Gamma Factory

Technical aspects, R&D and Proof-of-Principle

ECFA Plenary Meeting, November 2020

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CERN, TE-ABT-BTP

Outline of the talk

- Why
- Who
- Technical choices
  - Ion and transition choices
  - Modelling of laser-ion interaction
  - Laser system
- Implementation in the SPS
  - Operational constraints
  - Interaction region geometry
  - Laser room and integration
- How
  - PSI production and storage
  - PoP experimental procedure and plans
- When

Why: PoP objectives

- Demonstrate integration and operation of a laser and a Fabry-Perot cavity in a hadron storage ring
  - Laser commercially available but limited experience in hadron ring
  - Operation compatible with other ring users
- Benchmark simulations of atomic excitation rates
  - Modelling of laser-ion collisions requires new numerical tools
- Control of ion and photon bunches
  - Control of spatial, time and spectral overlap
- Demonstrate laser cooling of relativistic beams and investigate different approaches
  - Models show different cooling regimes depending on collision scheme
- Investigate feasibility of relativistic atomic physics measurements
  - Accurate and absolute measurement of deep electronic transition energies are highly relevant to fundamental physics (see next talk)

Breakthrough in accelerator physics

Breakthrough in atomic physics

Who

- 85 people from 35 institutes from 15 countries
- With experience in all the different aspects of the project

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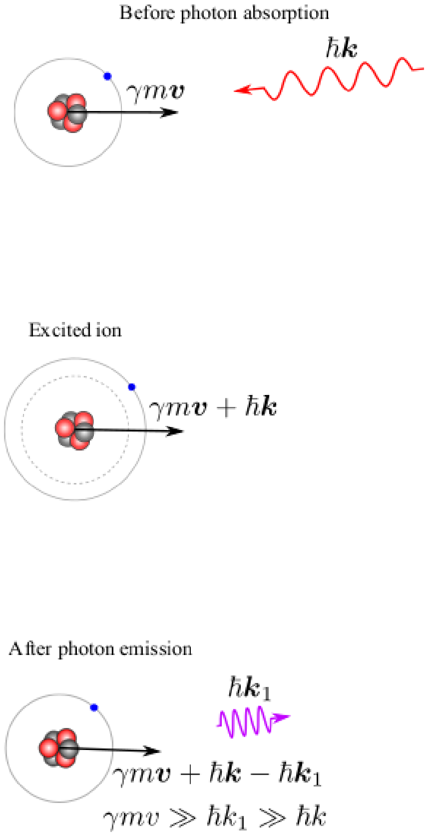
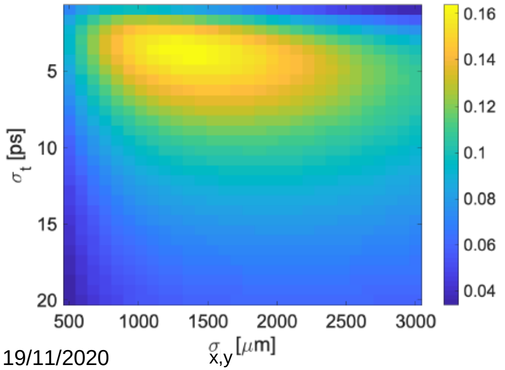
Ion and transition choices

- Constraints
  - Transition energy reachable by common laser technology
  - High production yield of the ion charge state and experience in producing the ion at CERN
  - Ion magnetic rigidity below 1500 Tm for pulsed operation or below 900 Tm for coasted operation
  - Long enough lifetime of the ion in the SPS ring
  - Short enough excited state lifetime
- Choice
  - Lead 208 ion
    - 3 electrons, so called lithium-like lead
    - Magnetic rigidity of 787.53 Tm
  - $1s^2\ 2s\ {}^2S_{1/2}$ to $1s^2\ 2p\ {}^2P_{1/2}$
    - computed transition energy of ~230.81 eV
    - mean lifetime of spontaneous emission of 76.6 ps (≡ 2.2m in lab frame)
  - Laser photon energy of 1.2 eV in the lab frame

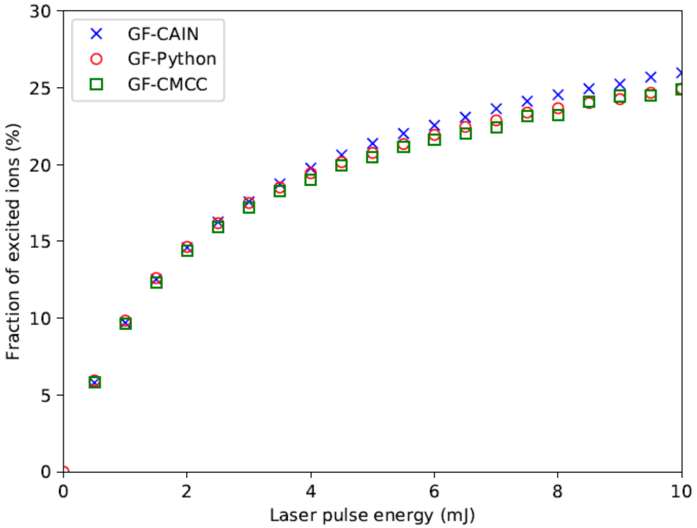


Modelling of laser-ion interaction

- Simultaneous modelling of beam dynamics and laser-ion interaction
- 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 configurations each ion is excited multiple times per crossing
- Modelling necessary
  - to optimize the beam and laser parameters
  - to predict their evolution over long durations



The maximum fraction of the excited ions (color coded) versus the RMS pulse duration and the RMS transverse laser beam size.



The fraction of excited ions per bunch crossing as a function of the laser pulse energy. Predictions of the GF-CAIN, GF-CMCC and GF-Python simulation codes

Laser system

- Constraint
  - Interact with consecutive bunch in the SPS, separated by a minimum of 75 ns
  - Pulse energy ~5 mJ and duration ~5 ps to maximise the fraction of excited ions
  - Make use of existing and proven laser technologies
- Choice
  - 2 mirrors Fabry-Perot cavity at 40 MHz capable of reaching 5 mJ pulse, equivalent to 200 kW
  - Laser oscillator and amplifier commercially available

Built and operated by IJCLab (Orsay) team in low emittance KEK ATF ring

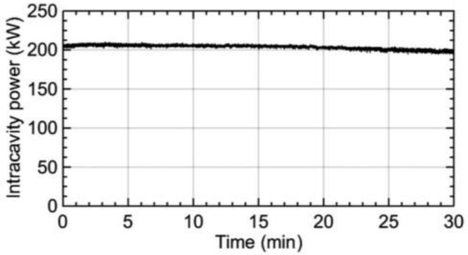
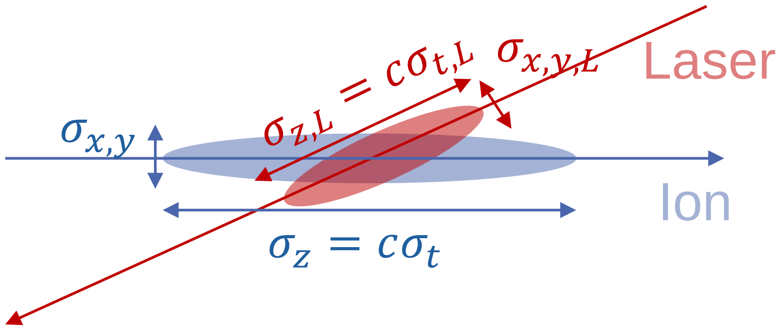


Fig. 7. Laser intracavity power for 30 min, measured by transmission of a cavity mirror.

Recent R&D achievement for the ThomX Compton source

PoP experimental parameters

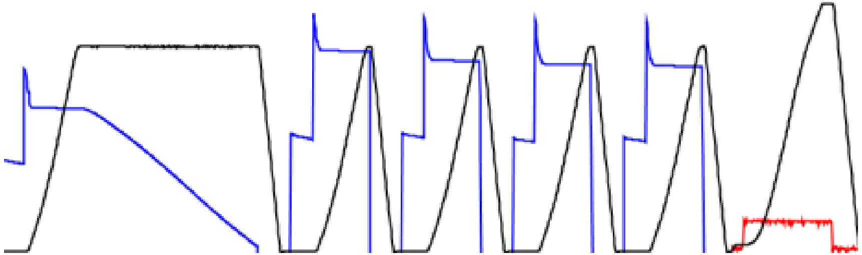
- Combining the different studies on ion production, laser system and laser-ion interaction to establish the set of experimental parameters for the PoP
- Vertical crossing scheme



PSI beam	$^{208}Pb^{79+}$
m – ion mass	193.687 GeV/c^2
E – mean energy	18.652 TeV
$\gamma = E/mc^2$– mean Lorentz relativistic factor	96.3
N – number ions per bunch	0.9×10^8
σ_E/E – RMS relative energy spread	2×10^{-4}
ϵ_n – normalised transverse emittance	1.5 mm mrad
σ_x – RMS transverse size	1.047 mm
σ_y – RMS transverse size	0.83 mm
σ_z – RMS bunch length	6.3 cm
Laser	Infrared
λ – wavelength ($\hbar\omega$ – photon energy)	1034 nm (1.2 eV)
σ_λ/λ – RMS relative band spread	2×10^{-4}
U – single pulse energy at IP	5 mJ
σ_L – RMS transverse intensity distribution at IP ($\sigma_L = w_L/2$)	0.65 mm
σ_t – RMS pulse duration	2.8 ps
θ_L – collision angle	2.6 deg
Atomic transition of $^{208}Pb^{79+}$	$2s \rightarrow 2p_{1/2}$
$\hbar\omega'_0$ – resonance energy	230.81 eV
τ' – mean lifetime of spontaneous emission	76.6 ps
$\hbar\omega_1^{max}$ – maximum emitted photon energy	44.473 keV

SPS implementation constraints

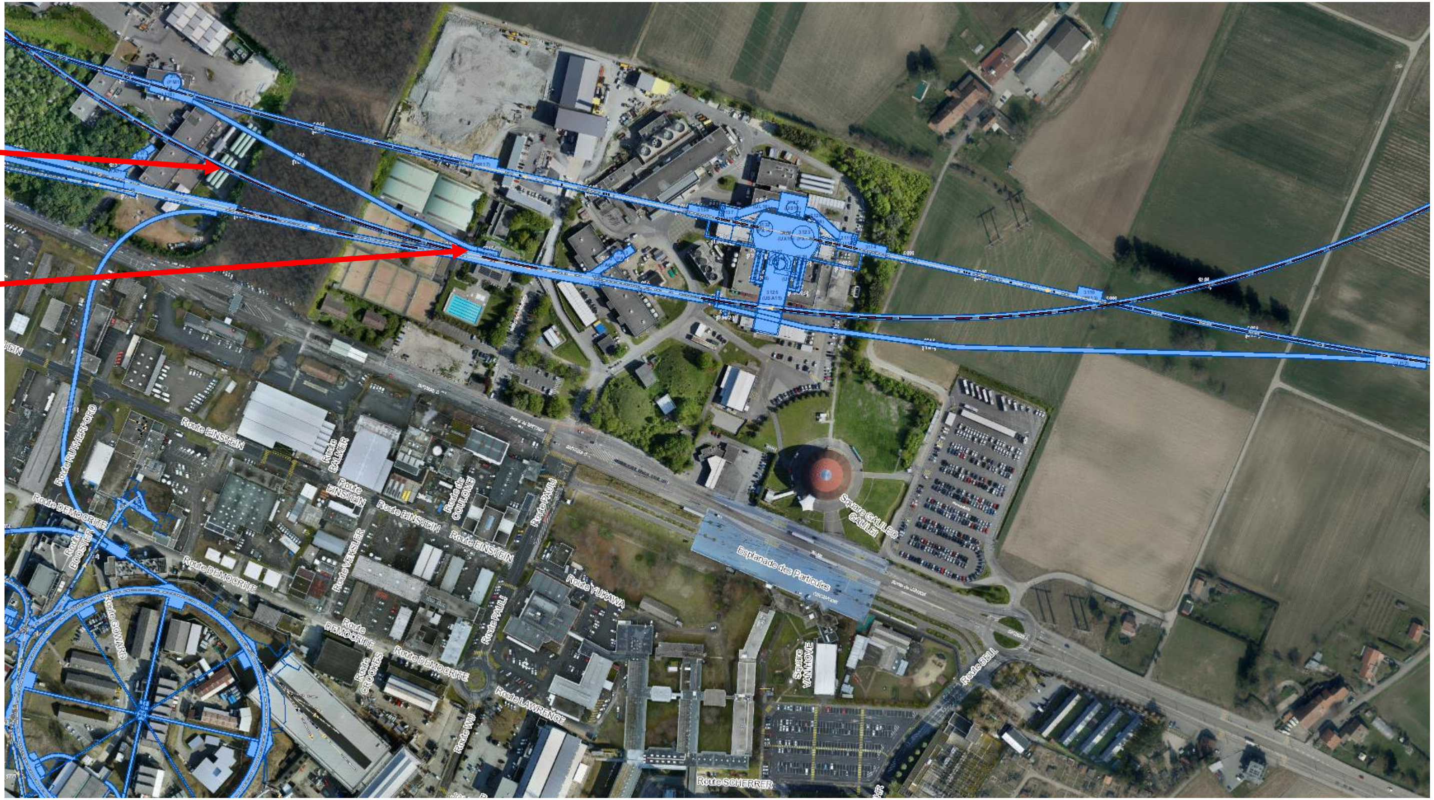
- Location
  - Laser cavity placed in an available straight section
  - The laser room installed close-by and shielded from radiation
- Operation
  - Capable of remote operation
  - Compatible with cycling operation of the SPS and the parallel beam delivery to multiple experiments



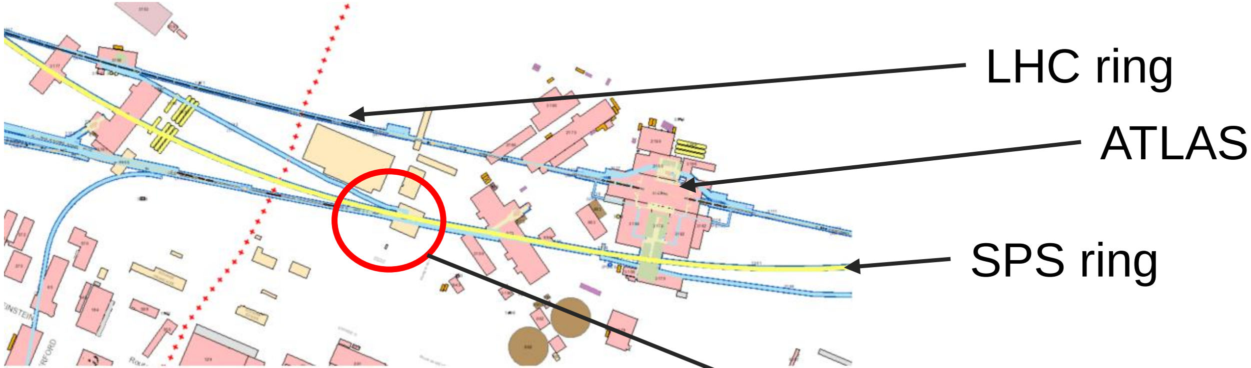
Interaction region location

SPS

PoP location

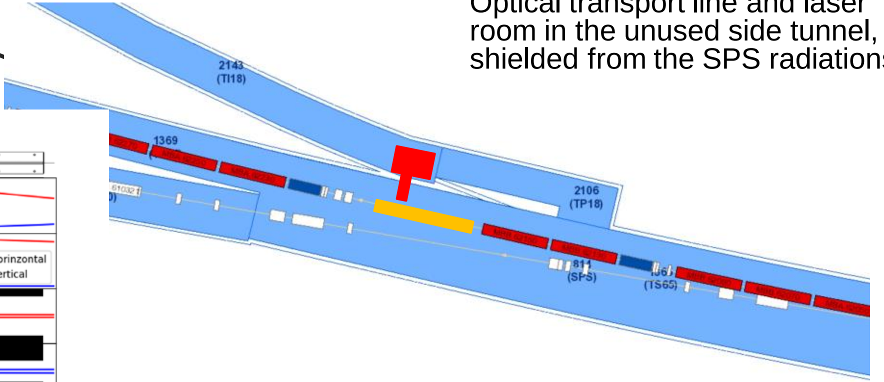


Interaction region location



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

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



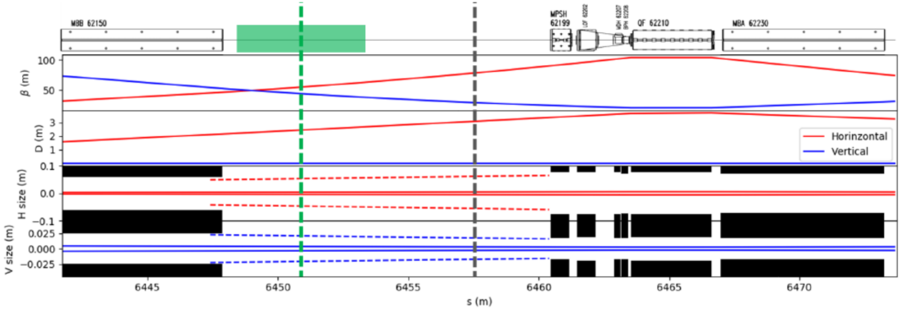
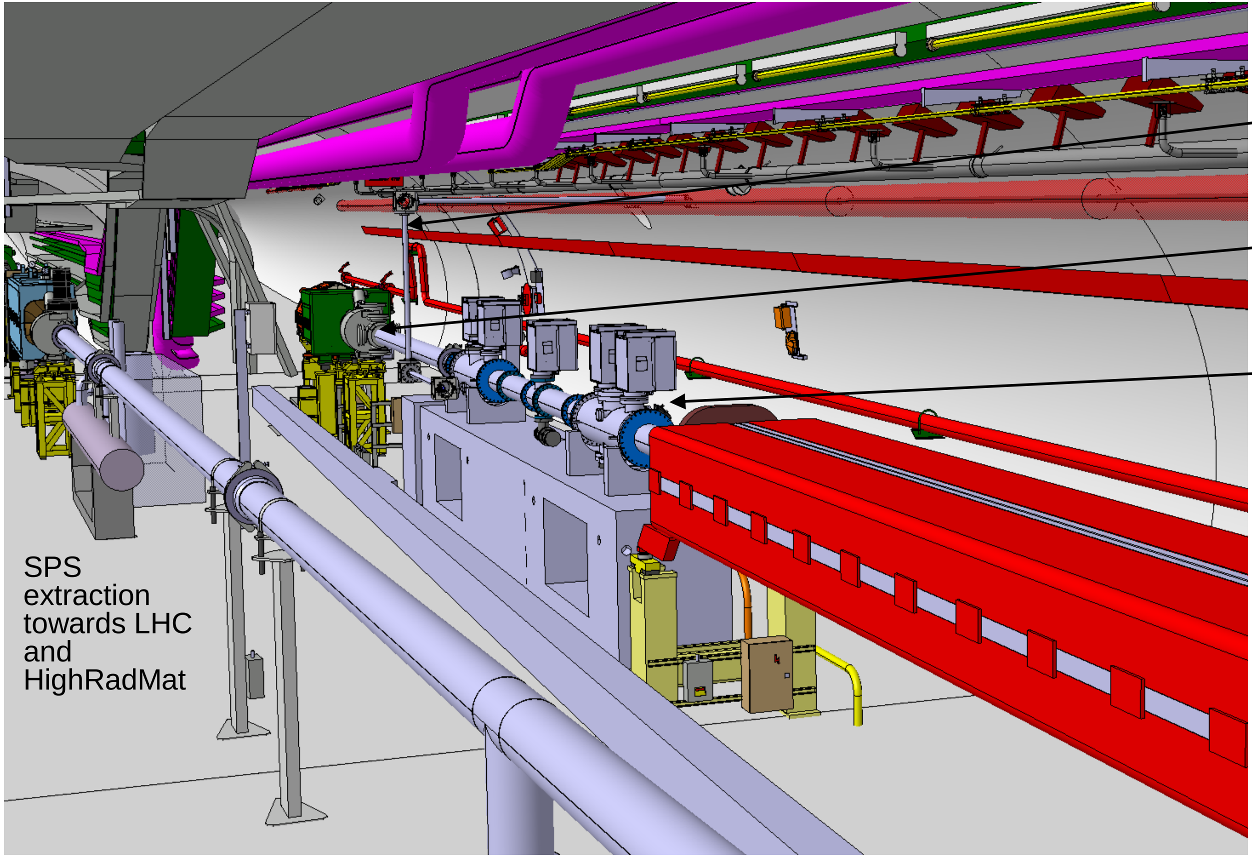


Fig. 7: Layout, optical functions and beam sizes with aperture limits around the interaction region. The IP is represented by a vertical green dotted line and the laser cavity by the green box. The vertical grey dotted line represents the location of the X-Ray detector. Note that the beam goes from left to right.

Integration studies



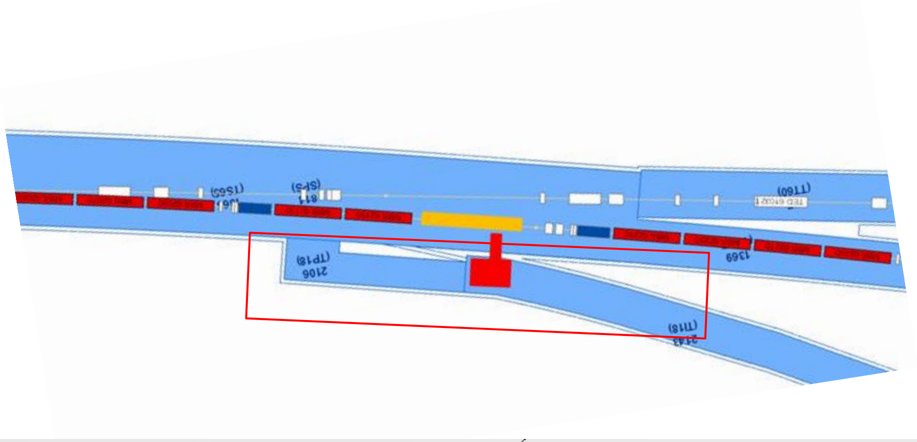
Laser transport line

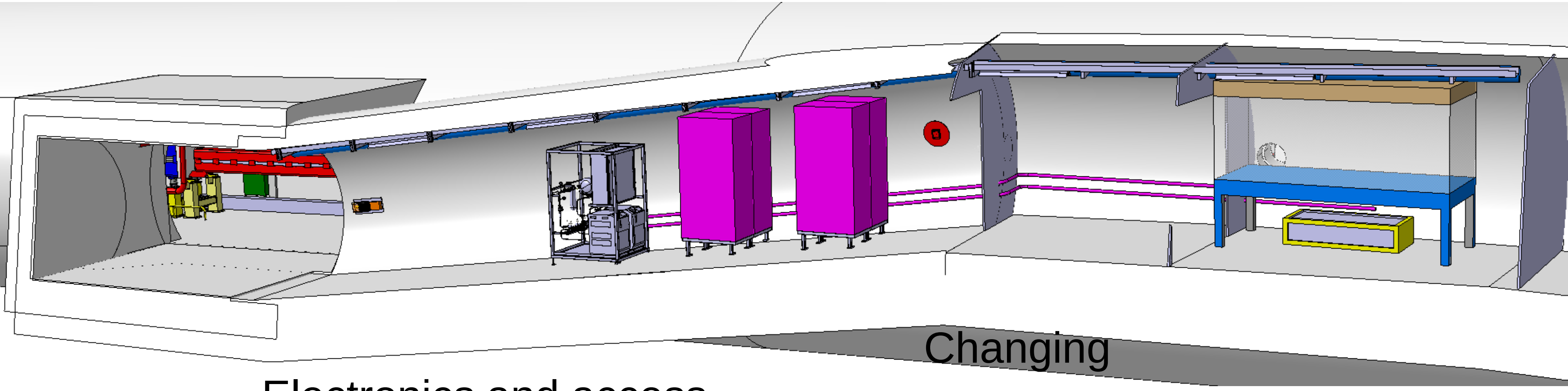
X-rays detector

Laser cavity

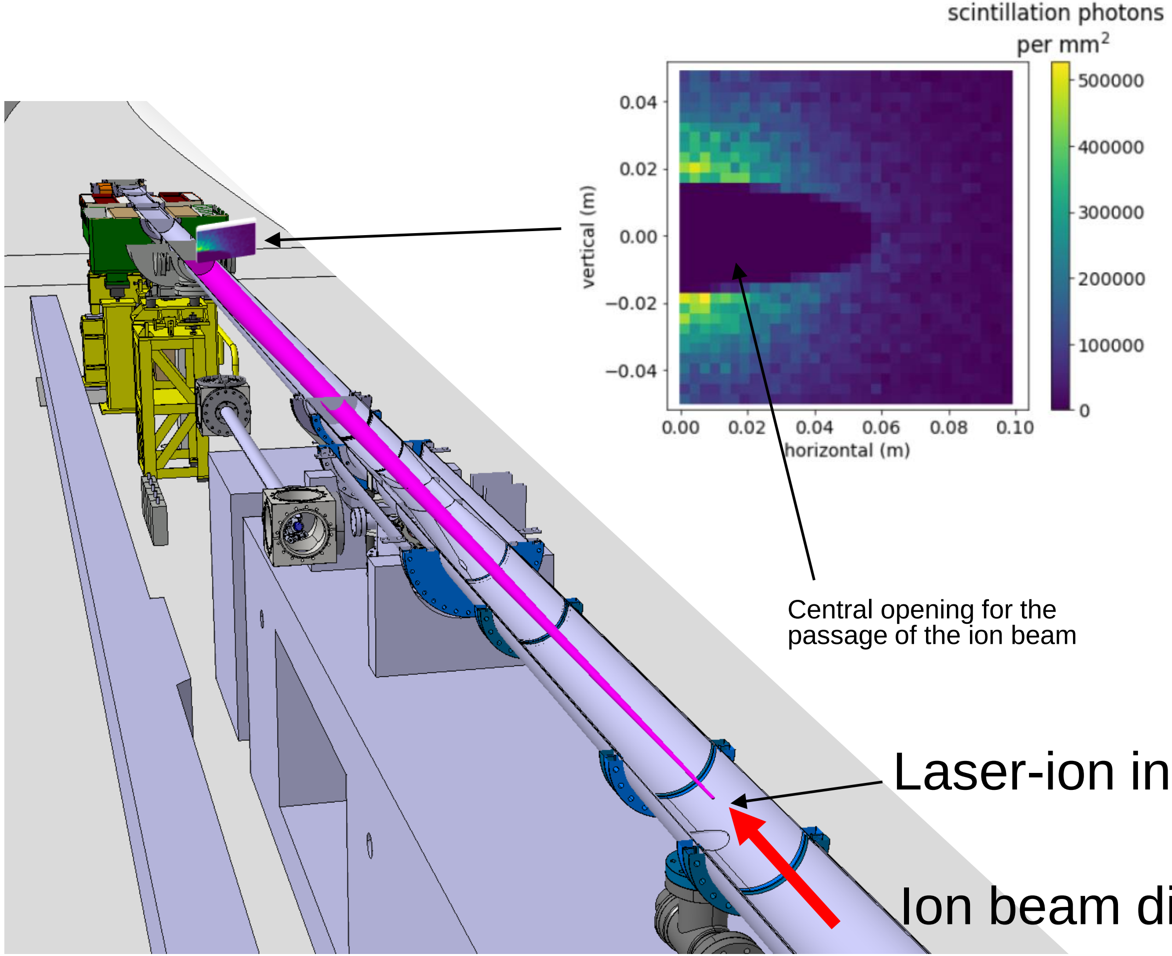
Upstream dipole

Laser room integration





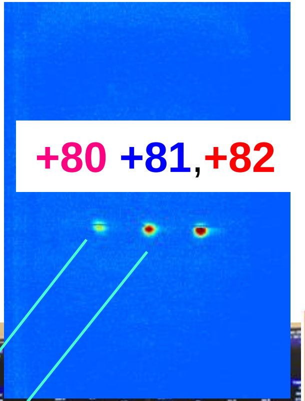
X-rays detection system

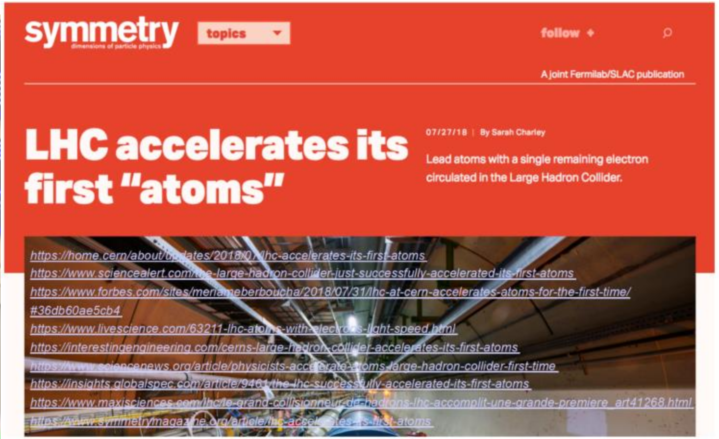


- Constraints
  - Detect the X-ray photons produced at the IP
  - Simple and reliable, making use of existing
- Choice
  - Movable YAG:Ce scintillating screen with camera 7m downstream the IP
  - Central hole for the passage of the ion bunch
  - System using existing SPS beam screen design

Production of PSI

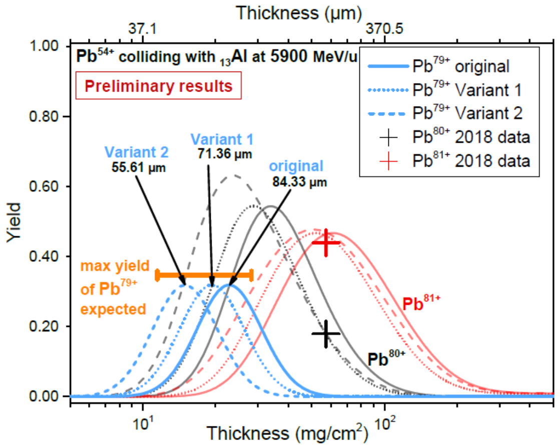
- Demonstrated in 2018 with partially stripped lead
  - Using existing hardware
  - Injected into the LHC





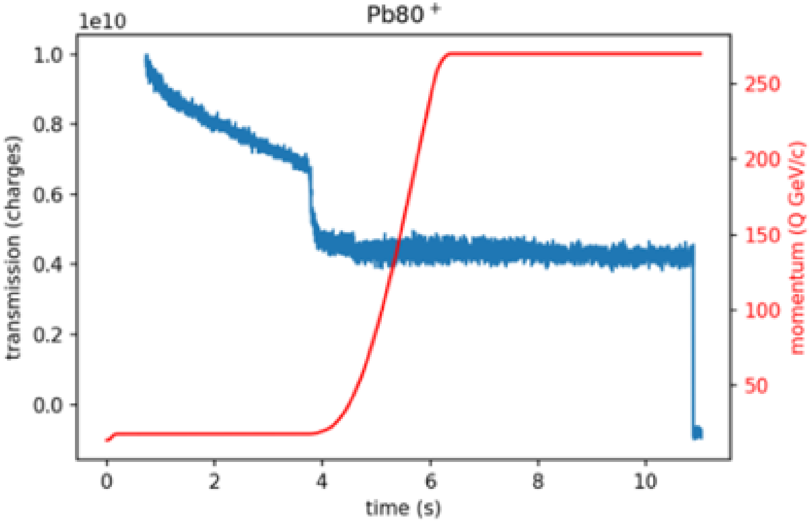
Production of PSI

- Stripping efficiency
  - Complex modelling
  - results obtained in 2018 used to benchmark models
- New stripper
  - To allow cycle-by-cycle foil switching
  - 4 foils with controllable tilt to adjust the effective thickness
  - Ongoing design for installation during Run3
  - Will allow parasitic operation of the PoP in parallel with the SPS other physics programs in consecutive cycles



Storage of PSI

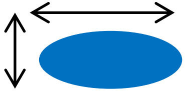
- PSI lifetime is limited by vacuum conditions
  - Electrons get easily stripped from the ion by the rest gas
  - Beam lifetime is linked to vacuum levels but hard to simulate
- 2018 measurements
  - Measured in the SPS with Pb^{80+}
  - Extrapolated to ~100s for Pb^{79+}
- Production and storage of the selected ion in the SPS with sufficient time is ensured



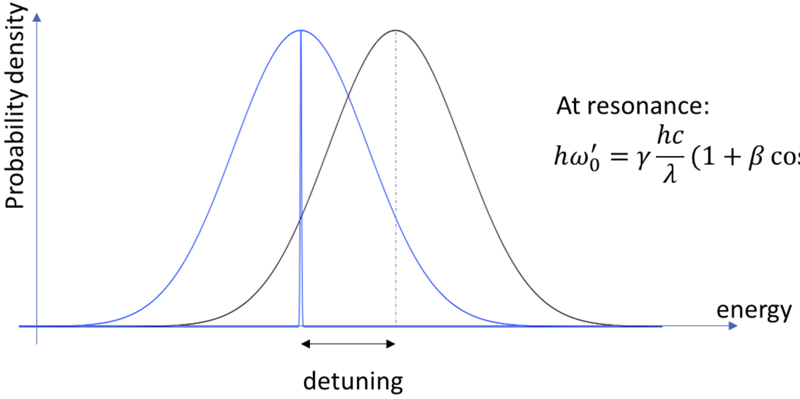
Experimental procedure : phase 1 – resonance finding

- Spatial transverse overlap
  - Ensured by 2 BPMS on either side of the cavity
- Temporal overlap
  - Measured by the cavity BPMs and laser diodes
  - Controlled on the beam side by the ion bunch phasing
- Spectral overlap
  - Ion beam energy spread ~ bandwidth of laser spectrum (in ref. frame of atoms)
  - Controlled by the ion energy and SPS dipole field
- Systematic and computer-controlled scanning tools of the 3 spaces
- The detection of X-rays proves the resonant excitation
- Estimated beam time required
  - 24h parallel
  - 8h dedicated

Ion bunch is 1.2 x 0.8 mm

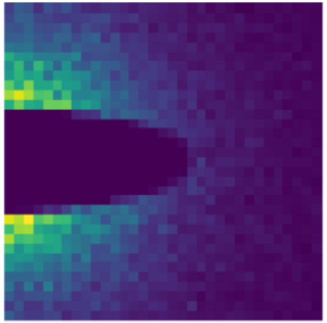


Laser beam size is 0.65 mm



At resonance:

$$h\omega_0' = \gamma \frac{hc}{\lambda}(1 + \beta \cos(\vartheta))$$

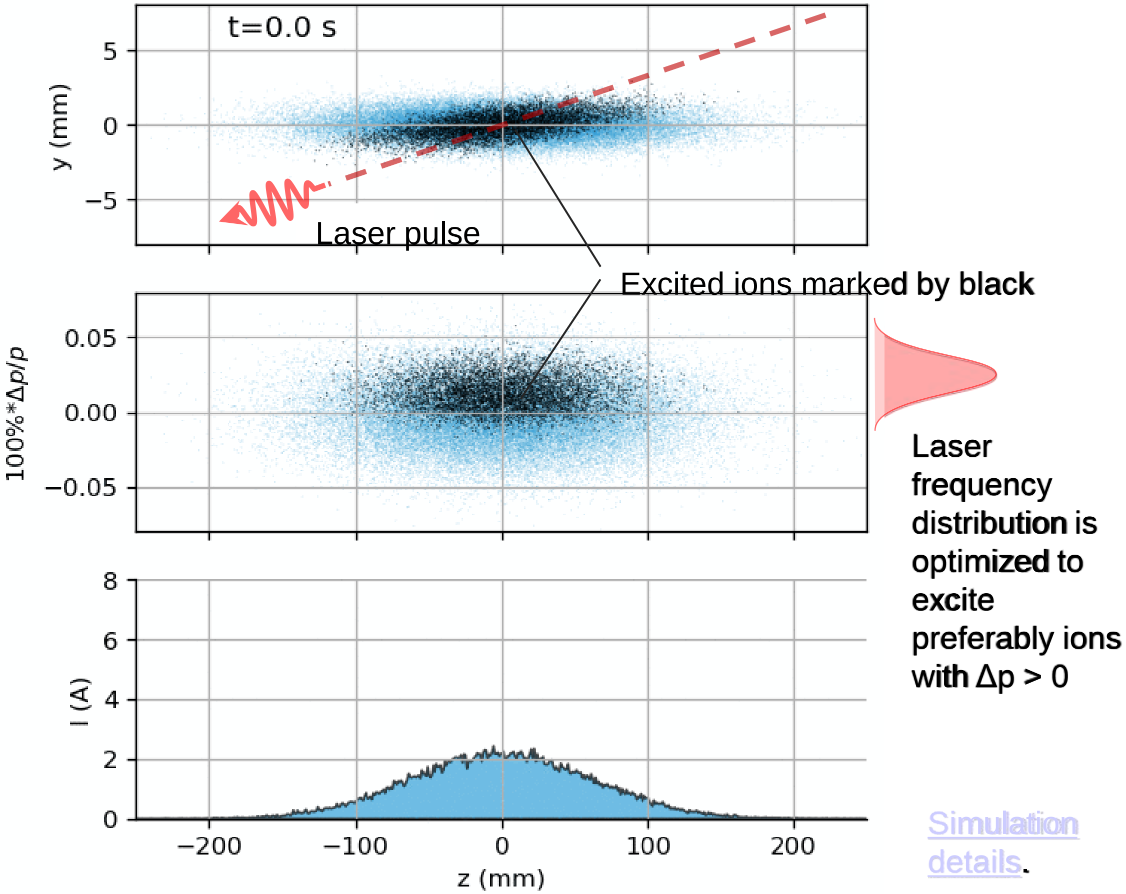


Experimental procedure : phase 2 – Optimisation and Characterisation

- Characterisation of the excitation
  - Characterisation of the dependencies of the X-ray signal with available parameters
  - Reproducibility and stability with different machine conditions
  - Control of the excitation in the different dimensions using the tools developed
- Optimisation of the excitation regime
  - Maximisation of the X-ray flux
  - Continuous and controlled excitation over long time scales ~100s
- Estimated beam time required
  - 8h parallel
  - 8h dedicated

Experimental procedure : phase 3 – Cooling demonstration

- Requires the control of the resonant conditions over long durations ~10s
  - Fast cooling is achieved when the laser only excites ions with higher energy than the reference particle
- Observed with fast increase in peak current
- Further scheme of fast transverse cooling is under investigation
- Estimated beam time required
  - 8h parallel
  - 16h dedicated



Simulation details.

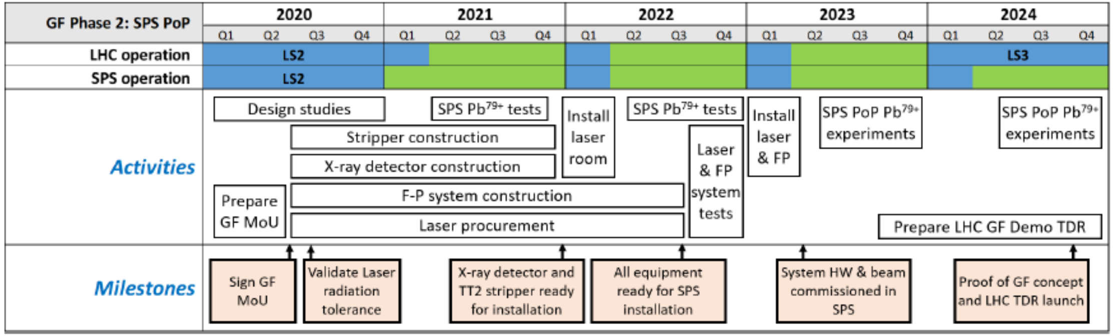
Experimental procedure : phase 4 – Atomic physics demonstration

- Most challenging phase
- Relies on accurate and independent calibration of the ion beam energy
- Absolute measurement of the transition energy
  - First measurement of the “Lamb-like-shift" in high-Z Lithium-like atoms by their direct excitation
  - A precision below the 10^{-4} level would allow us to study the relativistic, vacuum polarisation, electron–electron interaction and weak interaction effects with unprecedented precision
- Further atomic physics measurements considered for a second phase
  - Transition energy with different isotopes
  - Excited state lifetime
- Estimated beam time required
  - 8h parallel
  - 16h dedicated

When

- Schedule and cost estimates established in 2019 for the Letter of Intent submitted to the SPSC

	Item	Cost [kCHF]
1	**Stripping foil** unit (design, assembly, tests, installation – in synergy with a foreseen stripper upgrade)	125
2	**FPC** (optics, support, interface, vacuum system)	180
3	**Laser system** (oscillator, amplifier, electronics, controls, assembly, lab tests, shipping, installation)	800
4	**Laser clean room and UHV transport line** (in SPS tunnel)	600
5	**Photon detection system** (design, detector, controls, vacuum chamber, assembly, tests, installation)	100
6	**Beam position monitor** (detector, cabling, electronics)	50
7	**Infrastructure and services** (cabling, supports, shielding)	80
8	**Manpower** (Doctoral Student/PDRA subsistence)	350
9	**Collaboration support** (travel, subsistence)	80
	Total	2365



When

- LoI submitted to the SPSC (SPSC-I-253) in 2019 and recently reviewed
  - “The SPSC recognizes the Gamma Factory's potential to create a novel research tool, which may open the prospects for new research opportunities in a broad domain of basic and applied science at the LHC.”
  - “The SPSC recognizes the GF-POP experiment as a path finder in the GF R&D process. The SPSC encourages GF to better specify the scope and impact of the proof-of-principle experiment, and it looks forward to further details of how the GF proto-collaboration intends to deliver this programme.”

Future

- Beam dynamics studies
  - More complex cooling scheme, such as fast transverse cooling are being investigated
  - Long term beam dynamics and cooling-heating equilibrium
- Technical studies
  - Extraction and exploitation of the X-ray produced at the interaction point
  - Comprehensive modelling of the radiation environment and quantified effect on the laser systems electronic
- Same process will apply to an LHC implementation

Conclusion

- Status
  - LoI of the Proof-of-Principle submitted in September 2019 to the SPSC
    - Cemented the proposal and its review by the SPSC did not highlight any technical or operational concern
    - Formalizing the collaboration around the deliverables of the PoP
    - Continuing to seek approval from the scientific comitee
    - Review of the current schedule for an SPS implementation after LS3
  - Ongoing integration and planning studies of the laser system and laser room in the SPS
- The Proof-of-Principle covers a wide range of physics topics
  - Unique opportunity to bring together the wider physics community
  - But needs building its own community
- Existing support
  - Strong support by the CERN Physics Beyond Colliders initiative
  - Further support by other laboratories and funding agencies requires a stronger endorsement from local instances

Thank You