The Gamma Factory

ARIES Annual Meeting, Riga, May 2018

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LPNHE, CNRS-IN2P3 and University Paris Sorbonne
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, 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 may take a long time to be approved, financed and built.*
- *It is very likely that the CERN-LHC research program 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 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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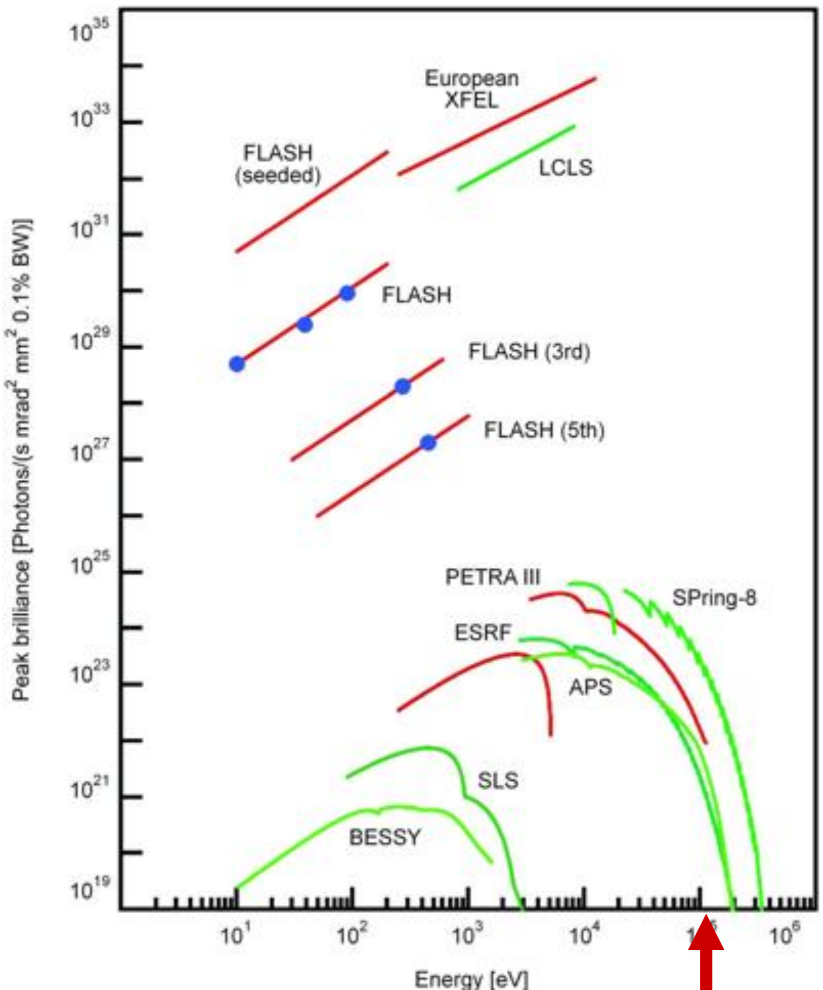
GF study group is open to everyone willing to join this initiative!

contact person: krasny@lpnhe.in2p3.fr, mieczyslaw.witold.krasny@cern.ch,

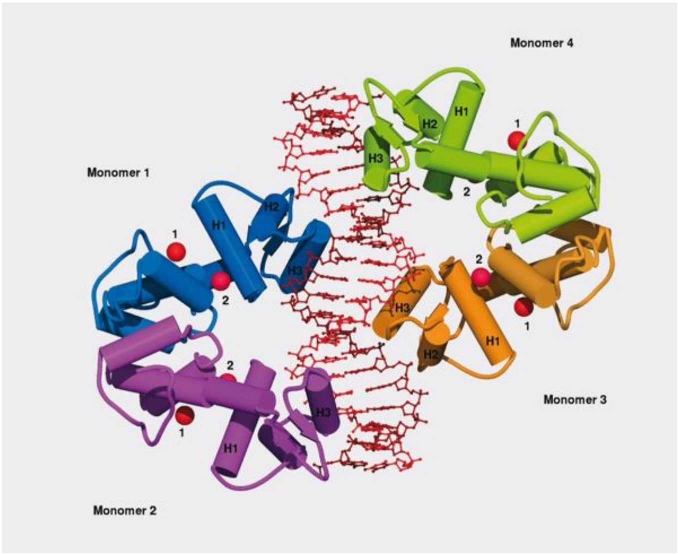
Gamma Source

X-ray sources



100 KeV

atomic structures →



How about the quanta capable of resolving/manipulating the nuclear structure and allowing to convert light into matter (γ-ray domain)?

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–

*

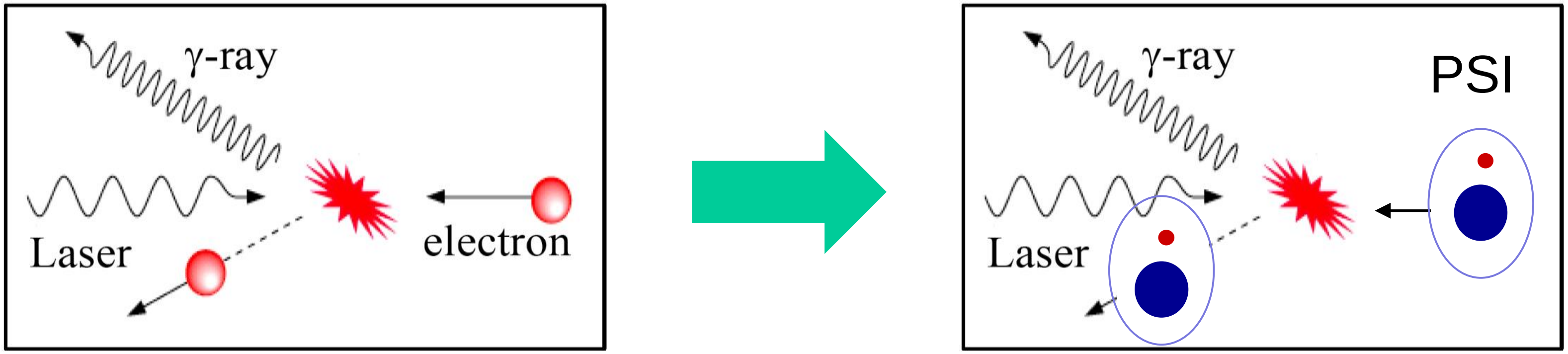
The Gamma Factory goal: achieve comparable fluxes in the MeV domain as those in the KeV domain – DESY FEL: ***10^{12} – 10^{17} photons/s***

**(the ELI facility (under construction) may reach the intensity of ~10^{12} ph/s for E< 20 MeV)*

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 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:

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

Partially Stripped Ions:

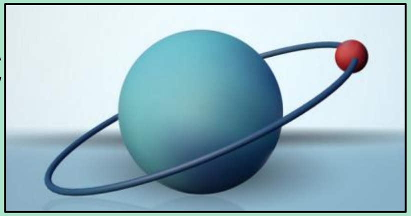
$$\sigma_{res} = 5.9 \times 10^{-16}\ \text{cm}^2$$

Numerical example: λ_{laser} = 1540 nm

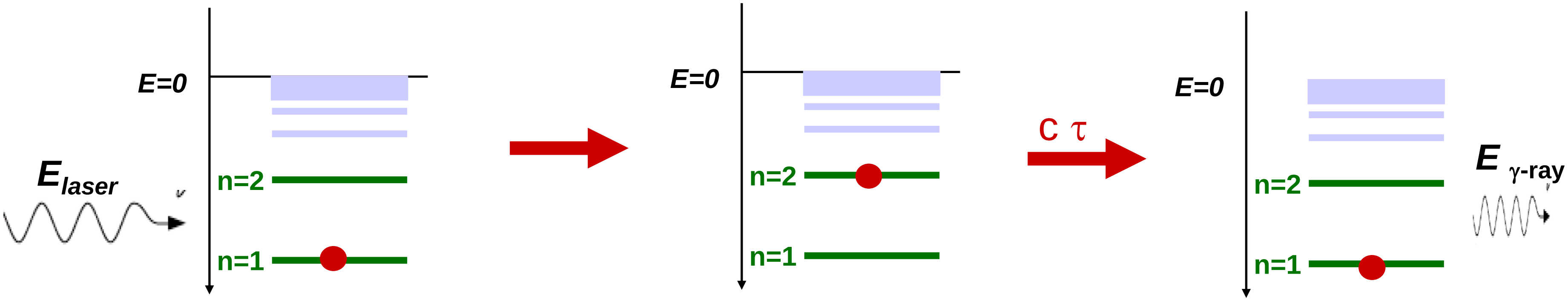
~ 9 orders of magnitude difference in the cross-section

~ 7 orders of magnitude increase of gamma fluxes

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

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

$\gamma_L = E/M$ - Lorentz factor for the ion beam

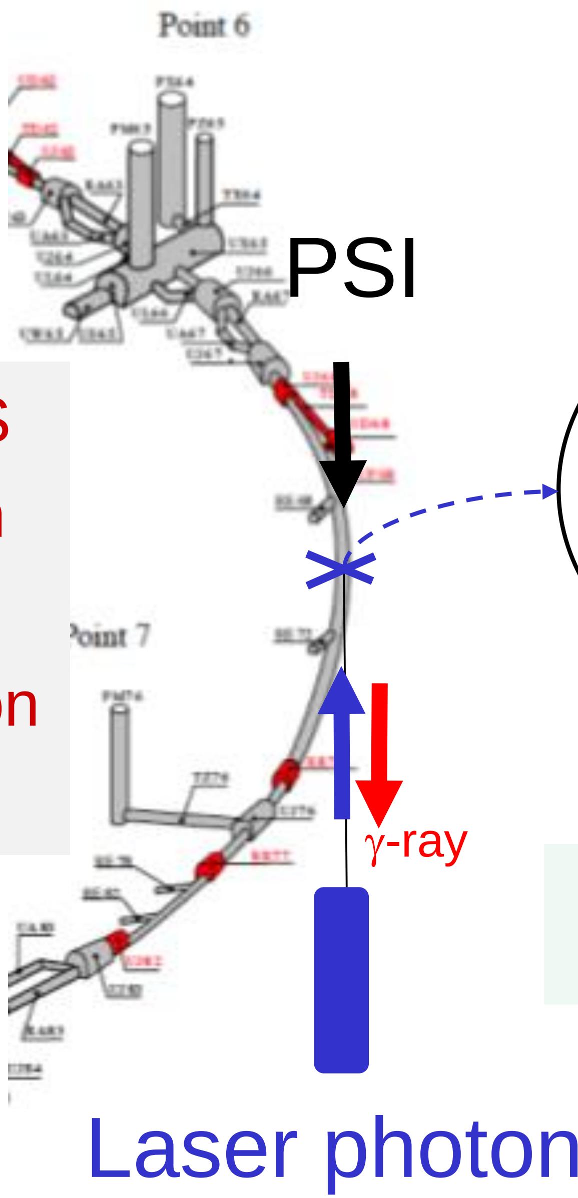
The tuning of the beam energy, the choice of the ion type, the number of left electrons and of the laser type allows to tune the γ-ray energy, at CERN, in the energy domain of 40 keV – 400 MeV.

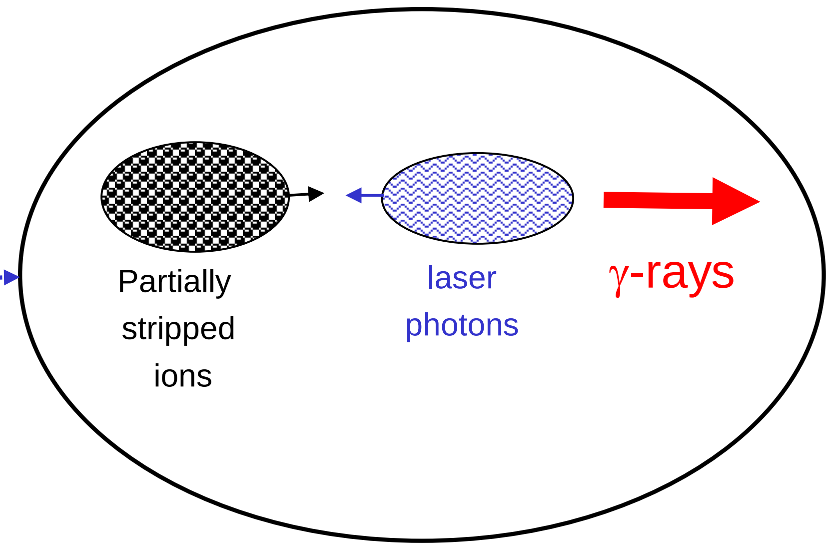
Example (maximal energy):

LHC, Pb^{80+} *ion,* $\gamma_L = 2887$, 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

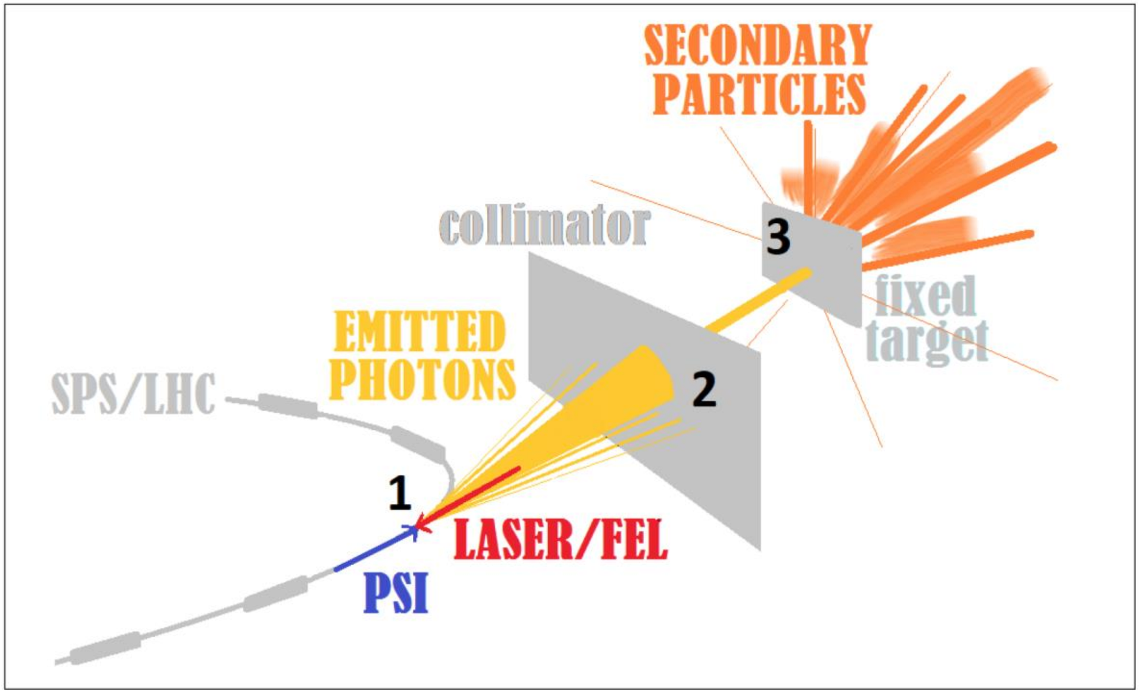




Decay length in the LAB frame $c\,\tau \sim \gamma_L/Z^4$

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

Gamma Factory



Beams and collision schemes

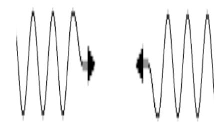
primary beams:

- **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

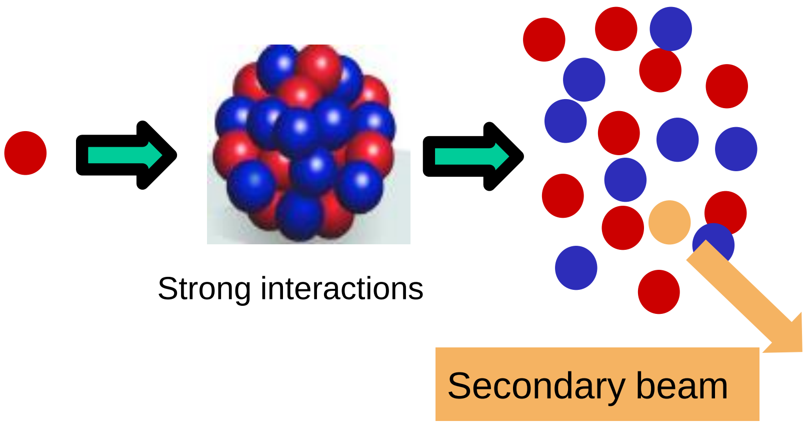
γ–p(A), ep(A) collisions,

E_{CM} = 4 – 200 GeV

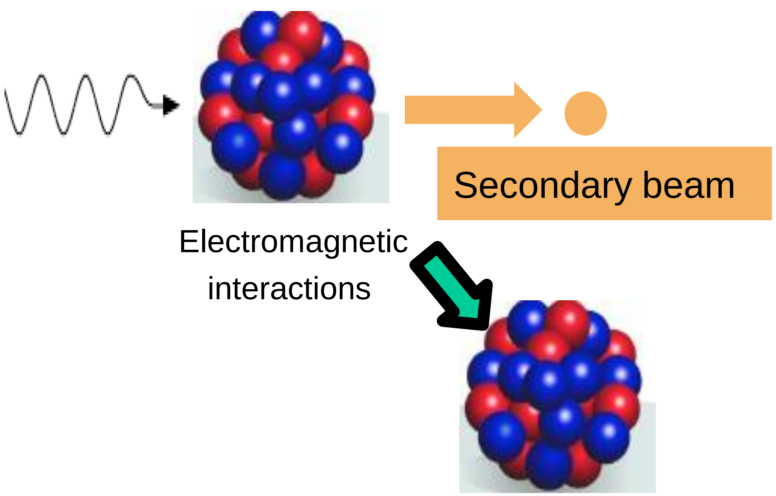
Gamma Factory secondary beams

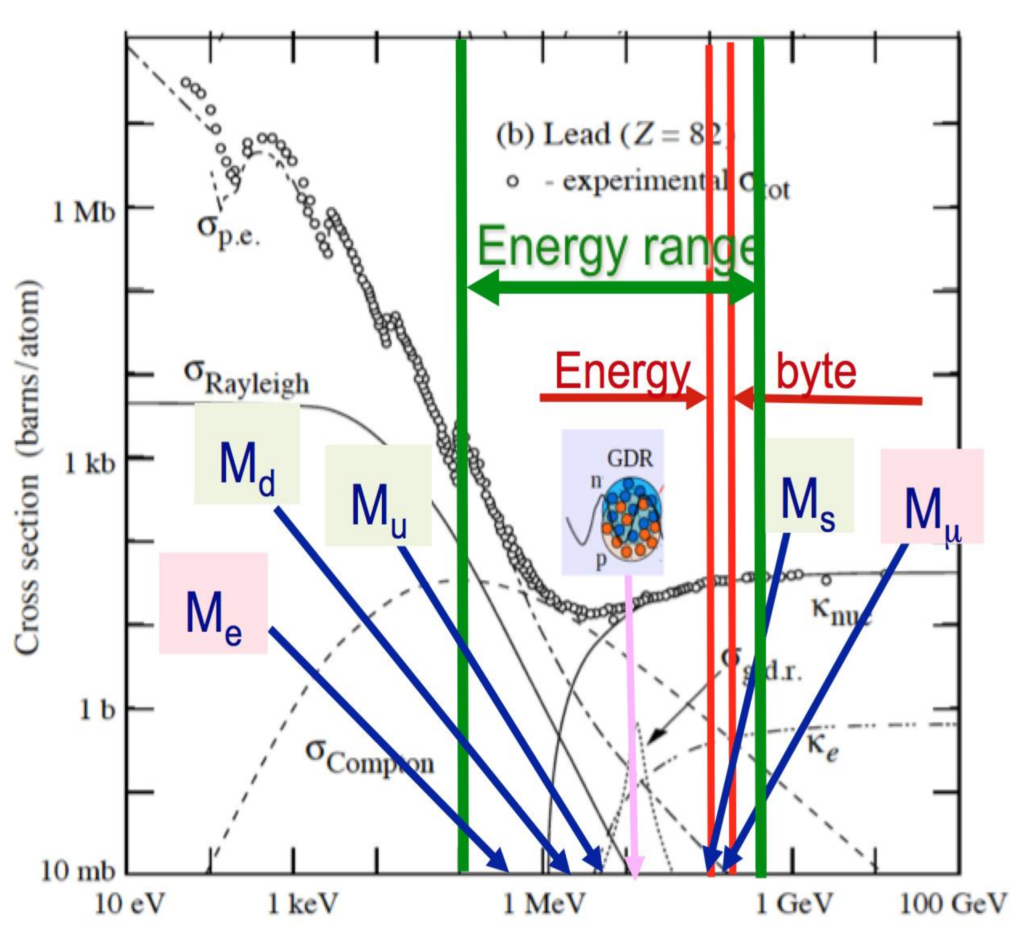
(from “mining” paradigm to “production-by-demand” paradigm)

“mining” paradigm:



“production” paradigm:





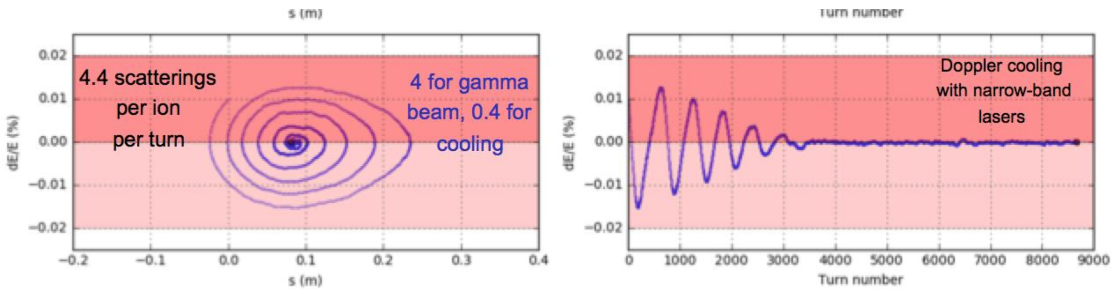
CERN accelerators

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 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 e.g. ALTO*

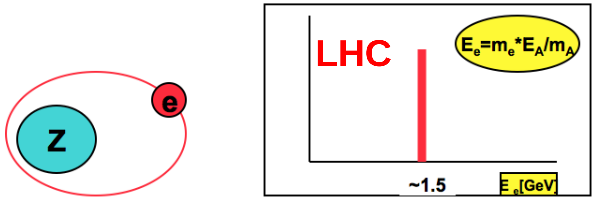
Potential impact of the Gamma Factory R&D on the on-going CERN programme (examples)

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



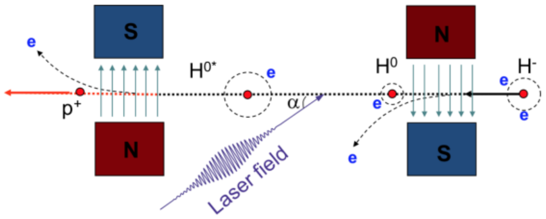
SPS simulations: A. Petrenko

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



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

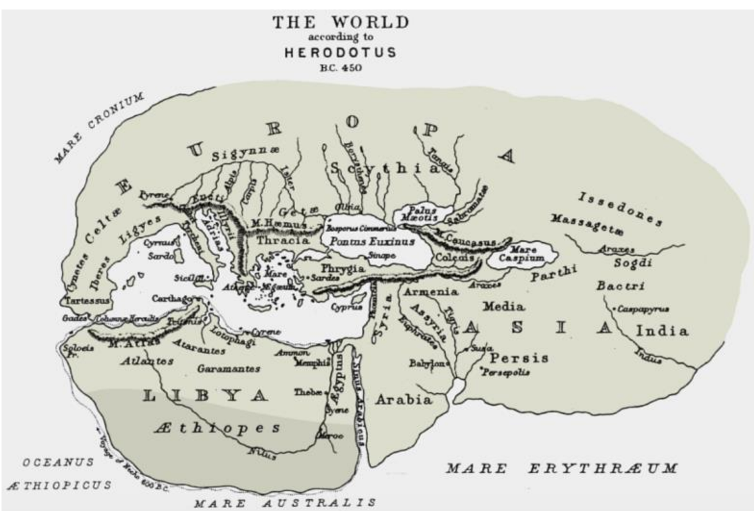
- *H^- injection scheme to circular machines*



recent progress: PRL 118, 074801 (2017)

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 PSI beams in the CERN accelerator complex (choice of ions, viable ion stripping schemes, beam transfers, understanding the PSI beam dynamics (IBS), understanding of the PSI beam particles losses) –* ***to be achieved by December 2018!***

2. *Development of the simulation tools for collisions of photon and ion bunches.*

3. *Import to CERN the existing Laser and F-P resonator technologies (developed at DESY, KEK, LAL, ELI for electron machines).*

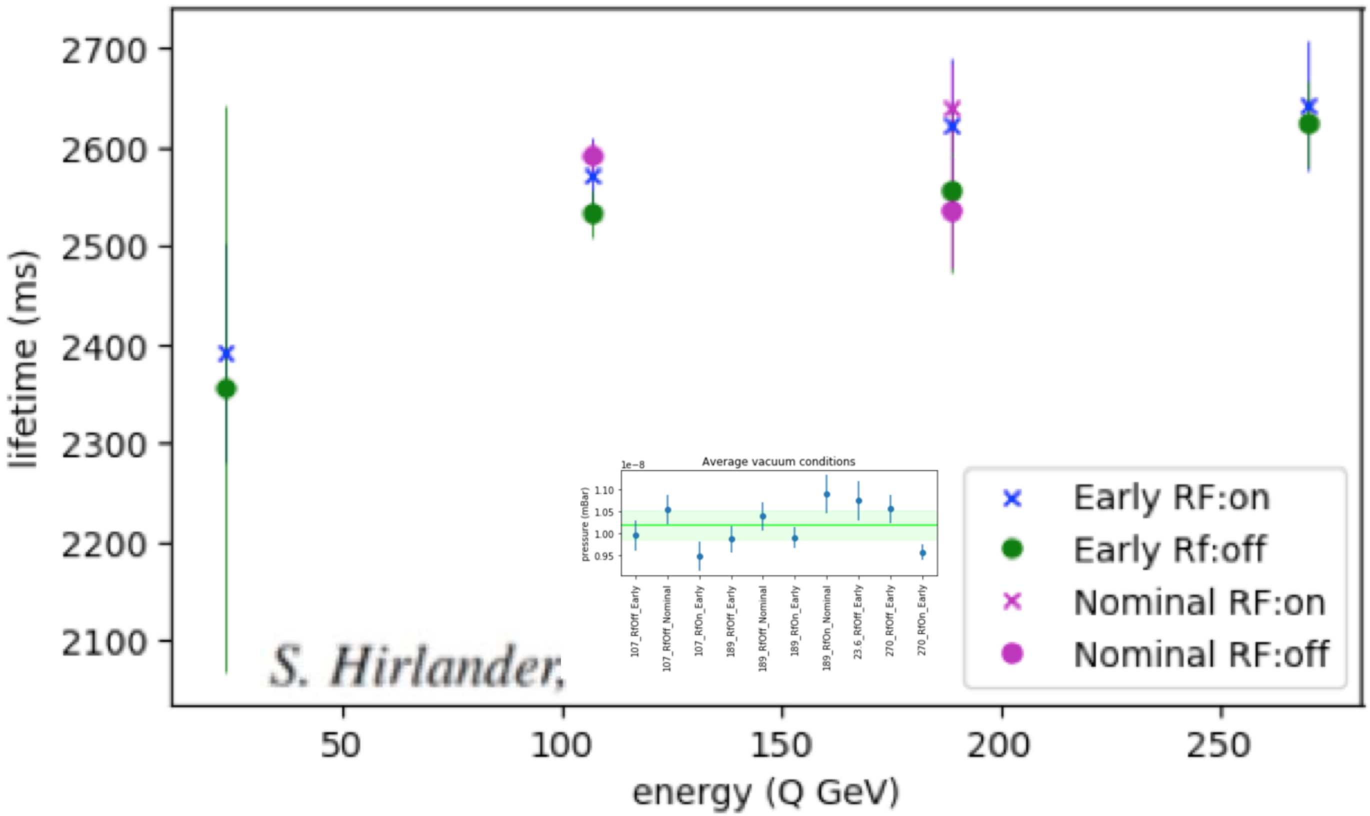
4. *Adaptation (and extension)of these technologies to the CERN-specific accelerator complex requirements (ion species, mechanical constraints, IP designs, bunch lengths and bunch frequency, gamma beam extraction, beam security, radioprotections issues etc.).*

5. *POP experiment in the SPS ring including PSI beam cooling demonstration.*

1. *Gamma Factory project TDR.*

What we have already learned from the 2017 Xe+39 SPS MDs ?

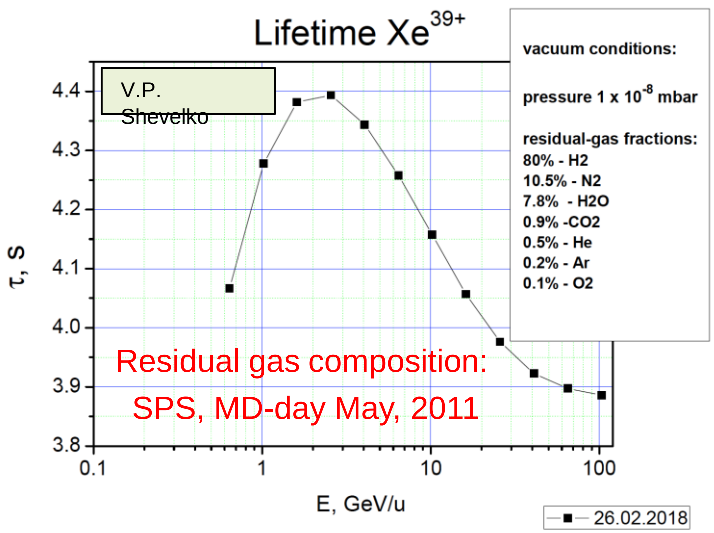
Xe+39 beam life time, as expected, is driven predominantly by the losses of ions due to electron stripping by the rest gas molecules.

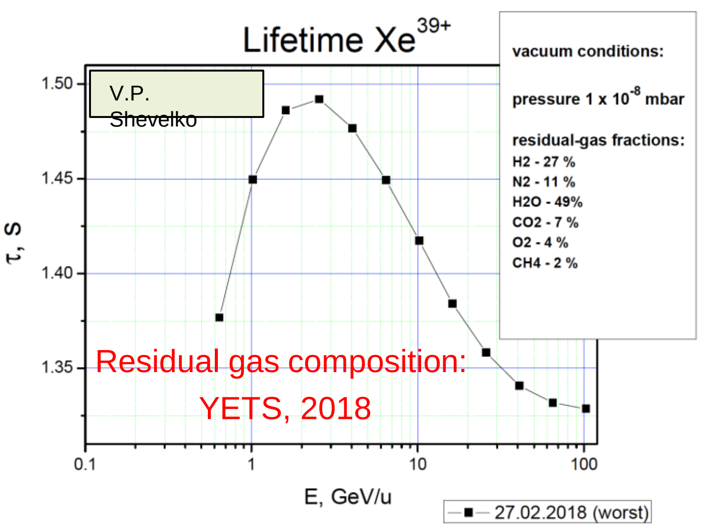


What we have already learned from the 2017 Xe+39 SPS MDs ?

The 2017 SPS measurements allowed us to:

1. *Constrain the vacuum quality and the rest gas molecular content.*
2. *Cross-check the simulation software tools which we use in the extrapolations to other ions species and LHC energies.*





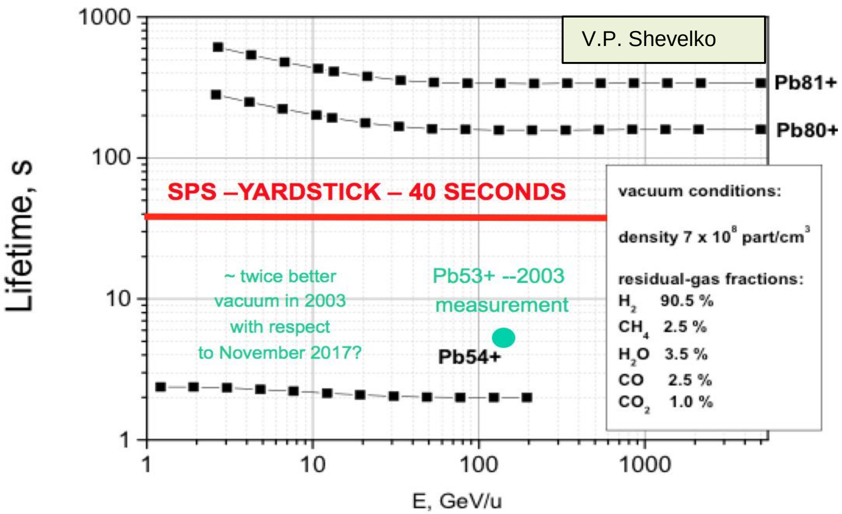
Residual gas composition: Chiara Pasquino

What we have already learned from the 2017 Xe+39 runs in the SPS?

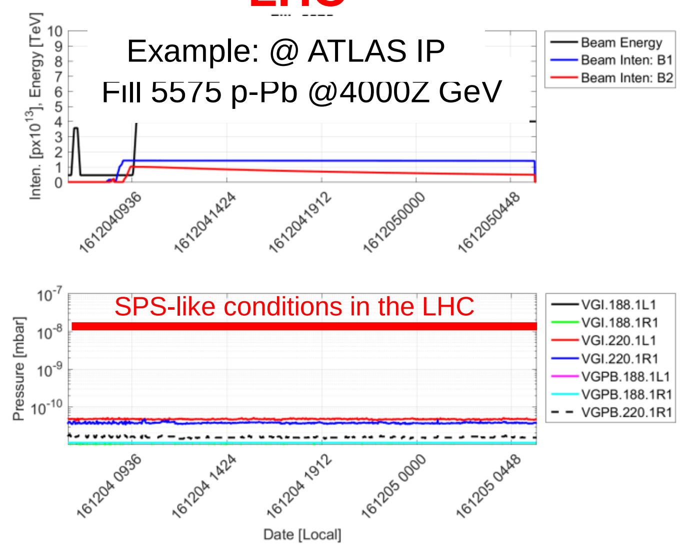
The source of optimism for our 2018 MDs with He- and H-like Pb beams:

- *The expected Pb+80 and Pb+81 beam life time, for the vacuum conditions of the 2017 Xe+39 runs, exceeds comfortably the SPS injection + ramping time!*
- *Significantly better vacuum in the LHC rings – lifetime rise by a factor of 100, w.r.t SPS expected (if dominated by the electron stripping in beam-gas collisions)!*

SPS



LHC



Christina Yin Vallgren,
Patricia Ribes Metidieri,
Roberto Kersevan

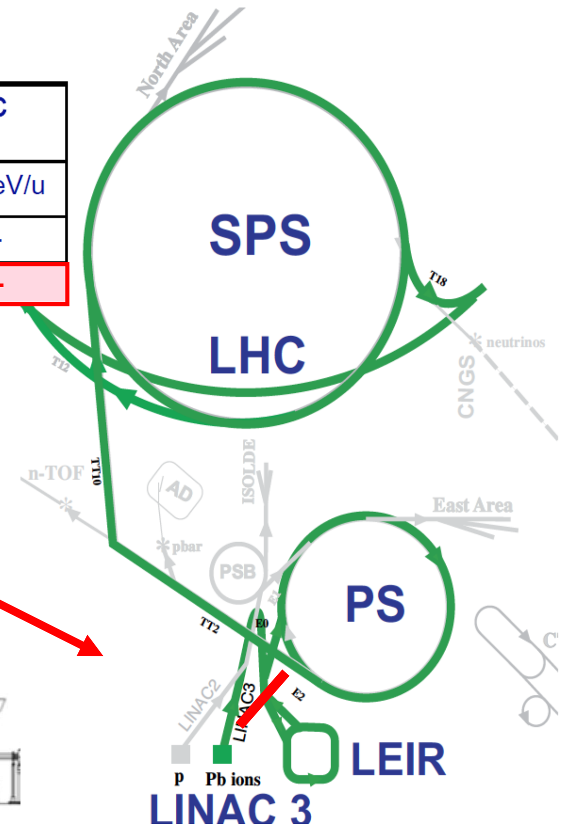
Assuming:
H_2: 90.5%
H_2O: 3.5%
CH_4: 2.5%
CO: 2.5%
CO_2: 1%
Total molecules @ 10^{-11}mbar:
5.5×10^{11} molecule/m^3

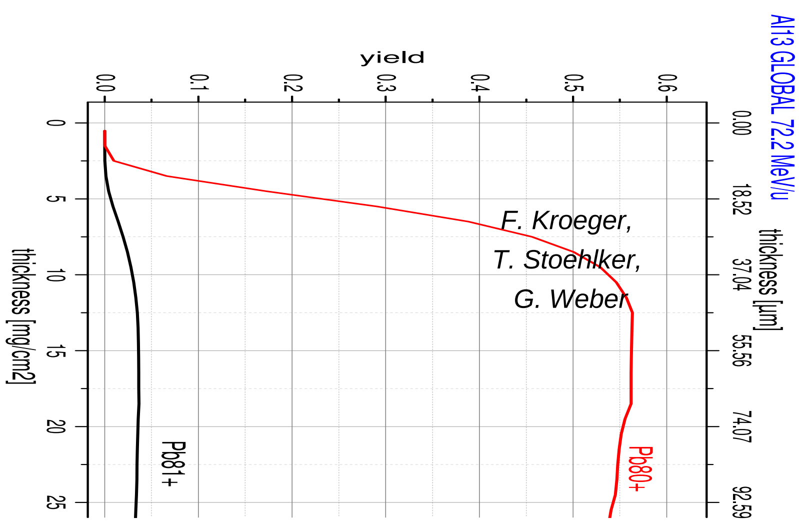
Go to the next step: preparation of the 2018 SPS and LHC MDs

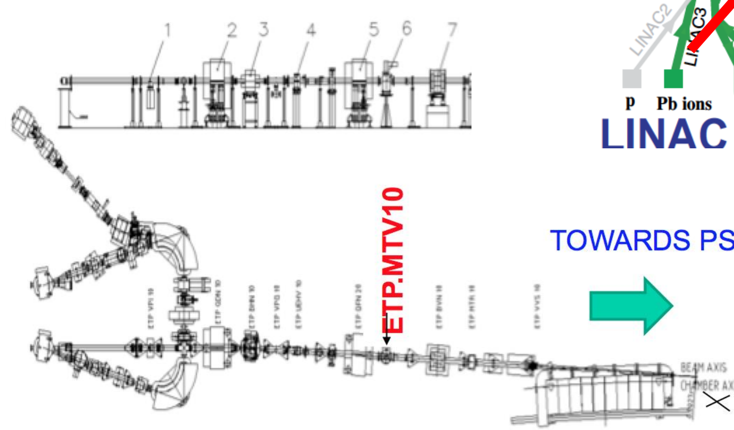
Optimal way to produce Pb+80 beam (follow BNL strategy):

produce a new stripper for the ETP.MTV10 screen frame

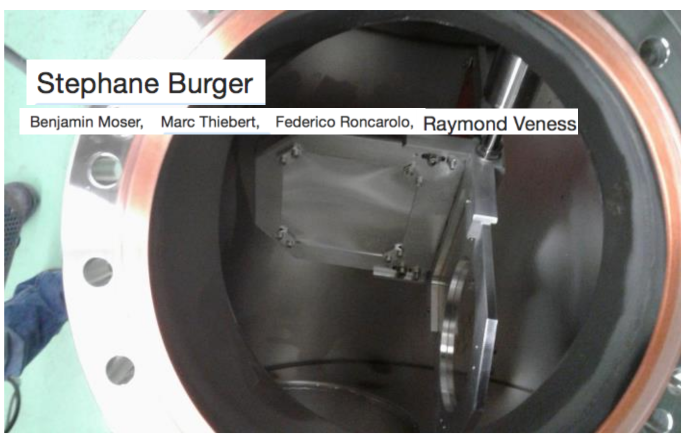
	ECR Source	Linac 3	LEIR	PS	SPS	LHC
Output energy	2.5 KeV/u	4.2 MeV/u	72.2 MeV/u	5.9 GeV/u	177 GeV/u	2.76 TeV/u
^{208}Pb charge state	29+	29+ → 54+	54+	54+ → 82+	82+	82+
			54+ → 80+	**80+**	**80+**	**80+**

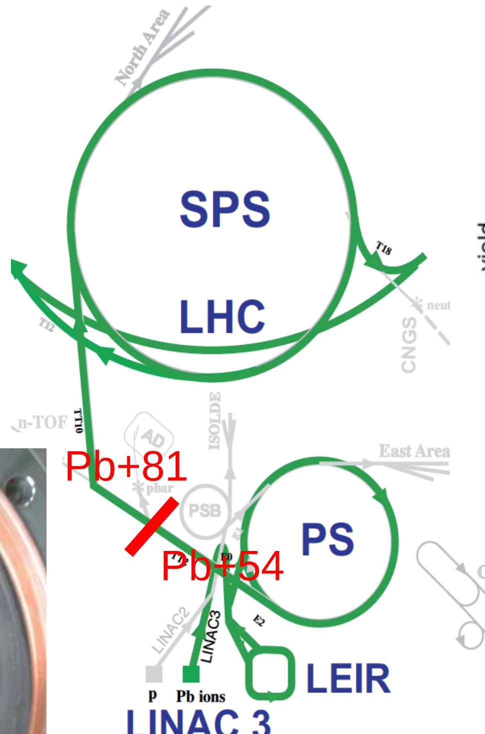


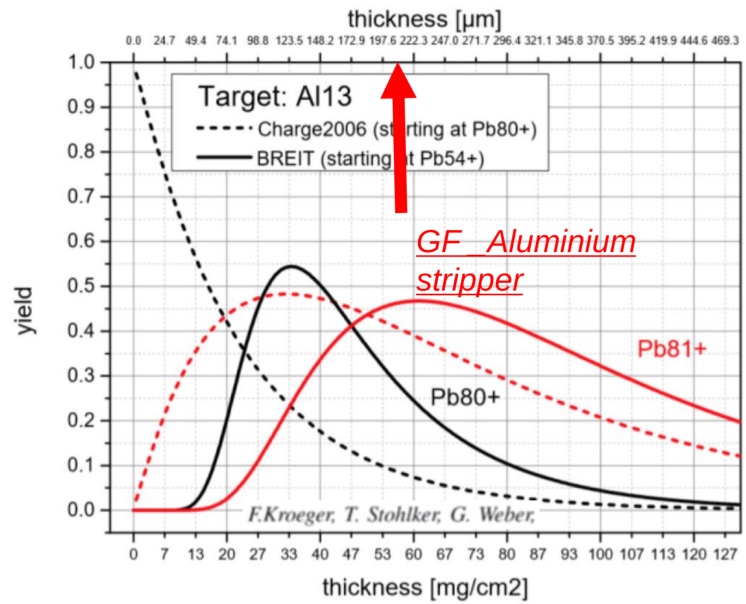




Ion stripping scheme for the 2018 MDs – the "minimal interference" approach: **Pb+81 beam**



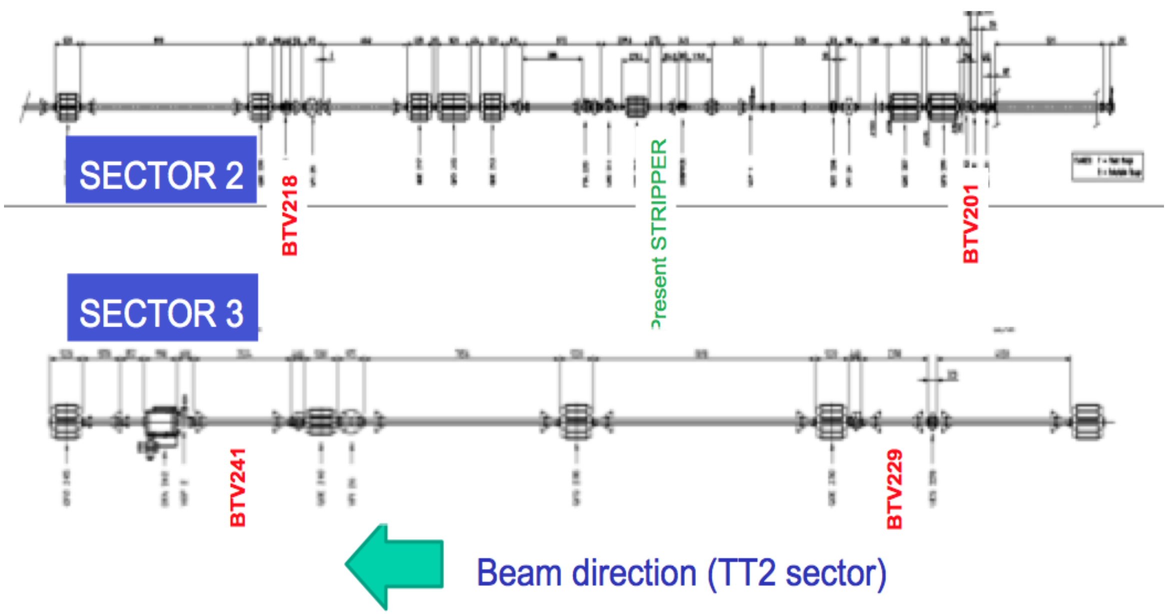


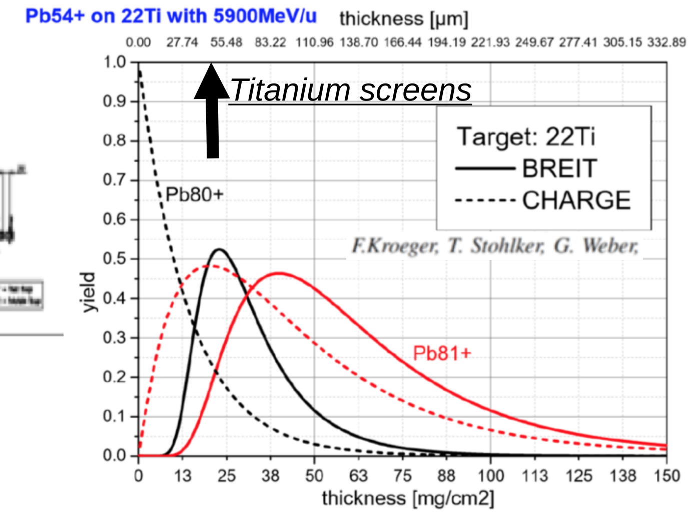


26.01.2018

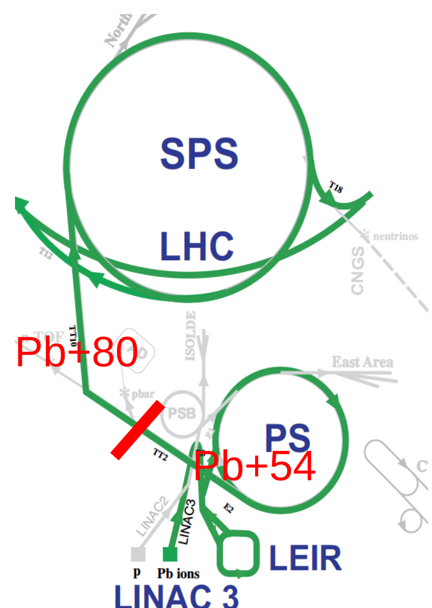
The 150μm (212μm crossed by the beam as installed at 45 degrees) thick Al foil has been installed on the FT16.BTV352 in the TT2 line!

Ion stripping scheme for the 2018 MDs – the “minimal interference” approach: **Pb+80 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 +81 Pb beam intensity



2018 SPS and LHC MDs – strategy

SPS

- *Calibrate the 2018 vacuum with the initial PB+54 runs.*
- *Studies of Pb+54 → Pb+80 and Pb+54 → Pb+81 stripping efficiencies (AWAKE?)*
- *SPS test of the relative importance of multi-electron and single electron losses.*
- *Measurement of the strength of the intra-beam-stripping processes (intensity and energy dependence of the beam life-time).*
- *Realistic extrapolation of the beam life-time to the LHC case (following an experimental verification of all the modelling assumption).*
- *Pb+80 versus Pb+81 choice for the LHC runs.*

LHC

- *Start with the life time measurement of a single bunch at the injection energy and at the top energy, loss maps, vacuum quality evolution, beam emittance evolution.*
- *Vary bunch intensity.*
- *Study the dynamical vacuum and BLM signals as a function of the number of bunches.*

Software development ("ab nihilo")

- *Start by factorising the PSI beam stability aspects from the production aspects of gamma rays (an approach allowed by high rigidity of the PSI beams)*

- *PSI beam specification (at present) in terms of constant: bunch length, bunch emittances, and fixed β^*_x and β^*_y (can be modified later on)*

- *Laser photon bunches specification (at present) in terms of the laser wavelength, pulse energy, pulse length, Rayleigh length, transverse waist size*

- *Two independent codes for the cross-check: (1) Cracow code bases on the CAIN specification of the parameters of the bunches by W. Placzek (GF-CAIN) and (2) Milano code derived form the ICS code developed by C. Curatolo (CMCC)*

Factorising beam stability and gamma production aspects

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:

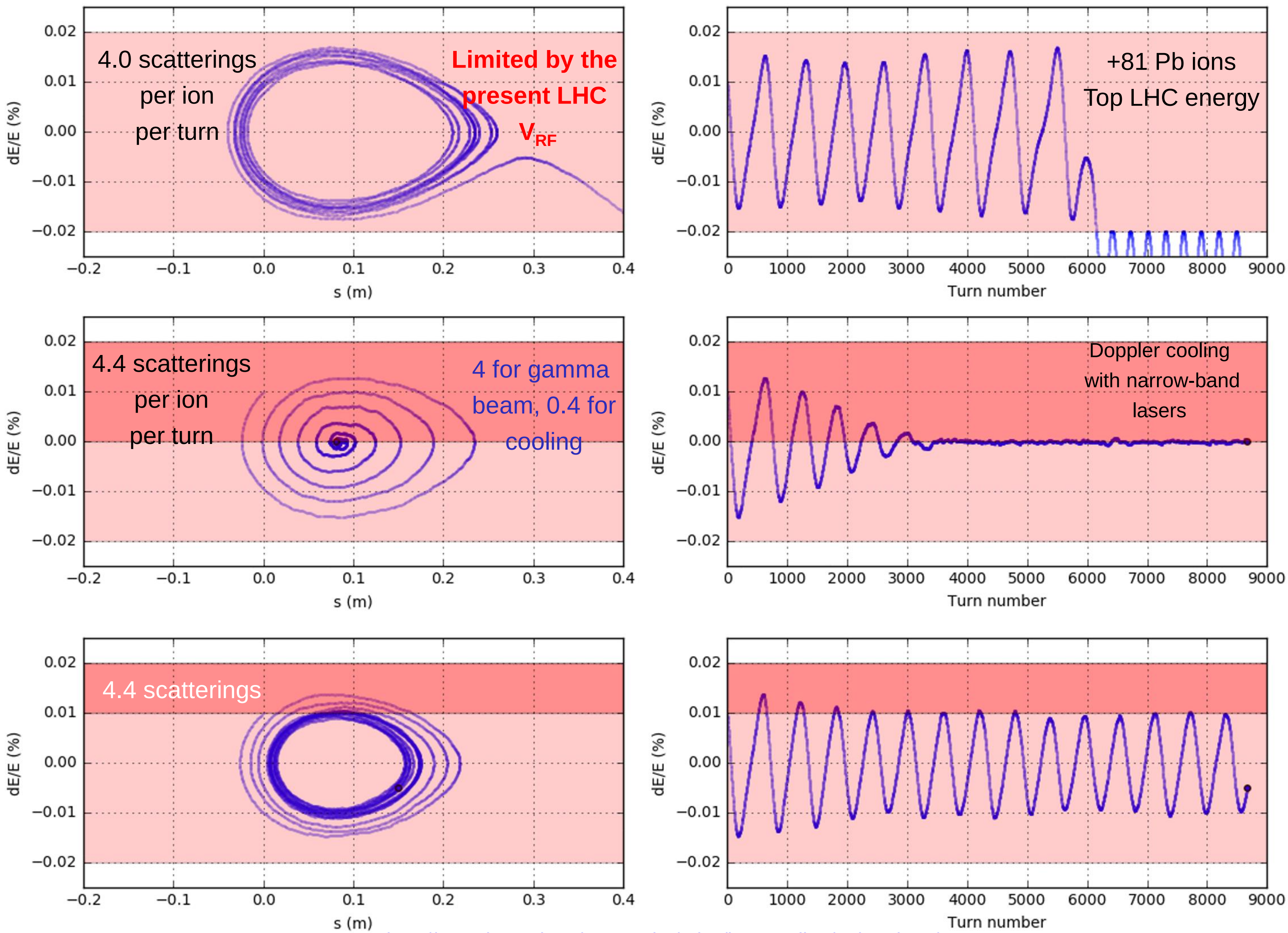
$E_\gamma/E_{beam} = 2.6 \times 10^{-7}$

(ion undisturbed!)

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

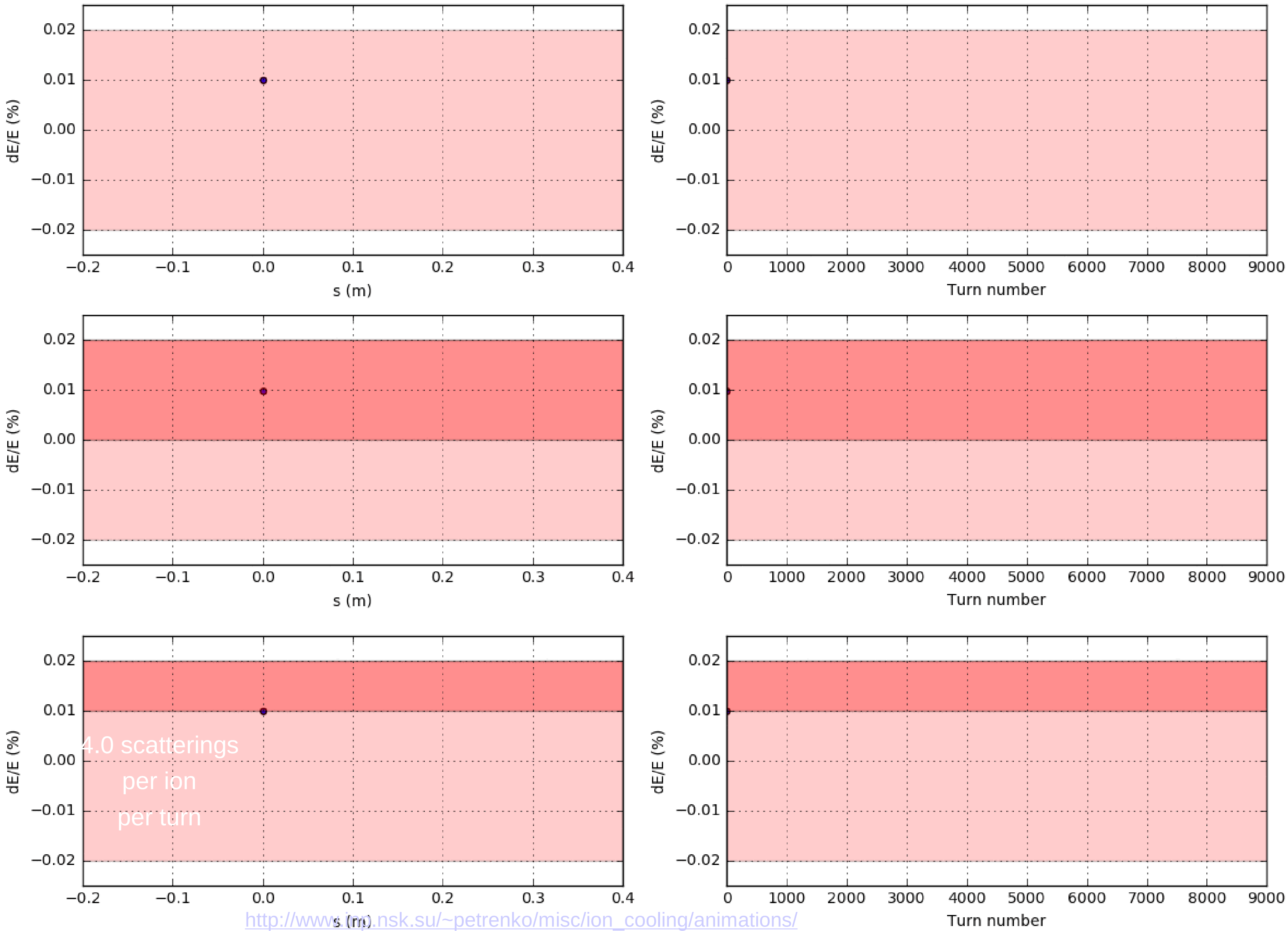
The source intensity is driven by the power of the storage ring RF cavities!

PSI beam stability studies and cooling simulations



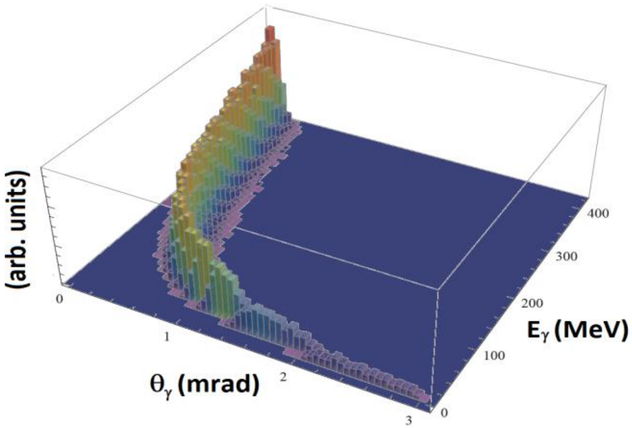
http://www.inp.nsk.su/~petrenko/misc/ion_cooling/animations/

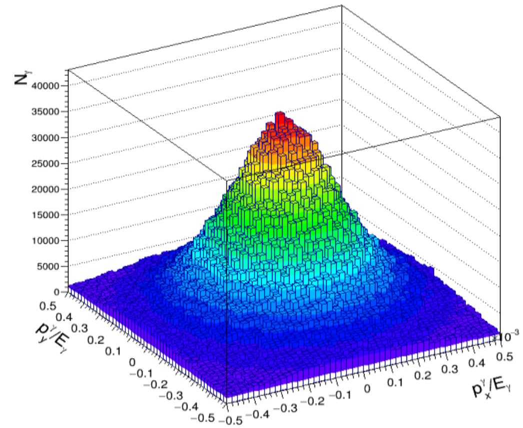
PSI beam stability and cooling simulations

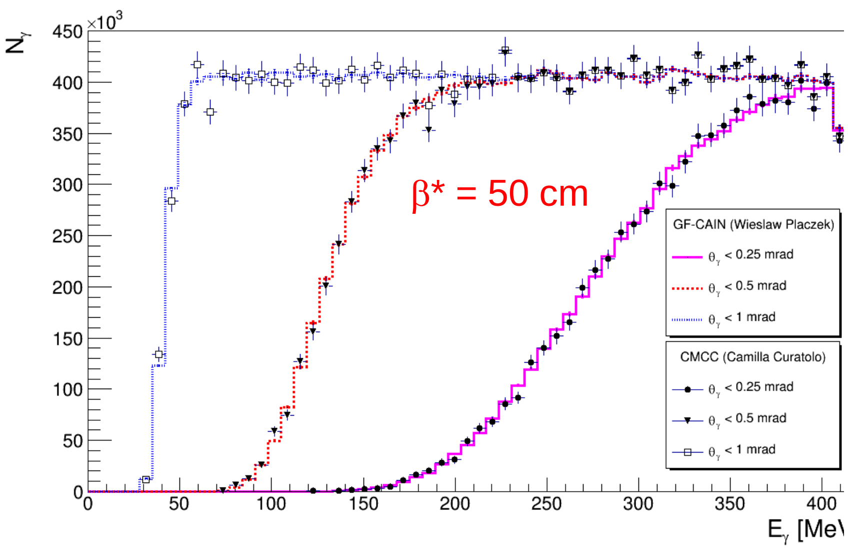


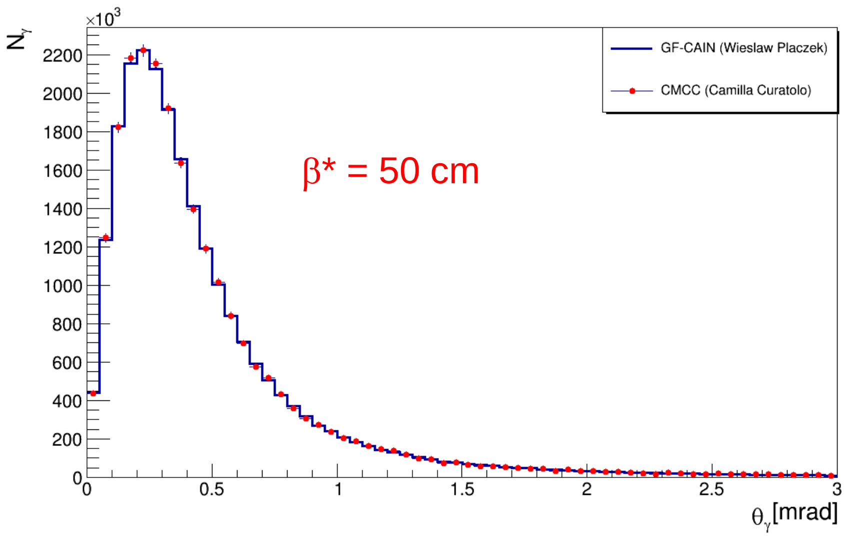
http://www.inp.nsk.su/~petrenko/misc/ion_cooling/animations/

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









Towards a PoP experiment at the SPS

Multi-parameter choice of:

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

Constrains:

- *availability of the ions source*
- *viable stripping scheme*
- *beam life time in the SPS (under the present vacuum conditions)*
- *beam cooling time*
- *acceleration time to flat-top in the SPS*
- *double photon absorption cross-section*

Large number of ion candidates evaluated -- so far two candidates retained…

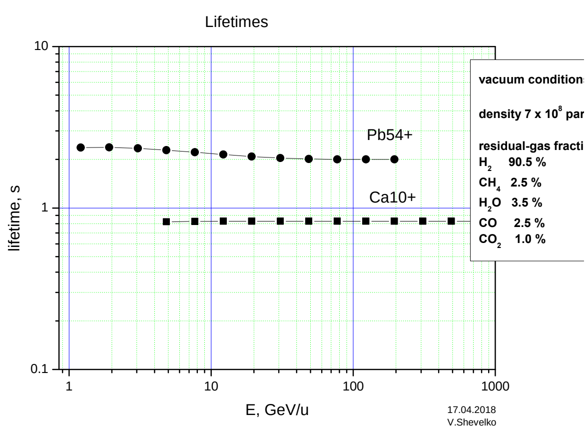
Neon-like Calcium: Ca+10

- ATOMIC GROUND STATE : 1s^2 2s^2 2p^6 $1S_0$
- CHOICE OF EXCITED STATE: 1s^2 2s^2 2p^5 3s $1P_0$
- TRANSITION ENERGY: $E = 352.1$ eV
- LIFE TIME (excited state) : $\tau = 6$ ps

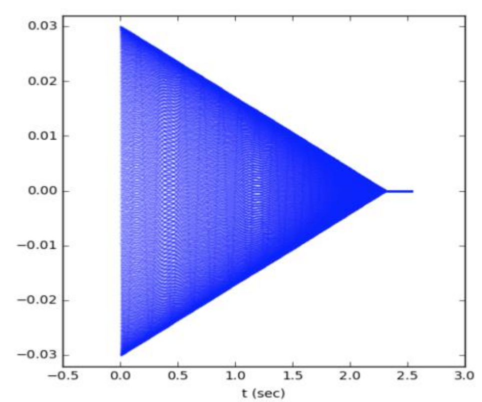
Sodium-like Lead Pb+71

- ATOMIC GROUND STATE : 1s^2 2s^2 2p^6 3s1 $2S_{1/2}$
- CHOICE OF EXCITED STATE: 1s^2 2s^2 2p^5 3p $2P_{1/2}$
- TRANSITION ENERGY: $E = 189$ eV
- LIFE TIME (excited state): $\tau = 18$ ps

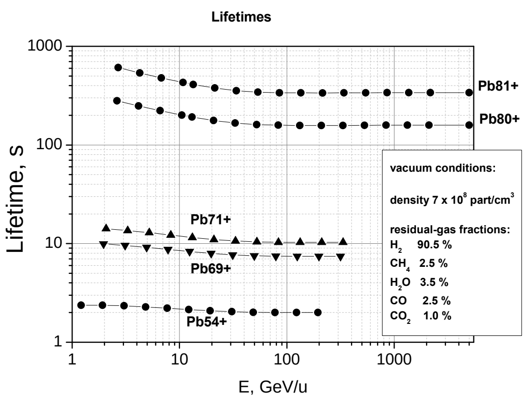
Ca+10 beam life-time in the SPS



Cooling time in the SPS
(~1 ph absorption/ revolution/ion)



Pb+71 beam life-time in the SPS



Conclusions

In the present phase of the accelerator-based HEP research -- when we no longer have a 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, Breakthrough-Seeking Initiatives (BSIs) become particularly important.

The target goal of the Gamma Factory, BSI initiative presented in this talk is to try 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.

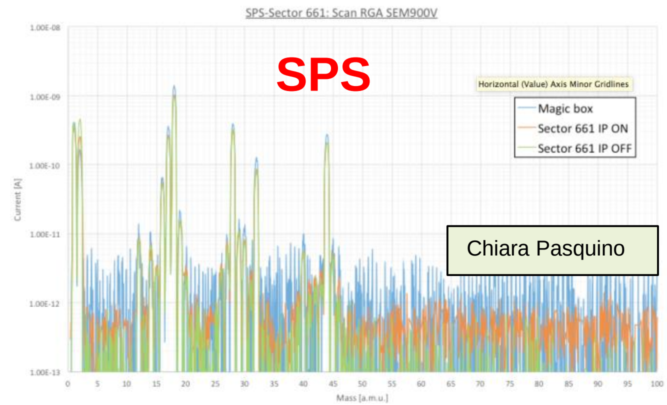
Following the phase of its conceptual development the Gamma Factory initiative enters the initial phase of its experimental tests and simulation studies aiming to prove its feasibility (first step: dedicated GF SPS and LHC test runs with partially stripped ions in 2017 and 2018) – ***stay tuned... and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

Extra transparencies

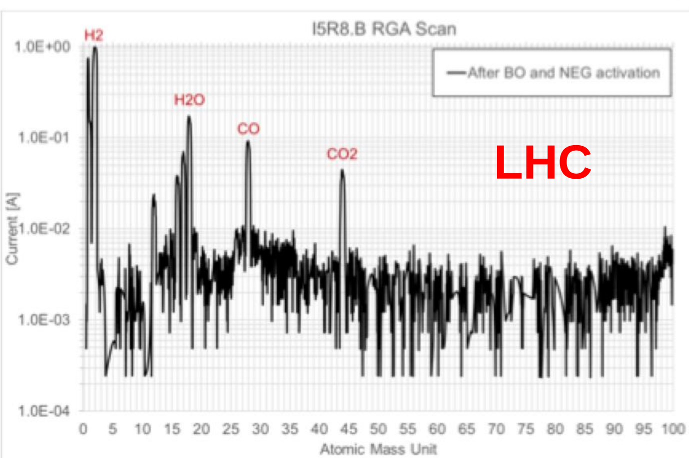
GF research highlights

- ***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, …).*

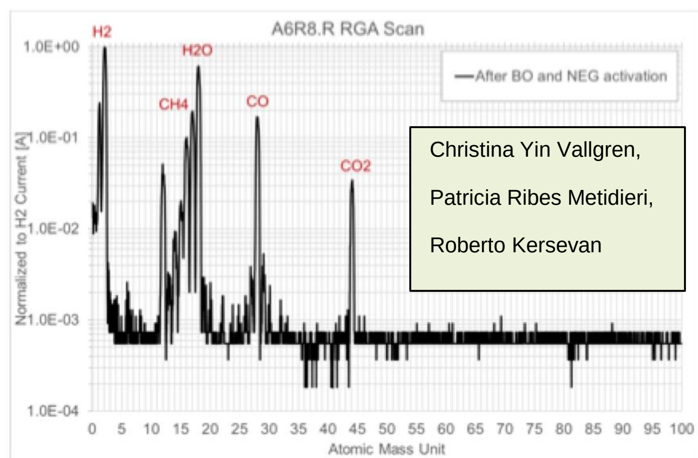
Residual gas composition: SPS and LHC(warm vacuum chamber)



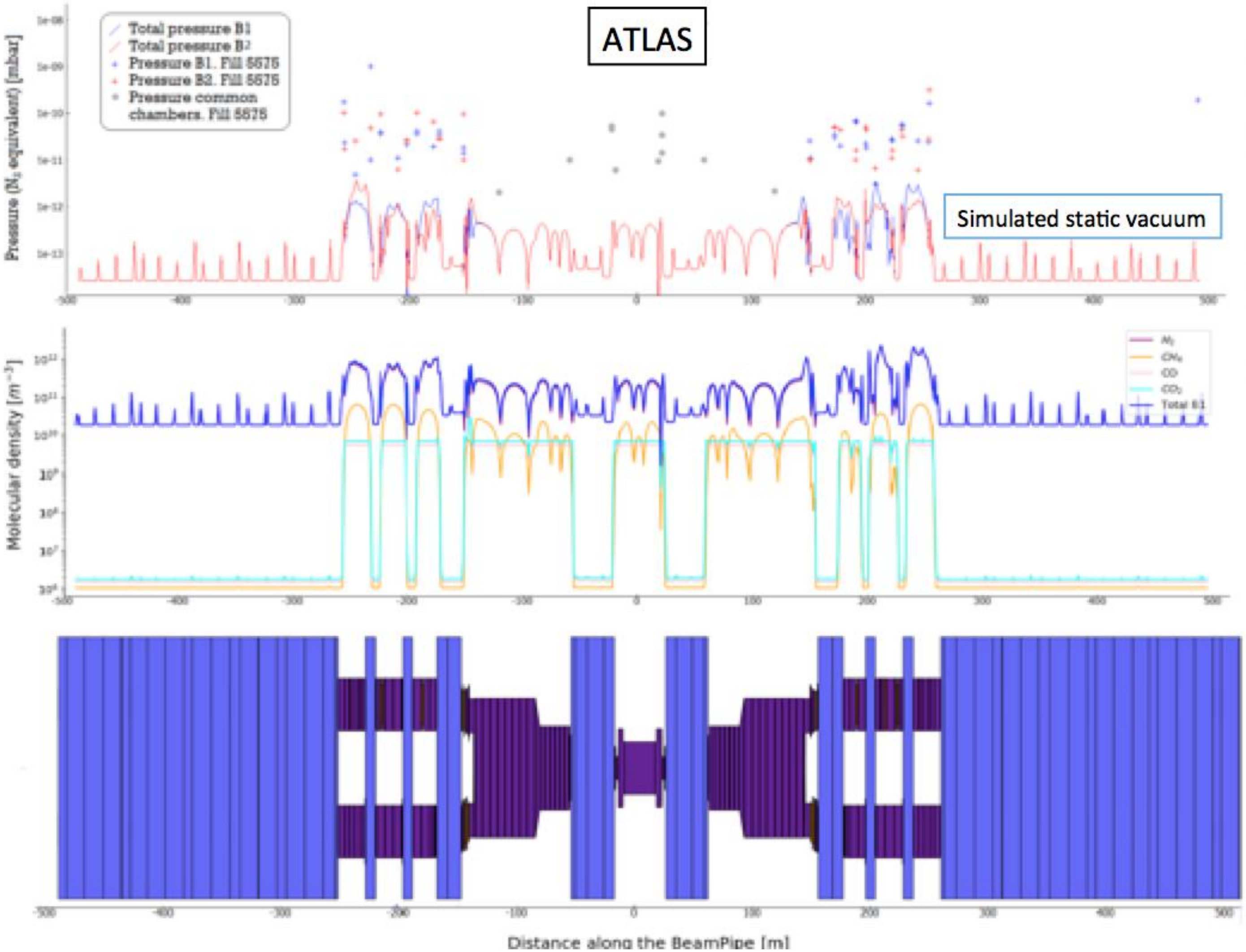
1. Normalized to the H2 peak.
2. H2 as dominant gas after the bake-out and NEG activation.
3. The main gases in the warm LHC vacuum chamber: H2, CO, CO2, CH4 and H2O.



Interconnects between the MKIs



Injection line at Point 8



Measured pressure is at range of 10^{-11} - 10^{-10} mbar (about a factor of 10 higher than the simulated static pressure):

1. Pressure gauge has a measurement limitation at 10^{-11} mbar.
2. In the simulation, the nominal pumping speed is considered.

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