Progress in Inertial Fusion and Fusion Technology at DENIM

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Abstract

Radiation hydrodynamics simulations have been performed for inertial fusion performing numerical tests of radiation transport to quantify the differences between the Sn model and the M1 mode. Radiative shocks experiments hold at high-energy laser installations relevant for astrophysical situations has also been simulated. Simulations using ARWEN are being performed for jet impact fast ignition and compared with present experiments. DENIM has been devoted for years to develop models and codes for computing plasma optical properties. New models (analytical) have been developed for computing NLTE populations, opacities and emissivities for optically thin and thick plasmas, which have been successfully compared with proven codes and experiments. A new methodology for 3D neutronic calculations suitable for complex and extensive geometries has been implemented and applied to the KOYO-FI, and also for description of ITER beam ports and Test Blanket modules. Primary damage behaviour using ACAB code of the low activation steel Eurofer was studied under irradiation in the high flux test module of IFMIF, in the first structural wall of the magnetic (ITER, DEMO) and inertial (HYLIFE-II, HAPL) fusion reactors. Main responses are temporal evolution and average gas production rates and gas to dpa production ratio. The effect of activation cross section uncertainties in the hydrogen and helium production is also analysed. Tritium dispersion study has been extended to new meteorological situations and doses, considering soil and vegetables desorption, are presented. A full system of multiscale modeling codes has been already implemented for study materials under irradiation and under extreme conditions (pressure, etc). Molecular dynamics considering magnetic effects, new parallel kinetic MonteCarlo algorithm and implementation and study of dislocation dynamics, allows studying He effects in Ni and FeCr, comparison with ion irradiation (Fe, FeCr) and modeling metallic foam and ultrahigh strength materials. In addition to work performed in IFMIF-EVEDA safety and test cells, a large effort is being performed to define a Laboratory for Fusion Technology in collaboration with CIEMAT, that includes Remote Handling testing under irradiation, materials irradiation and characterization, advanced materials processing, liquid metal loop and laboratory for numerical simulation.

1.- Radiation-Hydrodynamics modeling and jet ignition

Radiation hydrodynamics simulations in relation with radiative shocks experiments hold at high-energy laser installations relevant for astrophysical situations have shed into light the importance of radiative losses on the shocks topology and dynamics. These losses can bend the shock, decrease significantly the time needed to reach the stationary regime and sharpen the luminosity of the shock around a privileged direction. In the context of inertial fusion, numerical tests are performed of radiation transport in order to quantify the differences between the Sn model and the M1 model. Advantages and drawbacks of each method are remarked in order to know which is better suited to model a given physical situation. We show that in the simple case of a Marshak wave, the differences can reach almost 20% on the matter temperature, and we are developing a series of case tests to enhance this comparison. Calculations using ARWEN for Jet Impact Fast Ignition have been performed and experiments already at PALS laser facility by IPPLM Warsow group. Results from numerical simulations of the jet impact fast ignition concept explain the reduction of the critical angle for jets produced by strong shocks. It could open the possibility to increase even more the velocity of the jets by reducing the angle of the cone. For the first time, experimental results have demonstrated the production of adiabatic jets by externally illuminating a cone target. The jet velocities measured are still well below the minimum to be practical for fast ignition scenario, but shaping the cone profile and material should increase the jet velocity and density. [1]. See Figure 1.

2.- Atomic Physics Modeling

Calculation of plasma radiative properties is a complex task since the number of the atomic levels involved, and therefore the amount of atomic data to obtain is huge and approximations must be made in order to include them. Due to this fact, the calculation of plasma ion populations and radiative properties is still an open question and continuous efforts are made to develop new models and numerical codes that improve the currently available ones. In this sense, we have developed a computation package composed by two codes called ABAKO and RAPCAL that calculate atomic data and plasma level populations (ABAKO) and radiative properties such as opacities, emisivities, intensities or radiative power losses (RAPCAL) for optically thin and thick plasmas, both under LTE and NLTE conditions. In particular, plasmas of elements such as carbon, aluminium, argon, iron, krypton, xenon and gold have been studied in several plasma situations (Corona, NLTE or LTE, optically thin and thick,…) and density and temperature conditions, obtaining accurate results. [2-5]. See Figure 2.

3.- Neutronics, Activation, Safety and Environment and Power Plant systems.

Calculations on KOYO-FI design neutronics have been performed [6] by using a very detailed 3D CAD code generating the input to MCNP transport code, See Figure 3. From those neutronics results, conclusions have been obtained on activation and primary damage of the different areas of the conceptual reactor. Vessel material activation after 30 years of nominal operation has been analyzed using the ACAB code, the EAF2005 data library, and the neutronic flux and energy spectrum in the vessel from previous MCNPX calculations. The total activity after 30 years of operation rises up to 0,64 Ci/cm^3, downshifts to 0,28 Ci/cm^3 after the first year decay and finally stabilizes around 5x10^{-5} Ci/cm^3 for periods longer than 100 years.The most important isotopes, from the radioactivity contribution point of view, are Fe55 and Cr51 during the first month. Until the 10th year, almost all the radioactivity is caused by Fe55; afterwards the contribution of C14 sharply increases, representing more than 75% of the total activity after 100 years.

The primary damage behaviour of the low activation steel Eurofer [7] was studied under irradiation in the high flux test module of IFMIF and in the first structural wall of the magnetic (ITER, DEMO) and inertial (HYLIFE-II, HAPL) fusion energy reactors, see Figure 4. The depletion of the main constituents of Eurofer, Fe and Cr, is not significant. However, the prediction of minor constituents of Eurofer, such as Ti, V and Mn, increase in all cases, except for HYLIFE-II. In general, the concentration of newly generated elements is insignificant. The highest generation of Re and Os occurs in HYLIFE-II due to a softer neutron environment. The evolution of the elemental composition during irradiation shows a linear dependence with the irradiation time. There are a few exceptions such as B, Co and Ni. The total H and He production are comparable to some initial constituents and this production is due to (n,xH) and (n,xHe) reactions in Fe. We have calculated the effect of activation cross section uncertainties in the assessment of transmutation using the Monte Carlo method implemented in ACAB. The transmutant uncertainty analysis shows that the maximum relative errors for H and He production are in HFTM/IFMIF, 6.5% and 5.2%, respectively. We have found significant uncertainties in the transmutation responses for B, C, Al, P, Cr, Ni, Nb and Ta. In the case of H- and He- gas production the maximum uncertainty is below 7%. [7], and see Figure 5.

A first attempt to identify the tools needed for Computational Fluidynamcs (CFD) has been started, in order to understand the power plant systems of cooling and breeding that are also extremely useful for the systems already in preparation such as IFMIF [8]

3.- Tritium Atmospheric Dispersion

Primary phase of tritium emission to the atmosphere in a fusion system follows with a secondary phase (tritium deposited in the surface soil and vegetables). The meteorological conditions of the environment are critical in the final consequences. We perform calculations with detail analysis of meteorological parameters every hour, different velocity of deposition under normal operation, and considering that in eventual cases there is always tritium in the means; the concentrations were measured at times of more rain intensity and speed smaller than the wind. We conclude that if the season of vegetables growth coincides with a high intensity of rain, the tritium concentrations internal doses is maximal. 3D neutronics calculations for complex geometry are performed for KOYO-FI and ITER and assessment of fluid dynamics in Blanket Modules for inertial and magnetic concepts [6, 9].

4.- Radiation Damnage of Materials

Fe-Cr system is the basis for the low activation steels which are being developed in the EU fusion materials community. A series of Fe-Cr alloys in the range from 1-15 at% Cr were produced under well controlled conditions from high purity elements by arc-melting in an Argon atmosphere at CIEMAT. These alloys are being irradiated with Fe ions at different temperatures in the form of thin foils suitable for transmission electron microscopy (TEM) characterization in CIEMAT. We look for a better understanding of the basic mechanisms of damage production and microstructure evolution under irradiation in Fe-Cr alloys. Simulations in FeCr will be performed in addition to those already done for comparison of Fe with/without magnetic interatomic potentials. The production of high levels of He during operation of future fusion reactors could affect the mechanical properties of structural materials, particularly in austenitic steels [10]. We study the particular case of Ni using kinetic Monte Carlo with input from molecular dynamics calculations and *ab initio* data available in the literature, some of them will be reviewed by new *ab initio* calculations. Simulations are performed to study the implantation of He in Ni under different conditions of irradiation dose and temperature. He desorption during isochronal and isothermal annealing is obtained and results are compared with available experimental data. From these calculations, relevant mechanisms of He diffusion and He-V complex stabilities are revealed that provide insight on the initial stages of bubble and void nucleation in f.c.c. metals. Results are discussed and compared to other calculations in b.c.c. metals; in particular Fe. The H diffusion in amorphous silica has been studied identifying the defects and the diffusion coefficients have been computed for different situations [11], see Figure 6. A new parallel kinetic Monte Carlo has been developed [12] and used now for extension to higher doses, and the study of partial dislocation in fcc metals dislocation dynamics has also be published [13], see Figures 7 and 8. We will work the initiative for multiscale modelling highly porous metallic foam, and ultrahigh strength materials, proposing the tools needed and some results [14]. In addition to work performed in IFMIF-EVEDA safety and test cells, a large effort is being performed to define a Laboratory for Fusion Technology (Technofusion) in collaboration with CIEMAT, that includes Remote Handling testing under irradiation, materials irradiation and characterization, advanced materials processing, liquid metal loop and laboratory for numerical simulation.

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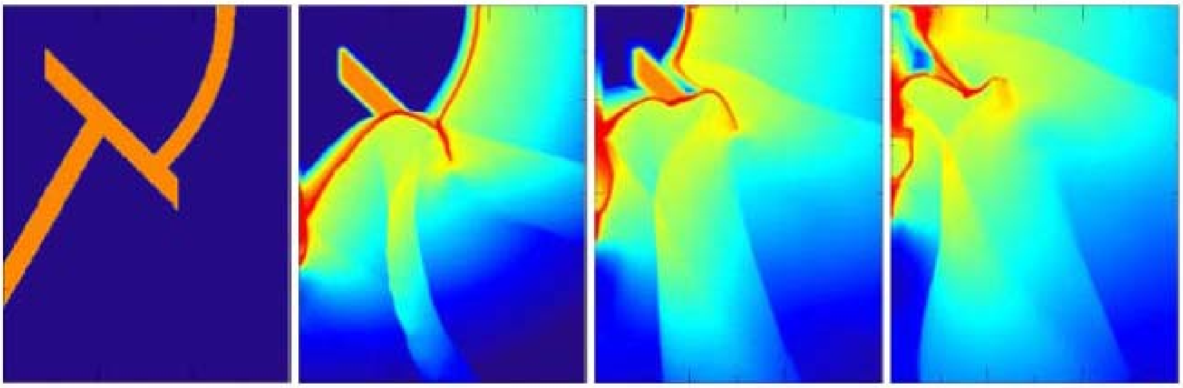


Figure 1.- Temporal evolution of the jet production and target compression for 290 eV

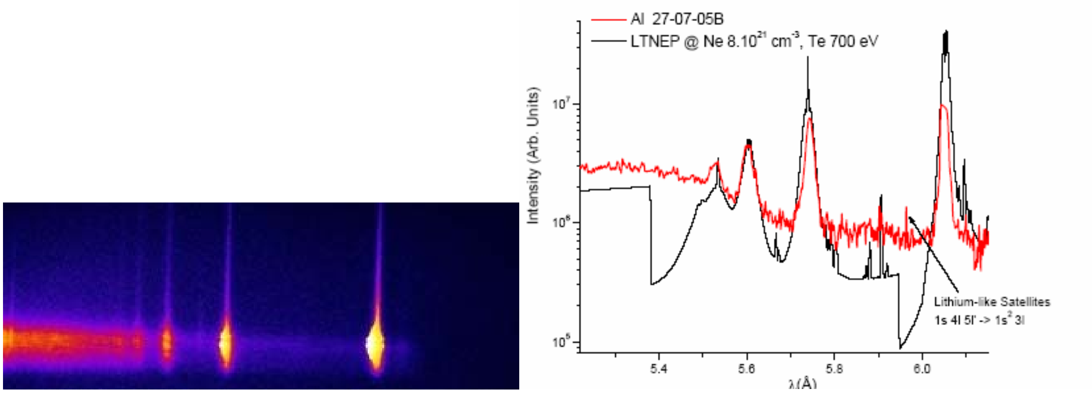


Figure 2.- Comparison of experiments (left by Dalimier et al. at LULI) and modelling with LTNEP code, showing the good agreement between them.

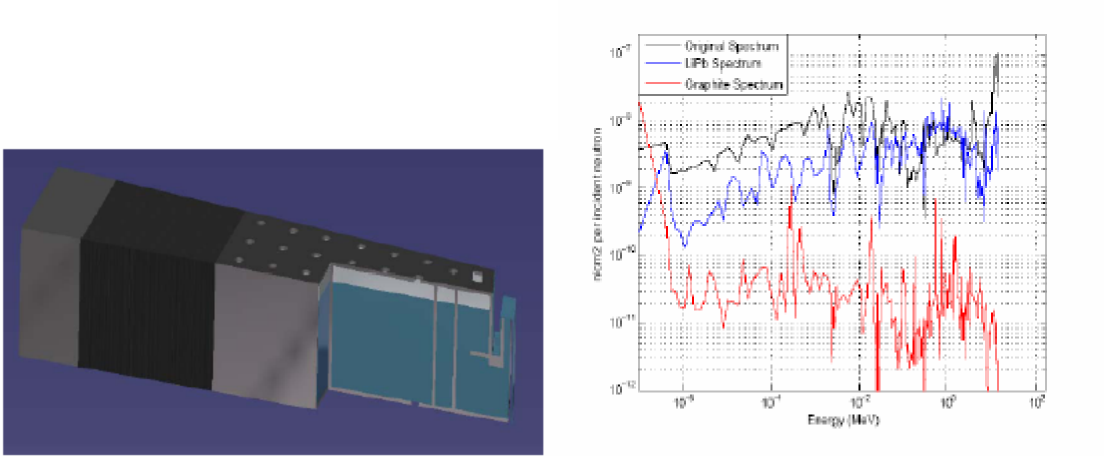


Figure 3.- 3D fully described CAD-MCNP input for KOYO.FI, and neutron spectra in different areas of the systems from where consequences in activation and damage are obtained

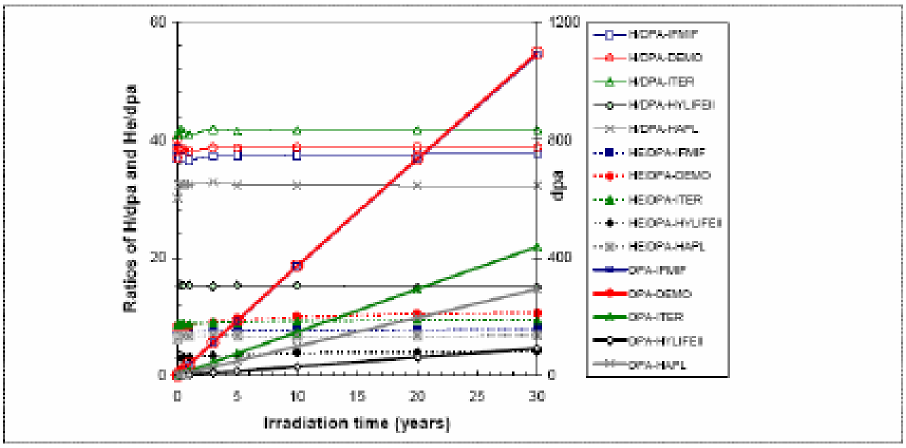


Figure 4.- Primary damage results in different neutron spectra corresponding to different fusion facilities using ACAB code.

		HFTM/IFMIF		DEMO		ITER		HYLIFEII		HAPL	
DPA		38		38		15		3		10	
Element	Initial appm	appm	ε%	appm	ε %	appm	ε %	appm	ε %	appm	ε %
H	0	1346	6.5	1404	2.2	596	2.1	44	2.0	307	2.0
He	0	292	5.2	327	3.7	135	4.2	16	6.3	67	3.7
B	51	4	9.6	-1	12.7	-0.1	39.4	-3	5.7	0.2	12.9
C	4860	-4	52.6	-2	164.8	-1	162.9	0.2	49.6	-1	135.4
N	1191	-5	7.8	-6	15.2	-2	15.5	-1	5.6	-1	12.7
O	348	-1	7.3	-0.4	6.2	-0.2	6.4	-0.03	7.0	-0.1	6.5
Al	206	1	7.3	0.3	19.1	0.1	23.1	-0.02	11.5	0.04	27.1
Si	990	-2	6.3	-1	10.9	-1	11.0	-0.1	9.2	-0.3	10.7
P	90	-0.2	31.8	-0.3	48.6	-0.1	44.7	0.04	13.2	-0.1	43.2
S	87	-0.3	11.0	-0.4	18.3	-0.2	16.8	-0.01	13.6	-0.1	16.2
Ti	116	29	11.8	25	11.6	10	12.0	1	33.1	5	13.3
V	2183	207	3.1	225	2.2	90	2.2	9	7.5	43	2.3
Cr	96233	128	22.3	97	8.2	45	6.6	2	30.6	28	5.2
Mn	4048	918	7.0	777	4.0	326	3.8	-34	5.6	161	3.3
Fe	885883	-1282	6.8	-1126	2.8	-472	2.6	18	10.6	-237	2.6
Co	47	0.1	12.0	2	1.8	1	2.1	4	23.3	0.2	1.4
Ni	47	-0.1	17.5	0.1	40.8	0.01	221.2	0.4	20.1	-0.02	26.5
Cu	44	-0.2	7.2	-0.5	8.3	-0.2	7.8	-0.3	16.3	-0.1	8.0
Nb	6	0.02	25.3	0.01	95.2	0.01	86.6	0.000	33.4	0.01	90.9
Mo	29	-0.1	7.6	-0.1	7.9	-0.1	9.1	-0.1	7.4	-0.03	10.0
Ta	215	4	17.4	-17	31.2	-3	48.0	-29	22.4	0.3	54.1
W	3327	-10	6.8	-128	9.9	-33	10.0	-159	11.2	-5	6.0
Re	0	5	4.2	132	8.1	34	8.6	167	9.1	5	6.1
Os	0	0.01	0.00	12	20.6	1	20.1	21	21.7	0.02	17.5

Figure 5.- Uncertainties calculations using ACAB code capabilities for impurities generation affecting materials evolution.

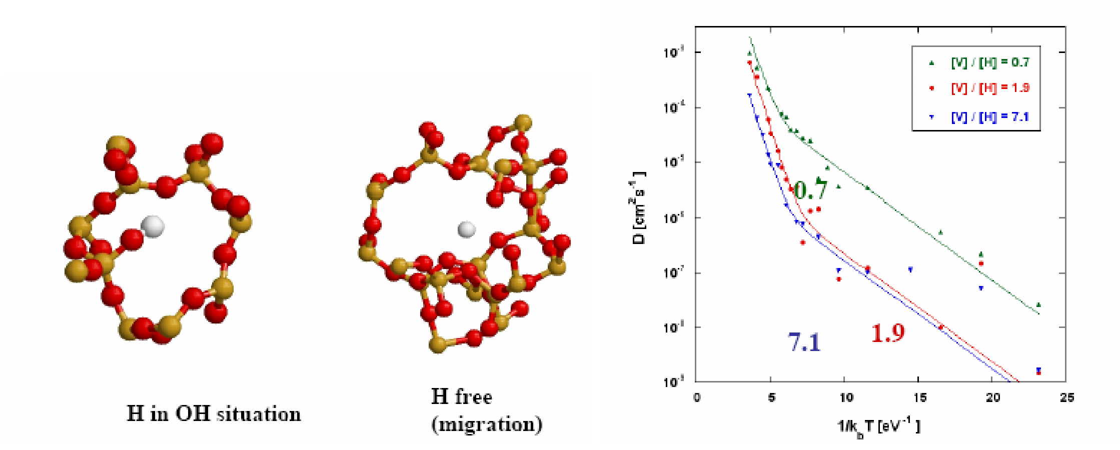
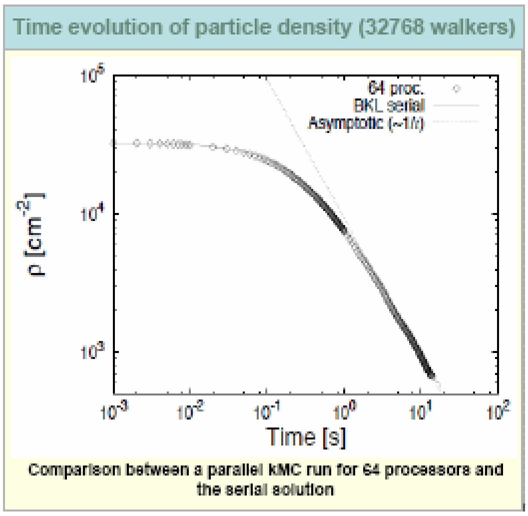


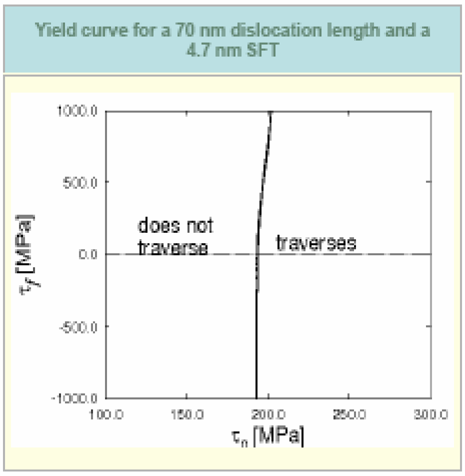
Figure 6.- Defects identification in amorphous silica and diffusion coefficients for different ratios of H to Vacancies generated n the material under irradiation.



Time evolution of particle density (32768 walkers)

Comparison between a parallel kMC run for 64 processors and the serial solution

Figure 7.- Evolution of results using our new Kinetic MonteCarlo (KMC) and the correct upgrading of the model with the number of processors.



Yield curve for a 70 nm dislocation length and a 4.7 nm SFT

Figure 8.- Dislocation Dynamics for Partial Dislocation using new code: strength of SFT to the screw passage