Updates from the Gamma-Factory Study Group at CERN

CNFS Workshop, Stony Brook, March 2024

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"*Gamma Factory*" studies

The Gamma Factory proposal for CERN †

† An Executive Summary of the proposal addressed to the CERN management.

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~100 physicists form 40 institutions have contributed so far to the Gamma Factory studies

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Gamma Factory studies are anchored, and supported by the CERN Physics Beyond Colliders (PBC) framework.

More info on all the GF group activities:

https://indico.cern.ch/category/10874

*We acknowledge the crucial role of the CERN **PBC** framework in bringing our accelerator tests, GF-PoP experiment design, software development and physics studies to their present stage!*

Gamma Factory beams

Gamma Factory photon source

1. Point-like, small divergence

- $\Delta z \sim l_{PSI\text{-}bunch}$, $\Delta x, \Delta y \sim \sigma^{PSI}{}_{x}, {}^{PSI}{}_{y}$, $\Delta(\theta_x)$, $\Delta(\theta_y) \sim 1/\gamma_L < 1$ mrad

2. Huge jump in intensity:

- **6–8 orders of magnitude** w.r.t. existing (being constructed) γ-sources **up to 10^{18} photons/sec**

3.Very wide range of tuneable energy photon beam :

- **10 keV – 400 MeV --** extending, by a factor of **~1000**, the energy range of the FEL photon sources

4. Tuneable polarisation:

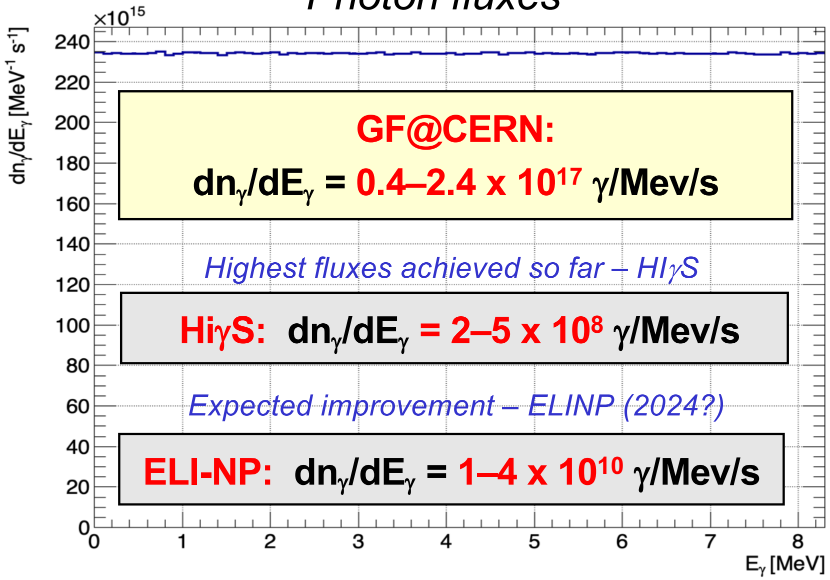
- γ–**polarisation transmission** from laser photons to γ-beams of **up to 99%**

5. Unprecedented plug power efficiency (energy footprint):

- **LHC RF power can be converted to the photon beam power.** Wall-plug power efficiency of the **GF photon source is** by a factor of **~300 better than that of the DESY-XFEL!**

A concrete example: Nuclear physics application: He-like, LHC Calcium beam, $(1s \rightarrow 2p)_{1/2}$ transition, TiSa laser

Photon fluxes

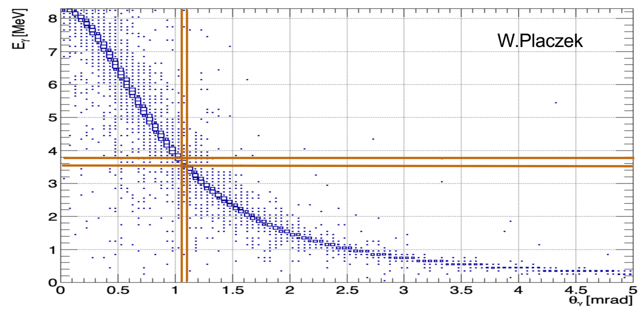


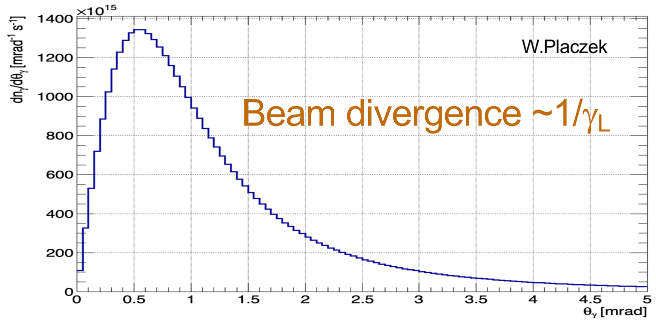
laser pulse parameters

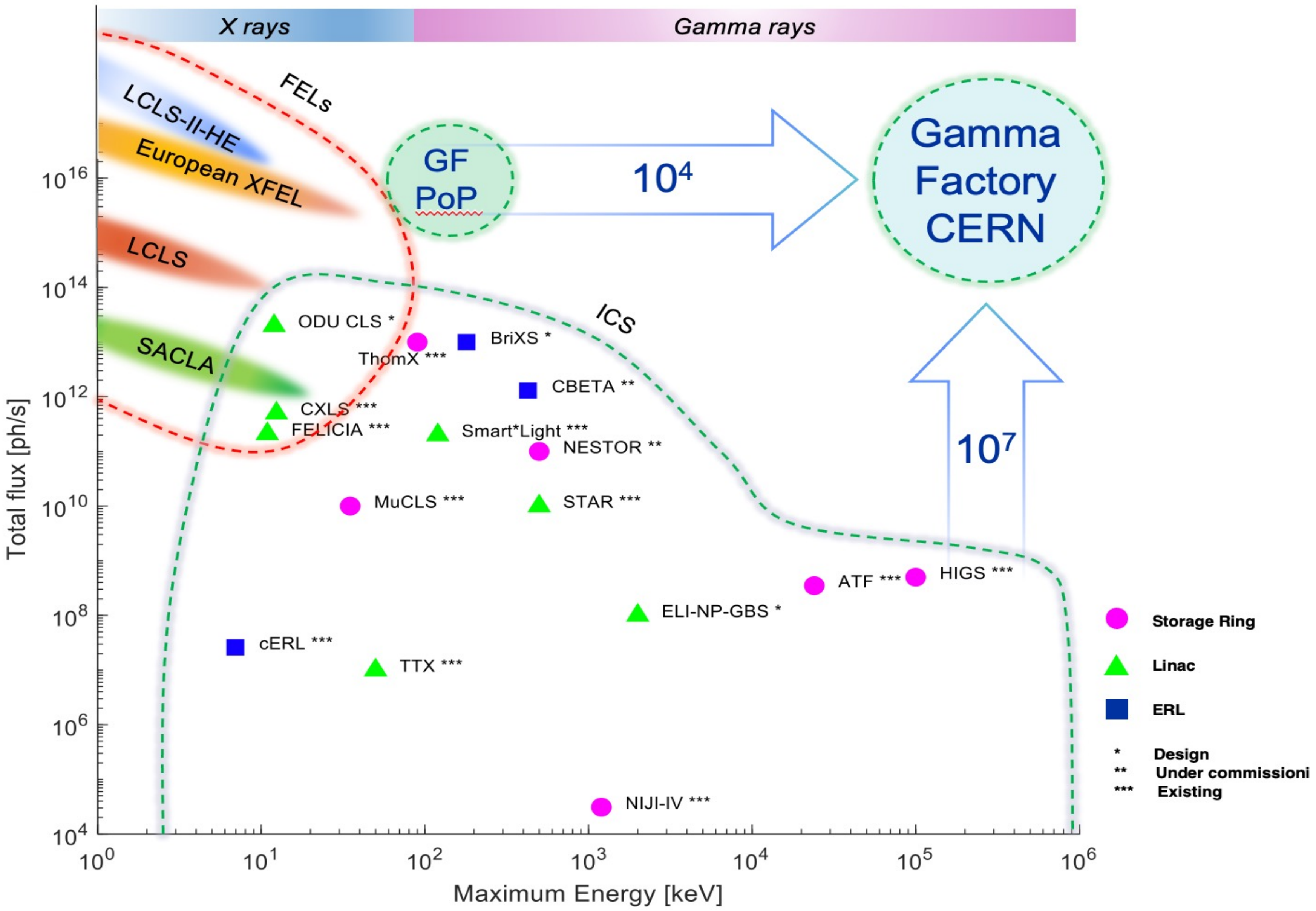
- Gaussian spatial and time profiles,
- photon energy: E_photon = 1.8338 eV
- photon pulse energy spread: sigma_{omega}/omega = 2 x 10^{-4},
- photon wavelength: lambda = 676 nm,
- pulse energy: W_{l} = 5 mJ,
- peak power density 1.12 x 10^13 W/m^2
- r.m.s. transverse beam size at focus: sigma_{x} = \sigma_{y } = 150 um (micrometers),
- Rayleigh length: R_{L,x} = R_{L,y} = 7.5 cm,
- r.m.s. pulse length: l_{l} = 15 cm.

6. Highly-collimated monochromatic γ–beams:

- *the beam power is concentrated in a narrow angular region (facilitates beam extraction)*
- *the $(E_\gamma, \Theta_\gamma)$ correlation can be used (collimation) to "monochromatise" the beam*







X rays
Gamma rays
FELs
LCLS-II-HE
European XFEL
LCLS
SACLA
GF
PoP
10⁴
Gamma
Factory
CERN
10⁷
ICS
ODU CLS *
ThomX ***
BriXS *
CBETA **
CXLS ***
FELICIA ***
Smart*Light ***
NESTOR **
MuCLS ***
STAR ***
ATF ***
HIGS ***
ELI-NP-GBS *
cERL ***
TTX ***
NIJI-IV ***
Storage Ring
Linac
ERL
* Design
** Under commissioni
*** Existing
Total flux [ph/s]
Maximum Energy [keV]

Secondary beams' sources – Intensity/quality targets

- ***Polarised positrons*** – *potential gain of up to a factor of 10^4 in intensity w.r.t. the KEK positron source, satisfying both the LEMMA and the LHeC requirements*
- ***Pions*** – *quasi-monochromatic pion source (spectral width of ~30 MeV in momentum and transverse momentum) -- of comparable intensity to that of FNAL and KEK (~10^{14} pions/s)*
- ***Muons*** – *potential gain by a factor of 10^3 in intensity w.r.t. the PSI muon source, charge symmetry ($N\mu^+ \sim N\mu^-$), polarisation control*
- ***Neutrinos*** – *fluxes comparable to NuMAX but: (1) Very Narrow Band Beam, driven by the small spectral density pion beam and (2) unique possibility of creating flavour- and CP-tuned beams driven by the beams of polarised muons*
- ***Neutrons*** – *potential gain of up to a factor of 10^4 in intensity of primary MeV-energy neutrons per 1 MW of the driver beam power*
- ***Radioactive ions*** – *potential gain of up to a factor 10^4 in neutron-rich isotopes*

Gamma Factory quasi-monochromatic pion source:

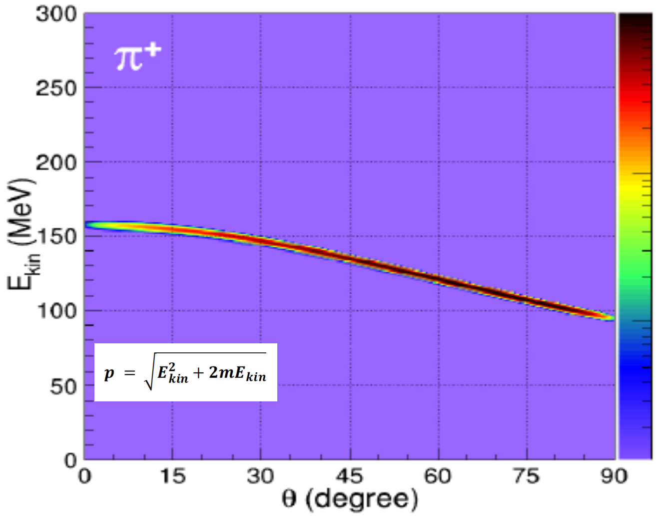
Idea: De-randomising pion spectra and restoring their charge symmetry

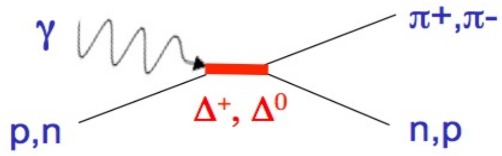
CM frame:

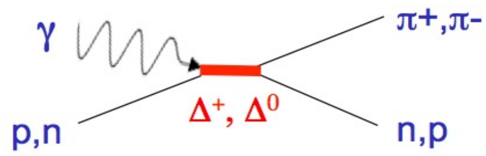
Monochromatic pions

Laboratory frame:

- *Pion energy and transverse momentum fully specified by one parameter: the pion emission angle, θ*





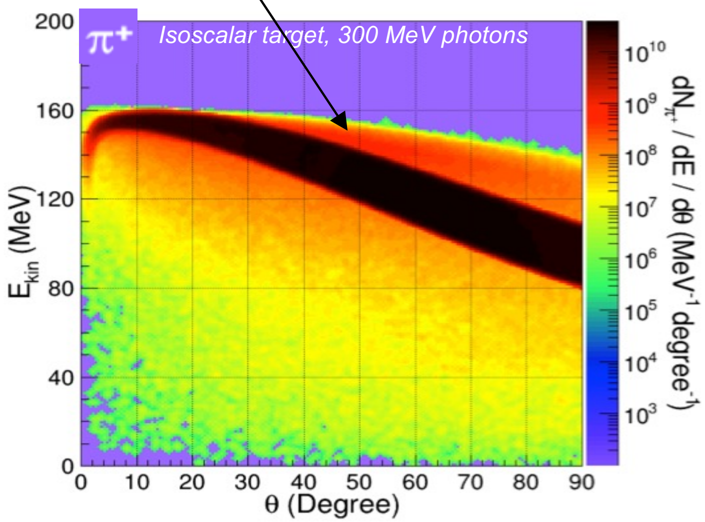


Z=A/2, (N_p=N_n)

Isoscalar target choice:

assures almost exact charge symmetry of π^+ and π^- production (below 2π production threshold)

(note the effect of the nucleon Fermi motion smearing – relative to hydrogen target)



Three Laser/LHC-beam scenarios for the muon beam production

3. Heliumlike ytterbium scenario

A possible remedy to increase the photon beam energy is to use ions with a higher atomic number Z. This can be done at the cost of further reducing the laser photon wavelength to the value of $\lambda = 129.25$ nm. Photons of such a wavelength can be produced by performing three consecutive frequency doubling stages of the $\lambda = 1034$ nm photons generated by the GF-PoP laser. They can resonantly excite the $1s^2\,{}^1S_0 \rightarrow 1s2p\,{}^1P_1$ atomic transition of heliumlike ytterbium beam particles, ${}^{174}_{70}Yb^{68+}$, provided that the relativistic Lorentz factor γ_L of the beam particles is chosen to be $\gamma_L^{Yb} = 2731$. It corresponds to the equivalent proton energy of 6.47 TeV. This value is within the allowed LHC-beam momentum range. The maximal photon beam energy to be reached in this scheme is 286.2 MeV. A GF photon beam of power up to 4 MW can be generated in this scheme with the presently operating LHC cavities and 1000 bunches of 10^9 ions per bunch.

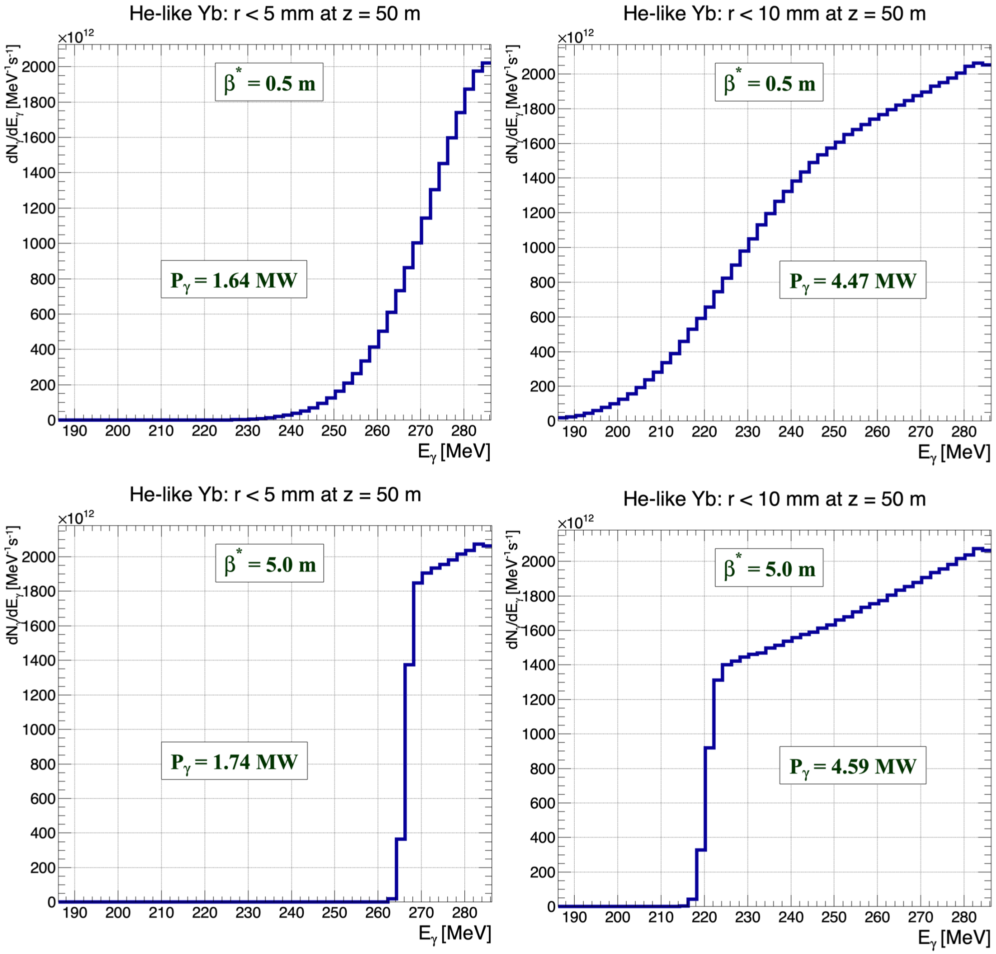
1. Heliumlike tin scenario

The laser-photon wavelength to resonantly excite the $1s^2\,{}^1S_0 \rightarrow 1s2p\,{}^1P_1$ atomic transition of the heliumlike tin beam particles, ${}^{120}_{50}Sn^{48+}$, is chosen to be $\lambda = 517$ nm. This photon wavelength can be obtained by doubling the frequency of the photons produced by the GF-PoP $\lambda = 1034$ nm laser. In this scenario, the relativistic Lorentz factor γ_L of the beam particles which satisfies the resonance condition for head-on collisions of the ${}^{120}_{50}Sn^{48+}$ ions with the laser pulses is $\gamma_L^{Sn} = 5362$. It corresponds to the equivalent proton energy of 12.47 TeV. Such energy cannot be reached with the present LHC dipoles but can be realized in the future HE-LHC project [14]. Photon beams of power up to 2.8 MW with the maximal photon energy of 275.8 MeV can be generated by the ${}^{120}_{50}Sn^{48+}$ beam with the presently operating LHC cavities and 1000 bunches of 10^9 ions per bunch circulating in the LHC ring.

2. Heliumlike xenon scenario

The laser-photon wavelength to resonantly excite the $1s^2\,{}^1S_0 \rightarrow 1s2p\,{}^1P_1$ atomic transition of heliumlike xenon beam particles, ${}^{129}_{54}Xe^{52+}$, is chosen to be $\lambda = 258.5$ nm. Photons at this wavelength can be produced by two consecutive frequency doubling stages of the GF-PoP $\lambda = 1034$ nm laser photons. In this scenario, the relativistic Lorentz factor γ_L of the beam particles which satisfies the resonance condition is $\gamma_L^{Xe} = 3149$. It corresponds to an equivalent proton energy of 7.27 TeV, which is slightly above the allowed LHC-beam momentum range, reflecting the present quench-protection limit of the maximal current of the LHC dipoles. The maximal photon-beam energy that could be reached in this scheme is 190.2 MeV. Photon beams of the power up to 3 MW can be generated by the ${}^{129}_{54}Xe^{52+}$ beam with the presently operating LHC cavities and 1000 bunches of 10^9 ions per bunch. Due to the

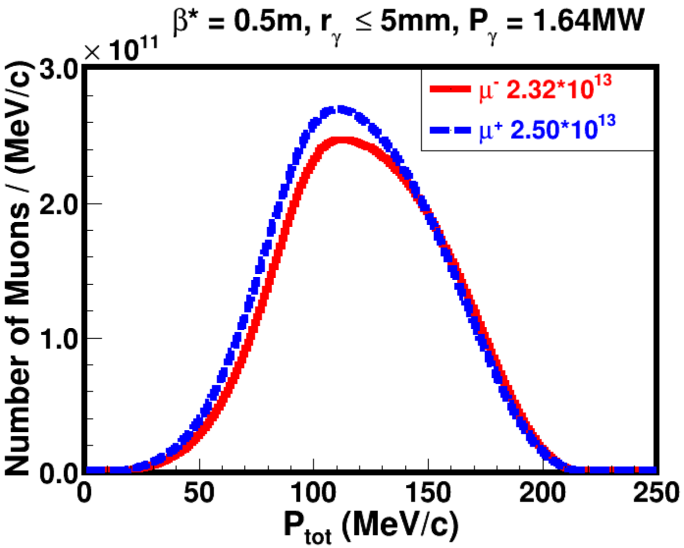
GF photon beam for muon production

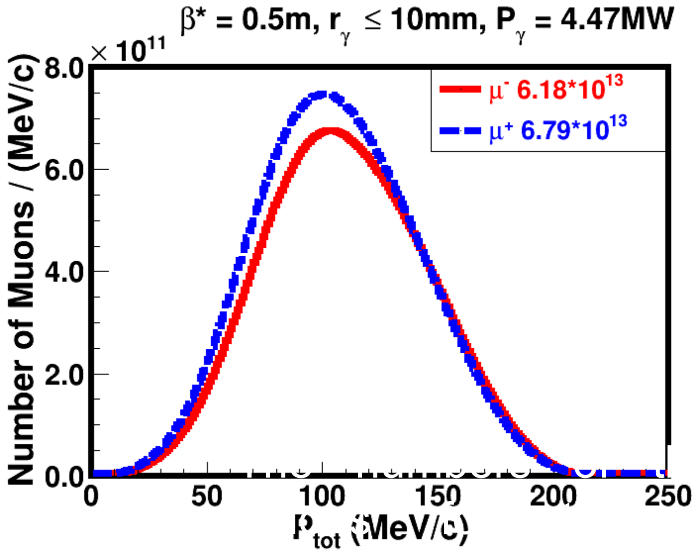


PSI beam	${}^{174}_{70}\mathrm{Yb}^{68+}$
m – ion mass	161.088 GeV/c^2
E – mean energy	440 TeV
$\gamma_L = E/mc^2$– mean Lorentz relativistic factor	2731.3
N – number ions per bunch	10^9
σ_E/E – RMS relative energy spread	2×10^{-4}
$\beta_x = \beta_y$ – β-function at IP	0.5 m
$\sigma_x = \sigma_y$ – RMS transverse size	16 μm
σ_z – RMS bunch length	15 cm
Bunch repetition rate	20 MHz
Laser	Yb:YAG
λ – photon wavelength	129.25 nm
$\hbar\omega$ – photon energy	9.5926 eV
σ_λ/λ – RMS relative band spread	2×10^{-4}
U – single pulse energy at IP	5 mJ
$\sigma_x = \sigma_y$ – RMS transverse intensity distribution at IP	20 μm
σ_z – RMS pulse length	15 cm
θ_l – collision angle	0 deg
Atomic transition of ${}^{174}_{70}\mathrm{Yb}^{68+}$	$1s^2\,{}^1S_0 \to 1s2p\,{}^1P_1$
$\hbar\omega'_r$ – resonance energy	52.4 keV
τ' – mean lifetime of spontaneous emission	1.01×10^{-16} s
g_1, g_2 – degeneracy factors of the ground and excited states	1, 3
$\hbar\omega_1^{max}$ – maximum emitted photon energy	286.2 MeV

W.Placzek

Number of produced μ^+ and μ^-





Muons	$r_\gamma \leq 5$mm	$r_\gamma \leq 10$mm
μ^-	2.32×10^{13} s^{-1}	6.18×10^{13} s^{-1}
μ^+	2.50×10^{13} s^{-1}	6.79×10^{13} s^{-1}

Details in the presentation of Armen Apyan at the last year CNFS workshop and in Phys.Rev paper:

PHYSICAL REVIEW ACCELERATORS AND BEAMS **26,** 083401 (2023)

Gamma Factory high-intensity muon and positron source: Exploratory studies

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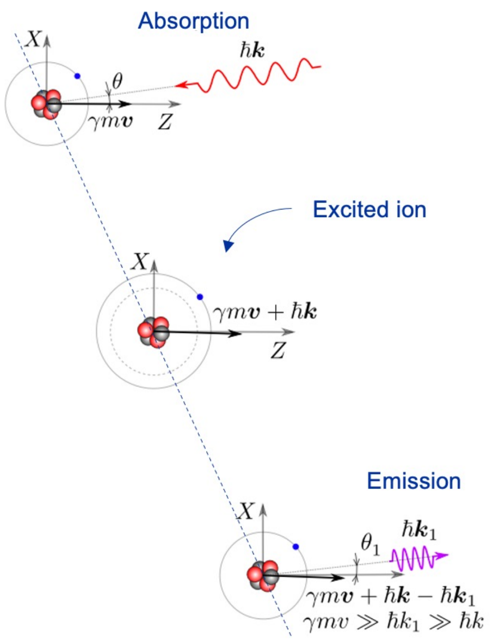
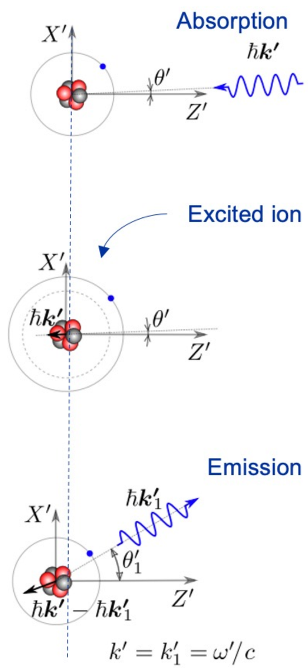
Gamma Factory principles

Energy leap: High energy atomic beams play the role of passive light-frequency converters:

In the lab frame



In the ion frame



Absorption

Lorentz transformation

$$\omega' \sin\theta' = \omega \sin\theta, \qquad \Delta\theta' \approx \frac{\Delta\theta}{2\gamma}$$

$$\omega' = (1 + \beta\cos\theta)\gamma\omega \approx \left(1 + \beta - \beta\frac{\theta^2}{2}\right)\gamma\omega \approx 2\gamma\omega.$$

Emission

$$\omega_1 \sin\theta_1 = \omega' \sin\theta'_1 \;\Rightarrow\; \sin\theta_1 = \frac{\sin\theta'_1}{\gamma(1 + \beta\cos\theta'_1)},$$

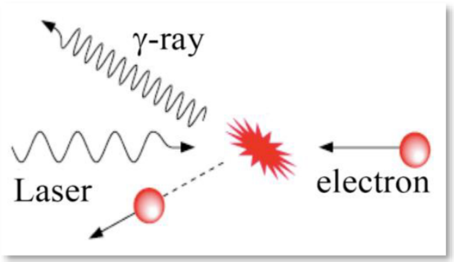
$$\omega_1 = \gamma(1 + \beta\cos\theta'_1)\omega' \approx 2\gamma^2(1 + \beta\cos\theta'_1)\omega.$$

$$\nu^{max} \longrightarrow (4\,\gamma_L^2)\,\nu_i$$

$\gamma_L = E/M$ - Lorentz factor for the ion beam

Intensity leap: large cross-section for atomic collisions

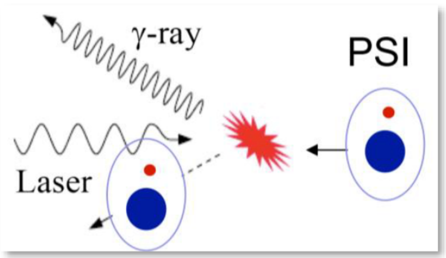
Inverse Compton scattering



Cross-section	Requirements
Electrons:	E_{beam} = 1.5 GeV
$\sigma_e = 8\pi/3 \times r_e^2$	LINAC or LWFA
r_e - classical electron radius	Electron fractional energy loss: emission of 150 MeV photon: $E_\gamma/E_{beam} = 0.1$
$\sigma_e = 6.6 \times 10^{-25}$ cm^2	(electron is lost!)

$\sigma \times 10^9$

Gamma Factory



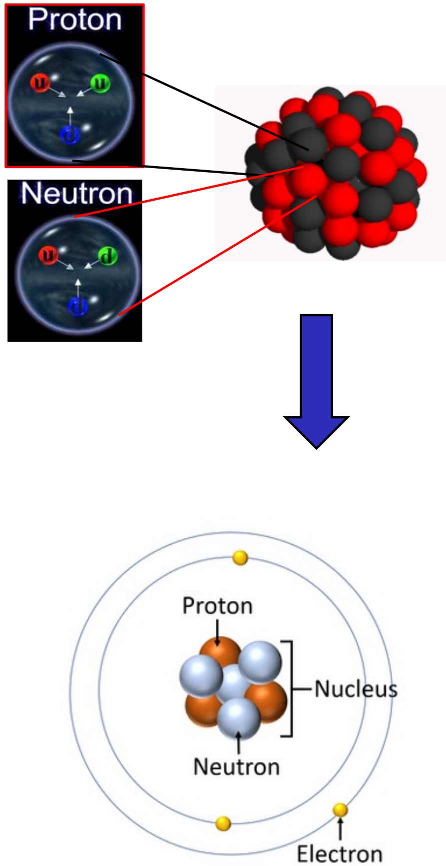
Example: Pb, hydrogen-like ions, *stored in LHC* γ_L = 2887

Cross-section	Requirements
Partially Stripped Ions:	E_{beam} = 574 000 GeV
$\sigma_{res} = \lambda_{res}^2/2\pi$	(LHC)
λ_{res} - photon wavelength in the ion rest frame	Electron fractional energy loss: emission of 150 MeV photon: $E_\gamma/E_{beam} = 2.6 \times 10^{-7}$
$\sigma_{res} = 5.9 \times 10^{-16}$ cm^2	(ion undisturbed!)

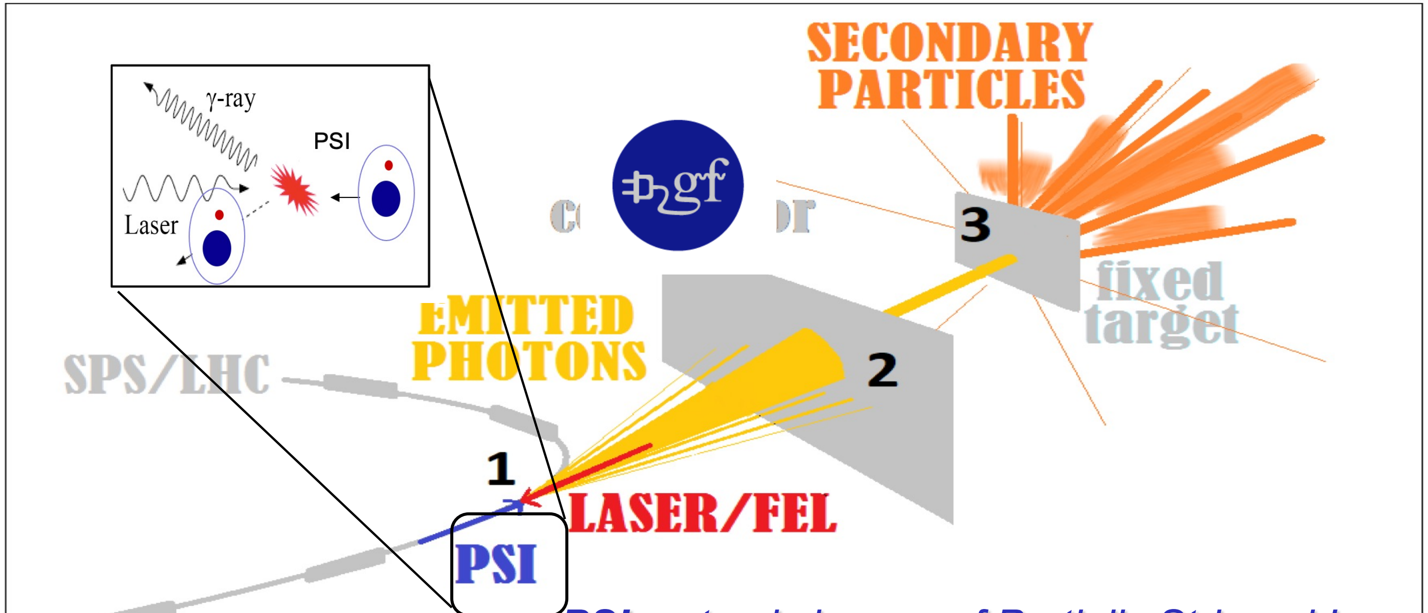
Gamma Factory requirements:

Atomic beams

LHC beams

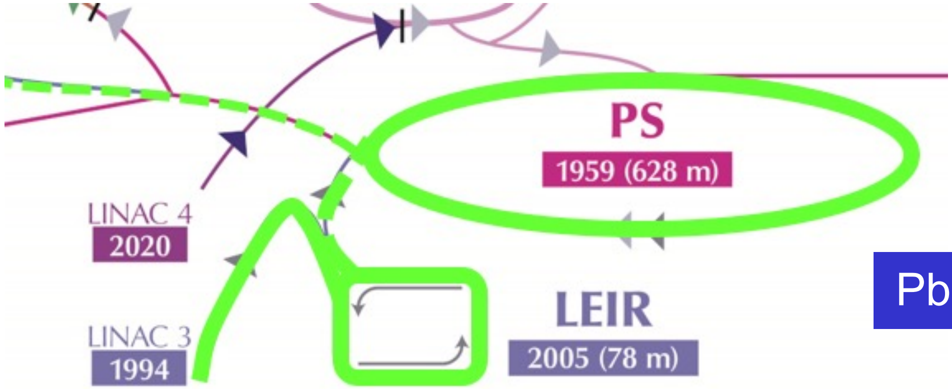


- *Include* ***atomic beams of partially stripped ions*** *in the LHC menu*
- *Collide them with laser pulses (circulating in Fabry-Pérot resonators) to* ***produce beams of polarized photons*** *and secondary beams of polarized electrons, positrons, muons, neutrons and radioactive ions*



PSI *– atomic beams of Partially Stripped Ions*

Ion Source

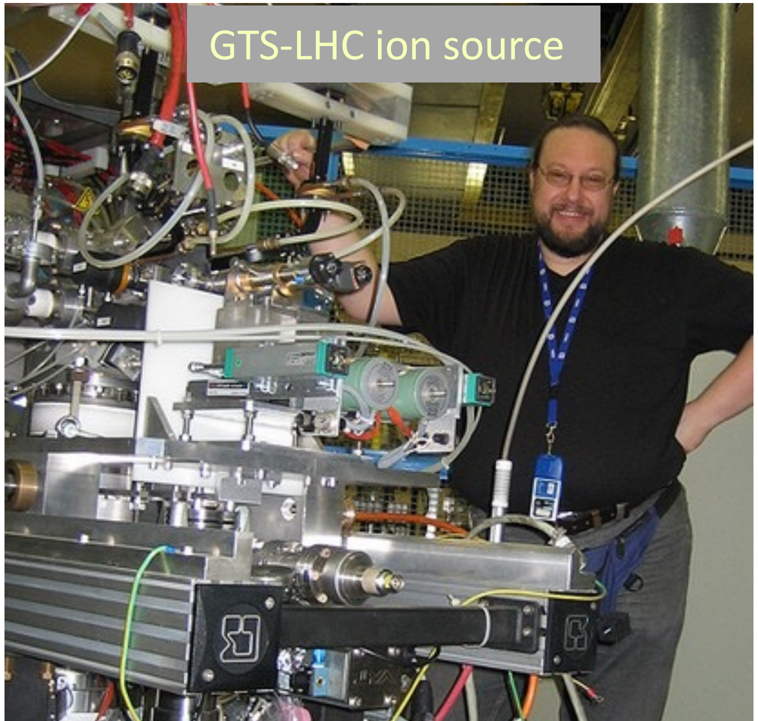


Pb operation

Small sliver of solid isotopically pure 208Pb is placed in a ceramic crucible that sits in an "oven"

- Pulsed operation in afterglow mode, produces ~ms long pulses at 10Hz, only ~200 us pulses are accelerated, not all pulses.
- Equipped with gas injection and 2 microovens

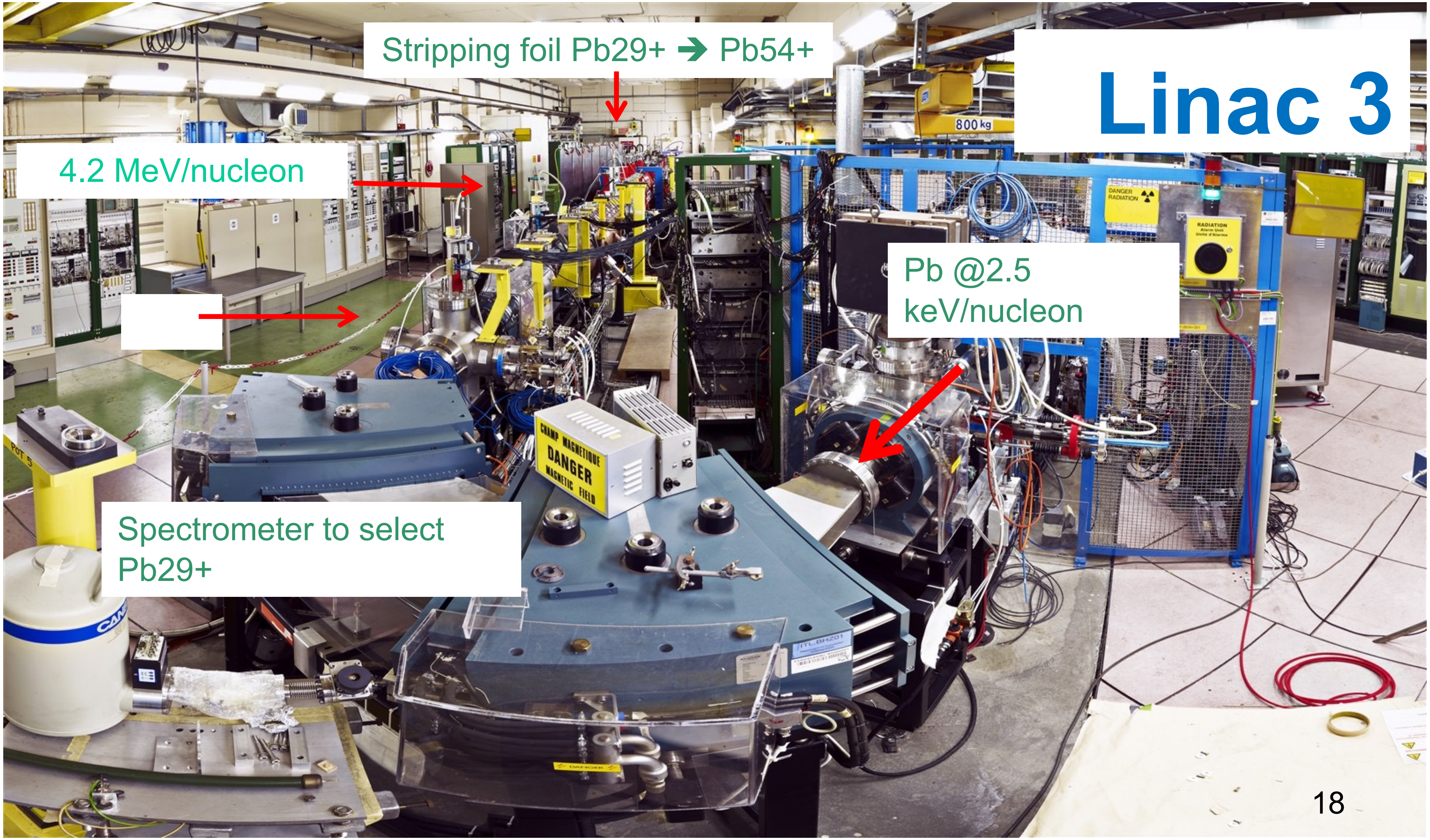
GTS-LHC ion source



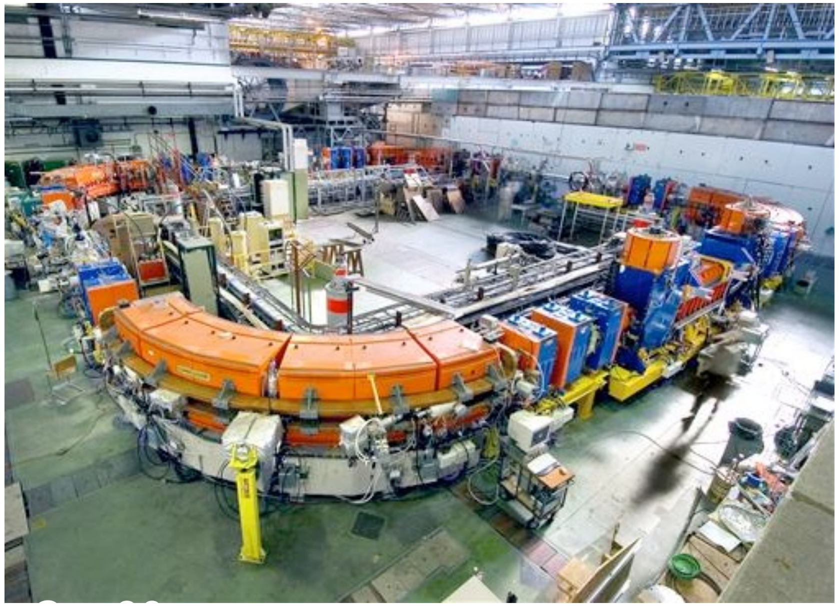
The metal is heated to around 800° C and ionized to become plasma. Ions are then extracted from the plasma and accelerated up to 2.5 keV/nucleon.

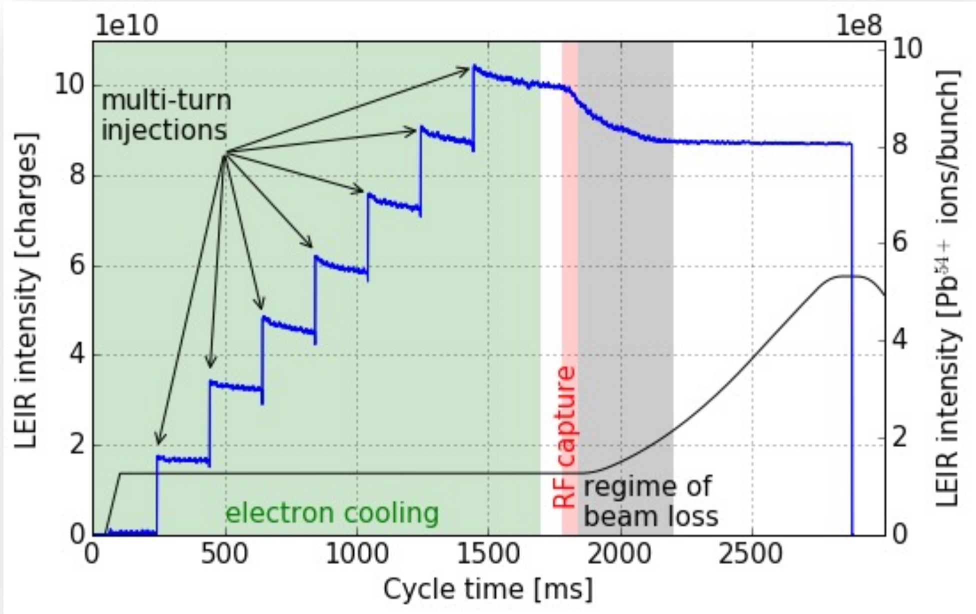
The source can also be set up to deliver other species…
O, Ar, Xe …

Linac 3


Stripping foil Pb29+ ➔ Pb54+
4.2 MeV/nucleon
Pb @2.5
keV/nucleon
Spectrometer to select
Pb29+
800 kg
DANGER

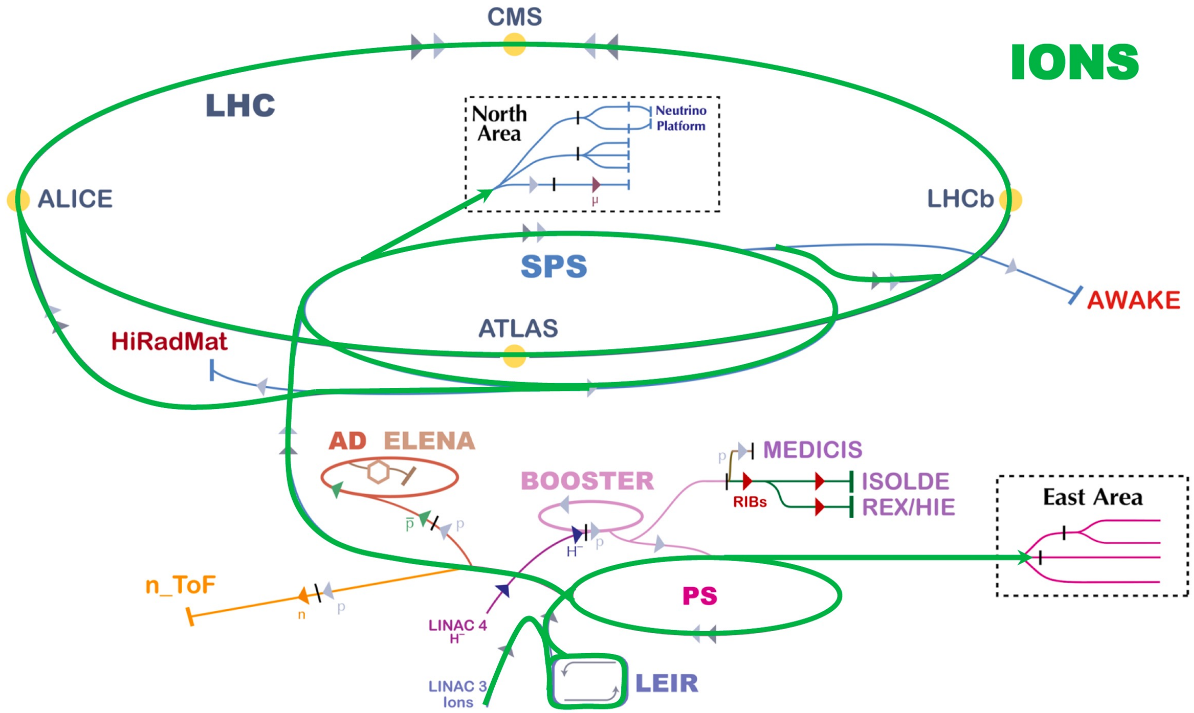
Ion Chain : Low Energy Ion Ring





LEIR accumulates the 200 μs pulses from Linac3; then it bunches the beam (1 or 2 or 3bunches) Electron Cooling is used to achieve the required brightness. Acceleration to 72 MeV/nucleon (Pb) before transfer to the PS. LEIR Cycle is 2.4 s or 3.6 s. Pb54+ is fully stripped to Pb82+ in the transfer line from PS to SPS

Sustainability: Re-use of already existing accelerator infrastructure – CERN

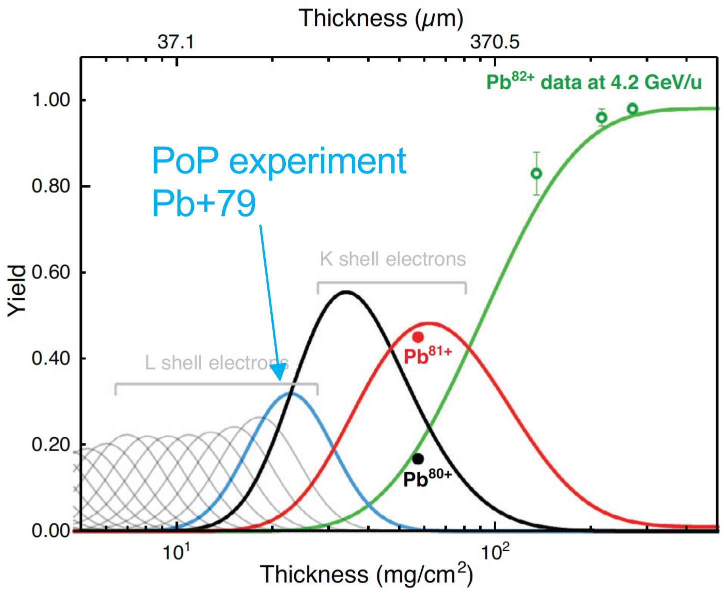


Gamma Factory (additional) requirements:

- modification of the ion stripping scheme,
- storage of atomic beams

Status 2024: Requisite TT2 stripper system installed

Stripping of Pb+54 ions in the TT2 PS-→ SPS transfer line



Charge-State Distributions of Highly Charged Lead Ions at Relativistic Collision Energies

Felix M. Kröger, Günter Weber, Simon Hirlaender, Reyes Alemany-Fernandez, Mieczyslaw W. Krasny, Thomas Stöhlker, Inga Yu. Tolstikhina, and Viacheslav P. Shevelko*

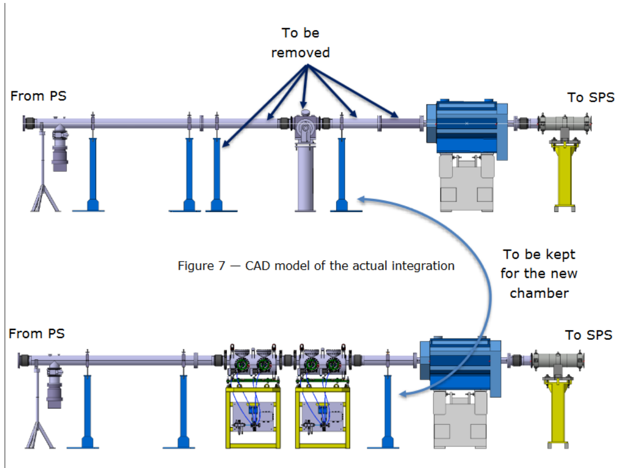
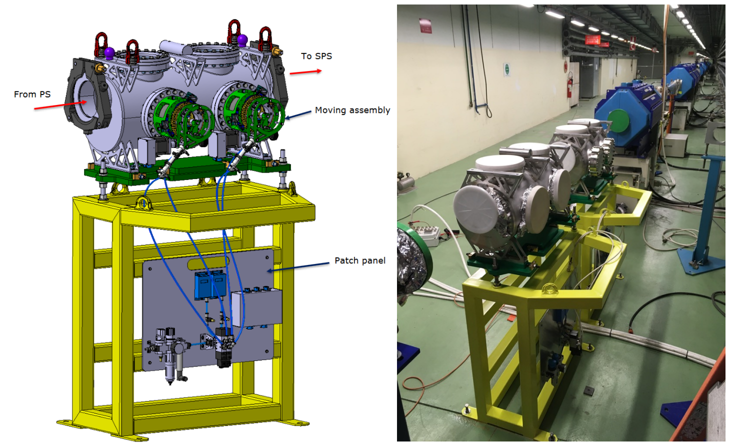


Figure 7 — CAD model of the actual integration

Figure 8 — CAD model of the new integration

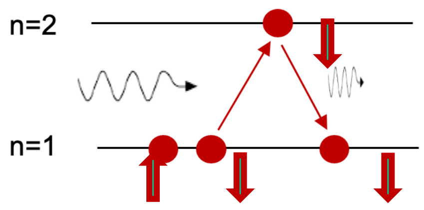


R. Alemany-Fernandez (BE.OP), E. Grenier-Boley and D. Baillard (SY.STI)

The two tanks of the new stripper system were installed during YETS 2021-2022 and YETS 2022-2023. Four stripper foil mechanisms operating at ~Hz frequency.

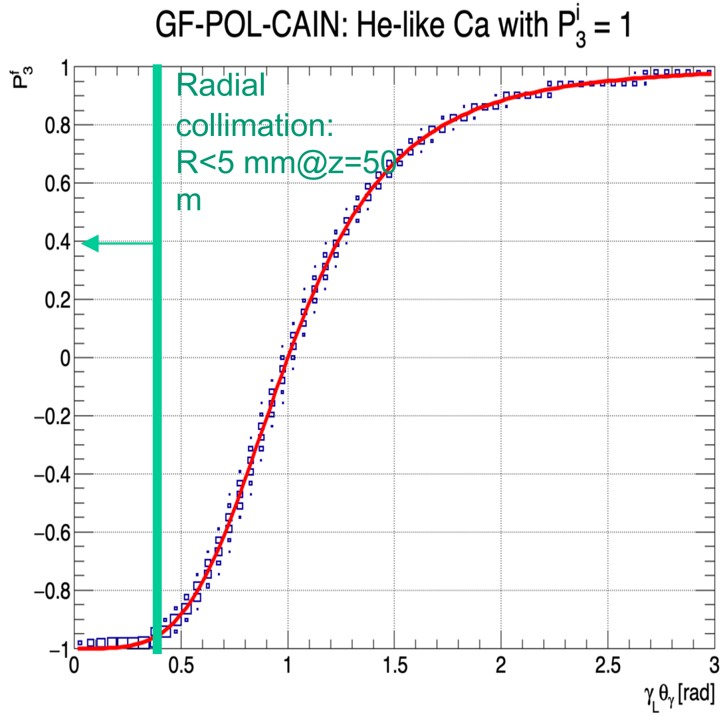
Polarised beams in GF: He-like beams (Er:glass laser (1522 nm))

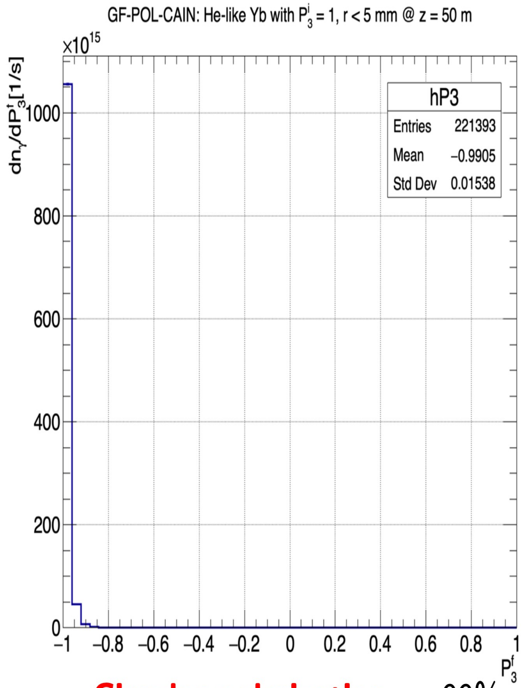
A trick: $1s^2\ {}^1S_0 \rightarrow 1s^1\ 2p^1\ {}^1P_1$ transition in He-like atoms



$$nS_0 \rightarrow n'P_1 \rightarrow nS_0$$

Closed transition in Helium-like atoms (n=1, n' =2) preserve initial polarisation of the laser light

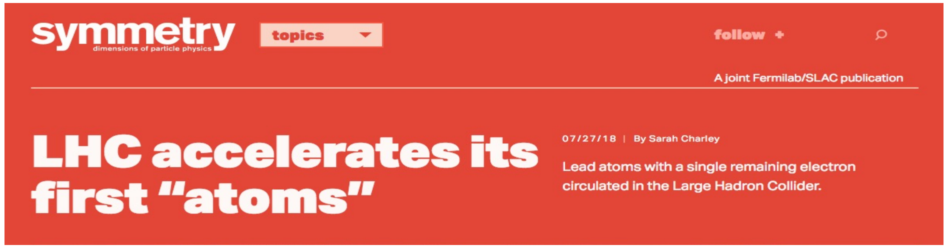




→ Circular polarization ≈ 99%

For more details see presentations at our recent, November 2021, Gamma Factory workshop: https://indico.cern.ch/event/1076086/

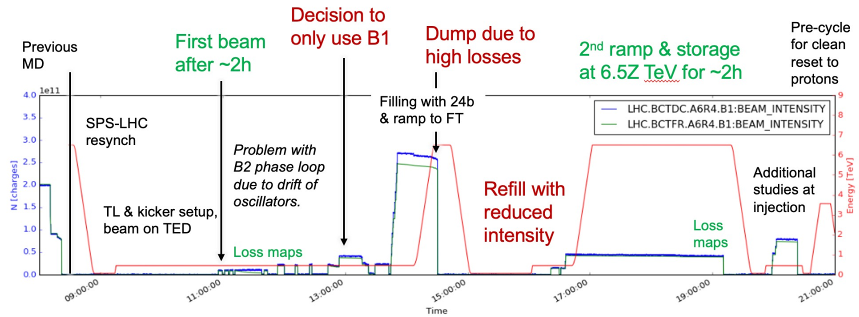
Atomic beams in the LHC – beam collimation


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.




CERN-ACC-NOTE-2019-0012

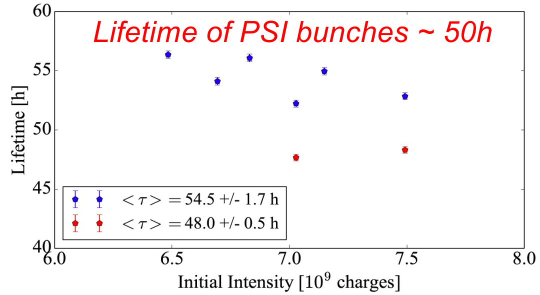
8 May 2019

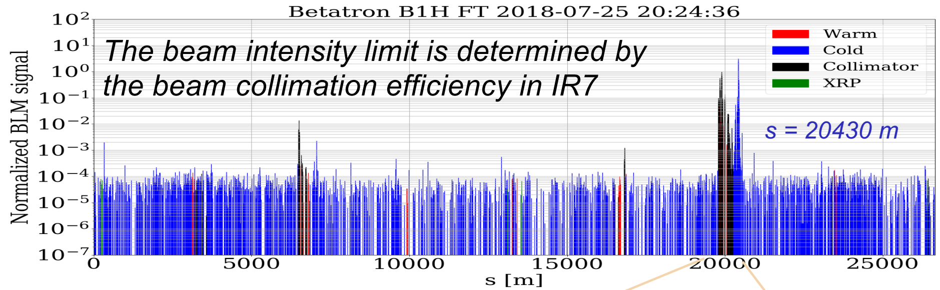
Michaela.Schaumann@cern.ch

MD3284: Partially Stripped Ions in the LHC

M. Schaumann, A. Abramov, R. Alemany Fernandez, T. Argyropoulos, H. Bartosik, N. Biancacci, T. Bohl, C. Bracco, R. Bruce, S. Burger, K. Cornelis, N. Fuster Martinez, B. Goddard, A. Gorzawski, R. Giachino, G.H. Hemelsoet, S. Hirlaender, M. Jebramcik, J.M. Jowett, V. Kain, M.W. Krasny, J. Molson, G. Papotti, M. Solfaroli Camillocci, H. Timko, D. Valuch, F. Velotti, J. Wenninger

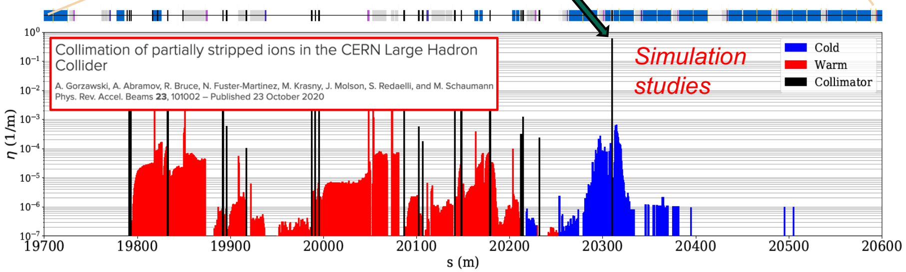
CERN, CH-1211 Geneva 23





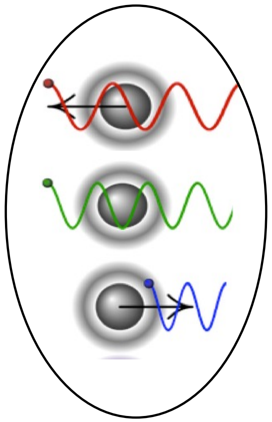
Mitigation strategies:

1. *Dispersion suppressor collimator (TCLD)*
2. *Crystal collimation*
3. ***Laser collimation***.

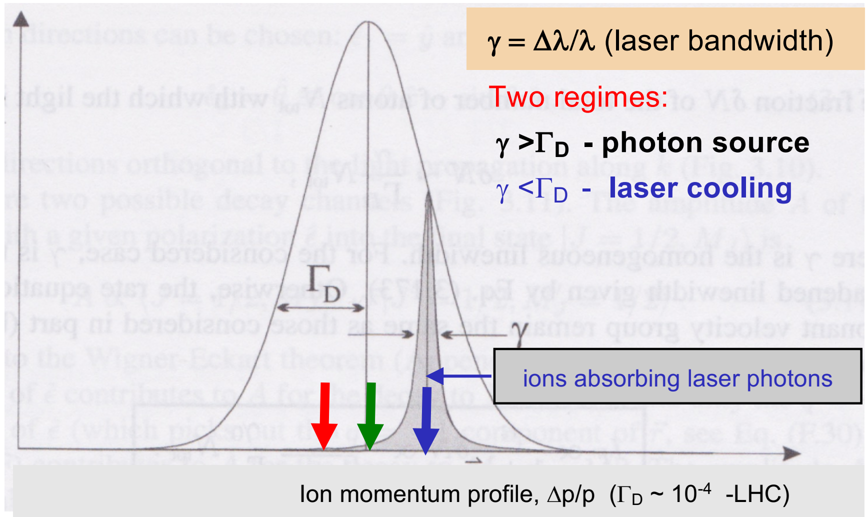


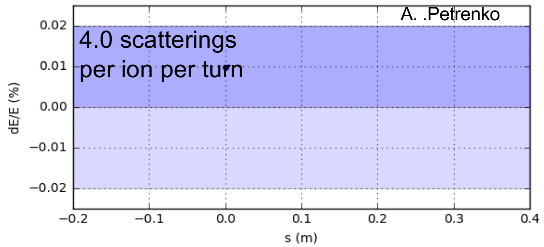
A dedicated LHC MD with crystal collimation of the PSI (H-like Pb) beam is a natural next step…

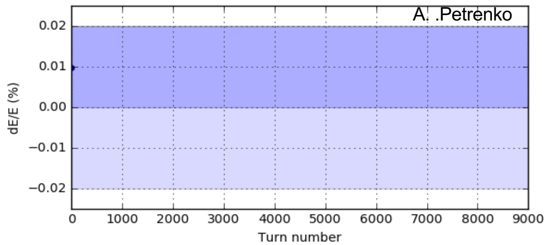
Atomic beams in the LHC - laser cooling



Bunch



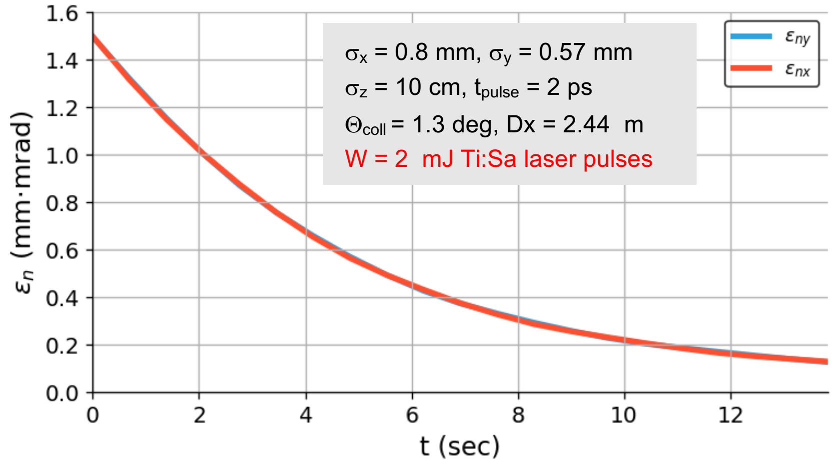




***Beam cooling**: the laser wavelength band is chosen such that only the ions moving in the laser pulse direction (in the bunch rest frame) can resonantly absorb photons.*

Opens a possibility of forming at CERN **high-energy** hadronic bunches of the required longitudinal and transverse emittances and population, (bunch merge + cooling) within a seconds-long time scale.

Prog.Part.Nucl.Phys. 114 (2020) 103792



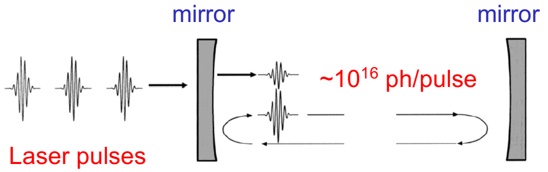
Simulation of laser cooling of the lithium-like Ca(+17) bunches in the SPS: **transverse emittance evolution.**

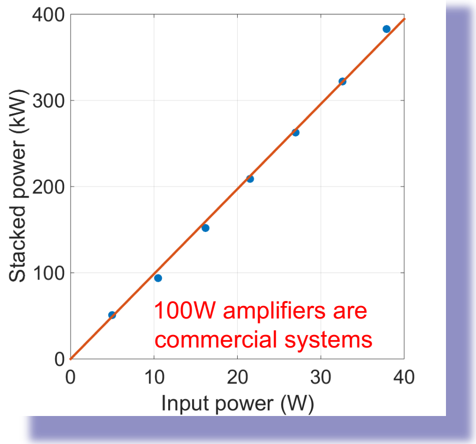
Gamma Factory requirements:

Laser system

Fabry-Pérot (FP) resonators
and their integration in the electron storage rings

Fabry-Pérot resonator

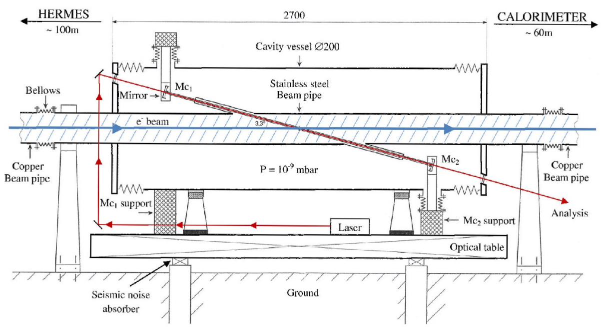




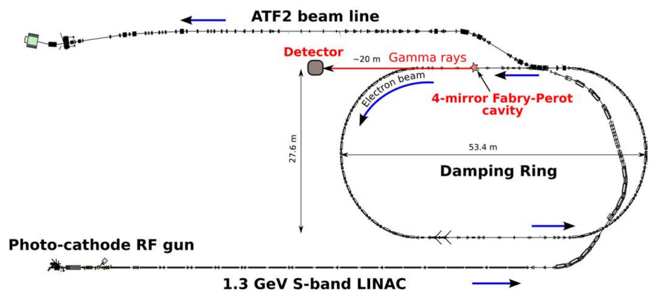
Amoudry L. et al., Applied Optics 59(2020)116

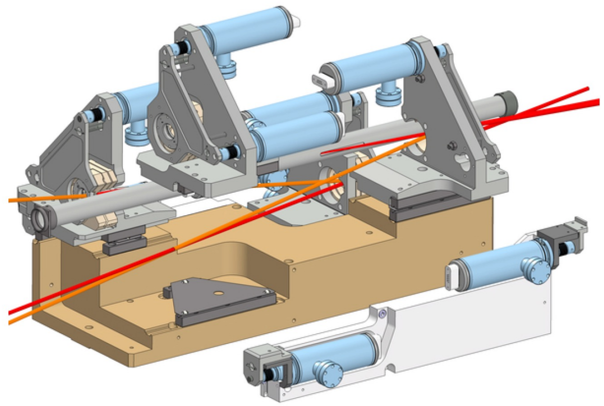
GF requirement:
< 5mJ pulses @ 40MHz,
(200kW photon beam)

HERA storage ring



KEK – ATF ring

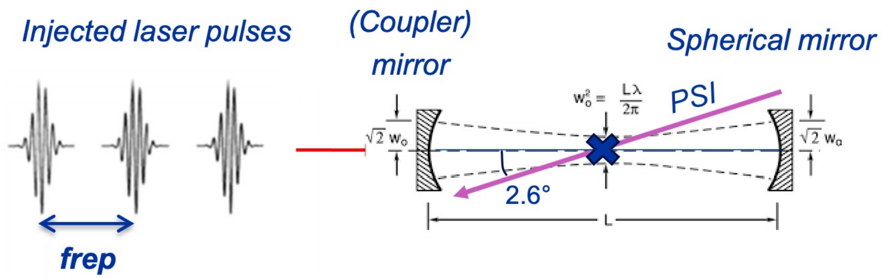




Towards the first integration of the FP resonator in the hadron storage ring →

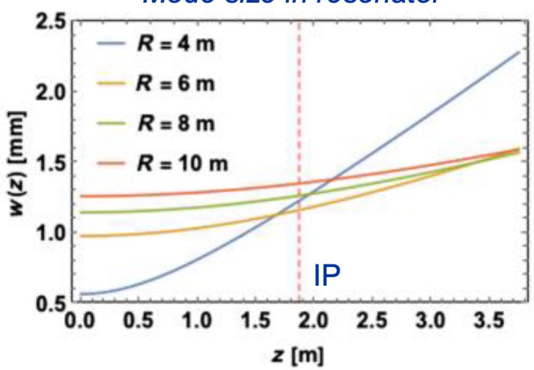
Fabry-Pérot (FP) enhancement

- **Optical cavity**
  - **Recycle** the laser
  - Enhance the injected power due to resonance
- **Hemi-spherical cavity mode**
  - Spherical mirror: waist size control
  - Planar mirror: compensates for length change
- **Injected beam and cavity mode:**
  - Same repetition rate
  - Beam profile matching
  - Polarization matching
  - Phase matching
- **Allows significant enhancement factors on the laser power** (10^3~10^4)

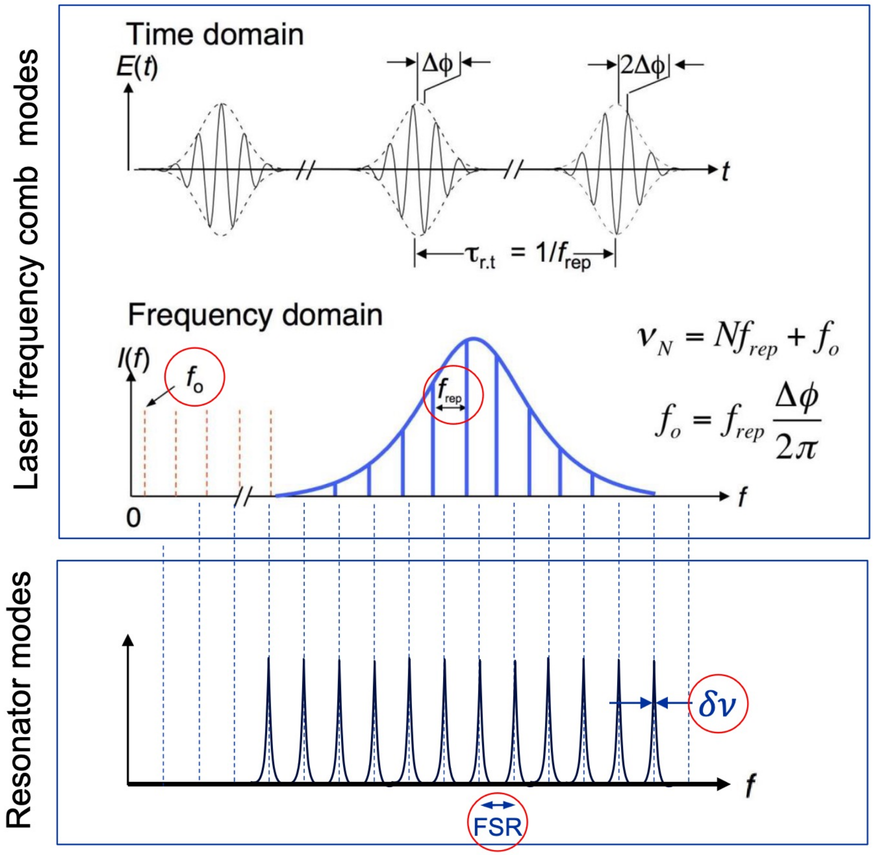


$$FSR = \frac{c}{L_{rt}} = f_{rep} = 40\ MHz \rightarrow \boldsymbol{L = 3.75\ m}$$

Mode size in resonator



Fabry-Pérot (FP) enhancement -- challenges



Maximizing the intracavity power

Large cavity gain

$\mathcal{F} = 10{,}000 \approx 2\pi/\mathcal{L} \Rightarrow G \approx 4T_1/\mathcal{L}^2 \approx$ **5000**

$\mathcal{L} = A_1 + A_2 + D_1 + D_2 + T_1 + T_2$

Absorption 10^{-6} | Diffraction 10^{-5} | Transmission 10^{-4}

$$\frac{\delta\nu}{\nu} = \frac{\lambda}{L\,\mathcal{F}} = 3\times10^{-11}$$

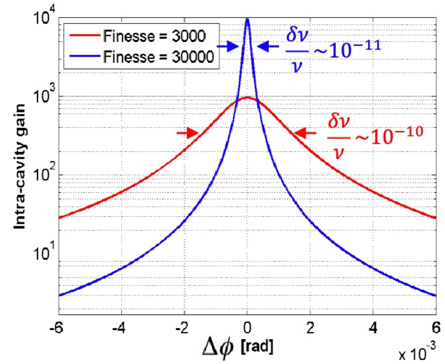
$\delta\nu$ **~ 10 kHz**

Excellent mirrors and stability

Excellent spectral mode matching

$FSR = f_{rep}$ $\quad$ $f_o < \delta\nu$

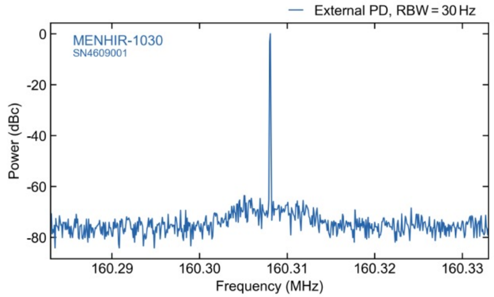
$$f_o = f_{rep}\frac{\Delta\phi}{2\pi}$$

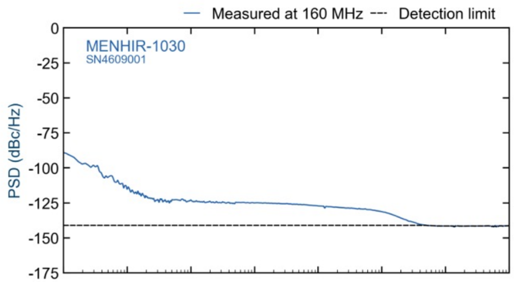


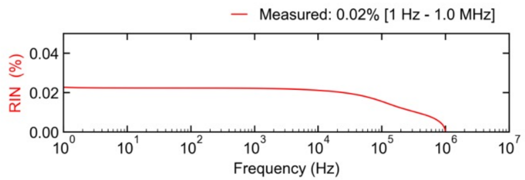
Minimal phase noise

GF Laser was procured (fall 2023) and is being tested

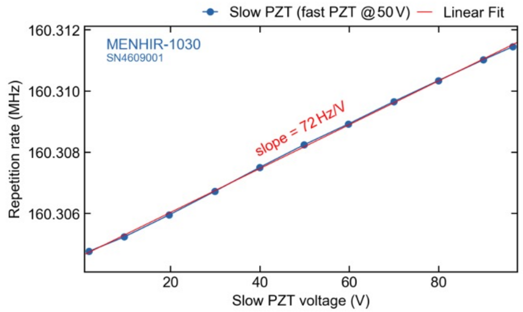
Excellent phase-noise performance

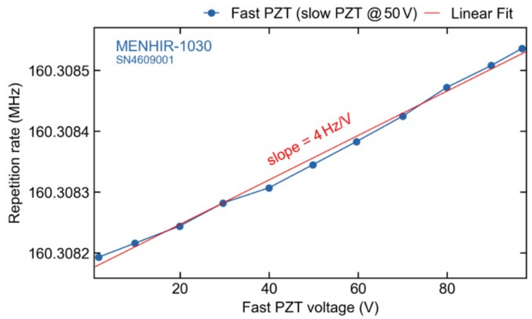




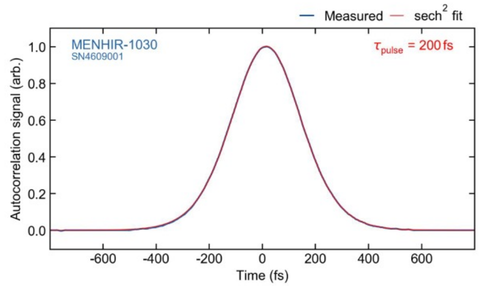


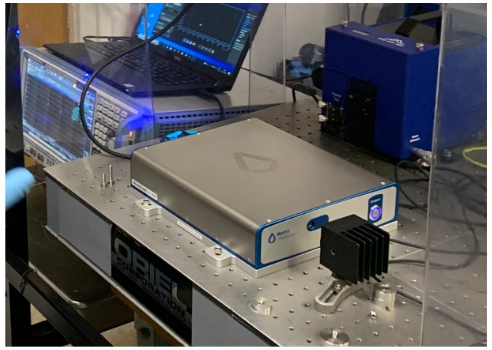
Piezos tuning ranges





Pulse duration





Supply accepted and shipped to IJCLab
Nov 2023 for further testing with FP cavity

Status: February 204

	Current status	GF PoP
FSR	160 MHz	40 MHz
Cavity linewidth	10 kHz	4 kHz
Finesse	17,000	10,000
Gain	3,400	5,000
Coupling efficiency	70%	70%
Amplified power	70 W	50 W
Estimated power	**170 kW**	**180 kW**

Feb 2024

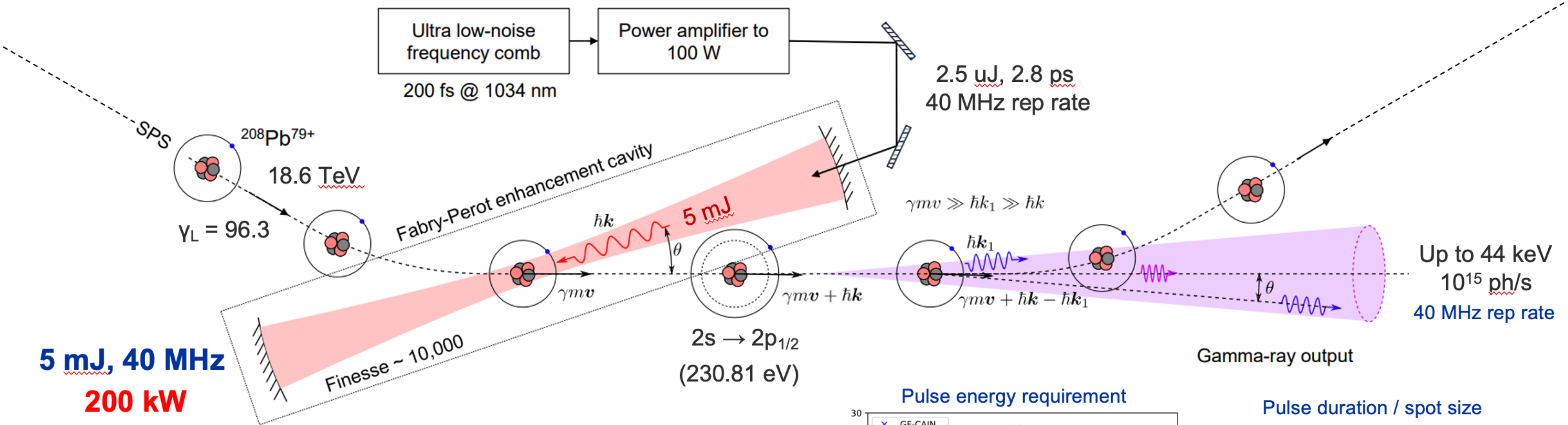
GF PoP – Gamma Factory proof-of-principle experiment

Proof of Principle at SPS

The purpose of the GF SPS PoP experiment

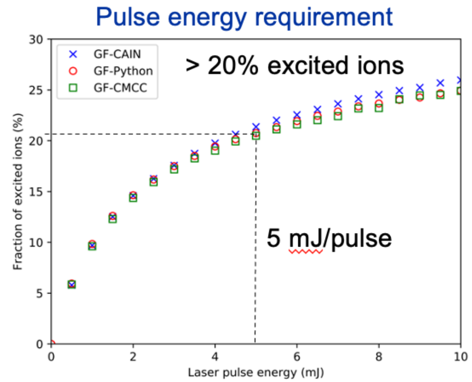
1. Demonstrate that an adequate laser system (5mJ@40MHz) can be (remotely) operated in the high radiation field of the SPS.
2. Demonstrate that very high rates of photons are produced : almost all PSI's are excited in single collision of the PSI bunch with the laser pulse
3. Demonstrate stable and repeatable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

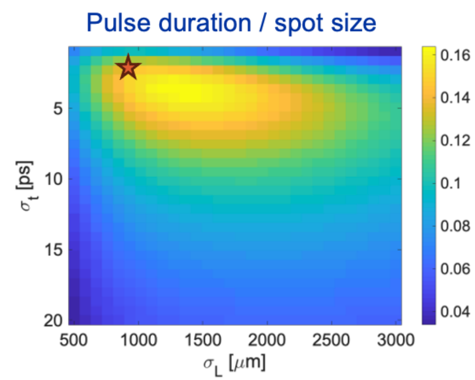
Estimated cost of the experiment 2.5 MCHF

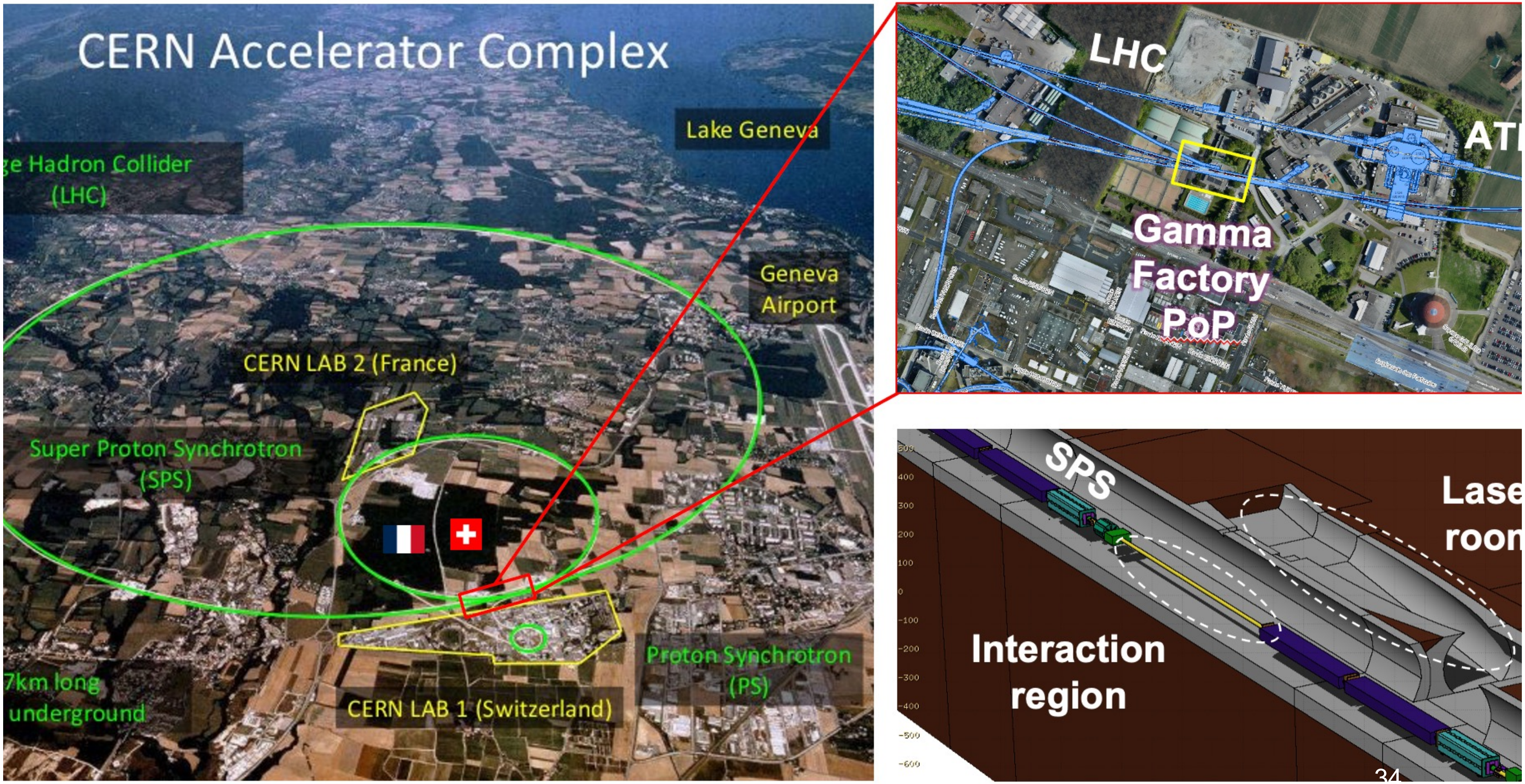


Frequency comb linewidth < 2 kHz

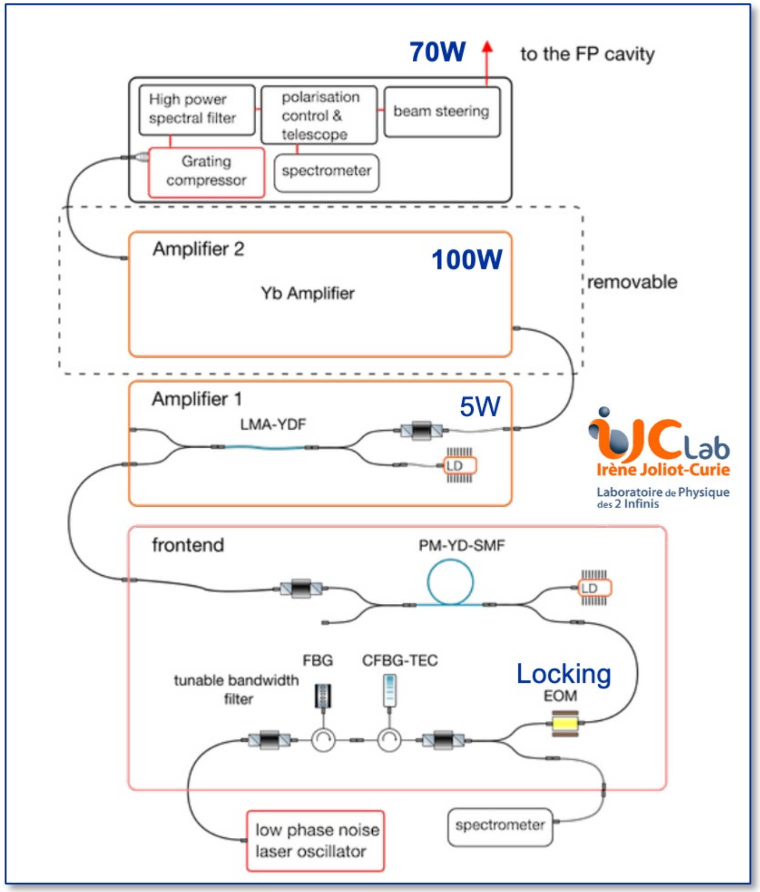
"LIGO-type" mirrors



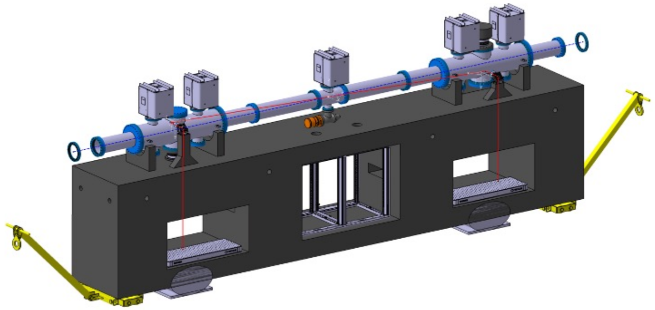



CERN Accelerator Complex
Lake Geneva
ge Hadron Collider (LHC)
Geneva Airport
CERN LAB 2 (France)
Super Proton Synchrotron (SPS)
Proton Synchrotron (PS)
7km long underground
CERN LAB 1 (Switzerland)
LHC
AT
Gamma Factory PoP
SPS
Lase roo
Interaction region

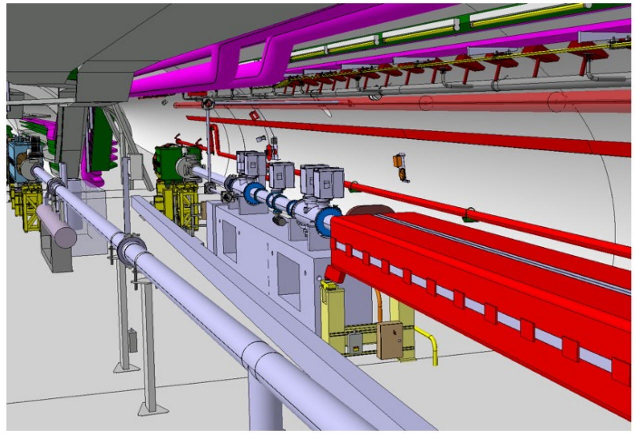
Laser system



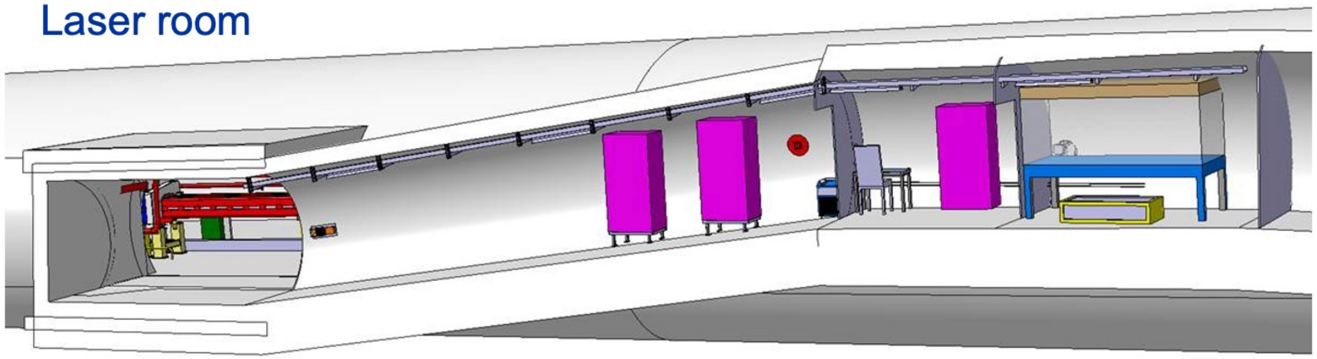
Fabry-Perot cavity assembly

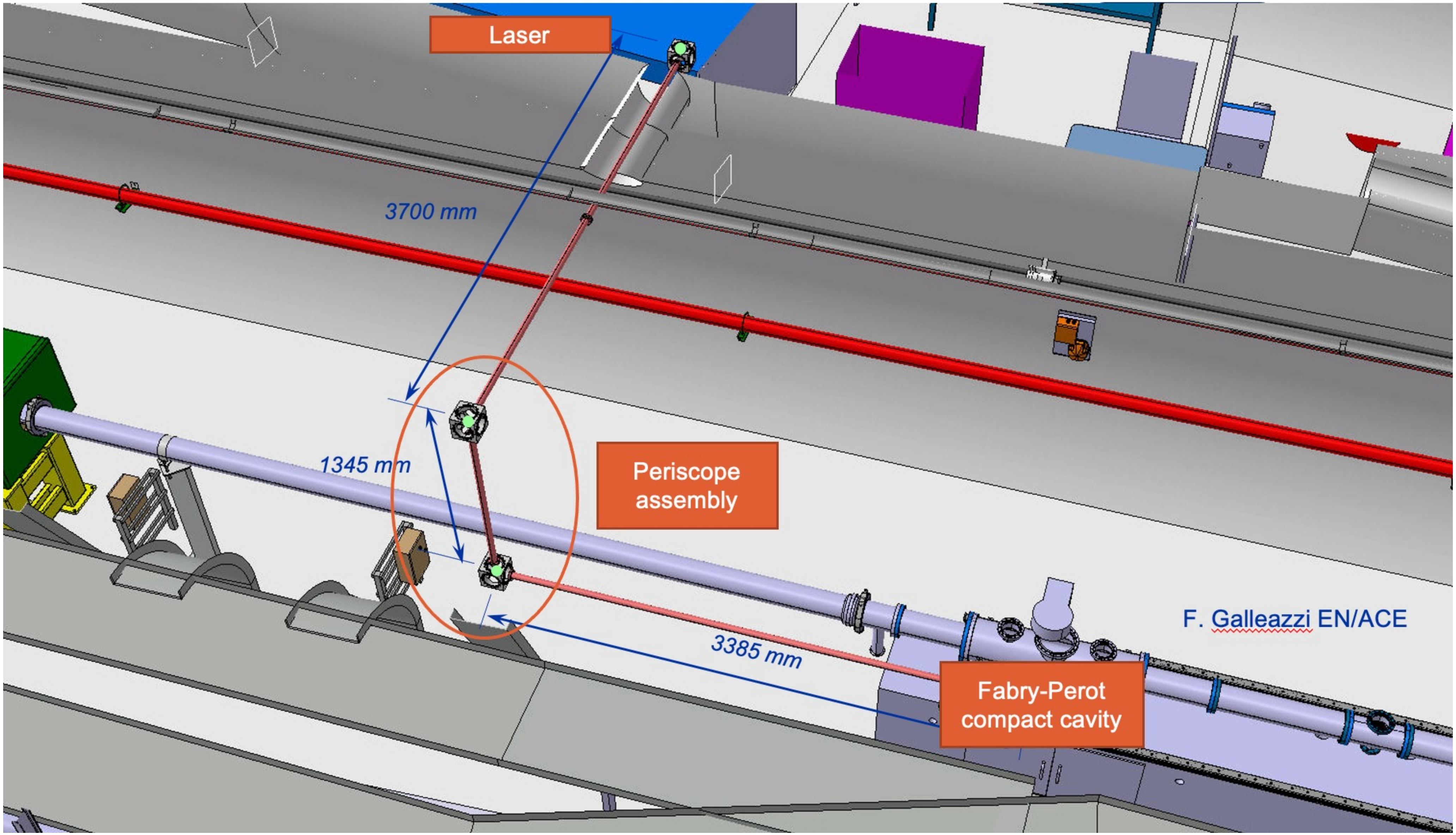


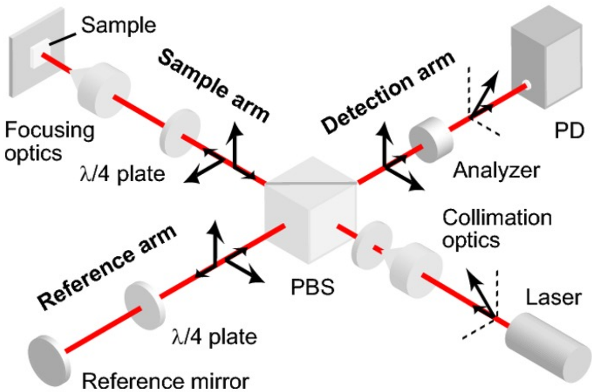
Integration in SPS

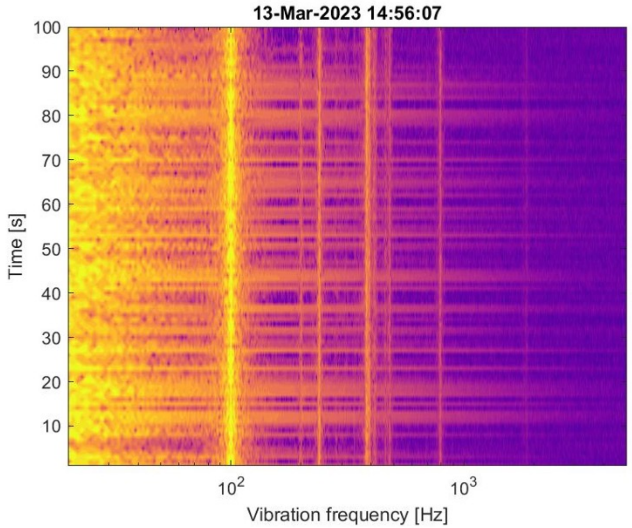


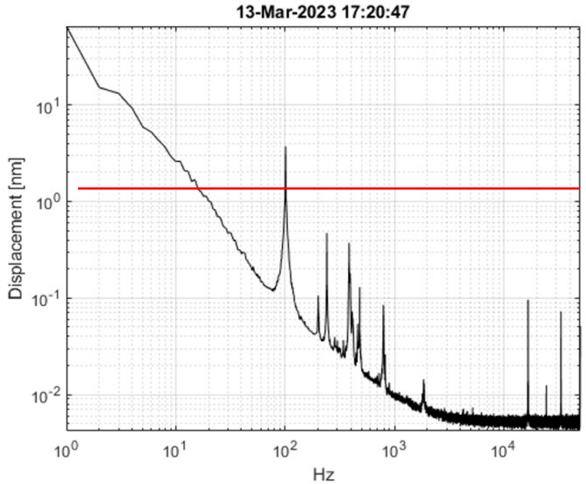
Laser room



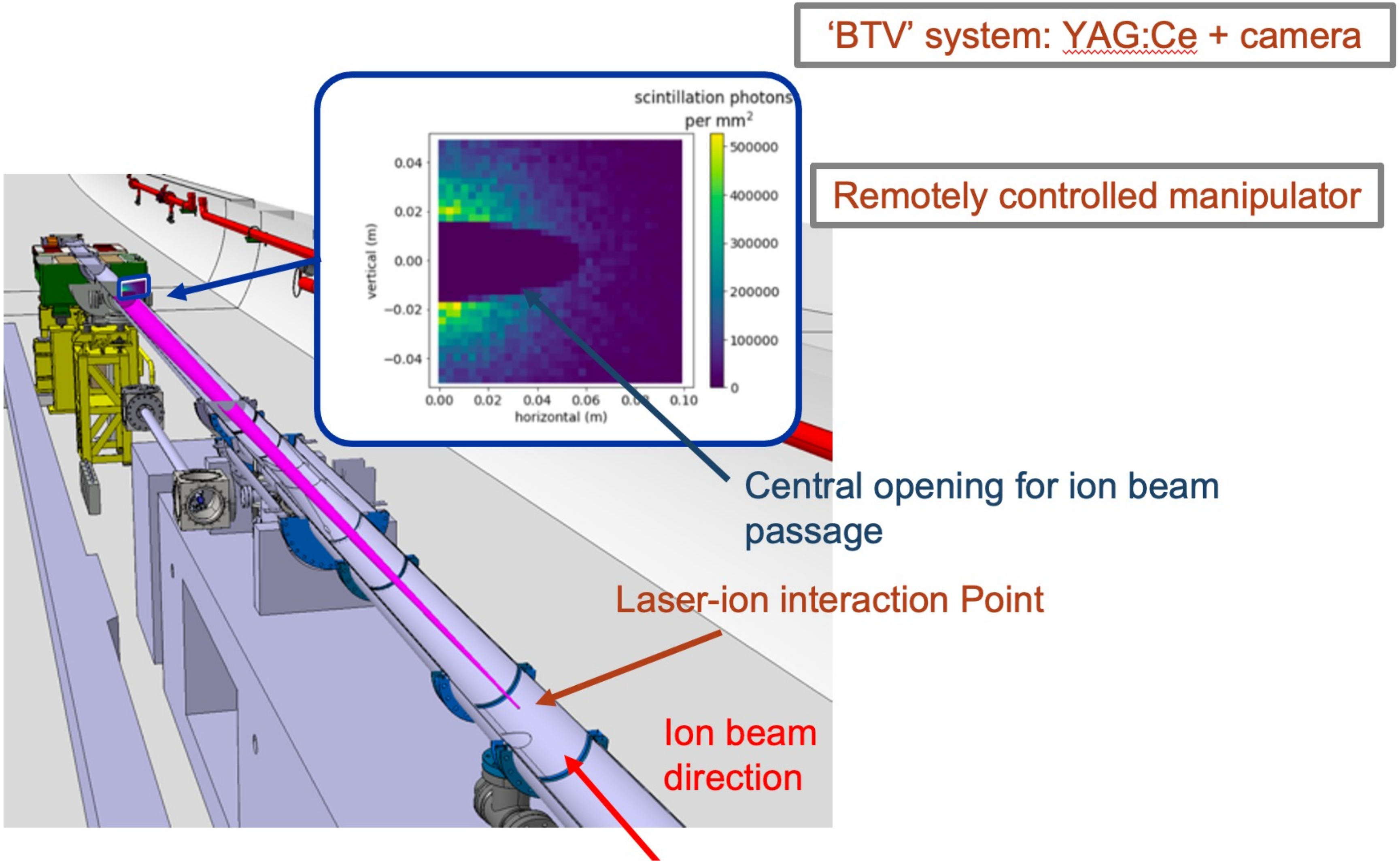

Laser
3700 mm
1345 mm
Periscope assembly
3385 mm
Fabry-Perot compact cavity
F. Galleazzi EN/ACE







- Measured the vibration spectral content during 6 hours with SPS equipment switched ON.
- Accuracy was down to few pm in length and up to 10 kHz in frequency.
- Largest contributions are acoustics below 1 kHz, with eventual tones at 2.3 kHz.
- Need to check the coupling of vibrations to future laser beamline and with a Fabry-Perot cavity resembling the future experiments



'BTV' system: YAG:Ce + camera
Remotely controlled manipulator
scintillation photons per mm^2
500000
400000
300000
200000
100000
0
0.04
0.02
0.00
−0.02
−0.04
vertical (m)
0.00
0.02
0.04
0.06
0.10
horizontal (m)
Central opening for ion beam passage
Laser-ion interaction Point
Ion beam direction

Status of the ingredients for lasers for PoP experiment (and next steps):

- TI18 area, conversion to a laser lab in LS3
- Fabry-Perot Cavity with large gain factor at IJCLab and transfer to CERN
- Ultra low-phase noise laser and amplification chain procurement and commissioning
- Laser beam delivery system, controls and diagnostics at IP
- Full remote end-to-end operation of laser beams

Main areas of activity of the Gamma Factory group in 2024

- ***GF –PoP experiment preparation (to be installed in the LS3 shutdown)***

(not discussed in this presentation)

- *Beam cooling scenarios studies*
- *Gamma Factory based subcritical reactor with waste transmutation capacity studies*
- *Photon beam production scheme in the EM field zone – conceptual developments*
- *Scheme to produce twisted photon beams – conceptual development*
- *Gamma Factory polarised positron source – simulations*