
September 25, 2019

Gamma Factory
Proof-of-Principle Experiment

LETTER OF INTENT

Gamma Factory Study Group

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Gamma Factory:

Proof of Principle Experiment

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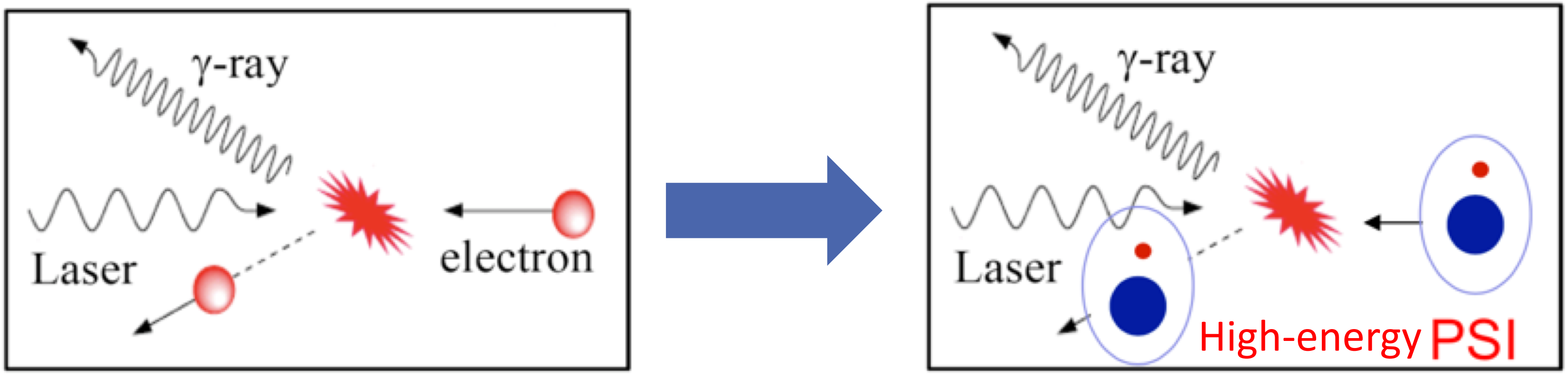
88 people from 34 institutes from 15 countries

Physics concept

💡: Exploit high cross-section of atomic resonances & existing CERN accelerator complex



High-energy **PSI**

PSI: Partially stripped ions

Very similar with Inverse Compton scattering but $O(10^9)$ larger cross-section !

For instance

Energy upshifting by a factor $4\gamma^2$

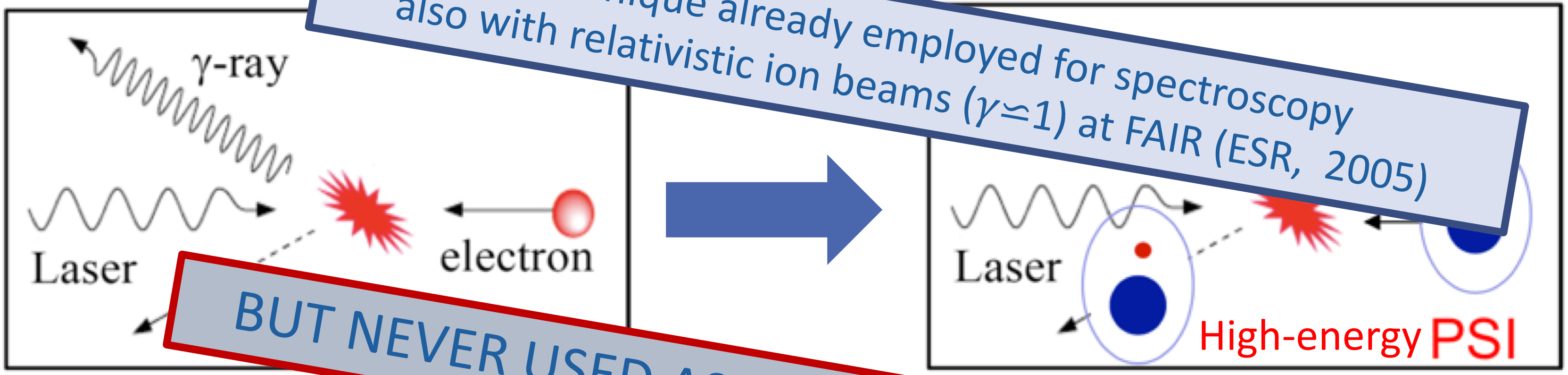
- H-like Xenon at LHC (γ=3000) → 180 MeV
- Li-like Calcium at SPS (γ=130) → 80 keV

E. J. Bessonov & K.J. Kim Phys. Rev. Lett. 76, 431, M.W. Krasny arXiv:1511.07794,
D Winters et al 2015 Phys. Scr. 2015 014048

Physics concept

💡 : Exploit high c ection of atomic resonances & existing CERN accelerator complex

A technique already employed for spectroscopy also with relativistic ion beams ($\gamma \simeq 1$) at FAIR (ESR, 2005)



PSI: Partially stripped ions

BUT NEVER USED AS A PHOTON SOURCE SO FAR !!!

Very similar with Inverse Compton scatter ection !

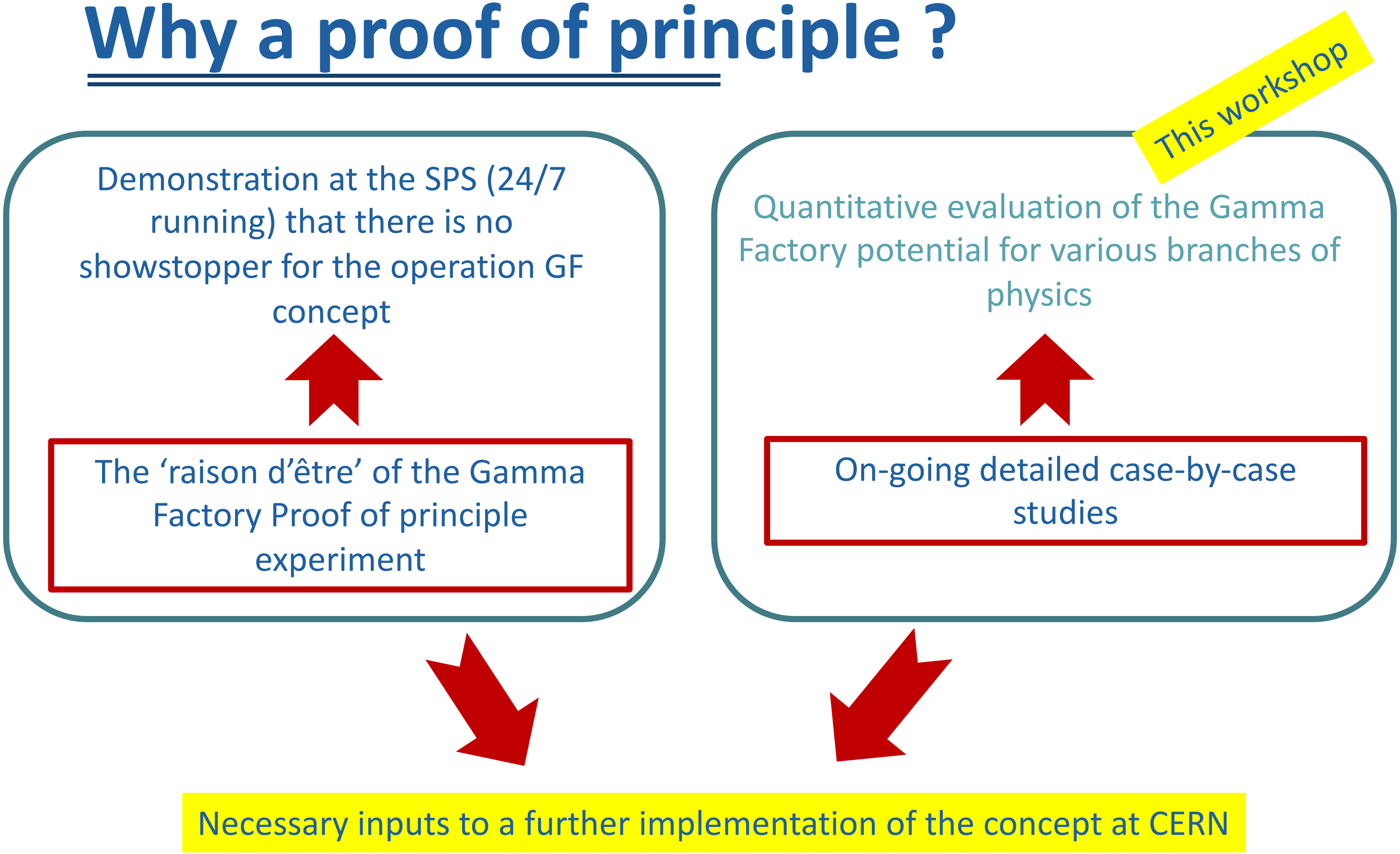
For instance

Energy upshifting by a factor $4\gamma^2$

- H-like Xenon at LHC (γ=3000) → 180 MeV
- Li-like Calcium at SPS (γ=130) → 80 keV

E. J. Bessonov & K.J. Kim Phys. Rev. Lett. 76, 431, M.W. Krasny arXiv:1511.07794,
D Winters et al 2015 Phys. Scr. 2015 014048

Why a proof of principle ?



This workshop

Demonstration at the SPS (24/7 running) that there is no showstopper for the operation GF concept

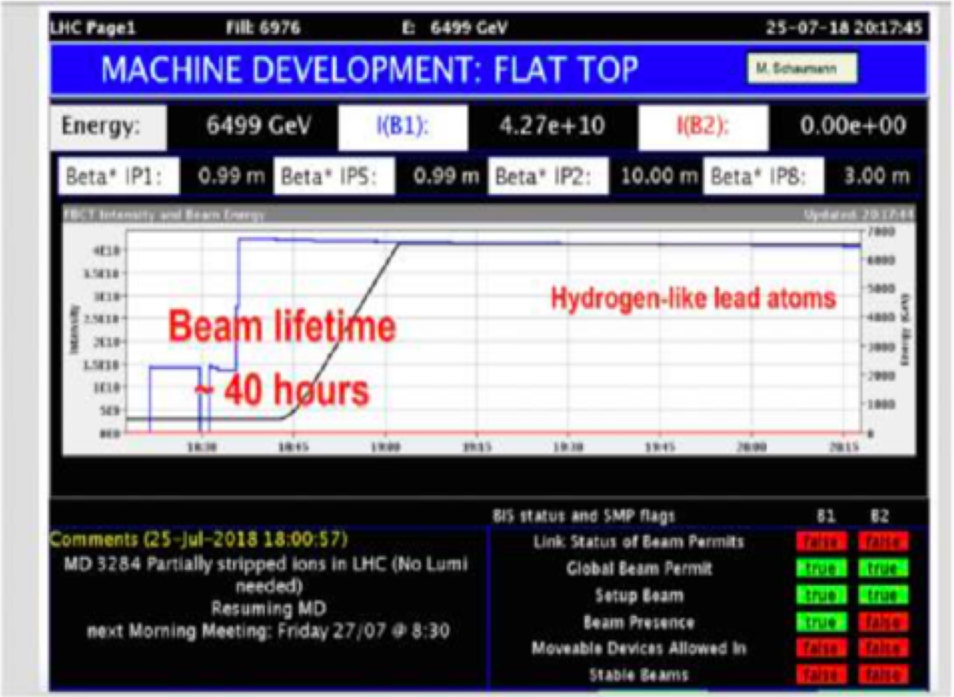
The ‘raison d’être’ of the Gamma Factory Proof of principle experiment

Quantitative evaluation of the Gamma Factory potential for various branches of physics

On-going detailed case-by-case studies

Necessary inputs to a further implementation of the concept at CERN

Atoms in the LHC !



LHC Page1 Fill: 6976 E: 6499 GeV 25-07-18 20:17:45

MACHINE DEVELOPMENT: FLAT TOP

M. Schaumann

Energy: 6499 GeV I(B1): 4.27e+10 I(B2): 0.00e+00

Beta* IP1: 0.99 m Beta* IP5: 0.99 m Beta* IP2: 10.00 m Beta* IP8: 3.00 m

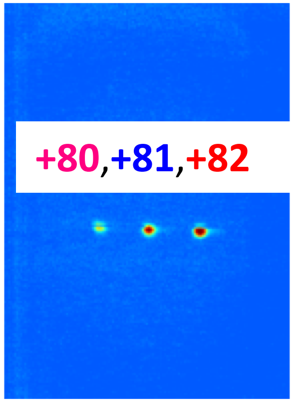
Beam lifetime

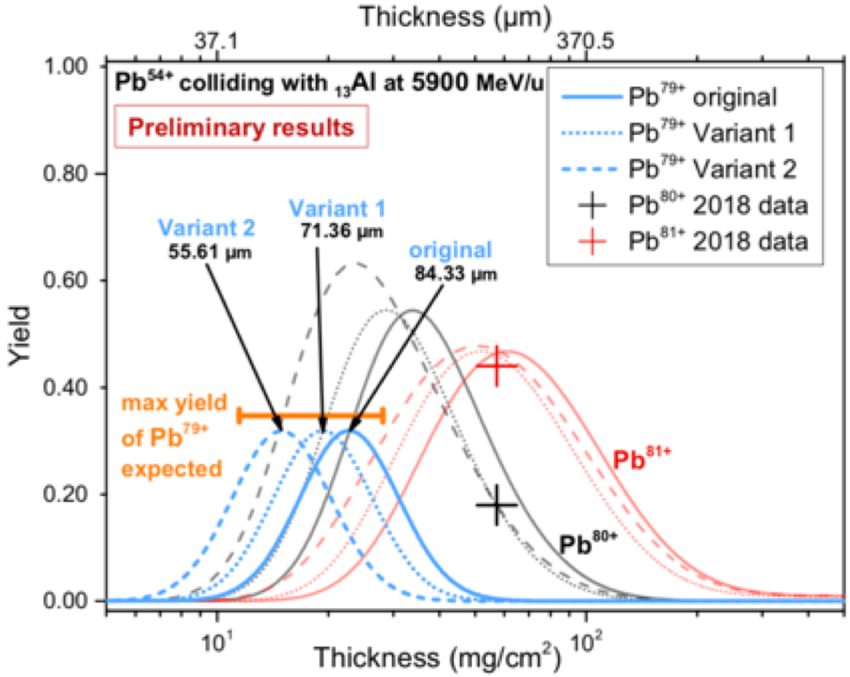
~ 40 hours

Hydrogen-like lead atoms

Comments (25-Jul-2018 18:00:57)
MD 3284 Partially stripped ions in LHC (No Lumi needed)
Resuming MD
next Morning Meeting: Friday 27/07 @ 8:30

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	false	false
Global Beam Permit	true	true
Setup Beam	true	true
Beam Presence	true	false
Moveable Devices Allowed In	false	false
Stable Beams	false	false





2018 demonstration allowed us to calibrate stripping efficiencies predictions

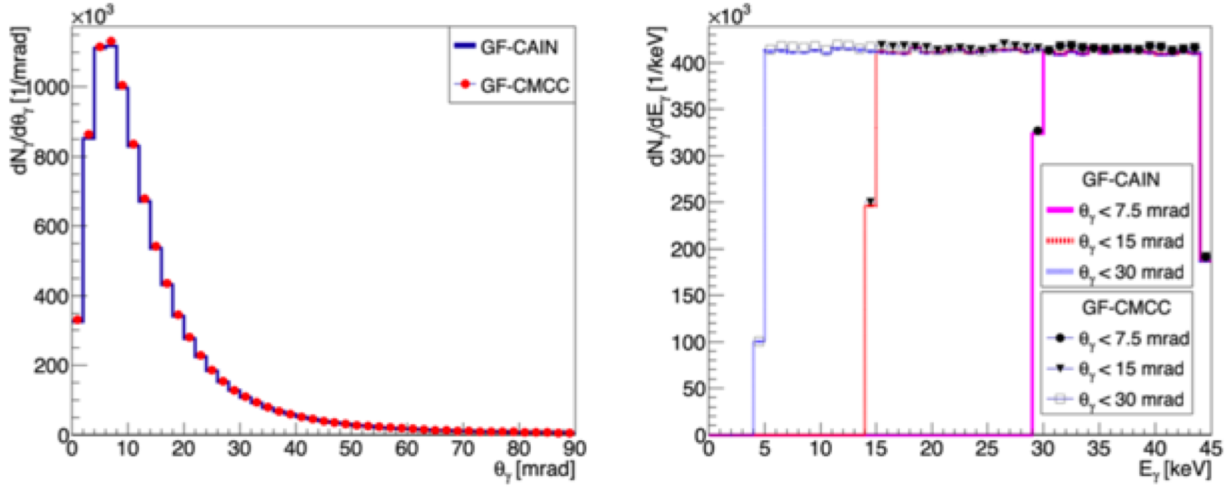
Simulation tools: cross-checked

Talk by W. Placzek

Two existing softwares improved for GF use + dedicated ones provi nsistent

- Excitation rates
- Angular distributions
- Energy distributions
- Polarisation (on-going)

M. W. Krasny et al. SPSC-I-253



What for ?

1. Demonstrate that an adequate laser system (5mJ@40MHz) can be (remotely) operated in the high radiation field of SPS and LHC.
2. Demonstrate that very high rates of photons are produced : almost all PSI's excited for every bunch crossing
3. Demonstrate stable and repeatable operation
4. Confront data to simulations
5. Demonstrate ion beam cooling: longitudinal and then transverse
6. Perform atomic physics measurement

Ion and transition choice

Few atomic species available w/ existing hardware

Long enough beam lifetime in SPS (vacuum of SPS)

Pb^{79+}

$1s^2\ 2s\ {}^2S_{1/2} \rightarrow 1s^2\ 2p\ {}^2P_{1/2}$

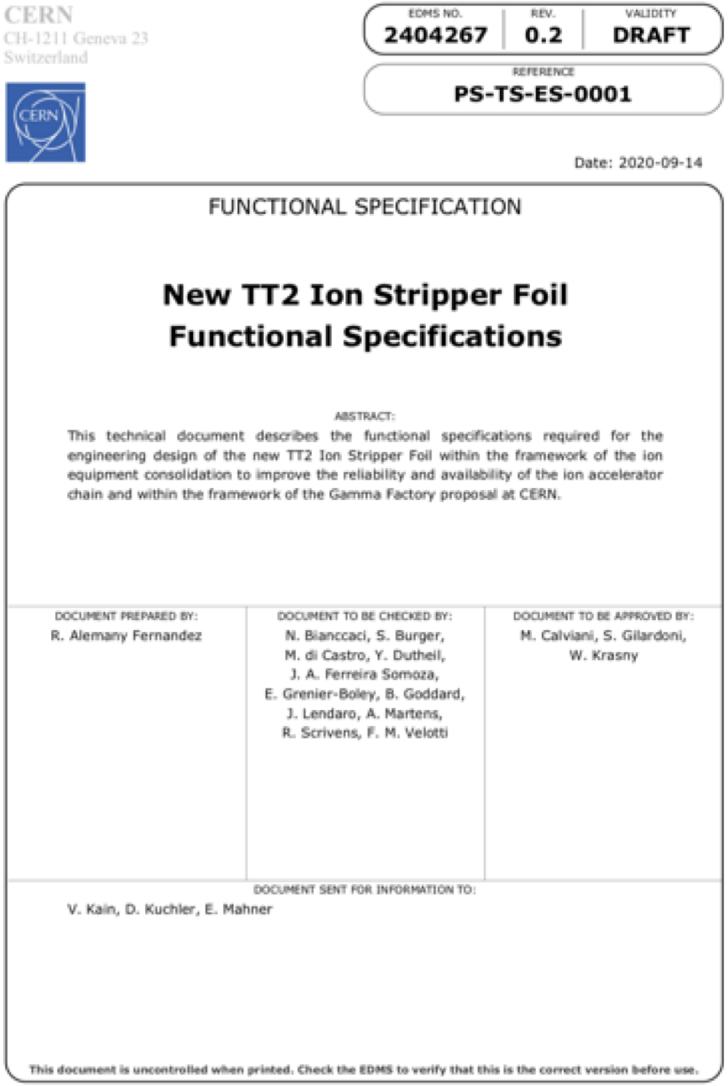
230eV transition (1µm laser)

Short enough excited state lifetime

Accessible transition with convenient laser system

Different types of atoms and transitions could be targeted with more investments

New ion stripper foils system



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REFERENCE
PS-TS-ES-0001

Date: 2020-09-14

FUNCTIONAL SPECIFICATION

New TT2 Ion Stripper Foil
Functional Specifications

ABSTRACT:

This technical document describes the functional specifications required for the engineering design of the new TT2 Ion Stripper Foil within the framework of the ion equipment consolidation to improve the reliability and availability of the ion accelerator chain and within the framework of the Gamma Factory proposal at CERN.

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Common need with other experiments to add flexibility in stripping capability:

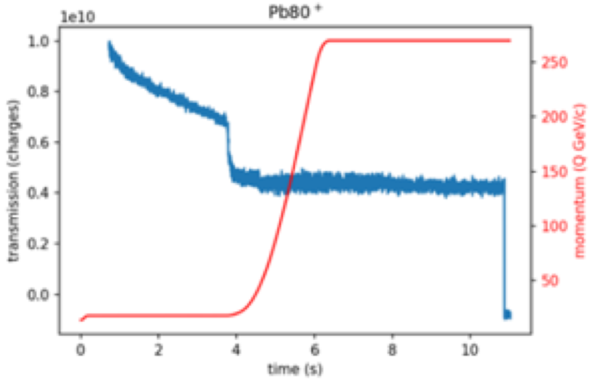
- 4 foils
- Angle (thickness) can be tuned
- Pulse to pulse operation !
- 35% stripping efficiency for Pb^{79+}

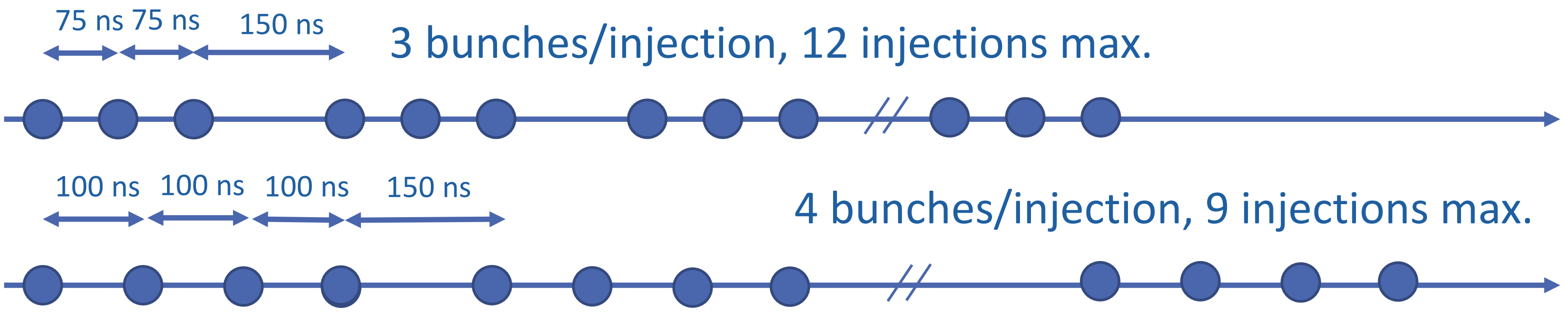
Will allow *parasitic* Gamma Factory Proof of principle operation

As extrapolated from 2018 run meassurements and ordinary SPS operations with ions

Beam parameters

Lifetime is long enough at flat top for Pb^{80+}
→ Extrapolated for Pb^{79+}: about 100s





3 bunches/injection, 12 injections max.

4 bunches/injection, 9 injections max.

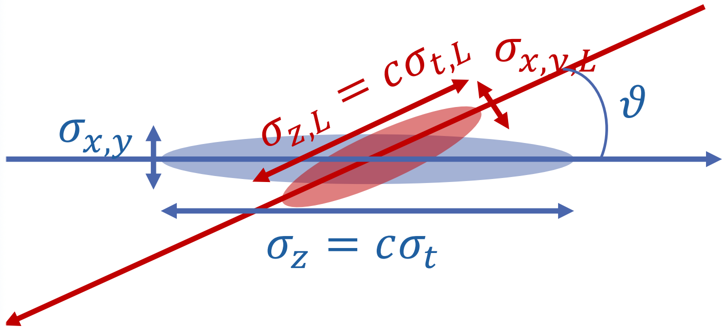
Common harmonic frequency=40MHz

Transverse normalised emittance	1.5 mm mrad
Bunch length	213 ps
Momentum spread	2×10^{-4}
Expected lifetime	100 s
Ions per bunch at injection	0.9×10^{8}
Maximum number of bunches in the ring	36

M. W. Krasny et al. SPSC-I-253, M.W. Krasny arXiv:1511.07794

Collision scheme

NB: pulsed (frequency comb) laser



Beams must be aligned, synchronized

Not specific to Gamma Factory scheme

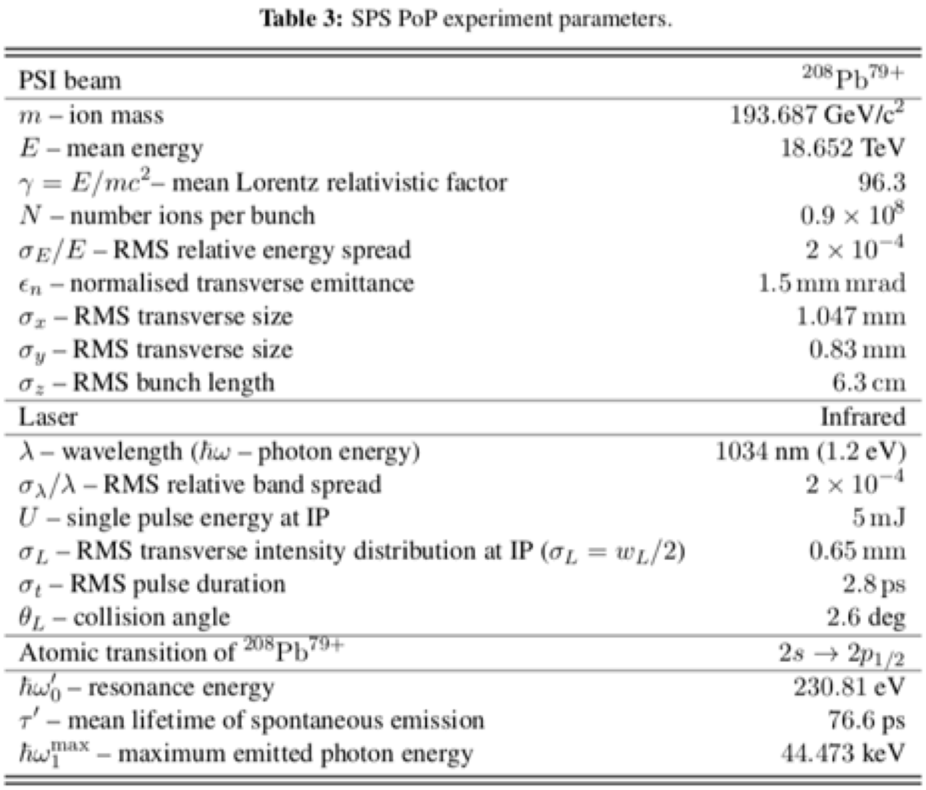


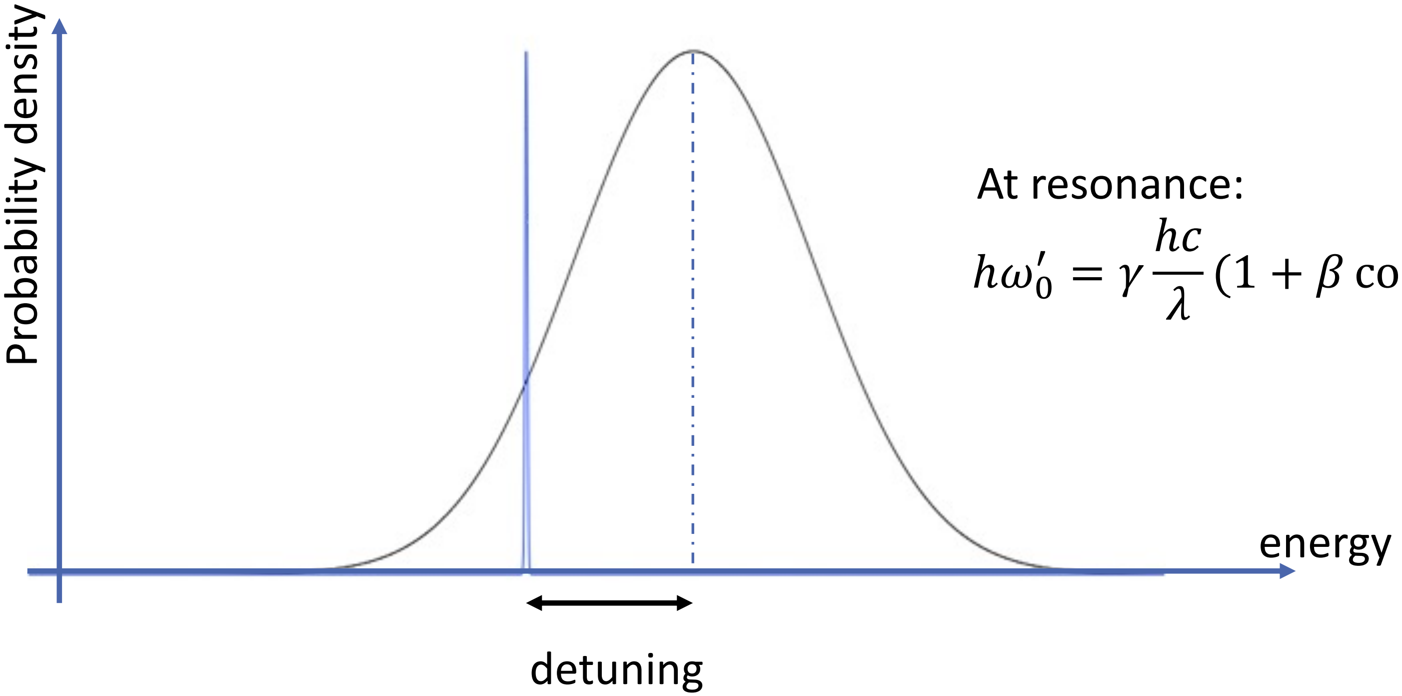
Table 3: SPS PoP experiment parameters.

PSI beam	$^{208}\mathrm{Pb}^{79+}$
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 $^{208}\mathrm{Pb}^{79+}$	$2s \rightarrow 2p_{1/2}$
$\hbar\omega'_0$ – 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

M. W. Krasny et al. SPSC-I-253

Spectrum matching

Linewidth of atomic resonance << bandwidth of laser spectrum (in ref. frame of atoms)

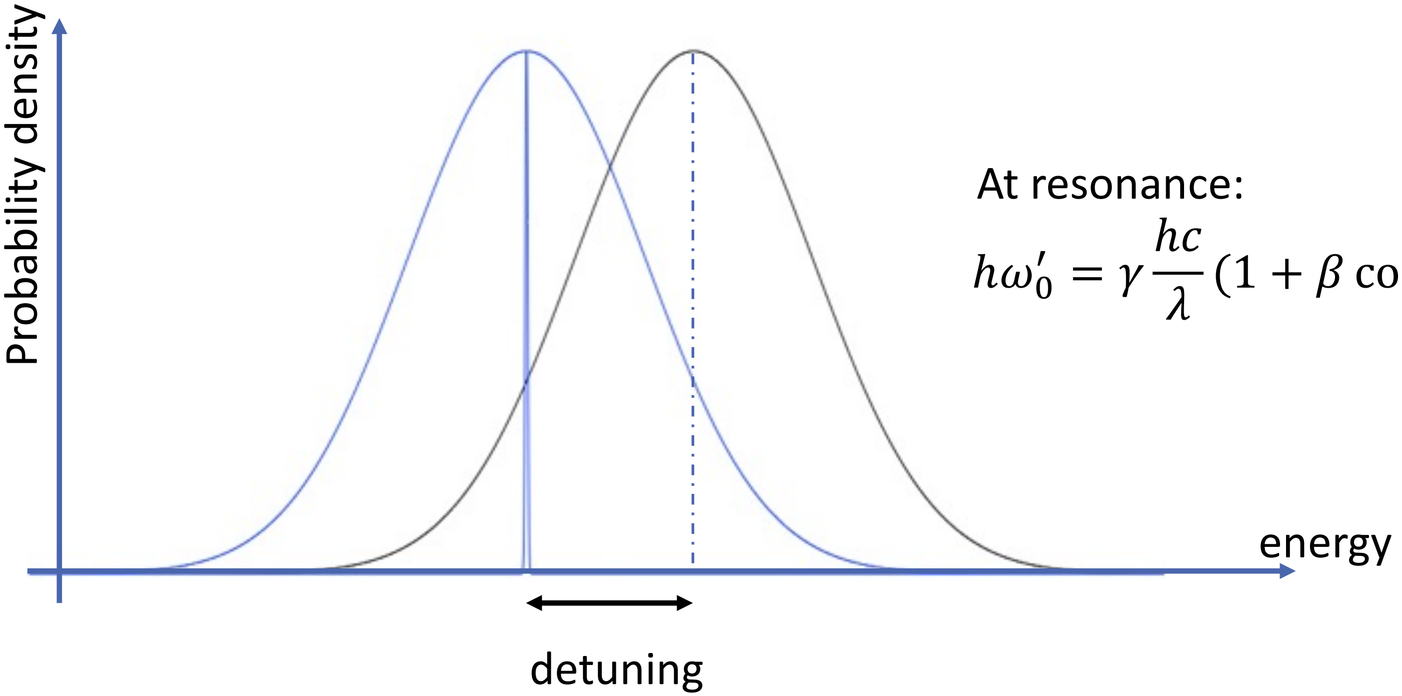


At resonance:

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

Spectrum matching

Atomic (PSI) beam energy spread ≃ bandwidth of laser spectrum (in ref. frame of atoms)



At resonance:

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

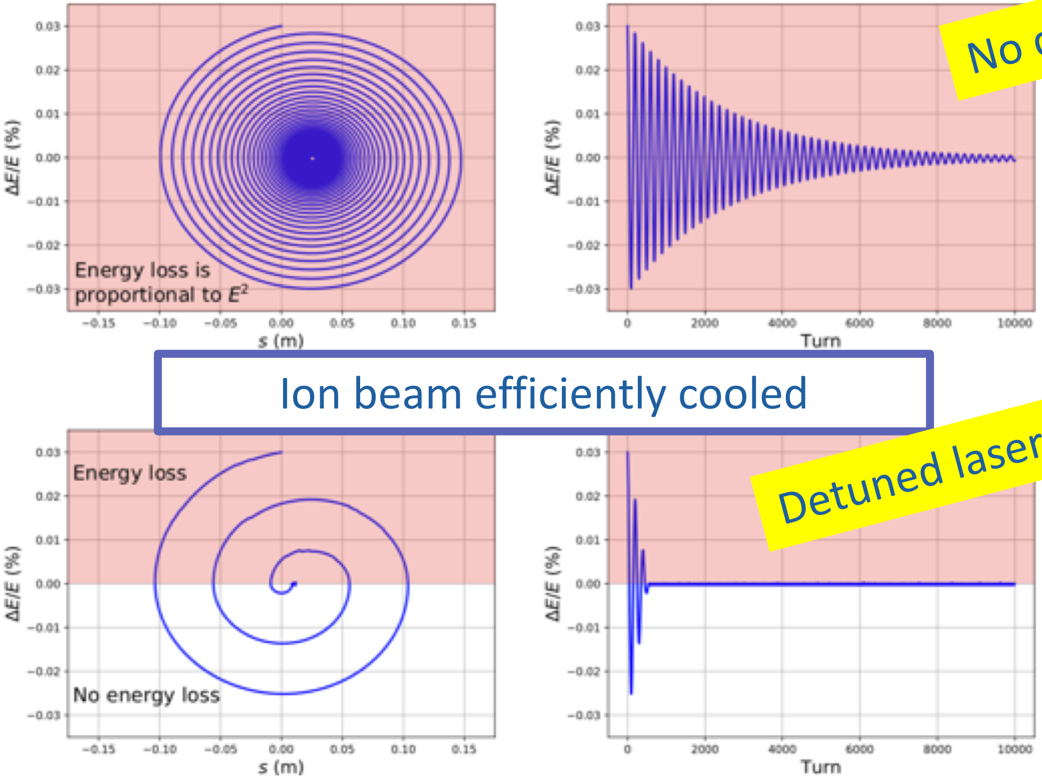
- A relatively high laser energy is required to excite nearly all atoms

- Excitation rate of atoms depend on their position in the energy spectrum

About 10^{14} ph/s at the SPS

Ion beam cooling

interesting application:
→ talk by A. Petrenko

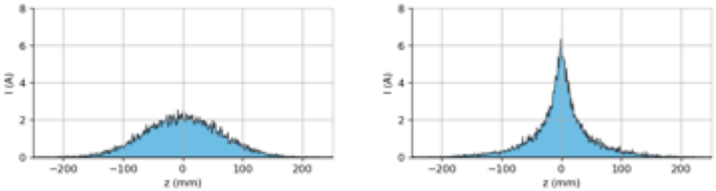


No detuning

Ion beam efficiently cooled

Detuned laser spectrum

Observe it with wall current monitors



Large (horizontal) dispersion relation at the interaction point:
→ transverse cooling in a similar fashion by mis-aligning the beams

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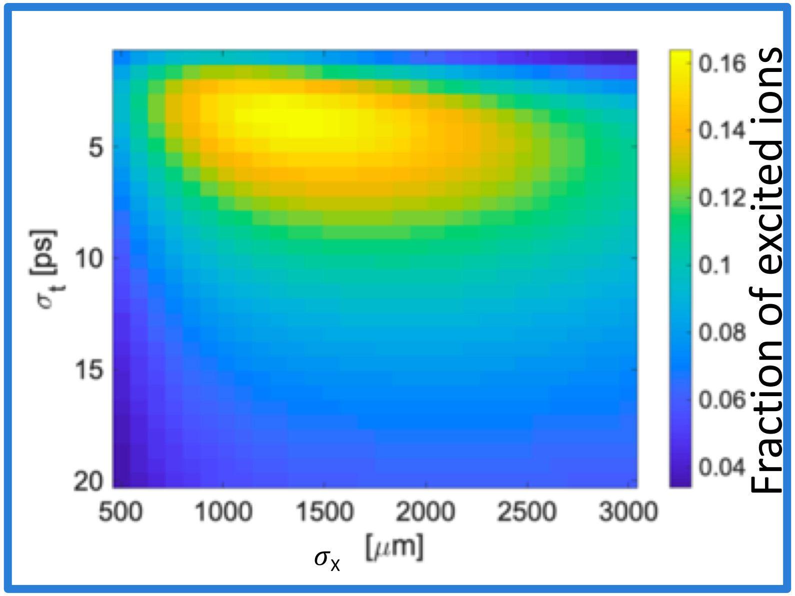
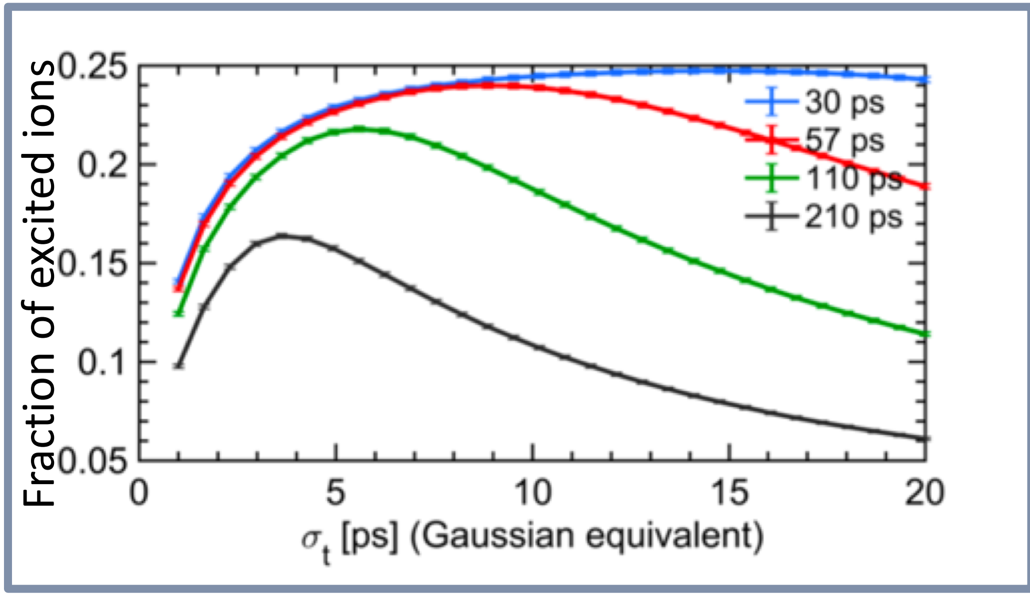
Optical system optimization



A muti-dimensional approach to optimize the laser beam parameters



Optimum parameters depend on ion-bunch length

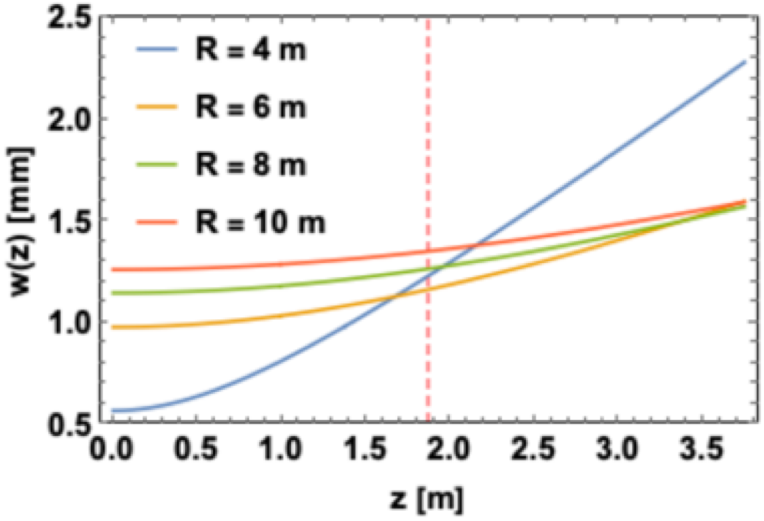
Laser pulse duration/spectrum tunability is an asset

Optical system: design

A several mJ pulsed laser at 40 MHz is a natural candidate:

- Compatible with the atoms filling schemes
- Compatible with what one would naturally expect for LHC operations
- State of the art technology: pulsed laser (freq. comb) + amplifier + resonant cavity

A 2-mirror (plano-concave) cavity is considered:
→ simpler operation, delivers naturally beam sizes close to optimum



A 10m mirror Radius of curvature is preferred

We expect to operate the optical cavity with an enhancement factor >5000

>4.5mJ pulses @ 40MHz, 180kW in cavity

Laser system at the state of the art

L. Amoudry et al., Applied Optics 59 (2020) 116; Chaikovska et al., Scientific Reports 6 (2016) 36569

Fabry-Perot resonator to reach about 5mJ at 40MHz→ 200kW already exists

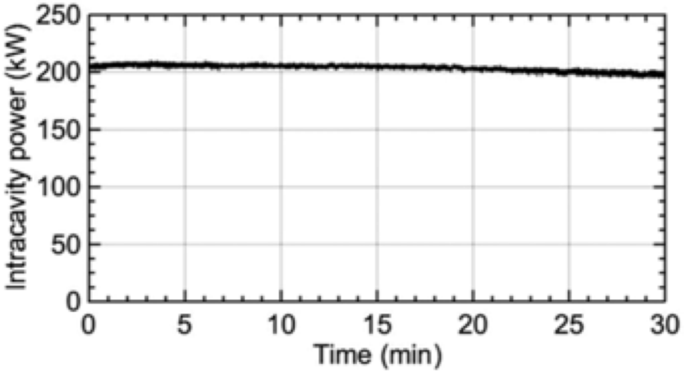


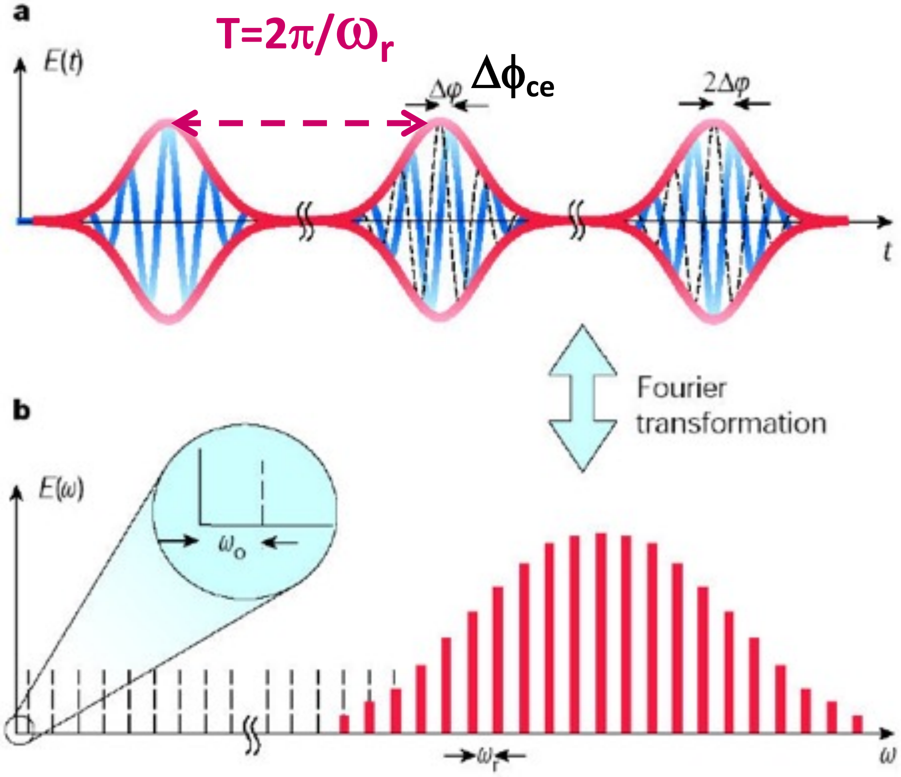
Fig. 7. Laser intracavity power for 30 min, measured by transmission of a cavity mirror.

Built and operated by IJCLab (Orsay) team

State of the art system, already operated in low emittance KEK ATF ring

But: need to ensure the system can be operated fully remotely

Laser phase noise



T. Udem et al. Nature 416 (2002) 233

The whole comb must be locked:
dilatation (f_{rep})
translation (f_{CEP})

$$F = \frac{\nu}{\Delta\nu} = 20000$$

$$\nu = 40MHz$$

$$\Delta\nu = 2kHz$$

Phase noise of the laser must be low to lock to a high finesse cavity

Noise limits coupling

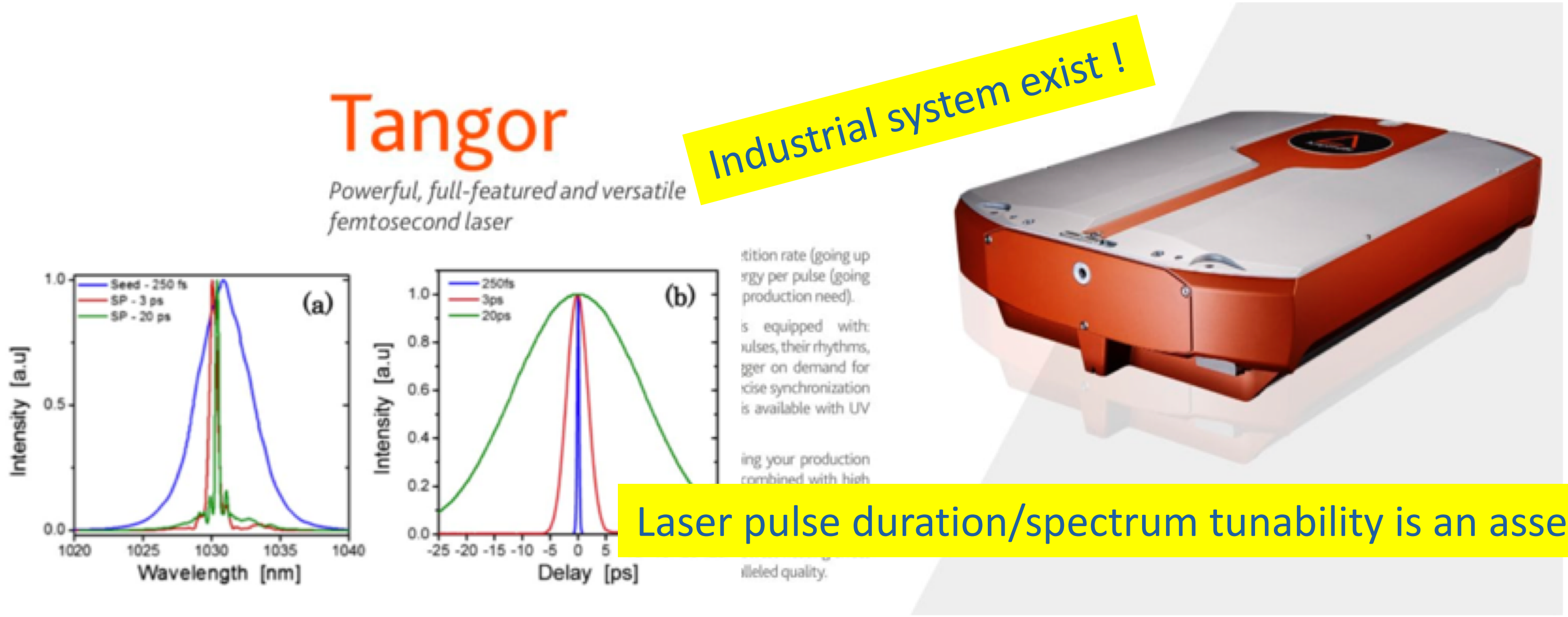
Optical system: laser and amplifier

Lock of laser to optical cavity of finesse 20k and length 7.5m → very low phase noise laser

Up to now: we know only one provider that delivered compliant performances

Risk mitigation:

1. reduce cavity selectivity i.e. finesse and gain (change coupling mirror, not expensive)
2. Use laser amplifier with higher average power to keep intracavity pulse energy high



Industrial system exist !

Laser pulse duration/spectrum tunability is an asset

Pouysegur et al. Opt. Lett. 40, 5184-5187 (2015)

Bottomline: such an industrial system, with spectrum/pulse duration tunability should be very robust compared to any home made solution

Synchronisation & alignment

Not specific to Gamma Factory

- Already realized in the past (for instance KEK ATF exp.)
- Alignment provided by BPMs on the girder of optical cavity
- Only needs to be adapted to SPS specifics

Cavity tuning range is limited

- Beam with constant revolution frequency at flat-top
- Varying transverse beam alignment: use existing orbit correctors

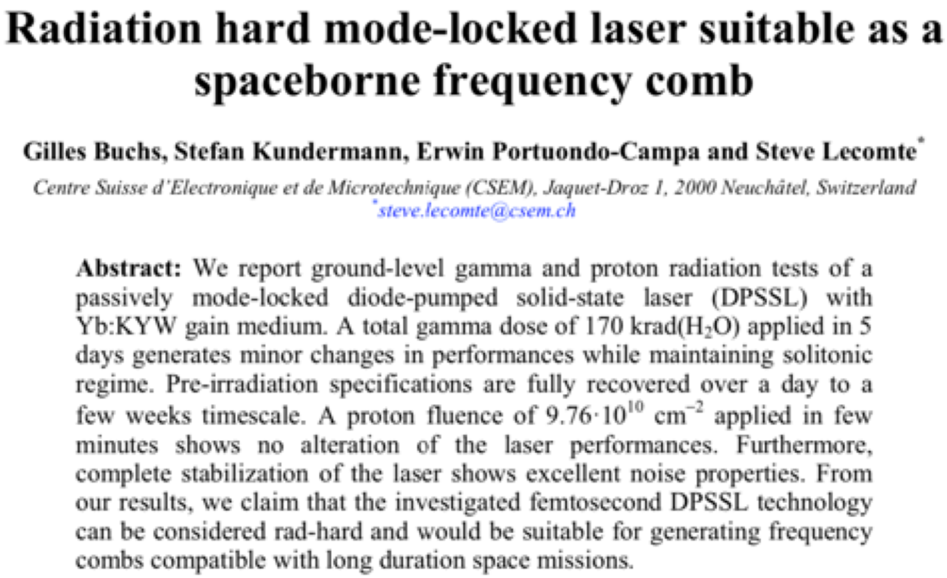
Similar to AWAKE

H. Damerau et al. IPAC2016-THPMY039; Chaikovska et al., Scientific Reports 6 (2016) 36569

Inputs from relevant experts at CERN : H. Damerau (RF) and V. Fedosseev (Laser)

Radiation hardness

Ageing of laser system's components is not expected to be limitation if TID<150krad



Radiation hard mode-locked laser suitable as a spaceborne frequency comb

Gilles Buchs, Stefan Kundermann, Erwin Portuondo-Campa and Steve Lecomte*
Centre Suisse d'Electronique et de Microtechnique (CSEM), Jaquet-Droz 1, 2000 Neuchâtel, Switzerland
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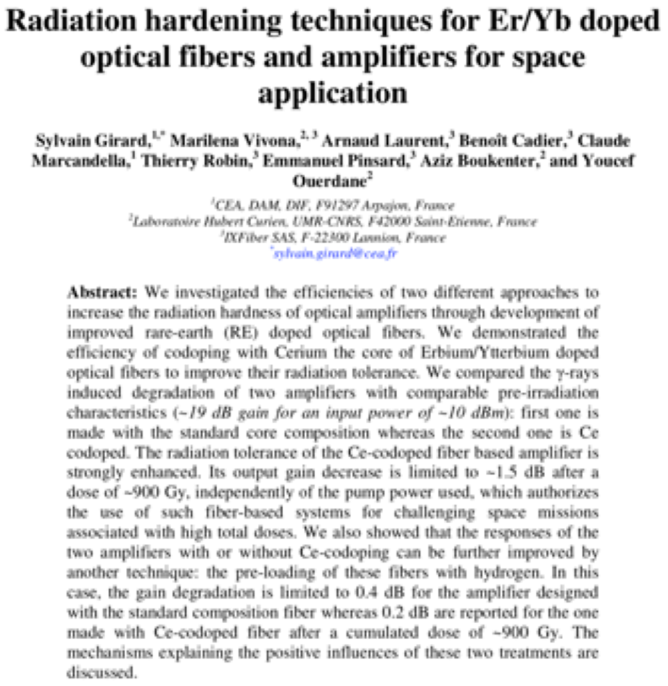
Abstract: We report ground-level gamma and proton radiation tests of a passively mode-locked diode-pumped solid-state laser (DPSSL) with Yb:KYW gain medium. A total gamma dose of 170 krad(H_2O) applied in 5 days generates minor changes in performances while maintaining solitonic regime. Pre-irradiation specifications are fully recovered over a day to a few weeks timescale. A proton fluence of $9.76 \cdot 10^{10}$ cm^{-2} applied in few minutes shows no alteration of the laser performances. Furthermore, complete stabilization of the laser shows excellent noise properties. From our results, we claim that the investigated femtosecond DPSSL technology can be considered rad-hard and would be suitable for generating frequency combs compatible with long duration space missions.



Radiation hardening techniques for Er/Yb doped optical fibers and amplifiers for space application

Sylvain Girard,[1,*] Marilena Vivona,[2,3] Arnaud Laurent,[3] Benoît Cadier,[3] Claude Marcandella,[1] Thierry Robin,[3] Emmanuel Pinsard,[3] Aziz Boukenter,[2] and Youcef Ouerdane[2]
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Abstract: We investigated the efficiencies of two different approaches to increase the radiation hardness of optical amplifiers through development of improved rare-earth (RE) doped optical fibers. We demonstrated the efficiency of codoping with Cerium the core of Erbium/Ytterbium doped optical fibers to improve their radiation tolerance. We compared the γ-rays induced degradation of two amplifiers with comparable pre-irradiation characteristics (*~19 dB gain for an input power of ~10 dBm*): first one is made with the standard core composition whereas the second one is Ce codoped. The radiation tolerance of the Ce-codoped fiber based amplifier is strongly enhanced. Its output gain decrease is limited to ~1.5 dB after a dose of ~900 Gy, independently of the pump power used, which authorizes the use of such fiber-based systems for challenging space missions associated with high total doses. We also showed that the responses of the two amplifiers with or without Ce-codoping can be further improved by another technique: the pre-loading of these fibers with hydrogen. In this case, the gain degradation is limited to 0.4 dB for the amplifier designed with the standard composition fiber whereas 0.2 dB are reported for the one made with Ce-codoped fiber after a cumulated dose of ~900 Gy. The mechanisms explaining the positive influences of these two treatments are discussed.

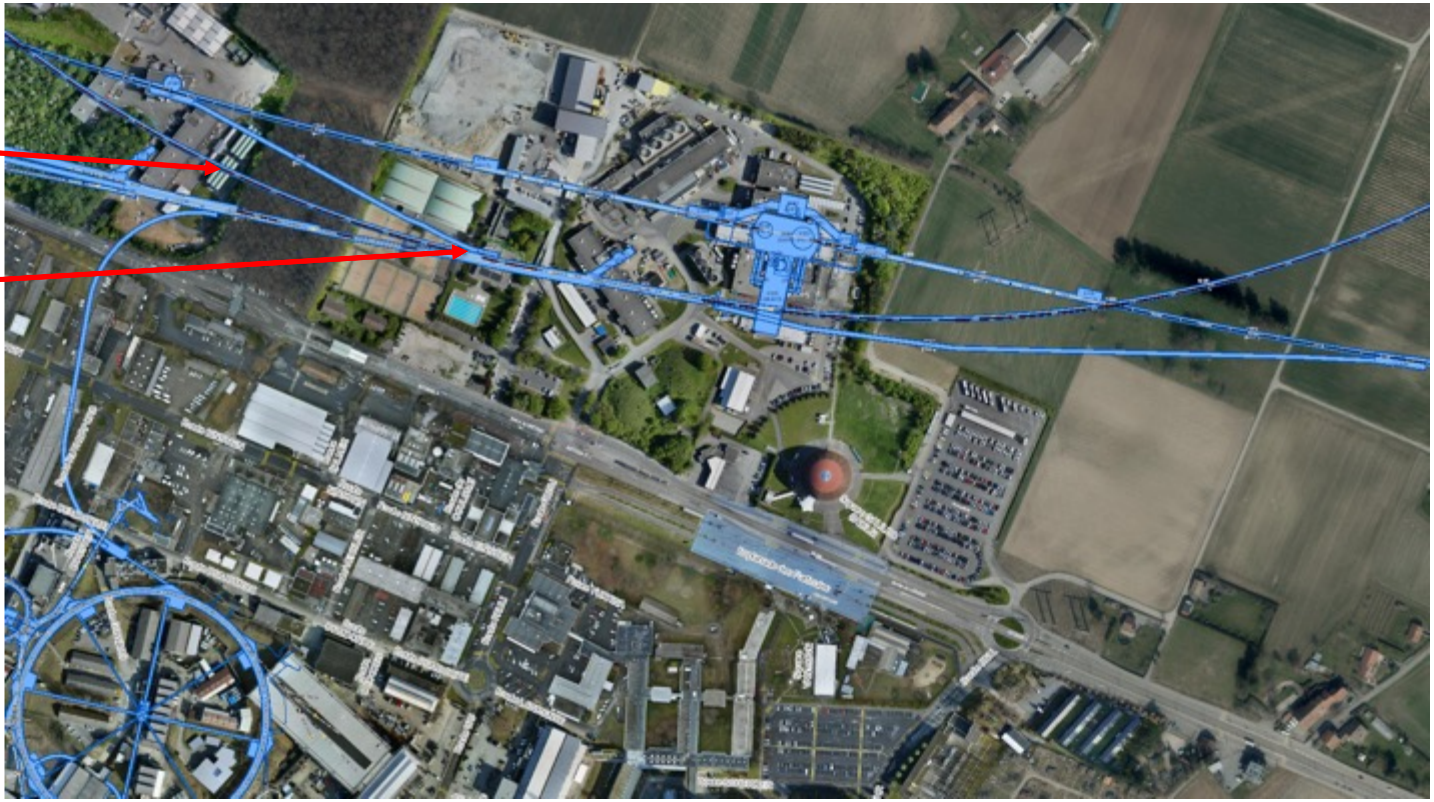
Gamma Factory PoP laser will only operate a few weeks a year

Sensitive laser-system must be shielded (side TI18 tunnel)

With R2E team: FLUKA simulations to be done to decide on the need of extra shielding or not

G. Buchs et al., Opt. Express 23 (2015) 9890 ; S. Girard et al., Opt. Express 20 (2012) 8457

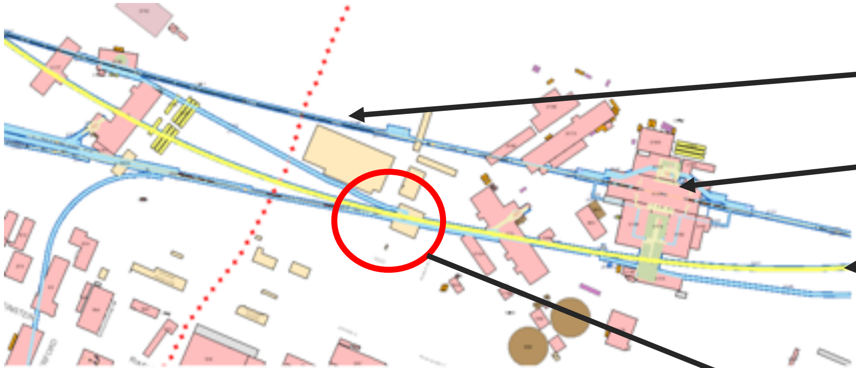
Interaction region location



SPS

PoP location

Interaction region location

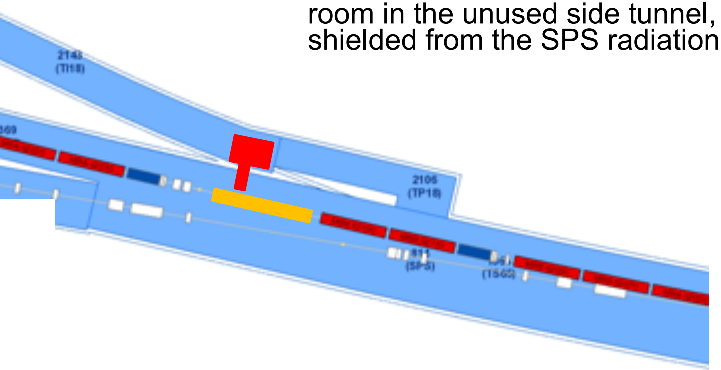


LHC ring

ATLAS

SPS ring

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



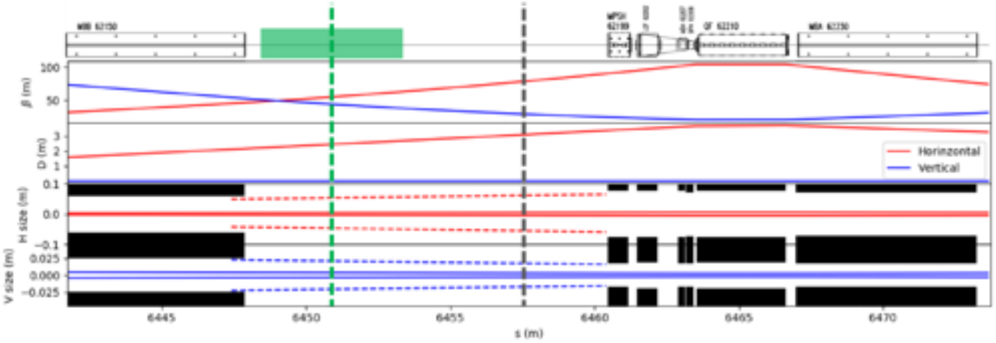
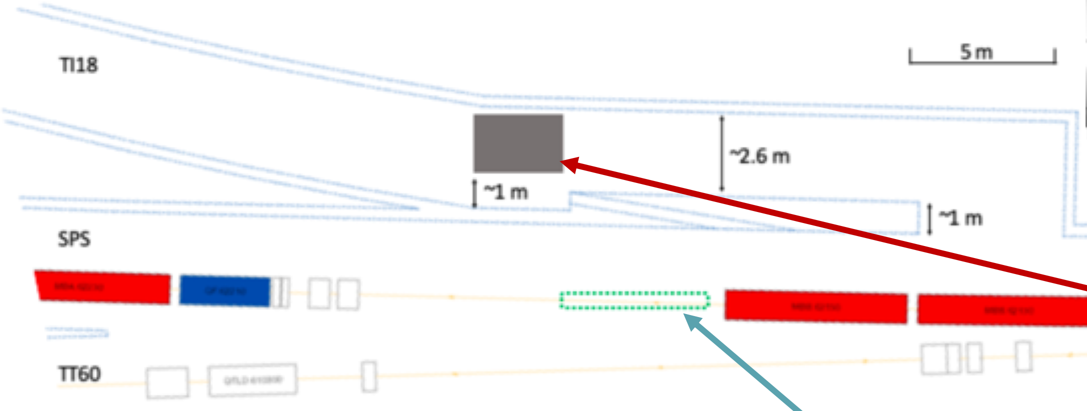
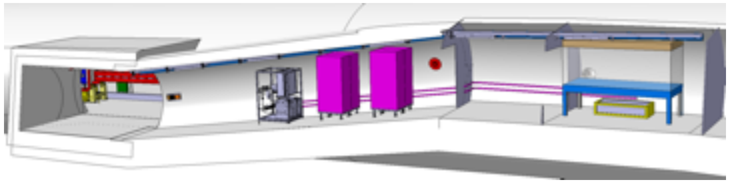
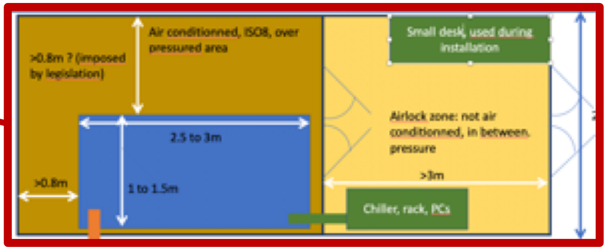


Fig. 7: Layout, optical functions and beam sizes with aperture limits around the interaction region. The IP is represented by a vertical green dotted line and the laser cavity by the green box. The vertical grey dotted line represents the location of the X-Ray detector. Note that the beam goes from left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

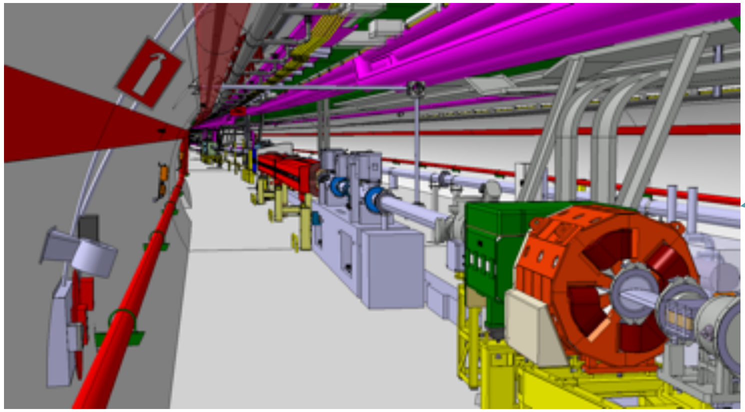
Optical system: integration

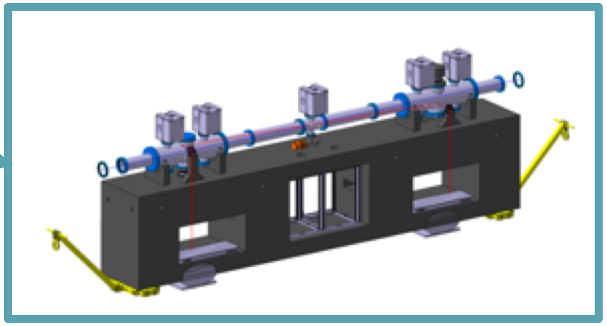






SPS half-cell 621 with side tunnel TI18





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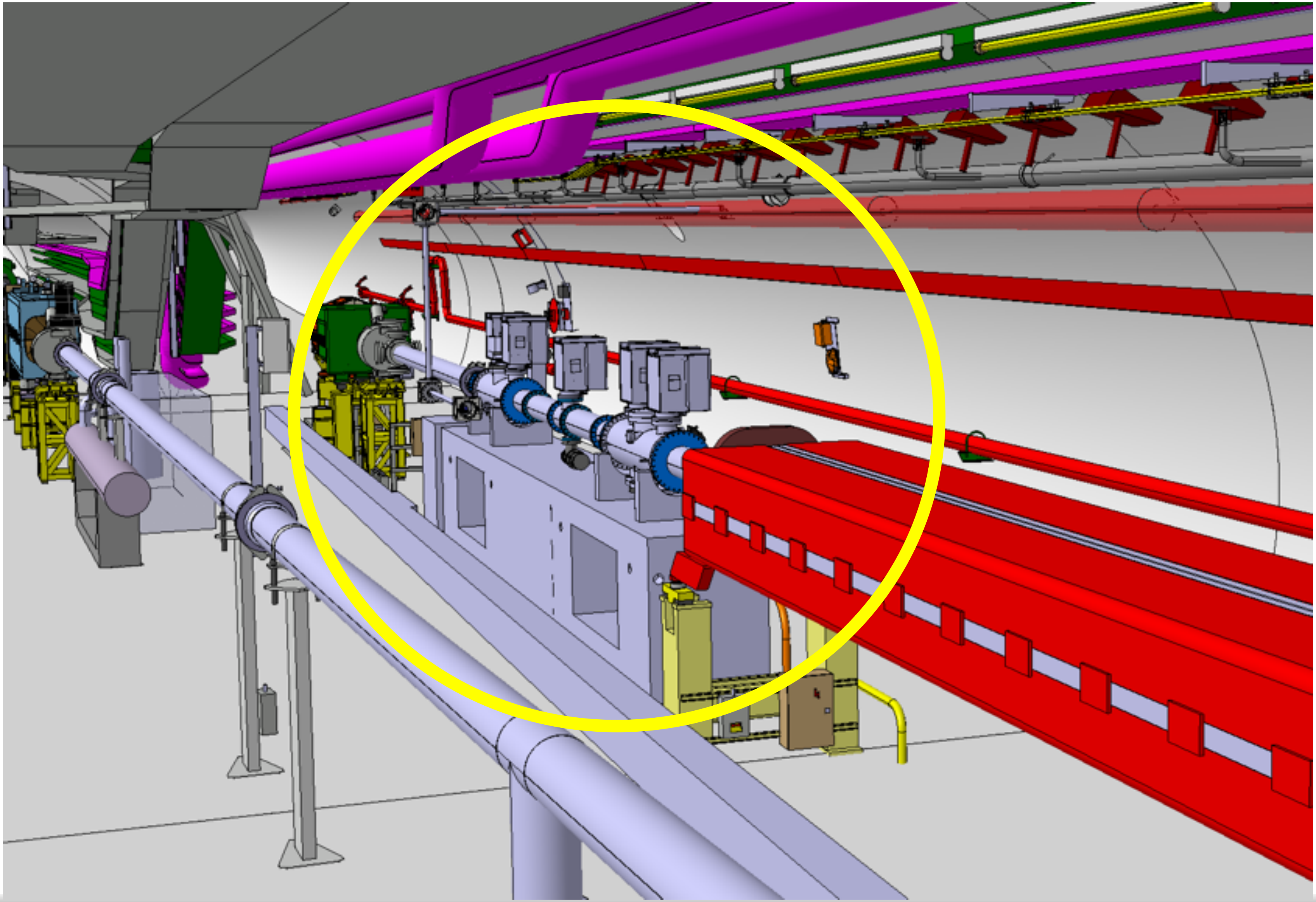
SPS half-cell 621 with side tunnel TI18

Optical system: integration



Thanks to Liam Dougherty for the help

Detection system

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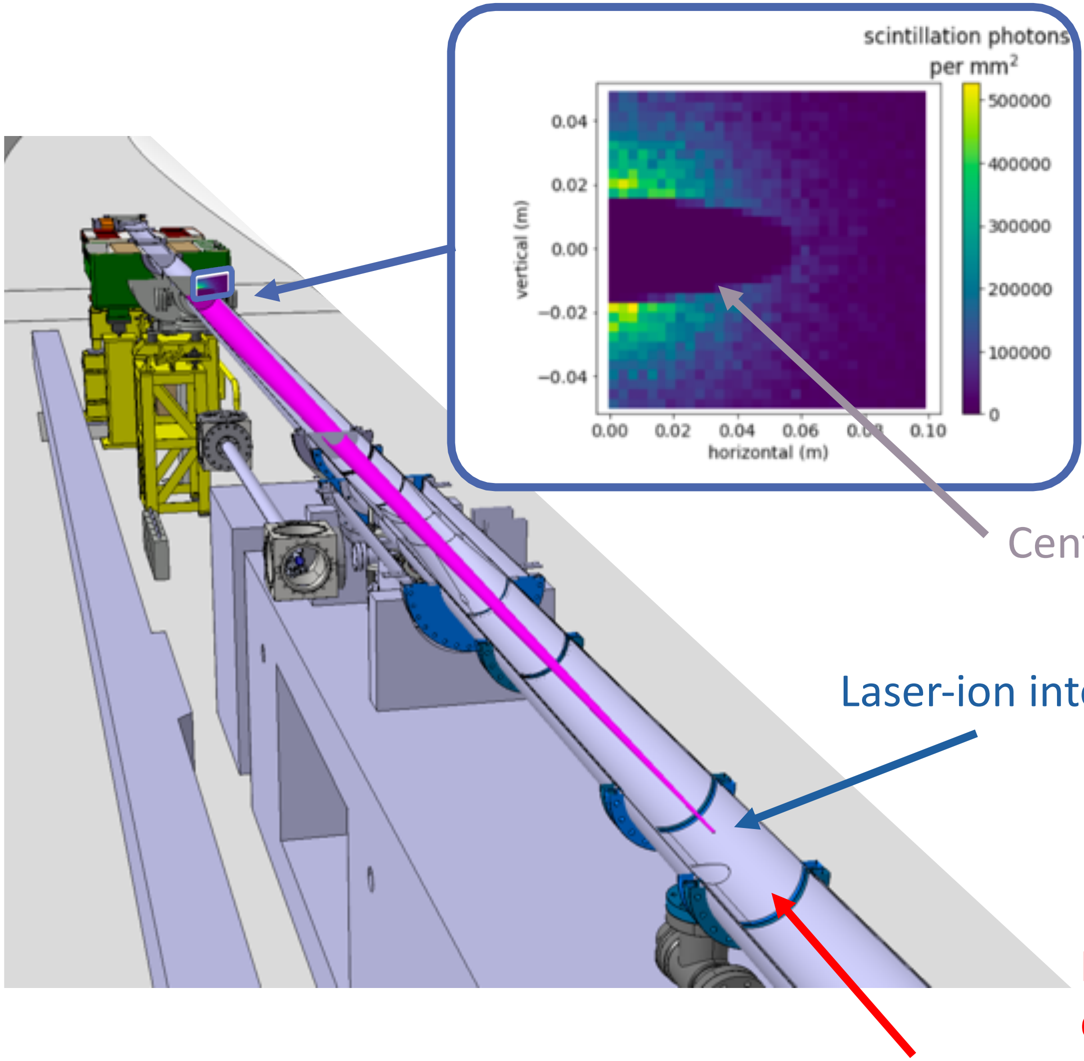


‘BTV’ system: YAG:Ce + camera

Remotely controlled manipulator

Central opening for ion beam passage

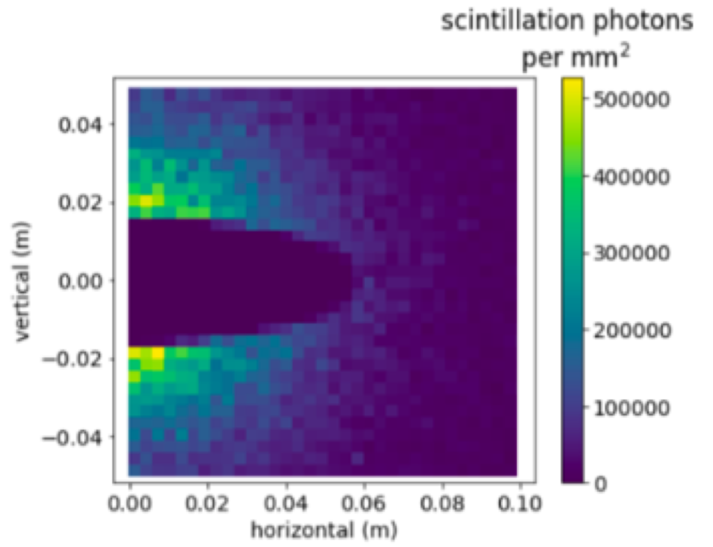
Laser-ion interaction Point

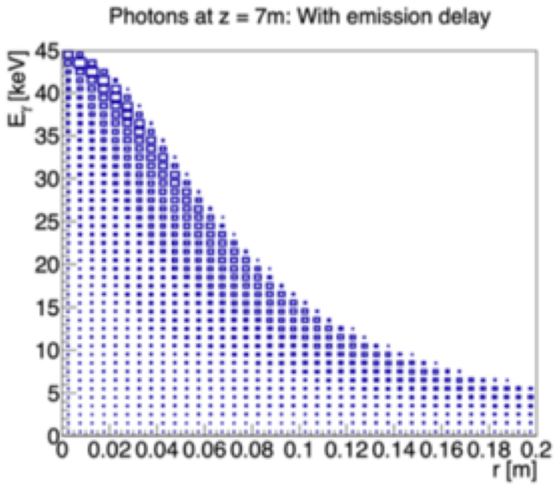
Ion beam direction

X-ray detector

‘BTV’ system: YAG:Ce + camera

Remotely controlled manipulator to go to garage position for non GF operations





>10^{11} visible photons/second
→ above sensitivity of standard camera

Post LS3 upgrade ability to mesaure energy-position correlations, timepix ?

Current status of the PoP

25/09/2019	LOI submission
23/01/2020	Questions received
18/02/2020	answer document issued
08/05/2020	Follow-up questions
28/05/2020	updated answer document issued
13/10/2020	presentation at SPSC meeting
20/10/2020	Feedback from SPSC

September 25, 2019

Gamma Factory
Proof-of-Principle Experiment

LETTER OF INTENT

CERN-SPSC-2019-031 / SPSC-I-253
25/09/2019

Gamma Factory Study Group

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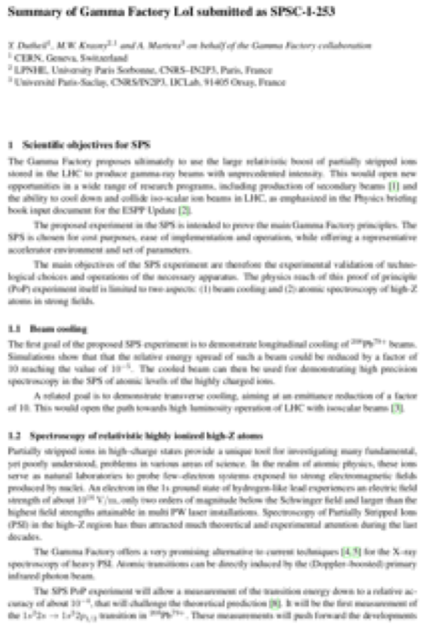
Y. Dutheil, yann.dutheil@cern.ch – **Gamma Factory PoP study – CERN coordinator**



Summary of Gamma Factory LoI submitted as SPSC-I-253

Y. Dutheil[1], *M.W. Krasny*[2,1] *and A. Martens*[3] *on behalf of the Gamma Factory collaboration*
[1] CERN, Geneva, Switzerland
[2] LPNHE, University Paris Sorbonne, CNRS–IN2P3, Paris, France
[3] Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France

1 Scientific objectives for SPS

The Gamma Factory proposes ultimately to use the large relativistic boost of partially stripped ions stored in the LHC to produce gamma-ray beams with unprecedented intensity. This would open new opportunities in a wide range of research programs, including production of secondary beams [1] and the ability to cool down and collide iso-scalar ion beams in LHC, as emphasized in the Physics briefing book input document for the ESPP Update [2].

The proposed experiment in the SPS is intended to prove the main Gamma Factory principles. The SPS is chosen for cost purposes, ease of implementation and operation, while offering a representative accelerator environment and set of parameters.

The main objectives of the SPS experiment are therefore the experimental validation of technological choices and operations of the necessary apparatus. The physics reach of this proof of principle (PoP) experiment itself is limited to two aspects: (1) beam cooling and (2) atomic spectroscopy of high-Z atoms in strong fields.

1.1 Beam cooling

The first goal of the proposed SPS experiment is to demonstrate longitudinal cooling of $^{208}\mathrm{Pb}^{79+}$ beams. Simulations show that that the relative energy spread of such a beam could be reduced by a factor of 10 reaching the value of 10^{-5}. The cooled beam can then be used for demonstrating high precision spectroscopy in the SPS of atomic levels of the highly charged ions.

A related goal is to demonstrate transverse cooling, aiming at an emittance reduction of a factor of 10. This would open the path towards high luminosity operation of LHC with isoscalar beams [3].

1.2 Spectroscopy of relativistic highly ionized high-Z atoms

Partially stripped ions in high-charge states provide a unique tool for investigating many fundamental, yet poorly understood, problems in various areas of science. In the realm of atomic physics, these ions serve as natural laboratories to probe few-electron systems exposed to strong electromagnetic fields produced by nuclei. An electron in the 1s ground state of hydrogen-like lead experiences an electric field strength of about 10^{16} V/cm, only two orders of magnitude below the Schwinger field and larger than the highest field strengths attainable in multi PW laser installations. Spectroscopy of Partially Stripped Ions (PSI) in the high–Z region has thus attracted much theoretical and experimental attention during the last decades.

The Gamma Factory offers a very promising alternative to current techniques [4, 5] for the X-ray spectroscopy of heavy PSI. Atomic transitions can be directly induced by the (Doppler-boosted) primary infrared photon beam.

The SPS PoP experiment will allow a measurement of the transition energy down to a relative accuracy of about 10^{-4}, that will challenge the theoretical prediction [6]. It will be the first measurement of the $1s^2 2s \rightarrow 1s^2 2p_{1/2}$ transition in $^{208}\mathrm{Pb}^{79+}$. These measurements will push forward the developments

- "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."

Also presented @ 257th LHC Injector and Experimental Facilities Committee : https://indico.cern.ch/event/861645/

M. W. Krasny et al. SPSC-I-253, M.W. Krasny arXiv:1511.07794

Planned 2021 activities

Integration

- Detailed simulations to estimate radiation levels delivered to laser system
- Progress on optical room design

Beam dynamics studies

- Fast transverse cooling ?

'Project management'

- Formalize the work organization
- Find appropriate related budgets
- Formal collaboration agreements

Project funding

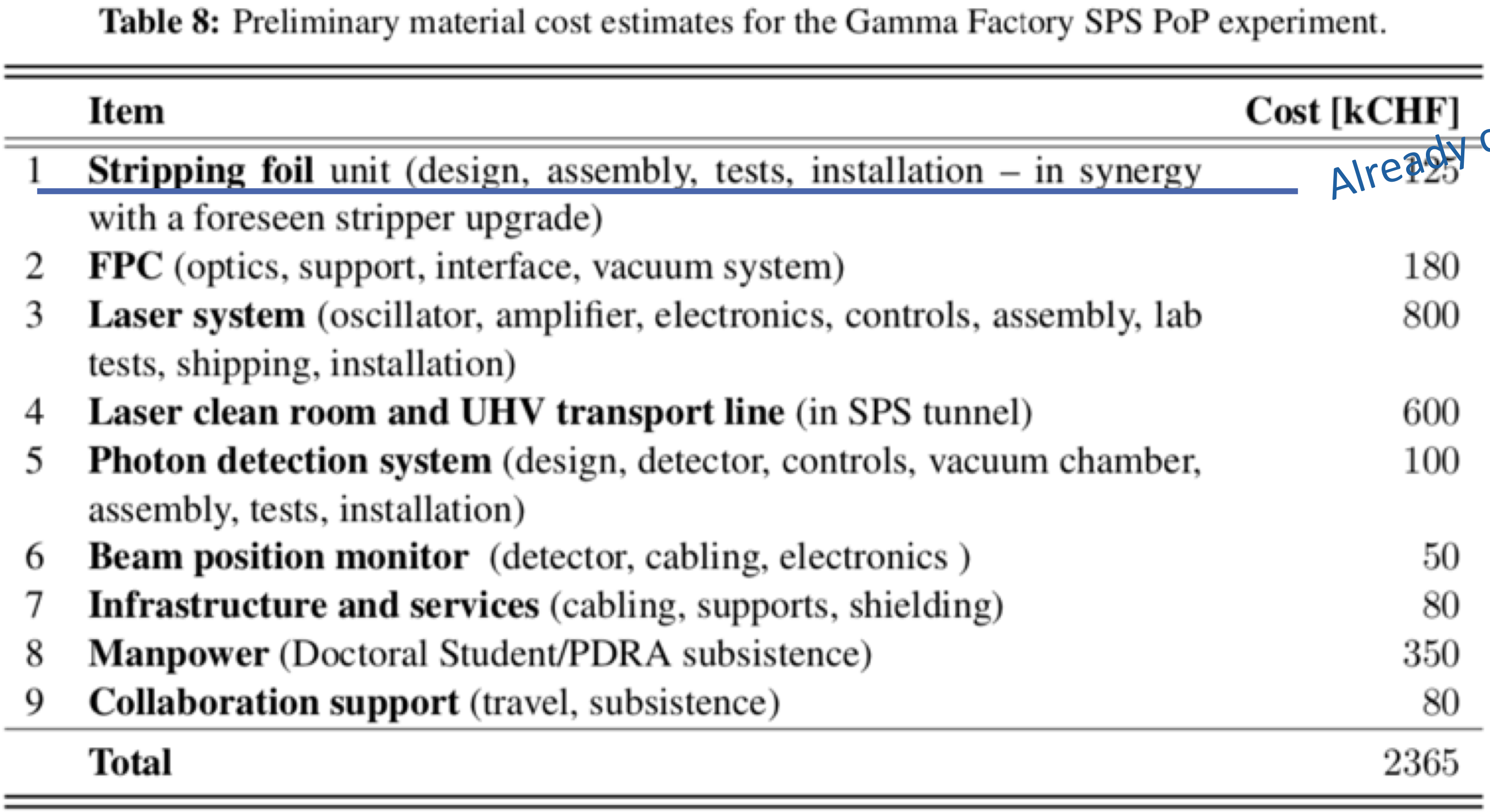


Table 8: Preliminary material cost estimates for the Gamma Factory SPS PoP experiment.

	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

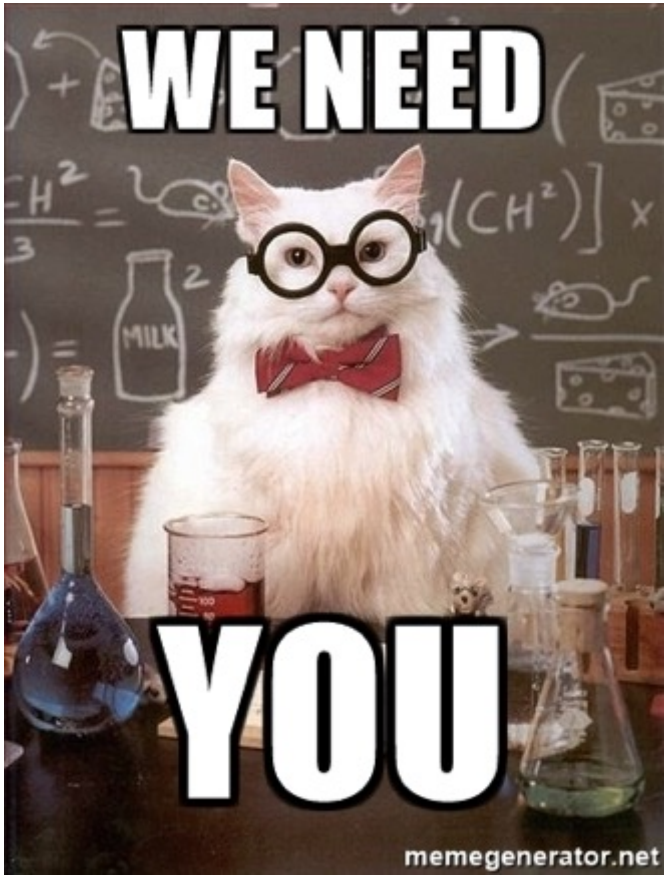
Already covered

The main question

Who will visit us by the end of the year ? Saint Nicholas or the bogeyman ?

Conclusion

The PoP collaboration is being formalized



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If you want to contribute to any of its aspects do not hesitate to contact us

BACKUP

Impact on regular SPS operations

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Vacuum

- Optical cavity requires similar or better vacuum compared to SPS
- Valves to break vacuum on a limited section of SPS → CERN experts

Impedance

- Past experience on low emittance KEK ATF
- Require formal validation of final design by CERN experts

Remote operations

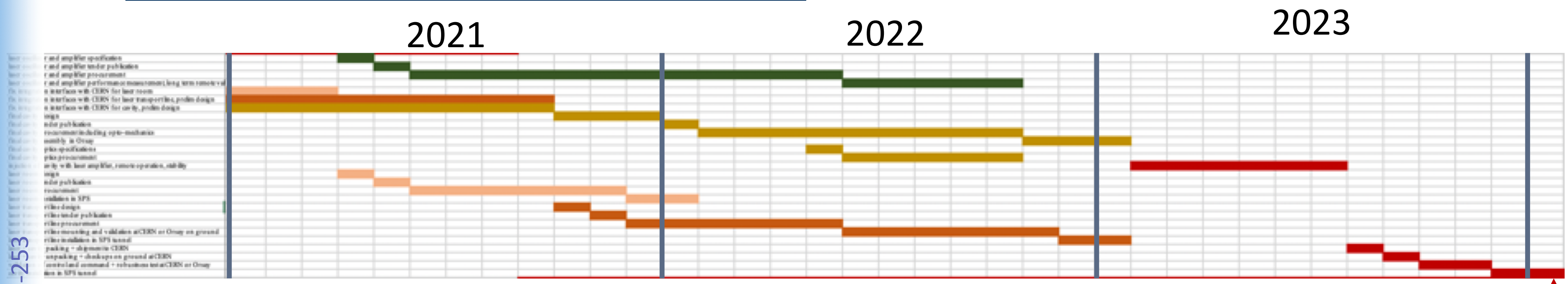
- Will be addressed during cavity and laser system implementation in lab

Parasitic operations

- Laser beam has no sizeable effect on proton/fully stripped hadronic beam

Project planning

Currently being re-assessed:
New target: installation over LS3 (2024)



2021: review infrastructure and radiation matters

Operational after 2023-2024 YETS

6 months of operation of optical cavity in lab

Installation of laser beam transport line in 2022-2023 YETS

optical cavity assembly in fall 2022

Laser room in TI18 during 2021-2022 YETS

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PoP milestones and beam requests

Could be done over a year at the SPS

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Resonance finding

Commissioning with PSI before yearly ion run	8h dedicated beamtime
Realize synchronization, alignment	4x8h in SPS supercycle // NA ops

Optimisation and characterisation

Optimize interaction rate	8h dedicated beamtime
Stable measured rate of photons over >5s	8h in SPS supercycle // NA ops

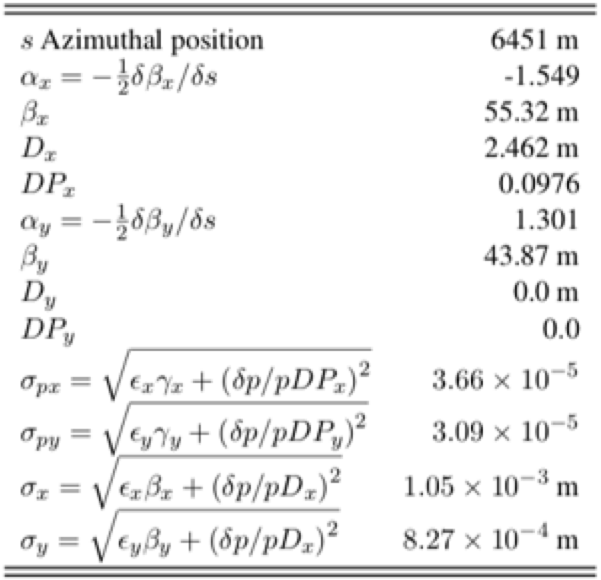
Cooling demonstration

Show increase of beam current at constant charge	2x8h dedicated beamtime
Measure transverse beam size reduction	8h in SPS supercycle // NA

Atomic physics precision measurement

First measurement of Pb79+ transition energy	8h in SPS supercycle // NA
Confront theory (strong field QED,…) to experiment	8h dedicated beamtime

Table 7: Optical parameters at the IP in the half-cell 621.



s Azimuthal position	6451 m
$\alpha_x = -\frac{1}{2}\delta\beta_x/\delta s$	-1.549
β_x	55.32 m
D_x	2.462 m
DP_x	0.0976
$\alpha_y = -\frac{1}{2}\delta\beta_y/\delta s$	1.301
β_y	43.87 m
D_y	0.0 m
DP_y	0.0
$\sigma_{px} = \sqrt{\epsilon_x\gamma_x + (\delta p/pDP_x)^2}$	3.66×10^{-5}
$\sigma_{py} = \sqrt{\epsilon_y\gamma_y + (\delta p/pDP_y)^2}$	3.09×10^{-5}
$\sigma_x = \sqrt{\epsilon_x\beta_x + (\delta p/pD_x)^2}$	1.05×10^{-3} m
$\sigma_y = \sqrt{\epsilon_y\beta_y + (\delta p/pD_x)^2}$	8.27×10^{-4} m