Study and conception of a high finesse Fabry-Perot cavity for the compact X-ray source ThomX

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The ThomX project

ThomX is a compact X-ray source, more accessible and cheaper than today's synchrotrons, able to deliver a higher photon flux than the machines currently available in hospitals.

X-rays are produced by a high average power pulsed laser by Compton back-scattering off electrons. The installation is planned to start in 2016 and the first lights will be delivered to users in 2017-2018.

Applications

Medicine

- Radiotherapy
- Tomography
- Mammography

Materials

- Art history
- R&D on polymers

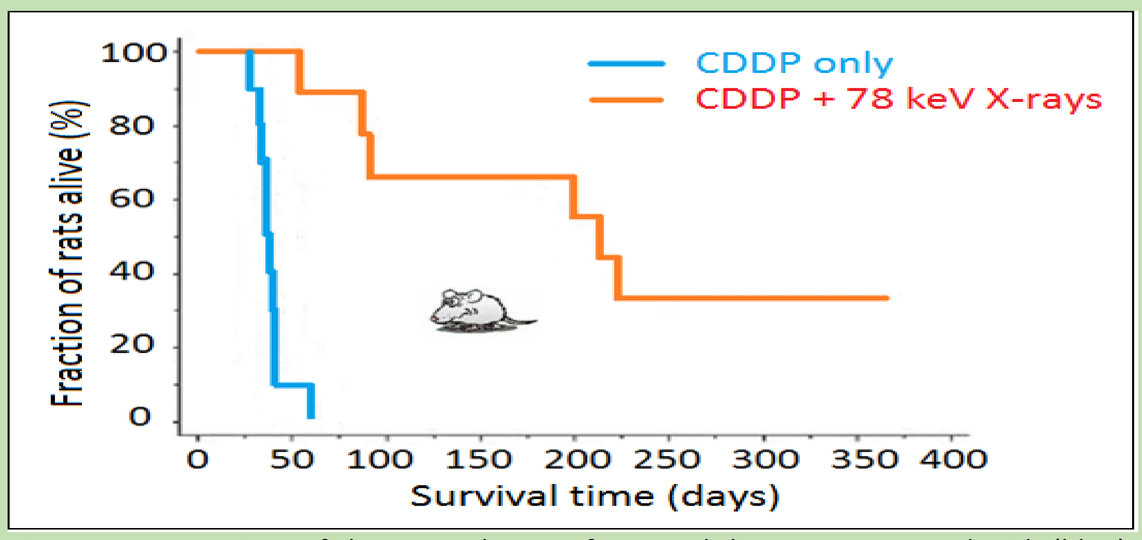


Figure 1: Comparison of the survival time of rats with brain cancer cured with (blue) cis-diamminedichloroplatinum (CDDP), a pharmaceutical drug; (red) same plus a 15 Gy dose of 78 keV X-rays.
Marie-Claude Biston et al. *Cancer Res* 2004;64:2317-2323

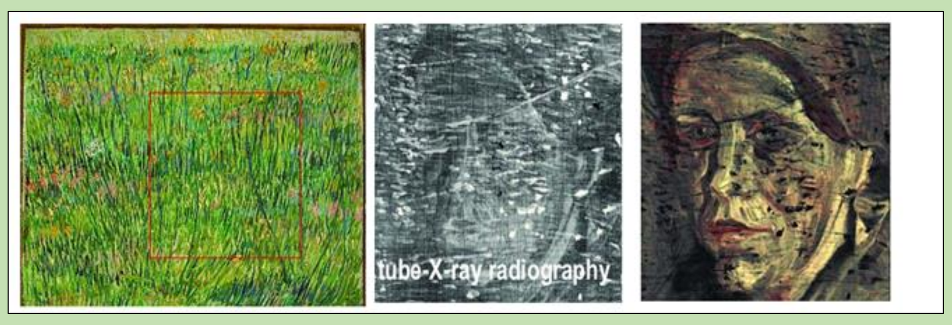
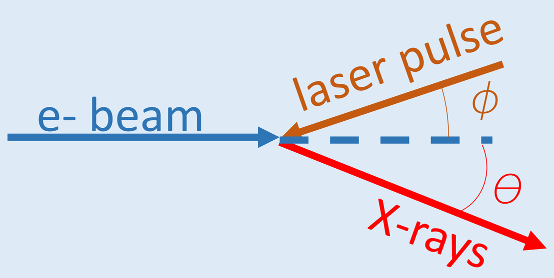


Figure 2: X-rays scan of a Van Gogh painting. A hidden face is found behind the grass.
Joris Dik et al. *Analytical Chemistry* 2008 *80* (16), 6436-6442

Inverse Compton Scattering



$$E_X \simeq h\nu \frac{4\gamma^2}{1+\gamma^2\theta^2+\frac{\phi^2}{4}}$$

E_x	Energy of the X-rays
$h\nu$	Energy of one laser photon
γ	Lorentz factor of the electrons beam
θ	Scattering angle
ϕ	Crossing angle

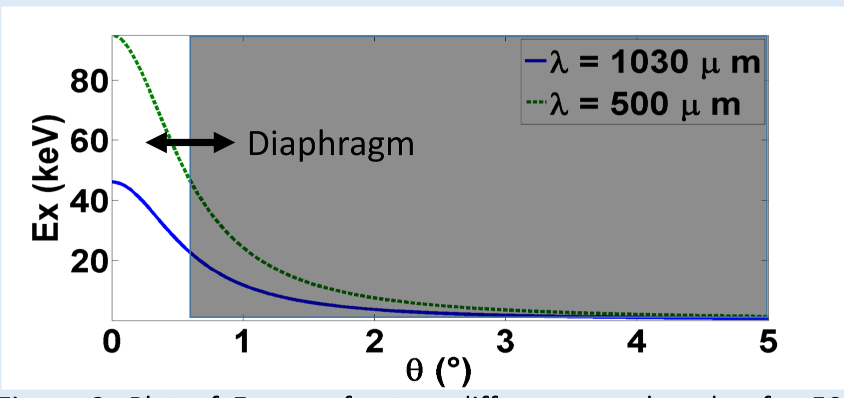


Figure 3: Plot of E_x vs θ for two different wavelengths, for 50 MeV electrons and ϕ = 1°. X-rays energy tunable with a simple diaphragm.
Peskin, M. E. & Schroeder, D. V. (1995), *An Introduction To Quantum Field Theory (Frontiers in Physics)*, Westview Press

The machine

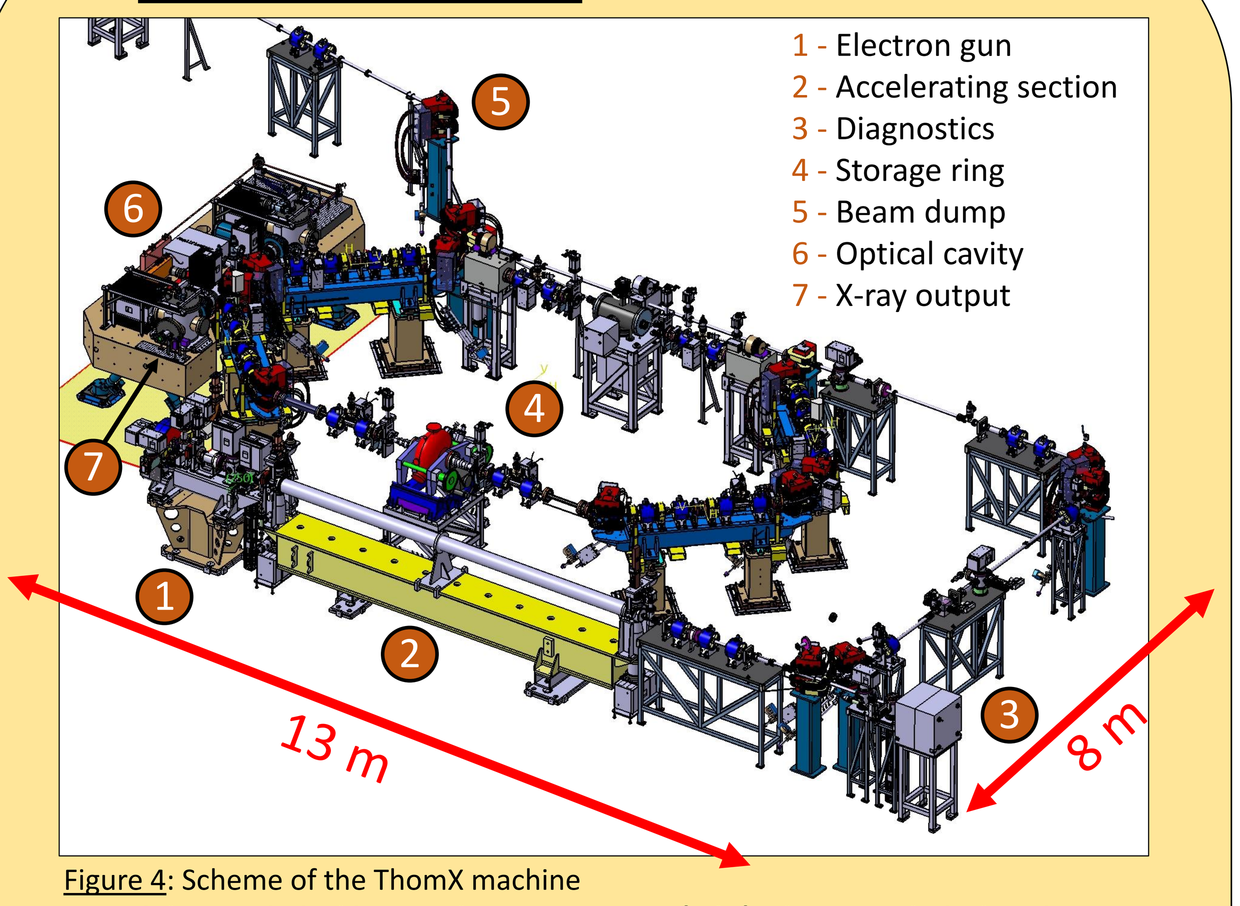


Figure 4: Scheme of the ThomX machine
A. Variola, J. Haissinski, A. Loulergue, F. Zomer, (eds). ThomX Technical Design Report. 2014

Storage ring parameters	Values
Electrons bunch energy	50 – 70 MeV
Electrons bunch length	30 ps
Electrons bunch charge	1 nC
Ring circumference	16.8 m
Revolution frequency	16.7 MHz

The optical system

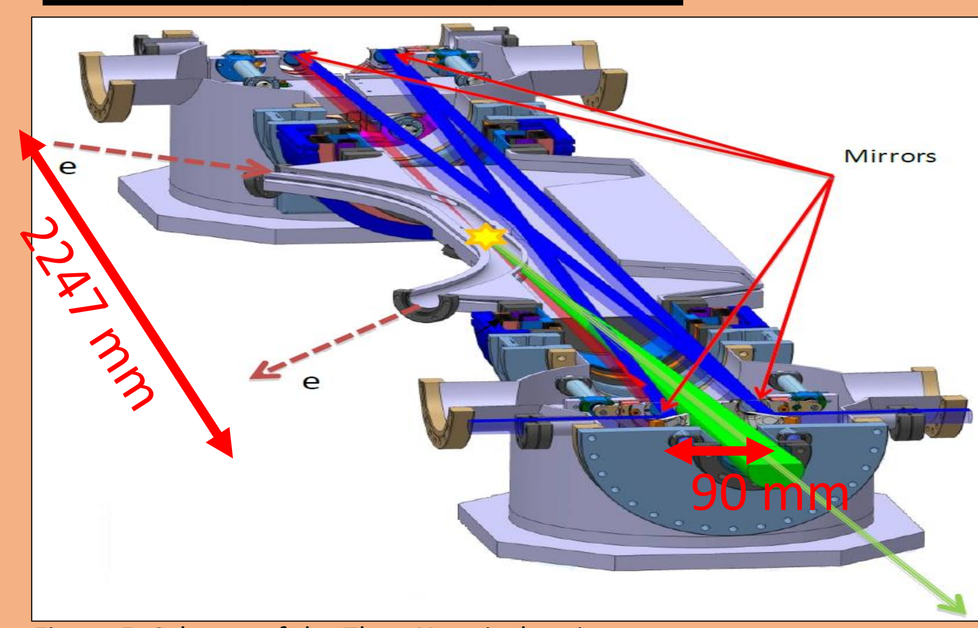


Figure 5: Scheme of the ThomX optical cavity
A. Variola, J. Haissinski, A. Loulergue, F. Zomer, (eds). ThomX Technical Design Report. 2014.

Parameters	Typical values
Laser repetition frequency	33.3 MHz
Laser wavelength	1031 nm
Laser pulse temporal length	50 ps rms
Cavity optical length	8.994 m
Cavity finesse	30 000
Cavity waist size	80 μm
Injected power	100 W
Circulating power	600 kW
X-rays flux	10^{13} photons/s

Performance limitations: intra-cavity thermal effects

Heat loads on mirrors

- Reflective surface deformation
- Thermal lensing

Impact

- Laser/cavity coupling deteriorated
- Cavity/electrons coupling deteriorated
- X-rays flux lowered

Simulation have shown

- Crucial choice of the material substrate: ULE chosen
- Need careful design of the mirrors' mountings
- Cavity circulating beam size largely affected by surface deformations

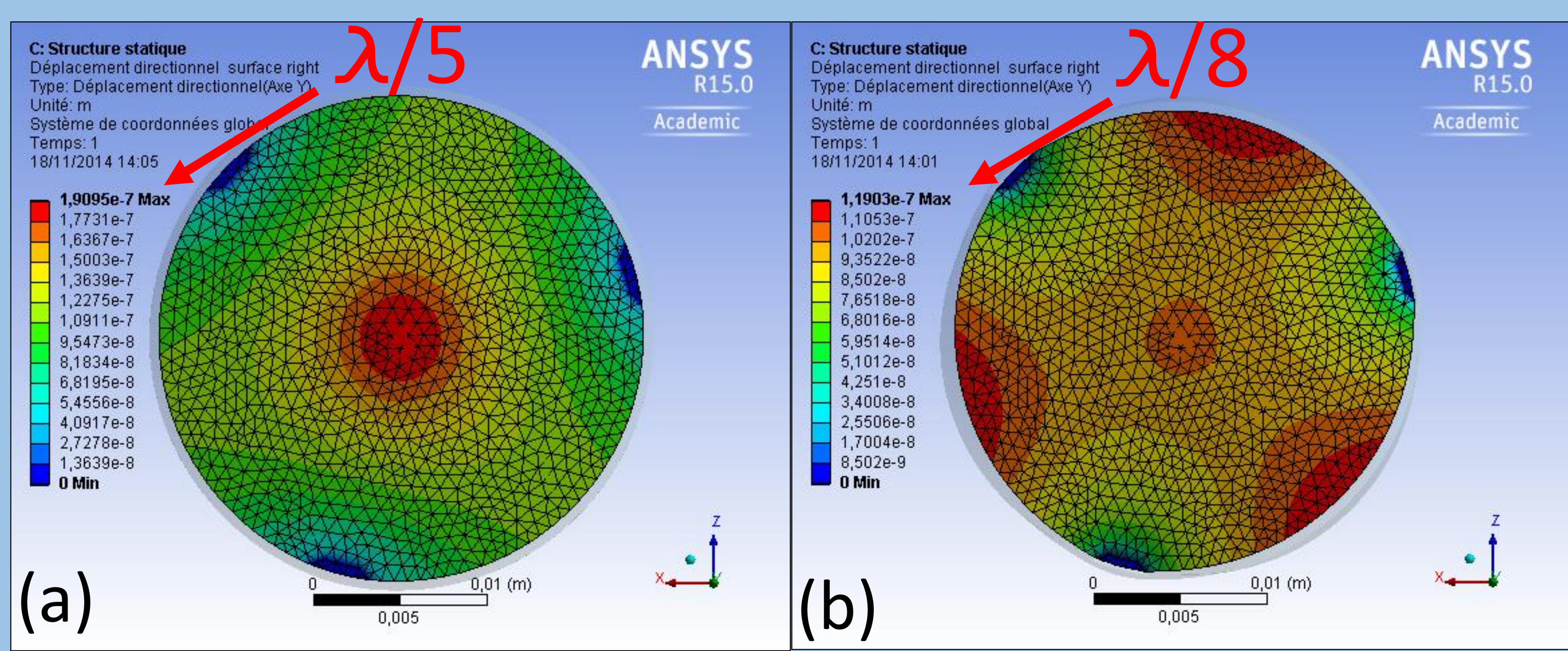


Figure 6: Simulation of surface deformation with ANSYS for 1 MW circulating power for (a) HERAEUS Suprasil, (b) CORNING ULE. Mirrors were initially flat. The two materials exhibit different deformation amplitudes and patterns.
ANSYS® Academic Research, Release 15.0
For ULE performances on optical cavities, see **H. Carstens et al., "Cavity - Enhanced 196 kW Average - Power Infrared Pulses" *Advanced Solid-State Lasers Congress*, 2013**

Change in curvature depth at one beam radius from the center
W. Winkler et al. *Phys. Rev. A* **44**, 7022

$$\delta s \approx \frac{\alpha}{4\pi\kappa} a_c P_{circ}$$

Coating abs : 1ppm

	α (10^{-7} K^{-1})	κ (W/m/K)	$\delta s/\delta s_{ULE}$
Fused Silica	5.5	1.31	57.6
Suprasil	5.1	1.38	50.7
ULE	0.1	1.38	1

The prototype

- Test simulation results on thermal effects
- Mirror surface monitoring with a wavefront sensor
- Real-time coupling enhancement with adaptive optics
- Real-time finesse measurement with parallel CW laser injection

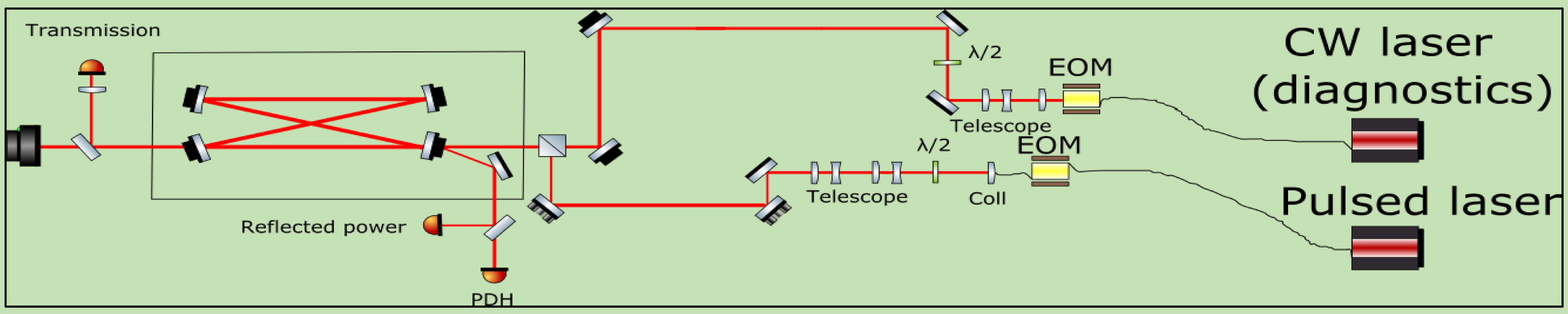


Figure 9: Setup of the protoype injection lines for the real-time Finesse measurement

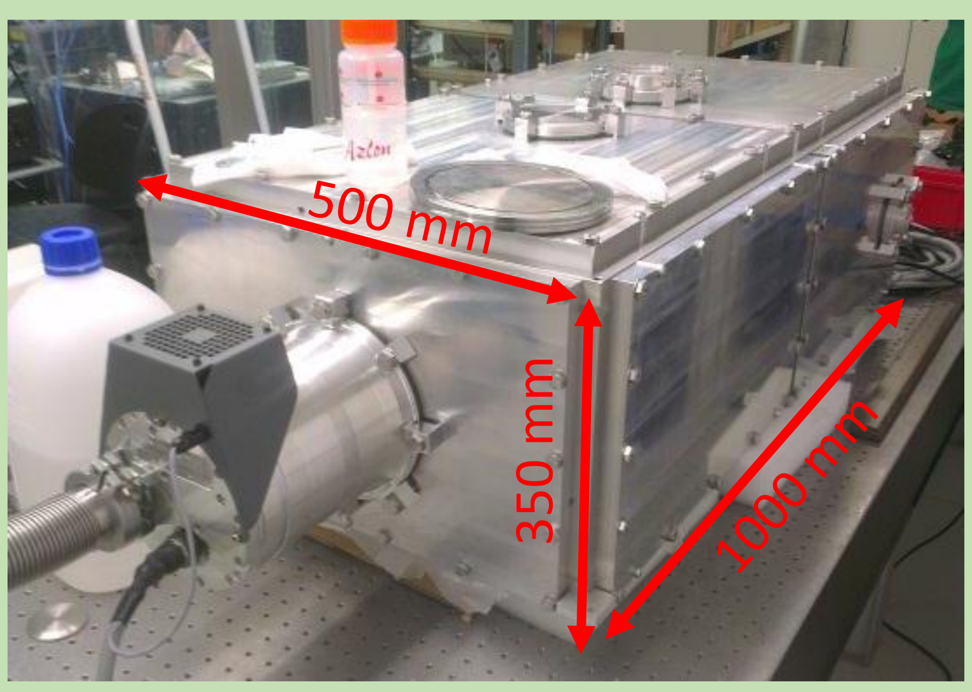


Figure 7: Prototype vacuum chamber

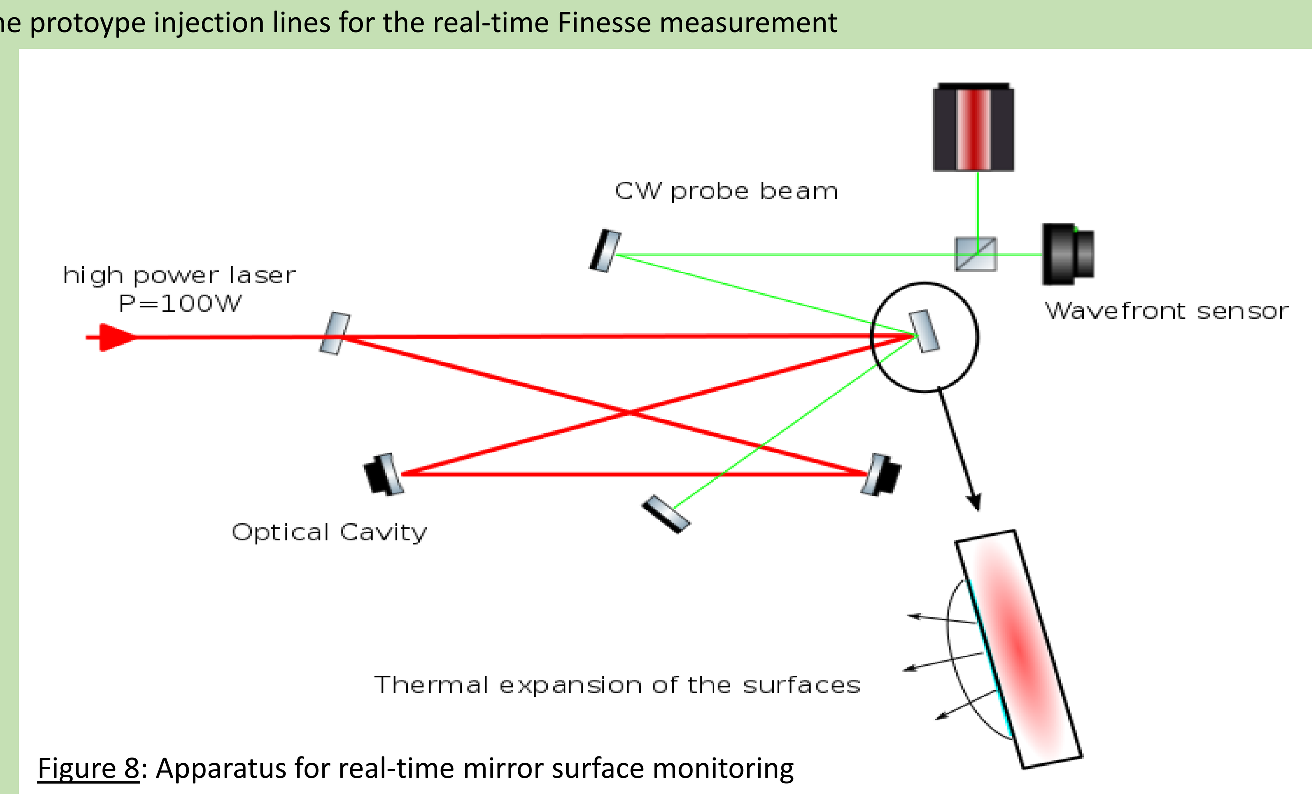


Figure 8: Apparatus for real-time mirror surface monitoring

Conclusions

ThomX goals

- Unique light source for societal applications
- High X-rays flux

Extensive R&D on optical cavities in the pulsed regime

- Large thermal effects
  - ULE substrates
  - Adaptive optics
- Real-time monitoring
  - Finesse
  - Wavefront (phase is also critical)