Why we need Integral Concepts to reach the challenges in the Physics of the IFE Chambers

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J. M. Perlado[1], J.P. Catalán[1,2], M. Cotelo[1], R. González-Arrabal[1], R, Juarez[1,2], F. Ogando[1,2], E. Oliva[1], O. Peña-Rodriguez[1], A. Rivera[1], J. Sanz[1,2], P. Sauvan[1,2], P. Velarde[1]

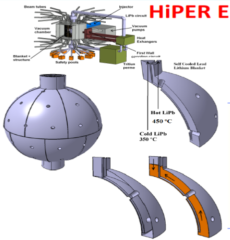
[1]Instituto de Fusión Nuclear "Guillermo Velarde"/ETSII/ Universidad Politécnica de Madrid

[2]TECF3IR, Universidad Nacional de Educacion a Distancia

Integral concepts such as European ESFRI Project HiPER (CCFE/UK, Academy Sciences Czech Republic, National Programs in France, Spain, Italy and European Union funding) gave to the different laboratories an unique opportunity to join efforts and link the design and responses of laser, target and chamber among them in a more realistic scenario for integrated design of a potential IFE Reactor.

The design uses Direct Drive emissions on time to give 3Dspace-time responses in fluid-dynamics, materials performance, corrosion and tritium breeding.

HiPER European Project



- ✓8 years running
- ✓Stopped as European funded 2014

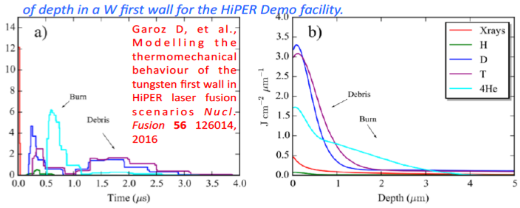
SHOCK IGNITION

DRY WALL

✓Advanced Progress in Materials and Reactor design research under Spanish National Programs with significant Spin-off in other areas of science

	HiPER 4a	HiPER 4b (Power plant)	
	EXPERIMENTAL	PROTOTYPE	DEMO
Description	Bunch mode	Relaxed operation	Pre-commercial power plant
Operation	Bunches of 100 shots, max. 5 DT explosions	Continuous (24/7)	Continuous (24/7)
Yield (MJ)	<20	>20	>100
Rep. rate (Hz)	1-10	1-10	10-20
Power (GWt)	-	<0.5	1-3
T cycle	No	Yes	Yes
Blanket	No	Yes	Yes

a) Power per unit area as a function of time and b) energy fluence as a function of depth in a W first wall for the HiPER Demo facility.



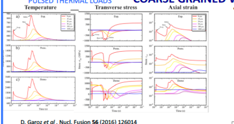
Garoz D, et al., Modelling the thermomechanical behaviour of the tungsten first wall in HiPER laser fusion scenarios *Nucl. Fusion* **56** 126014, 2016

PLASMA FACING MATERIALS

PLASMA FACING MATERIALS

COARSE GRAINED W LIMITATIONS

PULSED THERMAL LOADS

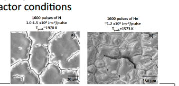


D. Garoz *et al* . Nucl. Fusion **56** (2016) 126014

Appropriate chamber geometry, radiation mitigation strategies, materials engineering and a reduced target yield may lead to an acceptable thermomechanical response. But, atomistic effects cannot be avoided.

SYNERGISTIC EFFECTS

- Combined effects of large pulsed thermal load and atomistic damage hamper W to properly work under IC, direct drive reactor conditions



HiPER

	Experimental	Prototype	Demo
Frequency	Few shots per bunch	1 Hz	10 Hz
Shot Energy (MJ)	20	50	154
Inner chamber radius (m)	5	6.5	6.5
Operation time limit based on thermomechanical considerations (hours)	No	14x10^3 (580 days)	28
Operation time limit based on synergistic effects (thermal loads + He irradiation)	~1x10^{3}shots	minutes	seconds

R.Gonzalez-Arrabal *et al.* submitted

Conclusion: Coarse grained W does not work

FINAL LENSES

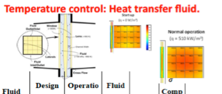
Challenge: proper lenses performance

- Temperature control during operation
- Ion mitigation

Temperature control

Temperature variations during operation → aberrations

Temperature control: Heat transfer fluid.

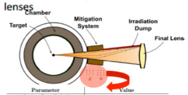


Fluid	Design T_0 (K)	Operation Regime	Fluid T_f (K)	Foot	Comp.	Shock
He	947	Start-up	985	0.17%	0.18%	0.46%
		Normal	950	0.16%	0.23%	0.46%

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

Partial ion mitigation

- Ions lead to thermomechanical failure
- Partial mitigation enough?
- If so, swift heavy ions will reach the lenses

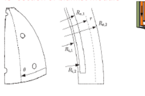


Parameter	Value	
System Length (m)	1	
Iron Gap (m)	0.35	
Deflected Angle (mrad)	85	
Curvature Radius (m)	11.6	
Deflected Ion	He	Au
Charge State	1	6
Energy (MeV)	20	45
Magnetic Rigidity (T m)	1.3	2.3
Magnetic Field (T)	0.1	0.2

A.R. Paramo PhD Thesis 2017

Thermo-fluid dynamics

45° section of blanket module



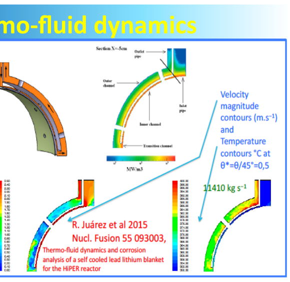
$R_{i,1}$ = 6.51 m, $R_{i,2}$ = 6.59 m

$R_{o,1}$ = 6.81 m, $R_{o,2}$ = 7.51 m

Parallel latitudes: 69.77° (4 holes), 42.97° (8 holes) and 15.05° (12 holes)

mass flow rate of Pb–15.7Li:

5993, 8557 and 11410 kg s^{-1}



Velocity magnitude contours (m.s^{-1}) and Temperature contours °C at θ*=θ/45°=0,5

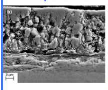
R. Juárez et al 2015 Nucl. Fusion 55 093003, Thermo-fluid dynamics and corrosion analysis of a self cooled lead lithium blanket for the HiPER reactor

Research is now running in the physics challenges of IFE Reactor Chamber which conducts to advance developments and spin-off in modeling and experiments

Corrosion and Plasma Facing Materials

Challenge:
development of corrosion resistant coatings

Corrosion problems: ODS-steel suffer from corrosion



	Li	Pb–17 Li
F/M steel	550–600°C	450°C
V alloy	650–700°C	~650°C
Nb alloy	~1300°C	>600°C (>1000°C in Pb)
Ta alloy	>1370°C	>600°C (~1000°C in Pb)
Mo	>1370°C	>600°C
W	>1370°C	>600°C
SiC	<550°C	>800°C

S. J. Zinkle, Fusion Engineering and Design: 51-52, (2000) 55-71

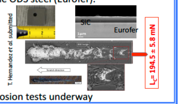
- Maximum operation temperatures of structural ODS steels in contact with LM, and cost of potential coatings

Material	Cost per kg
Fe-9Cr steels	≤$5.50 (plate form)
SiC/SiC composites	>$1000 (CVI processing) ~$200 (CVR processing of CFCs)
V-4Cr-4Ti	$200 (plate form–average between 1994-1996 US fusion program large heats and Wah Chang 1993 "large volume" cost estimate)
CuCrZr, CuNiBe, ODS copper	~$10
Nb-1Zr	~$100
Ta, Ta-10W	$300 (sheet form)
Mo	~$80 (3 mm sheet); ~$100 for TZM
W	~$200 (2.3 mm sheet); higher cost for thin sheet

Coating development: SiC

- In collaboration with Nano4Energy we have developed a set up to cover by sputtering the inner walls of pipes.

- We have optimized the sputtering procedure to obtain coating well adhered to the ODS steel (Eurofer).

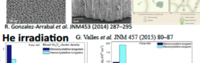


T. Hernandez *et al.* submitted

- Corrosion tests underway

NEW APPROACHES: NANOSTRUCTURED W

Nanostructures ↔ More Radiation Resistance



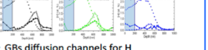
R. Gonzalez-Arrabal *et al.* JNM453 (2014) 287–295

G. Valles *et al.* Acta Materialia 122 (2017) 277-286

- **He irradiation** G. Valles *et al.* JNM 457 (2015) 80–87

- Grain Boundaries trap He
- He_nV_m clusters less pressurized in NW

- **H irradiation** M. Panizo-Laiz *et al.* Nucl. Fusion 59 (2019) 086055



- GBs diffusion channels for H
- H_nV_m clusters less pressurized in NW

Conclusion: NW favours the He and H retention in low populated vacancies, it may shift the fluence threshold for blistering to happen to higher values.

More research needed

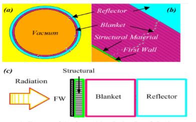
Blanket Modules

Variable TBR breeder blanket

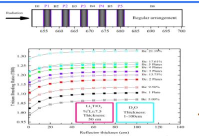
- Tritium economy essential for a Nuclear Fusion Power Plant (key parameter tritium breeding ratio, (TBR=bred tritium / burnt tritium)
- Excess tritium production is a safety issue
- Too low tritium production a fuel shortage problem
- TBR changes during plant life time
- Tritium demand can also change
- In addition, important uncertainties [*] exist regarding tritium generation
- Thus, a blanket with variable TBR (1.0 – 1.1) capabilities is required

[*] L.A. El-Guebaly el al. Fusion Engineering and Design. 84 (2009) 2072–2083.

- Our novel approach is based on a ceramic **breeder** (Li_2TiO_3) with a Be **multiplier** and a neutron **reflector**
- Reflector (**water tank**) responsible for TBR tunability during operation, simply by filling or emptying the tank.

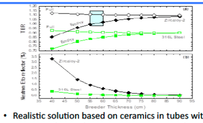


A. Fierro et al. Under revision Fusion Eng. & Design



- Effect of tank filling (reflector thickness) with **Be** in regularly inserted plates or mixed with ceramic & **unenriched** ceramic.
- Neutronics show there is a window to easily vary the TBR up to very high values

Fierro et al. Under revision Fusion Eng. & Design



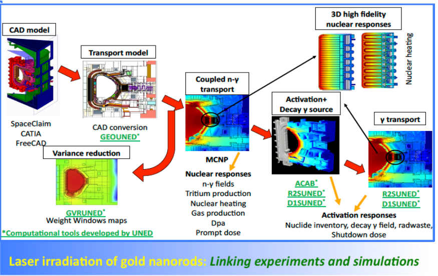
- Realistic solution based on ceramics in tubes with 1 Be plate (2.5 cm) and a heavy water tank (full or empty).
- An operational window shows that it is possible to easily modify the TBR from 1.0 to 1.1 during operation.
- This overcomes design uncertainties and assures tritium supply with a low tritium inventory
- Room for many other designs based on this concept

Neutronics for heating, tritium, damage

- Monte Carlo (MCNP) approach for neutronics simulations.
- Development of dedicated methods and computational tools.
- Computationally intensive, high resolution transport and shutdown dose analyses, involving large and complex geometries (i.e. ITER)
- High fidelity geometry representation in MC simulations
- Improve the computational efficiency of MC transport calculations: GVR method, optimization of MCNP memory management and built-in acceleration techniques
- 3D calculations of decay photon fields and shutdown dose rates (SDR): general solution for strong spatial gradients of the neutron flux

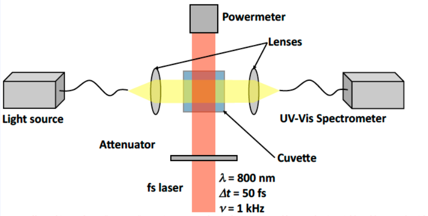
- Our SDR approaches are references within ITER and EUROfusion programmes.
- Verification and validation of the calculation tools: contribution at JET on the computational pre- and post-analyses of the benchmark experiments
- Qualification of their input data: participation within Nuclear Data Activities of the EUROfusion Consortium
- Nuclear Design Analyses: ITER, IFMIF-DONES, European DEMO programme, HYPER and more in the past NIF and different IFE concepts.

[1] Development of the R2SUNED Code System for Shutdown Dose Rate Calculations P Sauvan, JP Catalan, F Ogando, R Juarez, J Sanz IEEE Transactions of Nuclear Science 63 (1), 375-384
[2] D1SUNED system for the determination of decay photon related quantities P Sauvan, R Juárez, G Pedroche, J Alguacil, JP Catalan, F Ogando, J Sanz Fusion Engineering and Design 151, 111399
[3] Uncertainty propagation from neutron flux to decay gamma source in R2S methodology J Alguacil, P Sauvan, JP Catalan, J Sanz Fusion Engineering and Design 146, 1100-1103
[4] Assessment and optimization of MCNP memory management for detailed geometry of nuclear fusion facilities J Alguacil, P Sauvan, R Juarez, JP Catalan Fusion Engineering and Design 136, 386-389



*Computational tools developed by UNED

Laser irradiation of gold nanorods: *In situ* measurements



G. González-Rubio, P. Díaz Nuñez, O. Peña, A. Rivera, A. Prada, et al., Femtosecond laser reshaping yields gold nanorods with ultranarrow surface plasmon resonances, Science 358 (2017) 640–644

Laser irradiation of gold nanorods: *Nanorod reshaping*

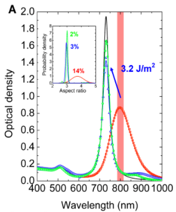
V = 11x10^3 nm^3

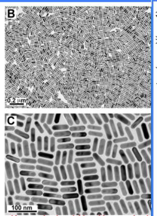
ρ_0 = 3.57

F = 3.2 J/m^2

[CTAB] = 1 mM

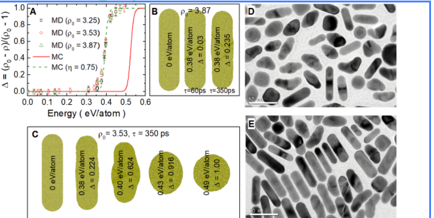
Hexadecyltrimethylammonium bromide





G. González-Rubio, P. Díaz Nuñez, O. Peña, A. Rivera, A. Prada, et al., Femtosecond laser reshaping yields gold nanorods with ultranarrow surface plasmon resonances, Science 358 (2017) 640–644

Laser irradiation of gold nanorods: *Linking experiments and simulations*



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