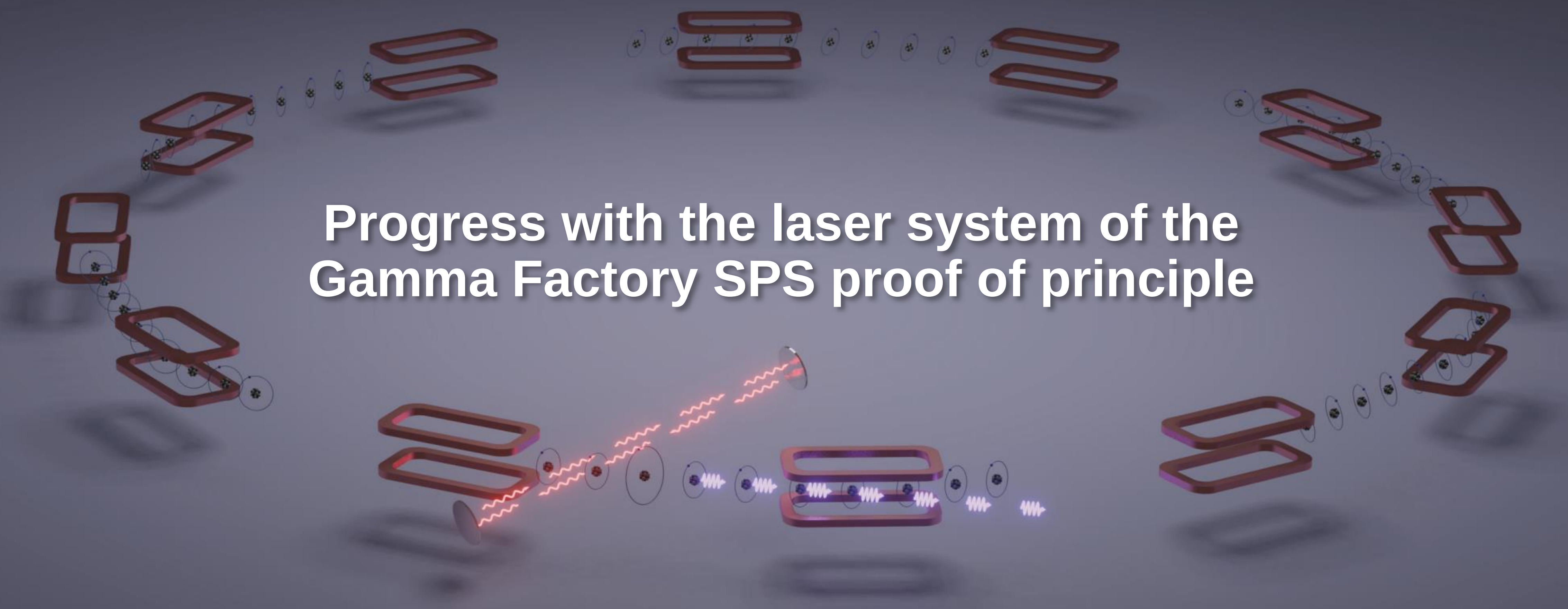


Progress with the laser system of the Gamma Factory SPS proof of principle

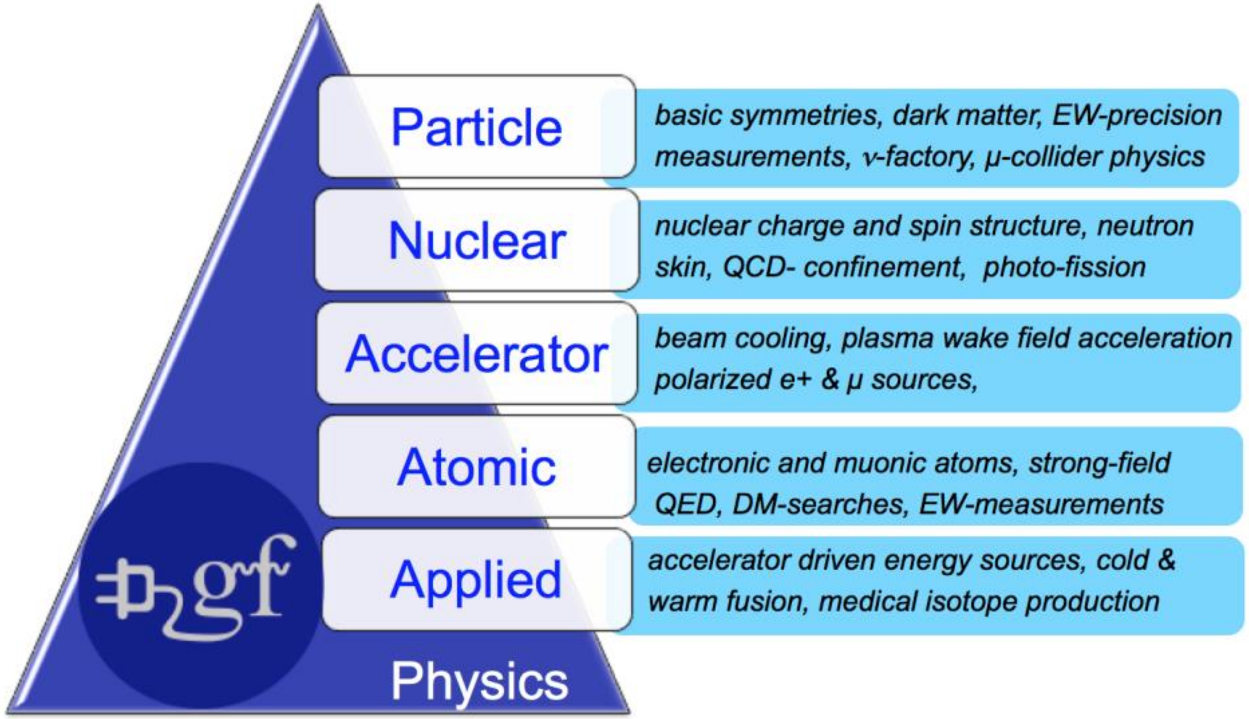
Eduardo Granados SY/STI-LP for the Gamma Factory Collaboration

25th March 2024

Outline

- **Introduction:**
    - **Aim** of the project.
    - **Concept**: exploiting the Doppler effect in ultra-relativistic partially stripped ion beams
    - The **magnitude** of the Gamma-ray photon flux leap
- **Roadmap** – Proof of principle experiment in SPS, final experiment in the LHC
- **Status**:
    - Laser systems, beamline design
    - Experimental area (TI18)
    - Expected performance: IJCLab collaboration
- **Conclusions**

Physics Beyond Colliders: The Gamma Factory at CERN



Physics	
Particle	*basic symmetries, dark matter, EW-precision measurements, ν-factory, μ-collider physics*
Nuclear	*nuclear charge and spin structure, neutron skin, QCD- confinement, photo-fission*
Accelerator	*beam cooling, plasma wake field acceleration polarized e+ & μ sources,*
Atomic	*electronic and muonic atoms, strong-field QED, DM-searches, EW-measurements*
Applied	*accelerator driven energy sources, cold & warm fusion, medical isotope production*

Examples of physics opportunities (from 2021)
Now **many more** additional papers have been published

Volume 534, Issue 3

Special Issue: Physics Opportunities with the Gamma Factory

March 2022

Issue Edited by: Dmitry Budker, Mikhail Gorchtein, Mieczyslaw Witold Krasny, Adriana Pálffy, Andrey Surzhykov

Review

Open Access
☐ Expanding Nuclear Physics Horizons with the Gamma Factory

Research Articles

Full Access
☐ Local Lorentz Invariance Tests for Photons and Hadrons at the Gamma Factory

Full Access
☐ Electric Dipole Polarizability of Neutron Rich Nuclei

Open Access
☐ Vacuum Birefringence at the Gamma Factory

Full Access
☐ Double-Twisted Spectroscopy with Delocalized Atoms

Full Access
☐ Delta Baryon Photoproduction with Twisted Photons

Open Access
☐ Resonant Scattering of Plane-Wave and Twisted Photons at the Gamma Factory

Full Access
☐ Probing Axion-Like-Particles at the CERN Gamma Factory

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

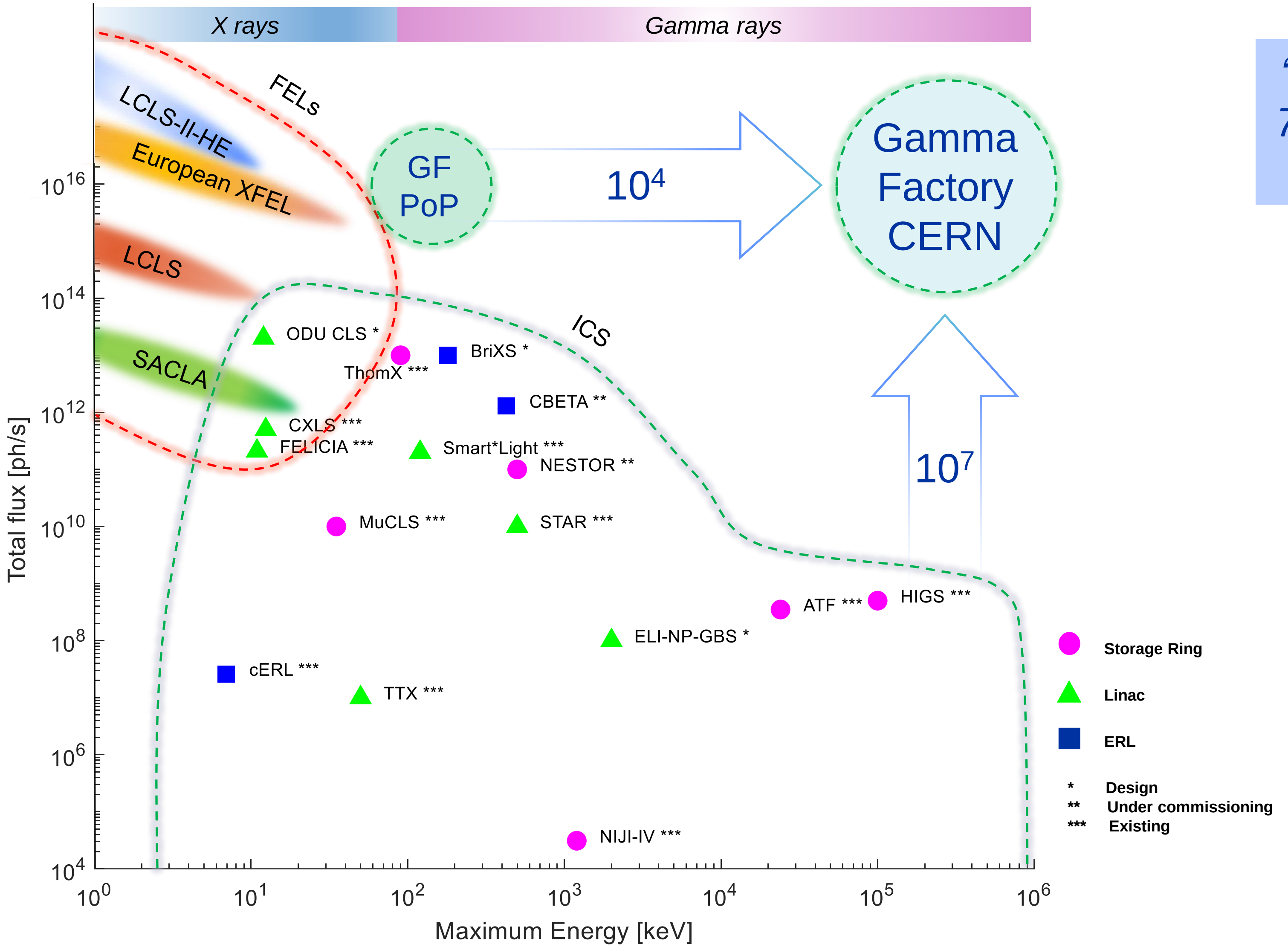
Open Access
☐ Access to the Kaon Radius with Kaonic Atoms

Full Access
☐ Radioactive Ion Beam Production at the Gamma Factory

Open Access
☐ Possible Polarization Measurements in Elastic Scattering at the Gamma Factory Utilizing a 2D Sensitive Strip Detector as Dedicated Compton Polarimeter

Full Access
☐ Polarization of Photons Scattered by Ultra-Relativistic Ion Beams

Comparison to other X-ray and Gamma-ray sources



"Can one make a technological leap of 7 orders of magnitude to deliver similar fluxes to FELs in the Gamma-rays?"

Example (GF for nuclear physics app):

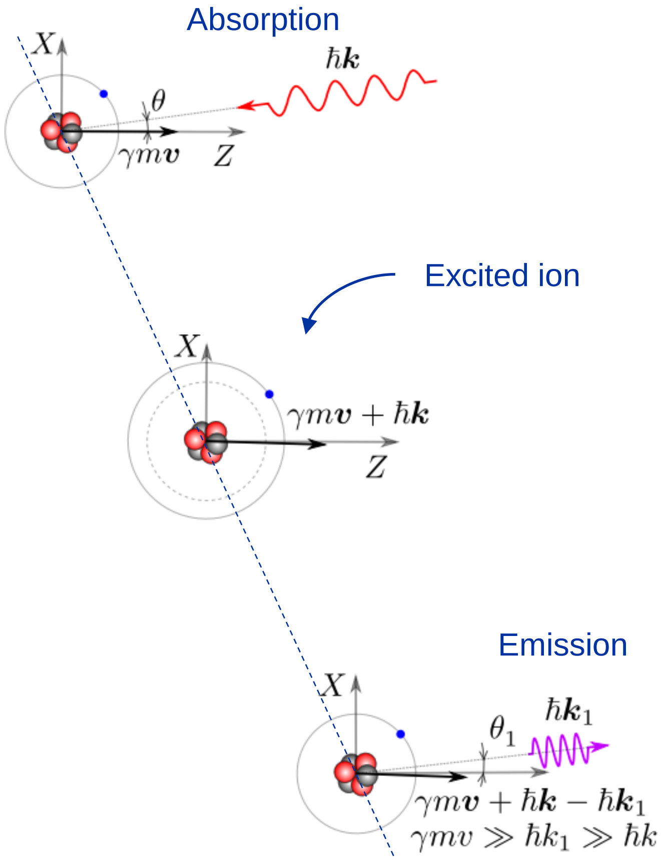
European XFEL	Gamma Factory
27,000 pulses/s	20 MHz
24 keV	18 MeV
10^{16} photons/s	3.6 x 10^{17} photons/s
1.4 mJ/pulse	5 mJ/pulse (laser)
38 W (J/s)	**570 kW (kJ/s)**

The Gamma Factory operates with **MW** electric power and 10s **MJ** of stored beam energy

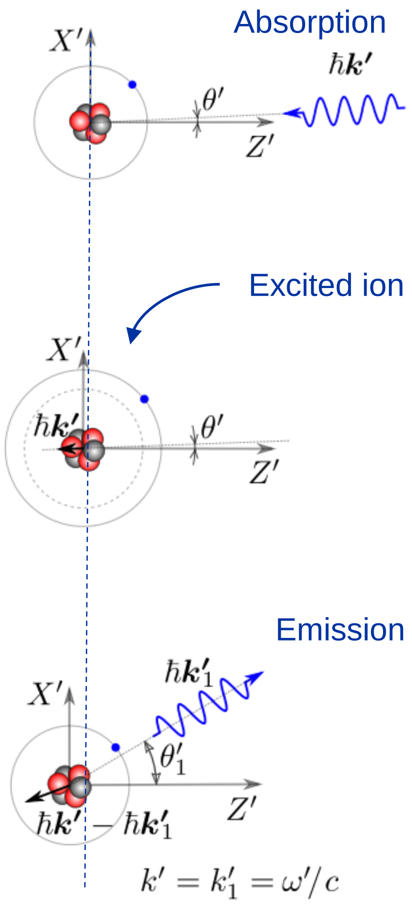
So far, the *only* facility currently providing such parameter space is the **LHC**

Basic idea: Use the Doppler effect with ultra-relativistic ions

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

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

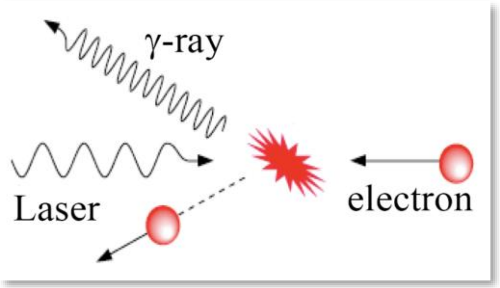
$$\omega_1 = \gamma(1 + \beta\cos\theta'_1)\omega' \approx 2\gamma^2(1 + \beta\cos\theta'_1)\omega.$$

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

Gamma Factory Proof of Principle LoI, M. W. Krasny et al
https://cds.cern.ch/record/2690736/files/SPSC-I-253.pdf

The magnitude of the Gamma source intensity leap

Inverse Compton scattering



Cross-section

Electrons:

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

r_e - classical electron radius

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

Requirements

$E_{beam} = 1.5$ GeV

LINAC or LWFA

Electron fractional energy loss:

emission of 150 MeV photon:

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

(electron is lost!)

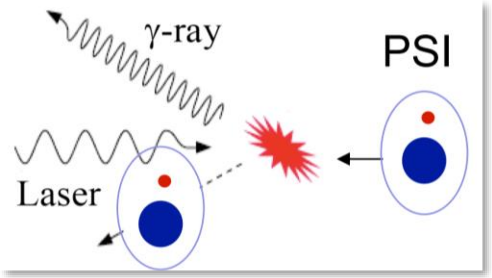
Features

- Relatively “compact”
- Large laser system
- Low γ photon flux (10^9 ph/s)

⇩ $\sigma \times 10^9$

⇩ x 10^7 ph/s

Gamma Factory



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

Partially Stripped Ions:

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

λ_{res} - photon wavelength in the ion rest frame

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

$E_{beam} = 574\,000$ GeV

(LHC)

Electron fractional energy loss:

emission of 150 MeV photon:

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

(ion undisturbed!)

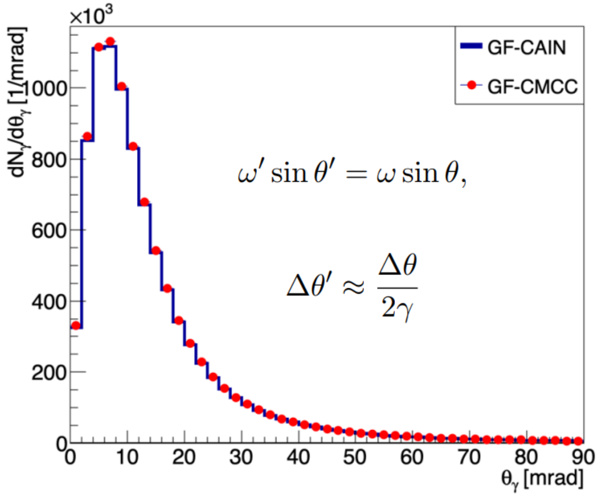
- Unique Gamma-ray beam
- Modest laser requirements
- Ultrahigh γ photon flux (10^{16} ph/s)
- Transparent to accelerators
- Beam cooling capability

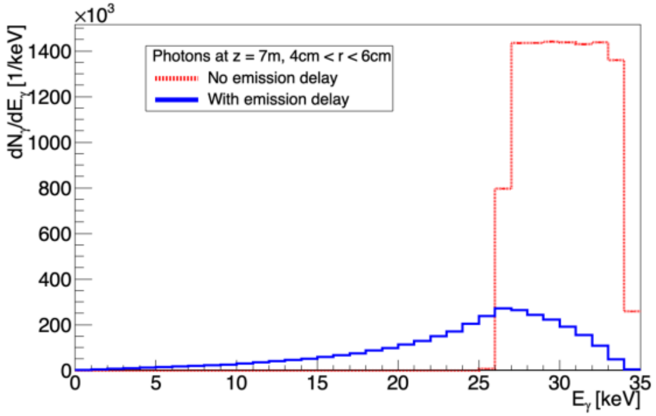
M . W. Krasny “The CERN Gamma Factory proposal”
https://indico.cern.ch/event/604619/contributions/2474166/

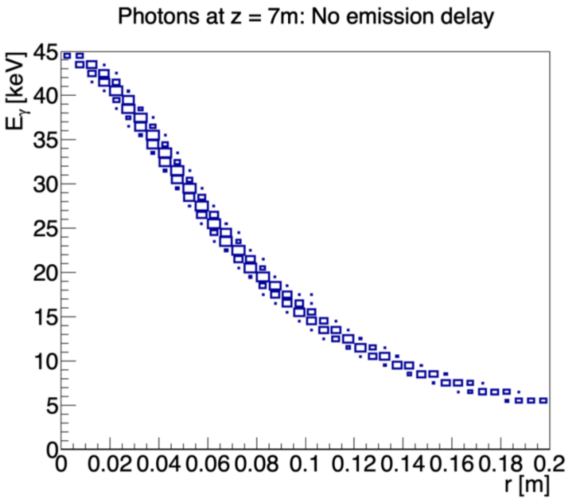
Expected performance of the PoP experiment at SPS

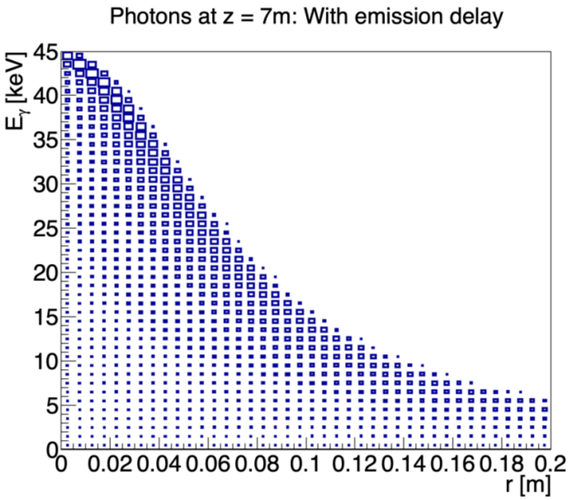
Proposed parameters for GF PoP experiment

	GF PoP
Ion beam	$^{208}Pb^{79+}$
	18.652 TeV (SPS)
	40 MHz
Produced photons	**Up to 44 keV**
	10^{15} photons/s
	0.2 uJ/pulse
	7 W (J/s)



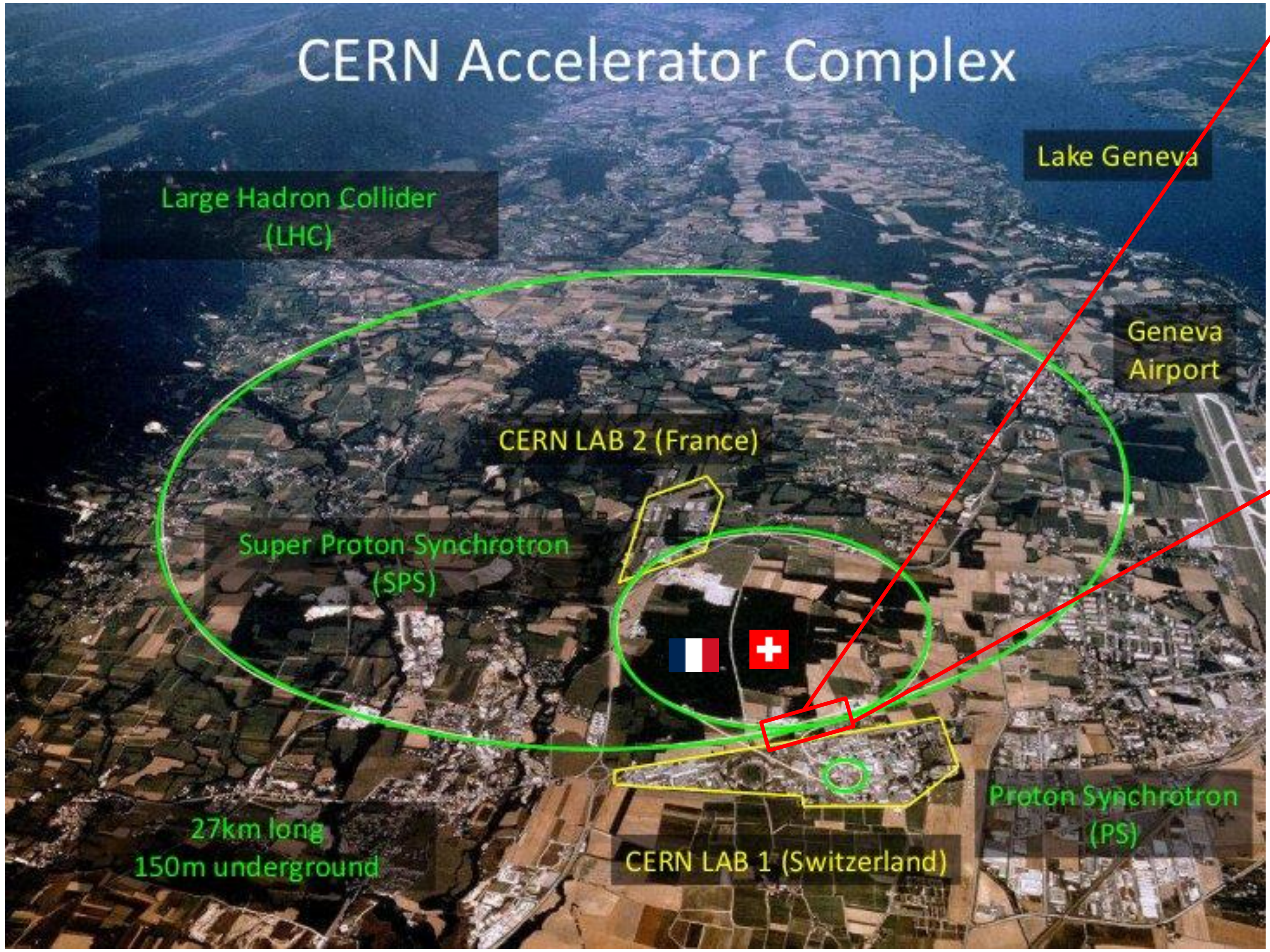


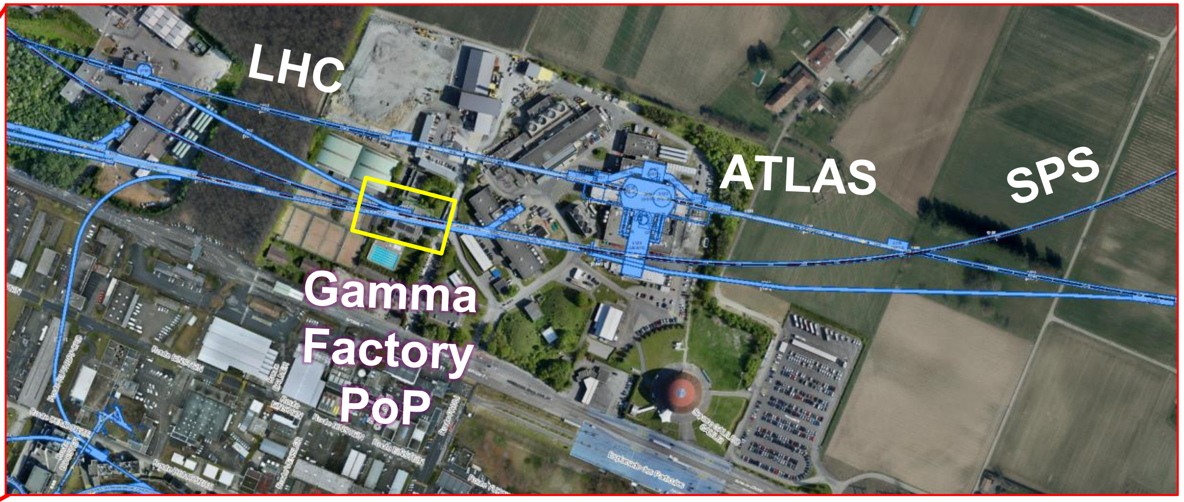


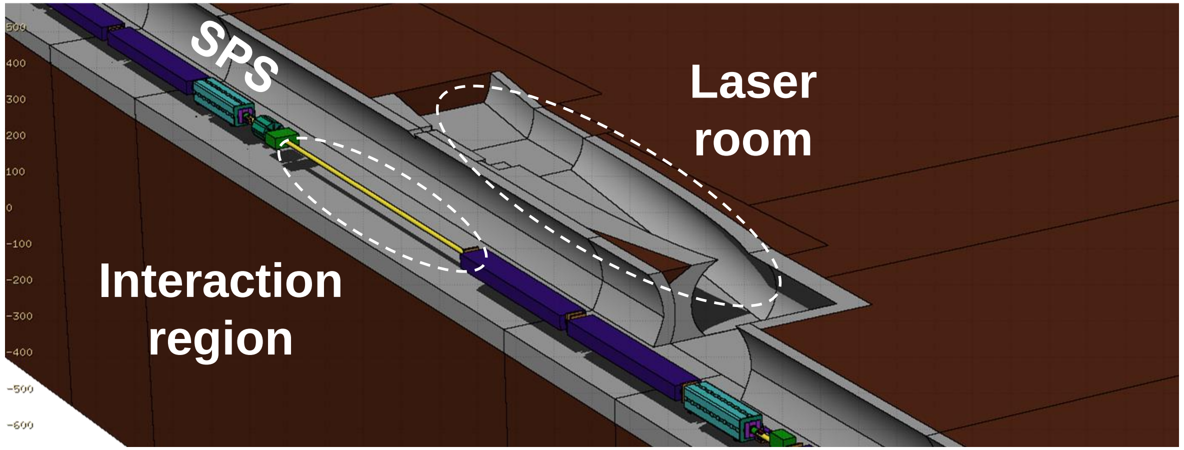


J. Bieroń, M. W. Krasny, W. Płaczek, S. Pustelny, Optical Excitation of Ultra-Relativistic Partially Stripped Ions. *ANNALEN DER PHYSIK* 2022, 534, 2100250.

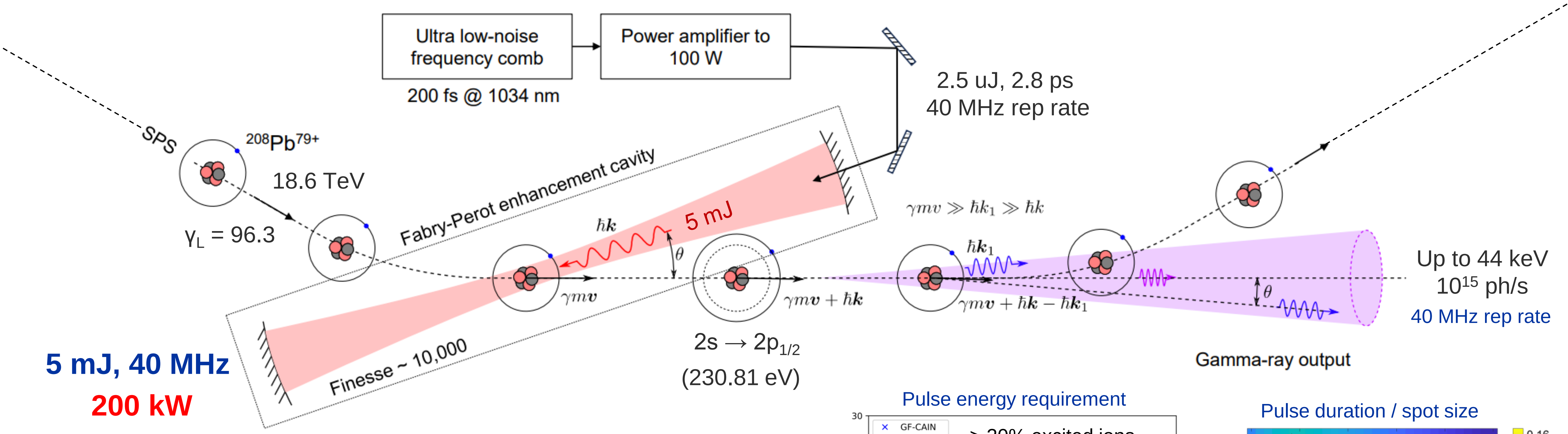
Proof of principle experiment location







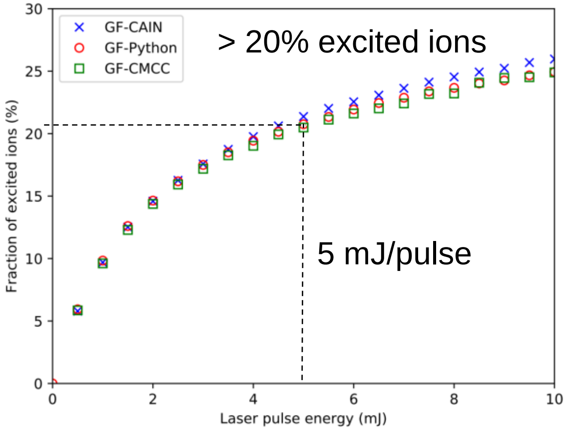
Proof of principle experimental setup



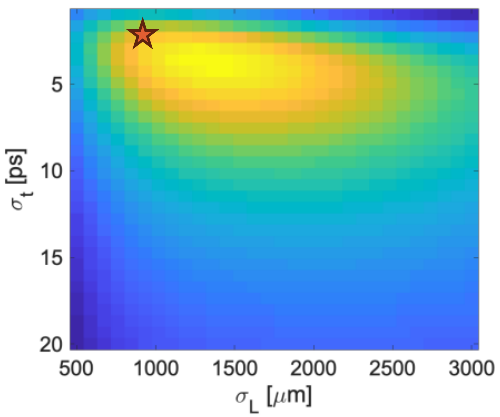
5 mJ, 40 MHz

200 kW

Pulse energy requirement



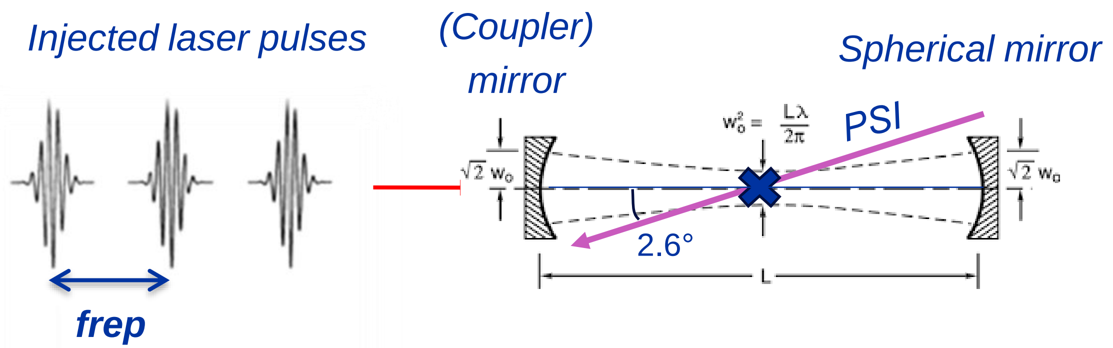
Pulse duration / spot size



Aurélien Martens, et al. Phys. Rev. Accel. Beams **25**, 101601 (2022)

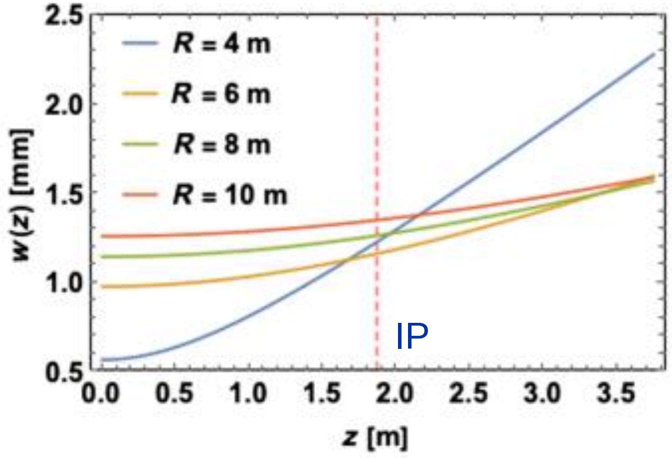
Fabry Perot enhancement cavity principle

- **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)

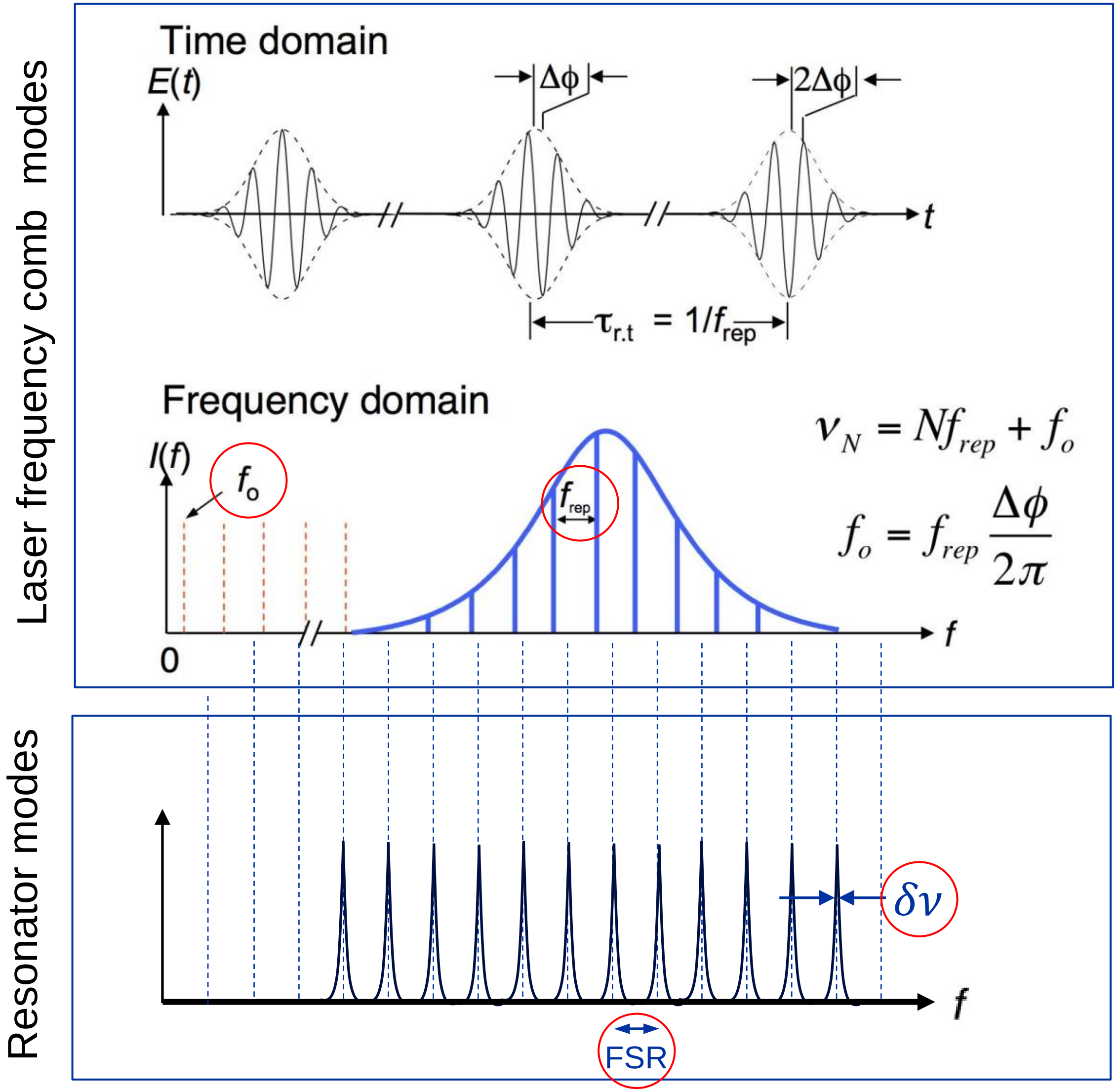


$$FSR = \frac{c}{L_{rt}} = f_{rep} = 40\ MHz \rightarrow \boldsymbol{L = 3.75\ m}$$

Mode size in resonator



Fabry Perot enhancement cavity principle



Maximizing the intracavity power

Large cavity gain

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

$$\mathcal{L} = \underbrace{A_1 + A_2}_{\text{Absorption } 10^{-6}} + \underbrace{D_1 + D_2}_{\text{Diffraction } 10^{-5}} + \underbrace{T_1 + T_2}_{\text{Transmission } 10^{-4}}$$

$$\frac{\delta\nu}{\nu} = \frac{\lambda}{L\,\mathcal{F}} = 3 \times 10^{-11}$$

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

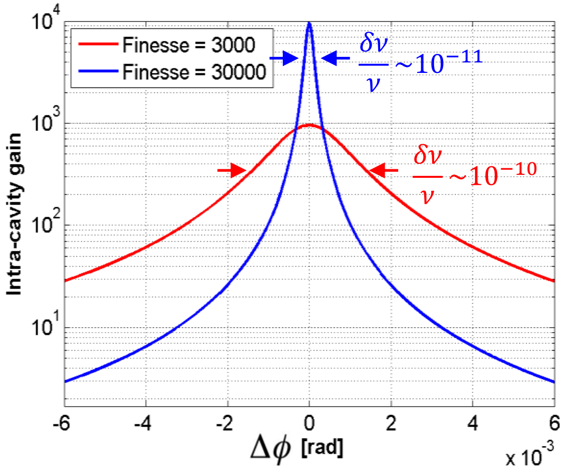
Excellent mirrors and stability

Excellent spectral mode matching

$FSR = f_{rep}$

$f_o < \delta\nu$

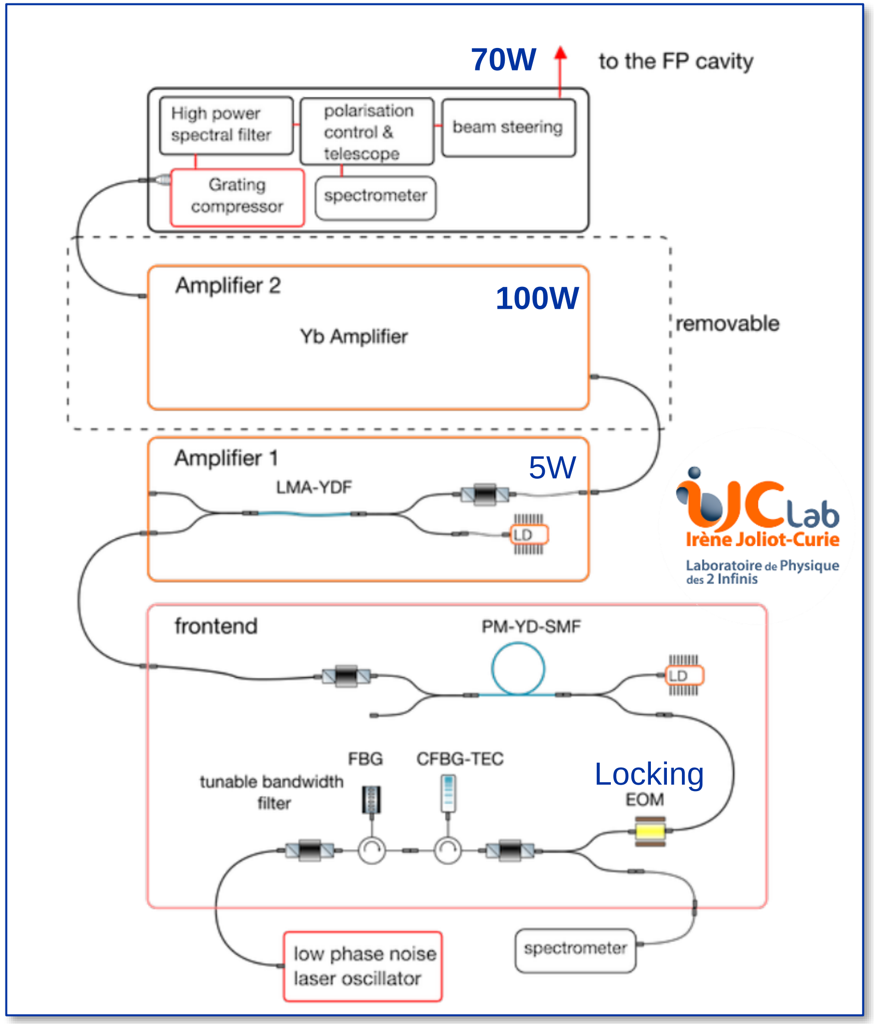
$$f_o = f_{rep}\frac{\Delta\phi}{2\pi}$$



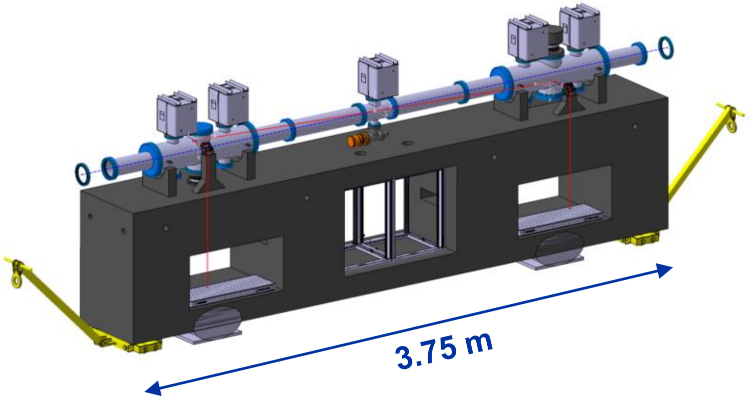
Minimal phase noise

Laser systems and integration into SPS: ingredients

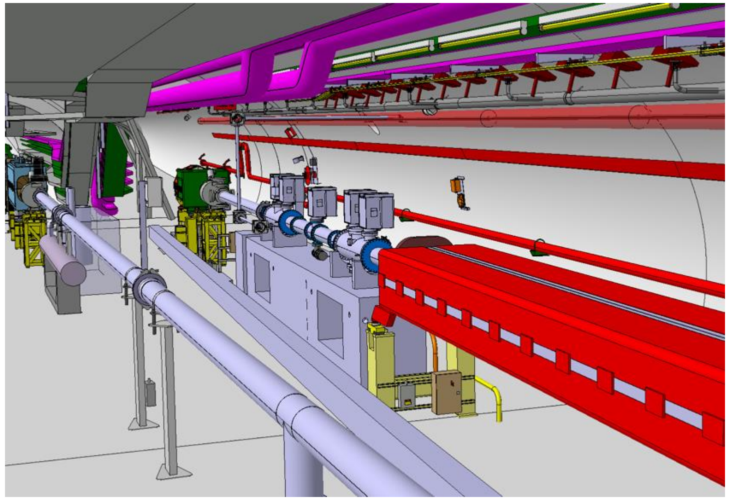
Laser system



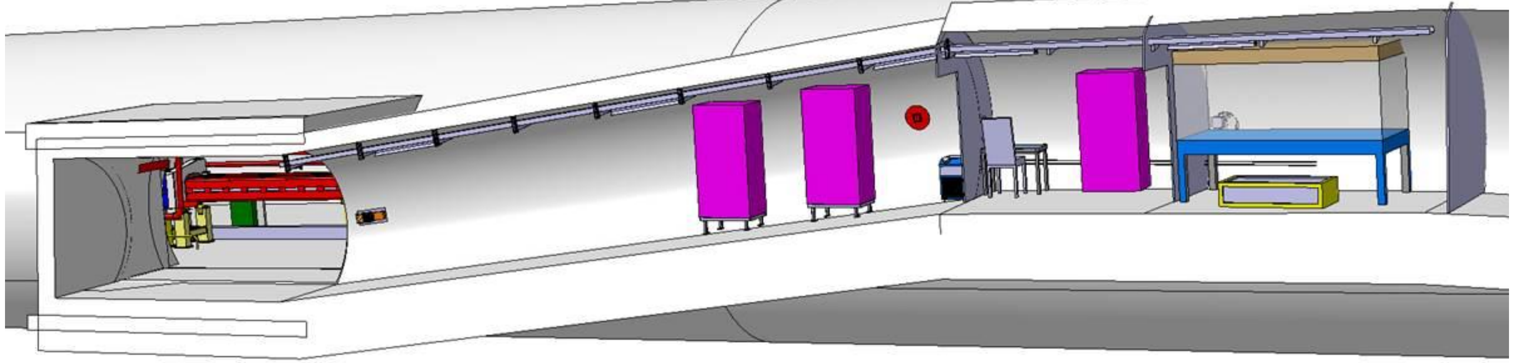
Fabry-Perot cavity assembly



Integration in SPS

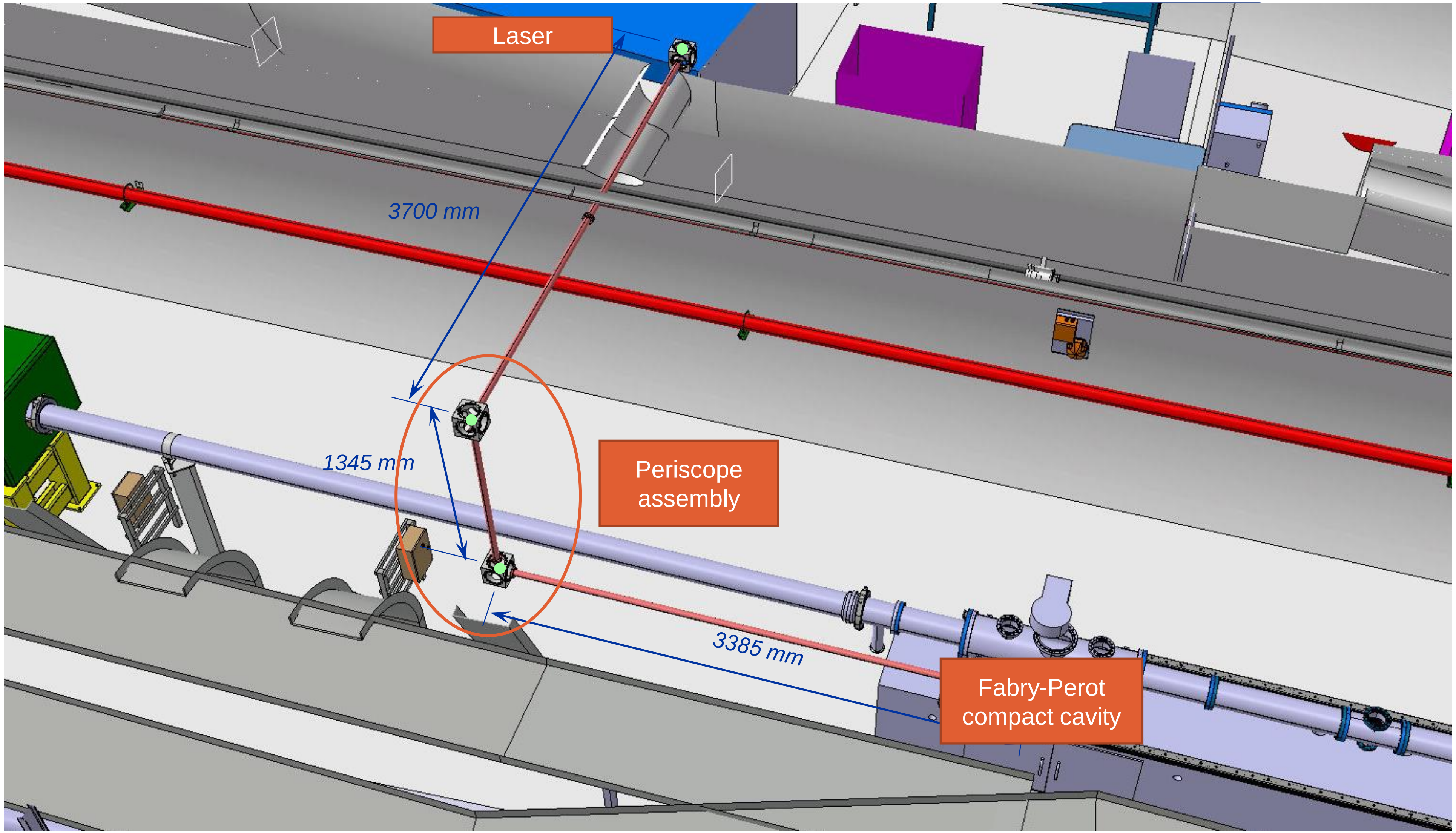


Laser room



Gamma Factory Proof of Principle LoI, M. W. Krasny et al
https://cds.cern.ch/record/2690736/files/SPSC-I-253.pdf

Laser transport beamline



F. Galleazzi EN/ACE

Sensitivity of the Fabry-Perot cavity to misalignments

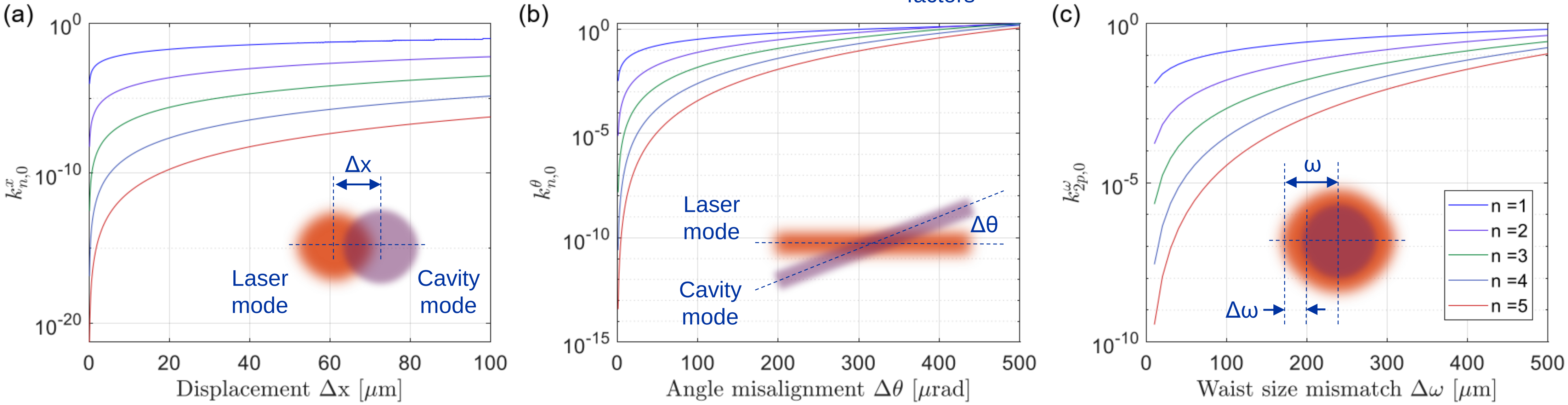
The couplings *k* between an input Gaussian beam and cavity Cartesian modes n > 0,0 and cylindrical modes p > 0,0 due to geometrical perturbations from alignment may be derived from the equations of Bayer-Helms. We consider here couplings due to displacement, angle mismatch and waist size mismatch only.

$$\psi^{(o)}_{m,n}(x^{(o)}, y^{(o)}, z^{(o)})\, \exp\{ik(z - z^{(o)})\} = \sum_{\overline{m}=0}^{\infty} \sum_{\overline{n}=0}^{\infty} k^{(x.x)}_{m,n,\overline{m},\overline{n}}\, \psi_{\overline{m},\overline{n}}(x, y, z) \qquad \sum_{\overline{m}=0}^{\infty} \sum_{\overline{n}=0}^{\infty} \left|k_{m,n,\overline{m},\overline{n}}\right|^2 = 1,$$

Input laser mode (assume TEM00)

Coupling factors

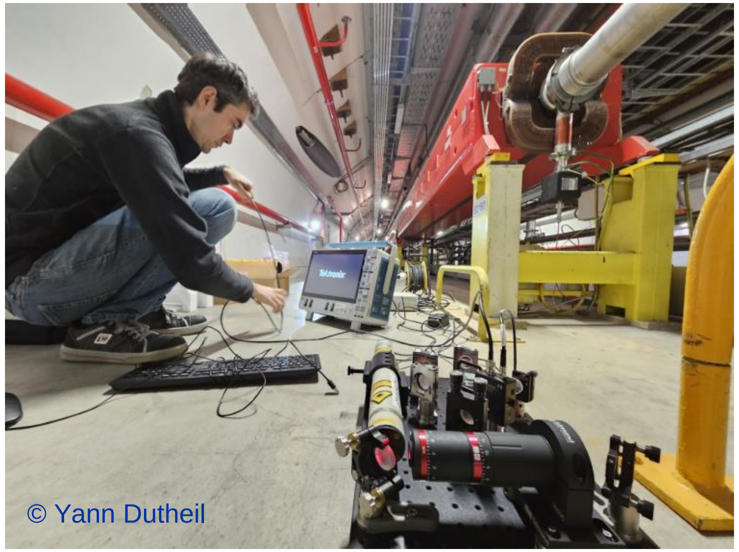
Cavity Cartesian modes

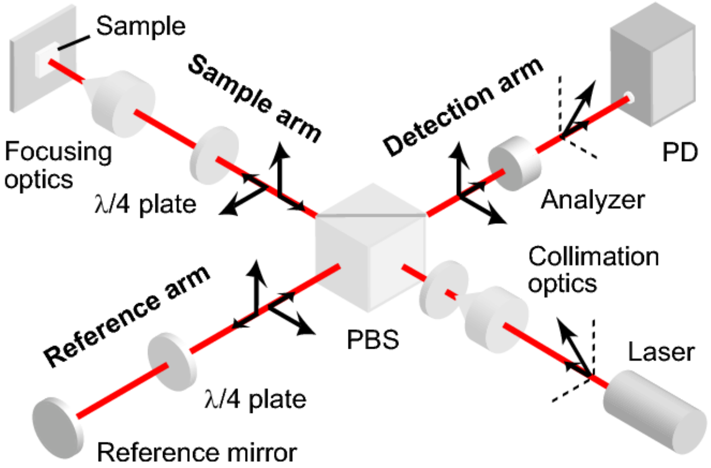


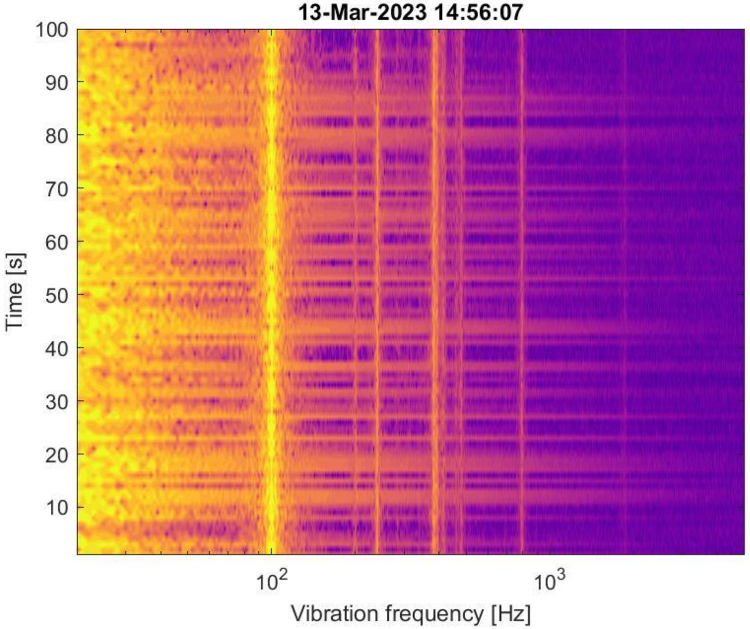
- The injection is **most sensitive to angle** misalignment
- Not so sensitive to lateral displacement or waist size mismatch mainly because the cavity spot size is relatively large (1 mm diameter)
- Prioritize angle stability rather than position -> **avoid image relay** systems such as 4f telescopes.
- Recommend to use beam pointing stabilization system -> Check **radiation exposure to electronics (R2E)**.

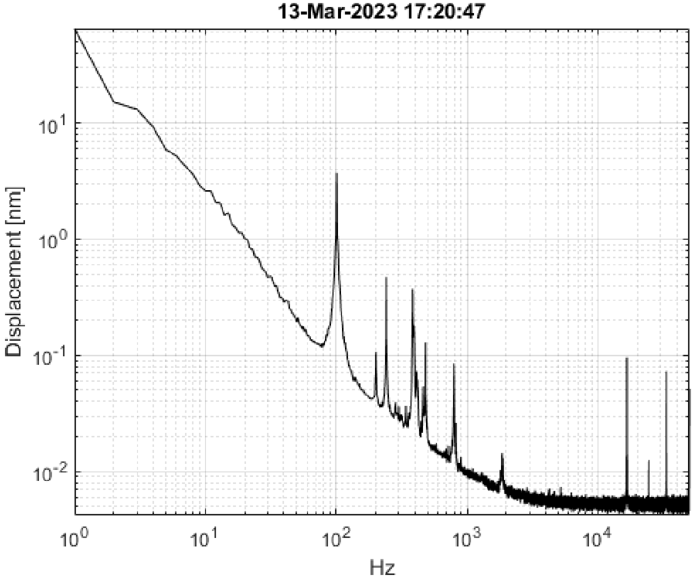
E. Granados et al. “Laser beam transport and stabilization considerations for the Gamma Factory proof-of-principle experiment” CERN-PBC-Notes-2023-007 (https://cds.cern.ch/record/2868829)

SPS Vibration study for laser beamline stabilization


© Yann Dutheil



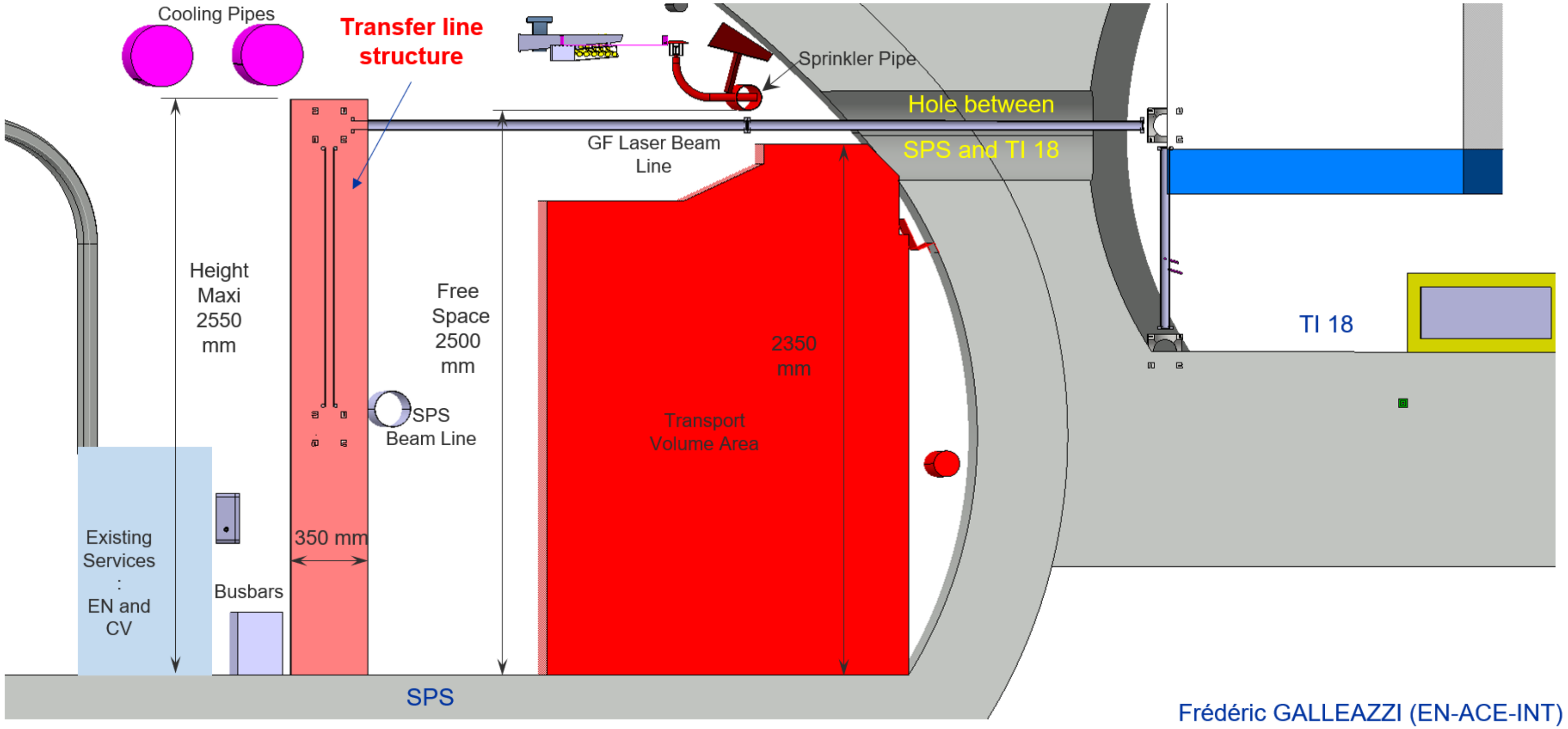




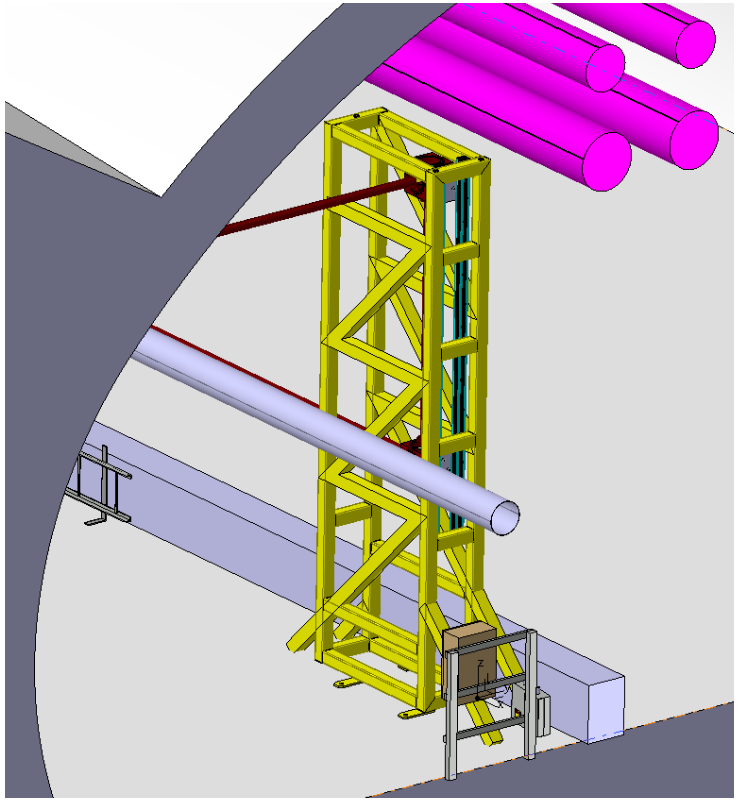
- Measured the vibration spectral content during 6 hours with SPS equipment switched ON.
- Accuracy was down to few pm in length and up to 10 kHz in frequency.
- Largest contributions are acoustics below 1 kHz, with eventual tones at 2.3 kHz.
- Need to check the coupling of vibrations to future laser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

E. Granados et al. “Laser beam transport and stabilization considerations for the Gamma Factory proof-of-principle experiment” CERN-PBC-Notes-2023-007 (https://cds.cern.ch/record/2868829)

Laser transport system pillar design



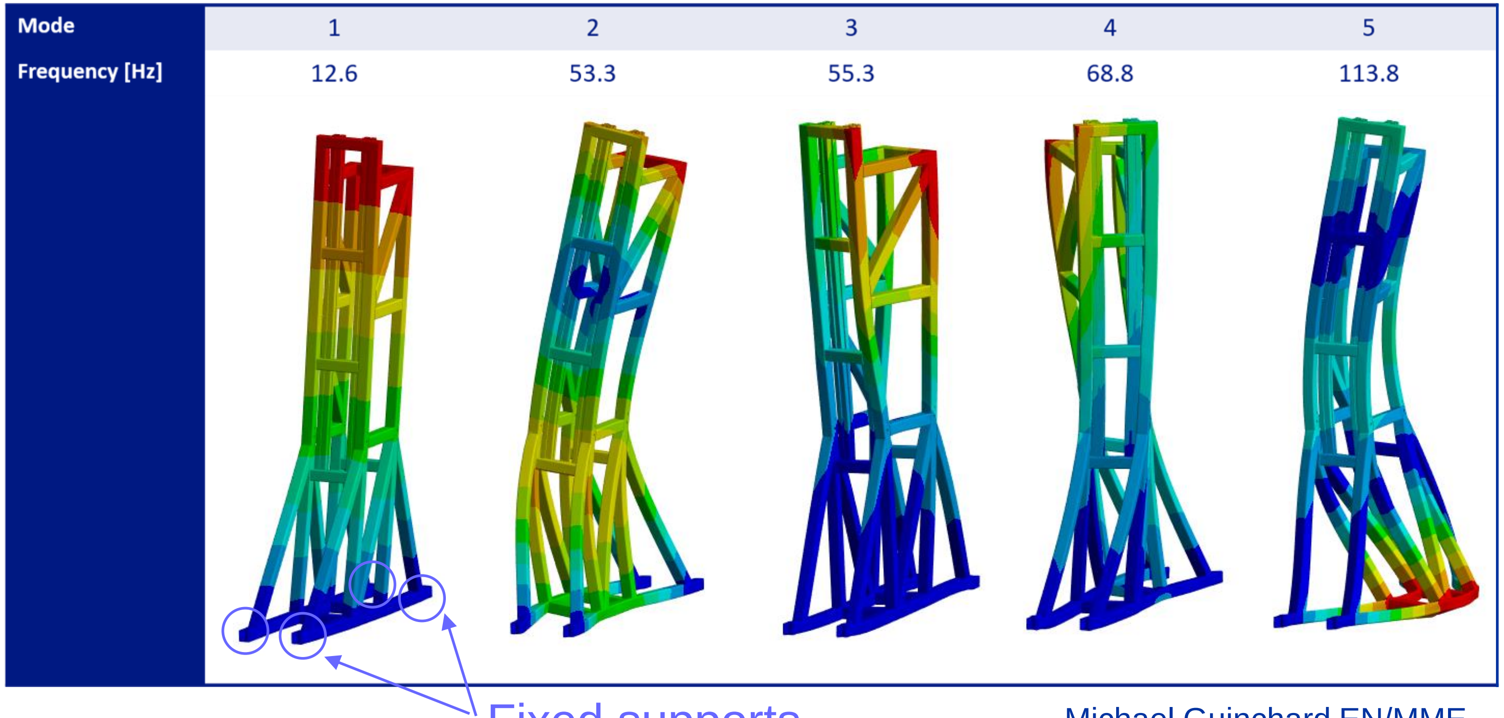
Frédéric GALLEAZZI (EN-ACE-INT)



R. Seidenbinder SY/STI-TCD

- Simple stainless structure with extrusion to mount vacuum cubes
- Requires drilling on SPS ring floor and attachment to ceiling -> ECR document
- Tests for stability will be carried out in the North Area in the summer

Pillar resonances

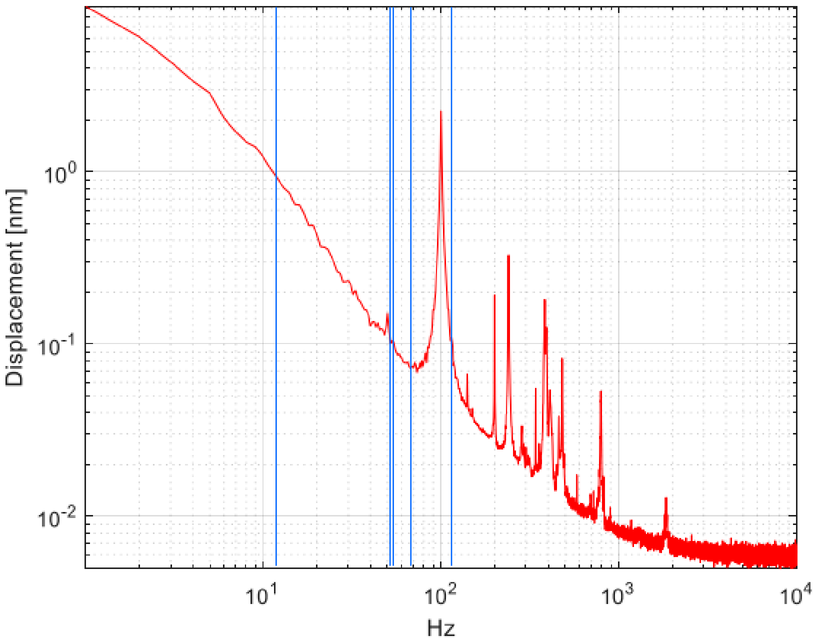


Mode	1	2	3	4	5
Frequency [Hz]	12.6	53.3	55.3	68.8	113.8

Fixed supports

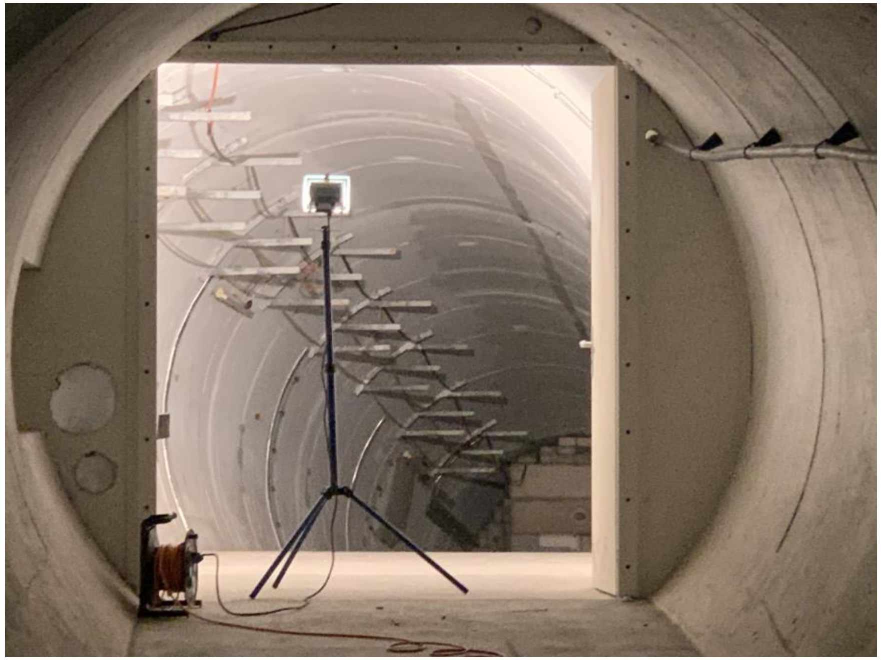
Michael Guinchard EN/MME

Mismatch to SPS vibration spectrum



- Analysis of resonant modes without attachment to ceiling.
- All the contacts are bonded. No additional mass on the structure was considered
- The modes are mismatched to the existing vibrational modes found in SPS
- An experiment using a reference Fabry-Perot cavity and a single-frequency CW laser will be performed in the North Area.

TI18 tunnel inspection in 2023

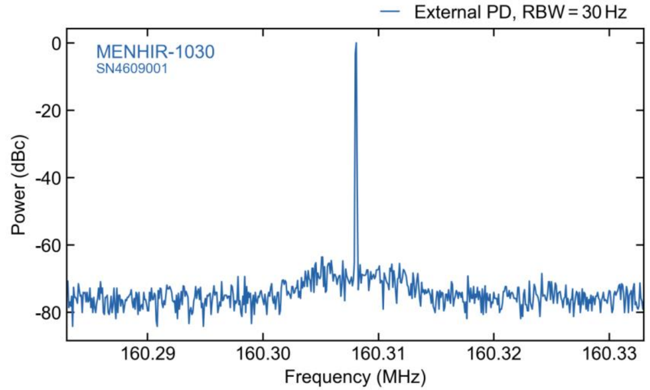


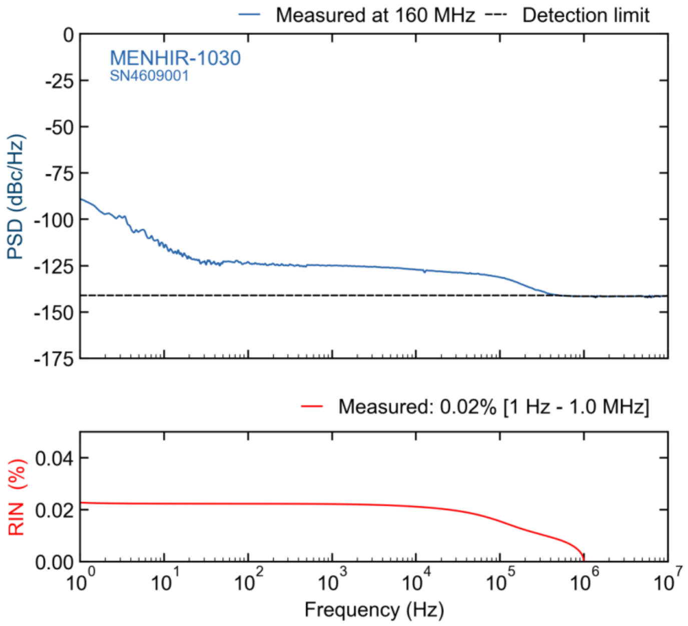
Fire brigade inspects TI18

- TI18 tunnel was opened during fall 2023. Inspection by the **fire brigade** was completed: air in tunnel is relatively clean, dusty atmosphere after chicane.
- **RP inspection** was completed.
- First section of the tunnel (corresponding to future laser room) was **3D scanned**.
- **Batmons** radiation monitors (2 of them) were installed inside the tunnel.

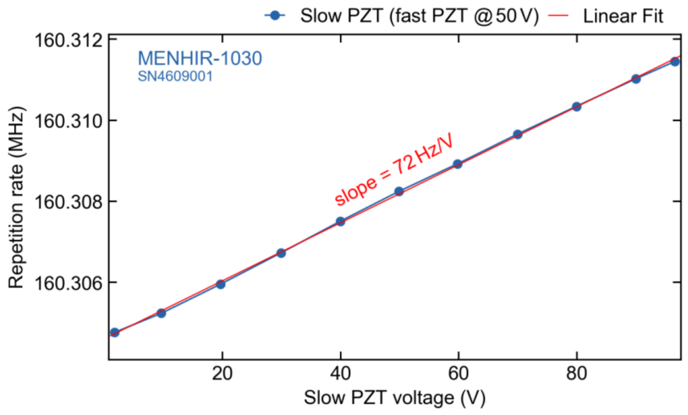
Laser front-end was procured and tested at CERN

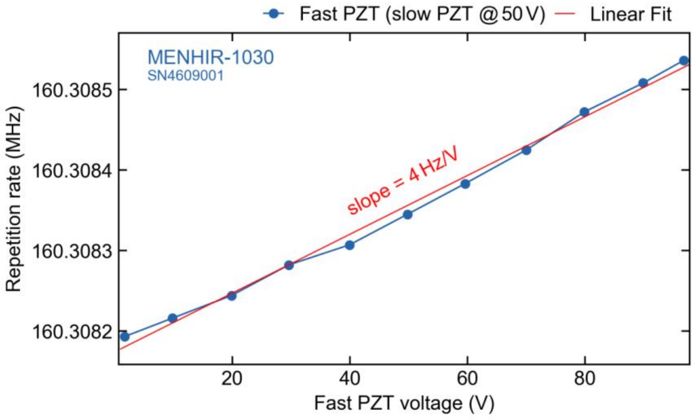
Excellent phase-noise performance



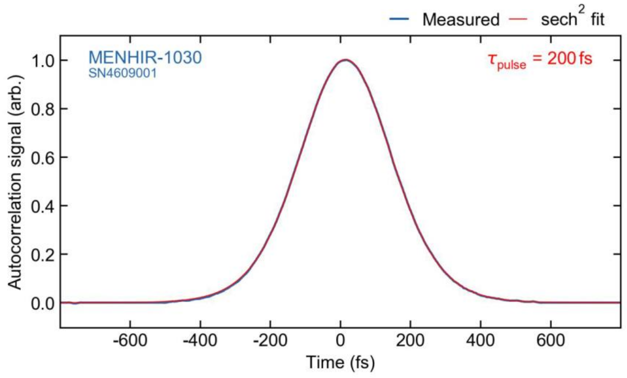


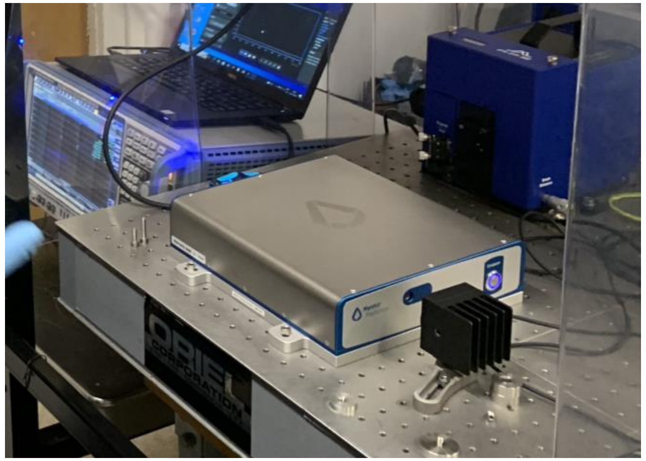
Piezos tuning ranges





Pulse duration

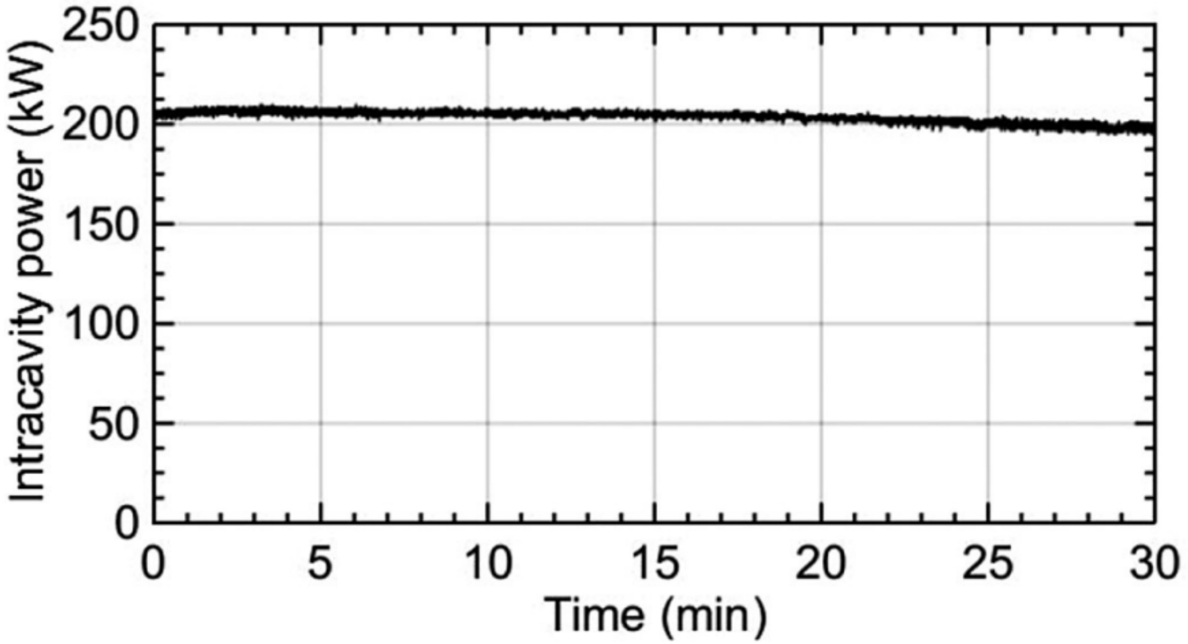




Supply accepted and shipped to IJCLab Nov 2023 for further testing with FP cavity

Testing of laser at IJCLab: Goal

- 200kW measured with ThomX prototype cavity (long-term)



IJCLab record :

- 50kW measured with ThomX cavity (long-term, Gain ~ 10,000)
- 400kW measured with ThomX prototype cavity (not stable)
- 200kW measured with ThomX prototype cavity (long-term)

World record :

- Cavity average power = **670kW@10ps ; 400kW@250fs** (not stable)
- Laser + amplifier : 420W @ 250 MHz
- Gain ~ 2,000

Carstens et al. Opt Lett 39 (2014) 2595

- Current goal: reproduce these results with Gamma Factory PoP laser at 160 MHz

L. Amoudry, et al. "Modal instability suppression in a high-average-power and high-finesse Fabry–Perot cavity." Applied Optics 59.1 (2020): 116-121.

Testing of laser at IJCLab: Steps

① Seeder power measurement

② Power measurement after fiber injection

③ Phase noise measurement

④ Cavity alignment and locking with CW laser and old mirrors

⑤ Cleaning environment

⑥ Replacement with new mirrors and lock the cavity

⑦ Measure finesse and FSR with CW laser

⑧ Operate with pulsed laser

  I. Alignment
  II. CEP tuning
  III. Telescope tuning
  IV. Lock cavity (PDH technique)
  V. Quantification of power inside + size of beam on mirrors + pulse duration

⑨ Raise power slowly

Testing of laser at IJCLab: laser power measurements

Laser start

Power meter	Readout
Thorlabs S310C	181.5 +/- 0.5 mW

First 2 hours

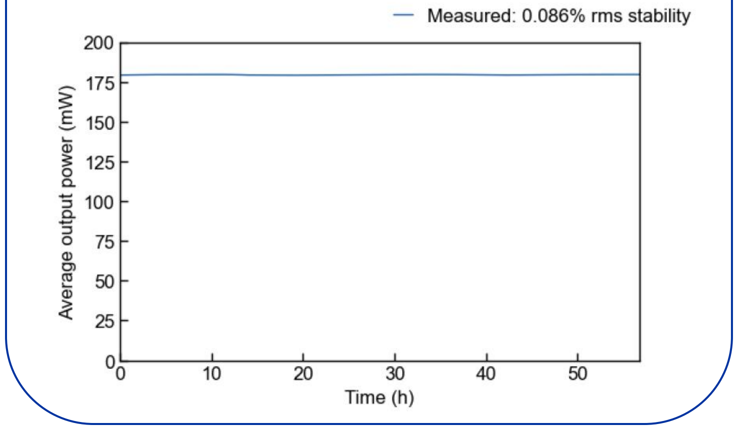
Parameter	Value
Average Power	181.5 mW
Min Power	180.7 mW
Max Power	182.1 mW
Variance / RMS Stability	268 uW (0.148%)
Ratio Max/Min, Pk-Pk	1.008:1 (0.03 dB)

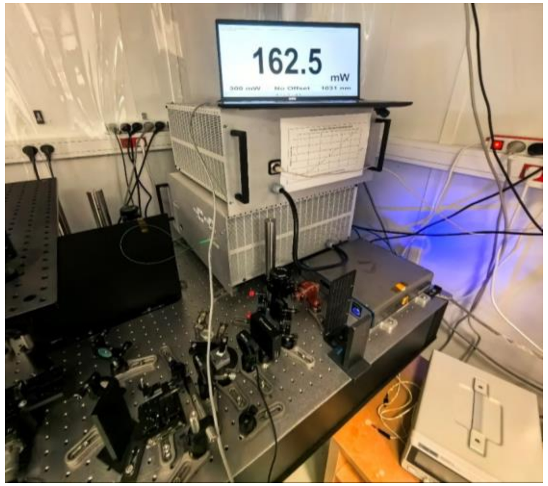
Overnight (8 hours)

Parameter	Value
Average Power	180.0 mW
Min Power	179.4 mW
Max Power	180.5 mW
Variance / RMS Stability	151.6 uW **(0.084%)**
Ratio Max/Min, Pk-Pk	1.006:1 (0.03dB)

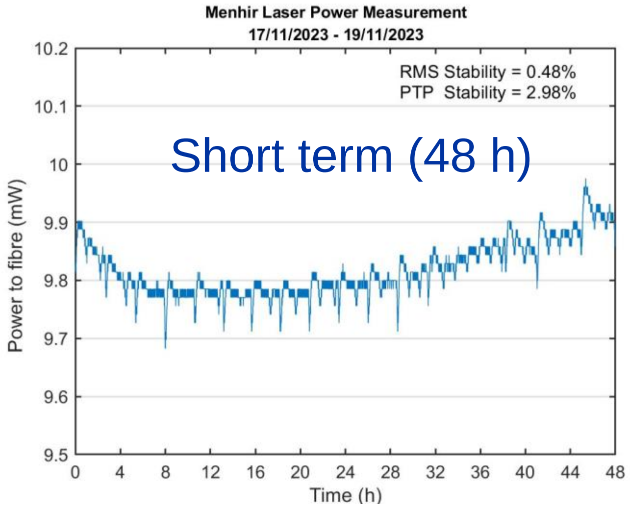
"WARMED UP"

At the laser output (CERN)

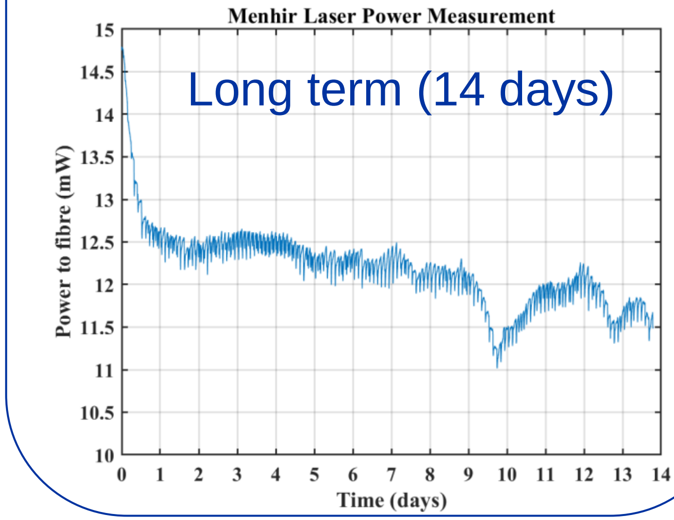




Coupled to fiber (IJCLab)



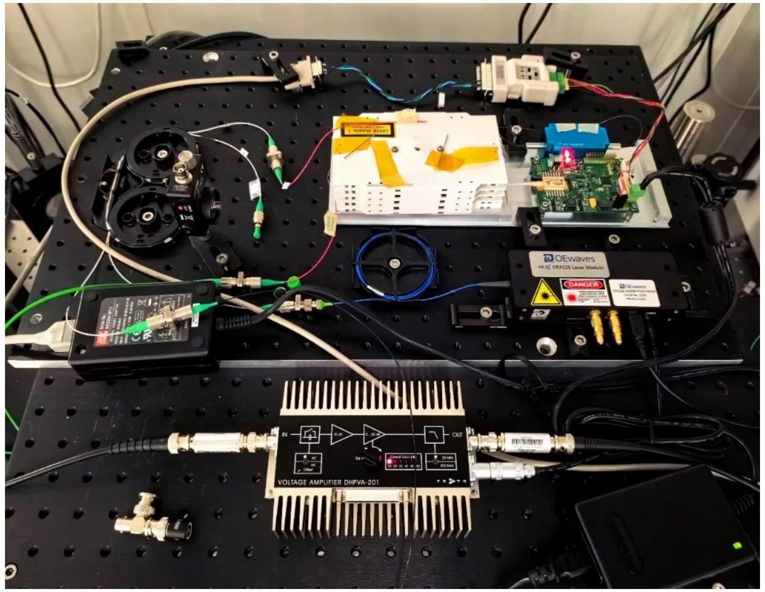
Short term (48 h)

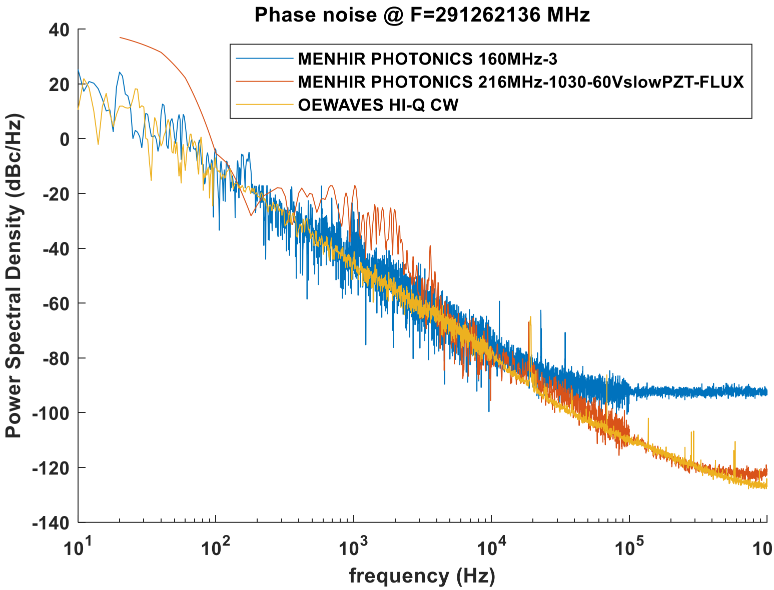


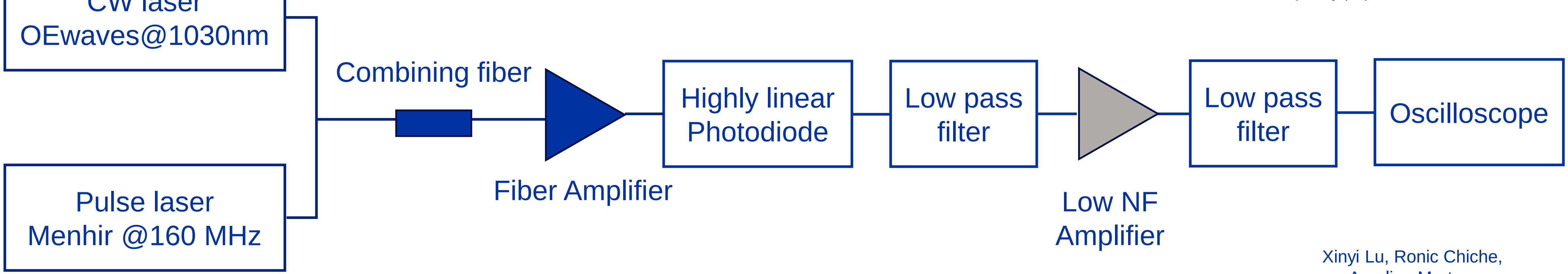
Long term (14 days)

Phase noise measurements at IJCLab

Heterodyne frequency beating against the OEwaves ultrastable CW laser reference







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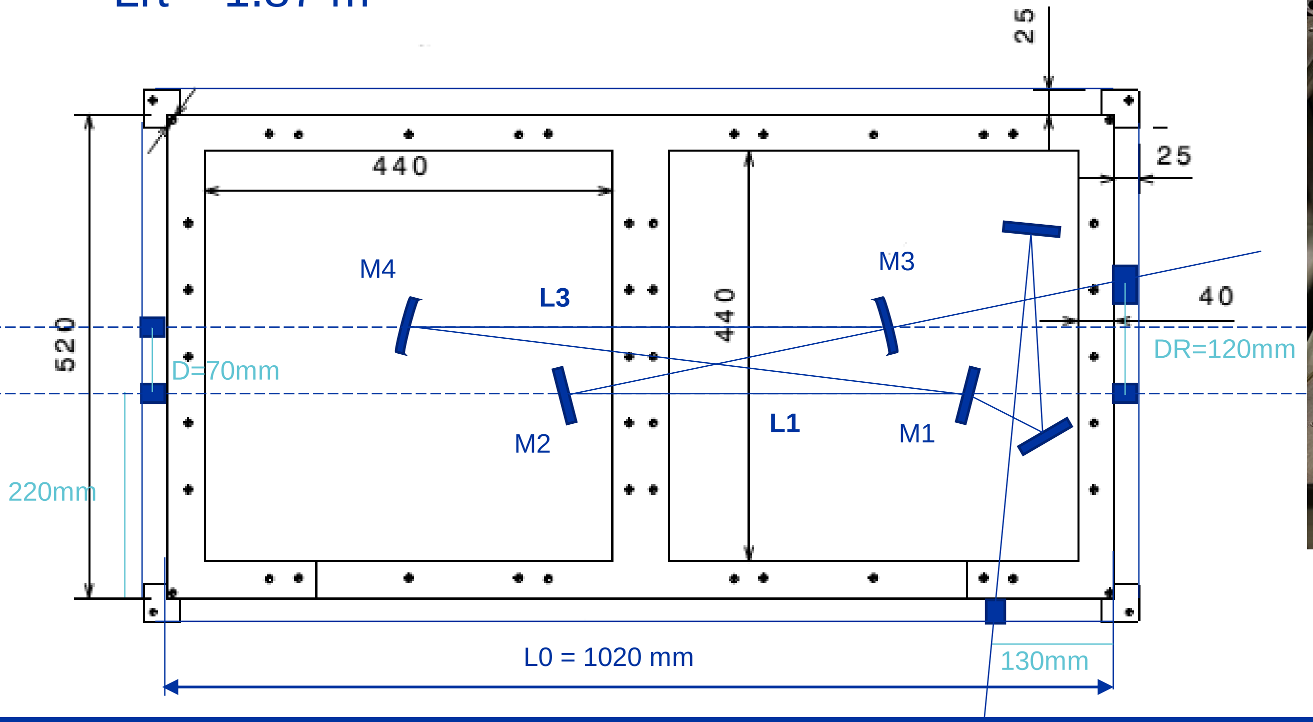
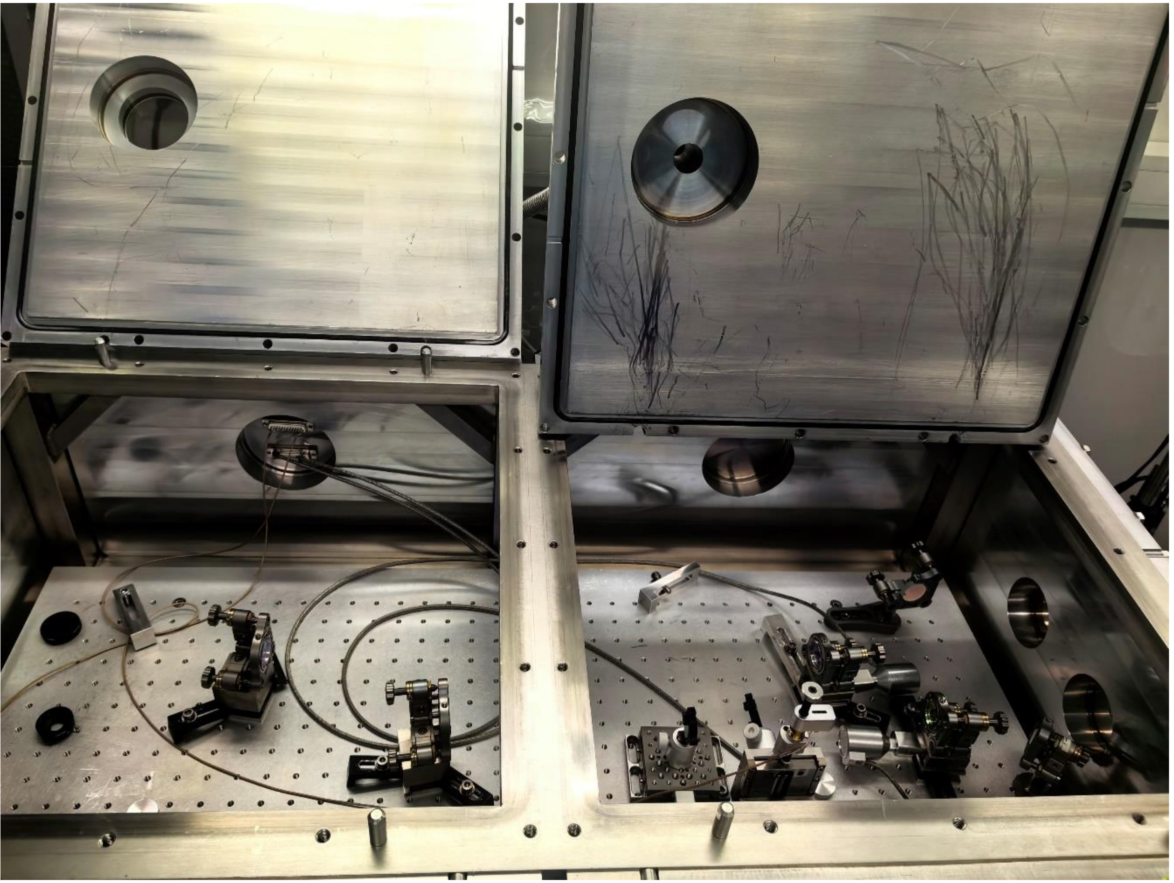
Testing of laser at IJCLab

SBOX optical setup with 1:10 scale

SBOX size : 1020 x 520 mm
Windows diameter : 20mm (small) / 40mm (large)
Mounts width : 60mm
FSR = 160.27MHz
Lrt = 1.87 m





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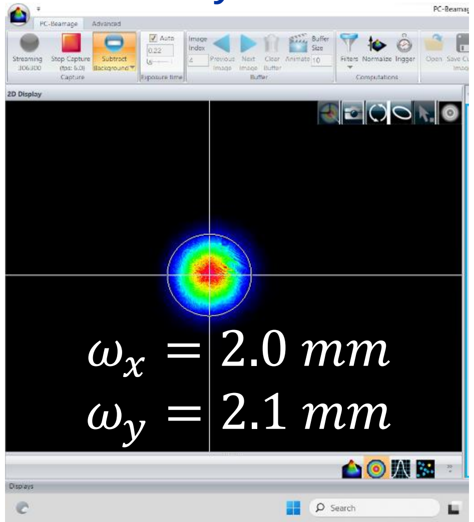
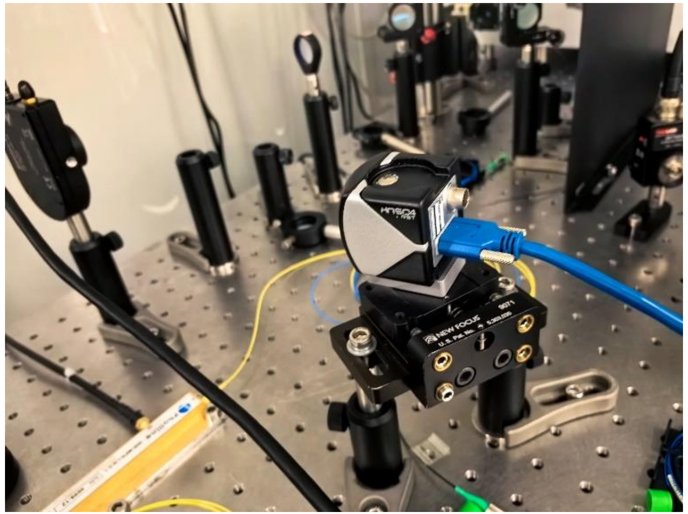
Testing of laser at IJCLab: improving coupling efficiency

Cavity mode

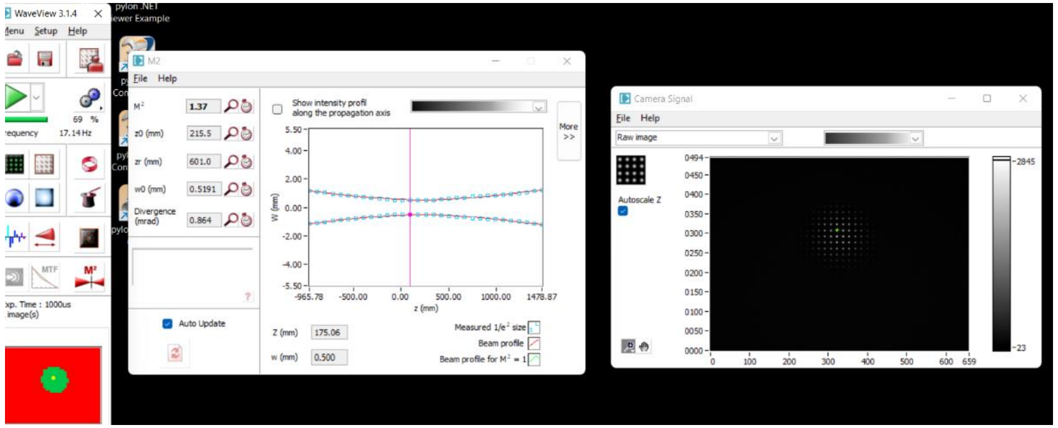


$$\omega_x = 2.0\ mm$$
$$\omega_y = 2.1\ mm$$

HASO Wavefront sensors



Telescope



M^2 1.37

z0 (mm) 215.5

zr (mm) 601.0

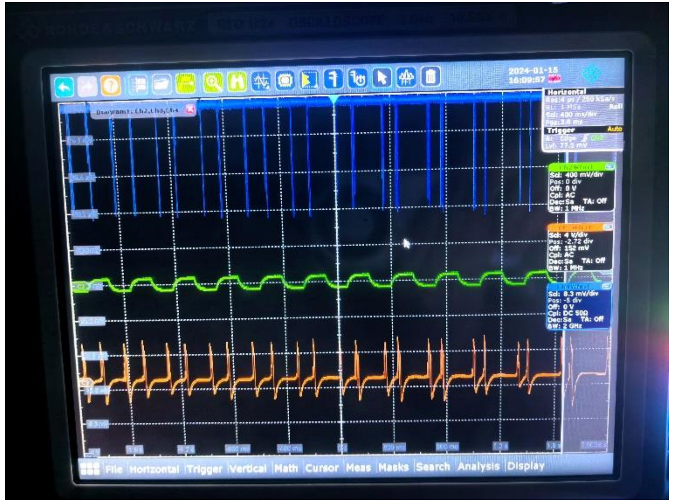
w0 (mm) 0.5191

Divergence (mrad) 0.864

☑ Auto Update

Z (mm) 175.06

w (mm) 0.500



Electrically controlled injection mirrors

Current status:
coupling efficiency
~ 30%

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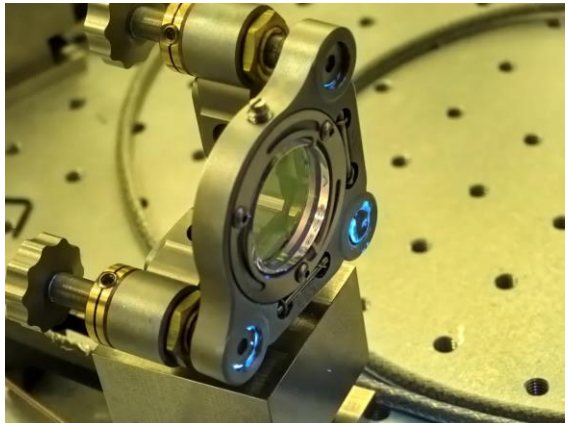
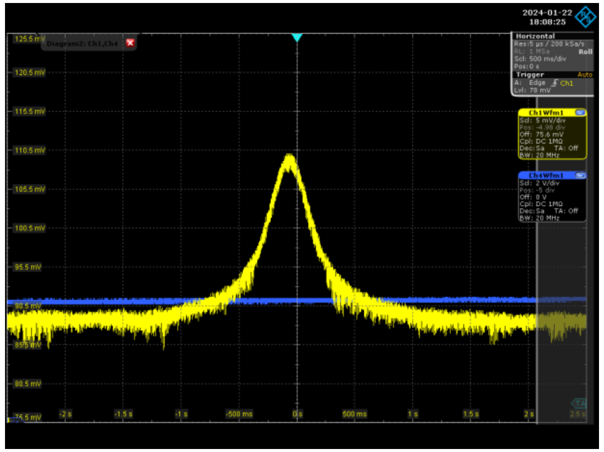
Testing of laser at IJCLab: new cavity mirrors

Mirror	Nom	Type	Substrate	Transmission @1031nm(ppm)	Diffusion at center @ 1064 nm (ppm)	Diffusion @ 1064 nm (ppm)	Absorption @1064 nm(ppm)
M1	17/2	Plane	FS	115	2.5	3	<0.6
M2	18/4	Plane	ULE	3	3	7	<0.6
M3	18/11	Concave	ULE	3	3.8	4.5	<0.6
M4	18/12	Concave	ULE	3	2.8	4	<0.6

- Mirrors manufactured by “Laboratoire des Matériaux Avancés” (LMA)
- **Metal deposit** in the coating layers from the **coating machine**



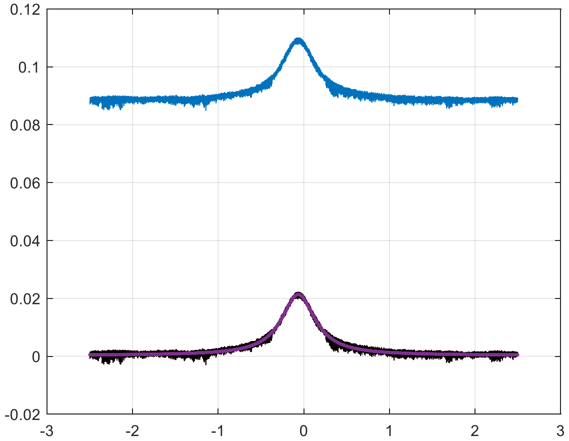
Newport ZeroDrift™ optical mirror mounts compensate the mount for temperature-induced alignment drift. This innovation has resulted in an 85% improved optical pointing stability compared to other stainless steel mounts.



Horizontal
Res:5 µs / 200 kSa/s
RL: 1 MSa Roll
Scl: 500 ms/div
Pos: 0 s
Trigger Auto
A: Edge Ch1
Lvl: 78 mV

Ch1Wfm1
Scl: 5 mV/div
Pos: -4.98 div
Off: 75.6 mV
Cpl: DC 1MΩ
Dec:Sa TA: Off
BW: 20 MHz

Ch4Wfm1
Scl: 2 V/div
Pos: -5 div
Off: 0 V
Cpl: DC 1MΩ
Dec:Sa TA: Off
BW: 20 MHz



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Exp RTL = 145 ppm
Exp finesse = **43,332**
Exp linewidth = 3.7 kHz

Real finesse = **16,760**
Extra loss = 230 ppm

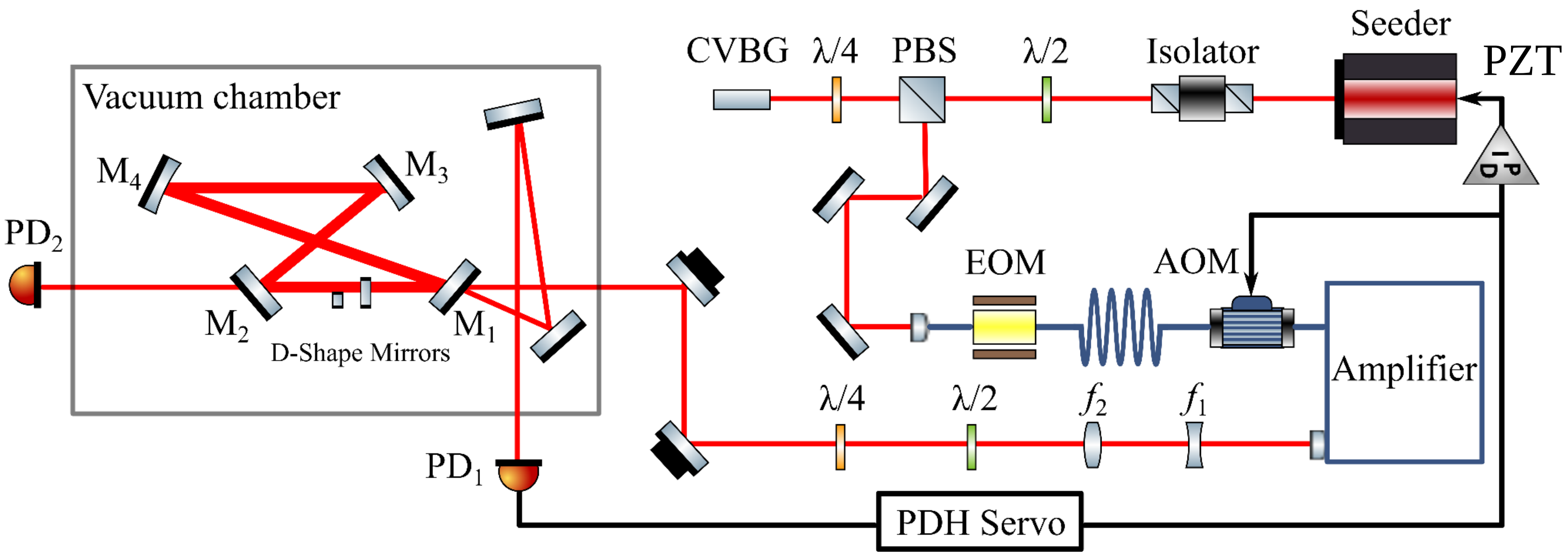
Finesse is related to loss. Reasons for lower finesse maybe:

- Dust on the mirror
- Laser beam is not in the center of the mirror
- ……

Testing of laser at IJCLab: Next steps

Obtain higher stable circulating power by using new seed laser and new mirrors.

- **New seed laser (CERN property):** Menhir, frep = 160 MHz, low phase noise, good stability
- **New mirrors (ThomX RD budget):** LMA, absorption loss < 0.6 ppm with no hot point absorber, ROC 0.5m → 4 mirror cavity at 160MHz



Target value:

FSR = 160 MHz
Cavity Linewidth < 5.3 kHz
Finesse > 30,000
Gain > 10,000
Amplified power ~ 70 W
Coupling efficiency ~ 70%
Circulating power > 400 kW

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Testing of laser at IJCLab: Summary

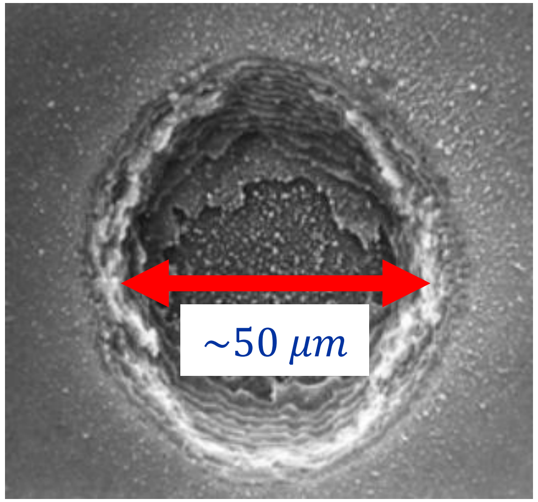
To Do:

- Improve finesse: clean the mirrors one by one, realign the cavity, replace and observe the mirror with a microscope…
- Replace the CW laser with the pulsed laser.
- Finally, raise injected power.

	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

Issue when increasing average power



Damage spot due to heating

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Next steps:

Tender amplifier to 100W

Installation at SPS in 2025-27

Conclusions

Gamma Factory

- Proof of principle experiment starting 2027 to produce up to 44 keV photons at 10^{15} ph/s
- Gamma Factory in LHC various scenarios considered producing photons of 10s-100s MeV at up to 10^{17} ph/s

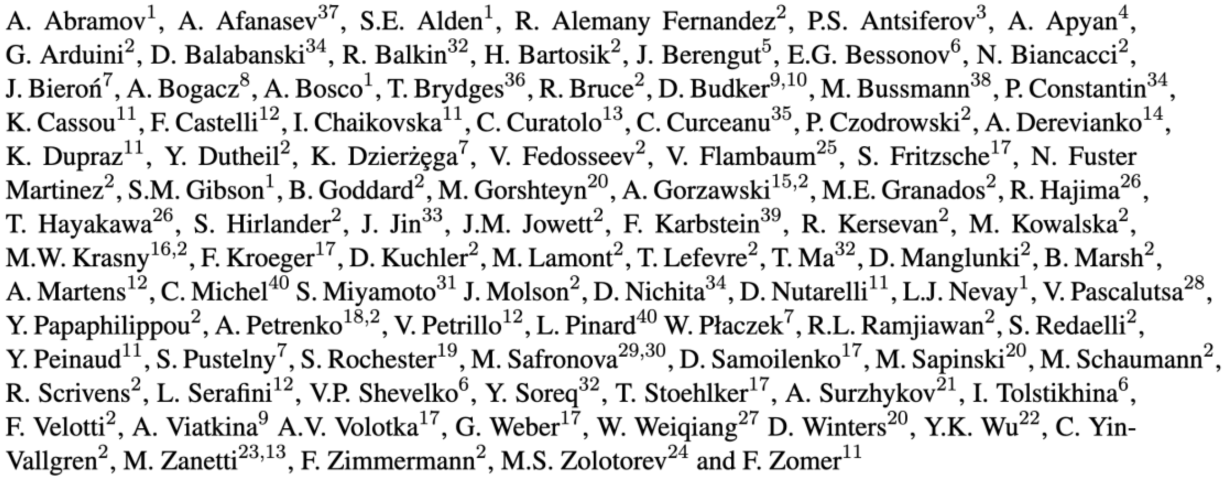
Status of the optical systems for PoP experiment

- TI18 area, conversion to a laser lab in LS3
- Ultra low-phase noise laser and amplification chain procurement and commissioning
- Fabry-Perot Cavity with large gain factor pumped by 100W laser at IJCLab. After successful test transfer to CERN
- Laser beam delivery system testing, controls, integration and diagnostics at IP
- Demonstrate full remote end-to-end operation of laser beams and Fabry-Perot cavity

Acknowledgements

Gamma Factory Collaboration:

100+ physicists from 40 institutes in 15 countries contributed to the GF studies in its various aspects



A. Abramov[1], A. Afanasev[37], S.E. Alden[1], R. Alemany Fernandez[2], P.S. Antsiferov[3], A. Apyan[4], G. Arduini[2], D. Balabanski[34], R. Balkin[32], H. Bartosik[2], J. Berengut[5], E.G. Bessonov[6], N. Biancacci[2], J. Bieroń[7], A. Bogacz[8], A. Bosco[1], T. Brydges[36], R. Bruce[2], D. Budker[9,10], M. Bussmann[38], P. Constantin[34], K. Cassou[11], F. Castelli[12], I. Chaikovska[11], C. Curatolo[13], C. Curceanu[35], P. Czodrowski[2], A. Derevianko[14], K. Dupraz[11], Y. Dutheil[2], K. Dzierżęga[7], V. Fedosseev[2], V. Flambaum[25], S. Fritzsche[17], N. Fuster Martinez[2], S.M. Gibson[1], B. Goddard[2], M. Gorshteyn[20], A. Gorzawski[15,2], M.E. Granados[2], R. Hajima[26], T. Hayakawa[26], S. Hirlander[2], J. Jin[33], J.M. Jowett[2], F. Karbstein[39], R. Kersevan[2], M. Kowalska[2], M.W. Krasny[16,2], F. Kroeger[17], D. Kuchler[2], M. Lamont[2], T. Lefevre[2], T. Ma[32], D. Manglunki[2], B. Marsh[2], A. Martens[12], C. Michel[40] S. Miyamoto[31] J. Molson[2], D. Nichita[34], D. Nutarelli[11], L.J. Nevay[1], V. Pascalutsa[28], Y. Papaphilippou[2], A. Petrenko[18,2], V. Petrillo[12], L. Pinard[40] W. Płaczek[7], R.L. Ramjiawan[2], S. Redaelli[2], Y. Peinaud[11], S. Pustelny[7], S. Rochester[19], M. Safronova[29,30], D. Samoilenko[17], M. Sapinski[20], M. Schaumann[2], R. Scrivens[2], L. Serafini[12], V.P. Shevelko[6], Y. Soreq[32], T. Stoehlker[17], A. Surzhykov[21], I. Tolstikhina[6], F. Velotti[2], A. Viatkina[9] A.V. Volotka[17], G. Weber[17], W. Weiqiang[27] D. Winters[20], Y.K. Wu[22], C. Yin-Vallgren[2], M. Zanetti[23,13], F. Zimmermann[2], M.S. Zolotorev[24] and F. Zomer[11]

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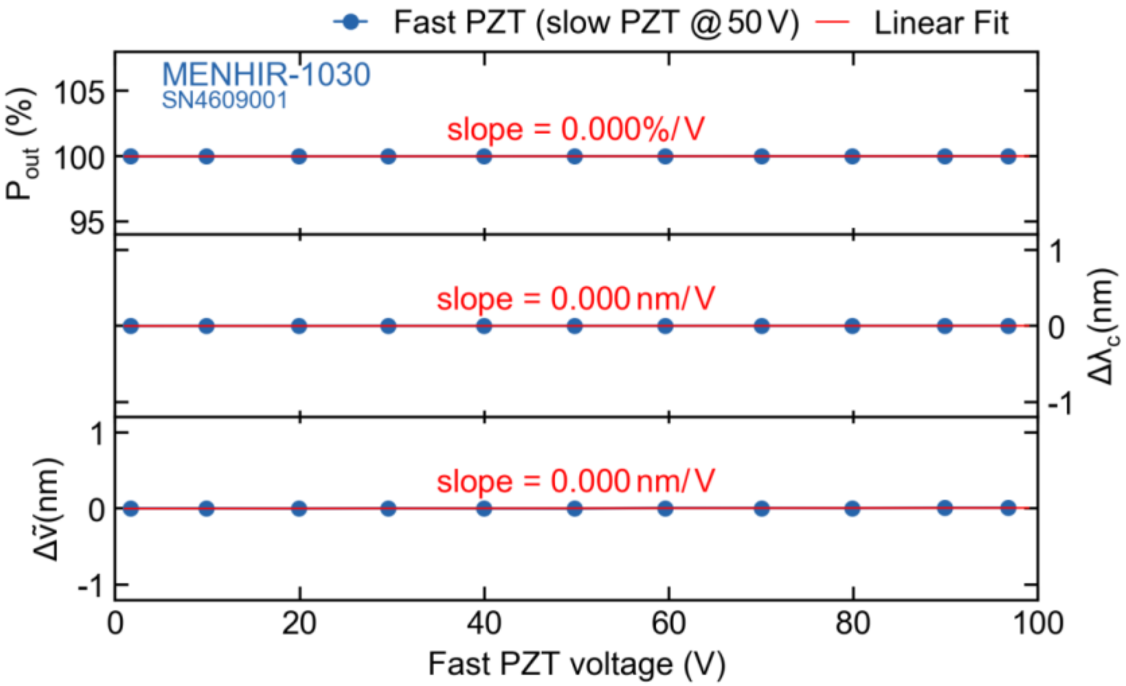
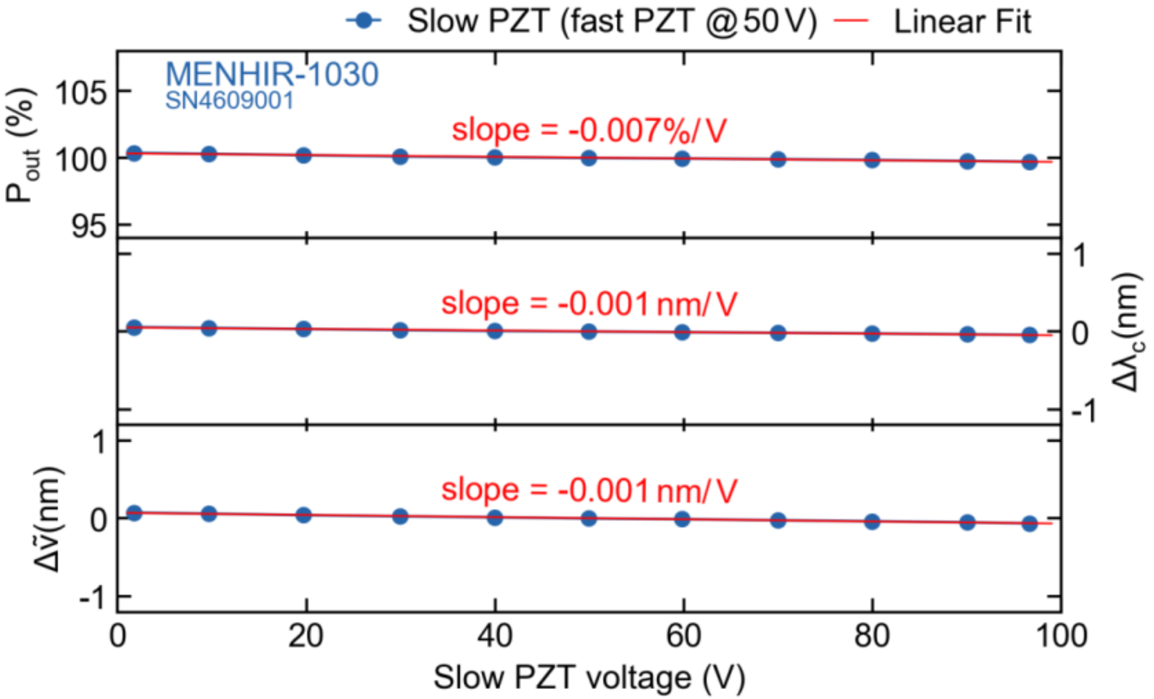
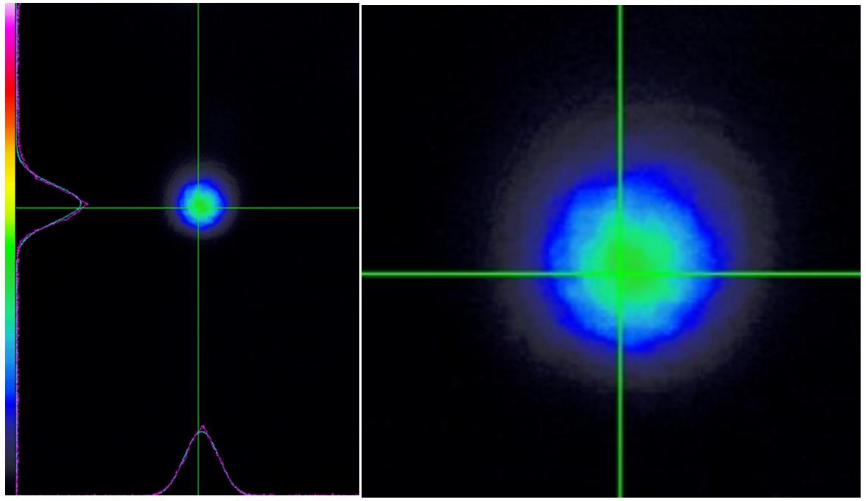
Variation of output power, center wavelength and bandwidth changing PZT voltages

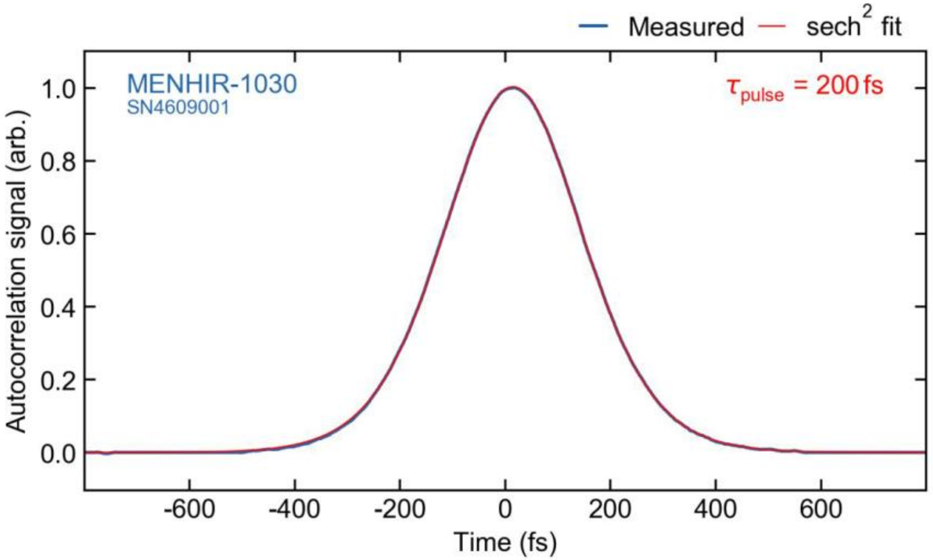


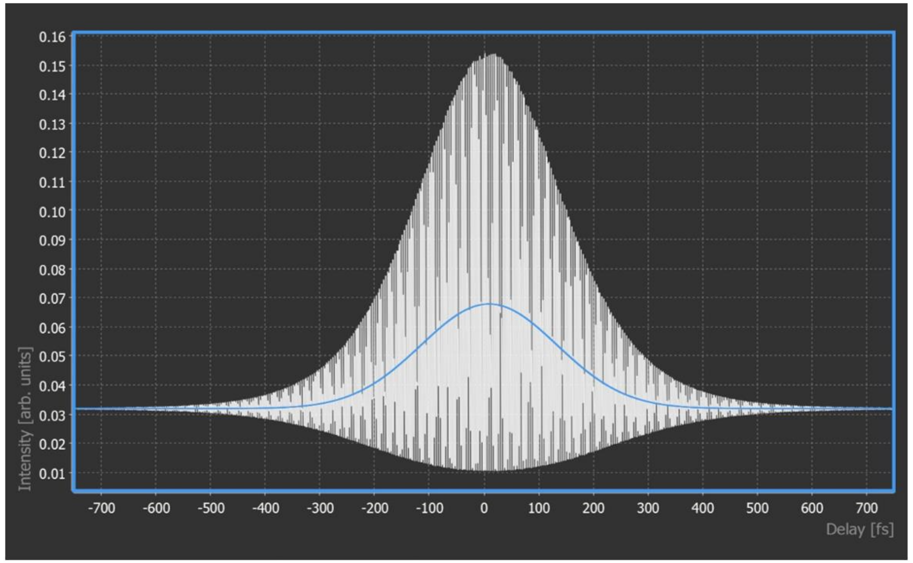


Beam profile and pulse duration



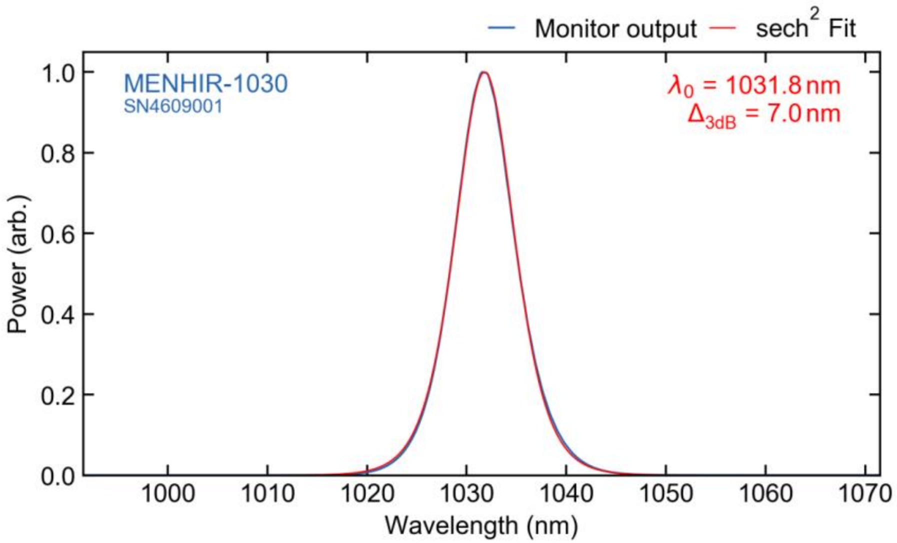
Parameter	Value
Effective diameter (86.5%)	1.171 mm
Gaussian fit 86.5% diameter	0.972 mm, 0.956 mm
Effective area	1.459 mm^2

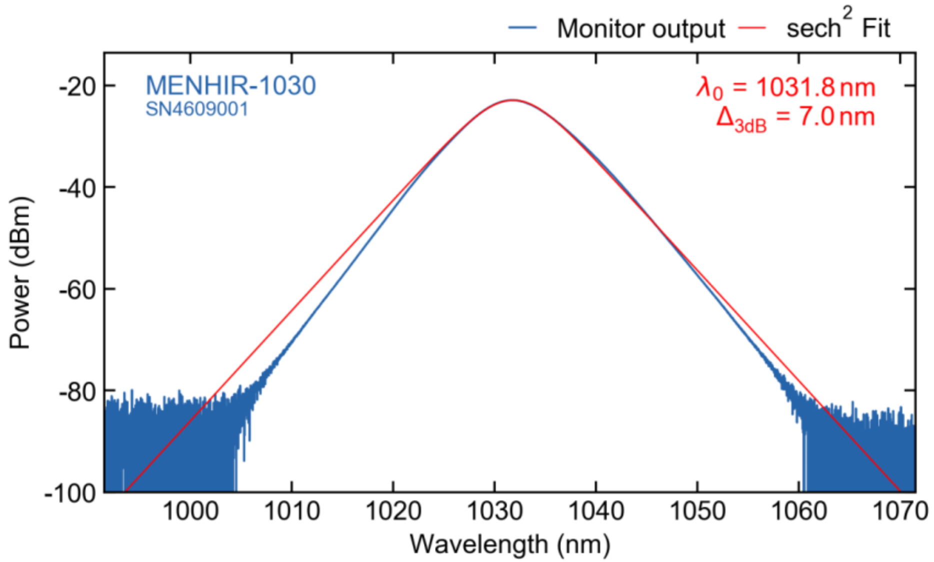


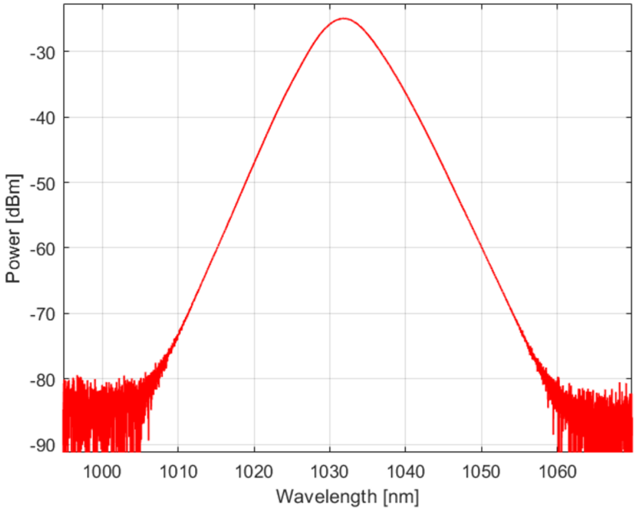


Measurement	Pulse duration
Sech fitting	189 fs
Gaussian fit	207.5 fs
Factory acceptance test (FAT)	200

Output spectrum







Measurement	**SAT**	**FAT**
Center wavelength	1031.8544 nm	1031.8 nm
3 dB bandwidth	7.0399 nm	7.0 nm