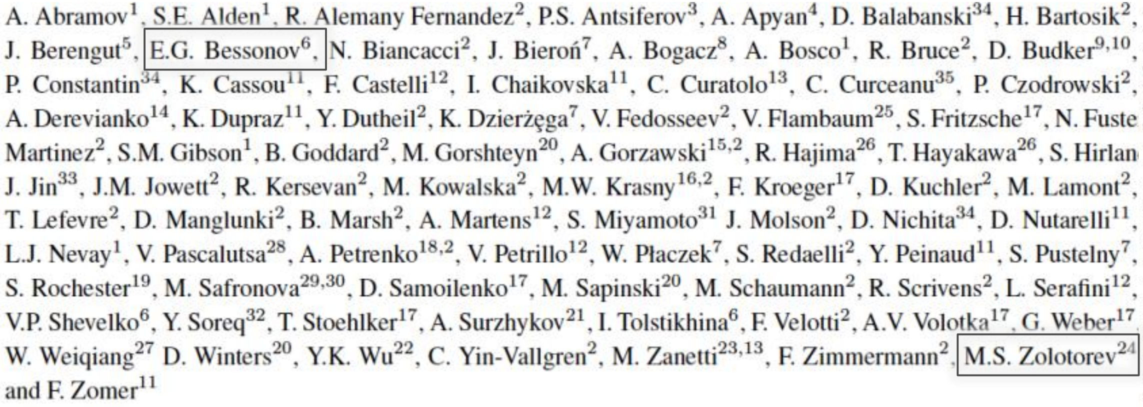

CERN

Producing an intense gamma beam at the Gamma Factory

Valentin Fedosseev, CERN
On behalf of the Gamma Factory collaboration

Using slides from Witek Krasny and Yann Dutheil

Gamma Factory (PBC) study group



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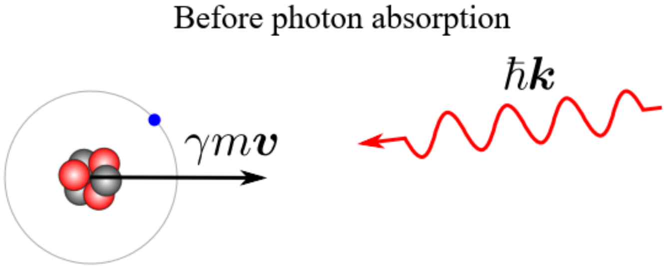
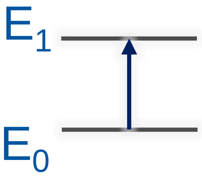
The Gamma Factory initiative (arXiv:1511.07794 [hep-ex]) was supported by the CERN management by creating (February 2017) the Gamma Factory study group, embedded within the Physics Beyond Colliders studies framework.
~90 physicists from 35 institutions have contributed so far to the development of the project. The GF group is open for everyone who wants to contribute.

Basic principle



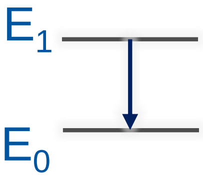
Two-step backward resonance scattering by ultra-relativistic partially stripped ion:

1. Resonant absorption of Doppler-shifted laser photon by accelerated ion in ions reference frame



$$h\nu_{tr} = E_2 - E_1 = \gamma(1+\beta) \times h\nu_{las}$$

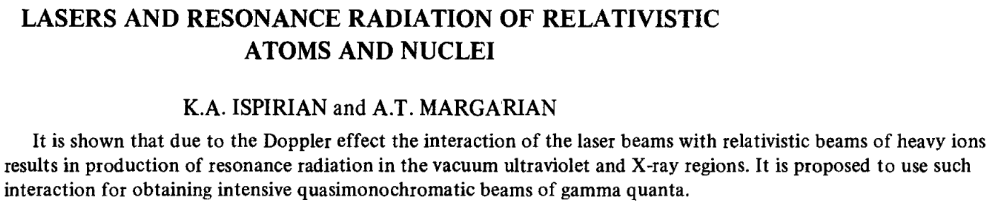
2. Spontaneous decay of excited ion with emission of additionally Doppler-shifted photon in the laboratory reference frame



$$h\nu_{rad} = \gamma(1+\beta) \times h\nu_{trs} = \gamma^2(1+\beta)^2 \times h\nu^{las}$$

Historical references

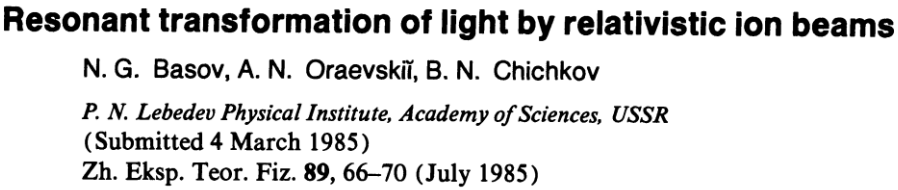
Phys. Lett. A 44 (1973) 377-378



LASERS AND RESONANCE RADIATION OF RELATIVISTIC ATOMS AND NUCLEI

K.A. ISPIRIAN and A.T. MARGARIAN

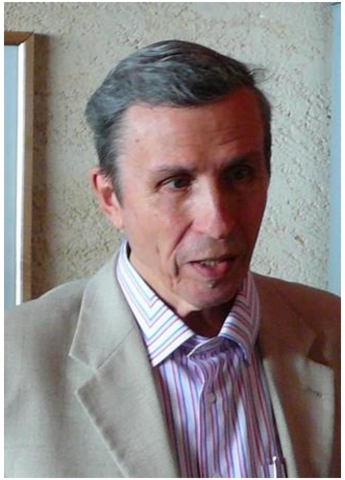
It is shown that due to the Doppler effect the interaction of the laser beams with relativistic beams of heavy ions results in production of resonance radiation in the vacuum ultraviolet and X-ray regions. It is proposed to use such interaction for obtaining intensive quasimonochromatic beams of gamma quanta.



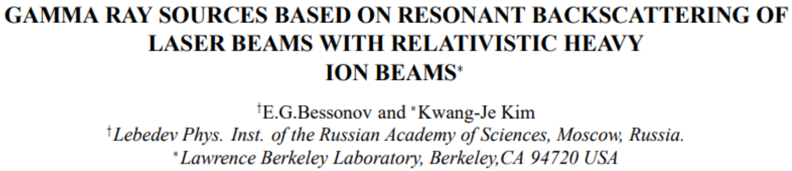
Resonant transformation of light by relativistic ion beams

N. G. Basov, A. N. Oraevskiĭ, B. N. Chichkov

P. N. Lebedev Physical Institute, Academy of Sciences, USSR
(Submitted 4 March 1985)
Zh. Eksp. Teor. Fiz. **89**, 66–70 (July 1985)

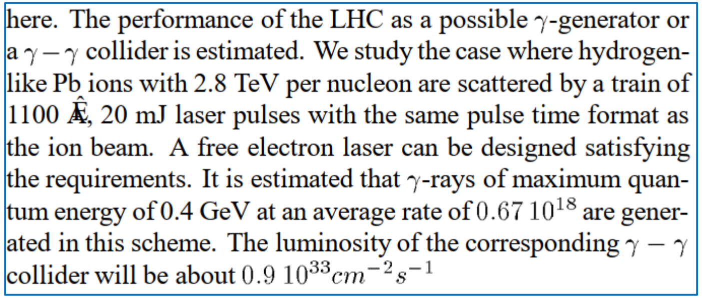


In Proc. of the 1995 Part. Accel. Conf. and Int. Conf. on High-Energy Accelerators, NY, p.2895

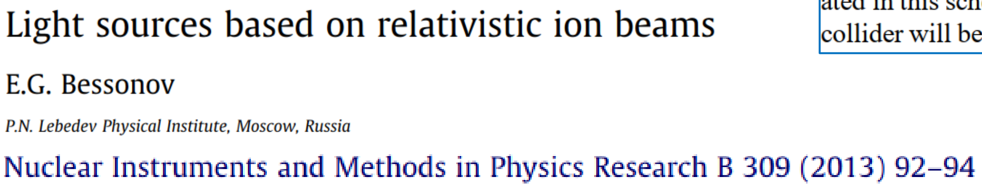


GAMMA RAY SOURCES BASED ON RESONANT BACKSCATTERING OF LASER BEAMS WITH RELATIVISTIC HEAVY ION BEAMS*

†E.G.Bessonov and *Kwang-Je Kim
†*Lebedev Phys. Inst. of the Russian Academy of Sciences, Moscow, Russia.*
**Lawrence Berkeley Laboratory, Berkeley,CA 94720 USA*



here. The performance of the LHC as a possible γ-generator or a $\gamma-\gamma$ collider is estimated. We study the case where hydrogen-like Pb ions with 2.8 TeV per nucleon are scattered by a train of 1100 Å, 20 mJ laser pulses with the same pulse time format as the ion beam. A free electron laser can be designed satisfying the requirements. It is estimated that γ-rays of maximum quantum energy of 0.4 GeV at an average rate of $0.67\ 10^{18}$ are generated in this scheme. The luminosity of the corresponding $\gamma-\gamma$ collider will be about $0.9\ 10^{33} cm^{-2} s^{-1}$



Light sources based on relativistic ion beams

E.G. Bessonov

P.N. Lebedev Physical Institute, Moscow, Russia

Nuclear Instruments and Methods in Physics Research B 309 (2013) 92–94

Gamma Factory: photon beam properties

High energy partially stripped ion beams play the role of high-stability light-frequency converters:

$$\nu^{\mathrm{max}} \longrightarrow (4\,\gamma_L^{2})\,\nu_{\mathrm{Laser}}$$

for photons emitted in the direction of incoming ions, $\gamma_L = E/M$ is the Lorentz factor for the ion beam

1. Point-like:

- *For high-Z, hydrogen- and helium-like atoms:* ***decay length ($c\tau\gamma_L$) << 1 cm***

Gamma Factory: photon beam properties

2. High intensity:

- ***Resonant** process. A leap in the intensity by **6–8 orders of magnitude** w.r.t. electron-beam-based Inverse Compton Sources (ICS) (at fixed γ_L and laser power)*

$$\sigma_{\max} = \sigma|_{\omega_{\mathrm{tr}}=\omega_l'} = g_2\lambda_{\mathrm{tr}}^2/2\pi g_1$$

Effective cross-section for broad-band laser

$$\bar{\sigma} = \pi f_{1,2} r_e \lambda_{tr}(\omega_l/\Delta\omega_l)$$

$$\approx 10^{-18}\ cm^2$$

ICS cross section

$$\sigma_e = 8\pi/3 \times r_e^2$$

$$\approx 10^{-25}\ cm^2$$

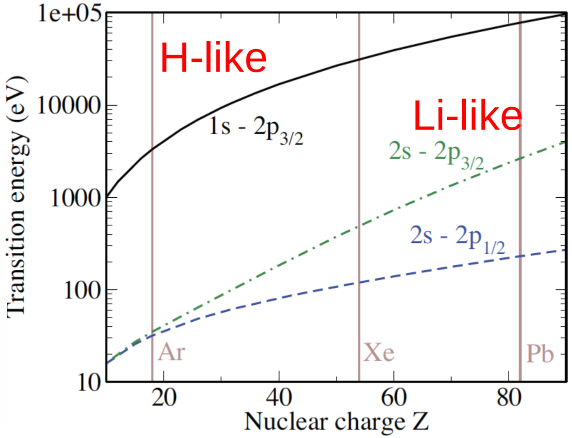
Gamma Factory: photon beam properties

3.Tuneable energy:

- *The tuning of the beam energy (SPS or LHC), the choice of the ion, the number of left electrons and of the laser type allow to tune the γ-ray energy at CERN in the energy range of 10 keV – 400 MeV* *(extending, by a factor of* ***~1000****, the energy range of the FEL X-ray sources)*

Hydrogen-like Ions

Transition energy $\Delta E_{nn'}$	$\propto (Z\alpha)^2$
Fine–structure splitting	$\propto (Z\alpha)^4$
Hyperfine–structure splitting	$\propto \alpha(Z\alpha)^3 m_e/m_p$
Lamb shift	$\propto \alpha(Z\alpha)^4$



Example (maximal energy):

LHC, Pb^{81+} *ion,* γ_L = 2887, n=1→2, λ_{laser} = 104.4 nm, E_γ (max) = 396 MeV

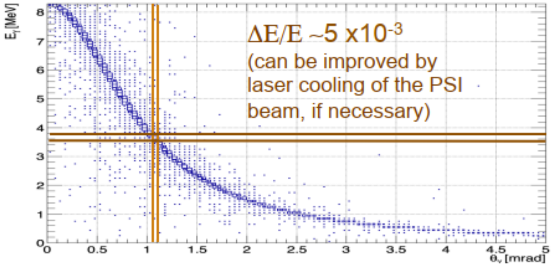
Gamma Factory: photon beam properties

4. Plug power efficient:

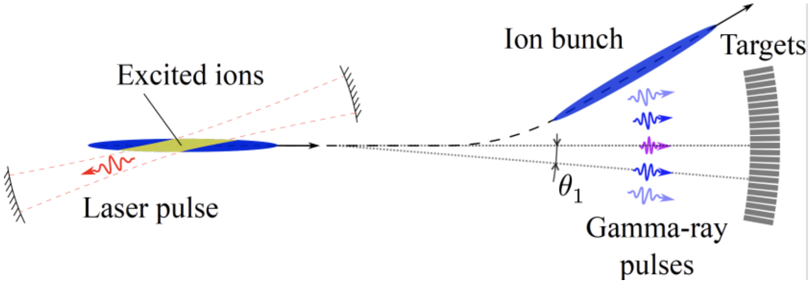
- ➢ *Atoms loose a tiny fraction of their energy in the process of the photon emission. Important: No need to refill the driver beam. The RF power is fully converted to the power of the photon beam*

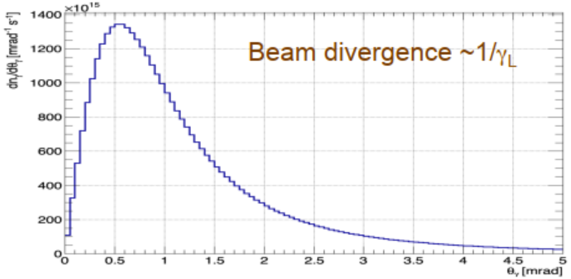
5. Highly-collimated monochromatic γ–beams:

- ➢ *the beam power is concentrated in a narrow angular region (facilitates beam extraction)*
- ➢ *the (E_γ,Θ_γ) correlation can be used (collimation) to "monochromatise" the beam*



$\Delta E/E \sim 5 \times 10^{-3}$
(can be improved by laser cooling of the PSI beam, if necessary)

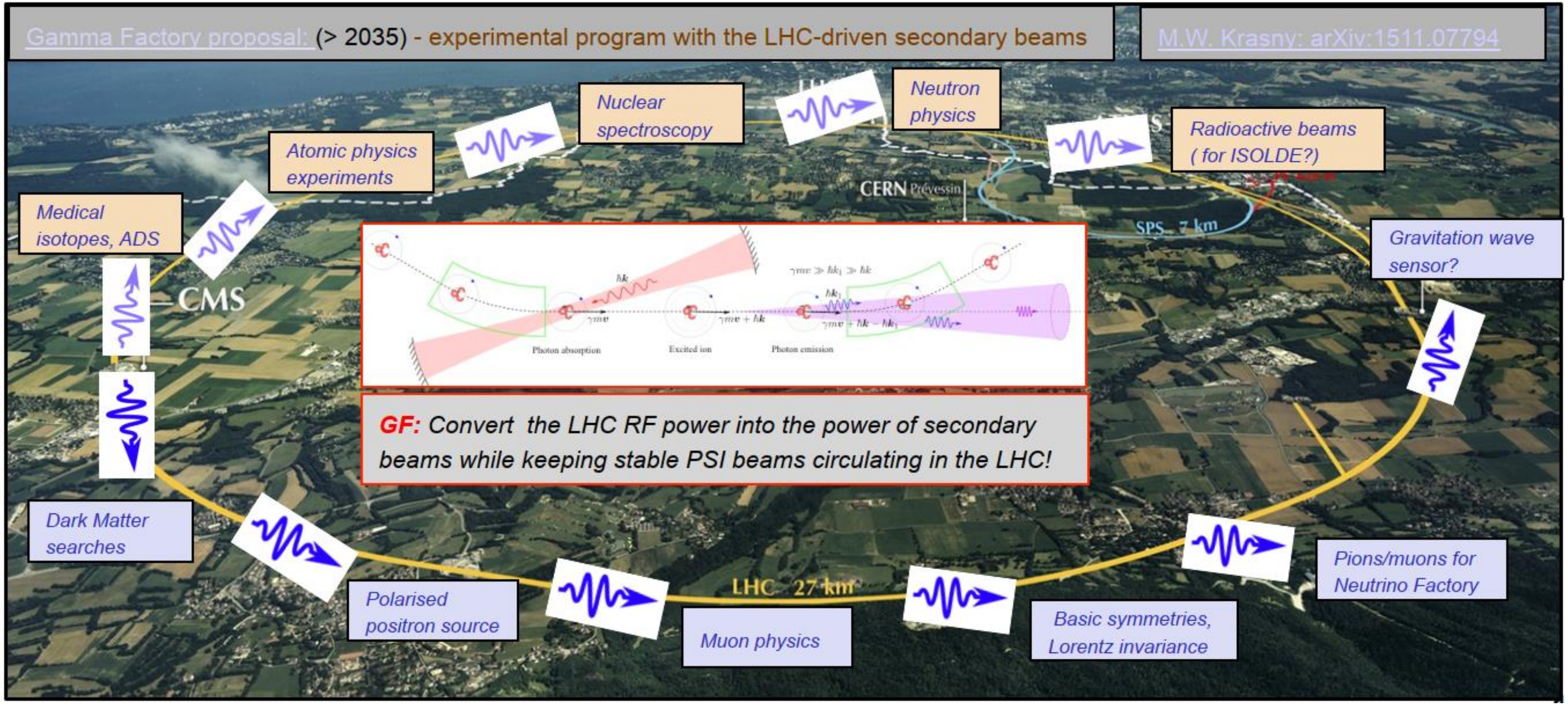




Beam divergence $\sim 1/\gamma_L$

W.Placzek

LHC as a driver of secondary beams



Gamma Factory proposal: (> 2035) - experimental program with the LHC-driven secondary beams

M.W. Krasny: arXiv:1511.07794

GF: Convert the LHC RF power into the power of secondary beams while keeping stable PSI beams circulating in the LHC!

Opportunities for nuclear physics

arXiv.org > nucl-ex > arXiv:2106.06584

Nuclear Experiment

[Submitted on 11 Jun 2021]

Expanding Nuclear Physics Horizons with the Gamma Factory

Dmitry Budker, Julian C. Berengut, Victor V. Flambaum, Mikhail Gorchtein, Junlan Jin, Felix Karbstein, Mieczyslaw Witold Krasny, Yuri A. Litvinov, Adriana Pálffy, Vladimir Pascalutsa, Alexey Petrenko, Andrey Surzhykov, Peter G. Thirolf, Marc Vanderhaeghen, Hans A. Weidenmüller, Vladimir Zelevinsky

The Gamma Factory (GF) is an ambitious proposal, currently explored within the CERN Physics Beyond Colliders program, for a source of photons with energies up to ≈ 400 MeV and photon fluxes (up to ≈10^{17} photons per second) exceeding those of the currently available gamma sources by orders of magnitude.

submitted to the forthcoming special issue of Annalen der Physik on Physics Opportunities with the Gamma Factory

Gamma Factory milestones – where we are?

1. Successful demonstration of efficient production, acceleration and storage of PSI beams in the CERN accelerator complex

Done

2. Development “ab nihilo” the requisite Gamma Factory software tools.

Done

3. Building up the physics cases for the LHC-based GF research programme and attracting wide scientific communities to evaluate and use (in the future) the GF tools in their respective research.

Work on-going

4. Successful execution of the GF Proof-of-Principle (PoP) experiment in the SPS tunnel.

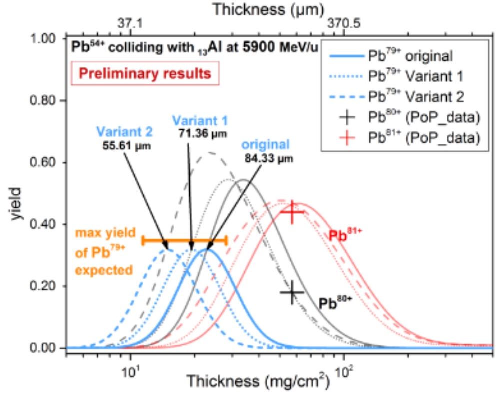
LoI submitted to the SPSC on 25/09/2019 public presentation on 13/10/2020

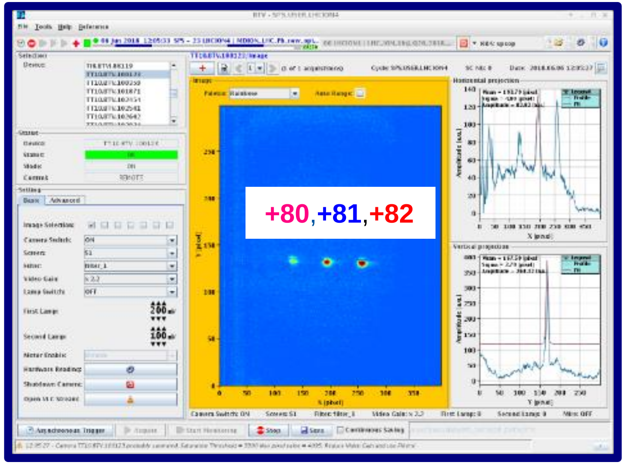
future

5. Extrapolation of the PoP experiment results to the LHC case and precise assessment of the performance figures of the GF Development (prior to the next European Strategy Update).
6. Elaboration of the TDR for the LHC-based GF research programme

Progress : PSI production

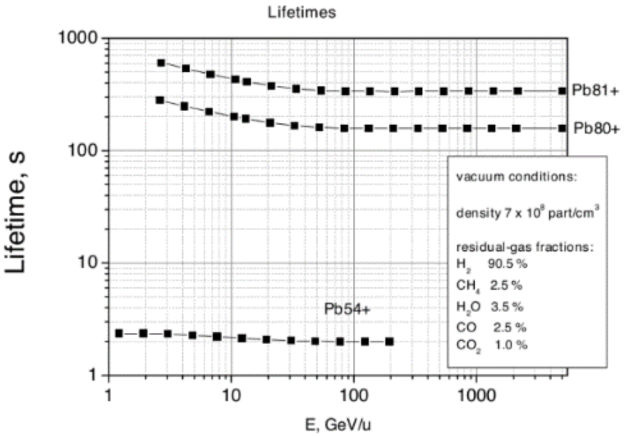
- Detailed simulations to optimize the stripping efficiency
  - 150 μm thick aluminum foil inclined at 45° installed between the PS and the SPS
  - Excellent agreement with measured efficiency, with the single foil, at
~20% for Pb^{80+}
~50% for Pb^{81+}
- In 2018, Pb^{80+} and Pb^{81+} were successfully accelerated in the SPS and Pb^{81+} to the maximum LHC energy



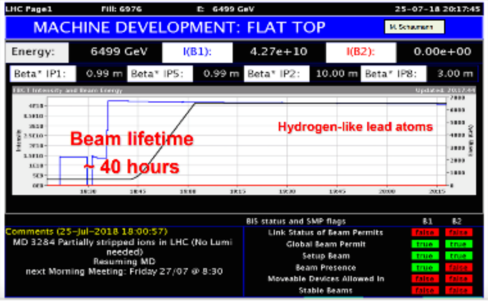


Progress : PSI lifetime measurement

- Electron stripping by the residual gas limits the lifetime of PSI beams in the SPS
    - Lifetime is function of species, energy, residual pressure and composition
- Measurement of the lifetime in the SPS
    - For Pb^{81+} lifetime is 660 ± 30 s
    - For Pb^{80+} lifetime is 350 ± 50 s
- Measurement of the Pb^{81+} lifetime in the LHC
    - 20.5 ± 2.5 h at injection energy
    - 54.5 ± 1.7 h at top energy



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



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

MACHINE DEVELOPMENT: FLAT TOP

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

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

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

10

Challenges : primary photon source

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

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

Challenges : beam dynamics

- Ion beam stability and control
  - Reliable and reproducible ion excitation requires a high level of control of the ion beam
  - Typical relative beam momentum stability needs to be in the order of 10^{-5}
  - Optimize the fraction of excited ions per crossing

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

SPS Proof-of-Principle : objectives

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

SPS Proof-of-Principle : parameters

- Species and transition choice
  - Lithium like lead, Pb^{79+} with $\gamma=96$
  - $(2s \rightarrow 2p)_{1/2}$ transition with $\Delta E=230$ eV
- Primary photon source
  - Mode-locked laser at 1034 nm and 40 MHz with Fabry-Pérot cavity
- Gamma photon characteristics
  - Decay length of the excited state in the laboratory frame is ~2 m
  - Maximum photon energy 44 keV
- Concept is described in CERN-SPSC-2019-031 ; SPSC-I-253

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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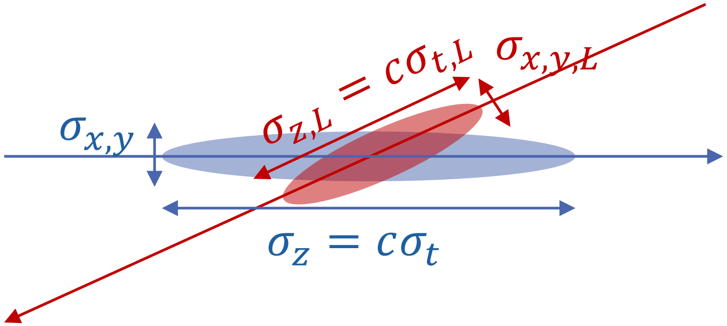
A. Martens, martens@lal.in2p3.fr – **Gamma Factory PoP experiment spokesperson**

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

Laser-ion interaction scheme



Beams must be
- Aligned,
- Synchronized
- Tuned (energy – wavelength)

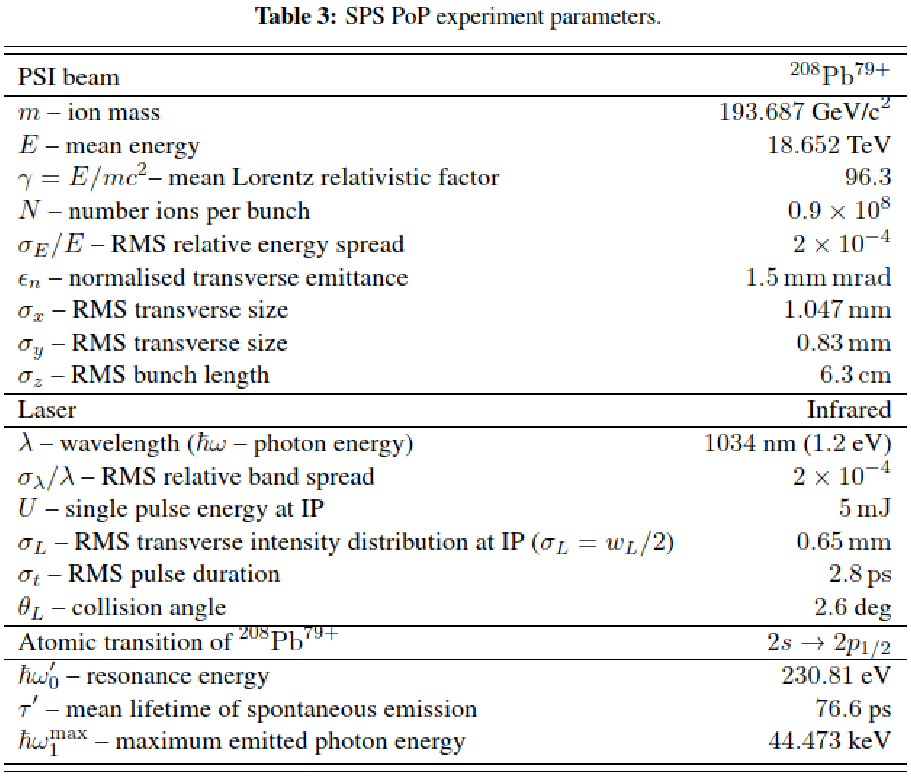
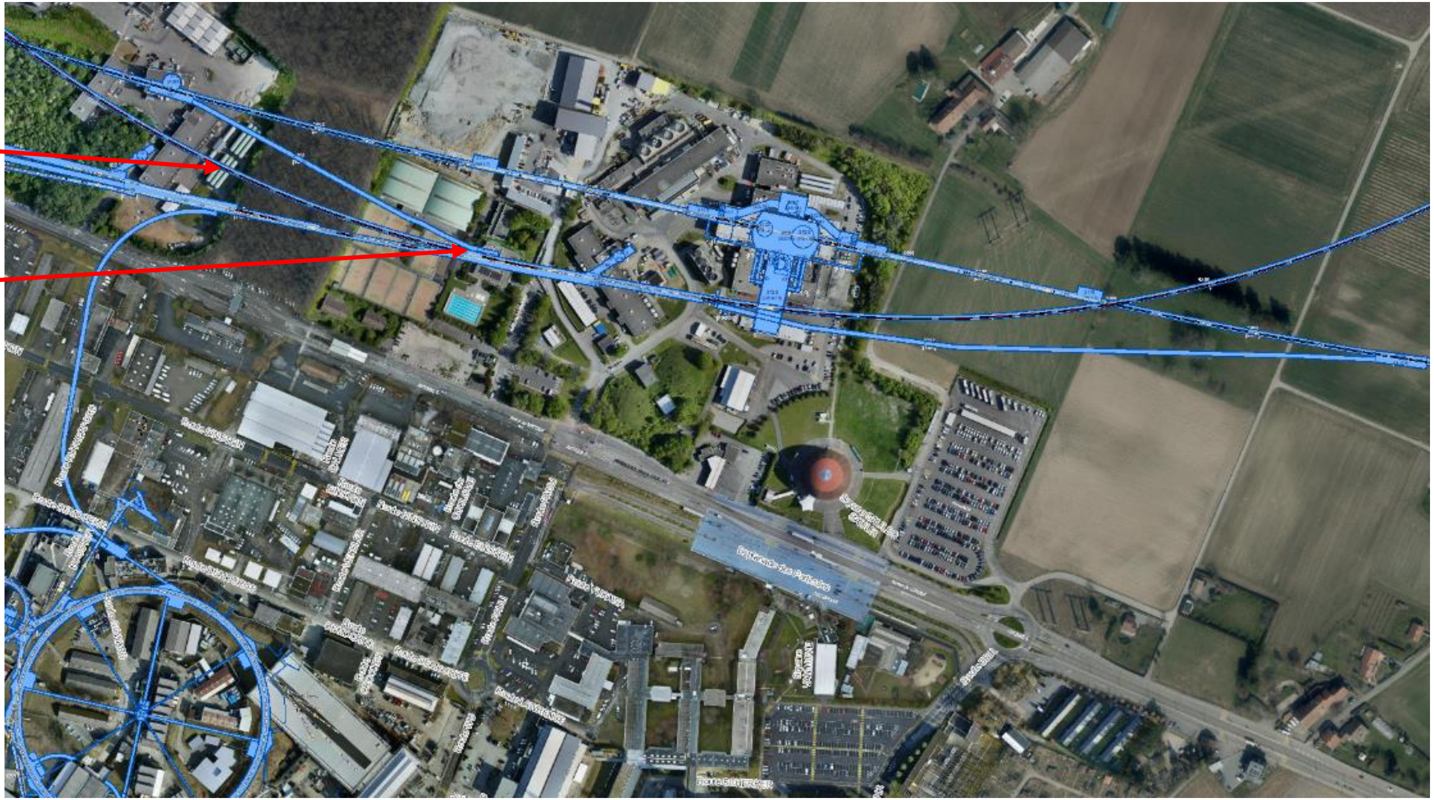


Table 3: SPS PoP experiment parameters.

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

SPS Proof-of-Principle : SPS LSS6

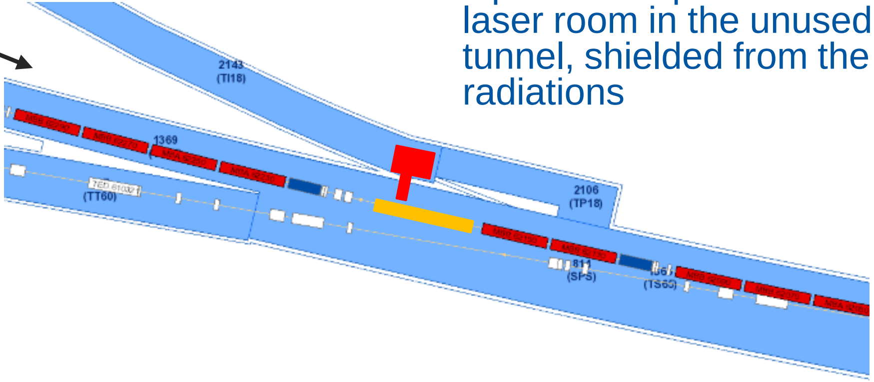


SPS Proof-of-Principle : Integration

LHC ring

ATLAS

SPS ring



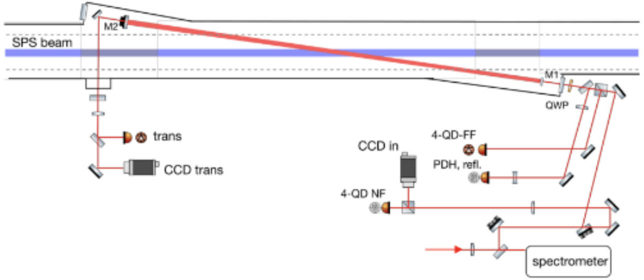
2 mirrors, 4 m Fabry-Perot optical cavity on the SPS ring

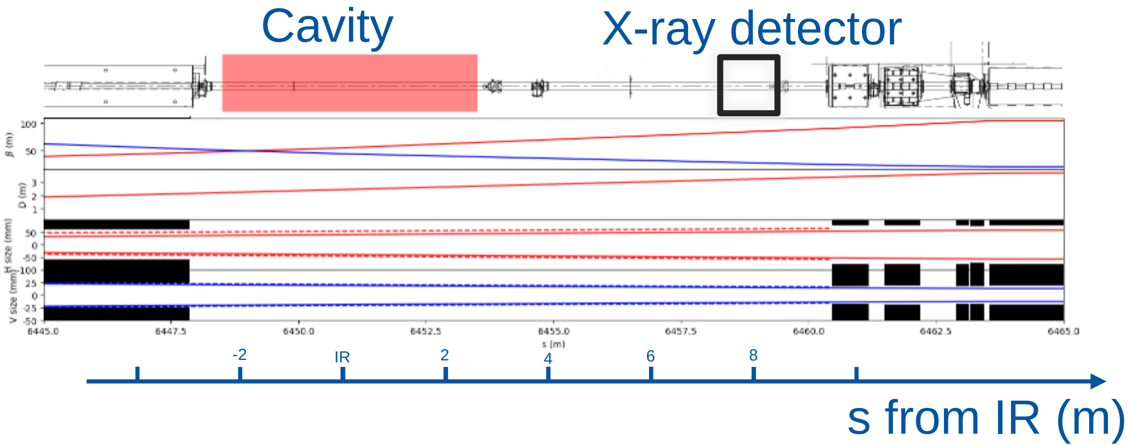
Optical transport line and laser room in the unused side tunnel, shielded from the SPS radiations

Cavity

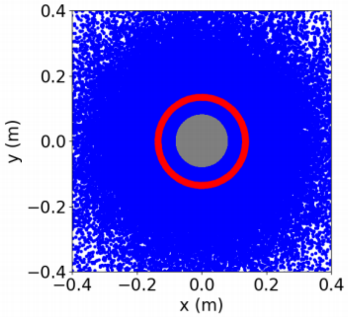
SPS Proof-of-Principle : Layout

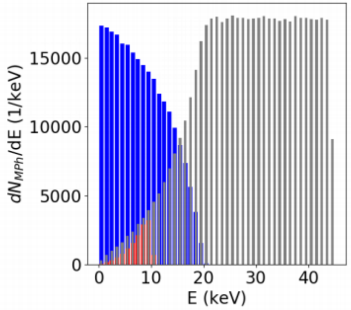
Vertical schematic cross section of the laser cavity





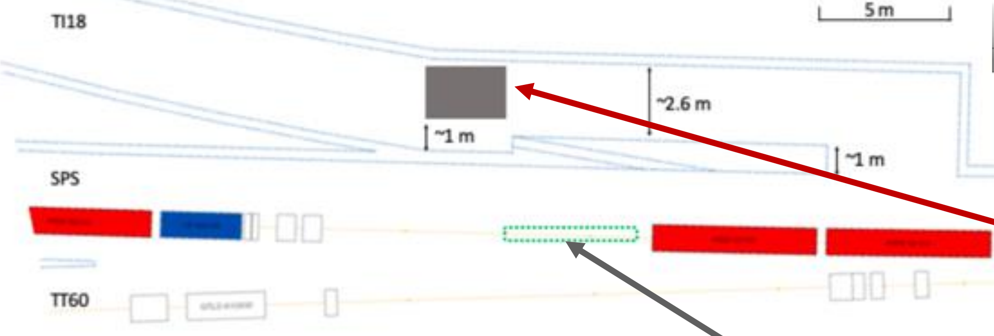
- 2 mirrors Fabry-Perot cavity with vertical crossing of 2.6˚
- Apertures and shapes ensure the cavity is transparent for nominal SPS activities
- For forward X-ray we plan to use a movable ring shaped scintillating screen

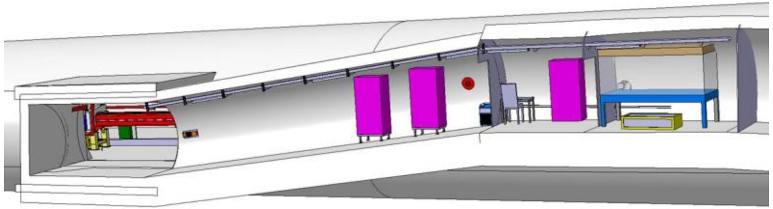


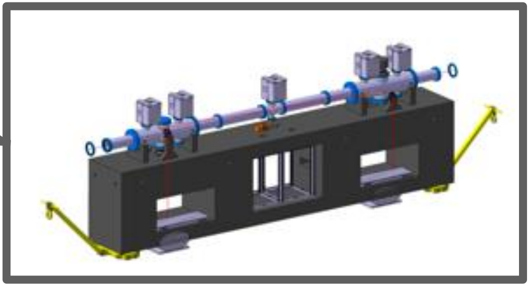


Laser system integration

SPS half-cell 621 with side tunnel TI18



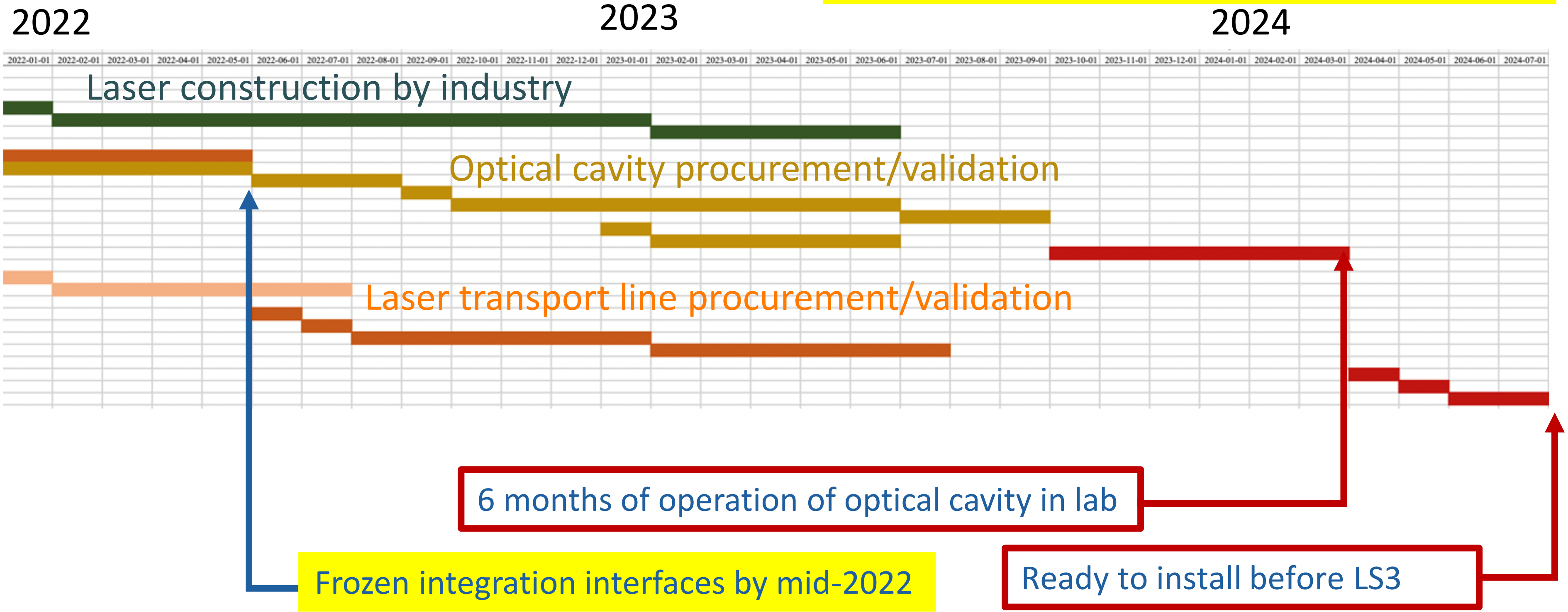




Project planning

Target: installation over LS3 (2025)

Assumes funds are available from Jan 2022



Laser construction by industry

Optical cavity procurement/validation

Laser transport line procurement/validation

6 months of operation of optical cavity in lab

Frozen integration interfaces by mid-2022

Ready to install before LS3

Feedback from the SPSC Committee

As received from referees on 20th Oct. 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

Thank you

Spare slides

LHC scenario : High energy photon production

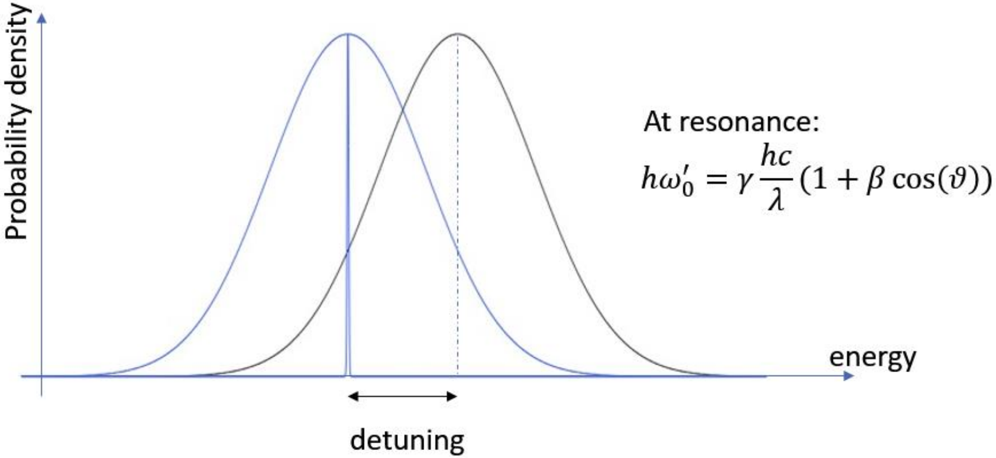
- Xe^{53+}
    - Hydrogen like Xenon
    - Lifetime of ~250 s in the SPS and ~20 h in the LHC
- Transition $(1s \rightarrow 2p)_{1/2}$ and ΔE=34 keV
    - Long decay length of ~1.5 cm
    - Laser minimum energy of 5.2 eV
    - Maximum photon energy 182 MeV
    - Gamma flux : possibly limited by double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

LHC scenario : High flux photon production

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

Spectrum matching

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



A relatively high laser pulse energy is required to excite nearly all ions

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

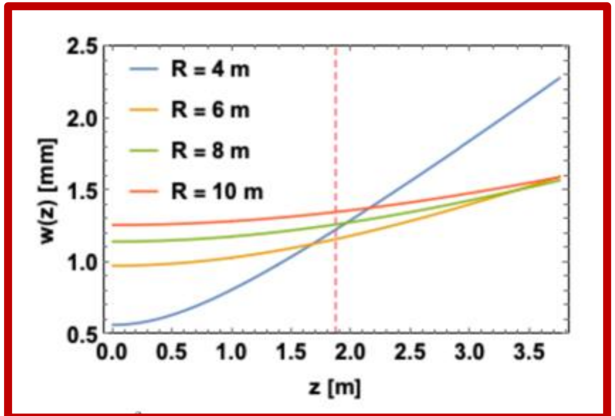
Excitation rate of ions depend on their position in the energy spectrum

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 + 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

Optical cavity with an enhancement factor >5000

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

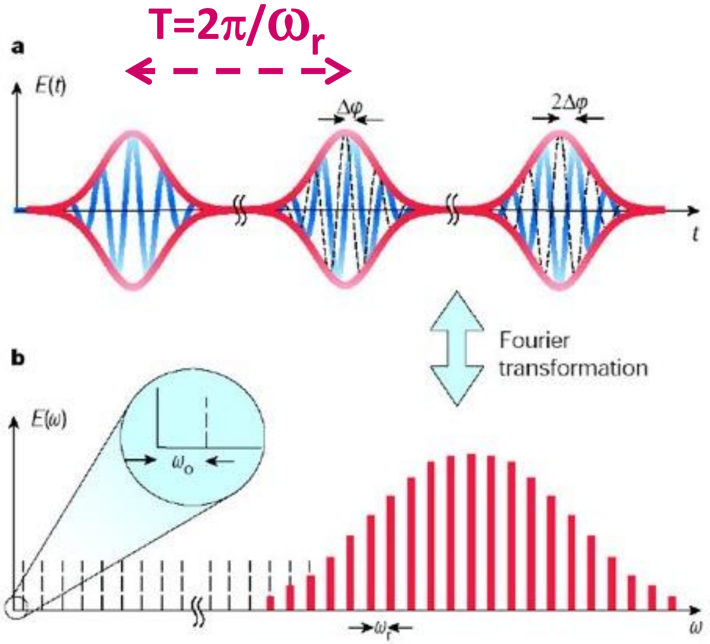
Laser phase noise

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

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

$$\nu = 40MHz$$

$$\Delta\nu = 2kHz$$



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

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