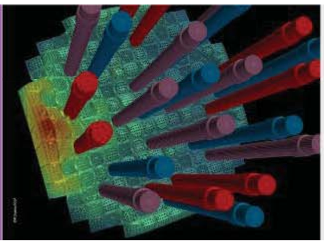

FISA 2022

30 May - 3 June 2022
Lyon, France

TOWARDS A SINGLE EUROPEAN SRIA ON NUCLEAR MATERIALS FOR ALL REACTOR GENERATIONS THROUGH DEDICATED PROJECTS

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Outline

- ORIENT-NM and the all-generation nuclear materials SRIA
- EERA-JPNM portfolio in H2020: GEMMA, INSPYRE, M4F
- GEMMA results
- INSPYRE results
- M4F results

What is ORIENT Nuclear Materials?

Organisation of the European Research Community on Nuclear Materials (ORIENT-NM) is a Coordination and Support Action partially funded by Euratom, WP 2019-20, NFRP-08

Goals as from the call:

- Consolidate the domain of nuclear materials in Europe
- Avoid duplication, improve complementarity
- Involve EERA (JPNM) and SNETP (NUGENIA)

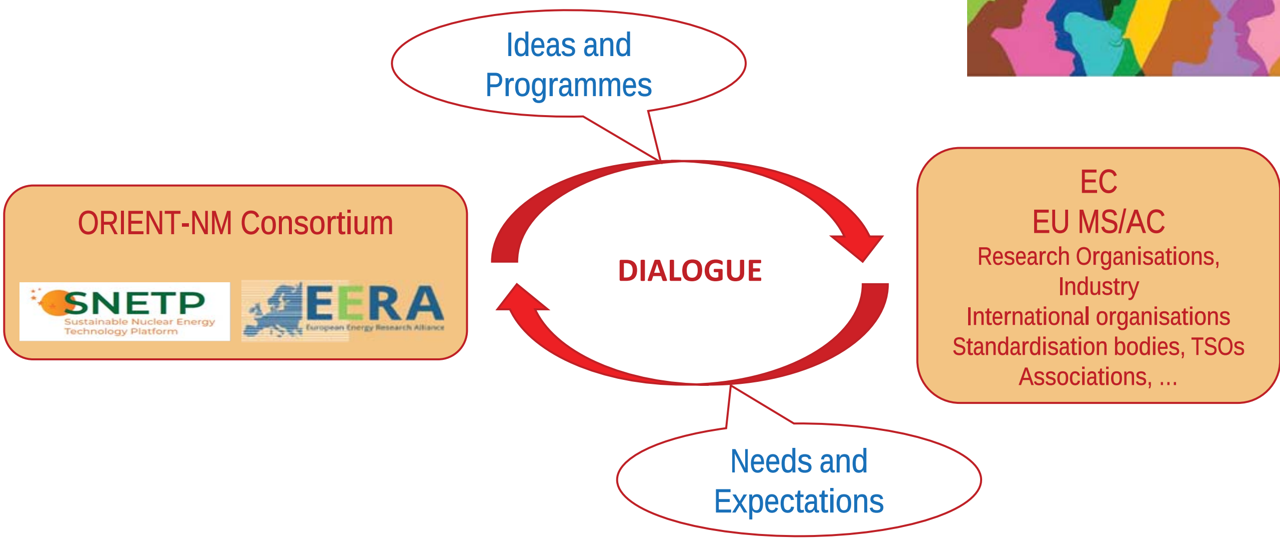
In practice:

- Explore the ground for a European Partnership* on nuclear materials

ORIENT-NM Budget:
Total: 1.6 M€
Euratom contribution: 1.1 M€

**European Partnerships in HEU replace among others H2020 European Joint Programmes, EJP*

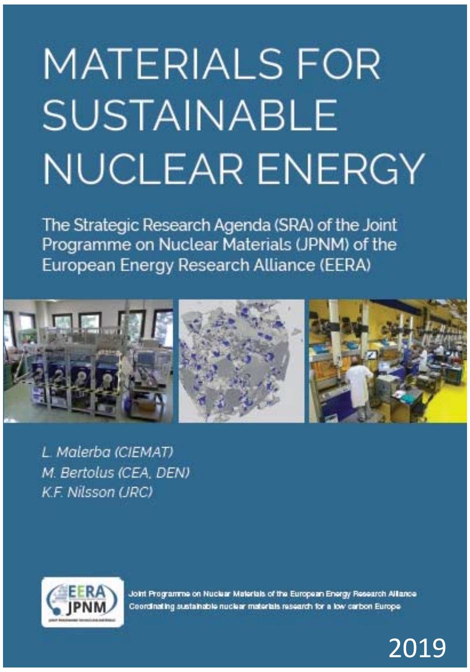
How is ORIENT-NM working?



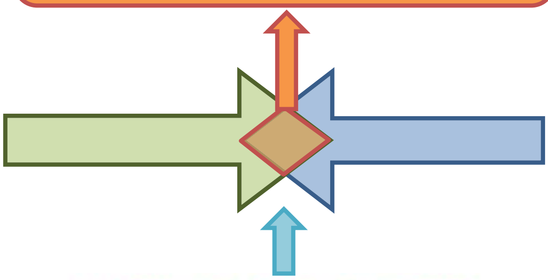
What is ORIENT-NM producing?

1. Single Vision Strategic Reasearch Agenda on Nuclear Materials <u>for the benefit of ALL reactor generations</u> until 2040
2. Most suitable governance, structure and implementation design for the European Partnership
3. Plan of interaction of the European Partnership with all interested stake-holders

The roots of ORIENT-NM's SRIA

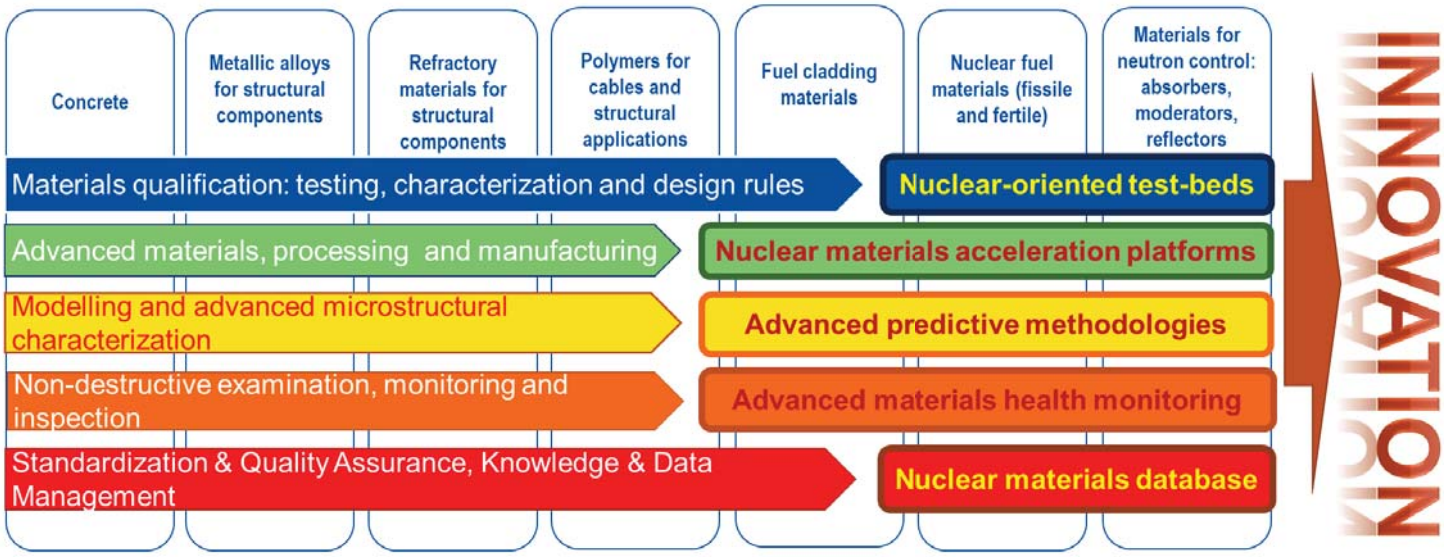


ORIENT-NM SRIA
https://doi.org/10.3390/en15051845

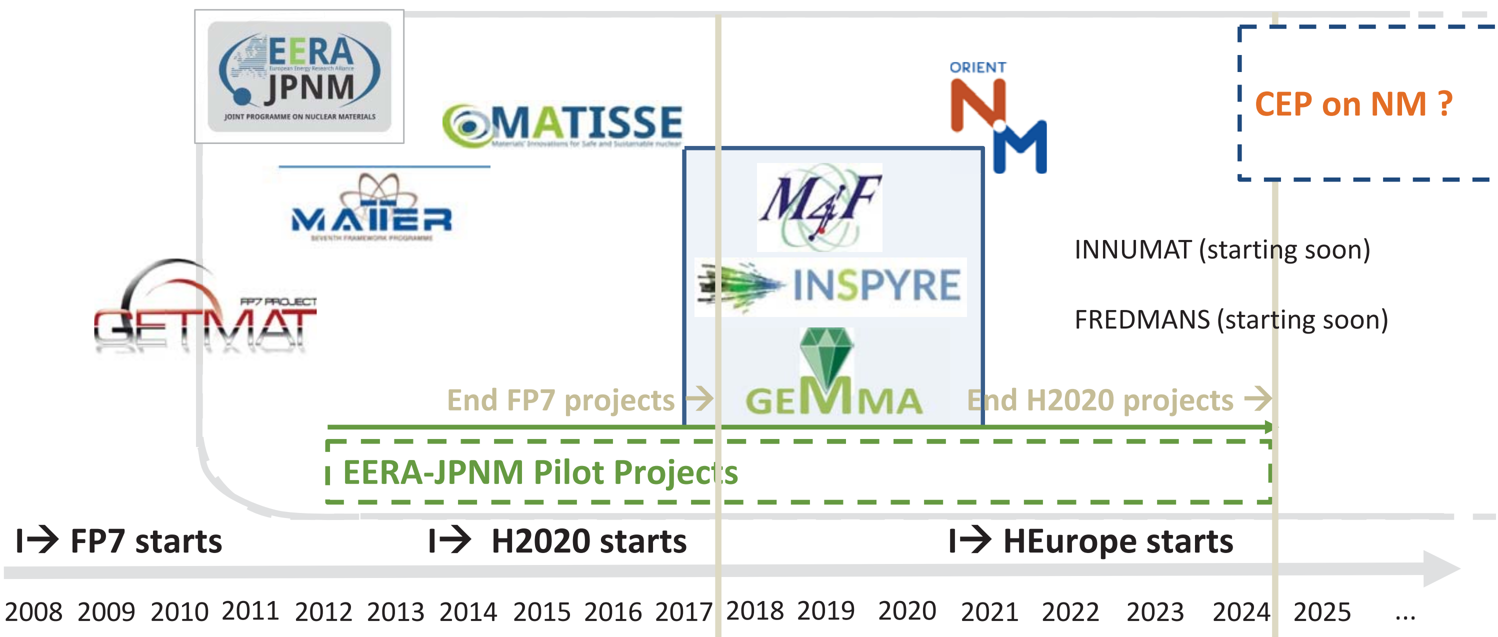


The ORIENT-NM SRIA in a nutshell

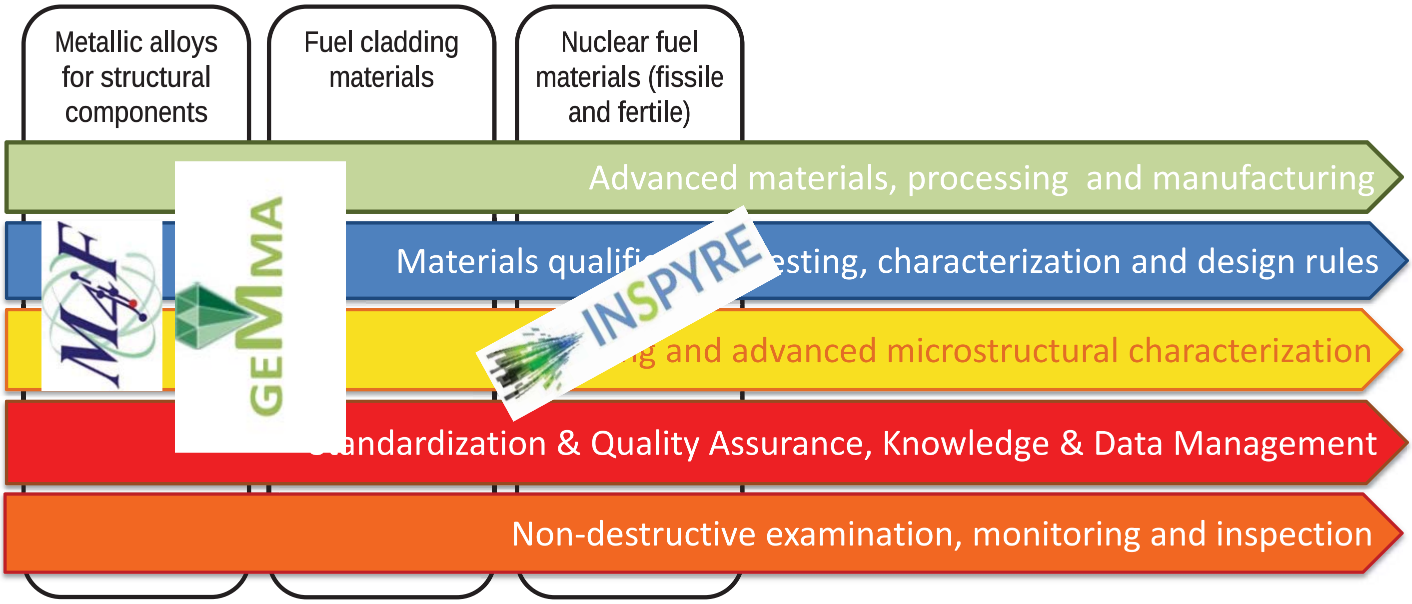
Technology independent matrix:
Materials classes and cross-cutting research lines are of relevance for any reactor generation
Emphasis is given to modern materials science practices that rely on advanced digital tools and techniques



EERA Joint Programme on Nuclear Materials: Research Project Portfolio



GEMMA, INSPYRE and M4F: examples of SRIA research lines' application



GEMMA: GenIV Materials Maturity

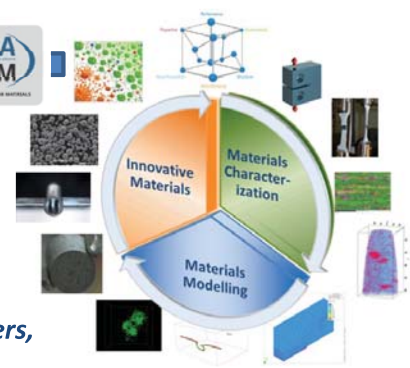
H2020 Project (2017-2021): 6.6/4.0 M€, 23 participants, coord. P. Agostini (ENEA)

GEMMA deals with EU GEN IV material issues, reflecting the EERA JPNM three-fold approach to materials studies

	Compatibility with coolants	Neutron irradiation effects
Materials Characterization in view of codification	WP2: Welding development and characterization; WP4: Compatibility with HLM and He coolant	
Materials Modelling	WP4: Compatibility with HLM and He coolant	WP3: Irradiation effects: modelling and experiments
Innovative Material Solutions	WP1: Advanced corrosion mitigation strategies	

Large amount of experimental data have been generated.

Useful rules, for system and component designers, have been deduced.

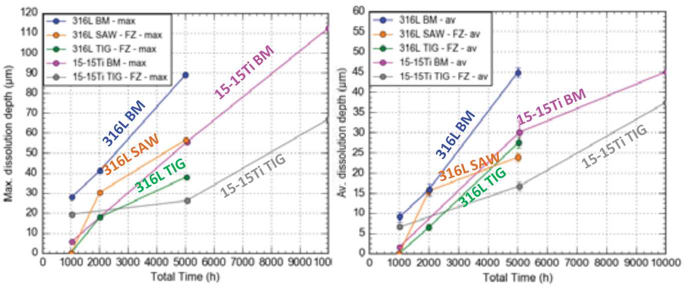


The data are expressed in a suitable way for inclusion in the Design Rules of the RCC-MRx code

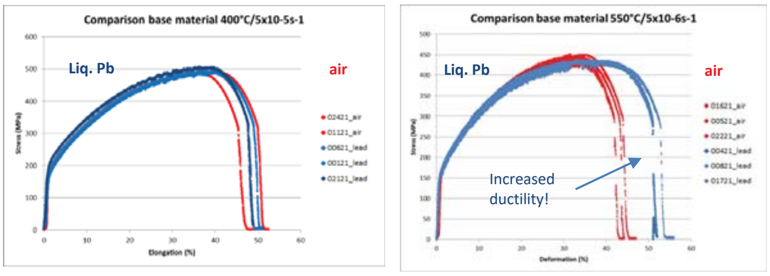
The generated data have been stored in JRC repository MAT-DB http://www.eera-jpnm.eu/gemma

Qualification of existing materials: compatibility with liquid Pb

GOOD BEHAVIOUR OF WELDED AUSTENITIC STEELS VERSUS BASE MATERIALS (static tests in Pb @ 480°C and low Ox)



NO LIQUID METAL EMBRITTLEMENT IN 316L IN CONTACT WITH LIQUID Pb

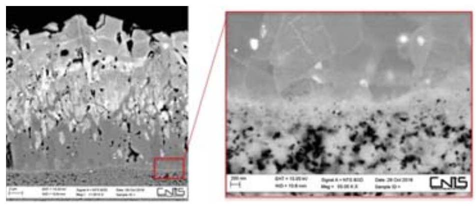


NEGLIGIBLE CORROSION AFTER 16000h IN FLOWING Pb @ 480°C and low Ox, BOTH BASE MATERIAL AND WELDS

316L 16000 h | TIG 316L 16000 h | SAW 316L 16000 h | 15-15 Ti 16000 h

CORROSION RATE INCREASES AT HIGH T (550ºC)

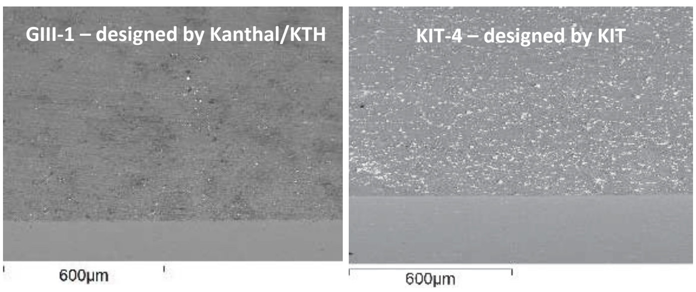
At 550°C Pb wets magnetite's grain boundaries, creating fast diffusion paths for oxygen, which increases corrosion



10th European Commission Conference on EURATOM Research and Training in Safety of Reactor Systems
30 May - 3 June 2022 | Lyon, France

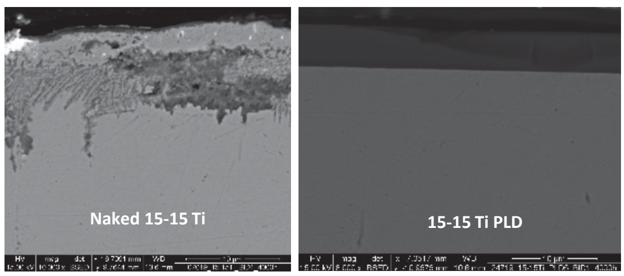
Advanced materials: Alumina Forming Steels and Coatings

ALUMINA FORMING AUSTENITIC STEELS (AFA)



NO INDICATION OF CORROSION ATTACKS AFTER EXPOSED IN STAGNANT LIQUID LEAD AT 600°C FOR 1000H.

AL_2O_3 CERAMIC COATINGS ON STEELS



PULSED LASER DEPOSITED (PLD) ALUMINA COATING CONFIRMS GOOD PROTECTION ON 15-15 TI AT 550°C (LOW OXYGEN, FLOWING PB 4000 H)

10th European Commission Conference on EURATOM Research and Training in Safety of Reactor Systems
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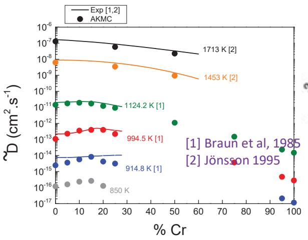
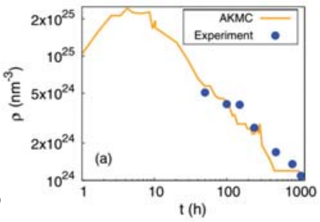
Advanced physcal modelling and data management

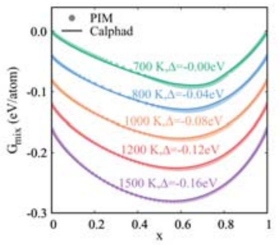
Atomistic kinetic models fitted to ab initio computations simulate correctly thermodynamic-driven processes in Fe-Cr and Fe-Ni alloys



Fe-Cr Interdiffusion Coefficients



α-α' decomposition size and number of precipitates



Free energy of mixing G_mix from equilibrium Monte Carlo simulations in Fe-Ni alloys, including effect of magnetism – good agreement with experiment-fitted data

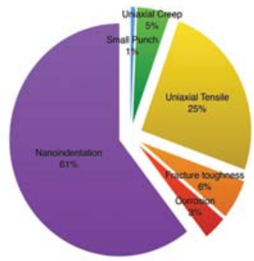
Repository of GEMMA Experimental Data @ https://odin.jrc.ec.europa.eu

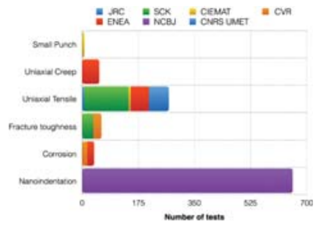
Test	N.
Small Punch	7
Uniaxial Creep	53
Uniaxial Tensile	270
Fracture toughness	60
Corrosion	37
Nanoindentation	656
Tot	*1083*

1083 validated test results with metadata:

- source
- material pedigree
- specimen
- test conditions.

All GEMMA data are citable with DataCite DOIs.





INSPYRE: Investigations Supporting MOX Fuel Licensing in ESNII Prototype Reactors

H2020 Project (2017-2022): 9.4/4.0 M€, 14 participants, coord. M. Bertolus (CEA)

INSPYRE **STRATEGIC OBJECTIVES** EERA JPNM

- Make major breakthrough in understanding and describing fast reactor MOX behaviour under irradiation in a large variety of conditions by coupling
  - Separate effect experiments
  - Multiscale and thermodynamic modelling
  - PIE results on neutron-irradiated fuel from past campaigns
- Focus on four operational issues: Margin to fuel melting; atom transport and fission product behaviour; mechanical properties; fuel thermochemistry and interaction with the cladding
- Advance predictive capabilities of fast reactor fuel performance codes by:
  - Transferring knowledge acquired into operational tools
  - Bringing together experts to develop and capitalize on the synergy between the various approaches
- Transfer results and approach of proposal to users and develop training to prepare next generation of researchers

http://www.eera-jpnm.eu/inspyre/

Advances in the understanding and simulation of nuclear fuels

HIGHLIGHTS

Analysis of available data and models and identification of gaps

Assessment of current versions of fuel performance codes on previous irradiation experiments

Development of new experimental set-ups in hot labs enabling characterization of Pu and Am oxides

Thermochemical behaviour of MOX

- Experiments and models for U-Pu-Am oxides and fission products for improved thermodynamic description of U-Pu-Am-O and Cs-I-Te-Mo-U-Pu-O
- Experimental study of MOX/steel interaction at high temperature
- Improved correlations for melting temperature and thermal conductivity of irradiated MOX and Am-bearing MOX

Thermomechanical properties of UO_2 and MOX

- Combined experimental and modelling study of mechanical properties of fresh UO_2 and MOX fuels
- Modelling of impact of primary damage on mechanical properties
- Investigation of thermal and irradiation induced creep of UO_2
- Physics-based mechanical models for creep and rupture of MOX fuel in normal and off-normal conditions

Atomic transport properties and fission gas behaviour

- Modelling of thermal and irradiation-induced defects in MOX
- Study of the MOX fuel self-diffusion from the atomic to the macroscale
- Combined modelling and experimental study of fission gas behaviour in UO_2
- TEM characterisation of irradiated MOX
- Physics-based models of inert gas behaviour in high burn-up structure and in transient conditions

Implementation of data obtained and models developed in fuel performance codes were applied to irradiation experiments representative of ESNII reactor cores

High importance given to Education & Training activities

Summer schools to disseminate results and approach toward young researchers

- May 2019: Nuclear fuel cycle in Delft (The Netherlands)
- November 2020: European School on Nuclear Materials Science 2020, online

Collaboration with other European initiatives

Organization or co-organization of workshops to disseminate results and approach to nuclear materials research community and users

- Co-organisation of MMSNF-Nufuel 2019 in PSI
- Financial support to Nufuel 2021 in Bangor (UK)
- Organisation of the final international workshop

Training through research:

20 PhDs and Post-Docs invovled in the technical activities of the project

Mobility scheme: support of travel & accommodation costs to foster exchange of researchers between partner institutes of the project and give access to facilities or expertise

M4F: Multiscale Modelling for Fusion and Fission Materials

H2020 Project (2017-2021): 6.5/4.0 M€, 20 participants, coord. L. Malerba (CIEMAT)

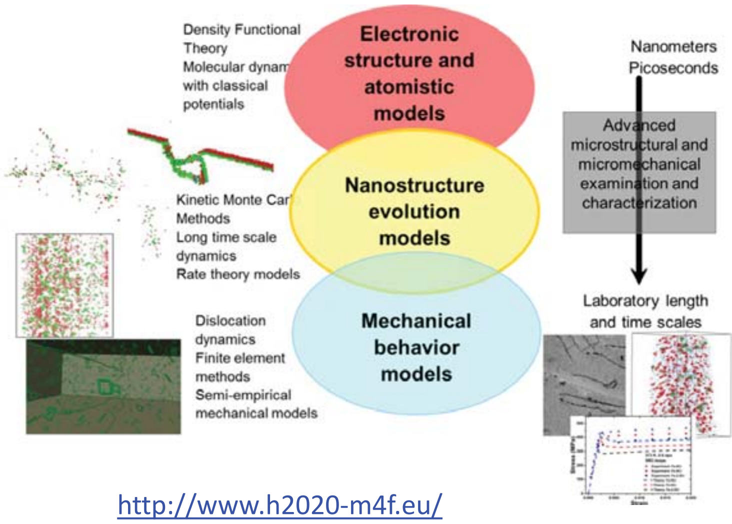
GUIDING OBJECTIVES

Bring together fusion & fission materials communities

Develop physical understanding and predictive models of the origin of **localised deformation** under irradiation and its consequences on the mechanical behaviour of components

Develop a methodology to use **ion irradiation as a tool** to evaluate radiation effects on microstructure and mechanical behaviour of materials, minimising artefacts with respect to neutron irradiation experiments

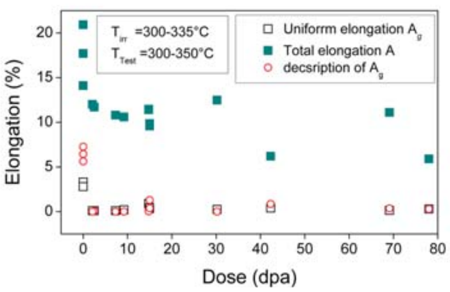
MULTISCALE MODELLING APPROACH



http://www.h2020-m4f.eu/

Localisation of deformation: problem and results

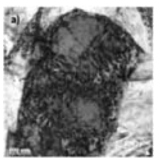
E. Gaganidze, J. Aktaa, Fusion Eng. Des. 88 (2013)



Problem:
Current design rules consider the elongation as only indicator of ductility → F/M steels are unusable according to this criterion!

S. Zinkle, B.N. Singh, J. Nucl. Mater. 351 (2006)

Traditionally loss of elongation is attributed to creation of clear bands free of defects, removed by moving dislocations, observed in Fe



Electron microscopy on Eurofer97 in M4F suggests that in some grains loops are absorbed with dislocation wall formation → preferential channels for plastic deformation causing softening

- **Three models were developed in M4F to address the problem of the effect of dislocation channel formation on mechanical behaviour in 9%Cr Fe alloys :**
  - Mean field continuum model at aggregate level
  - Full field continuum model, also at aggregate level
  - Constitutive equations enabling FEM at component level
- **Dose dependent formation of shear bands was correctly predicted**

Tools to assess the effect of plastic flow localisation at the component level were produced, which are of use to produce design rules for both fission and fusion

Good practices for ion irradiation

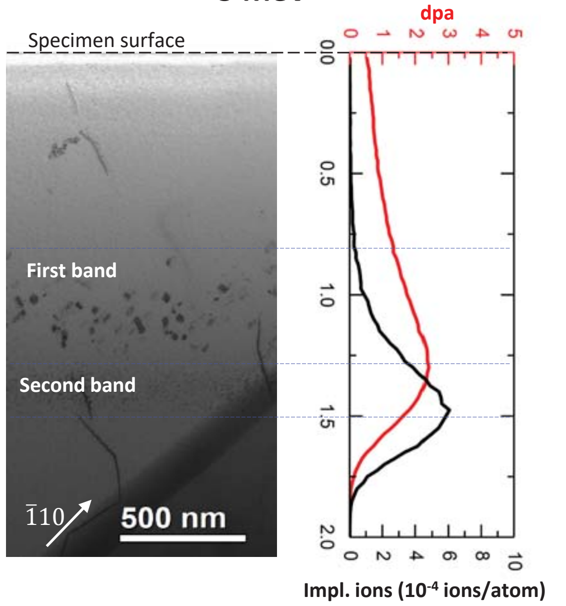
- **Ion irradiations were performed applying different parameters**
  - Different ion energy, focused beam versus rastering, different doses and temperatures, but same materials
  - Most difficult variable to control: C contamination

  This clarified several effects and suggested good practices to mimick neutron irradiation

- **Three new different microstructure evolution models have been developed, each offering new modelling opportunities, not available before**
  - Simulation of the whole ion penetration thickness
  - Simulation of Cr concentrated alloys including precipitation
  - Simulation of the effect of minor solutes

- **Good practices to assess the mechanical properties of ion irradiated materials using nanoindentation** have been drafted
  - Standards for testing have reached the level of a **CEN workshop** and relevant publication

5 MeV



Standard pattern versus depth have ben identified

Concluding remarks

- A Nuclear Materials Strategic Research and Innovation Agenda that serves all reactor generations is being produced
- It is based on the application of modern materials science practices that are being used in many other fields, too, which pivot around advanced digital tools and techniques
- The SRIA foresees accordingly 5 research lines, that are expected to host projects on, a priori, any of the 7 nuclear materials classes that have been identified
- The three just concluded EERA JPNM projects, GEMMA,INSPYRE, and M4F, are examples that fall within the identified research lines
- They show that:
  - Similar approaches are common to different materials and applications
  - Cross-cutting issues between fission and fusion exist in the field of materials and can be addressed together