Plasmonic nanoparticles for the protection of the final optics in inertial confinement fusion facilities: Capabilities and limitations

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People involved

Simulations and experiments of damage in optical elements

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Outline

- Final lenses in laser fusion plants
  - Challenges for the protection of the final lenses
- Plasmonic nanoparticles
  - Radiation resistance
- Conclusions

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Nuclear Fusion

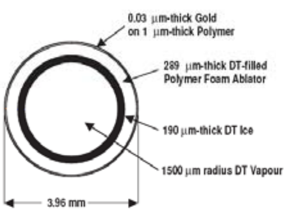
Gravity | **Magnetic fields** | **Inertia**

Lawson criterion must be fulfilled. This implies reaching a high compression to reach ignition

HiPER, LIFE and NIF

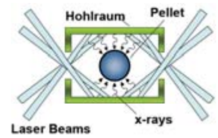
- **H**igh **P**ower laser **E**nergy **R**esearch facility
  - European project for laser fusion
- **L**aser **I**nertial **F**usion **E**nergy
  - USA project for laser fusion
- **N**ational **I**gnition **F**acility
  - Experimental facility (USA)

Pellet



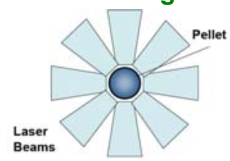
Indirect vs. direct target

Indirect target



- Used in NIF and LIFE
- Easier for obtaining an homogeneous compression
- Providing high enough gain for pure fusion energy is challenging

Direct target

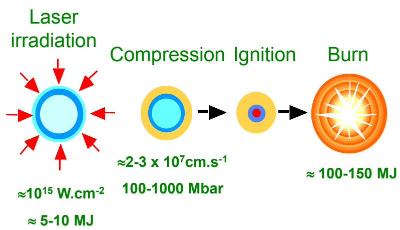


- Projected for HiPER
- More efficient use of laser light, and greater flexibility in applying drive provides potential for much higher gains

Laser fusion

Direct target

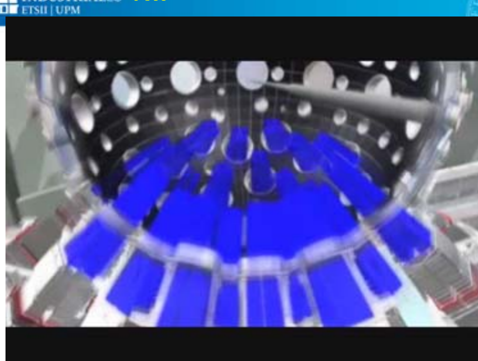
Central ignition



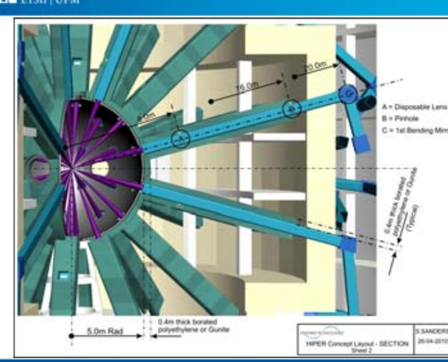
Repeating this process by injecting targets at a rates 5-20 Hz ≈ 1000 MWe

HiPER

NIF

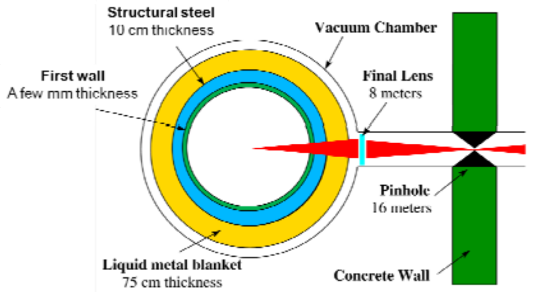


Final optics in HiPER



Oxford Technologies

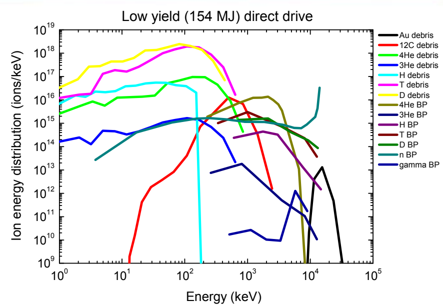
Sketch of HiPER



Final lenses

- They must face the target explosions during operation, being only a few meters away
- Moreover, they must have:
  - Low laser absorption
  - Good thermo-mechanical properties
  - High radiation resistance
- Silica is proposed as the best candidate due to its good properties and low cost

Direct target



Neutrons ~69%, Ions ~30%, X-rays ~1%

LASNEX simulations by J. Perkins

HiPER

	HiPER Prototype	HiPER Demo
Operation	Continuous (24/7)	Continuous (24/7)
Yield (MJ)	<50	>100
Rep. rate (Hz)	1-10	10-20
Power (GWt)	< 0.5	1-3
T cycle	Yes	Yes
Blanket	Yes	Yes

Neutrons ~69%, Ions ~30%, X-rays ~1%

Energy deposited

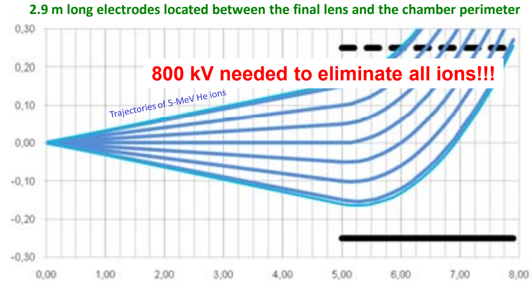
	HiPER				
	<E> (MeV)	Pulse width (ns)	Pen-depth (mm)	ED demo (J/cm^3)	ED prot. (J/cm^3)
Burnt products (^{4}He)	2.1	400	6.4	**3788.48**	**1230.03**
Debris ions (D)	0.15	2200	1.4	**19627.93**	**6372.7**
X-rays	0.007	0.17	few10^3	261.11	84.78
Neutrons	12.4	60	-	0.142	0.046
Indirect gammas	-	»60	-	0.051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

Ions must be mitigated somehow!!!

Avoiding ions

Ions must be mitigated

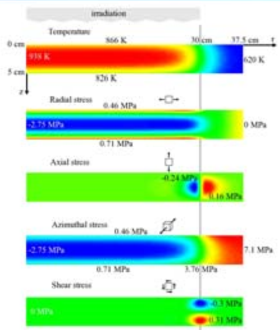
2.9 m long electrodes located between the final lens and the chamber perimeter



B. Rus

Potential of collection of unburned T on the negative electrode!

INDUSTRIALES ETSII | UPM — Thermo-mechanical effects

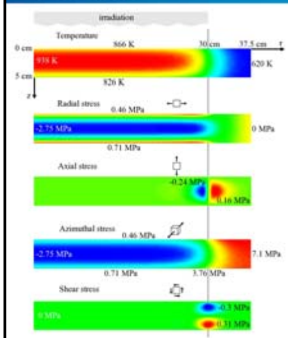


- Steady-state operations (50 MJ)
  - Stresses lower than yield strength (48 MPa) → silica lenses can withstand the radiation-induced mechanical stresses
  - Thermal loads mainly due to X-rays but too low to induce fatigue failure
- In DEMO (>100 MJ) temperature limit exceeded.

Lenses must be moved away!!!!

Garoz *et al.*, Nuclear Fusion, In press

INDUSTRIALES ETSII | UPM — Thermo-mechanical effects



- The focal distance changes 4 cm from cold to the stationary state
- The temperature profile induces aberrations

Lenses must be pre-heated!!!!

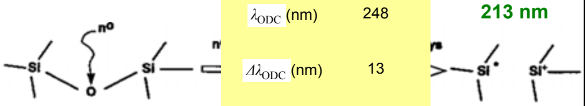
Garoz *et al.*, Nuclear Fusion, In press

INDUSTRIALES ETSII | UPM — Point defects

Color center evolution model

E'

213 nm



Parameter	Value
σ_{ODC} (cm^2)	1.7×10^{-17}
λ_{ODC} (nm)	248
$\Delta\lambda_{ODC}$ (nm)	13
$\sigma_{E'}$ (cm^2)	3.2×10^{-17}
$\lambda_{E'}$ (nm)	214
$\Delta\lambda_{E'}$ (nm)	15

$$\frac{dN_{ODC}}{dt} = \frac{M_n\varphi_n}{\lambda_n} - \beta_E D_\gamma^{'} N_{ODC}$$

$$\frac{dN_{E'}}{dt} = \beta_E D_\gamma^{'} N_{ODC} - \frac{N_{E'}}{\tau_{anneal}}$$

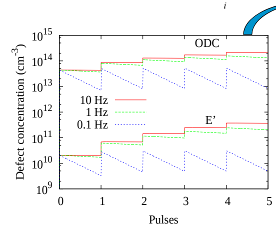
$$\alpha(\lambda) = \sum_i \sigma_i N_i L_i(\lambda)$$

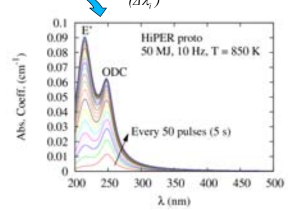
$$L_i(\lambda) = \frac{1}{1+\frac{(\lambda_i-\lambda)^2}{(\Delta\lambda_i)^2}}$$

Marshall *et al.*, J. Non-Cryst. Sol. 212 (1997) 59

INDUSTRIALES ETSII | UPM — Point defects

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





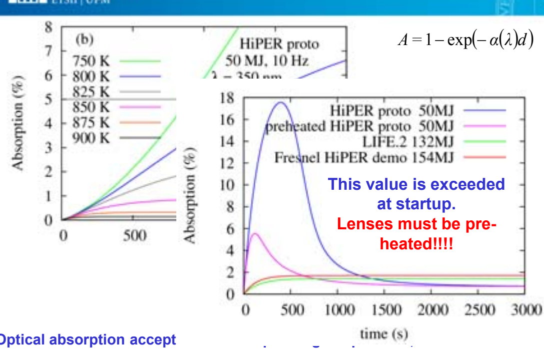
γ-dose is too low to promote effective ODC-E´ conversion

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

Garoz *et al.*, Nuclear Fusion, In press

INDUSTRIALES ETSII | UPM — Point defects

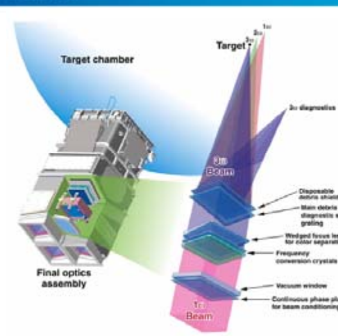
$A = 1 - \exp(-\alpha(\lambda)d)$



Optical absorption accept

Garoz *et al.*, Nuclear Fusion, In press

INDUSTRIALES ETSII | UPM — First and second harmonic



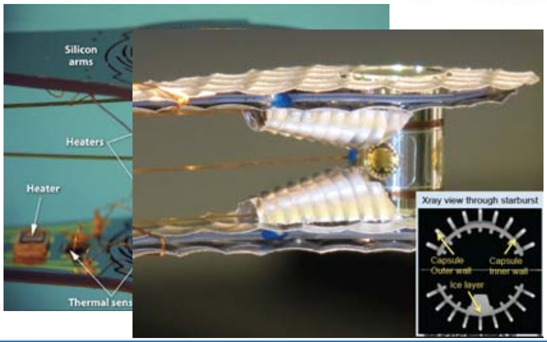
1ω -> 1053 nm

2ω -> 526.5 nm

3ω -> 351 nm

NIF website (https://lasers.llnl.gov/)

Avoiding first and second harmonic



S. H. Glenzer

In summary

- In HiPER's operating conditions:
  - The energy deposited by the ions is able to instantly (and locally) melt the final lenses
    - ➢Ions must be mitigated!!
  - The energy deposited by the neutrons can lead to a hot stationary state where the final lenses melt
    - ➢Lenses must be moved away!!

Moreover…

- In HiPER's operating conditions:
  - The heating of the lenses during the startup can shift the focus, produce aberrations and create unacceptable quantities of point defects
    - ➢Lenses must be pre-heated!!
  - Some quantities of 1ω and 2ω light can reach the Hohlraum, preheating the Pellet and producing unwanted effects
    - ➢First and second harmonic should be eliminated!!

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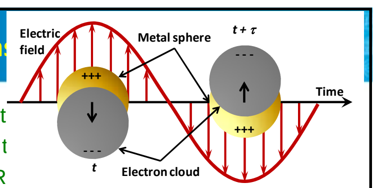
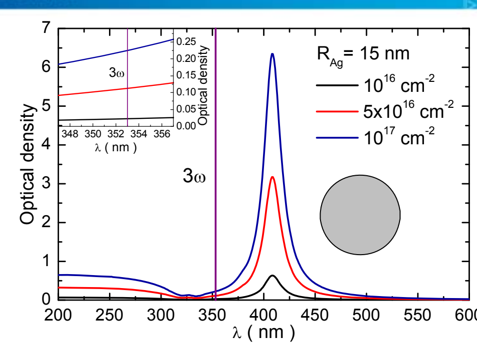
Pla



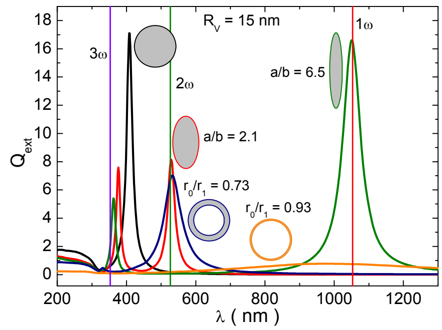
- The defining feat nanoparticles is t resonance (LSPR
- The position and intensity of the LSPR mainly depends on the size, shape and composition
  - This opens up the possibility of tuning the optical response
- They have important applications in fields ranging from biology and medicine to optoelectronics
- But, also in nuclear fusion?

Why not?

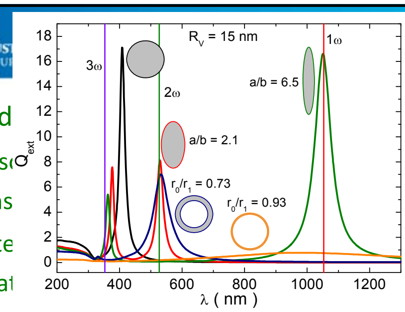


Silver NPs are highly transparent at 3ω (353 nm)

Moreover…



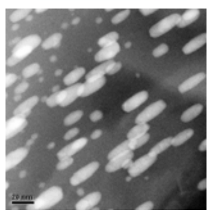
Their optical response can be tuned



- Could
  - Abs… ions … tics
  - Filte… e- heat
- But, can they withstand the irradiation conditions?

Effects of SHI on the NPs

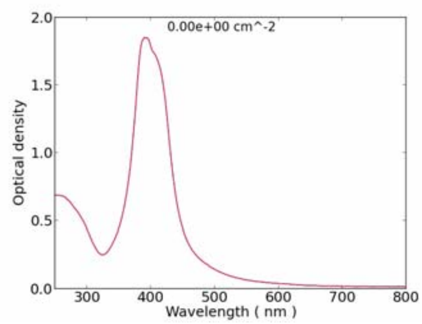
- The effects of the SHI on metallic NPs have been studied for several years
- It is well known that spherical NPs are transformed into anisotropic particles whose larger axis is along the ion beam
- However, the deformation process is not well understood yet and there is not detailed information of the intermediate stages



Si at 8 MeV

Rodríguez-Iglesias *et al.*, Opt. Lett. 35 (2010) 703

Evolution of the optical response vs. fluence



Si at 20 MeV

In summary

- There are three clearly defined regions
  - < 5×10^{12} cm^{-2}: No damage
  - 5×10^{12} - 5×10^{13} cm^{-2}: Elongation
  - > 5×10^{13} cm^{-2}: Dissolution
- The "dissolution" regime can be reached after ~5×10^4 cycles
- Fortunately, the high temperatures reached in the lenses during normal operation can alleviate this problem
- In the worst case, the metallic NPs can be deposited in the backside of the lenses, avoiding the SHI.

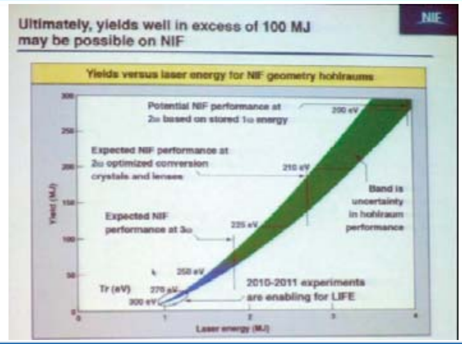
Conclusions

- Many unresolved issues remain, before the final lenses can withstand the extreme conditions to which they are subjected
- Furthermore, a certain amount of the first and second harmonic can reach the Hohlraum, preheating the Pellet and seriously affecting the fusion process
- Plasmonic NPs are viable candidates to filter the unwanted harmonics and, probably, to reduce the damage produced by SHI; however, many questions should be answered before this possibility can be confirmed or ruled out

Thank you

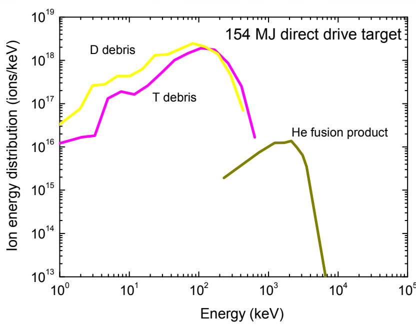
for your attention

Switch to the green?



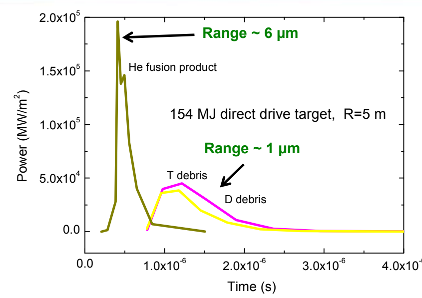
E. Moses, MR1.00001

Direct target



LASNEX simulations by J. Perkins

Direct target



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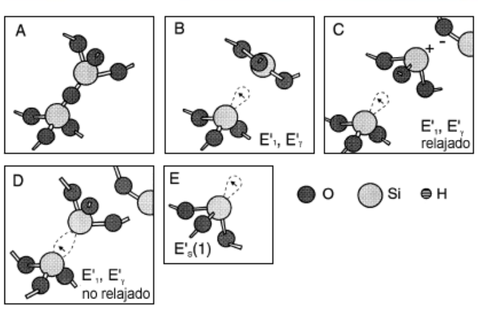
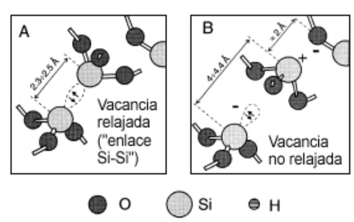
LASNEX simulations by J. Perkins

E' centers



ODC



NBOHC

$$\equiv Si\text{-}O\text{-}Si\equiv \;\rightarrow\; \equiv Si\text{-}O\bullet \;\; \bullet Si\equiv$$