Gamma Factory:
Proof of Principle Experiment

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The Gamma Factory study group

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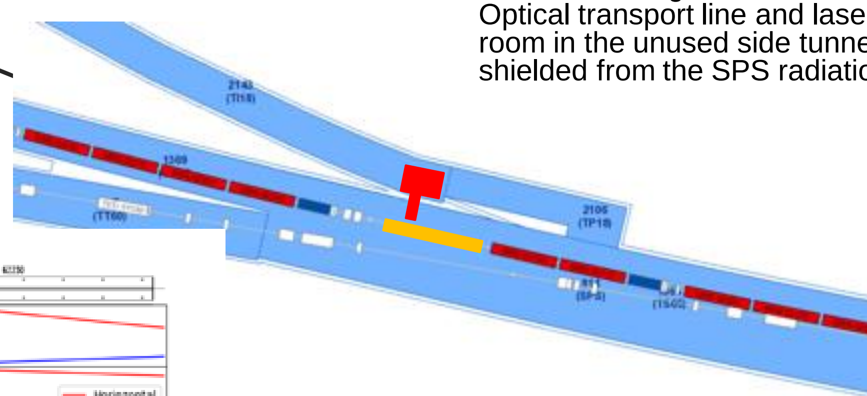
88 people from 34 institutes from 15 countries

The scheme – artist's view

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



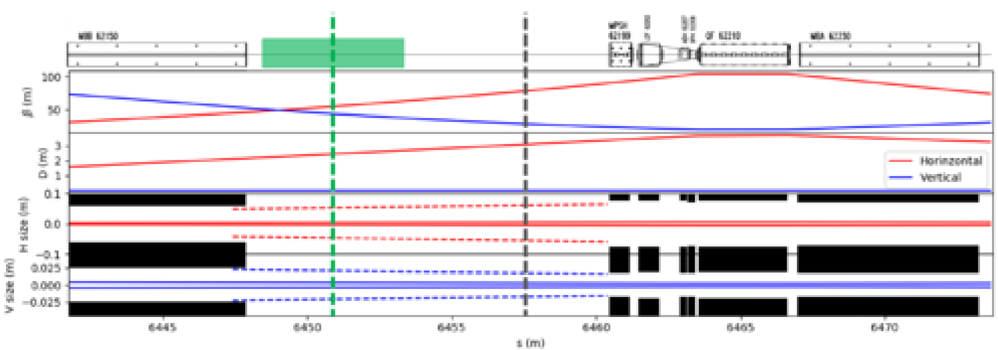
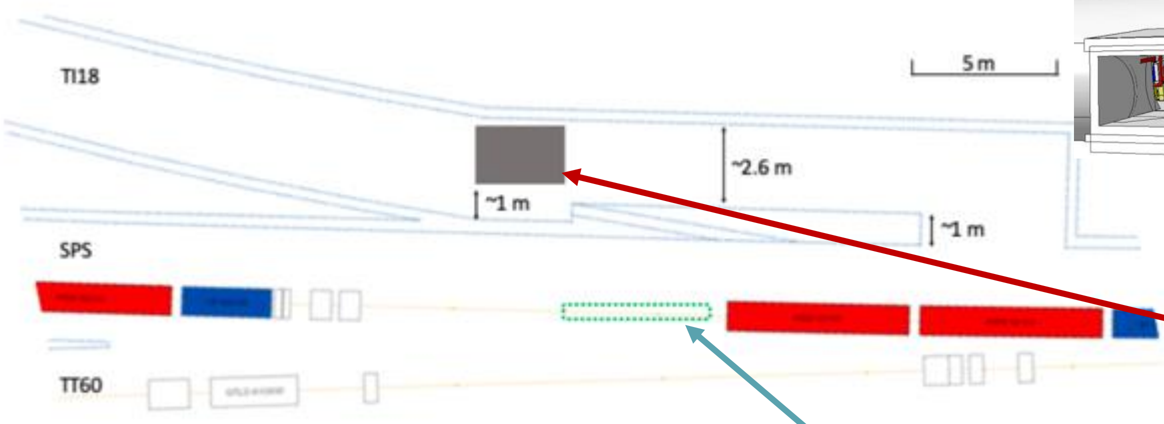
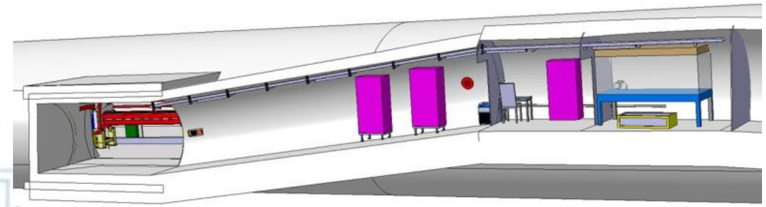
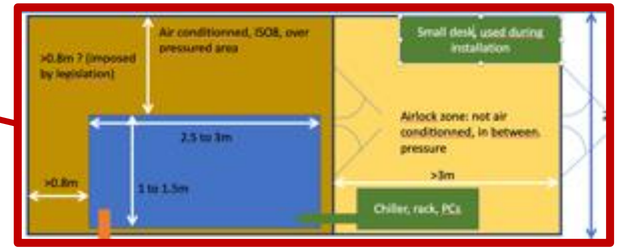


Fig. 7: Layout, optical functions and beam sizes with aperture limits around the interaction region. The IP is represented by a vertical green dotted line and the laser cavity by the green box. The vertical grey dotted line represents the location of the X-Ray detector. Note that the beam goes from left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

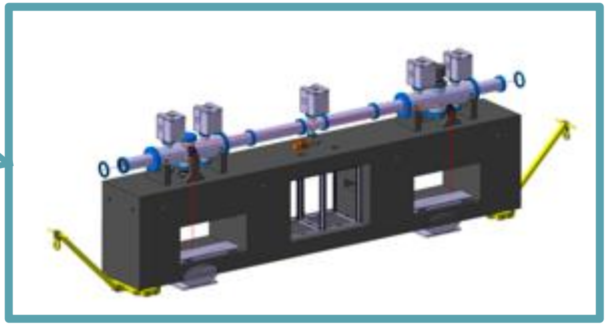
Optical system: integration







SPS half-cell 621 with side tunnel TI18



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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

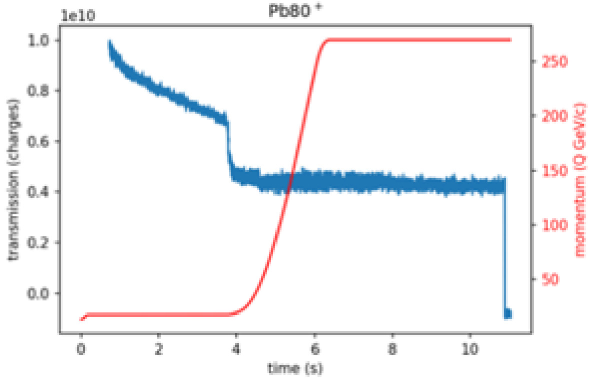
Accessible transition with convenient laser system

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

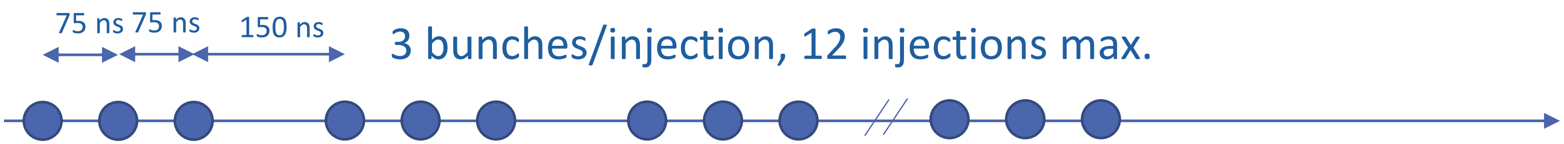
Beam parameters

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

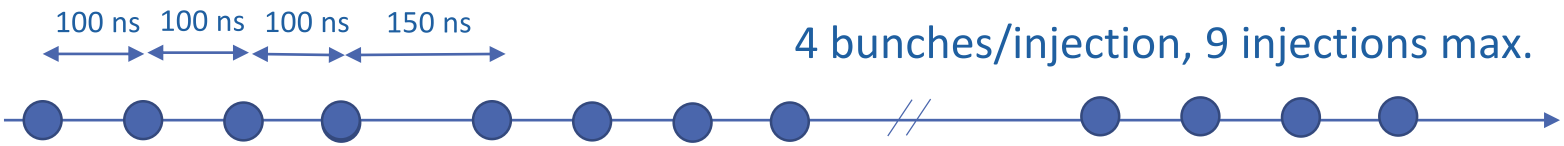
Lifetime is long enough at flat top for Pb^{80+}
→ Extrapolated for Pb^{79+}: about 100s



3 bunches/injection, 12 injections max.



4 bunches/injection, 9 injections max.

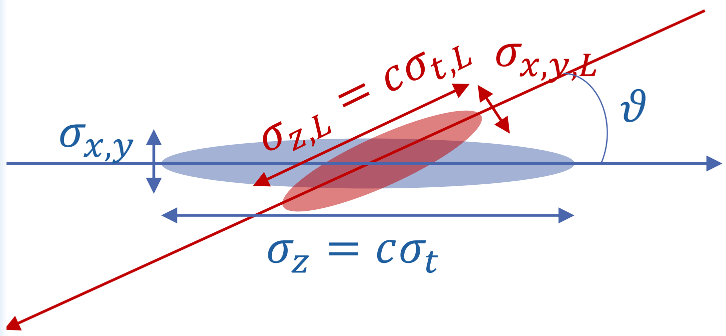


Common harmonic frequency=40MHz

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

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

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

Synchro. & alignment with beam

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

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

Final design still needs to be drawn and cost estimate be consolidated

Optical cavity at the state of the art

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

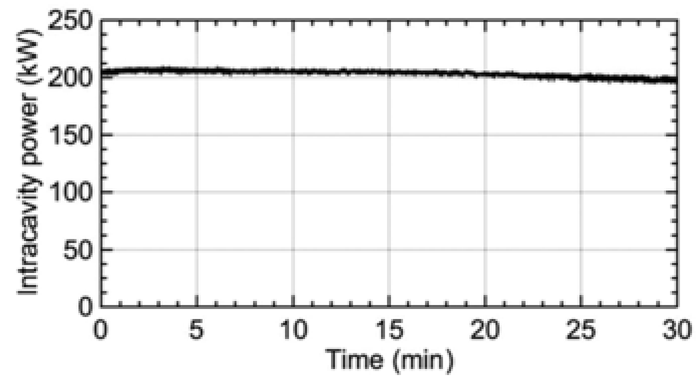


Fig. 7. Laser intracavity power for 30 min, measured by transmission of a cavity mirror.

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

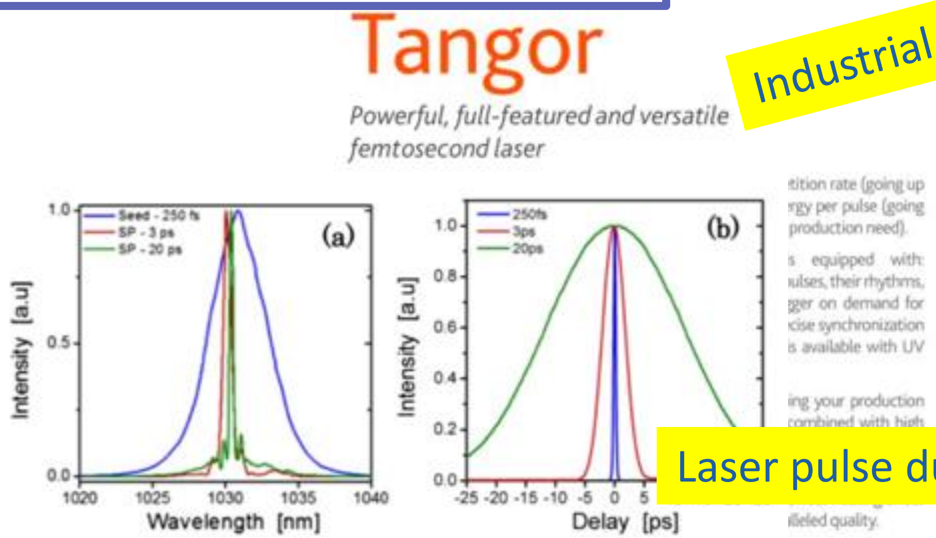
L. Amoudry et al., Applied Optics 59 (2020) 116; Chaikovska et al., Scientific Reports 6 (2016) 36569

Laser system

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

Versatile 50-100W laser amplifier



Industrial system exist !

Laser pulse duration/spectrum tunability is an asset

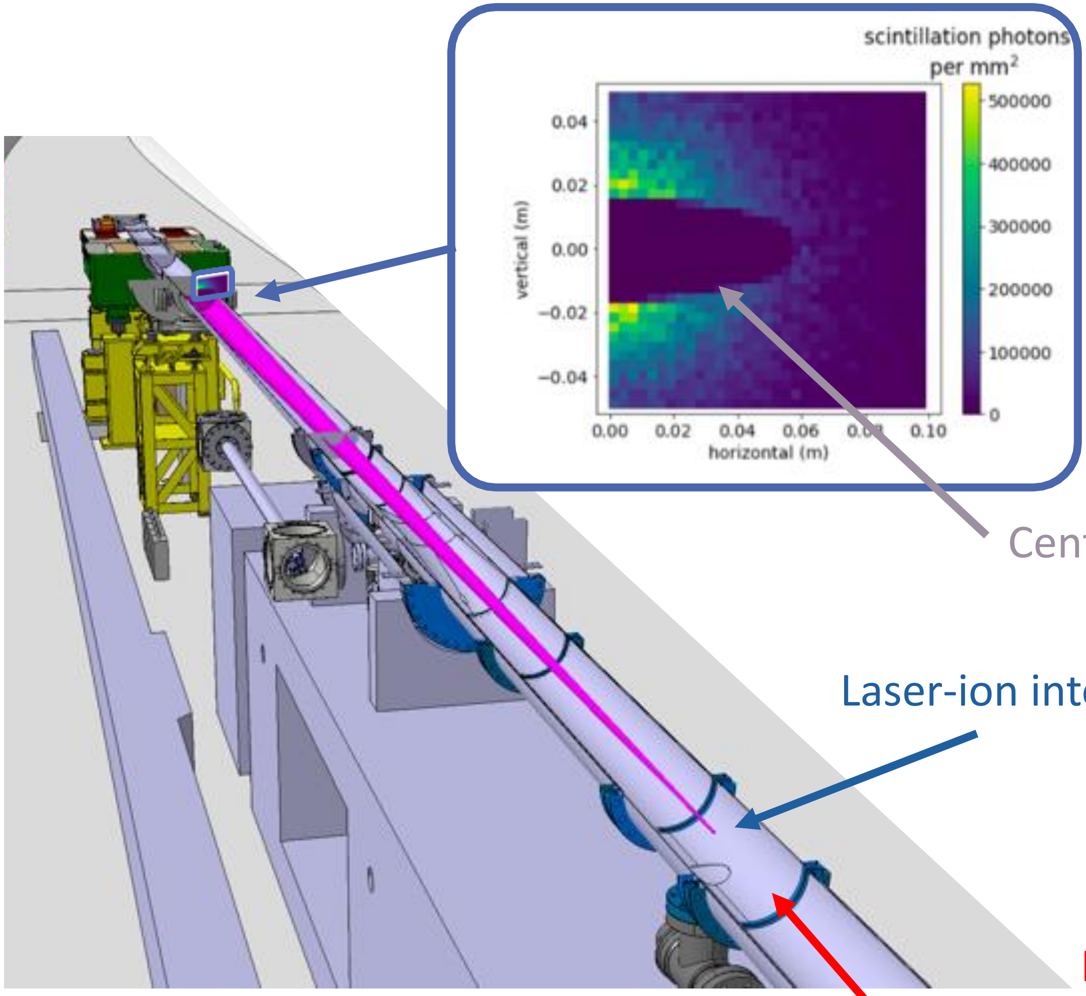
Pouysegur et al. Opt. Lett. 40, 5184-5187 (2015)

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

Detection system

'BTV' system: YAG:Ce + camera

Remotely controlled manipulator



Central opening for ion beam passage

Laser-ion interaction Point

Ion beam direction

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Ion beam cooling

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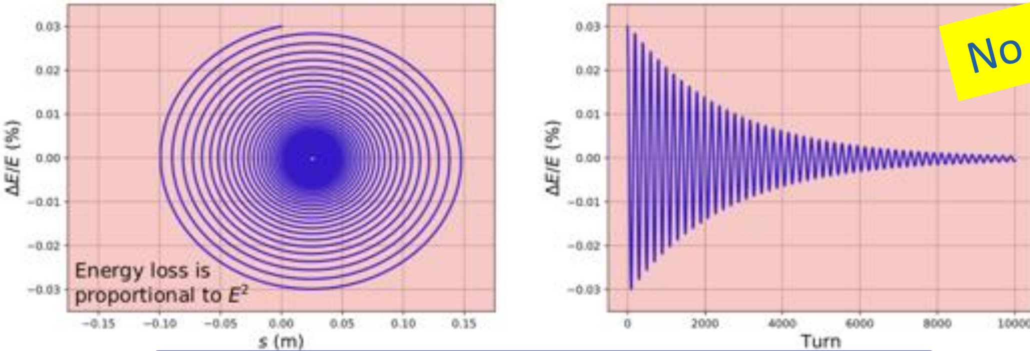
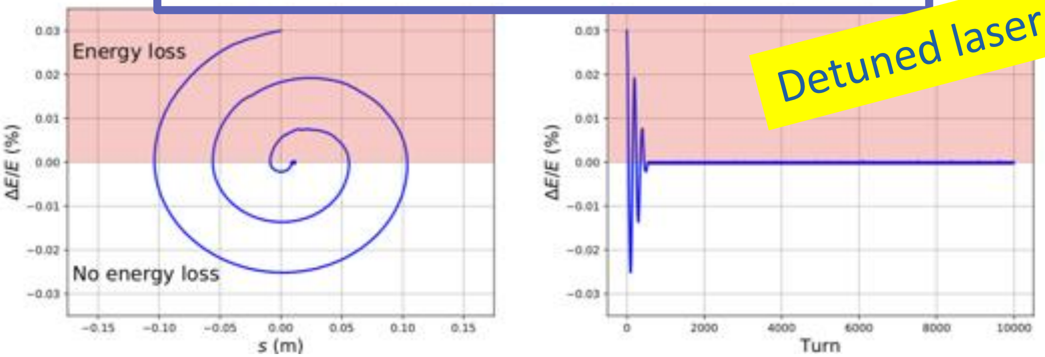
No detuning



Ion beam efficiently cooled

Detuned laser spectrum



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Review

High-luminosity Large Hadron Collider with laser-cooled isoscalar ion beams☆

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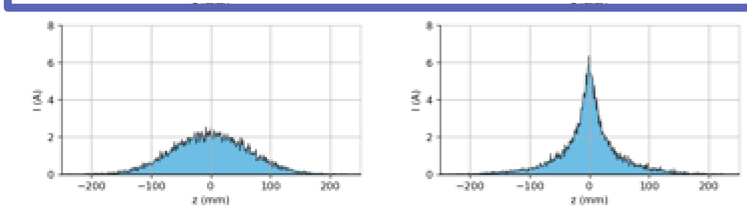
ABSTRACT

The existing CERN accelerator infrastructure is world unique and its research capacity should be fully exploited. In the coming decade its principal *modus operandi* will be focused on producing intense proton beams, accelerating and colliding them at the Large Hadron Collider (LHC) with the highest achievable luminosity. This activity should, in our view, be complemented by new initiatives and their feasibility studies targeted on re-using the existing CERN accelerator complex in novel ways that were not conceived when the machines were designed. They should provide attractive, ready-to-implement research options for the forthcoming *paradigm-shift* phase of the CERN research. This paper presents one of the case studies of the *Gamma Factory* initiative (Krasny, 2015) – a proposal of a new operation scheme of ion beams in the CERN accelerator complex. Its goal is to extend the scope and precision of the LHC-based research by complementing the proton–proton collision programme with the *high-luminosity* nucleus–nucleus one. Its numerous physics highlights include studies of the exclusive Higgs-boson production in photon–photon collisions and precision measurements of the electroweak (EW) parameters. There are two principal ways to increase the LHC luminosity which do not require an upgrade of the CERN injectors: (1) modification of the beam-collision optics and (2) reduction of the transverse emittance of the colliding beams. The former scheme is employed by the ongoing high-luminosity (HL-LHC) project. The latter one, applicable only to ion beams, is proposed in this paper. It is based on laser cooling of bunches of partially stripped ions at the SPS flat-top energy. For isoscalar calcium beams, which fulfil the present beam-operation constrains and which are particularly attractive for the EW physics, the transverse beam emittance can be reduced by a factor of 5 within the 8 seconds long cooling phase. The predicted nucleon–nucleon luminosity of $L_{NN} = 4.2 \times 10^{34}\,s^{-1}cm^{-2}$ for collisions of the cooled calcium beams at the LHC top energy is comparable to the levelled luminosity for the HL-LHC proton–proton collisions, but with reduced pile-up background. The scheme proposed in this paper, if confirmed by the future Gamma Factory proof-of-principle experiment, could be implemented at CERN with minor infrastructure investments.

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

Impact on regular SPS operations

Vacuum

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

Impedance

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

Remote operations

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

Parasitic operations

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

Costing

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

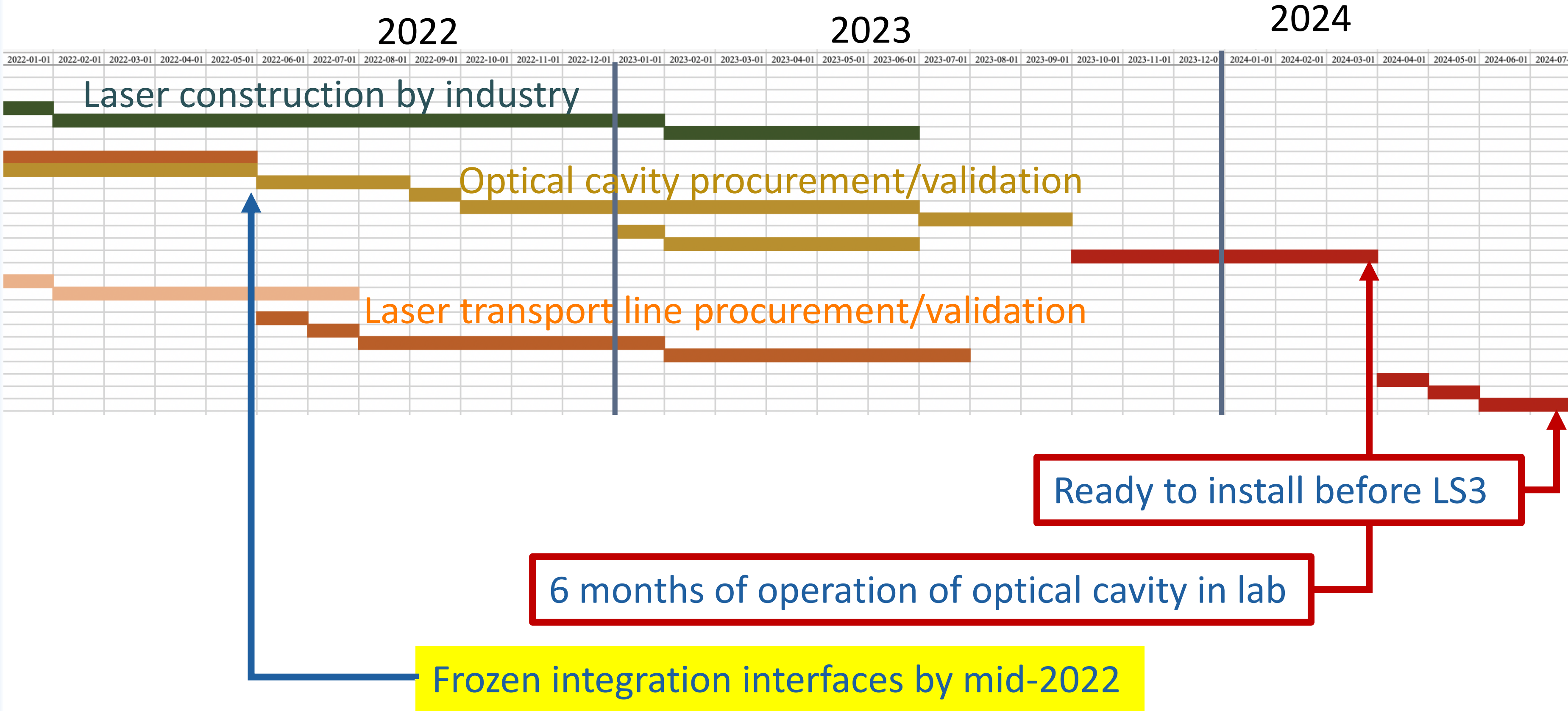
Already covered

Consolidation of costing for infrastructure and services is ongoing

Project planning

Target: installation over LS3 (2025)

Assumes funds are available from Jan 2022



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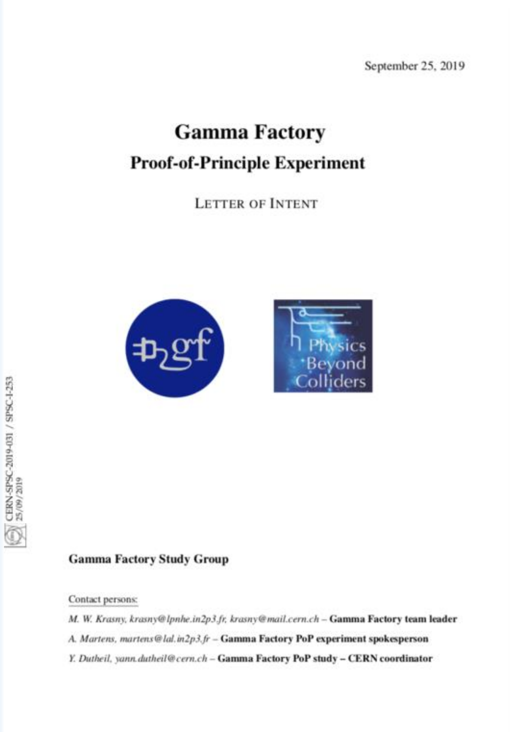
Feedback from SPSC committee

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


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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As received from referees on oct. 20th 2020

« 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. »

We are currently formalizing the collaboration → MoU

Summary: planned 2021 activities

Implementation

- Compatible with installation in 2025 (injector's LS3)
- Detailed simulations to estimate radiation levels delivered to laser system
- Finalize design of synchronization system
- Progress on optical room design, ventilation, safety, vacuum, … → costing

Physics

- Many ongoing studies → long term implications, see Witek's & Reuven's for instance

'Project management'

- Formalize the work organization → MoU
- Experiment funding is getting critical

BACKUP

Radiation hardness

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

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
*steve.lecomte@csem.ch

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

New ion stripper foils system

CERN
CH-1211 Geneva 23
Switzerland

EDMS NO.	REV.	VALIDITY
2404267	0.2	DRAFT

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.

DOCUMENT PREPARED BY:	DOCUMENT TO BE CHECKED BY:	DOCUMENT TO BE APPROVED BY:
R. Alemany Fernandez	N. Bianccaci, S. Burger, M. di Castro, Y. Dutheil, J. A. Ferreira Somoza, E. Grenier-Boley, B. Goddard, J. Lendaro, A. Martens, R. Scrivens, F. M. Velotti	M. Calviani, S. Gilardoni, W. Krasny

DOCUMENT SENT FOR INFORMATION TO:

V. Kain, D. Kuchler, E. Mahner

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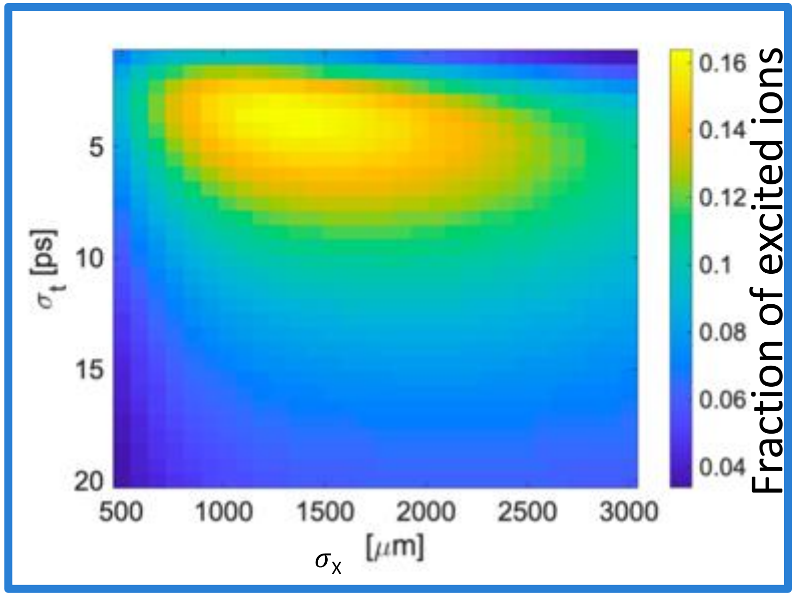
Common need with other experiments to add flexibility in stripping capability:

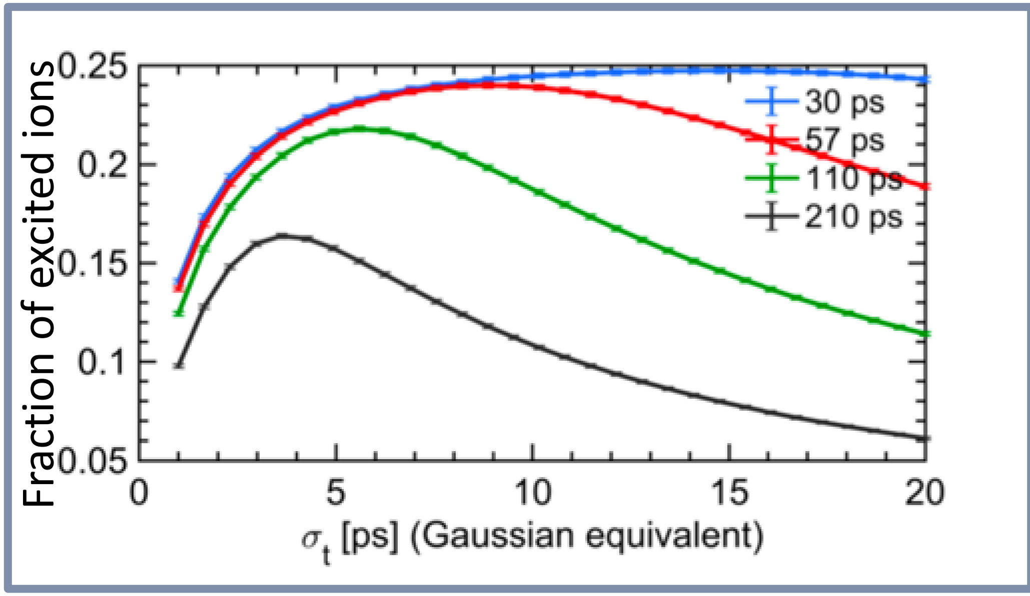
- 4 foils
- Angle (thickness) can be tuned
- Pulse to pulse operation !
- 35% stripping efficiency for Pb^{79+}

Will allow *parasitic* Gamma Factory Proof of principle operation

Optical system optimization



A muti-dimensional approach to optimize the laser beam parameters



Optimum parameters depend on ion-bunch length

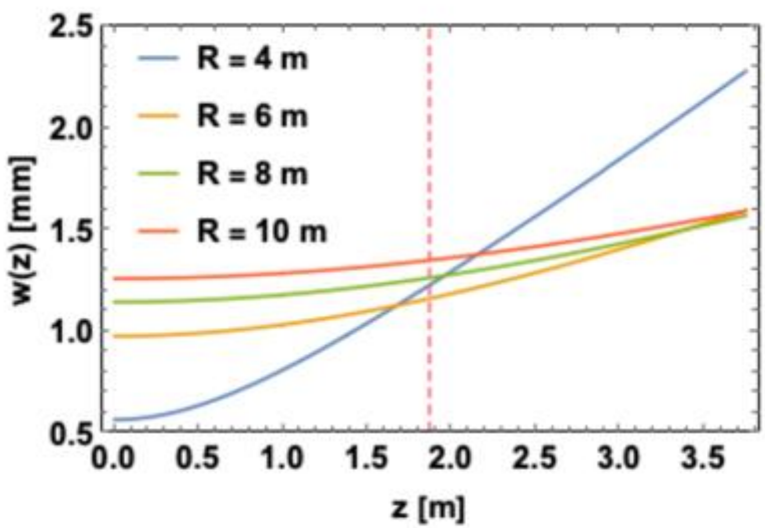
Laser pulse duration/spectrum tunability is an asset

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

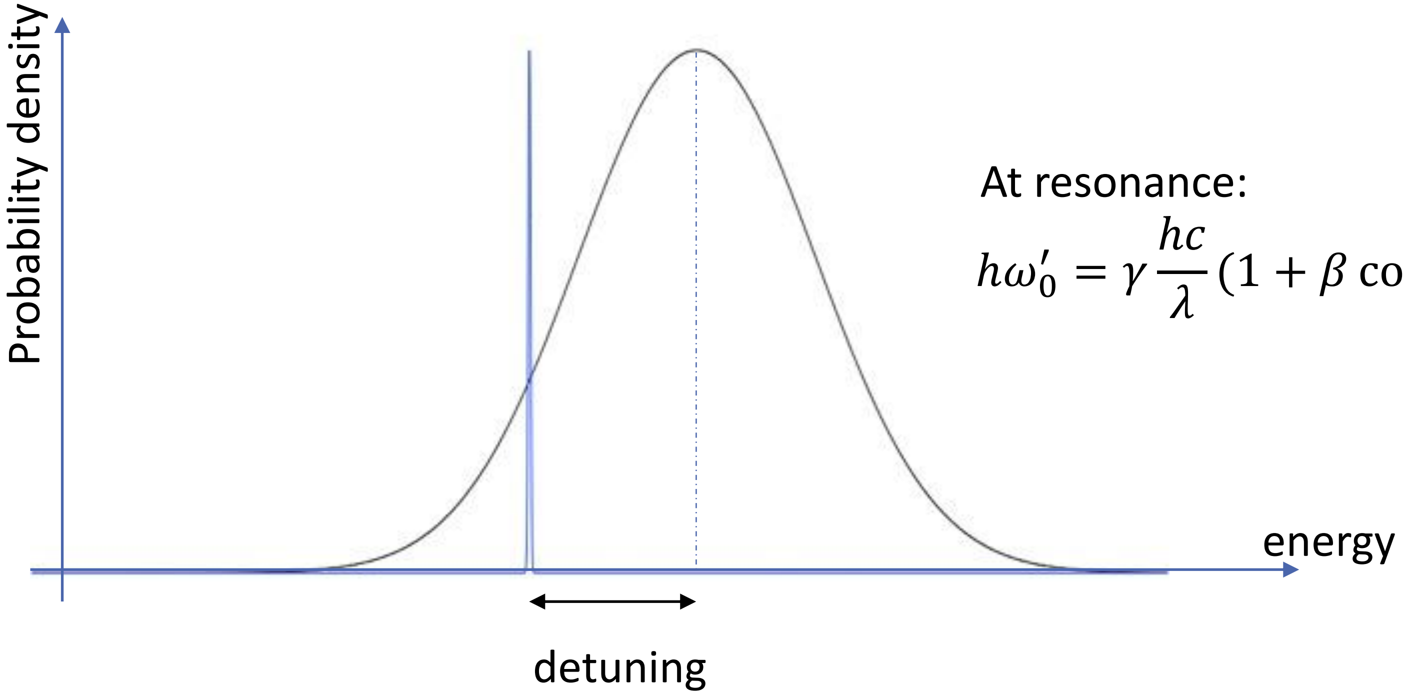
>4.5mJ pulses @ 40MHz, 180kW in cavity

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

Spectrum matching

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

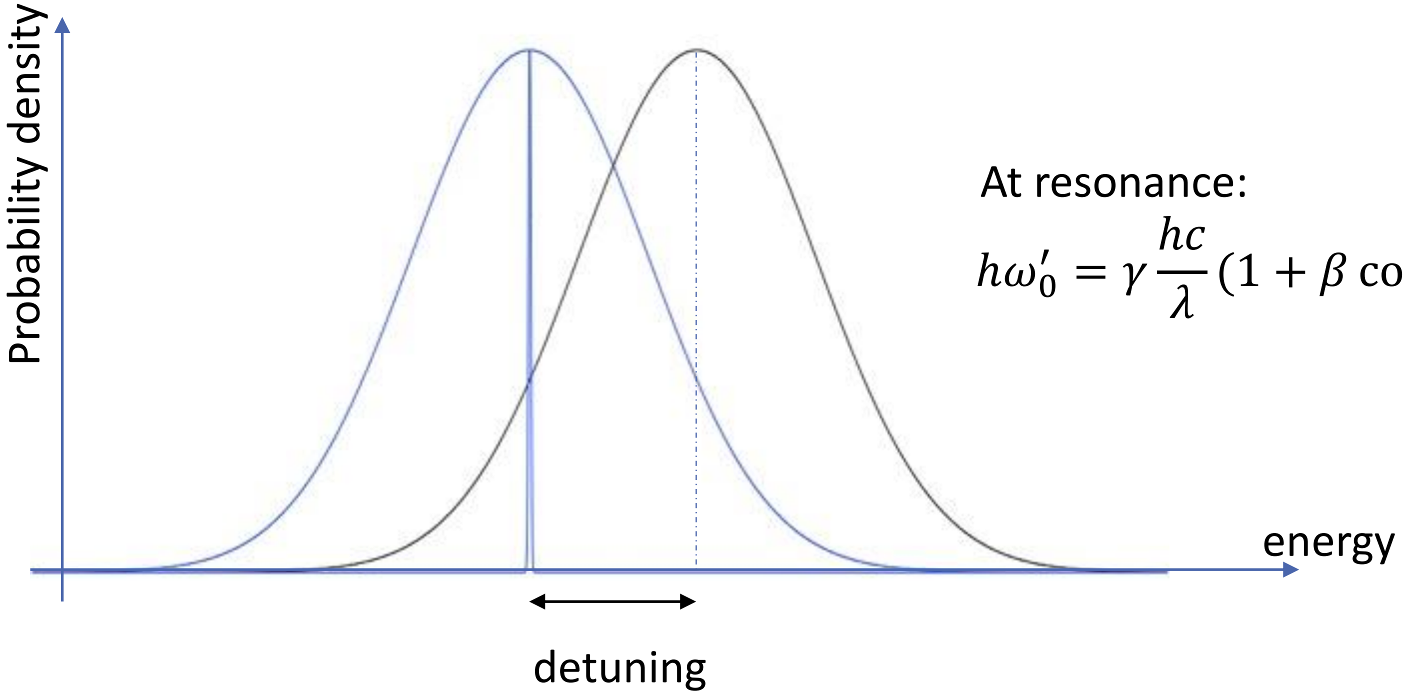


At resonance:

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

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

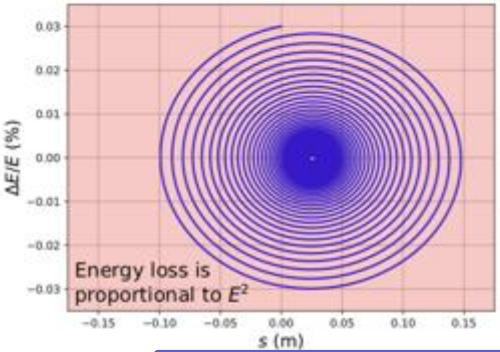
About 10^{14} ph/s at the SPS

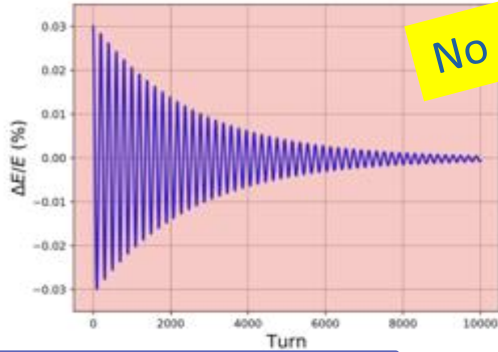
Excitation rate of atoms depend on their position in the energy spectrum

Ion beam cooling

interesting application:
→ talk by A. Petrenko

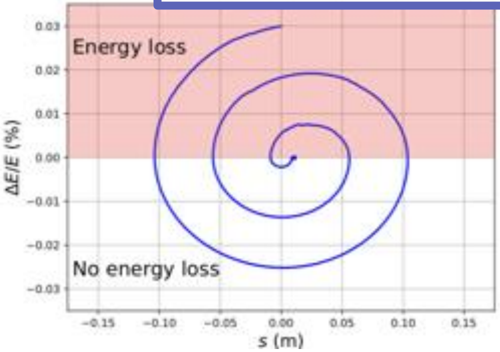
No detuning

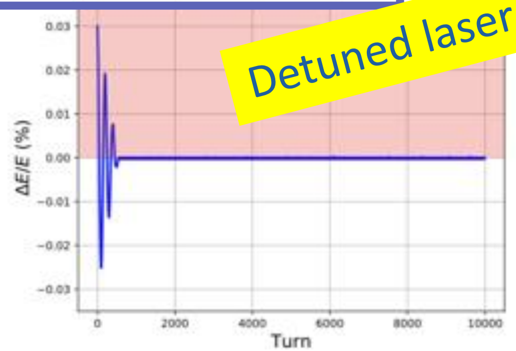




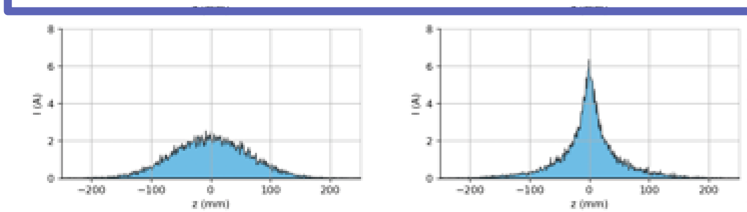
Ion beam efficiently cooled

Detuned laser spectrum





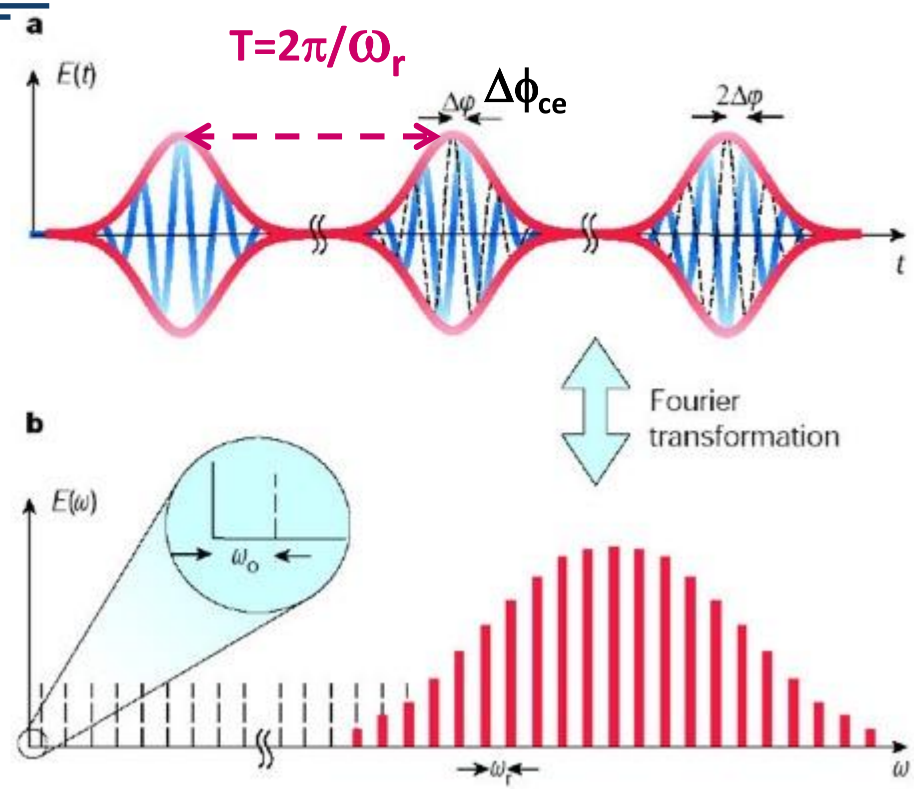
Observe it with wall current monitors



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

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

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

PoP milestones and beam requests

Could be done over a year at the SPS

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

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

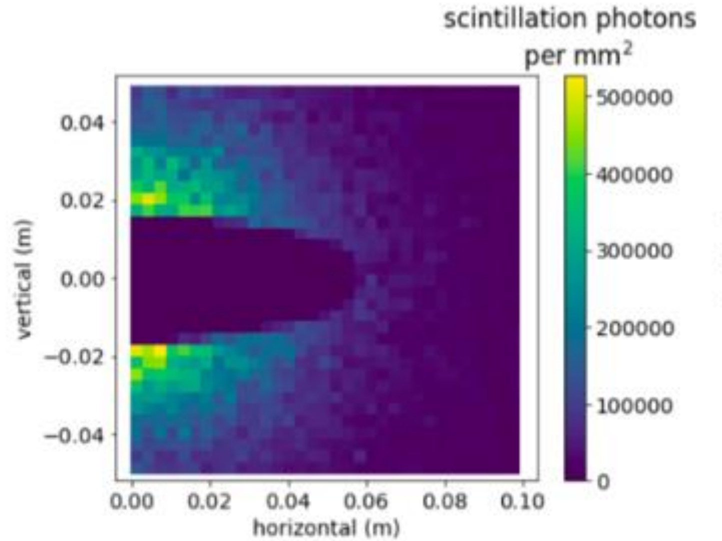
Atomic physics precision measurement

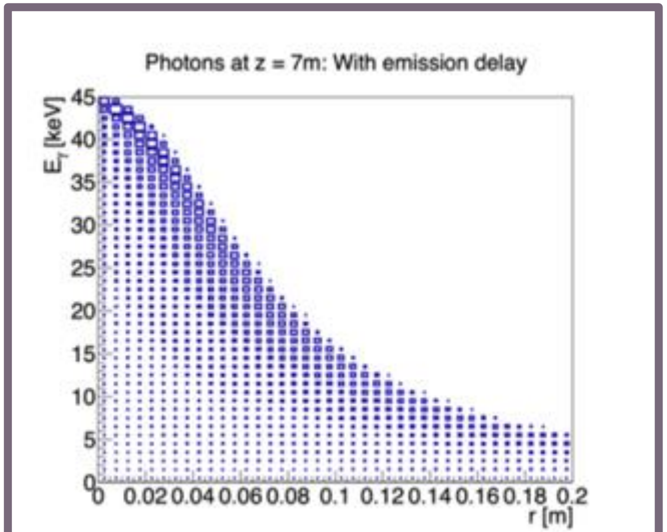
- First measurement of Pb79+ transition energy — 8h in SPS supercycle // NA
- Confront theory (strong field QED,…) to experiment — 8h dedicated beamtime

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 ?

SPS half-cell 621 with side tunnel TI18

Optical system: integration

Thanks to Liam Dougherty for the help

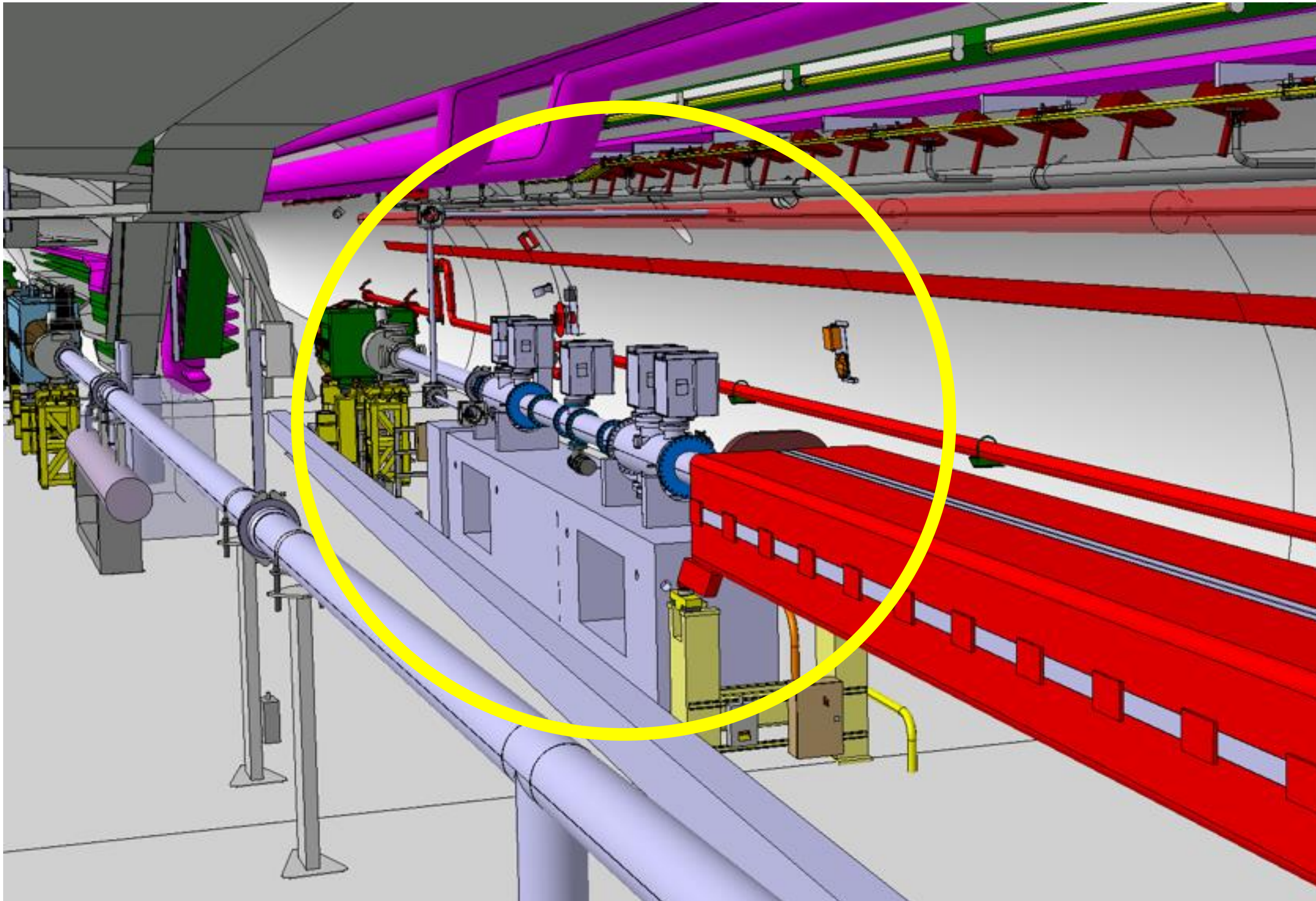


Table 7: Optical parameters at the IP in the half-cell 621.

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