The Gamma Factory

Muon Collider workshop, Padova, July 2018

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representing Gamma Factory study group

The Gamma Factory in a nutshell

1. *Accelerate and store high energy beams of **Partially Stripped Ions (PSI)** 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, 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

- *It is very likely that the CERN-LHC research program will reach soon (…if not already) its "discovery potential saturation" (no physics gain by extending the running time).*

- *In such a case, a strong need will arise for a novel research programme in basic and applied science which could re-use its existing, world-unique 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]) 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.

Gamma Factory group members

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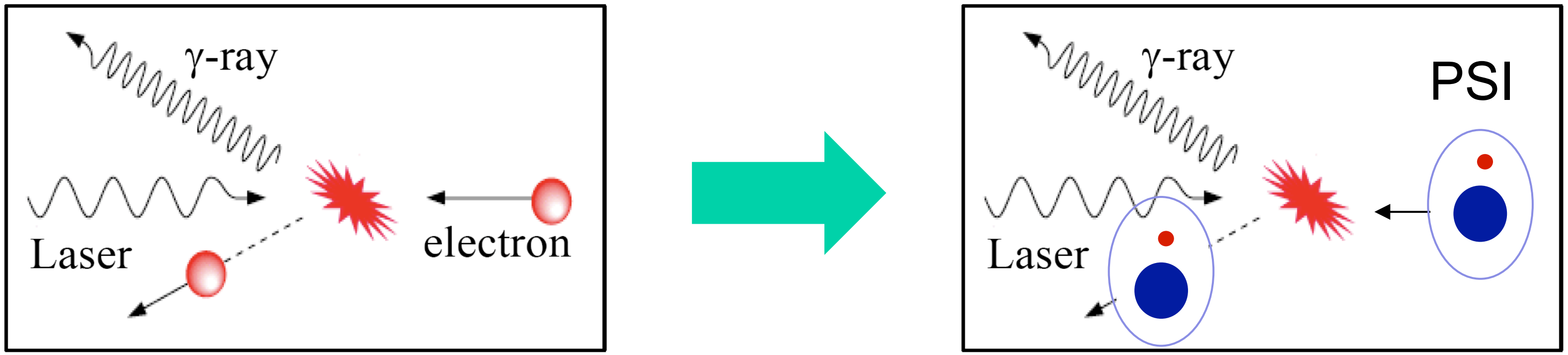
GF study group is open to everyone willing to join this initiative!,

Gamma Source

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. A. BOGACZ
E.G. BESSONOV, K-J. KIIM, M.W. KRASNY…

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:

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

Partially Stripped Ions:

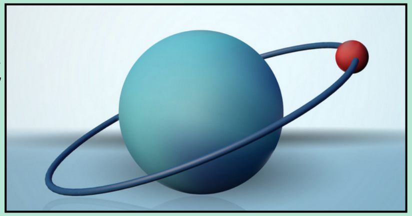
$\sigma_{res} = 5.9 \times 10^{-16}\ cm^2$

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

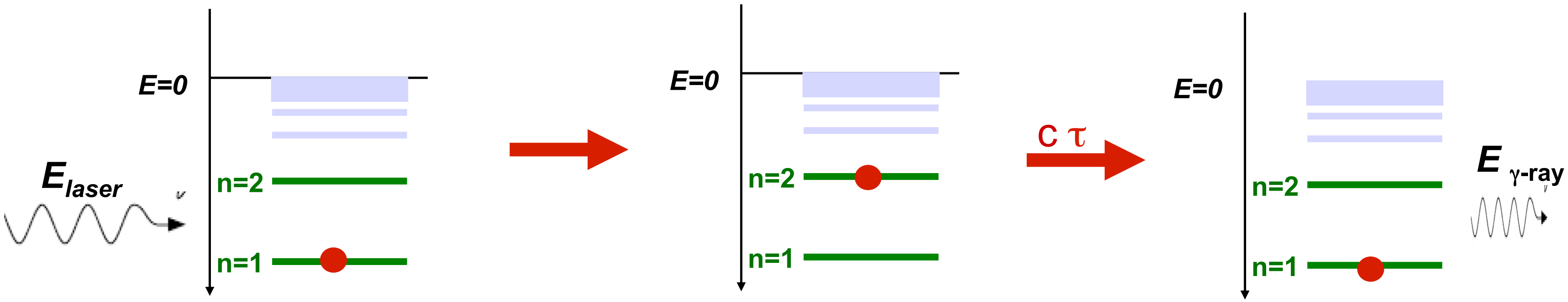
~ 9 orders of magnitude difference in the cross-section

~ 7 orders of magnitude increase of gamma fluxes

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



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



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

Partially Stripped Ion 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

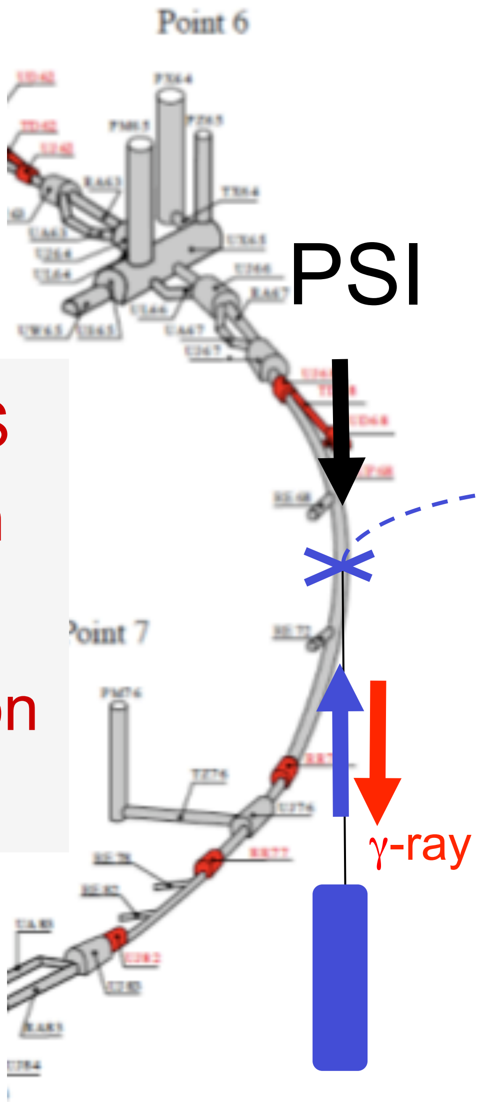
The tuning of the beam energy, the choice of the ion type, the number of left electrons and of the laser type allows to tune the γ-ray energy, at CERN, in the energy domain of 40 keV – 400 MeV.

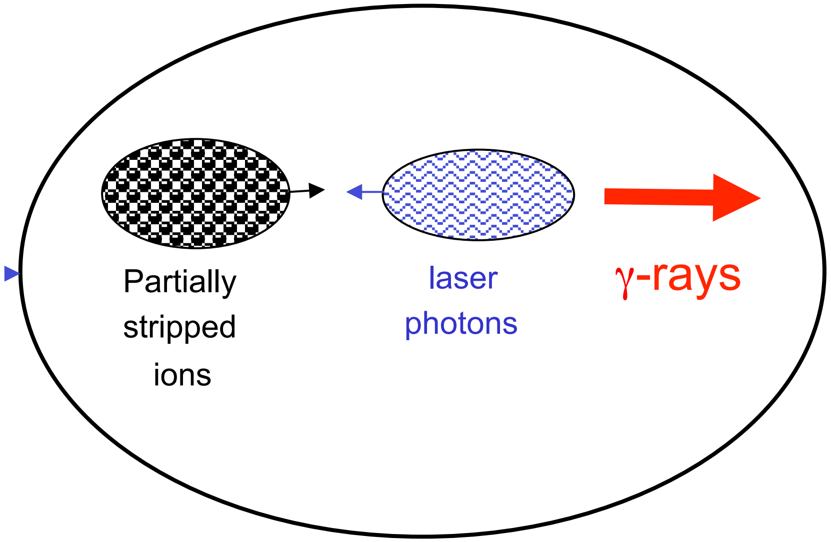
Example (maximal energy):

LHC, Pb^{80+} *ion,* γ_L = 2887, n=1→2, λ = 104.4 nm, E_γ (max) = 396 MeV

The γ-ray source scheme for CERN

LHC/SPS filled with partially stripped ion bunches





Laser photon

Decay length in the LAB frame $c\,\tau \sim \gamma_L/Z^4$
~ 0.04 *mm for* $Pb^{81+}(2p) \rightarrow Pb^{81+}(1s) + \gamma$

Principal advantages of the ion-based light sources

Energy tunability:

Four dimensional flexibility of the HIGS ($E_{laser(FEL)}$, γ_L, Z_{ion}, n.). Easy to optimize for a required narrow band of the γ-beam energy over a large E_γ domain. For the previous LCS sources two parameter tuning.

Beam divergence:

Excellent: Below 0.3 mrad

Polarizability

Flexible setting. Reflect, in both cases the polarization of the laser light

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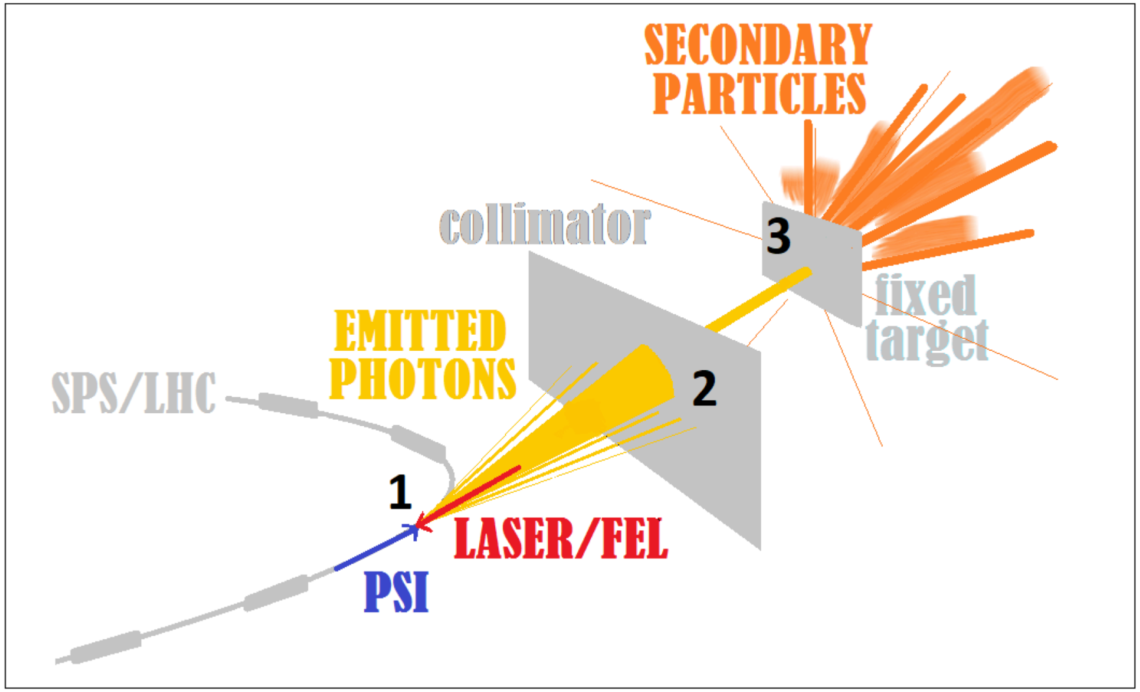
Note:

For maximal energies (e.g. scenario 1) HIGS must be driven by a <100 nm FEL photons.

For lower energies standard ~300-1500 nm lasers and FP cavities are sufficient

Gamma Factory



Beams and collision schemes

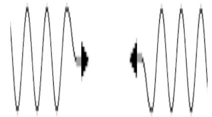
primary beams:

- **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

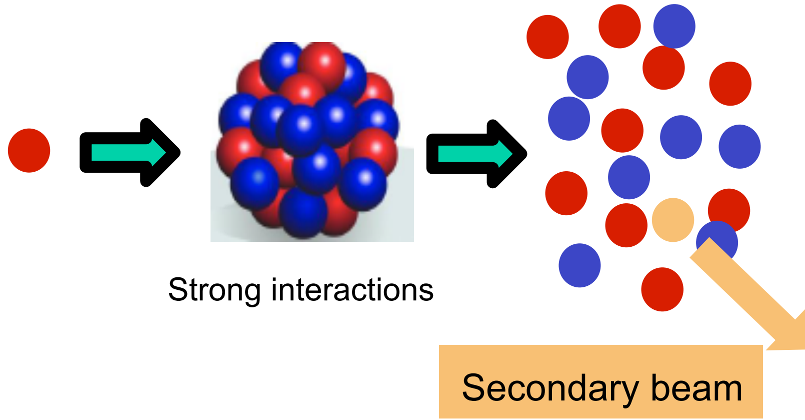
γ–p(A), ep(A) collisions,

E_{CM} = 4 – 200 GeV

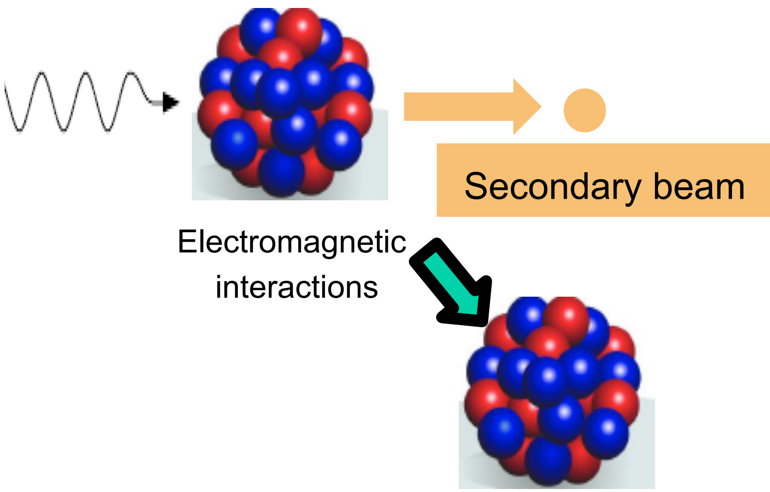
Gamma Factory secondary beams

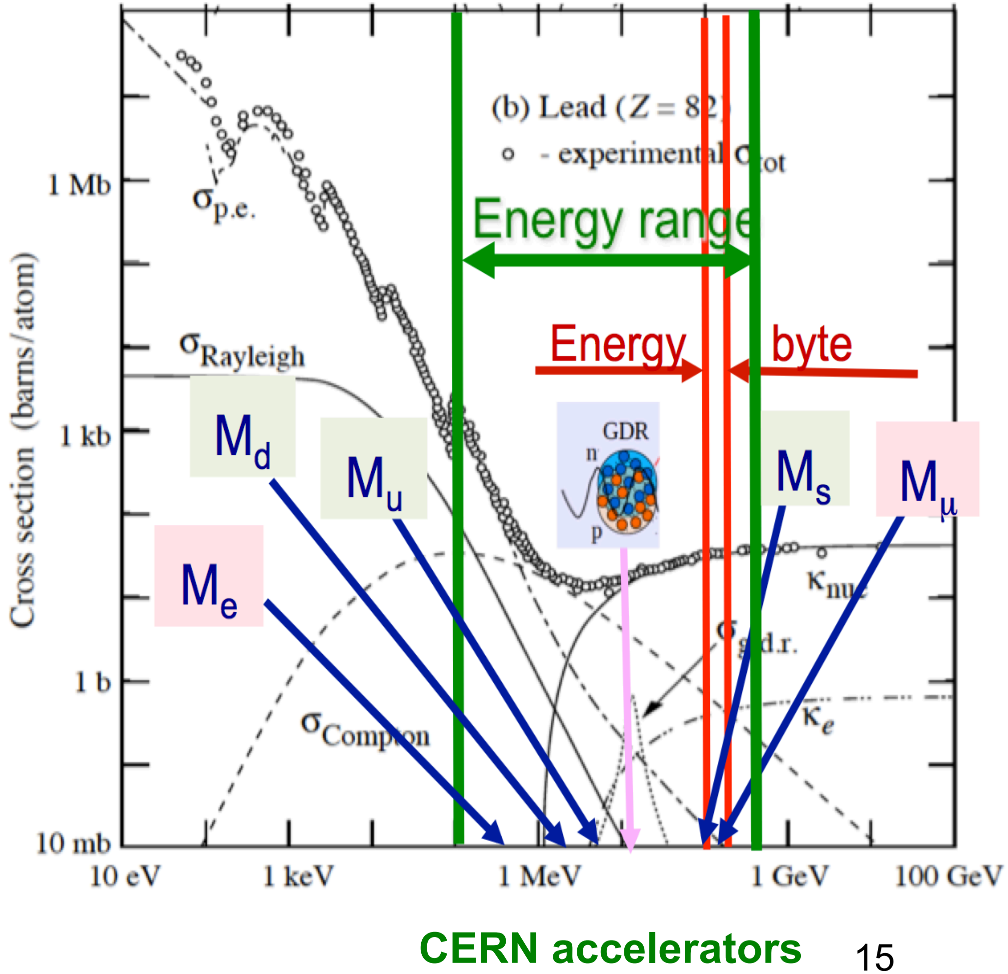
(from "mining" paradigm to "production-by-demand" paradigm)

"mining" paradigm:



"production" paradigm:





Gamma source for positron and polarised muon production

Towards an optimal gamma source to maximise production of polarised positrons and muons

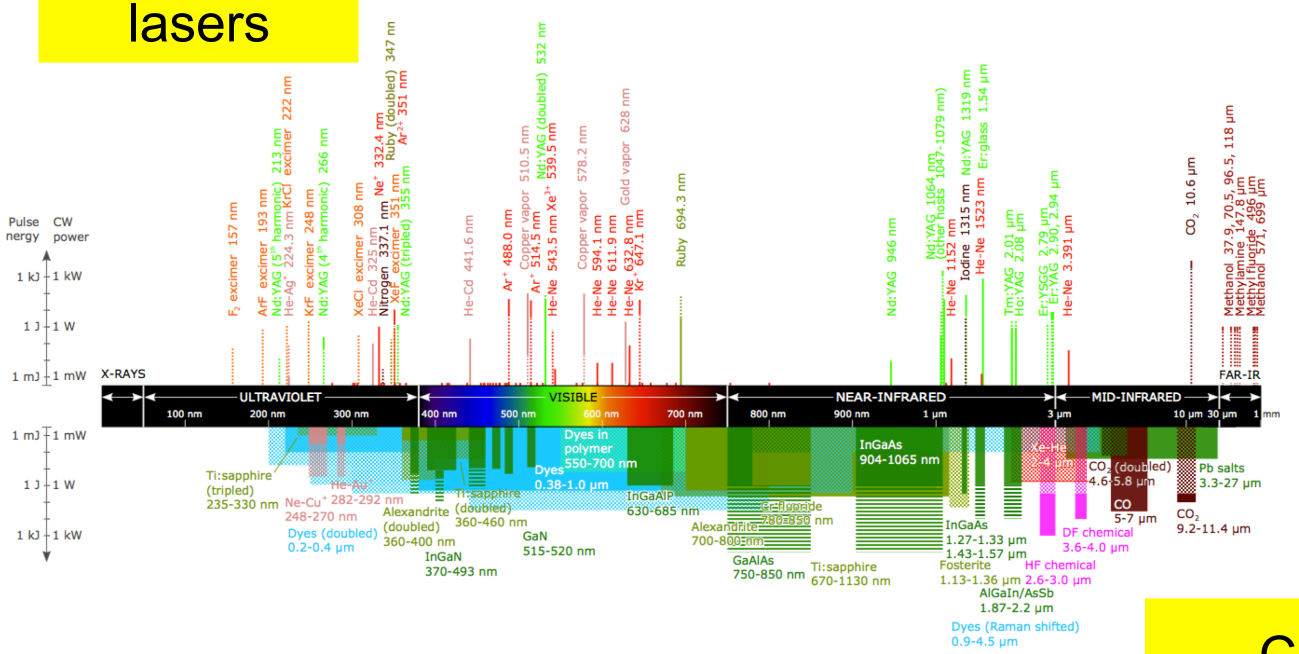
Multi-parameter choice of the gamma source energy band:

- *ion type,*
- *number of left over electrons,*
- *atomic excitation level (energy, oscillator strength, life time of the excited atoms),*
- *the beam energy*
- *the laser (FEL) type*

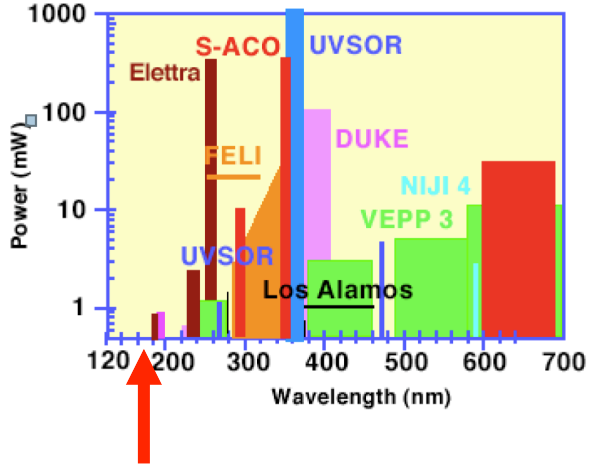
Constrains:

- *availability and yield of the ion source*
- *viable stripping scheme*
- *SPS and LHC vacuum*
- *Intra-beam stripping*
- *Stark effect*
- *RF circumferential voltage of the storage ring*
- *double photon absorption ionisation*
- *…*

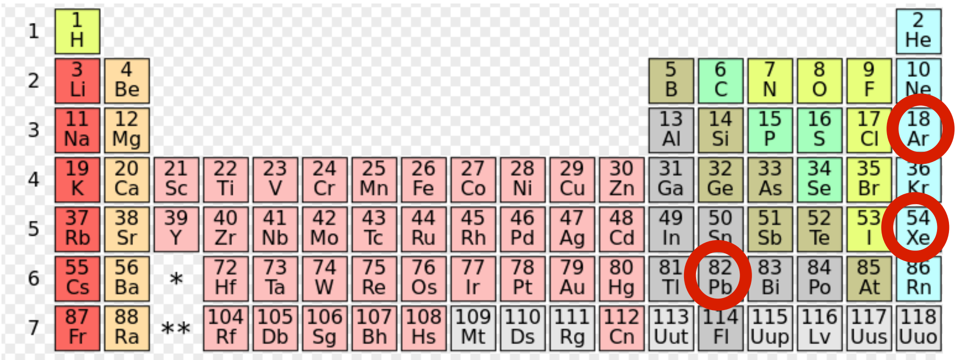
lasers



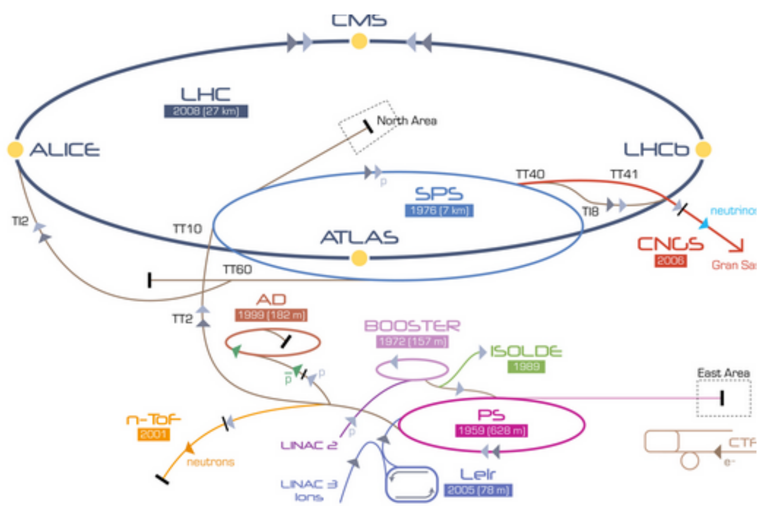
mirrors



Ions



CERN accelerators



Ion	O^{6+}	O^{7+}	Ar^{12+}	Ar^{16+}	Ar^{17+}	Ca^{12+}	Ca^{14+}	Xe^{30+}	Bi^{30+}	Bi^{41+}	U^{36+}	U^{40+}
I, eμA	3000	1400	1400	350	50	670	270	320	710	100	150	20

Towards an optimal gamma source to maximise production of polarised positrons and muons

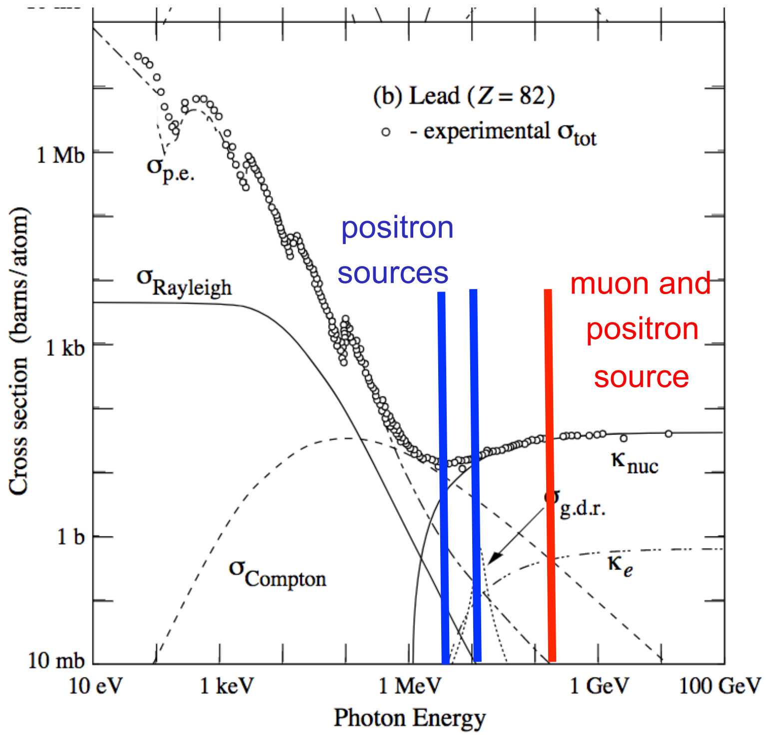


Figure 33.15: Photon total cross sections as a function of energy in carbon and lead, showing the contributions of different processes [51]:

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

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

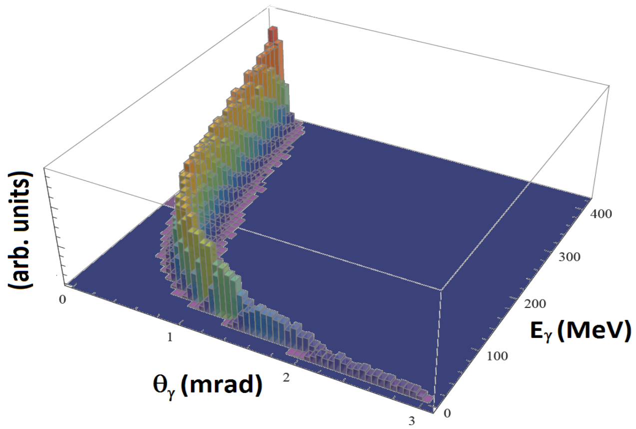
σ_{Compton} = Incoherent scattering (Compton scattering off an electron)

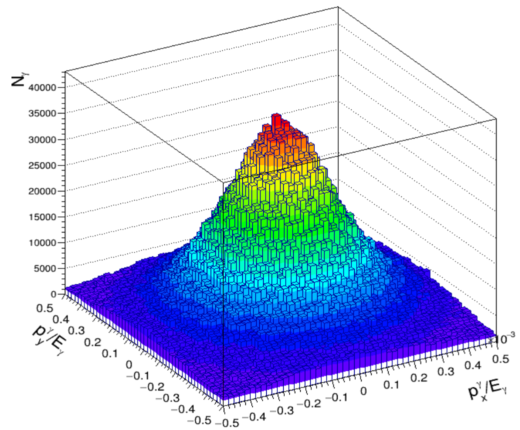
κ_{nuc} = Pair production, nuclear field

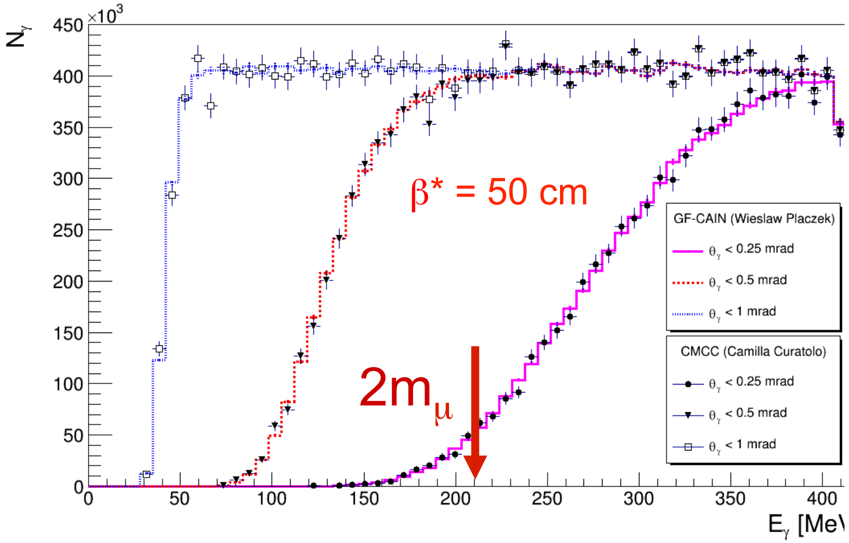
κ_e = Pair production, electron field

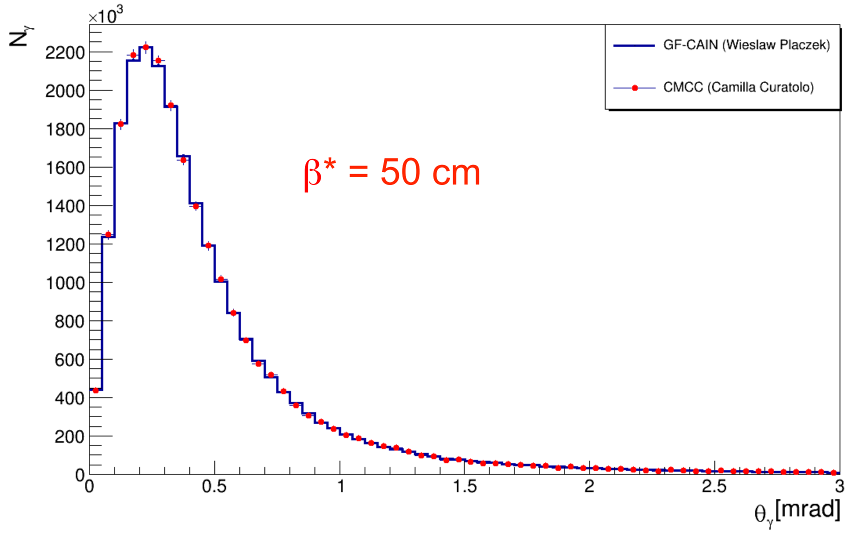
$\sigma_{\text{g.d.r.}}$ = Photonuclear interactions, most notably the Giant Dipole Resonance [52]. In these interactions, the target nucleus is broken up.

Gamma ray production spectra for +81 Pb beam collisions with photon bunches at the top LHC energy









Possible scenarios - Preliminary

Scenario 1 (muon production) :

FEL: 104.4 nm, Pb^{80+} *ion*, γ_L=2887, n=1→2 transition,

E_γ (max) = 396 MeV

Scenario 2 (positron production -- energy and cost recovery):

Erbium doped glass laser: 1540 nm, Ar^{16+} *ion*, γ_L=2068,

n=1→2, E_γ (max) = 13.8 MeV

Scenario 3 (positron production:) :

Yb:Yag laser 1030 nm, Pb^{79+} *ion*, γ_L=1115, n=2

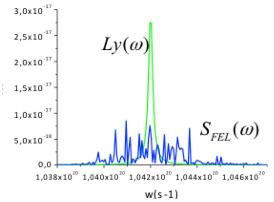
$S_{1/2}$ → $P_{3/2}$ transition, E_γ (max) = 6 MeV

Initial estimates of the achievable γ- fluxes for the three LHC scenarios

Scenario 1 :

FEL: 104.4 nm, Pb^{80+} *ion*, γ_L=2887, n=1→2, $E_\gamma^{(max)}$ = 396 MeV,

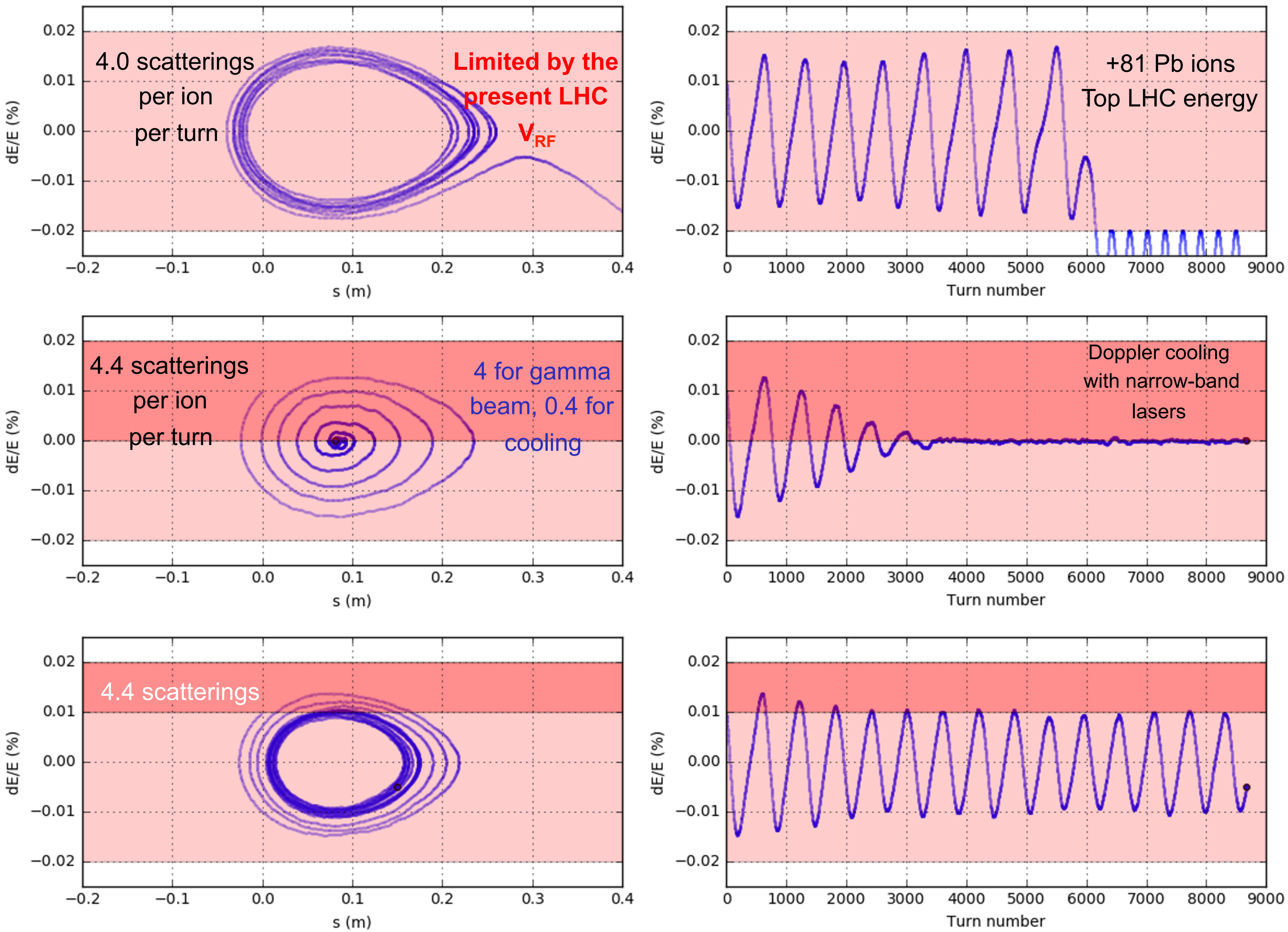
- Ultimate: N^{max}_γ **~ 7 x 10^{17}**[1/s] (Bessonov, Kim)
  (FEL parameters: 20 mJ/pulse, 10 MHz, pulse length 500 ps, average power 150 kW, bandwidth 2x10^{-4};, beam parameters: $\sigma_x = \sigma_y$ = 10μm, σ_z= 7.5 cm, N_i/bunch)= 10^9, $\delta\gamma/\gamma = 10^{-4}$)
- Present LHC constraint: N^{max}_γ **~ 6 x 10^{15}**[1/s] (1) **- 2 x 10^{16}**[1/s](2) (MWK)
  (for the LHC RF system -- 16 MV circumferential voltage)
- "Matrix FEL" example: N^{max}_γ **~ 3 x 10^{12}**[1/s]
  (Milano *Matrix* FEL, Vittoria Petrillo, Fabrizio Castelli)



Comments:

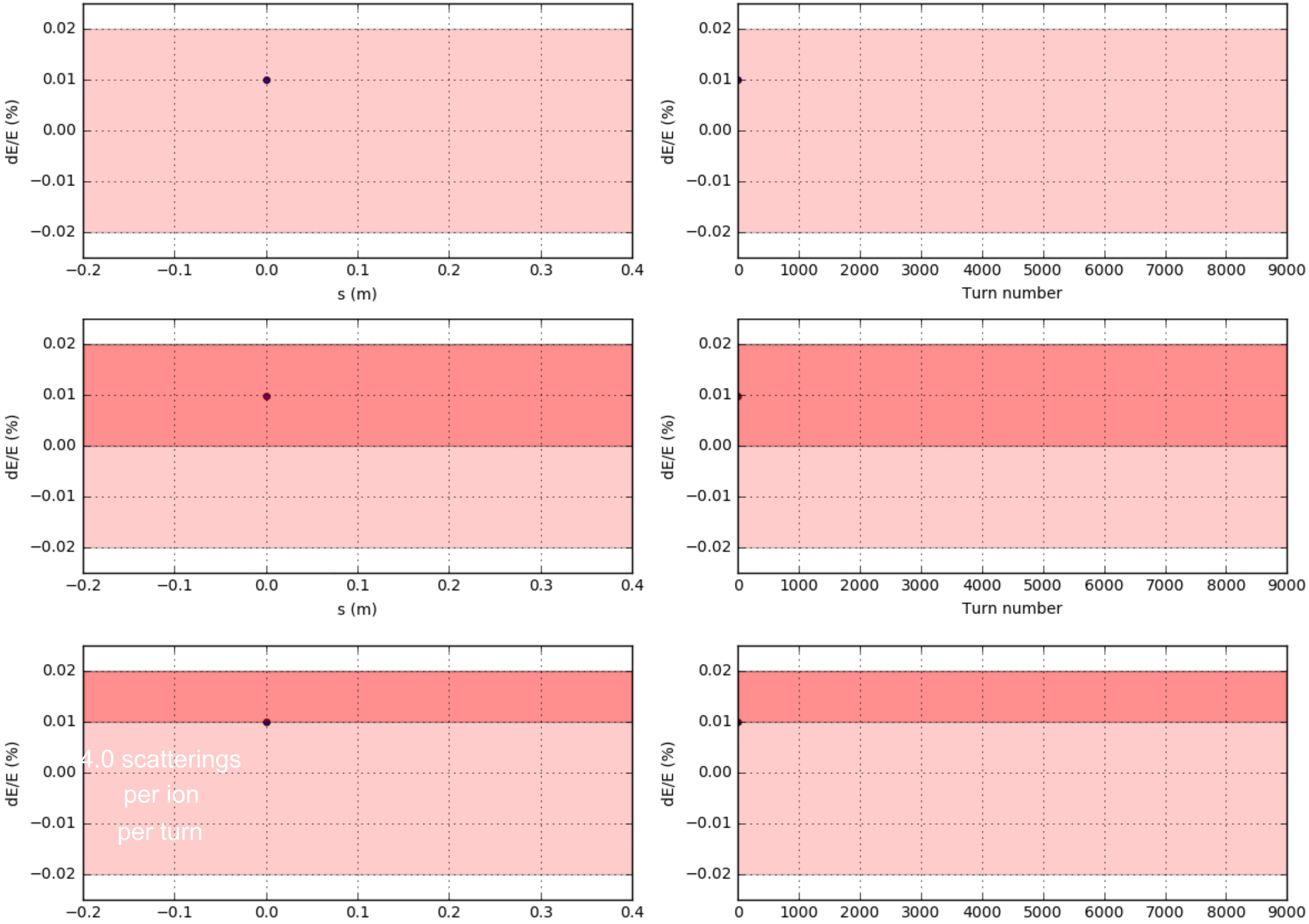
(1) $N^{\gamma}_{max} = N^{ion}_{bunch} \times N_{bunches} \times f$ [1/s] x RF [MV] x Z / <E_γ [MeV]>; (2) with cooling.

PSI beam stability studies and cooling simulations



http://www.inp.nsk.su/~petrenko/misc/ion_cooling/animations/

PSI beam stability and cooling simulations



http://www.inp.nsk.su/~petrenko/misc/ion_cooling/animations/

Initial estimates of the achievable γ- fluxes for the three LHC scenarios

Scenario 2:

Erbium doped glass laser: 1540 nm + FP, Ar^{16+} *ion*, γ_L=2068, n=1→2, $E_\gamma^{(max)}$ = 13.8 MeV

- **N^{max}_γ ~ 3 x 10^{17}** [1/s] (but short beam life-time in the LHC <1 hour – beam burning by the double photon absorption processes (*$c\tau_{exited\ ion}$ = 1.2 cm*). Requires improving the SPS vacuum pressure in the SPS by a factor of ~ 40 (injection efficiency)!

A trick: stay within the same n – excite spin and angular momentum of the electron:

Scenario 3 (positron production:) :

Yb:Yag laser 1030 nm + FP, Pb^{79+} *ion*, γ_L=1115, n=2

$S_{1/2}$ → $P_{3/2}$ transition, E_γ (max) = 6 MeV

- **N^{max}_γ > 10^{17}** [1/s] (limits due to (1) double photon absorption processes and (2) the SPS vacuum circumvented but needs multiple IPS in the straight section, and or an improvement in the ion source yield)

A comment: Long term future -- HE-LHC scenario

HE-LHC scenario :

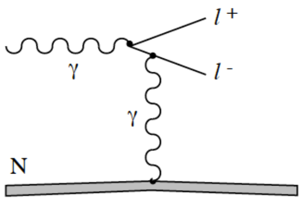
Ar laser: 488 nm, Xe^{53+} *ion*, γ_L=5866, n=1→2, $E_\gamma^{(max)}$ = 350 MeV

N^{max}_γ ~ **2 x 10^{17}**[1/s] (already for the present LHC RF system -- 16 MV circumferential voltage, and larger if extra cavities added)

- No longer **FEL and mirror reflectivity constraints** – gamma flux limited only by the circumferential voltage of the LHC and the maximal power which can be absorbed by the photon conversion target
- Note a gain is the Xe source yield w.r.t. to Pb – less collisions per ion, per turn at fixed gamma flux

GF-based polarised positron and polarised muon sources

Gamma Factory based polarised lepton source



Replace the 4.5 X0 Converter by a ~1-2 X0 converter – **only primary conversions**

Replace Primary Electrons by Polarised Gamma

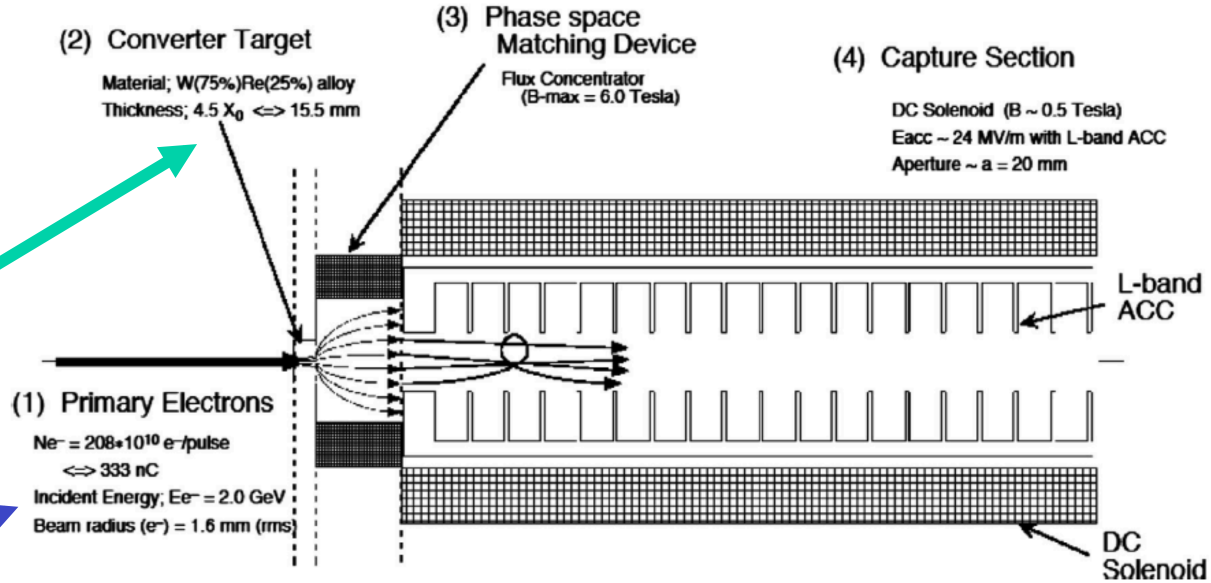


Fig. 2. Layout of the CLIC e⁺ source with a single target.

Principal gains of a *GF based* polarised lepton source:

- High positron/electron flux (no necessity to stack the positrons in the pre damping or damping ring)
- Highly polarized electrons/positrons (circular gamma polarisation)
- Significantly lower target heat load per produced positron
- Precious admixture of muon pairs (if E_γ above muon production threshold)

Problems which need to be solved:

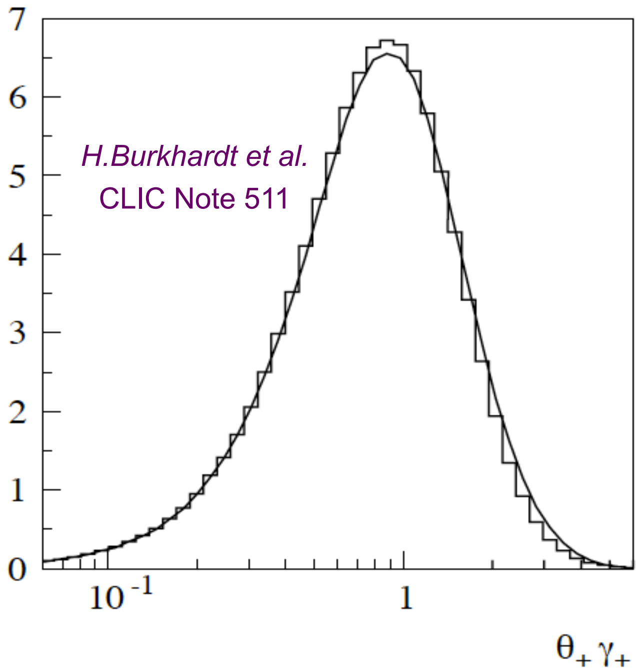
- For e.g. E_γ ~ 300 MeV, muons constitute only a small (<10^{-5}) fraction of all the photon conversion pairs.
  How to filter them out?

- The Gamma converter must be placed at a certain distance from the gamma production point (irreducible emittance growth -- recoil effect)
  How to minimise the emittance growth w.r.t that of the parent ion bunches?

- Muons produced mainly at significantly larger angles than electrons and may be emitted at large angles ($\gamma_e >> \gamma_\mu$).
  How to collect them to preserve the small longitudinal and transverse bunch sizes of the parent photon bunches?

Hint1

The conversions, especially on high Z material, lead to a simple relation between the outgoing muon energy and angle:



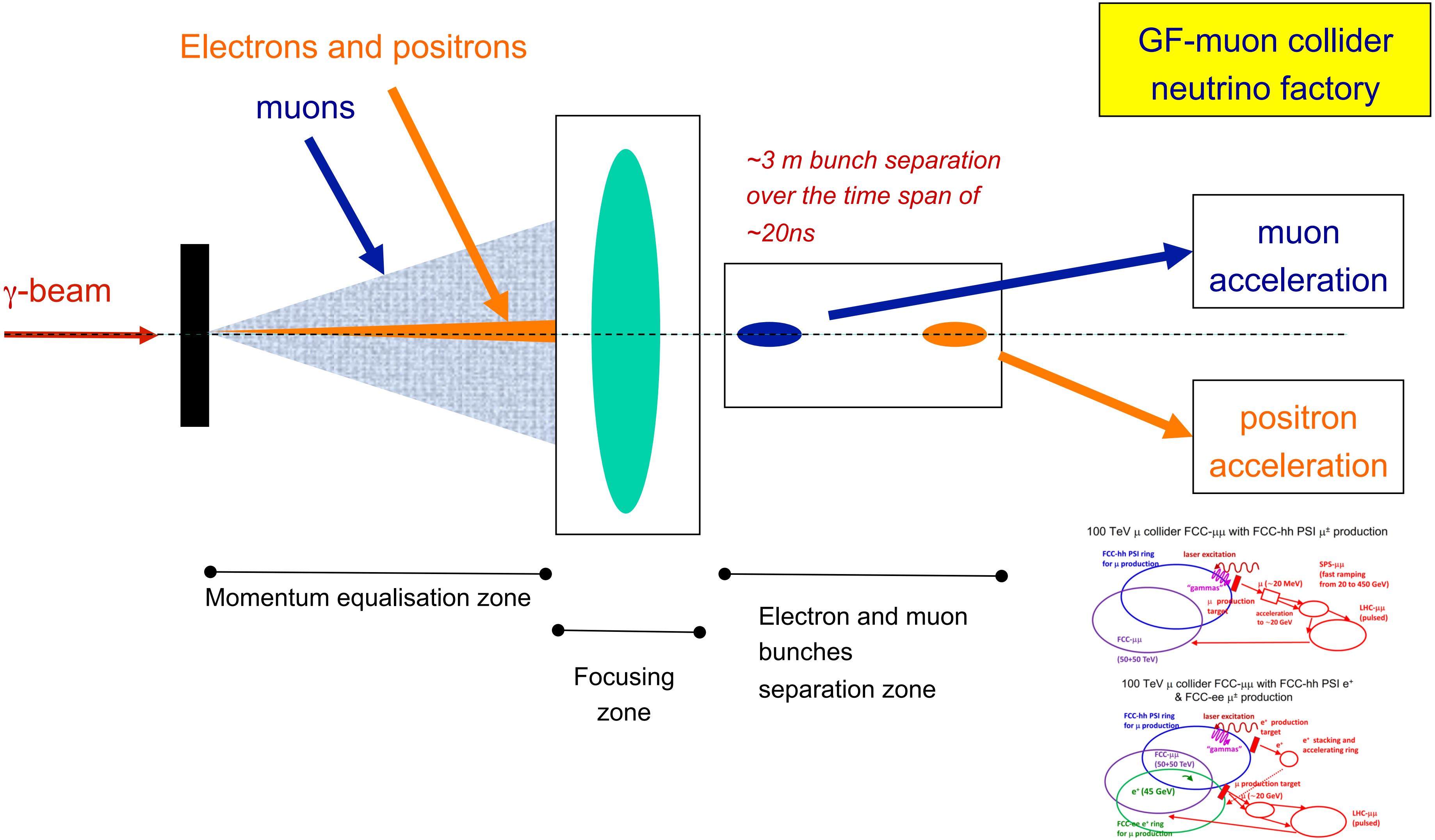
Hint2

Electrons are relativistic, muons are not:

$\beta_e = 1, \langle\beta_\mu\rangle \sim 0.5$

20 ns following the collision of the photon bunch with the conversion target, electron and muon bunches are separated by (on average) 200 cm allowing for their efficient separation

initial ideas…



The way forward

- *Development of the specialized generator for photon conversion into muon pairs close to the production threshold*
- *Realistic design of the gamma production IP, gamma beam extraction, and the gamma conversion target*
- *Realistic design of the muon/electron beam separator and the beam transport including “muon beam emittance corrector”*

Conclusions:

GF research highlights

- ***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:

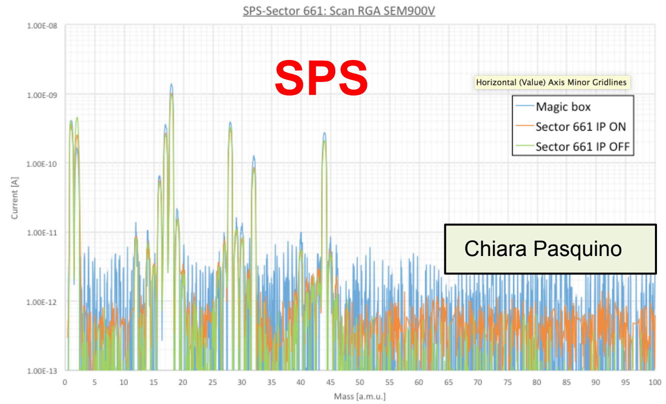
GF and the muon collider

Following the phase of its conceptual development the Gamma Factory initiative enters the initial phase of its experimental tests and the construction phase of the simulation tools aiming to prove its feasibility (dedicated GF SPS and LHC test runs with partially stripped ions in 2017 and 2018 -- Reyes talk).

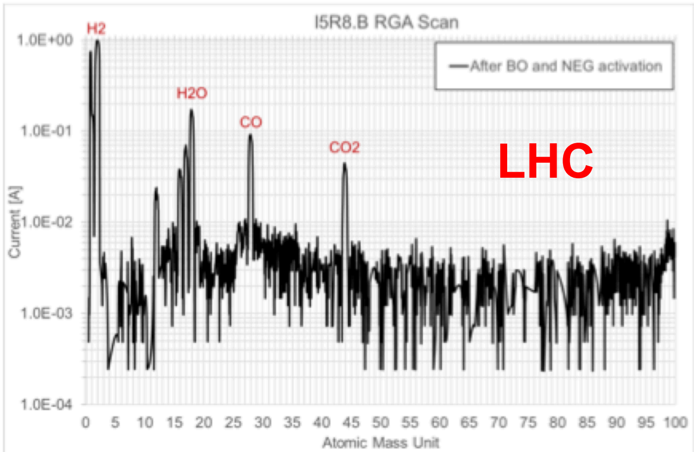
The goal of these studies is to provide realistic estimates of the gamma fluxes which could be achieved using the present CERN accelerator complex and define the necessary upgrades (e.g. SPS vacuum system) to achieve even higher fluxes.

The Gamma Factory capacity in producing low emittance beams of fully polarised leptons: (muons and electrons) revive an interest in the muon collider and the neutrino factory concepts based on the low emittance, electromagnetically produced muon beams.

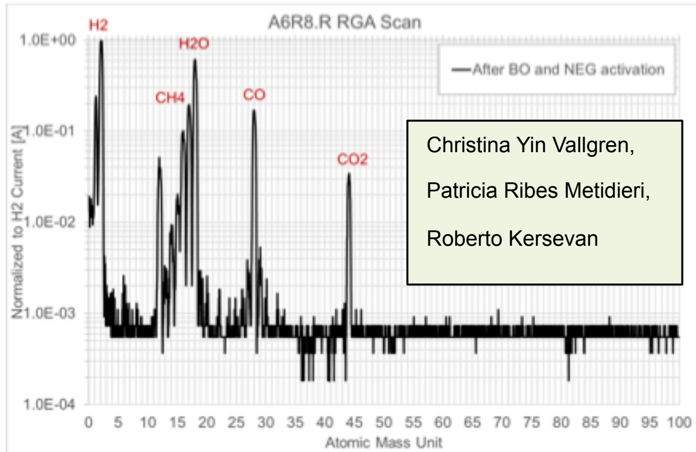
SPS bottleneck -- the vacuum quality



1. Normalized to the H2 peak.
2. H2 as dominant gas after the bake-out and NEG activation.
3. The main gases in the warm LHC vacuum chamber: H2, CO, CO2, CH4 and H2O.



Interconnects between the MKIs



Injection line at Point 8

… an idea of the secondary positron beam producing station with sustainable research -- the electric power and cost recovery..