CERN

What we have learned from the Test Runs With Highly Charged Xe And Pb Ions in the SPS and LHC Accelerator Rings At CERN

S. Hirlaender
On behalf of the Gamma Factory

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Current members of the Gamma Factory project

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[1] *CERN, Geneva, Switzerland*
[2] *Institute of Spectroscopy, Russian Academy of Science, Moscow, Russia*
[3] *A. I. Alikhanyan National Science Laboratory,Yerevan, Armenia*
[4] *P. N. Lebedev Physical Institute, Moscow, Russia*
[5] *Marian Smoluchowski Institute of Physics, Jagiellonian University, Kraków, Poland*
[6] *Center for Advanced Studies of Accelerators, Jefferson Lab, USA*
[7] *Helmholtz Institute, Johannes Gutenberg University, Mainz, Germany*
[8] *LAL Orsay, France*
[9] *Department of Physics, INFN–Milan and University of Milan, Milan, Italy*
[10] *LPNHE, University Paris Sorbonne, CNRS–IN2P3, Paris, France*
[11] *HI Jena, IOQ FSU Jena and GSI Darmstadt, Germany*
[12] *FEL Laboratory, Duke University, Durham, USA*
[13] *Center for Beam Physics, LBNL, Berkeley, USA*

What is the Gamma Factory?

- A novel concept of the light source
- The backbone of the Gamma Factory initiative is a

  Partially Stripped Ion beam driven light source
- Could be realized at CERN by using the infrastructure of the already existing accelerators
- Push the intensity limits of the presently operating light sources by 7 orders of magnitude, reaching the flux of up to 10^{17} photons/s
- Operating in a particularly interesting γ-ray energy domain of

$$0.1 \leq E_\gamma \leq 400 \text{ MeV}$$

How does it work?

Concept:

1. Resonant absorption of the laser photon by the high energetic Partially Stripped Ion (PSI) beam

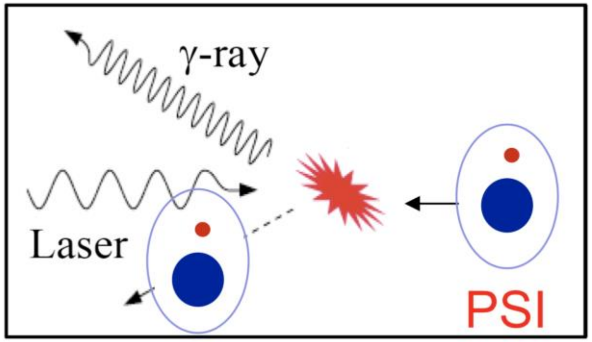
2. Followed by a spontaneous atomic-transition emissions of secondary photons

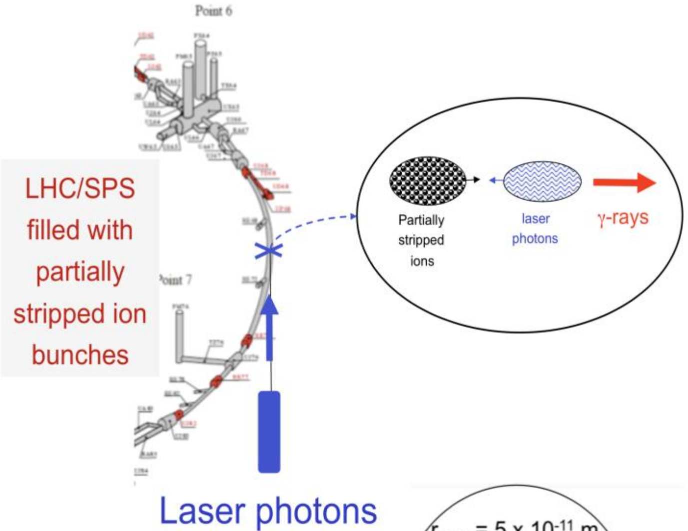
3. The initial laser-photon frequency is boosted by a factor of up to $4 \times \gamma_L^2$, where γ_L is the Lorenz factor of the partially stripped ion beam

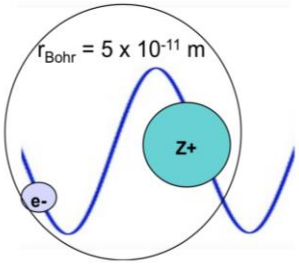
4. The light source in the energy range of $1 \leq E_\gamma \leq 400$ MeV must be driven by the high-γ_L, LHC-stored, PSI beams

5. The cross-section for the resonant absorption of laser photons by atomic systems is in the giga-barn range, while the cross section for the point-like electrons is in the barn range

6. The photon beam intensity is expected to be limited no longer by the laser light intensity but by the available RF power







(*Details:* arXiv:1511.07794 [hep-ex])

Gamma Factory

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

•***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, ...).*

The stability challenge of the feasibility

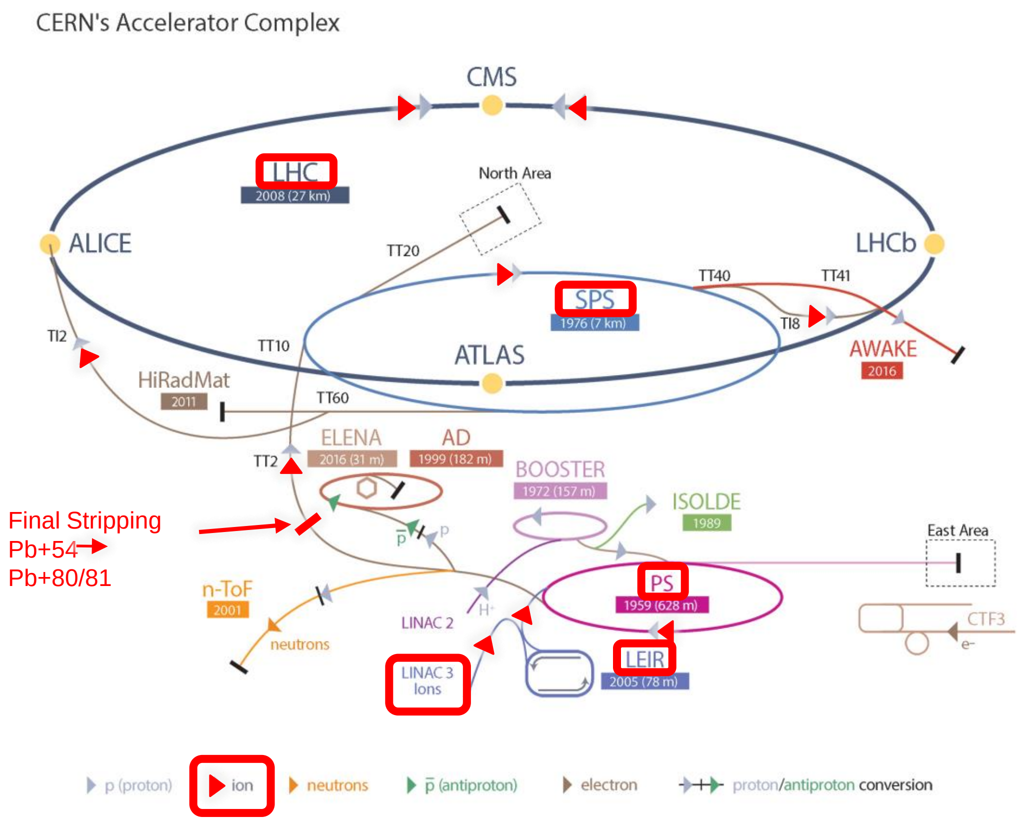
Stability of the partially stripped ion beams in the high energy storage rings

Possible expected sources of beam losses in the accelerators:

- Electron stripping by the residual gas
- Electron stripping by intra-beam scattering

Relative contributions have to be determined experimentally

The CERN ion injector chain



Previous ions in the complex:

- Fully Stripped:
  - Ar+18 SPS
  - Pb+82 LHC
  - Xe+54 SPS
- Exceptional partially stripped:
  - Pb+53 (calibration)

First partially stripped ions in the complex during these tests:

- Xe+39 LHC at 6.5 TeV/c (proton equivalent)
- Pb+80 SPS 270 GeV/c (proton equivalent)
- Pb+81 LHC at 6.5 TeV/c (proton equivalent)

CERN beam tests:

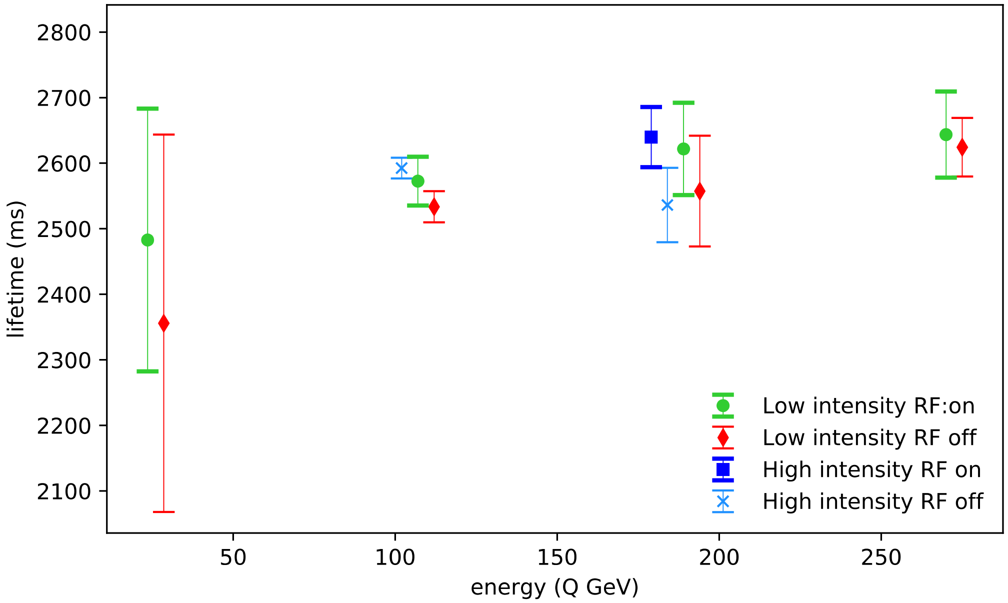
- 2017:
  - First tests using partially stripped ion Xe+39
  - Extrapolation used for feasibility of Pb partially stripped ion tests
- 2018:
  - First tests using Pb+80 and Pb+81
  - Determine best candidate
  - Inject into LHC

Strategy of the Xe+39 tests (2017)

- Why Xe+39? Availability! (used for NA61 fixed-target physics program)
- Inject the PSI Xe+39 for the first time into the CERN ion chain (up to LHC)
- Perform measurements concerning the lifetime (in SPS) Use results to estimate the lifetime and simulate optimal stripping foils of the PSIs Pb+80/+81
- Based on these results adapt the strategy for the Pb+80/+81 tests

Xe+39 lifetime measurements in the SPS

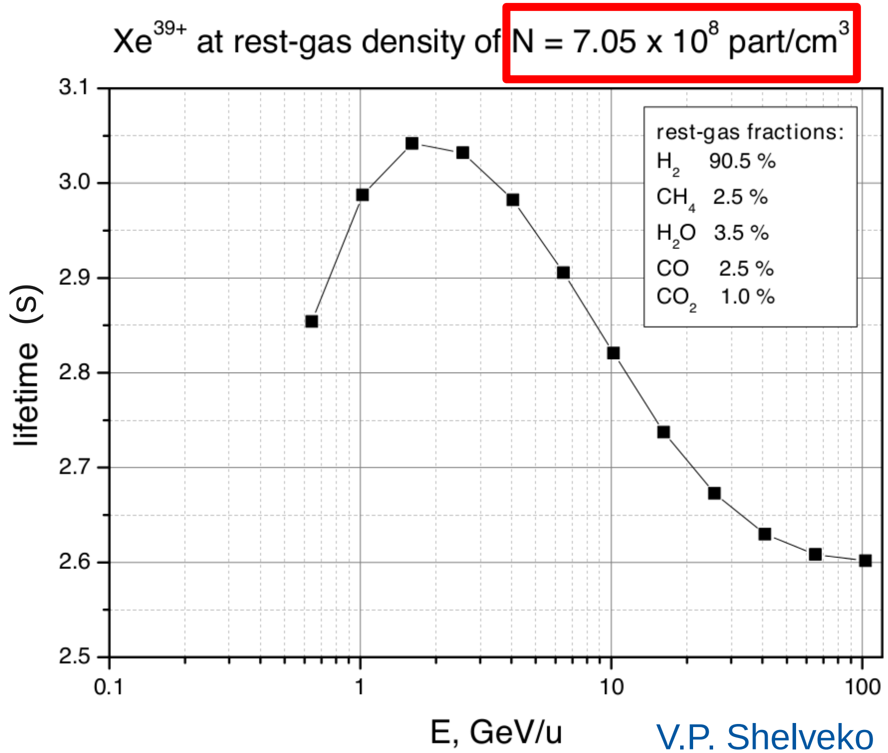
Find the relative strength of the processes for PSI beam losses



- Different conditions:
  - Four different beam energies
  - Two different beam intensities
  - Unbunched and bunched beams
- Weak energy, intensity, bunch dependence
- No evidence of the importance of intra-beam stripping for the Xe+39 runs
- Dominant source of the beam losses: collisions with the residual gas in the ring
- Anholt & Becker (PhysRevA.36.4628):
  - Weak energy dependence ->
    - Coulomb contribution
    - Weak transverse contribution
  - Characteristics given by composition of the rest gas (molecular content)

Hirlaender, S. & others
Lifetime and Beam Losses Studies of Partially Strip Ions in the SPS (129Xe39+)
(IPAC'18) **2018**, 4070-4072

Simulations – determining the gas density

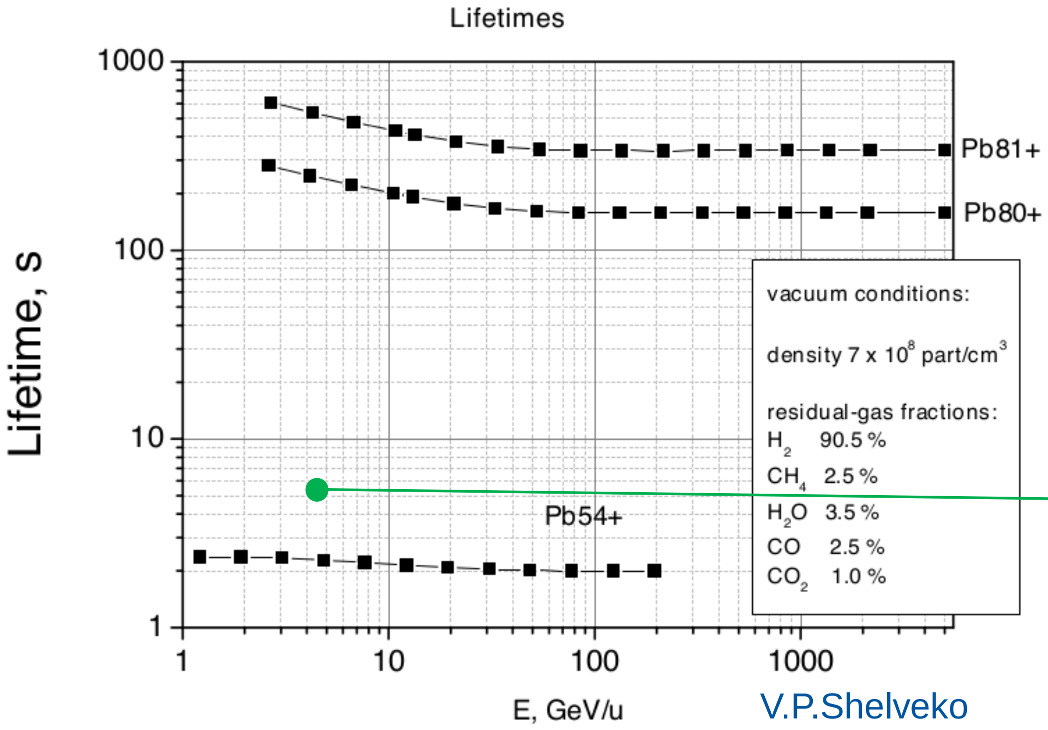


V.P. Shelveko

- Used codes: RICODE-M and CAPTURE (V.P. Shelveko)
- Composition as in 1984 (CERN SPS/83-34 (AMR)) as input
- Measured lifetime as input
- Gas density at the beam location derived

V.P. Shevelko, Yu. A. Litvinov, Th. Stöhlker, I. Yu. Tolstikhina, Lifetimes of relativistic heavy-ion beams in the High Energy Storage Ring of FAIR, NIMB: Beam Interactions with Materials and Atoms, 2018

Simulation – Pb lifetime extrapolation



V.P.Shelveko

- Based on previously derived density
- Lifetime for Pb ions extrapolated

Only known value:
Measured in 2003
Pb+53, tau = 5.3 s
at 6.6 GeV/u
(AB-Note-2003-014 OP)

Results of the Xe+39 studies:

- Lifetime estimates for Pb+80/Pb+81 based on Xe+39 measurements showed:
  - ✓ The predicted lifetime is sufficient for further studies
- Only residual gas interaction (irreducible losses)
  - Measured lifetime in SPS of Xe+39 at ~ 2.550 ± 0.085s
  - Mainly caused by Coulomb contribution

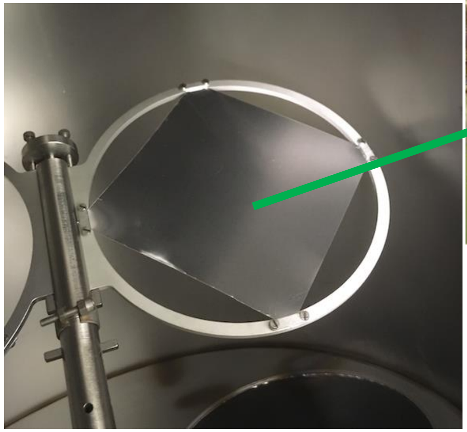
Beam tests 2018

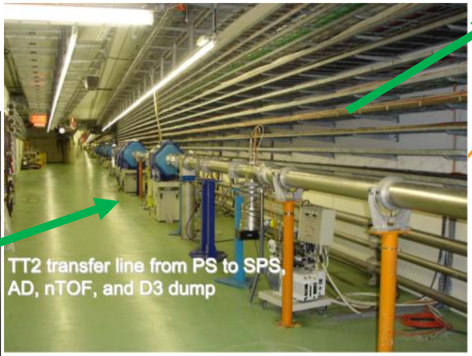
Limited time for tests - minimal interference with the experiments

- **On the 6th of June:** successful production (stripping) of the Pb+81 and Pb+80 beams and their transmission up to the SPS ring entry
- **On the 27th of June:** the Pb+81, and subsequently the Pb+80 beam were successfully injected to the SPS and accelerated to 270 GeV/c (proton equivalent) – first life time measurements/stripper foil measurements
- **On the 4th of July** the SPS team successfully prepared the cycle to inject and ramp the Pb81+ to 450 GeV/c (proton equivalent -LHC injection momentum).
  First successful setting up of the LHC-SPS synchronization

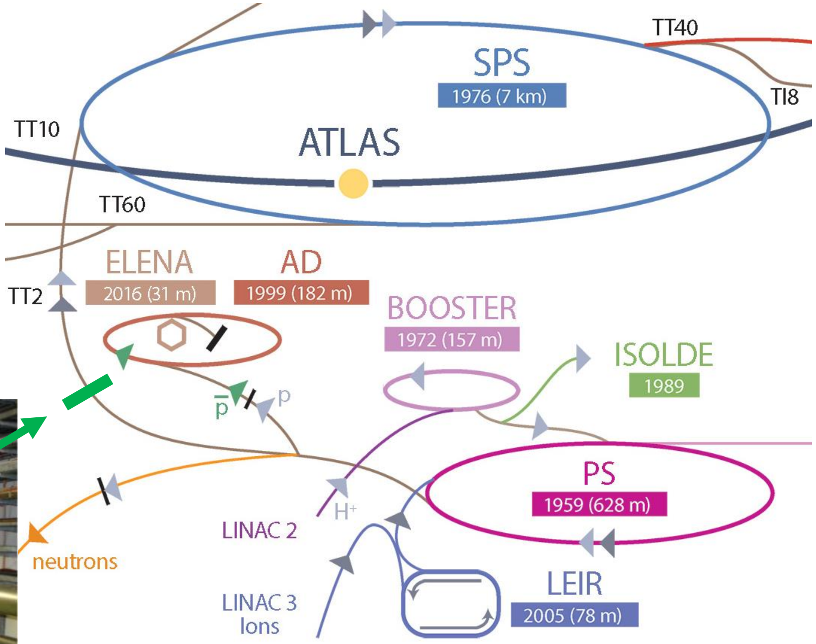
The stripper foil – set up

- In the F16.BTV.379 sector of the PS-SPS transfer line TT2
- Aluminum with a thickness of 150 um and a declination of 45 deg.
- Installed in 2018 after first test
- Optimization of optics for Pb+54 to Pb+81 charge transition
- Energy of the particles at ~5.9 GeV/u



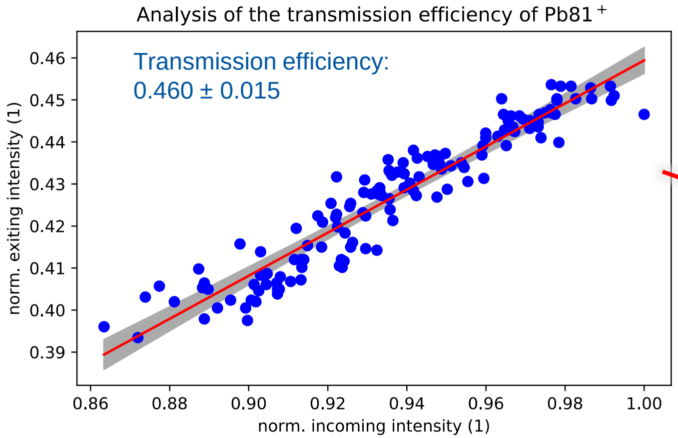


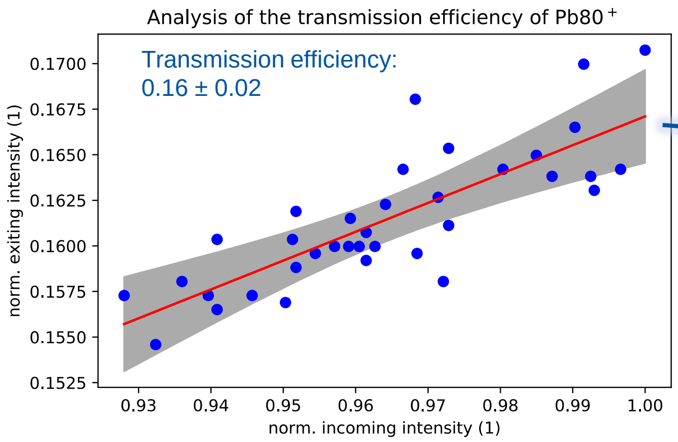
S. Burger, J.A. Ferreira Somoza



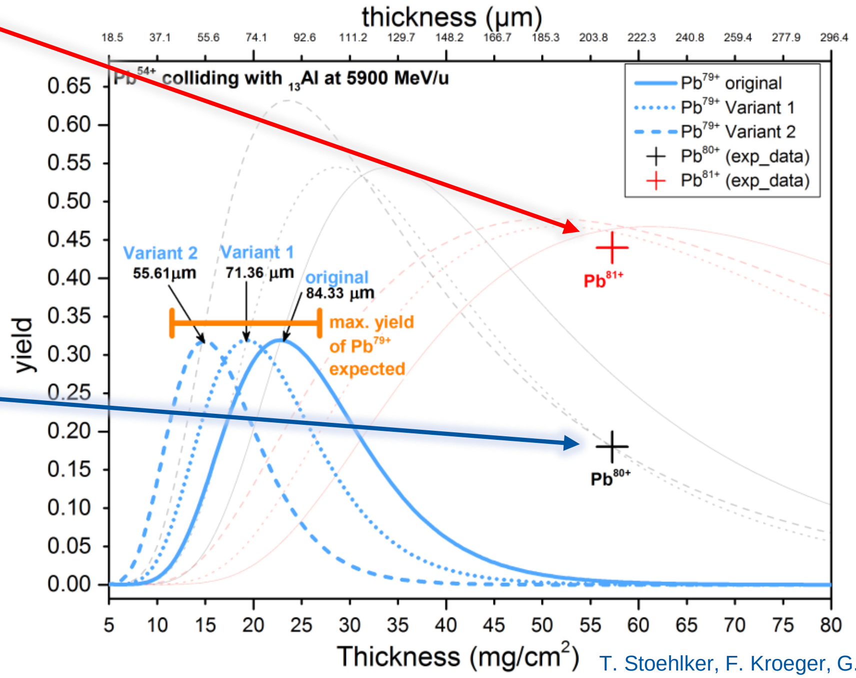
Analysis of the stripping/transmission efficiency

Preliminary results



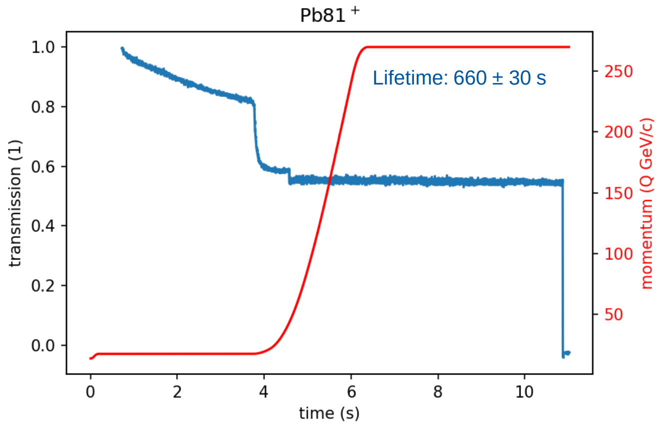


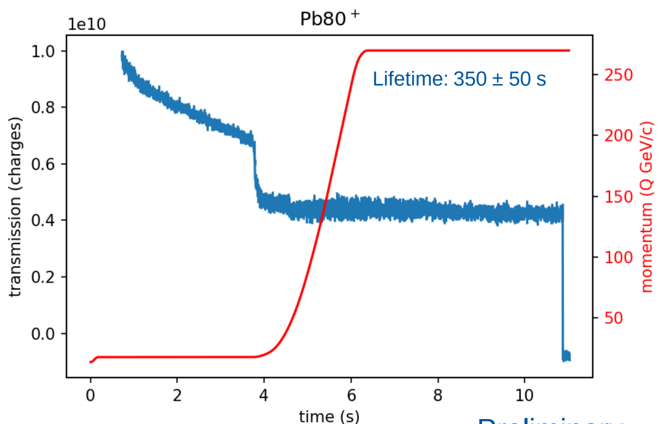
- Measured in PS and SPS ring
- Benchmark and update the simulations (BREIT) - good agreement with the predictions by F. Kroeger, G. Weber, T. Stoehlker



T. Stoehlker, F. Kroeger, G. Weber

Analysis of the Pb+80/+81 lifetime
in SPS – first milestone





Preliminary

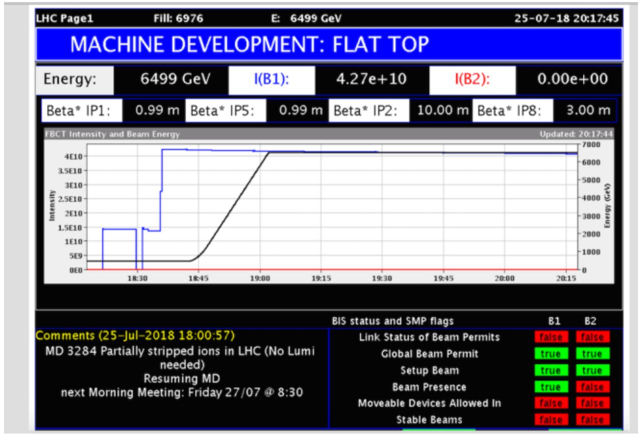
- It was possible to accelerate Pb+80/+81 to 270 GeV/c in SPS and the measured lifetime was sufficient (>time needed to fill, accelerate and inject the full set of the SPS bunch-trains to the LHC - order of 40 s)
- In agreement with the calculations of V.P. Shelveko - within the uncertainty of the molecular composition of the SPS ring residual gas
- Sufficient bunch intensity of the Pb+81 beam, of ~8 10^9 charges, (> than that required for monitoring such bunches in LHC)

First PSI Pb+81 in LHC (at top energy)

- Pilot bunches circulating with 10 hours lifetime at the injection energy (470 GeV/c proton equivalent)
- The LHC filled with Pb+81 - ramped to the maximal LHC energy at 6.5 TeV/c (proton equivalent) and observed for two hours
- The Pb+81 beam at 6.5 TeV/c (proton equivalent) lifetime was measured to be ~38 hours (preliminary)

For the first time ever the LHC rings saw both:

- The beam of atoms!
- The ~1.3 GeV electron beam was circulating in the LHC rings!



Summary and outlook

- The tests showed excellent results so far:
  - The highly charged ions Xe+39, Pb+80 and Pb+81 could be accelerated
  - The simulations were accurate and the stability was sufficient
- The Xe+39, Pb+80 and Pb+81 runs and their results were crucial to see and to quantify all the constraints which have to be taken into account for the next steps

- Outlook:
  - Current candidate for the next test Pb+79:
    - ✓ Available ion source
    - ✓ SPS vacuum quality sufficient
    - ✓ Available lasers and mirrors for required energy
  - Design proof of principle experiment
  - Install laser system in the SPS tunnel

The Gamma Factory is one step closer to be feasible