IFMIF
Necessity and Status of Preparation

Presented by Eberhard Diegele, F4E

International Workshop, MFE Road Mapping in the ITER Era

8th September 2011, Princeton

Elements of a Strategy for Materials R&D – for the next Two Decades (I)

RAFM steels „only“ choice for TBM (alternative options with high risk)

- Development mission driven. Technology part of the programme
- Full characterisation of RAFM steels in the next decade (for TBM use).
- „Code qualification“ required up to some dpa [RCC-MRx/SDC].
- Irradiation campaigns in fission reactors („Material Test Reactors“). Test materials with fission neutrons from nuclear reactors:
  - Adequate flux.
  - BUT
  - Energy spectrum: not adequate, high energy tail missing.
  - Insufficient H and He production by transmutation.

Elements of a Strategy for Materials R&D – for the next Two Decades (II)

Construct and start operation of a 14 MeV neutron facility (IFMIF)

- **Adequate flux,**
- **Fusion typical irradiation temperatures**
- **At "homogeneous" test conditions throughout a sample.**
- **Stable irradiation conditions (T) (#)**

IFMIF

is „mandatory" to generate <u>engineering data</u> for DEMO design rules for End of Life conditions.

is useful in testing materials and sub-components prior to approval for application in power plants. DEMO will provide the endurance component tests.

<u>Is a most valuable source for verifications of multi-scale modelling predictions.</u>

Code qualify material:
Property f (T, Tirrad, fluence, environment, load-stress-strain) – This allows to together with a code framework transferability to other conditions
With temperature excursions (annealing of defects) – risk to loose data point

Elements of a Strategy for Materials R&D – for the next Two Decades - (III)

The He issue

- Fission reactors produce insufficient rates of He and H
- Irradiation in fission reactors gives only non-conservative approach for degradation of materials.

Various tricks or methods used:

- B and Ni-doped steels in MTR: ~a few appm He/dpa.
- Fe^{54} enriched steels in MTR: ~2 appm He/dpa.
- Mixed spallation-neutron spectrum: ~100 appm He/dpa
- (Multi) Ion beam irradiation: up to 10000 appmHe/dpa.

Different material

Cost. 1kg 500k$

- Transmutations
  - pulsed

10 micro-meter

- All these experiments needed to increase knowledge and understanding of the microstructure.
- Modelling and understanding of irradiation results under various conditions is clearly needed.

Elements of a Strategy for Materials R&D – for the next Two Decades - (IV)

- Accompanying programs:
  - Modeling of irradiation effects towards an understanding of irradiation damage over the full scale (from quantum physics to engineering analyses).
  - "Extrapolation" of dislocation damage from fission data to fusion environment.
  - Simulations with predictive capability.
  - Integrated approach with "physics-based" modeling and simulations in the meso to macro scale at the interface between materials science and technical application (simulating "real conditions" and "real components") will be an key for success.

Elements of a Strategy for Materials R&D – for the next Two Decades - (V)

- ❑ **In parallel: Optimization and further development of RAFM steels**
  - **For use with DEMO**
- ❑ **In parallel: Optimization and further development of ODS/NCF-type steels**
- ❑ **In parallel: Development of „new“/“advanced“ materials for high temperature application.**

Including, both

Irradiation campaigns in fission reactors (high fluence, ~100 dpa).

<u>Strong science based programme</u> to accumulate knowledge and understanding of irradiation effects to „design materials“.

FUSION FOR ENERGY

This summary could have been from yesterday

However, it is from ... 2006 ...

Long Term Materials Development

The EU Road Map

E. Diegele

EDFA-CSU Garching

IEA-Meeting July 10-12, 2006, Tokyo, Japan

Fusion Materials Development Path

FUSION FOR ENERGY

Materials Performance/Component specific Loading - Stage- IV

Demonstrate solution to concept-specific issues

Performance under complex loading history (T, stress, multi-axial strain fields & gradients) & environmental conditions

Qualified Material, Demonstration of Performance - Stage- III

Complete database for final design & licensing

Validate constitutive equations & models

Demonstrate life time goals (He issue)

Demonstration of Performance Limits - Stage- II

Database for conceptual design

Demonstrate proof-of-principle solutions, design methodology

Evaluation-modification cycle to optimize performance

Materials Screening & Materials “Design”` - Stage- I

Identify candidate alloy composition, compatibility, irradiation stability, proof of principle for fabrication and joining technologies -Validation of models and tools (microstructure)

Fusion Materials Development Path
Facilities needed

FUSION FOR ENERGY

Performance under component specific loading Stage IV

„FNT(S)F“ CTF

Not any facility existing

IFMIF and FNSF are complimentary in an INTERNATIONAL Road Map or approach

Qualified materials, full demonstration of performance Stage III

14 MeV neutrons or fusion specific n-spectra >>> IFMIF

To some limited extend ITER-TBM

Demonstration of performance limits Stage II

Fission reactors (MTR of next generation like Jules-Horowitz)

(IFMIF)

Materials “Design” R&D Stage I

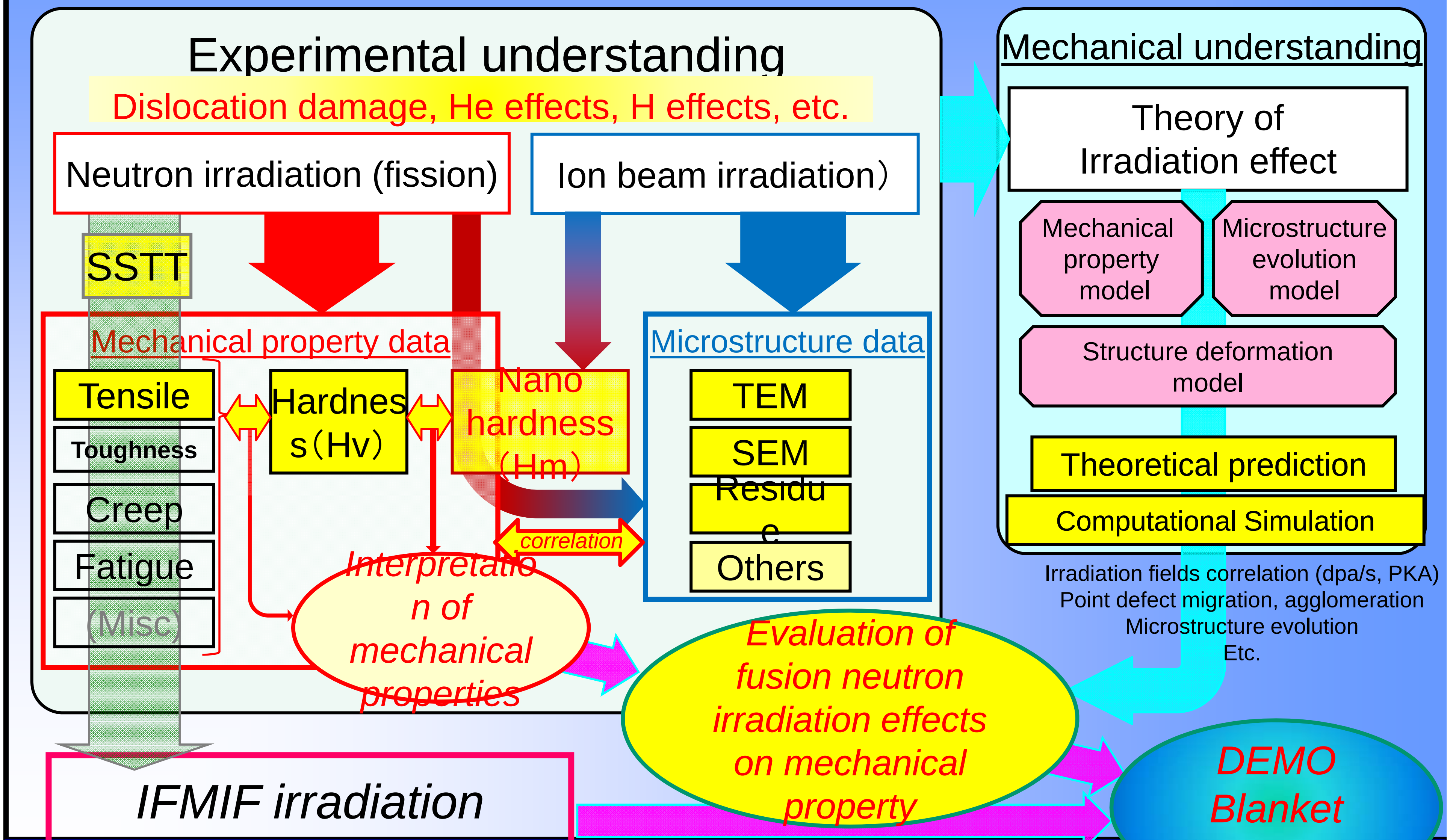
Fission reactors (MTR)

Multi-ion-beam irradiation facilitiers

Complementary Modelling essential

Strategy on the address fusion neutron irradiation effects

FUSION FOR ENERGY



H. Tanigawa, Vienna Dec 2011, IAEA, modified

FNSF/DEMO Nuclear Facility Needs

- **Fission Reactors**
  - The capability to perform irradiation experiments in fission reactors is essential for identifying the most promising materials and specimen geometries for irradiation in an intense neutron source.
- **Fusion Relevant Neutron Sources**
  - Overcoming radiation damage degradation is the rate-controlling step in fusion materials development.
  - Evaluation of radiation effects requires simultaneous displacement damage (~150 dpa) and He generation (~1500 appm).
- **Fusion Nuclear Science Facility (predecessor to DEMO)**
  - Nuclear facility to explore the potential for synergistic effects in a fully integrated fusion neutron environment. Data and models generated from non-nuclear structural test facilities, fission reactor studies and the intense neutron source will be needed to design this facility.

Rick Kurtz, 7th Sept Princeton

Long History – Recall from...

Rick Kurtz, 7th Sept Princeton

Early History

Need for a Neutron Source to Test & Qualify Materials for DEMO Recognized for > 30 y*

- U.S. Pathways Study [M.A. Abdou *et al*., Fus. Tech. 8 (1985) 2595-2645]
  - **Concluded that fission reactors & accelerators "are useful and their use should be maximized worldwide, but that they have serious limitations"**
  - **Reactor use & new non-neutron facilities recommended "over next 15 years"**
  - **Low total power, high power density D-T devices then required for integrated tests & validation**
- IEA Study [Doran, *et al*, J. Fus. Energy 8, (1989) 137-141]
  - **Evaluated plasma sources (RFPs, high-density Z pinches, beam-plasma mirrors) and accelerator-based sources (d-Li, spallation)**
  - **Recommended further investigation of 3 options: d-Li, spallation, beam-plasma**
- Subsequent analysis [D.G. Doran *et al*., J. Nucl. Mat. 174 (1990) 125-134]
  - **Concluded that differences in damage parameters not great enough to permit a selection of preferred alternative on basis of displacement rate, primary recoil spectrum, & important gaseous and solid transmutations.**
- Follow-on IEA Review [T. Kondo *et al*., J. Nucl. Mat. 191-194 (1992) 100-107]
  - **Concluded that D-Li neutron source concept (basis of IFMIF) was preferred because of relatively lower neutron energy tail & most mature technology base**
    - Beam plasma source found to provide best simulation of a fusion reactor, but scientific feasibility was still in question
    - Spallation source found not generally favored by materials community - would be "a viable candidate only if it can be attained at much less expense than the alternatives."

*T.H. Batzer et al, *Conceptual Design of a Mirror Reactor for a Fusion Engineering Research Facility*, Proc. 5th IAEA Conf. on Plas. Phys. & Contrl. Nucl. Fus. Res. (1974); and E.W. Pottmeyer, Jr., *FMIT Facility at Hanford*, J. Nucl. Materials 85-86 (1979) 463-465.

Long History – Recall from...

Rick Kurtz, 7^{th} Sept Princeton

Recent U.S. History

Similar Need for a Fusion Irradiation Facility Recently Articulated by the U.S. Community

- 2007 FESAC (Greenwald) report
  - Selected fusion irradiation facility as one of nine unprioritized initiatives
  - Recognized such a facility is the IFMIF mission
  - Recommended assessing potential for alternative facilities to reduce or possibly eliminate the need for the US to participate as a full partner in IFMIF
- 2009 FES Research Needs Workshop (ReNeW)
  - Advocated a fusion-relevant neutron source to be an essential mission requirement
  - Cited 3 options (same as1989 IEA) as examples for further evaluation and selected based on technically attractiveness and cost effectiveness
- 2011 FES Fusion Nuclear Science Pathways Assessment

Indicate that slides was provided by this group of authors

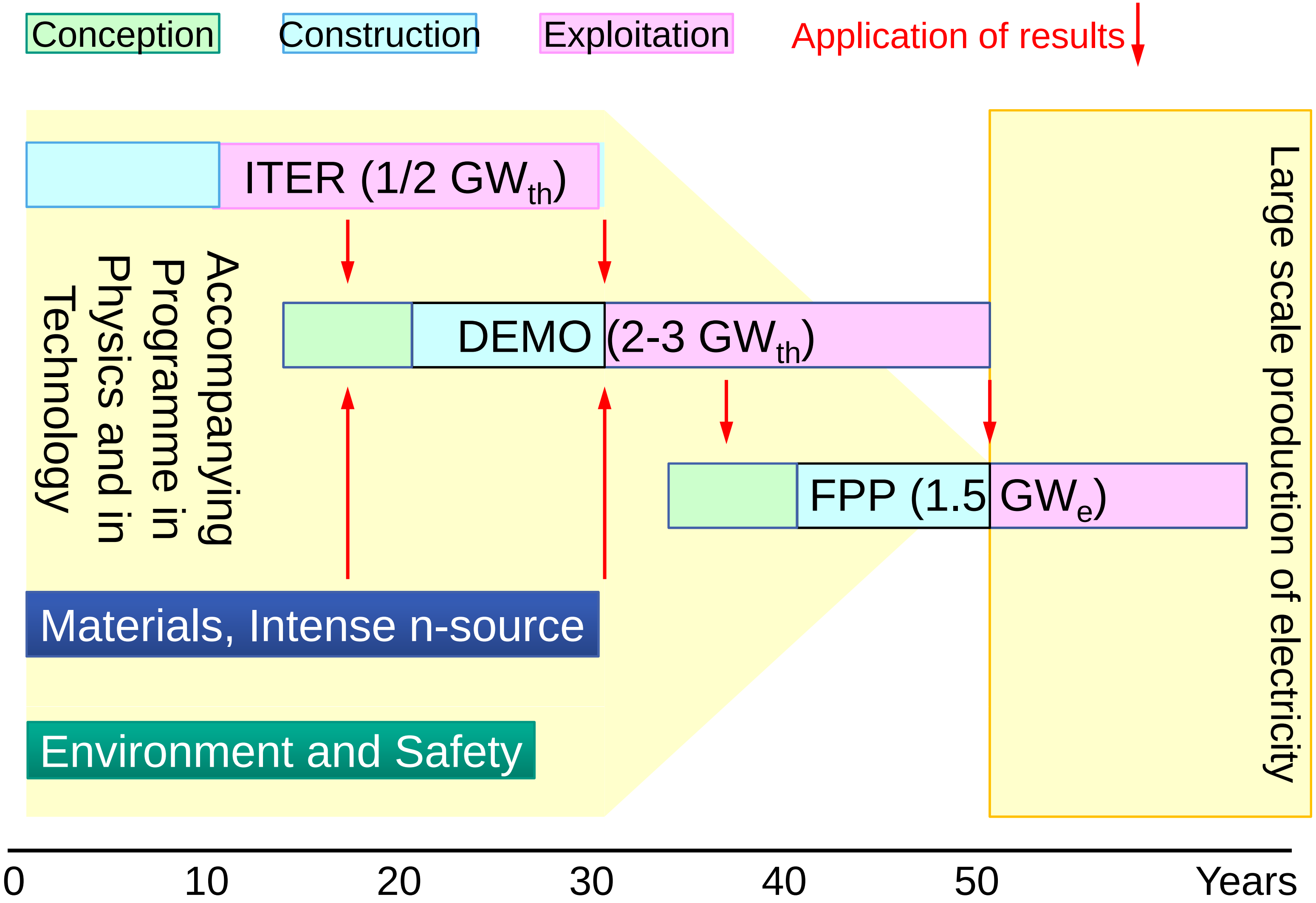
Karlsruhe Institute of Technology

IFMIF in the Context of Materials Research

A. Möslang, N. Baluc, E. Diegele, U. Fischer, R. Heidinger, A. Ibarra, P. Garin, V. Massout, G. Micciché, A. Mosnier, P. Vladimirov

Authors on behalf of the fusion materials and IFMIF community

Perspectives for fusion



A. Möslang et al.

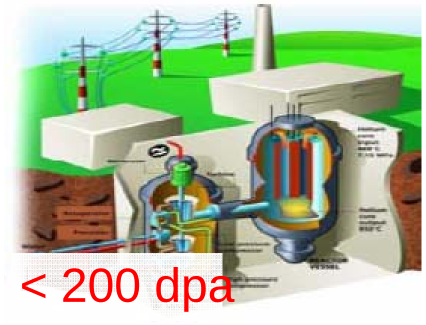
High Performance Materials for Energy

First Reactors

Current Reactors

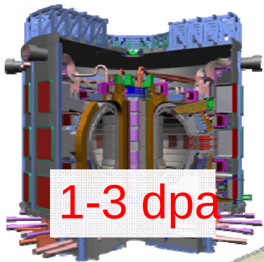
Advanced Reactors

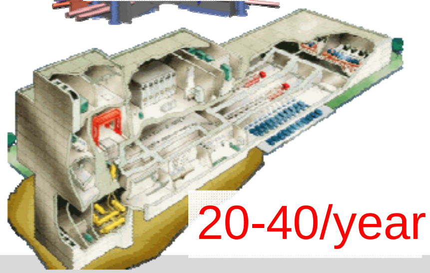
Future Systems



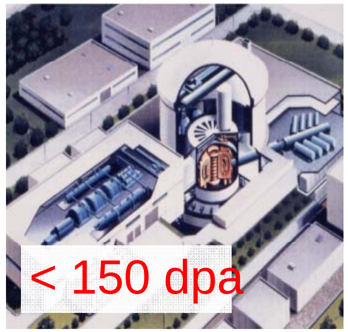
1950 1970 1990 2010 2030 2050

ITER IFMIF





DEMO, Fusion Reactor



Strategic Missions:

- Electricity, Hydrogen, Heat
- Contribute to lower greenhouse gas emission

Specific challenges for fusion:

- Short development path
- More demanding loading conditions

A. Möslang et al.

Main missions of an intense neutron source in roadmaps to fusion power

- **Qualification of candidate materials**, in terms of generation of *engineering data* for **design**, **licensing** and **safe operation** of a fusion DEMO reactor, up to about full lifetime of anticipated use of DEMO
- **Completion, calibration and validation of databases** (today mainly generated from fission reactors and particle accelerators)
- Advanced material irradiation (towards power plant application)
  - Promote, verify or confirm selection processes
- Validation of fundamental understanding of radiation response of materials hand in hand with computational material science
  - Science-related modeling of irradiation effects should be validated and benchmarked at length-scale and time-scale relevant for engineering application
  - Experiments performed in IFMIF would validate assumptions or adjust parameters

TOP Level Requirements for an Intense Neutron Source

- **Neutron spectrum**

  Should simulate the first wall neutron spectrum of a fusion reactor as closely as possible in terms of PKA spectrum, important transmutation reactions, and gas production (He, H)

- **Neutron fluence accumulation**

  Up to 120 dpa_{NRT} in <4 years applicable to 0.5 litre volume.

- **Neutron flux and temperature gradients**

  Flux gradient <10% over the gauge volume of the Small Scale Specimens
  Temperature gradient ±3% within individual capsules (~90 specimens).

- **Machine availability** ≥ 70%
- **Time structure** quasi continuous operation
- Good accessibility of irradiation volume & high flexibility for further upgrades

High ranking International Advisory Panels (late 80-ies to mid 90-ies) concluded that these requirements can be best fulfilled with a D-Li stripping source.

→ **IFMIF was born**

TOP Level Requirements for an Intense Neutron Source

- **Neutron spectrum**

  Should simulate the first wall neutron spectrum of a fusion reactor as closely as possible in terms of PKA spectrum, important transmutation reactions, and gas production (He, H)

- **Neutron fluence accumulation**

  Up to 120 dpa_{NRT} in <4 years applicable to 0.5 litre volume.

- **Neutron flux and temperature gradients**

  Flux gradient <10% over the gauge volume of the Small Scale Specimens
  Temperature gradient ±3% within individual capsules (~90 specimens).

- **Machine availability** ≥ 70%
- **Time structure** quasi continuous operation
- Good accessibility of irradiation volume & high flexibility for further upgrades

High ranking International Advisory Panels (late 80-ies to mid 90-ies) concluded that these requirements can be best fulfilled with a D-Li stripping source.

→ **IFMIF was born**

Fusion Power Plants: Material Challenges beyond ITER

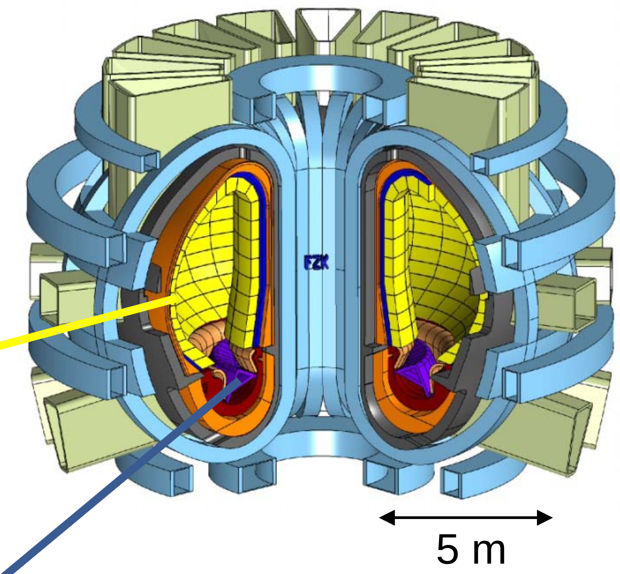
Blanket: ≤30 dpa/yr, 2.5MW/m^2

- Reduced Activation Structural Materials:
  - RAFM Steels (EUROFER) 300-550 °C
  - EUROFER-ODS 350-650 °C
  - SiC_f/SiC for sophisticated concepts
- Functional materials
  - neutron multipliers, breeder ceramics
- Special purpose materials (diagnostic,…)

Divertor: ≤10 dpa/yr, 10-15 MW/m^2

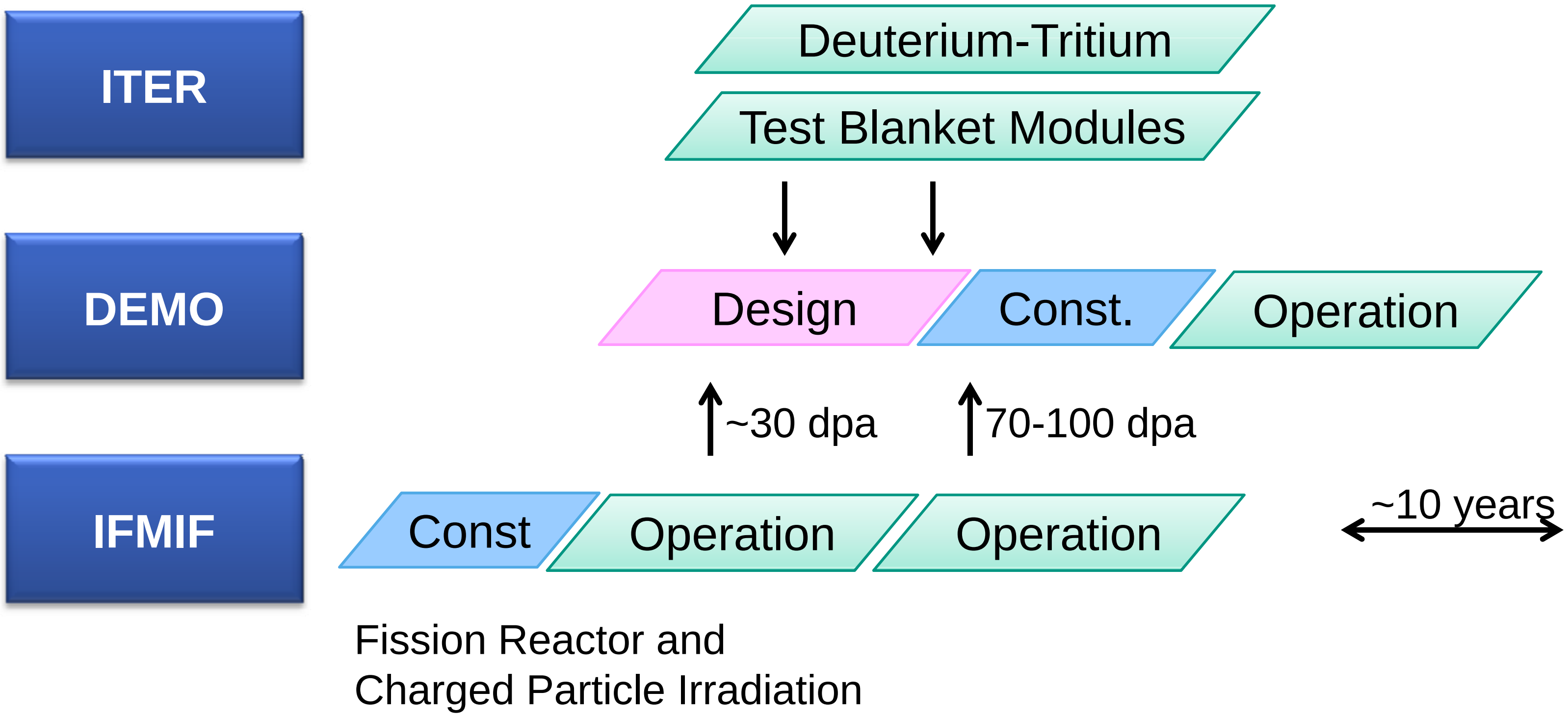
- Refractory alloys (e.g. W-ODS)
  - 850-1200 °C → ~600 - 1300 °C
- Nano-scaled RAF-ODS Steels
  - 350-650 °C → ~250 - 800 °C

DEMOnstration Reactor Concept



Power: 1.30 MW_e
Plant Efficiency: 37-45%

Main Relations between ITER, IFMIF and DEMO

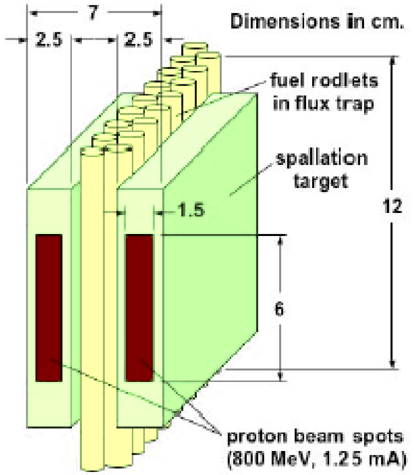


A. Möslang et al.

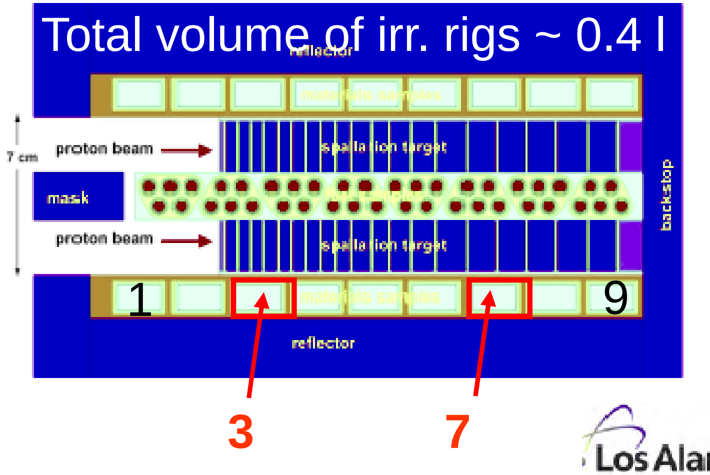
Is today IFMIF still the best choice?

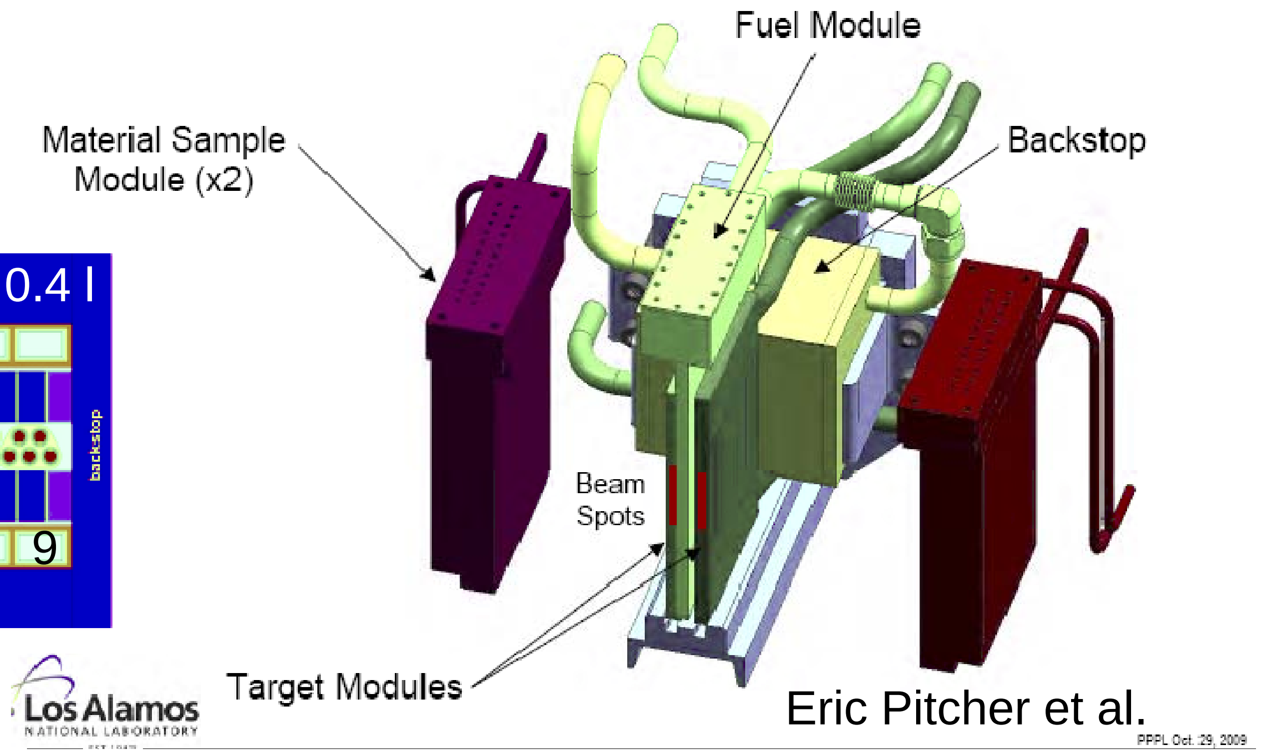
Neutronics: IFMIF vs. the Spallation source MaRIE (1/8)

- **Ma**tter **R**adiation **I**nteractions in **E**xtremes -



The Materials Test Station (MTS) is a spallation source facility whose prime mission is the irradiation of fuels and materials in a fast neutron spectrum.



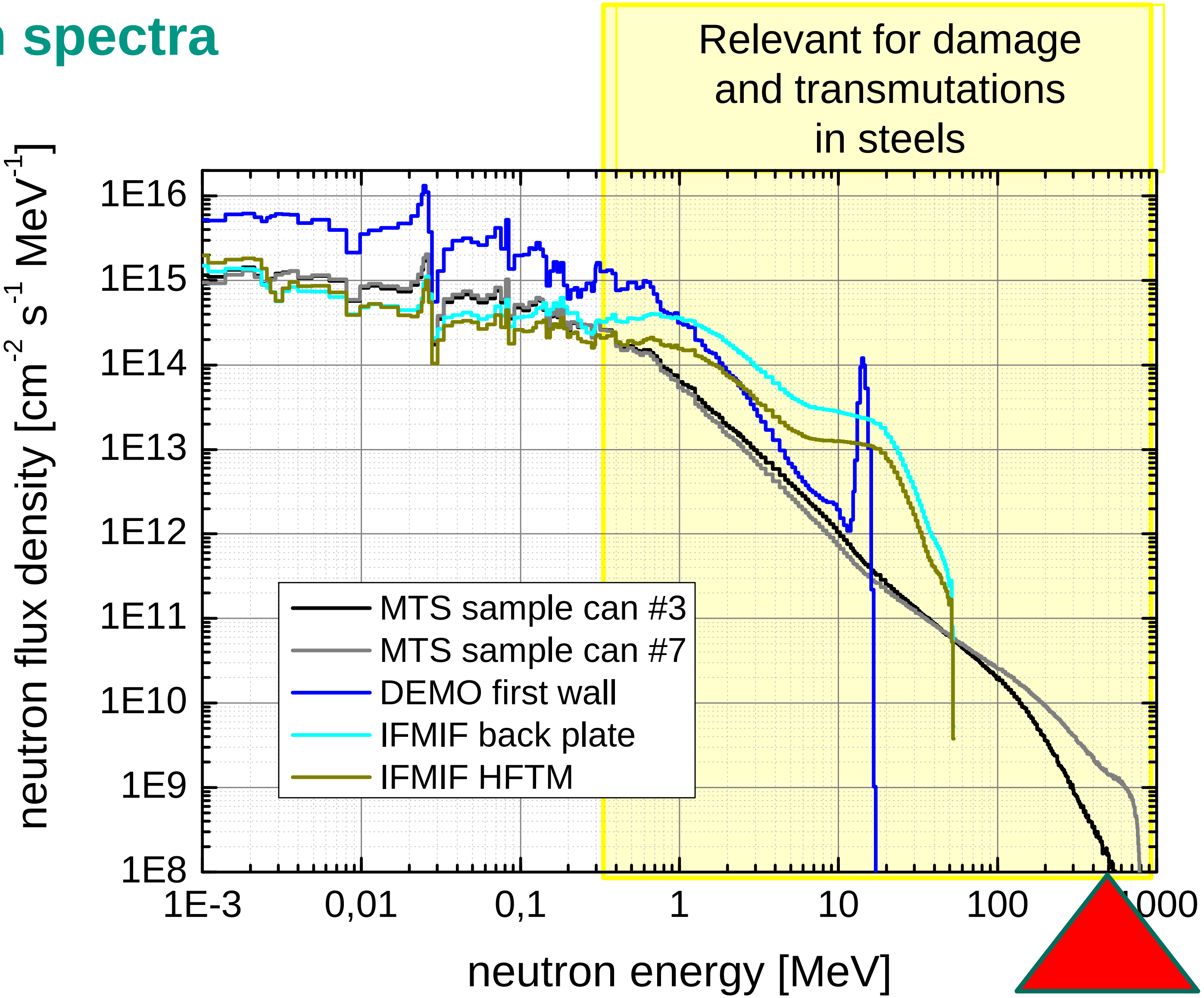


Eric Pitcher et al.

PPPL Oct. 29, 2009

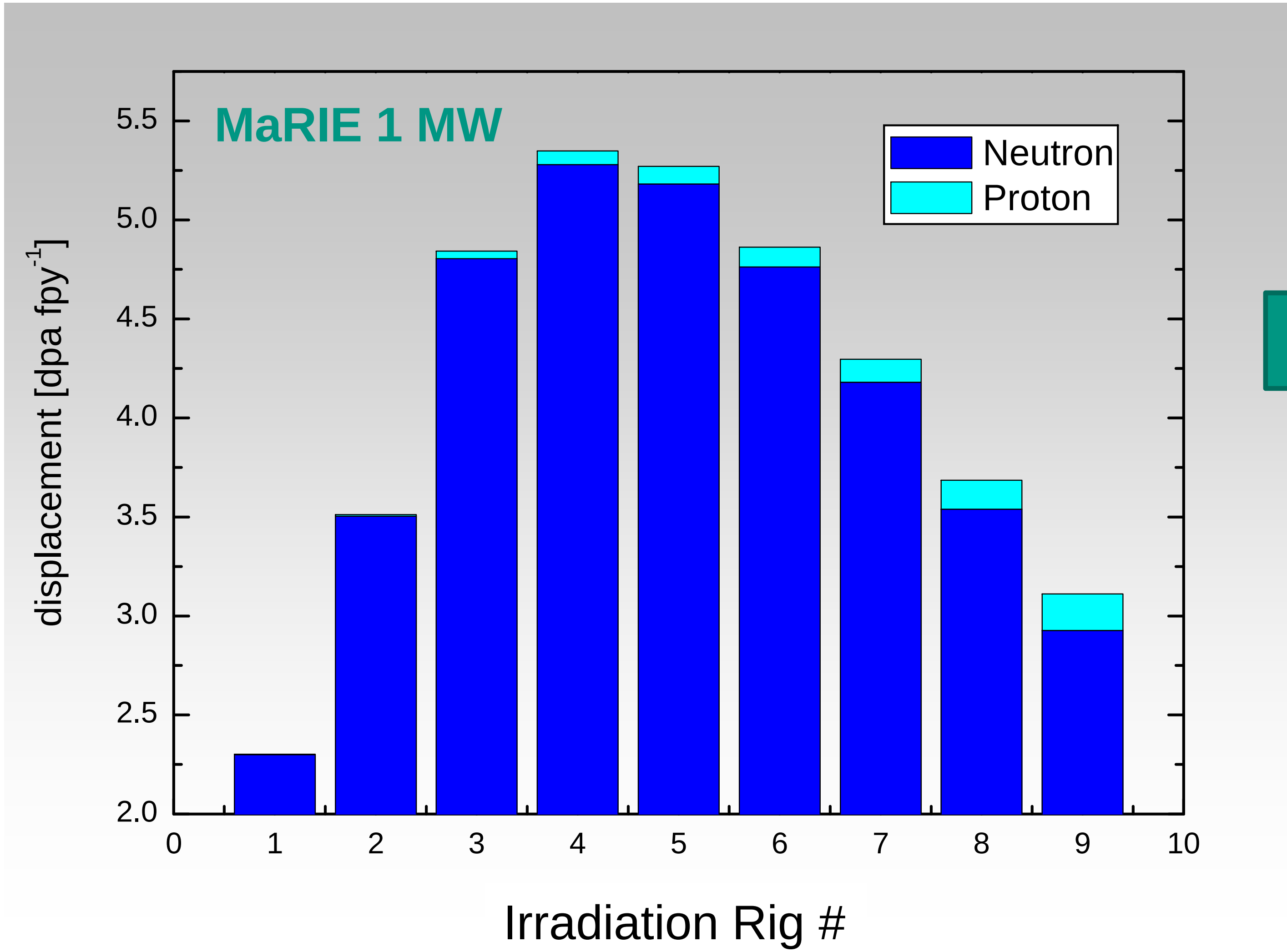
IFMIF vs. the Spallation source MaRIE (2/8)

Neutron spectra



IFMIF vs. the Spallation source MaRIE (3/8)

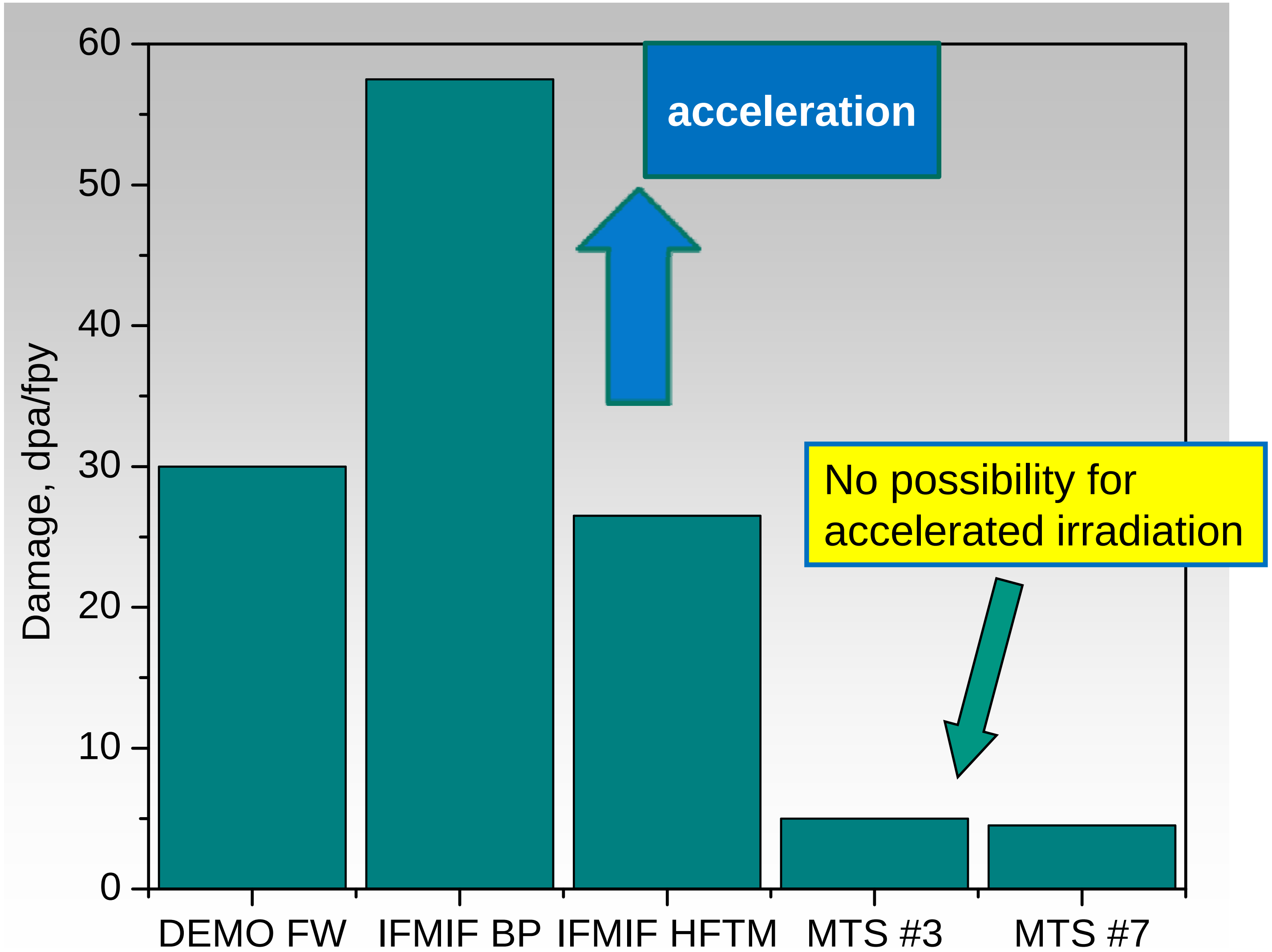
Displacement Damage for different rigs



5 dpa/y

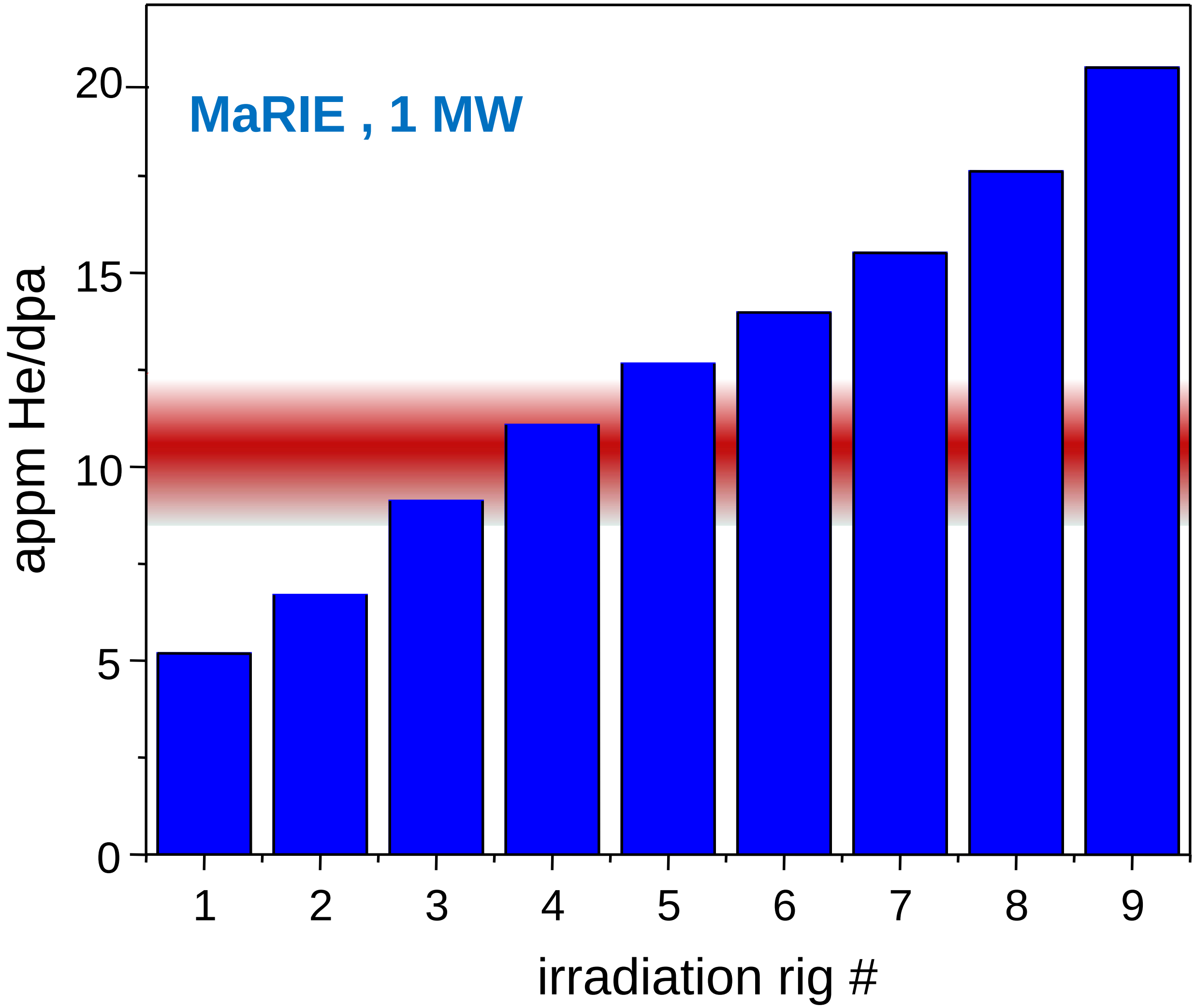
IFMIF vs. the Spallation source MaRIE (4/8)

Displacement Damage: Comparison of facilities



IFMIF vs. the Spallation source MaRIE (5/8)

Helium Production

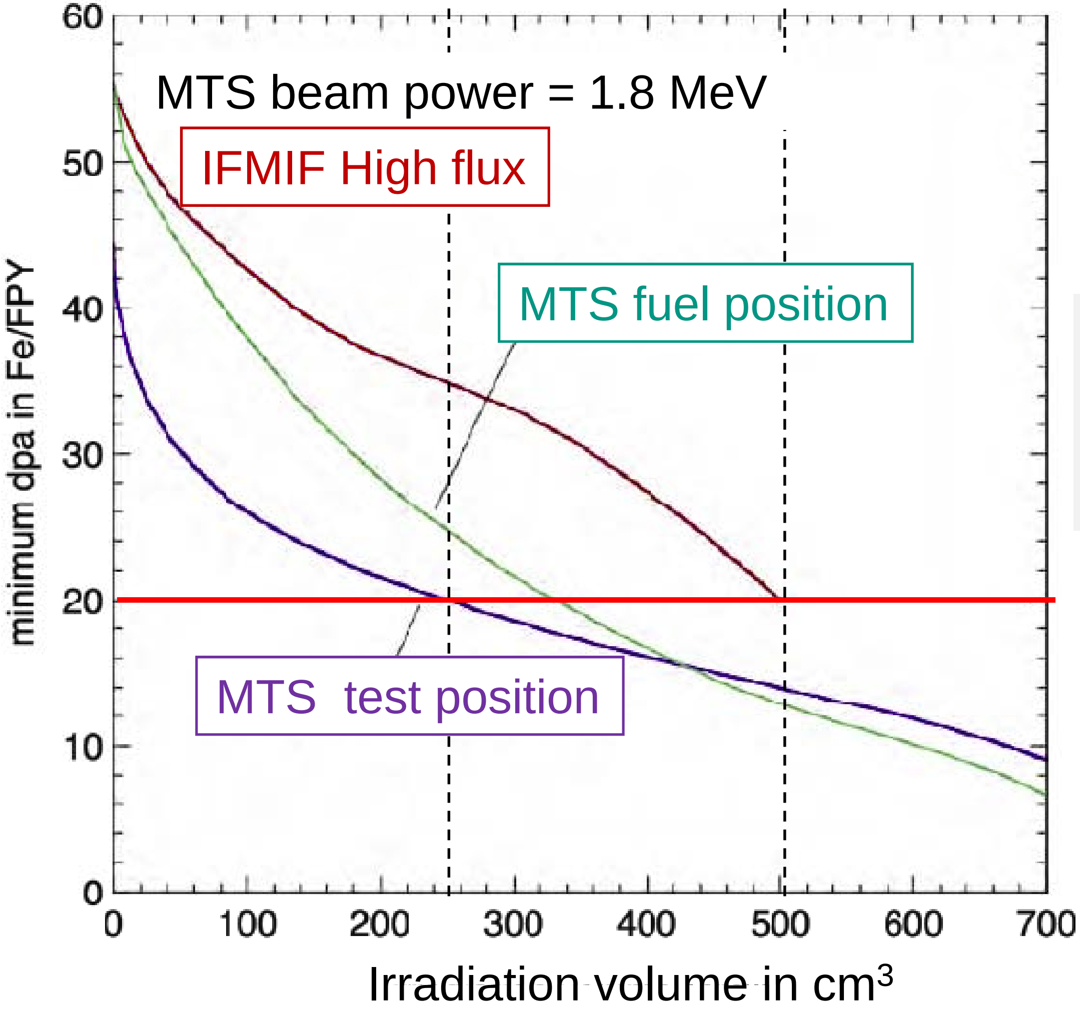


DEMO relevant He/dpa ratio in steels.

IFMIF meets the relevant ratio in all test modules

IFMIF vs. the Spallation source MaRIE (6/8)

Flux/volume considerations



Volume for 20 dpa/fpy

IFMIF :	~ 500 cm^3
MTS:	~ 250 cm^3

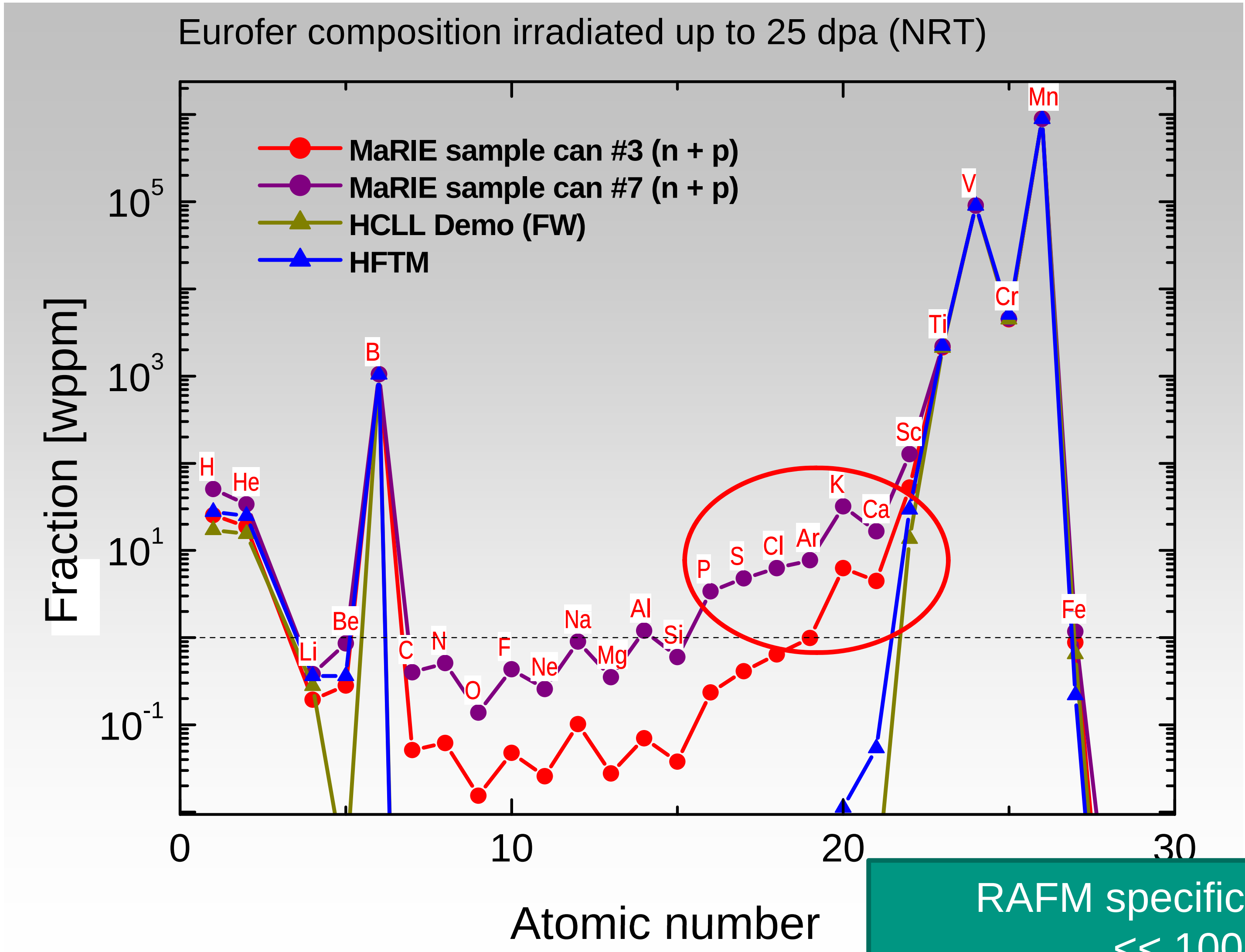
Volume for 30 dpa/fpy

IFMIF :	~ 360 cm^3
MTS:	~ 40 cm^3

E. Pitcher, LANL

IFMIF vs. the Spallation source MaRIE (7/8)

Spallation product accumulation



P & S !!

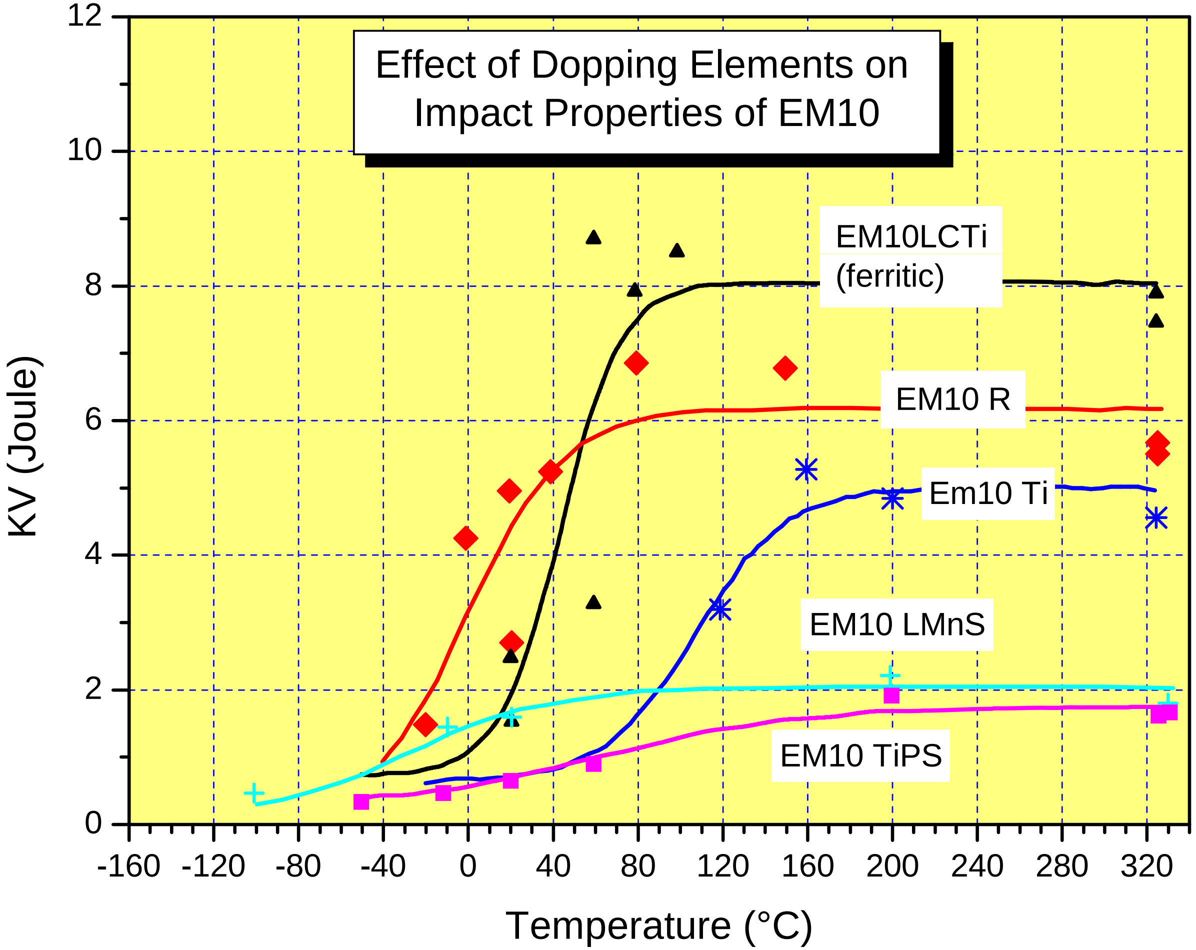
RAFM specification on S + P
<< 100 appm !
Segregation at grain boundaries
And promotes fracture

IFMIF vs. the Spallation source MaRIE (8/8)

Effect of spallation elements on Ductile Brittle Transition

O. DANILOVA, D. HAMON, Y. de CARLAN, A. ALAMO

First SPIRE Progress meeting, Madrid. June 14-15, 2001



Drop of upper shelf energy:

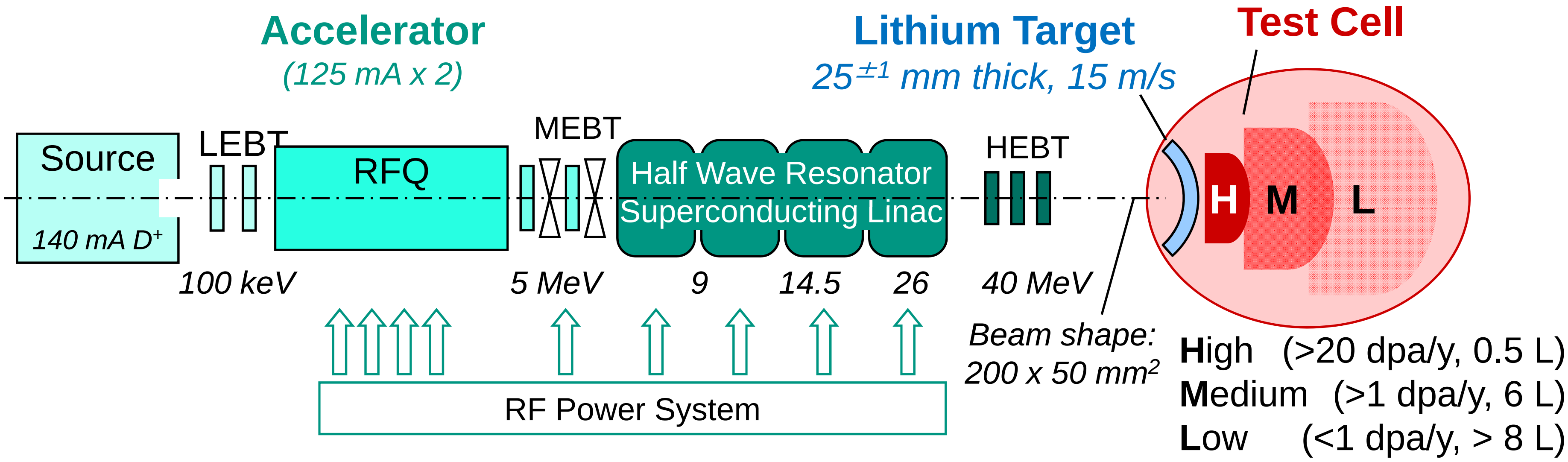
+0.25% Ti
+0.96% C

+0.04% S
- 0.5% Mn

+0.02% P

Elements like S, P enhance severely the brittleness of Cr-steels

Principle of IFMIF



Typical reactions

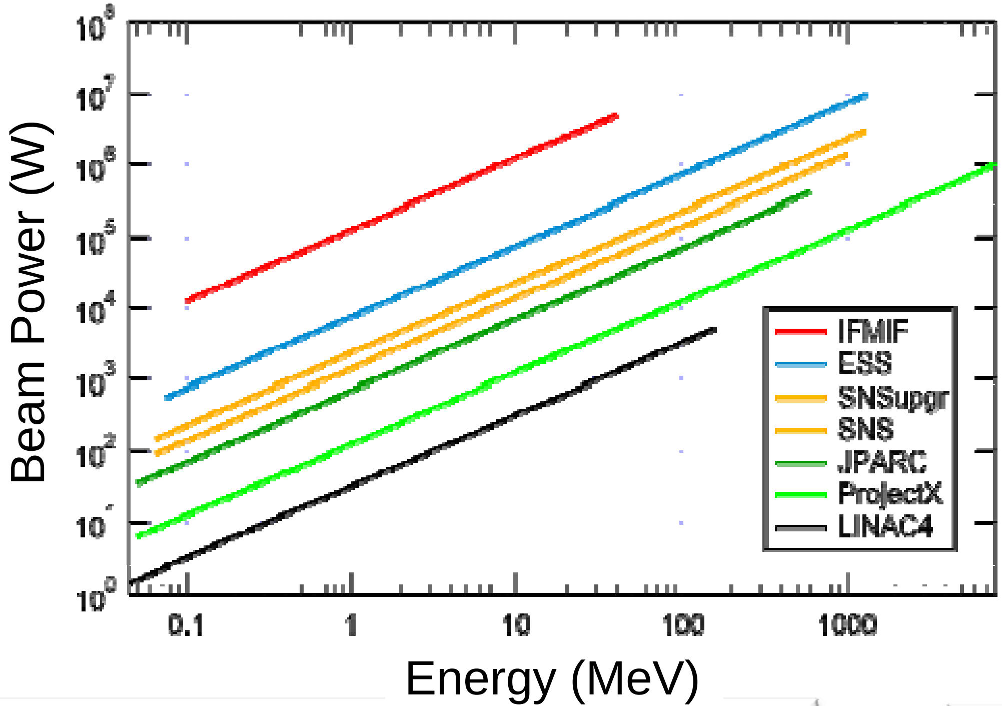
$^{7}Li(d,2n)^{7}Be$

$^{6}Li(d,n)^{7}Be$

$^{6}Li(n,T)^{4}He$

A. Möslang et al.

IFMIF: The Accelerator of all records!



Unprecedented challenges

- highest intensity
- highest space charge
- highest power
- longest RFQ
- Very high availability & reliability

True "Laboratory" for studying physics of High Intensity Beams (halo formation, core – halo interaction, emittance growth, sudden particle loss)

A. Möslang et al.

Current activities: EVEDA

- The Engineering Validation and Engineering Design Activities, conducted in the framework of the Broader Approach aim at:
  - Providing the **Engineering Design of IFMIF**
  - **Validating the key technologies**, more particularly
    - The low energy part of the accelerator (very high intensity, D^+ CW beam)
    - The lithium facility (flow, purity, diagnostics)
    - The high flux modules (temperature regulation, resistance to irradiation)

- Strong priority has been put on Validation Activities, through
  - The **Accelerator Prototype** (Constructed in EU,tested in Rokkasho, JA)
  - The **EVEDA Lithium Test Loop** (to be tested in Oarai, Japan)
  - Two complementary (temperature range) designs of High Flux Test Modules and an in-situ Creep fatigue Test Module

IFMIF: Implementation and Actors of the Project

IFMIF/EVEDA Integrated Project Team

Project Leader

EU Coordinator + FG Leaders

JA Coordinator + FG Leaders

Project Team
In Rokkasho

International Fusion Materials Community (Users)

A. Möslang et al.

Engineering Validation Activities

The Accelerator Prototype

Whole Accelerator with Beam Dump

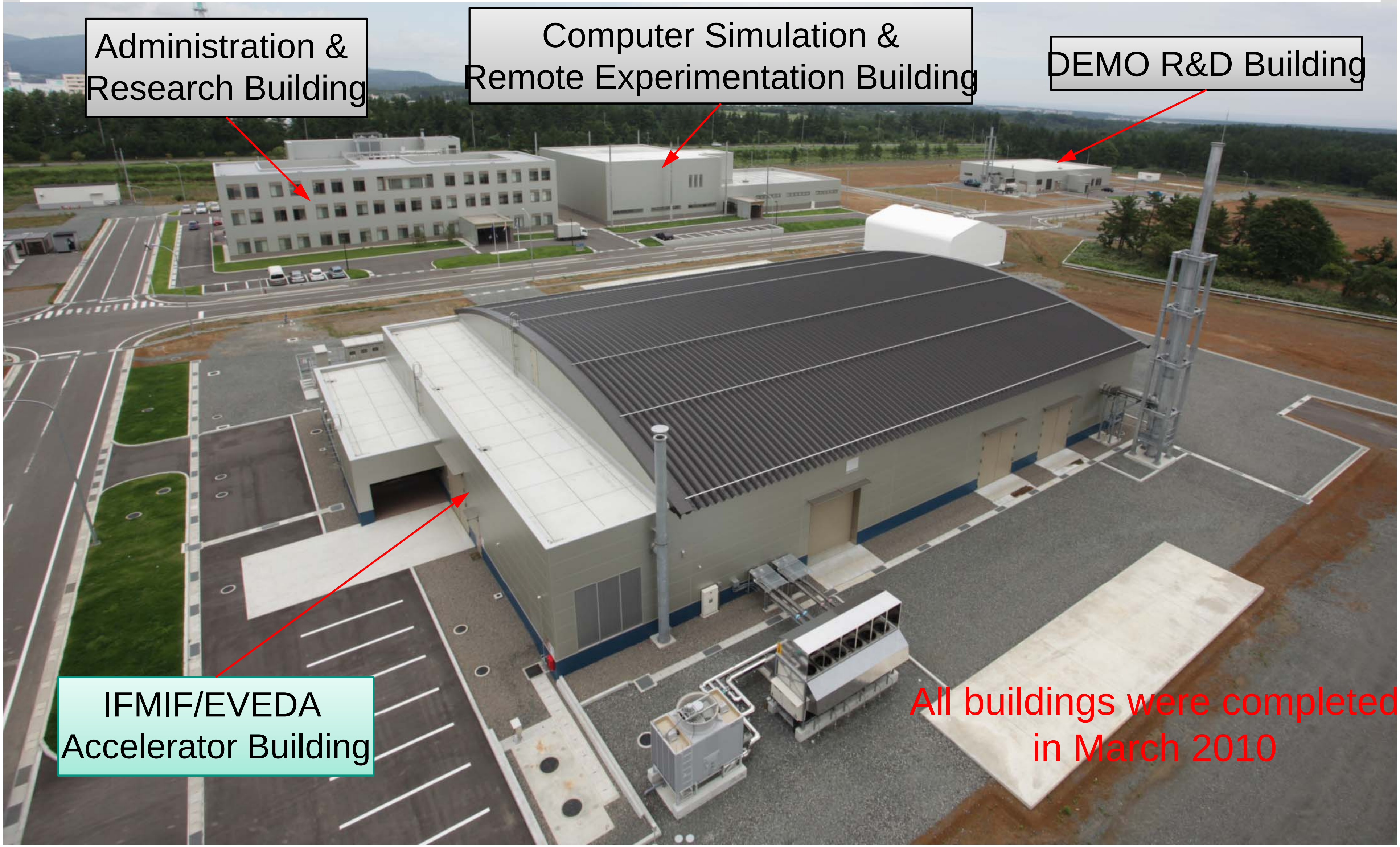
Injector
& LEBT

Radio Frequency
Quadrupole

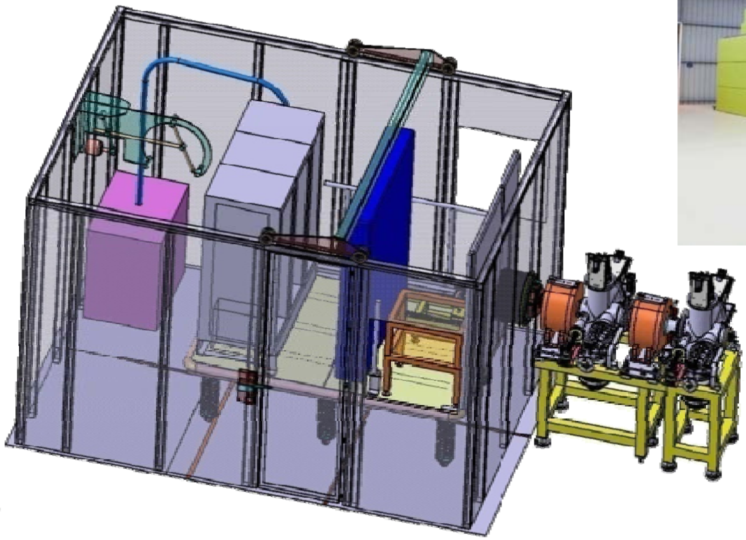
SRF Linac
Cryomodule

HEBT

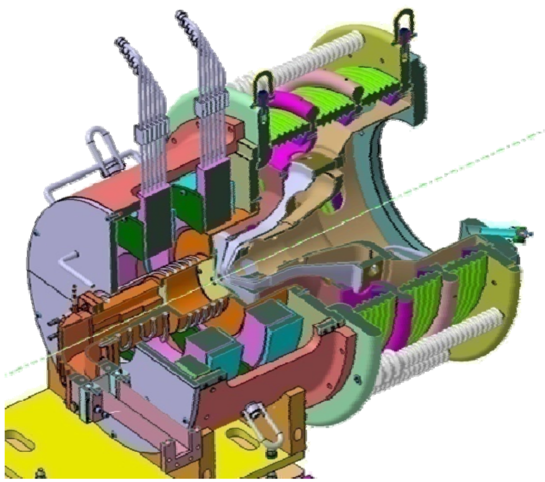
International Fusion Energy Research Centre



Manufacturing of the injector



Blockhouse at Saclay



Ion Source

Solenoid
magnetic measurement

High Voltage Power Supply

Assembly of the EVEDA Lithium Test Loop

Facility Building
[40m^{W}, 80m^{L}, 33m^{H}]
JAEA Oarai

- Commissioning undergoing
- Start of the experiments: June 2011

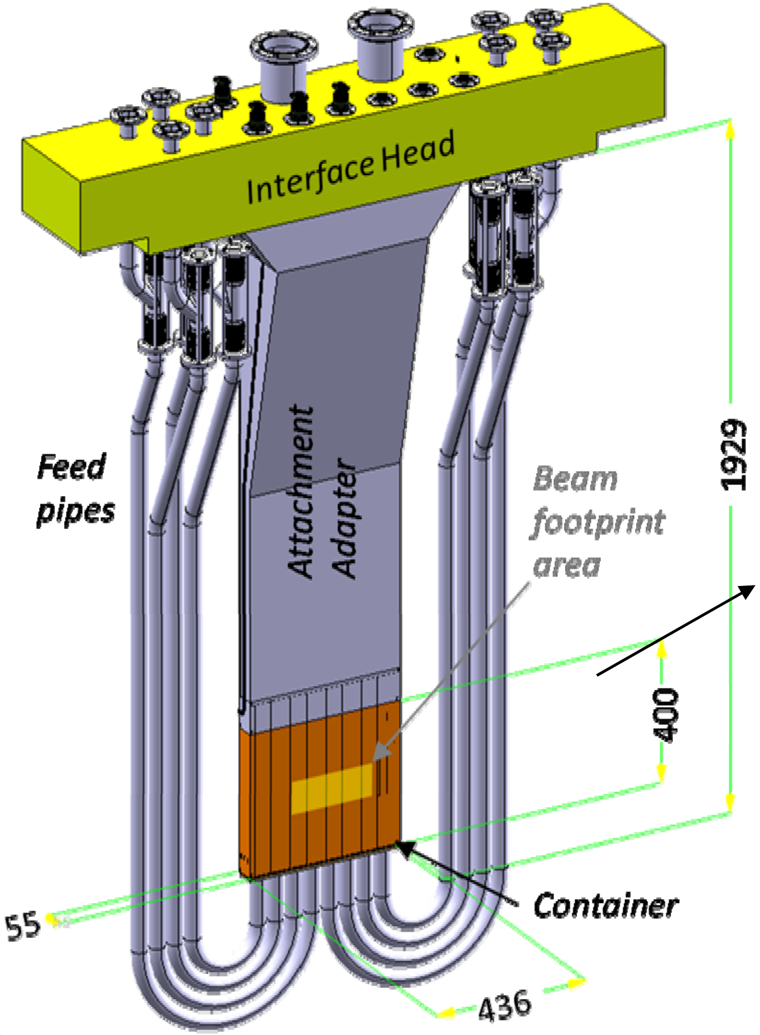
A. Möslang et al.

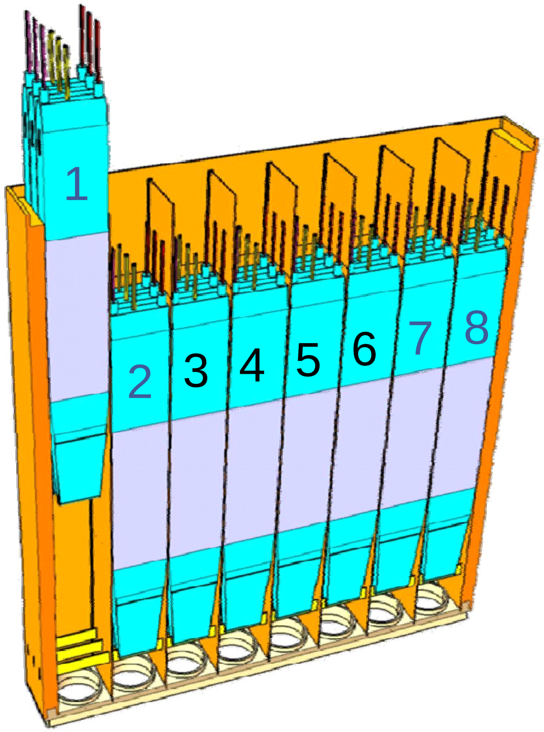
Karlsruhe Institute of Technology

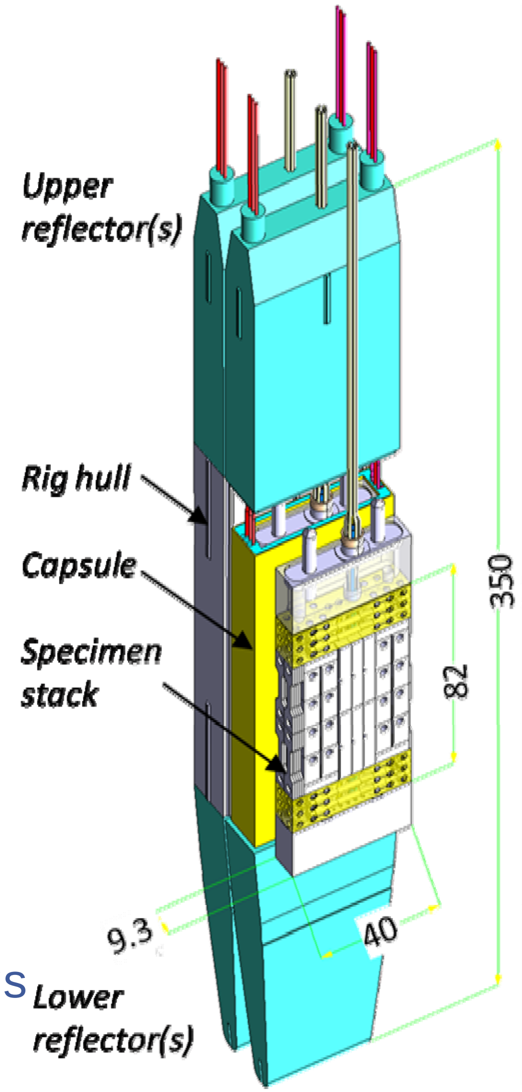
Engineering Validation Activities

The High Flux Test Module

High Flux Test Module current design







3,4,5,6: Irradiation Rigs

1,2,7,8: Companion Rigs

About 1000 samples

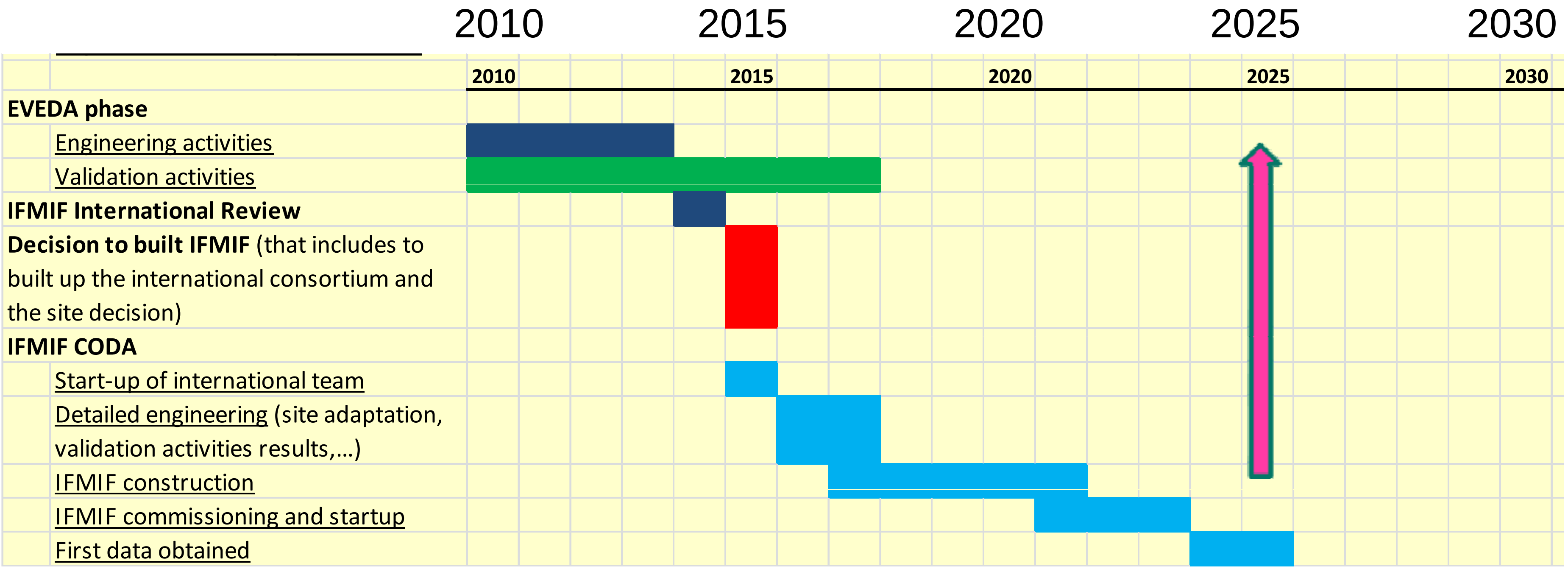
A. Möslang et al.

HELOKA-LP
Full scale helium gas coolant loop


Test section area


Compressor station

IFMIF schedule - Optimistic scenario



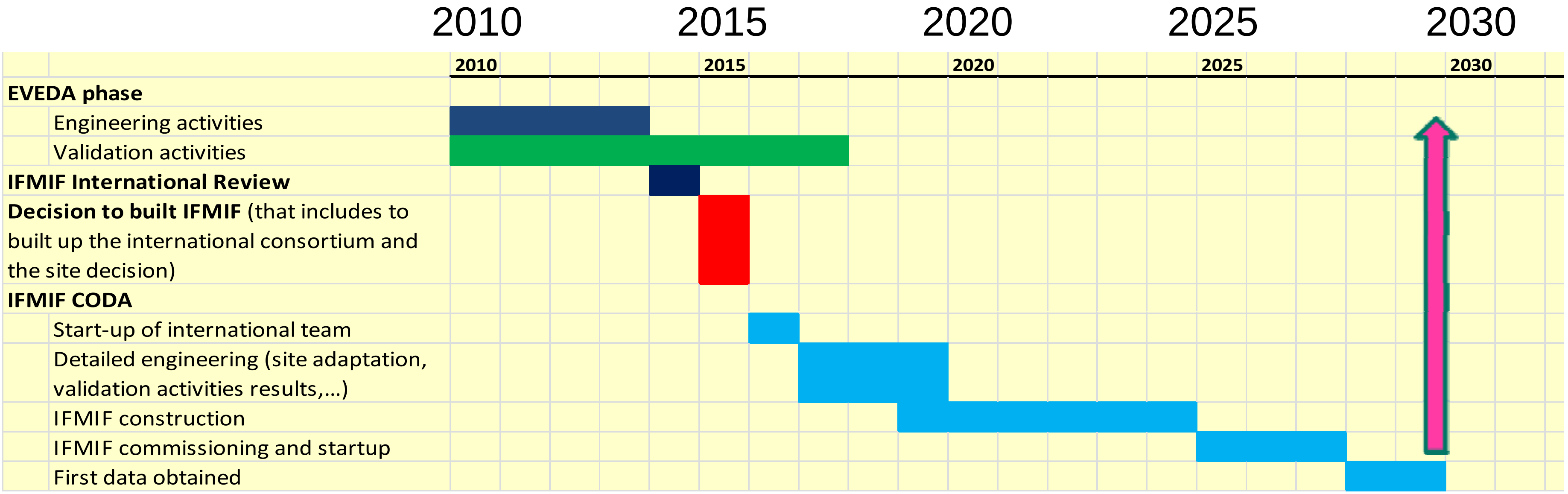
Advantages

- On time for DEMO design
- Possible some impact on ITER TBM operation
- Present IFMIF team and expertise is maintained along the time

Challenge

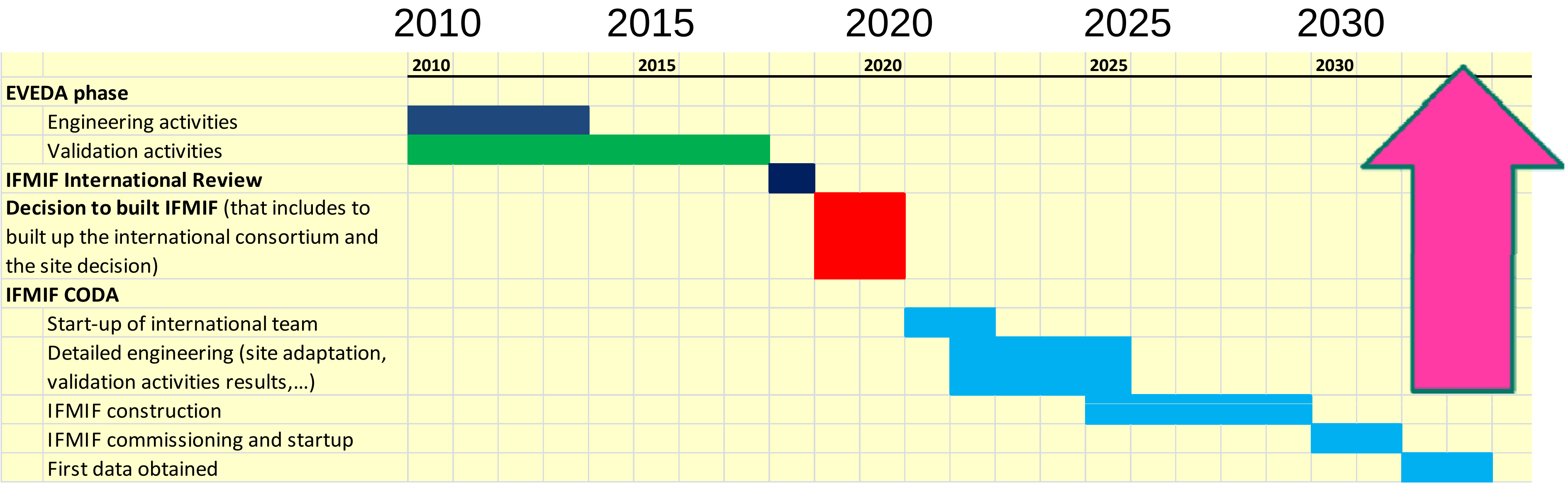
- Significant EU budget required during FP8 2014-2020

IFMIF schedule - Reference scenario



- **Advantages**
  - IFMIF close to the time for DEMO (first data of IFMIF at same time than ITER DT results)
  - Relatively low EU budget required before 2020 (the Host country can offer to support the International Team during some time)
  - Expertise and team developed during EVEDA can be maintained

IFMIF schedule - Pesimistic scenario



Advantages

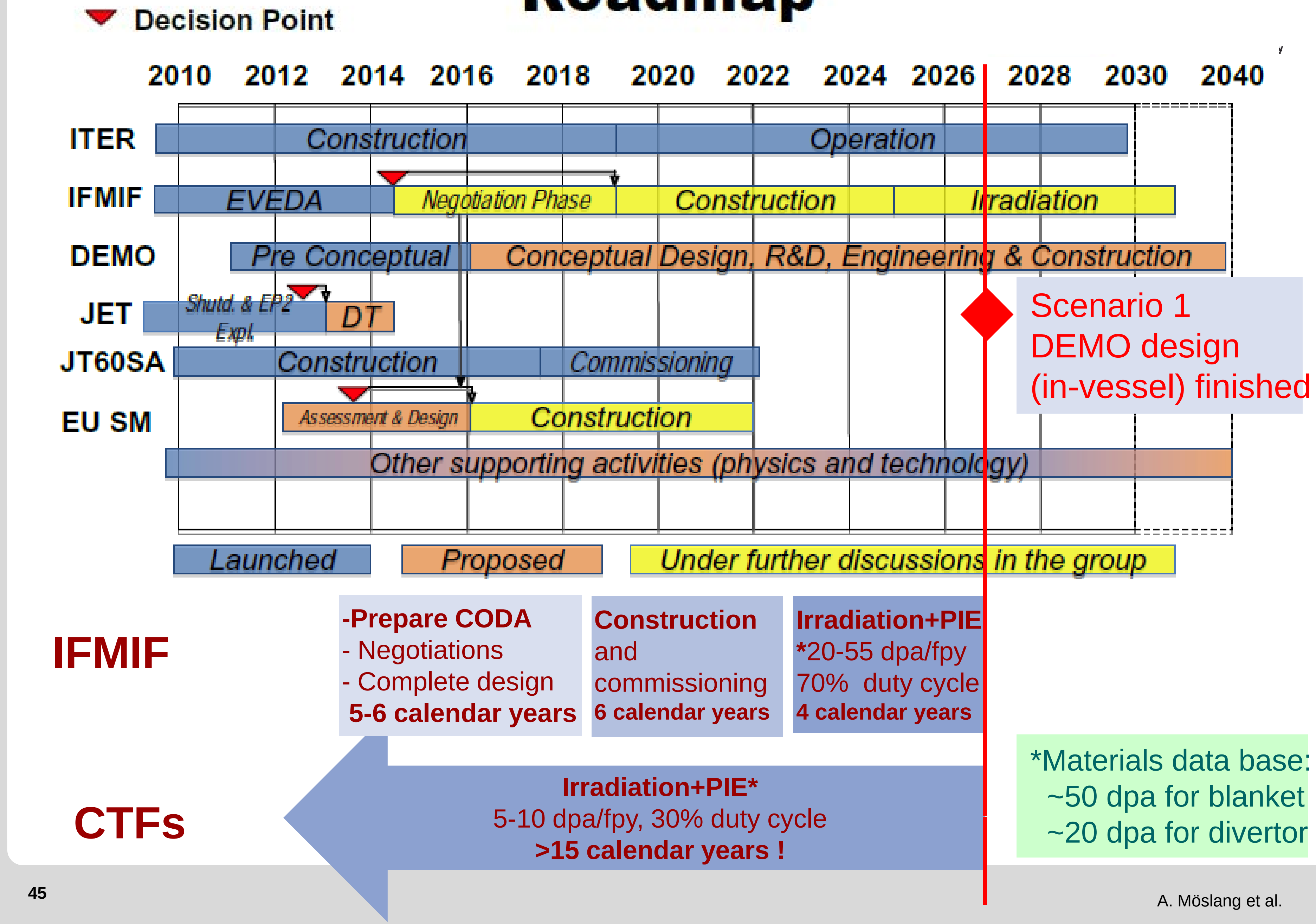
- No EU budget required before 2020

Problems

- **IFMIF in the critical path of DEMO**
- The expertise developed during the EVEDA phase will be lost

"Hasinger Report", 2010

Roadmap



A. Möslang et al.

Summary and Conclusions

- IFMIF meets fully the mission and the requirements of an intense fusion neutron source and is able to deliver timely the major pillars of a materials database for construction, licensing and safe operation of a DEMO reactor
- Main Milestones:

  June 2013: Delivery of the Intermediate IFMIF Engineering Design Report

  June 2015: Start of the experiments of the whole Accelerator Prototype

  June 2017: End of the studies in the framework of the BA agreement

  Dec. 2013: End of IFMIF EVEDA for all activities not contributing to the Accelerator Prototype
- It is expected that the Intermediate IFMIF Engineering Design Report will be the basis for an evaluation through for an international review panel. Based on that results, siting negotiations could start immediately
- IFMIF needs funding during 2014-2020. Otherwise,
  - IFMIF will be at the critical path for DEMO, and
  - the power of the present team and its competence will be lost