R&D on optical resonators : storing several hundreds kW of laser power in high-finesse optical cavities

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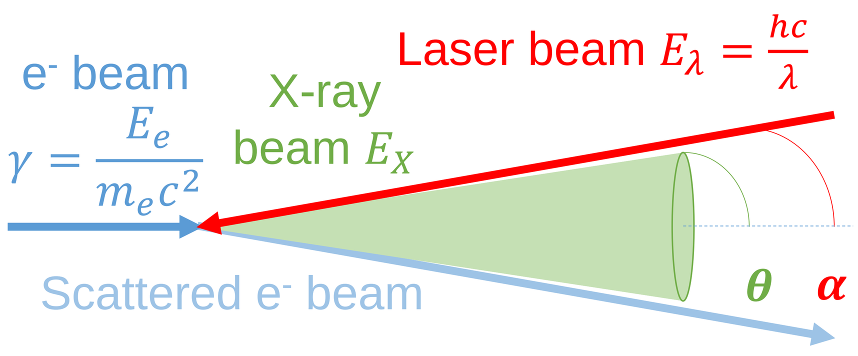
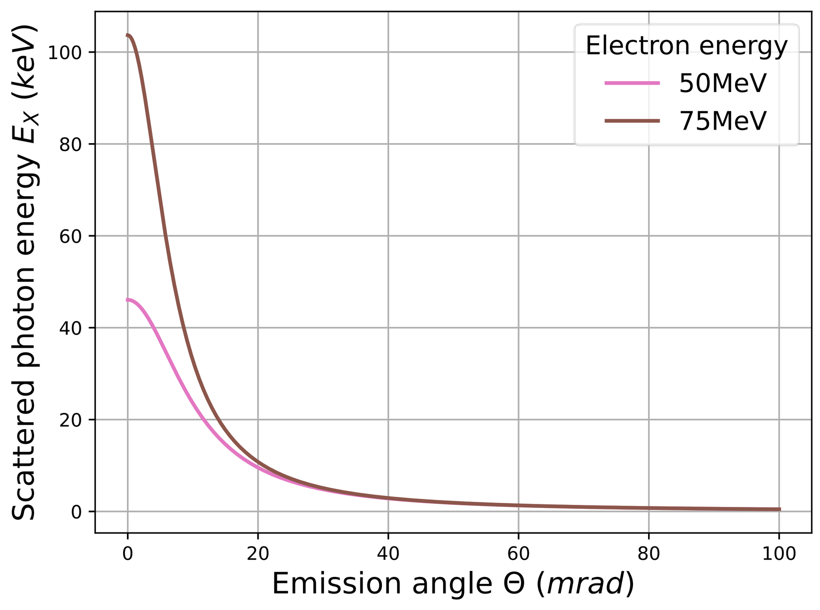
IJCLab's Laser-Electrons Interaction group has been developing high-gain, high-average power (several hundreds kW) optical cavities operated in pulsed regime. The main application of this technology is the production of highly monochromatic X-ray beams through inverse Compton scattering[1, 2]. The storing of such optical powers remains challenging, namely regarding the seeder laser's phase noise, the mirrors' coatings and the management of thermal effects, but new records were recently set in both pulsed[3, 4] and CW regimes, which could enable new applications.

Compton scattering[1, 2]



$$E_X \simeq E_\lambda \frac{2\gamma^2(1-\cos\alpha)}{1+\gamma^2\theta^2}$$

$$E_{X,max} \simeq E_\lambda \times 4\gamma^2$$

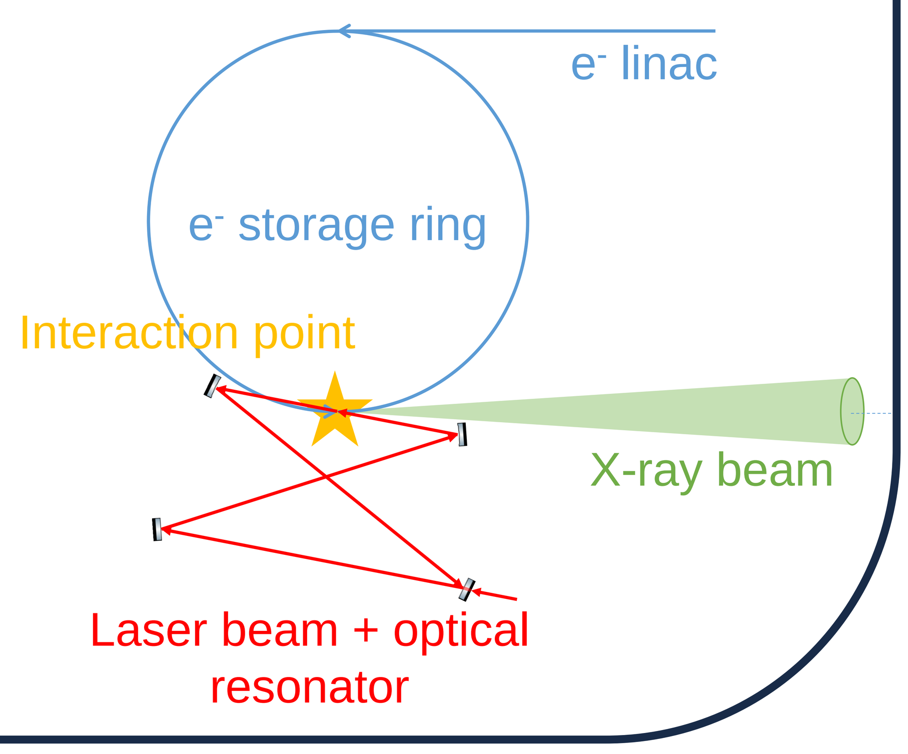


$\lambda = 1030nm \rightarrow E_\lambda = 1.2eV$

Inverse Compton Sources[1, 2]

ThomX @ IJCLab[2] **:**

- $\lambda = 1030nm \rightarrow \boldsymbol{E_\lambda = 1.2eV}$
- $\boldsymbol{E_e = 50 - 70MeV}$
- $\boldsymbol{E_X = 45 - 90keV}$
- **Flux : 10^{11}-10^{13} ph.s^{-1}**



One can maximize the X-ray flux only by **maximizing the laser average power** → use of an **optical resonator (optical enhancement cavity)**.

High intracavity power experiment at Tsinghua University (Beijing, China) (CW regime)

Experimental setup

- $L_1 = 833mm$
- $L_2 = 910mm$
- $L_3 = 1020mm$
- $L_4 = 948mm$

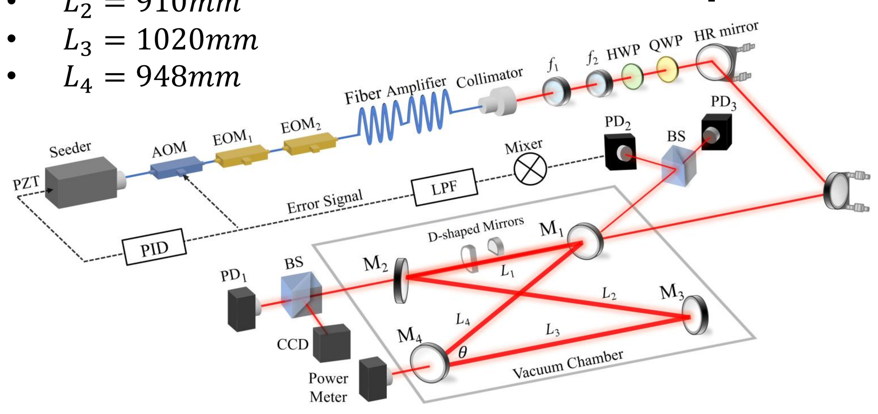
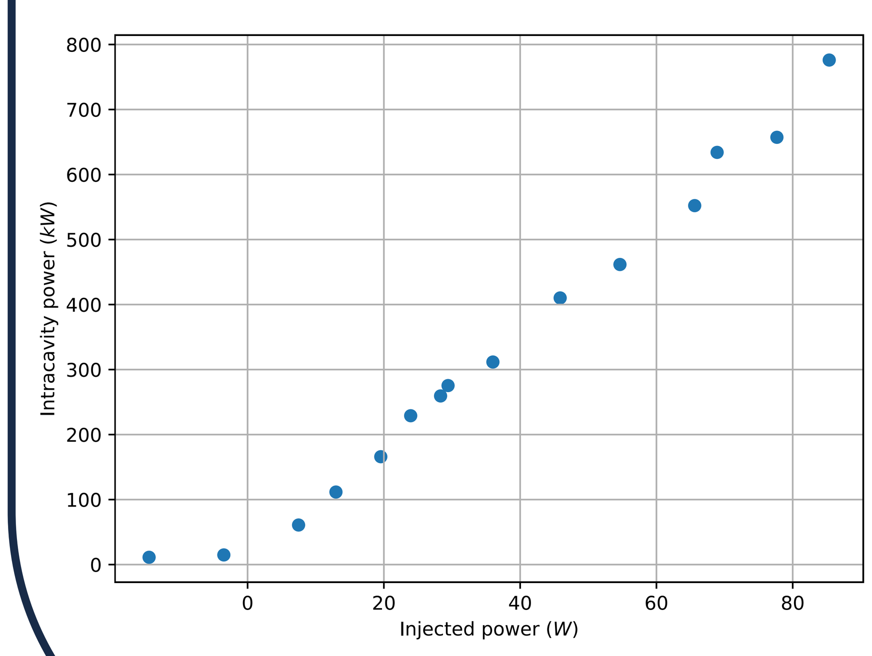


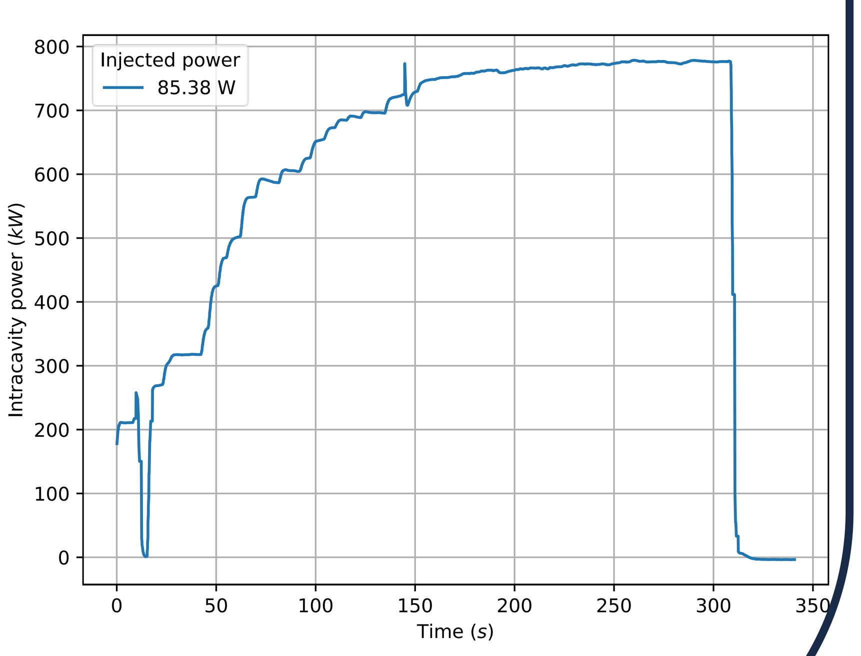
Image source : Tsinghua University

- $FSR \simeq 80.92MHz$ ($L \simeq 3.7m$)
- Measured linewidth : $\Delta\nu \simeq 3.4kHz$
- **Finesse : $F \simeq 26,000$** ($F_{th} = 32,000$)
- **Enhancement factor : $G \simeq 9,000 - 12,000$** ($G_{th} = 17,500$)
- $\lambda = 1064nm$

Results

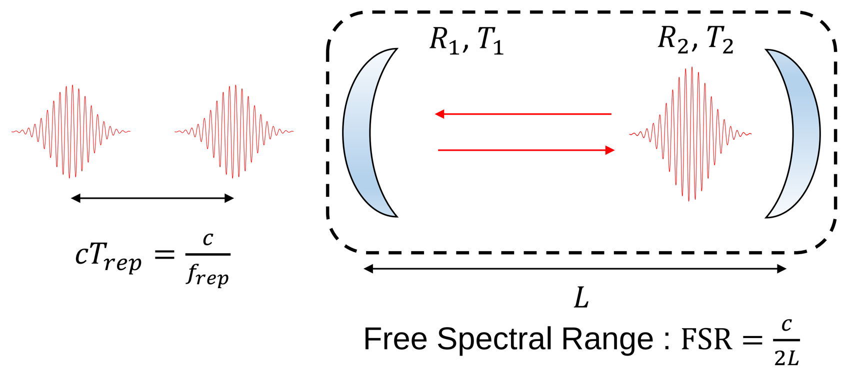


Intracavity power and gain



Temporal stability of the intracavity power

Optical resonators : optical enhancement cavities (pulsed regime)[1]



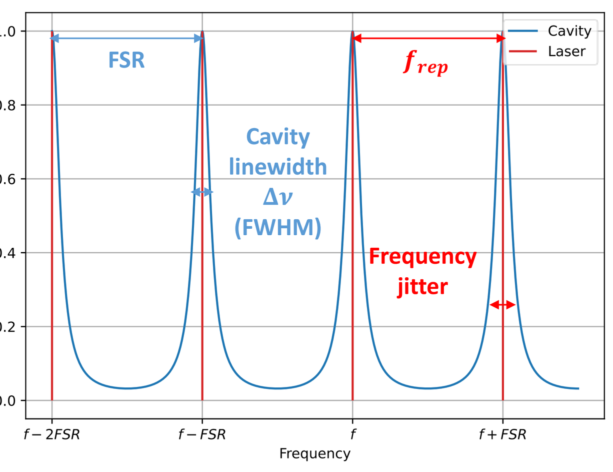
R : power reflection coefficient
T : power transmission coefficient

- Finesse : $F = \frac{\mathrm{FSR}}{\Delta\nu} = \frac{\pi(R_1R_2)^{\frac{1}{4}}}{1-(R_1R_2)^{\frac{1}{2}}}$
- Enhancement factor : $G \simeq \frac{T_1F^2}{\pi^2(R_1R_2)^{\frac{1}{2}}}$
- Intracavity power : $P_{cavity} = G \times P_{incident}$

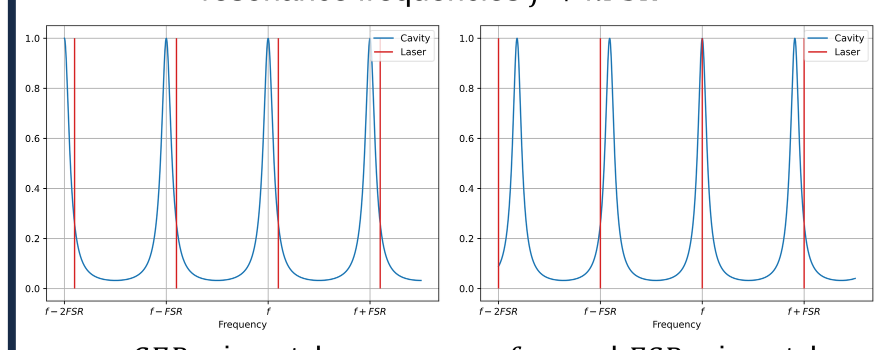
Laser-cavity coupling[1, 3, 4]

Temporal coupling (pulsed regime)

- Combs lines spacing matching : $f_{rep} = FSR$
- Combs positions matching : carrier envelope phase (CEP)



Seeder laser's spectrum and cavity's resonance frequencies $f + nFSR$



CEP mismatch　　f_{rep} and FSR mismatch

Spatial coupling

Make the cavity mode's and the laser's waist positions and sizes match by means of a 2-lense telescope.

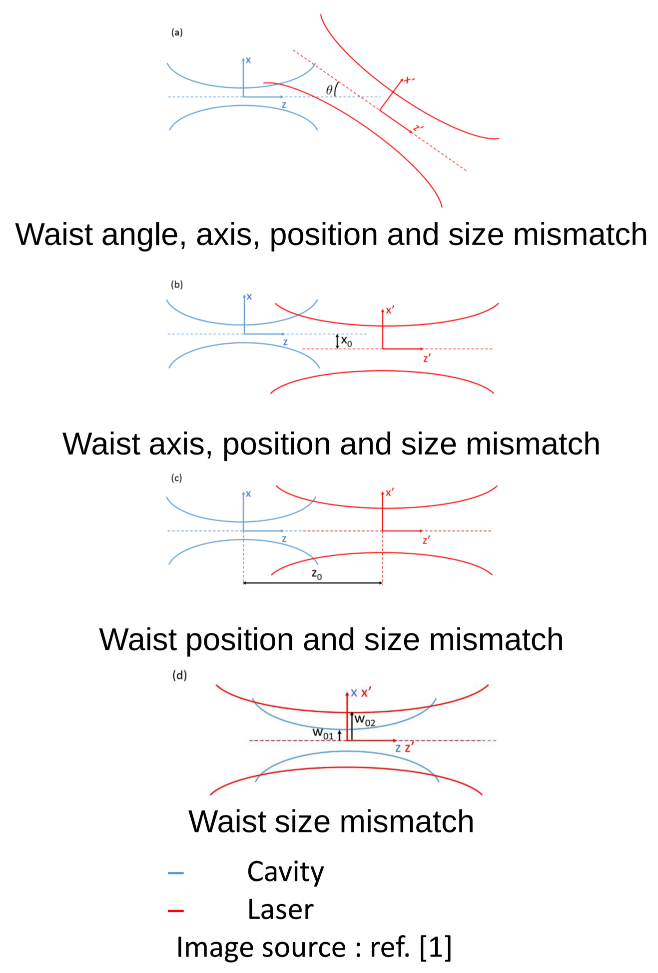


Image source : ref. [1]

Some challenges[1, 3, 4, 5]

- **Seeder laser phase noise** : frequency jitter $\leq \Delta\nu$ ($\simeq$ a few kHz). $1\mu m$ CW laser optical frequency $\simeq 300THz$ → very low phase noise
- **Mirrors surface** : high reflectivity, low absorption and scattering
- **Thermal effects** with a high intracavity power → changes in the mirrors' radii of curvature → changes in the cavity's transverse mode(s) and in the cavity's resonance frequencies → coupling losses

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- **Maximum stored power in pulsed regime (IJCLab)** : **$710kW$ for a $47.5W$ input** in a 2-mirror cavity[3] and **$550kW$ for a $75W$ input** in a 4-mirror bow-tie cavity[4] (stable for $\geq$ 10 minutes with a relative standard deviation $\leq 0.6\%$ in both cases) in 2024
- **Maximum stored power in CW regime (Tsinghua University)** : **$780kW$ for a $85W$ input** in April 2025 (stable for 2 minutes with a relative standard deviation $\leq 0.6\%$) and **$\geq 800kW$ for a $\simeq 100W$ input** (stable for 1 minute) in a 4-mirror bow-tie cavity in June 2025
- **Current applications** : gravitational waves detectors (LIGO, VIRGO[6]), high-harmonic generation, X-ray production[1, 2]
- **Potential future applications** : steady-state microbunching of electrons for the production of high-power and high-repetition rate EUV beams for EUV lithography, photoneutralization of negative hydrogen and deuterium ion beams for nuclear fusion experiments

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