Materials in nuclear fusion power plants

School on Materials Irradiation: from Basics to Applications
Trieste, Italy, Feb. 2025

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Contents

Recommended Book: https://oa.upm.es/69109/

Published in the framework of COST Action CA17126
"Towards understanding and modelling intense electronic excitation (TUMIEE)"

Nuclear fusion

Maximum released energy per unit mass of fuel

Reactions	Chemical	Fission	Fusion
Examples	$C + O_2$	$n + {}^{235}U$	D + T
Fuel	Coal	UO_2 (3% ^{235}U)	Deuterium, lithium
Released energy (J/kg)	$3.3 \cdot 10^7$	$2.1 \cdot 10^{12}$	$3.4 \cdot 10^{14}$

DT reaction is by far the fastest fusión reaction

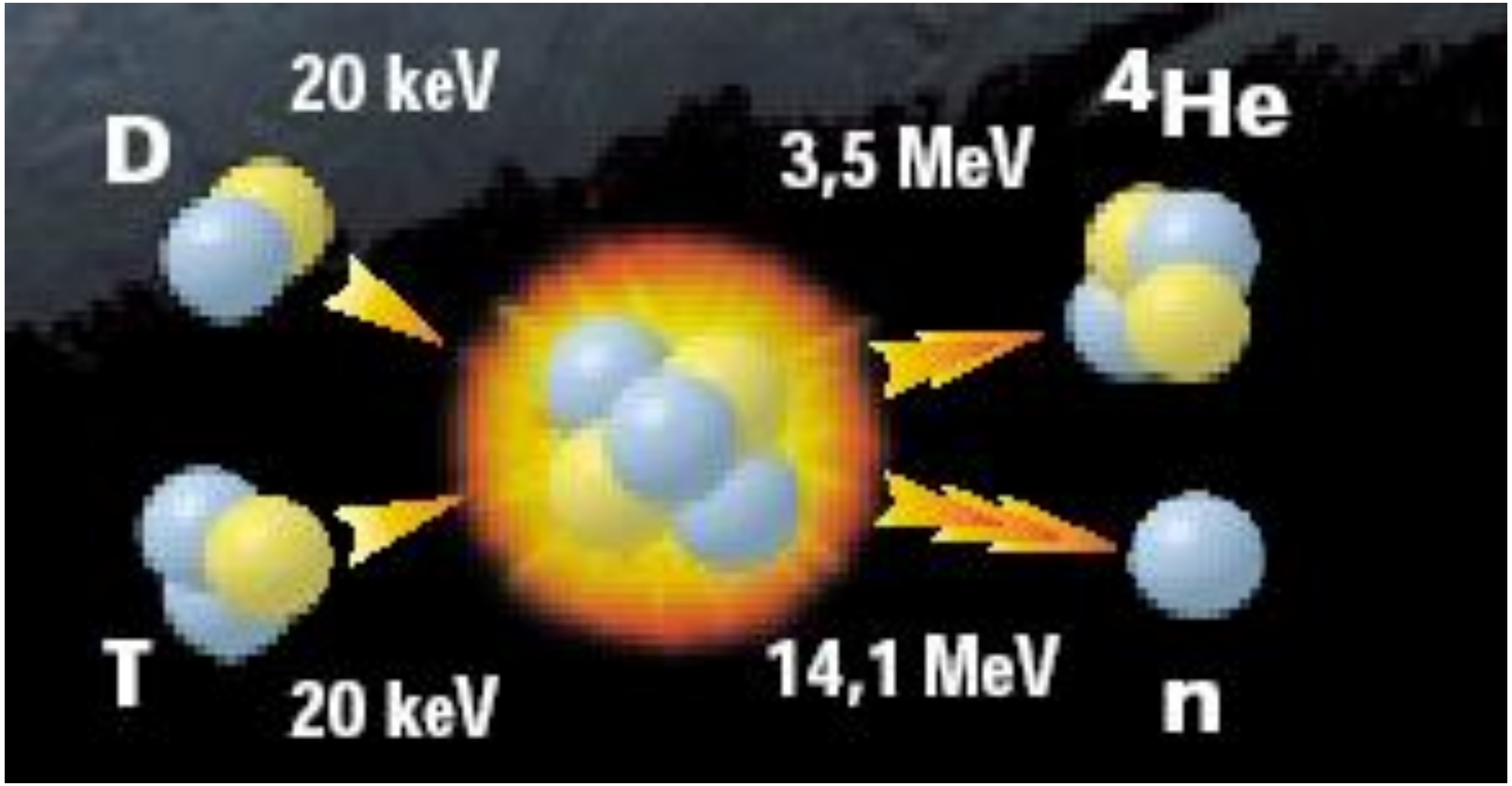
1. Introduction

D and T are charged particles that repel each other

Heating is necessary

Matter in plasma state

$$D + T \Rightarrow {}^{4}He + {}^{1}n$$



Plasma confinement

Gravity Magnetic fields Inertia

Lawson criterion must be fulfilled. This implies that the product of concentration multiplied by confinement time must be high

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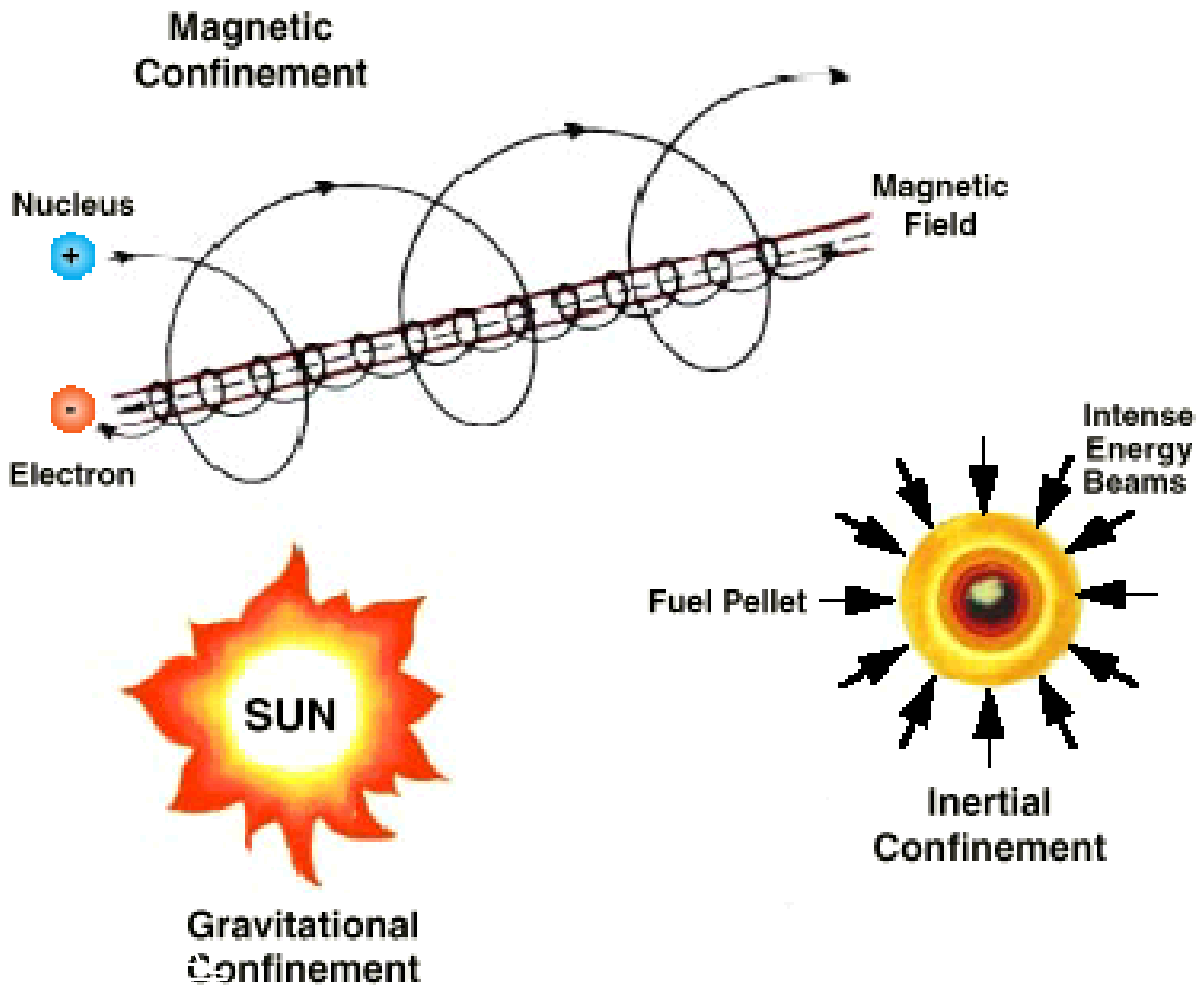
1. Introduction

Confinement



1. Introduction

R&D pathway

Nuclear fusion

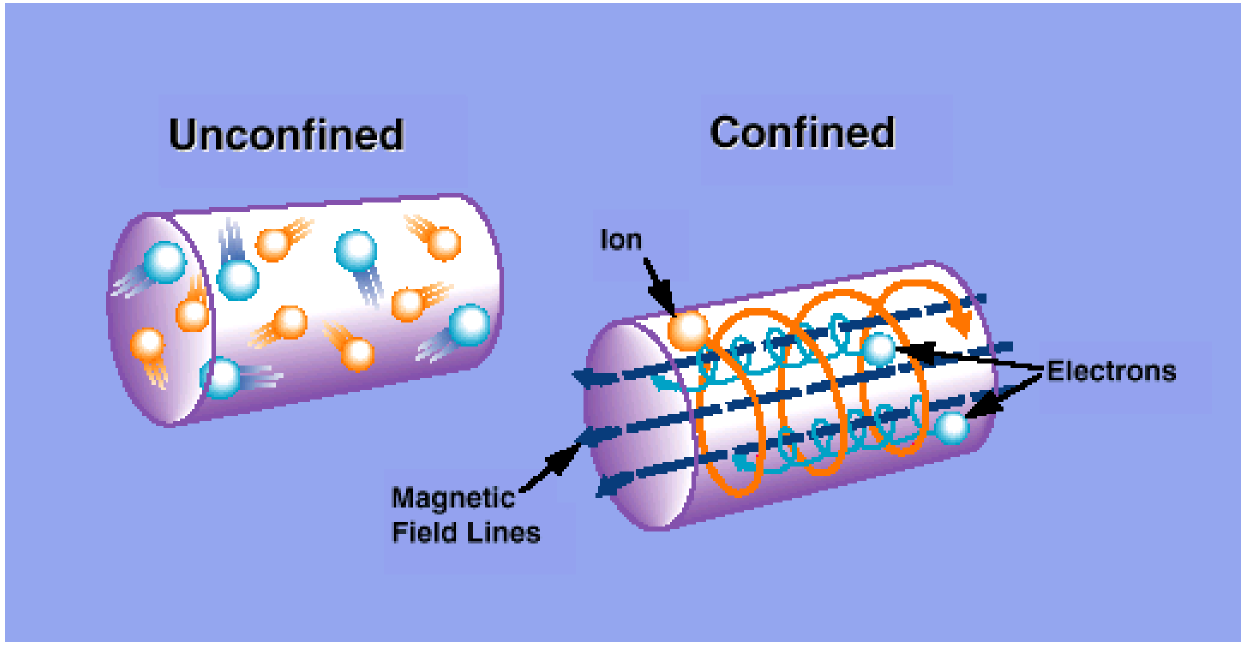
↓

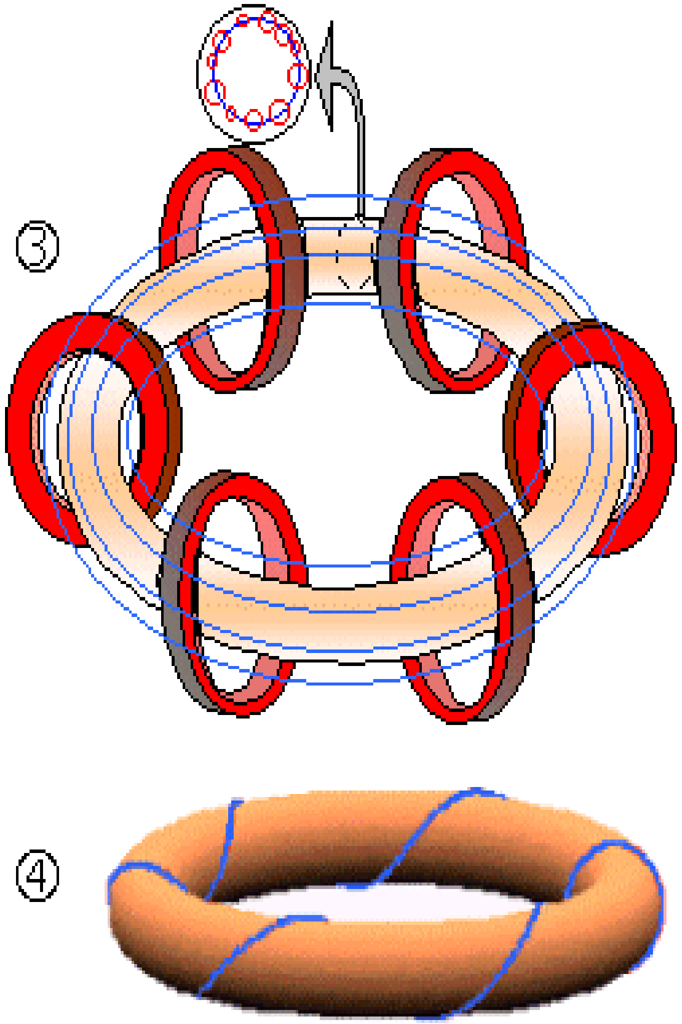
Plasma confinement

	↓	↓
	ICF	MCF
	↓	↓
	Direct / indirect target	Tokamak stellarator
	↓	↓
Scientific viability	NIF, LMJ	ITER
	↓	↓
Technological viability	LIFE, HiPER	DEMO

1. Introduction

Magnetic confinement fusion (MCF)

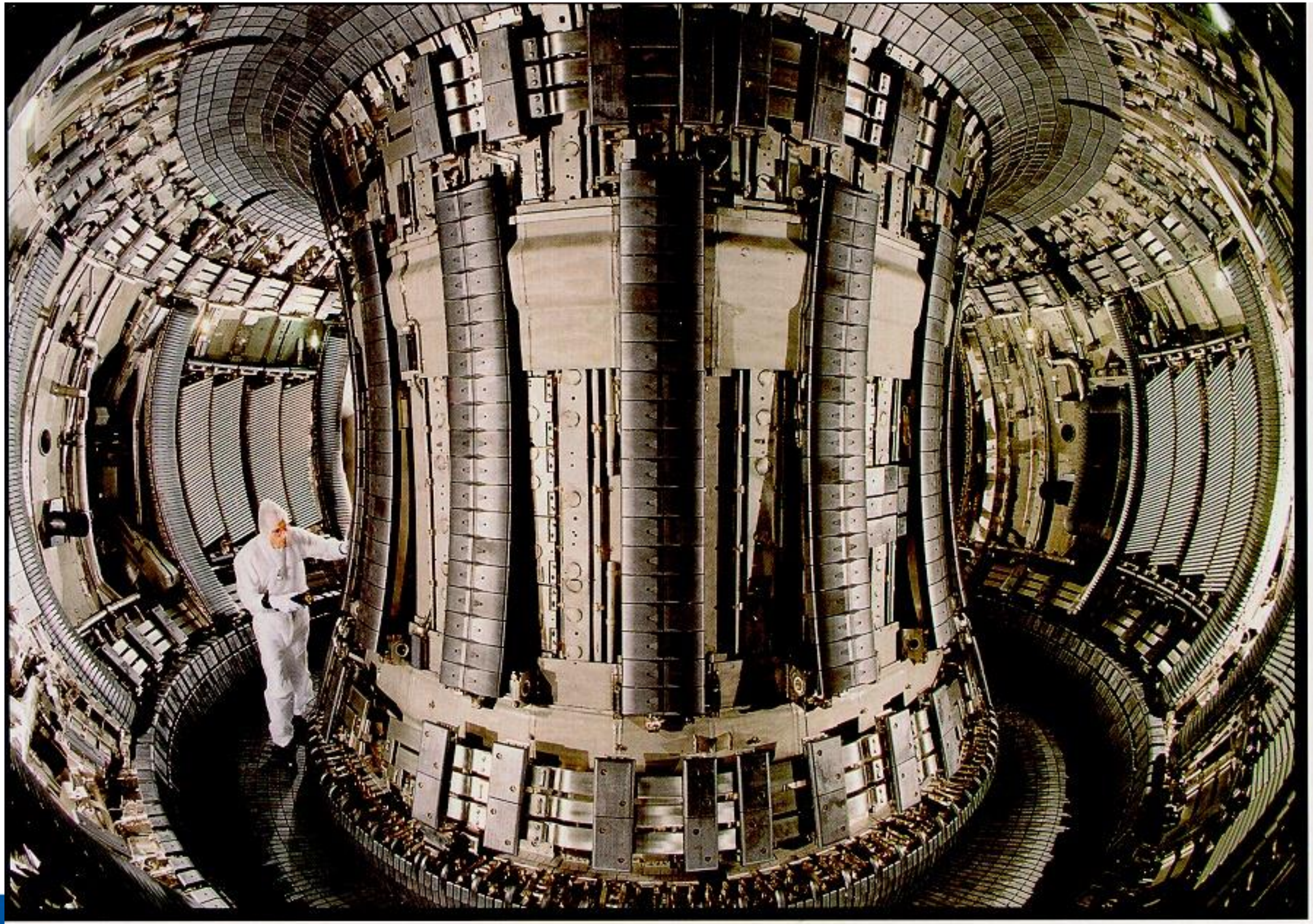




1. Introduction

JET

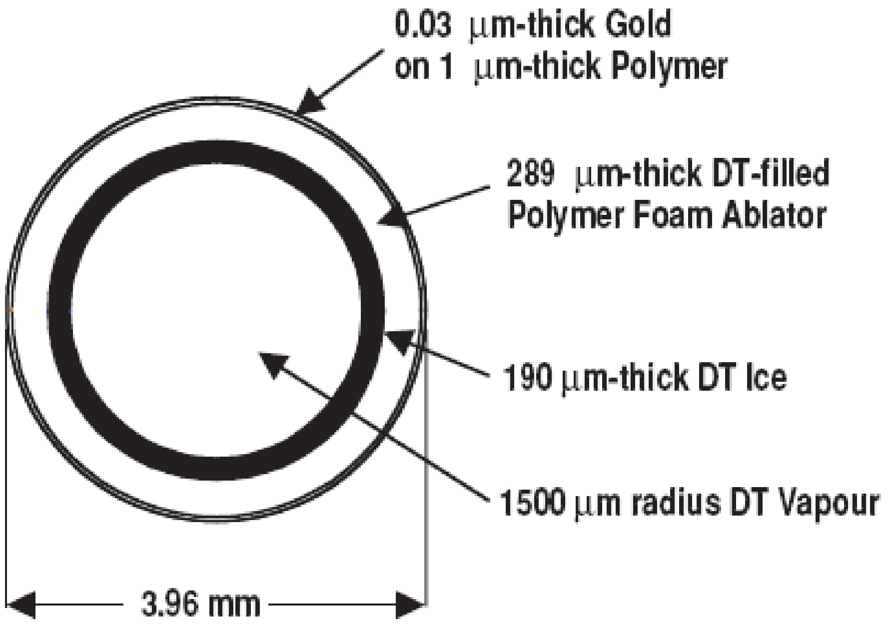
Experimental facility

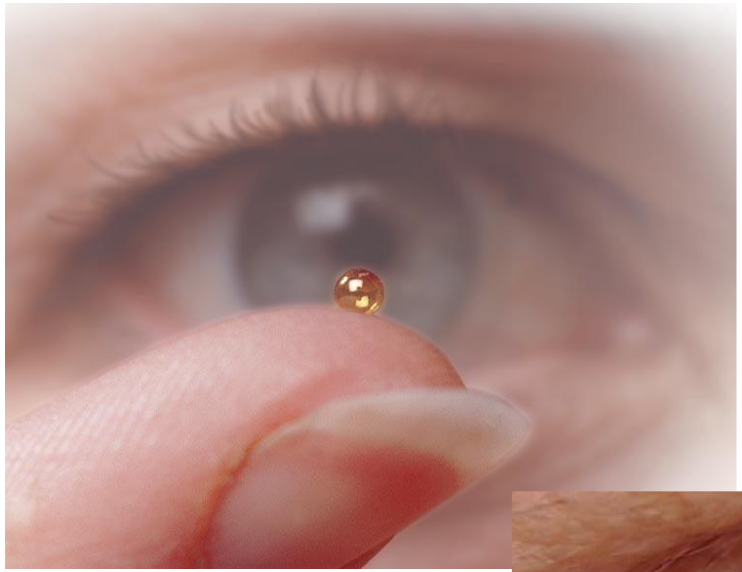


JET
Experimental facility

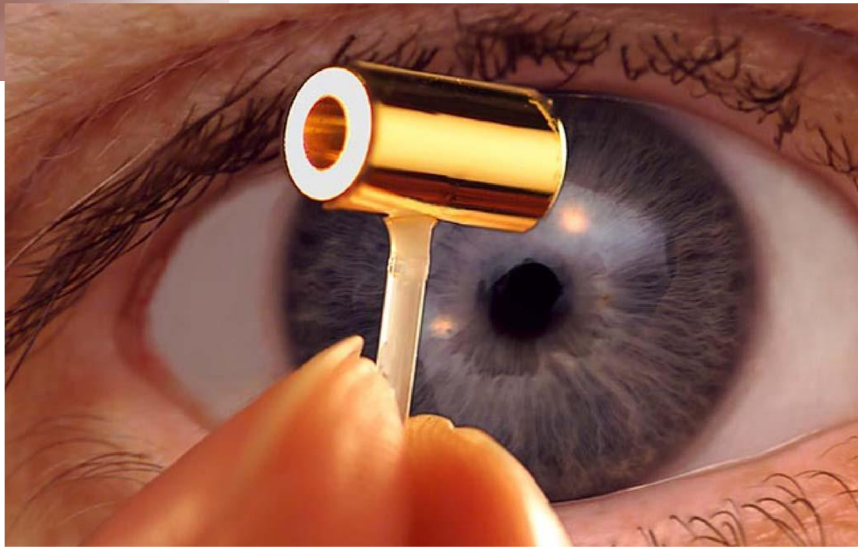
1. Introduction

Intertial confinement fusion (ICF) or laser fusion





Direct drive target

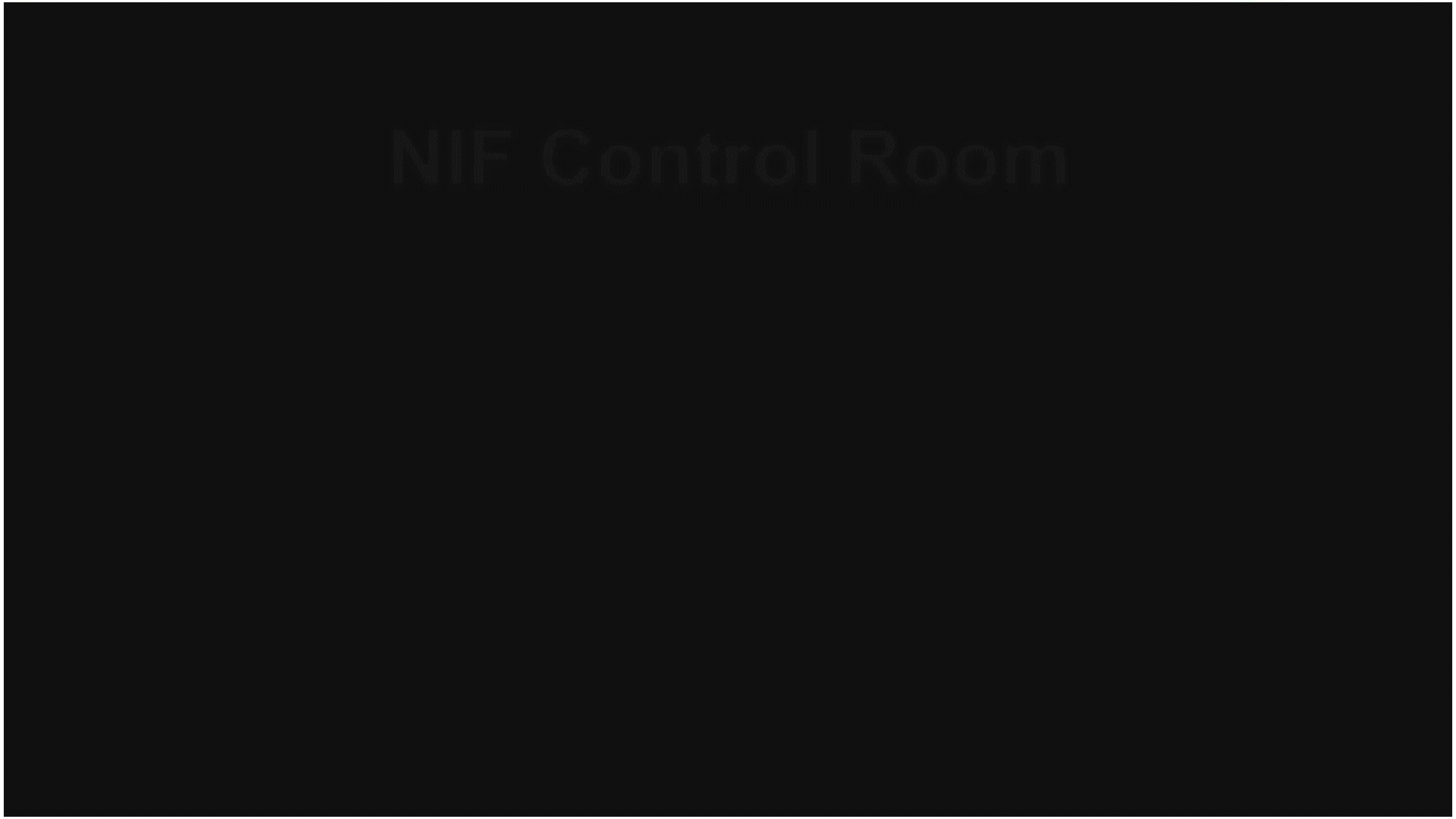


Indirect drive target

1. Introduction

NIF

Experimental facility

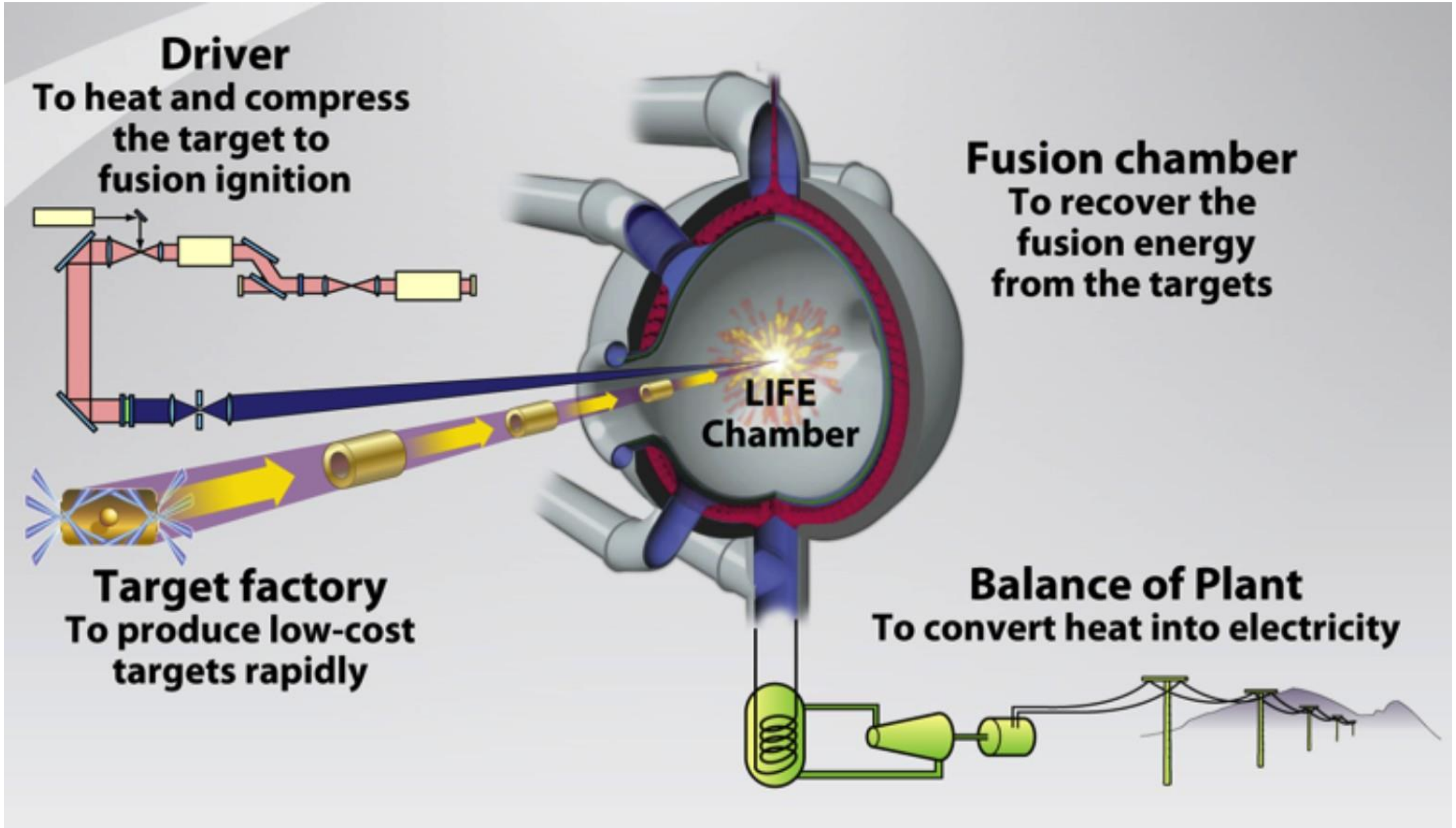


1. Introduction

Ignition in NIF in year 2022

1. Introduction

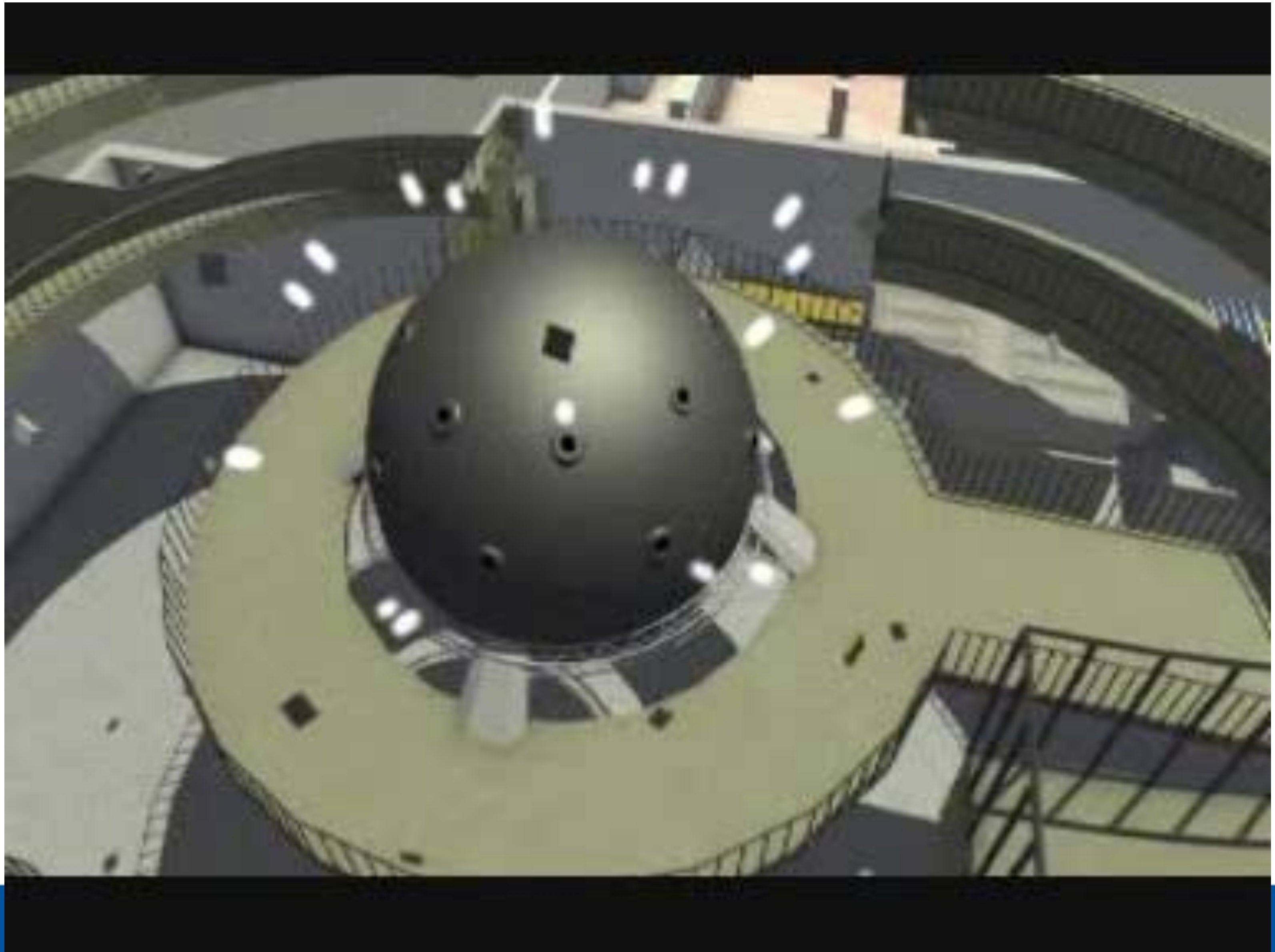
Power plants require continuous operation



1. Introduction

HiPER

Power plant project



2. Radiation fluxes

- **In both fusions approaches energy is released in the form of kinetic energy of the products of the deuterium-tritium fusion reaction.**

$$\mathbf{D+T \Rightarrow {}^{4}He\ (3.56MeV) + n\ (14.03MeV)}$$

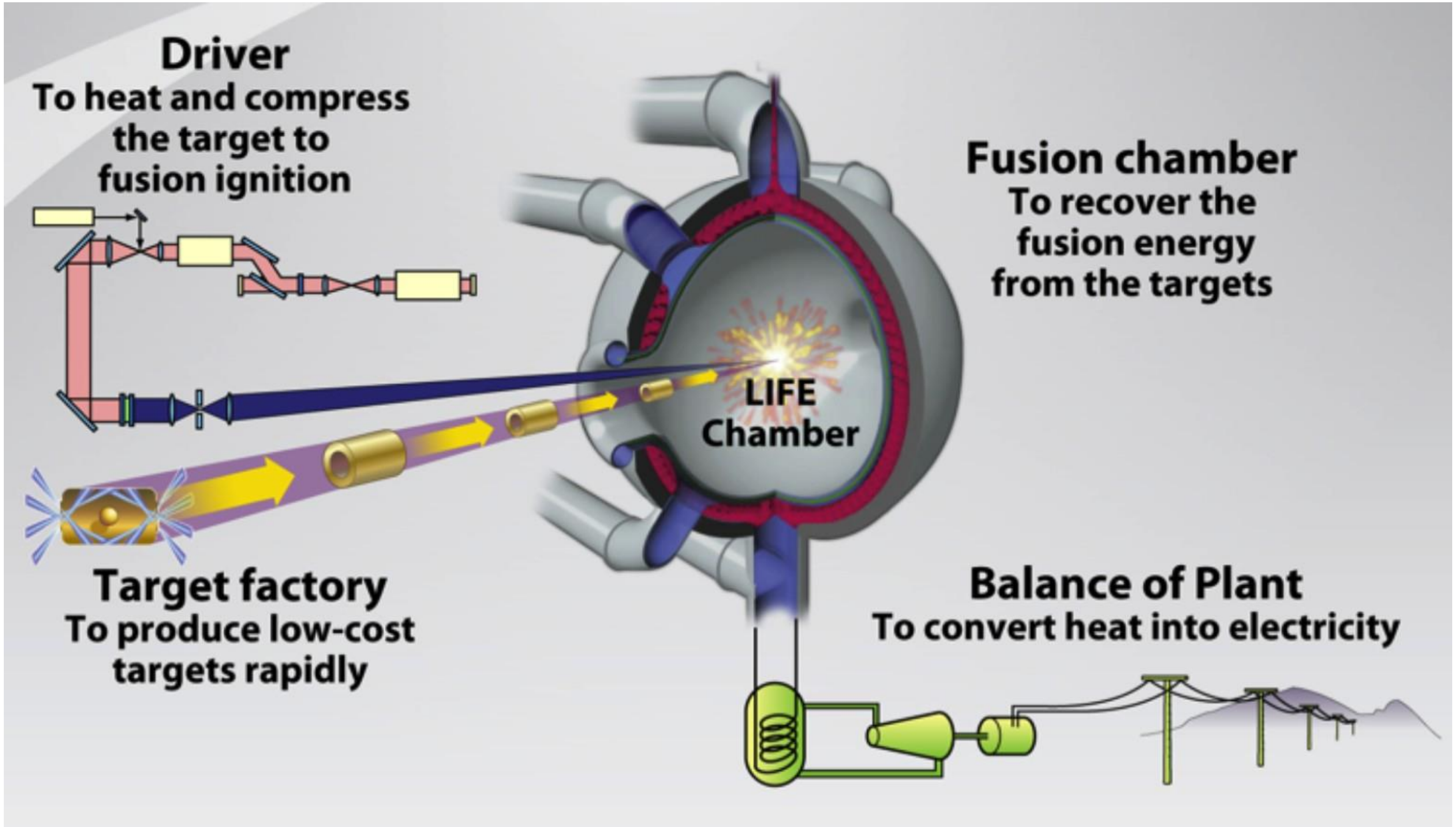
- **ICF and MCF are radically different in the way they achieve the plasma densities and the required temperatures to produce ignition:**
- ***ICF:***
  - **Based on a sudden compression and heating of small DT pellets to very high density (~10^{31} particles/m^3) for a few hundred picoseconds producing explosions from tens to hundreds of MJ.**

- ***MCF:*** **aims at confining a large volume of a hot (T_e= 15-20 KeV) low-density plasma (n=1.2 $\times 10^{20}$ m^{-3}) for long periods (minutes) using helicoidal magnetic field configurations**

→ The radiation nature, dose levels, dose rates, energy spectra and time scale are quite different..

2. Radiation fluxes

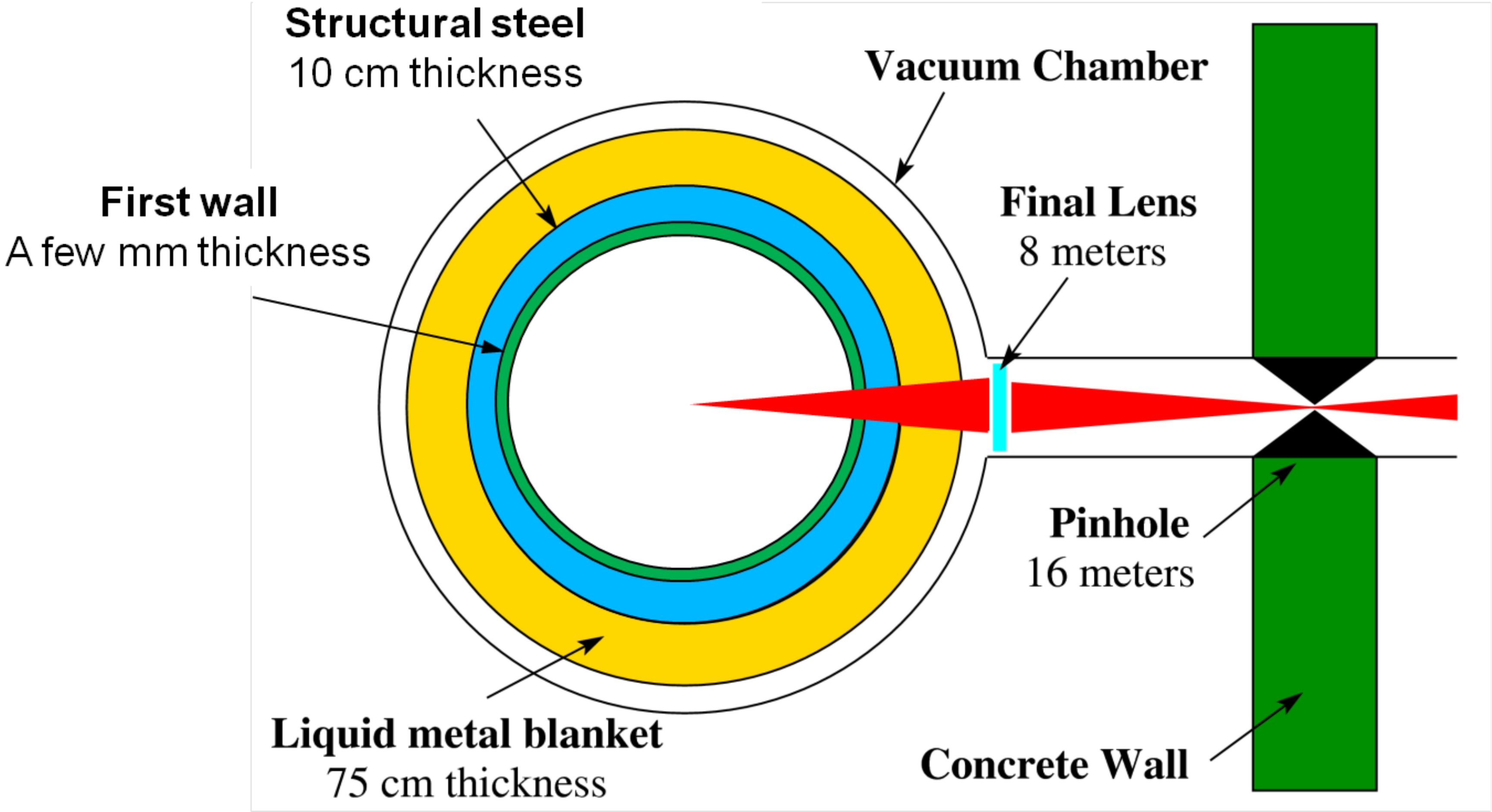
ICF



2. Radiation fluxes

ICF

Materials for HiPER power plant

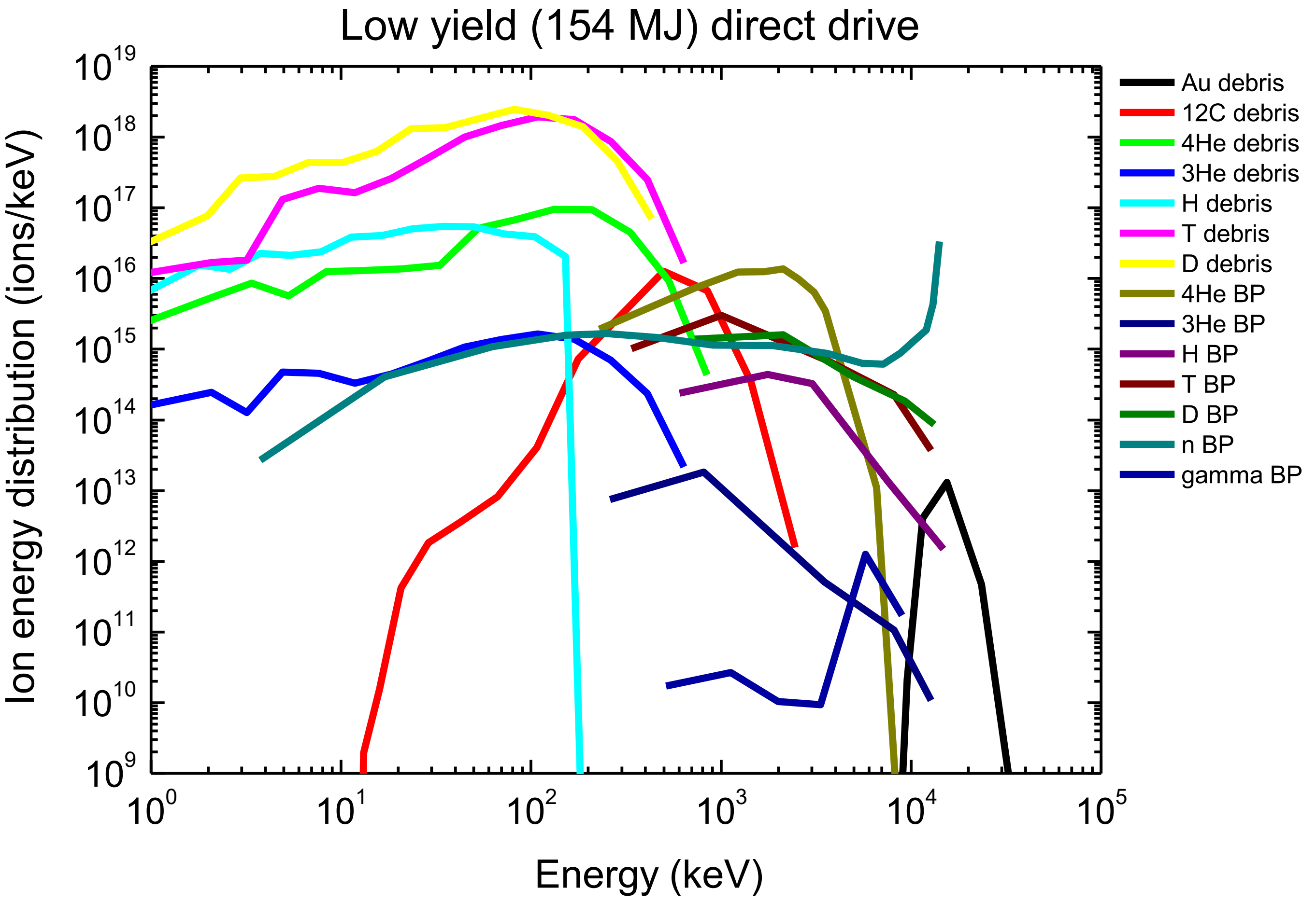


2. Radiation fluxes

Since power plants do not exist, how radiation fluxes are determined?

Direct target

LASNEX code

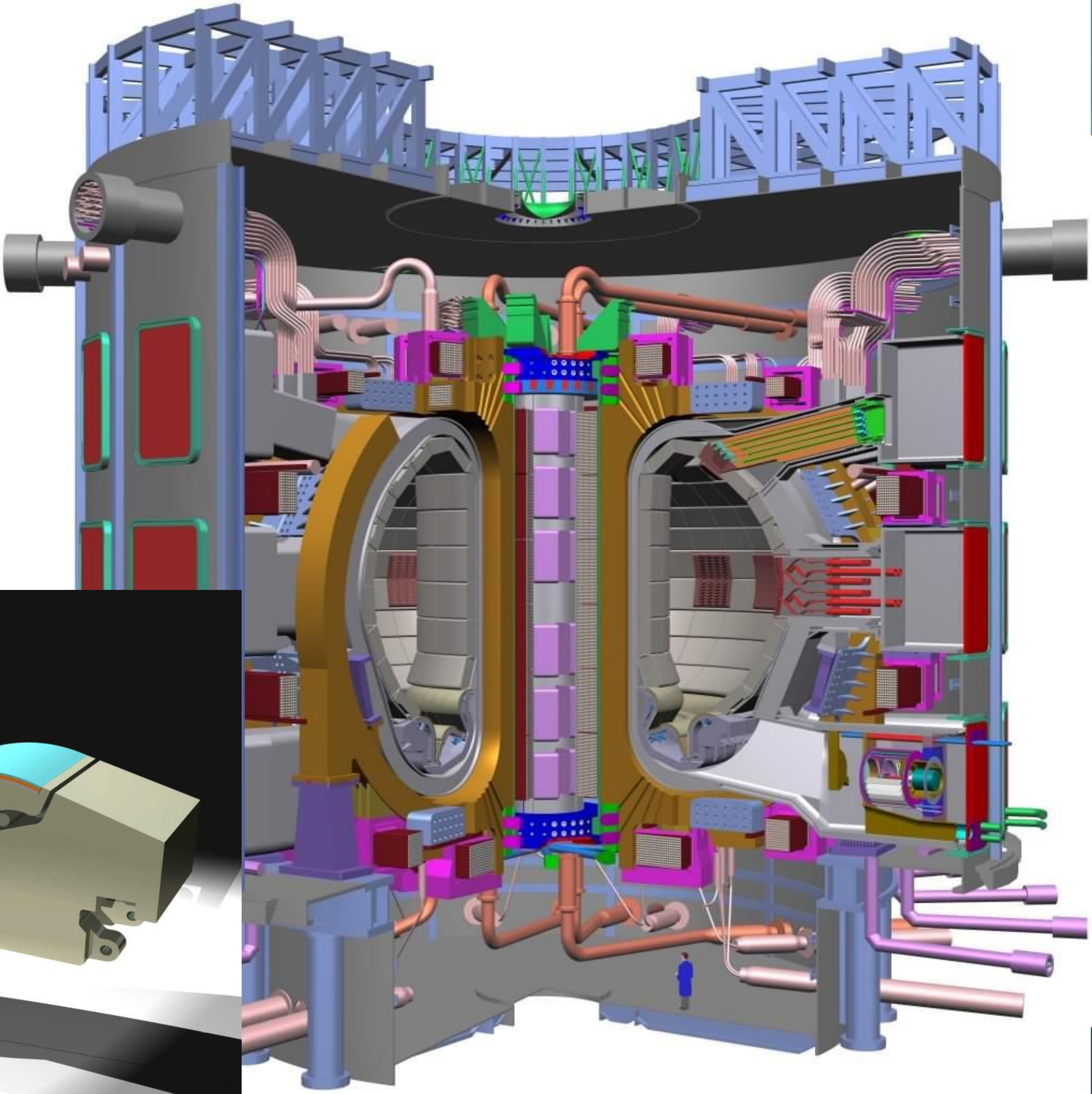


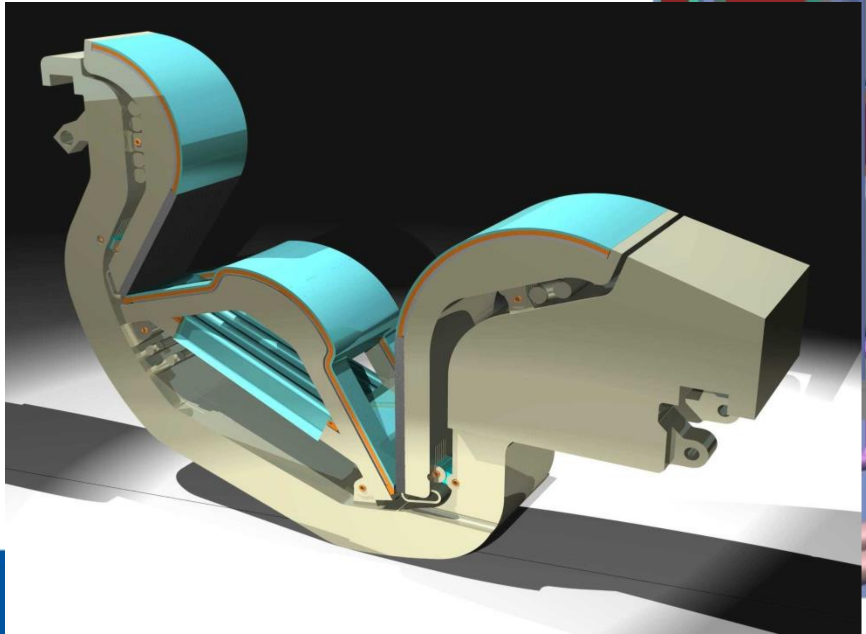
J. Perkins with LASNEX,
see http://aries.ucsd.edu/ARIES/WDOCS/ARIES-IFE/SPECTRA/

2. Radiation fluxes

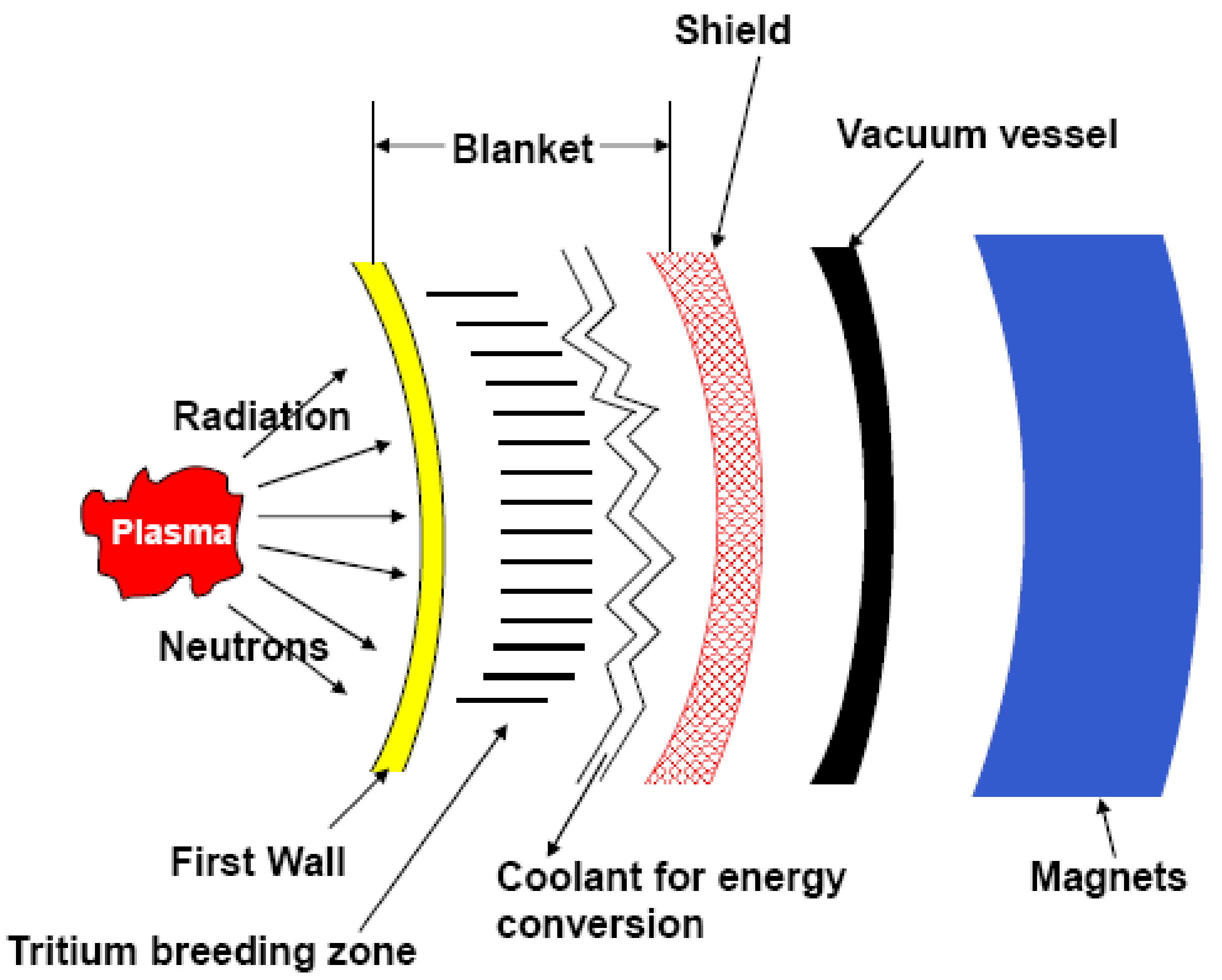
- The radiation fluxes depend on the type of target (direct or indirect)
- High energy **neutrons** and alpha particles are produced by fusion reactions. They are unavoidable.
- In addition, **ion pulses** (dominant with direct targets) and **X-ray pulses** (dominant with indirect targets) will affect surrounding materials.
- Threats:
  - Plasma facing materials: X-rays, ions (no solution with direct drive)
  - Structural materials: neutrons
  - Blanket: neutrons
  - Final lenses: X-rays, ions, neutrons, shrapnel (indirect targets, hard to handle)

Magnetic fusion





Breeding Blanket radial build



2. Radiation fluxes

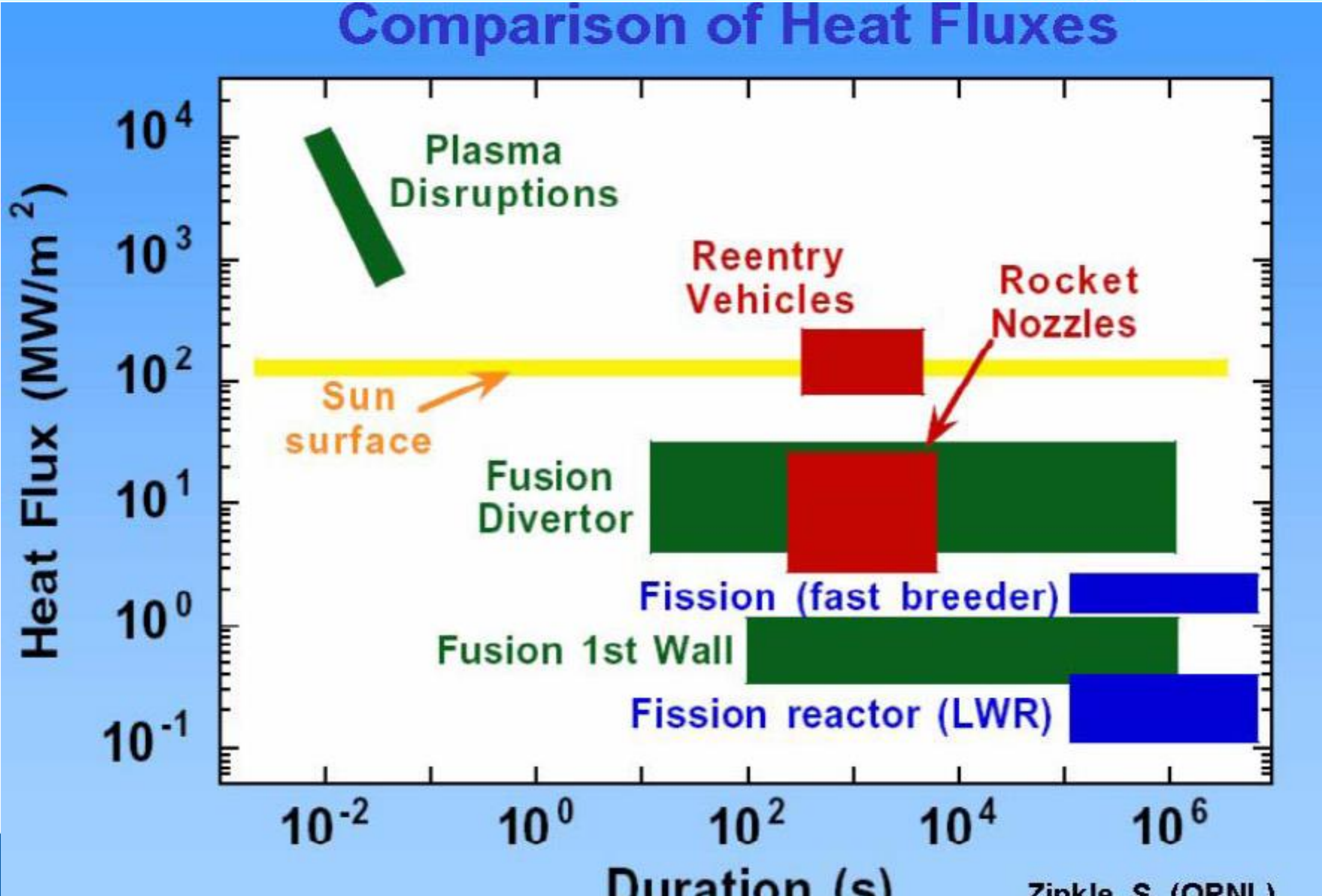
MCF

- Low energy ions produce high thermal loads mainly on first wall and divertor
- In particular, the divertor must withstand very adverse conditions
- In this case the ion irradiation is of pulsed nature very difficult to handle
- Even if plasma control mitigates the discharges, no solution is easily applicable to the divertor

2. Radiation fluxes

Continuous heat fluxes

Pulsed discharges are much more detrimental



2. Radiation fluxes

LASER vs. MAGNETIC FUSION - NEUTRONS

- Laser fusion operates in a explosion-based mode
- Magnetic fusion operates in a quasi-continuous mode
- Therefore, plants producing the same output power will produce the same number of neutrons averaged on long term
- However, in laser fusion they arrive in intense pulses
- In magnetic fusion, they arrive quasicontinuously
- These ways of irradiation may produce effects in materials due to subtle changes in the kinetic evolution of the microstructure

2. Radiation fluxes

DIRECT TARGET LASER vs. MAGNETIC FUSION – IONS

- With direct targets 30% of the energy is produced in the form of ion pulses
- The most detrimental situation in magnetic fusion is found in the divertor where ion pulses are discharged
- In laser fusion the ions have a significant energy (keV-MeV) whereas in magnetic fusion their energy is below 100 eV
- This difference produces different atomistic effects but in terms of thermal load the low energy ions are worse due to the resulting high power density (see next)

2. Radiation fluxes

INDIRECT TARGET LASER vs. MAGNETIC FUSION – X-RAYS

- With indirect targets 30% of the energy is produced in the form of X-ray pulses
- These ions produce a huge thermal load in all materials a few meters away from the target to the extend that means to mitigate the X-rays are necessary (**residual gas**)
- In terms of thermal loads the situation is anlogous in the magnetic fusion divertor when subject to disruption discharges
- In this case mitigation strategies are more difficult, and for this reason the **divertor is compromised**

3. Power plant conepts

- Many plant concepts have been proposed.
- The major challenge is how to resist irradiation
- If no solution appears the community focus is to develop new materials
- The solution is a compromise to solve many concerns
- Next a summary of concepts to operate under different scenarios is given for ICF power plants

3. Power plant conepts

Compatibility of ignition and chamber schemes

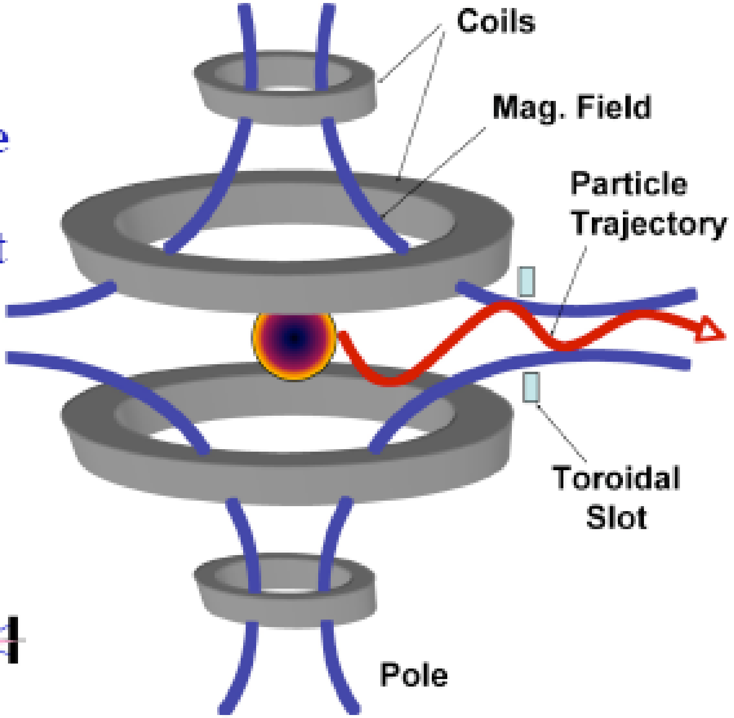
Target Type	Dry Wall Chamber	Dry Wall Gas Protected Chamber (Xe density in the range 10^{-2} mbar @ST)	Wet Wall Chamber
Central ignition-Indirect target Hohlraum	Too high thermal load due to X-ray pulses	Provided gas does not interfere injection, tracking or laser	?
Central ignition-Direct target	Provided first wall and final lens materials exist	Probably it is impossible to inject target	?
Fast ignition-Direct target (shell and cone)	Provided first wall and final lens materials exist	Gas incompatible with PW laser for fast ignition	?
Shock ignition-Direct target	Provided first wall and final lens materials exist	Probably it is impossible to inject target	?

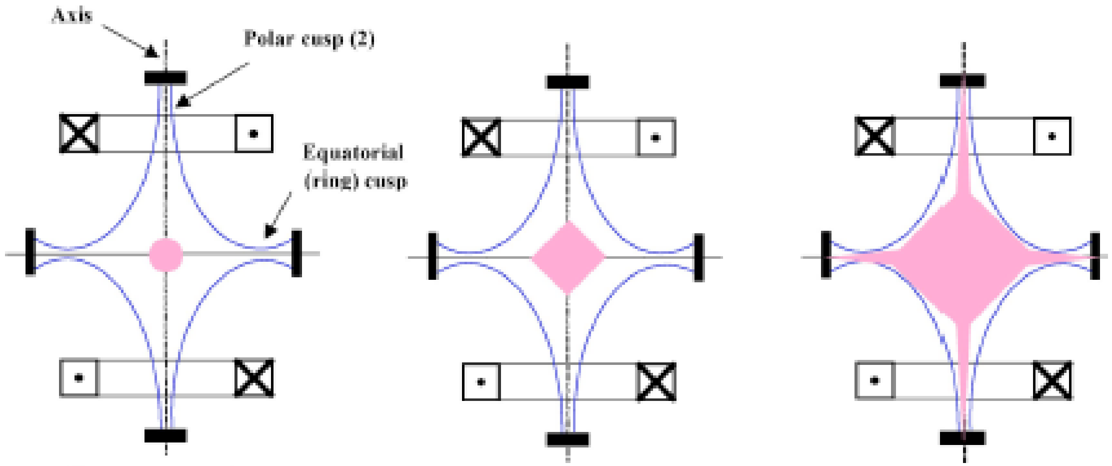
3. Power plant conepts

- Gas protected ICF chambers operating with indirect drive targets seem to work… but if one thinks of the final optics (shrapnel) cannot be so sure
- More work will be needed
- Exotic designs have also appeared, e.g., magnetic intervention, or HYLIFE... next

Utilizing a Cusp Field to Create a Magnetic Bottle Preventing the Ions from Reaching the Wall and Guiding them to Specific Locations at the Equator and Poles

- Utilization of a cusp field for such magnetic diversion has been experimentally demonstrated previously
  - 1980 paper by R.E. Pechacek et al.,
- Following the micro-explosion, the ions would compress the field against the chamber wall, the latter conserving the flux. Because of this flux conservation, the energetic ions would never get to the wall.





Plasma expansion initially spherical

Ion cloud deforms as it encounters cusp field

Ions leak out through the cusps

3. Power plant conepts

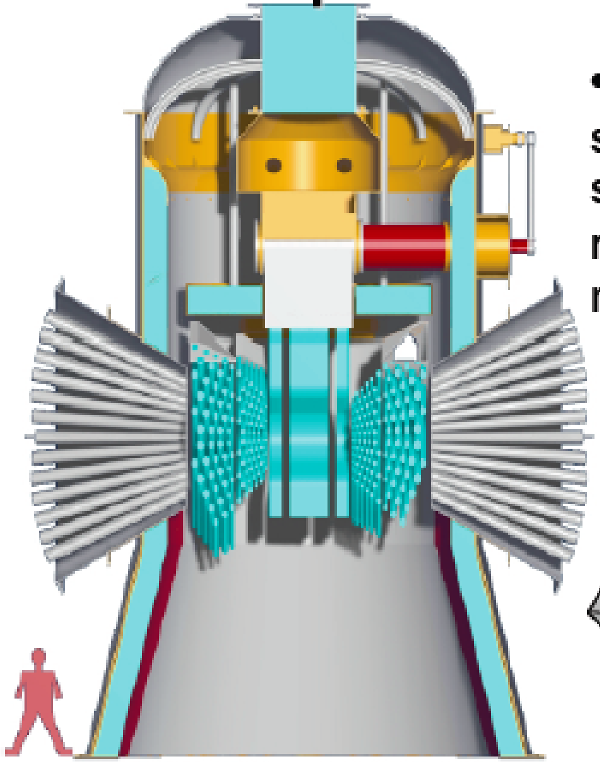
Magnetic intervention

- It can be a solution for ion mitigation
- However, the technical complexity makes us to explore alternative routes (new materials development)

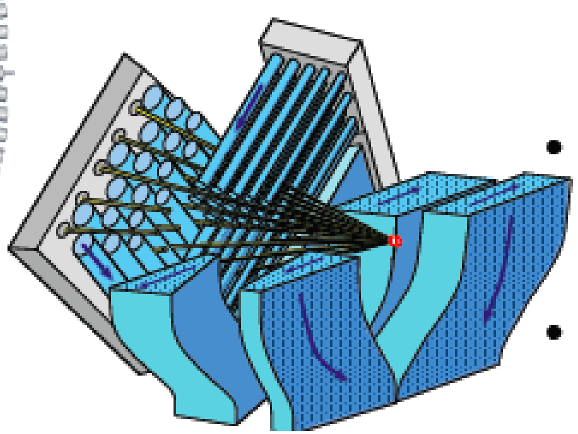
3. Power plant conepts

Reactor / Power Plant System Possibilities of Blankets

HYLIFE is a prime example of a thick liquid wall chamber concept



- Thick liquid "pocket" shields chamber structures from neutron damage and reduces activation



- Oscillating jets dynamically clear droplets near target (clear path for next pulse)
- Lifetime of FW can be greatly extended, possibly for life-of-plant, depending on material choice and liquid thickness
- Well suited to indirect-drive targets, currently favored by HIF (and Z-pinch) community
- Preferred liquid: $LiF\text{-}BeF_2$ (Flibe)

3. Power plant conepts

HYLIFE

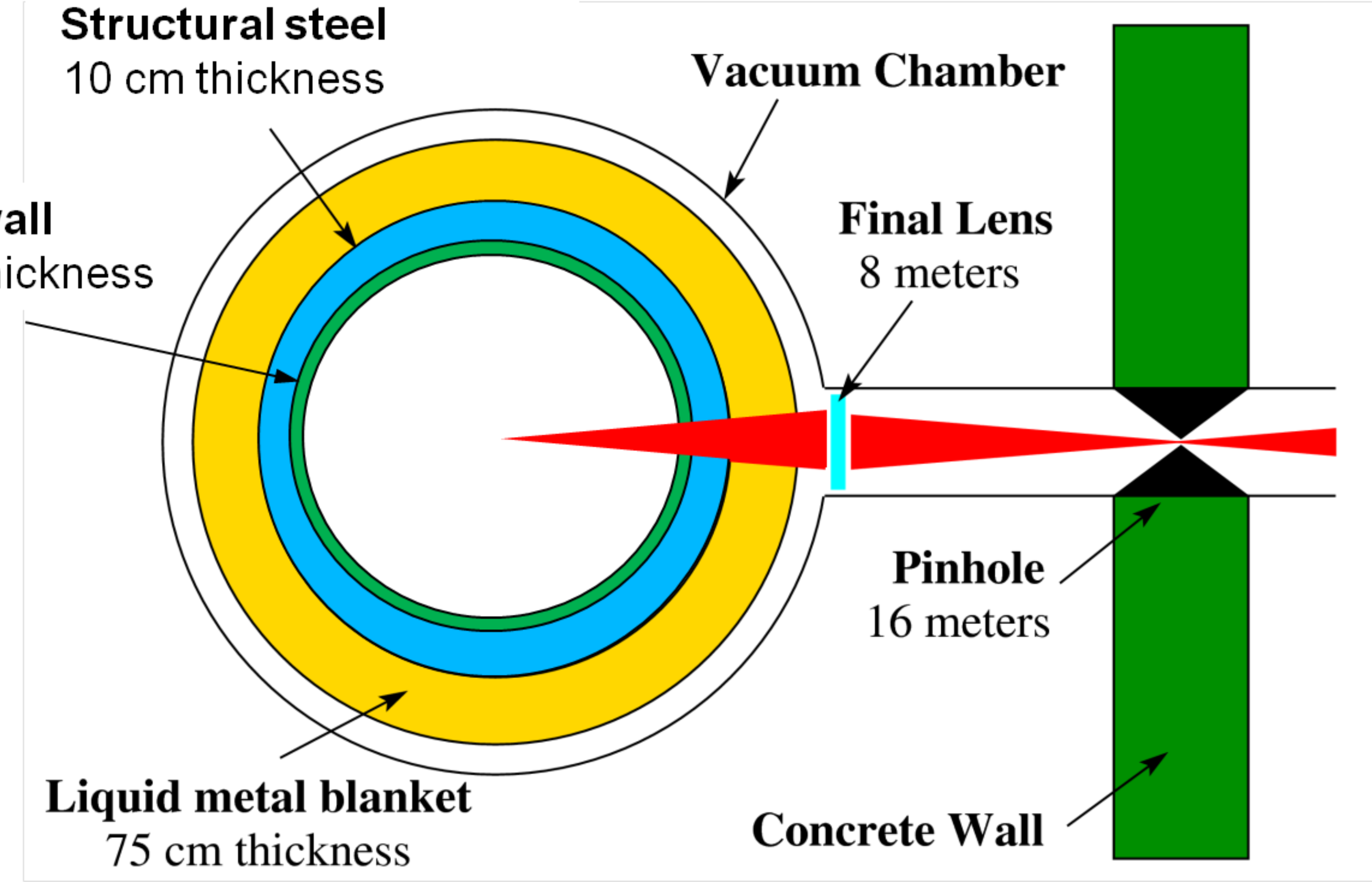
- HYLIFE is a special case
- Technically difficult
- Keeping laminar flow might be difficult

4. Final optics

- Optical elements are necessary in every plant
- They are exposed to irradiation
- We focus next on final optics in ICF with direct drive targets
- Very complex problem
  - Neutron irradiation produces color centers
  - In addition, neutron irradiation leads to non-uniform temperature profile resulting in aberrations
  - Pulsed ion irradiation must be mitigated
  - Swift ions lead to high electronic excitation problems

4. Final optics

Sketch of HiPER power plant



4. Final optics

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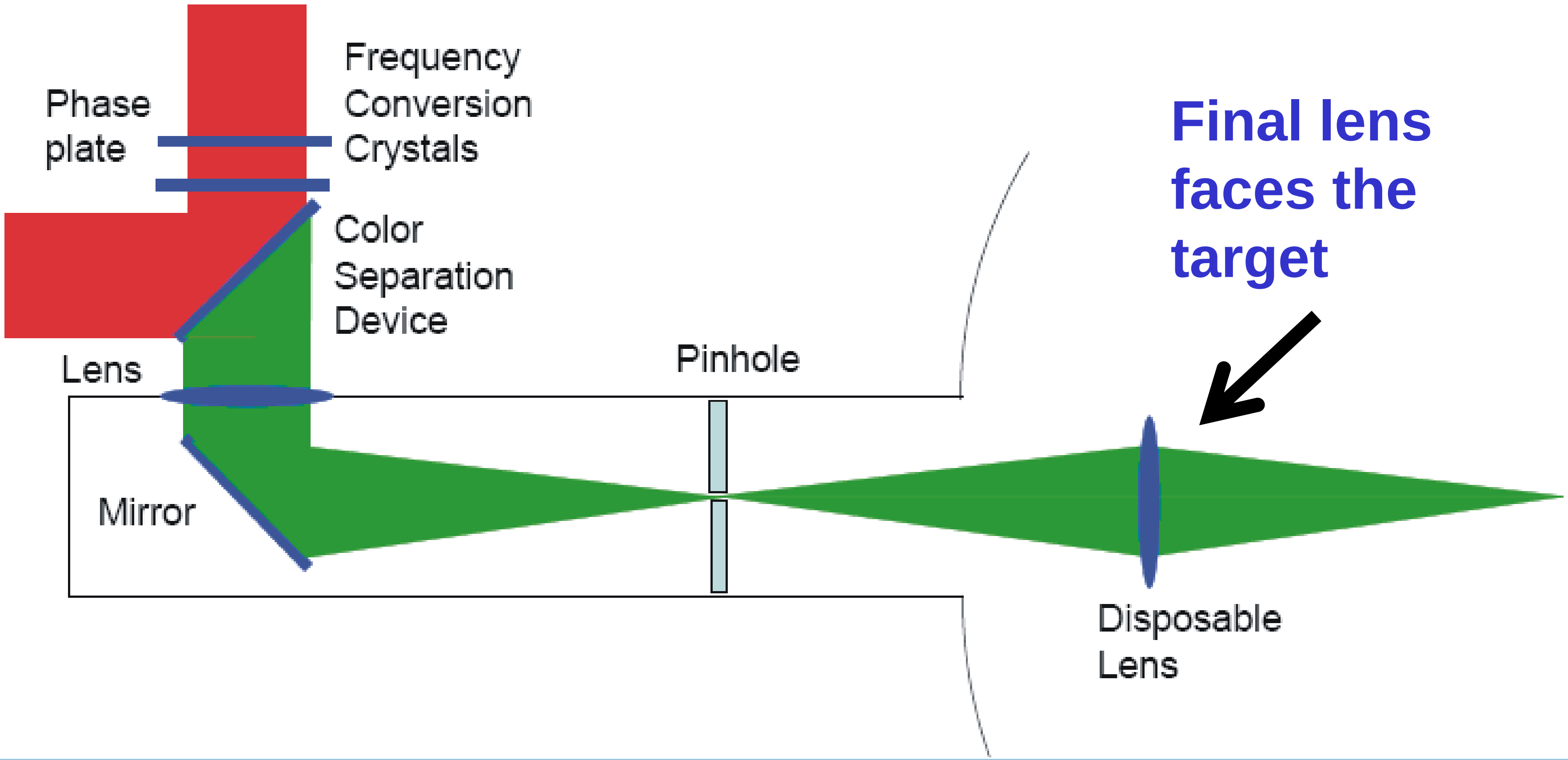
4. Final optics

Transmission optics offers simple solutions

- small spot $\Rightarrow$ small focus



Final lens faces the target

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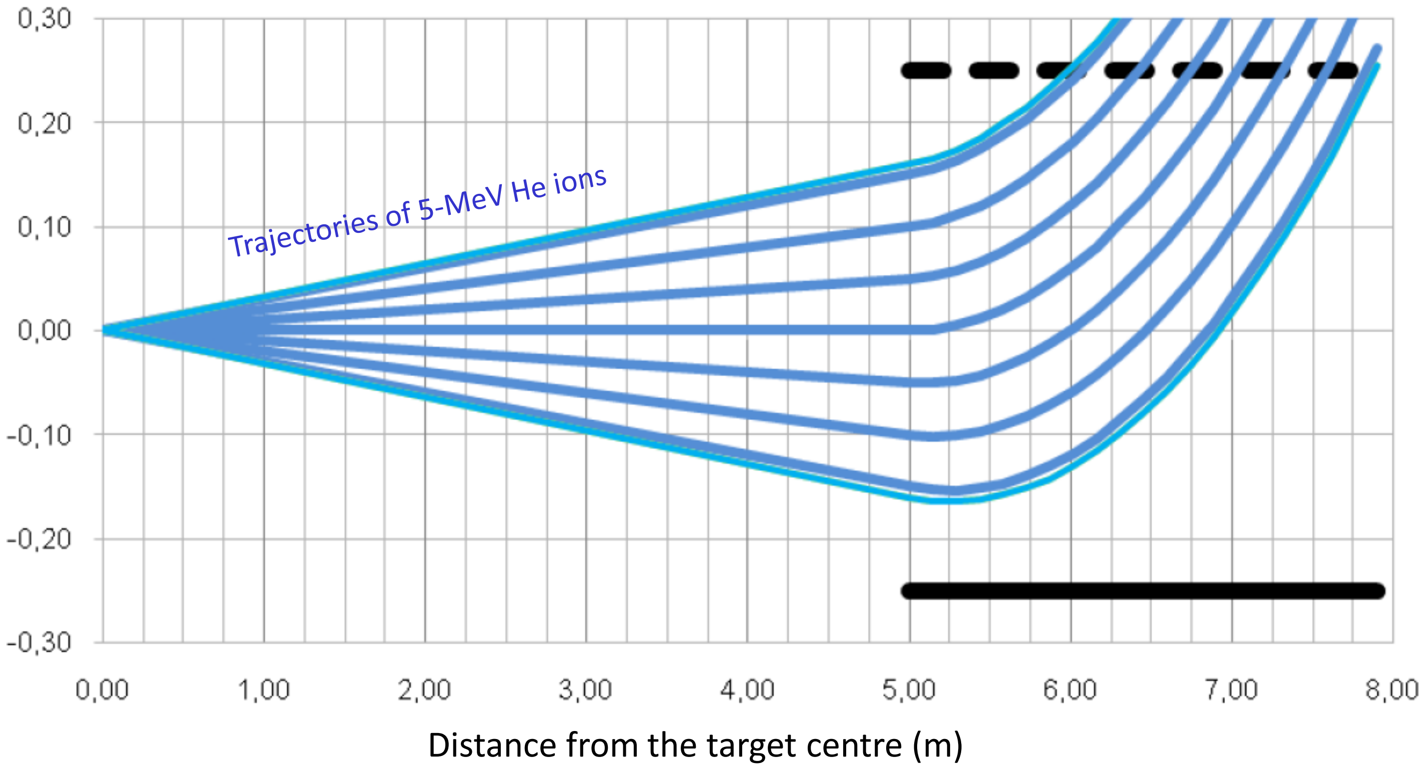
4. Final optics

	HiPER				
	<E> (MeV)	Pulse width (ns)	Pen-depth (mm)	ED demo (J/cm^3)	ED prot. (J/cm^3)
Burnt products (^4He)	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

Lenses at 8 m:
Ions must be somehow mitigated

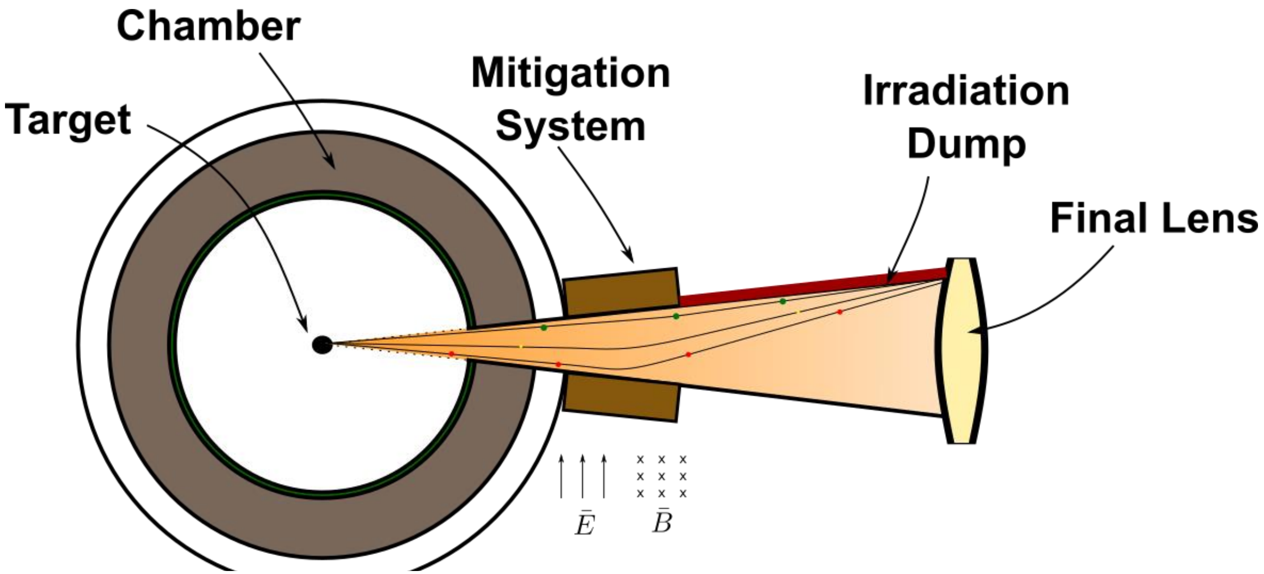
4. Final optics

Ion mitigation (not trivial)



B. Rus

4. Final optics

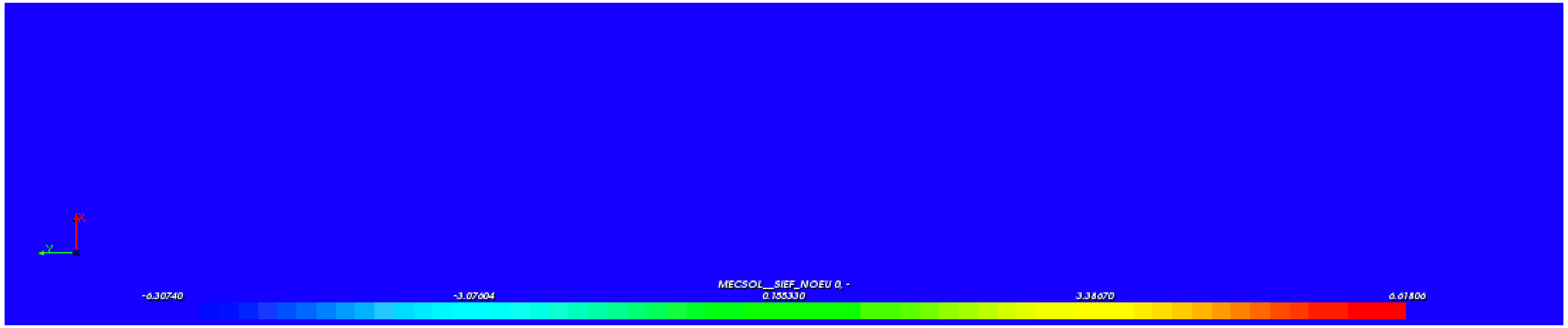


Parameter	Value	
System Length (m)	1	
Iron Gap (m)	0.35	
Deflected Angle (mrad)	85	
Curvature Radius (m)	11.6	
Deflected Ion	He	Au
Charge State	1	6
Energy (MeV)	20	45
Magnetic Rigidity (T m)	1.3	2.3
Magnetic Field (T)	0.1	0.2

A.R. Paramo, PhD thesis

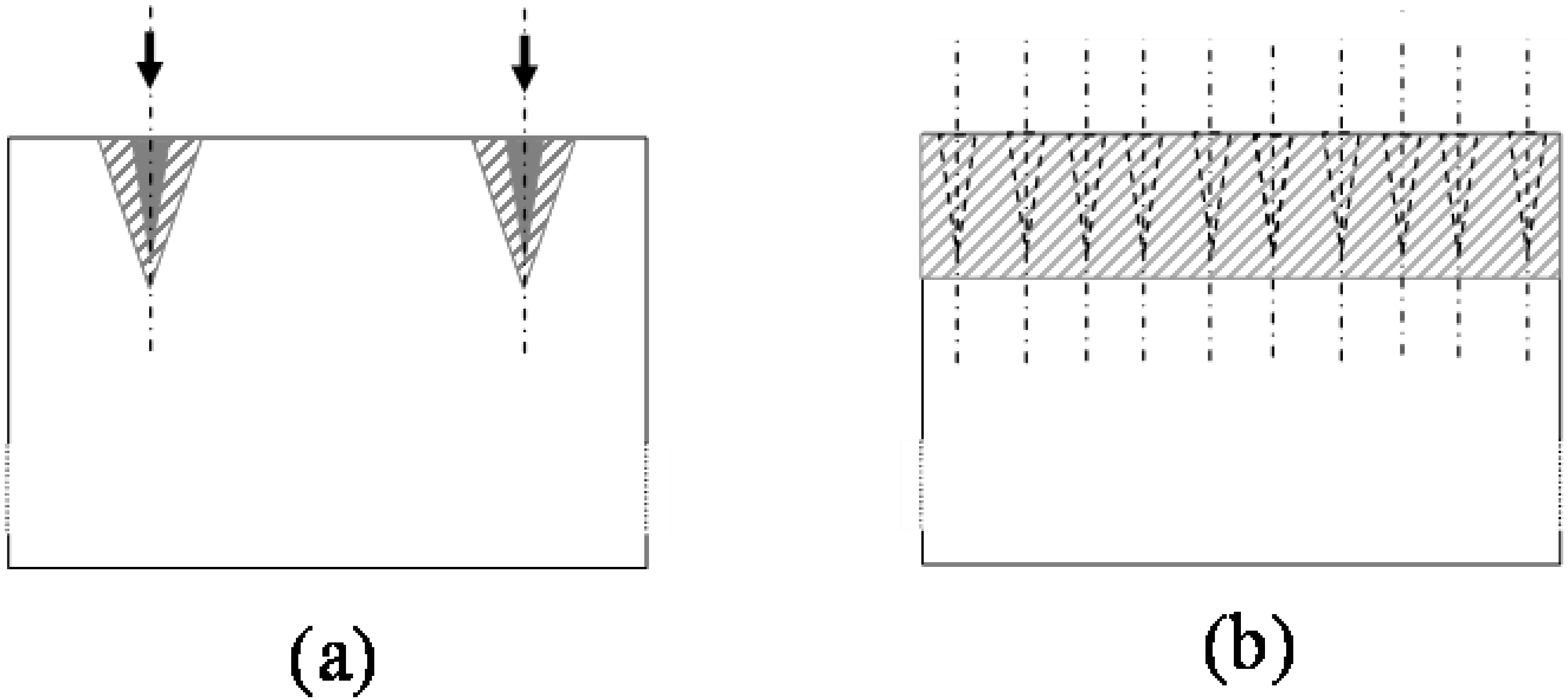
4. Final optics

Partial mitigation of ions might be not enough, particularly, due to the presence of swift ions



- Electronic sputtering
- Nano-crater
- Nano-track
- Severe modification of properties
- Defect formation

4. Final optics

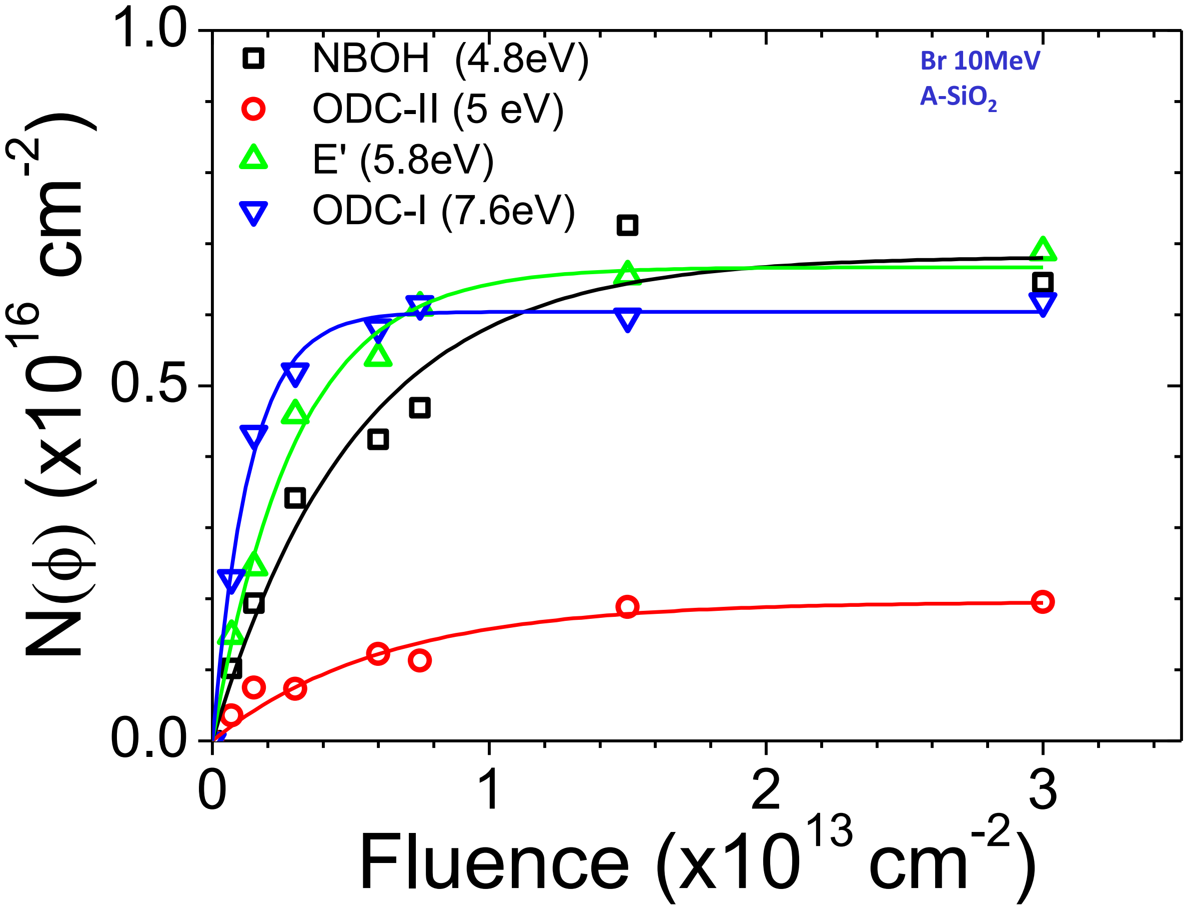


Ion tracks

4. Final optics

Color centers due to swift ion irradiation

Observed by means of in situ optical absorption measurements

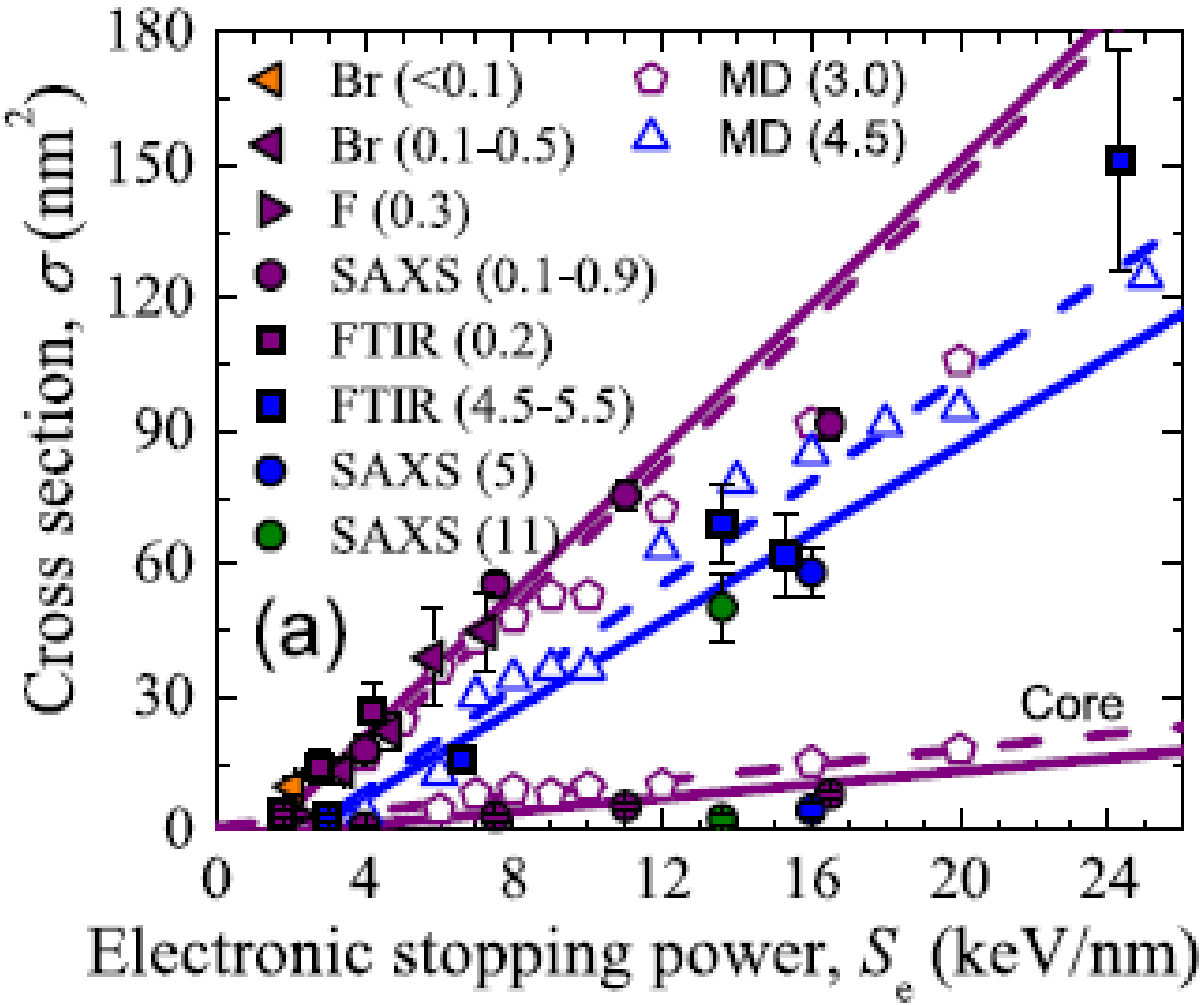


4. Final optics

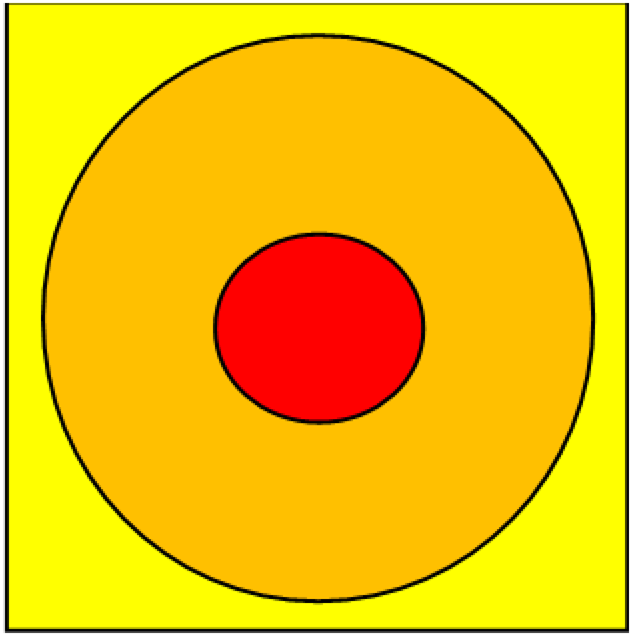
Measurements and simulations show the cross-section of tracks produced by swift ion irradiation in silica

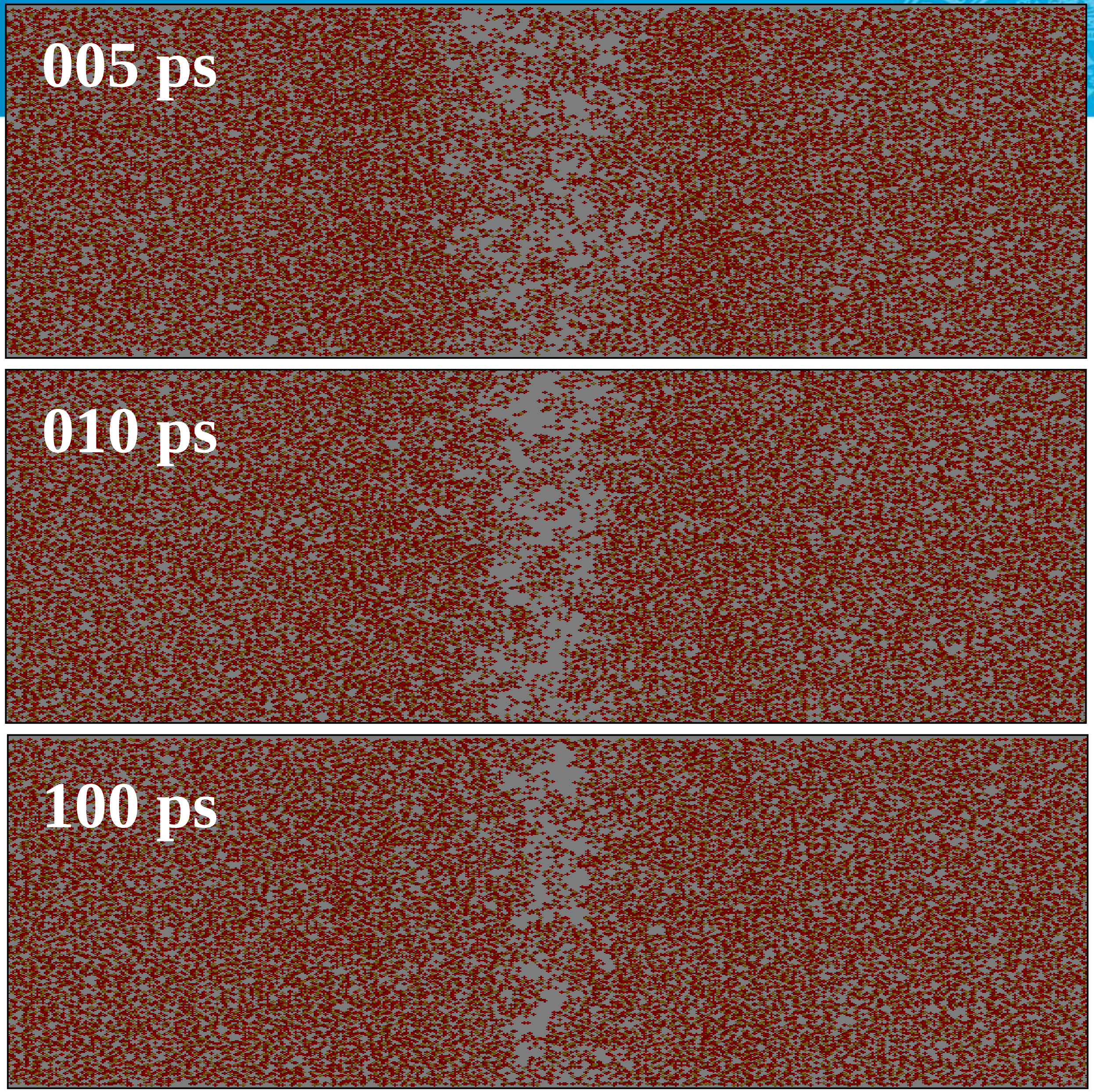
Cross section = πR^{22}

R is the track radius



MD applied to this problema with good results
Partial ion mitigation is a concern for ICF

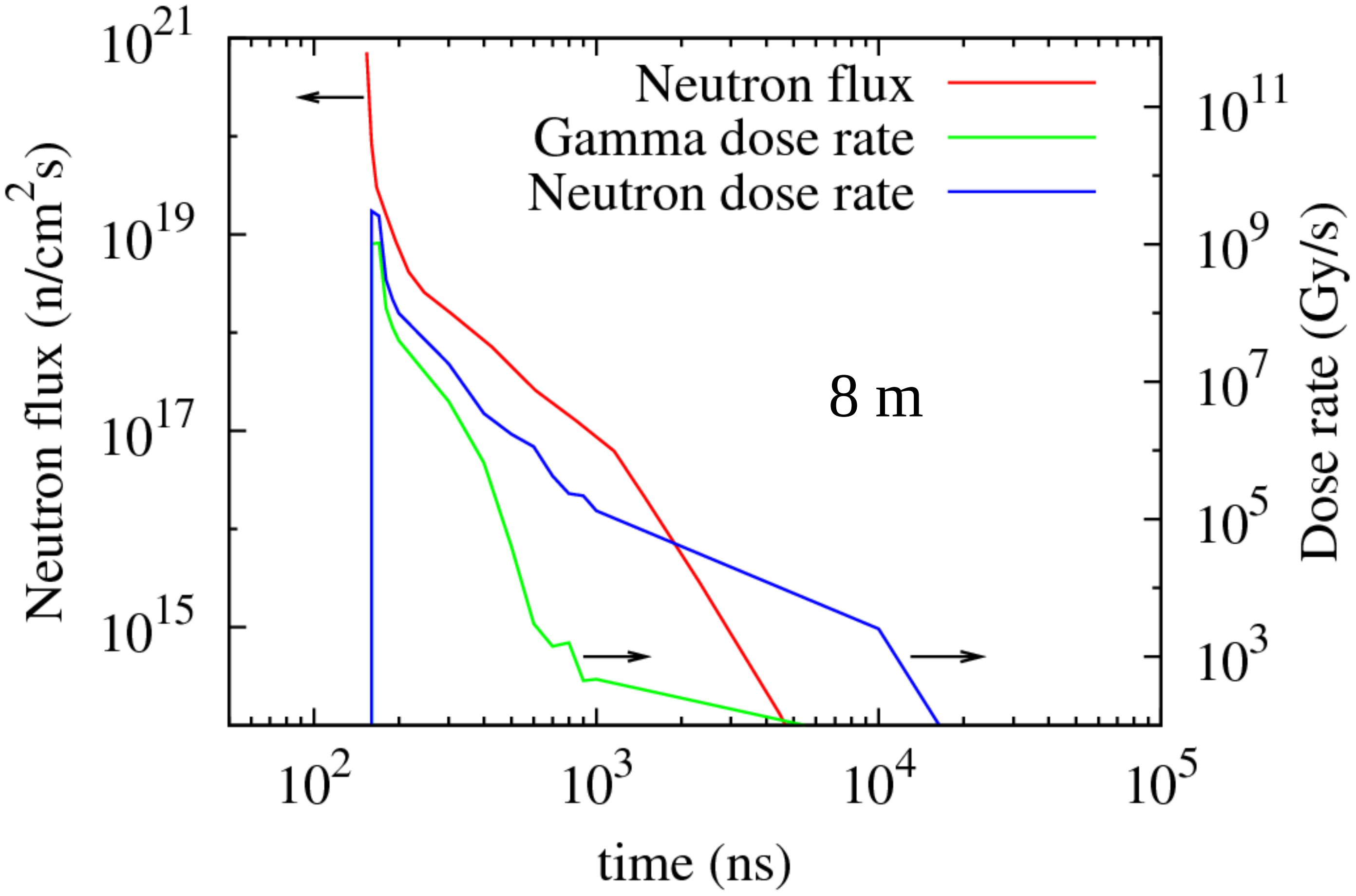




Rivera et al. Scientific Reports 7, 10641

4. Final optics

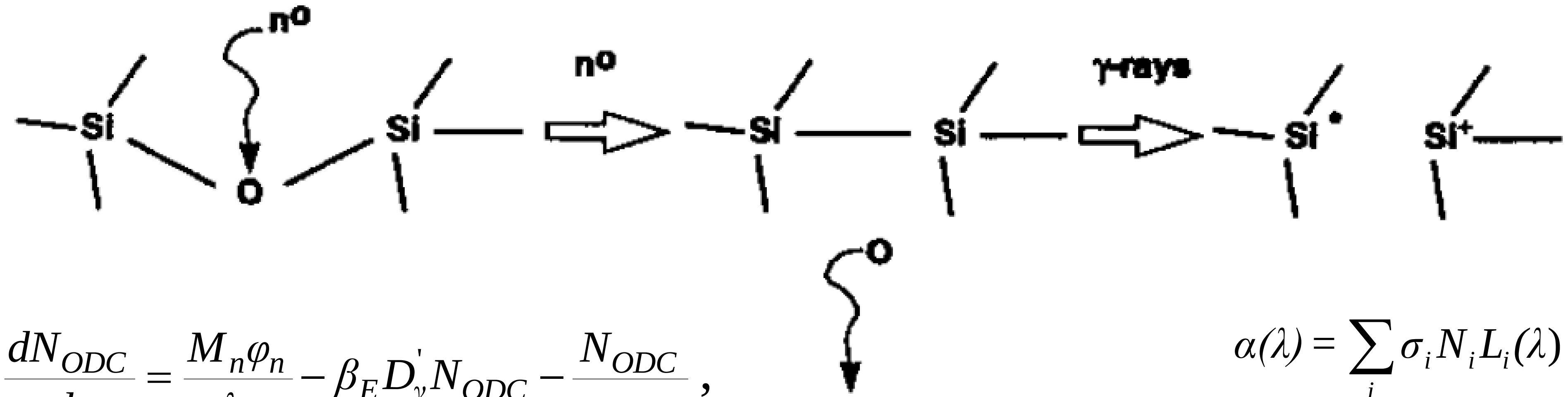
Neutrons and gammas will unavoidably reach the lenses



Color center evolution based on model

ODC
245 nm

E'
213 nm



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

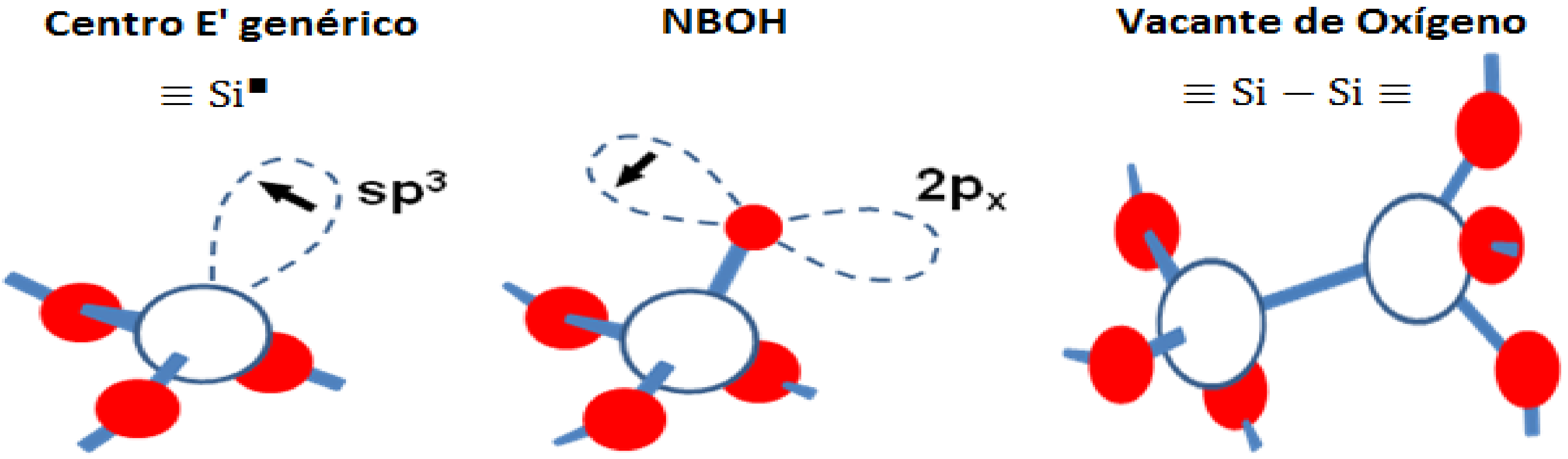
$$\frac{dN_{E'}}{dt} = \beta_E D_\gamma^{'} N_{ODC} - \frac{N_{E'}}{\tau_{anneal}} \, ,$$

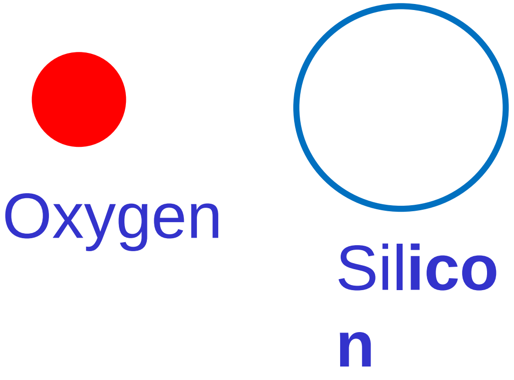
$$\alpha(\lambda) = \sum_i \sigma_i N_i L_i(\lambda)$$

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

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

4. Final optics

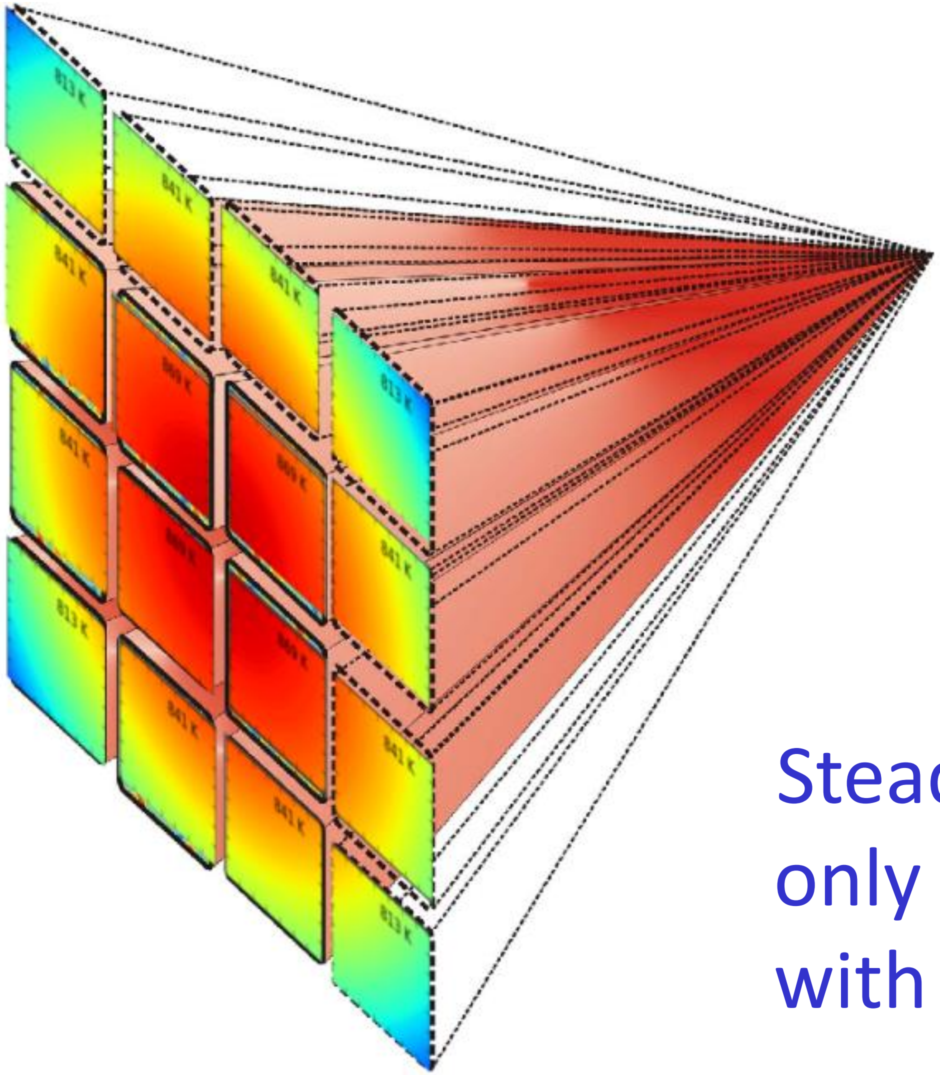




Neutron irradiation produces color centers

Constant temperature needed (>800K) to anneal them out

4. Final optics



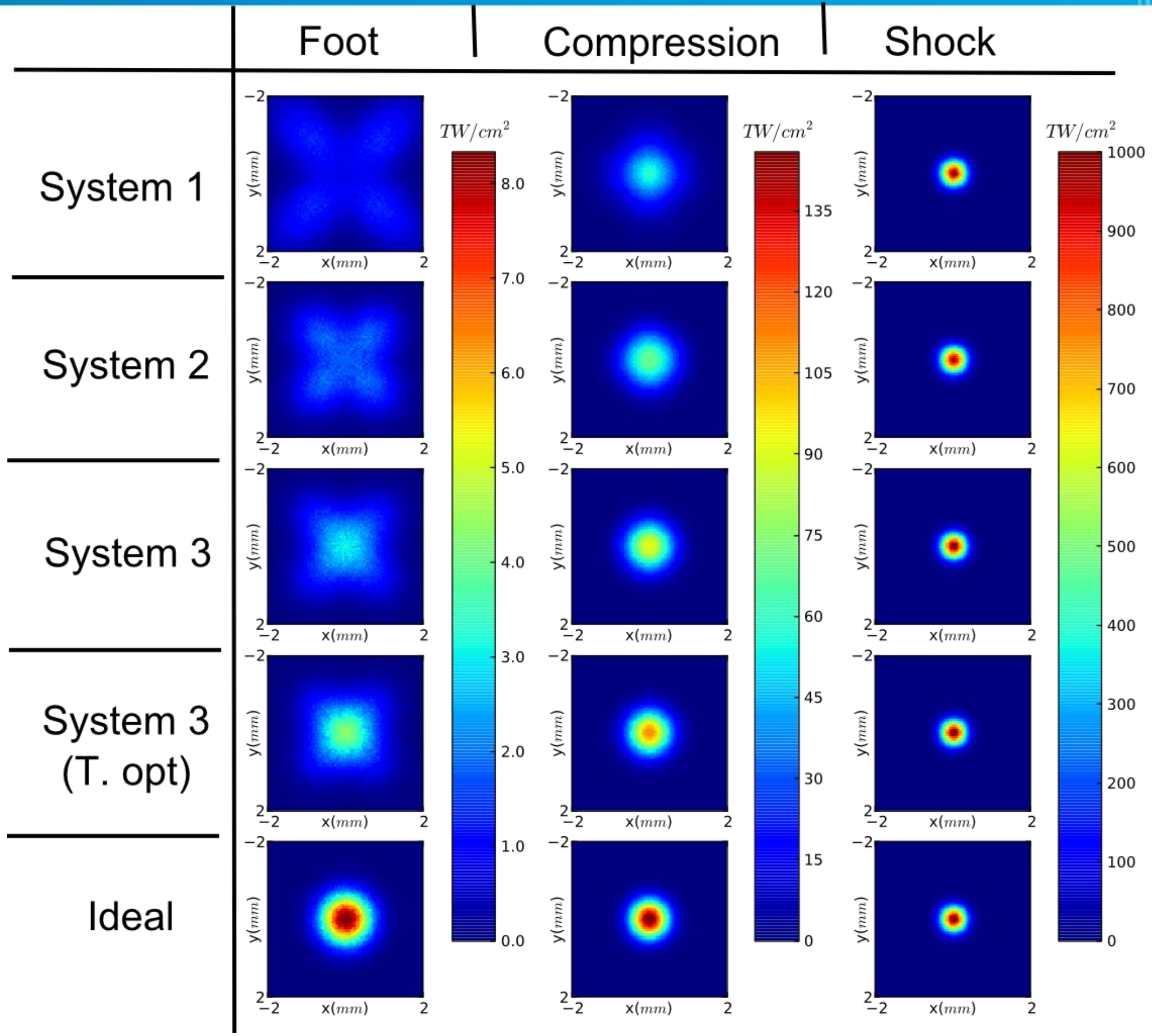
Final lenses of a laser fusion reactor

Steady temperature considering only neutron irradiation simulated with FE methods

4. Final optics

Temperature control by contact resistances (different cases tested) not appropriate to avoid aberrations due to the low thermal conductivity of silica

Monte Carlo ray tracing to study aberrations



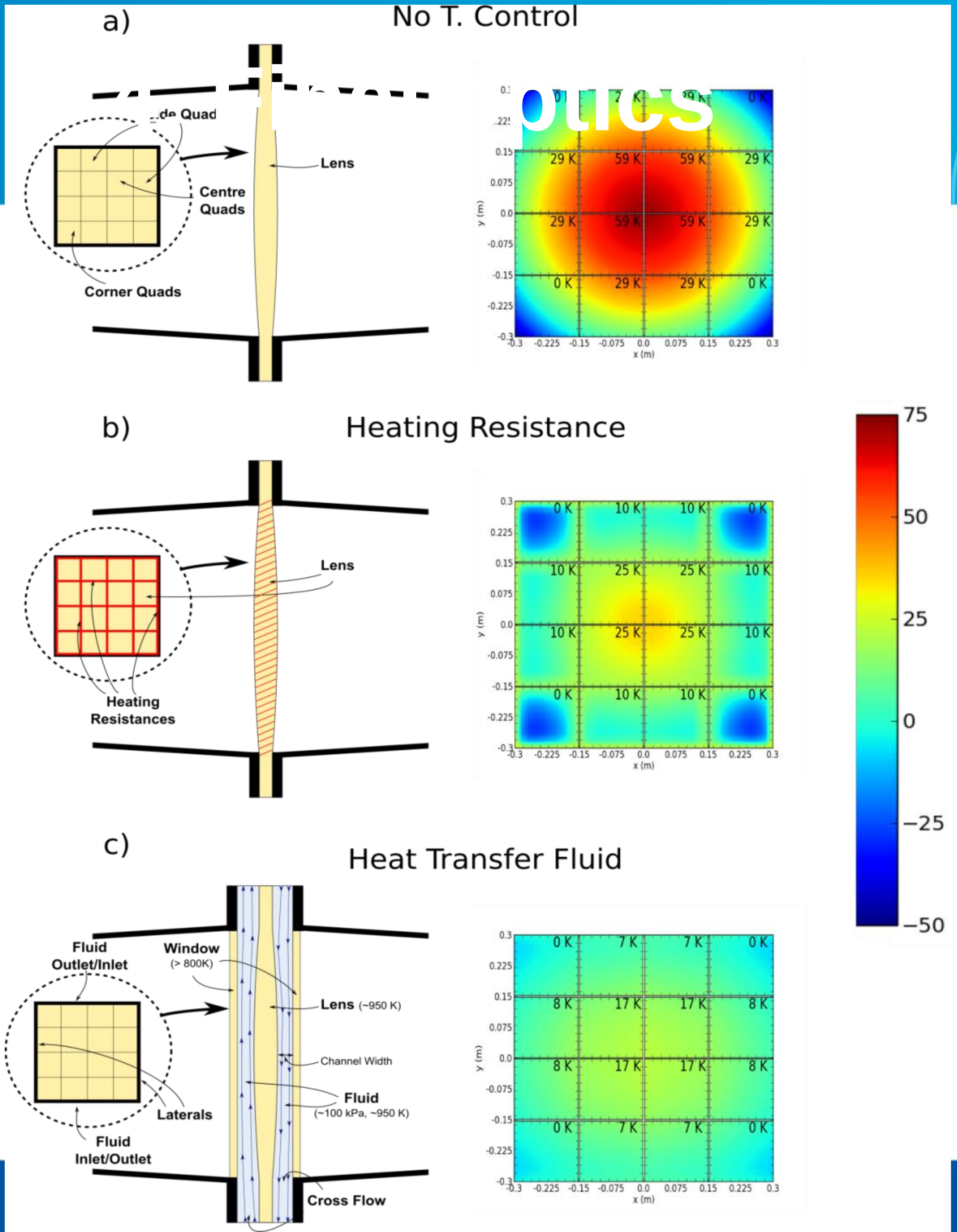
To operate under pre-commercial power plant conditions (150 MJ @ 10 Hz):

Lenses at 16 m

Smooth temperature only possible by means of a heat transfer fluid.

Possible solution!

A.R. Páramo et al. Nucl. Fusion 54 (2014) 123019



4. Final optics

- Ions must be mitigated (partial mitigation probably not enough)
- To anneal out color centers high temperature is needed
- To avoid aberrations a temperature control system based on fluid flow is needed
- Pre-commercial conditions require to position the lenses at large distance (16 m conservative)
- Shrapnel not addressed

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5. First wall materials

First wall materials = plasma facing materials

Their role is to protect other materials

They need to survive extreme conditions

No solution for some applications (divertor, ICF with direct target)

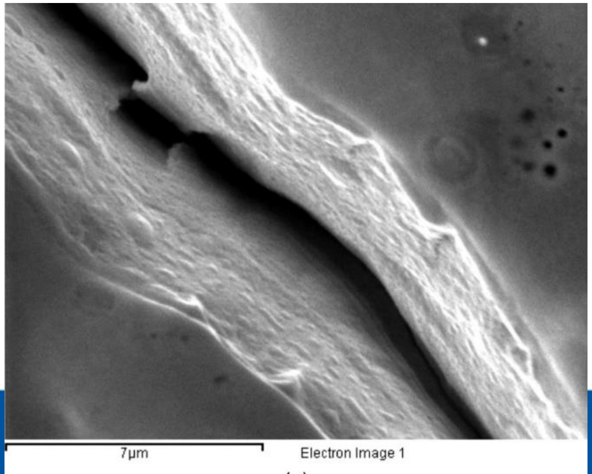
We focus on a **promising solution** based on hollow nanoparticles

5. First wall materials

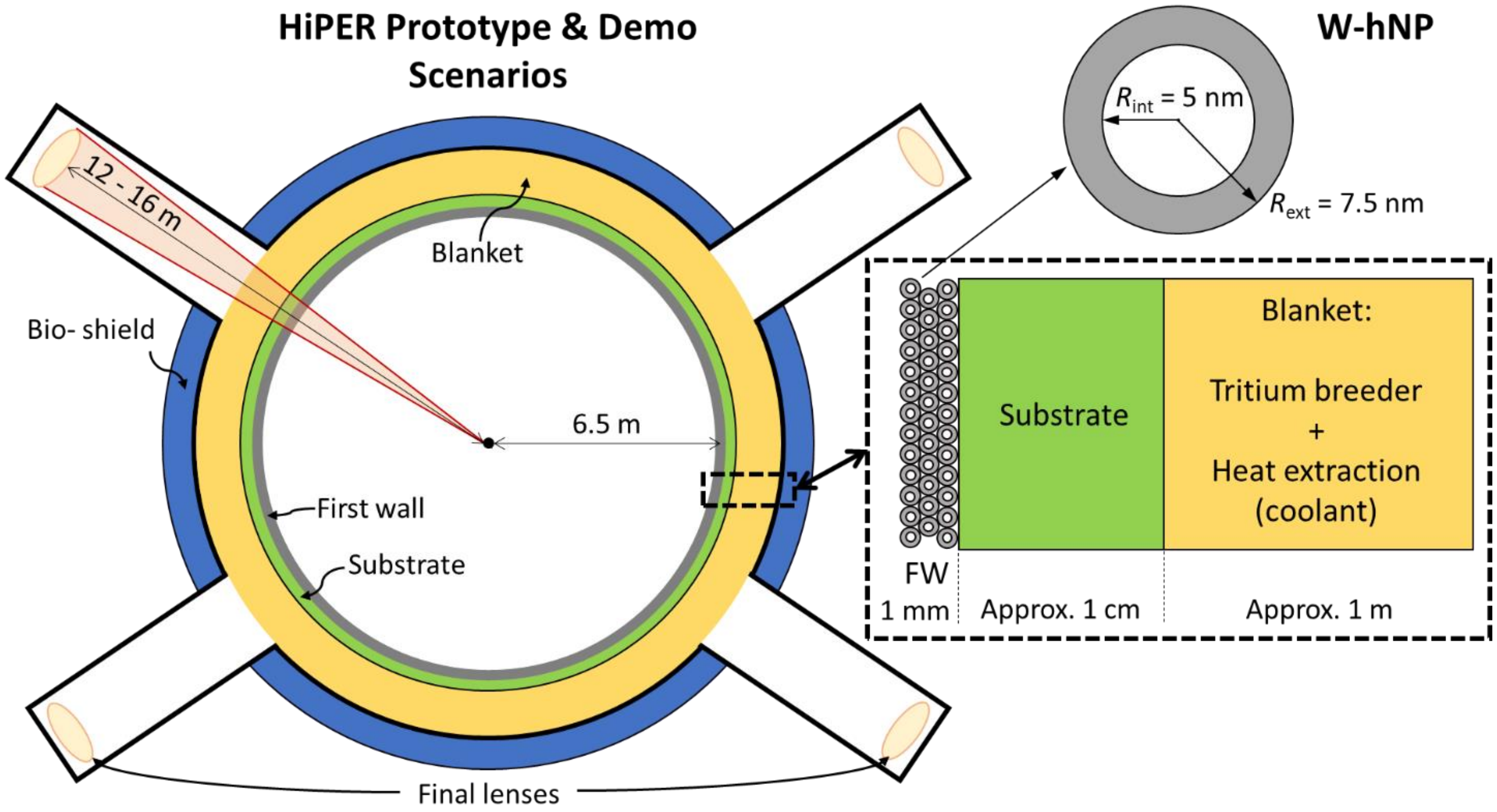
- The most extreme conditions appear in pulsed events.
- **Laser fusion**
  - Target explosion
  - Dry wall evacuated chambers ⇒ ~25% energy in **ion pulses**
  - No materials to withstand the pulses ⇒ No solution
- **Magnetic fusion**
  - Plasma discharges in edge localized modes (ELM)
  - **High flux of slow ions** that affect mainly the divertor
- Despite the good properties of W, defect generation is the ultimate concern

Severe cracking even at low fluence
(10^{15} He cm^{-2} in pulses of 500 ns, energy ~600 keV)

Renk et al. Fus. Sci. Tech. 61 (2012) 57



5. First wall materials



. Díaz-Rodríguez et al. Nuclear Fusion 60 (2020) 096017

Hollow nanoparticles:

- Self-healing material
- They resist huge temperatures and pressures
- When pressurized better ion stopping properties and better heat conductivity

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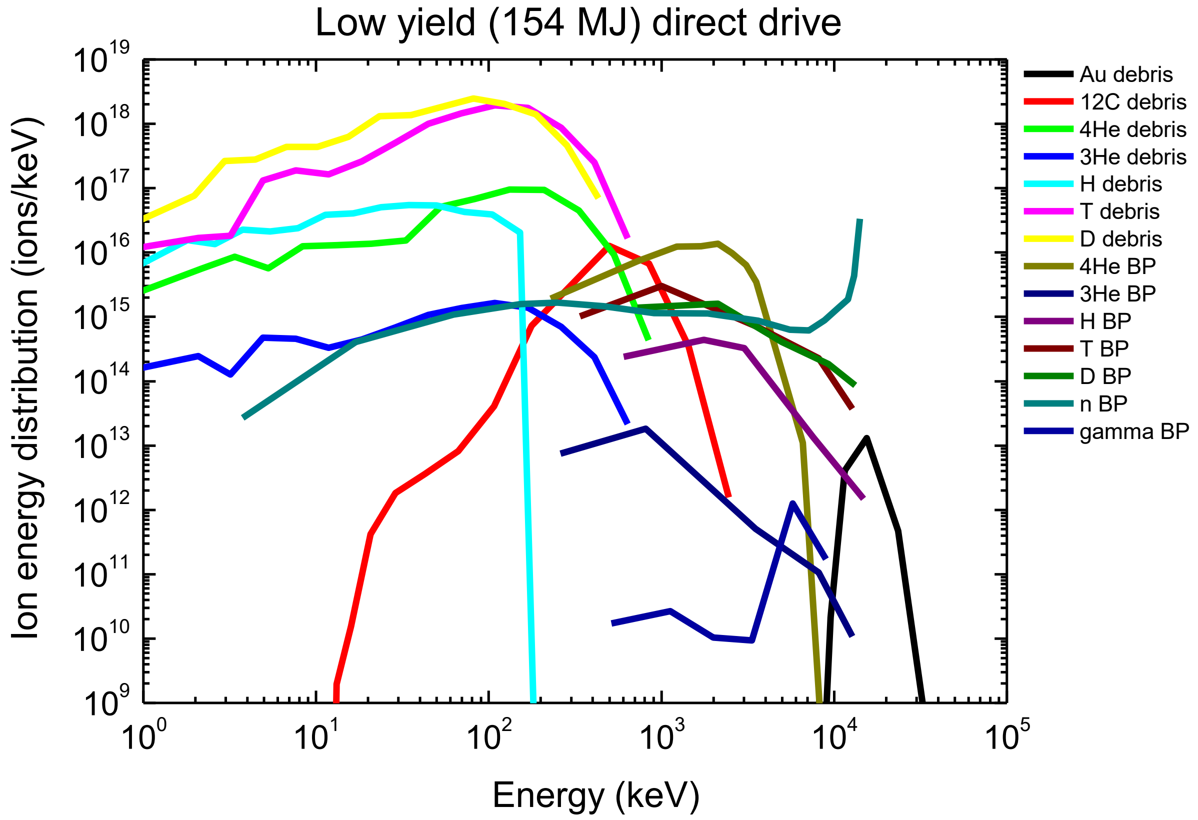
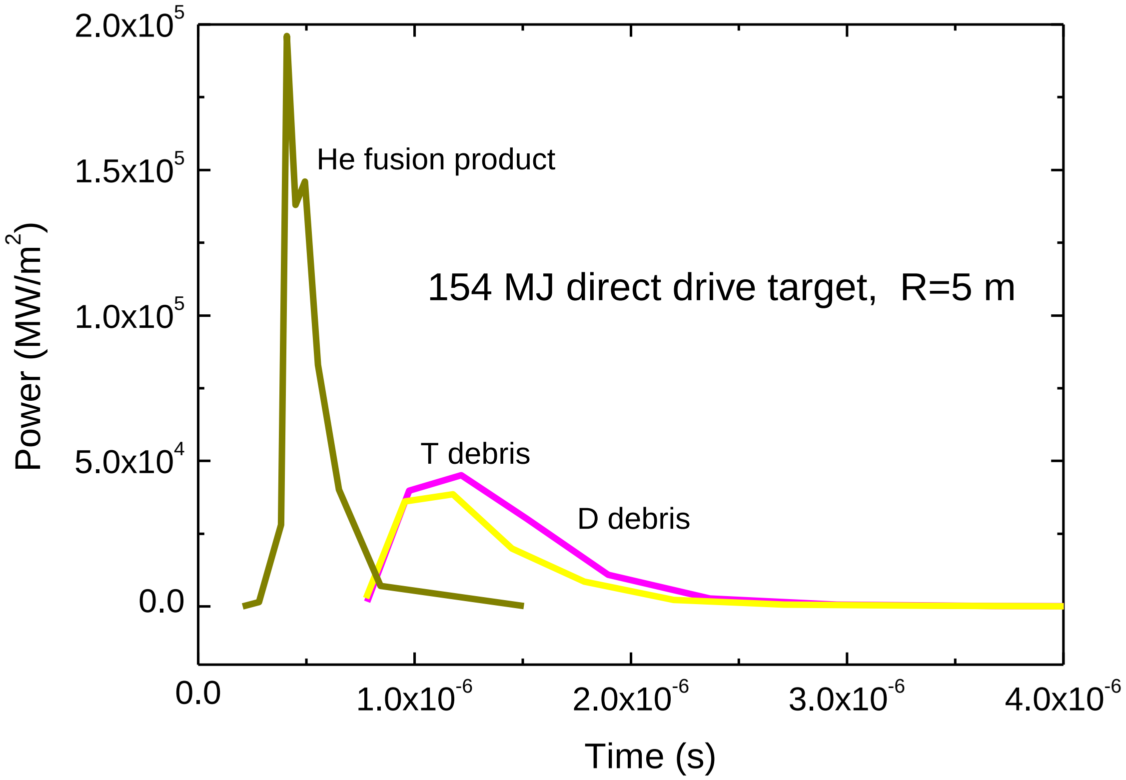
5. First wall materials

Ion pulses in laser fusion





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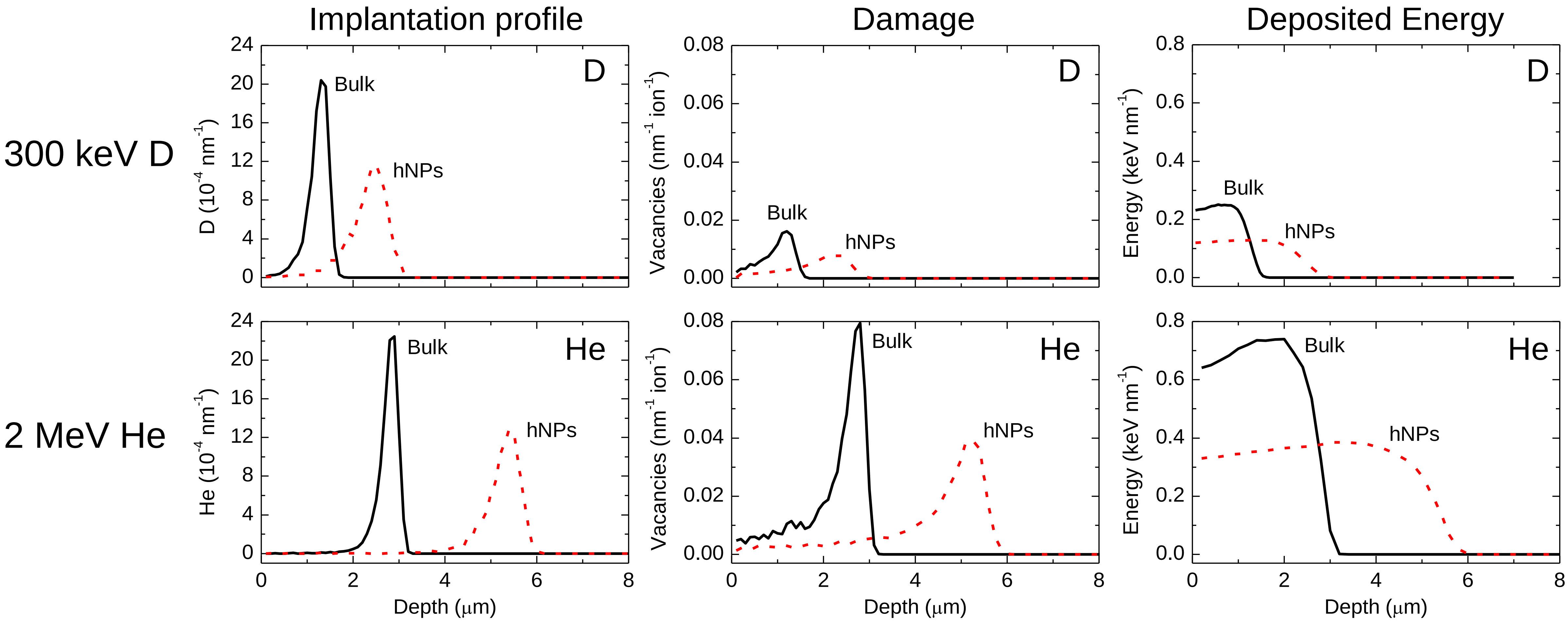

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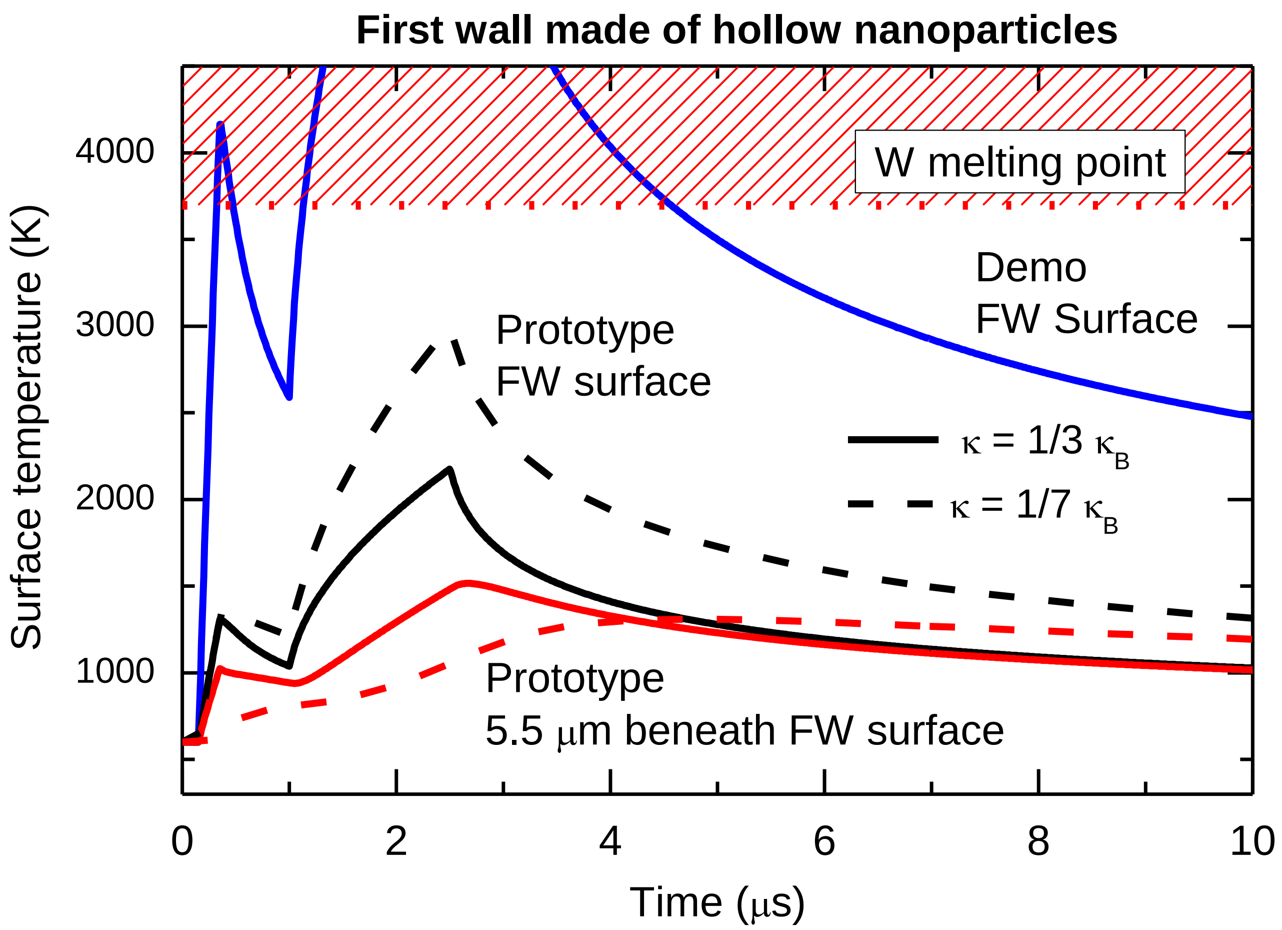
Ion pulses in laser fusion

HiPER	*Prototype*	*Demo*
Yield (MJ)	50	154
Rep. Rate (Hz)	1 – 10	10 – 20
Power (GW)	< 0.5	> 1



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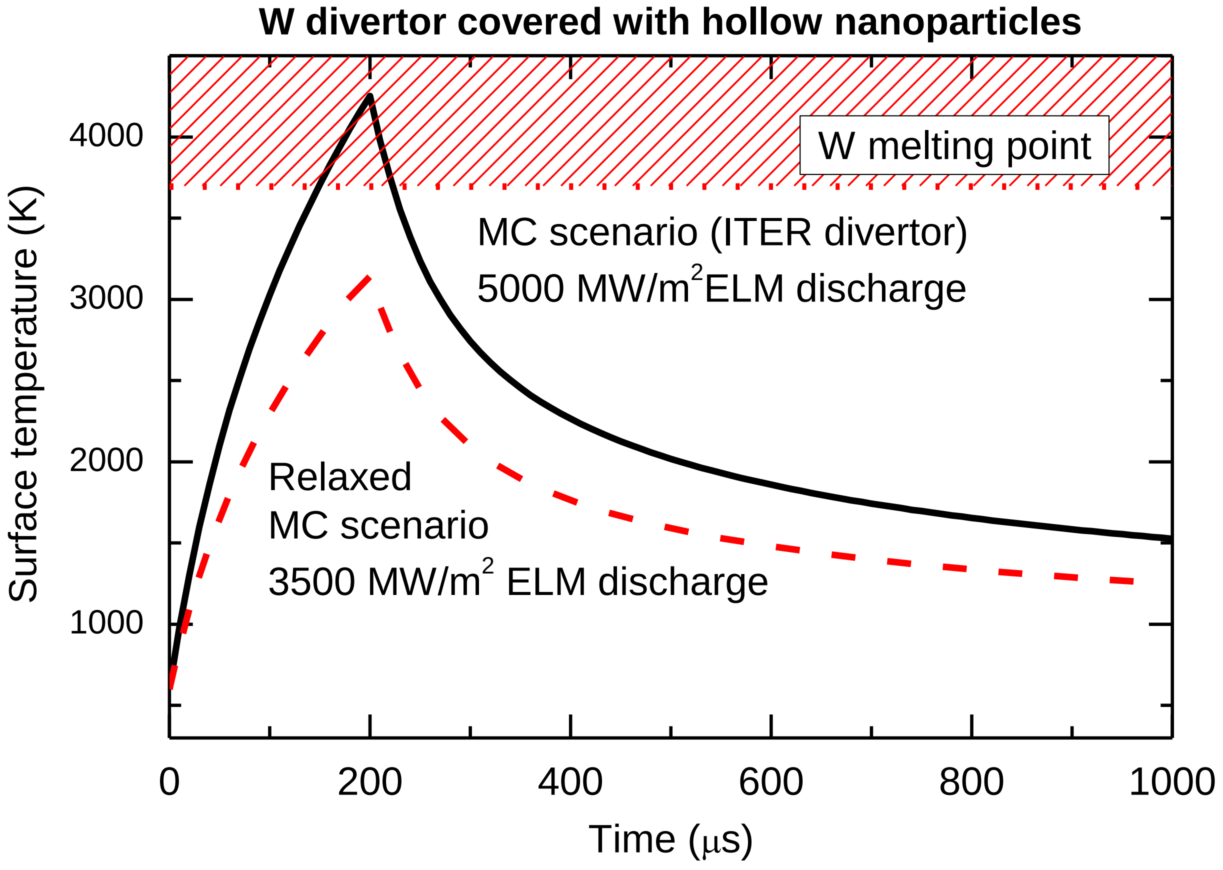
ELM in Magnetic Fusion

Plasma discharge during 0.2 ms
Total energy per discharge 1 MJ/m^2
Low energy ions ⇒ low penetration

	ITER	*70% ITER*
Potencia (MW/m^2)	5000	3500



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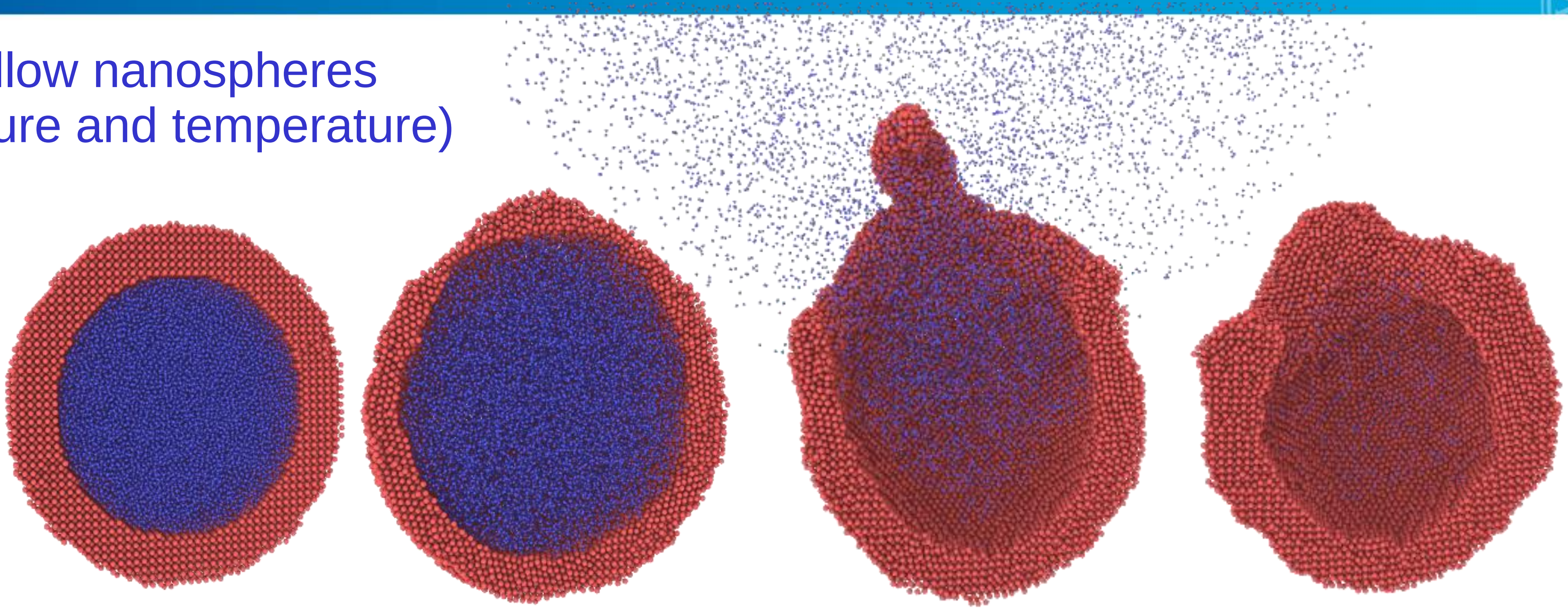
Hollow nanospheres
(pressure and temperature)



Molecular dynamics simulations of a nanosphere at 3000 K
Red: W atoms, Blue: He atoms

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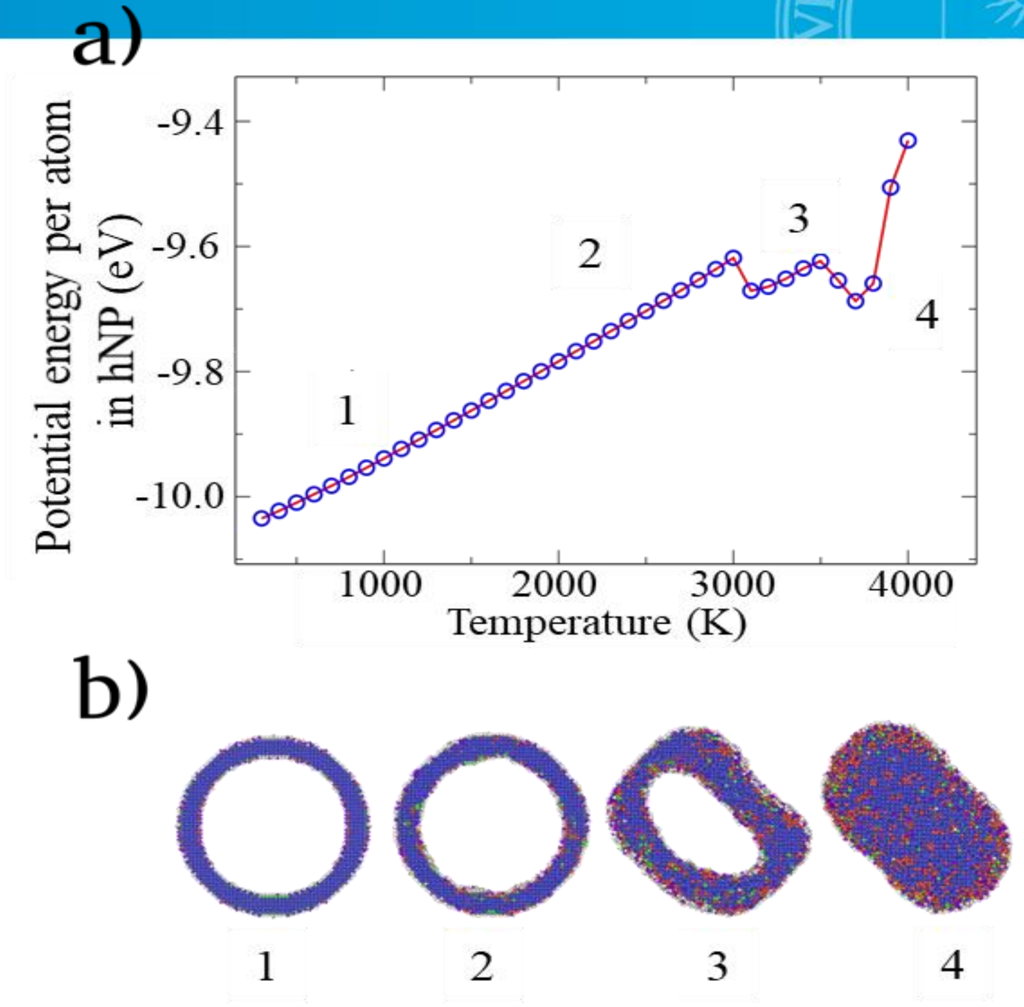
Astonishing resistance at high temperatures



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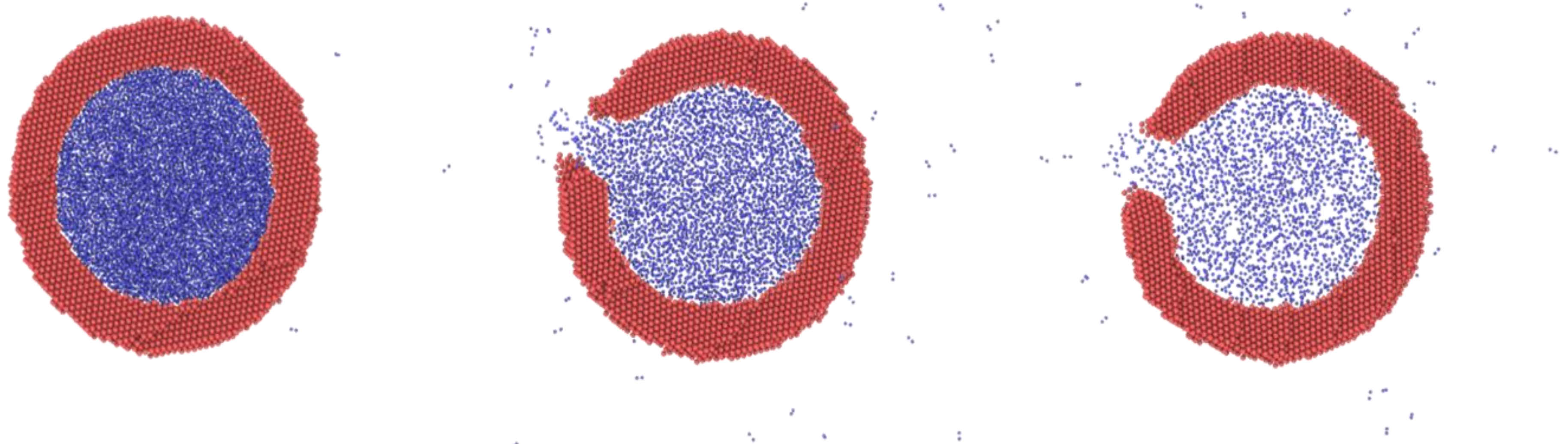
Astonishing resistance to high pressures

However, beyond certain pressure (temperature dependent) nanoparticle rupture occurs to relief the pressure

Temperature (K)	Number of He atoms in the cavity prior to rupture	Inner pressure (GPa)
300	52,100	10.5
1000	48,900	7.5
2000	37,500	6.7
3000	32,000	5.5



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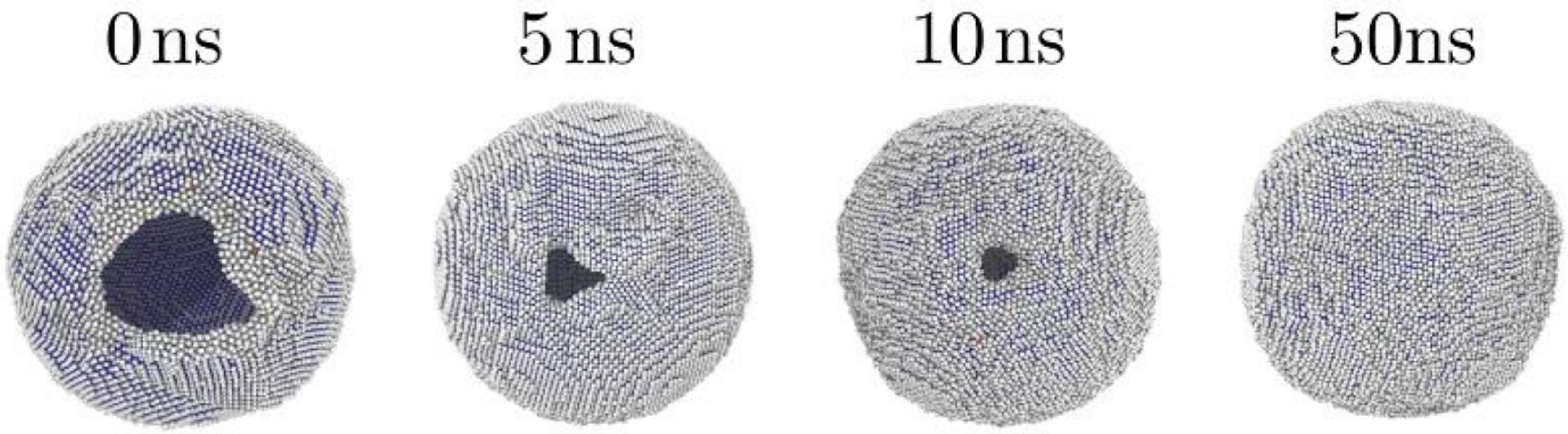
Self-healing mechanism under gentle irradiation conditions (laser fusion)

In magnetic fusion, the massive arrival of ions leads to nanoparticle rupture



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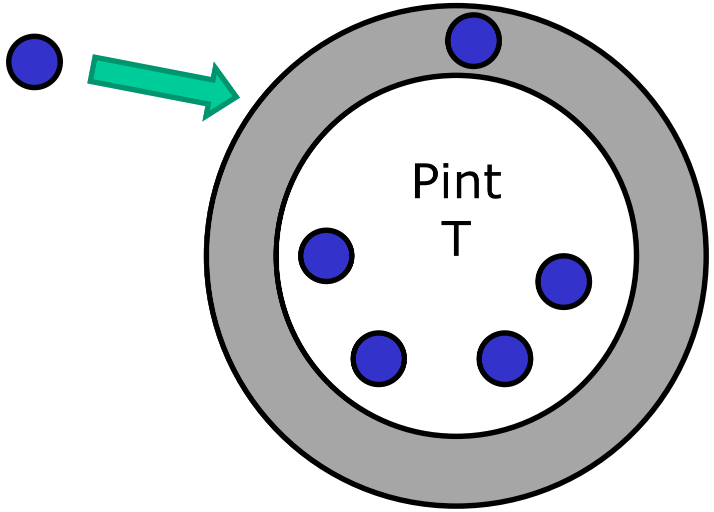
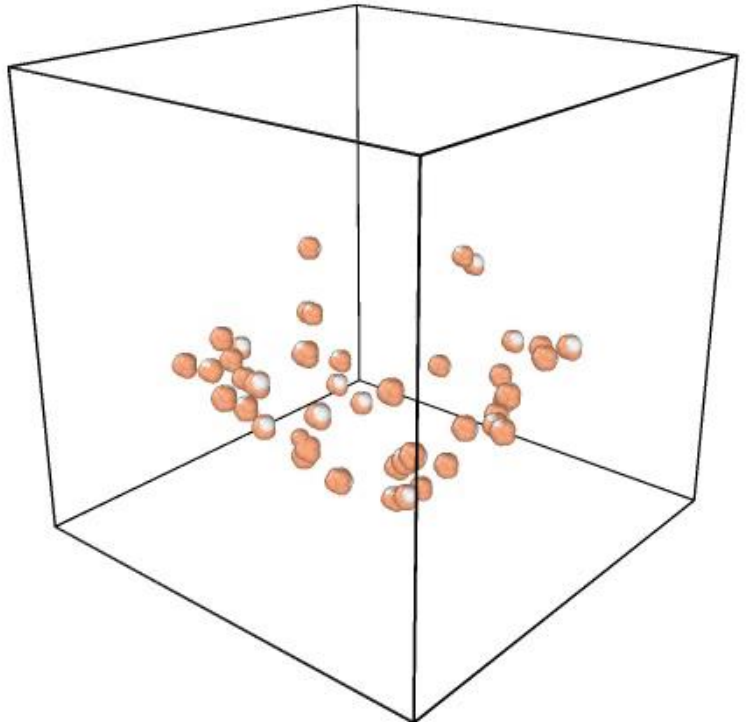
Object kinetic Monte Carlo makes possible to study the defect generation and evolution





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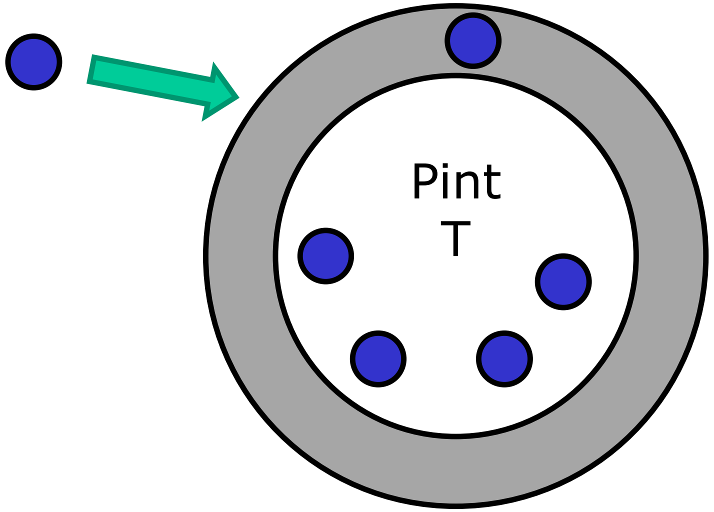
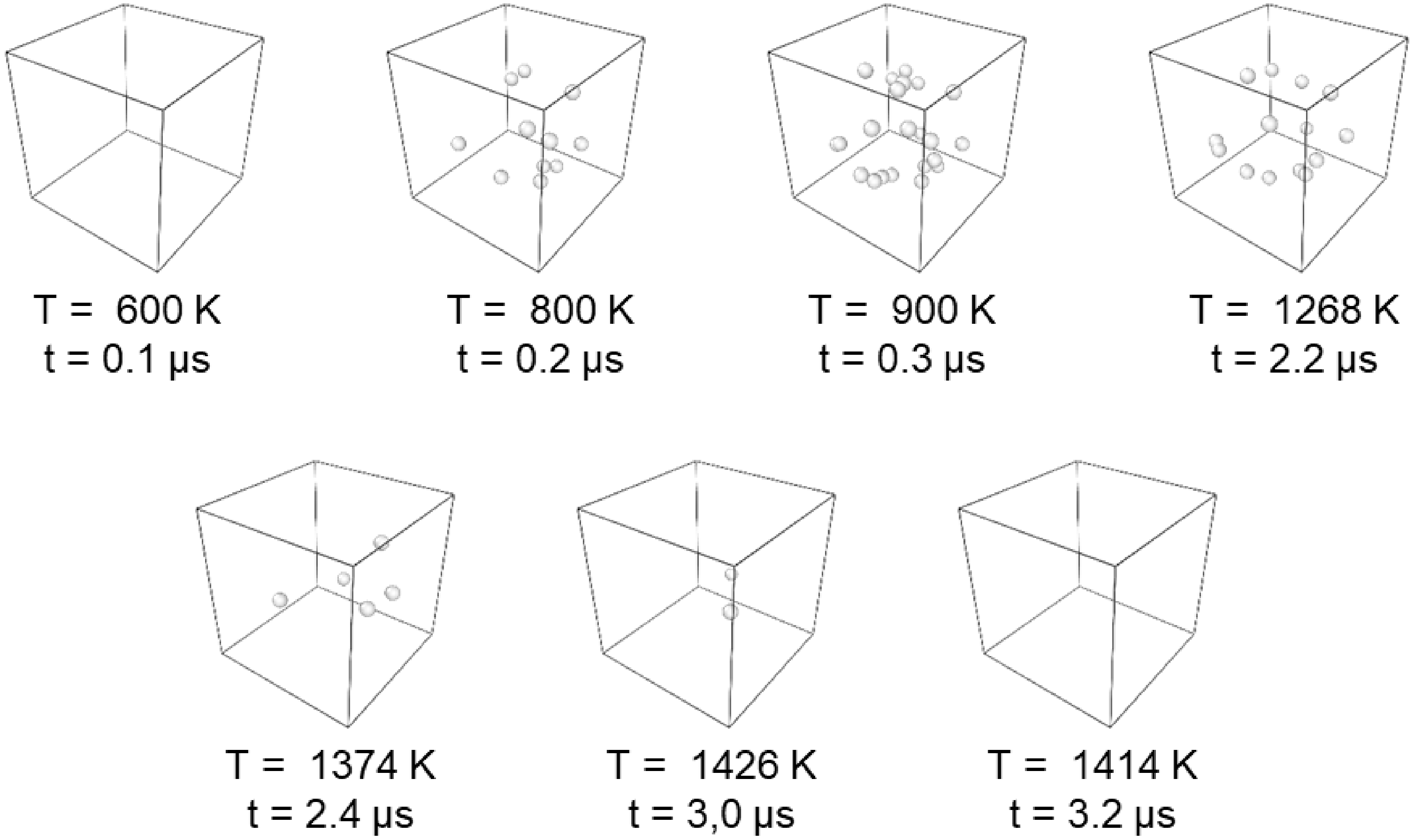
In Laser Fusion, even under conditions stricter than those of the prototype scenario, a second self-healing mechanism is observed leading to defect annihilation





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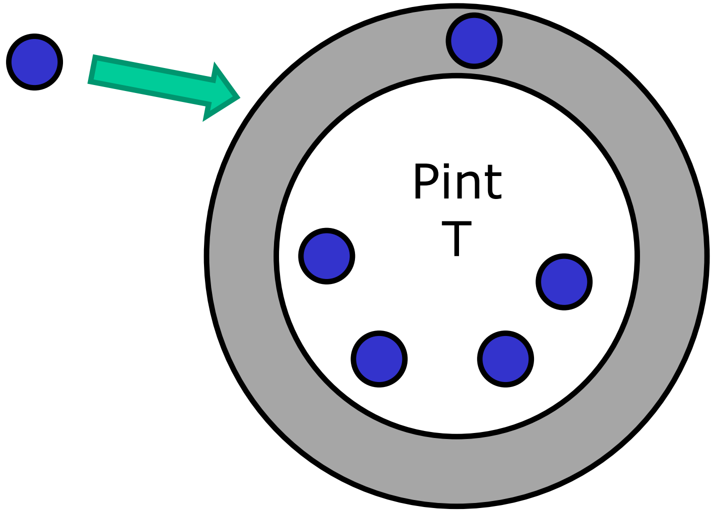
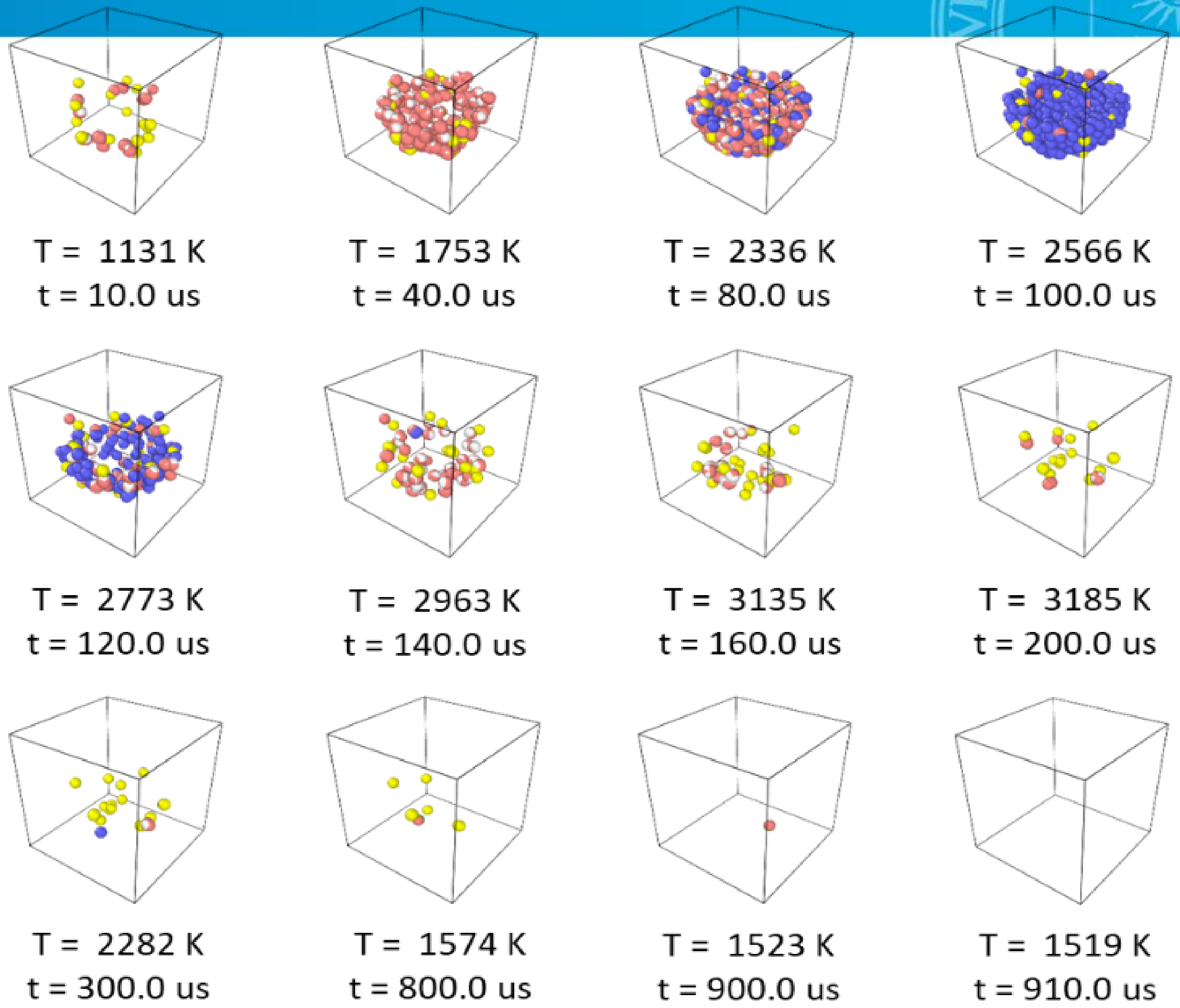
The second self-healing mechanism is so efficient than it would work even under the extreme conditions of magnetic fusion





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Novel proposal for first wall based on hollow tungsten nanoparticles

These nanoparticles are very resistant at high temperatures and pressures

Two self-healing effects observed:

1. Under gentle conditions (Laser Fusion) the nanospheres are able to relief the internal pressure
2. Due to the thin shell, the defects annihilate easily

In Magnetic Fusion the arrival of slow ion pluses makes the proposal unfeasible

In Laser Fusion:

Scenario Demo: The expected temperature is too high

Scenario Prototype: The nanospheres are promising, this is fresh air in a long-standing unsolved problem

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