Silica final lens performance in laser fusion facilities: HiPER and LIFE

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Outline

- Motivation.
- Chamber design
- Radiation fluxes at final lenses
- Thermo-mechanical performance
- Color center formation and optical properties (absorption)
  - Steady-state operation
  - Reactor startup.
- Conclusions.

Motivation

- Fusion energy is foreseen to become within the next two decades in a real alternative to fossil fuels-
- Nowadays, with NIF in the last optimization stages to demonstrate ignition with energy gain → increasing interest in Inertial fusion
  - High Power Laser Energy Research (HiPER):Europe
  - Laser Inertial Fusion Energy (LIFE): USA

	HiPER Exp.	**HiPER Prot.**	**HiPER Demo.**	**LIFE.2**
Operation	Bunches of 100 shots, max. 5 DT explosion	Continuous (24/7)	Continuous (24/7)	Continuous (24/7)
Yield (MJ)	<20	<50	>100	132
Rep. rate (Hz)	1-10	1-10	10-20	16
Power (GWt)	-	< 0.5	1-3	2.2
T cycle	No	Yes	Yes	Yes
Blanket	No	Yes	Yes	Yes

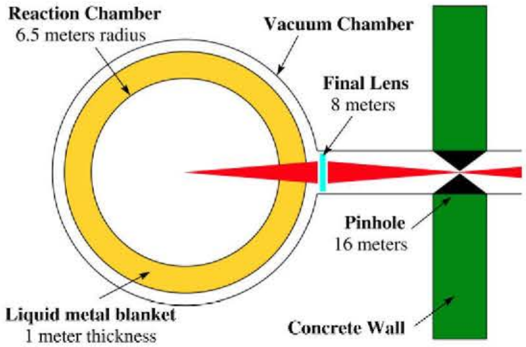
Motivation

- One of the main bottle neck for fusion to become a reality is the lack of materials able to withstand the harsh radiation environment (Thermal loads and atomistic damage).

- In particular in laser fusion the development of materials for **final optics** is a point of concern since **the ignition process itself depends on them.**

Reactor chamber designs

- HiPER chamber design is currently under way. Some advanced concepts have been already published.

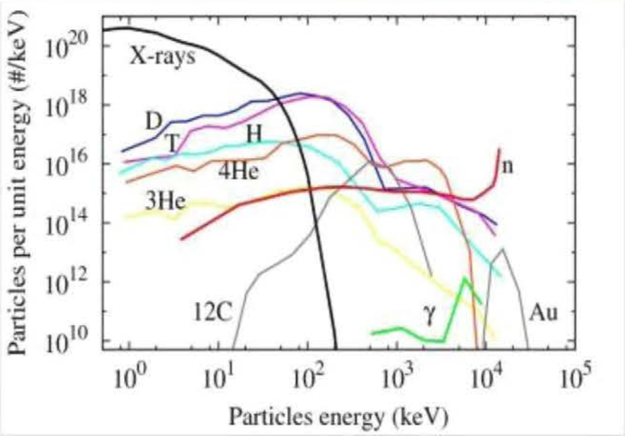


- **HiPER (prototype and demo):**
    - Chamber: 6.5 inner radious
    - Final lenses: cylinders (diameter 75 cm, thickness 5cm) 8 m far away from the center
- **LIFE2:**
    - Final lenses: cylinders (diameter >48 cm, thickness 0.5cm) 17 m far away from the center.

Radiation fluxes

•HiPER:
- •Direct drive
- •Dry wall

- 71% neutrons
- 28% ions
- 1% X-Rays



•LIFE:
- •Indirect drive
- •Dry wall + gas protection→ X-ray mitigation delaying of the order of μs the energy delivery to the walls.

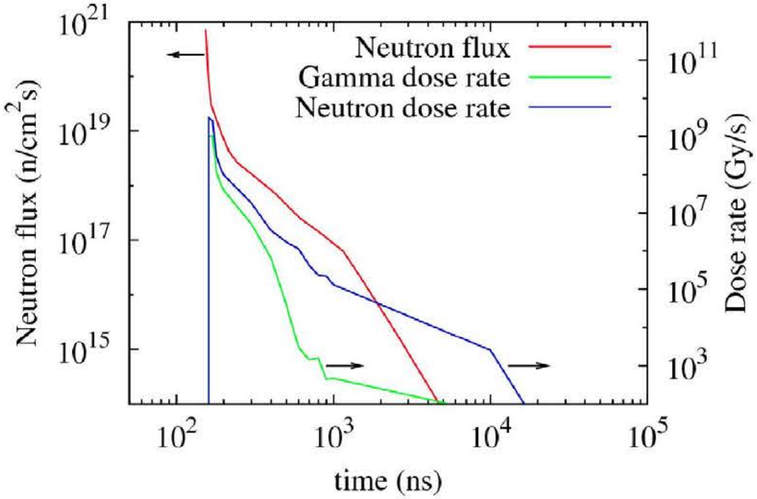
- 69% neutrons
- 6% ions
- 25% X-Rays

Final lenses: Direct particles stemming from the target explosion and indirect ones (scattered neutrons and γ-rays from the (n,γ) reactions)

Radiation fluxes: HiPER

•The neutron flux and neutron and γ-ray doses absorbed by the silica lenses in HiPER are accurately calculated as a function of time with MCNPX.

•The reactor geometry is designed with CATIA and converted with MCAM into a valid geometrical input for MCNPX. Mean free path for calculation are obtained from the ENDF-VII data base



•Final lenses are simultaneously subjected to neutron and gamma radiation pulses.

Radiation

	HiPER						LIFE. 2
	<E> (MeV)	Pulse width (ns)	Pen-depth (mm)	ED in exp. (J/cm^3)	ED prot- (J/cm^3)	ED demo (J/cm^3)	ED (J/cm^3)
Burnt products (^{4}He)	2.1	400	6.4	**492.0**	**3788.48**	**1230.03**	~0
Debris ions (D)	0.15	2200	1.4	**2549.08**	**19627.93**	**6372.7**	~0
X-rays	0.007	0.17	few10^3	33.91	261.11	84.78	~0
Neutrons	12.4	60	-	0.018	0.142	0.046	0.03
Indirect gammas	-	»60	-	0.007	0.051	0.017	0.012

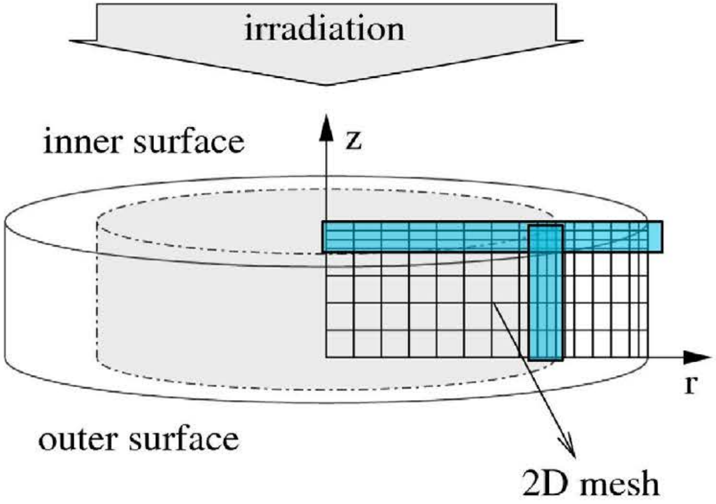
The energy density deposited by ions in HiPER prototype and demo is so high that it would drive to temperature enhancements higher than the Silica melting point→ For the lenses to work **ions must be somehow mitigated**

Thermomechanical response calculations

- The finite element solver CODE ASTER is used
- Lenses are considered to have a cylindrical geometry.
- To achieve a detailed estimation of the temperature gradients and local stresses, the mesh is refined with small elements of 100 nm.
- For temperature calculation, the lens surfaces are considered to emit radiation and the surrounding temperature is supposed to be constant.

Considerations:

- X-rays (even when very penetrating up to the cm range) deposit almost all their energy in the first few microns (<10 µm) near inner surface.
- Neutrons and gammas homogeneously deliver their energy along practically the whole lens volume.



Steady-state operation

•When working in continuous mode, the average lens temperature increases if the energy deposited during each pulse is higher than that radiated by the lenses surface.

•**Steady-state** is reached when the deposited energy and the radiated during one pulse are equal.

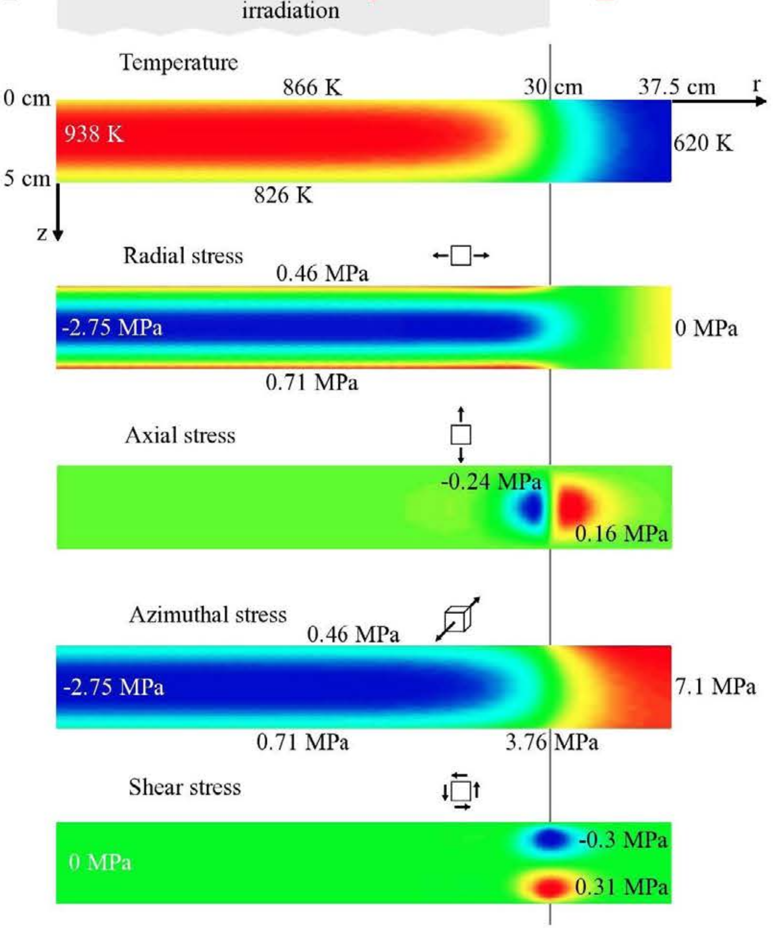
•HiPER prototype: 32.000 pulses

•HiPER demo: 25.000 pulses (~40 min- after the first shot)

•LIFE2: 18.000 pulses

Thermomechanical response: HiPER prototype

Temperature radial, axial, azimuthal and shear stresses at the end of each pulse **in steady-state operations** conditions for HiPER prototype



Thermal loads mainly due to X-rays.

In all cases the calculated stresses are observed to be lower than the silica tensile strength (48 MPa) → silica lenses can withstand the radiation-induced mechanical stresses

Thermomechanical response: HiPER demo

Even when disregarding ions, in HiPER demo the temperature enhancement at the inner surface is higher 1304 K than the silica melting temperature (1223 K).

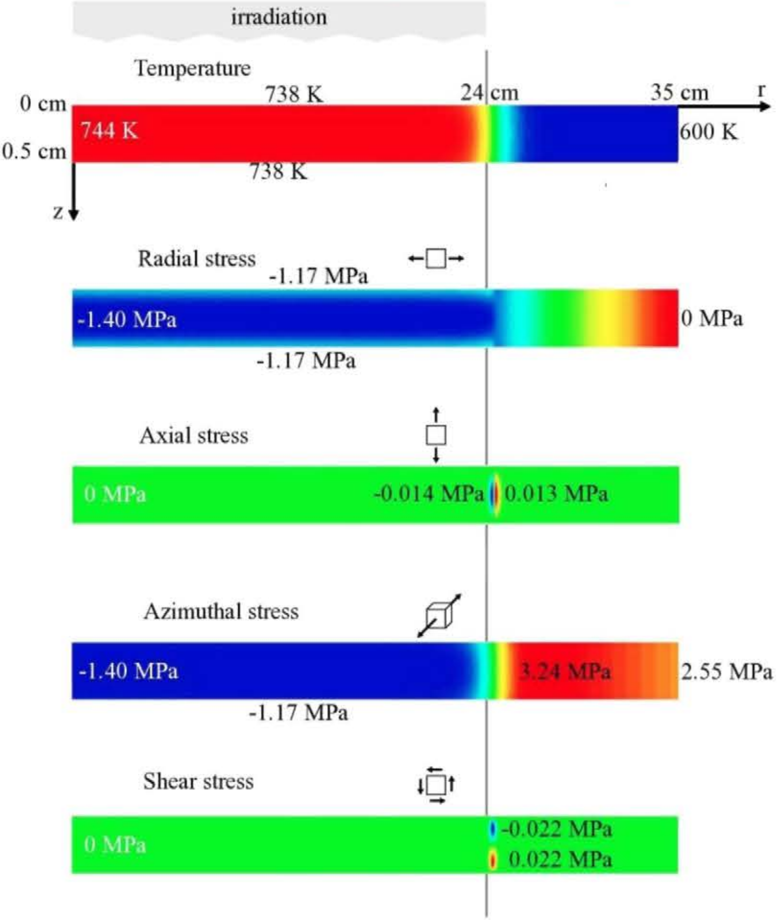
Alternative solution:

Decrease the surrounding temperature 600 K→ 500 K. This drives to a lens temperature reduction of only 10 K which is still far above the limit.

Conclusion: Silica lenses cannot operate under demo reactor conditions in its present configuration

Thermomechanical response: LIFE2

Temperature radial, axial, azimuthal and shear stresses at the end of each pulse **in steady-state operations** conditions for HiPER



Thermal loads mainly due to neutrons and γ-rays. The laser irradiation has to be also considered-

$$q_{laser} = F_{laser}\nu\left(1-\exp(-Ad)\right)$$

In all cases the calculated stresses are observed to be lower than the silica tensile strength (48 MPa) → silica lenses can withstand the radiation-induced mechanical stresses

$\sqrt{\pi a}$

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What about the brittle fracture?

Under the assumption of linear elastic fracture mechanics, cracks starts to develop when the intensity factor (K_I) and the fracture toughness are equal.

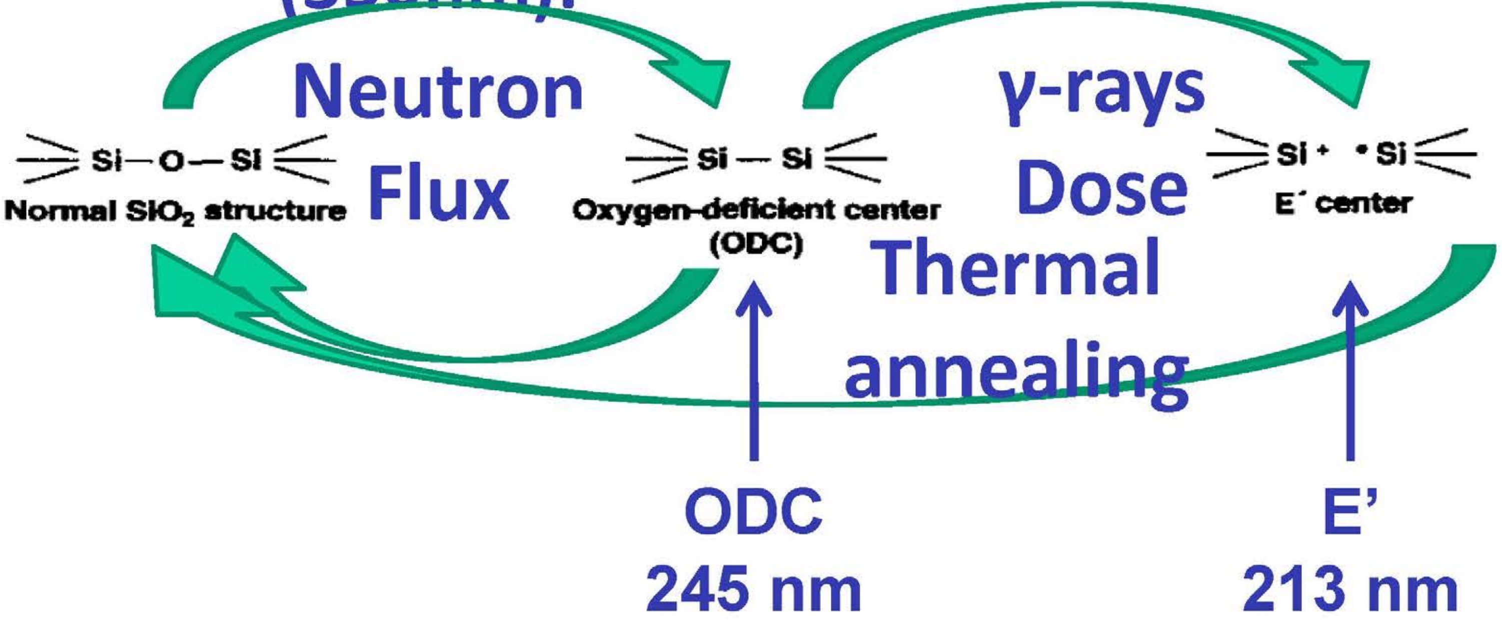
	HiPER prototype	HiPER Demo	LIFE.2
Critical crack length (mm)	6.6	2.04	32.12
$\Delta\sigma$ (MPa)	$0.12\sqrt{\pi a}$	$0.46\ \sqrt{\pi a}$	$0.52\sqrt{\pi a}$
ΔK_I (Mpa/m$^{1/2}$) 1 mm crack	0.00058	0.001	0

- Only cracks longer than those will drive to brittle fracture in HiPER (prototype and demo).
- No cracks are predictable in LIFE lenses.
- $\Delta K_I < \Delta K_{th}$ (0.3 Mpa/m1/2 for silica)→ crack growth is negligible.

Atomistic damage: Color center formation

Radiation-induced defects can substantially modify the lens optical properties. In particular the lens absorption.

Absorption at 3ω wavelength (350nm):



Neutron Flux

γ-rays Dose

Thermal annealing

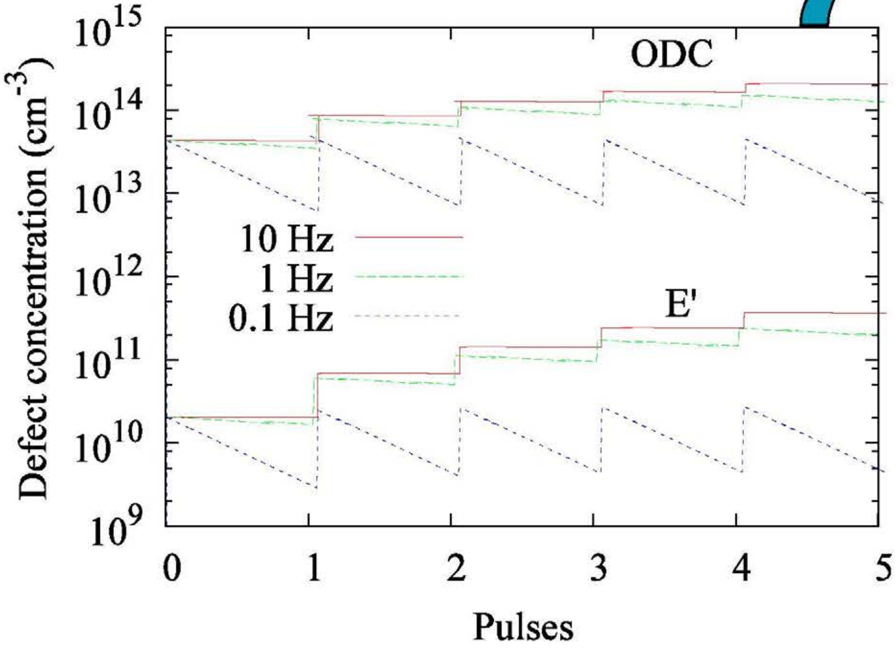
ODC
245 nm

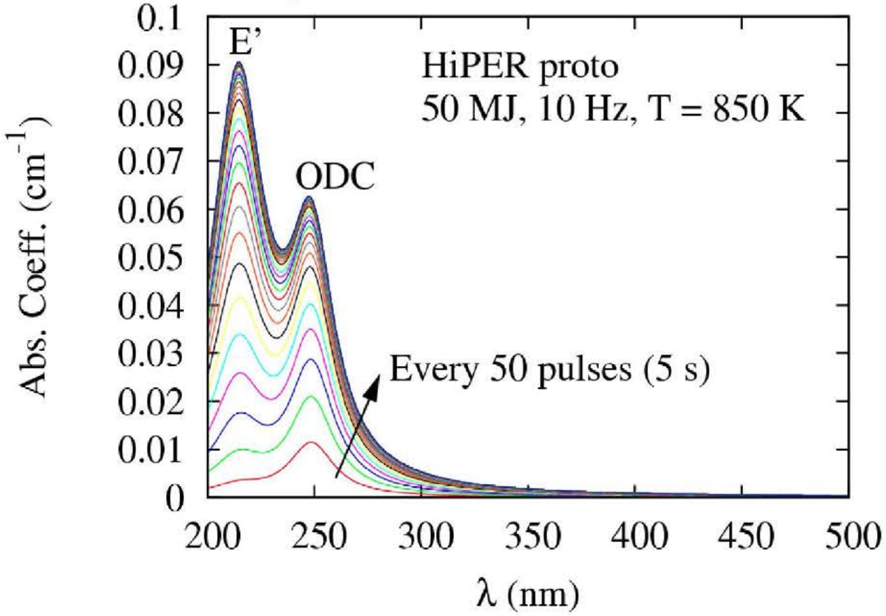
E’
213 nm

Marshall et al. J. Non-Crystalline Solids. 212, 59 (1997)

Color center evolution based on Marshall´s model

$$\alpha(\lambda) = \sum_i \sigma_i N_i L_i(\lambda) \quad \text{with} \quad L_i(\lambda) = \frac{1}{1 + \frac{(\lambda_i - \lambda)^2}{(\Delta\lambda_i)^2}}$$





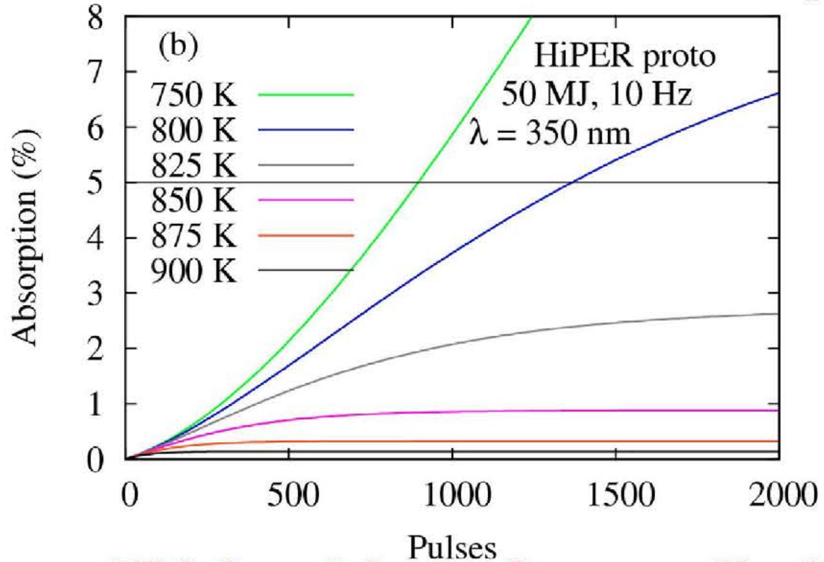
γ-dose is too low to promote effective ODC-E´conversion

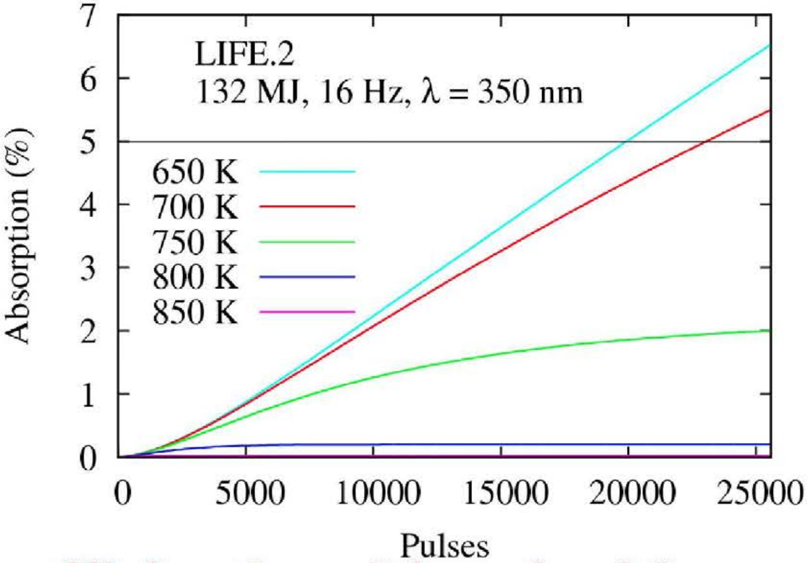
Saturation in intensity value after 1000 pulses→ limits the lens absorption

Optical absorption

Remember: the lens optical transparency in the 350 nm region should be as high as possible to minimize laser power loses.

$$A = 1 - \exp\left(-\alpha(\lambda)d\right)$$

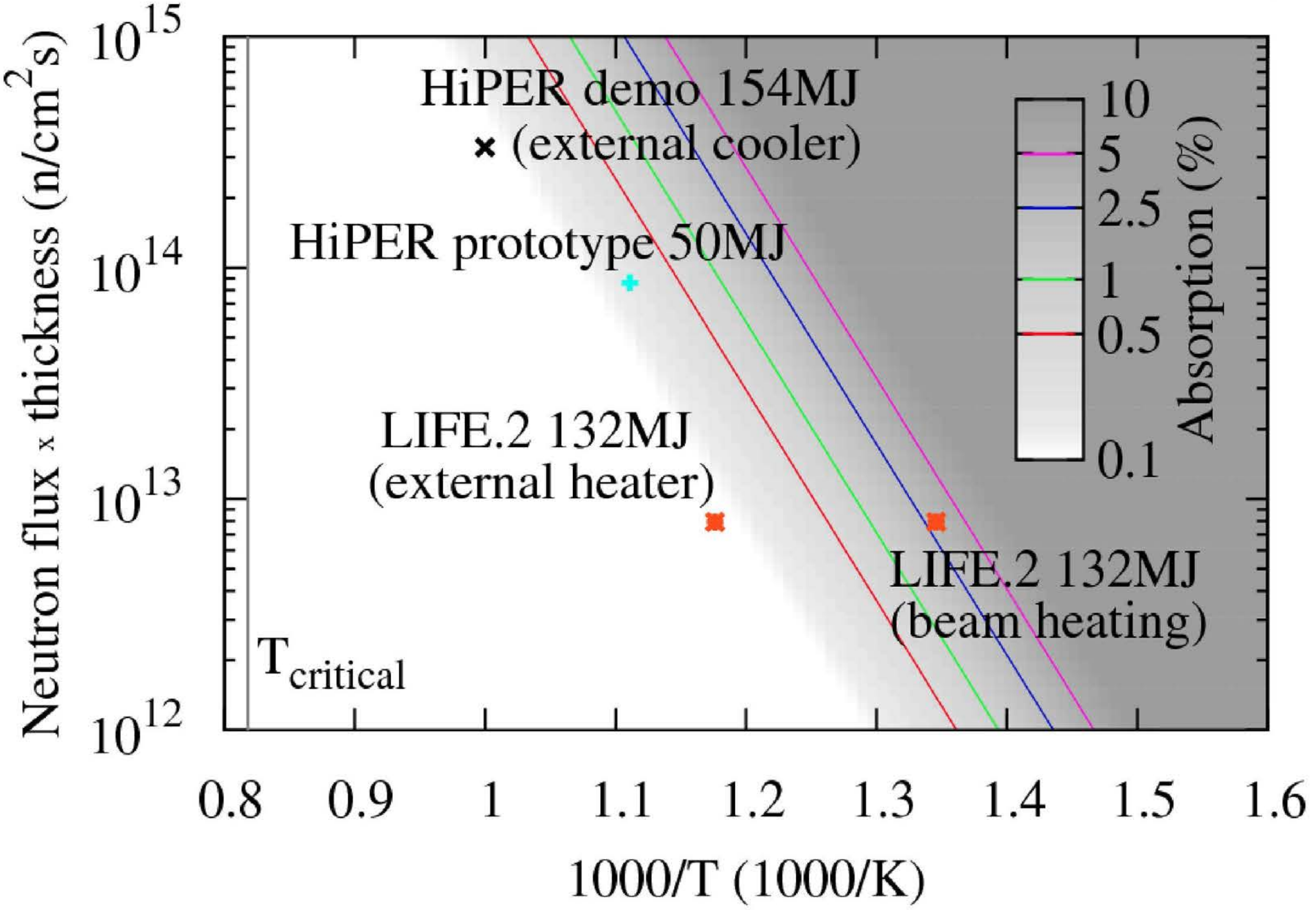




5% is a kind of upper limit to efficiently achieve ignition

- The optical absorption at steady state operation for HiPER prototype and LIFE2 is bellow 5%.
- **At low temperatures a is quite high.**

Parametric representation in steady state operation

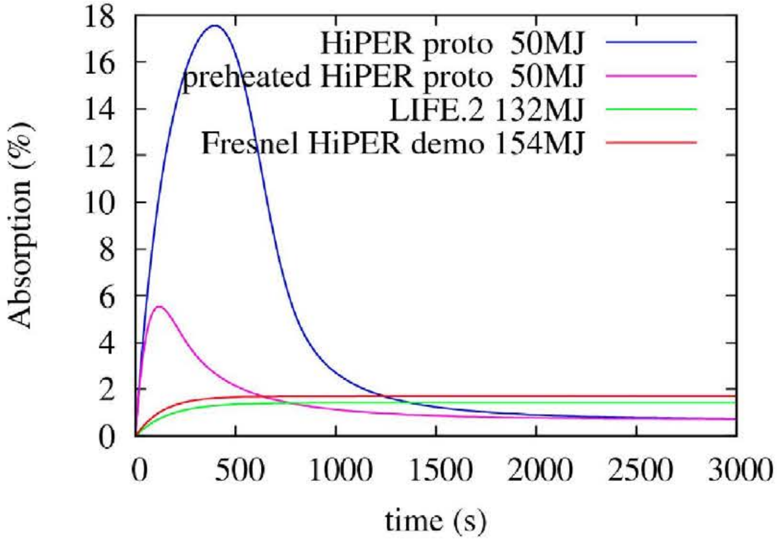


What is the optical absorption during the reactor startup?

- The lenses behavior during the reactor startup is evaluated by calculating (simplified 1D model) the temperature (z) and the color center concentration evolution.

- For these calculations the neutron and gamma dose rate, the neutron flux, as well as silica properties (are considered to be constant.

- The deposited laser energy is calculated every time step taken into account the absorption due to color centers concentration at a given moment.



- In HiPER prototype high A values → possible problems to achieve ignition.
  - Possible solution: heat up the lenses during the reactor startup-

- Fresnel lenses are not expected to give rise to ignition problems.

Conclusions

- Ions MUST be mitigated-

- The calculated steady-state temperature is bellow the silica melting temperature in HiPER prototype and LIFE2, but it is above in HiPER demo.

- Decreasing the surrounding temperature in HiPER demo lenses is not a solution.

- Silica lenses would not work in actual HiPER demo configuration-

- The radiation-induced temperature gradient drives to stress generation.

- In all cases the calculated stresses are lower than the silica tensile strength→ silica lenses can withstand the generated stresses-

Conclusions

- Particle and purely ionization radiation generate color center.
- The concentration of color centers at a given moment depends on their formation/annihilation ratio which ultimately depends on temperature.
- At steady-state operation the optical absorption is bellow 5% for all the different HiPER facilities and for LIFE2.
- The optical absorption is unacceptable high (17%) during the HiPER prototype startup →ignition problems?
    - Possible solution : external heating of the lenses.

In summary, we illustrate the capabilities and weak points of silica lenses as final optics elements, proposing alternative solution to overcome predictable problems

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