Strategy of Fusion Materials Development and the Intense Neutron Source IFMIF

A. Möslang

Institute for Materials Research I
Metals Department

Overview

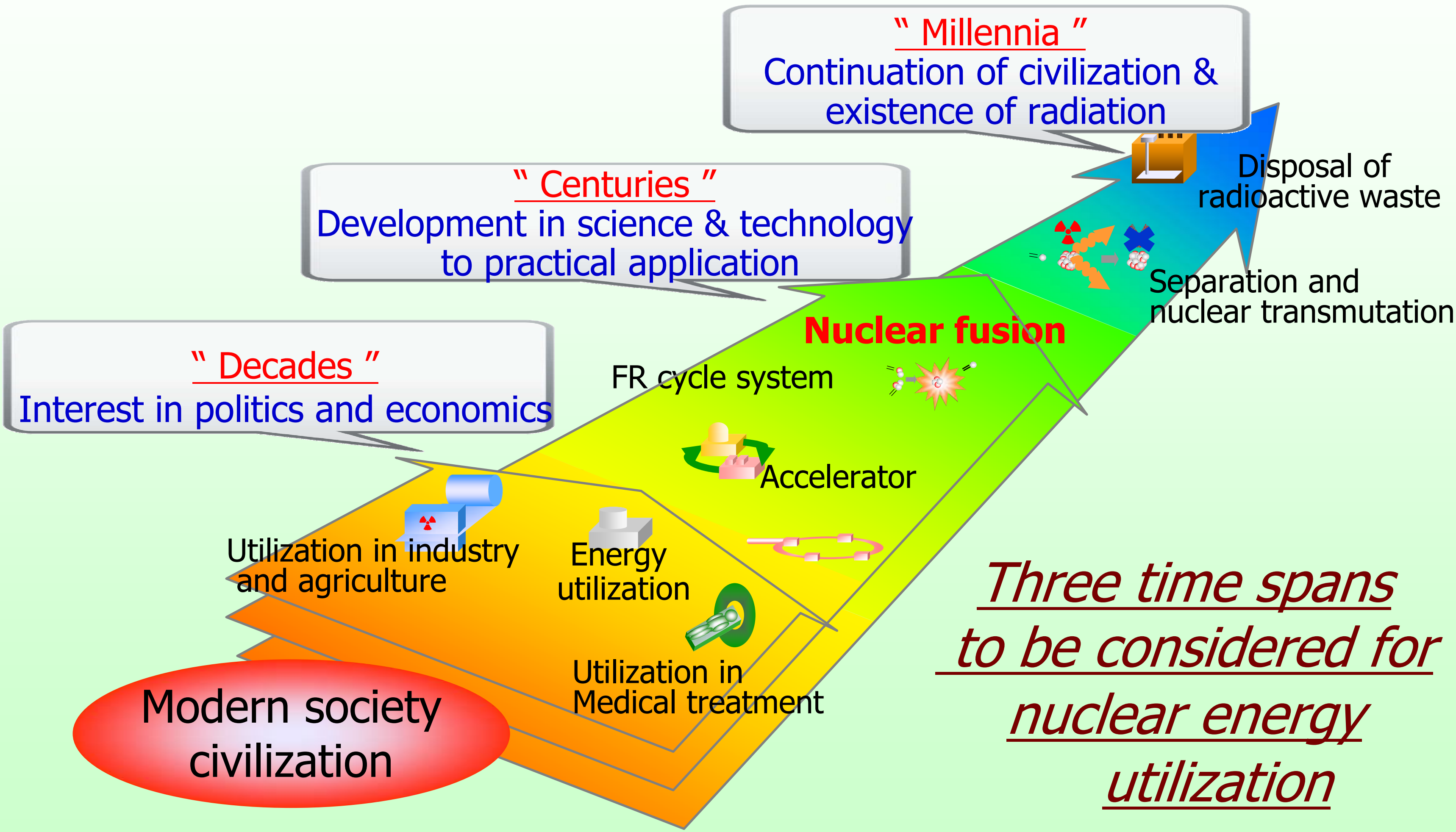
- **Global Fusion Strategy**
  - Performance goals for fusion reactor materials
  - Material development strategies
  - Why a dedicated fusion neutron source?
- **Intense fusion neutron source**
  - Mission & requirements
  - Small scale specimens
- ***IFMIF* – The worlds most powerful neutron source**
  - Anatomy
  - Neutronics & irradiation conditions
  - Design overview
  - Schedule and costs
- **Conclusions**

Global Fusion Strategy

- Performance goals for fusion reactor materials
- Material development strategies
- Why a dedicated fusion neutron source?

Atomic Energy Commission of Japan

Y. Fujii Chairman; 2004



Three time spans to be considered for nuclear energy utilization

Government of Japan - Cabinet Office

H. Imura; 12 2003

JT-60
JET

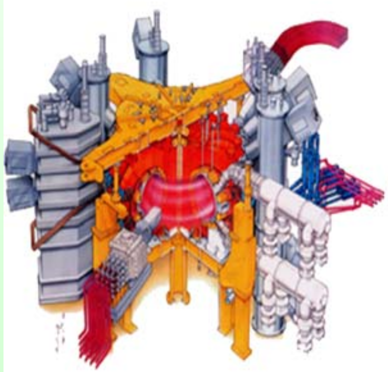
Break-even

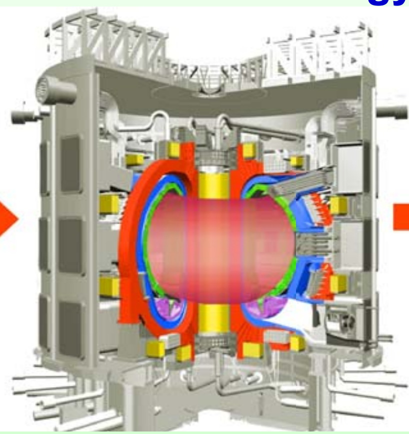
Experimental Reactor (ITER)

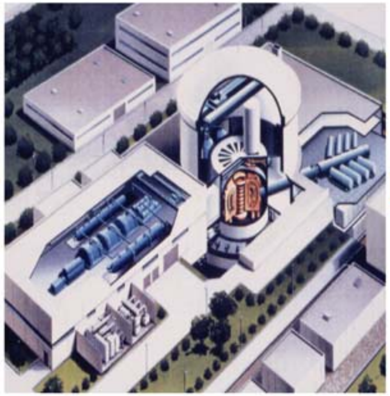
Long-burn
Integration of Fusion Technology

Demonstration Reactor (DEMO)

Electric Power Generation
~1000 MWe







Public Use

Q~0.5-1 ~10sec

Q ≥10 300~500sec

Q =30~50

Irradiat. Damage: **≤3dpa / lifetime** **≤30pda / year**

dpa: displacements per atom; e.g, 3 dpa means: each atom is displaced in average 3 times during irradiation

Main technological Problem for ITER:

Plasma facing materials — Lackner, former EU-EFDA head

Issues for the CFC divertor:

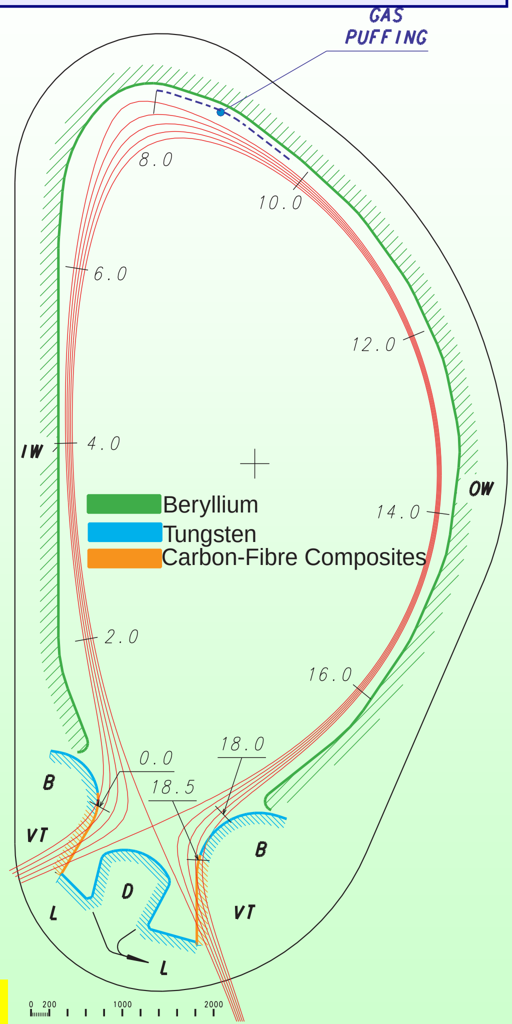
Erosion lifetime (chemical sputtering), T-co-deposition (450g T limit inside the vessel) & C dust production (~200kg limit)

Issues for the Be First Wall:

Be dust production (100kg limit) in particular on hot surfaces (6kg limit) -> Hydrogen production in off normal events

Issues for W clad divertor:

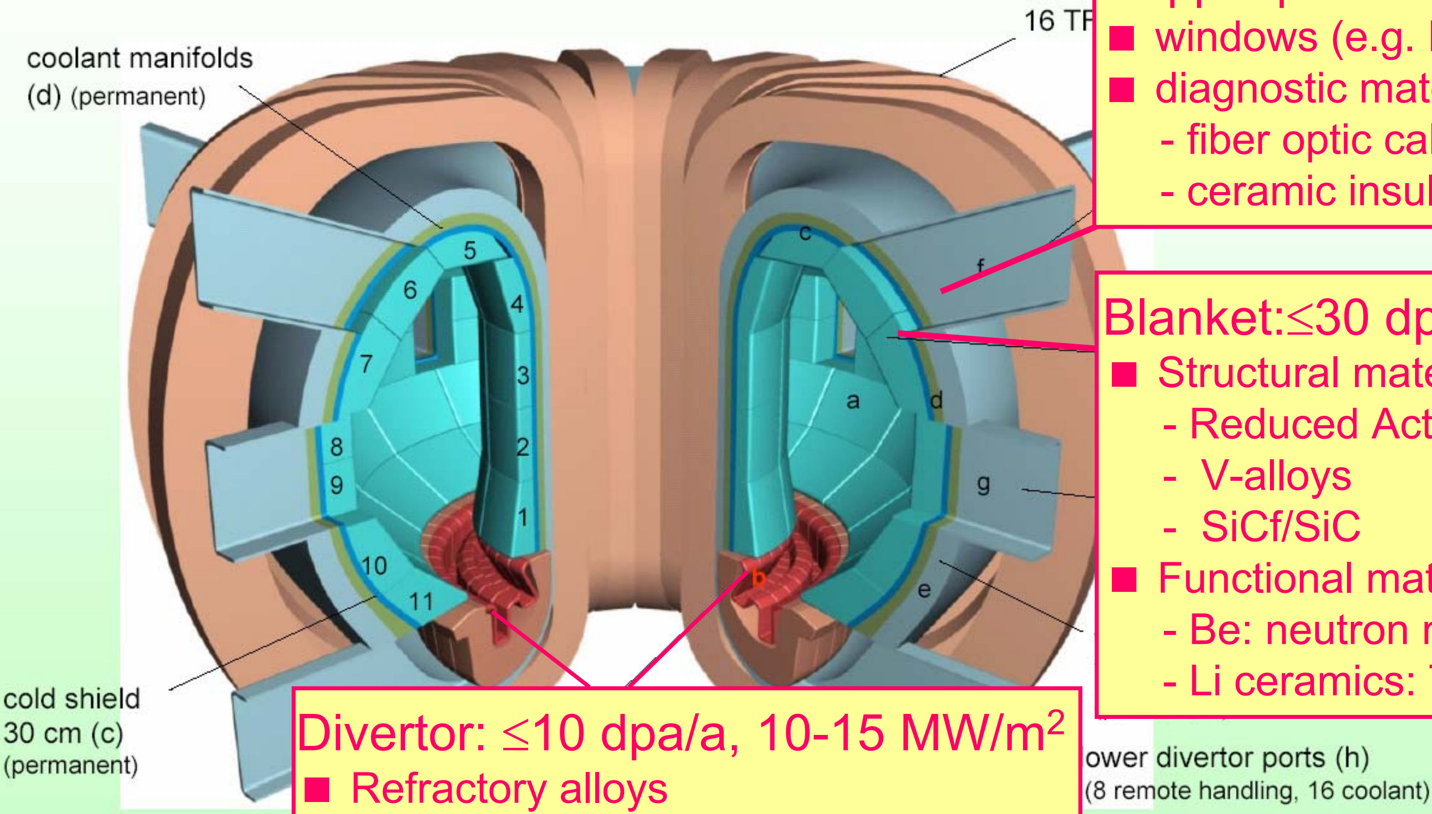
- W dust production (100 - 300kg limit) can cause a radiological hazard
- Disruption erosion - melt-layer loss
- Plasma compatibility



Present preference: 3 different materials

Fusion Power Reactor (PPCS-12)

- Materials challenges -



8 upper ports: ~0.1 dpa

- windows (e.g. PVD-diamond)
- diagnostic materials
  - fiber optic cables
  - ceramic insulators

Blanket: ≤30 dpa/a, 2.5MW/m²

- Structural materials, e.g.
  - Reduced Activation Steels
  - V-alloys
  - SiCf/SiC
- Functional materials
  - Be: neutron multiplier
  - Li ceramics: T breeders

Divertor: ≤10 dpa/a, 10-15 MW/m²

- Refractory alloys
  - e.g. W & W-alloys
- Dispersion strengthened steels
  - e.g. nano-composed RA-steels

International Key Data for Materials Development

	ITER	DEMO	REACTOR
Fusionpower	0.5 – 0.7 GW	2 - 4 GW	3-4 GW
Blanket (First Wall): - Neutronic Load - Integral Load - Integral Irradiation damage	0.5 – 0.7 MW/m^2 0.2 – 0.4MWy/m^2 2 - 4 dpa	2 - 3 MW/m^2 3 - 8 MWy/m^2 30 - 80 dpa	2 – 3 MW/m^2 10 - 15 MWy/m^2 100-150 dpa
Divertor: - Heat load - Integral Irrad. damage	~10 MW/m^2 ≤2 dpa	10-15 MW/m^2 ≤ 27 dpa	10-15 MW/m^2 ≤50 dpa
Operational Mode	Pulsed (>400 s) < $5 \cdot 10^4$ Cycles	Quasicontinuous	
Plant lifetime			~30 full power year (fpy)
Net Plant Efficiency			≥ 35 %

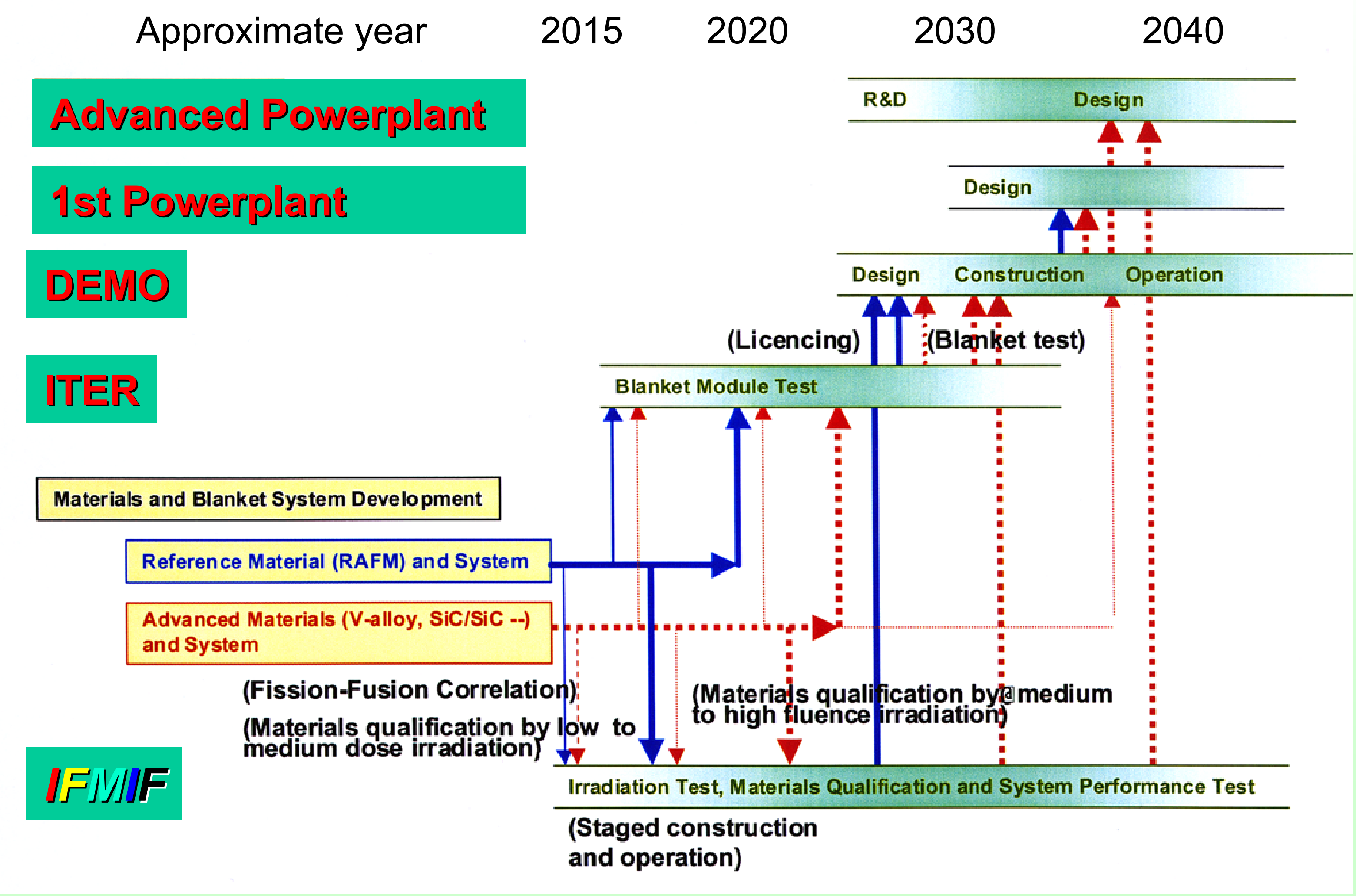
Materials issues and major areas for R&D

RA-F/M Steels (incl. oxide dispersion strengthened variants)	• Database development of Primary candidate alloys • Fracture toughness degradation by irradiation embrittlement • ODS-nanocomposite ferritics for high temp. (650 - 750°C)
Vanadium alloys	• Development of insulation coatings (MHD-Effekte) • Impurity (O, C, N) pick-up from environment → embrittlement • Fracture toughness degradation by irradiation embrittlement
SiC_f/SiC composites	• Design of composite structures for improved performance • Fundamental property response to irradiation • Development of a technology base for fabrication & joining
Tungsten alloys	• Fabrication & joining technologies • Radiological properties – low activation / waste disposal • Radiation embrittlement & compatibility
Functional Materials: Be (n-multiplier) Li-ceramics (breeders)	• Structural integrity during irradiation • Uncertainties in production and release of T and He • Fabrication technology

Red lines: Requires intense neutron source with fusion specific spectra

The Aggressive Strategies of the EU, J & US Identify **ITER** and **IFMIF** As Essential Facilities for a Demo Power Reactor Operating 2035—2040

(2000: Ehrlich, Kondo, Bloom, 2003: Zinkle)



Why a Dedicated Fusion Neutron Source? (1/2)

- There is presently no neutron source that combines
  - fusion similar spectrum
  - high fluence for accelerated testing
  - sufficiently large test volume

- ITER testing is limited:
  - restricted fluence accumulation ($\leq$ 3 dpa)
  - mode of operation is very different from DEMO

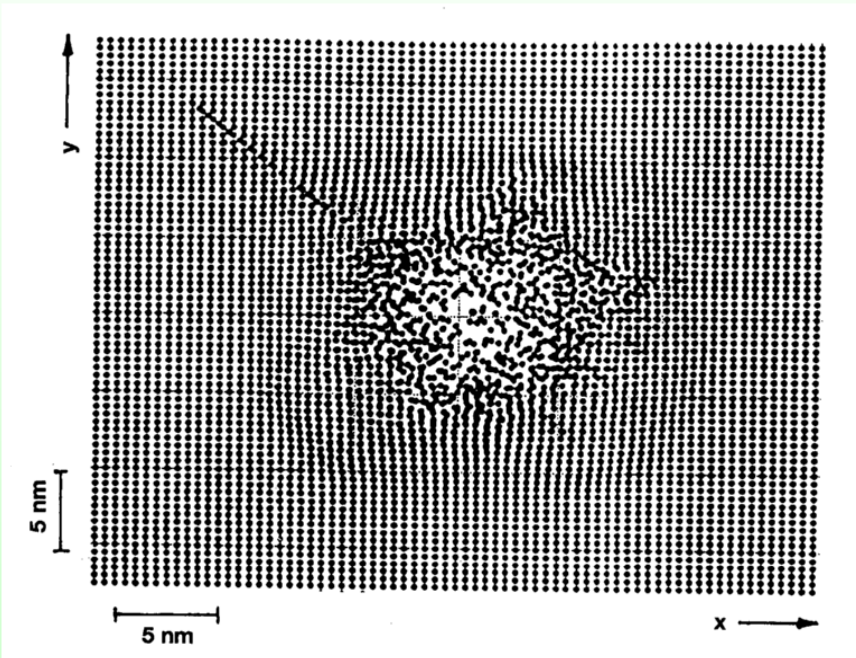
  However, ITER is a valuable test bed for integral testing (e.g. TBMs)

- High ranking advisory boards demanded several times an Intense Fusion Neutron Source

Why a Dedicated Fusion Neutron Source? (2/2)

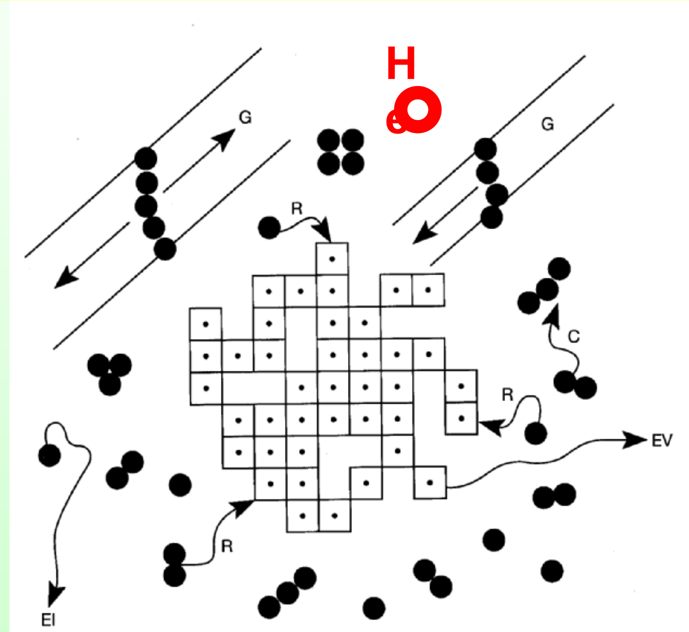
Irradiation damage: 2 elementary reactions

Atomic displacements („dpa“)



MD simulation of a displacement cascade produced by a 10 keV primary knock-on atom in an fcc lattice (Ghaly and Averback)

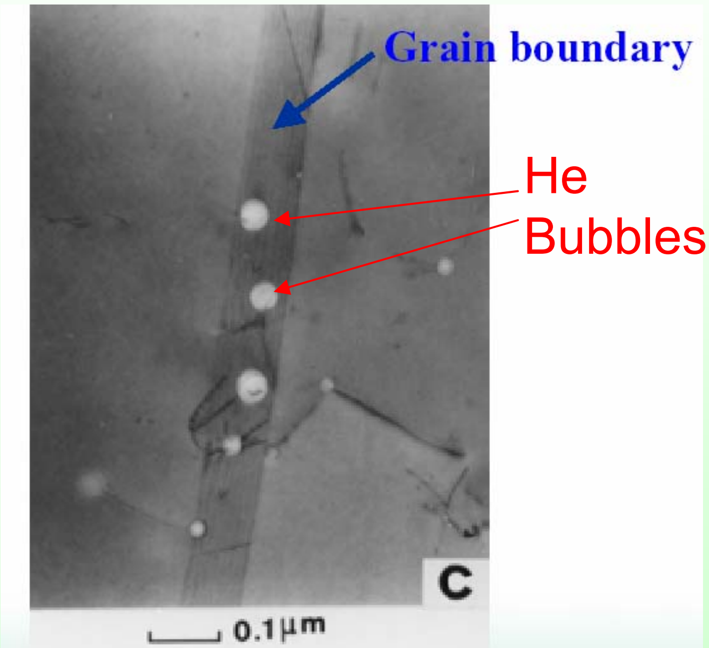
Nuclear reactions (e.g. He)

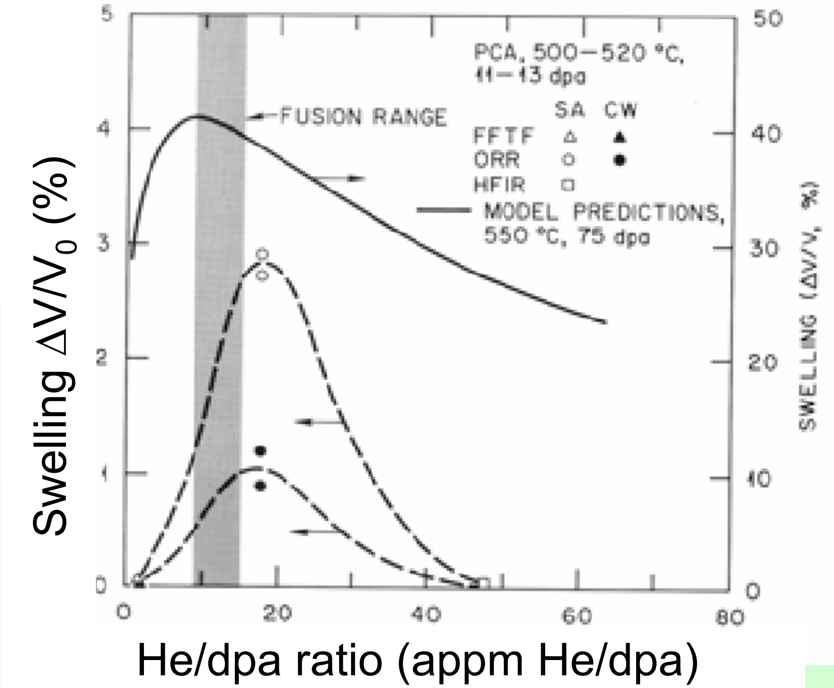


Defect arrangement in a displacement cascade (schematic)

He effects: no adequate simulation in existing irradiation facilities

Why is He/dpa ratio an important parameter for fusion materials R&D?





He bubbles

- can cause severe grain boundary embrittlement at high temp. (fcc alloys)
- can severely enhance fracture toughness degradation at low temp. (bcc alloys)

Intense fusion neutron source

- Mission & requirements
- Small scale specimens

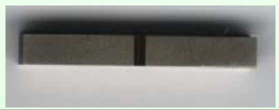
Intense Fusion Neutron Source

Mission:
- **Qualification of candidate materials up to about full lifetime of anticipated use in a fusion DEMO reactor**
- Advanced material development for commercial reactors
- Calibration and validation of data generated from fission reactors and particle accelerators

Requirements *(IEA workshop in San Diego 1989)*:

- **Neutron flux/volume relation**:
  2 MW/m^2 in a volume sufficient for some hundred samples
- **Neutron spectrum**: Meet FW spectrum as near as possible;
  Criteria include PKA spectrum, H, He, He/dpa
- **Neutron fluence accumulation**: DEMO fluence ~150 dpa in few yrs
- **Neutron flux gradient:** ≤10%/gauge volume
- **Machine availability:** 70%
- **Time structure:** Quasi continuous operation
- **Good accessibility of irradiation volume**

IFMIF Small Scale Specimens

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

Significant volume reduction (20-125 times) compared to conventional standards

Good progress is being made in developing further miniaturized specimens with proven scaling laws

IFMIF : The worlds most powerful neutron source

- Anatomy
- Neutronics & irradiation conditions
- Design overview
- Schedule and costs

Contributors to IFMIF (1995 - 2004)

EU

Andreani R, Ausset P., Cambi G., Frisoni M. ,Bernaudin P-E., Blandin C., Duperrier R., Ferdinand R., France A., Gobin R., Hudelot J.P., Lagniel J-M., Olivier M., Simoens F., Uriot D., Viola-Teres J.R. Bonade R., Spätig P., Tran M., Victoria M. ,Cozzani F., Paidassi S., Chen J., Andreani R., Gasparotto M., Lässer R.,Angelone M., Bailey A., Benamati G., Bianchi F., Burgazzi L., Cepraga D.G., Cevolani S., Cevolani S., Ciattaglia S., Esposito B., Fazio C., Filotto F., Giusti D., Martone M., Miccichè G., Monti S., Dell'Orco G., Di Pace L., Pensa A., Pinna T., Riccardi B., Scaddozzo G., Tinti R.,Natalizio A., Antonucci C., Daum E., Ehrlich K., Fischer U., Gordeev S., Heinzel V., von Möllendorff U., Möslang A., Roehrig H.D.,Simakov S.P., Vladimirov P., Wilson P.P.H., Bechthold A., Beller P., Deitinghoff H., Hollinger R., Jakob A., Klein H., Liebermann H., Maaser A., Meusel O., Podlech H., Pozimski J., Ratzinger U., Sauer, A., Schempp A., Tiede R., Volk K., Weber M., Tiseanu I., Bém P., Burjan V., Götz M., Kroha V., Novák J., Simecková E., Stursa J., Vesely F., Vincour J., Margoto E.

JA

Baba M., Hagiwara M., Kurishita H., Matsui H., Narui M., Yamamoto T., Hojo Y., Suzuki S., Saigusa M., Sazawa S. Kakui H., Miyauchi Y., Ogoshi M., Yamamura T., Ezato K., Fujii T., Ida M., Iga T., Imai T., Jitsukawa S., Katsuta H., Kato Y., Kinsho M., Kondo T., Konishi S., Maebara S., Maekawa H., Morishita T., Moriyama S., Nakamura Hideo, Nakamura Hiroo., Noda K., Oyama Y., Seki. M., Shiba K., Sugimoto M., Takatsu H., Takeda M., Takeuchi H., Watanabe K., Yutani T., Ara K., Hirabayashi M., Ohira H., Miyahara N., Nakamura Hiroshi, Ise H., Ebara S., Shimizu A., Watanabe Y., Yokomine, Yonemoto Y.,Kasada R., Kato Y., Kimura A., Kubo H., Morishita K., Shimizu K., Kohno Y., Muroga T., Nagasaka T., Nishimura A., Suzuki A., Horiike H., Iida T., Inoue S., Kurosaki K., Miyamoto S., Miyazaki K., Serizawa H., Uda N., Yamaoka N., Matsushita I.,Miyahara A., Kita Y., Nakayama K., Tanabe Y., Tanaka S., Terai T., Yoneoka T.

RF

Aksyonov J., Arnol'dov M., Berensky L., Chernov V.M., Chernov V. Fedotovsky V., Loginov N., Mikheyev A., Morozov V., Shishulin V. Chernogubovsky M.A.,Teplyakov V.A.Konobeyev A.Yu., Korovin Yu. A., Pereslavtsev P. E. Kalashnikov A., Zavialski L., Durkin A.P., Bondarev B.I., Vinogradov S.V., Votinov S.

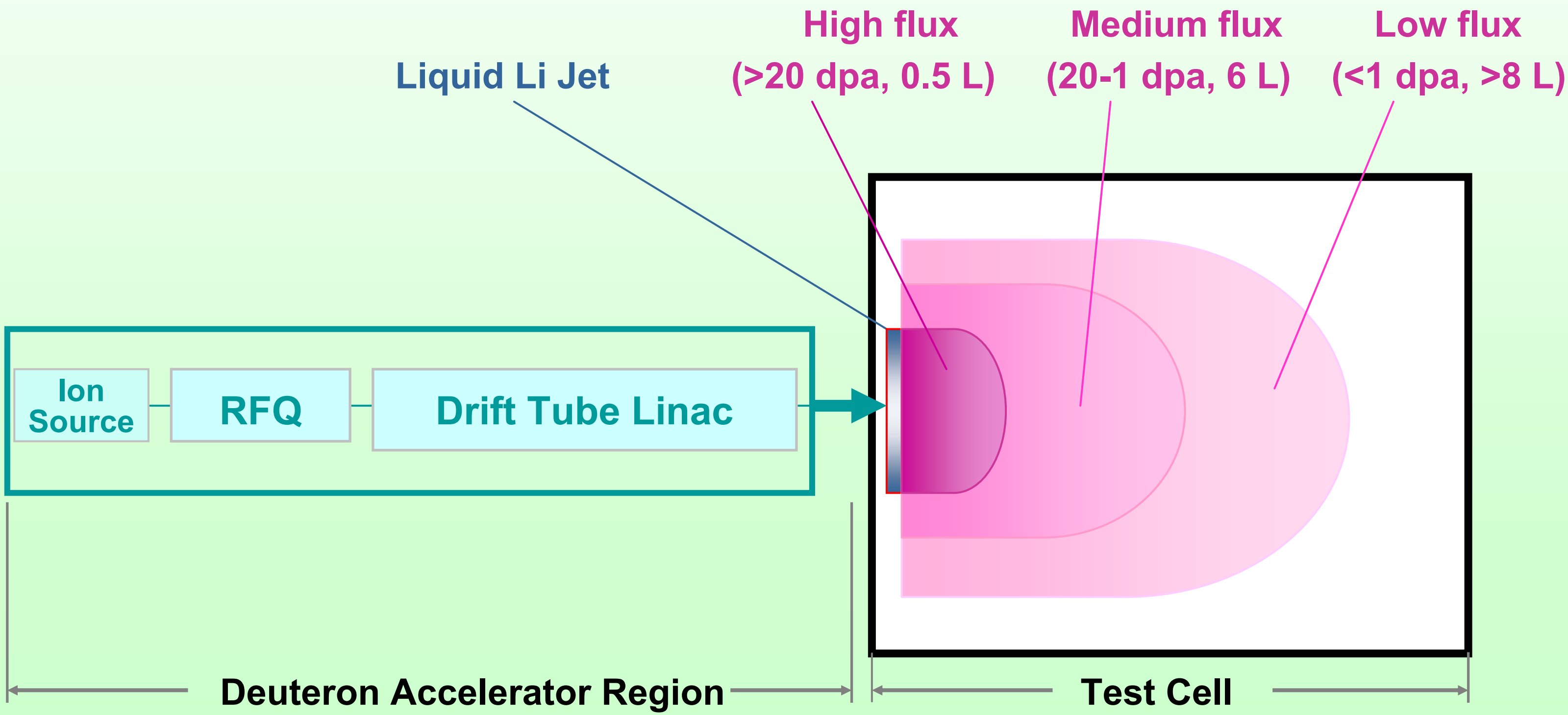
USA

BlindB., Jameson R.A, Myers T., Piaszczyk C., Rathke J., Schultheiss T., Sredniawski J., Todd A.,Gomes I.C., Hassanein A., Hua T., Smith D.L., Thomson S.L.,Wiffen F.W., Berwald D., Bruhwiler D., Peacock M. Haines J.R., Piechowiak E., Rennich M.J., Shannon T.E., Zinkle S.J.

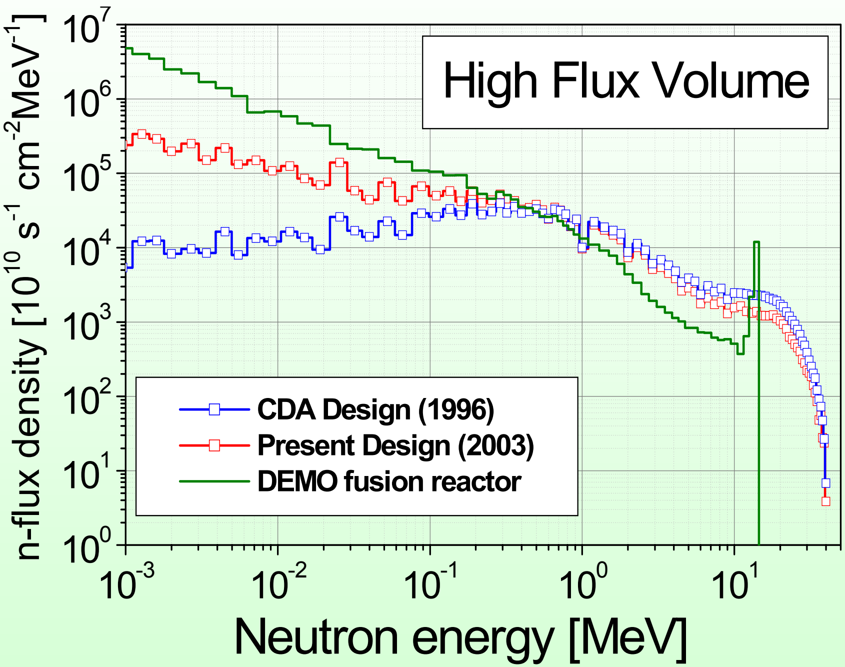
Anatomy of IFMIF

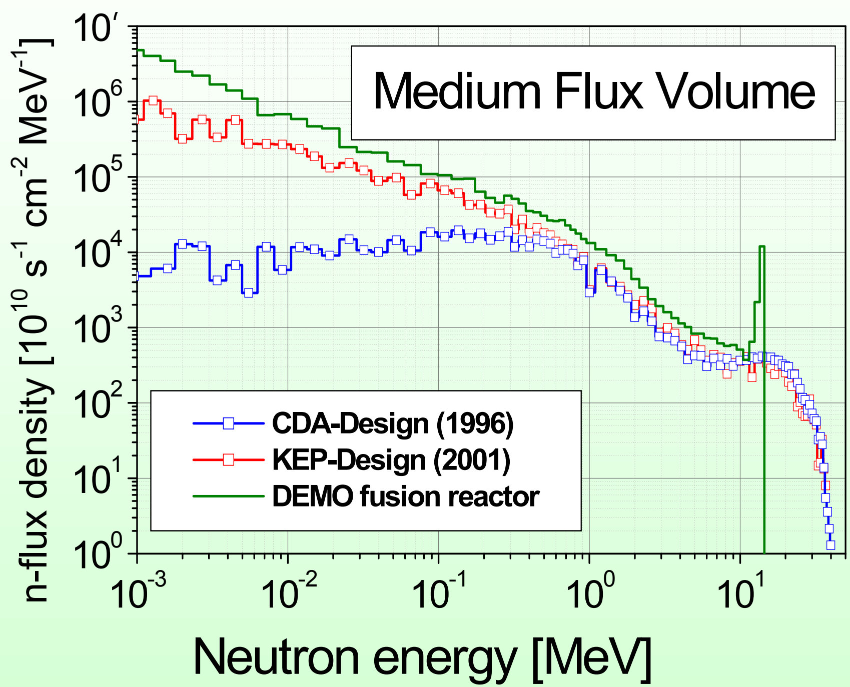
Typical Reactions: $^{7}Li(d,2n)^{7}Be$ $^{6}Li(d,n)^{7}Be$ $^{6}Li(n,T)^{4}He$

Deuterons: 40 MeV 2x 125 mA Beam footprint $5x20\ cm^2$



IFMIF Qualification   Neutron spectra



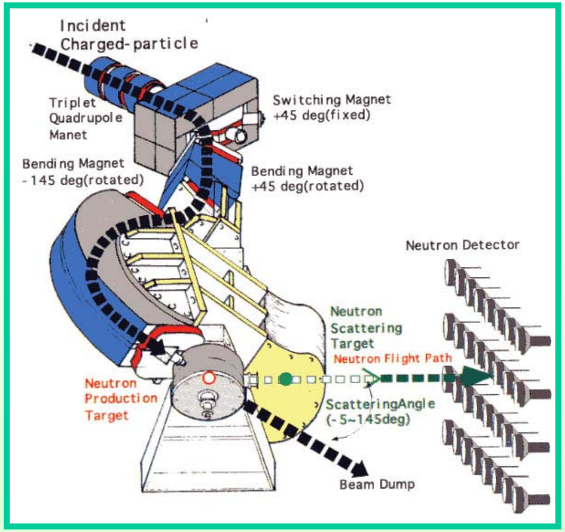


Neutron moderator & reflector:

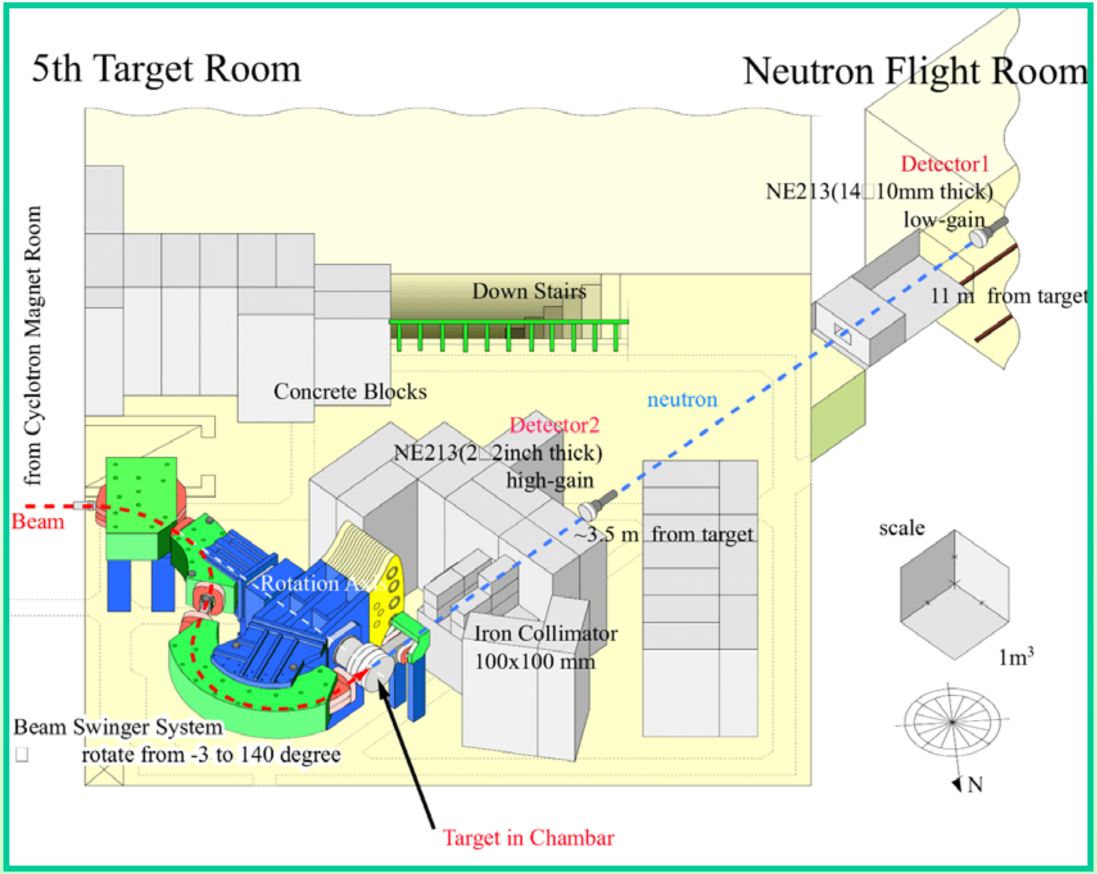
- Substantial improvements in neutron spectrum shape
- Increase of irradiation volume by ~20%

IFMIF Qualification Neutron source term

Prof. Baba, Tohoku Univ. Japan



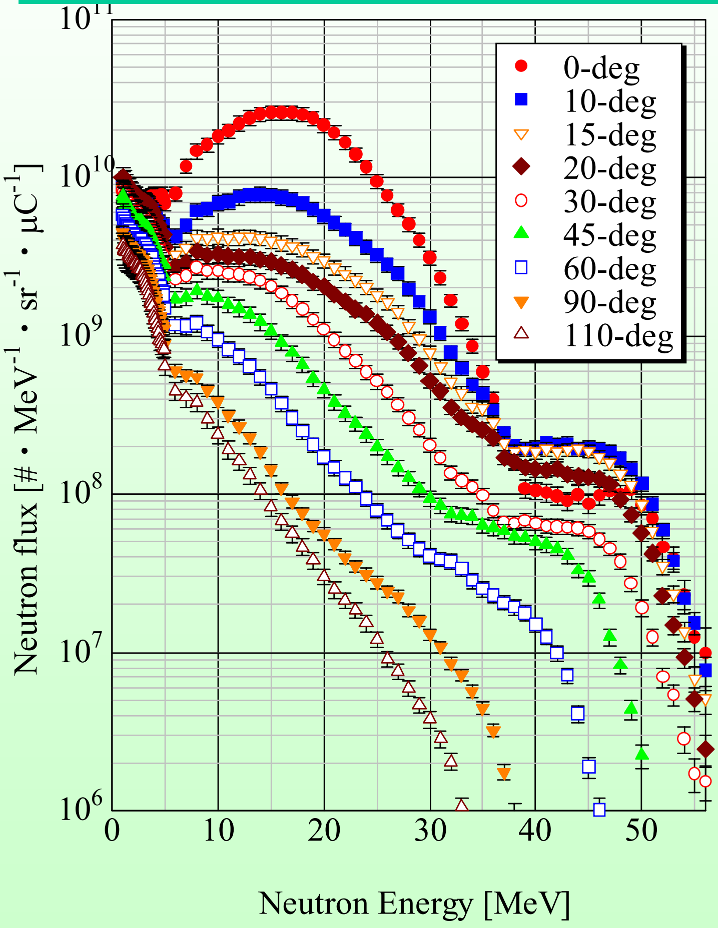
D-Beam (0-40 MeV) on Li-target:
Double differential cross section measurements by sophisticated time-of-flight experiments



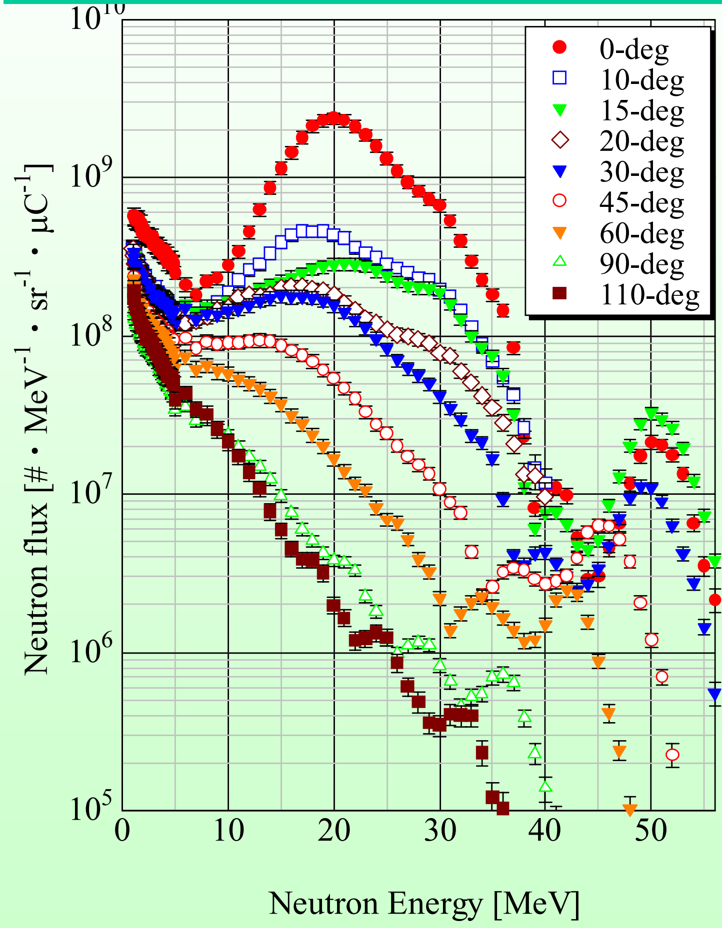
Neutron source term

Prof. Baba, Tohoku Univ. Japan

thick $^{nat}Li(d,xn)$ for E_d = 40 MeV



thin $^{nat}Li(d,xn)$ for E_d = 40 MeV



IFMIF Qualification   Irradiation Damage (1/4)

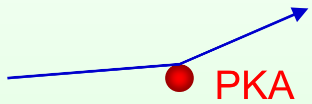
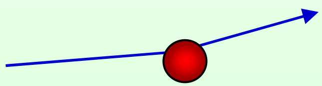
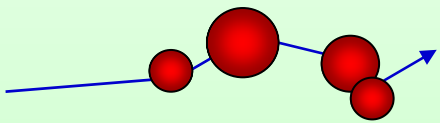
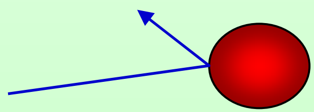
Irradiation Parameter	DEMO	ITER	IFMIF HFTM	IFMIF MFTM
Total n-flux, $(n/(cm^2\ s)$	$1.3\cdot 10^{15}$	$4\cdot 10^{14}$	$(4\div 10)\cdot 10^{14}$	$(2\div 6)\cdot 10^{14}$
H production, (appm/fpy)	1200	500	$1000\div 1500$	$300\div 500$
He production, (appm/fpy)	300	120	$250\div 600$	$70\div 120$
Displacement damage production, (dpa/fpy)	30	<2	$20\div 55$	$7\div 10$
H per dpa, (appm/dpa)	40	45	$40\div 50$	$30\div 50$
He per dpa, (appm/dpa)	10	11	$10\div 12$	$8\div 14$

MCNPX calculations in Fe-alloys based on extended nuclear data libraries & detailed geometry models
HFTM: High flux test module **MFTM: Medium flux test module**

- Correct scaling of He, H and dpa production
- Accelerated irradiation in limited volume

IFMIF Qualification Irradiation damage (2/4)

Sensitivity of energetic particles to recoil energy distribution

Particle type (E_{kin} = 1 MeV)	Typical recoil (or PKA) feature	Typical recoil energy T	Dominant defect type
Electron		25 eV	Frenkelpairs (FP: Vacancy-Insterstitial pair)
Proton		500 eV	
Fe-ion		24 000 eV	Cascades & sub-cascades
Neutron		45 000 eV	

Typical impact on materials properties:

- FPS as “freely migrating defects”: Alloy dissolution, segregation, irradiation creep
- Cascades & sub-cascades: Irradiation hardening, ductility reduction

IFMIF Qualification Irradiation damage (3/4)

Number of defects $\sigma_D(E_n, T)$ produced by PKAs with energies below T, initiated by a neutron with Energy E_n:

$$\sigma_{\mathrm{D}}(E_n, T) = \int_0^{T_{\max}} \frac{d\sigma^{PKA}(E_n, T)}{dT} \cdot \nu(T) \cdot dT$$

Different. cross section for PKA production by neutron with energy E_n

Number of defects Produced by PKAs with energy T

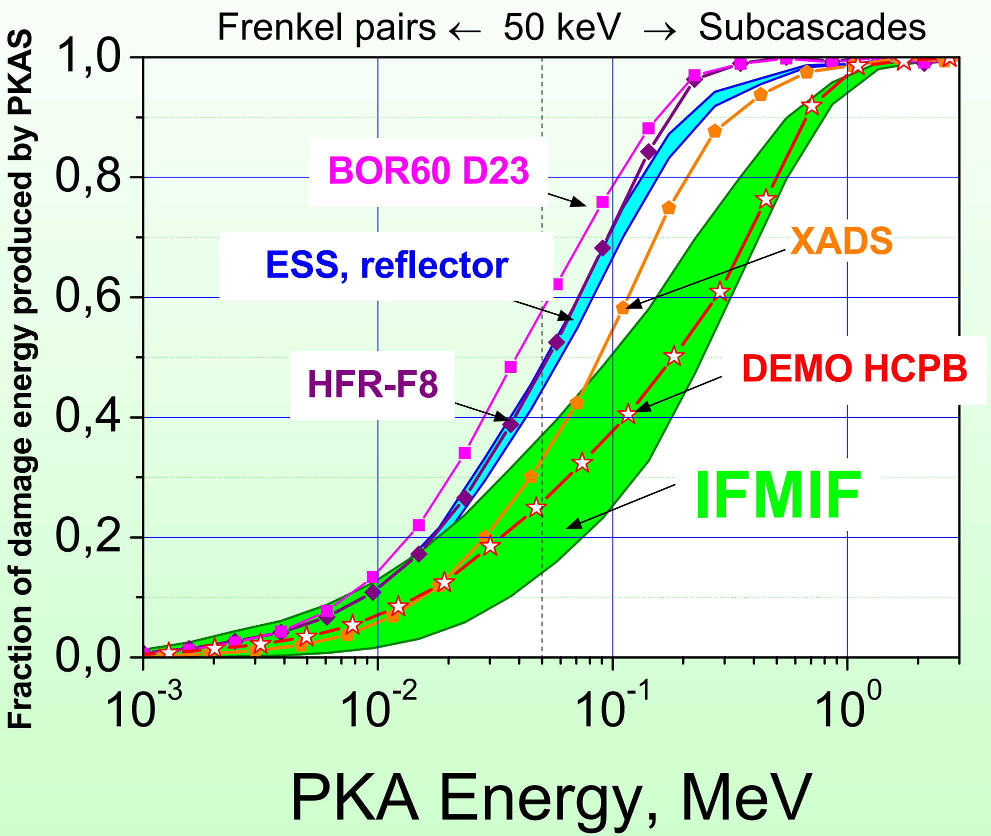
Fraction of damage $W(T)$ produced by all PKA with energy less than T

Neutron energy spectrum

$$W(T) = \frac{\int \frac{d\Phi}{dE_n} \cdot \sigma_D(E_n, T) \cdot dE_n}{\int \frac{d\Phi}{dE_n} \cdot \sigma_D(E_n, T_{\max}) \cdot dE_n}$$

IFMIF Qualification Irradiation damage (4/4)

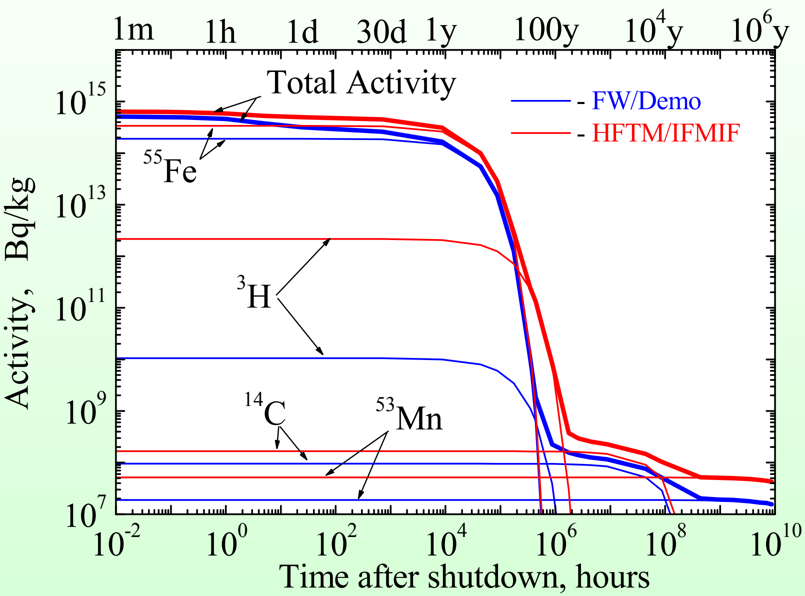
Sensitivity of neutron spectrum to recoil energy distribution



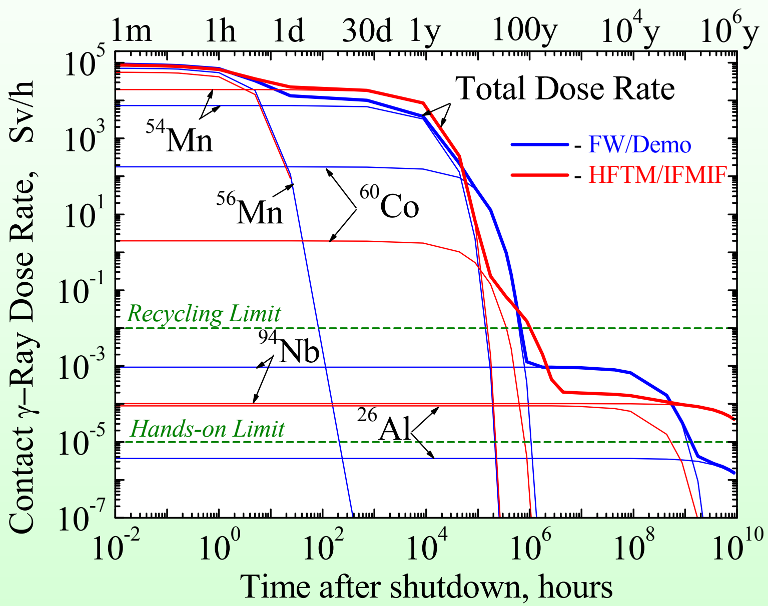
IFMIF (green area) meets perfectly the conditions of DEMO-reactor blankets

IFMIF Qualification Activation analysis

Activation: RA steel EUROFER

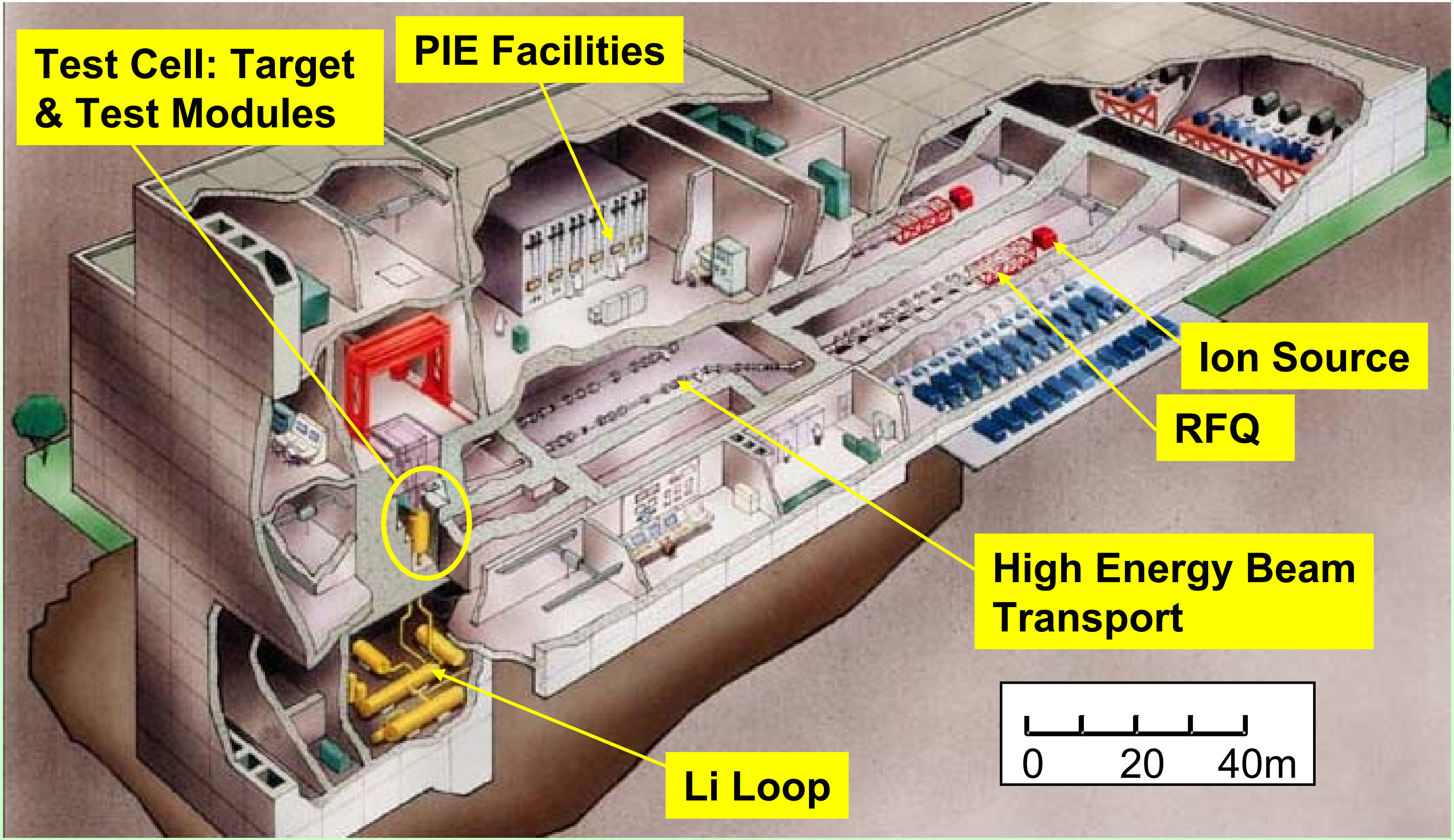


Dose rate: RA steel EUROFER



- Fusion reactors and IFMIF produce very similar nuclear inventory
- “Recycling limit” already after ~100 years
- No waste disposal needed for highly activated materials

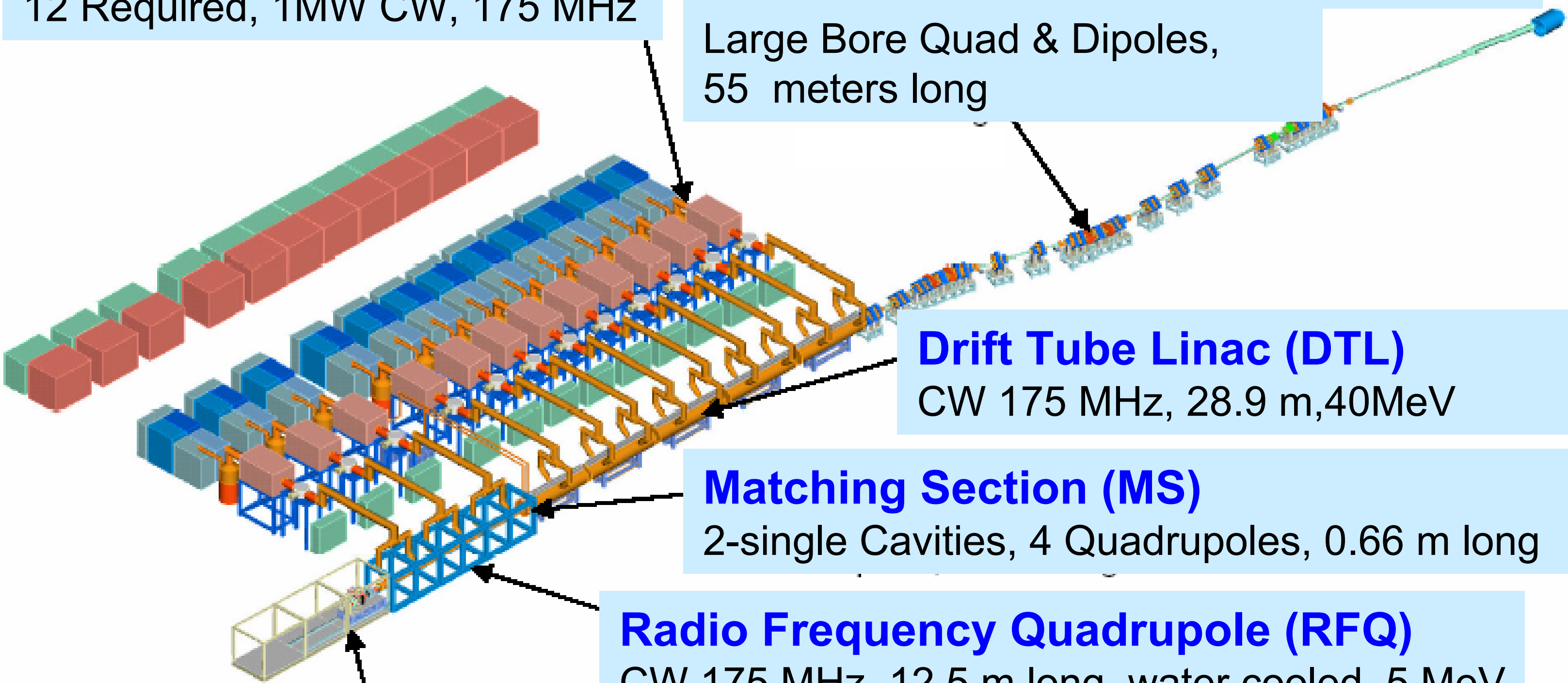
IFMIF Design Overview



IFMIF Accelerator System Baseline

RF Power System
12 Required, 1MW CW, 175 MHz

High Energy Beam Transport (HEBT)
Large Bore Quad & Dipoles,
55 meters long



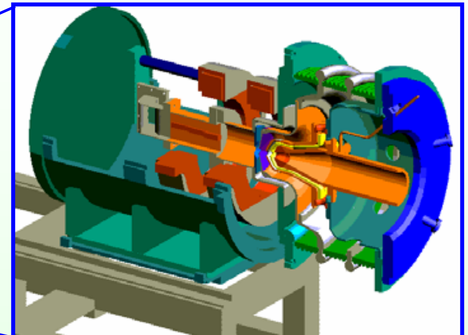
Drift Tube Linac (DTL)
CW 175 MHz, 28.9 m,40MeV

Matching Section (MS)
2-single Cavities, 4 Quadrupoles, 0.66 m long

Radio Frequency Quadrupole (RFQ)
CW 175 MHz, 12.5 m long, water cooled, 5 MeV

Ion Injector
CW ECR, Source, 140 mA D^+, 95 keV, Magnetic LEBT to RFQ

IFMIF Accelerator Source



SILHI Ion Injector (CEA/Sacley)
100 mA H+, 95 keV, (stable CW operat.
170 mA D+, 95 keV, (done pulsed)

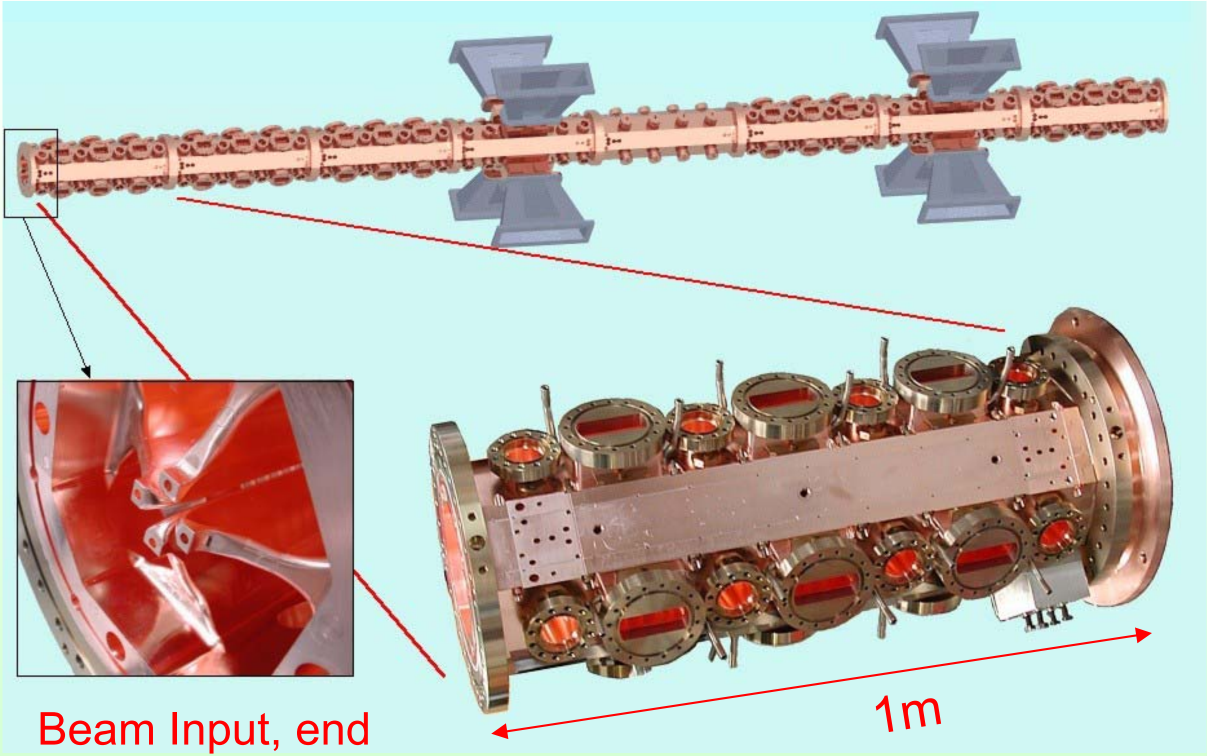
LEDA Injector (LANL)
110 mA H+, 95 keV, (stable CW operation)

Ion Injector

- Operation with D^+:
  Both, ECR & volume source achieves IFMIF performance
- 1000 hours reliability runs underway

IFMIF **Accelerator** Radio Frequency Quadrupole

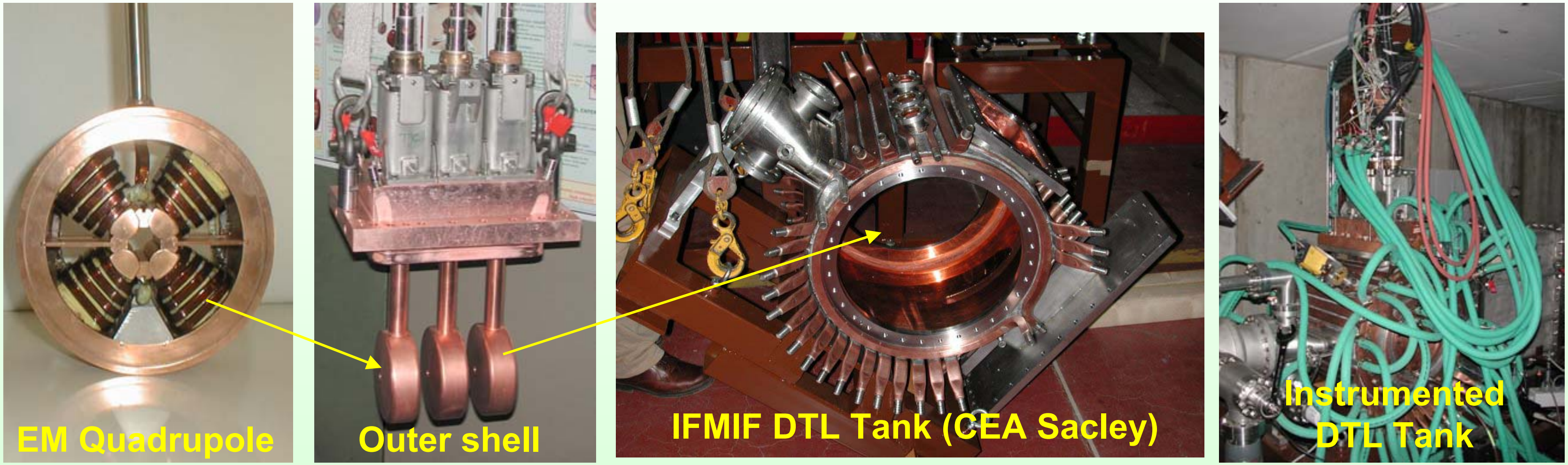
RFQ cold model,
(IPHI, CEA Sacley)



RFQ

- (CEA Sacley) - RFQ beam dynamics is finished
  - Beam emittance optimized for DTL, meets 125mA goal
- (LANL) - Long term experience at cw 100 mA H^+, 6,7 MeV

IFMIF Accelerator Drift Tube Linac



Drift tube linac DTL

- Comprehensive particle dynamics calculations from 5 to 40 MeV finished
  → full transmission
- Beam dynamics design released
- Same calculations done for SC alternative
  → lower rf losses, shorter linac, larger aperture

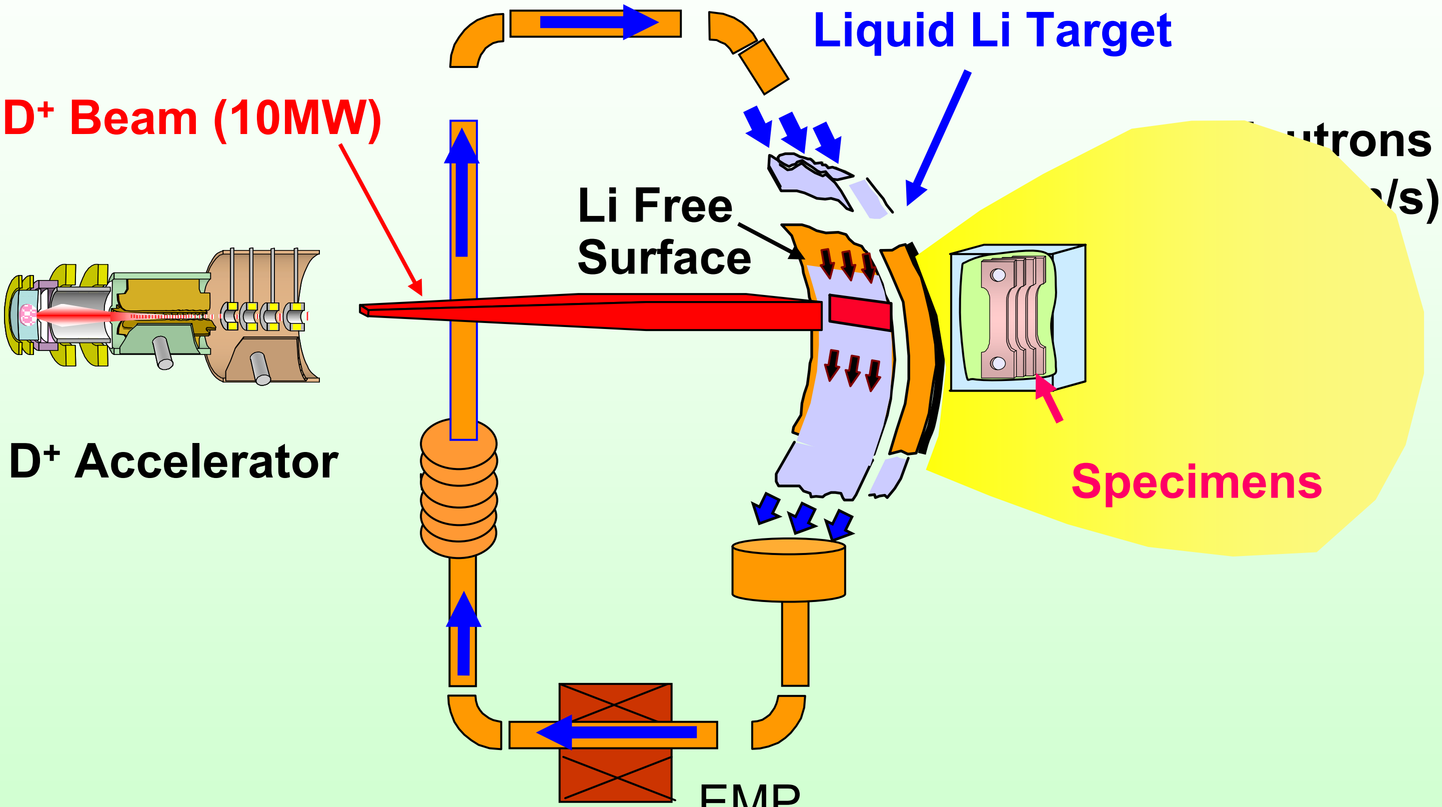
IFMIF Accelerator LEDA Experience

Low **E**nergy **D**emonstration **A**ccelerator at LANL (Los Alamos)

LEDA

- Demonstrated from 1999-2001 successful operation of a 6.7 MeV, 100 mA, cw Proton beam
- LEDA experience confirms the IFMIF design

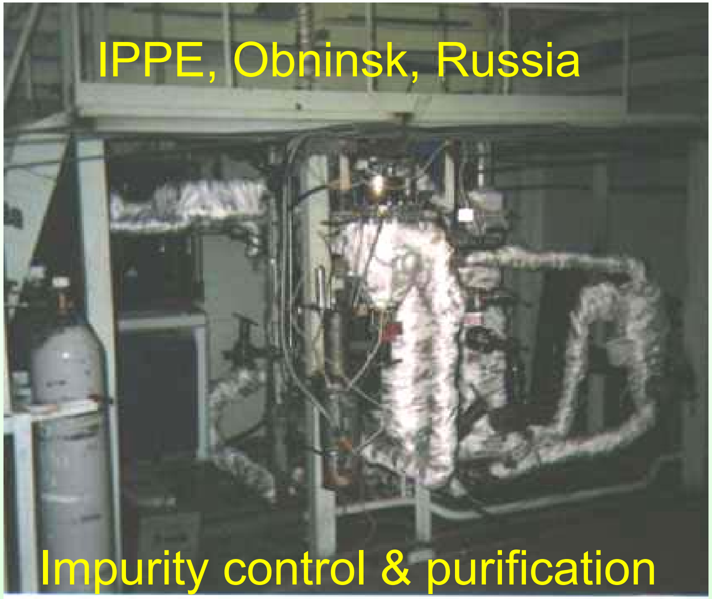
IFMIF Target Schematic view



Mission:

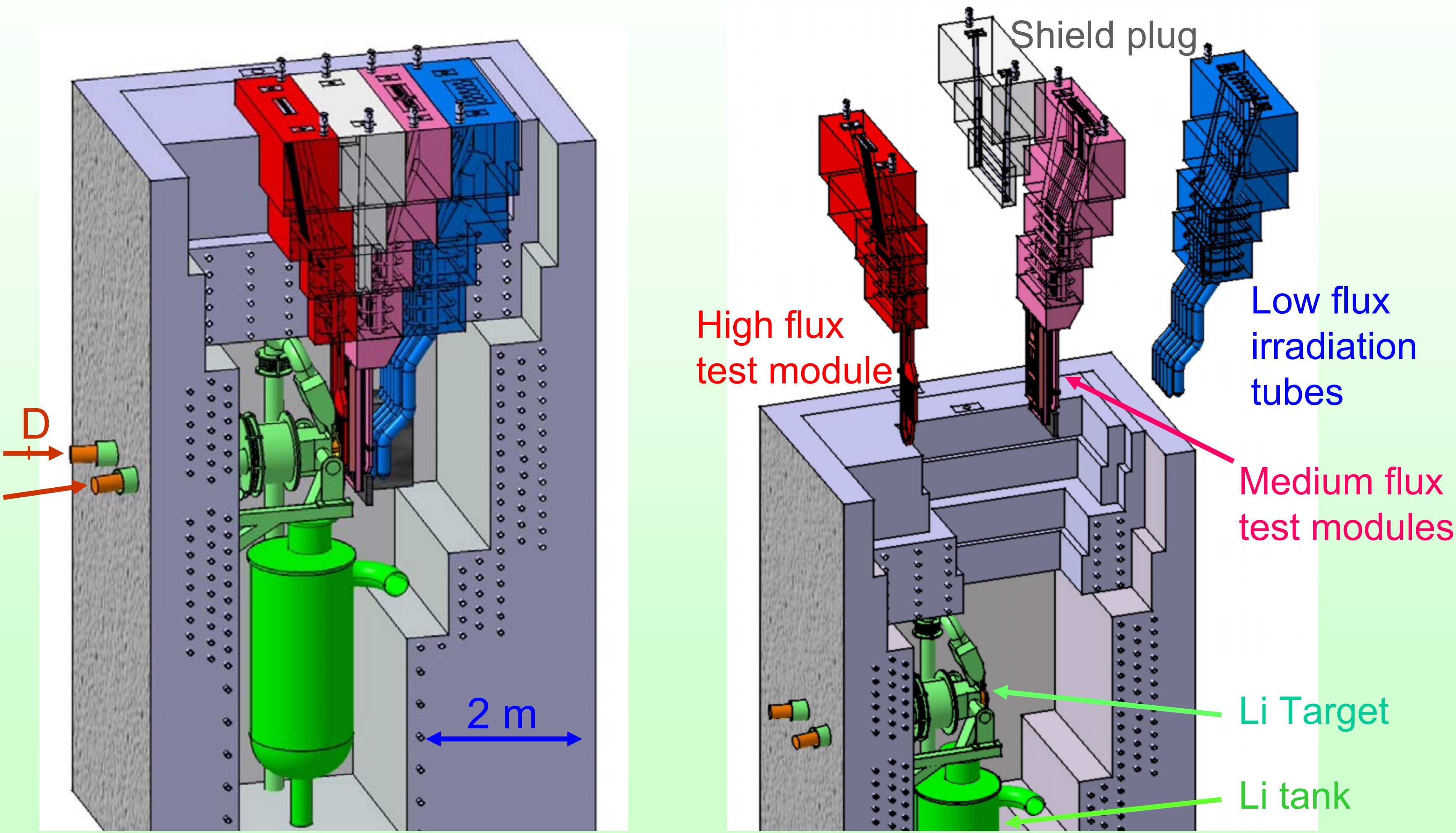
Obtain stable and high speed Li flow during 10 MW D^+ beam loading

IFMIF Target System   Li loop experiments

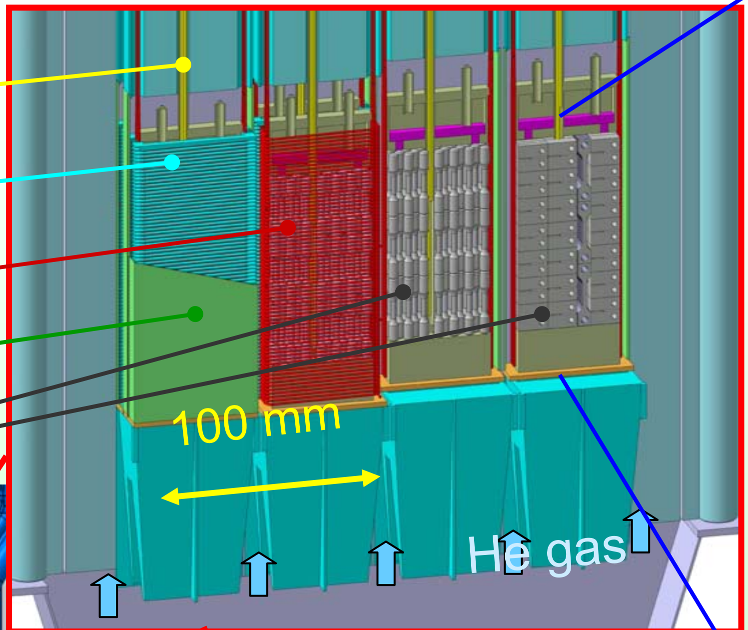


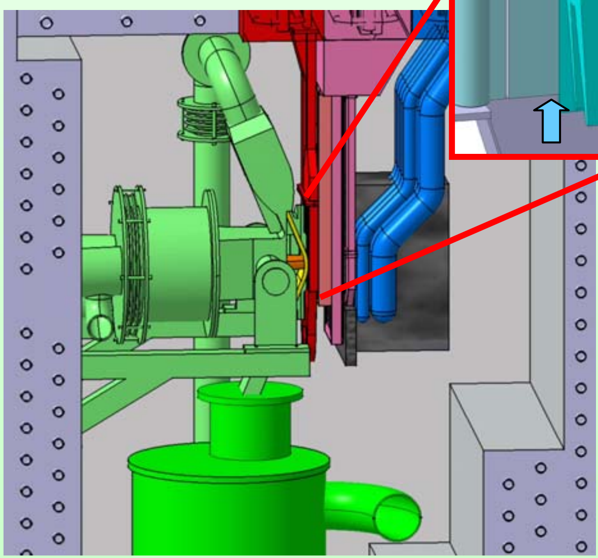
2.2 m/s   **13 m/s**

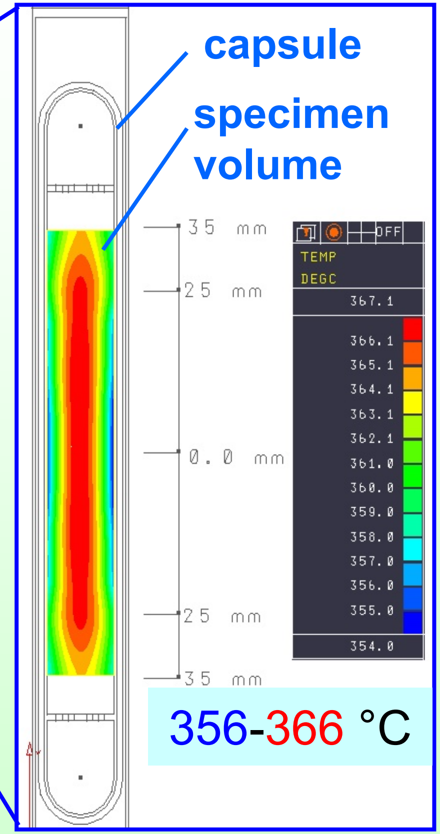
IFMIF Test Cell Design



IFMIF High flux test module (20-50 dpa/fpy)



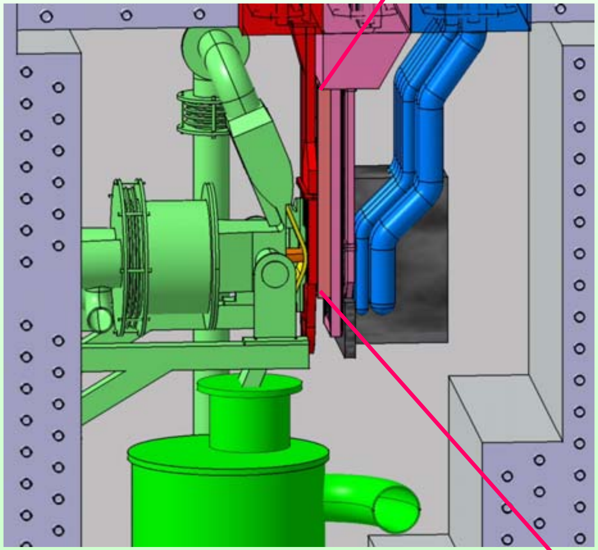


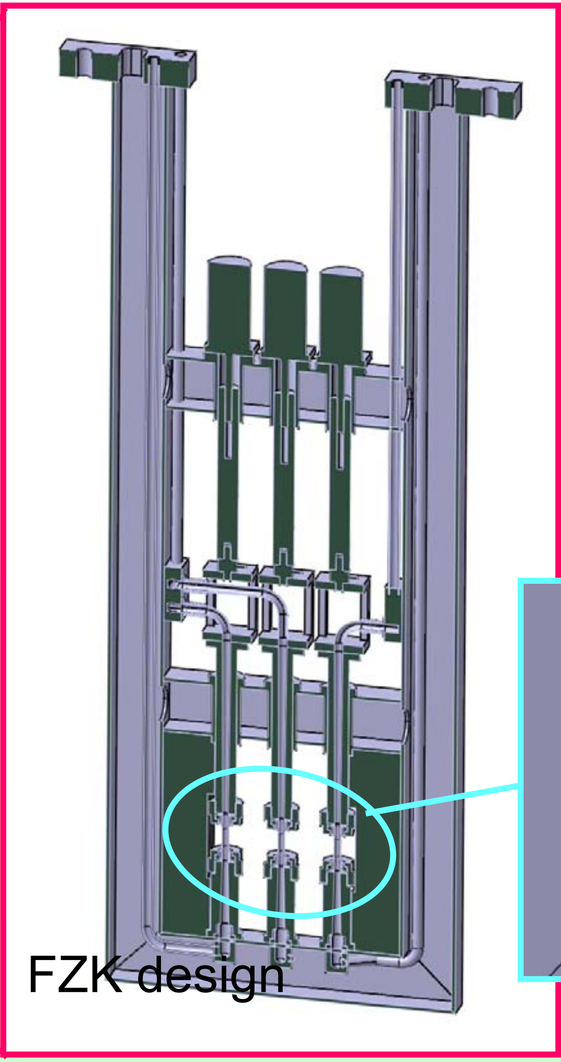


The IFMIF design meets all user requirements

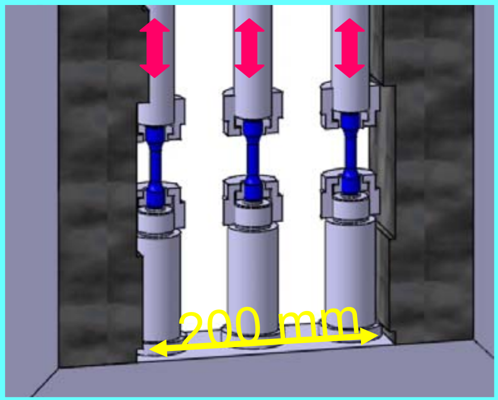
IFMIF Test Cell — Medium flux test modules

Medium flux volume
In situ creep-fatigue test module

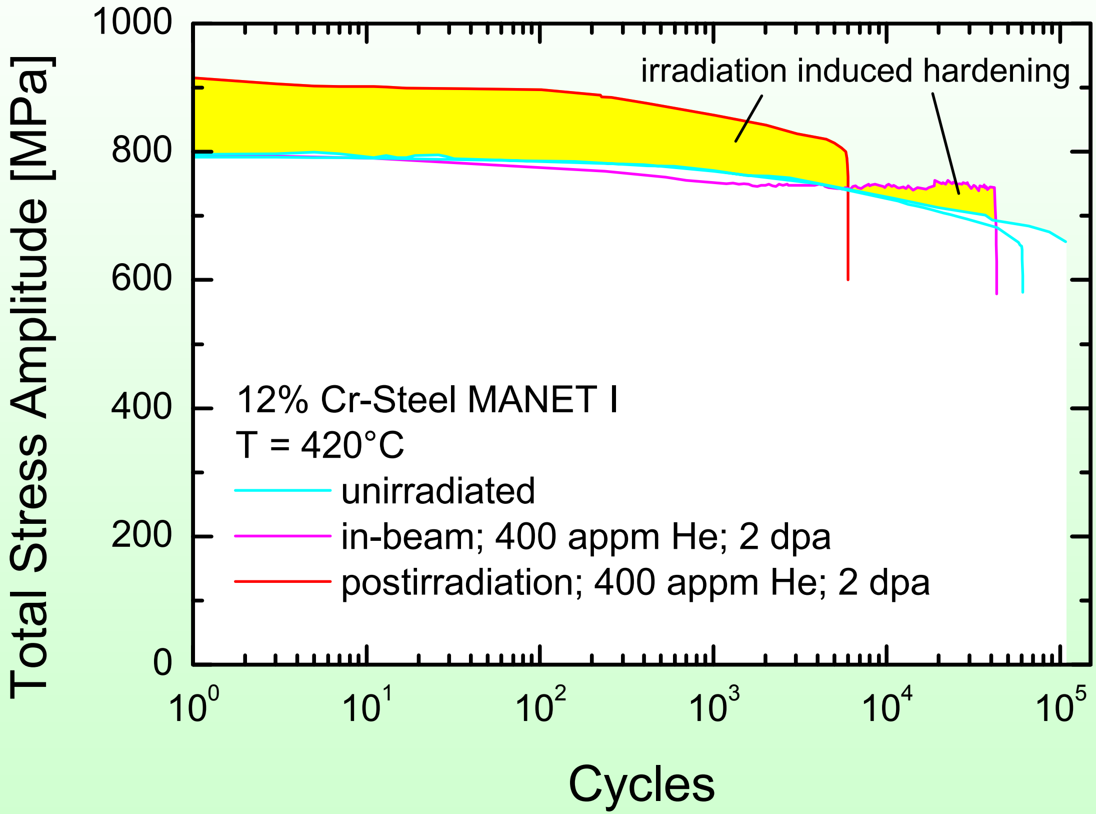


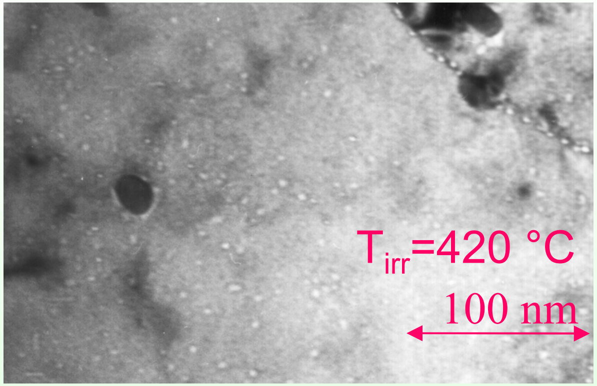


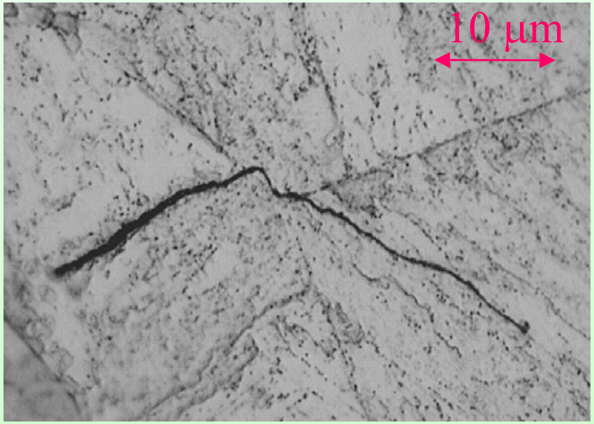
3 independent creep-fatigue tests within beam footprint



Why are In-situ experiments really needed?
Fatigue under Irradiation





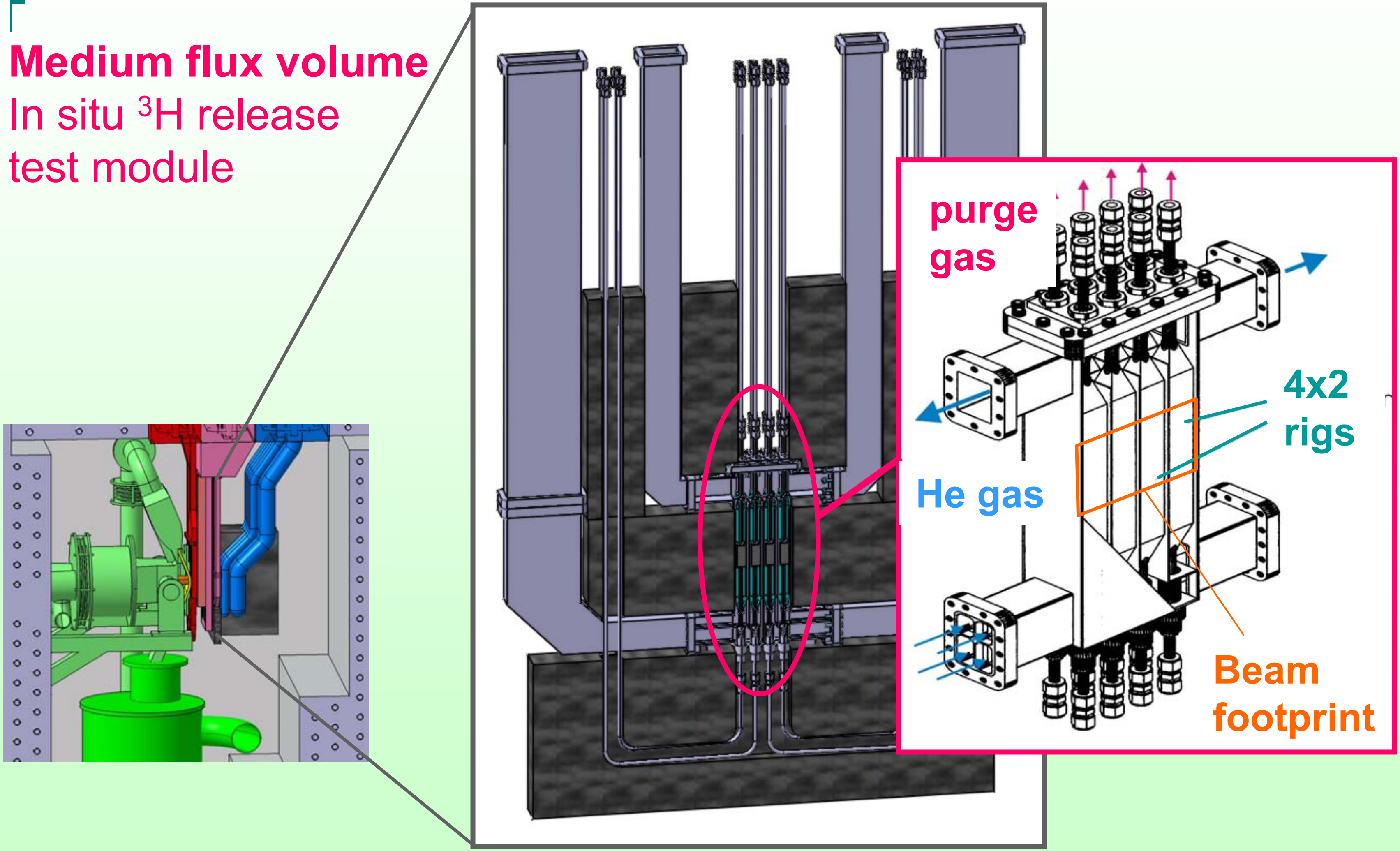


- In-situ irradiation less damaging than traditional postirradiation tests
- He-bubbles & $\Delta\sigma_{irr}$ don't change the principle mechanism of crack initiation

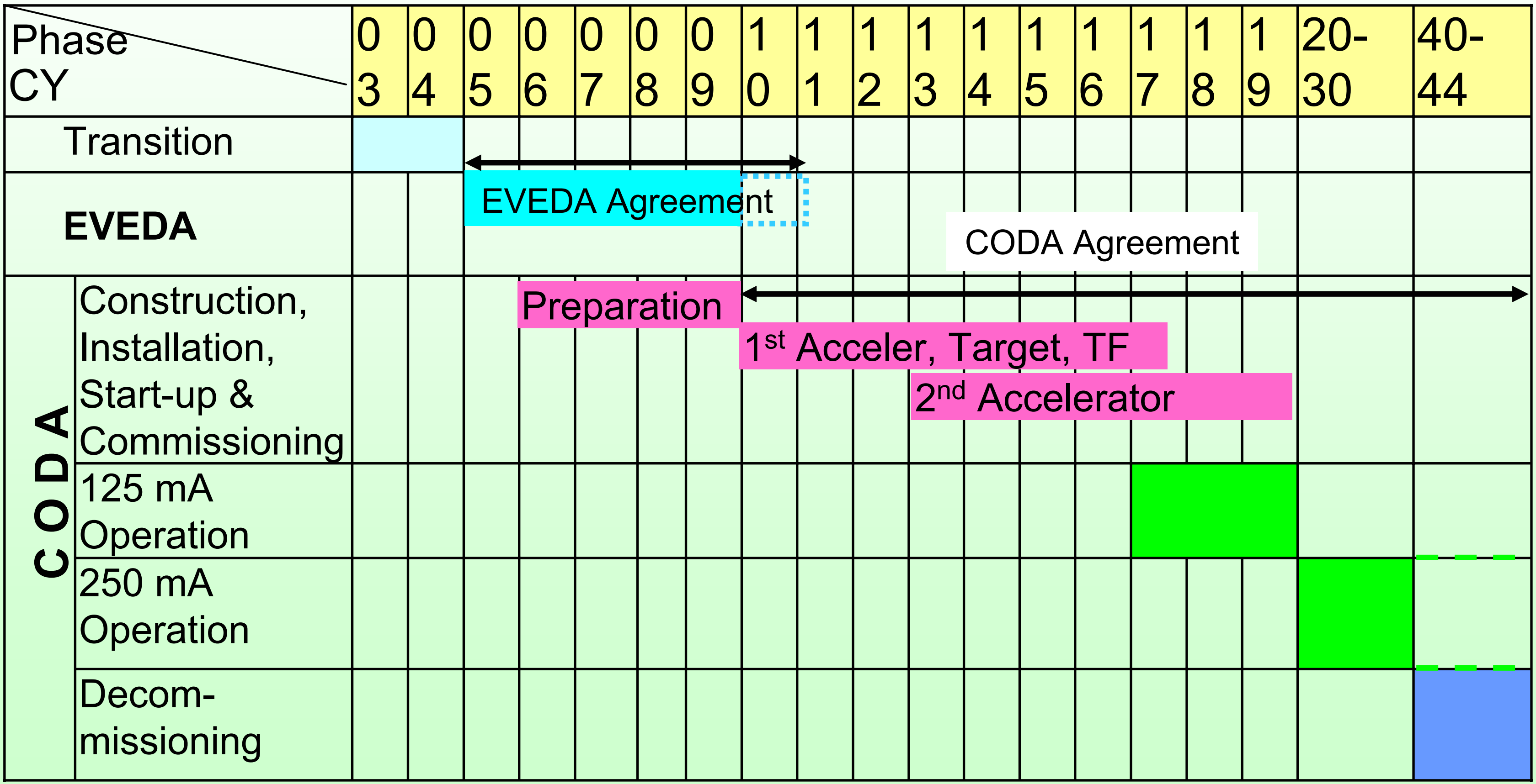
IFMIF Test Cell Test Module Achievements

Medium flux volume

In situ ^3H release test module



IFMIF Main Schedule



IFMIF Summary of Total Project Cost

Unit: MICF

Phase	EVEDA	CODA						
		Con-struction	Installation & Checkout	Startup & Commis-sioning	Operation			Decom-mission-ing
					125 mA Operation	250 mA Operation		
						Annual	Total	
Cost	**88.4**	**539.2**	**116.7**	**115.4**	**141.2**	**78.5**	**1,570**	**50.0**
Schedule	**2005-2009**	**2010-2019**	**2011-2019**	**2012-2019**	**2016-2018**	**20 years 2019-2039**		**2040-2044**

Detailed Cost Estimates exist for
- **E**ngineering **V**alidation & **E**ngineering **D**esign **A**ctivity (**EVEDA**), and
- **C**onstruction, **O**peration and **D**ecommissioning **A**ctivities (**CODA**)

Summary

1. **The availability of a dedicated neutron source is indispensable for the qualification of materials for design and safe operation of fusion power reactors.**

2. **Why the accelerator based D-Li neutron source *IFMIF*?**

   Suitability: ***IFMIF*** **meets all relevant user requirements**

   Feasibility:
   - ***IFMIF*** **is well developed, and ready to proceed to component testing and engineering design**
   - **The developed reference design is conceived for long-term operation with an annual availability of at least 70%**

3. **Future plans: *IFMIF* Implementing Agreement preparations are being made to start EVEDA January 2005**
   In this case, *IFMIF* operation could start during 2016, and full performance (250 mA beam current) could be reached ~3 years later

The *IFMIF* design is at a level of maturity that would readily justify a positive decision towards an engineering phase “EVEDA”.