

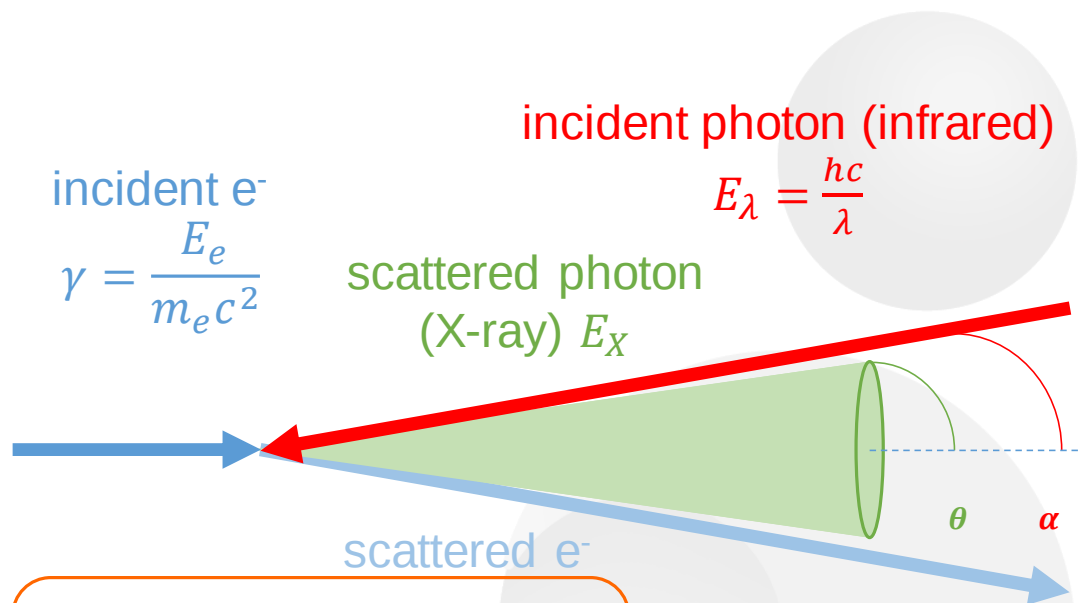
Design of a Fabry-Perot optical resonator for the storage of several hundreds kW and the interaction with particle beams : application to the PERLE ERL case

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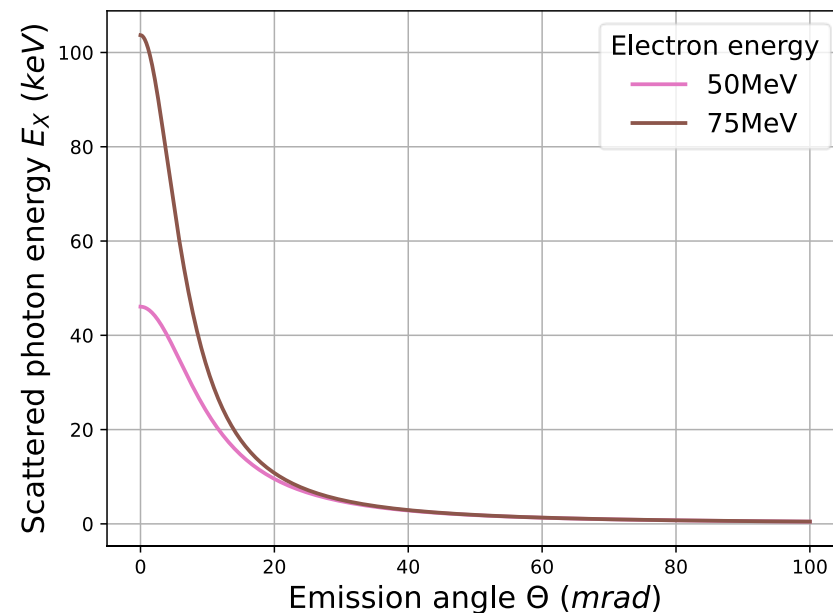
Journées “Accélérateurs” de la Société Française de Physique



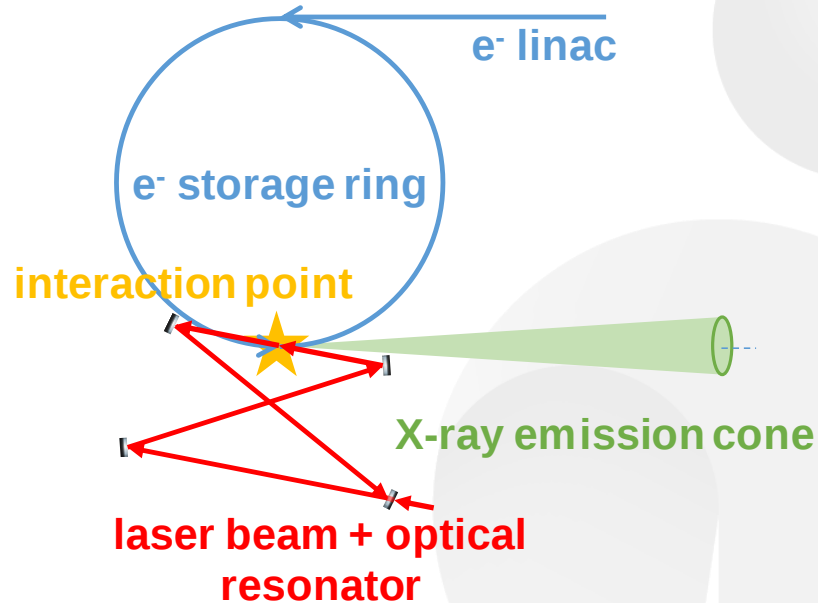
Inverse Compton scattering



$$E_X \simeq E_\lambda \frac{2\gamma^2(1 - \cos \alpha)}{1 + \gamma^2 \theta^2}$$
$$E_{X,max} \simeq E_\lambda \times 4\gamma^2$$



$$\lambda = 1030 \text{ nm} \rightarrow E_\lambda = 1.2 \text{ eV}$$



- Very small cross-section of the inverse Compton scattering process ($\approx 0.6 \text{ barn}$)
- Maximization of the X-ray flux
- Fixed e⁻ beam parameters
- **Very high average laser power needed : $\geq 100 \text{ kW}$**

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- X-ray energy : **45-90 keV**
- X-ray flux : **10^{11} - $10^{13} \text{ ph.s}^{-1}$**

• PERLE specifications :

- Space requirements

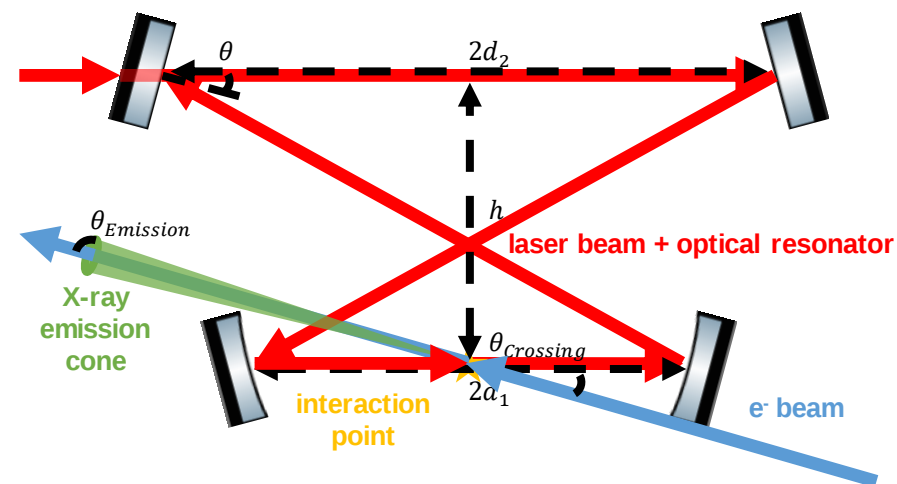
→ Choice of $f_{rep} \rightarrow L_{cav}, d_1, d_2, h, \theta_{crossing}$

• X-ray flux maximization :

- X-ray flux maximization without geometrical coupling
- Geometrical maximization
- Accounting for thermal effects → minimization of the flux and coupling losses due to changes in the fundamental transverse eigenmode of the cavity

→ Choice of R

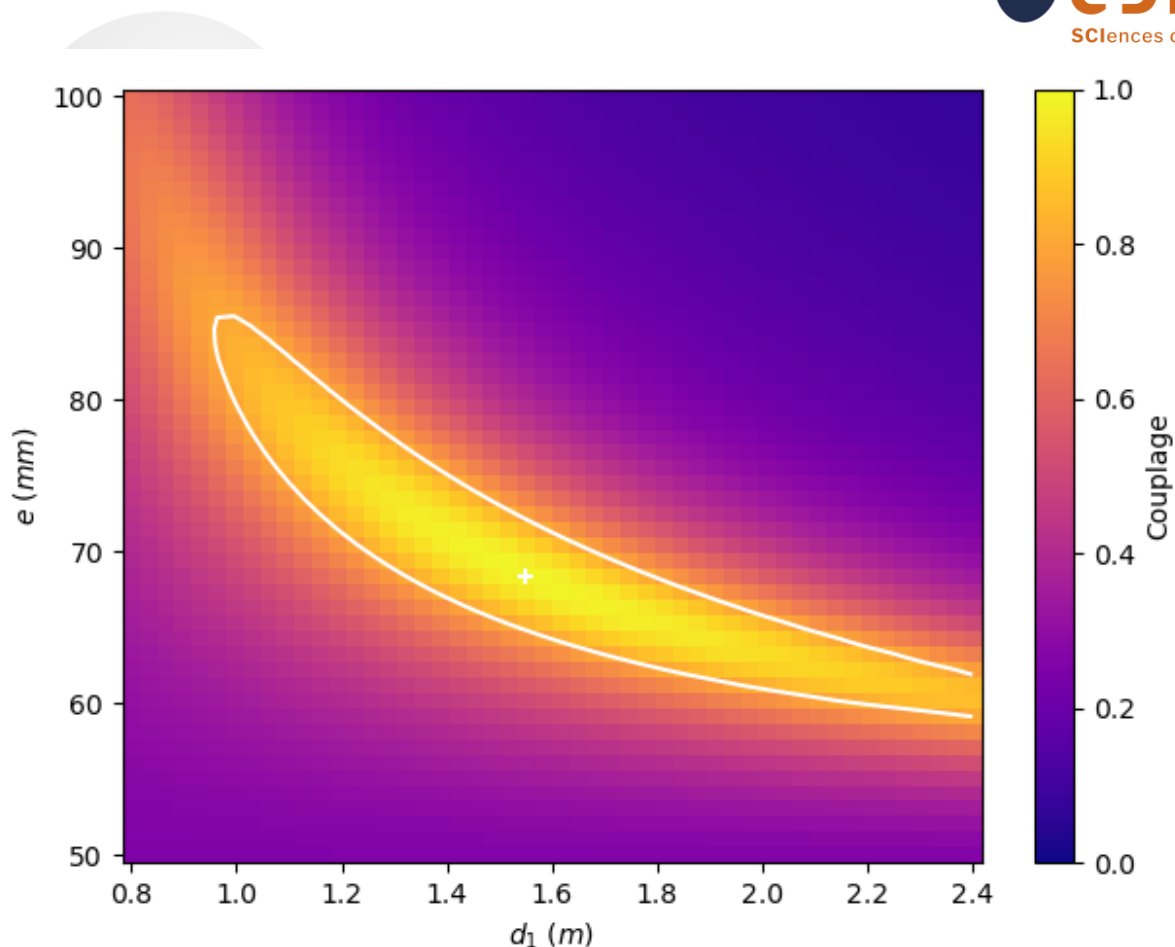
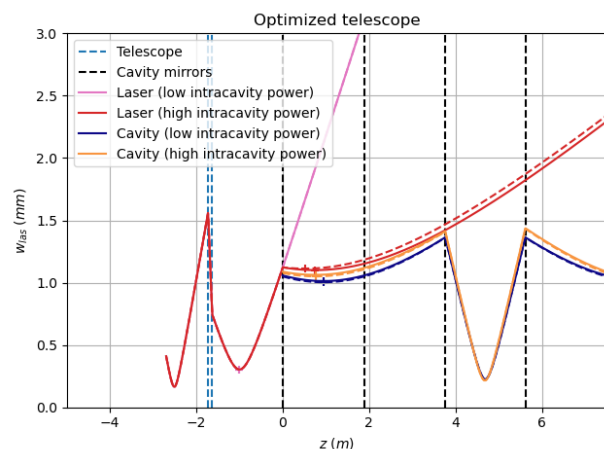
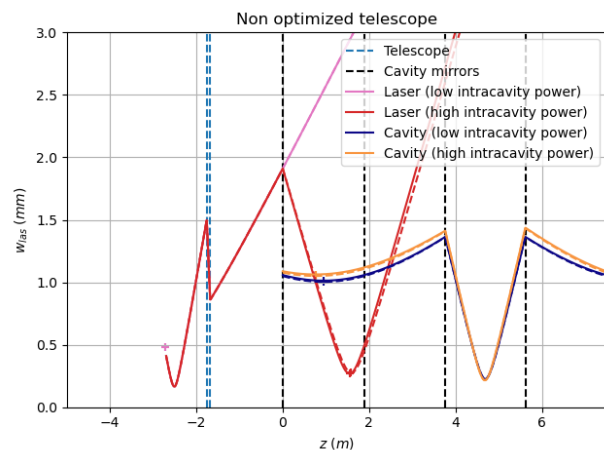
→ Telescope design





Design of a 515nm cavity for the PERLE ERL

- Design of a telescope :





Conclusion

- Design of a cavity for X-rays production with the PERLE ERL :
- Design of a cavity
- Design of a telescope
- Accounting for thermal effects occurring at a high intracavity power

→ Contribution to the Technical Design Report

→ Experimental R&D with these cavities

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

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UCLab'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 seed laser's phase noise, the mirrors' coatings and the management of thermal effects, but new records were recently set in both pulsed^{1,2} and CW regimes, which could enable new applications.

Compton scattering^{1,2}

$E_s = \frac{E_e}{1 + \frac{E_e}{m_e c^2}(1 - \cos \theta)}$

$E_{s,max} = \frac{2\gamma^2(1 - \cos \theta)}{1 + \gamma^2(1 - \cos \theta)}$

$E_{s,max} \approx E_e \times \frac{4\gamma^2}{1 + \gamma^2}$

$\lambda = 103.0 \text{ nm} \rightarrow E_s = 1.2 \text{ eV}$

Inverse Compton Sources^{1,2}

ThomX @ UCLab^{1,2}

- $\lambda = 103.0 \text{ nm} \rightarrow E_s = 1.2 \text{ eV}$
- $E_e = 50 - 70 \text{ MeV}$
- $E_s = 45 - 90 \text{ MeV}$
- Flux : $10^{11} - 10^{13} \text{ ph.s}^{-1}$

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

Optical resonators : optical enhancement cavities (pulsed regime)¹

- Finesse : $F = \frac{4\pi}{\lambda} \frac{L}{\Delta \nu}$
- Enhancement factor : $G = \frac{F^2}{4}$
- Intracavity power : $P_{\text{cavity}} = G \times P_{\text{incident}}$

Laser-cavity coupling^{1,3,4}

Temporal coupling (pulsed regime)

- Combs lines spacing matching : $\Delta \nu_{\text{cav}} = FSR$
- Combs positions matching : carrier means of a 2-lense telescope

Spatial coupling

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

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

Experimental setup

- $\lambda = 103 \text{ nm}$
- $L = 10 \text{ cm}$
- $\Delta \nu = 10 \text{ MHz}$
- $\Delta \nu = 10 \text{ MHz}$
- $FSR = 80.92 \text{ MHz} (L = 3.37 \text{ m})$
- Measured finesse : $\Delta \nu = 3.4 \text{ kHz}$
- Finesse : $F = 26,000 (F_{10} = 32,000)$
- Enhancement factor : $G = 9,600 - 12,500 (G_{10} = 17,200)$
- $\lambda = 104 \text{ nm}$

Image source : Tsinghua University

Results

Some challenges^{1,3,4,5}

- Seed laser phase noise : frequency jitter $\leq 1 \text{ sr}$ (a few kHz), 1 μm CW laser optical frequency = 300 THz → 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

Maximum stored power in pulsed regime (UCLab) : 710 kW for a 4-mirror bow-tie cavity¹ (stable for ≥ 10 minutes with a relative standard deviation $\leq 0.6\%$ in both cases) in 2024

Maximum stored power in CW regime (Tsinghua University) : 780 kW for a 85W input in April 2025 (stable for 2 minutes with a relative standard deviation $\leq 0.6\%$) and $\geq 800 \text{ kW}$ for a $\geq 100 \text{ W}$ input (stable for 1 minute) in a 4-mirror bow-tie cavity in June 2025

Current applications : gravitational waves detectors (LIGO, VIRGO), 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, photoionization of negative hydrogen and deuterium ion beams for nuclear fusion experiments

References

1. C. Dupraz, "Design of optical resonators for high-power laser beams for the next generation of X-ray FELs", PhD thesis, Université Paris-Saclay, 2017.
2. C. Dupraz, "Production of X-ray beams for the next generation of X-ray FELs", PhD thesis, Université Paris-Saclay, 2017.
3. C. Dupraz, "Thermal effects in optical resonators for high-power laser beams", PhD thesis, Université Paris-Saclay, 2017.
4. C. Dupraz, "Thermal effects in optical resonators for high-power laser beams", PhD thesis, Université Paris-Saclay, 2017.
5. C. Dupraz, "Thermal effects in optical resonators for high-power laser beams", PhD thesis, Université Paris-Saclay, 2017.



Thank you for your attention

Any questions ?