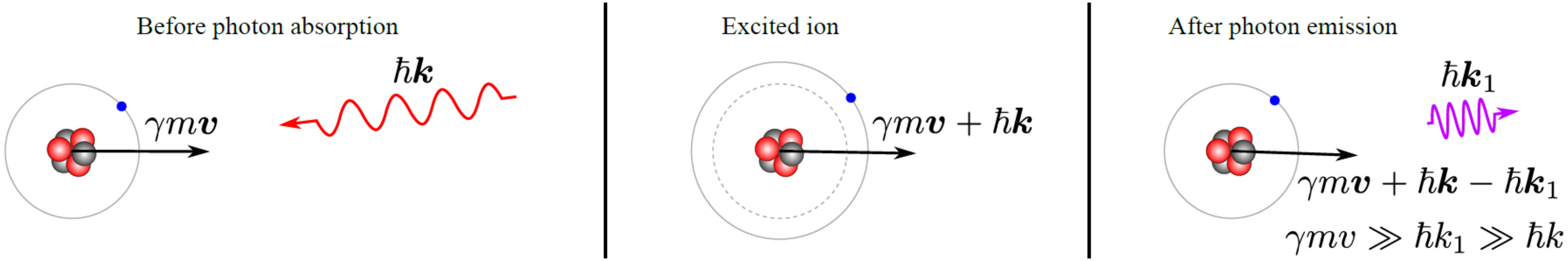
- *CM energy (ep collisions)* = *205 GeV*
- *β at IP* = *0.5 m*
- *Transverse normalized emittance* = *1.5 μ m*
- *Number of ions/bunch* = 10^{8}
- *Number of protons/bunch* = 4×10^{10}
- *Number of bunches* = *608*
- *Luminosity* = 0.8×10^{30} cm^{-2} s^{-1}

- *PIE = Parasitic Ion Electron collider*

(Electron beam for LHC, Nucl.Instrum.Meth. A540 (2005) 222-234)

Radiative Cooling by Broad-Band lasers

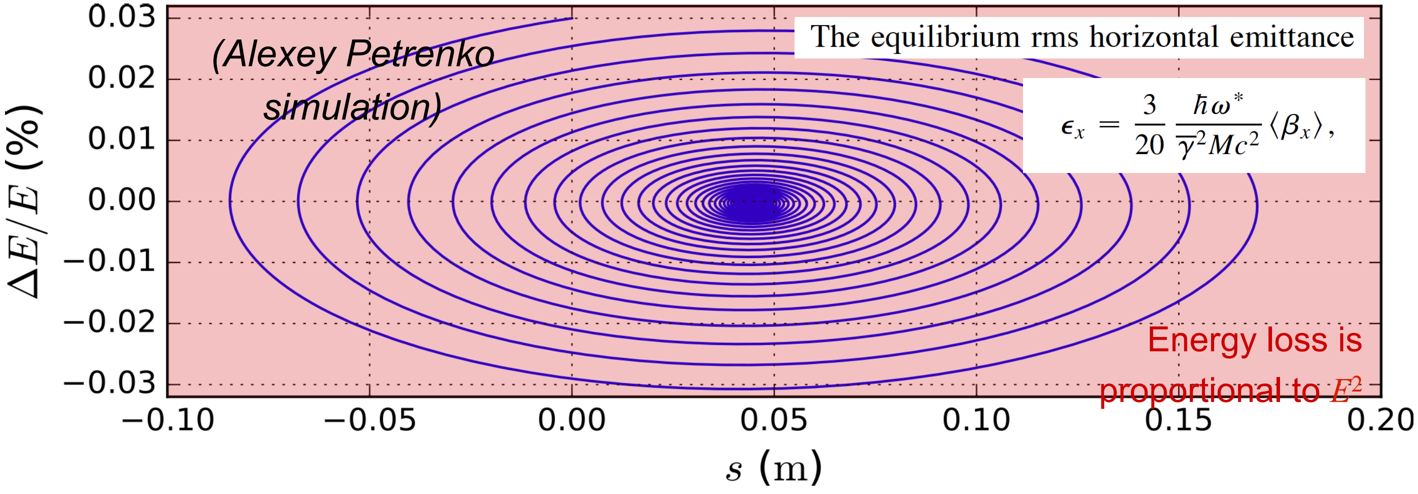
E. G. Bessonov and K.-J. Kim. PRL76, 431, 1996.



Broad-band laser covers the full spectrum of particle energies

Longitudinal cooling: energy loss grows with ion energy

Transverse cooling: all components of ion momentum are reduced by absorbing and re-emitting of photons but only the longitudinal component is restored in the RF cavity.



(Alexey Petrenko simulation)

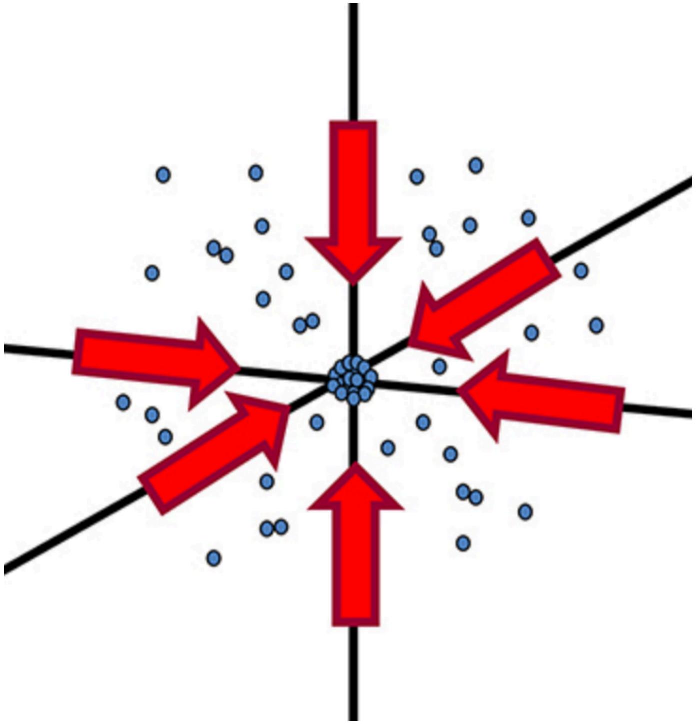
The equilibrium rms horizontal emittance

$$\epsilon_x = \frac{3}{20}\frac{\hbar\omega^*}{\overline{\gamma}^2 Mc^2}\langle\beta_x\rangle,$$

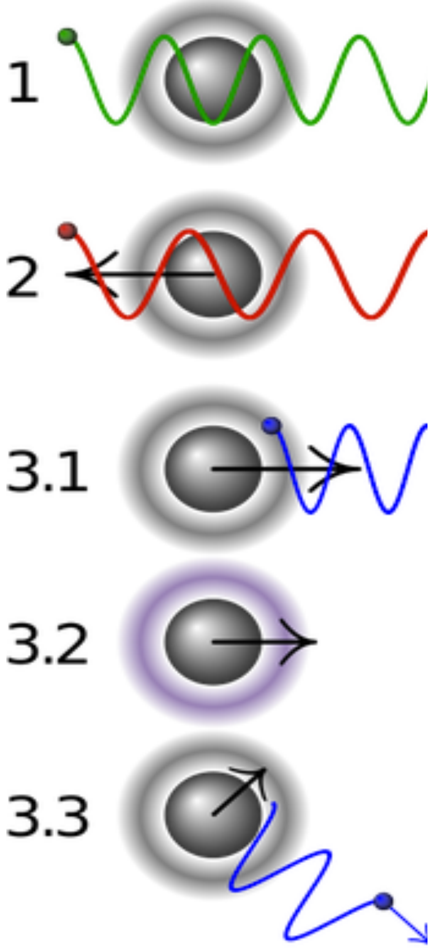
Energy loss is proportional to E^2

The time of cooling is the time to radiate full ion energy E

Laser cooling of stationary atoms (basic ideas)



Six “red –detuned” laser beams (optical molasses)



Simplified principle of Doppler laser cooling:

1 A stationary atom sees the laser neither red- nor blue-shifted and does not absorb the photon.

2 An atom moving away from the laser sees it red-shifted and does not absorb the photon.

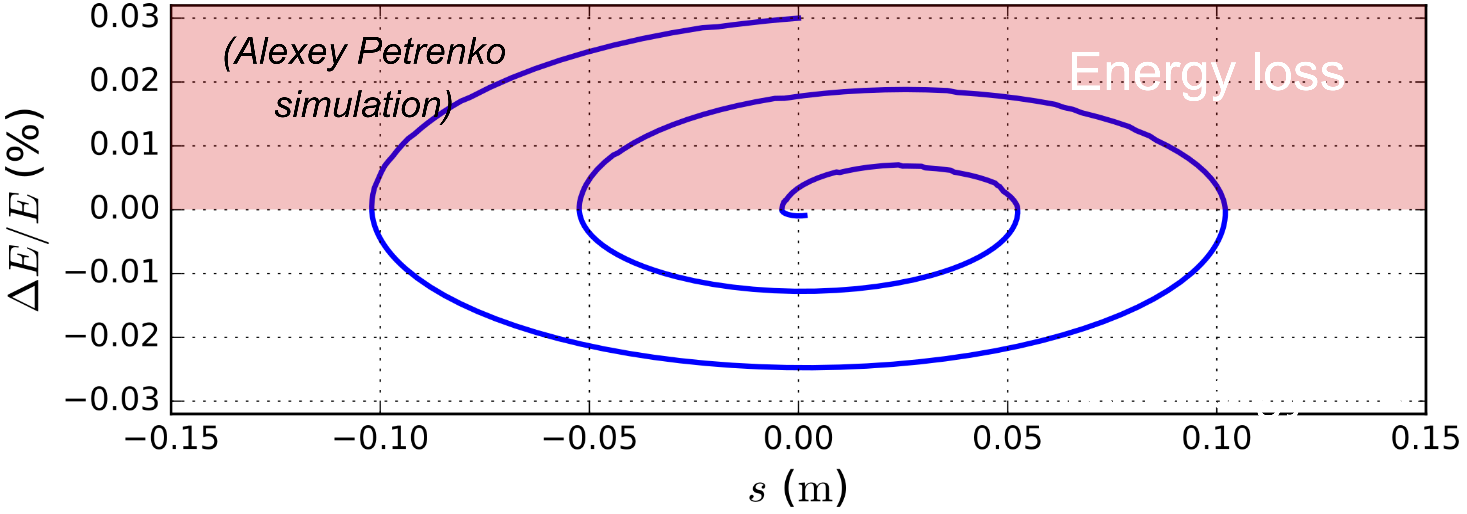
3.1 An atom moving towards the laser sees it blue-shifted and absorbs the photon, slowing the atom.

3.2 The photon excites the atom, moving an electron to a highe quantum state.

3.3 The atom re-emits a photon. As its direction is random, there is no net change in momentum over many absorption-emission cycles.

E. G. Bessonov, R. M. Feshchenko, RuPAC'2008.

Broad-band laser with a sharp frequency cut-off



*Significantly faster cooling, **but only longitudinal**. Time of cooling is the time to **radiate energy spread** ΔE **(below 1 second at SPS)***

Coupling schemes between longitudinal and transverse oscillations can be used to transfer the longitudinal cooling into the transverse plane – such coupling is present already in a realistic ring because of small tilts of dipoles and quadrupoles) –needs further studies