CERN

Gamma Factory for CERN

Concept and progress report

kevin Cassou, on behalf of the GammaFactory collaboration

GammaFactory collaboration today's

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special thanks based on Y. Dutheil, C. Curatolo, W. Krasny and M. Lamont materials

$\gamma-$ray sources around the world

Doppler upshifting of intense laser sources; *"monochromatic"* source; intense electron beam needed.

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:** get XFEL flux in the MeV range ! (DESY XFEL : $10^{11} - 10^{13}$ ph/pulse, $10 - 5000$ pulses/s $\rightarrow 10^{12} - 10^{17}$ **ph/s**

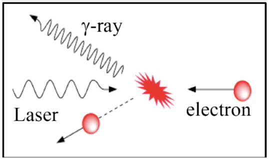
… **An intensity jump of $3 - 8$ orders of magnitude is required !!!**

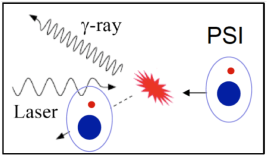
courtesy of W. Krasny

Principle

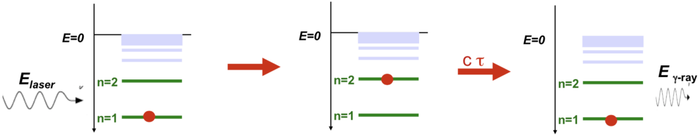
the basic idea... in the LHC context

- Replace an electron beam by a beam of highly ionised atoms (Partially Stripped Ions - PSI)





- PSI means here H-like, He-like or Li-Like ions.



PSI as a frequency converter

$$\omega^{\mathbf{max}} = (\mathbf{4}\gamma_{\mathbf{L}}^{\mathbf{2}})\omega_{\mathbf{i}}$$

where γ_L is the Lorentz factor and ω_i is the angular frequency of the transition.

Tuning :

- ion type, ion charge
- atomic excitation level (transition energy and lifetime)
- beam energy
- laser source

➠ At CERN, in the energy domain of 30 keV - 400 MeV.

Example (maximal energy case)
LHC, Pb^{80+} ion, $\gamma_L = 2887$, $n = 1 \to 2$, $\lambda_{laser} = 104.4\,\text{nm}$, $E_\gamma^{max} = 396\ \text{MeV}$

γ-ray source intensity leap

Electrons

$$\sigma_e = \frac{8\pi}{3r_e^2}$$

with r_e classical electron radius

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

Partially Stripped Ions

$$\sigma_{res} = \frac{\lambda_{res}^2}{2\pi}$$

λ_{res} wavelength in the ion rest frame.

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

$\sim$ **9 orders of magnitude difference in the cross section**

➠ **Numerical example**

Scenario 1 : FEL : 104.4nm, Pb^{80+} ion, $\gamma_L = 2887$, $n = 1 \rightarrow 2$, $E_\gamma^{max} = 396\,\mathrm{MeV}$, $N_\gamma^{max} \sim 6 \times 10^{15}$ ph/s... with the current LHC RF system.

Scenario 2 : Erbium doped laser : 1540 nm, Ar^{16+} ion, $\gamma_L = 2068$, $E_\gamma^{max} = 13.8\,\mathrm{MeV}$, $N_\gamma^{max} \sim 3 \times 10^{17}$ ph/s !! a 7 orders potential jump w.r.t Duke's HiGs

with $N_\gamma^{max} = N_{ion/bunch} \times N_{bunches} \times f[1/s] \times RF[MV] \times Z / < E_\gamma[MeV] >$

A leap in the γ-ray source efficiency

Example: Pb, hydrogen-like ions stored in LHC $\gamma_L = 2887$.

Electrons

$$E_{beam} = 1.5\,\mathrm{GeV}$$

Electron fractional energy loss emission of 150 MeV photon:

$$E_\gamma / E_{beam} = 0.1$$

➠ electron is lost !!!

Partially Stripped Ions

$$E_{beam} = 574000\,\mathrm{GeV}$$

Electron fractional energy loss emission of 150 MeV photon:

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

➠ ion undisturbed !!!

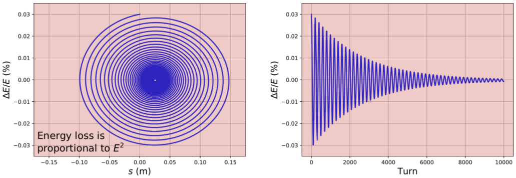
➠ stable ion beams in the regime of multi photon emission per turn

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

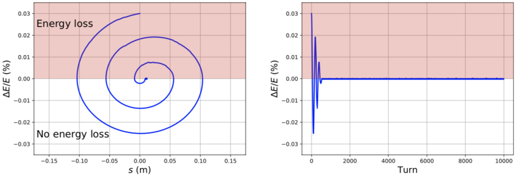
A cool side effect : beam cooling

As the ion momentum is much larger than the photon's, excitation only induces a very small deviation of the ion trajectory

- **Longitudinal cooling:** energy loss grows with ion energy



Longitudinal trajectory in case of the broad-band laser cooling

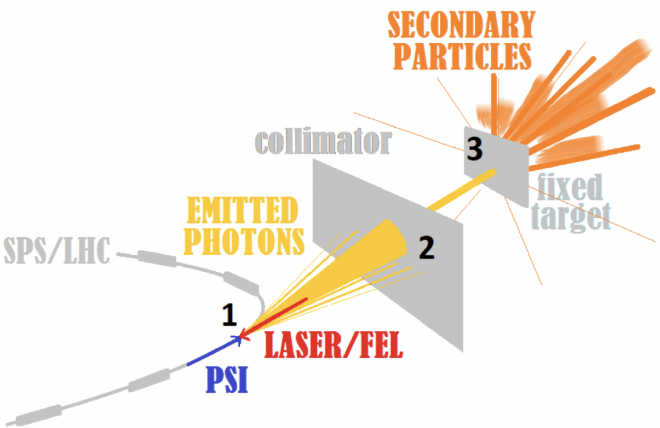


Longitudinal trajectory in case of the laser spectrum sharp cut-off fast cooling

- **Transverse cooling:** possible with a coupling between transverse and longitudinal component in dispersive sections in ring

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

GammaFactory



Camilla Curatolo
W. Placzek *et al.* - Gamma Factory at CERN – novel research tools made of light,
doi 10.5506/APhysPolB.50.1191

GammaFactory beams and collision schemes

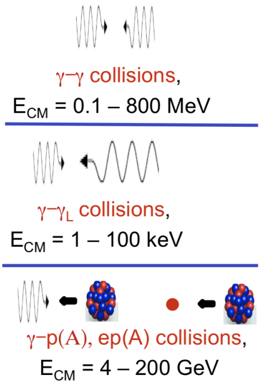
Primary beams:

- partially stripped ions : new at highly relativistic energy
- electron beams (LHC)
- gamma rays :10^4 intensity gain factor w.r.t present sources

Secondary beams:

- polarized e-
- polarized e+ : 10^4 intensity gain factor w.r.t KEK $e+$ source
- polarized muons : 10^3 intensity gain factor w.r.t PSI muon source
- neutron: 10^4 gain factor in flux with 1kW driver beam power
- radioactive nuclei: 10^4 gain in intensity w.r.t ALTO.

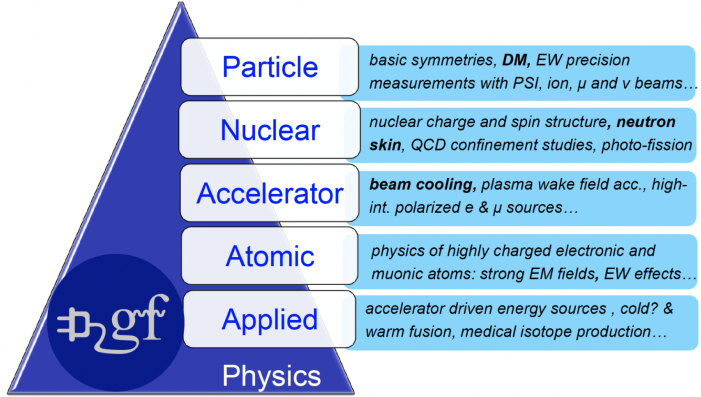
collider schemes



W. krasny, 2018 CERN presentation
M.W. Krasny, F. Dydak, F. Fayette, W. Placzek, A. Siodmok, Eur.Phys.J. C69 (2010) 379-397.

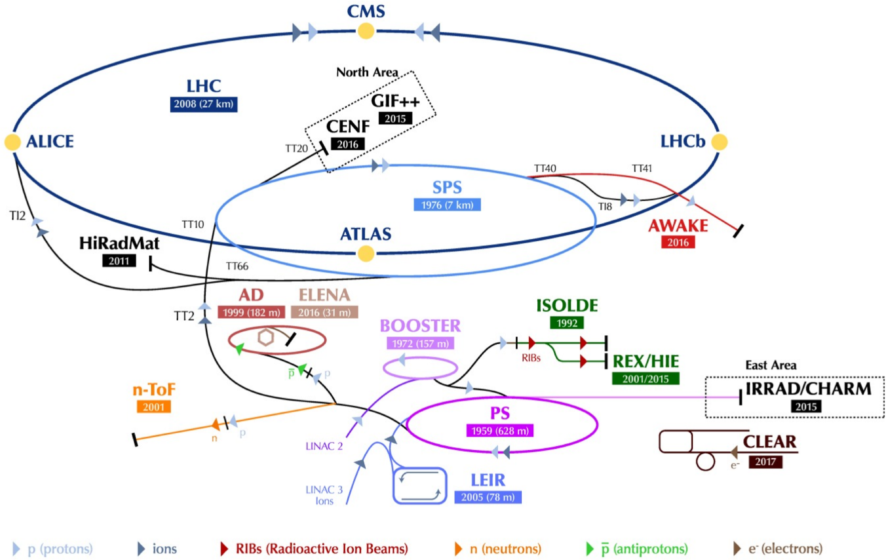
The Gamma Factory initiative (arXiv:1511.07794 [hep-ex]),2017

Gammafactory research programs

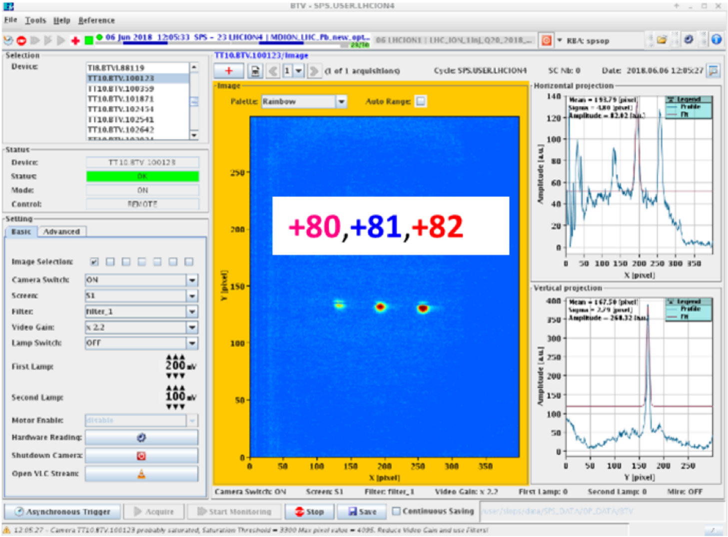


GammaFactory challenges

LHC accelerators complex

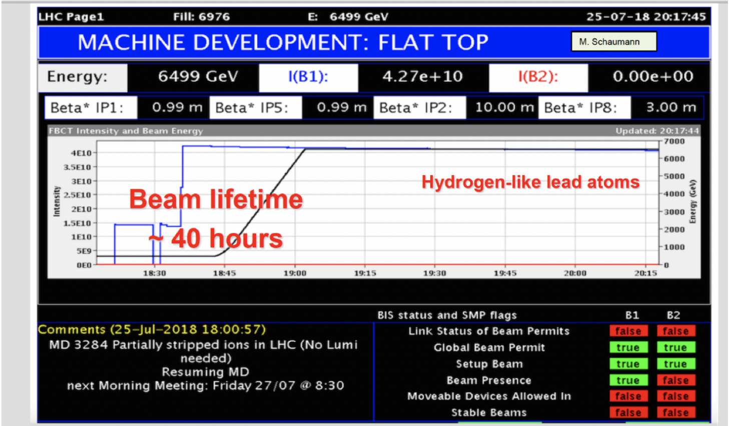


first PSI in the LHC in summer 2018 !



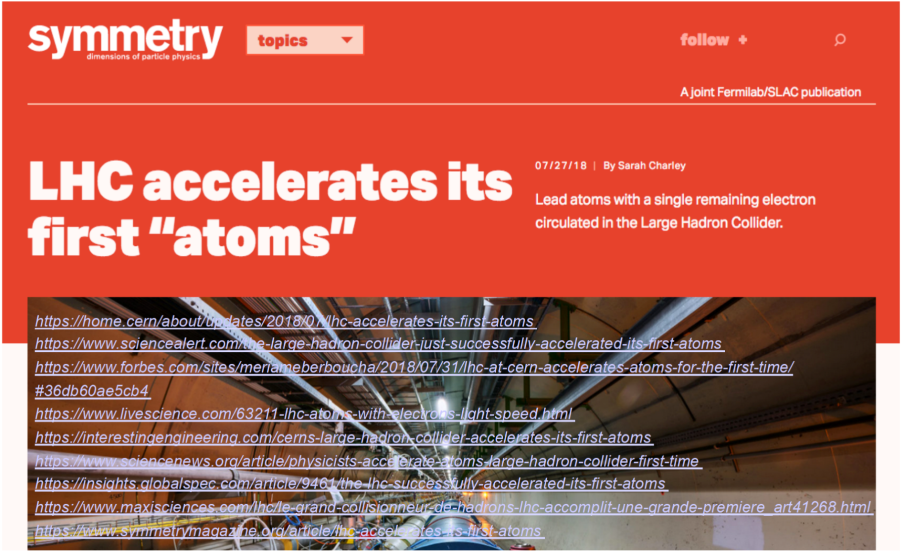
➠ successful injection in SPS of Pb^{80+}, Pb^{81+},Pb^{82+}, lifetime 660 $\pm$ 30 s

first PSI in the LHC in summer 2018 !



- successful injection in SPS of Pb^{80+}, Pb^{81+},Pb^{82+}, lifetime 660 ± 30 s
- $Pb^{81}+$ to the maximum LHC energy, intensity/bunch 7×10^9 charges 6 bunches circulating, lifetime 54.5 ± 1.7 h

first PSI in the LHC in summer 2018 !



symmetry
dimensions of particle physics

topics

follow +

A joint Fermilab/SLAC publication

LHC accelerates its first "atoms"

07/27/18 | By Sarah Charley

Lead atoms with a single remaining electron circulated in the Large Hadron Collider.

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

Challenges

- laser sources : integration $> 200\,\mathrm{kW}$, $40\,\mathrm{MHz}$ enhanced cavity seeded by high power laser in SPS/LHC tunnel
- beam dynamics : high level of control of the ion beam is required (relative beam momentum stability required $\sim 10^{-5}$)
- software tool : modeling codes are critical for optimization of beams parameters, 5 independent codes are developed (Russia, Italy, UK,France, Poland)

A GammaFactory Proof of Principle experiment

GammaFactory Proof of Principle (GFPOP) in SPS

Main objectives

- production and optimization of PSI beams
- development of embedded high power laser system for accelerator tunnel
- verify our simulation models

Demonstration of excitation

- Achieve PSI beam resonant excitation and maximise photon production
- Maintain the resonance over 100 s in SPS

Demonstration of beam cooling

- Observed longitudinal beam cooling in a few seconds
- Using correlation between position and energy of ion beams in the interaction region measure transverse beam cooling

... Possibly perform accurate measurement of the ion transition with accurate ion beam absolute energy.

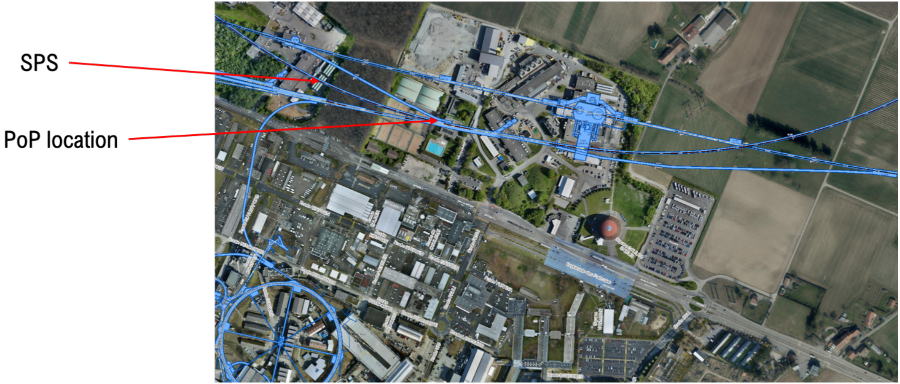
GFPOP in SPS : parameters

Generation of X-ray on SPS straight section with beam cooling of the PSI beam.
Two possibilities laser sources are considered single-pass or 36 bunches @ 20 MHz

Table 4: SPS PoP experiment parameters

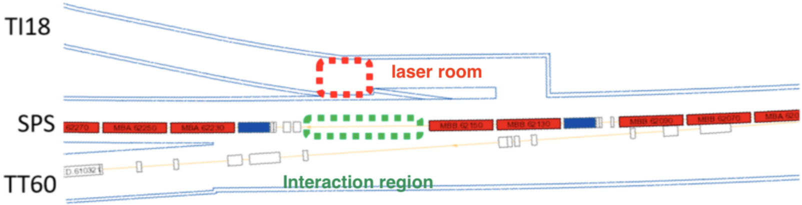
Parameter	Unit	FP cavity	Single-pass	Max uncertainly
Laser repetition frequency	MHz	40	0.0434	(locked to bunches)
Laser output pulse energy	μJ	1.2	5000	$\pm 10\%$
Average laser power	W	50	217	$\pm 10\%$
F_{rev} (Pb^{79+}_{208} γ86)	Hz	43,373		± 0.02
Atomic transition energy $2s_{1/2} \rightarrow 2p_{1/2}$	eV	230.823		± 0.047
Excited state lifetime (ion frame)	ps	76.6		± 0.1
Excited state decay length (lab frame)	m	2.19		± 0.01
Max. emitted photon energy (lab frame)	keV	44		± 0.05
Laser - PSI beam crossing angle	deg	2.6		± 0.05
Laser wavelength	nm	1034		± 0.01
PSI relativistic γ_L		96.3		± 0.02
RMS momentum spread in bunch		2×10^{-4}		$\pm 5 \times 10^{-5}$
Laser pulse energy at IP	mJ	5		$\pm 10\%$

GFPOP in SPS : interaction region



B. Goddard, F. Velotti, Y. Dutheil

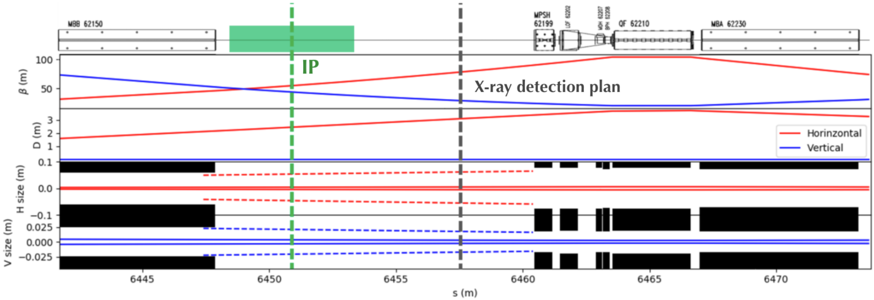
GFPOP in SPS : interaction region



(a)

(b)

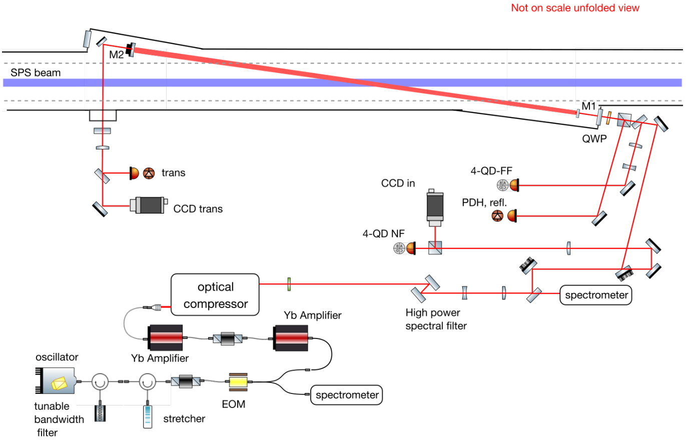
GFPOP in SPS : interaction region



B. Goddard, F. Velotti, Y. Dutheil

GFPOP in SPS interaction system

- A 2 mirrors, 4 m long Fabry Perot cavity, seeded > 50 W Yb fiber laser
- Laser frontend with tunable double FBG filter and temperature tunable CFBG.
- UHV Optical transport line and laser room in the unused side tunnel, shielded from the SPS radiations.



GFPOP in SPS interaction system

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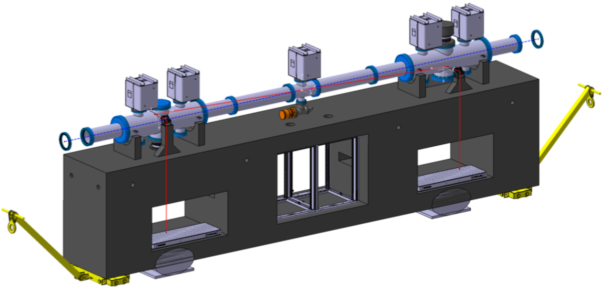
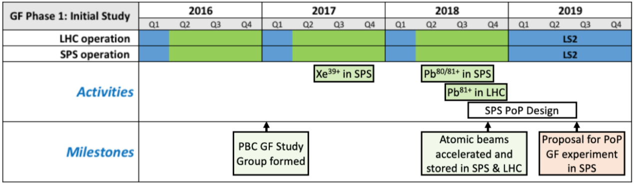


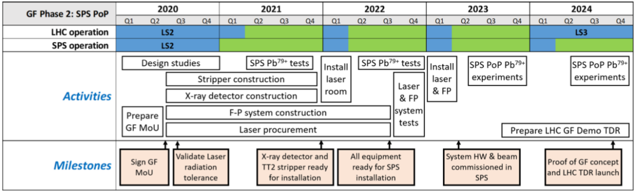
A. Martens, Y. Peinaud

GFPOP calendar

- Phase 1 : PSI



- Phase 2 : GFPOP in SPS



- Phase 3 : GF in LHC, reusing laser sources and IP system from GFPOP
  $15-87$ MeV photons with Pb^{79+} $2s \to 3p_{1/2}$ or $2s \to 2p_{3/2}$

Conclusion

- New sources of high flux and high energy photons at CERN
  - unconventional but innovative use of CERN accelerator complex
  - Opportunities with existing facilities for the HEP and broader physics community, including PWFA.
- The GF POP concept is being finalized, letter of intend for SPSC under review
- Yellow report in progress
- Gamma Factory community
  - 60+ researchers from 20+ institutions and growing.
  - Joint the effort !

home.cern

LHC scenario Pb^{79+}

Lithium like lead, lifetime in SPS $\sim 100\,s$ and $\sim 10\,h$ in LHC

$_{/2} \rightarrow 3p_{1/2}$ $\Delta E = 14.7\,\text{keV}$

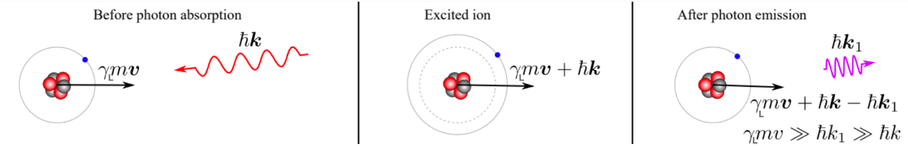
- long decay of $0.6m$
- laser : second harmonics of Yb laser
- maximum photon energy 87 MeV
- flux limited by double photon absorption process

$_{/2} \rightarrow 2p_{1/2}$ $\Delta E = 2.64\,\text{keV}$

- short decay of $1.5cm$
- laser : Yb laser at larger angle
- maximum photon energy 15 MeV
- flux not limited

Enjoy the relativistic magic twice

In the lab frame



Optical photon of angular frequency ω travelling against the PSI is boosted in the ion frame

$$\omega' = (1+\beta)\gamma_L \omega \approx 2\gamma_L \omega$$

A photon is spontaneously emitted, isotropically in the referential of the ion. Boosting back to the lab frame

- emitted photons concentrated in $\approx 1/\gamma_L$ in the ion beam forward direction
- angular frequency ω" of the photon propagating back along its incoming direction is boosted by another factor $2\gamma_L$:

$$\omega" \approx 2\gamma_L \omega' = 4\gamma_L^2 \omega$$

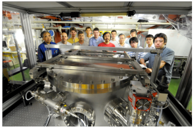
Challenge laser photon sources

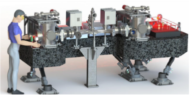
The main challenge is bringing high power laser system in CERN accelerator environment <=> embedded remotely controlled high reliability system

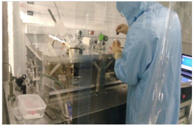
high power pulsed laser at 40 MHz → hundreds of kW

Constraints ... make the challenge transfer from optical lab to accelerator tunnel

- spectral tuning
- cavity environment integration → high radiation level
- machine integration → beam impedance
- very limited access to the interaction point system and laser system







Challenge 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 required $\sim 10^{-5}$

Cooling and beam stability

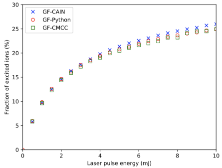
- Possibly fast cooling, down to a few seconds, may lead to very low emittance and instability
- Equilibrium between cooling and heating processes is needed for continuous photon production

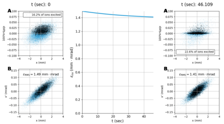
courtesy of Yann Dutheil

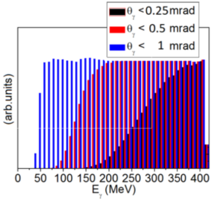
Challenge software tool

- Parallel development and benchmark of laser ion interaction on several modeling codes ➠ Currently 5 independent codes are developed
- Modelling codes are critical for optimization of beam and laser parameters
- Parallel development and benchmark of laser ion interaction on several modeling codes
    - Implementation in BDSIM and GEANT4 developments at RHUL UK by , *S. Alden, L. Nevay and S. Gibson*
    - Independent code at INFN Padova, Italy by *C. Curatolo*
    - Implementation in CAIN at the Jagiellonian University of Krakow, Poland by *W. Placzek*
    - Semi-analytical calculations at LAL, Paris by *A. Martens*
    - Python implementation at Budker Insitute, Novosibirsk, Russia by *A. Petrenko*

➠ Modelling codes are critical for optimization of beam and laser parameters







C. Curatolo *et. al*,"Novel high intensity gamma-source at CERN: the Gamma Factory Initiative", Sixth Annual Conference on Large Hadron Collider Physics (LHCP2018)

PSI productions

Transmission efficiency simulations (BREIT) of the stripper (stripping foils)