Neutronic Requirements for Fusion Relevant Reactor Material Irradiations

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Nuclear Physics & Astrophysics at CERN
NuPAC Meeting, 10-12 October 2005

Outline

- Background
- IFMIF Intense Neutron Source
- Neutronics Tools & Data
- Design Analyses
- Conclusions

High Flux Components in Fusion Reactors

- Materials have to withstand high irradiation, heat and mechanical loads during reactor operation.
- Elemental transmutation and activation under irradiation
  - deteriorate the material properties
  - lead to a radiation hazard potential

⇒ Need for testing and qualifying materials under fusion-specific irradiation conditions

Need for an Intense Neutron Source (INS)

- Dedicated to material test irradiations at fusion-specific conditions (Demo/Power reactor)
  - high neutron flux ($\approx 10^{15}$ cm^{-2} s^{-1}) and material damage accumulation ($\approx$ 150 dpa in few years)
  - suitable simulation of fusion neutron spectrum
  - sufficiently large irradiation volume

- Available irradiation facilities fulfil needs only partially
  - fission reactors: large irradiation volumes & appropriate neutron flux but neutron spectrum not adequate
  - accelerators (p, a, ..): appropriate dpa & gas production rates, favourable conditions for in-situ test but small volumes
  - (d,t) neutron generators: proper fusion neutron spectrum but source intensity limited to $\approx 10^{13}$ s^{-1} (max. flux $\approx 10^{10}$ cm^{-2} s^{-1})

Need for an Intense Neutron Source (INS)

- Limited testing in ITER
  - fluence accumulation low ($\approx$ 0.3 MWa/m^2 $\Rightarrow$ $\approx$ 3 dpa in iron)
  - operation mode very different from a Demo/power reactor
    - pulsed operation (pulse length $\approx$ 1000 s)
    - low temperature operation

- No irradiation facility available with combined capabilities for
  - simulation of fusion neutron spectrum
  - high fluence irradiation for accelerated material testing
  - sufficiently large irradiation test volumes

User Requirements for an INS

IEA Workshop, San Diego, 1989

- Neutron flux/volume relation
  - Equivalent to $2MW/m^2$ in 10 L volume [$1MW/m^2 \cong 4.4 \cdot 10^{13}$ n/cm^2s; E = 14 MeV; $3x10^{-7}$ dpa/s for Fe]
- Neutron spectrum
  - Should meet FW neutron spectrum as near as possible

    Quantitative criteria: - Primary recoil spectrum, PKA

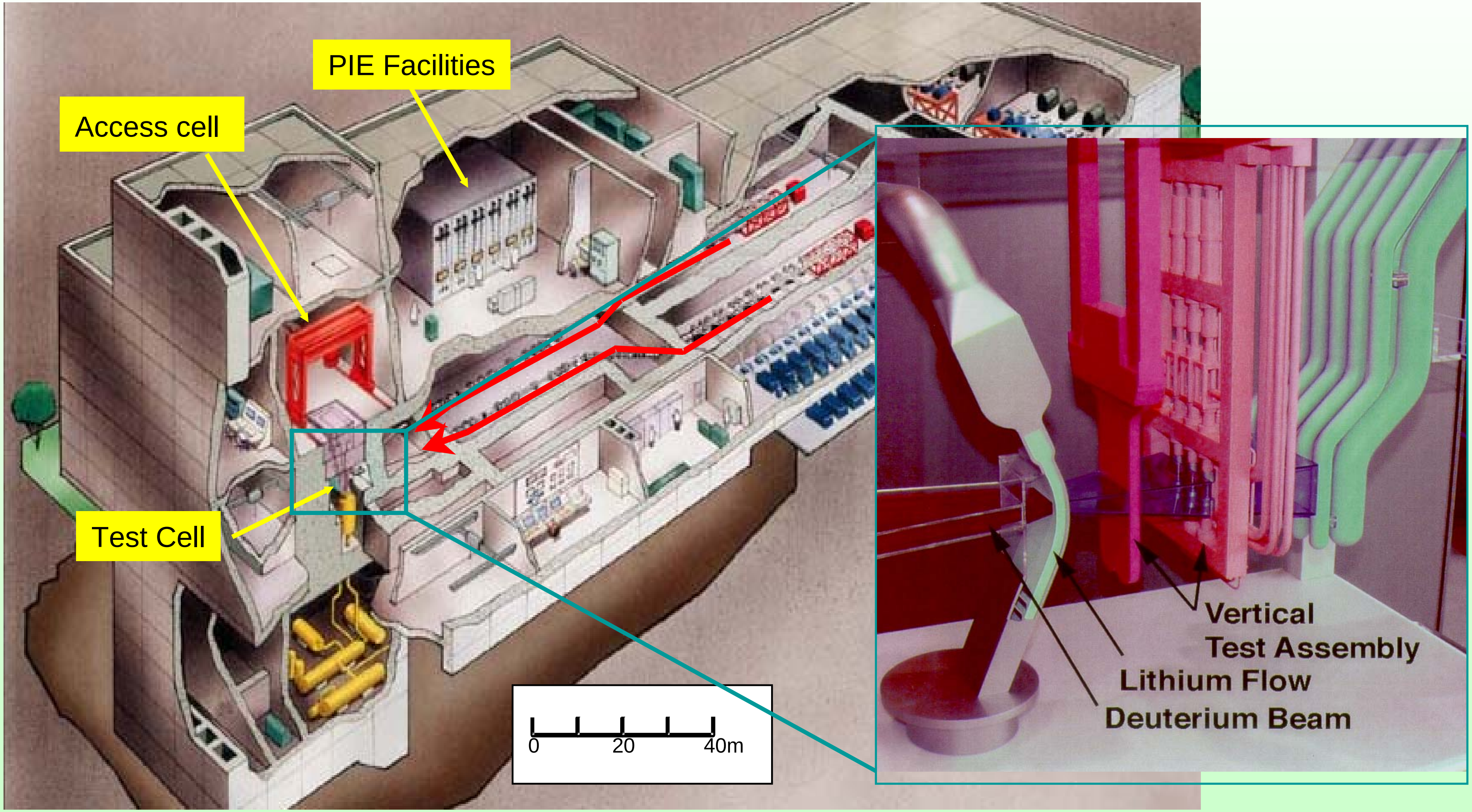
    - Important transmutation reactions: He, H.
- Neutron fluence accumulation:
  - Demo-relevant fluences of 150 dpa_{NRT} in few years
- Neutron flux gradient: $\leq$ 10 %/cm
- Machine availability: 70 %
- Time structure: Quasi continuous operation
- Good accessibility of irradiation volume for experimentation and instrumentation

1 $MWa/m^2 \approx 10$ dpa_{NRT} for Fe

INS → IFMIF

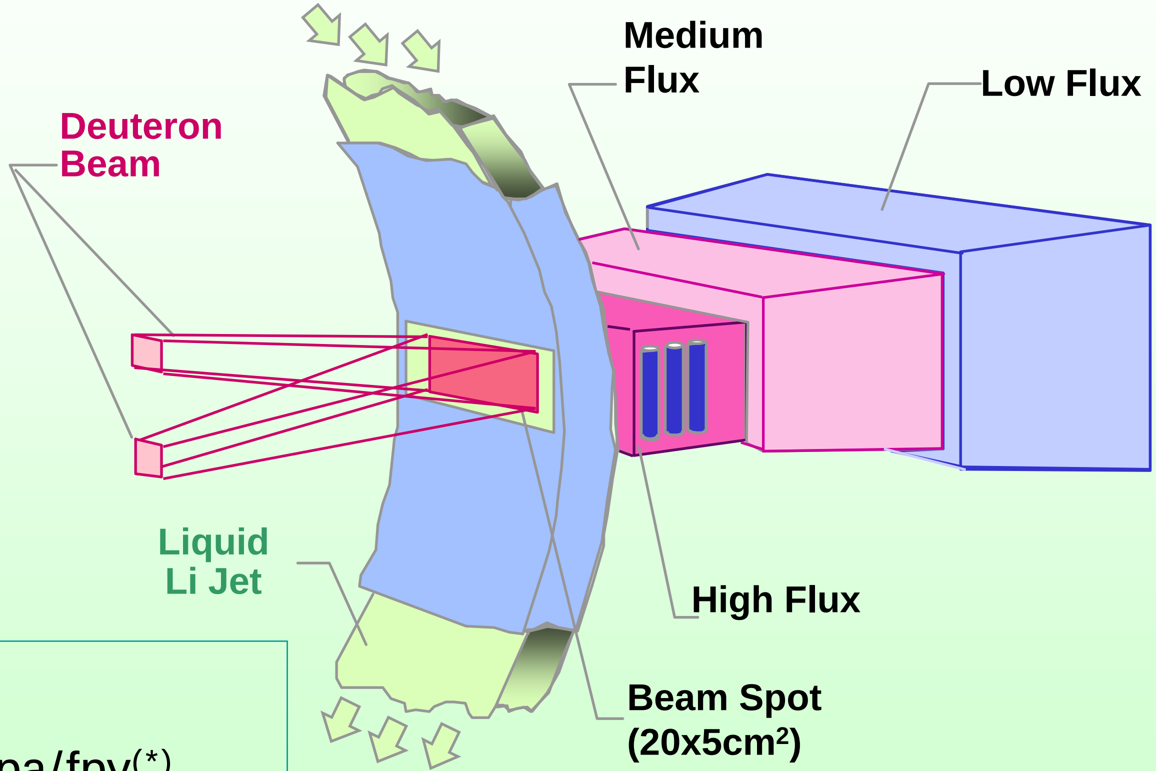
- IEA workshops 1989- 1994
  - San Diego 1989: review of INS concepts, evaluation of their suitability and feasibility, definition of key requirements, recommendation for viable INS options
  - **Karlsruhe 1992: consensus on accelerator based D-Li source**
  - Karlsruhe 1994: project planning
- Implementing agreement of IEA on IFMIF project:
  - Conceptual Design Activity (CDA), 1995 - 1996
  - Conceptual Design Evaluation (CDE), 1997 - 1999
  - Key Element Technology Phase (KEP), 2000 - 2002
  - Transition Phase, 2003-2005 (?)
- Engineering Validation, Engineering Design Activity (EVEDA), 2006 – (?)

IFMIF Intense Neutron Source



IFMIF Design Concept

- Deuteron beams:
  - 2 x 125 mA
  - E_d = 40 MeV
- Neutron production:
  - $\approx 1.1 \times 10^{17}\ s^{-1}$



- Test volumes:
  - high flux: 0.5 L > 20 dpa/fpy(*)
  - medium flux: 6 L > 1 dpa/fpy,
  - low flux: 7.5 L 0.1-1 dpa/fpy

(*) fpy = full power year

IFMIF Neutronics

Key role in establishing IFMIF as neutron source for fusion material testing:

⇒ Prove IFMIF's suitability as neutron source for fusion-specific simulation irradiations

⇒ Provide reliable data for the technical layout of facility

- Computational tools and data required
  - D-Li neutron source term simulation
  - Neutron transport (E_n> 20 MeV)
  - Activation and transmutation (E_n> 20 MeV)

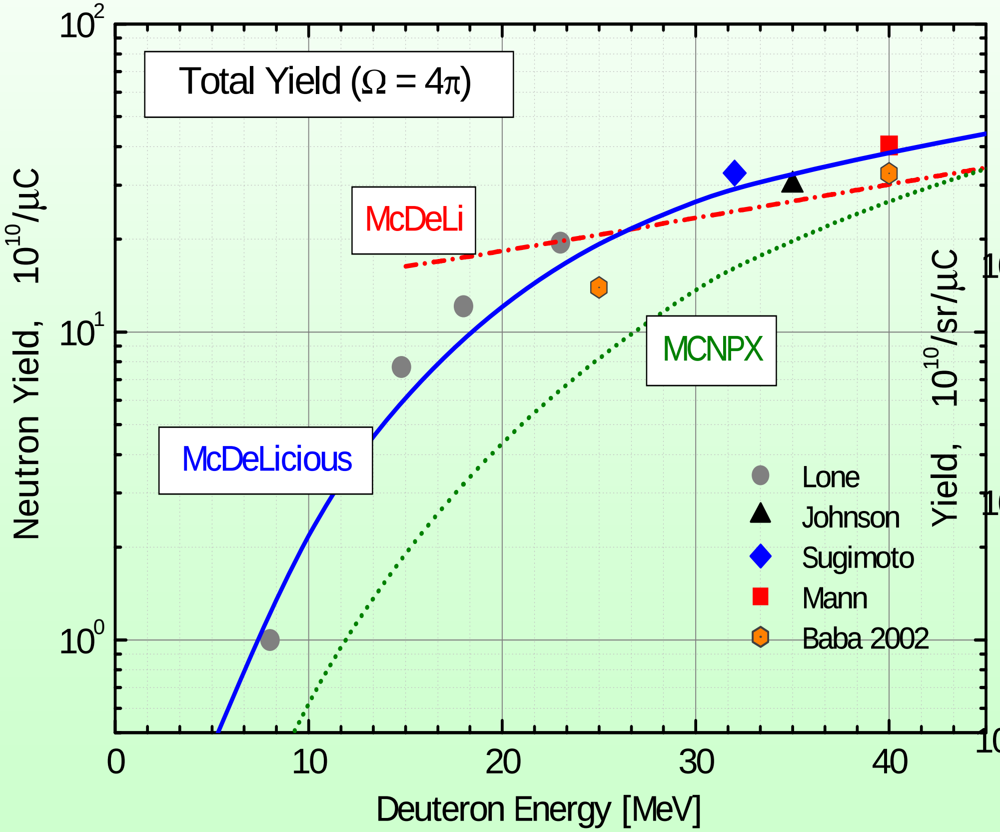
⇒ *Need for experimental data, need for validation*

IFMIF Neutronics Tools & Data

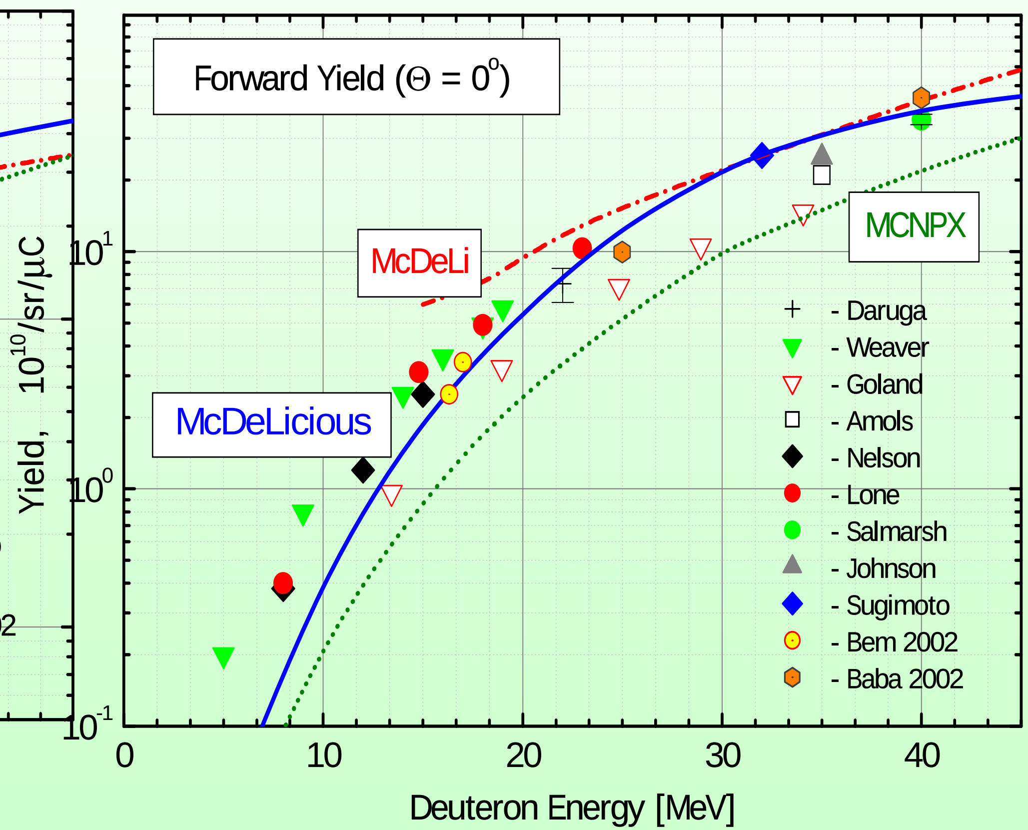
- D(Li,xn) source modelling
  - MCNP ⇒ M^{c}DeLi (semi-empirical reaction models)
  - M^{c}DeLi ⇒ M^{c}DeLicious (evaluated d + ^{6,7}Li data)
- Neutron transport
  - MCNP/ M^{c}DeLi/ M^{c}DeLicious
  - Neutron cross-section data (ENDF6) E$\geq$ 20 MeV
    - INPE Obninsk/FZK co-operation
    - HE data files (LANL, NRG, JENDL-HE)
- Activation & transmutation
  - Intermediate Energy Activation File IEAF-2001
  - ALARA activation code (P. Wilson, Univ. of Wisconsin)

Thick Li-target neutron yields

Total (4π) Neutron Yields



Forward (0°) Neutron Yields



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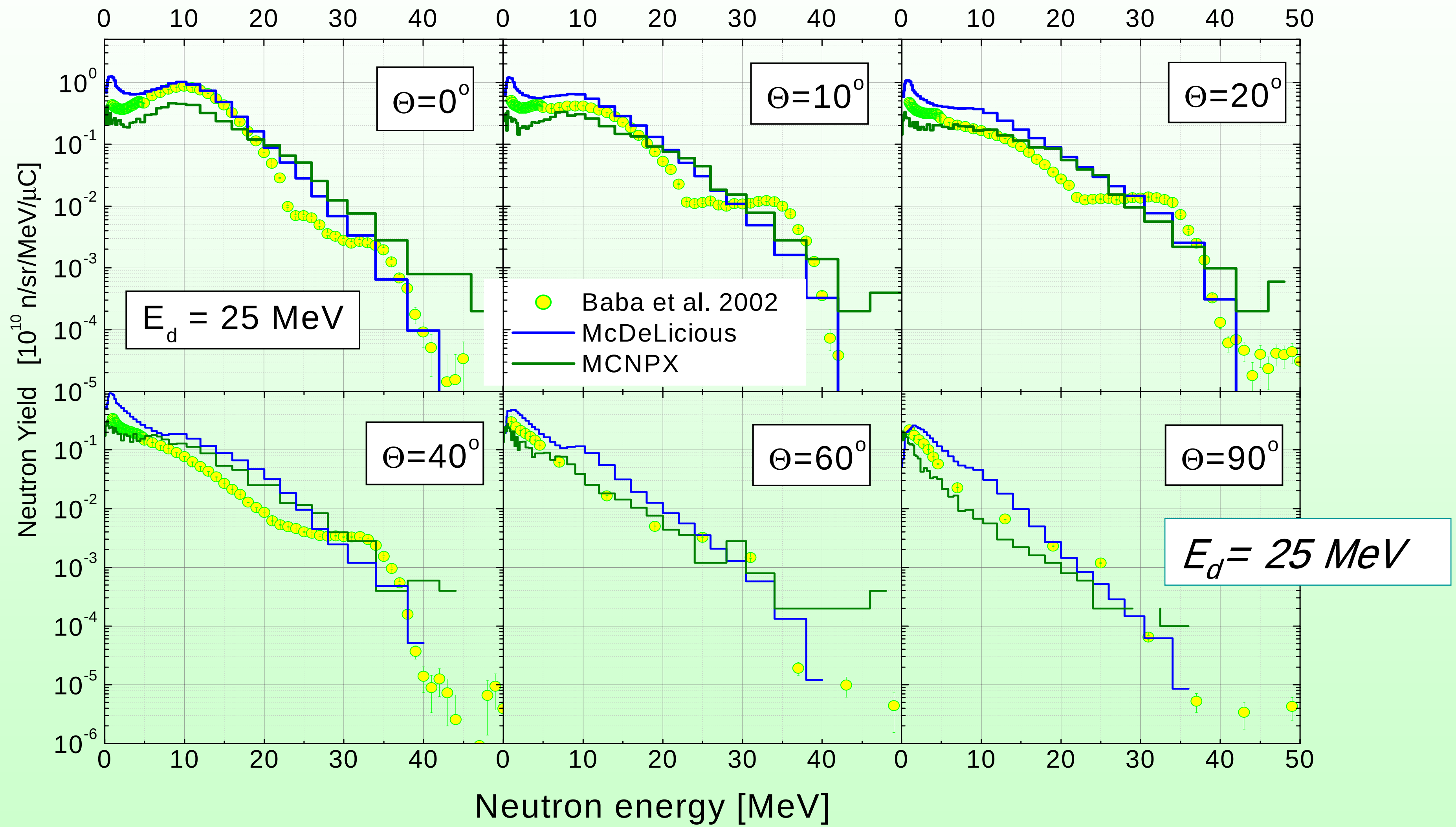
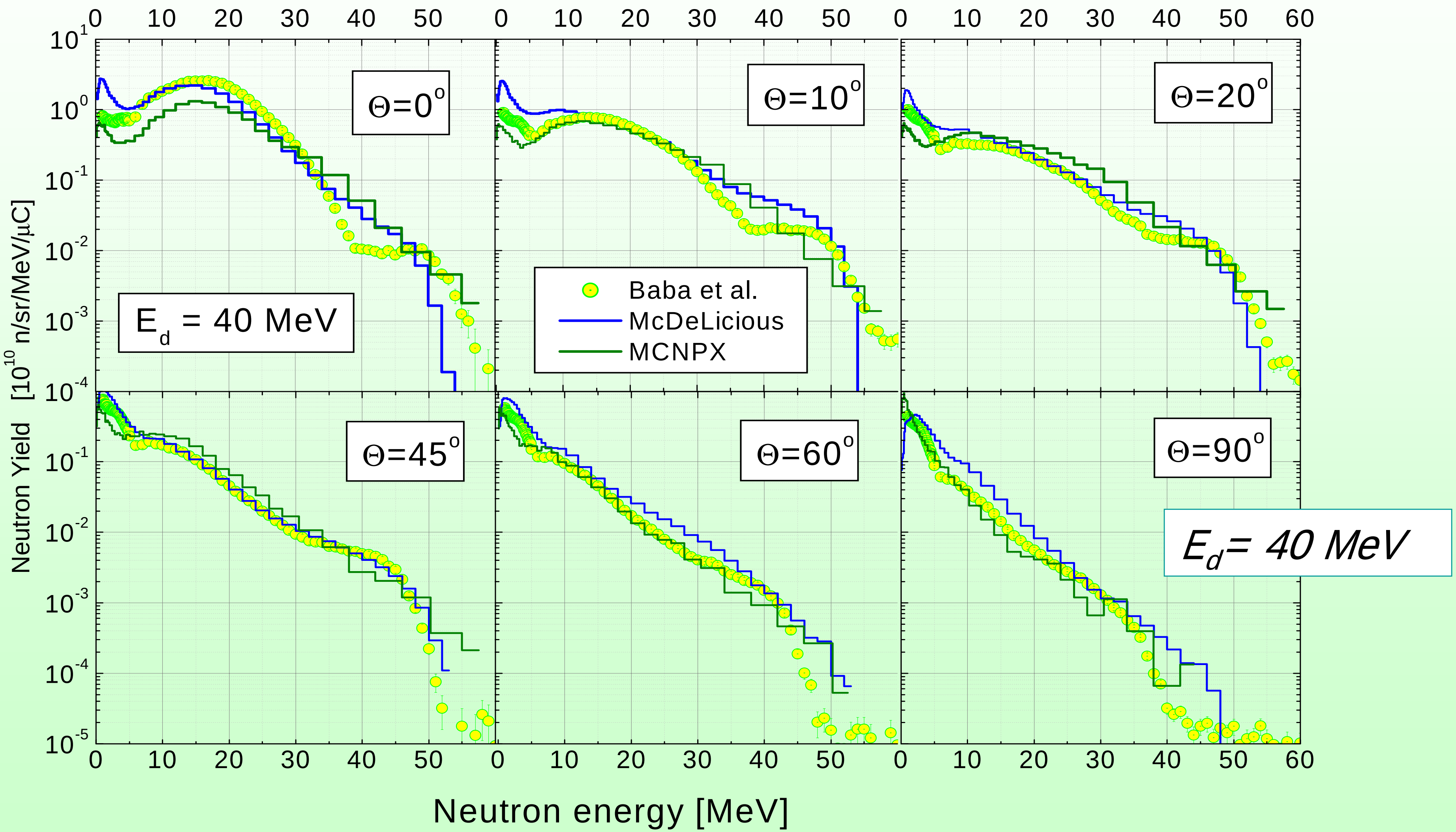
D-Li thick target neutron yield spectra

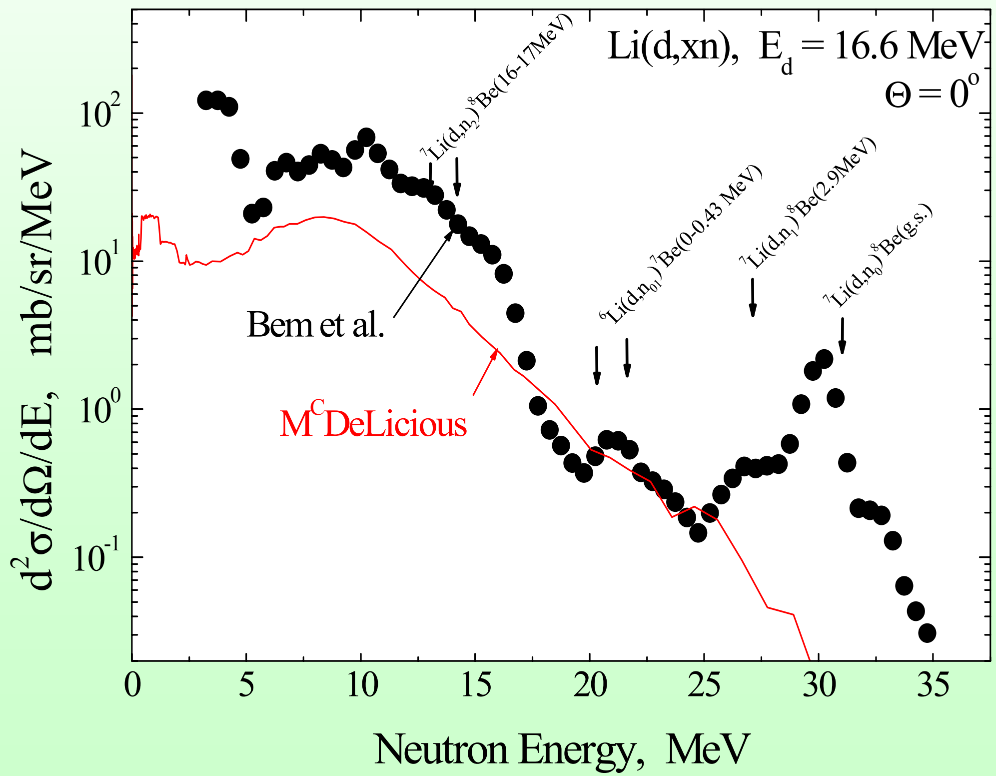


D-Li thick target neutron yield spectra

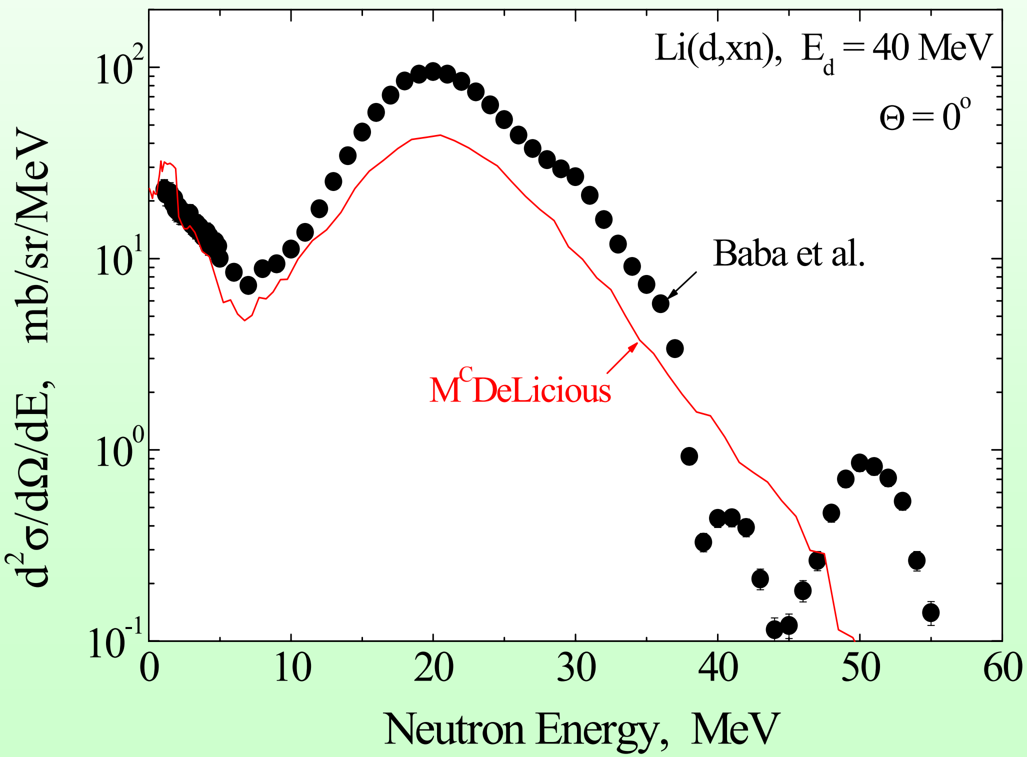


Li(d,xn) Double Differential Cross Sections

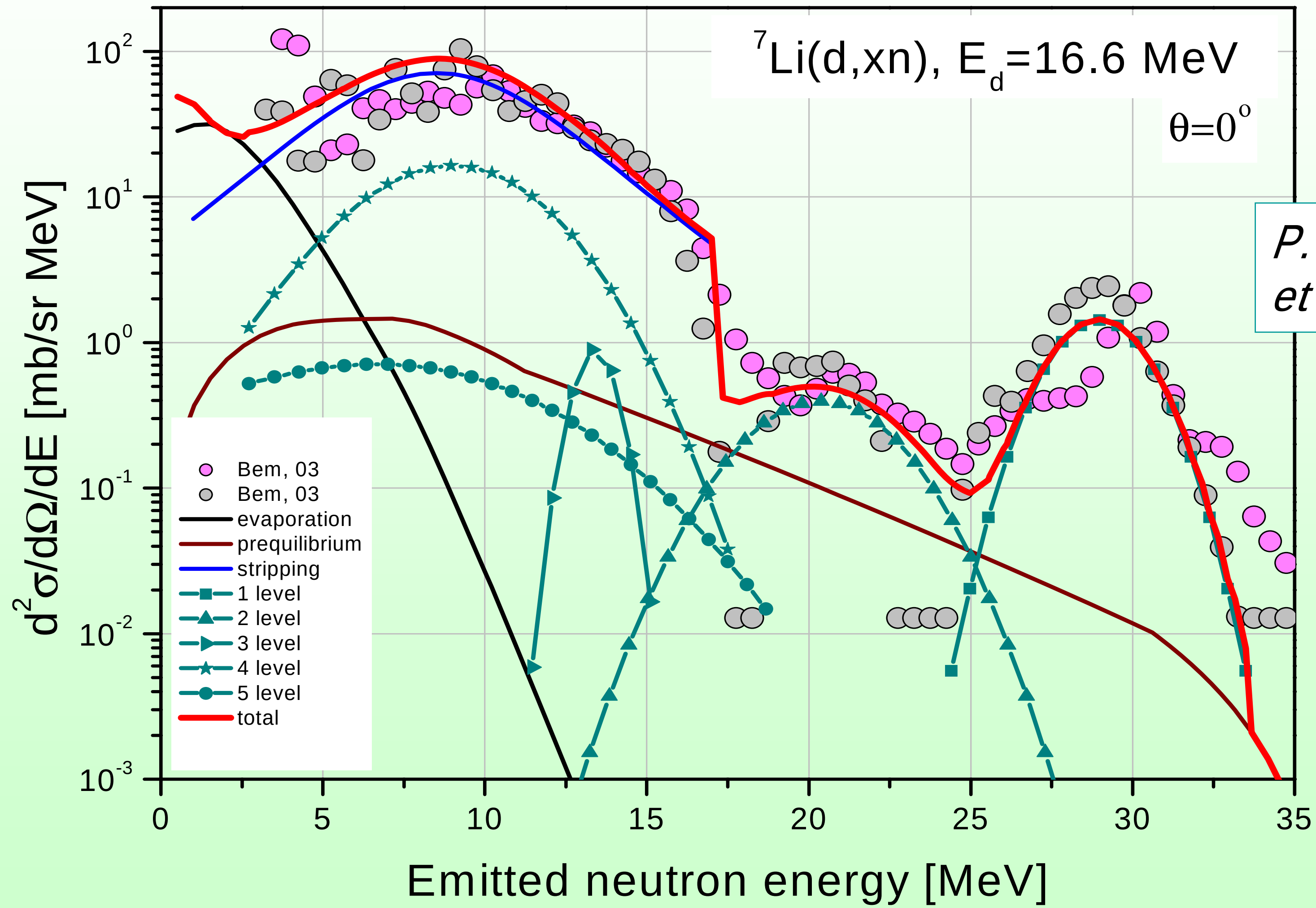
E_d = 17 MeV, Bem et al.



E_d = 40 MeV, Baba et al.

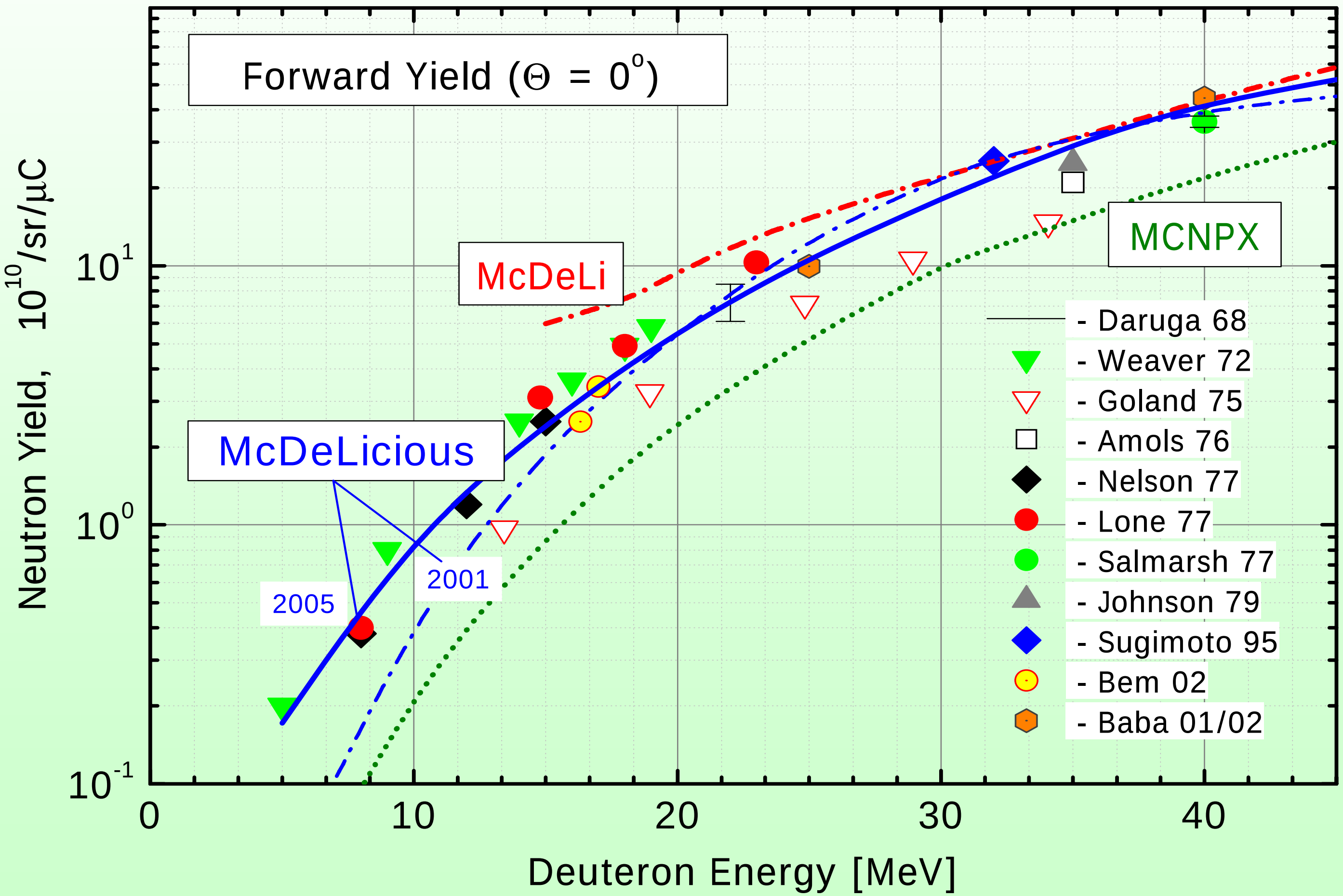


New d + Li Data Evaluation



P. Pereslavtsev et al, FZK 2005

Thick Li-target neutron yields using 2005 D-Li data evaluation (P. Pereslavstev et al.)



IFMIF Test Cell Calculations

- IFMIF' s primary mission is to generate a materials irradiation database for the design, construction, licensing and operation of DEMO

- Major neutronics task in this context:
  - Provide the data required for the design and optimisation of the irradiation test modules and the lay-out of the test cell

  ⇒ Neutron/photon transport calculations (McDeLicious) for flux distributions and nuclear responses such as nuclear heating, radiation damage accumulation and gas production.

Materials for IFMIF

- Highest priority: structural materials of the reduced activation ferritic-martensitic (RAFM) type (Eurofer, F82H).
  - ⇒ A variety of Eurofer specimens will be irradiated in the high flux test module (HFTM) up to the target fluence of 150 dpa.
- Other materials of (possibly) lower priority:
  - SiC, V/V-alloy, divertor materials (e. g. W)
  - Breeder materials, neutron multiplier
  - Ceramic insulators and others

Chemical Composition of RAFM Steel Eurofer

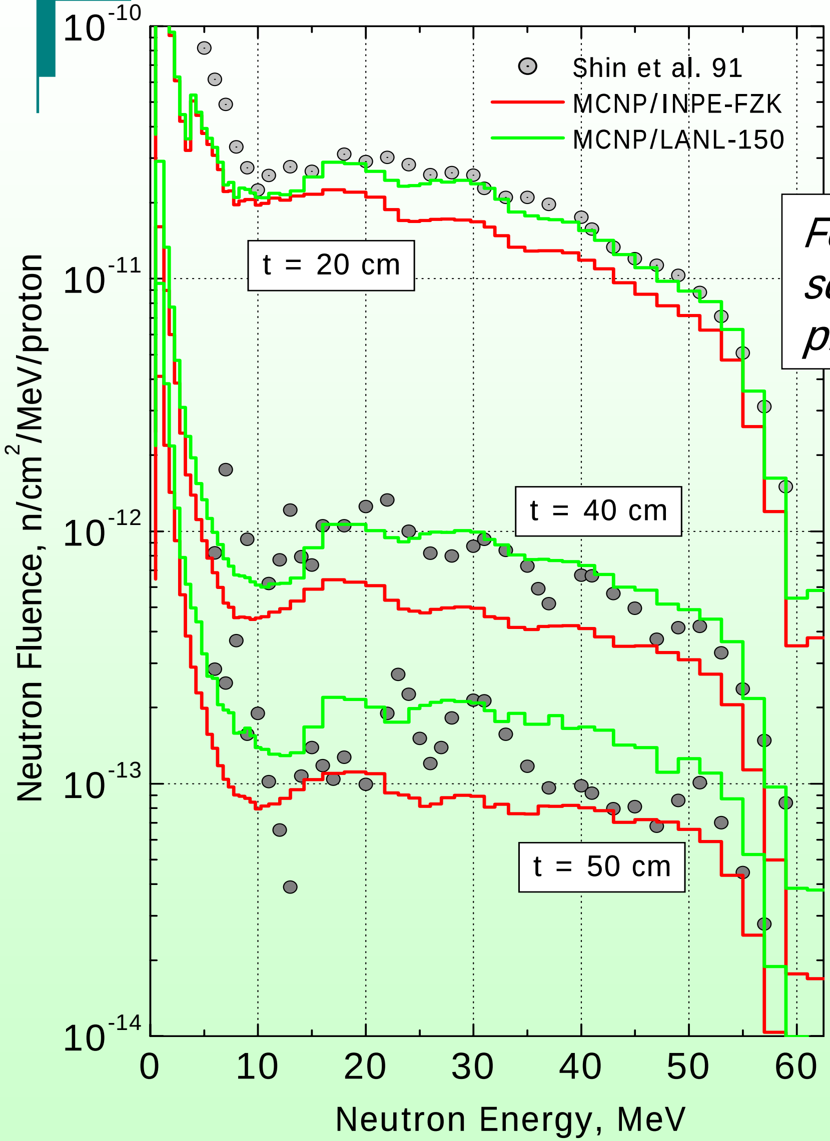
Element	Specification [w%]	Element	Specification [w%]
C	0.090-0120	W	1.0-1.2
Mn	0.20-0.60	Ti	<0.01
P	<0.005	Cu	<0.005
S	<0.005	Nb	<0.001
Si	<0.05	Al	<0.01
Ni	<0.005	N	0.015-0.045
Cr	8.50-9.50	B	<0.001
Mo	<0.005	Co	<0.005
V	0.15-0.25	O	<0.01
Ta	0.05-0.09	Fe	balance

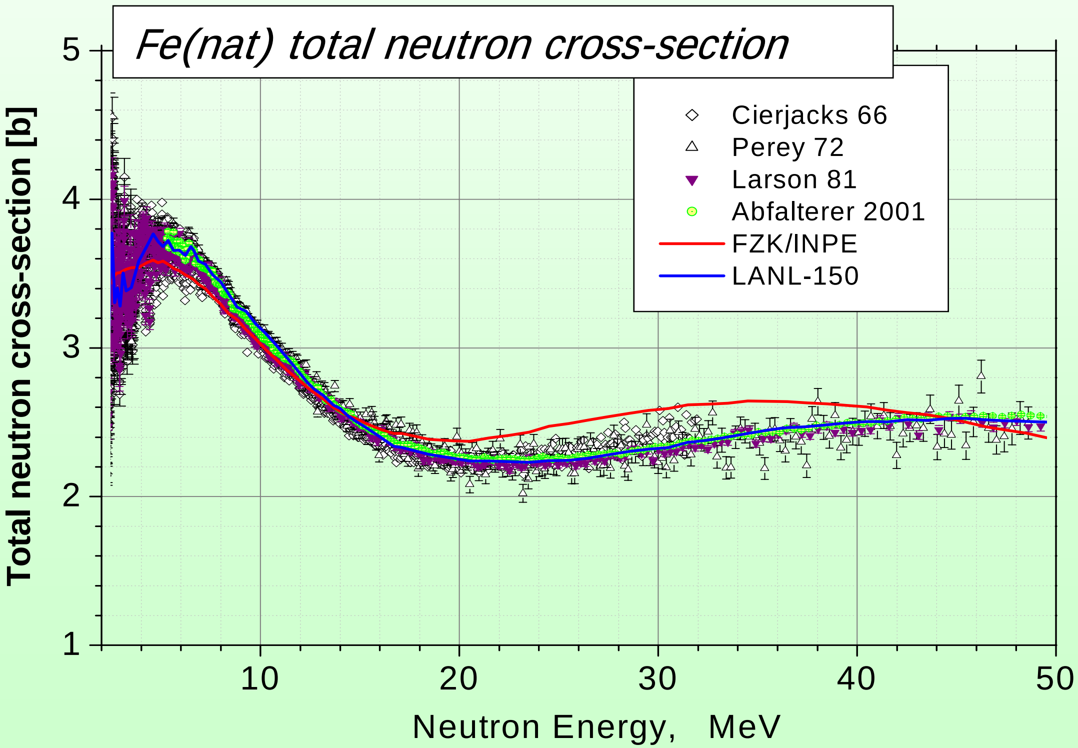
Neutron Cross-Sections E ≥ 20 MeV
- General purpose data ENDF evaluations -

- IFMIF project (INPE Obninsk/FZK)
  - ^{1}H, ^{56}Fe, ^{23}Na, ^{39}K, ^{28}Si, ^{12}C, ^{52}Cr, ^{51}V (50 MeV)
  - ^{6,7}Li, ^{9}Be (150 MeV)
- LANL 150 MeV data files (ENDF/B-VI.6)
  - ^{1,2}H, ^{12}C, ^{16}O, ^{14}N, ^{27}Al, ^{28,29,30}Si, ^{31}P, ^{40}Ca, ^{50,52,53,54}Cr, ^{54,56,57,58}Fe, ^{58,60,61,62,64}Ni, ^{63,65}Cu, ^{93}Nb, ^{182,183,184,186} W, $^{196,198, 199, 200, 201, 202, 204}$ Hg, $^{206, 20, 208}$ Pb, ^{209}Bi
- NRG evaluations
  – $^{40,42-44,46,48}$Ca- ^{45}Sc, $^{46-50}$Ti, $^{54,56-,58}$Fe, $^{70,72-74,76}$Ge, $^{204,206-208}$Pb, ^{209}Bi
- JENDL-HE data file
  – ^{1}H, ^{12,13}C, ^{14}N, ^{16}O, $^{24-26}$Mg, ^{27}Al, $^{28-30}$Si, ^{39,41}K, $^{40,42- 46,48}$Ca, $^{46-50}$Ti, ^{51}V, $^{50,52-54}$Cr, ^{55}Mn, $^{54,56-58}$Fe, ^{59}Co, $^{58,60-62,64}$Ni, ^{63,65}Cu, $^{64,66-68,70}$Zn, $^{90- 92,94,96}$Zr, ^{93}Nb, $^{180,182-184,186}$W, $^{196,198-202,204}$Hg

Iron Transmission Benchmark Experiment (Shin et al.)

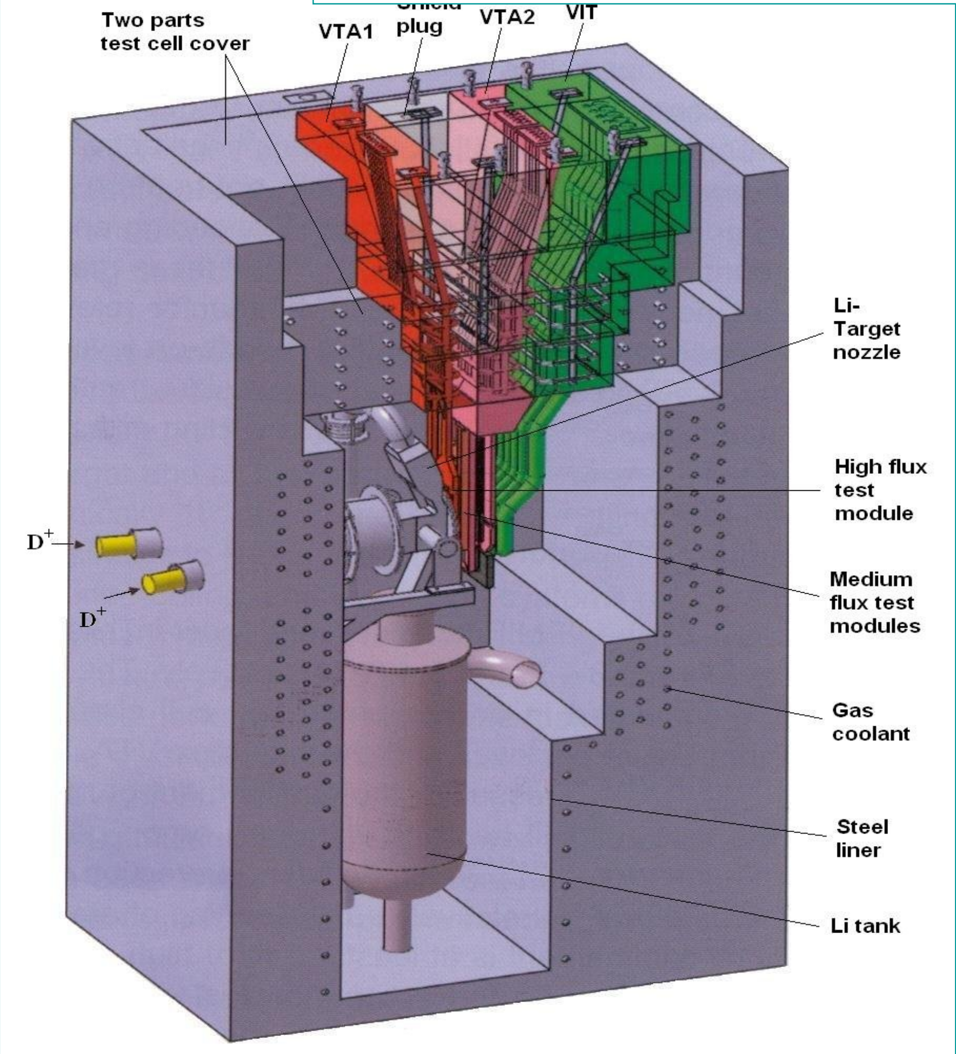
Fe slabs (20, 40 50 cm) irradiated with source neutrons produced by 65 MeV protons on Cu target



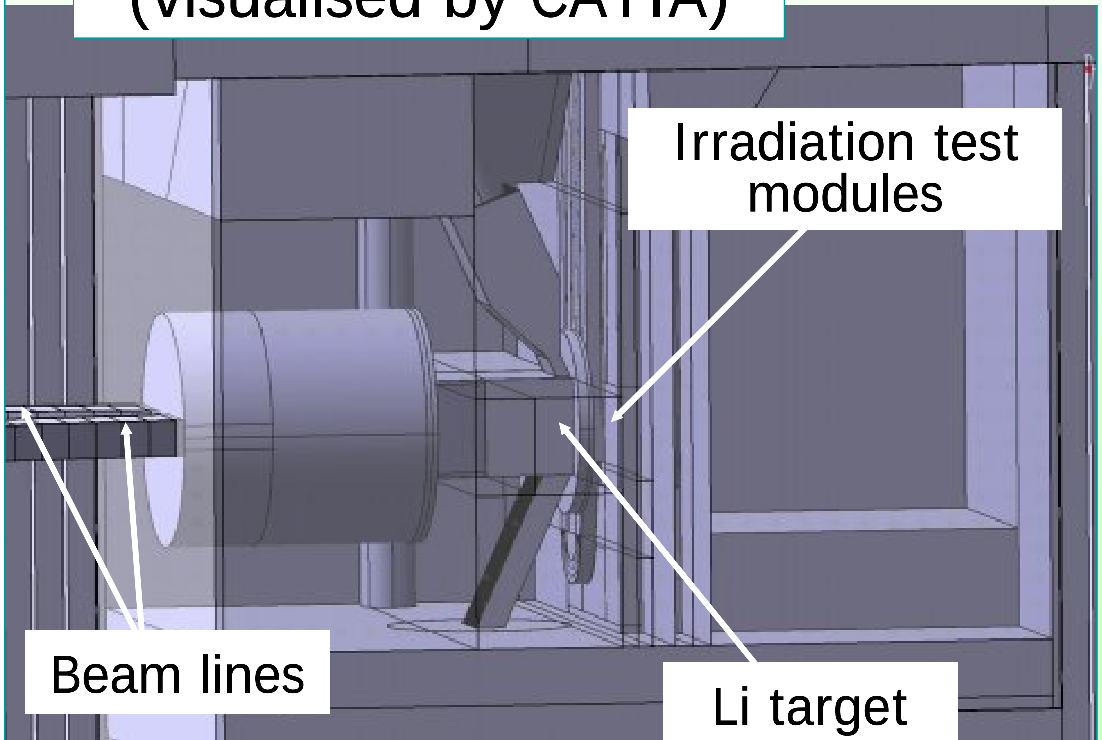


IFMIF Test Cell

CAD model (CATIA)



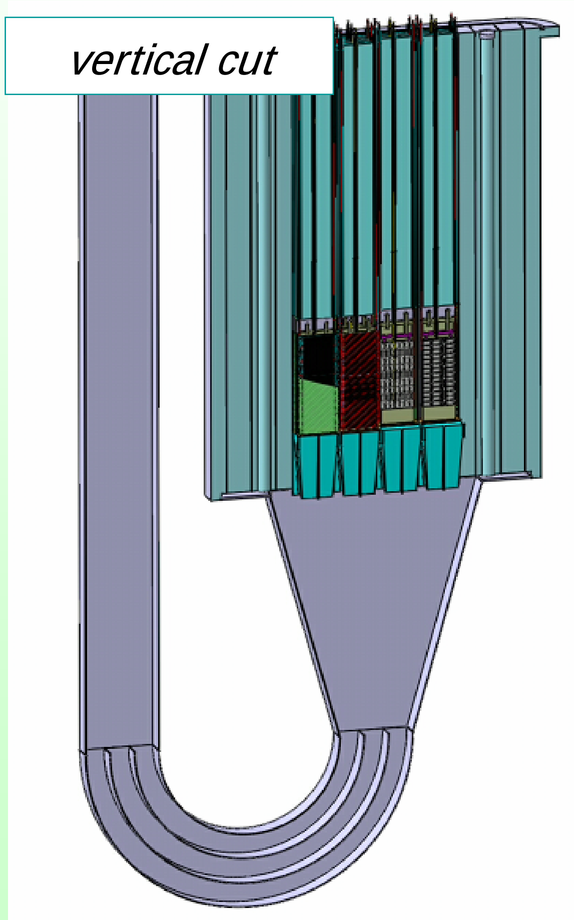
MCNP model (visualised by CATIA)



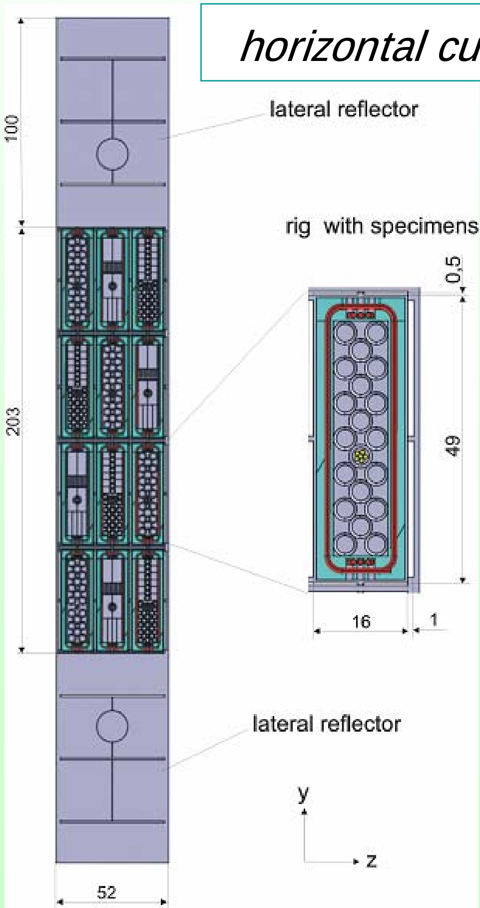
IFMIF High Flux Test Module (HFTM)

HFTM container

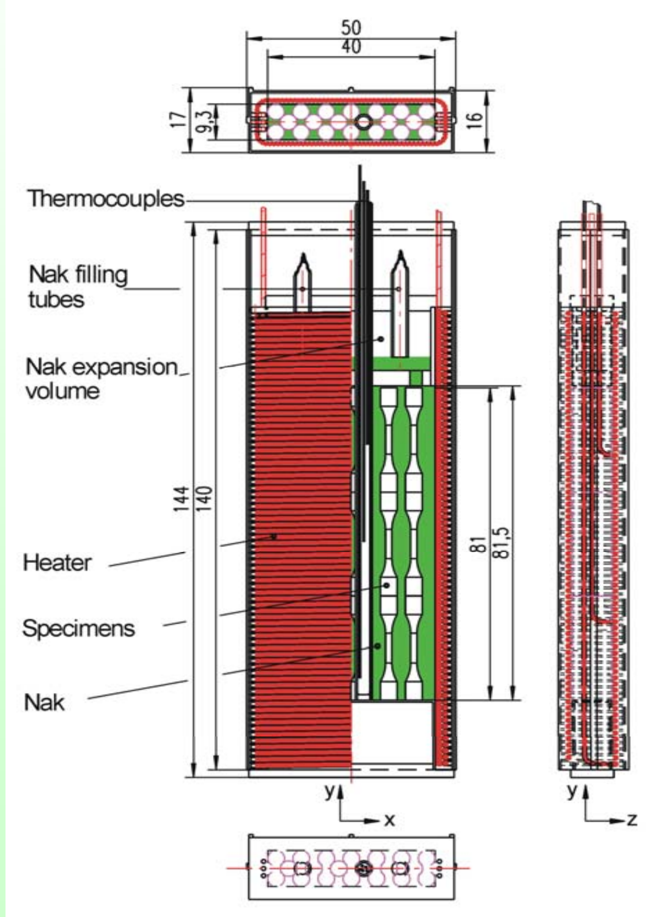
vertical cut



horizontal cut



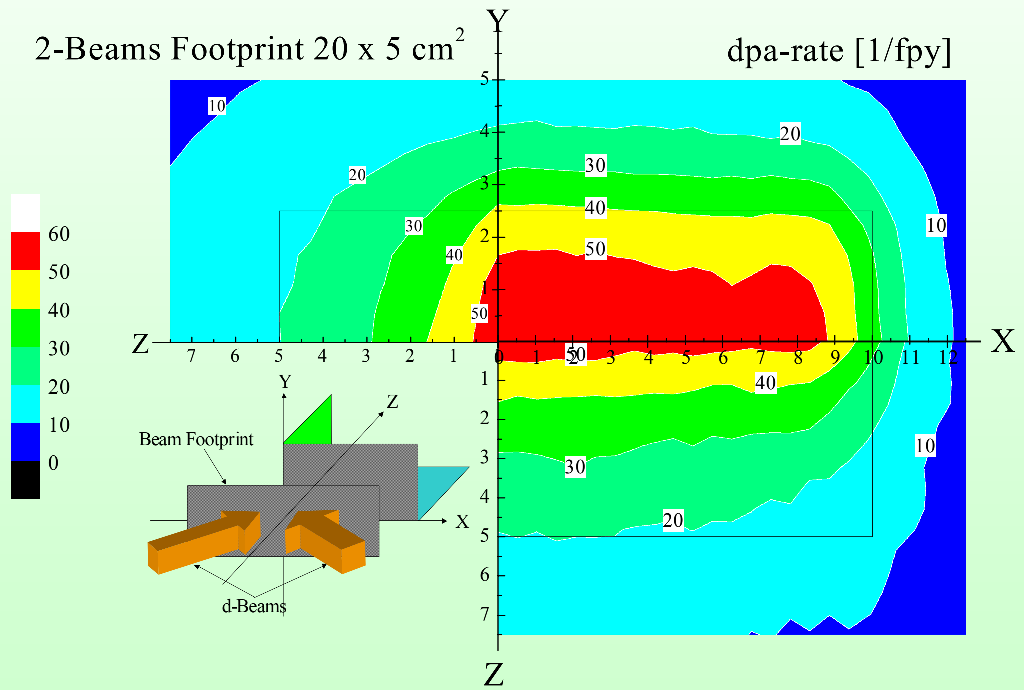
HFTM test rig

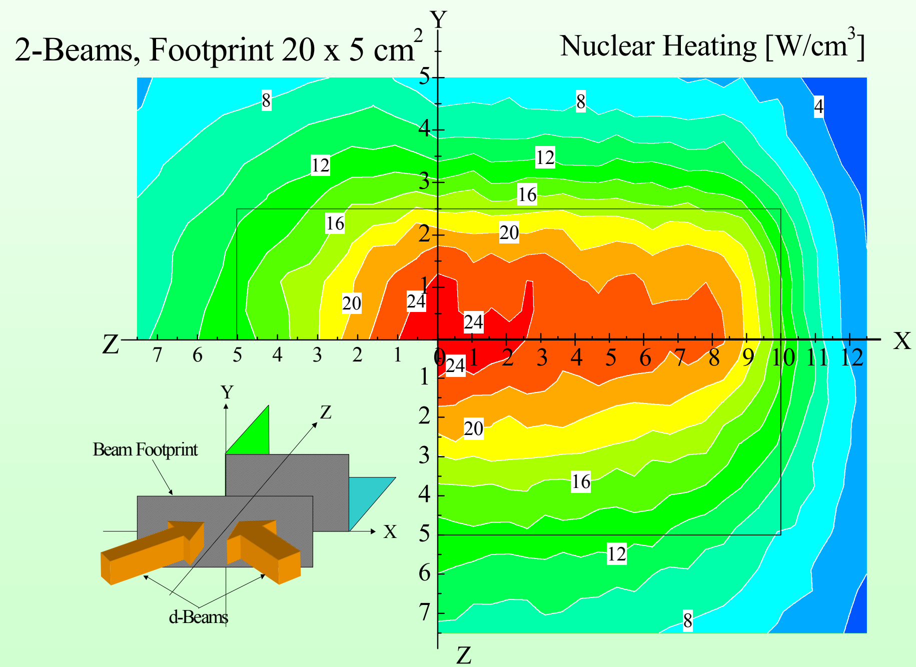


Distributions of nuclear responses in the HFTM

Displacement damage rate [dpa / fpy]

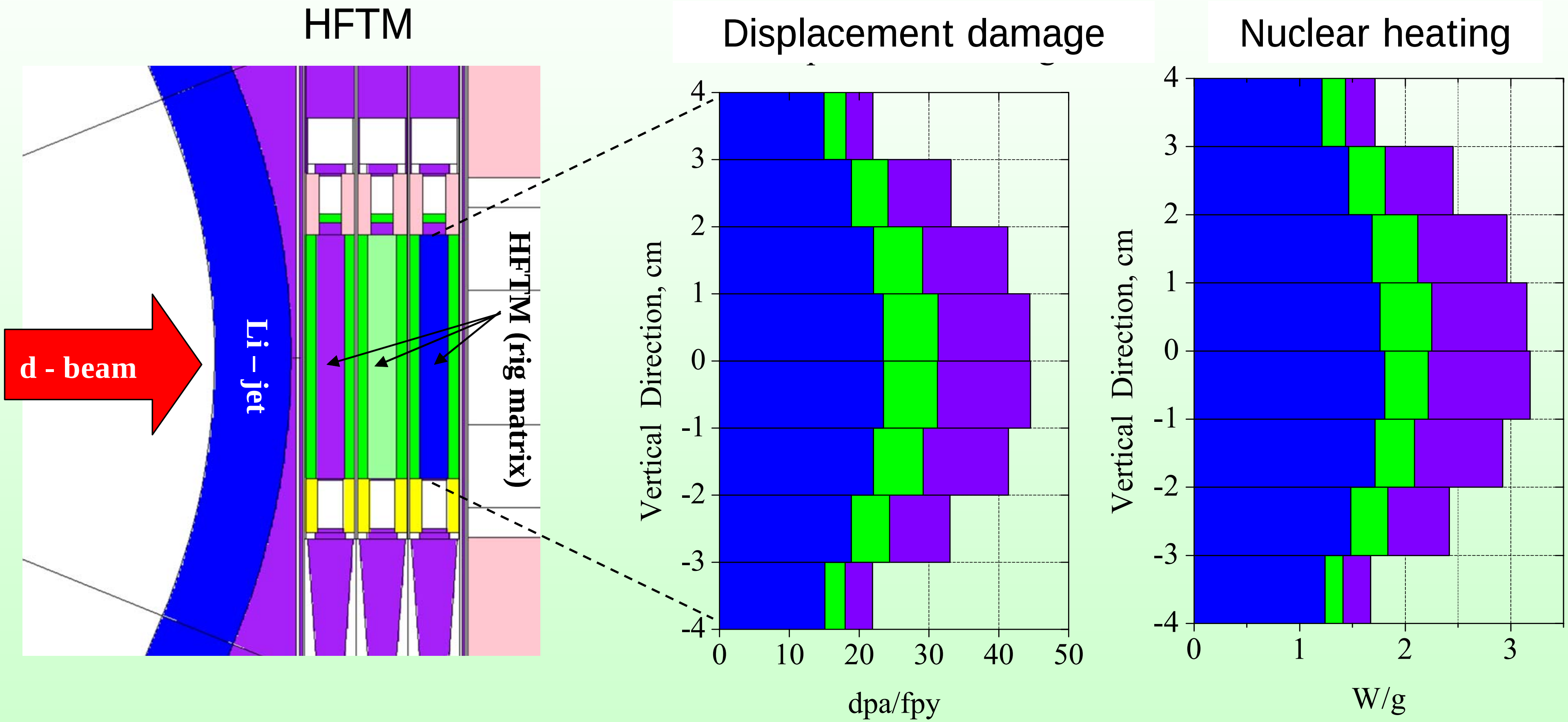
Nuclear heating [W/ cm³]





McDeLicious calculations with simplified geometry model

Distributions of nuclear responses in HFTM test rigs



McDeLicious calculations with detailed 3D geometry model

Irradiation Parameters

Irradiation parameter	IFMIF HFTM	ITER	DEMO
Total neutron flux [$cm^{-2}s^{-1}$]	10^{14} - 10^{15}	$4x10^{14}$	$7.1x10^{14}$
Neutron flux, E > 14 MeV [$cm^{-2}s^{-1}$]	$4x10^{13}$ - $2x10^{14}$	0	0
Hydrogen production [appm/FPY]	1000 – 2500	445	780
Helium production [appm/FPY]	250 – 600	114	198
Displacement production [DPA/FPY]	15 – 60	10	19
H/DPA ratio [appm/DPA]	35 – 50	44.5	41
He/DPA ratio [appm/DPA]	9.5 - 12.5	11.4	10.4
Wall load [MW/m^2]	3 – 8	1.0	2.2

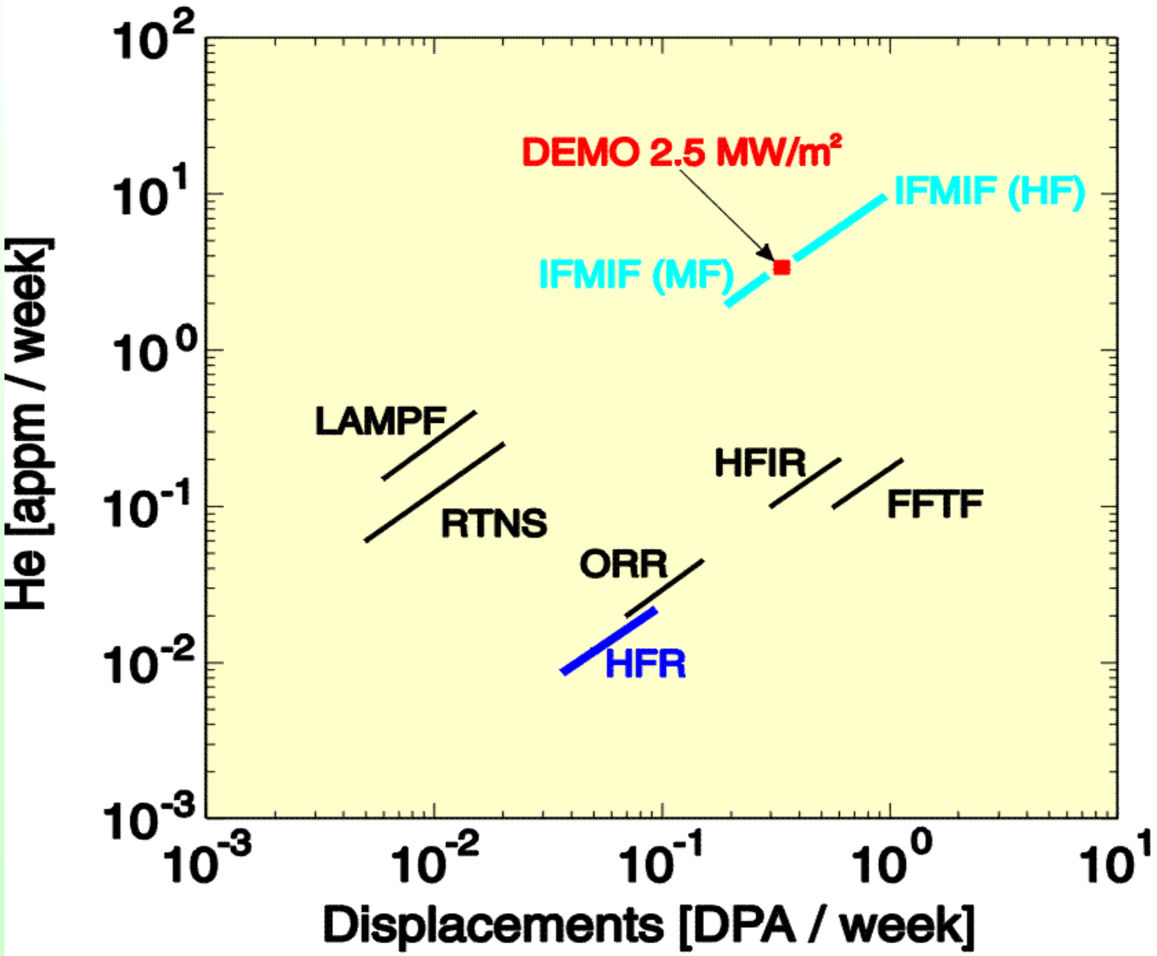
NB. Dpa and gas production data refer to iron.

Damage and gas production

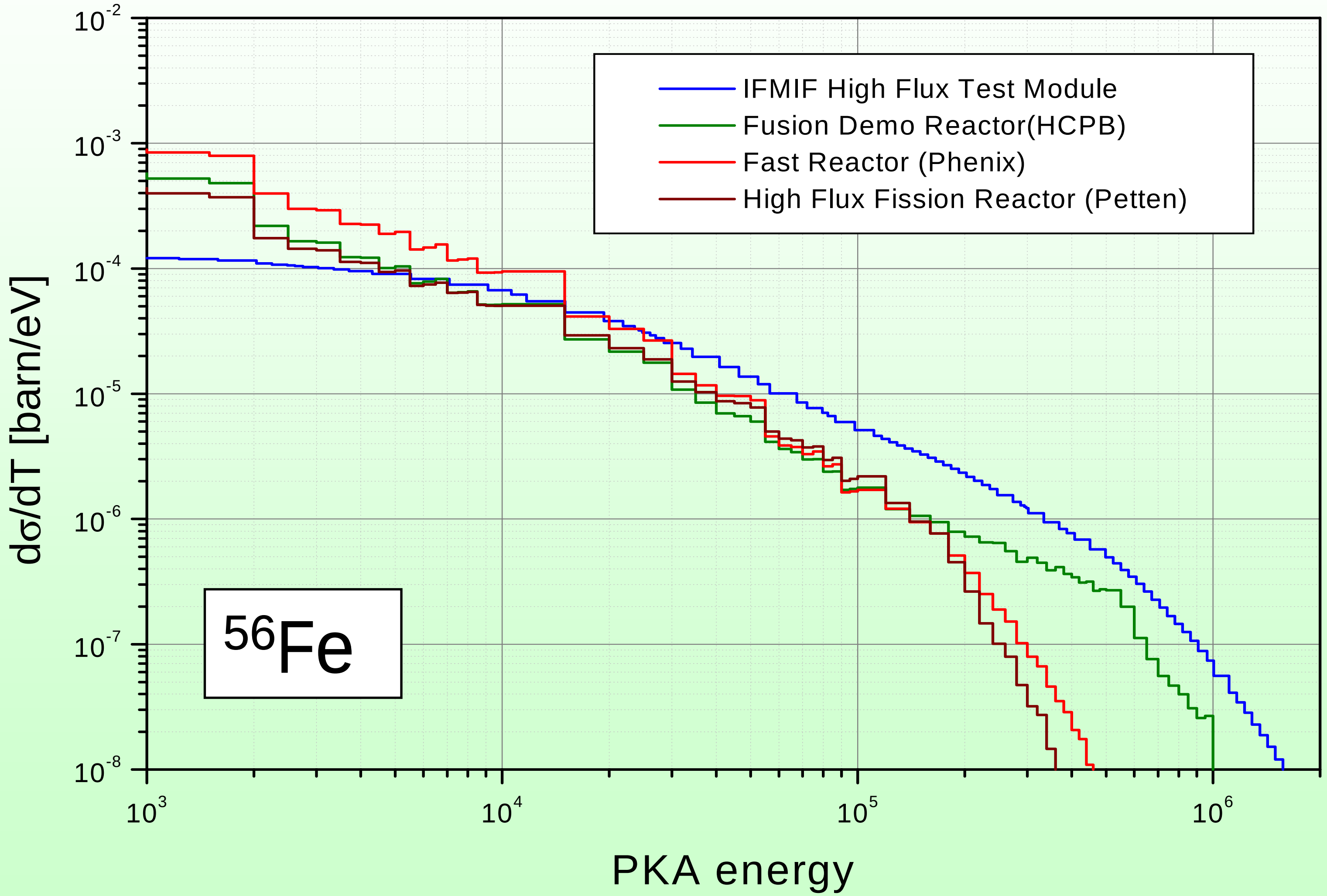
- Displacement damage and elemental transmutations primary responses of the materials under neutron irradiation
- Displacement damage induced by incident neutron through transfer of kinetic energy to colliding nucleus
  - "primary knock-on atom" (PKA) displaced from lattice site
  - PKA can initiate further atom displacements in a sequence of succeeding collisions ("collision cascades")
  - quantification of displacement damage by calculation of number of displacements per atom (dpa)
- Generation of gaseous transmutation products such as hydrogen (H) and helium (He) affects material irradiation behaviour (e. g. embrittlement and swelling)

⇒ Production ratios He/dpa and H/dpa primary parameters to characterise the suitability as fusion reactor material irradiation facility

Damage and Gas Production

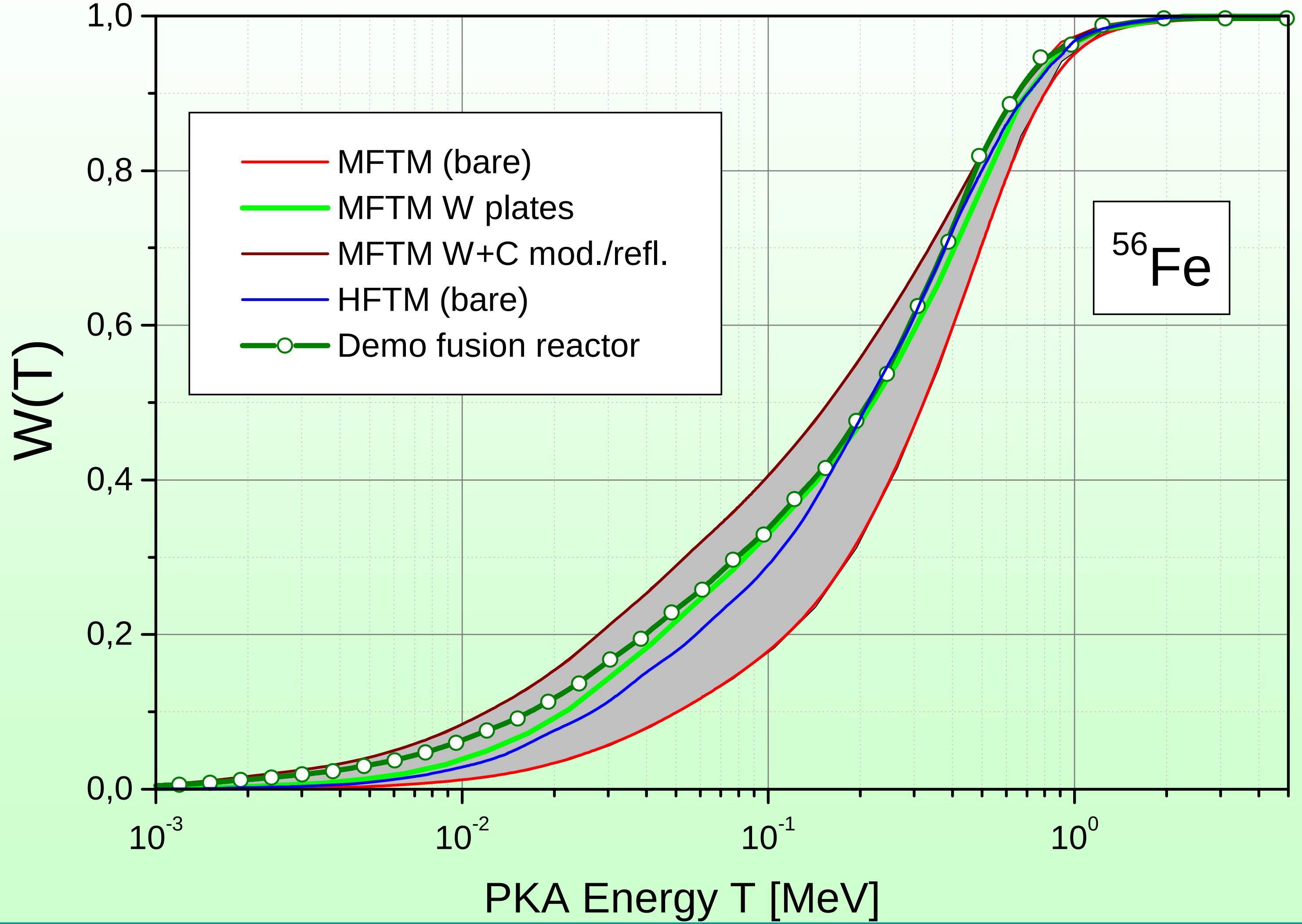


PKA spectra



IFMIF High Flux Test Module
Fusion Demo Reactor(HCPB)
Fast Reactor (Phenix)
High Flux Fission Reactor (Petten)
56Fe
dσ/dT [barn/eV]
PKA energy
10-2
10-3
10-4
10-5
10-6
10-7
10-8
10^3
10^4
10^5
10^6

Damage energy transfer function



Activation and Transmutation Analyses

Tools and Data

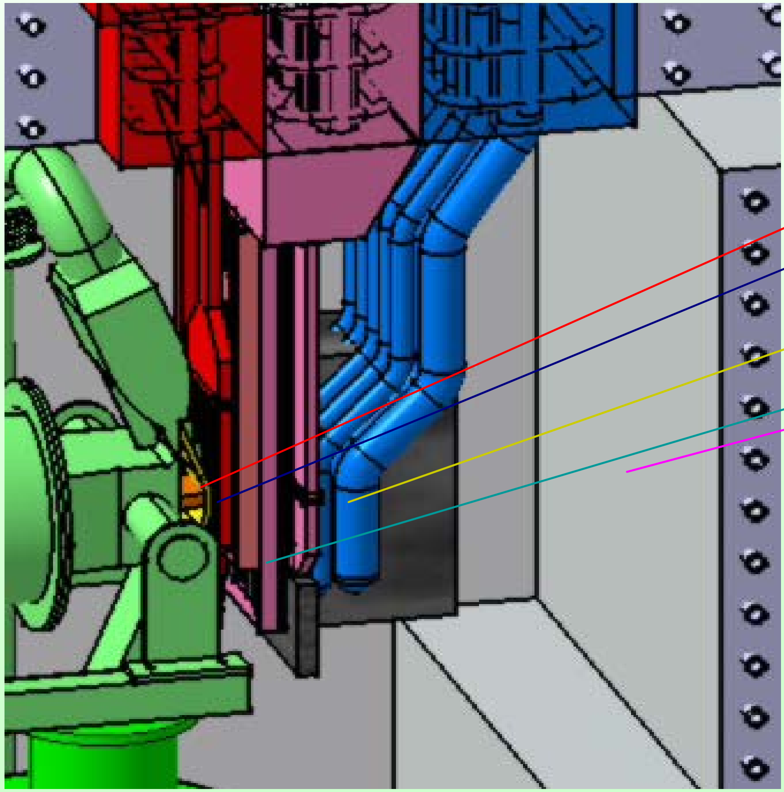
- Intermediate Energy Activation File IEAF-2001 (FZK/INPE)
  - Complete cross-section data library for activation and transmutation analyses up to $E_n \leq 150$ MeV ($1 \leq Z \leq 84$)
  - Validated through series of benchmark calculations, tested and qualified for SS-316 & V/V-alloy samples in IFMIF activation experiment

- ALARA activation code (P. Wilson, UW)
  - Analytical and Laplacian Adaptive Radioactivity Analysis
  - Capable of handling an arbitrary number of reaction channels

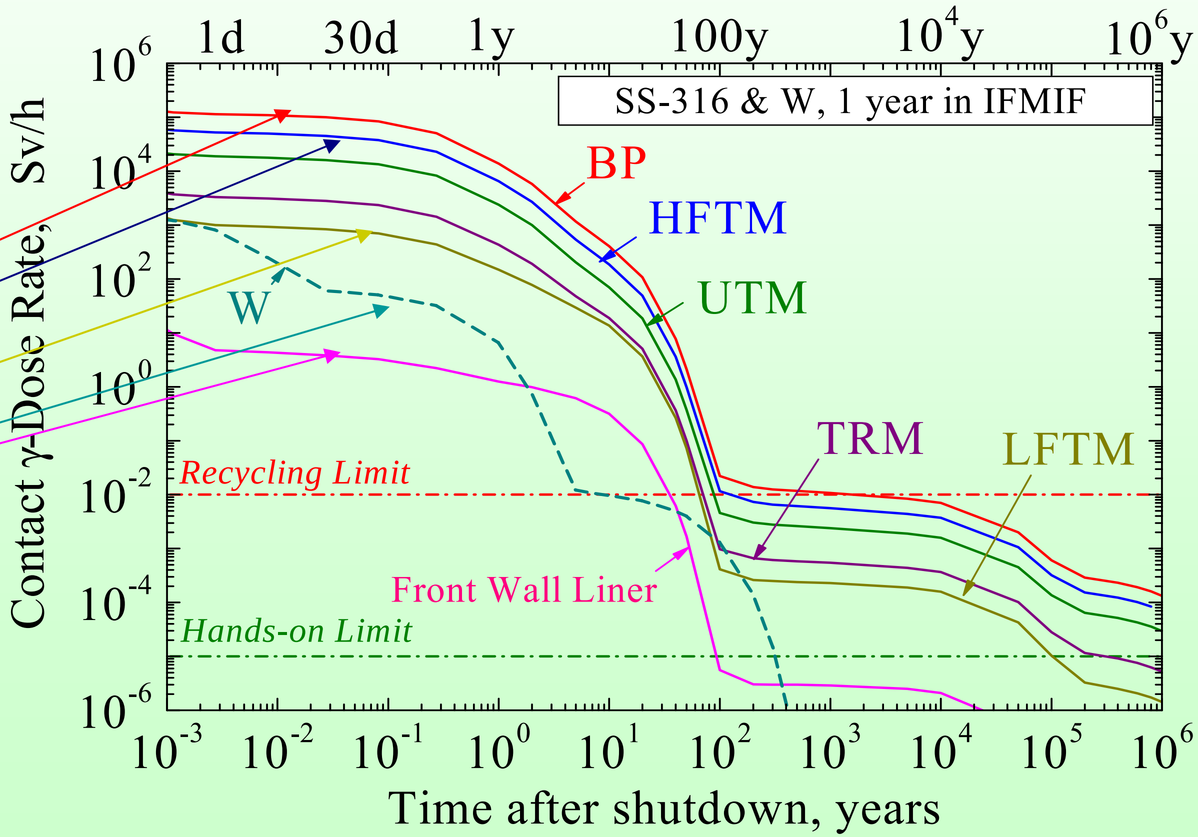
$\Rightarrow$ *EAF-2005 ($E_n \leq 60$ MeV) for FISPACT inventory calculations recently became available (UKAEA Culham)*

Induced radioactivity in the IFMIF HFTM components

IFMIF HTFM components (CAD model)

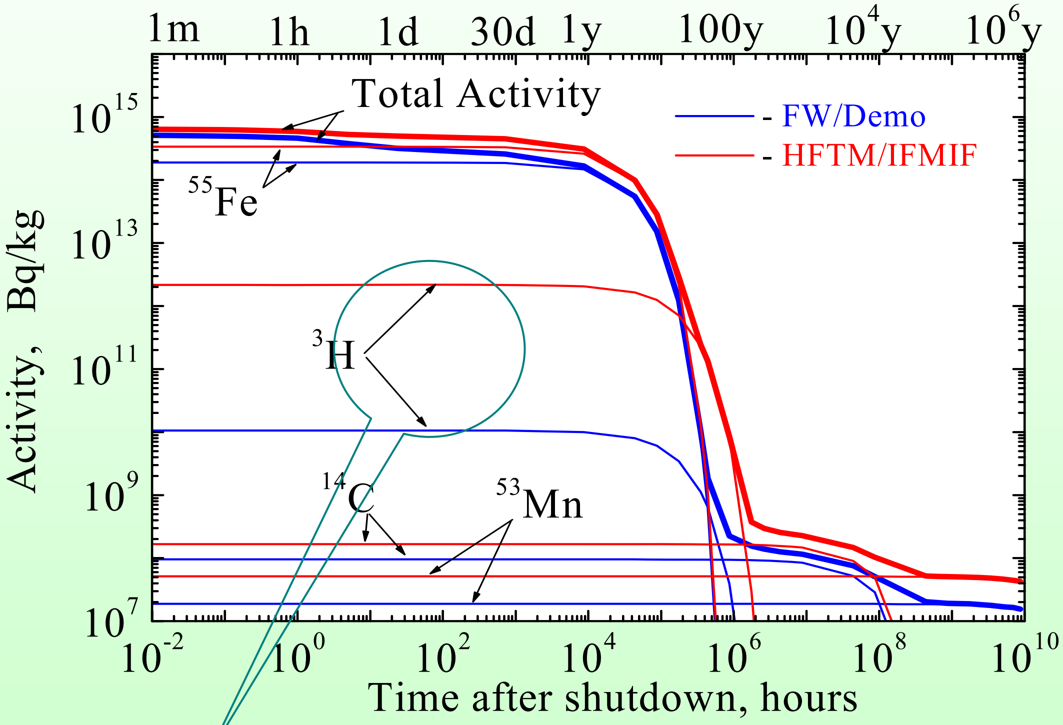


Contact γ - dose rate after IFMIF full power irradiation [Sv/h]



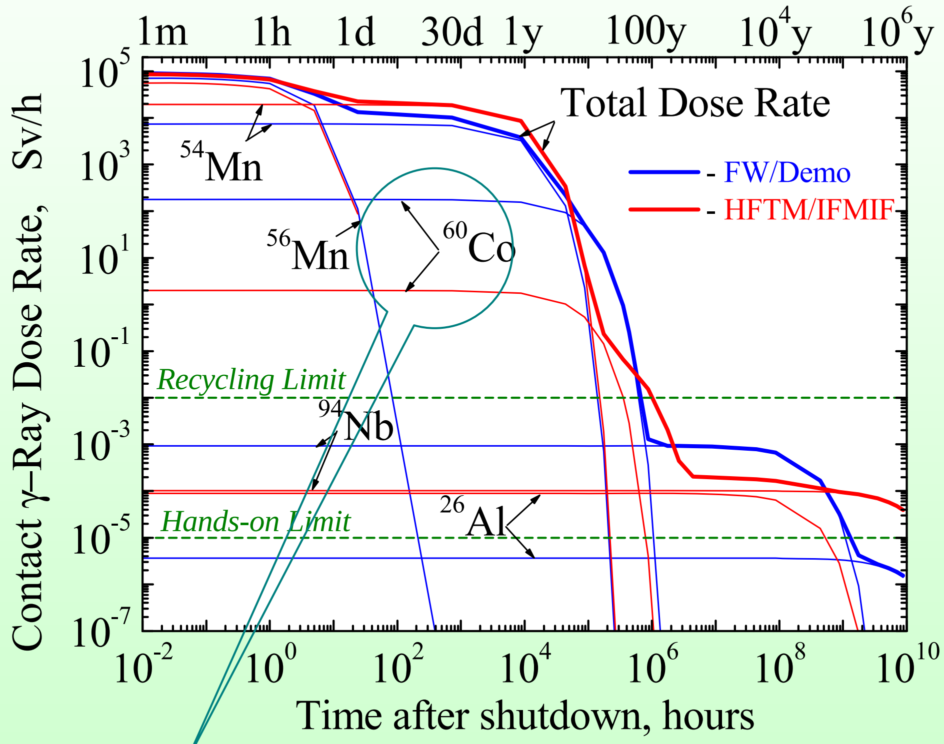
IFMIF vs. FPR: Activation Analysis

Eurofer Activity



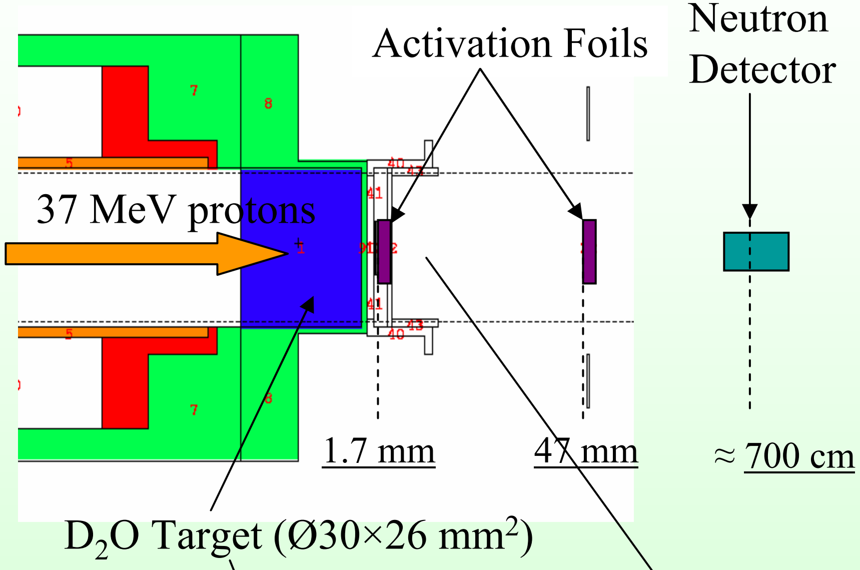
^{3}H yield: IFMIF > Demo due to ^{56}Fe(n,t), E_{thr} = 12 MeV

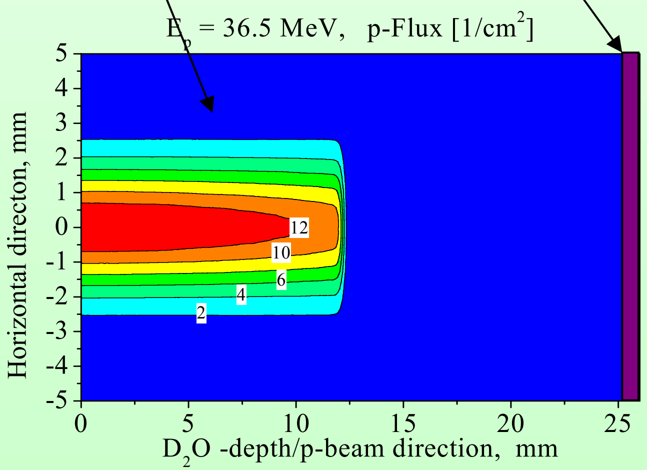
Eurofer γ-dose rate

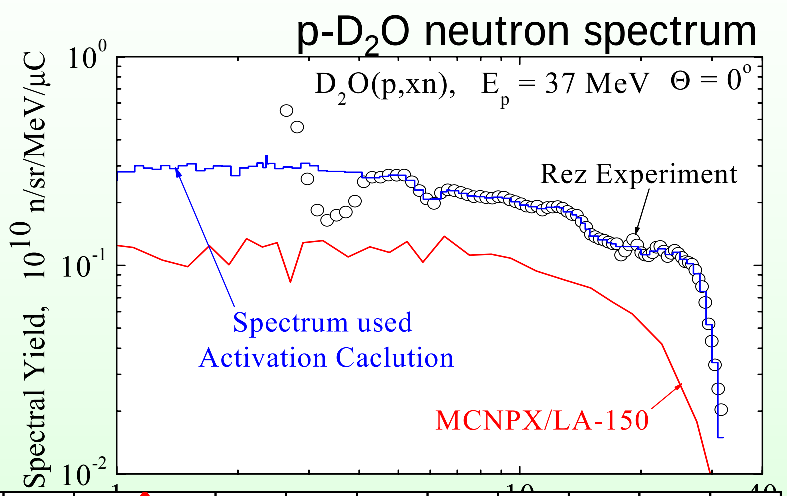


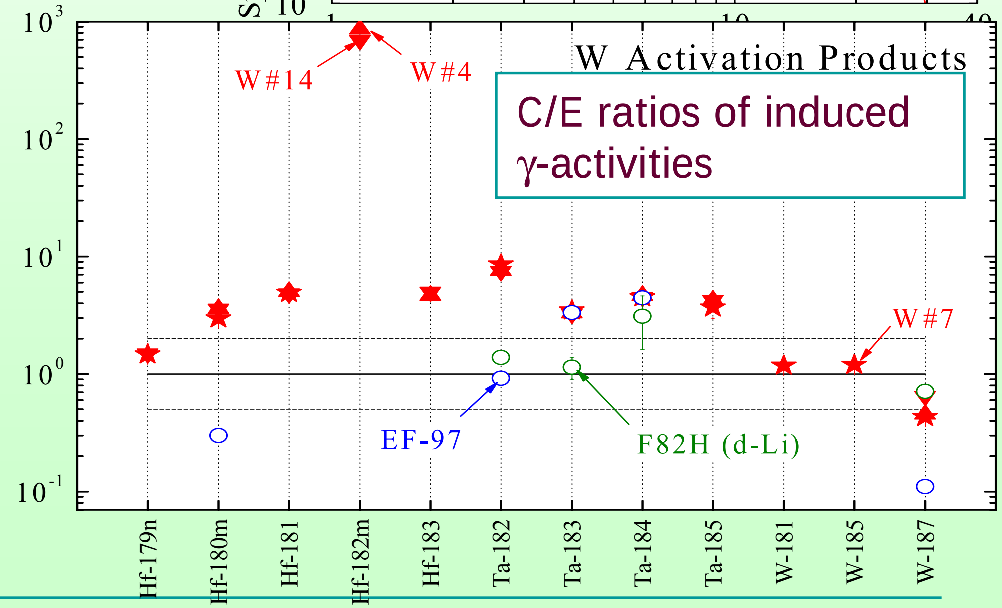
^{60}Co yield: IFMIF < Demo due to ^{59}Co(n,γ)^{60}Co

NPI Activation Experiment on W/Eurofer

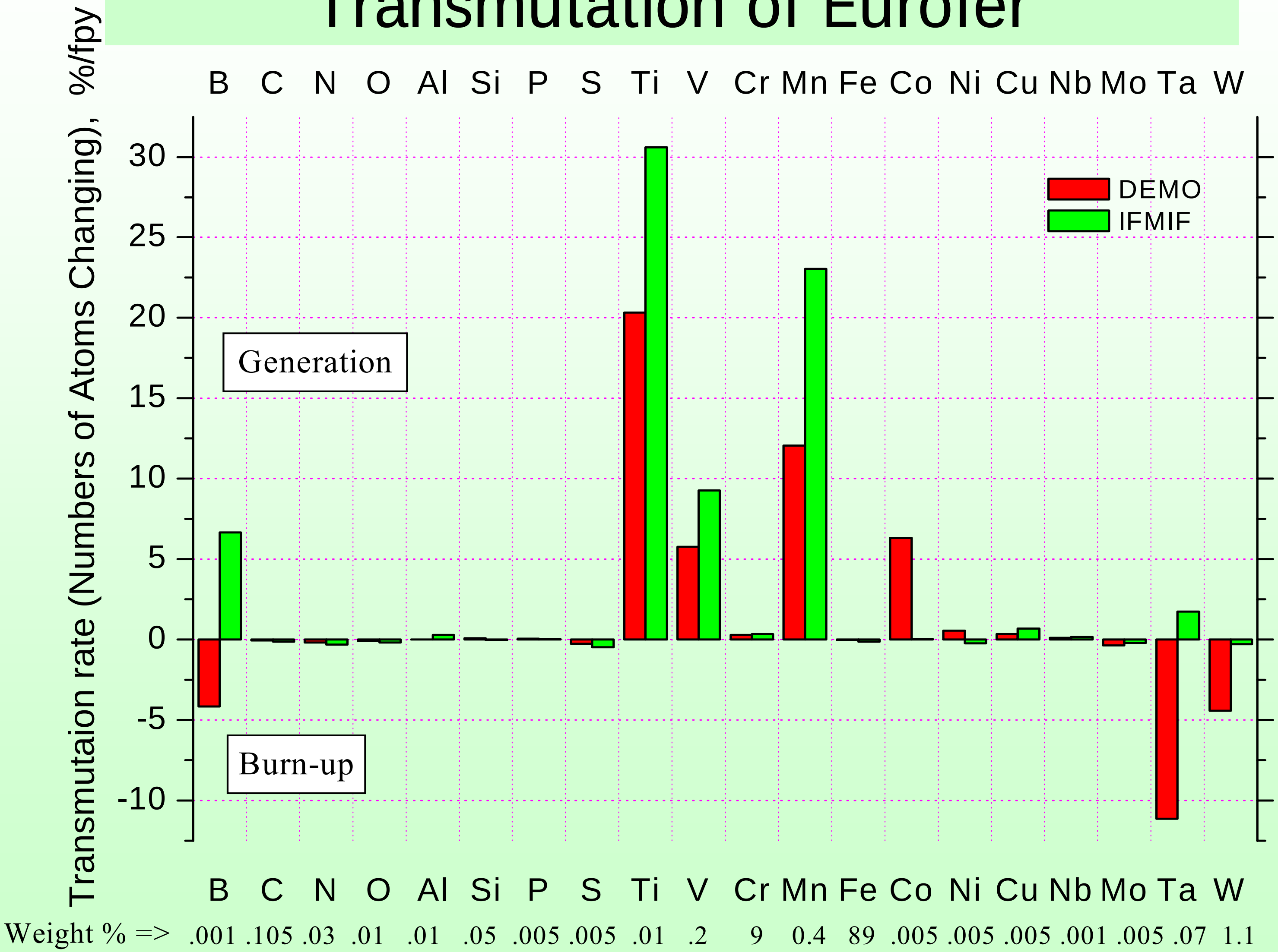




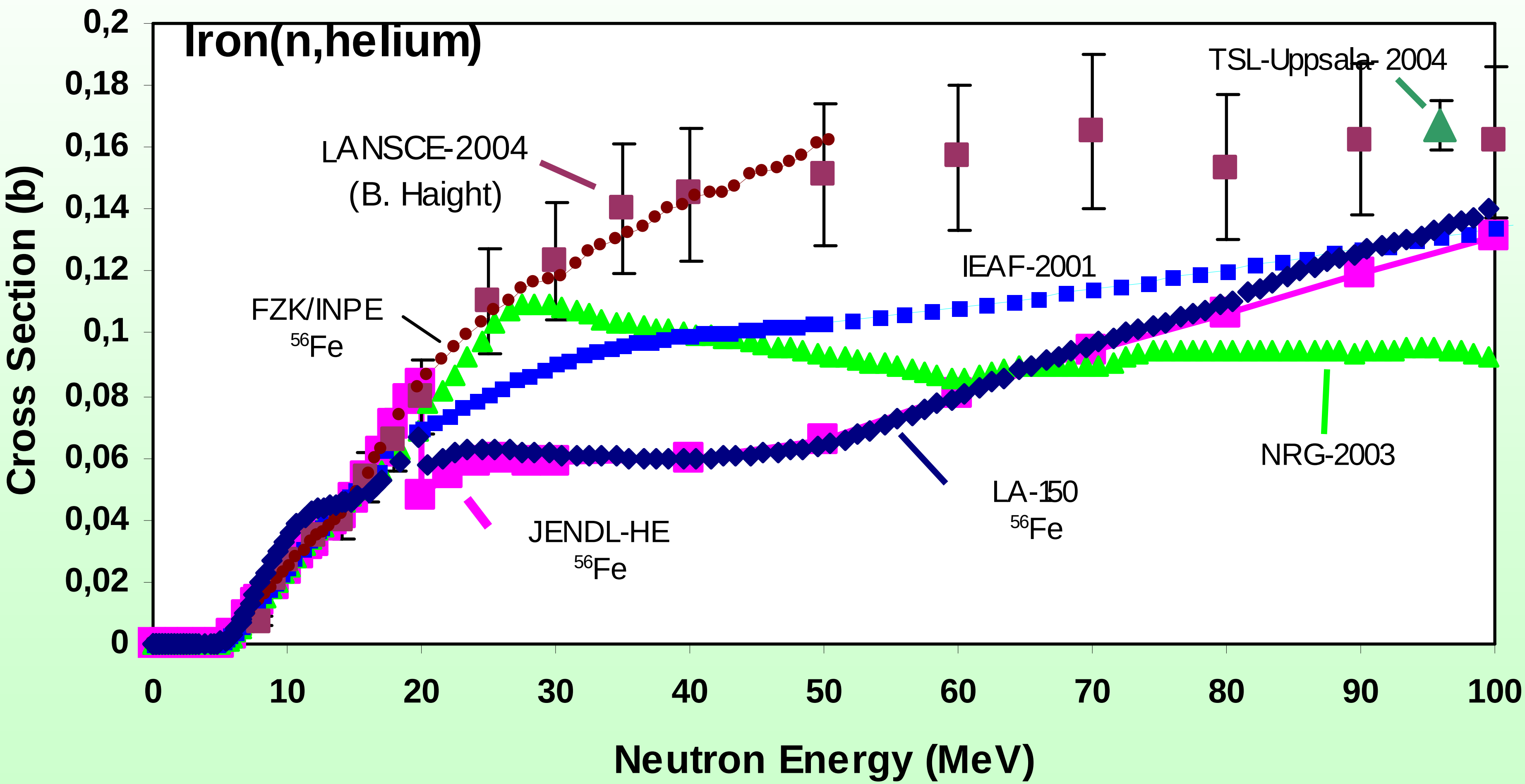




Transmutation of Eurofer



He production cross-section of Fe-nat up to 100 MeV



Neutron Data E> 20 MeV Required for IFMIF Neutronics

Priority	Isotopes	Available Data Evaluations
High		
	^{56}Fe	ENDF/B-VI.6, NRG, FZK/INPE (50), JENDL-HE
	^{52}Cr	ENDF/B-VI.6, FZK/INPE (50), JENDL-HE
	$^{182,183,\ 184,\ 186}W$	ENDF/B-VI.6, JENDL-HE
	^{9}Be	FZK/INPE
	$^{6,7}Li$	FZK/INPE
	^{28}Si	ENDF/B-VI.6, FZK/INPE (50), JENDL-HE
	^{12}C	ENDF/B-VI.6, FZK/INPE (50), JENDL-HE
	^{16}O	ENDF/B-VI.6, FZK/INPE (50), JENDL-HE
	^{23}Na	FZK/INPE (50),
	^{39}K	FZK/INPE (50), JENDL-HE

Neutron Data E> 20 MeV Required for IFMIF Neutronics

Priority	Isotopes	Available Data Evaluations
Medium		
	$^{54,\ 57,58}Fe$	ENDF/B-VI.6, NRG, JENDL-HE
	$^{50,\ 53,54}Cr$	ENDF/B-VI.6, JENDL-HE
	$^{29,30}Si$	ENDF/B-VI.6, JENDL-HE
	$^{63,\ 65}Cu$	ENDF/B-VI.6, JENDL-HE
	^{1}H	ENDF/B-VI.6, JENDL-HE
	^{181}Ta	-
	+ many more	
Low		
	$^{46,\ 47,48,49}Ti$	JENDL-HE
	+ many more	.

Conclusions

INS for testing and qualifying fusion materials must be suited to simulate fusion relevant irradiation characteristics:

- Neutron flux level & fluences
- Radiation damage & activation characteristics
  - He/dpa ratio
  - PKA spectrum, damage production function W(T)
  - Transmutation products
- Sufficient irradiation test volume
- IFMIF shown to be suitable INS

Conclusions

- Suitable computational tools, data and models available for IFMIF neutronics and activation analyses
  - McDeLicious Monte Carlo code for Li(d,xn) neutron source
  - Various general purpose intermediate/high energy data evaluations
  - Activation and transmutation data libraries (up to 150 MeV)

- General purpose (ENDF) data evaluations E> 20 MeV
  - Need for full IFMIF data library (validated data evaluations)

  ⇒ Cross-section measurements, benchmark experiments
- Activation/transmutation/gas production data
  - Need for validation (⇒ Benchmark experiments)
  - Need for cross-section measurements

IFMIF neutron flux spectrum