Gamma factory at CERN

Progress report

European Physical Society conference on High Energy physics
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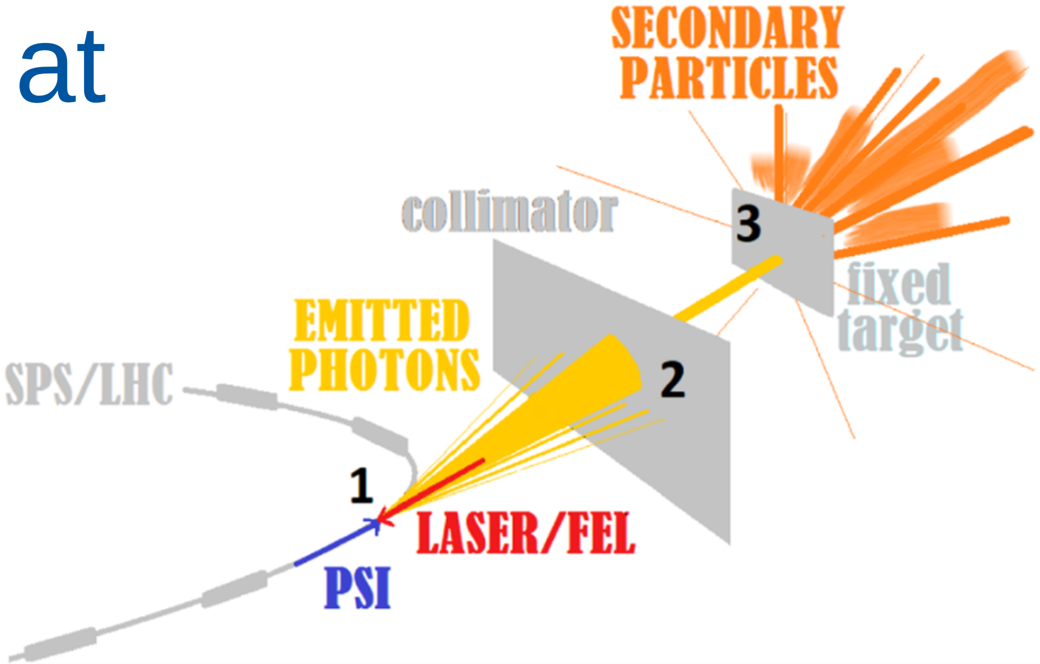
Y. Dutheil, CERN
On behalf of the Gamma Factory collaboration



Gamma Factory collaboration, today

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Content

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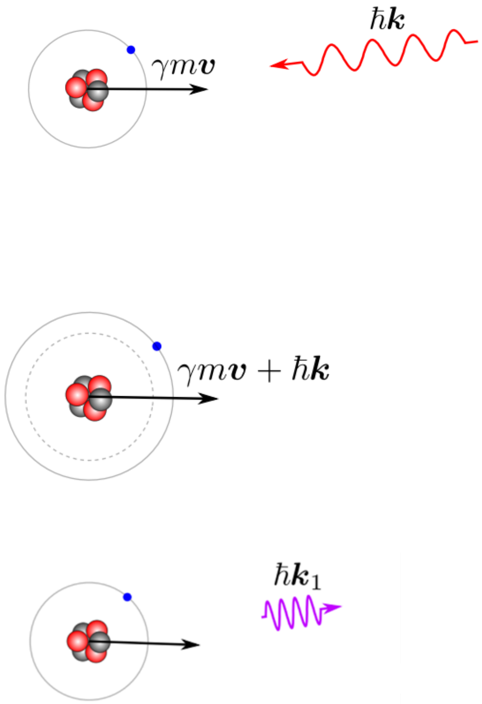
Physics principle

- Excitation of partially stripped ion at high energy
  - In the ion reference frame the photon gets a ~2γ boost
  - The change in momentum of the ion is very small
- The excited state is very short lived
  - A photon is spontaneously emitted, isotropically in the reference frame of the ion
  - The boost back to the rest frame provides another ~2γ boost to forward photons



Physics principle: Gamma photon beam

- High energy
  - The system effectively acts as photon frequency converter with maximum photon energy increased by a factor $\sim 4\gamma^2$
- High flux
  - As resonant systems, PSI (Partially Stripped Ions) have orders of magnitude larger photon-scattering cross-sections than those for bare ions or electrons, ensuring large gamma photon fluxes
- High efficiency
  - As the ion momentum is much larger than the photon's, excitation only induces a very small deviation of the ion trajectory
  - The energy transferred to the gamma photon is recovered from the RF cavity

Physics principle : Ion beam cooling

- Beam cooling
  - As the ion momentum is much larger than the photon's, excitation only induces a very small deviation of the ion trajectory
  - Example of simulated dynamics for fast longitudinal cooling

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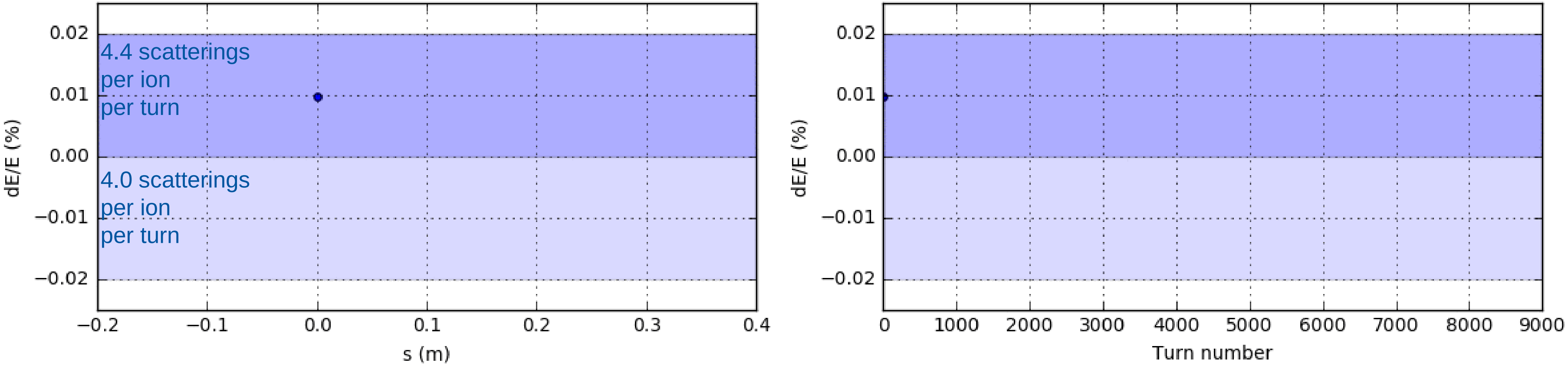


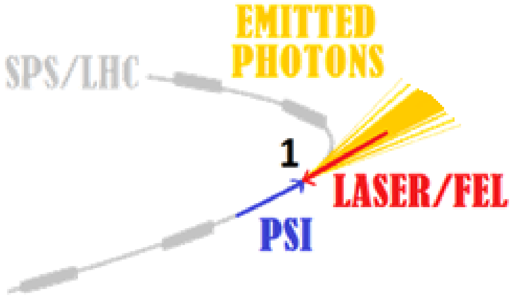
Physics opportunities

- 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 polarised 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: alpha-emitters for medical applications, …

Physics opportunities : Collider schemes

- Primary beams
  - Partially stripped ions
  - Electron beams
  - Gamma rays

- Two photon collider schemes
  - Two high energy gamma beams
  - One high energy gamma beam and one laser beam
- Gamma-hadron collisions
- Electron-ion collisions



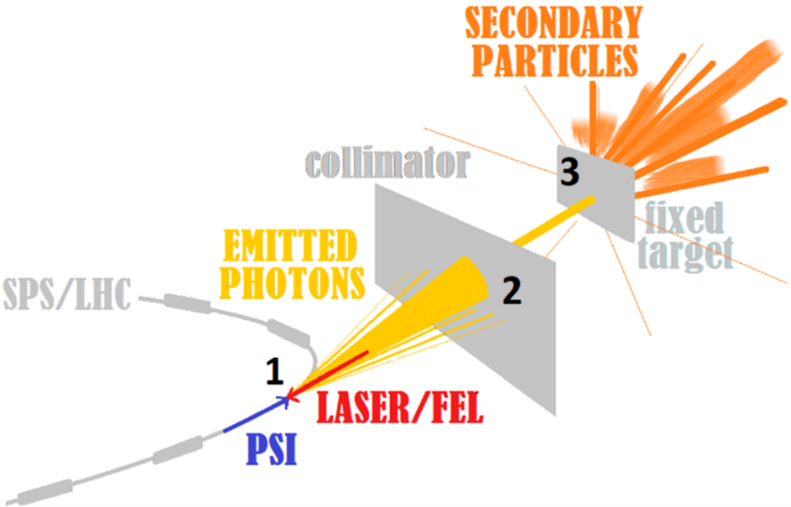
γ–γ collisions,
E_{CM} = 0.1 – 800 MeV

γ–γ_L collisions,
E_{CM} = 1 – 100 keV

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

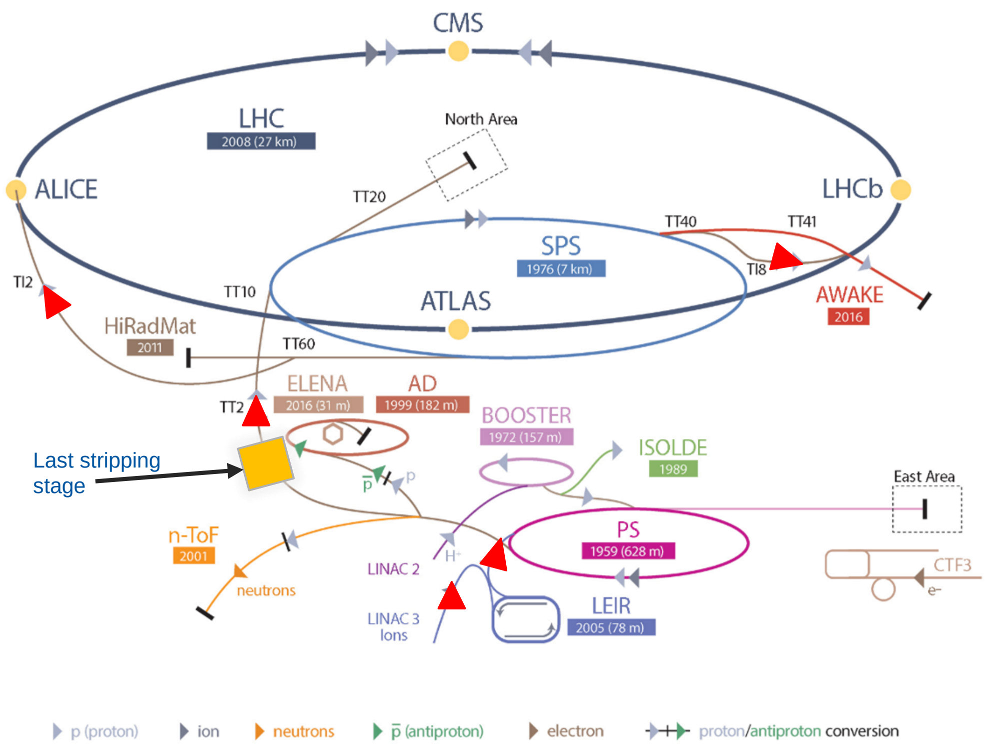
Physics opportunities : Secondary beams

- Polarised positrons
  - up to 10^{17} /s
- Polarised muons and neutrinos
  - low emittance beams for muon collider, high purity neutrino beams
  - up to 10^{12} /s and up to 4 x 10^{19} /year
- Neutrons
  - GDR in heavy nuclei: $\gamma + A \rightarrow A - 1 + n$
  - up to 10^{15} /s, mono-energetic
- Radioactive ions
  - photo-fission $\gamma + A \rightarrow A_1 + A_2 + n$
  - up to 10^{14} /s



Progress : PSI production

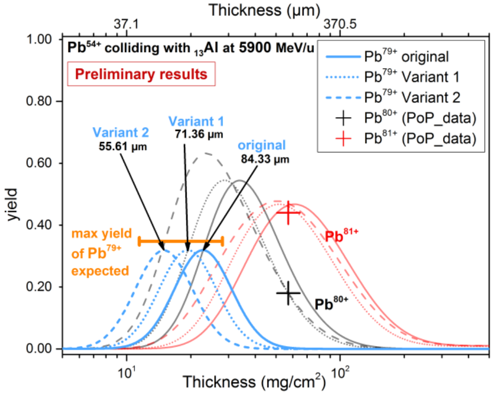
- CERN is already accelerating heavy ions to high energy
  - In particular lead, xenon, argon and soon oxygen
  - But gamma factory proposes to use other species such as calcium
- Nominal ion operation makes use of fully stripped ions
- PSI beam production requires new stripping schemes
  - Requires careful optimisation between stripping efficiency, available locations and accessible beam charge to mass ratio

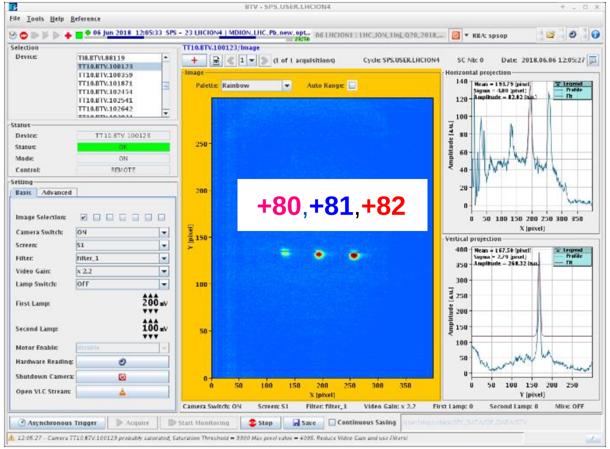


Progress : PSI production

- Detailed simulations to optimise the stripping efficiency
  - 150 μm thick aluminum foil inclined at 45° installed between the PS and the SPS
  - Excellent agreement with measured efficiency, with the single foil, at
    ~20% for Pb^{80+}
    ~50% for Pb^{81+}

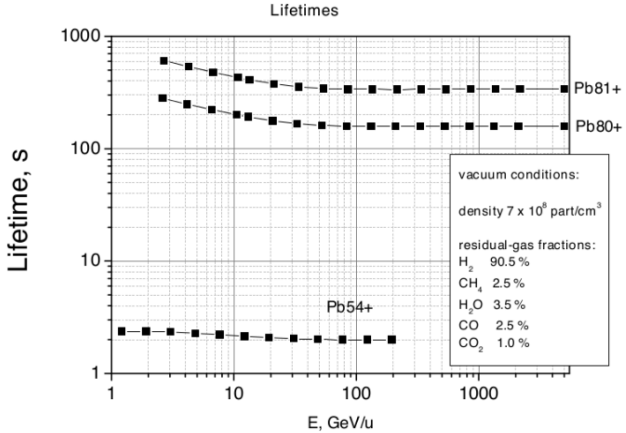
- In 2018, Pb^{80+} and Pb^{81+} were successfully accelerated in the SPS and Pb^{81+} to the maximum LHC energy



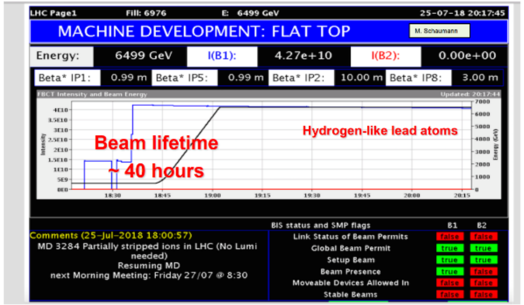


Progress : PSI lifetime measurement

- Electron stripping by the residual gas limits the lifetime of PSI beams in the SPS
  - Lifetime is function of species, energy, residual pressure and composition
- Measurement of the lifetime in the SPS
  - 660 ± 30 s for Pb^{81+}
  - 350 ± 50 s for Pb^{80+}
- Measurement of the Pb^{81+} lifetime in the LHC
  - 20.5 ± 2.5 h at injection energy
  - 54.5 ± 1.7 h at top energy
- Currently the PSI beam intensity in the LHC is limited by the efficiency of the collimation system
  - A new collimation device (TCLD), planned for installation during LS2, should allow to overcome this limit



2018 highlight: Successful production, injection, ramp and storage of the **hydrogen-like lead beam in LHC!**



➢ *Intensity/bunch (~7 x 10^9 charges), 6 bunches circulating.* 10

Challenges : primary photon source

- Several parameters need to be optimised
  - Laser beam transverse size at the interaction point
  - Laser beam pulse duration
  - Laser beam spectrum

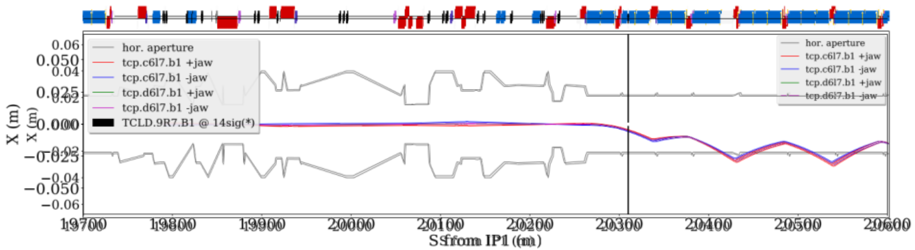
- Limited technological choices
  - Fabry-Perot resonant cavity to achieve the MHz level repetition rate associated with the typical distance between consecutive bunches
  - Single pass pulsed laser limited to kHz level repetition rate
  - Free electron laser to produce photons beyond a few eV

Challenges : Software tools

- Parallel development and benchmark of laser ion interaction on several modeling codes
  - Currently 5 independent codes are being developed
- Complex dynamics associated with large fraction of the ion beam excited at every crossing
  - In some configuration each ion is excited multiple times per crossing
- Modelling is necessary to optimise the beam and laser parameters and to predict their evolution over hours

Challenges : beam dynamics

- Ion beam stability and control
  - Reliable and reproducible ion excitation requires a high level of control of the ion beam
  - Typical relative beam momentum stability needs to be in the order of 10^{-5}
  - Optimise the fraction of excited ions per crossing
  - PSI beam lifetime in the LHC is limited by the efficiency of the collimation, although that effect should be mitigated by a new collimation device planned for installation



- Cooling and beam stability
  - Possibly fast cooling, down to a few seconds, may lead to very low emittance and instability
  - Equilibrium between cooling and heating processes is needed for continuous photon production

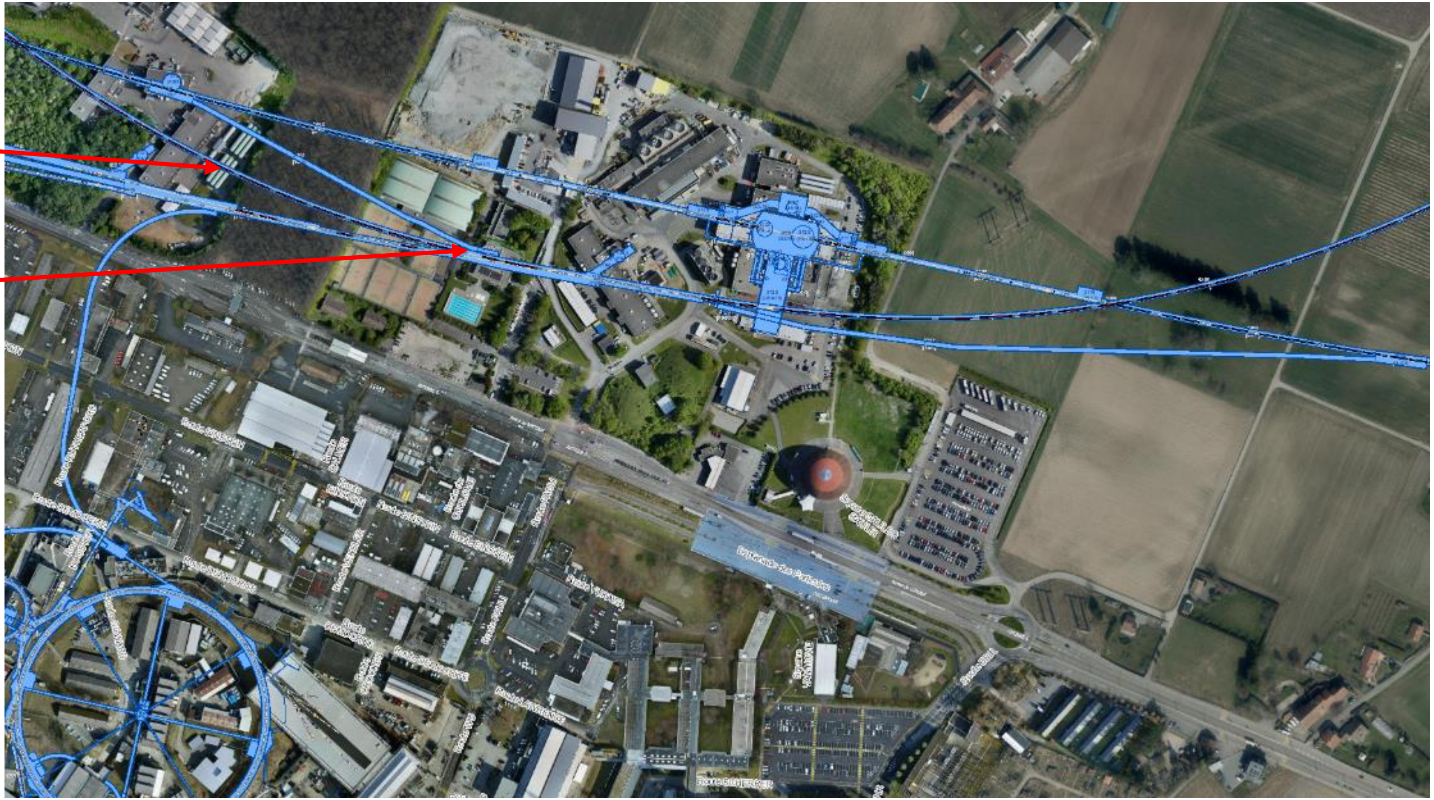
SPS Proof-of-Principle : objectives

- Main objectives
  - Development and operation of high-power laser in synchrotron ring
  - Verify simulation models for ion excitation and beam dynamics
- Demonstrate excitation
  - Achieve resonant excitation of the PSI beam and maximize produced photons flux
  - Optimise and maintain resonant condition for up to 100 s
- Demonstrate cooling
  - Through accurate control of the beam energy and position it is possible to observe longitudinal cooling in as little as a few seconds
  - Possibly measure transverse cooling by making use of the correlation between position and energy of the ion beam at the interaction point
- Accurately measure the ion transition energy by carefully calibrating the ion beam absolute energy

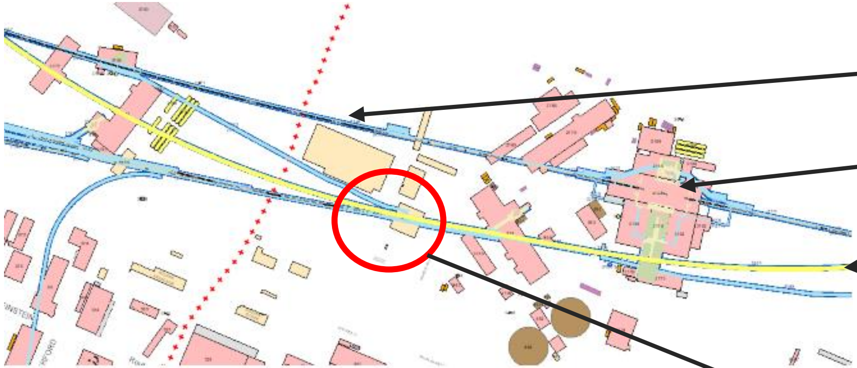
SPS Proof-of-Principle : parameters

- Species and transition choice
  - Lithium like lead, Pb^{79+} with $\gamma=96$
  - $(2s \rightarrow 2p)_{1/2}$ transition with $\Delta E=230.8$ eV
- Primary photon source
  - Fabry-Perot laser cavity 1.2 eV and 40 MHz
- Gamma photon characteristics
  - Decay length of the excited state in the laboratory frame is ~2 m
  - Maximum energy photon is 44 keV
- Concept is being finalized and a Letter of Intent is expected in 2019

SPS Proof-of-Principle : SPS LSS6



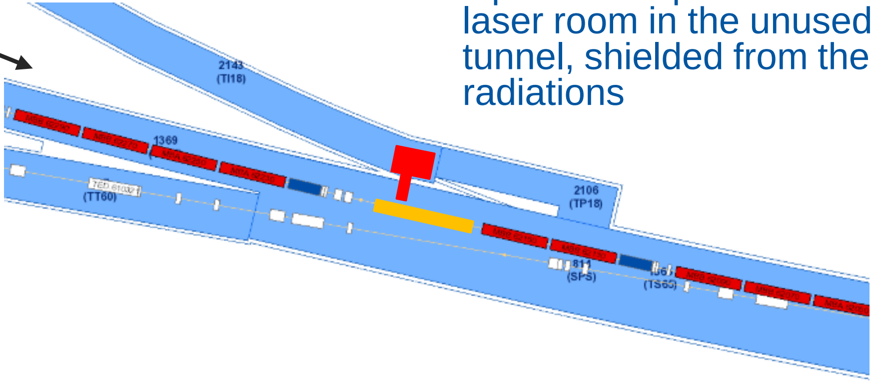
SPS Proof-of-Principle : Integration



LHC ring

ATLAS

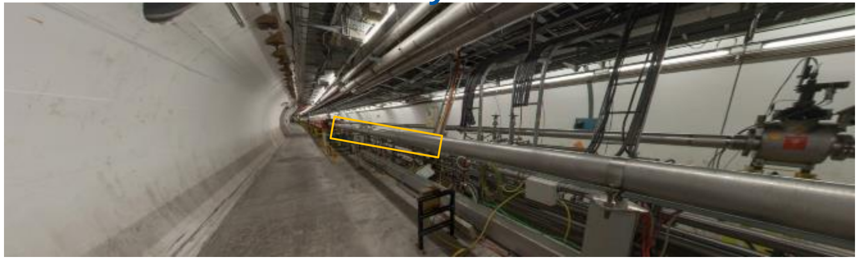
SPS ring



2 mirrors, 4 m Fabry-Perot optical cavity on the SPS ring

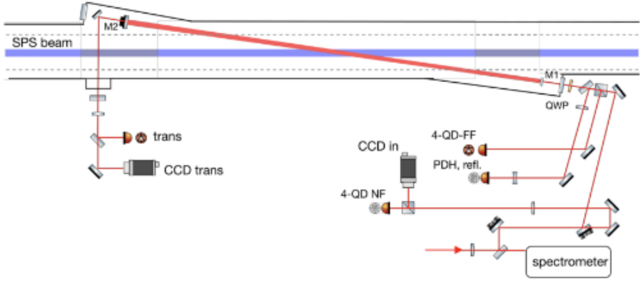
Optical transport line and laser room in the unused side tunnel, shielded from the SPS radiations

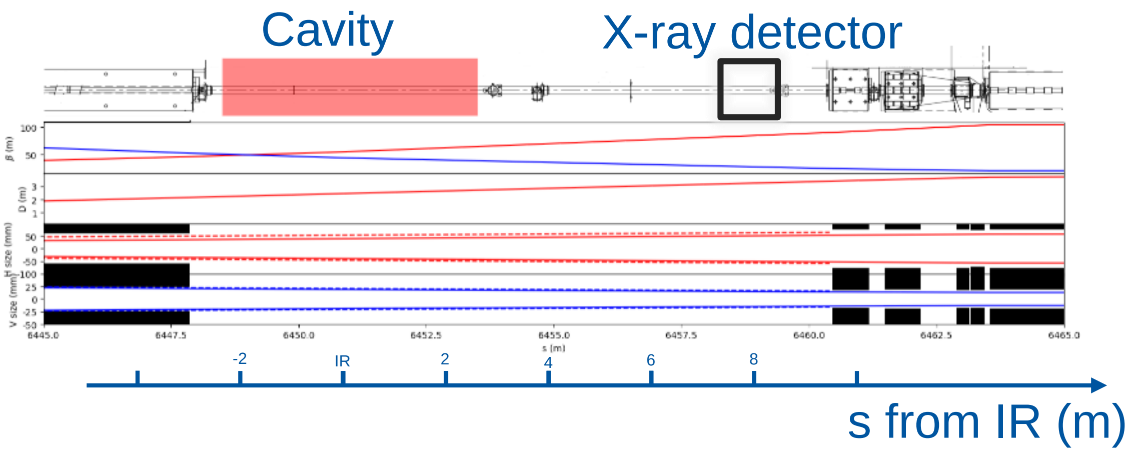
Cavity



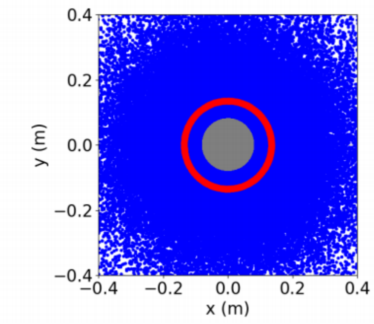
SPS Proof-of-Principle : Layout

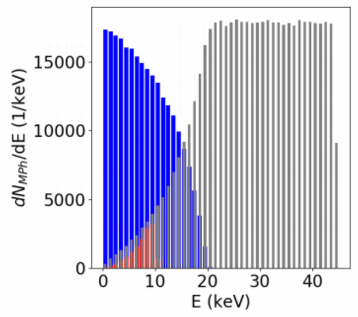
Vertical schematic cross section of the laser cavity



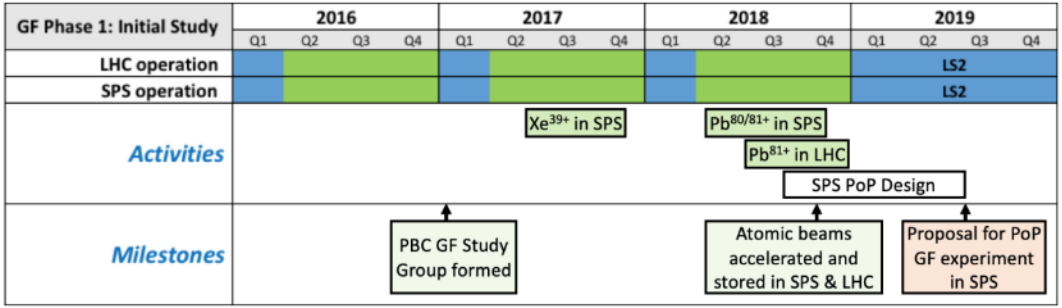


- 2 mirrors Fabry-Perot cavity with vertical crossing of 2.6˚
- Apertures and shapes ensure the cavity is transparent for nominal SPS activities
- For forward X-ray we plan to use a movable ring shaped scintillating screen

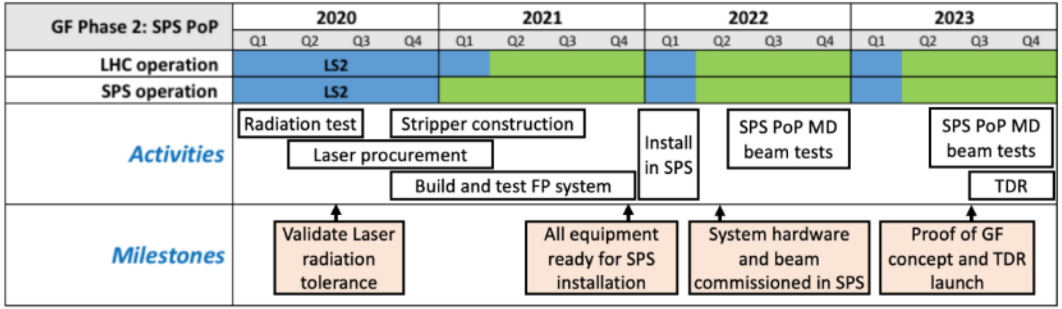




SPS Proof-of-Principle : Timeline



Acceleration and storage of PSI beams successfully demonstrated in 2017 and 2018.



LHC scenario : High energy photon production

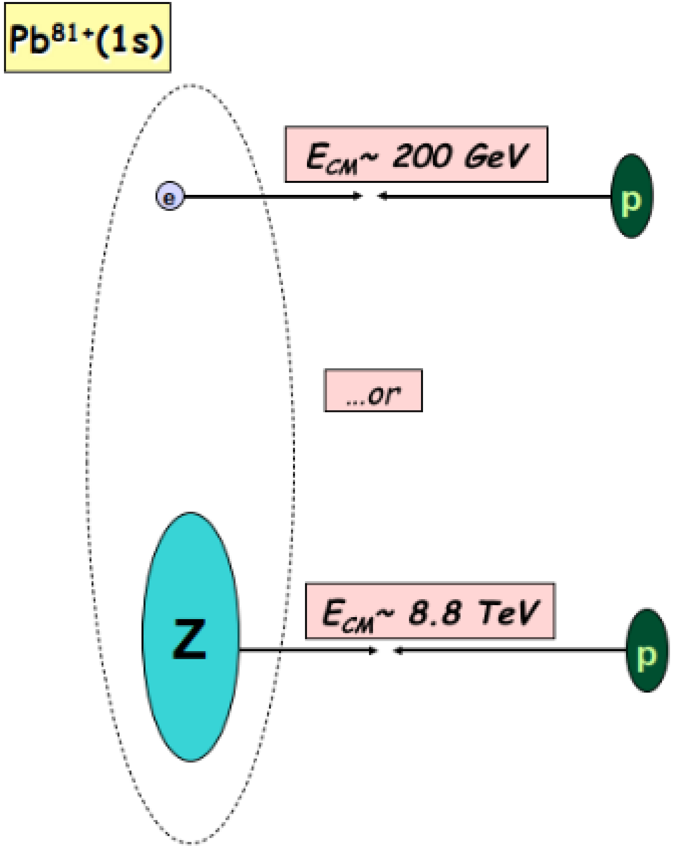
- Xe^{53+}
  - Hydrogen like Xenon
  - Lifetime of ~250 s in the SPS and ~20 h in the LHC
- Transition $(1s \rightarrow 2p)_{1/2}$ and ΔE=34 keV
  - Long decay length of ~1.5 cm
  - Laser minimum energy of 5.2 eV
  - Maximum photon energy 182 MeV
  - Gamma flux : possibly limited by double photon absorption and limited laser power
  - Laser system : possible with the same as for PoP at its 5th harmonic

LHC scenario : High flux photon production

- Ca^{18+}
  - He-Like calcium
  - Lifetime of ~30 s in the SPS and ~3 h in the LHC
- Transition $(1s \rightarrow 2p)_{3/2}$ and ΔE=3.9 keV
  - Long decay length of 6 mm
  - Laser minimum energy of 0.58 eV
  - Maximum photon energy 26 MeV
  - Gamma flux : possibly limited by double photon absorption
  - Laser system : possible with the same as for PoP

LHC scenario : other ideas

- Photon production in the MeV range using Pb^{81+} in the LHC and minimal impact on the physics program
- Calcium cooling in the SPS for high brightness calcium beams in the LHC
- Direct PSI collisions of Pb^{81+} with protons in the LHC for electron-ion collisions



Milestones

Present

1. Production, acceleration and storage of PSI beams at CERN : Done
2. Development *ex nihilo* of the requisite Gamma Factory software tools : Advanced
3. Proof-of-Principle experiment in the SPS tunnel : Concept being finalized

Future

1. Realistic assessment of the Gamma Factory performance figures
2. Physics highlights of the Gamma Factory based research program
3. Gamma Factory concept report : Writing in progress …

Conclusion

- New source of high flux and high energy photons
  - Unconventional but innovative use of CERN accelerator complex
  - Opportunities for the HEP and broader physics community
- The PoP concept is being finalized and we plan to submit a Letter of Intent
  - Possible start of the experiment in 2022
- Gamma Factory community
  - 60+ researchers from 20+ institutions, and growing
  - But it needs you !

Thank you

Thank you