The optical cavity for the

Gamma Factory
Proof of Principle Experiment

Aurélien MARTENS (IJCLab Orsay)on behalf of

The Gamma Factory study group

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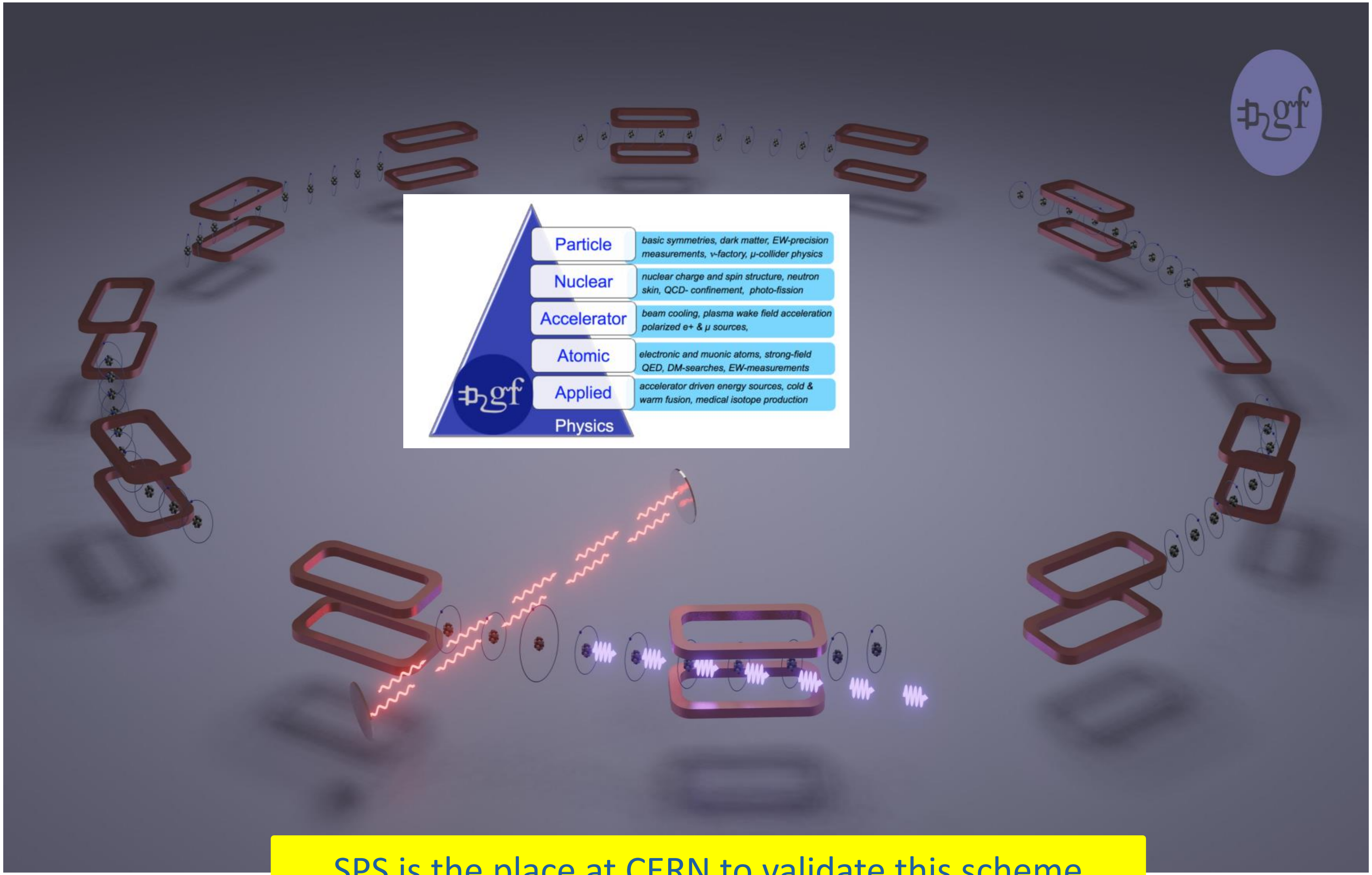
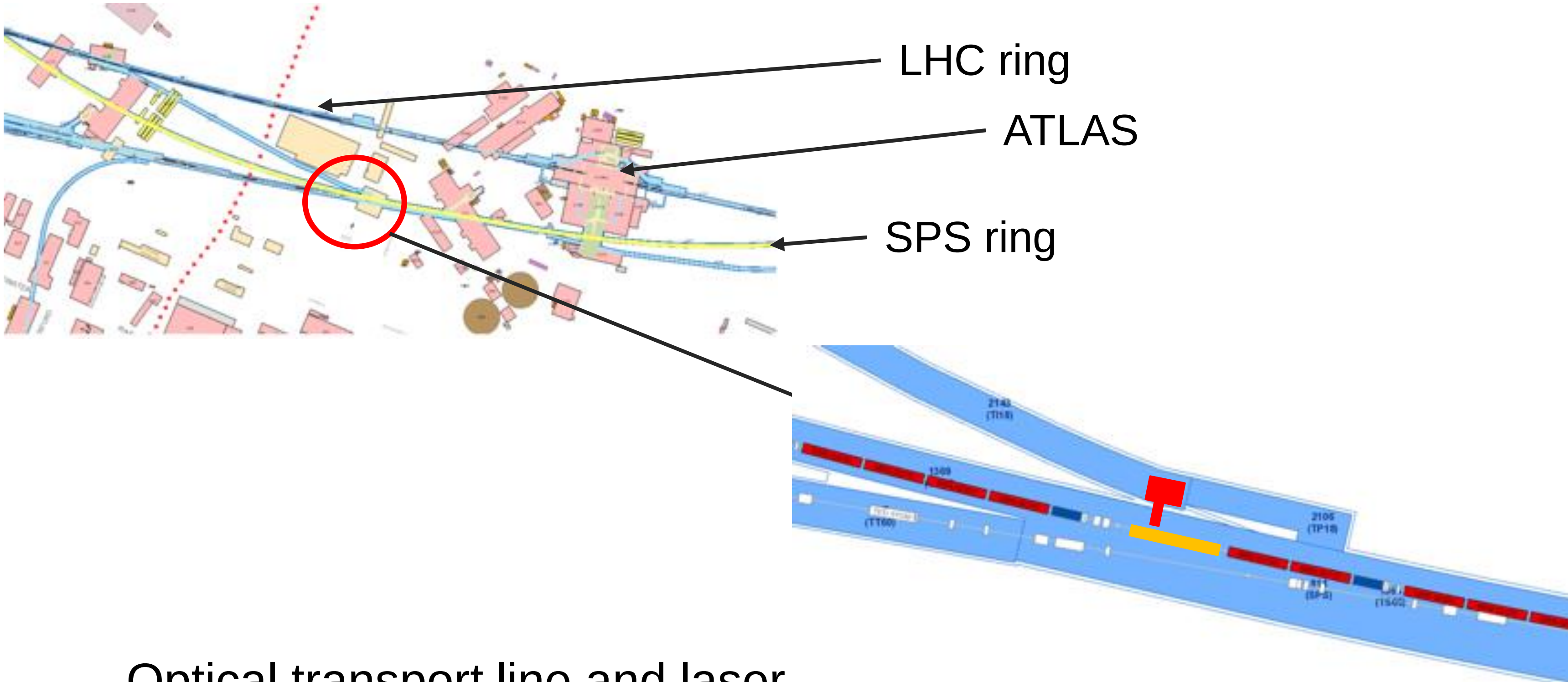
88 people from 34 institutes from 15 countries

The scheme



SPS is the place at CERN to validate this scheme

Interaction region location



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

Collision scheme

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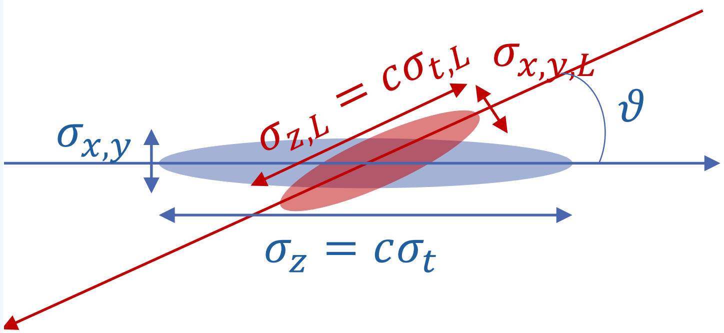


Beams must be aligned, synchronized

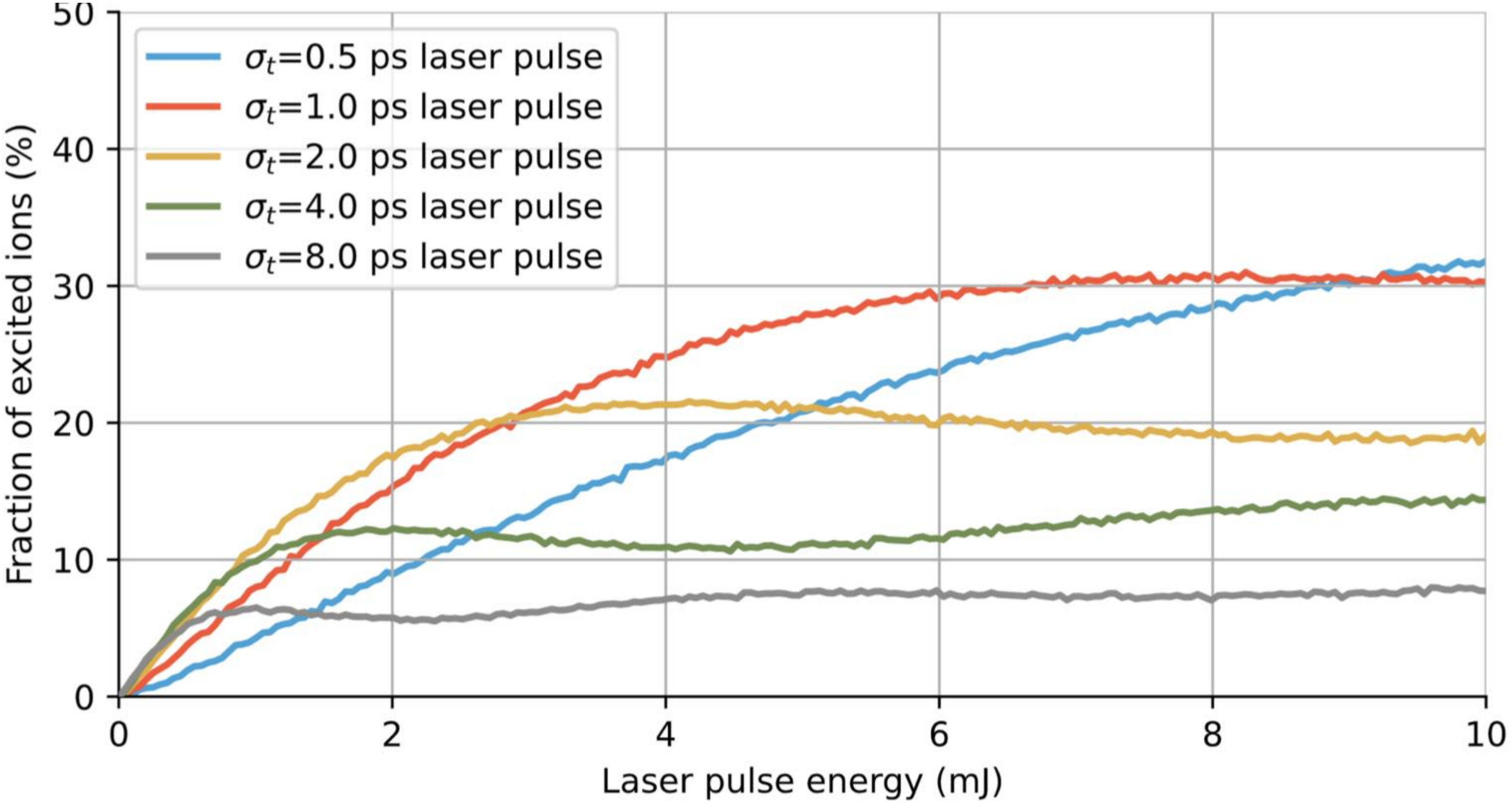
Not specific to Gamma Factory scheme

Table 3: SPS PoP experiment parameters.

PSI beam	$^{208}Pb^{79+}$
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 $^{208}Pb^{79+}$	$2s \rightarrow 2p_{1/2}$
$\hbar\omega'_0$ – 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

Laser parameters optimization

A muti-dimensional approach to optimize the laser beam parameters



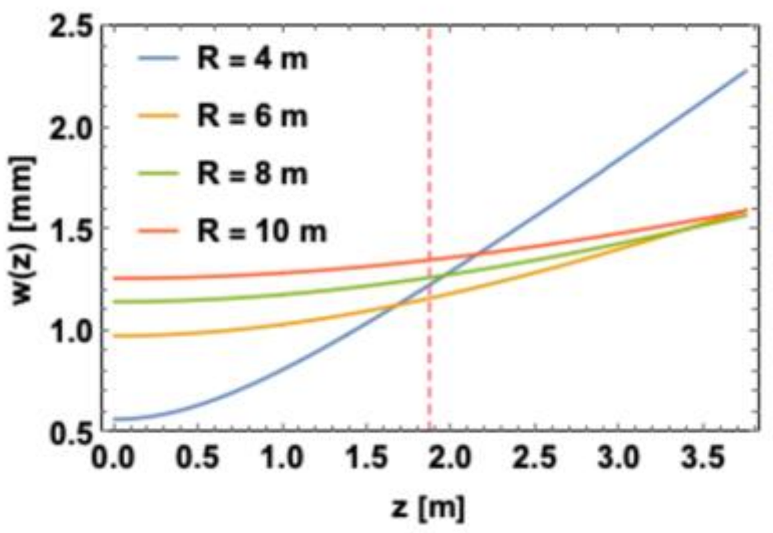
Laser pulse duration/spectrum tunability is an asset

Optical system: design

A several mJ pulsed laser at 40 MHz is a natural candidate:

- Compatible with the atoms filling schemes
- Compatible with what one would need for (later) LHC operations
- State of the art technology: pulsed laser (freq. comb) + amplifier + resonant cavity

A 2-mirror (plano-concave) cavity is considered:
→ simpler operation, delivers naturally beam sizes close to optimum



A 8 to 10m mirror Radius of curvature is preferred

We expect to operate the optical cavity with an enhancement factor >5000

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

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

Three pilars of the optical system

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

A high gain optical cavity

⇕

High finesse (selectivity)

A high power amplifier

⇕

Small quantum defect
Yb technology
100W amplifiers are commercial systems

An ultra-stable seed laser oscillator

NB: we are employing this approach at IJCLab since 2011
The ThomX project, being commissioned in Orsay, has similar requirements as GF-PoP

The oscillator

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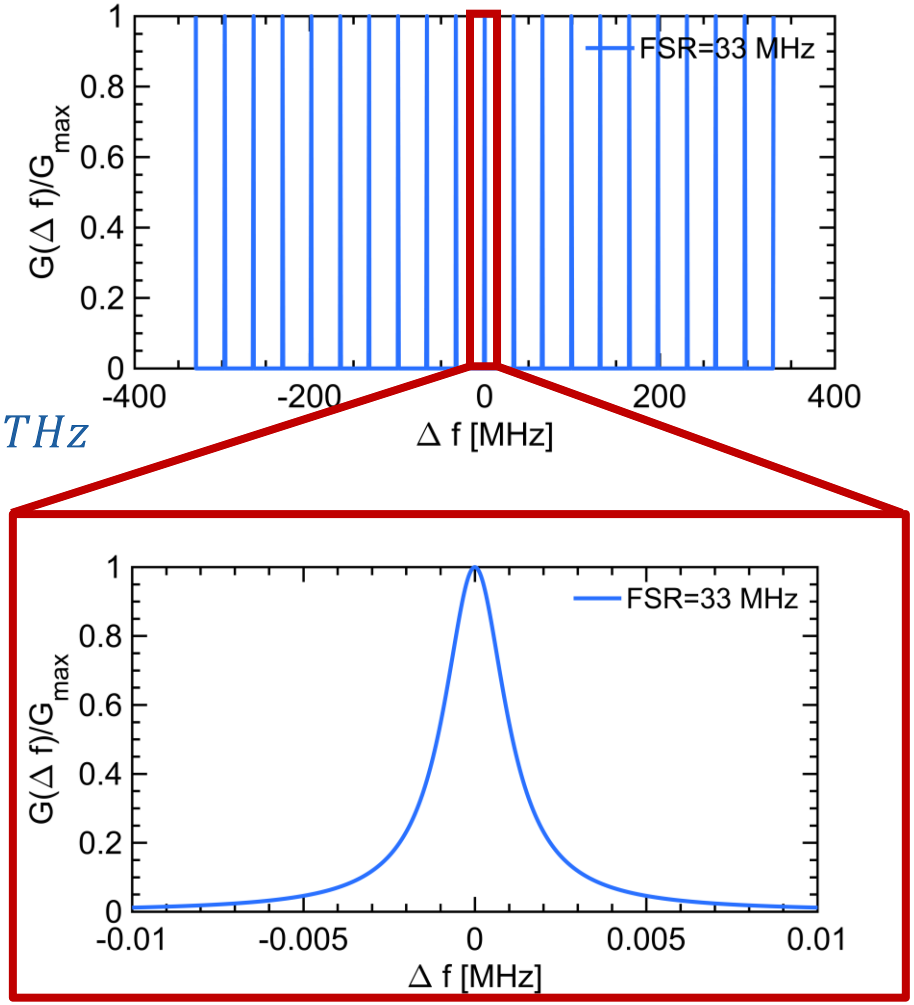
Fabry-Perot interferometric filter

Laser frequency must be precisely tuned
And remain stable !

$$F = \frac{FSR}{\Delta\nu} = 20000 \qquad \Delta\nu = 2kHz \; for \; FSR = 40MHz$$



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

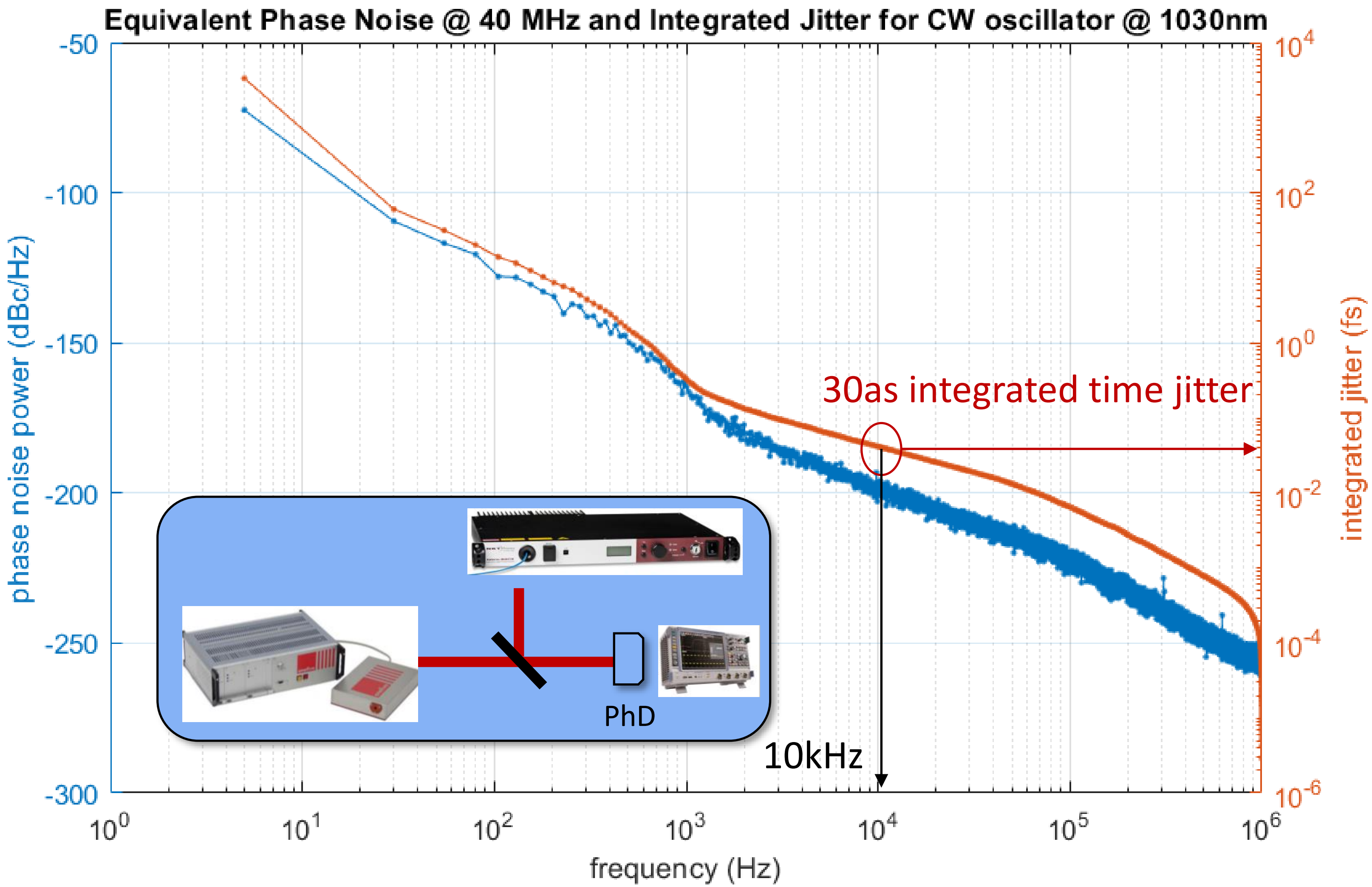
$$\frac{\Delta\nu}{\nu_0} < 10^{-11}$$

Metology-level requirement !
→careful choice of laser provider

Phase noise measurements

Noise measurement

Optical beating ~~*RF technique*~~



Phase noise measurements

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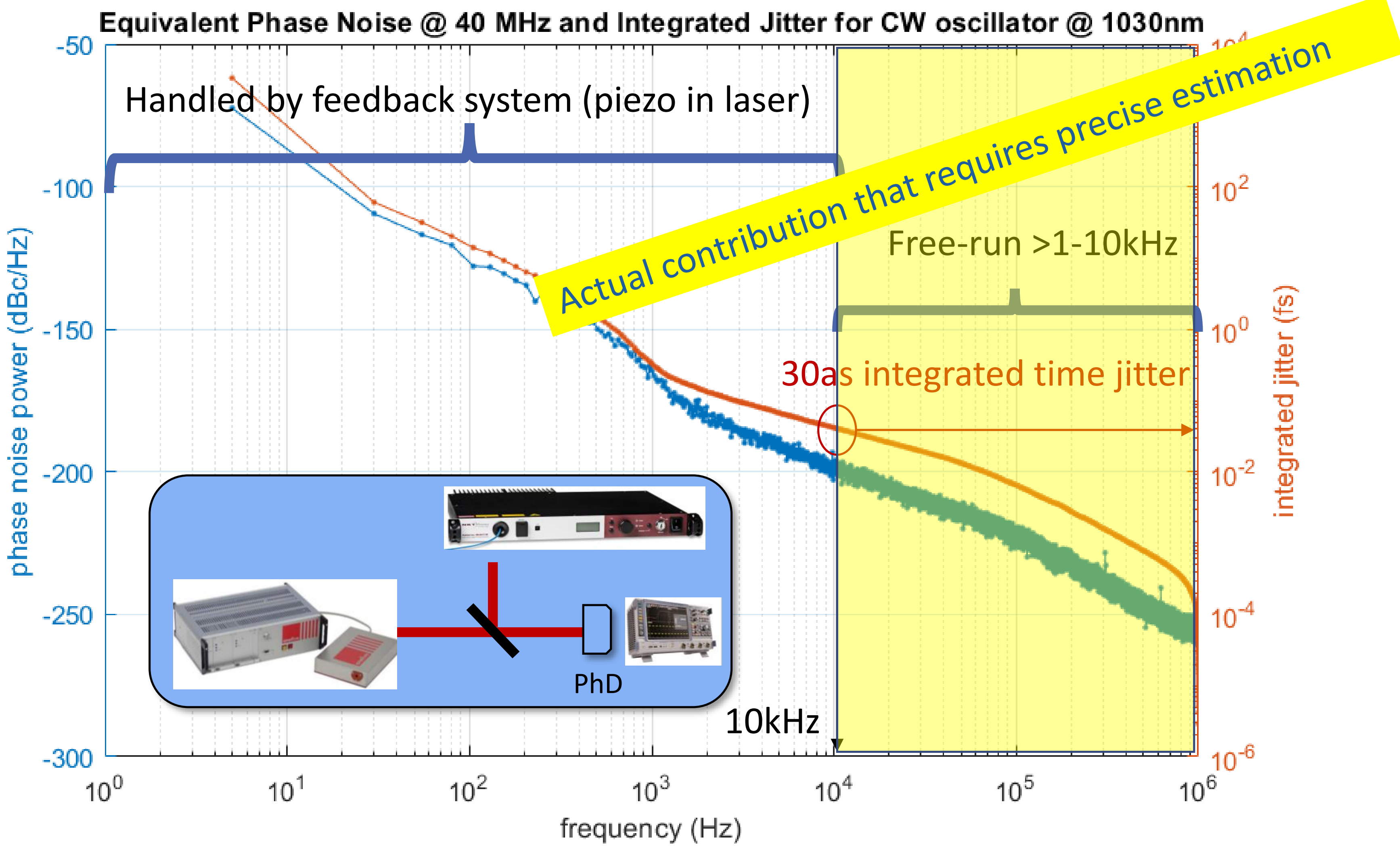

The amplifier

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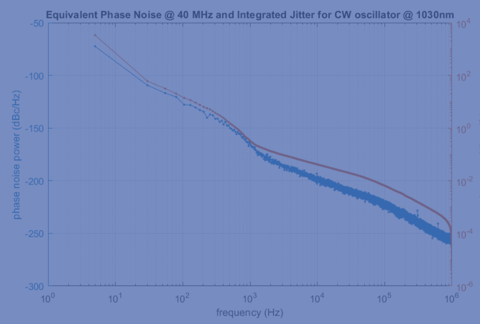

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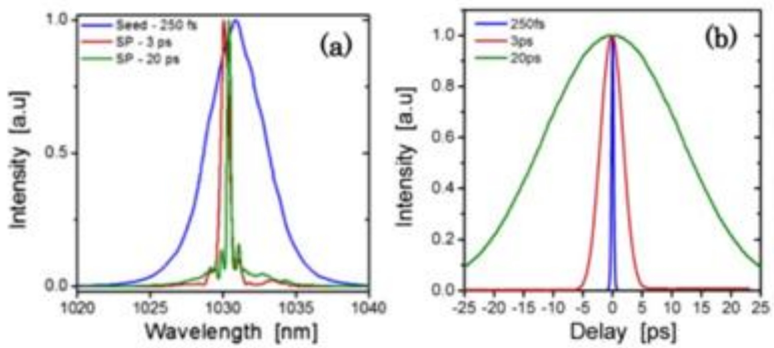
Amplifier

Use Chirped Pulse Amplification; System robustness is critical.

Hybrid 50-100W laser amplifier



Industrial system exists !

Fibre 50-100W laser amplifier

Pulse duration could be tuned with temperature-controlled fibre Bragg Gratings (stretcher) → needs R&D

Laser pulse duration/spectrum tunability is an asset

Robustness is critical

Pouysegur et al. Opt. Lett. 40, 5184-5187 (2015), https://amplitude-laser.com, https://www.alphanov.com

The optical cavity

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

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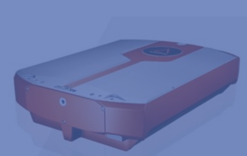
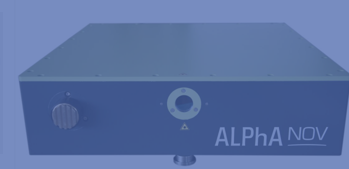
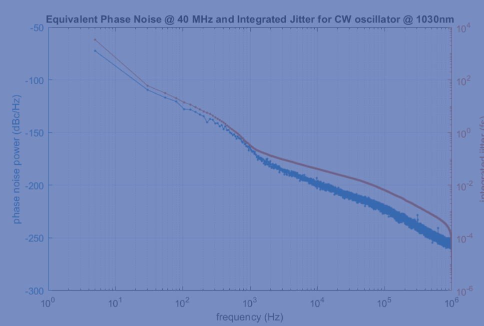




An ultra-stable seed laser oscillator



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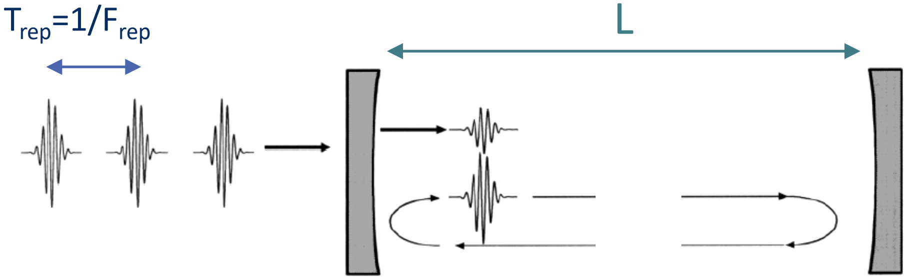
Fabry-Perot resonator

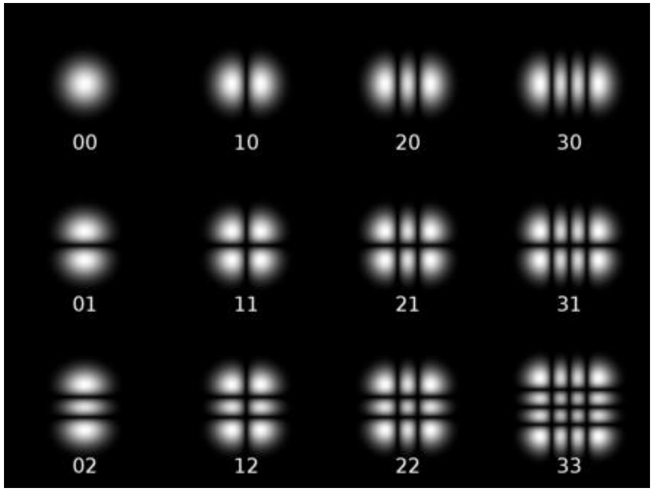
Optical mirrors from LMA,
see earlier presentation by Laurent

Input laser beam:
Few ps pulse duration



Input laser beam must be matched to the cavity:

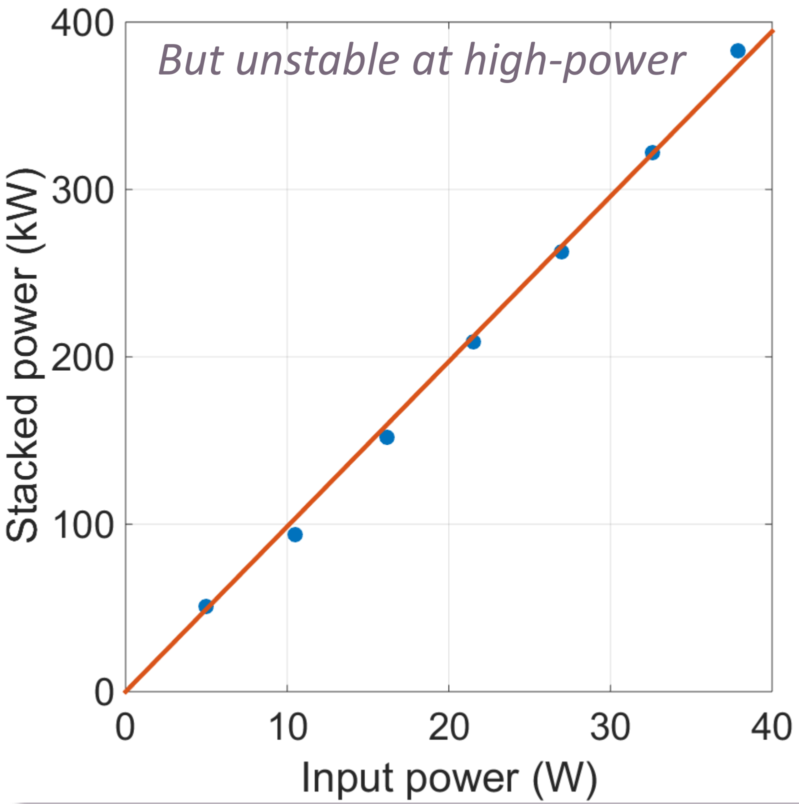
- Temporal superposition $2L/c=F_{rep}$
- Transverse mode matching

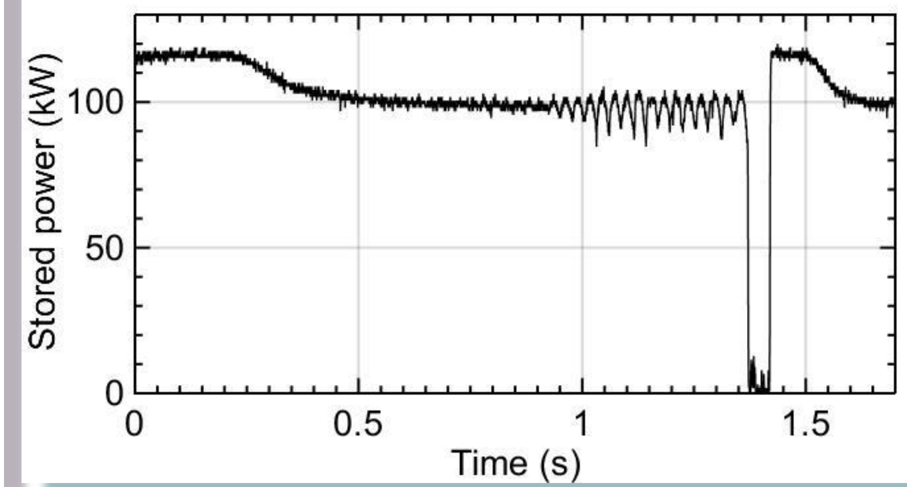


Resonate at different cavity lengths*

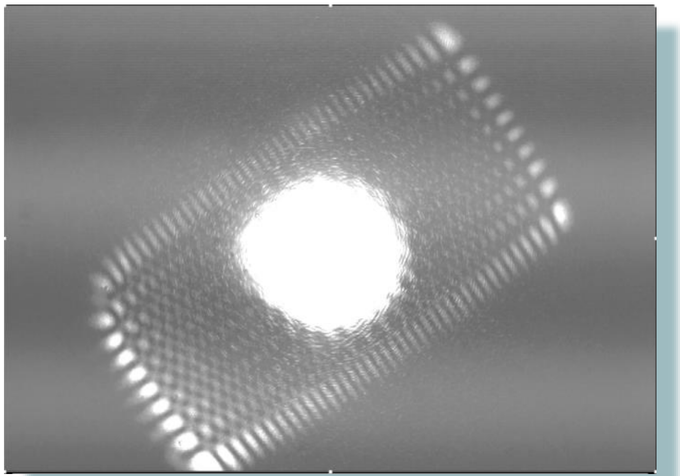
*for a non-degenerate cavity

High-order mode instability



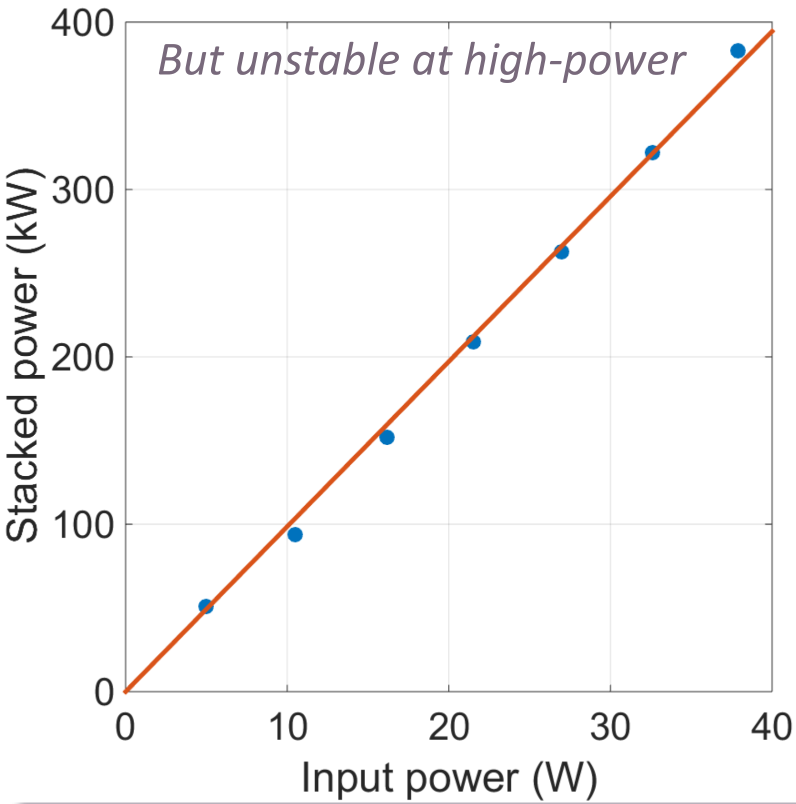


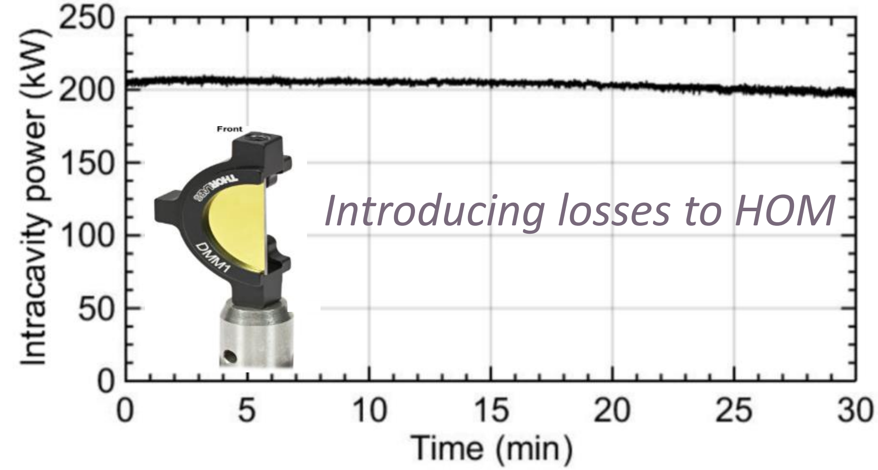
High-order mode instability



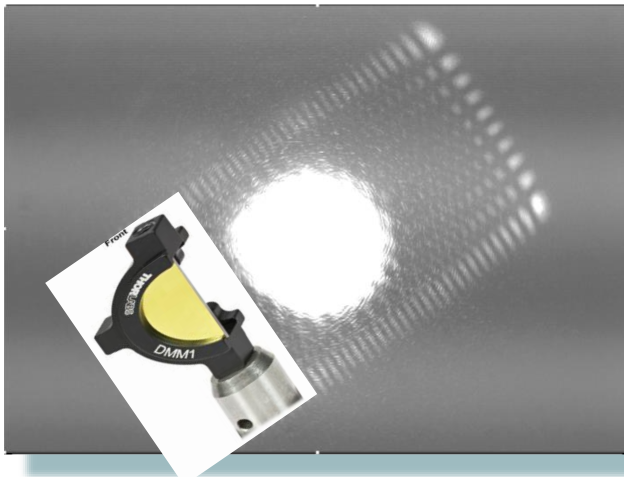
Favier P., Amoudry L. & H. Wang, PhD theses; Amoudry L. et al., Applied Optics 59(2020)116

Stable 200kW





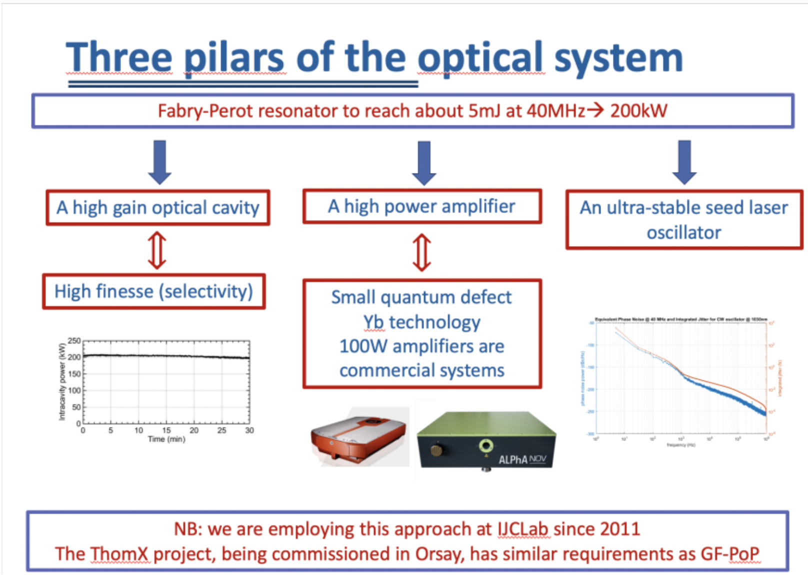
High-order mode instability



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

Favier P., Amoudry L. & H. Wang, PhD theses

Conclusion/Prospects



Know-how exists for this state of the art optical system

Main open points are :
- Stable laser beam transport
- operations (robustness, remote)

Selection of oscillator provider
Careful phase noise measurements

Decide on amplification techno
Cost vs R&D and robustness

Investigate modal instabilities
Max power in cavity

System robustness
Extensive stress tests
Remote operation of system