The Gamma Factory for CERN:

Conceptual Foundation, Feasibility Studies and Research Opportunities

PSI-Colloquium, November, 2018

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LPNHE, CNRS-IN2P3 and University Paris Sorbonne

Introduction

Revisiting three paths of progress in experimental science

1. Increasing precision of canonical measurements to test established theories and models (e.g. ~40 years of investigation of the SM).

2. New theories and theoretical models (e.g. 35 years of the "Supersymmetry Discovery Guide(s)").

3. A technological leap, opening new research tools … or increasing the precision of the existing ones by several orders of magnitude

…(A this moment, of particular importance, since we do not have any hints for a new physics "just arround the corner" – accessible with the present technologies with a reasonable cost)

The Gamma Factory group members

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

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CERN-based framework

The Gamma Factory initiative (arXiv:1511.07794 [hep-ex]) was 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

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.

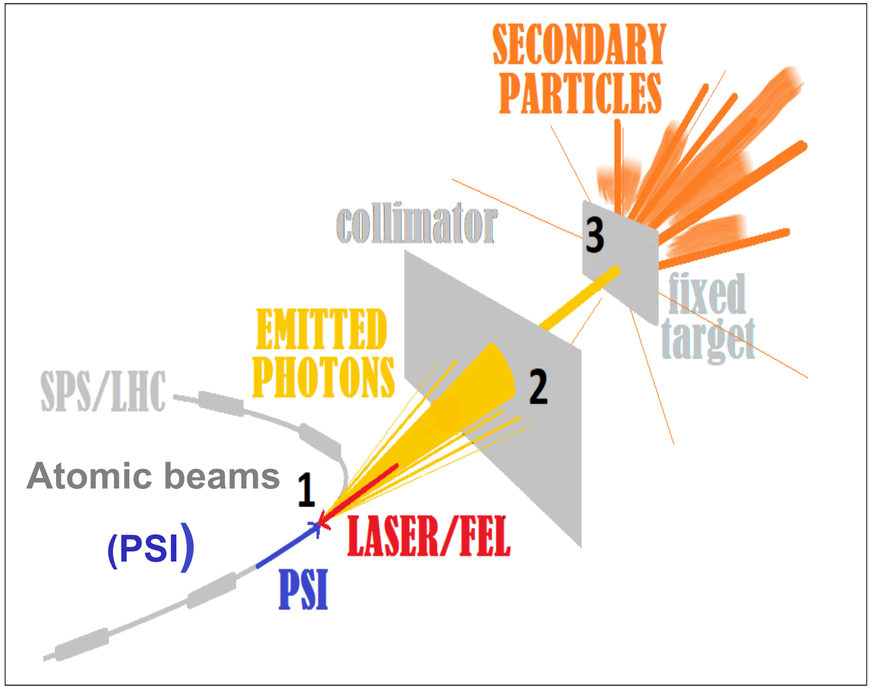
Gamma Factory in a nutshell

1. *Produce, accelerate and store high energy atomic beams of **Partially Stripped Ions (PSI).** 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 all the existing facilities.*

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

GF research tools: primary and secondary beams



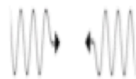
primary beams:

- 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:



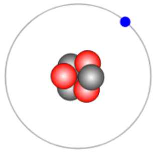
$\gamma-\gamma$ collisions,
E_{CM} = 0.1 – 800 MeV

$\gamma-\gamma_L$ collisions,
E_{CM} = 1 – 100 keV

γ–p(A), ep(A) collisions,
E_{CM} = 4 – 200 GeV

A leap in production efficiency, intensity and purity

Hydrogen-, Helium-like, high Z atomic beams



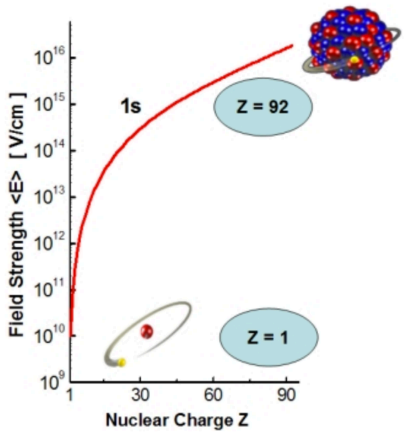


TABLE I. Z dependence of atomic characteristics for hydrogenic ions. In the given expressions, α is the fine structure constant, $\hbar = c = 1$, m_e is the electron mass, G_F is the Fermi constant, θ_w is the Weinberg angle, and A is the ion mass number.

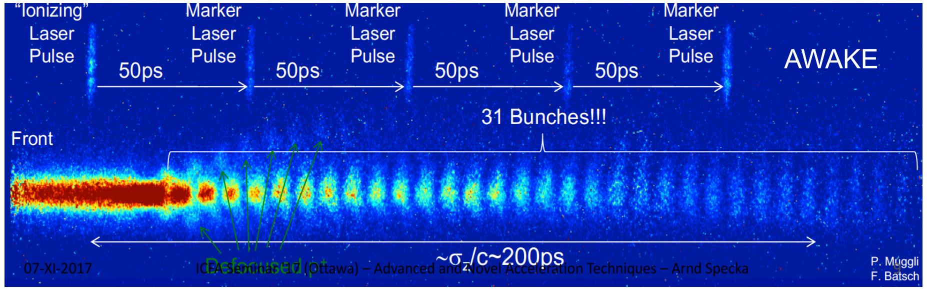
Parameter	Symbol	Approximate Expression
Transition energy	$\Delta E_{n-n'}$	$\frac{1}{2}(\frac{1}{n^2} - \frac{1}{n'^2})\alpha^2 m_e Z^2$
Lamb shift	ΔE_{2S-2P}	$\frac{1}{6\pi}\alpha^5 m_e Z^4 F(Z)^{a}$
Weak interaction Hamiltonian	H_w	$i\sqrt{\frac{3}{2}}\frac{G_F m_e^3 \alpha^4}{64\pi}\{(1 - 4\sin^2\theta_w) - \frac{(A-Z)}{Z}\}Z^5$
Electric dipole amplitude ($2S \to 2P_{1/2}$)	$E1_{2S\to 2P}$	$\sqrt{\frac{3}{\alpha}}\, m_e^{-1} Z^{-1}$
Electric dipole amplitude ($1S \to 2P_{1/2}$)	$E1$	$\frac{2^7}{3^5}\sqrt{\frac{2}{3\alpha}}\, m_e^{-1} Z^{-1}$
Forbidden magn. dipole ampl. ($1S \to 2S$)	$M1$	$\frac{2^{5/2}\alpha^{5/2}}{3^4}\, m_e^{-1} Z^2$
Radiative width	Γ_{2P}	$(\frac{2}{3})^8 \alpha^5 m_e Z^4$

[a]The function $F(Z)$ is tabulated in [1]. Some representative values are $F(1) = 7.7$; $F(5) = 4.8$, $F(10) = 3.8$; $F(40) = 1.5$.

Main advantages of the hydrogen(helium)-like high-Z beam:

- *Very strong electric field (high sensitivity to the QED-vacuum effects)*
- *Weak effects rise strongly with Z*
- *Hydrogen-like atoms - calculation precision and simplicity*
- *Atomic degrees of freedom can be excited by ordinary laser owing to large γ_L*
- *Small statistical errors (large $N_{ion/bunch}$ and repetition rate)*

Cooled atomic beams as a low emittance drivers for Plasma Wake Field acceleration

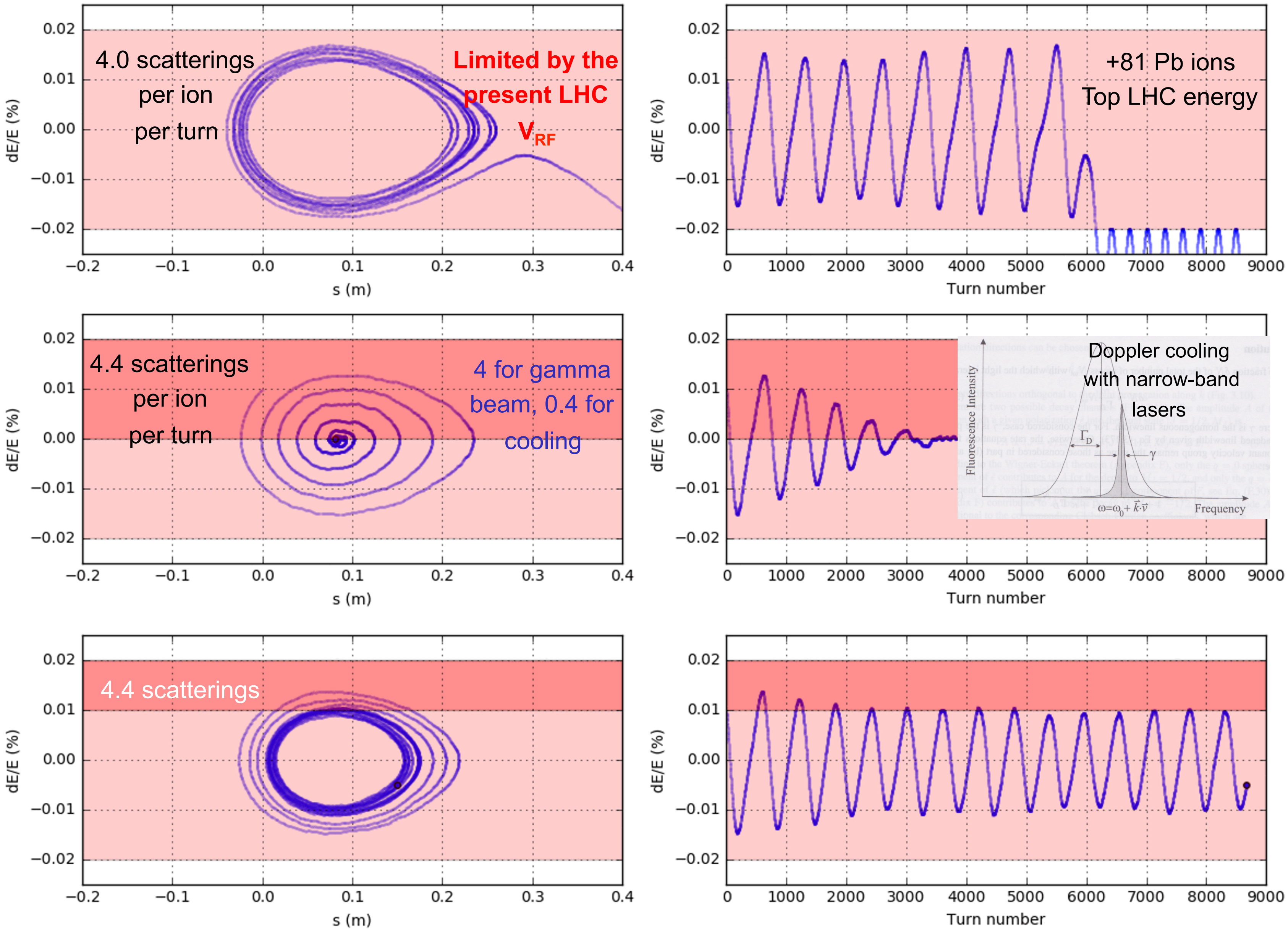


How to reach 30 GeV/m acceleration gradient over the large distance (for TeV-range electron or muon beams) ?

The principal limiting factor for the Plasma Wake Field (PWF) acceleration rate is the achievable hadron beam density (driven by the beam emittance).

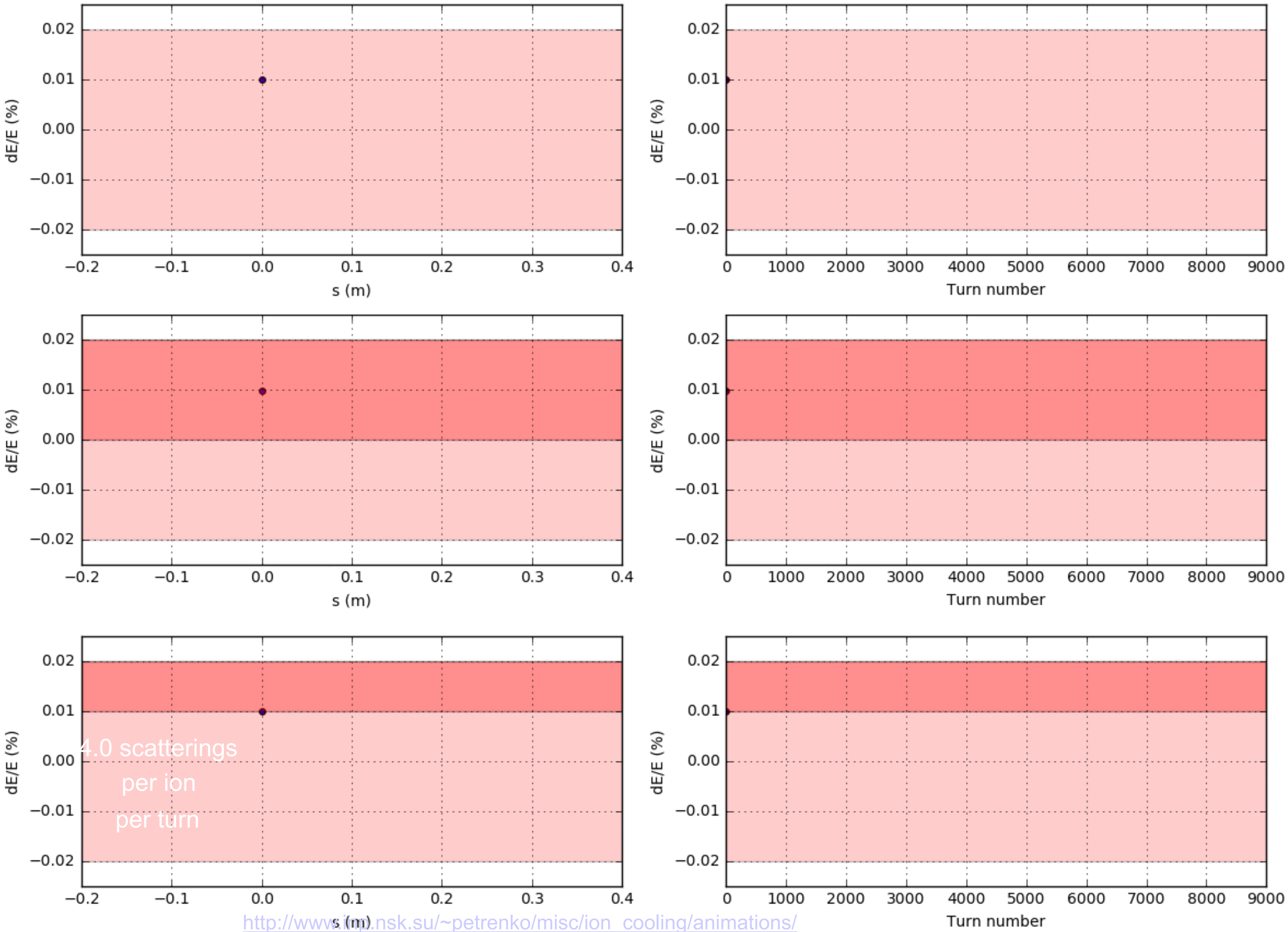
Atomic beams are the only hadronic beams which can be efficiently cooled by the Doppler cooling! Electrons ready to be accelerated!!!

Beam cooling simulations



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

Beam cooling simulations - animation



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

Cooled (low emittance) beams for
Precision EW physics at the LHC

The canonical LHC pp collision program (including HL-LHC) can hardly improve the measurement precision of the EW Standard Model parameters…

…nuclear collisions of light isoscalar ions are crucial for a progress in precision EW sector measurements at the LHC!

For the quantification of these statements see e.g..:

M.W. Krasny, F. Dydak, F. Fayette, W. Placzek, A. Siodmok, Eur.Phys.J. C69 (2010) 379-397.
F. Fayette, M.W. Krasny, W. Placzek, A. Siodmok, Eur.Phys.J. C63 (2009) 33-56.
M.W. Krasny, F. Fayette, W. Placzek, A. Siodmok, Eur.Phys.J. C51 (2007) 607-617.
M.W. Krasny, S. Jadach, W. Placzek, Eur.Phys.J. C44 (2005) 333-350.

Why isoscalar (Z=A/2) nuclei?

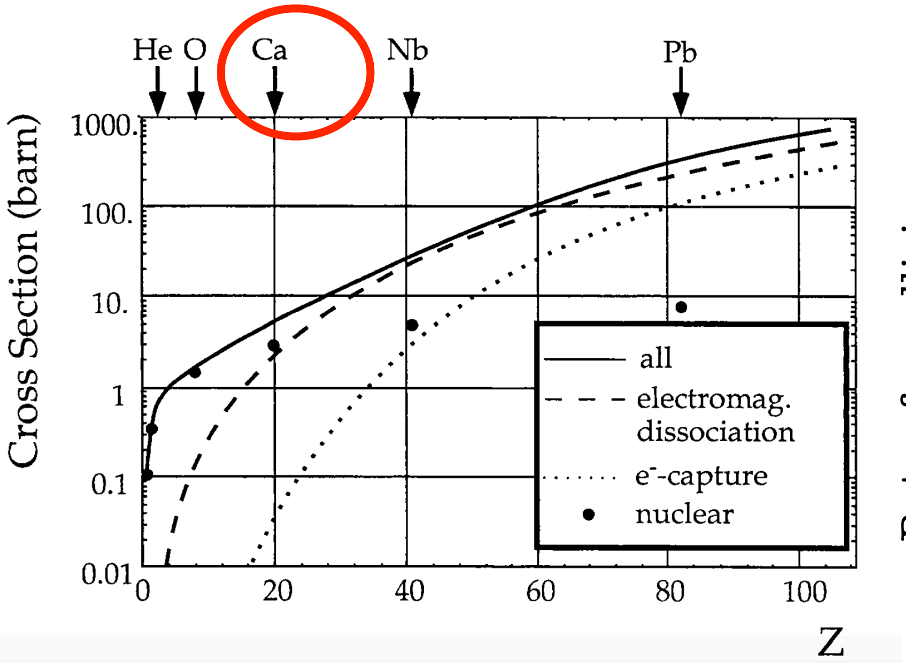
Example: M_W measurement

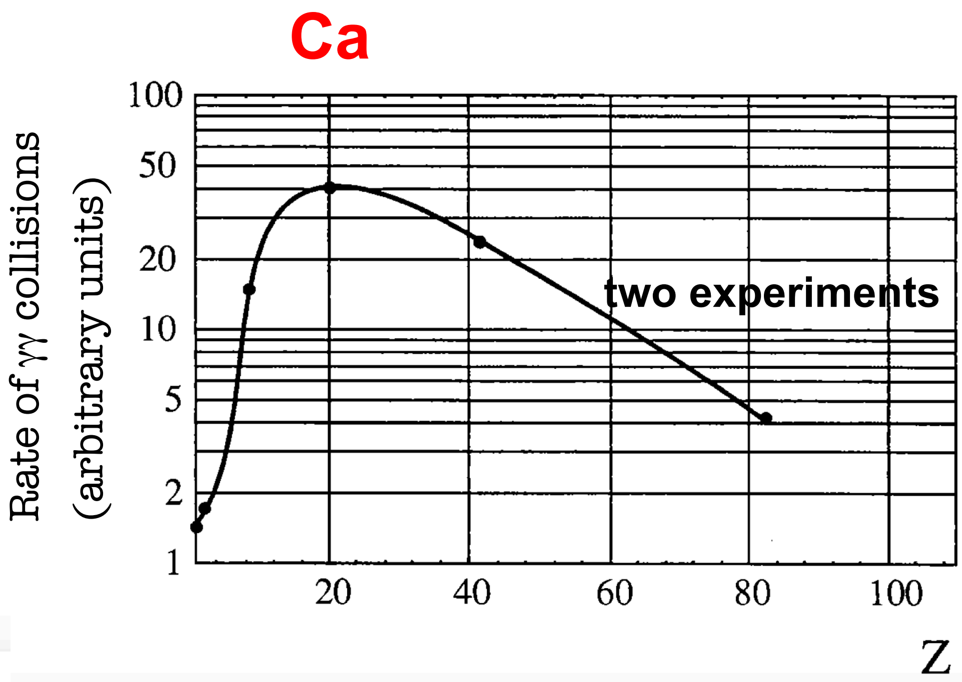
- Isoscalar beams $u^{(v)} = d^{(v)}$ cancel the majority of W^+, W^- and Z production differences (Z as a standard candle)
- The measurement of the W-boson charge asymmetry constrain directly the s-c distribution
- Analysis restricted to forward lepton pseudorapidities reduces errors due to b distribution uncertainty
- In addition, no need to assume $s(x)=\bar{s}(x)$, $c(x)=\bar{c}(x)$, $b(x)=\bar{b}(x)$

Drastic reduction of systematic errors of modelling the W and Z production and decay processes!

Why light nuclei ?

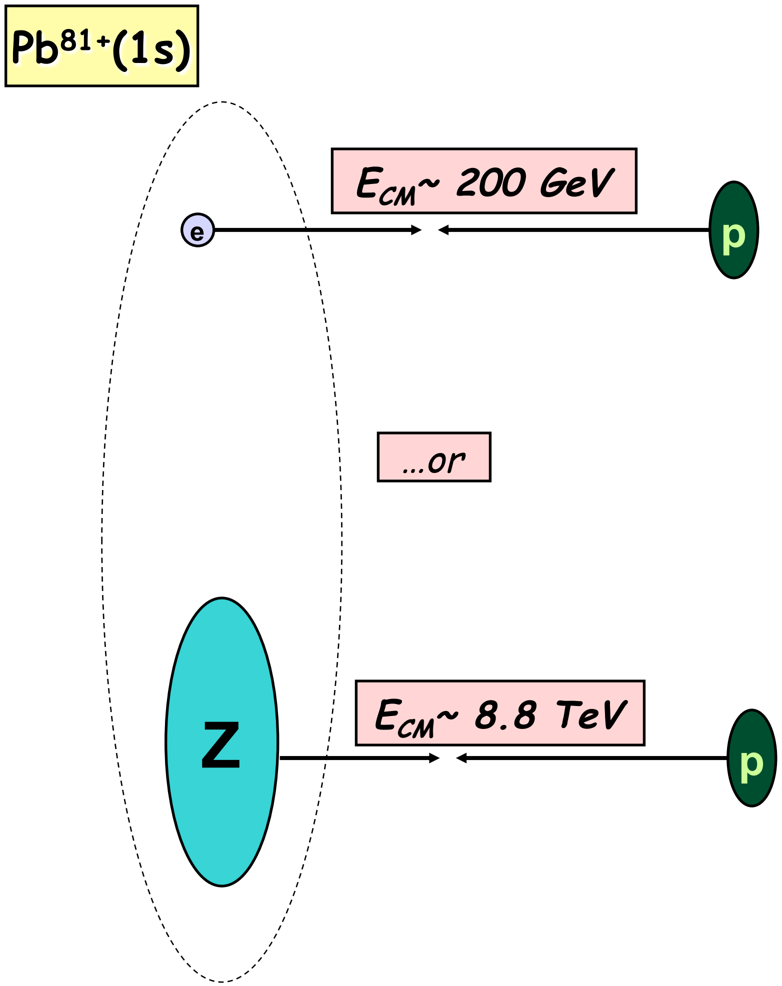
To drastically reduce the relative importance of the parasitic, beam-burning process which limit achievable nucleon-nucleon luminosity in AA collisions





D. Brandt

Cost-less electron beam for electron-proton collisions at the LHC



- *average distance of the electron to the large Z nucleus d ~ 600 fm (sizably higher than the range of strong interactions)*

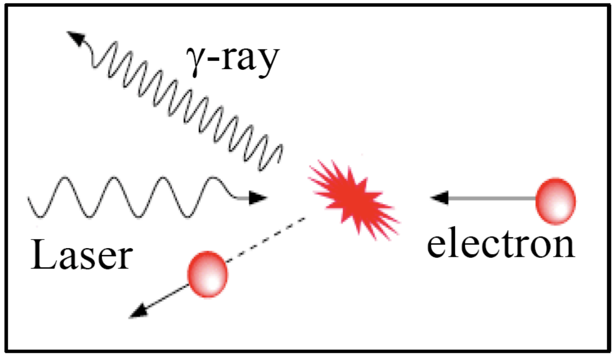
- *partially stripped ion beams can be considered as independent electron and nuclear beams as long as the incoming proton scatters with the momentum transfer q >> 300 KeV*

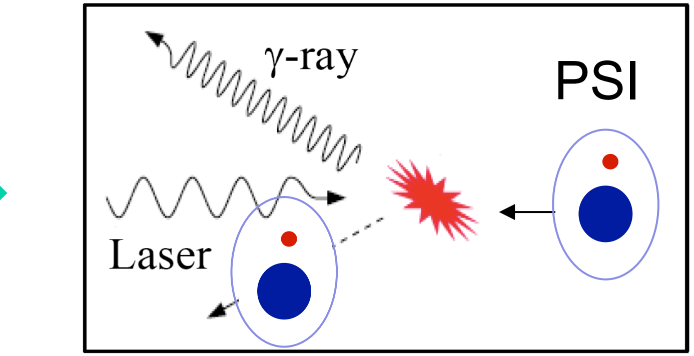
- *both beams have identical bunch structure (timing and bunch densities), the same β^*, the same beam emittance – the choice of collision type can be done exclusively by the trigger system (no read-out and event reconstruction adjustments necessary)*

High Intensity gamma beams

The idea: Replace electron beams by atomic beams

(giga-barn instead of barn cross sections!)





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:

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

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

Electrons:

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

Partially Stripped Ions:

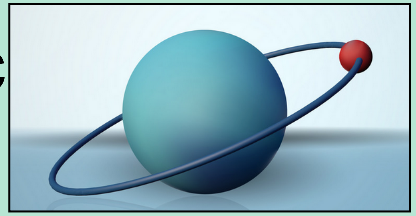
$$\sigma_{peak} = 5.9 \times 10^{-16}\ \mathrm{cm}^2$$

Numerical example: λ_{laser} = 1540 nm

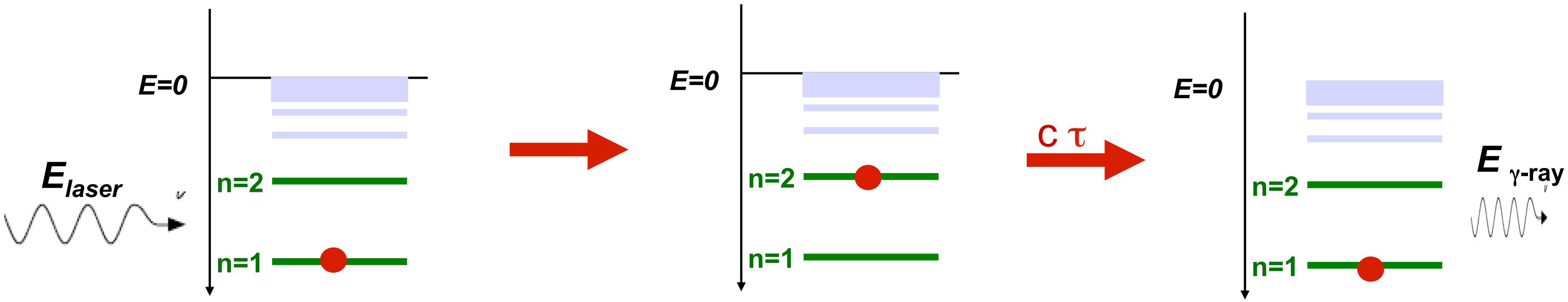
~ 9 orders of magnitude difference in the peak cross-section

~ 7 orders of magnitude increase of gamma fluxes

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



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



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

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

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.

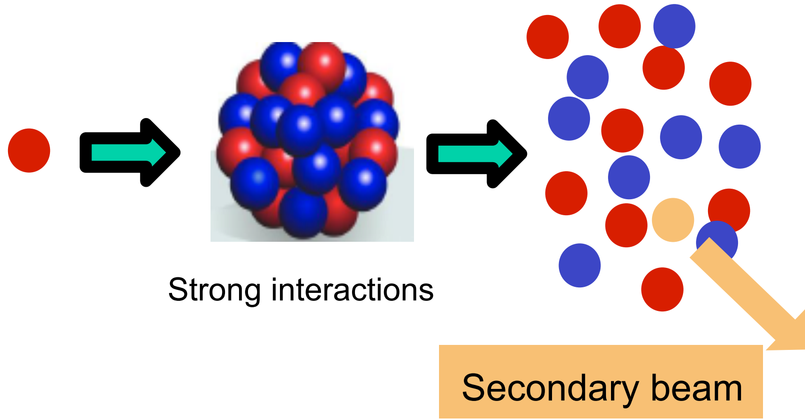
Example (Bohr model) (maximal energy):

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

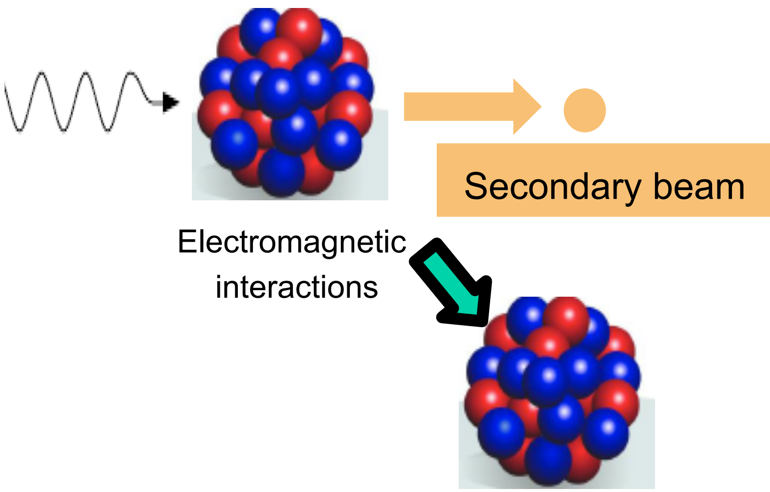
Secondary beams

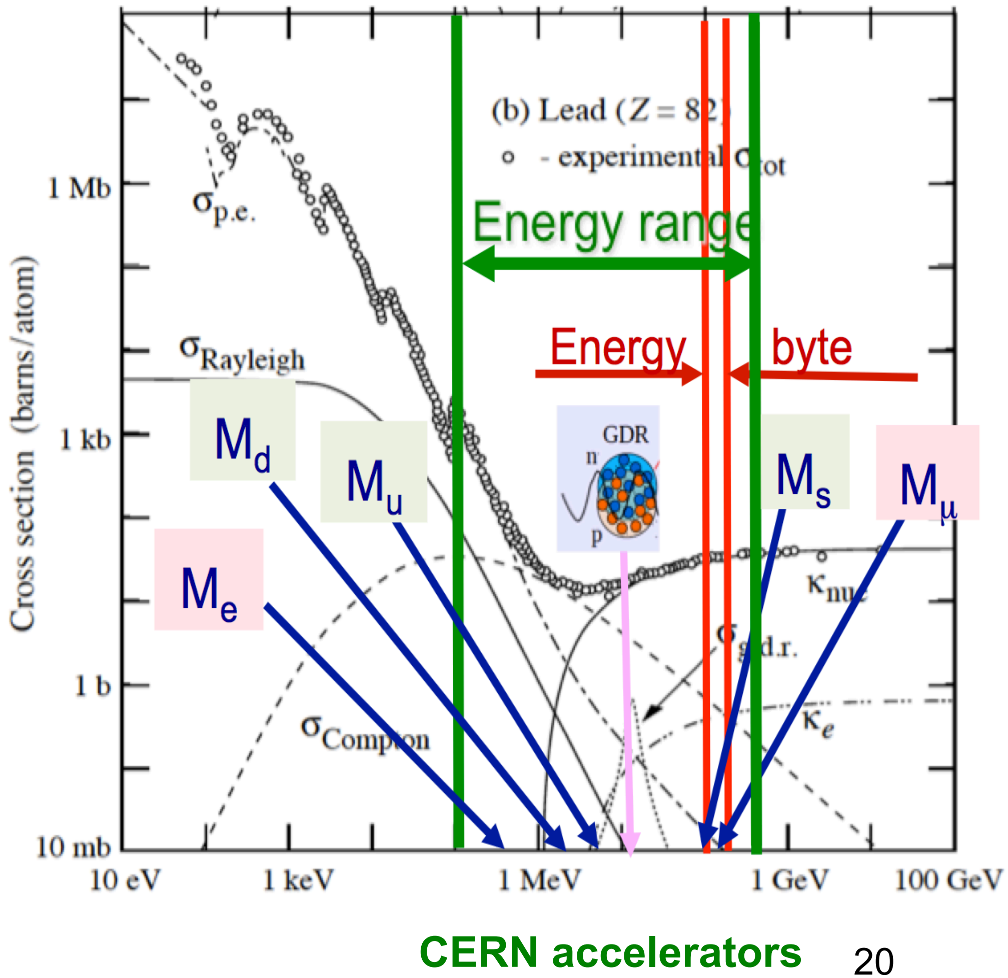
(from "mining" paradigm to "production-by-demand" paradigm)

"mining" paradigm:



"production" paradigm:





The Gamma Factory beam intensity targets

- ***Highly ionised atoms*** *– new at highly 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 10^4 (10^2) gain in intensity w.r.t to the PSI πE5 (future HiMB) muon beams – (low emittance beams → muon collider, high purity neutrino beams)*
- ***Neutrons*** *– up to a factor of 10^4 in flux of primary 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*

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), Pauli principle, parity violation, Lamb shift, …*
- ***applied physics*** *(accelerator driven energy sources , cold and warm fusion research, isotope production: e.g alpha-emitters for medical applications, …).*

The Gamma Factory project milestones

1. *Production, acceleration and storage of "atomic beams" at CERN*

2. *Development "ex nihilo" the requisite Gamma Factory software tools.*

3. *Proof-of-Principle experiment in the SPS tunnel.*

4. *Realistic assessment of the Gamma Factory performance figures.*

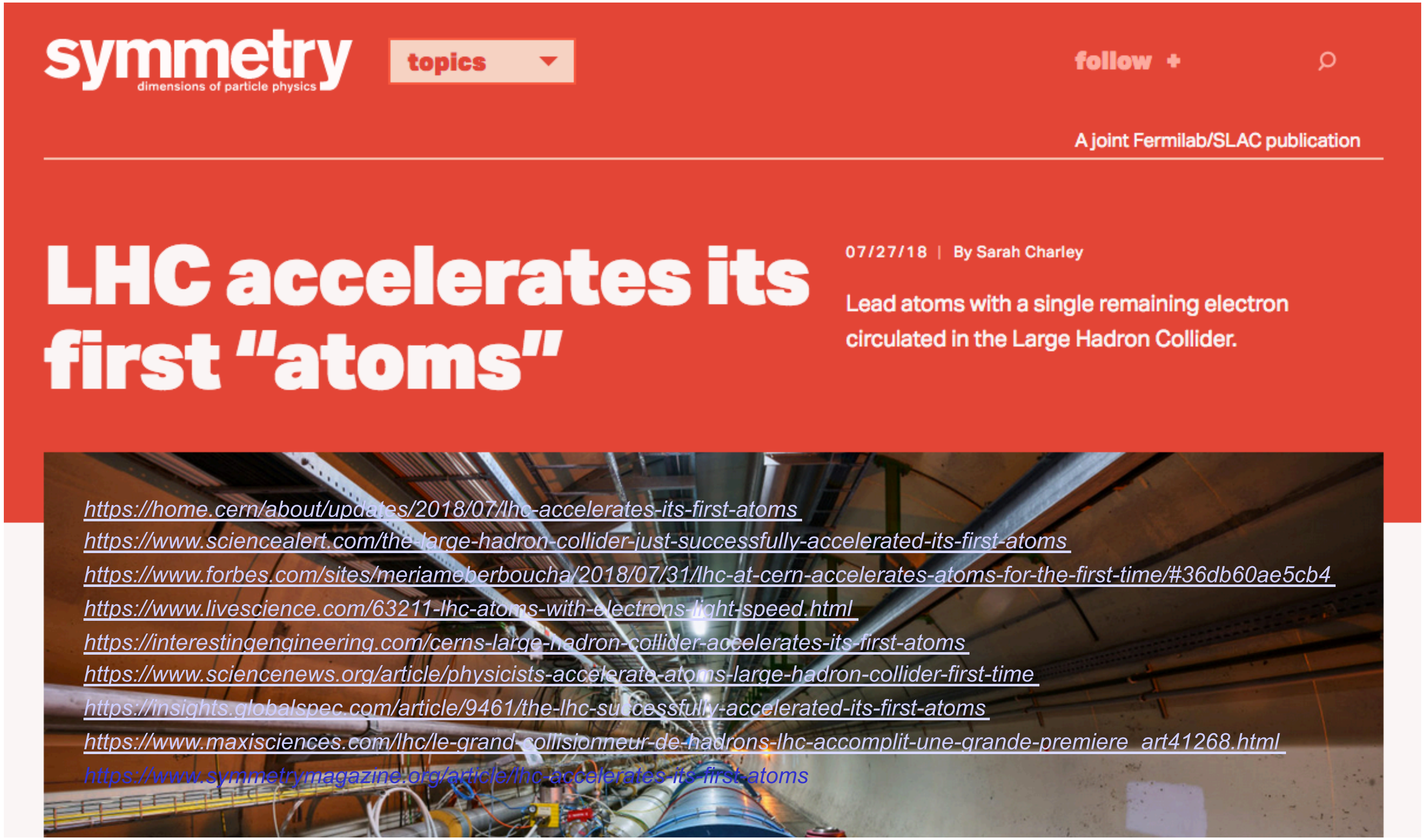
5. *Physics highlights of the Gamma Factory based research program.*

6. *Gamma Factory TDR*

Production, acceleration and storage of “atomic beams” at CERN accelerator complex

Results of the 2017 and 2018 **GF beam tests**

July, 2018: The Birth of Atomic Physics research at CERN



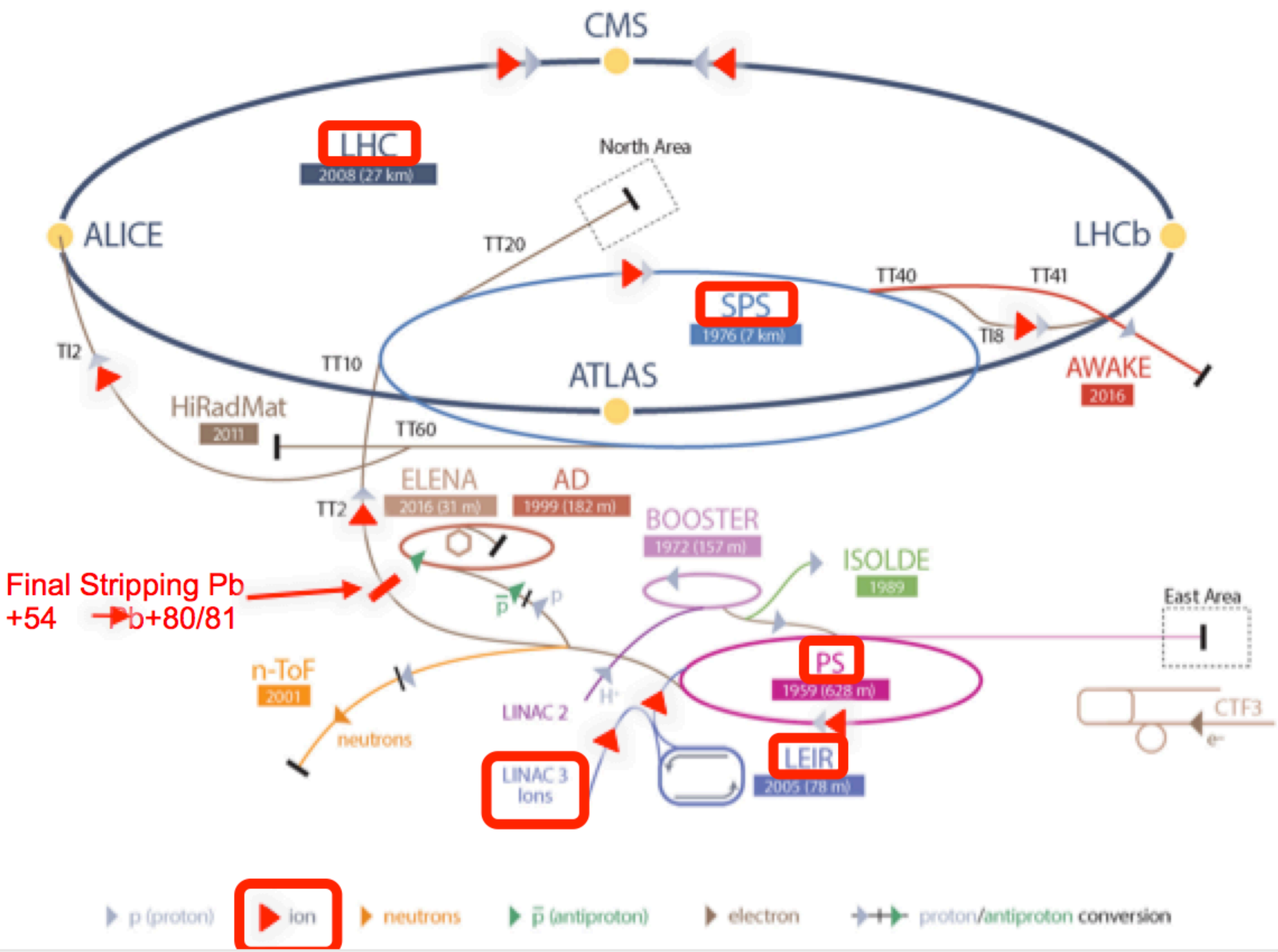
https://home.cern/about/updates/2018/07/lhc-accelerates-its-first-atoms
https://www.sciencealert.com/the-large-hadron-collider-just-successfully-accelerated-its-first-atoms
https://www.forbes.com/sites/meriameberboucha/2018/07/31/lhc-at-cern-accelerates-atoms-for-the-first-time/#36db60ae5cb4
https://www.livescience.com/63211-lhc-atoms-with-electrons-light-speed.html
https://interestingengineering.com/cerns-large-hadron-collider-accelerates-its-first-atoms
https://www.sciencenews.org/article/physicists-accelerate-atoms-large-hadron-collider-first-time
https://insights.globalspec.com/article/9461/the-lhc-successfully-accelerated-its-first-atoms
https://www.maxisciences.com/lhc/le-grand-collisionneur-de-hadrons-lhc-accomplit-une-grande-premiere_art41268.html
https://www.symmetrymagazine.org/article/lhc-accelerates-its-first-atoms

Acknowledgement:

The **Gamma Factory** beam tests over the year 2017 and 2018 involved dedicated work of the operation tams of the: Ion source, Linac, PS, SPS and LHC, the EN groups responsible for the installations of the GF strippers, vacuum teams, RF-experts and numerous other individuals.

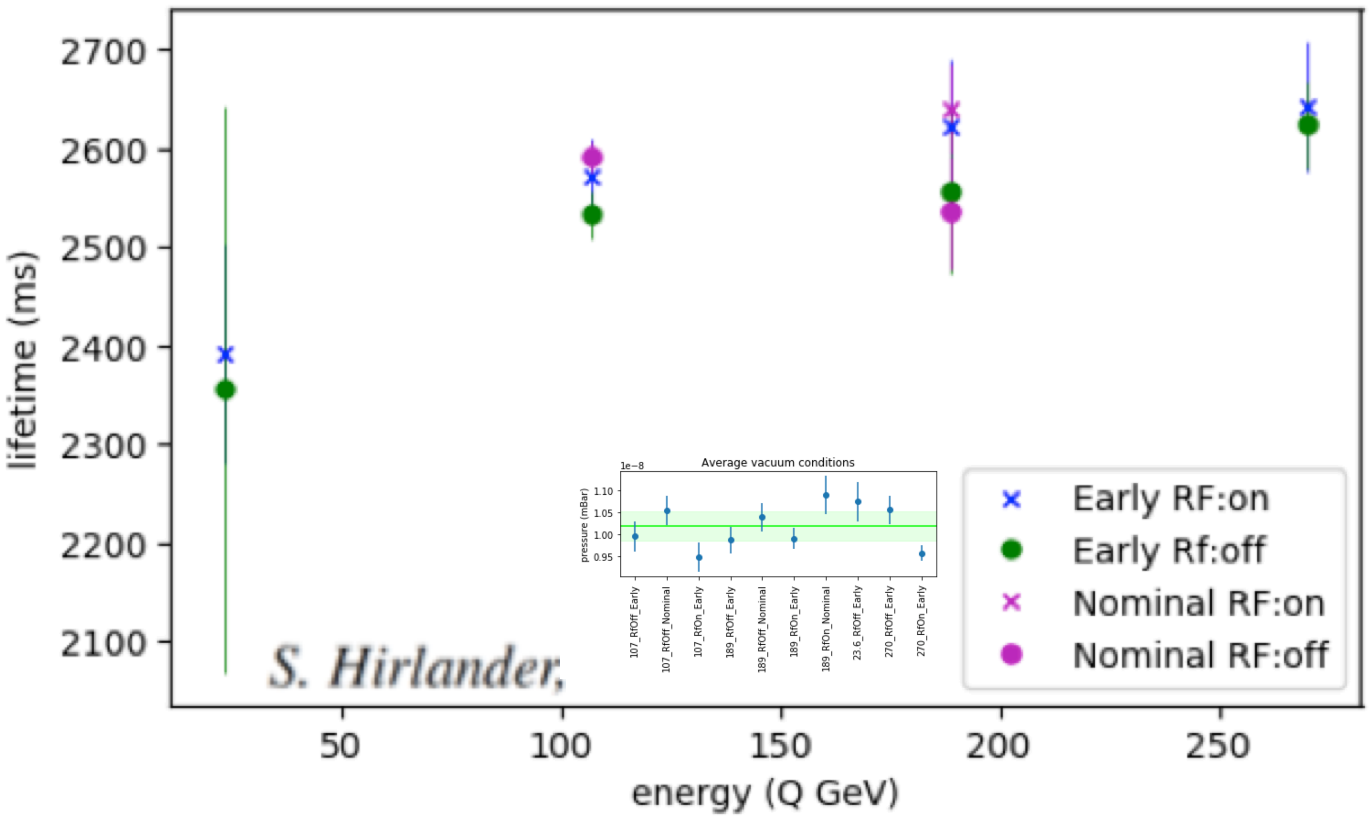
We (GF-group) acknowledge high quality of their work and and their enthusiasm in making these tests a success story!

CERN's Accelerator Complex



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

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

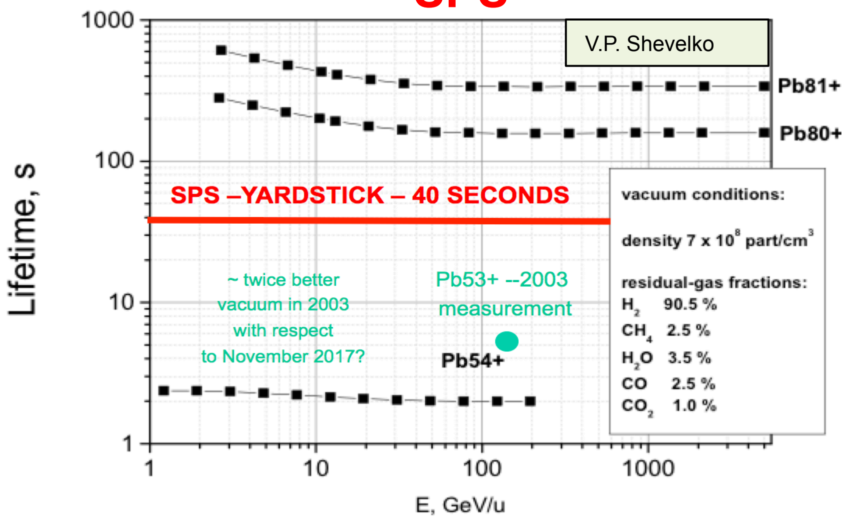


What we have already learned from the 2017 Xe+39 runs in the SPS?

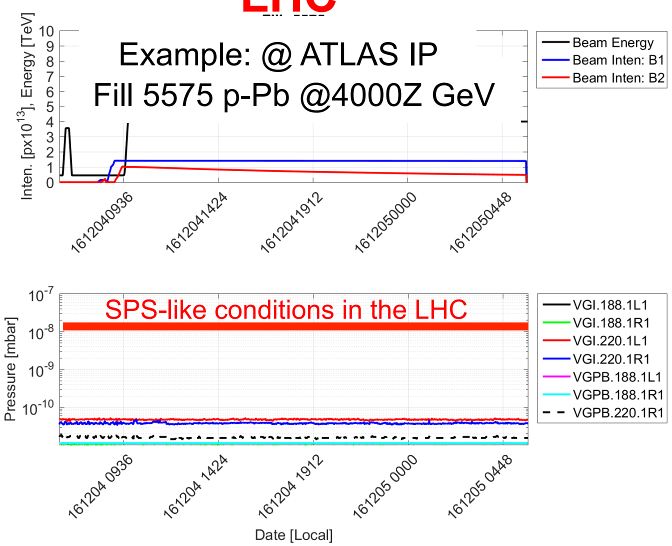
The expected Pb+80 and Pb+81 beam lifetime, for the vacuum conditions of the 2017 Xe +39 runs, (exceeds comfortably the SPS injection + ramping time)!

*Significantly better vacuum in the **LHC rings** – lifetime rise by a factor of 100, w.r.t SPS expected (**beam lifetime of at least ~10 hours** – if driven by the beam-gas collisions)!*

SPS



LHC

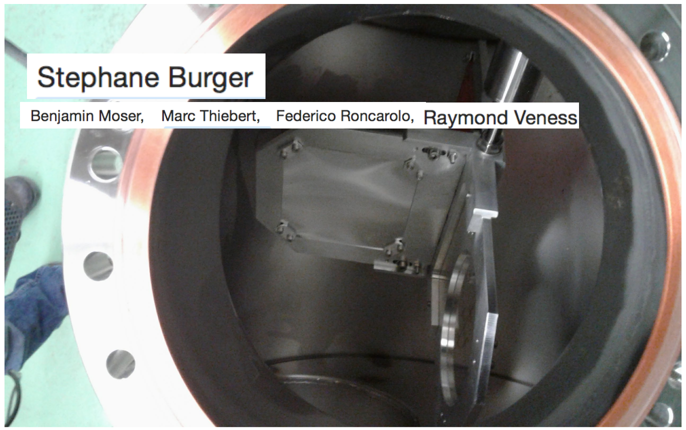


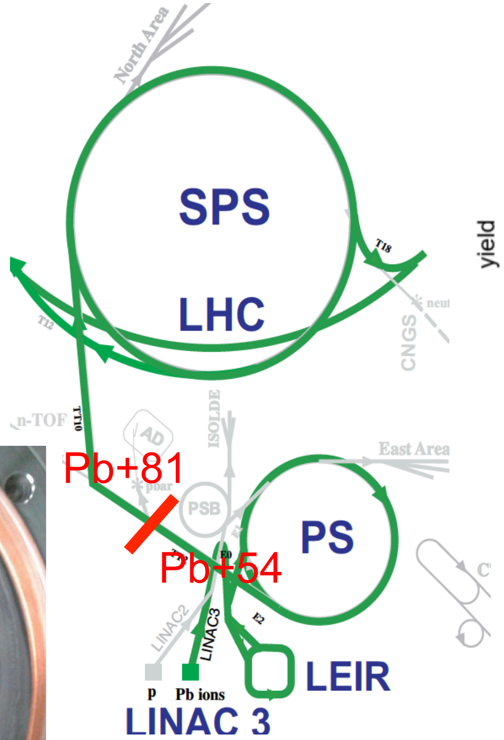
Christina Yin Vallgren,
Patricia Ribes Metidieri,
Roberto Kersevan

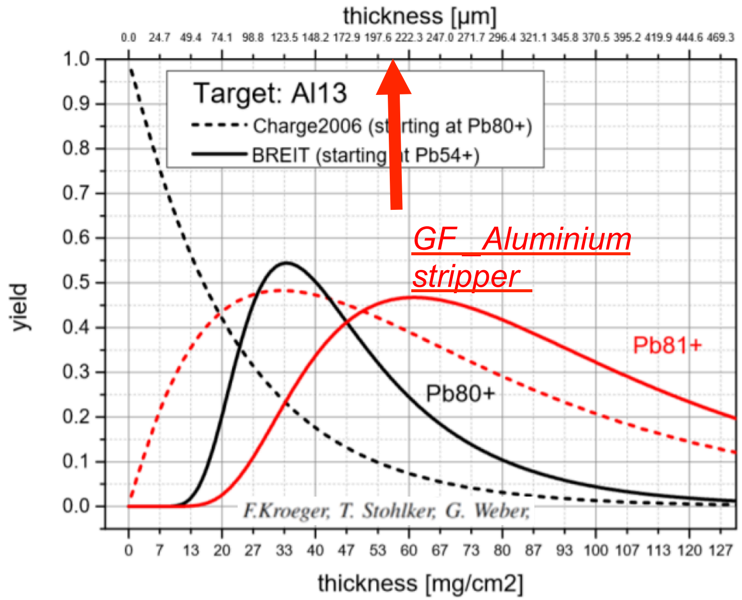
Assuming:
H_2: 90.5%
H_2O: 3.5%
CH_4: 2.5%
CO: 2.5%
CO_2: 1%
Total molecules @ 10^{-11}mbar:
5.5×10^{11} molecule/ m^3

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

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





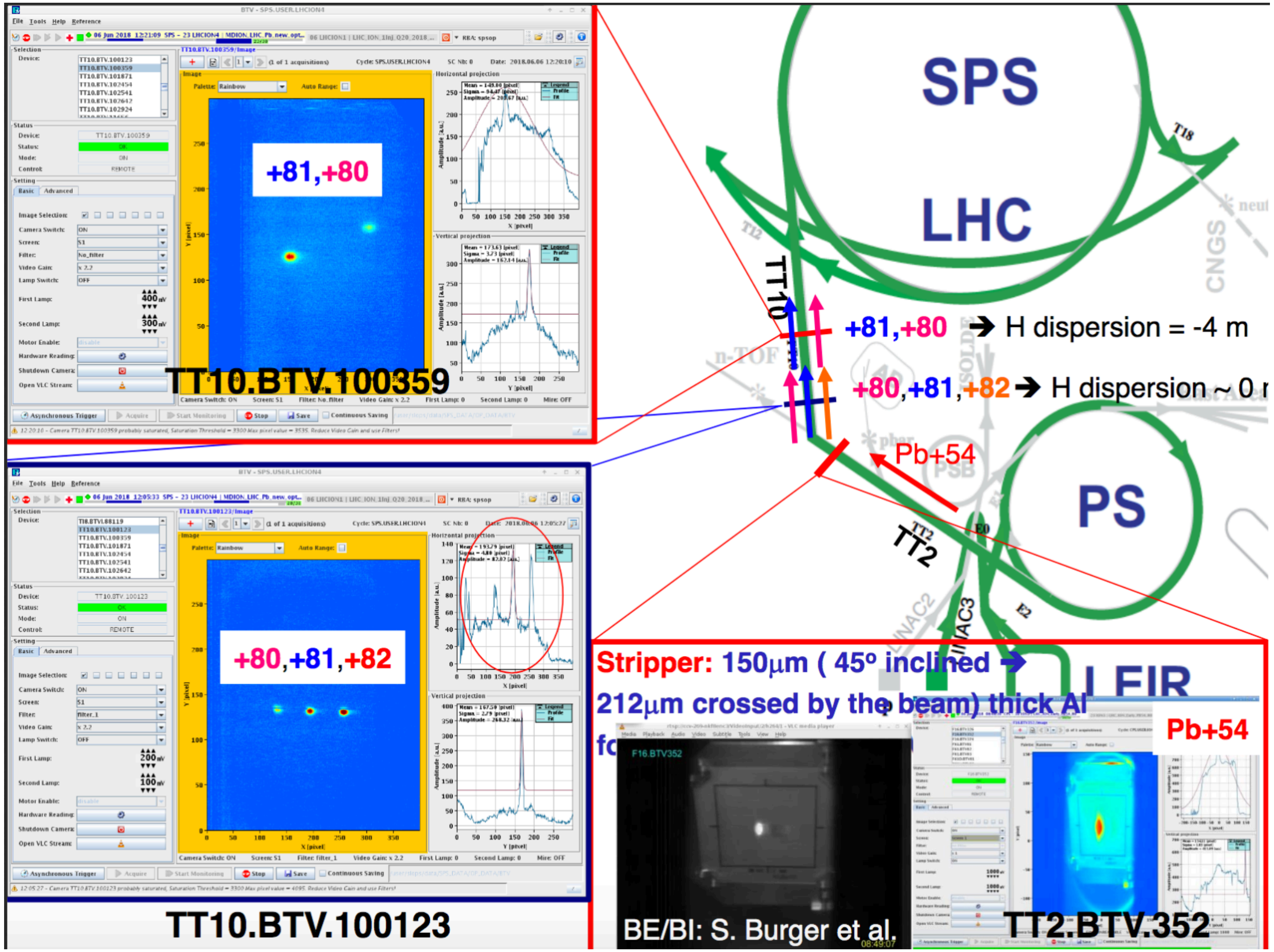


26.01.2018

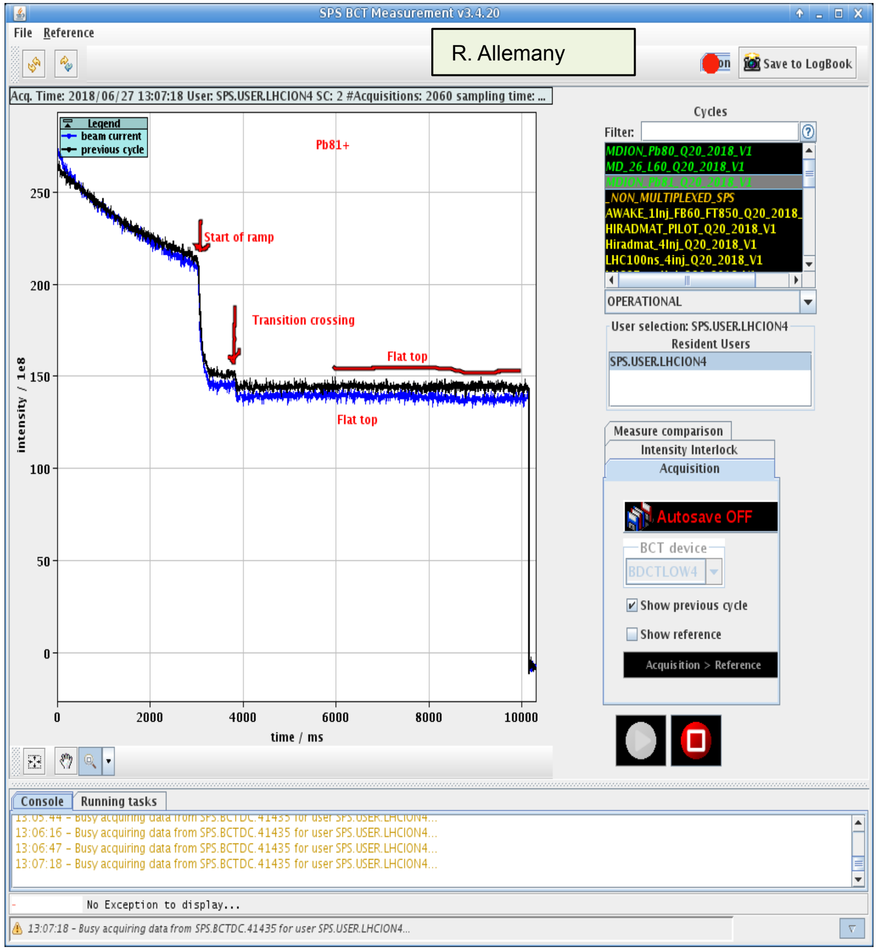
The 150μm (212μm crossed by the beam as installed at 45 degrees) thick Al foil has been installed on the FT16.BTV352 in the TT2 line!

Backup solution for Pb+80 beam – 4 titanium screens

June 2018 – Successful production of the Pb+80 and Pb+81 beams and their transport to the SPS entry.



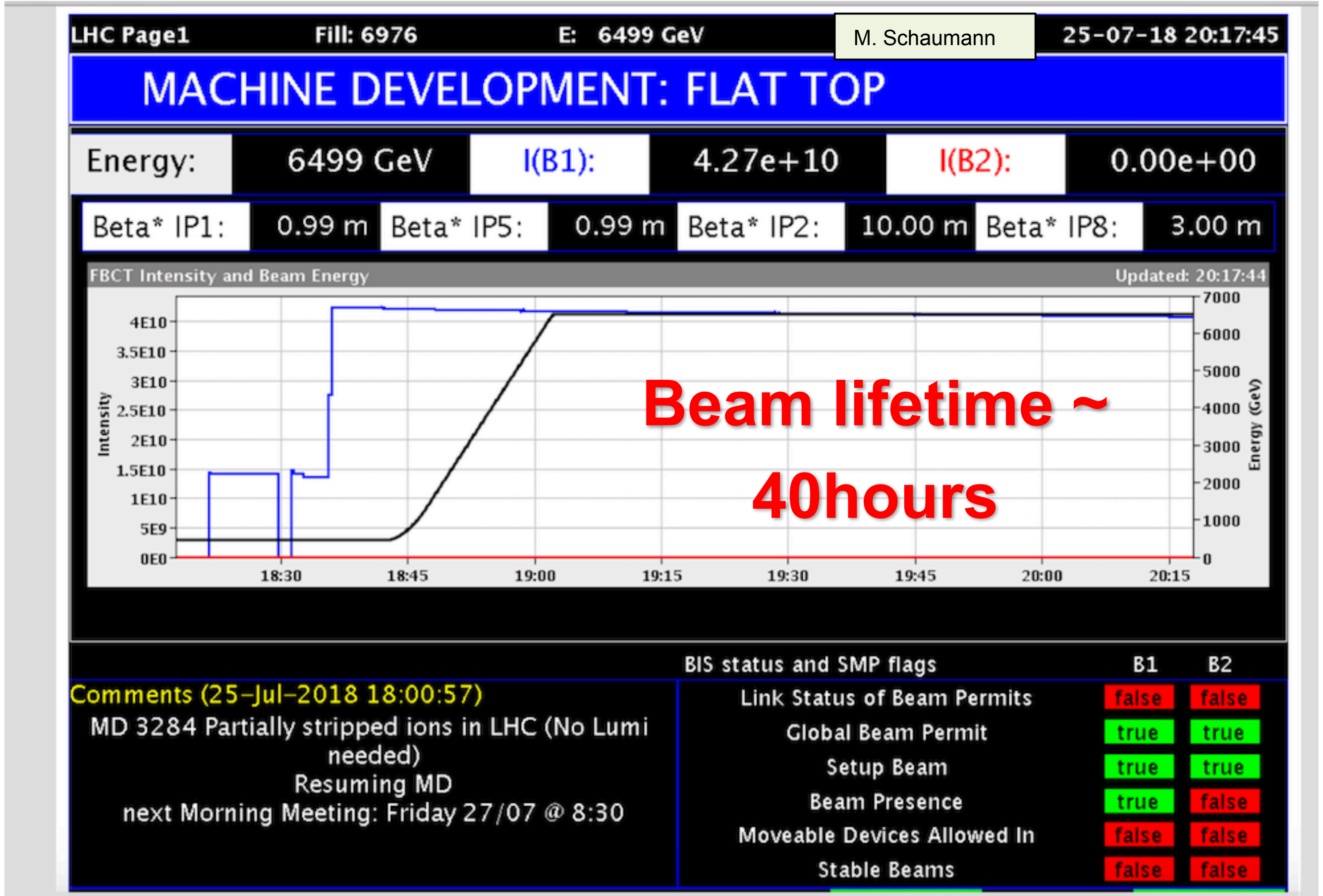
June and July 2018 – Successful injection, acceleration and storage of the Pb+80(+81) beams in the SPS



- Pb+81 bunch intensity: ~8 x 10^9 charges
- Beam lifetime exceeding 300 seconds
- Ramp up to injection energy to the LHC
- SPS-LHC transmission test
- SPS-LHC synchronisation

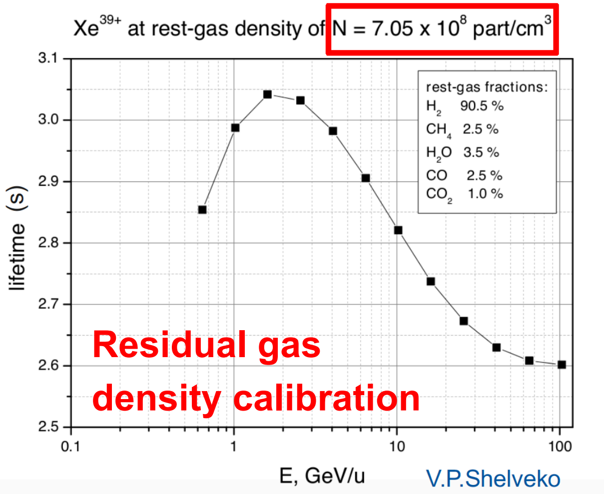
→ **ready to inject Pb+81 beam to the LHC**

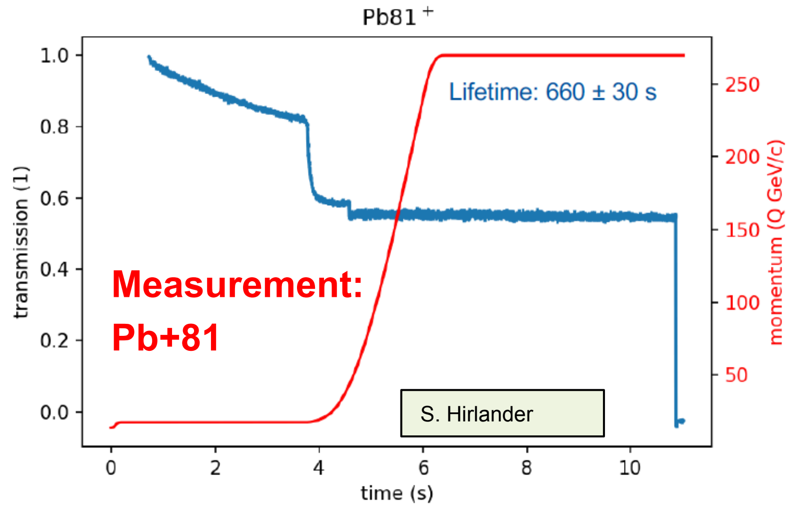
July 2018 – Successful production, injection, ramp and storage of the Hydrogen-like lead beam in the LHC!

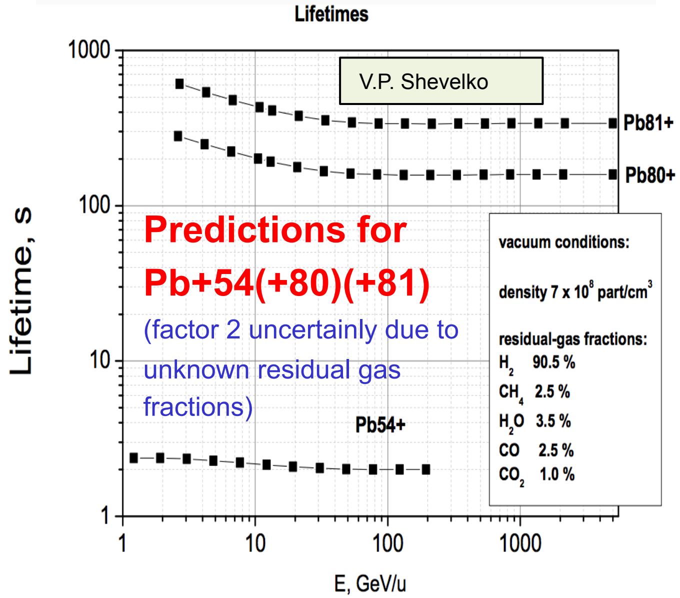


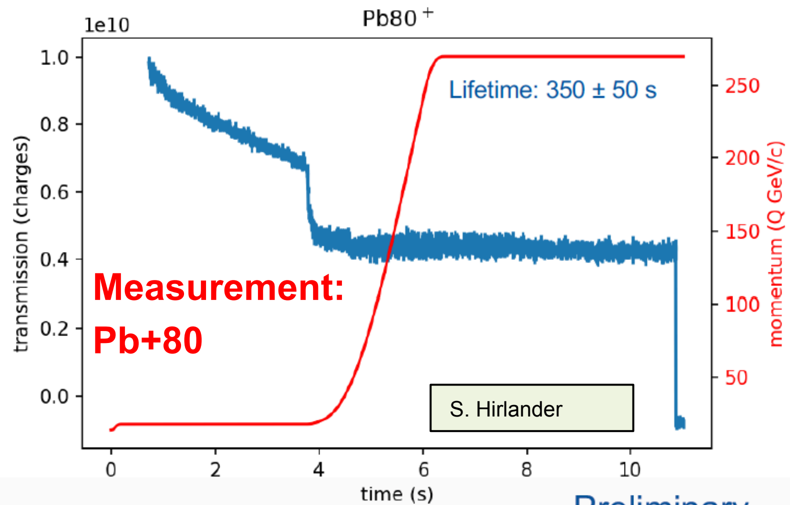
intensity/bunch (~7 x 10^9), 6 bunches circulating

What have we learned from the SPS beam test: (beam lifetime)









Preliminary

Gamma Factory LHC and SPS beam tests -- summary

We have reached the first of the Gamma Factory project milestones:
we have demonstrated that we can efficiently produce, accelerate and store bunches of high Z partially stripped ions in the CERN accelerator complex with the requisite bunch intensities.

Two outstanding issues requiring further investigations:

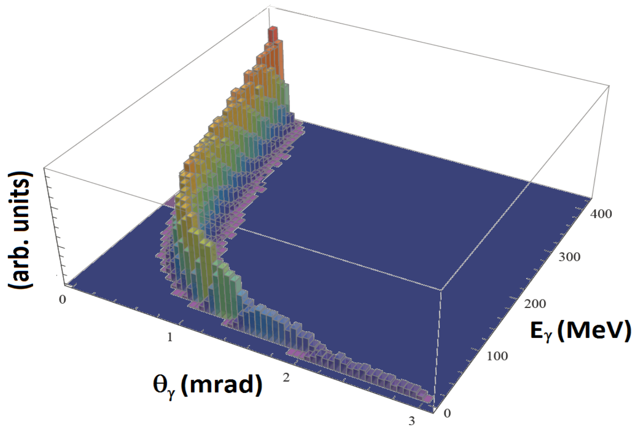
- poor SPS vacuum quality which limits the use of low Z ions
- optimisation of the collimation of the beam of partially stripped ions to maximise the number of bunches which can be accelerated and stored in the LHC (crystals?, and the installation of the TCLDs in LS2?).

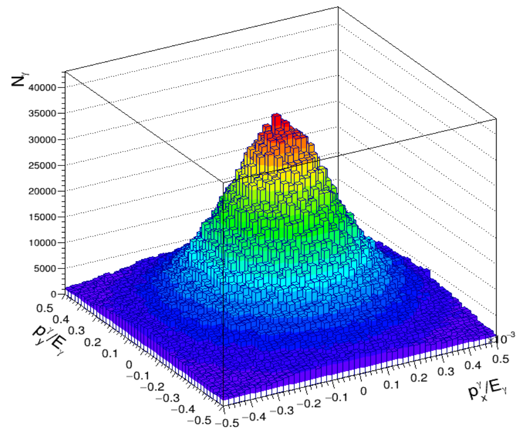
Development “ex nihilo” of the Gamma Factory software tools.

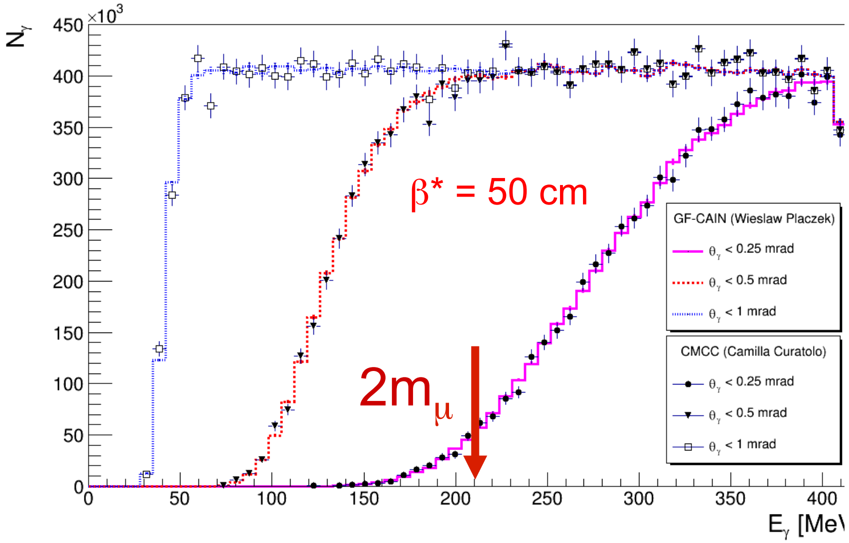
The requisite simulation tools

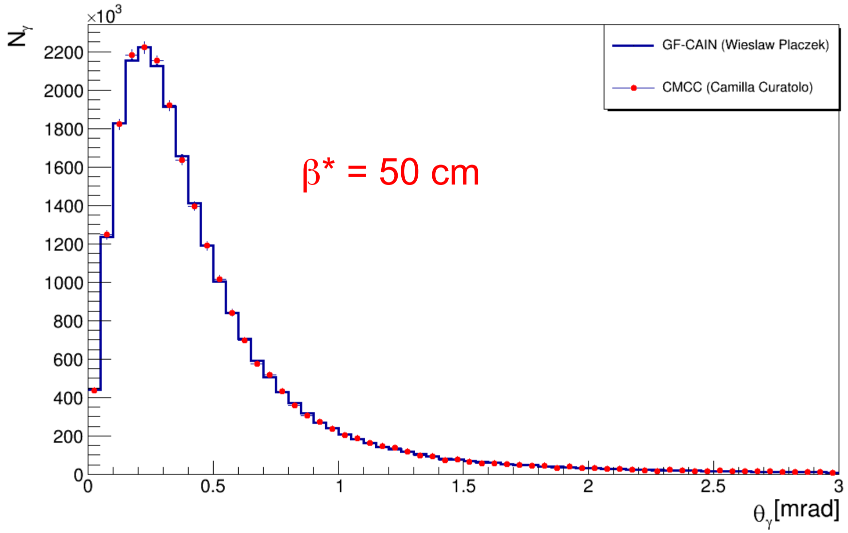
1. *PSI-beam simulation (beam cooling, IBS, IBS, Space Charge, Instabilities,….)*
2. *Simulation of electron stripping in metallic foils.*
3. *Simulations of collisions of atomic beams with the residual gas in the accelerator rings (including atomic excitations).*
4. *Collisions of PSI bunches with photons (laser +F-P cavity or FEL)*
5. *Production of secondary beams in collisions of photons with matter: positrons, polarised muons, neutrons, neutrinos, mesons, radioactive nuclei*

Example: Gamma ray production spectra for +81 Pb beam collisions with photon bunches at the top LHC energy (two generators being developed)









The Gamma Factory

Proof-of-Principle (PoP)

experiment in the SPS tunnel.

What we want to learn/demonstrate with the PoP experiment in the SPS?

1. *How to integrate of the laser + F-P cavity into the storage ring of hadronic beam?*
   (radiation hardness of the laser system, IP for high beam magnetic rigidity beam, etc…)
2. *How to maximise the rate of atomic excitations? (matching of the characteristics of the ion bunches to those of the laser bunches, matching laser light bandwidth to the width (lifetime) of the atomic excitation, timing synchronisation, etc.) ?*
3. *How to extract the Gamma-rays from the collision zone?*
4. *How to collimate the Gamma beam?*
5. *How to monitor/measure the flux of outgoing photons?*

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6. *Demonstrate new cooling method of hadronic beams (Laser Cooling)*
7. *Atomic Physics measurement programme (PNC, Lamb shift, …)*

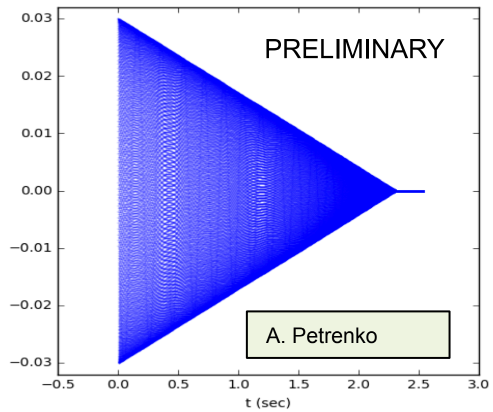
The choice of ions for the PoP experiment

Neon-like Calcium: Ca+10

(very important for the HL-LHC precision measurement programme)

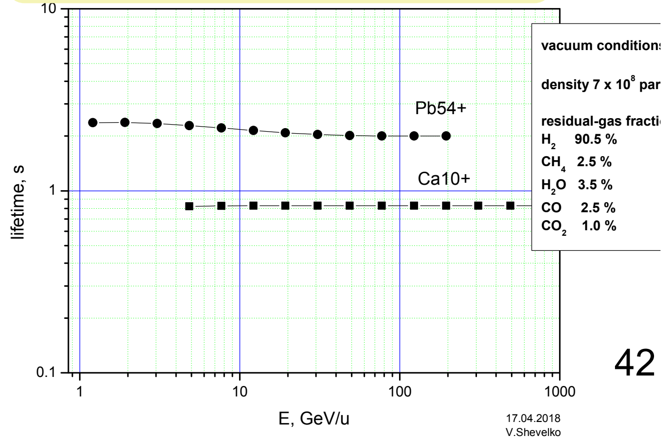
- ATOMIC GROUND STATE : 1s^2 2s^2 2p^6 $1S_0$
- CHOICE OF EXCITED STATE: 1s^2 2s^2 2p^5 3s $1P_0$
- TRANSITION ENERGY: E = 352.1 eV
- LIFE TIME (excited state) : τ = 6 ps

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



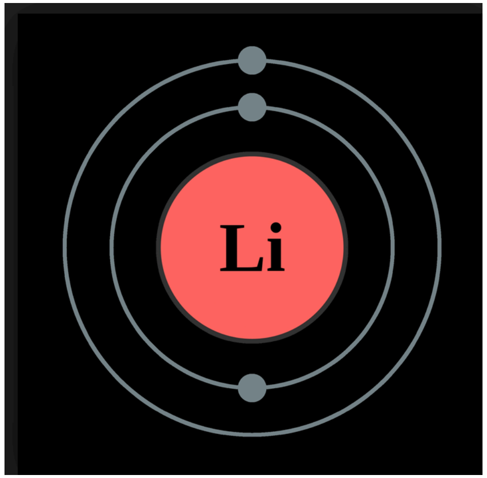
$\tau_{cooling} > \tau_{beam}$

Ca+10 beam life-time in the SPS



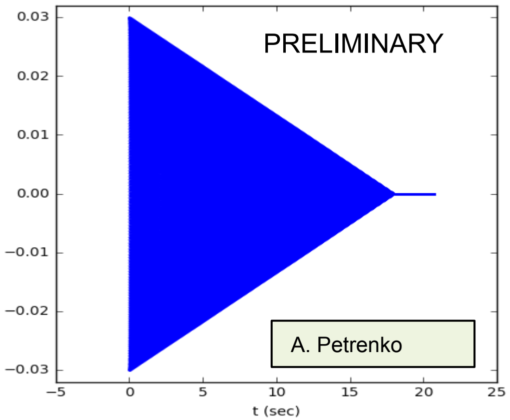
The choice of ions for POP experiment

Lithium-like Lead: Pb79



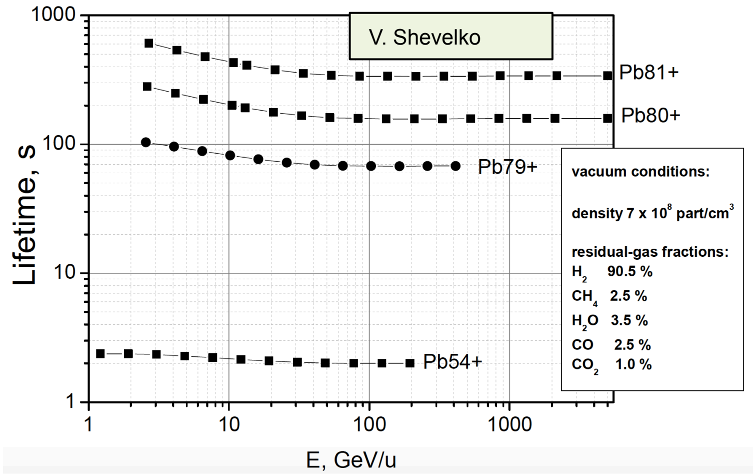
- ATOMIC GROUND STATE : 1s^2 2s^1 $1S_0$
- CHOICE OF EXCITED STATE: 1s^2 2p^1 $1P_0$
- TRANSITION ENERGY: $E = 230$ eV
- LIFE TIME (excited state) : $\tau = 77$ ps

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

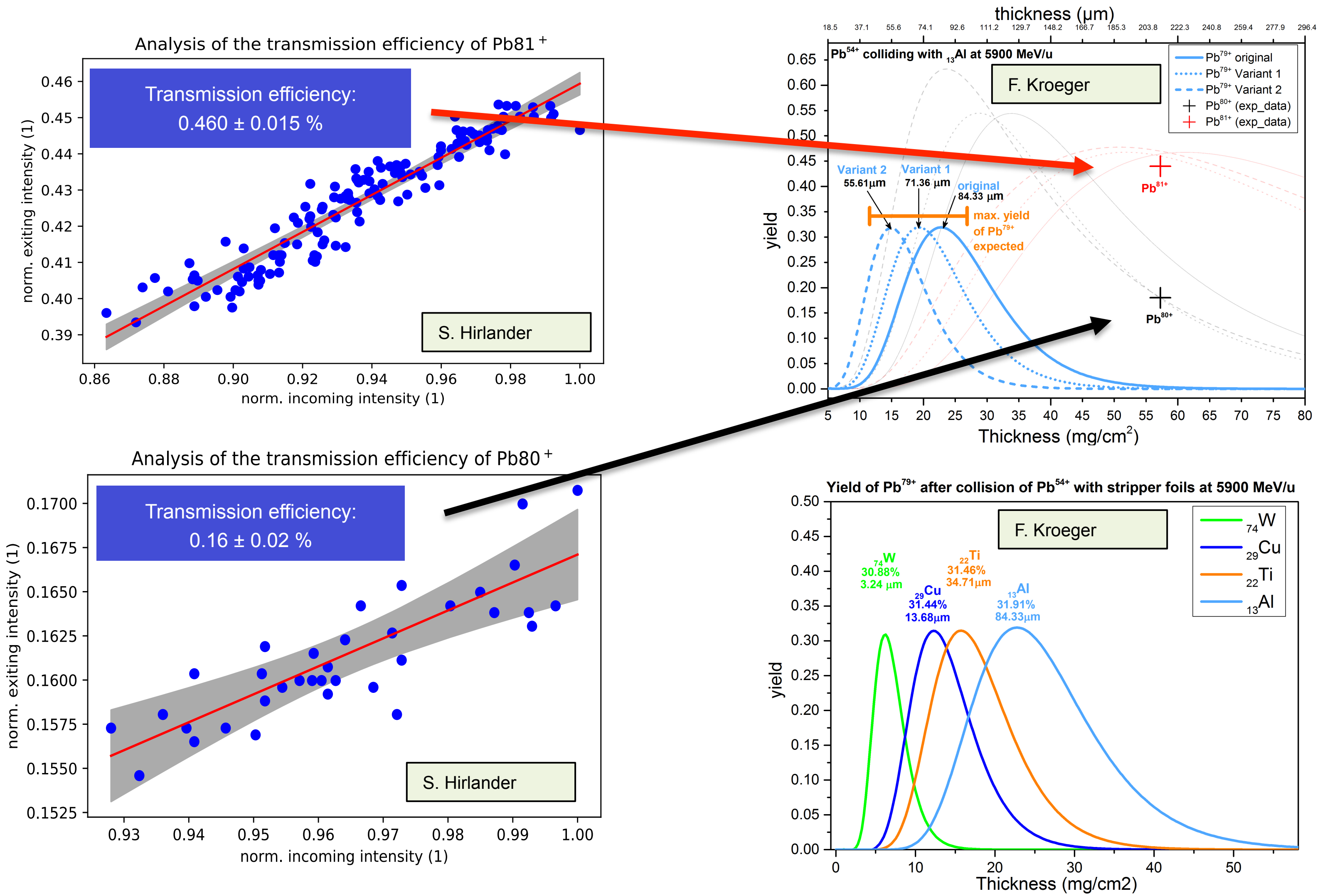


$\tau_{cooling} < \tau_{beam}$

Pb+79 beam life-time in the SPS



Stripper optimisation for PoP experiment

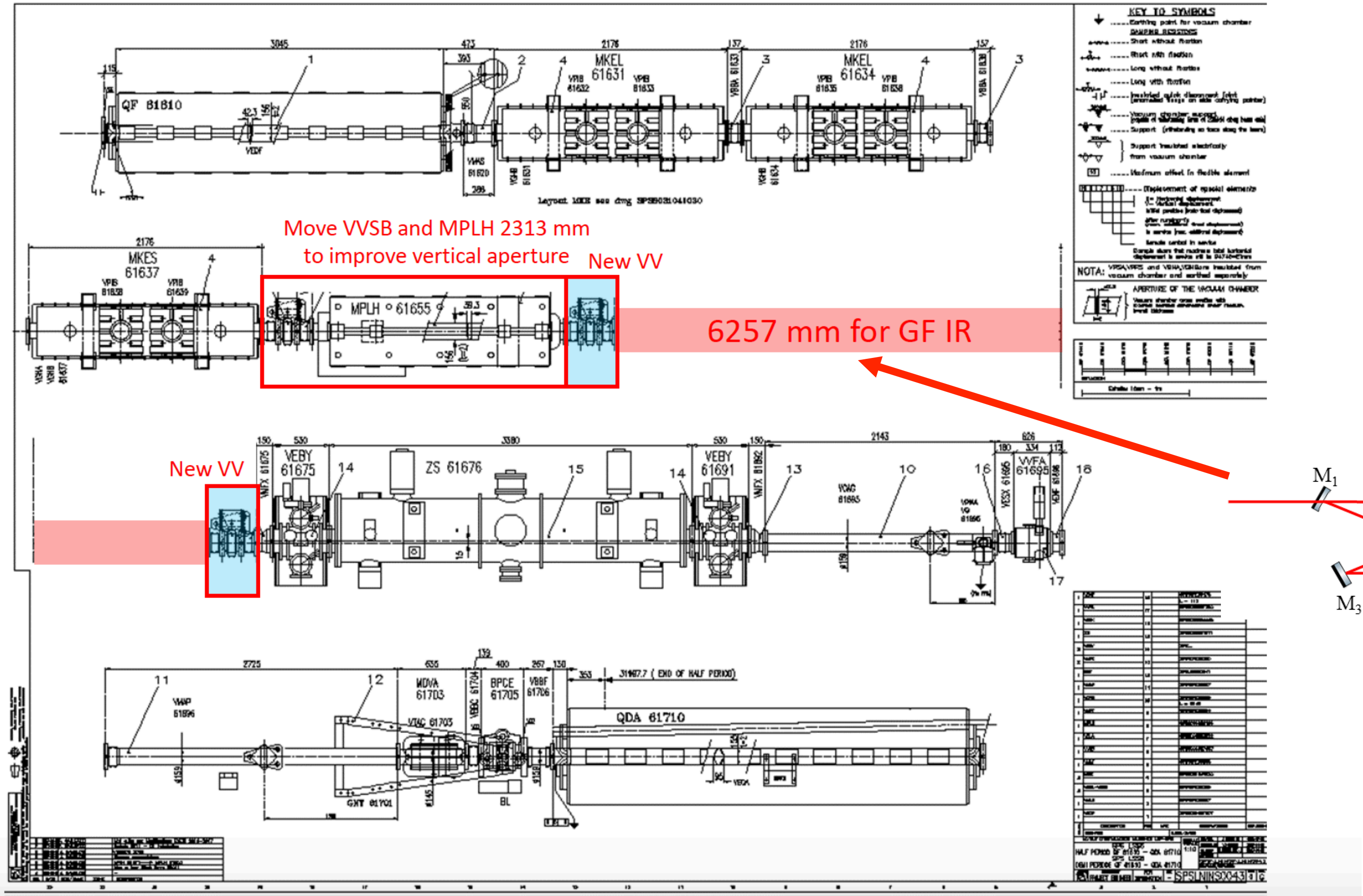


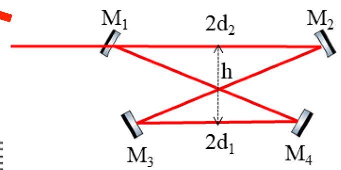
PoP experiment location – initial considerations:

LSS4: Laser-PSI interaction region: 616?

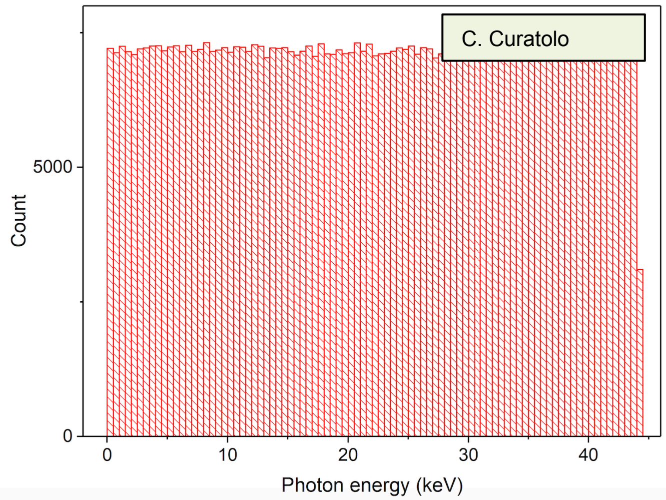
LSS6.616: present (post-LS2) layout

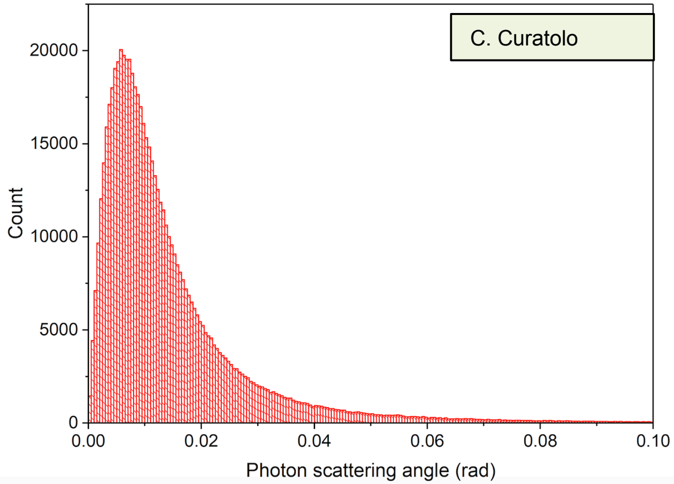
B. Goddard





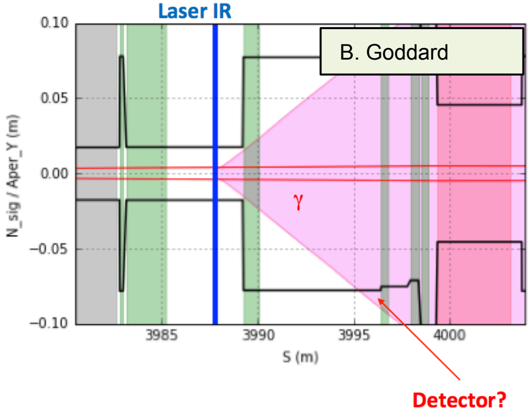
Characteristics of produced photons an their detection





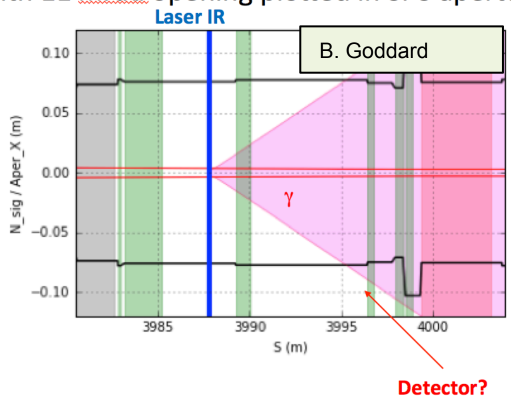
LSS4 H envelope and trajectories (V)

- X-ray cone with 11 mrad opening plotted in SPS aperture



LSS4 H envelope and trajectories (H)

- X-ray cone with 11 mrad opening plotted in SPS aperture

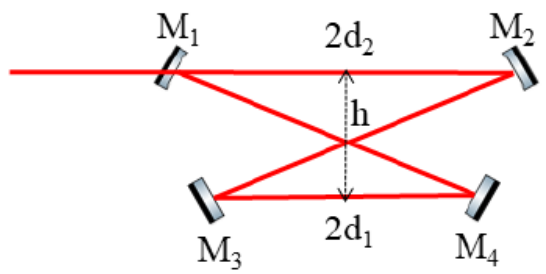


Laser-beam system optimisation

(studies of the realistic laser +F-P configurations have just started)

Description	Parameter name	Value
Number of ions per bunch	n_I	$2 \cdot 10^8$
Betatron function at the IP	β^*	53 m
Normalized emittance	ϵ	$1.5 \cdot 10^{-6}$ m
Transition energy	E_t	230.76 eV
Excited state lifetime	τ	76 ps
Ion rest mass	$M_i c^2$	193.687 GeV
Bunch spacing related frequency	F_{rep}	5 MHz
SPS revolution time	T_c	23 μs
Initial ion-beam energy spread	$\Delta E_i / E_i$	$3\ 10^{-4}$
RF voltage magnitude	V_{RF}	7 MV
Ion atomic number	Z	82
Number of remaining electrons in ion	N_e	3
Harmonic number in SPS	H	4620
SPS transition energy	$\gamma_t M_i c^2$	22.8
Laser-beam waist (horizontal plane)	$w_{o,h}$	200 μm
Laser-beam waist (vertical plane)	$w_{o,v}$	180 μm
Laser-beam central wavelength	λ_0	1030 nm

Configuration #	$\Delta\lambda$	θ	U
1	0.3 nm	9°	2 mJ
2	0.8 nm	9°	4 mJ
3	1.3 nm	9°	6 mJ
4	1.3 nm	6°	4 mJ



$2d_1$	$2d_2$	h	R	U_{max}	w_{0s}	w_{0t}
1.91 m	1.76 m	0.56 m	1.49 m	19 mJ	200 μm	180 μm

Description	Parameter name	Range
Laser-beam pulse FWHM	σ_t	[25,250] ps
Laser-beam bandwidth	$\Delta\lambda$	[0.3,1.3] nm
Beams crossing angle at IP	θ	[6,9] degree
Laser-beam pulse energy	U	[2,8] mJ

A. Martens

Next steps – Radiation hardness tests of the laser system

- *Measurement of the radiation level in 6 selected positions (both for pp and PbPb runs)*
- *Fluka simulations will have to be adjusted to the observed doses*
- *Controlled irradiation (at CERN's CHARM facility, or elsewhere) of various laser system components (including electronics – AMPLITUDE laser-company interested in such tests*

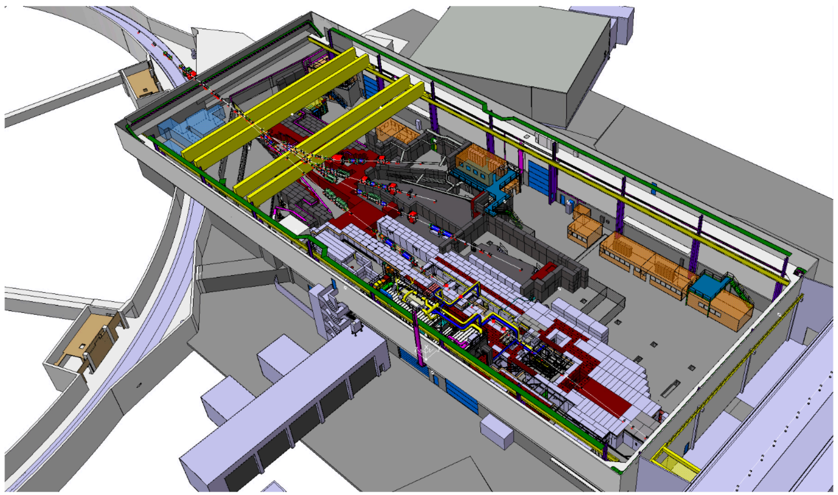


Fig. 2: A screen-shot from the 3D drawing of the PS East Area Hall. The IRRAD and CHARM facility are located in the southern part of the hall (bottom-right of the image).

Conclusions

Over the last 1.5 years the Gamma Factory initial ideas developed into a well defined project involving a group of ~ 50 physicists.

We have passed its most important milestone: the proof that we can produce, accelerate and store atomic beams in the CERN acclerator's infrastucture.

The Gamma Factory project enters its second phase of developing the requisite software tools and preparing the Letter of Intent for a Proof-of-Principle experiment at the CERN SPS.

We are preparing our input to the European Strategy Process and hope that our project will be retained as the future large-scale project for CERN.