

Progress towards the CERN Gamma Factory Proof of principle experiment

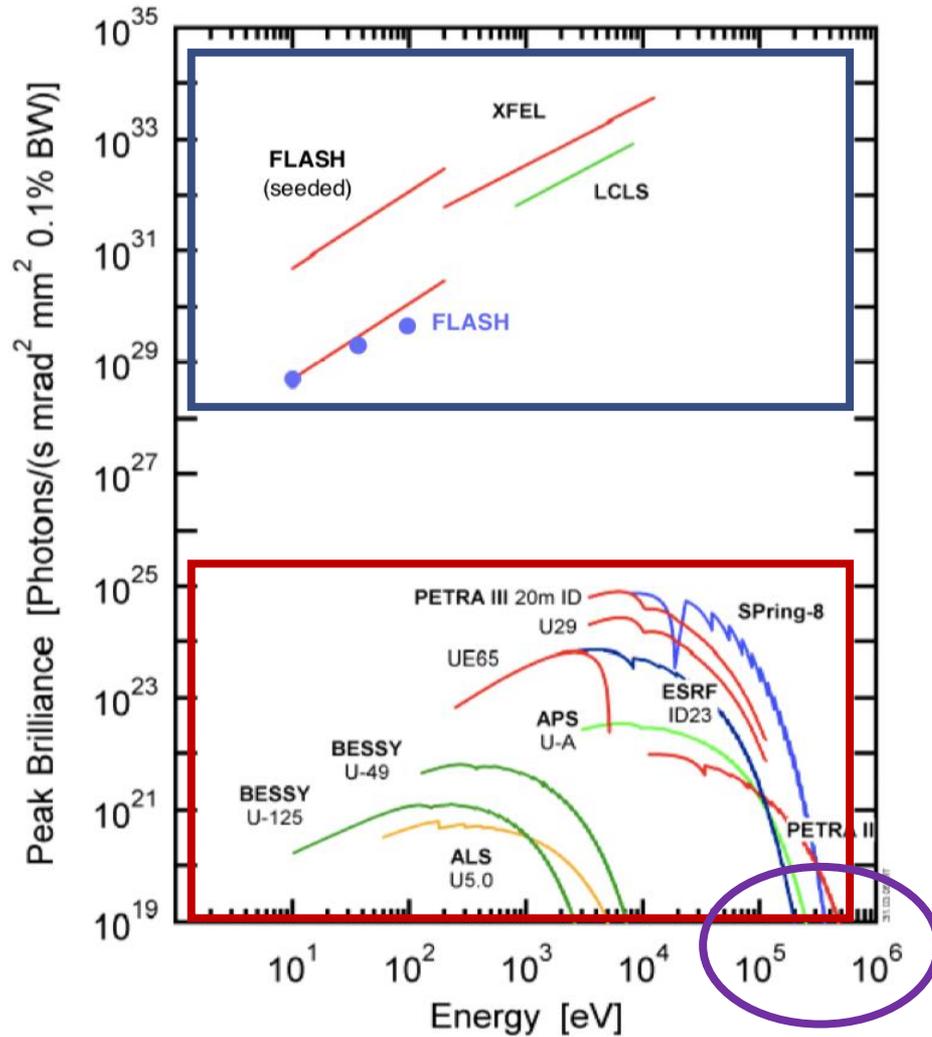
Aurélien MARTENS (IJCLab Orsay) on behalf of

The Gamma Factory study group

Gamma Factory:

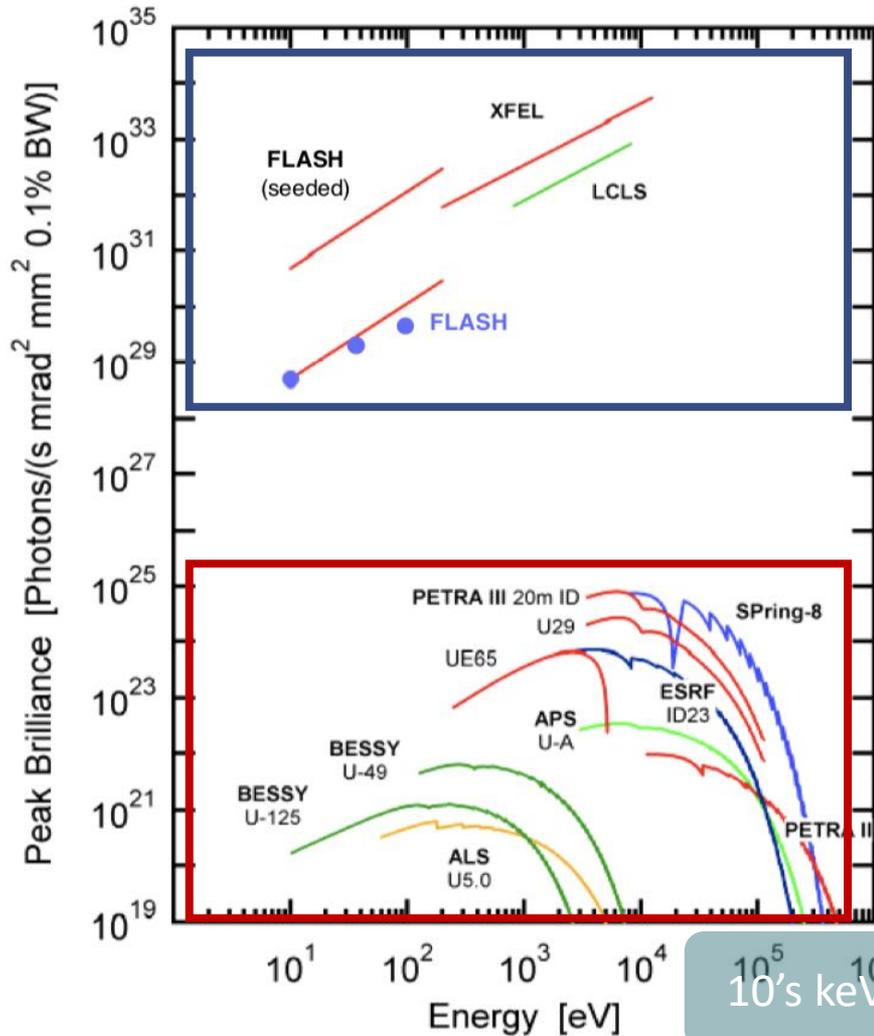
Scientific context

A striking fact



Few 100's keV at most

A striking fact



10's keV—100 MeV

Example : H γ S@Duke, 10¹⁰ ph/s, 1-100MeV

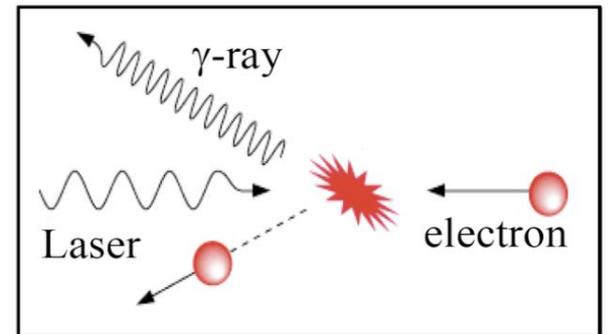
No bright photon source for nuclear and particle physics applications !

FEL and **synchrotron** impracticable



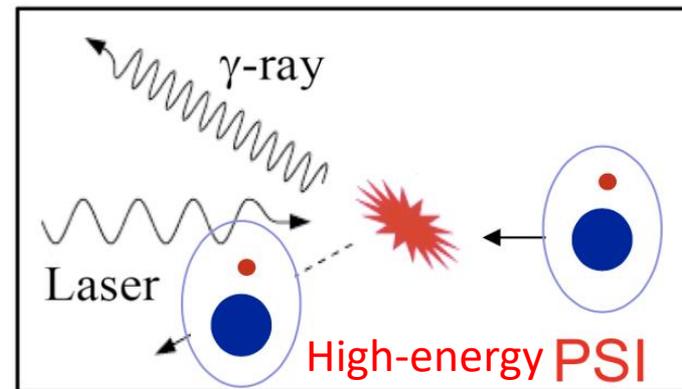
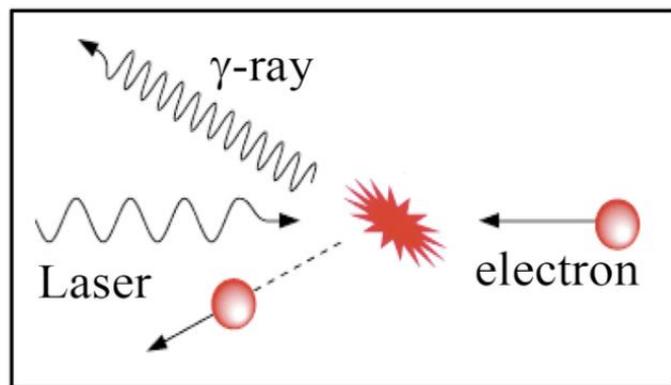
Inverse Compton scattering ?
Excellent monochromaticity but
O(1barn) cross-section is low !

ICS lie here



Physics concept

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



High-energy PSI
PSI: Partially stripped ions

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

For instance

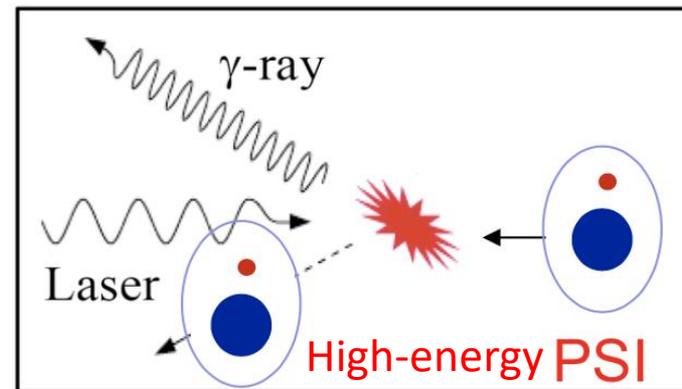
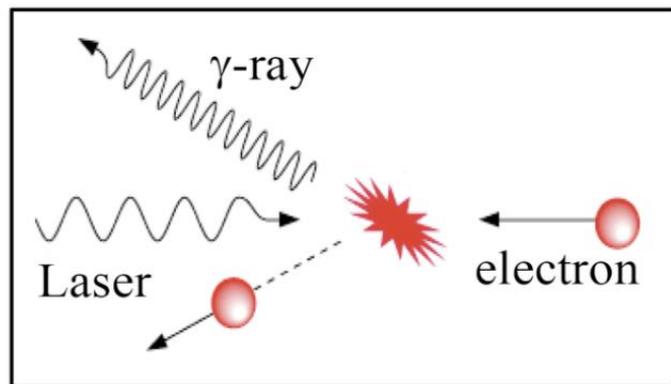
Energy upshifting by a factor $4\gamma^2$

H-like Xenon at LHC ($\gamma=3000$) \rightarrow 180 MeV

Li-like Calcium at SPS ($\gamma=130$) \rightarrow 80 keV

Physics concept

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



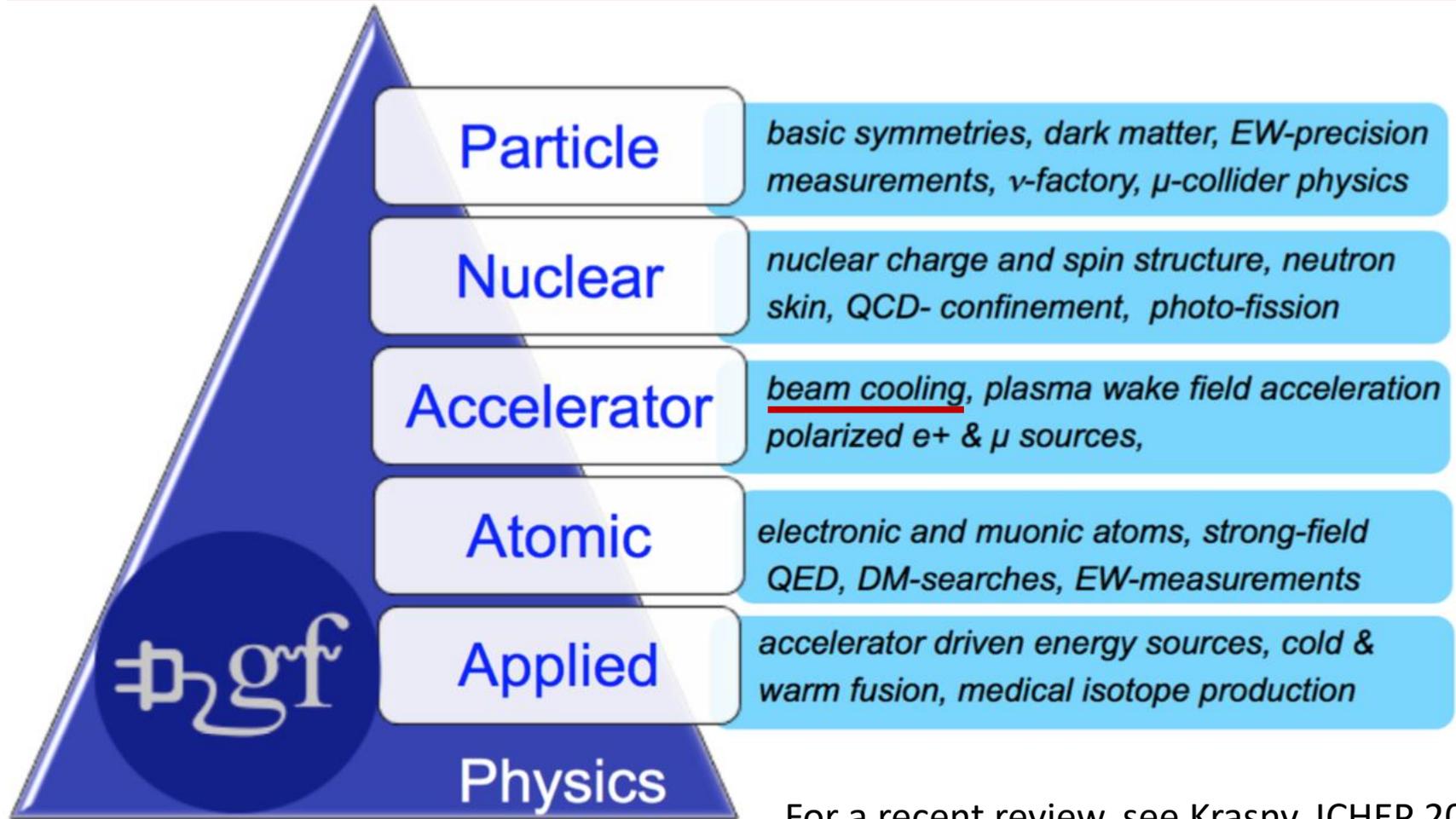
PSI: Partially stripped ions

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

- 👍 PSI recycling in ring is very efficient (relative energy loss \ll beam energy spread)
- 👍 Energy tunability provided by PSI species choice and ion beam energy (<400MeV w/ LHC)
- 👎 Laser wavelength must be « tuned » to PSI species and beam energy
- 👎 Laser must be placed in a harsher environment (compared to e^- accelerators)

Beyond a bright photon source

High potential to open new opportunities in many branches of physics

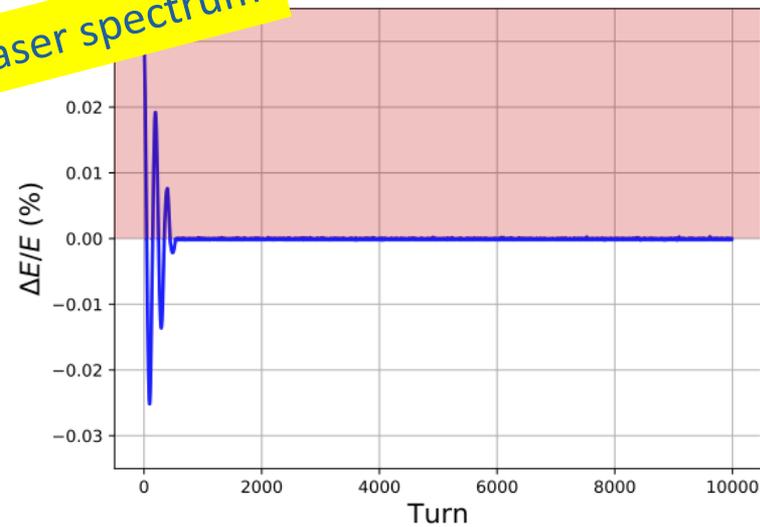
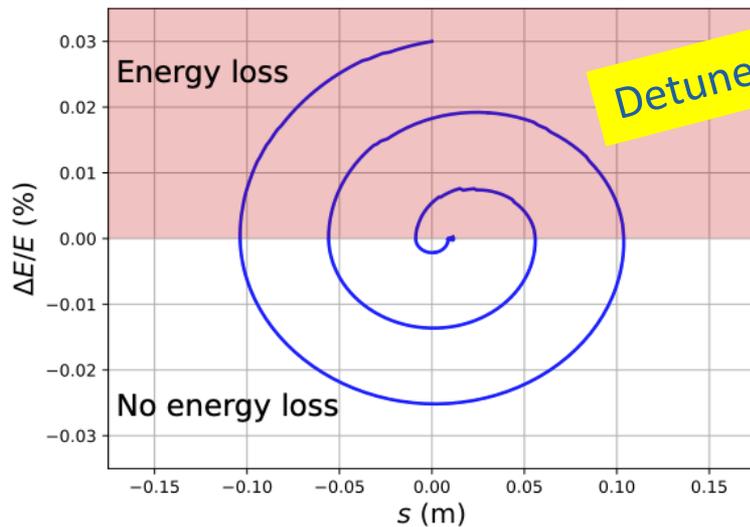
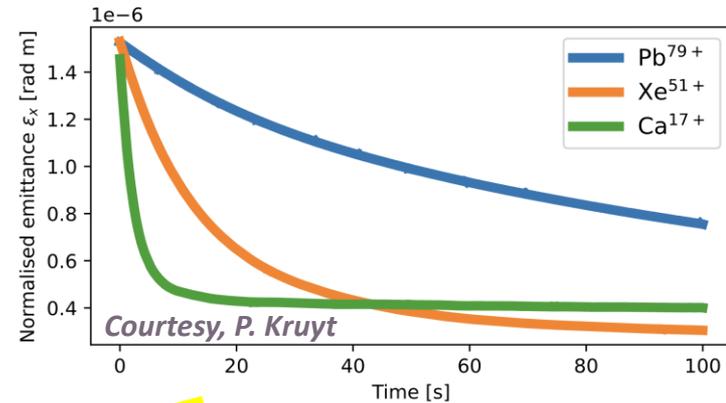


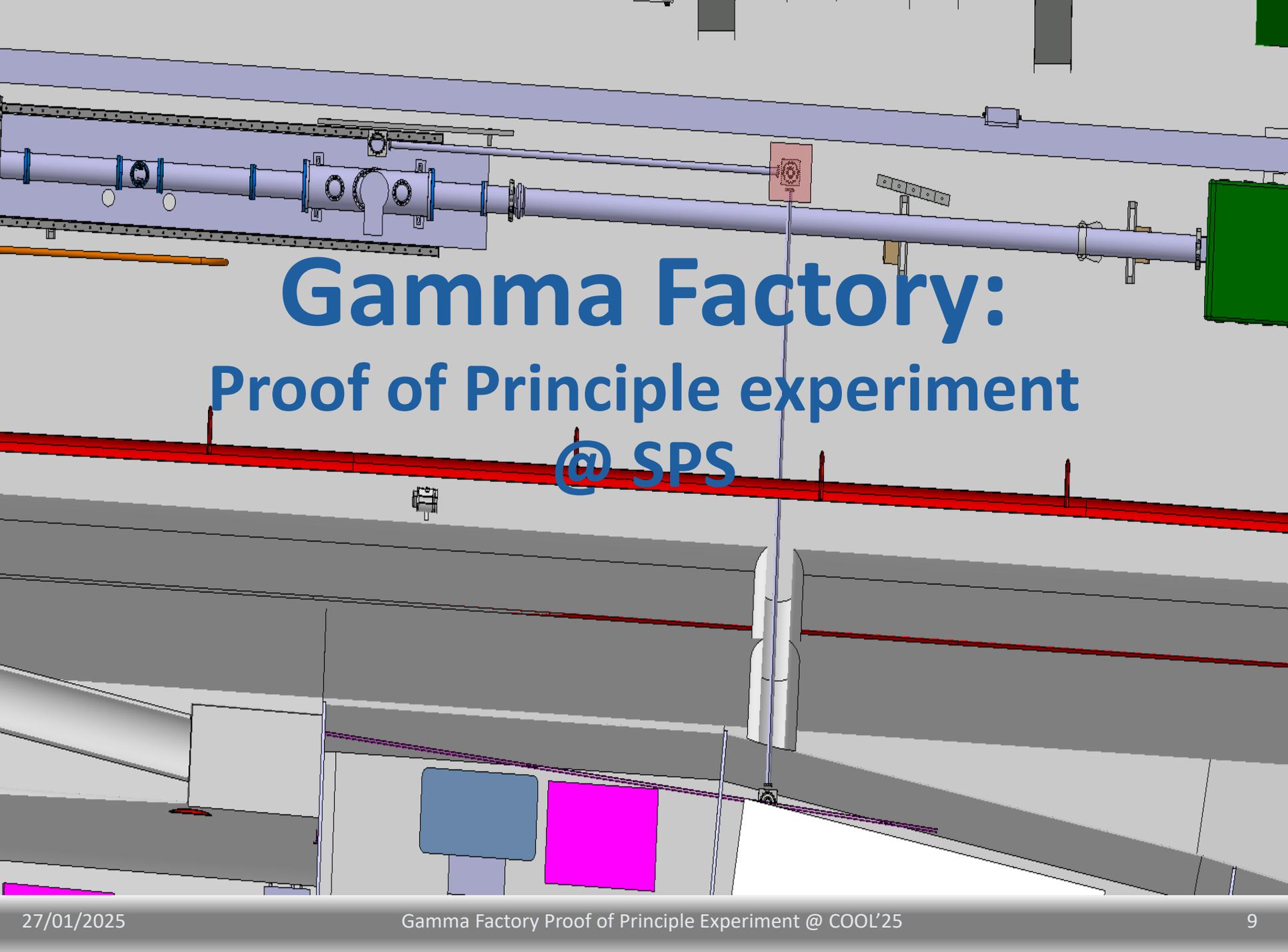
For a recent review, see Krasny, ICHEP 2025

Integrated in Physics Beyond Colliders initiative

Laser cooling of ion beam

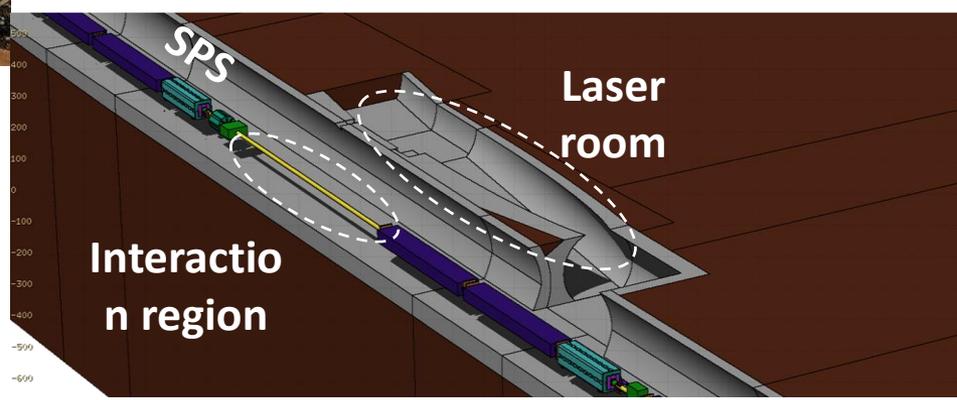
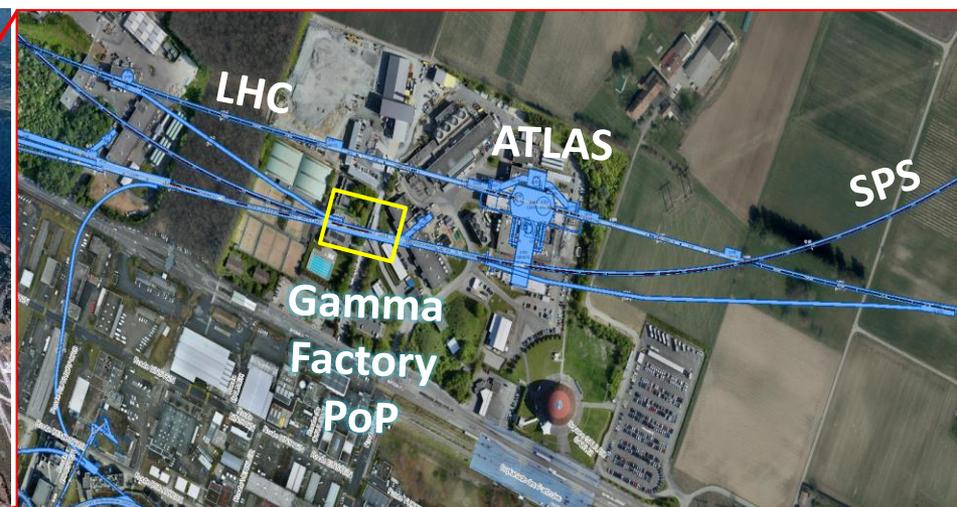
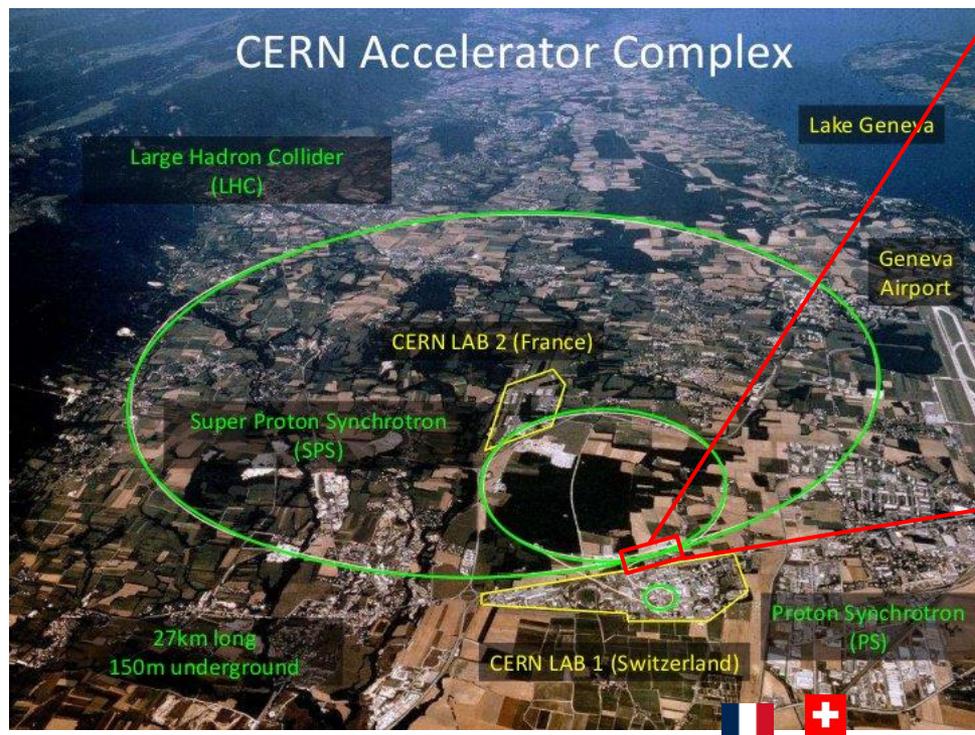
- Potential for the first demonstration of laser cooling of relativistic ions ($\beta \approx 0.99$)
- Potential to improve beam quality in LHC-like collider conditions.
- Simulation studies ongoing
 - see D. Gamba's [presentation](#)



A 3D CAD rendering of a particle accelerator tunnel. The main structure is a long, horizontal pipe with various components like flanges, valves, and sensors. A red line runs parallel to the main pipe, and a purple dashed line is visible in the lower part of the image. The background is a light gray wall with some structural elements.

Gamma Factory: Proof of Principle experiment @ SPS

Proof of principle experiment location

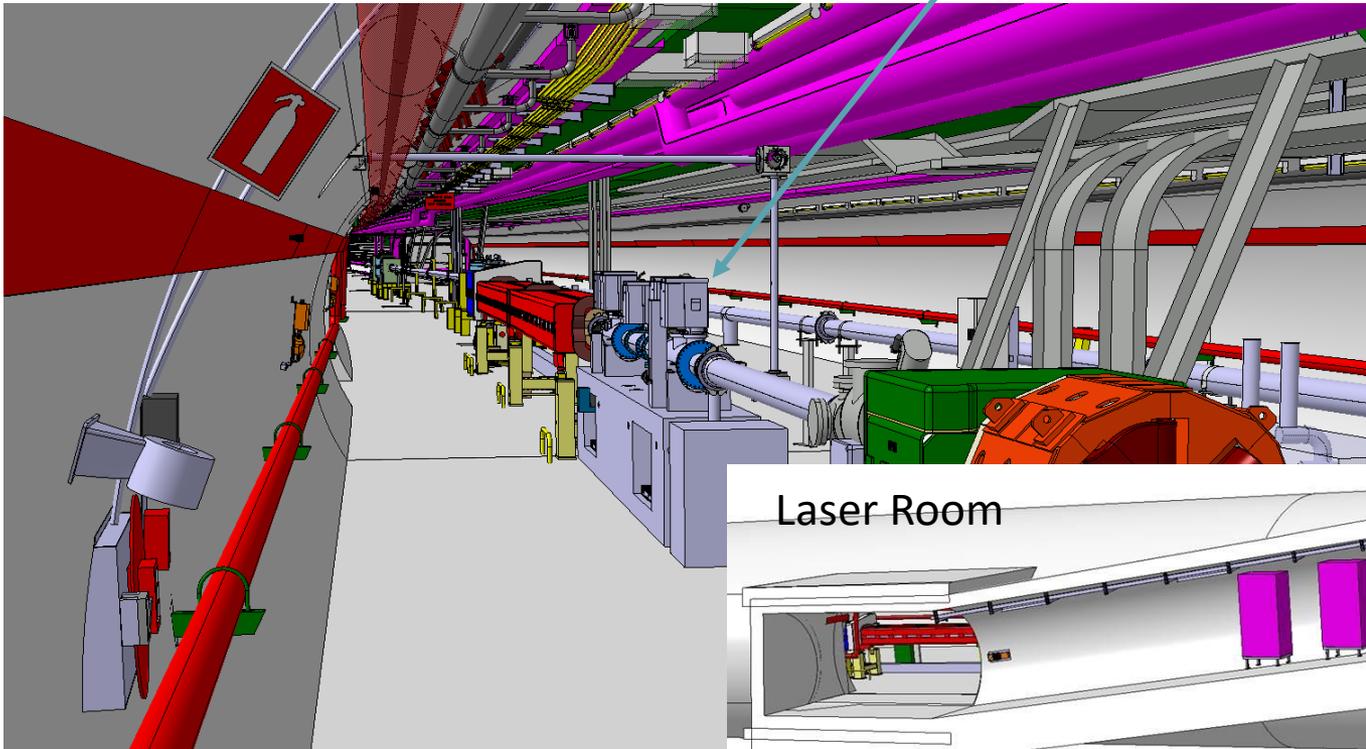
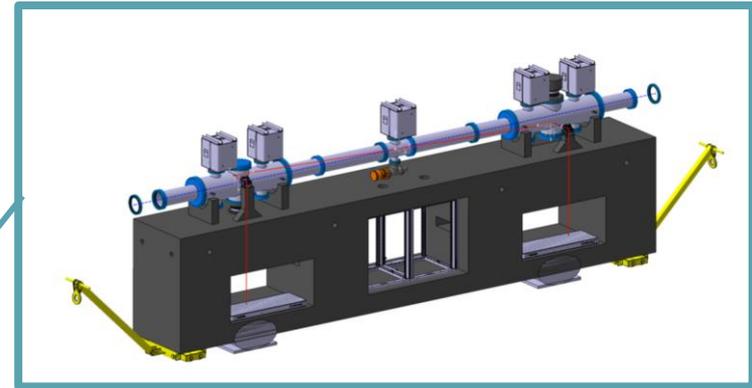


Optical system in SPS tunnel

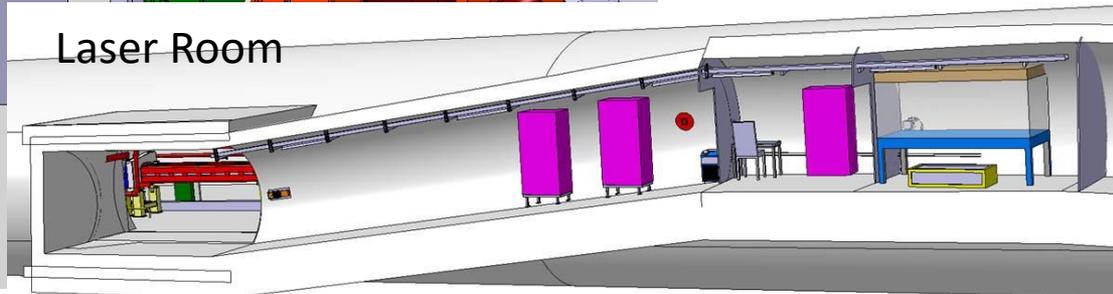
5mJ 40MHz (200kW) laser system

Challenges:

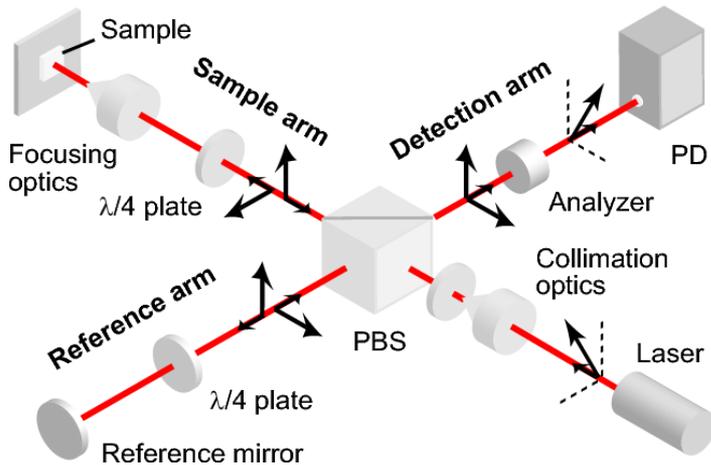
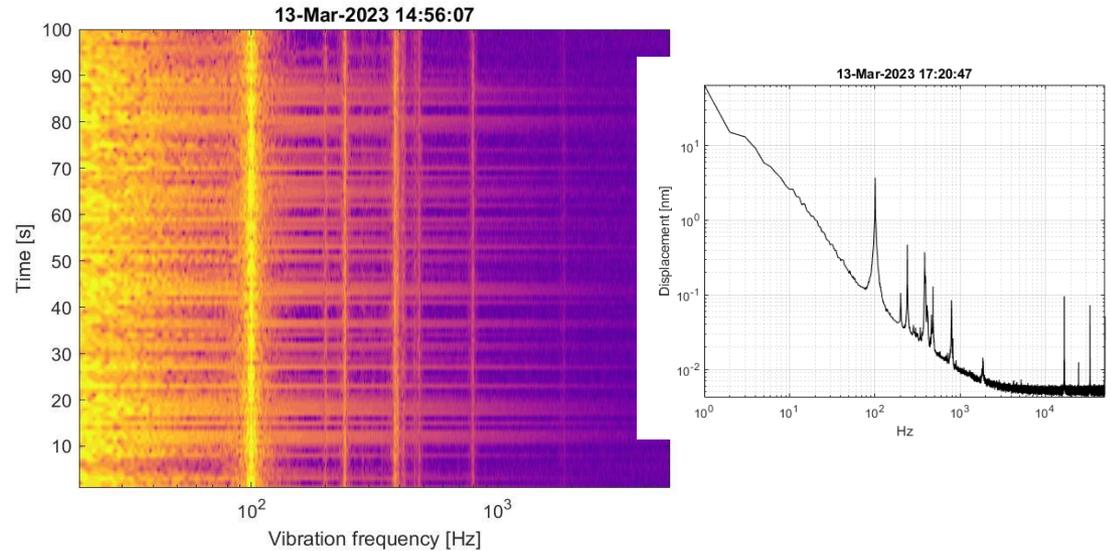
- Laser beam transport
- Full remote operation



Laser Room

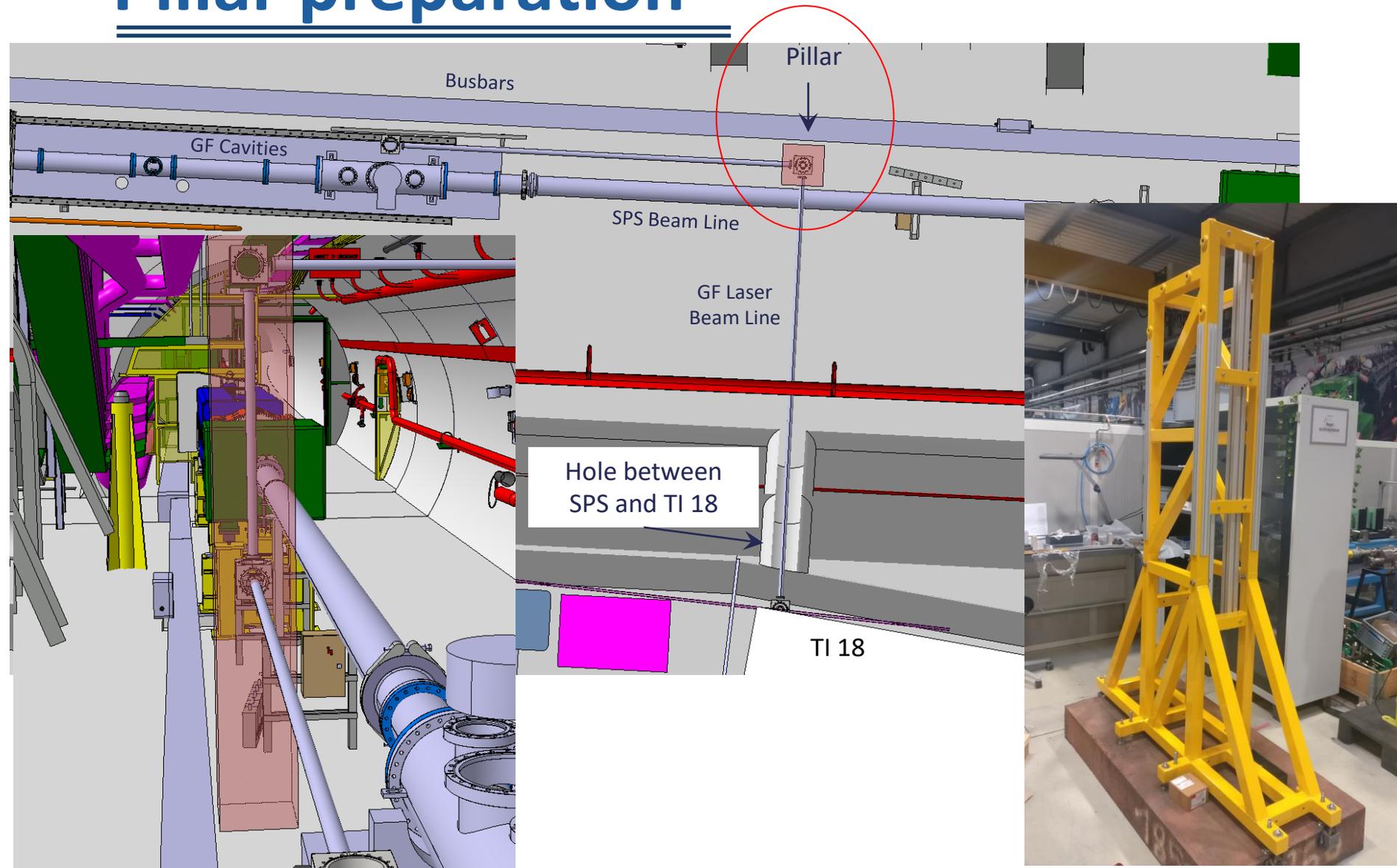


Laser beamline

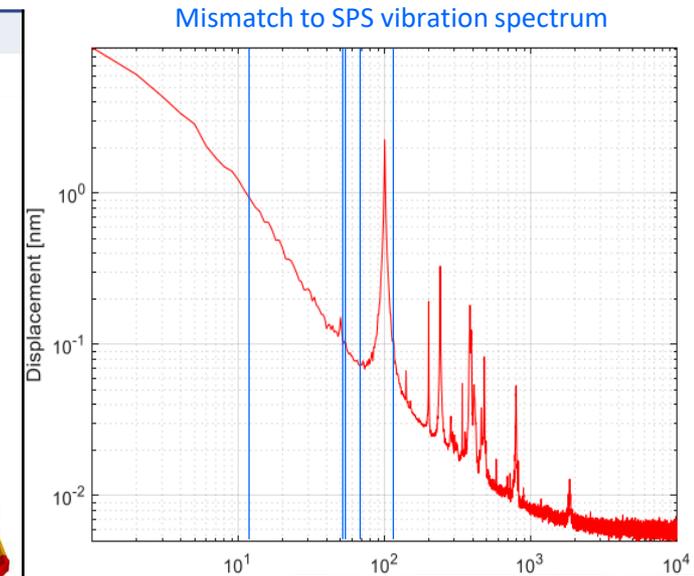
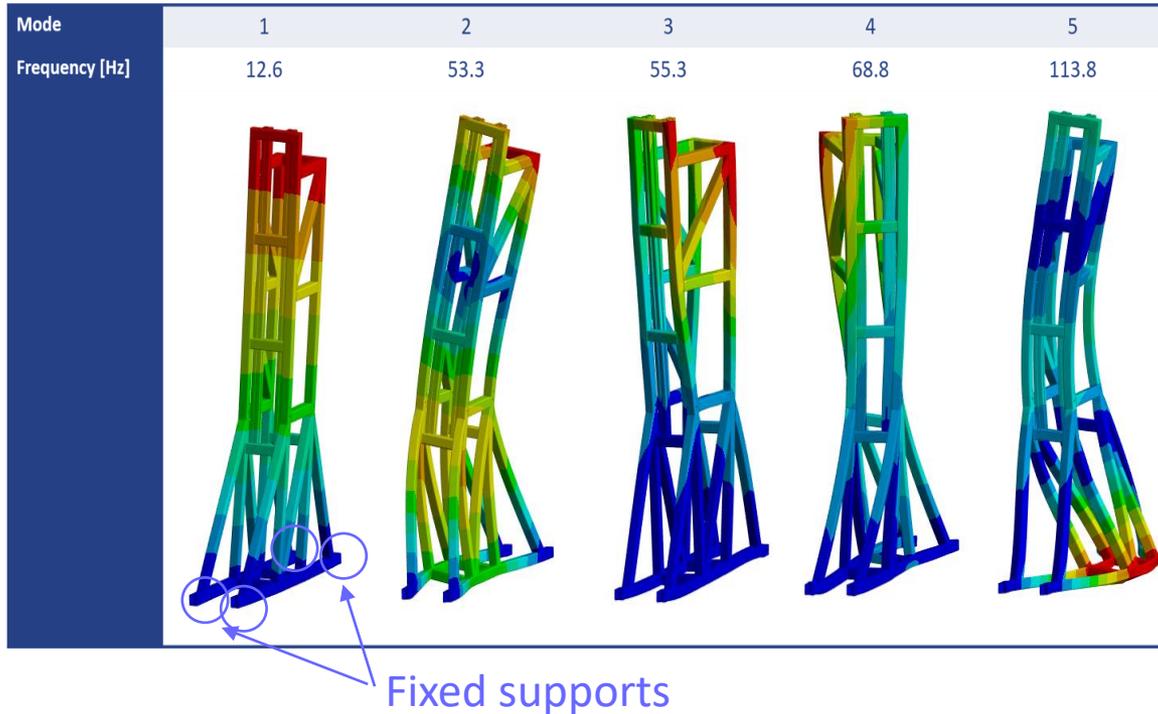


- Measured the vibration spectral content during 6 hours with SPS equipment switched ON.
- Accuracy was down to few pm in length and up to 10 kHz in frequency.
- Largest contributions are acoustics below 1 kHz, with eventual tones at 2.3 kHz.
- Avoid the coupling of vibrations to laser beamline and with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

Pillar preparation

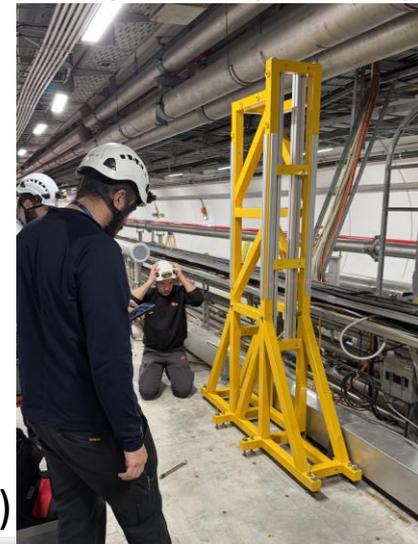


Pillar support simulations



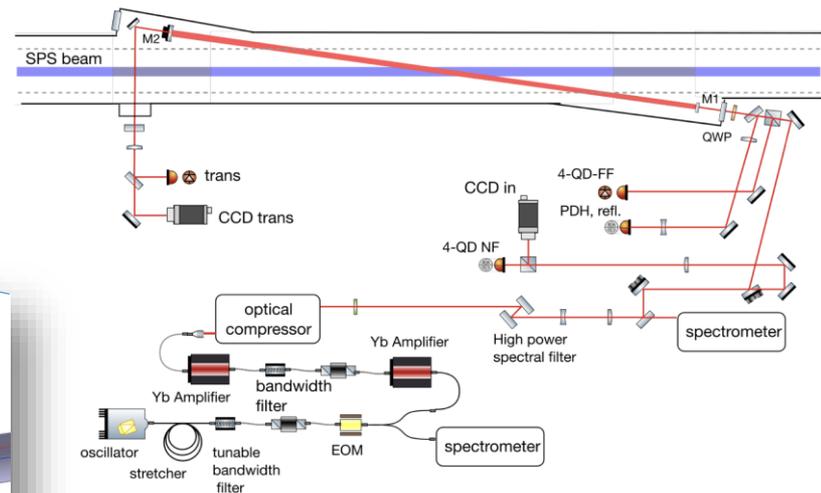
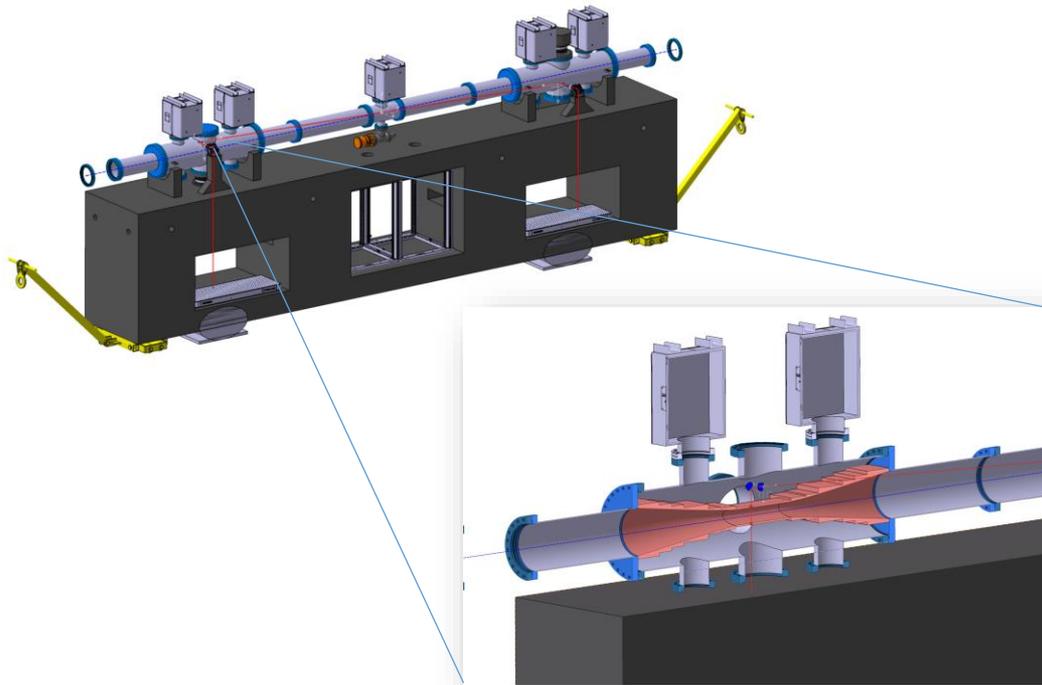
- Analysis of resonant modes without attachment to ceiling.
- All the contacts are bonded. No additional mass on the structure was considered
- The modes are mismatched to the existing vibrational modes found in SPS

First element installed in SPS (Jan'25)



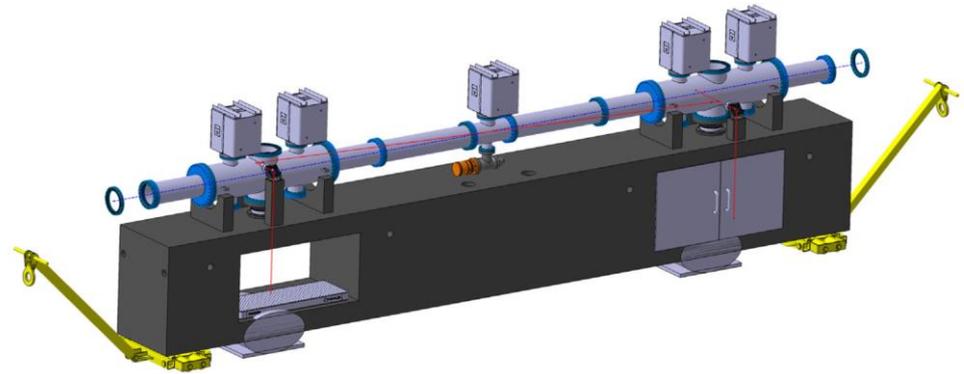
Fabry-Perot preparation

- Pre-design was done by IJCLab
- CERN is preparing the engineering design, possibly ready for procurement in 2026



Optical Cavity for Gamma Factory PoP

- Optical system scheme: 2-mirror **optical cavity coupled to the storage ring**
- Parameter design :
 - FSR = 40 MHz
 - Cavity Linewidth = 4 kHz
 - Finesse = 10,000**
 - Gain = 5,000**
 - Amplified power = 50 W
 - Coupling efficiency = 70%
 - Circulating power = 180 kW**
- Fully remote operation is needed



Fabry-Perot interferometric filter

First difficulty

Laser frequency must be precisely tuned
And remain stable !

$$F = \frac{FSR}{\Delta\nu} = 10000$$

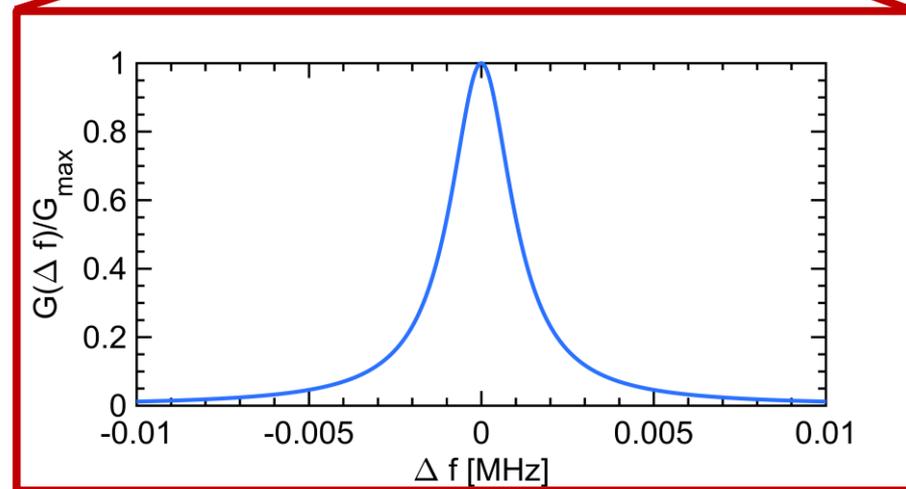
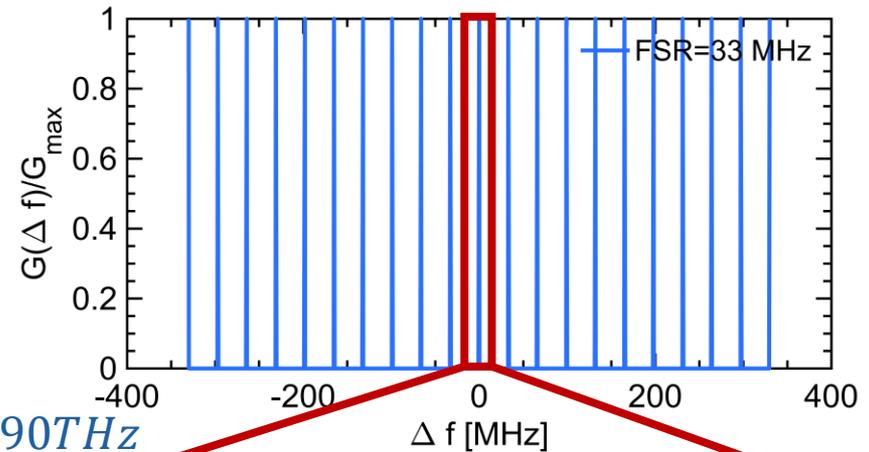
$$\Delta\nu = 4\text{kHz}$$

for $FSR = 40\text{MHz}$

NB: Compare with central frequency of $\nu_0 = 290\text{THz}$

$$\frac{\Delta\nu}{\nu_0} < 10^{-11}$$

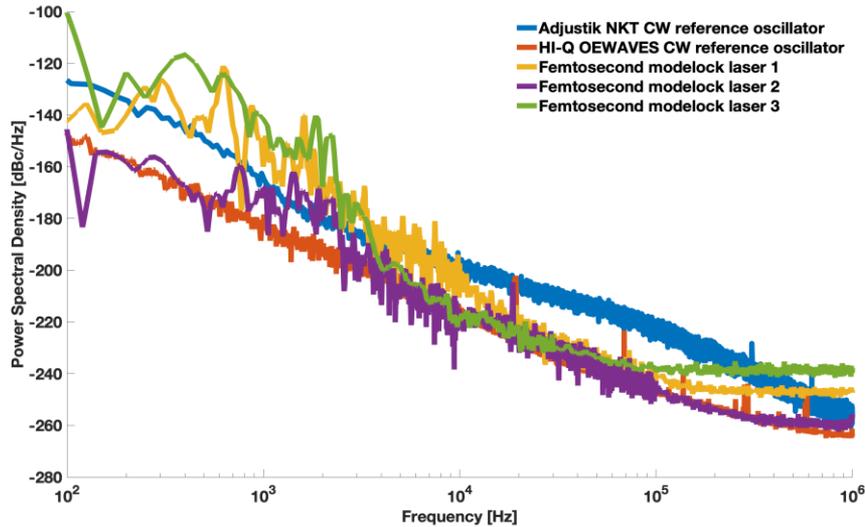
Metrology-level requirement !
→ careful choice of laser provider



Phase noise: choice of provider

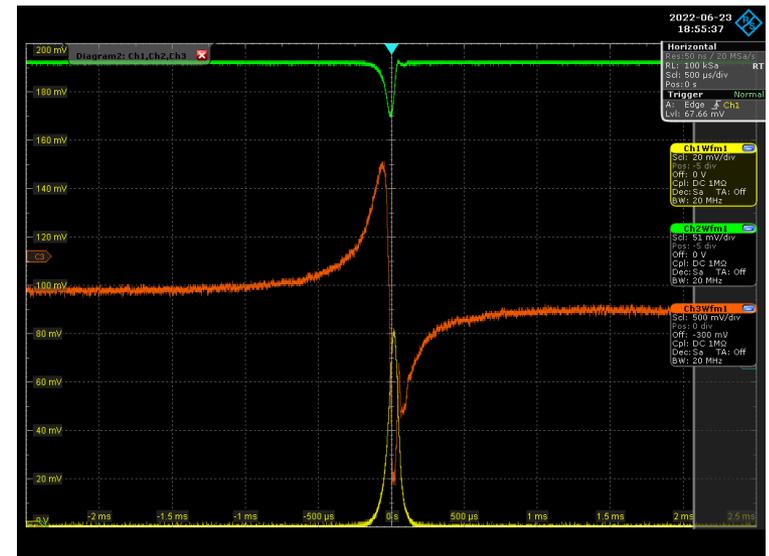
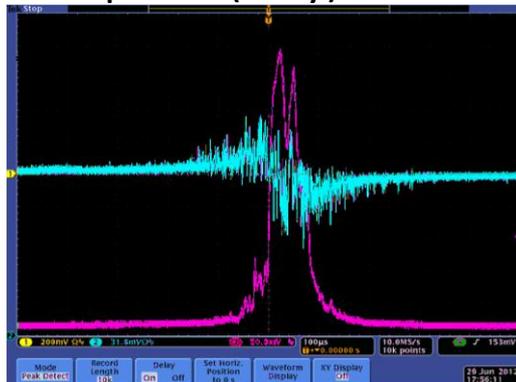
Laser provider identified, laser oscillator procured (160MHz)

Menhir
Photonics



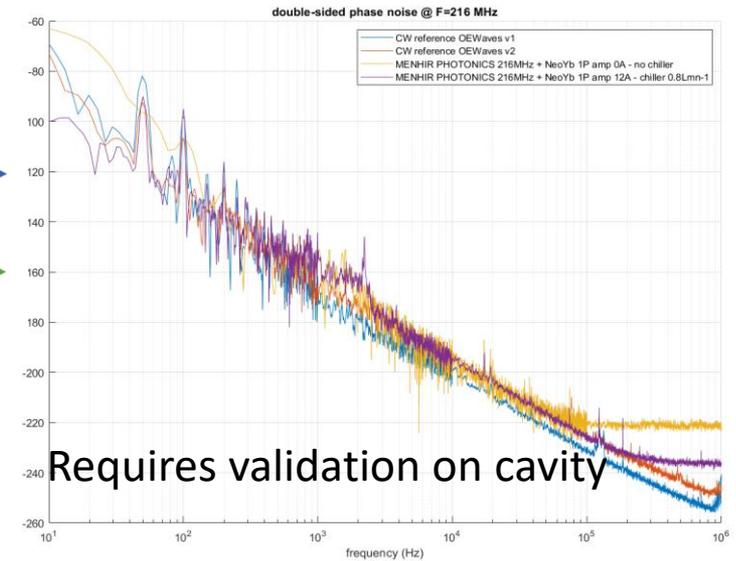
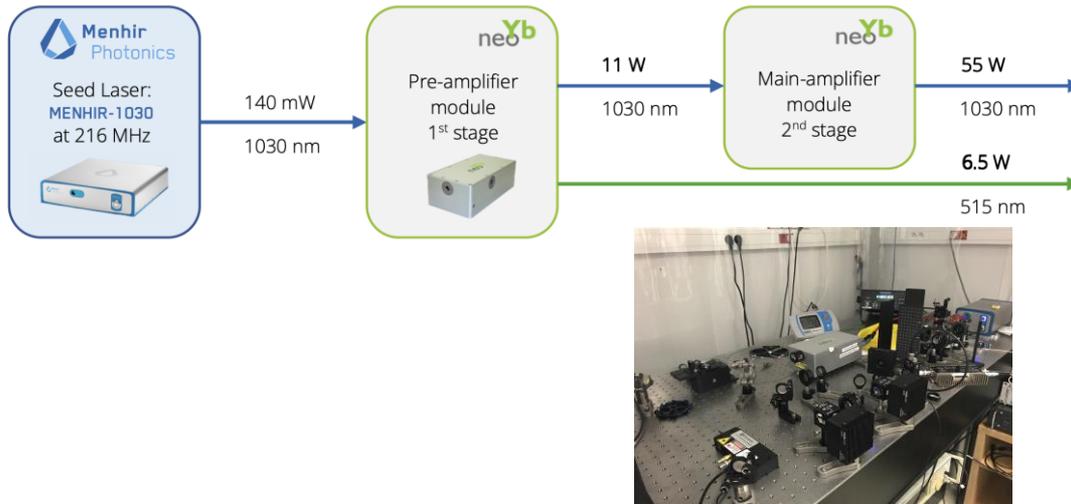
(Very) good laser

Example of (very) bad laser

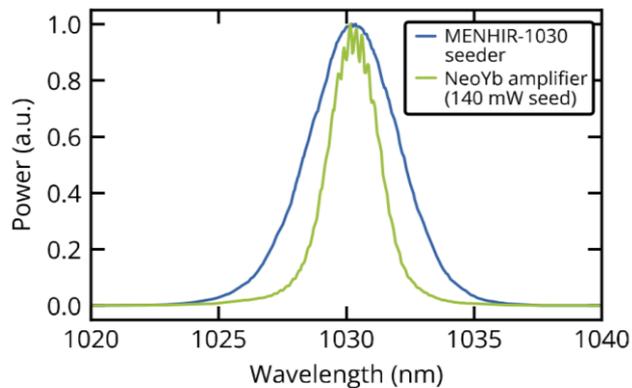


Amplifier choice - neoLase

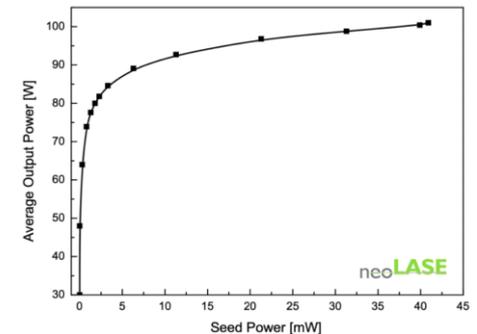
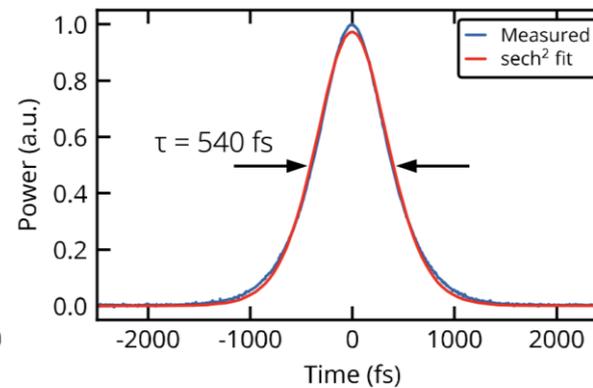
Amplifier procured, delivery end 2025



b) Optical spectrum

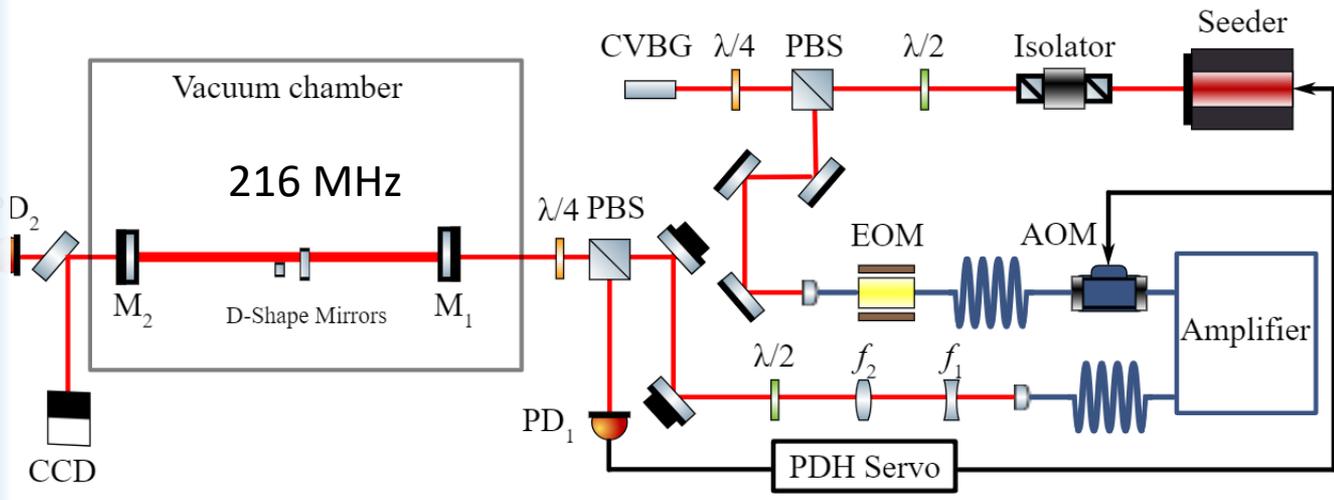


c) Pulse duration measurement



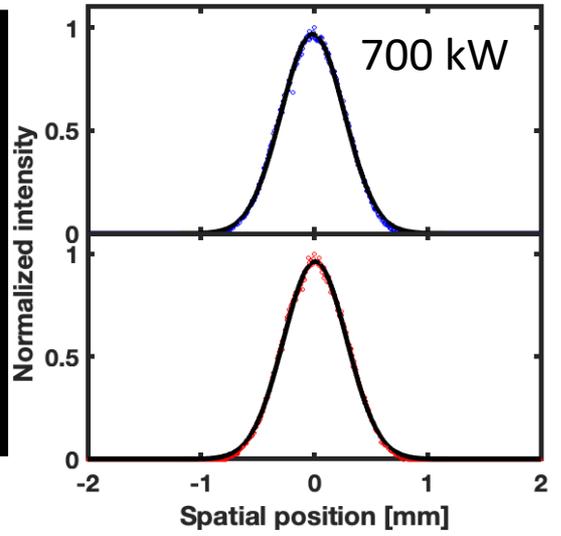
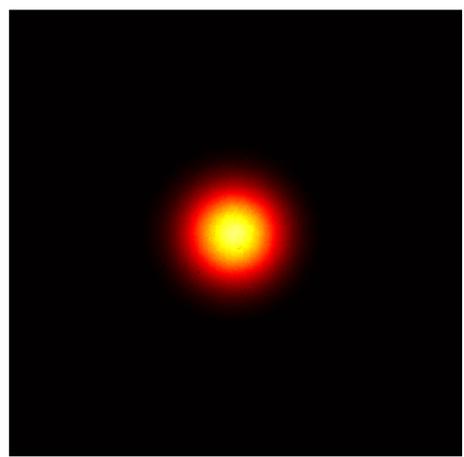
2-mirror cavity demo

X.Y. Lu, et al. Appl. Phys. Lett. 124, 251105 (2024)
X.Y. Lu, et al. Optics Letters 49 (2024) 6884

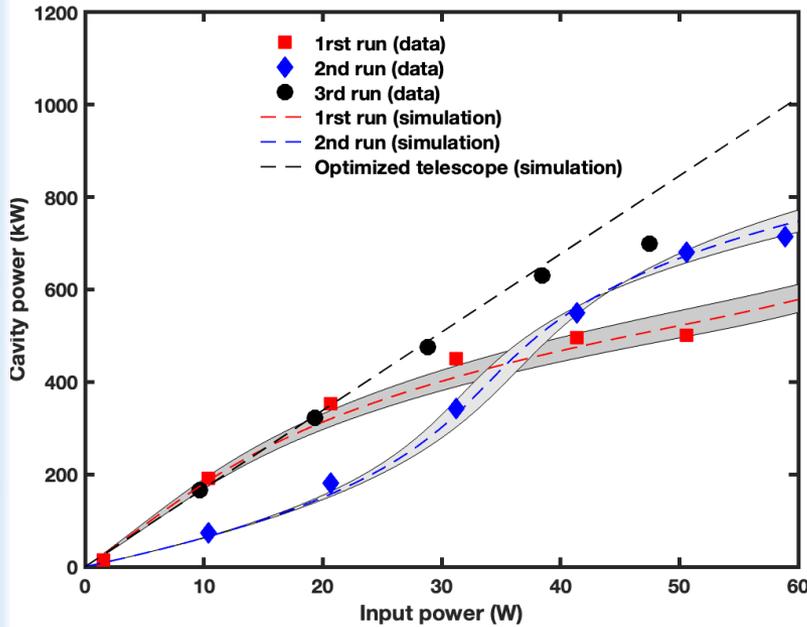


Uses GF-Pop seed laser
Amplifier is R&D

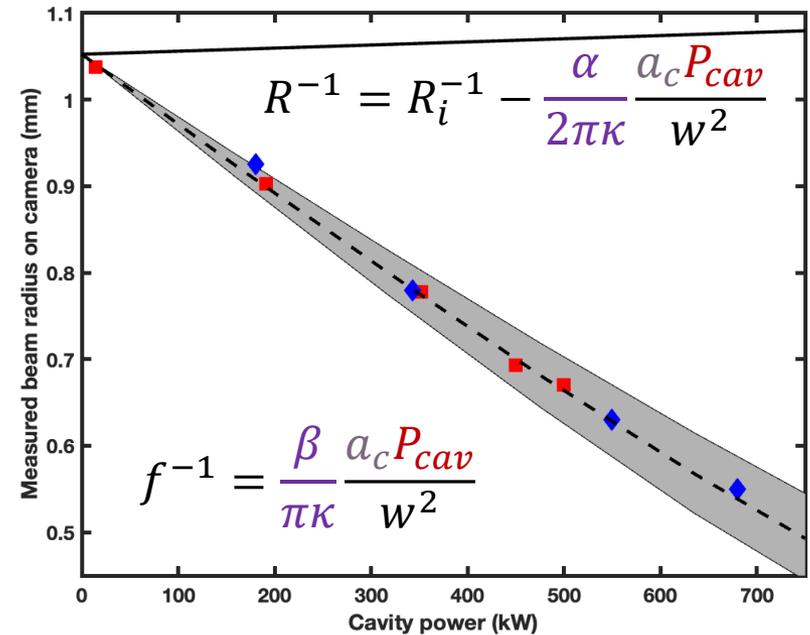
Finesse 45,000
Effective enhancement 18,000



Coupling difficulties



Transmission camera beam size



Lensing also occurs in input mirror (Suprasil 3001) similarly as in output coupler

Thermo-optic coefficient are similar

Strong mode mismatching at high power

Mode mismatching at low power can improve at high power depending on telescope setting

Expect new results from Tsinghua soon (context of SSMB → DENG X. presentation later this week)

Stability

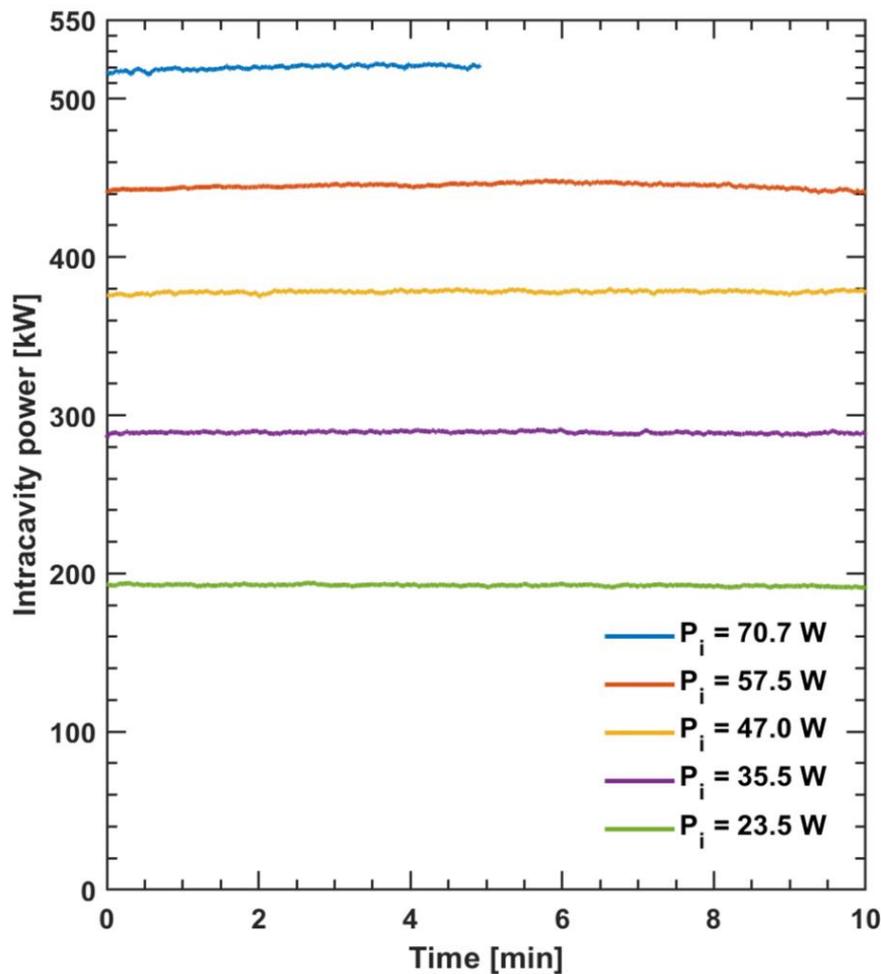


FIG. 3. Experimental measurements of intracavity power as a function of time for various values of injection power P_i .

- Excellent overall stability*
- *Limited by amplifier pump diodes temperature rise at high power*
- *Limited by the need to manually tune one laser piezo voltage (can be automatized)*

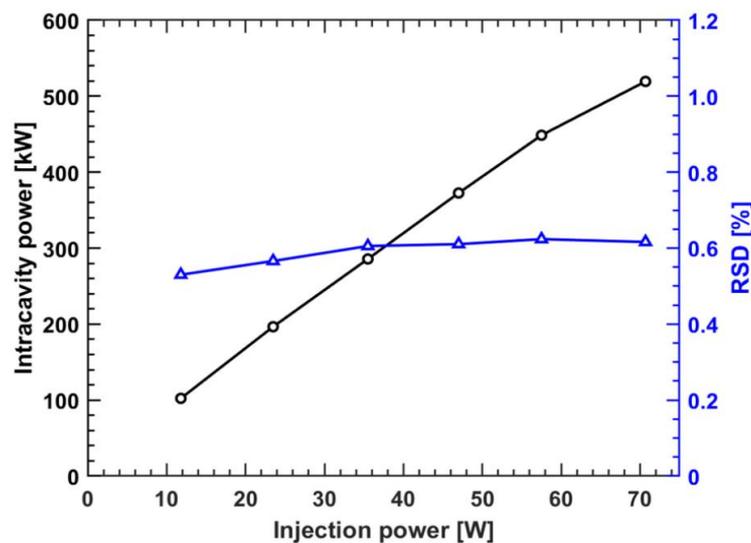


FIG. 4. Experimental measurements of the average intra-cavity power and its standard deviation relative to its average (RSD) as a function of injection power. Lines are drawn as a guide for the eye.

Conclusion/Prospects

- The Gamma Factory proof of principle experiment is a laser cooling experiment for the CERN SPS ion beam
- Comprehensive physics program beyond the Proof of Principle experiment
- Evident progress towards implementation over the past few years
- Hardware validation obtained at Orsay with parameters scalable to GF-PoP design
- World record in stored laser power in the long term
- Expect the laser system to be ready in 2026
- Fabry Perot could be procured in 2026
- Project on schedule for experiment start in 2028

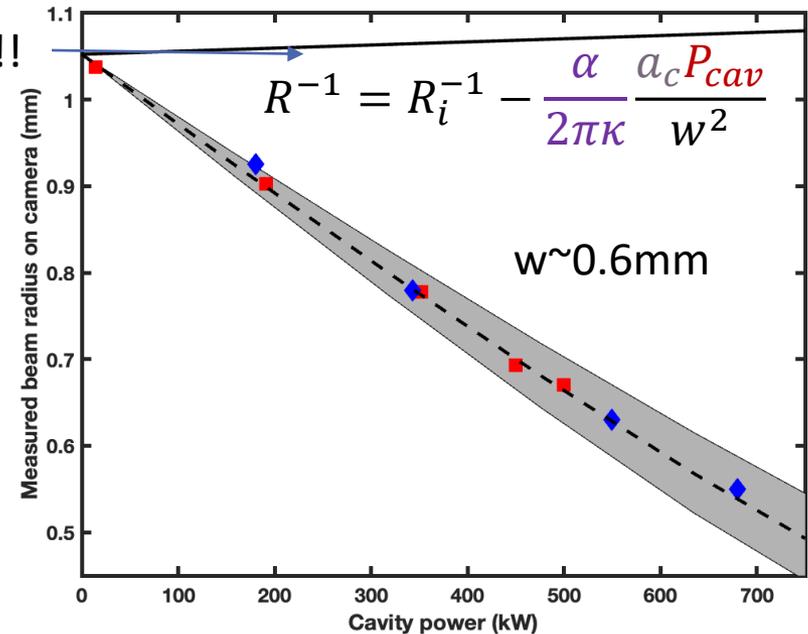
Beam size in transmission

Cannot be explained simply with a ROC change !!!

Lensing in transmission of the the output mirror (ULE) !!!

NB: cavity beam mode nearly unaffected.

Transmission camera beam size



$$f^{-1} = \frac{\beta}{\pi\kappa} \frac{a_c P_{cav}}{w^2} \approx 2 \text{ m}^{-1} \text{ at } 700 \text{ kW}$$

Assuming known material parameters (subject to systematic uncertainties) allows to estimate coating absorption $a_c \approx 0.35 \text{ ppm}$

Current situation

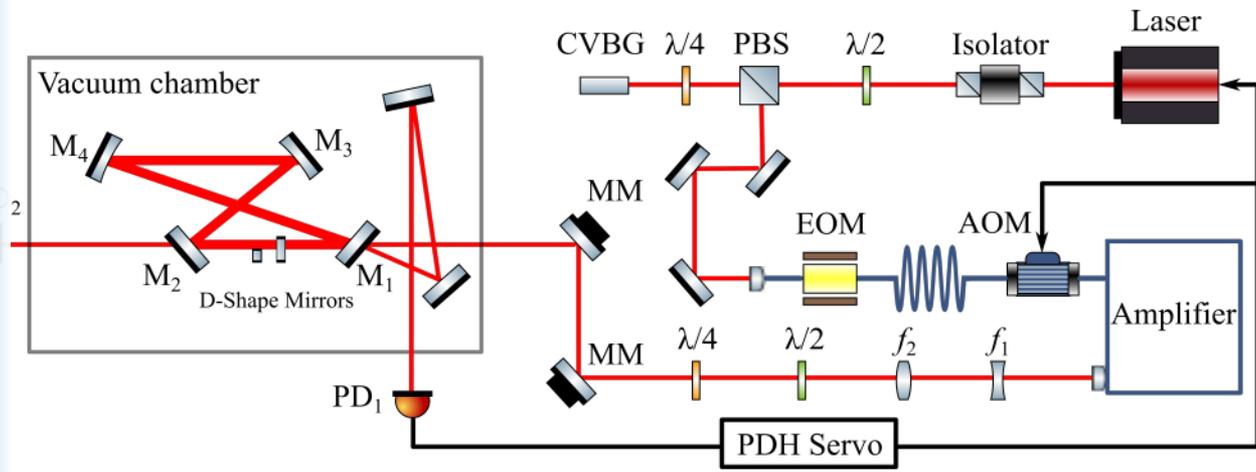
Parameter	R&D	ThomX	GF-PoP design
Frequency	160 MHz	33.3 MHz	40 MHz
Finesse	35000	30000	10000
Linewidth	4.5kHz	1.3kHz	4kHz
Amp. power	75 W	16 W*	>50 W
Cavity power	520 kW	80 kW	>200 kW
Coupling	70%	30 %	70%
Pulse duration	160 ps	5 ps	1-10 ps

We continue to learn and plan to increase power gradually in 2024-2025. We still learn from operation in accelerator at high power with this 4-mirror geometry:

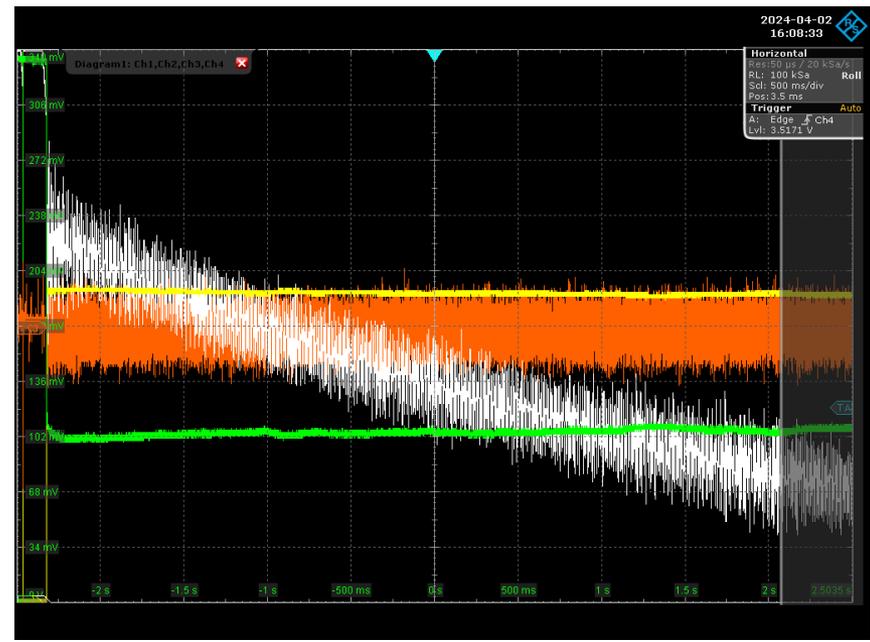
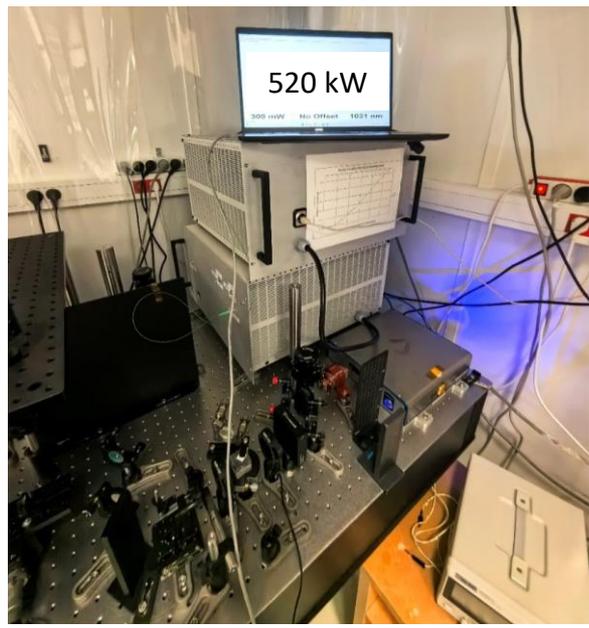
- **Drift of cavity length correlated with stacking of pulses in cavity → thermally induced ?**
- Dynamics is complicated but we manage to preserve lock of laser-cavity-RF by sliding the stepper-motors slowly without loss of lock ! (was not observed at KEK-ATF with 30kW)

It is the main point of attention for GF-PoP (+laser transport)

R&D setup: 4 mirror cavity



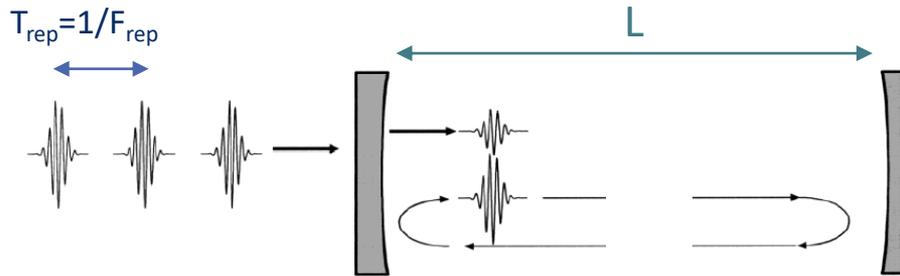
Finesse 35,000
 Effective enhancement 8,000
 ULE mirrors (M234)
 Suprasil input mirror (M1)



X.Y. Lu, et al. Appl. Phys. Lett. 124, 251105 (2024)
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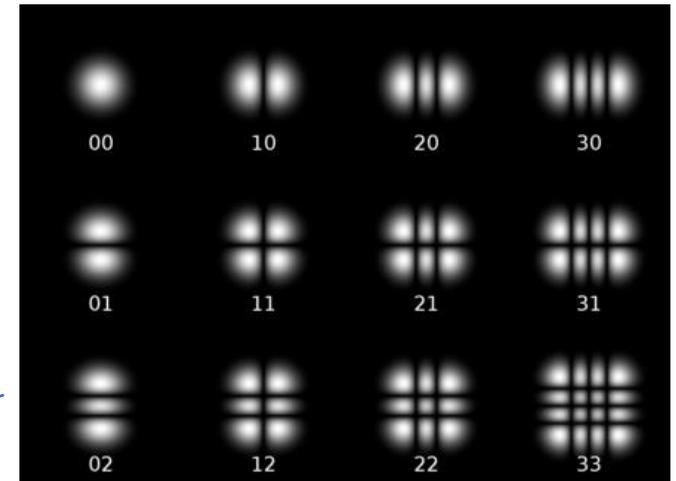
Fabry-Perot resonator

Input laser beam:
Few ps pulse duration



Input laser beam must be matched to the cavity:

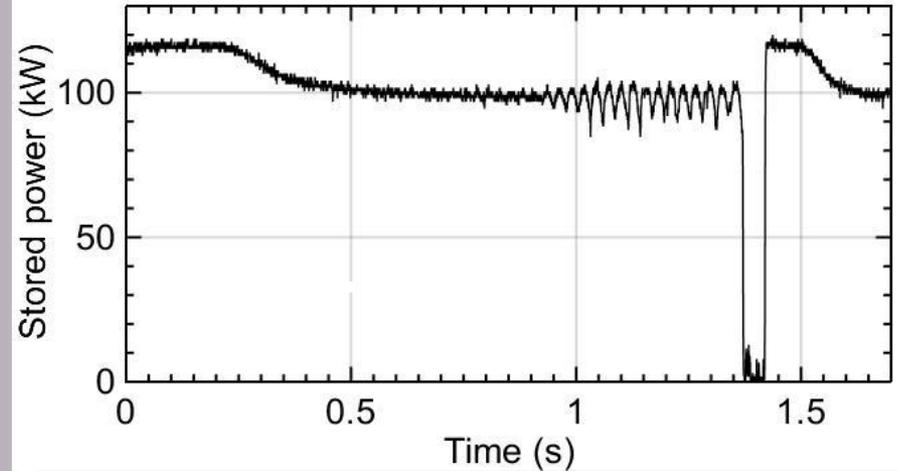
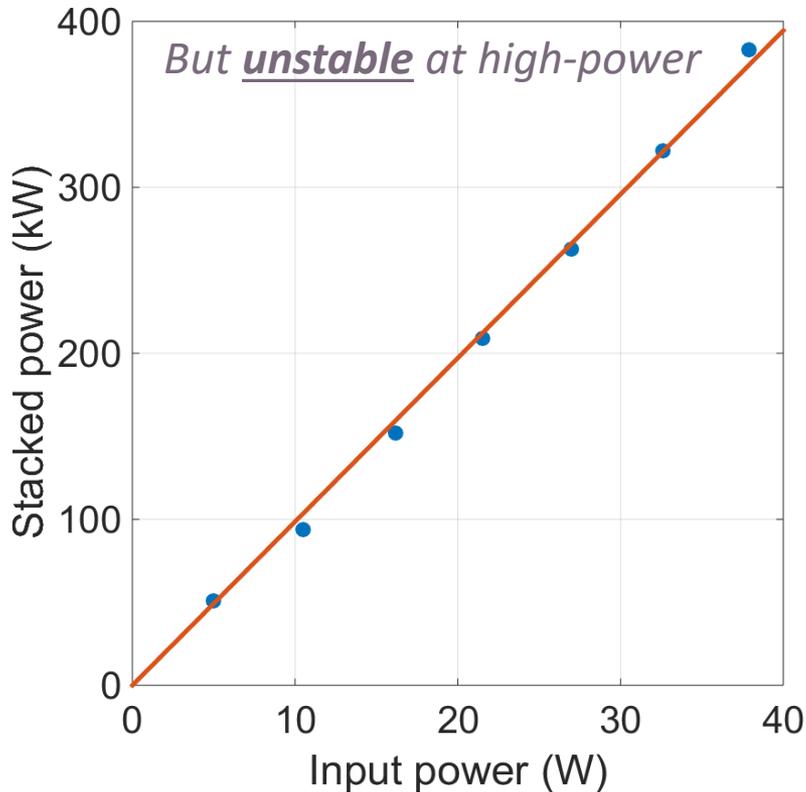
- Temporal superposition $2L/c = F_{\text{rep}}$
- Transverse mode matching



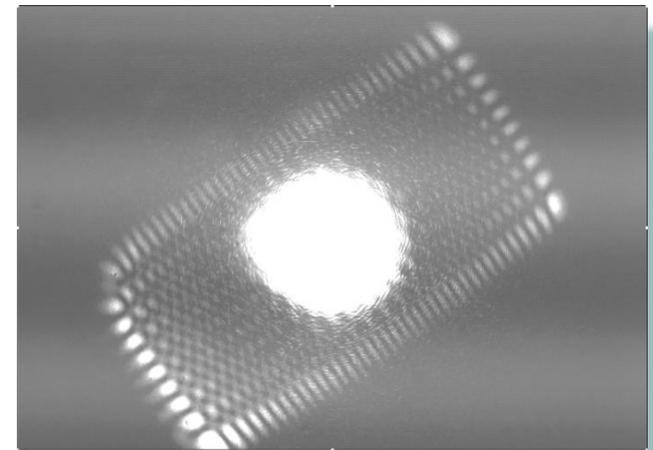
Resonant at different cavity lengths*

*for a non-degenerate cavity

Back in 2020: modal instabilities

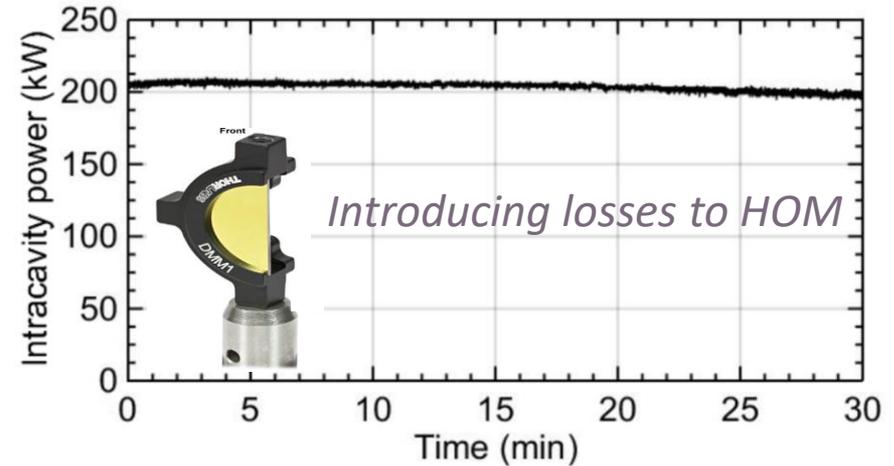
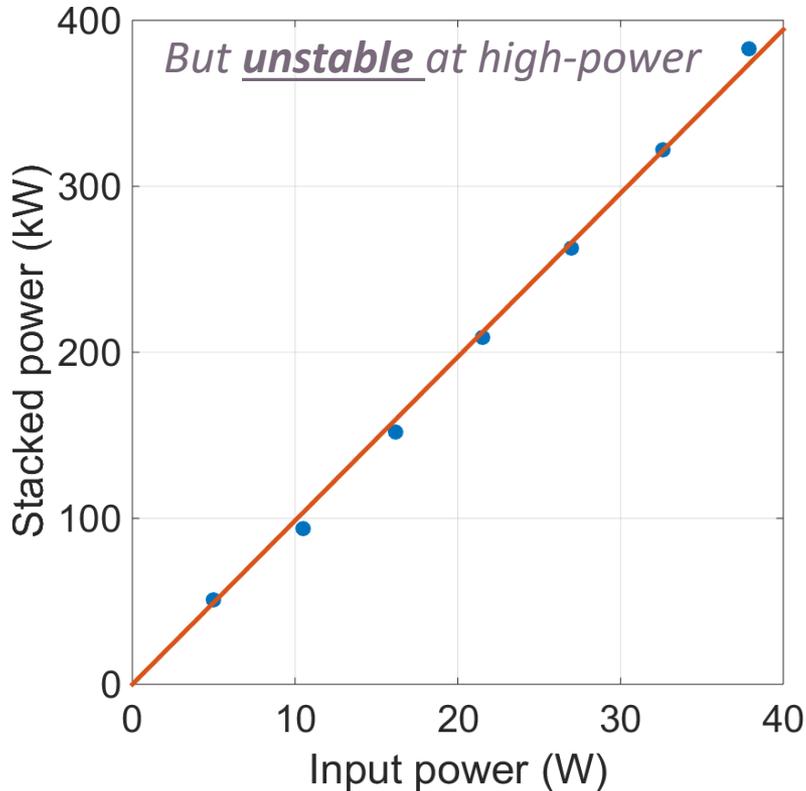


High-order mode instability

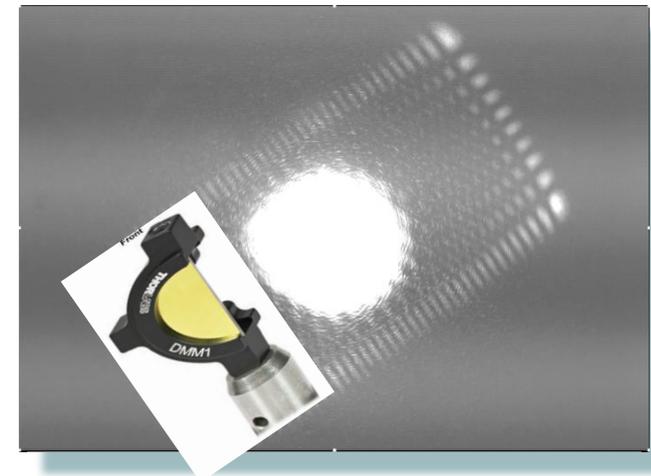


Highly sensitive to cavity topology
Rough understanding from simple simulations
→ *HOM damping with additional D-cut mirrors in cavity*

Back in 2020: D shape mirrors



High-order mode instability



Highly sensitive to cavity topology
Rough understanding from simple simulations
→ HOM damping with additional D-cut mirrors in cavity

Stability

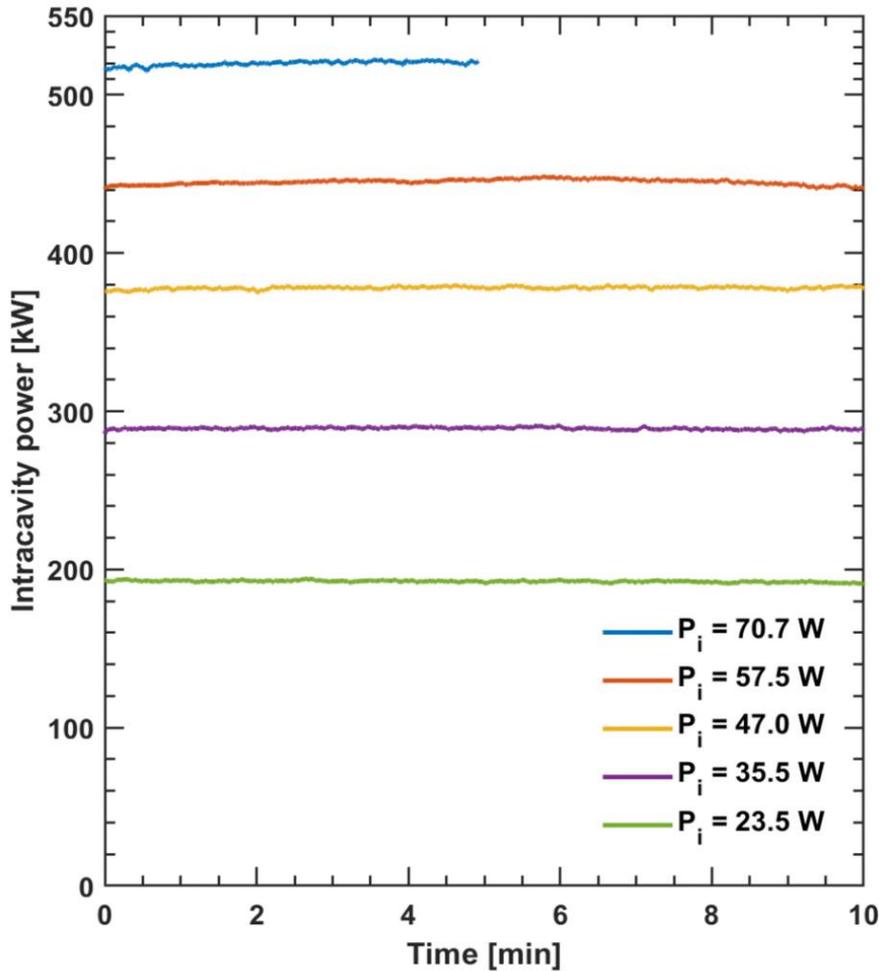


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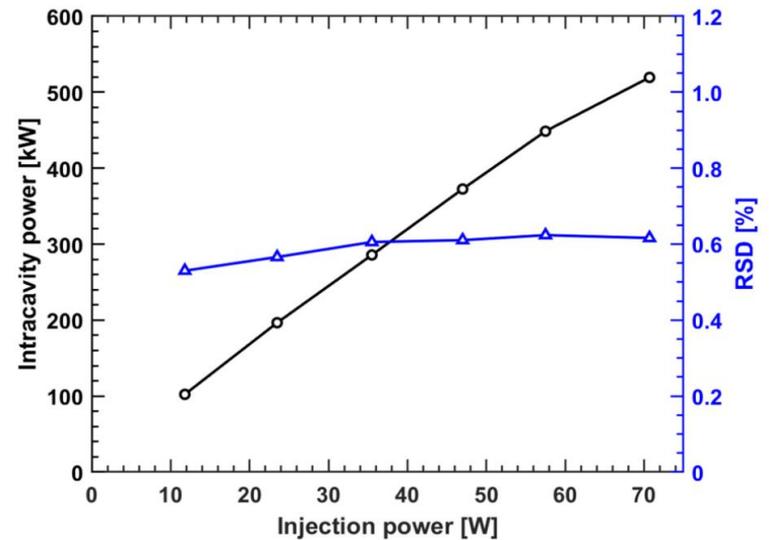
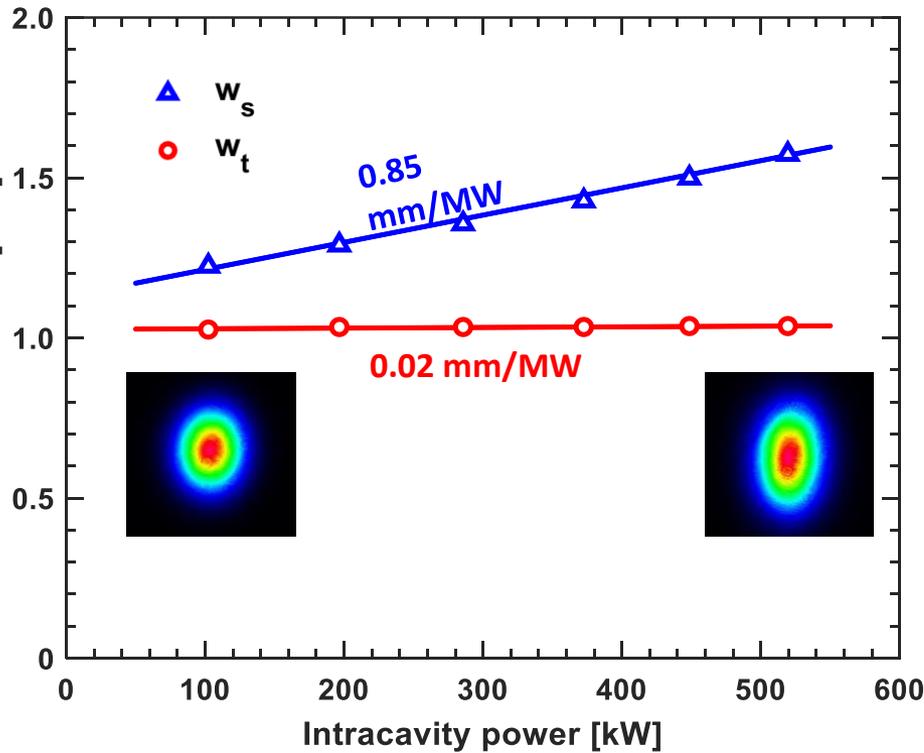


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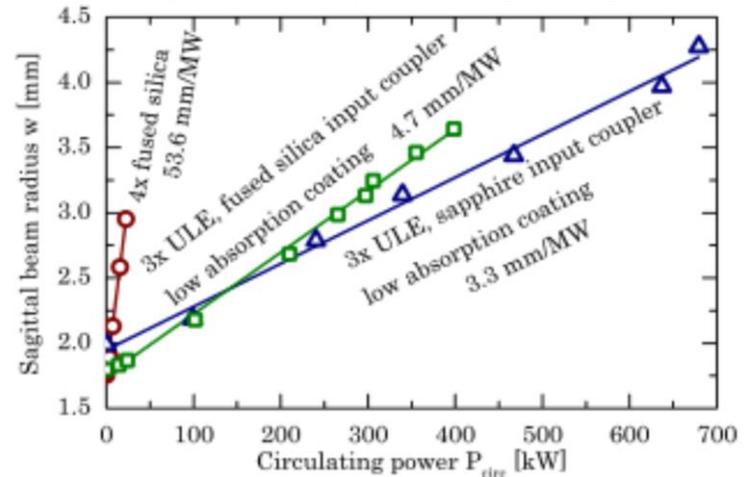
Beam mode



Iterative numerical calculation since w depends on ROC R , which depends on P_{cav}

$$R^{-1} = R_i^{-1} - \frac{\alpha}{2\pi\kappa} \frac{a_c P_{cav}}{w^2}$$

main approximate effect: ROC change



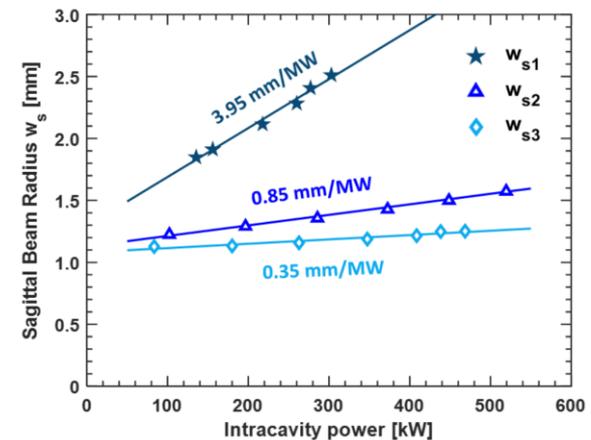
Carstens, *Optics letters* 39.9 (2014): 2595-2598.

Lower mode size increase

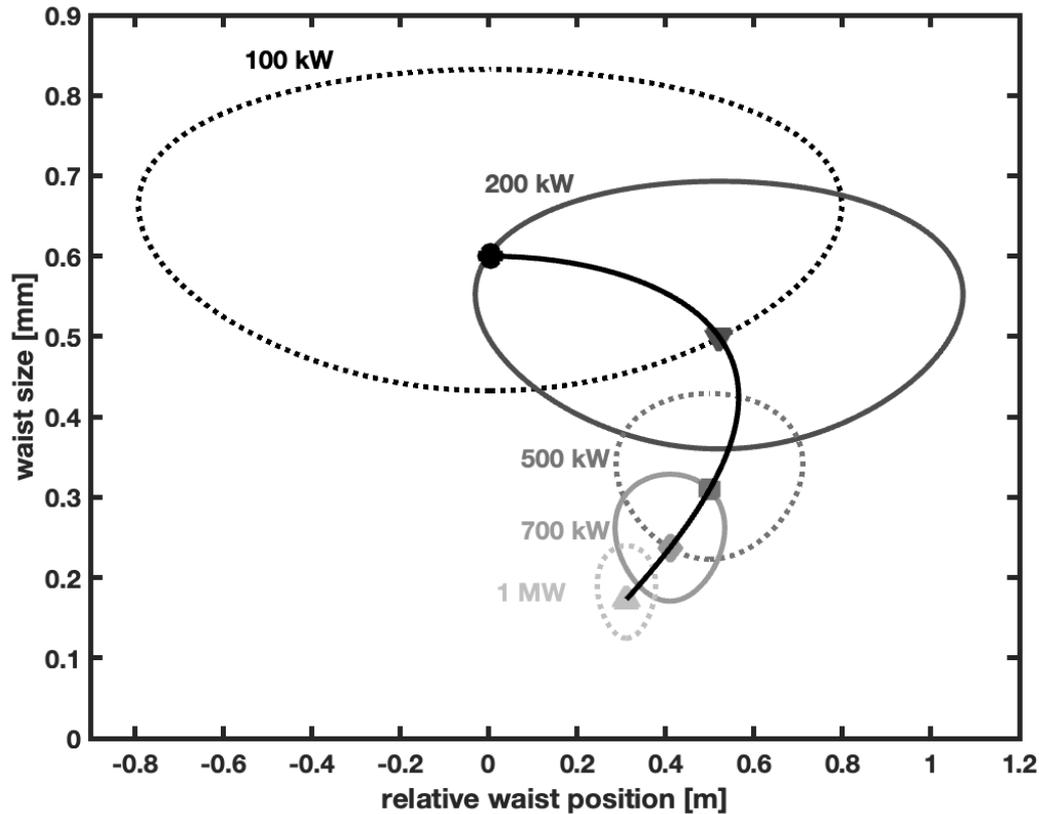
(than legacy work from Munich group)

→ *Much smaller coating's residual absorption*

→ *Can be "tuned" by choosing distance between spherical mirrors*



Coupling issues



Ideal waist size and position for perfect mode matching strongly evolves with stored power
Acceptable region to obtain small (<10%) residual mode mismatching gets extremely tight at high stored power

→ Adaptive telescope ?