EUROfusion

WPMAT

INTEGRATED EUROPEAN MATERIALS PROGRAMME FOR DEMO APPLICATIONS: RECENT ACHIEVEMENTS AND CHALLENGES

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F. Groeschel, KIT, Germany
J. Henry, CEA, France
G. Pintsuk, FZJ, Germany
M. Porton, CCFE, United Kingdom
R. Vila, CIEMAT, Spain

EFDA 2013: Topical Groups & Task Forces

Topical Group on Fusion Materials

ODSFS
- ODS ferritic steels

HHFM
- High heat flux materials

IREMEV
- Integrated radiation effects modelling & validation

MAR
- Materials assessment report

- **Budget for „Priority Support“ (40 %): <15 ppy, <350 k€**
- **„Baseline Support“ (20 %) for everything else**

EURO*fusion* 2014

Work Packages (WPs) | **WPDIV** | **WPMAT** | **WPBB** | …

Budget 2014: 49 ppy, 850 k€ (EC), 6 ppy (industry)

- Total EC contribution 2014: **4.4 M€**
- Total research budget 2014: **2.1 M€ + 55 ppy**

Budget 2014-2018: 261 ppy, 9.1 M€ (EC), 30 ppy (industry)

- Total EC contribution 2014-2018: **30 M€**
- Total research budget 2014-2018: **22.7 M€ + 291 ppy**

Funding Scheme

ppy → 50%, hardware → 40%, industrial ppy → 75% x 150 k€

Contents

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- **WPMAT - the MATERIALs Project**
  - **How is it structured and organized?**
  - **What will you get for the money?**
  - **Which are the strategies to reach the goals?**
- **Recent Achievements (examples only)**
  - **Steels**
  - **High Heat Flux Materials**
  - **Radiation Effects Modelling**

WPMAT

- CCFE
- CEA
- CIEMAT (+ CEIT,
  URJC, UPM, …)
- DTU
- ENEA
- ENEA-CNR
- FZJ
- HAS
- HELLENIC R.
- IPP
- IPPLM
- IST
- KIT
- LATVIA
- MEdC
- MESCS
- NRG
- ÖAW
- SCK.CEN
- TARTU
- TEKES
- VR

Project Structure

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M. Rieth (KIT)
Project Leader

S. Gonzalez (PMU)
Responsible Officer

F. Groeschel (KIT)
Project Manager

P. Yvon (CEA)
Project Board Chair

+ 21 board members

S. Dudarev (CCFE)
Group Leader

IREMEV
Integrated Radiation Effects Modelling and Validation

G. Pintsuk (FZJ)
Group Leader

HHFM
High Heat Flux Materials

J. Henry (CEA)
Group Leader

AS
Advanced Steels

R. Vila (CIEMAT)
Group Leader

FM
Functional Materials

M. Porton (CCFE)
Group Leader

EDDI
Engineering Data & Design Integration

Project Execution

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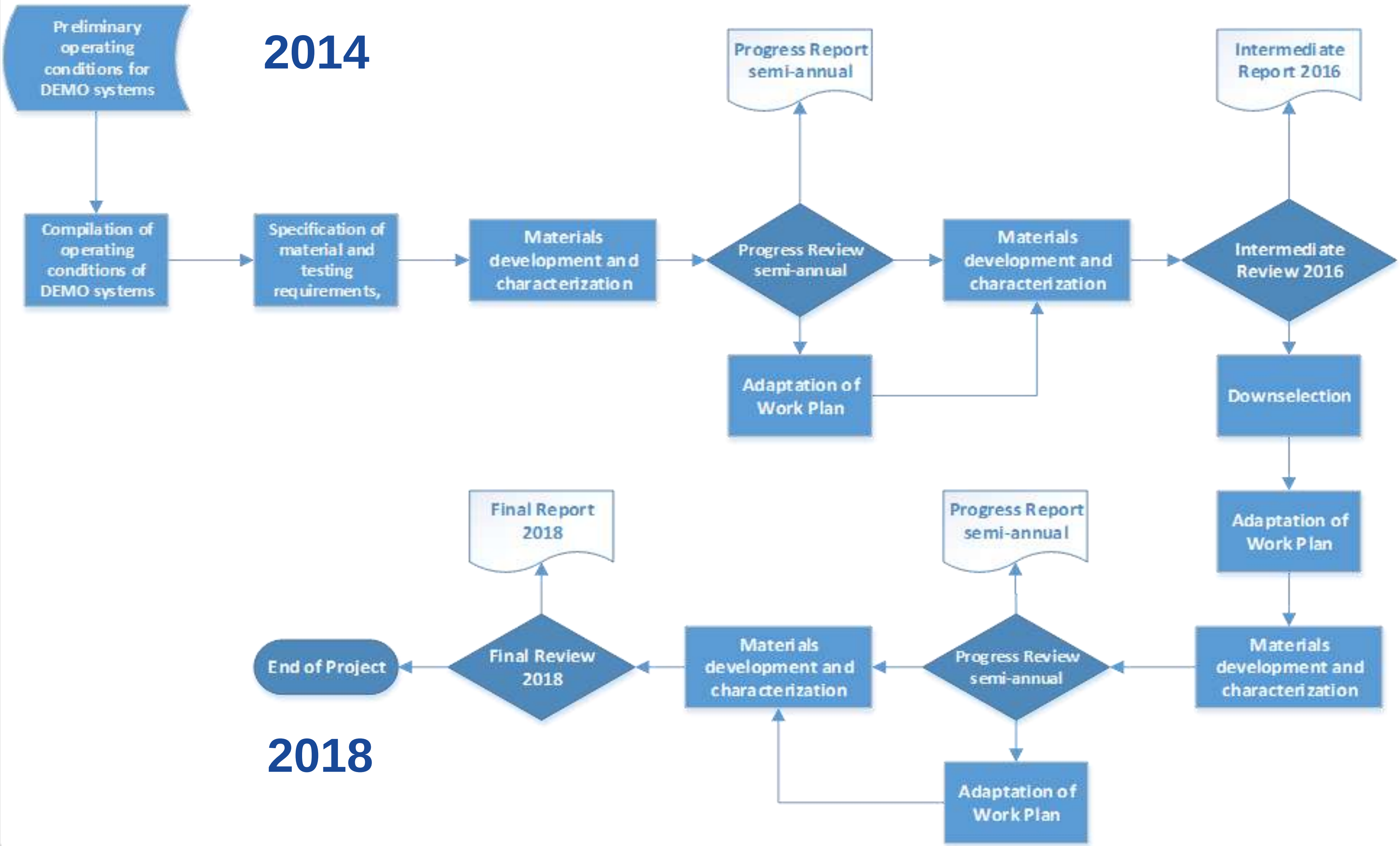

Project Requirements (examples)

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DEMO is a pulsed device with pulses of at least 2 h. The neutron wall load is ~1.3 MW/m^2 (conservative), 15 dpa/fpy in steel is taken as a benchmark. **Starter Blanket**: ~**1.33 fpy** or 4 calendar years.
→ Starter Blanket **steel dose 20 dpa (conservative)**
→ Starter Blanket **steel 6000** large-amplitude **fatigue cycles**

A **second Blanket**, lasting 11-16 calendar years could then be assumed. At 30% availability, this is **3.3-4.8 fpy** and corresponds to a **neutron damage** capability of **50-70 dpa**. This Blanket would have to withstand **13000-20000 fatigue cycles**.

DEMO will keep as back-up option the possibility to use water in the breeding blanket (such as the **Water Cooled Lithium Lead** concept in PPCS) and to rely on a full-established Fission Pressurized Water Reactor (PWR) technology in the BoP. For this, the **coolant inlet temperature must be reduced to $T_{inlet} < 300°C$**
→ **increased radiation embrittlement concerns for the ferritic steel structure**

High divertor power handling: ability to withstand power loads larger than 10 MW/m^2.
The **Divertor** replacement lifetime is assumed to be at least **2 fpy**. Hence, in the 20 year lifetime of the DEMO there are **3 Divertor replacements**.
→ Tungsten armour ~4 dpa/fpy (conservative) → **Tungsten maximum dose: 8 dpa**
→ Copper interface 3-5 dpa/fpy (min. in striking zone) → **Copper maximum dose: 6-10 dpa**

Project Objectives

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- **Consolidate the database and design codes** of the baseline materials
- **Develop, manufacture** - based on scalable processes - **and characterize advanced materials** as a mitigation measure
- **Develop models for neutron radiation effects**, specifically microstructural evolution and embrittlement, in iron alloys, steels, tungsten, and degradation of functional materials

Project Scope

- The **establishment of a materials handbook** of consolidated data on the baseline materials
- A **set of design codes** applicable for these baseline materials
- **Development of new materials** to mitigate requirements of advanced DEMO component designs
- **Demonstration of the production** of such materials in processes scalable to **industrial standards**
- **Characterization** of the properties of such materials

Project Strategies

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- **Project Management Plan, annual work programme with deliverables, progress monitoring, …**
- **Streamlining**
  - Pure academic issues are “outsourced” to Enabling Research
  - Exclusion of all technologies that cannot be up-scaled to the required level (e.g. planetary/shaker ball milling, Cu-Diamond/C mat., etc.)
  - Avoid duplication of work in characterisation tasks
- **Set focus on most important issues**
  - IREMEV focused on irrad. damage in steel and W (**NOT:** Be, Cu, etc.)
  - Starter Blanket requirements first
  - In general: concentrate lab resources on single topics
- **Communication**
  - Regular project managements meetings
  - Interfaces to external projects (e.g. WPBB, WPPFC, ITER, …)
  - Discussions between different groups (→ possible during monitoring)

Project Organization

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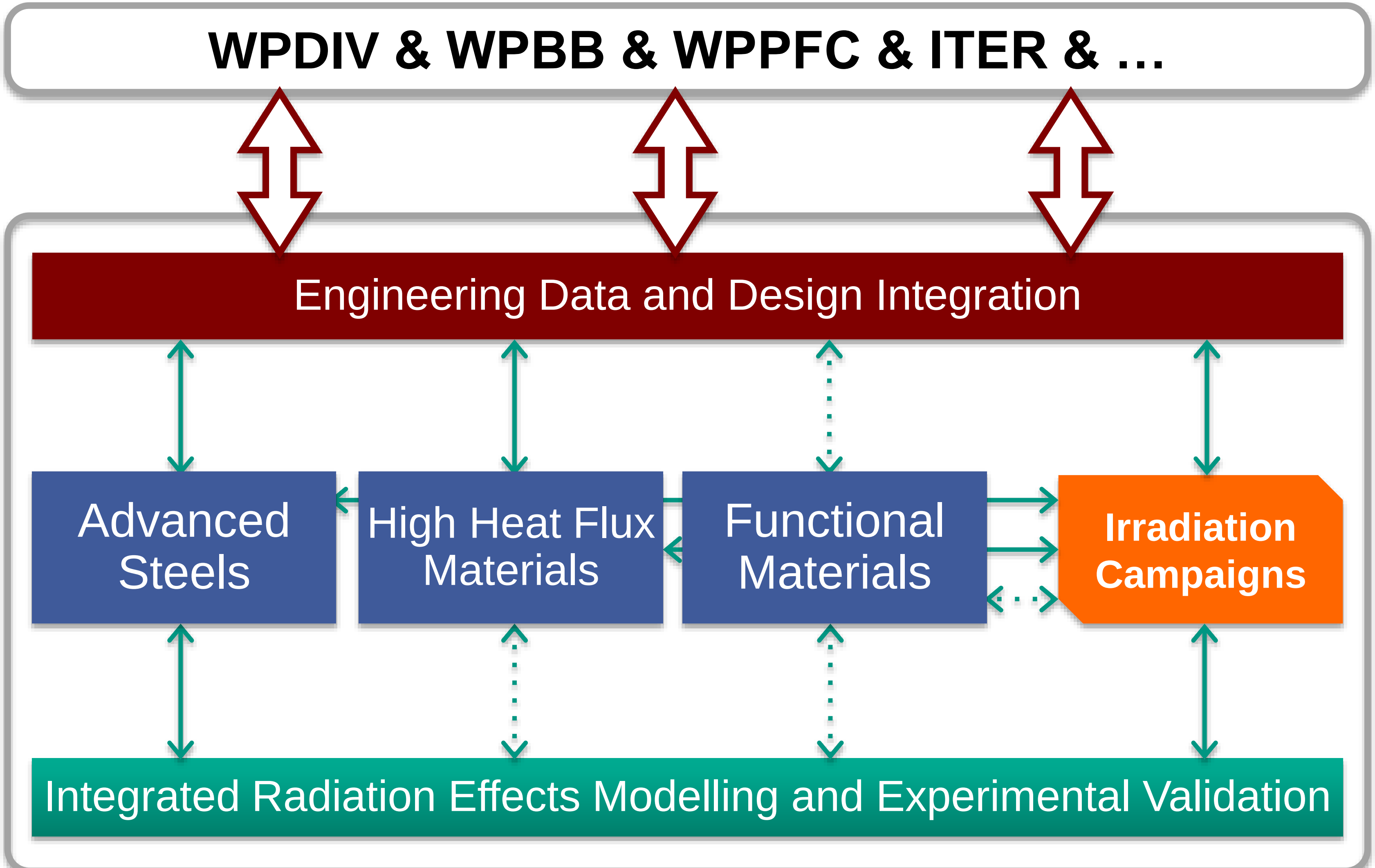

Engineering Data & Design Integration

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Work Programme

- **Coordination, communication, assistance**
  - Involvement in all MAT groups (readiness levels & evaluation system)
  - Close interaction with BB, DIV, …
- **Material Database & Handbook**
  - Transfer/continuation/modification of existing data base activities
  - Fusion Materials Handbook
- **Structural Design, Codes & Standards**
  - Evaluation of codes & standards (→ DEMO SDC-IC)
  - Analysis, adaptation, modification, extension of existing solutions in the fission programme
  - Survey and evaluation of experimental data and modelling approaches
- **Testing**
  - Design-specific experiments/characterisation
  - Close specific gaps in database

Functional Materials (FM)

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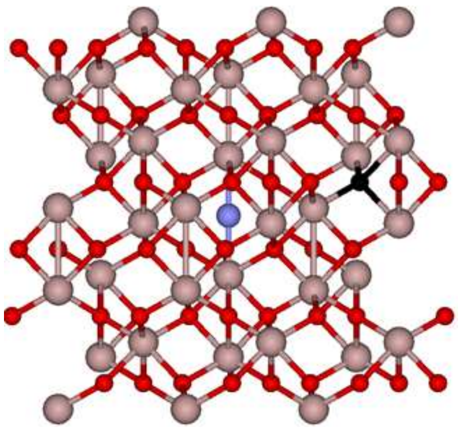
Scope

- Start-up and establish research teams
- **Focus: Optical & Dielectric Materials**
- Experimental testing of degradation under irradiation
- Solve fabrication problems in cooperation with industry
- Development, improvement of properties
- "Re-activation" of modelling tools



Work Programme

- Development and irradiation testing
- Modelling of radiation defect kinetics
- Radiation damage effects on the reflectivity of first mirrors for DEMO
- Improvement of dielectric properties of ECRH diamond window

Advanced Steels (AS)

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FW steel loads (conserv.)

- 20 dpa, 100 appm He
- 6000 fatigue cycles
- 12000 h creep

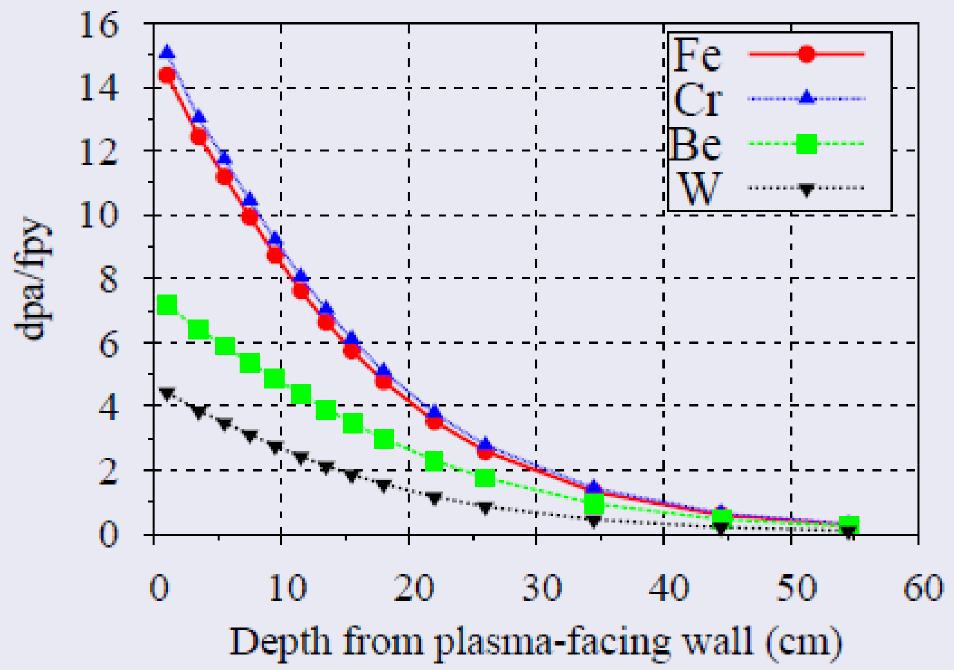
Strategy

- Baseline → **EUROFER**
- Development of steels with advanced properties for the plasma-facing part of the blanket (15-30 cm)
  → **Advanced Steels**

Topics

- RAFM for high temperatures
- RAFM for water cooling
- Ferritic ODS steels

dpa/fpy as a function of depth into the outboard equatorial FW



M. Gilbert, CCFE

Advanced Steels (AS)

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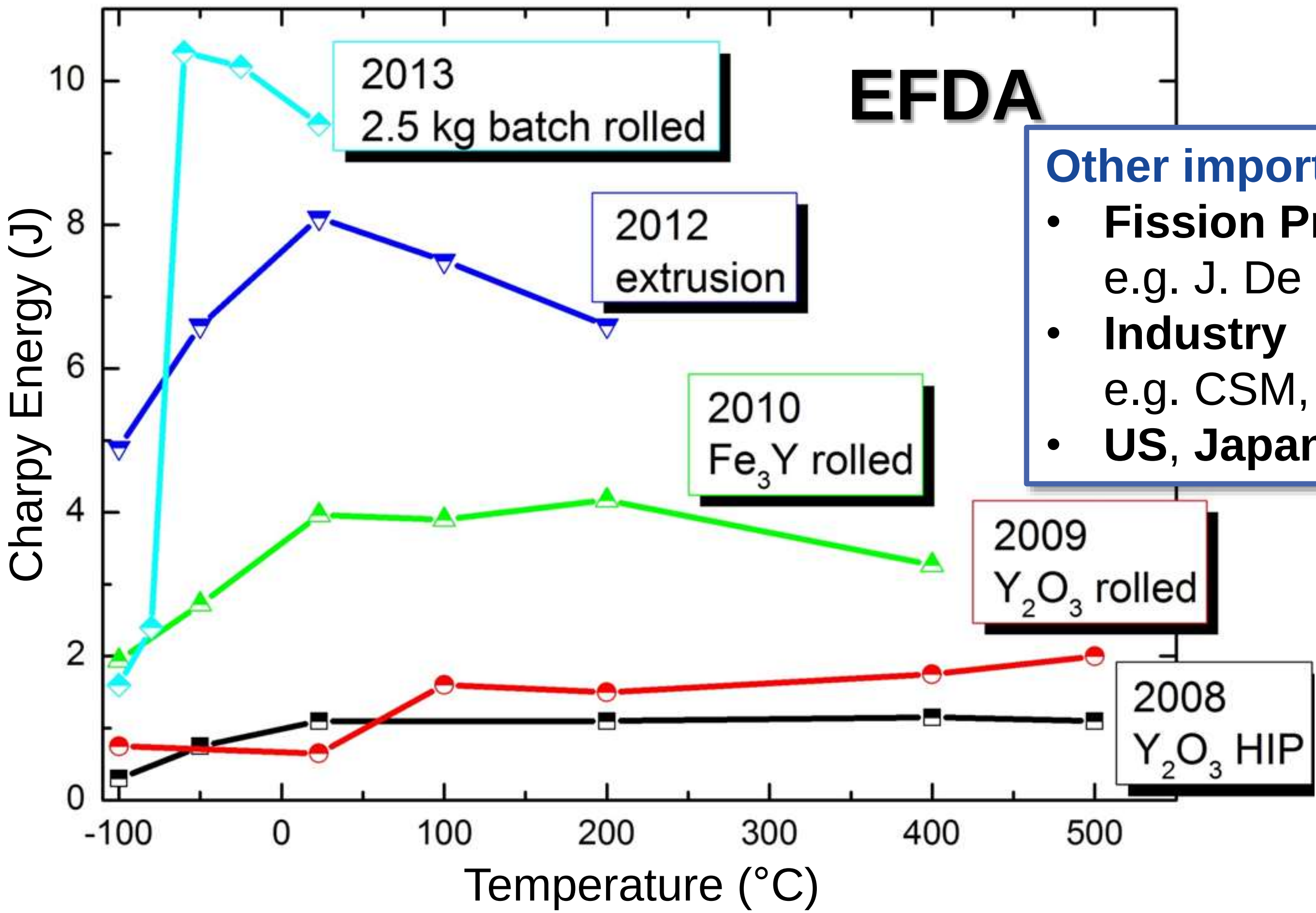
Recent Progress: 13-14% Cr ODS ferritic steels



Other important R&D Work

- **Fission Projects**
  e.g. J. De Carlan *et al.*, CEA
- **Industry**
  e.g. CSM, Italy
- **US**, **Japan**, …

J. Hoffmann *et al.*, KIT

Advanced Steels (AS)

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Work Programme

ODS steel: Fabrication & Demonstration

- Production of a 100 kg 14%Cr ODS steel batch by mechanical alloying
  - Plates: thickness 2 mm, size 2 m²
  - Demonstration of applicability to first wall
- Alternatives to mechanical alloying (feasibility studies and industrial fabrication)

Development of RAFM steels for high temperature applications

- Specific thermal treatments
- Fine tuning of the chemical composition
- Special thermo-mechanical treatments (TMT, „ausforming“, …)

Optimization of RAFM steels for possible water cooling

- Specific thermal treatments (for optimum DBTT)
- Change of chemical composition

High Heat Flux Materials (HHFM)

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From ITER to DEMO

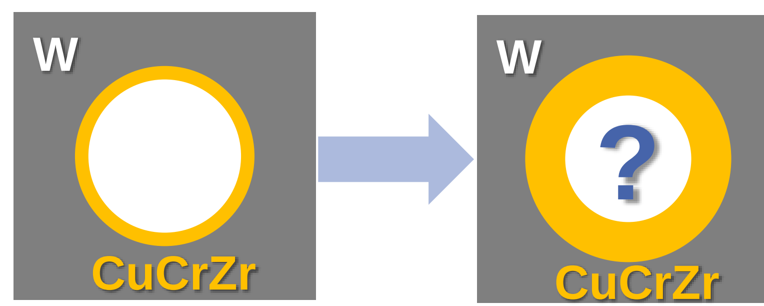
- Neutron damage has to be taken into account:
  → loss of thermal conductivity
  → embrittlement
  → swelling
- Effect of n-irradiation on CuCrZr and W is uncertain at relevant dose and temperature levels
- CuCrZr has upper temperature limit: 300-350 °C (loss of strength)
- W has lower temperature limit: 800-1000 °C (embrittlement)

→ Risk Mitigation

→ **DEMO**
?

Water: 100 °C, 4 MPa
150 °C, 4 MPa

CuCrZr pipes: <0.2 dpa/y — **3-5 dpa/fpy**
Max. heat: 10-20 MW/m² — 10-20 MW/m²



Baseline: ITER-like Divertor Concept

High Heat Flux Materials (HHFM)

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Work Programme

Risk Mitigation: Materials

- W (armour, plasma-facing) Materials
- Interlayer Materials
- Cu (structural, heatsink) Materials

Topics/Strategies
- W-W/fiber comopsites
- WC & SiC reinforced W
- W alloy development (PIM)
- Cu-W (fiber & particle) comp.
- W/Cu functionally graded
- Self-passivating W alloys

Risk Mitigation: Helium cooled divertor

- Structural Material
- Fabrication Technology

Topics/Strategies
- W-X laminated pipes

Continuation of the EFDA Programme

- Joining Techniques
- Large Facility (HHF) Testing
- Characterization
- Demonstration: Application & Industrial Scale-up

High Heat Flux Materials (HHFM)

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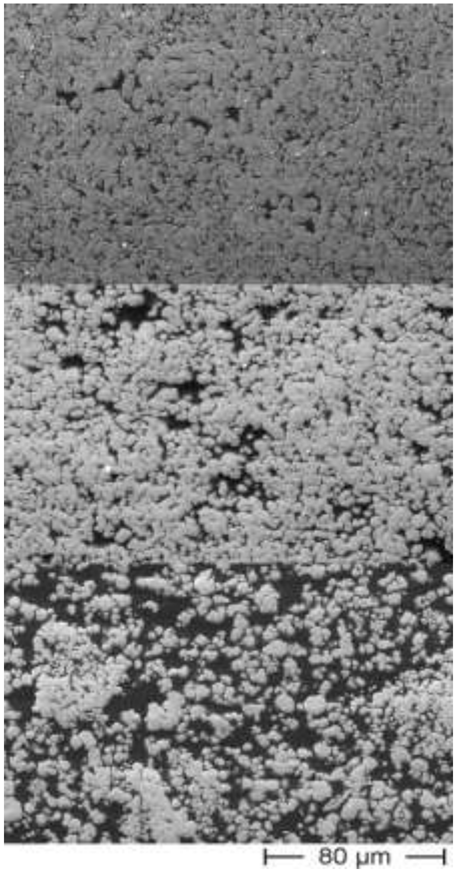
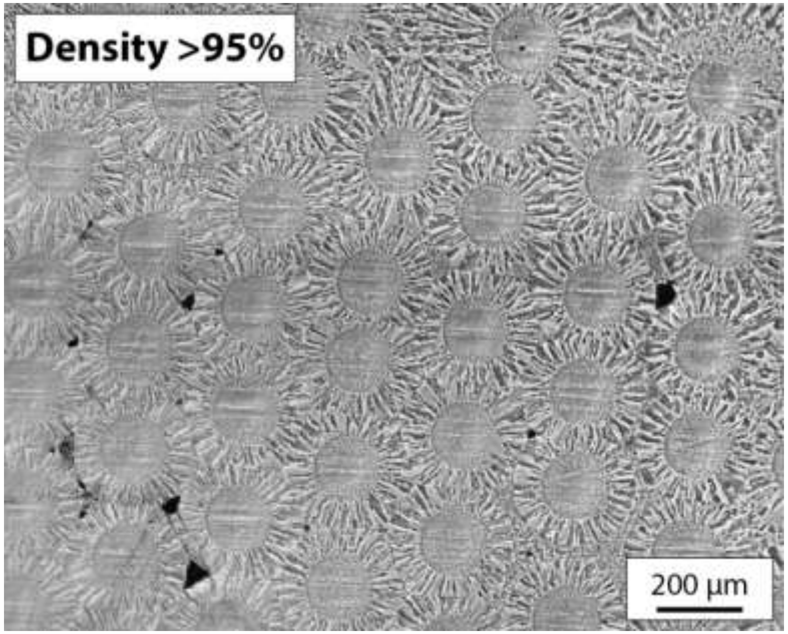
Recent Progress: Advanced Materials

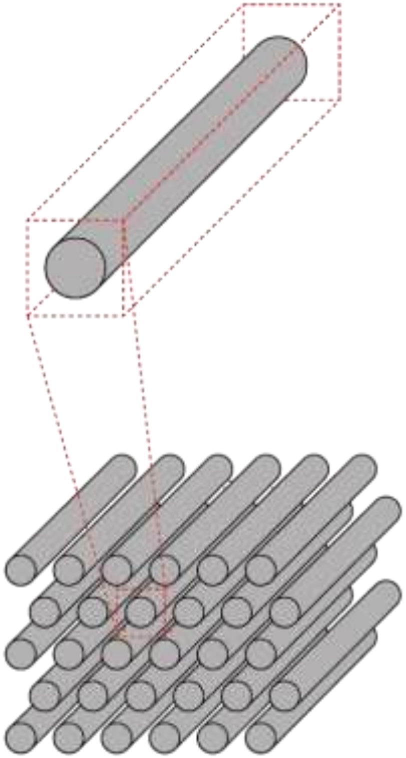
W-Cu graded composite by melt infiltration



S. Nawka (IFAM)

W/W-fiber reinforced composite by chemical vapour infiltration





Industrial scale-up
→ Chemical deposition

J. Riesch, T. Höschen, J.-H. You, R. Neu (IPP)

High Heat Flux Materials (HHFM)

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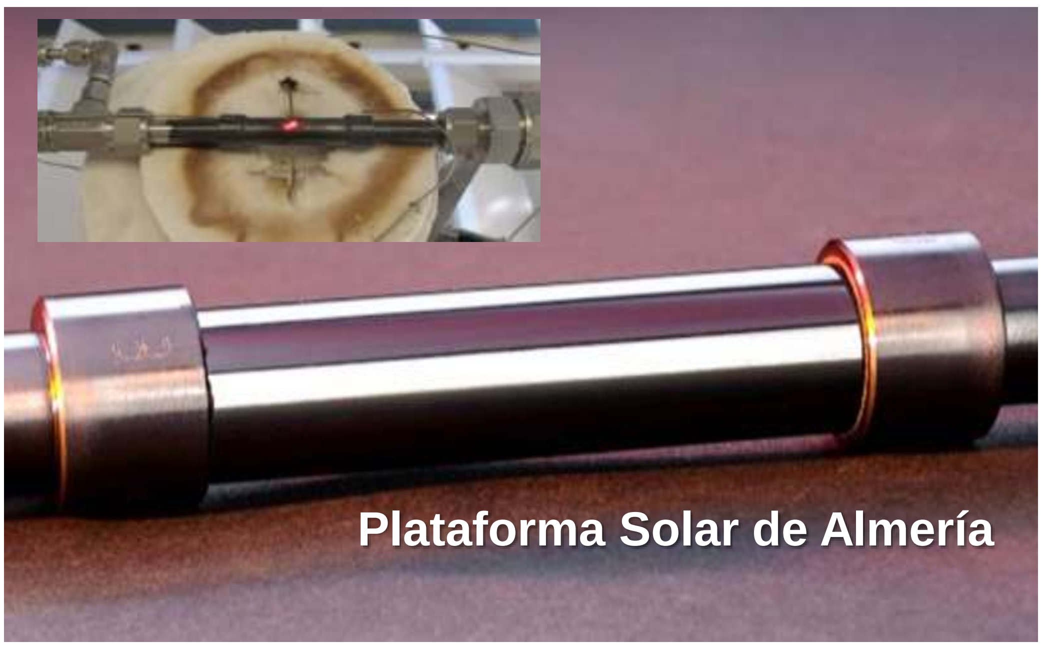
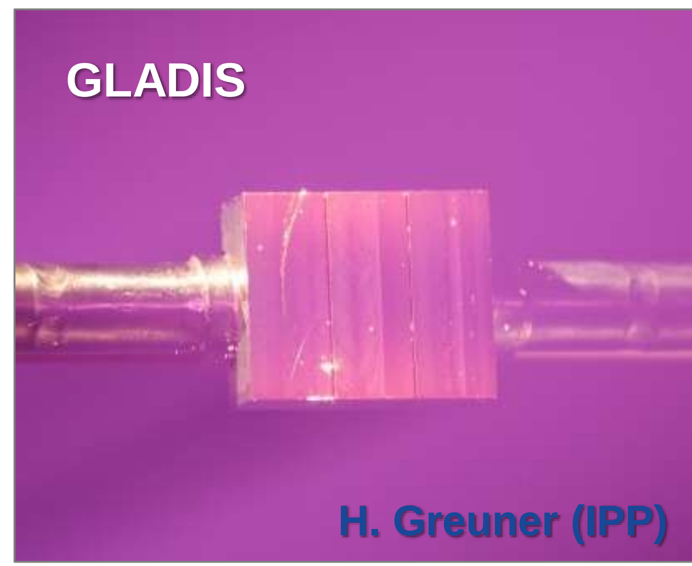
Recent Progress: Mock-up studies



J. Reiser *et al.* (KIT)





High Heat Flux Materials (HHFM)

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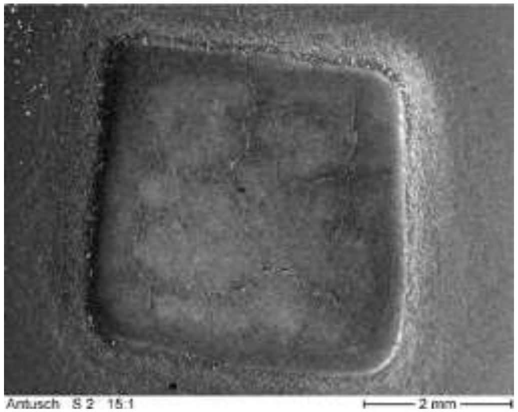
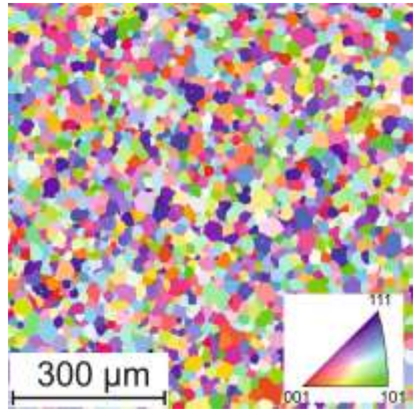
Progress: W armour alloys development & benchmarking

100 shots, P=1.13 GW/m², dt=5 ms



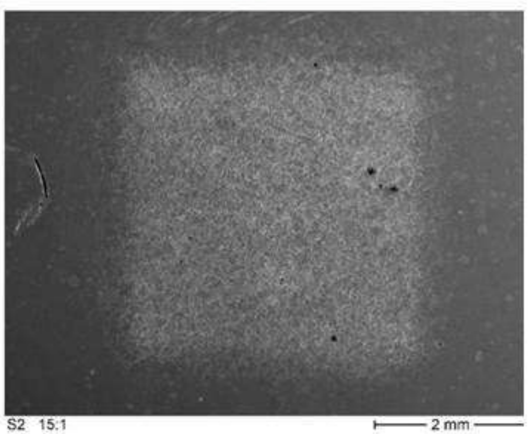


Highlights

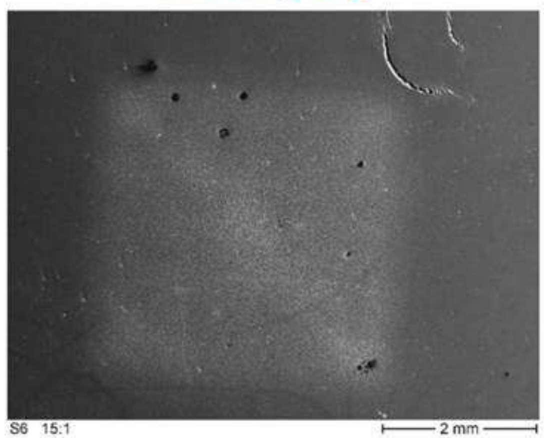
- Anisotropic microstructure
- Properties adjustable
  - ➢ e.g. YS: 600-1200 MPa
- W-nX: X=TiC, Y_2O_3, La_2O_3, …
  - ➢ e.g. n=0.5 – 2 wt.%
- Rapid alloy production

S. Antusch (KIT)

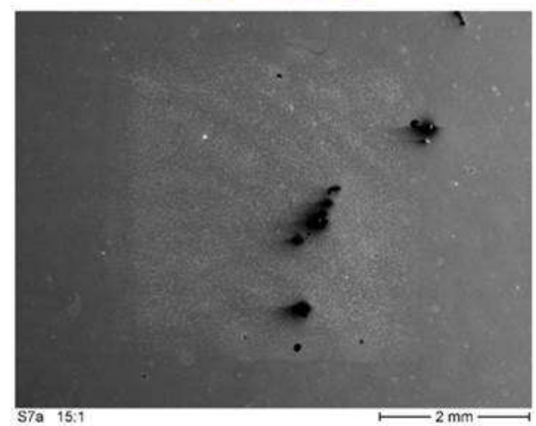
W



W-2Y_2O_3



W-1TiC



1000 shots, P=0.38 GW/m², dt=1 ms, T=1000 °C

G. Pintsuk (FZJ, JUDITH-1)

High Heat Flux Materials (HHFM)

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Recent Progress: W alloys produced by PIM

Highlights

- **Near net-shaped parts in many geometries:**
  - ITER geometries
  - WEST prototypes
  - Saddle types
  - Plates, pipes, …

- **Transfer of beneficial material properties**

- **Industrial mass fabrication process:**
  - Feedstock (KIT)
  - Green parts (RKT)
  - Sintering (PLANSEE)

S. Antusch (KIT)

Integrated Approach to Fusion Power Plant Design by IREMEV

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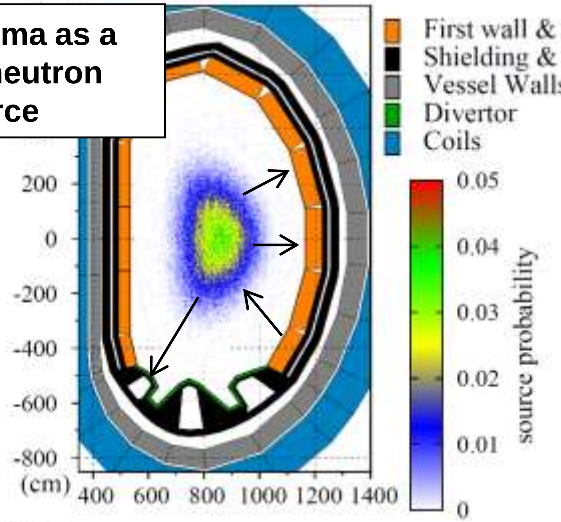
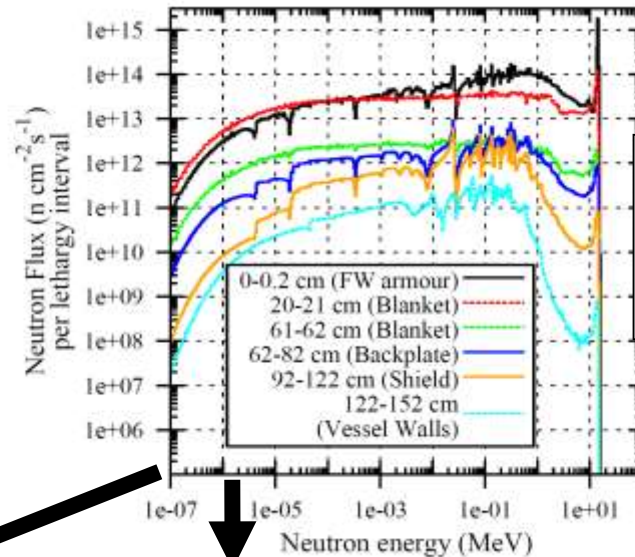
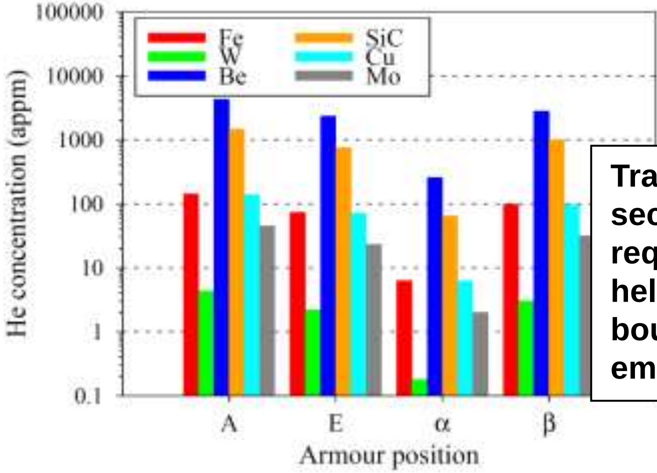
Plasma as a 3D neutron source



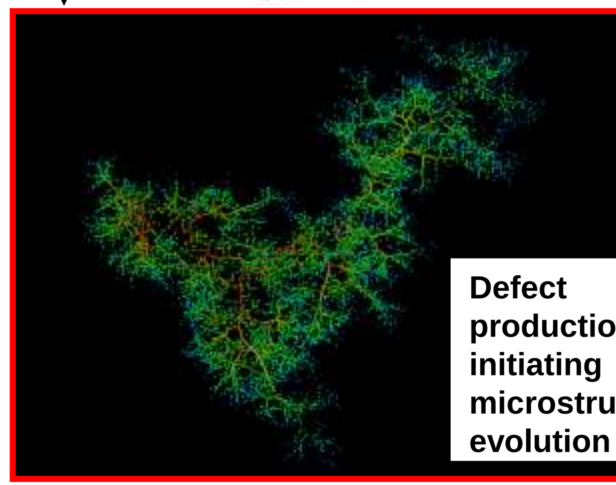


Neutron spectra at various locations in a tokamak



Transmutation cross-section data are required to predict helium-induced grain boundary embrittlement

M.R. Gilbert *et al*., Nucl. Fusion **52** (2012) 083019; J. Nucl. Mater. **442** (2013) S755



Defect production, initiating microstructural evolution

A. Sand *et al*. EPL **103** (2013) 46003

Integrated Radiation Effects Modelling and Experimental Validation (IREMEV)

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Work Programme

1. Models for Primary Radiation Damage
2. Evolution of Microstructure under Ion and Neutron Irradiation
3. Experimental Examination of Microstructure
4. Response of Irradiated Materials to Deformation: Hardening and Embrittlement

Recent Progress: Example (WP 1., 2., 3.) for Tungsten
→ from collision cascades to microstructure

IREMEV: from collision cascades to microstructure

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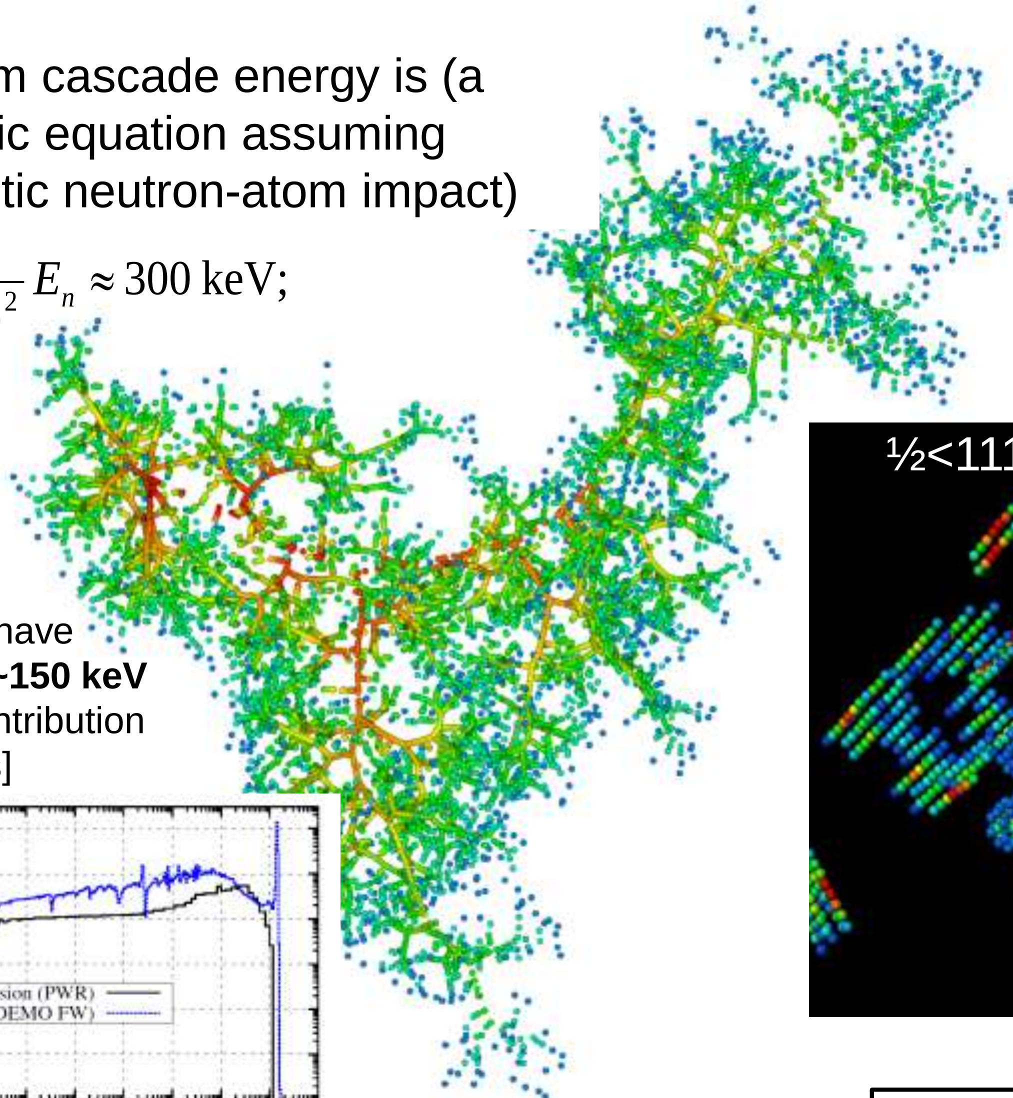
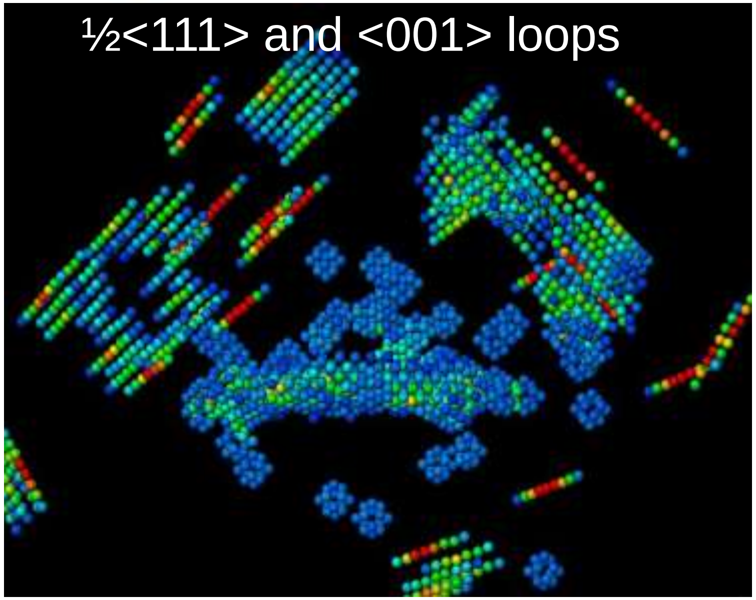
The maximum cascade energy is (a non-relativistic equation assuming head-on elastic neutron-atom impact)

$$E_{\max} \approx \frac{4mM}{(m+M)^2} E_n \approx 300\ \text{keV};$$

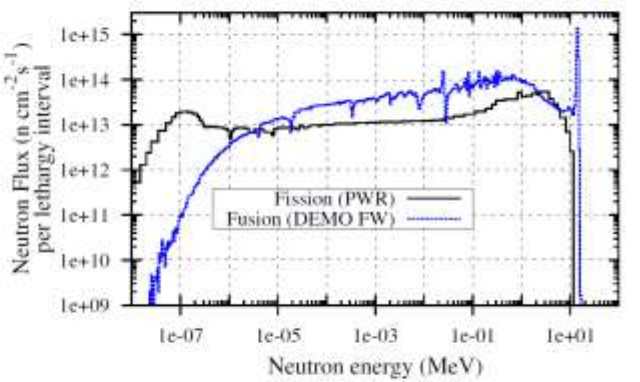
$$E_n = 14.1\ \text{MeV}$$



A **150 keV** cascade in **tungsten**: first MD simulations of high energy “fusion” cascades



Many cascades have energy close to **~150 keV** [this neglects contribution of (n,γ) reactions]



A.E. Sand *et al.*, EPL **103** (2013) 46003

M. Rieth, S. Dudarev, S. Gonzalez, F. Groeschel, J. Henry, G. Pintsuk, M. Porton, R. Vila: INTEGRATED EUROPEAN MATERIALS PROGRAMME FOR DEMO APPS

IREMEV: from collision cascades to microstructure

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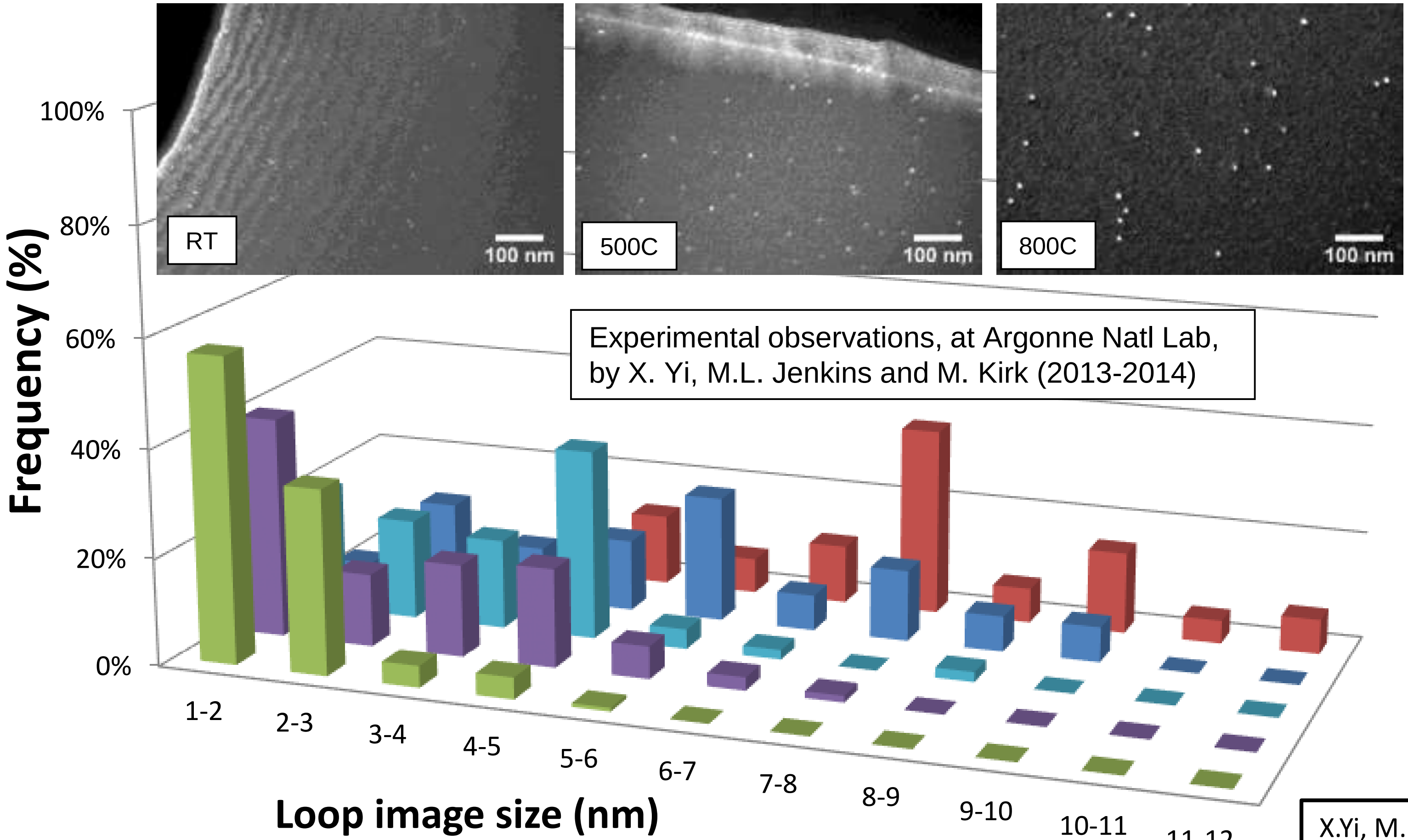
Size distribution of defects in W: 0.01dpa, RT-800°C



X.Yi, M.L. Jenkins et al., Philos. Mag. **93** (2013) 1715

Defect size distributions versus temperature.

IREMEV: from collision cascades to microstructure

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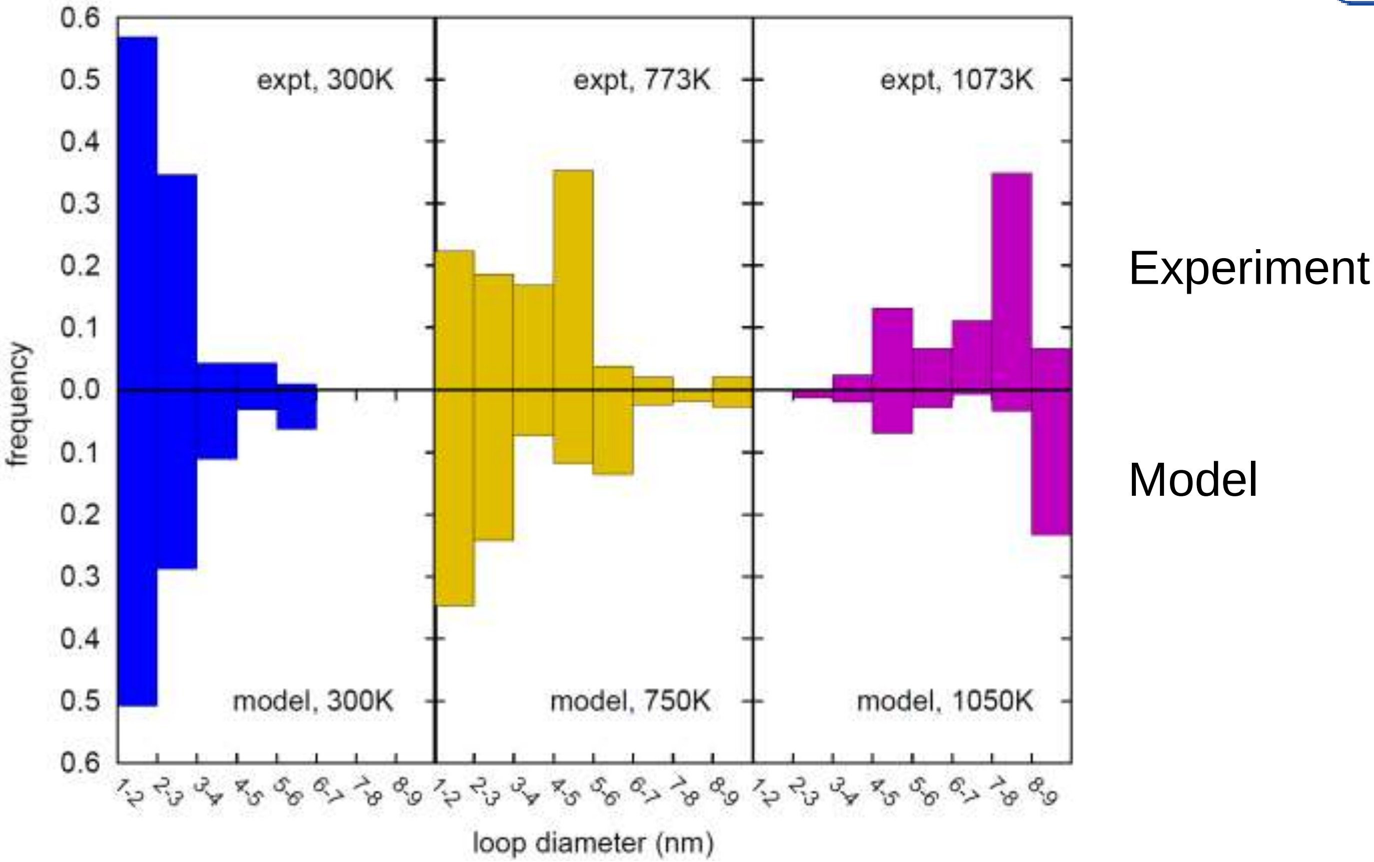

Comparison between the experimentally observed (upper part of each diagram) and predicted (bottom part of each diagram) distribution of sizes of dislocation loops generated in collision cascades.

Experimental observations were performed at Argonne National Laboratory by X. Yi (CCFE Fellow at the University of Oxford).

D.R. Mason et al. J. Phys.: Condens. Matter **26** (2014) 375701

IREMEV: from collision cascades to microstructure

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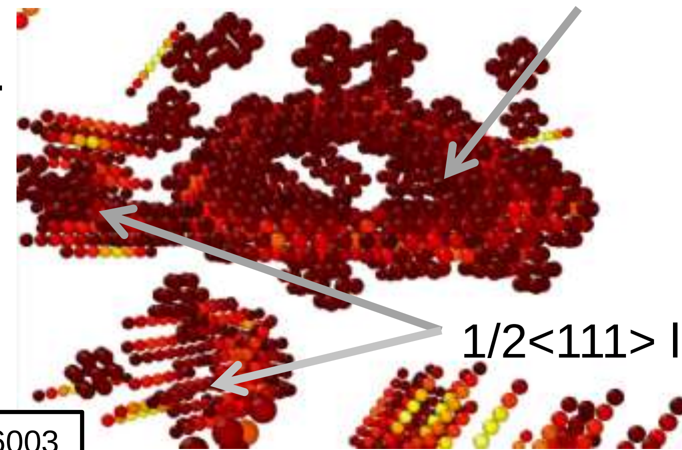
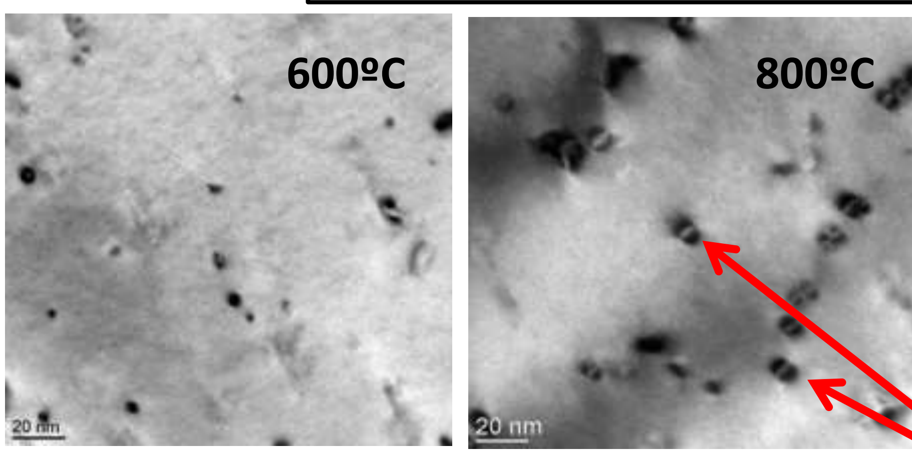
111 and 001 loops in tungsten

Loops with both ½<111> and <001> Burgers vectors have been found in cascade simulations. **Loops with two different Burgers vectors have different properties and contribute differently to microstructural evolution.** In tungsten that, unlike iron, is elastically isotropic, the occurrence of the <001> loops is <u>not</u> related to elastic anisotropy.

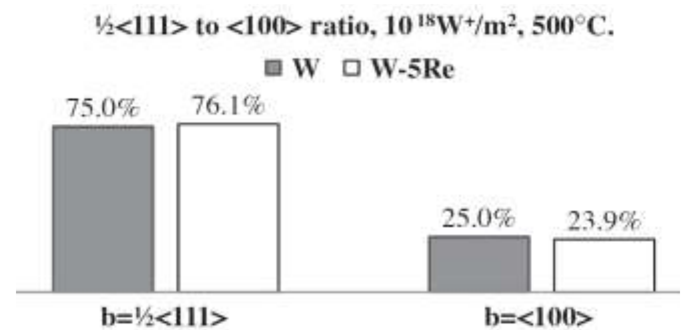


A.E. Sand *et al*., EPL **103** (2013) 46003



Microstructure of W irradiated to 1 dpa, note the temperature effect

Dislocation loops



X.Yi, M.L. Jenkins et al., Philos. Mag. **93** (2013) 1715

Summary

WPMAT

- Increased budget (manpower, hardware, industry)
- Narrow focus with clear priorities (fully DEMO oriented)
- Beside „classical“ materials R&D (now with „functional materials“), WPMAT includes „material physics“ (theory & modelling) as well as „data & design“ issues
- Clear strategies to reach the goals in all areas
- Close links to „Breeding Blankets“, „Divertor“ and „Plasma Facing Components“, but clear separation of topics (minimum overlap)

OUTLOOK → Optimistic !

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THANK YOU !