Status of R&D Activities on Materials for Fusion Power Reactors

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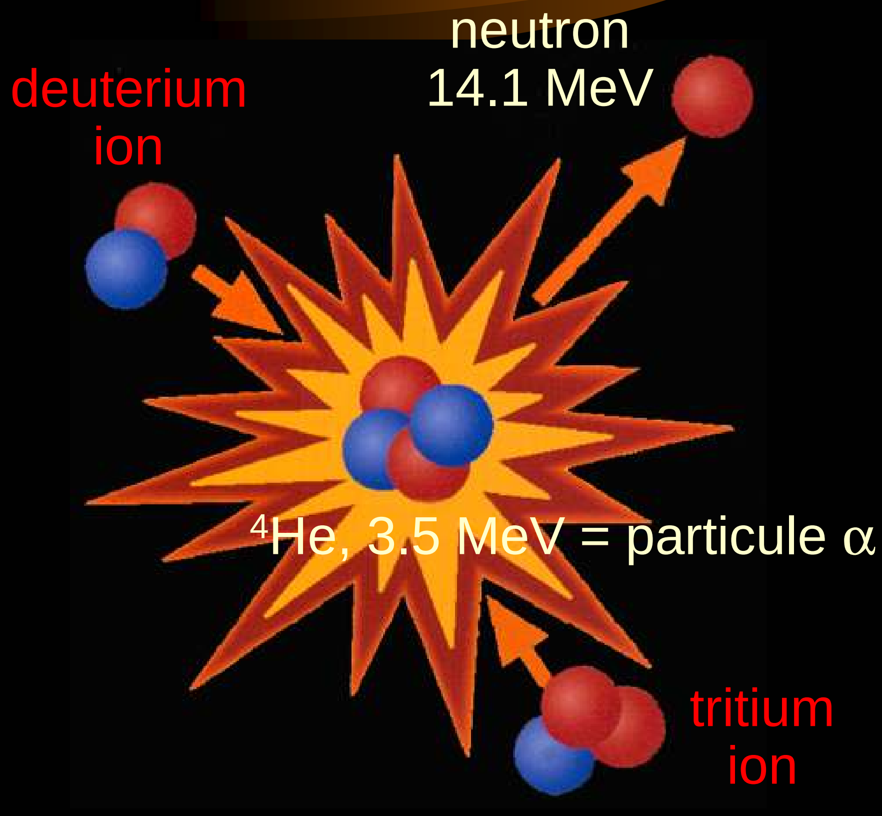
Materials Issues

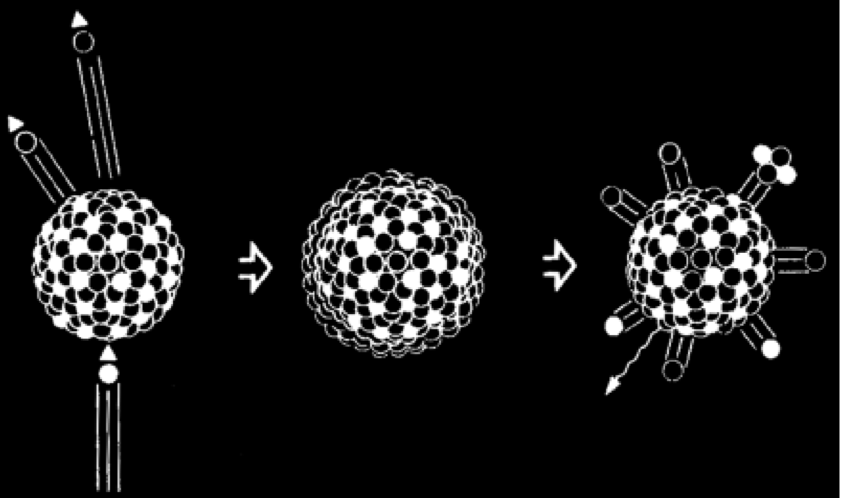
Products of D-T Fusion Plasma

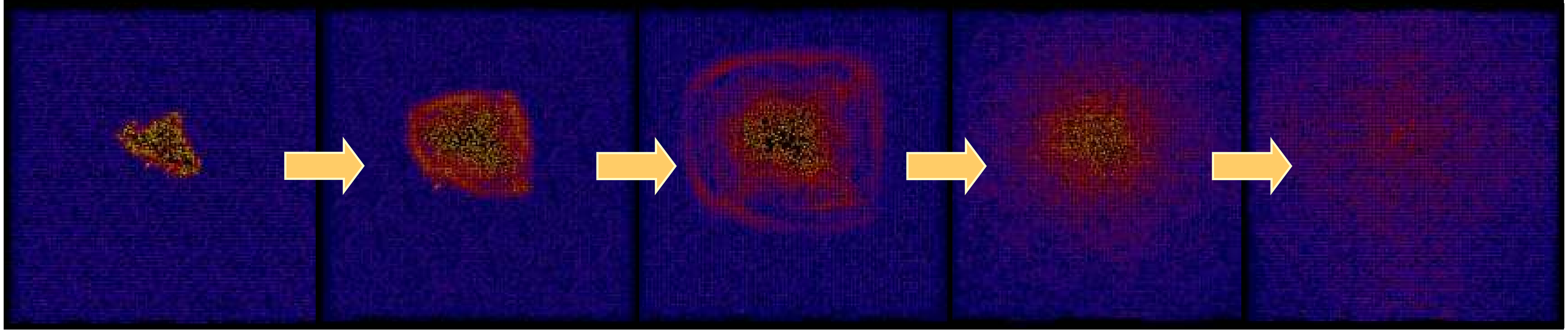
- Plasma facing (first wall, divertor) and breeding-blanket components:
  - exposed to plasma particles and electro-magnetic radiation
  - suffer from irradiation by an intense flux of 14 MeV neutrons



Effects of 14 MeV Neutrons

- The 14 MeV neutrons will produce transmutation nuclear reactions and atomic displacement cascades inside the materials.

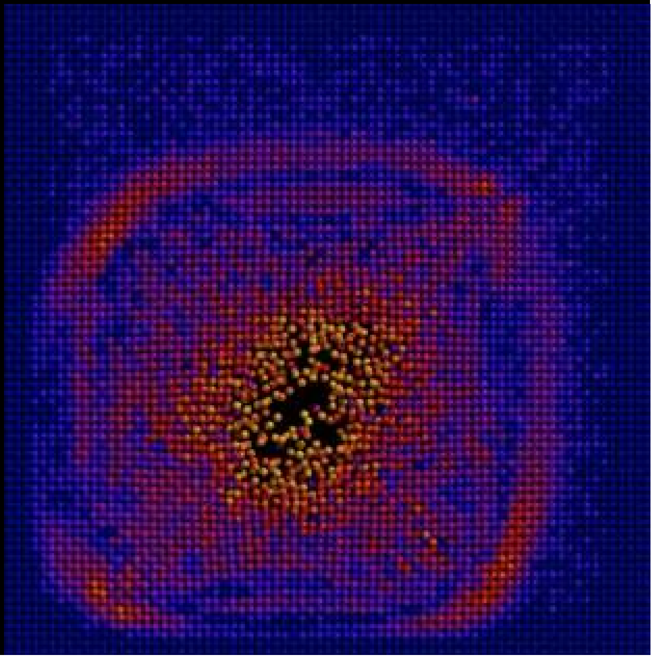




Evolution of the Microstructure

- Transmutation nuclear reactions:
  - impurities: He gas atoms, H gas atoms

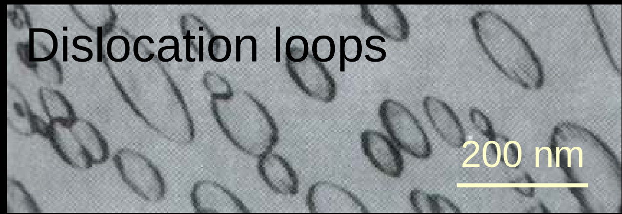
- Atomic displacement cascades:
  - point structure defects:
    vacancies, intersitials,
    clusters of vacancies,
    clusters of interstitials
  - segregation of alloying elements



Evolution of the Microstructure

- The final microstructure results from a balance between radiation damage and thermal annealing

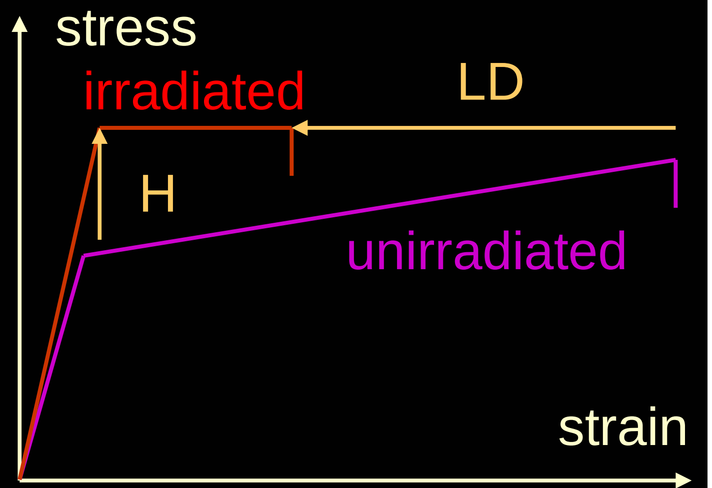
- <u>Complex secondary defects:</u>
- Small defect clusters
- Interstitial dislocation loops
- Vacancy dislocation loops
- Stacking fault tetrahedra
- Precipitates
- Voids
- He bubbles



Evolution of the Properties

- <u>Chemical composition:</u>
- Change in the chemical composition
- <u>Physical properties:</u>
- Decrease of electrical conductivity (low temperatures)
- Decrease of thermal conductivity (ceramic materials)
- <u>Mechanical properties:</u>
- Hardening (H)
- Loss of ductility (LD)
- Loss of fracture toughness
- Loss of creep strength
- <u>Dimensions:</u>
- Swelling, irradiation creep, irradiation growth
- <u>Environmental effects:</u>
- Irradiation-assisted stress corrosion cracking
- <u>Radioactivity:</u>
- Activation effects

Embrittlement effects



Key Irradiation Parameters

- Key irradiation parameters:
- Accumulated damage (in dpa)
- Damage rate (in dpa/s)
- Rates of production of impurities (e.g. appm He/dpa, appm H/dpa ratios)
- Temperature

dpa = number of displacements per atom

Evolution of the Properties

- Low temperatures (e.g. < 400℃ for steels):
- Embrittlement effects: hardening, loss of ductility, loss of fracture toughness, increase in DBTT (bcc materials)
- Intermediate temperatures (e.g. 300-600℃ for steels):
- Swelling: peaks at about 450℃ for RAFM steels
- High temperatures (e.g. > 600℃ for steels):
- Enhanced precipitation effects
- Enhanced creep effects

Current Irradiation Facilities

- The existing sources of 14 MeV neutrons have a small intensity and do not allow us to get important damage accumulation in a reasonable time.

- It is necessary to simulate irradiation by 14 MeV neutrons, by using either fission neutrons, or high energy protons, or heavy ions.

Irradiation Modes

- Fusion neutrons, fission neutrons, high energy protons:
- Strong differences in the production rates of impurities

Defect poduction (in steels)	Fusion neutrons (3-4 GW reactor, first wall)	Fission neutrons (BOR 60 reactor)	High energy protons (590 MeV)
Damage rate [dpa/year]	20-30	~ 20	~ 10
Helium [appm/dpa]	10-15	≤ 1	~ 130
Hydrogen [appm/dpa]	40-50	≤ 10	~ 800

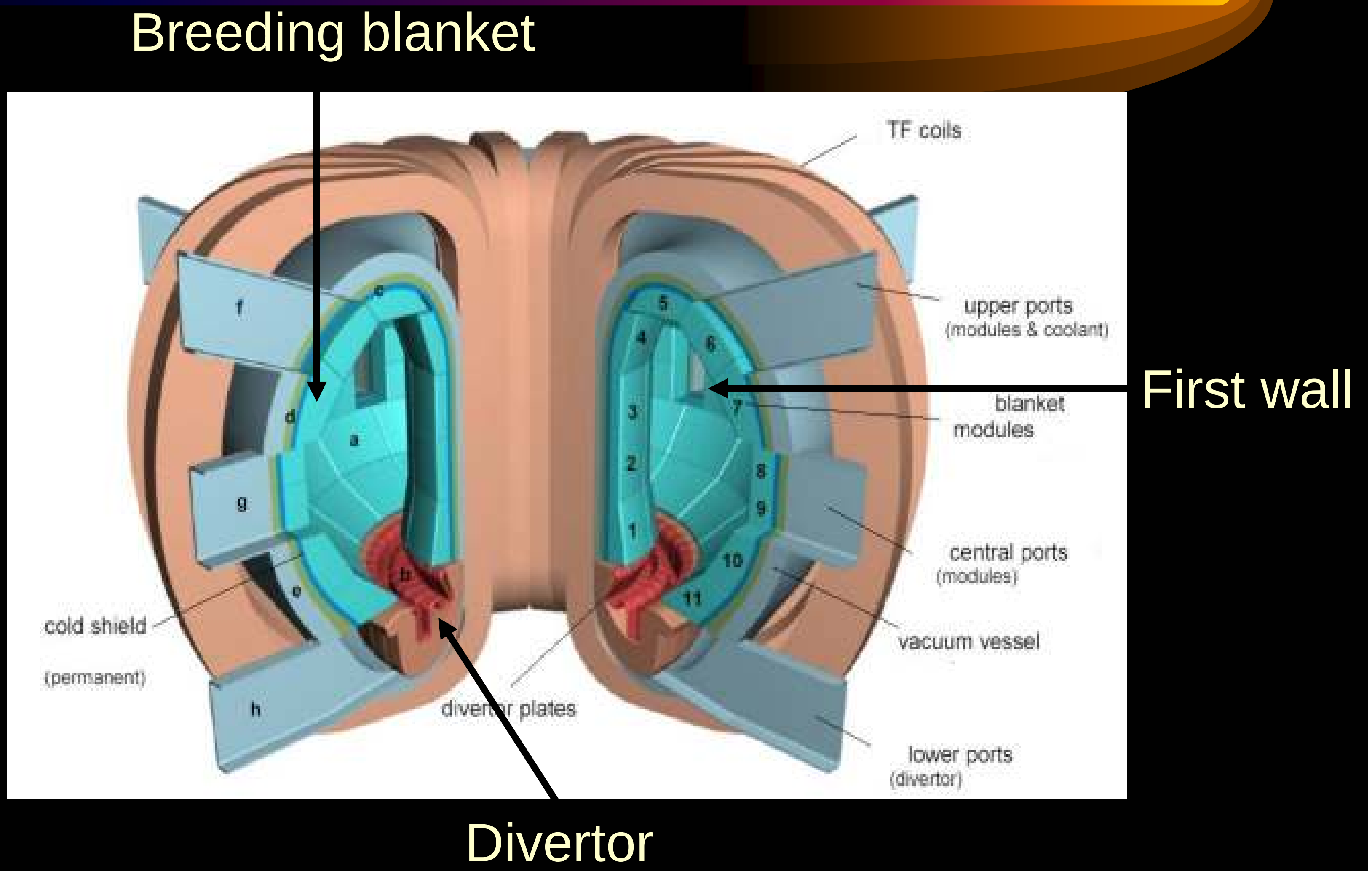
Present Approach

- Materials are irradiated with fission neutrons on the one hand and with high-energy protons on the other hand. The obtained results are tentatively interpolated for fusion irradiation conditions.

- It is difficult to separate effects of particle type, particle energy, temperature, accumulated damage, damage rate and rates of production of impurities.
- Materials have to be submitted to actual fusion irradiation conditions in order to be fully qualified for designers and engineers.

Components and Materials of Concern

Main Irradiated Components



Types of Irradiated Materials

- Plasma facing materials:
  - Serve as an armour for the other materials
- Functional materials:
  - Have one or several particular functions
- Structural materials:
  - Support the basic structure of the fusion reactor

Plasma Facing Materials

- The qualification of plasma facing materials is very demanding: They will be exposed to the fusion plasma.
  - High heat flux of energetic particles: 0.1-20 MW/m^2
  - High temperatures: 500-3200℃
  - Electromagnetic radiation
  - Sputtering erosion
  - High levels of neutron-irradiation: 3-30 dpa/year
  - Off-normal events: plasma disruptions, ELM (Edge Localized Mode) events
  - Hydrogen trapping

Candidate Plasma Facing Materials

- Selection of plasma facing materials is mainly limited by their capability for absorbing heat and minimizing plasma contamination.
  - W: high T_m, low erosion material, good heat load capability
  - Liquid metals: high heat load capability

Function	First wall	Breeding blanket	Divertor
Armour material	W-base alloy, W-coated ODS steel, flowing liquid metal: Li	-	W-base alloy, W-coated SiC/SiC, flowing liquid metal: Li, Ga, Sn, SnLi
Coolant	-	-	-

Functional Materials

- The qualification of functional materials is also very demanding:
  - Neutron multiplier, Tritium breeding material, ceramic insulators, dielectric and optical windows, optical fibres, complete sensor assemblies, ...
  - Their mechanical resistance under irradiation is presently not considered of primary concern.
  - But properties, like the Tritium release behaviour, the thermal conductivity or the entire structural integrity after prolonged neutron irradiation, are important concerns.

Candidate Functional Materials

- Selection of functional materials is very limited as it relies mainly upon the properties required by the envisaged function.

Function	First wall	Breeding blanket	Divertor
Neutron multiplier material	-	Be, $Be_{12}Ti$, $Be_{12}V$, Pb	-
Tritium breeding material	-	Li, eutectic Pb-Li, Li-base ceramic materials	-
Coolant	-	Water, helium, eutectic Pb-Li, Li	Water, helium

Functional Materials

- The lack of adequate functional materials meeting very high temperature design window is an important issue for fusion power reactors.
- Component lifetime will be determined by the resistance of functional materials as well by the resistance of plasma facing and structural materials.

Structural Materials

- The qualification of structural materials is fundamental
  - High temperatures
  - High levels of neutron irradiation
  - High mechanical stresses
  - High thermo-mechanical stresses

Structural Materials

- The thermal efficiency of a reactor is proportional to:
  - The temperature of the coolant at the exit of the reactor.
  - The difference between the temperature of the coolant at the exit of the reactor and the temperature of the coolant at the entrance of the reactor.

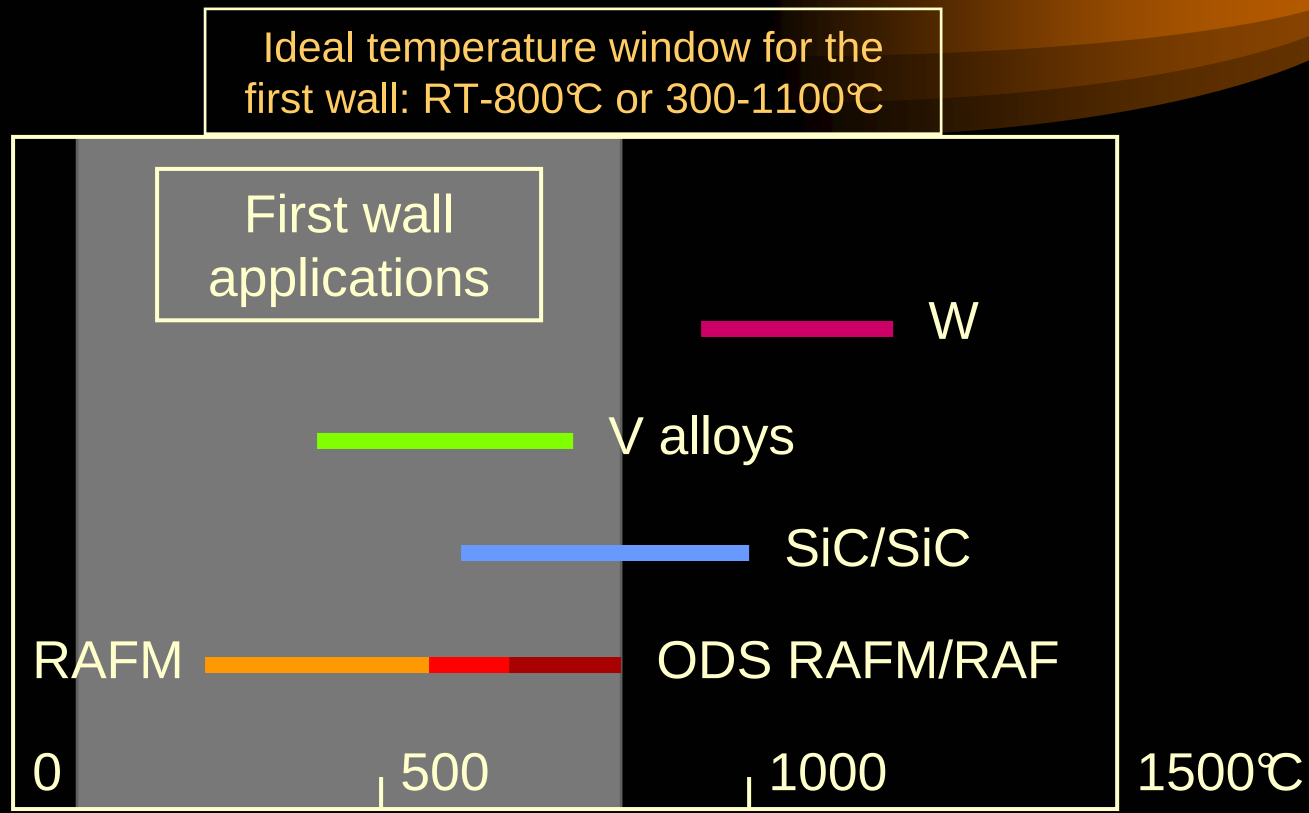
- These temperatures are mainly limited by the temperature window of use of the structural materials.
- The temperature window of use of the structural materials is mainly limited by their mechanical resistance under irradiation.

Candidate Structural Materials

Candidate structural materials have a chemical composition that is based on low activation elements:
Fe, Cr, V, Ti, W, Si, C

- Reduced activation ferritic/martensitic (RAFM) steels
- Oxide dispersion strengthened (ODS) RAFM steels
- Oxide dispersion strengthened RAF steels
- Vanadium-base alloys
- Tungsten-base alloys
- SiC/SiC_f ceramic composites

Temperature Windows of Use



Irradiation-induced embrittlement

Drop in mechanical strength / chemical compatibility

Candidate Structural Materials

- Various existing first wall / breeding blanket / divertor designs consider different combinations of materials.

Function	First wall	Breeding blanket	Divertor
Structural material	RAFM steel, ODS steel, V-base alloy, SiC/SiC	RAFM steel, ODS steel, V-base alloy, SiC/SiC	ODS steel, W-base alloy
Coolant	-	Water, helium, eutectic Pb-Li, Li	Water, helium

Most Promising Structural Materials

- RAFM steels remain presently the most promising structural materials for plasma facing components and breeding blanket applications:
  - A great technological maturity has been achieved: qualified fabrication routes, welding technology and a general industrial experience are almost available.
  - Compatibility with aqueous, gaseous, and liquid metal coolants permits range of design options.
  - Effects of high He/dpa ratio ?
  - Possible design difficulties due to ferromagnetic properties ?

On the Use of RAFM Steels

- Temperature window of use of RAFM steels: 350-550℃ .
- How to manage with it ?

- Possible solutions:
  - Maintaining the materials at 350-550℃:
    - Coolant temperature at the entrance of the reactor: 400℃
    - Coolant temperature at the exit of the reactor: 550℃
    - A difference of 150-200℃ should be sufficient to e nsure acceptable efficiency of first generation fusion power reactors.
  - Annealing regularly the materials to suppress radiation damage.

Waste Management

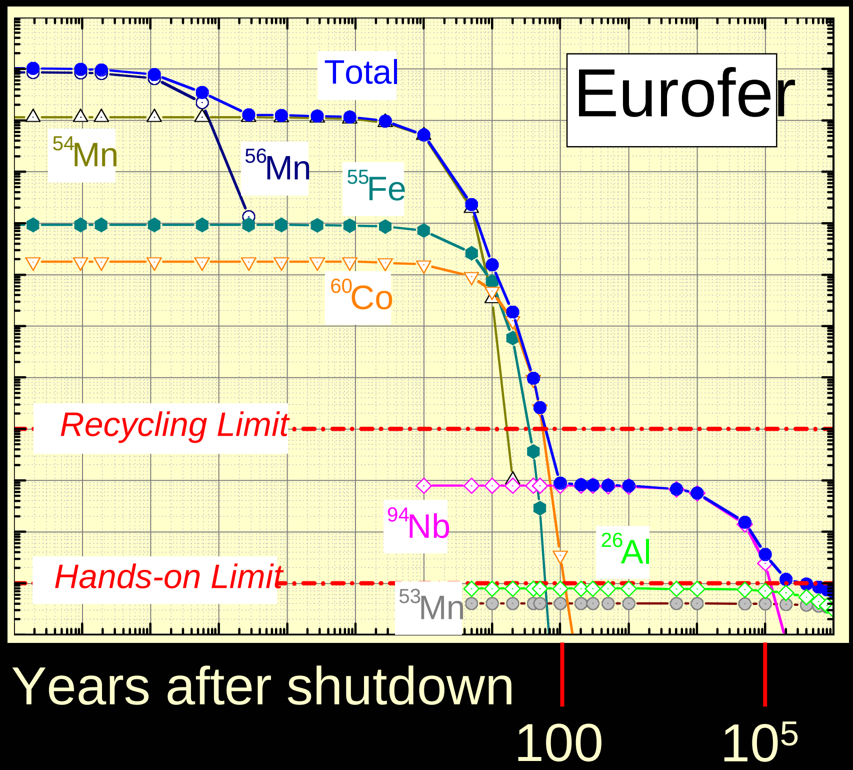
- General aim: to avoid geological repository.

- Recycling of low activated and contaminated metals:
- Current existing routes for fission plants, provided the tritium issue is resolved (i.e. industrial detritiation processes become available).
- Recycling of highly activated and toxic materials:
- Several challenges have to be overcome:
  - Development of recycling techniques
  - Separation of the various parts: Be cannot be recycled in a straightforward manner
  - Development of detritiation processes for tritium-contaminated water, structural and concrete materials
  - Construction of recycling plants: the available capacity is too low

U. Fischer and
S.P. Simakov,
June 2003

Activation of a RAFM Steel

- EUROFER 97:
- Recycling dose rate level of 10 mSv/h is achieved after 50-100 years
- Hands-on dose rate level of 10 µSv/h is achieved after 10^5 years



- Assumptions:
- HCLL PPCS reactor model B
- Fusion power: 3.3 GW
- First wall made of EUROFER 97
- Neutron flux: 1.53×10^{15} $cm^{-2}.s^{-1}$
- 5 full power year irradiation

Recycling

- Hands-on recycling of RAFM steels does not seem to be viable, even after 100 years.

- Hands-on recycling of V-Cr-Ti alloys should be possible.
  - It seems that the V-Cr-Ti alloy components could be purified from the activation products, using a radiochemical extraction reprocessing method consisting of about 50 extraction stages, down to an effective contact dose rate of about 10 μSv/h

Current R&D Activities

Current R&D Activities

- Characterization of the candidate materials in terms of mechanical and physical properties
- Assessment of irradiation effects

- Development of new high temperature, radiation resistant materials (e.g. nanocrystalline W-base alloys)
- Development of coatings that shall act as erosion, corrosion, permeation and/or electrical/MHD barriers
- Compatibility experiments (e.g. with He, liquid metals)
- Development of reliable joints
- Development and/or validation of design rules

On Fusion Relevant Irradiation Conditions

Critical Issues

- How to account for actual irradiation conditions:
  fusion-relevant neutron spectrum, temperatures, accumulated damages (dpa), damage rates (dpa/s), production rates of impurities (e.g. appm He/dpa, appm H/dpa) ?

Modelling of radiation damage and radiation damage effects	Construction of the International Fusion Materials Irradiation Facility (IFMIF)

International Fusion Materials Irradiation Facility IFMIF

Main Functions

- Intense source of 14 MeV neutrons (250 mA): the neutron spectrum should meet the first wall neutron spectrum as near as possible.

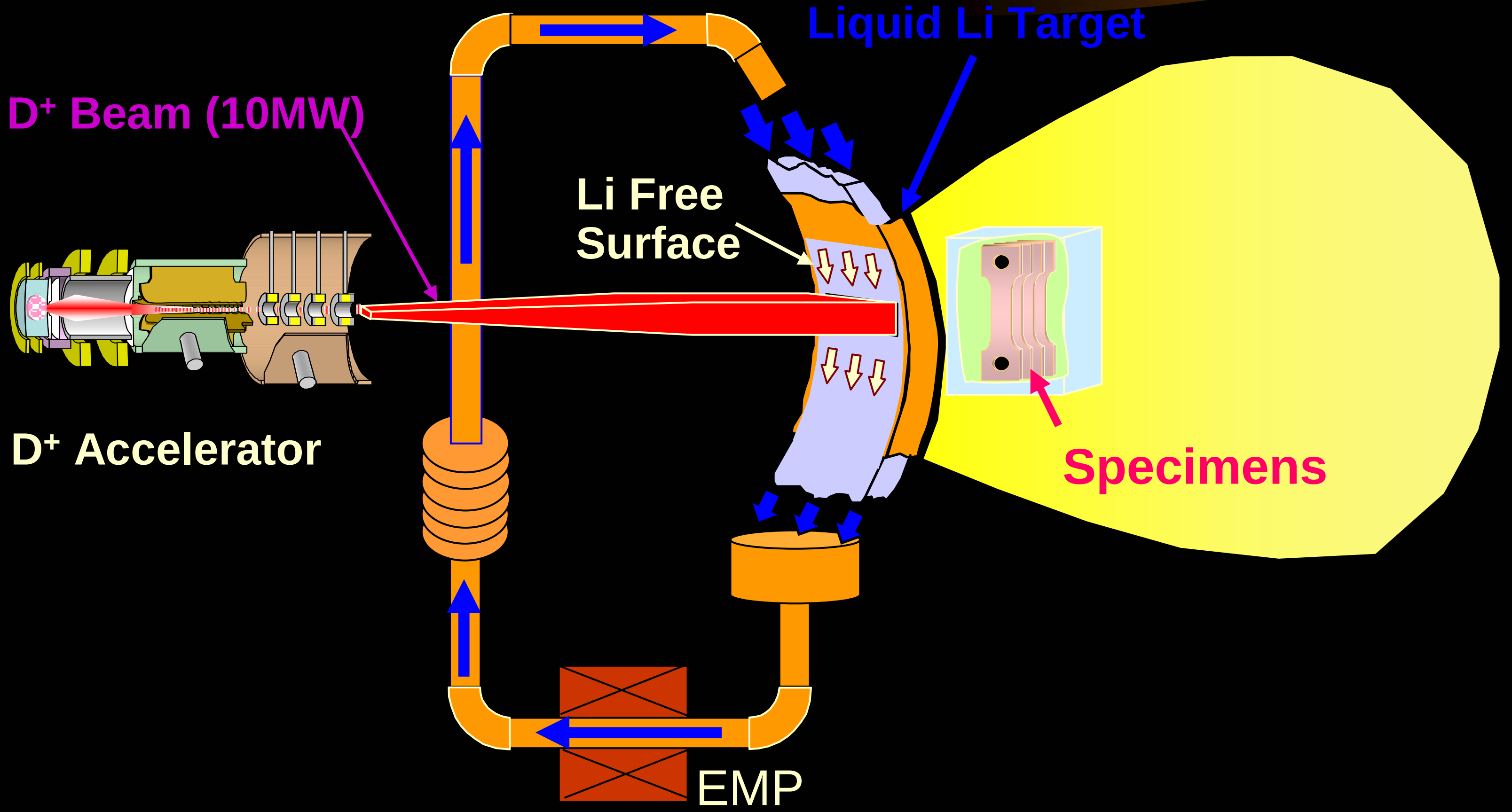
- Missions:
- Qualification of candidate materials up to about full lifetime of anticipated use in a fusion DEMO reactor
- Calibration and validation of data generated from fission reactors and particle accelerators
- Identify possible new phenomena which might occur due to the high energy neutron exposure

Features

Defect poduction (in steels)	Fusion neutrons (3-4 GW reactor, first wall)	Fission neutrons (BOR 60 reactor)	High energy protons (590 MeV)	IFMIF (High flux module)
Damage rate [dpa/year]	20-30	~ 20	~ 10	20-55
Helium [appm/dpa]	10-15	≤ 1	~ 130	10-12
Hydrogen [appm/dpa]	40-50	≤ 10	~ 800	40-50

H. Matsui, A. Möslang
SOFT Conference, 2004

Schematic View



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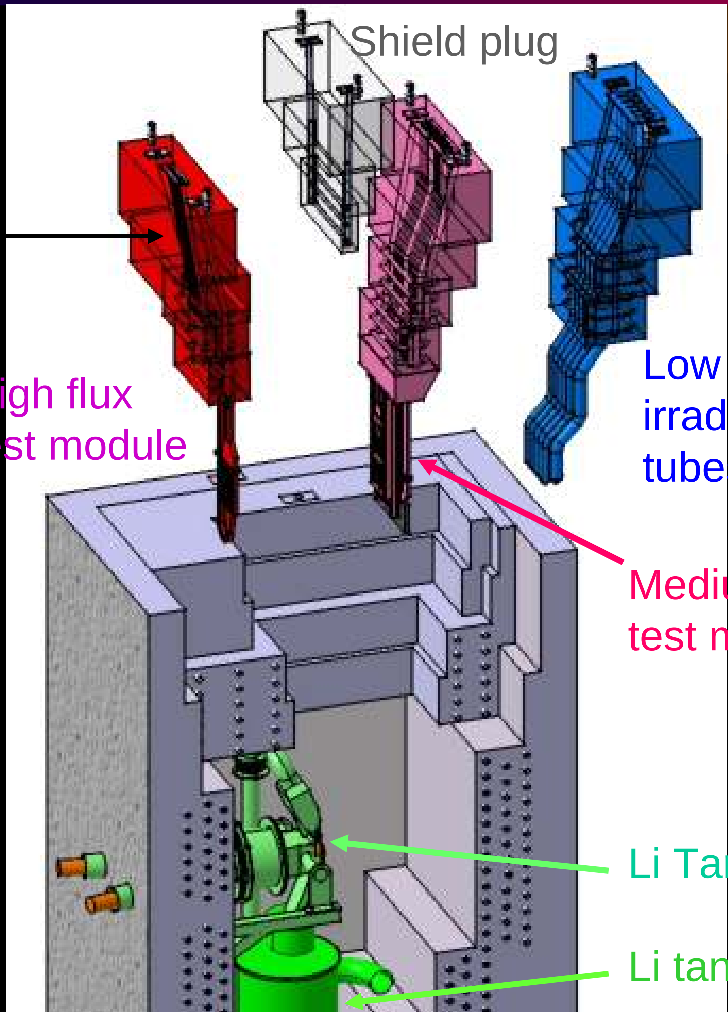
Test Cell

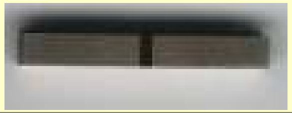
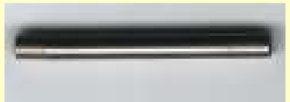
0.5 liter



H. Matsui, A. Möslang
SOFT Conference, 2004

Small Specimen Test Technology

- Using miniaturized specimens:
  - 80 dpa database for a few materials within five years for DEMO-predesign
  - 150 dpa database for a variety of materials within about 20 years

Specimen type	Present geometry	Comments
Tensile		developed
Fatigue		developed
Bend/Charpy DFT		Standard achieved; R&D ongoing
Creep		Miniaturization needs verification
Crack growth		International R&D ongoing
Fracture toughness		International R&D ongoing

1 cm

Broader Approach

- General idea: On the path to fusion power reactors the construction of IFMIF is of the same importance as the construction of ITER

- This idea led to the definition of a programme named Broader Approach whose final aim is the construction of DEMO
- The Broader Approach is the result of a EU-JA Bilateral Agreement

Broader Approach: Items

- The Broader Approach relates to 3 items:
  - IFMIF/EVEDA: EVEDA Phase (Engineering Validation and Engineering Design Activities).
  - IFERC: Creation of an International Fusion Energy Research Centre in Japan: DEMO Design R&D Coordination Centre, Computational Simulation Centre, ITER Remote Experimentation Centre.
  - Satellite Tokamak Programme: Upgrade and exploitation of a large tokamak in Japan: Advanced Superconducting Tokamak (JA is contributing to this project also outside the Broader Approach).

EFDA DATA

Broader Approach: Costs

- Total costs: about 700 million Euros
- The costs are shared equally by Europe and Japan

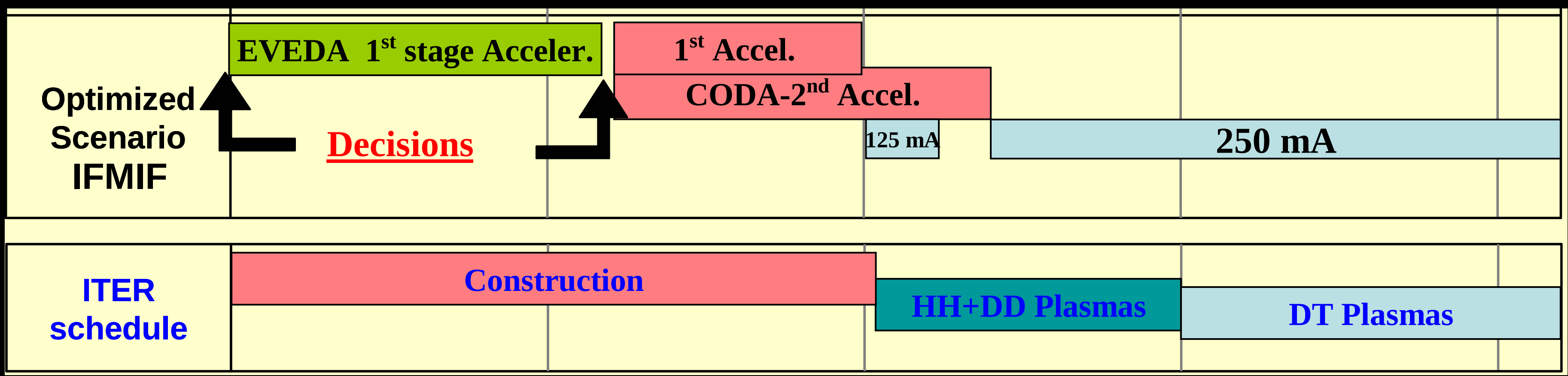
Project	Budget (100M¥)	EU (100M¥)	JA (100M¥)
IFMIF-EVEDA	202.62	132.25	70.37
NCT	435.00	217.5	217.5
IFERC	282.38	110.25	172.13
Total	920.00 ≅ 700M€	460.00	460.00

1 Euro ≅ 132.6 Yen

EFDA DATA

Planning of IFMIF

- EVEDA Phase (Engineering Validation and Engineering Design Activities): 2007-2012
- Construction Phase: 2012-2018
- Fully operational in 2018



Conclusion

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Materials: a key issue on the path to fusion power reactors
- Plant thermal efficiency
- Public acceptance of fusion as future energy source

- Material choices will not solve all design problems.
- The design is complex by nature and it will have to be used to overcome material limitations.
- Close discussions between designers and material scientists are strongly needed.

Thank You Very Much !