McDeLicious Workshop

13-14 March 2008

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What is McDeLicious code

- McDeLicious code

  was developed to enable a proper representation of the d-Li neutron source term in Monte Carlo transport calculations for IFMIF

- It is enhancement (set of subroutines) to MCNP5 with ability to sample the generation of d-Li source neutrons on the basis of tabulated double-differential d + ^{6,7}Li cross-sections:
  - modelling of deuteron beam configuration, orientation and profile
  - modelling of deuteron slowing down in the Lithium
  - sampling of source neutrons using evaluated d+ ^{6,7}Li data

History of McDeLicious code development

- 1999: McDeLi *(P. Wilson, Report FZKA 6218, 1999)*
  - enhancement to MCNP-4a to sample the generation
  of d-Li source neutrons on the basis of embed analytical formulas
  representing direct deuteron striping (Serber model) and compound reactions

- 2001: McDeLicious *(S.P.Simakov et al. J.Nucl.Mat.307-311(2002)1710, FZKA 6743)*
  - enhancement to MCNP-4b,c to sample the d-Li source neutrons
  on the basis of tabulated double-differential d + ^{6,7}Li cross-sections
  for deuteron energies up to 50 MeV
  (evaluated by *A. Konobeyev et al., NSE 139 (2001)1)*

- 2005: McDeLicious-05 – compilation with MCNP-5
  and use tabulated double-differential cross-sections from updated
  d + ^{6,7}Li evaluation *(made by P. Pereslavtsev et al., J.Nucl.Mat.367-370(2007)1531)*

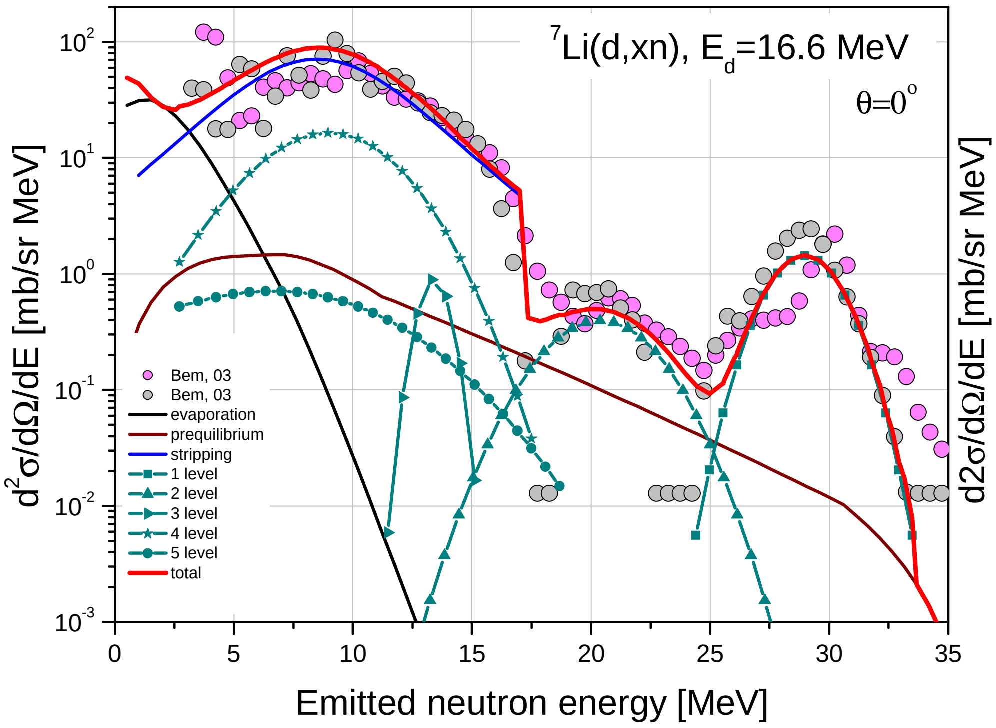
D-Li Neutron Source Term:

validation against measurements
performed at accelerators with
- thin Li-target - double differential cross sections
- thick Li-target - integrated & differential neutron yields

Double differential cross sections /thin Li-target/: new measurements and new d + ^{6,7}Li data evaluation

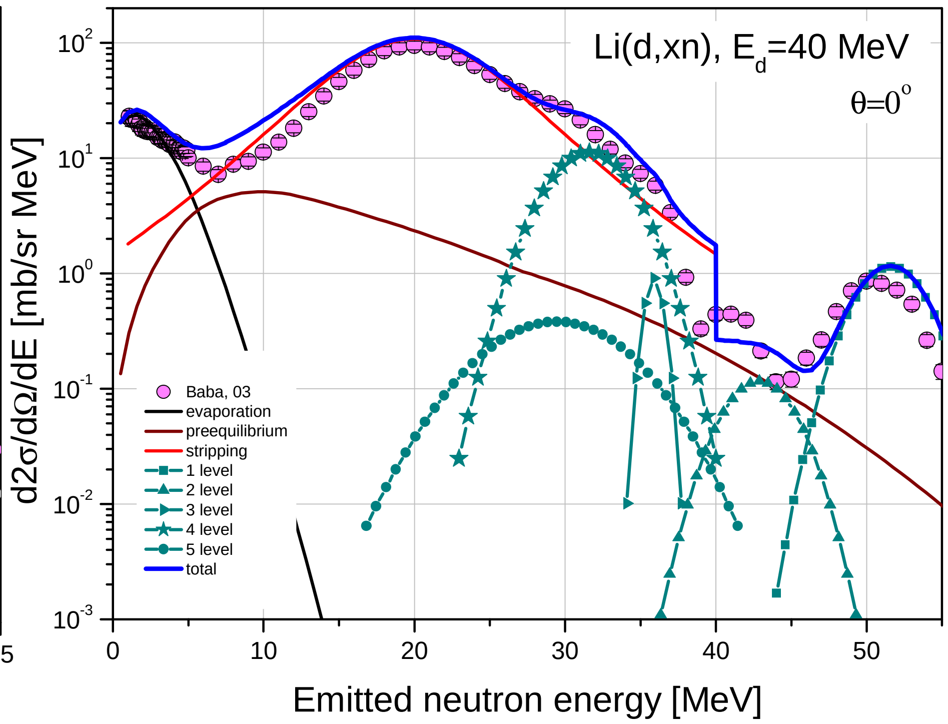
Ed = 17 MeV

Exp.: P.Bem et al. NPI EXP(EFDA)-05/2004



Ed = 40 MeV

Exp.: M.Hagiwara et al. Fus.Sci.Tech.48(2005)1320

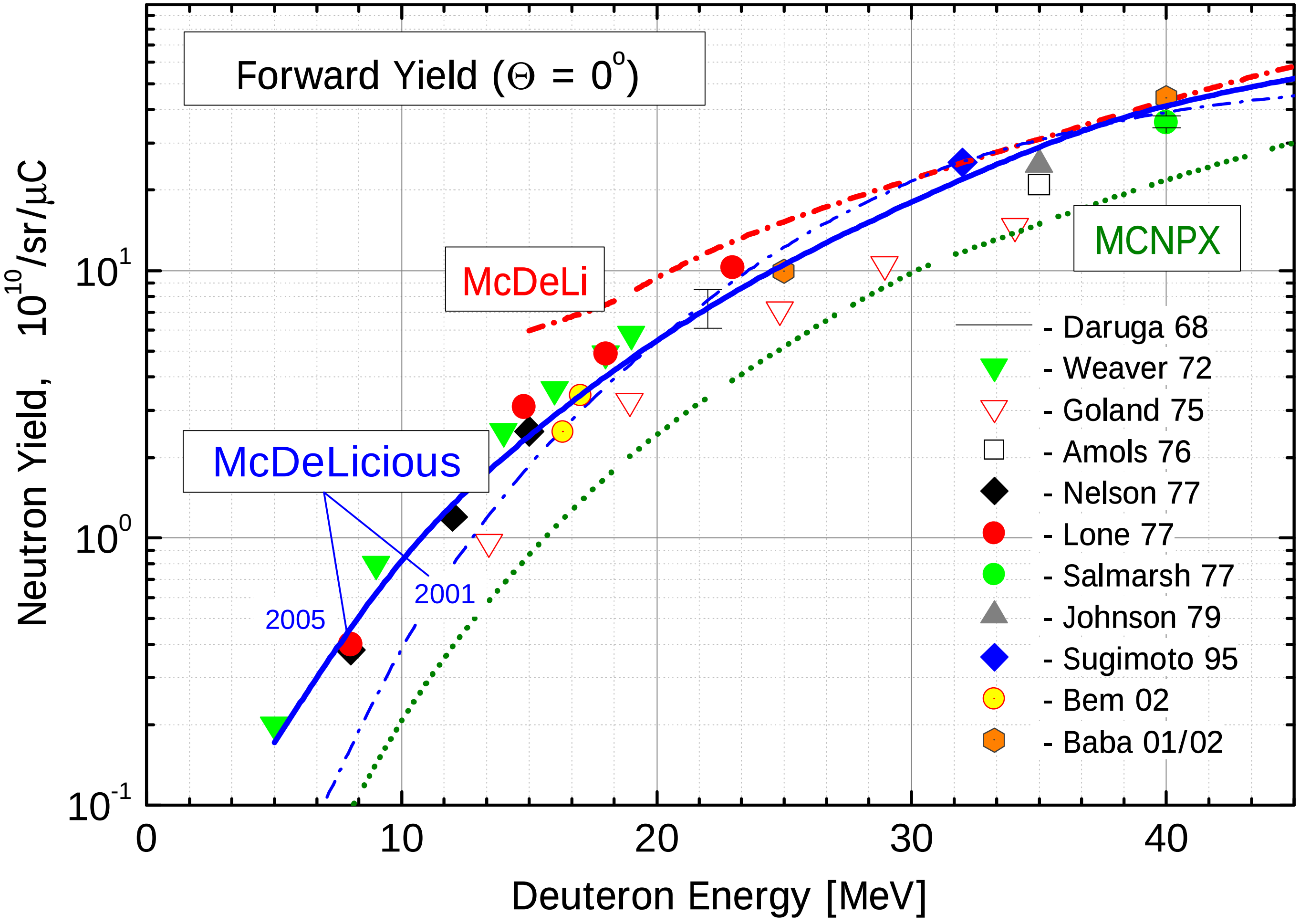


Evaluation by P. Pereslavtsev et al., JNM 367-370(2007)1531

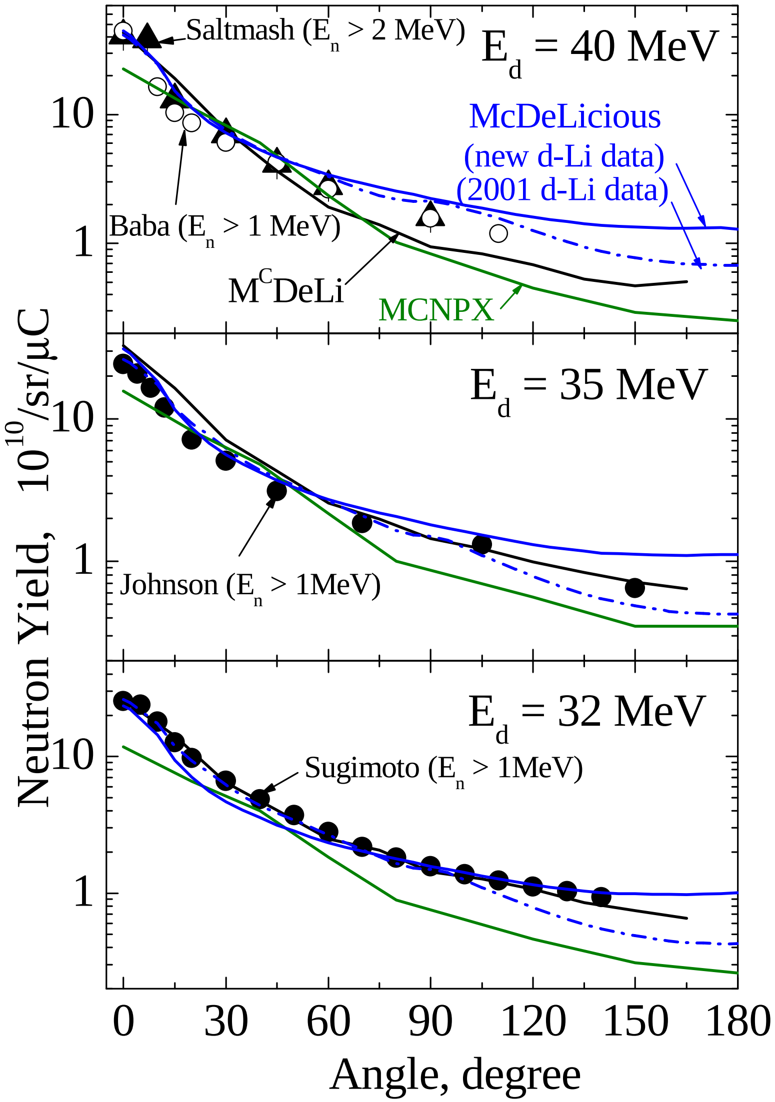
Neutron yield from thick Li-target: available experiments

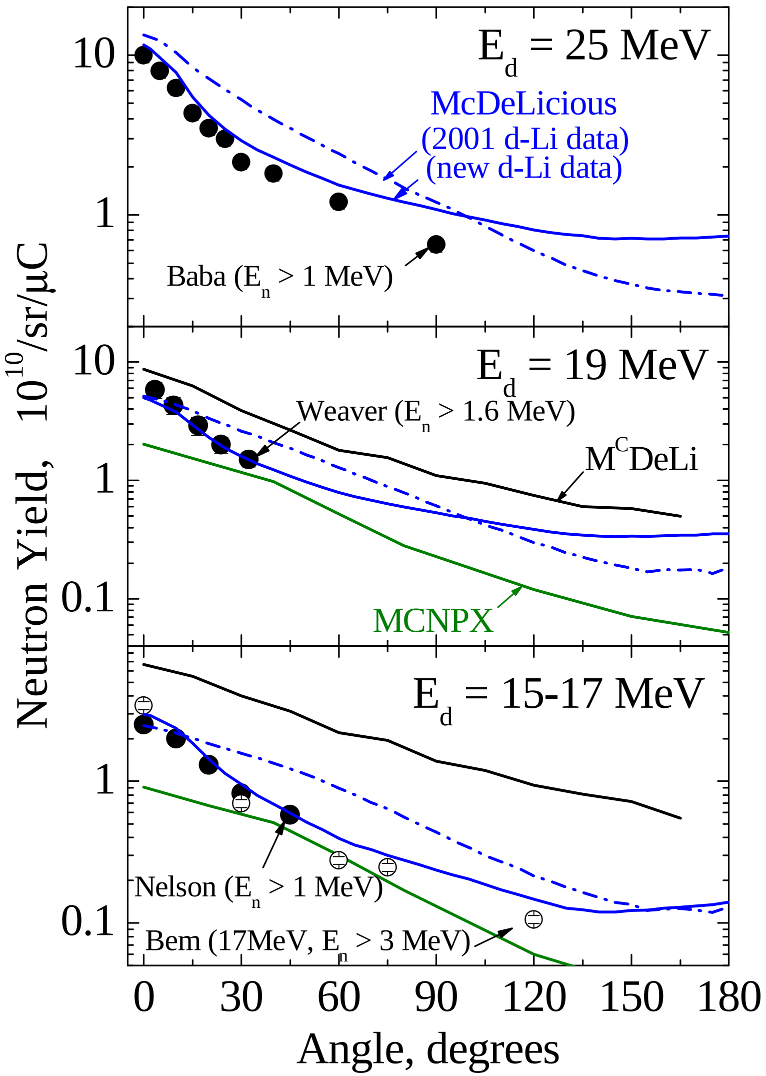
No	First Author, Year of Publ.	Laboratory, Country	Tar-get	E_d, MeV	Q, degrees	E_{thr}, MeV
1	V.K. Daruga 1968	Inst. of Physics & Power Eng., Russia	Li	22	0^o	1.8
2	A.N. Weaver 1972	Livermore Laboratory, USA	Li	5, 9, 14, 16, 19	3.5^o, 10^o, 18^o, 25^o, 32^o	2.5 1.6
3	A.N. Goland 1975	Naval Research Laboratory, USA	Li	13.4, 19, 25, 29, 34	0^o, 5^o, 10^o, 15^o, 20^o	3
4	H.I. Amols 1976	Fermi National Laboratory, USA	Li	35	0^o	5
5	C.E. Nelson 1977	Triangle University, USA	^{7}Li	8, 12, 15	0^o, 10^o, 20^o, 30^o, 45^o	1
6	M.A. Lone 1977	Chalk River Laboratory, Canada	^{7}Li	14.8, 18, 23	0^o, 10^o, 20^o, 30^o, 40^o	0.3
7	M.J. Saltmarsh 1977	Oak Ridge Laboratory, USA	Li	40	0^o, 7^o, 15^o, 30^o, 45^o, 60^o, 90^o	2
8	D.L. Johnson 1979	University of California, USA	Li	35	0^o, 4^o, 8^o, 12^o, 20^o, 30^o, 45^o, 70^o, 105^o, 150^o	1
9	M. Sugimoto 1995	Japan Energy Research Institute, Japan	Li	32	0^o,5^o,10^o,15^o,20^o,30^o, 40^o, 50^o, 60^o, 70^o, 80^o, 90^o, 100^o, 110^o,120^o, 130^o, 140^o, 150^o	1
10	M. Baba 2003	Tohoku University, Japan	Li	25, 40	0^o,5^o,10^o,15^o,20^o,25^o,30^o, 40^o,45^o,60^o,90^o, 110^o	1
11	P. Bém 2003	Nuclear Physics Institute, Rez	Li	16.3, 17.0	0^o	3

Thick Li-target neutron source: Forward Neutron Yield



Thick Li-target neutron source: Angular Neutron Yield





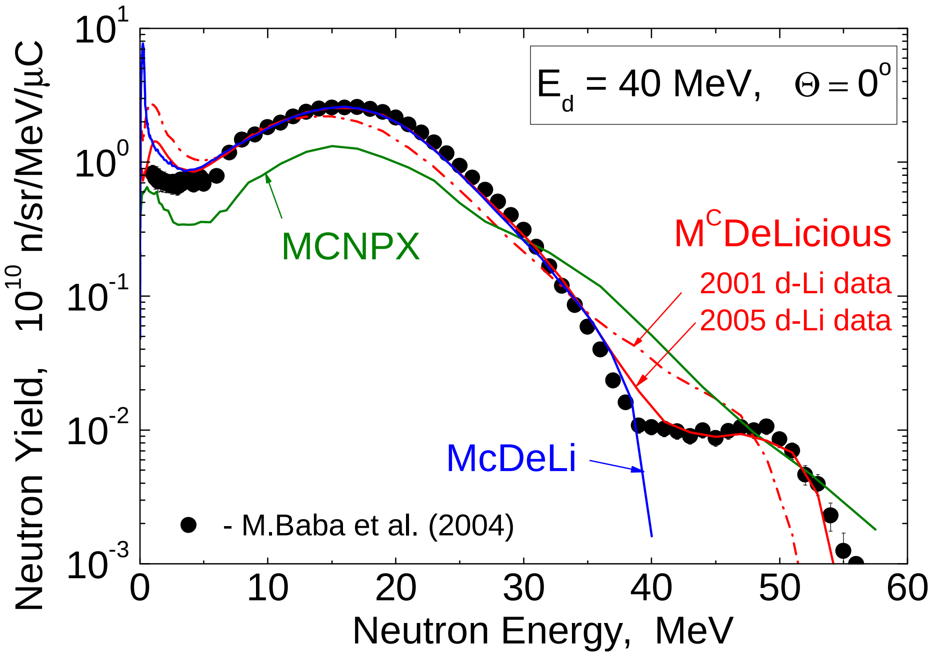
Thick Li-target neutron source: Energy-Angular Yield

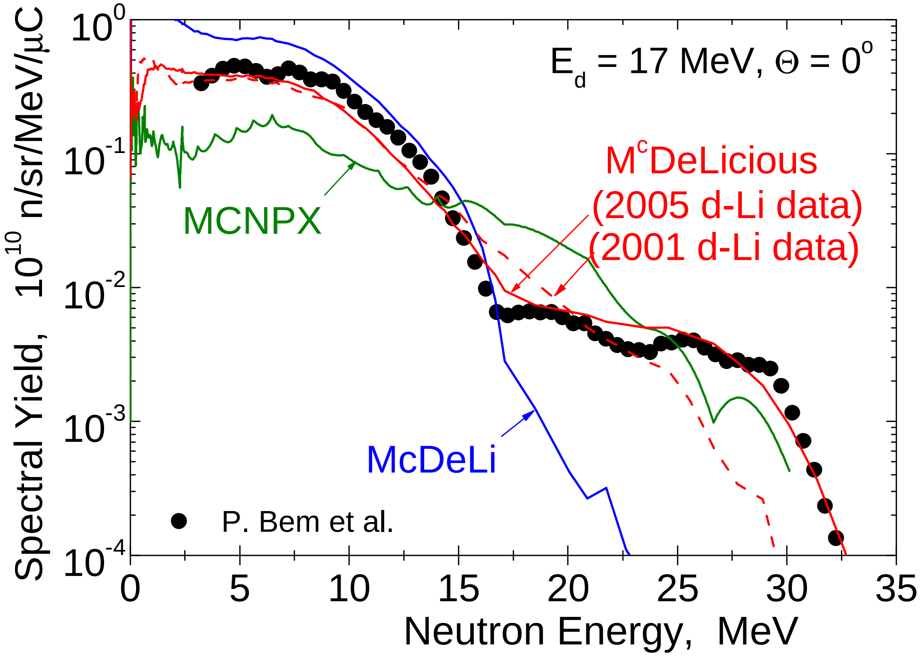
Ed = 40 MeV

Exp.: M. Hagiwara et al.

Ed = 17 MeV

Exp.: P. Bem et al.

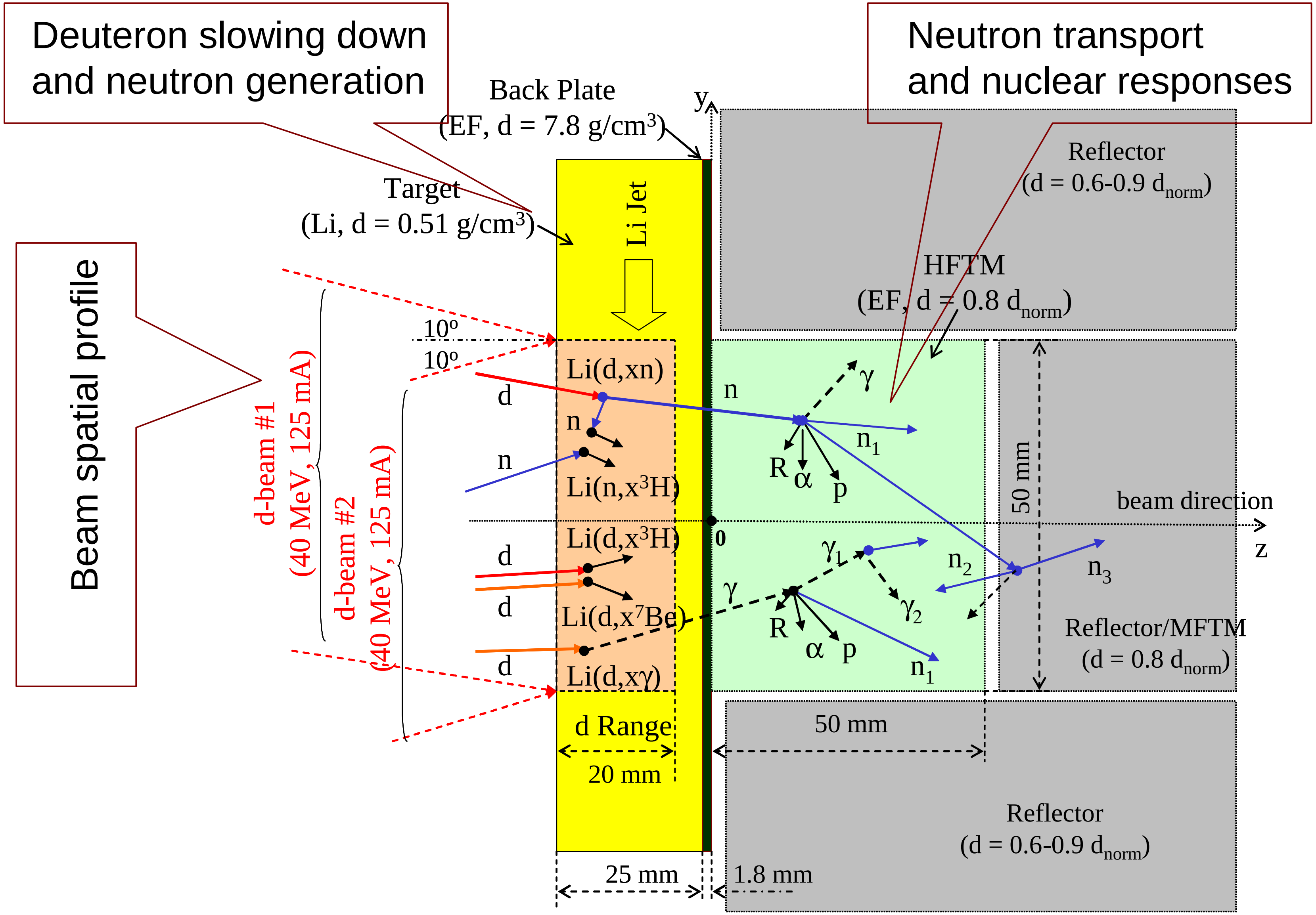




D-Li Neutron Source Term:

simulation of IFMIF source

Basic nuclear processes in IFMIF



Deuteron slowing down and neutron generation

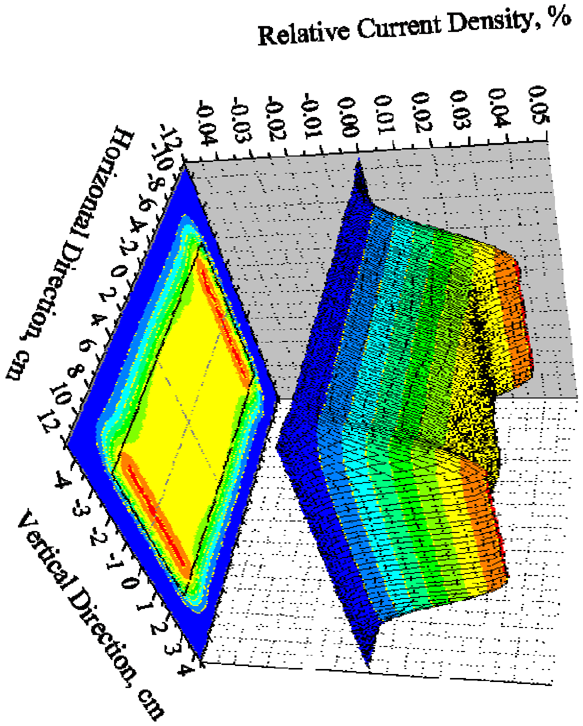
Neutron transport and nuclear responses

Beam spatial profile

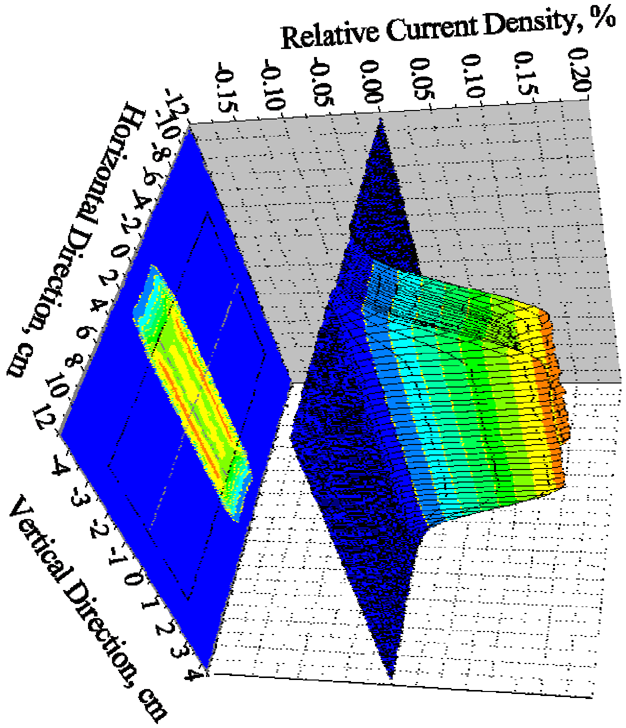
Dual deuteron beam spatial profile: each 40MeV @125 mA

Two 40 MeV @ 125 mA
beams:
+/- 10º declination
in horizontal plane

Full Footprint: 20×5 cm^2

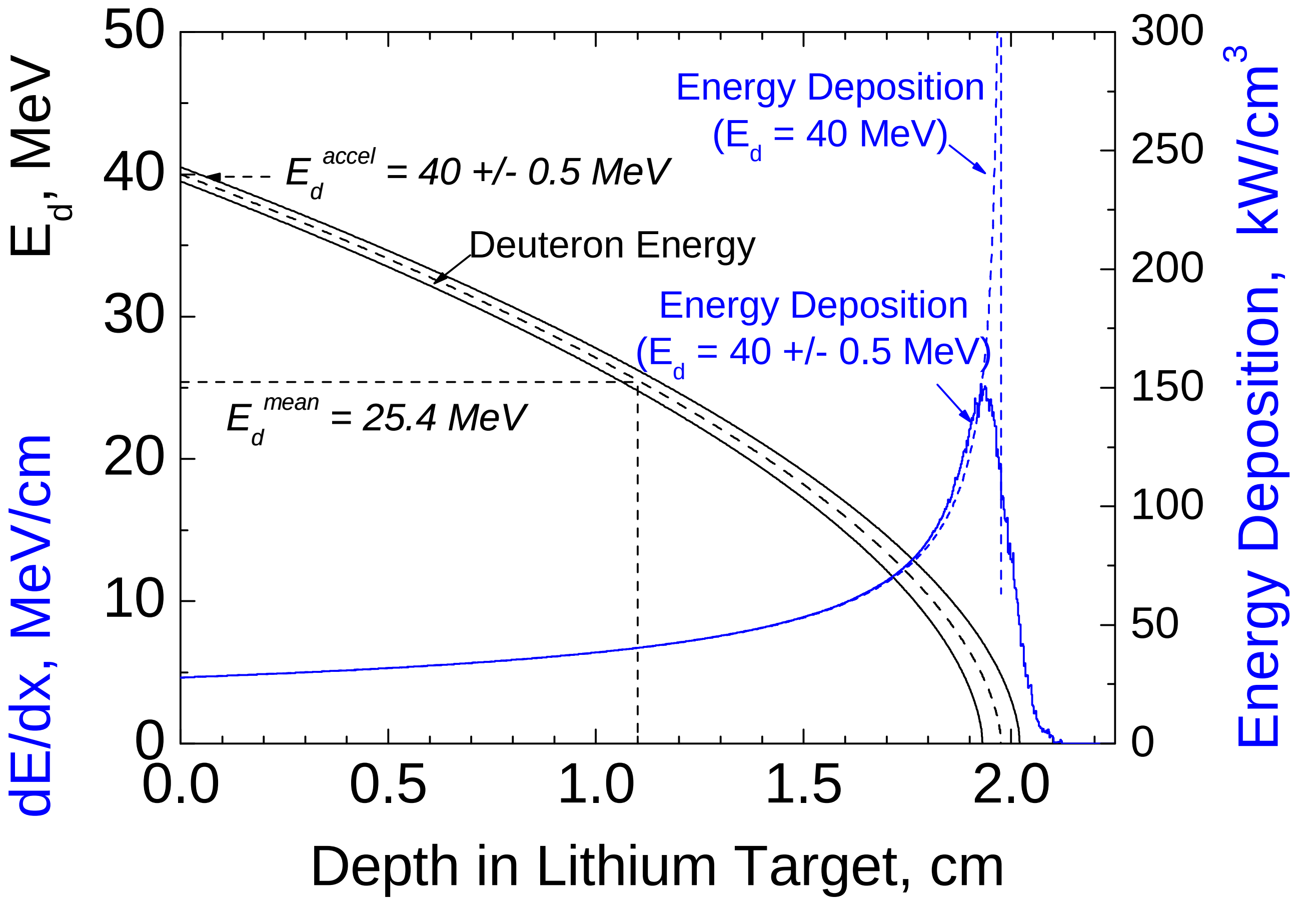


Reduced Footprint: 4×5 cm^2



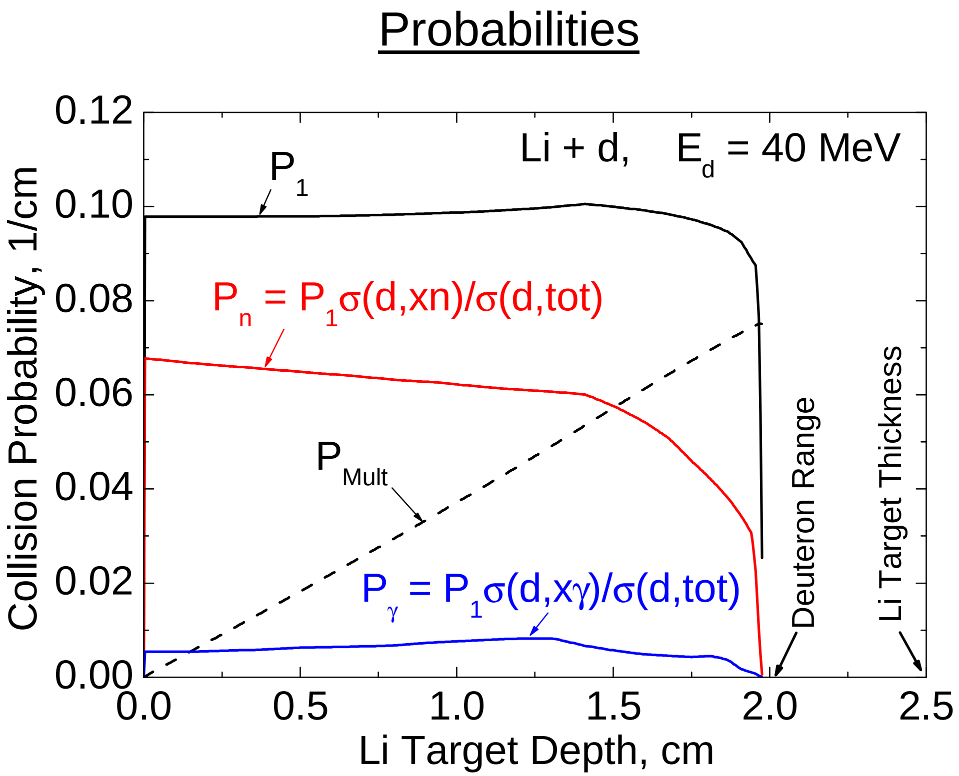
- d-beam current density variation inside the beam foot print amounts up to 20% ;
- d-beam current density gradient at the beam foot print edges (10 to 90)% per 1.5 cm
- d-beam current density 3-d distribution based on results obtained ≈10 years ago!

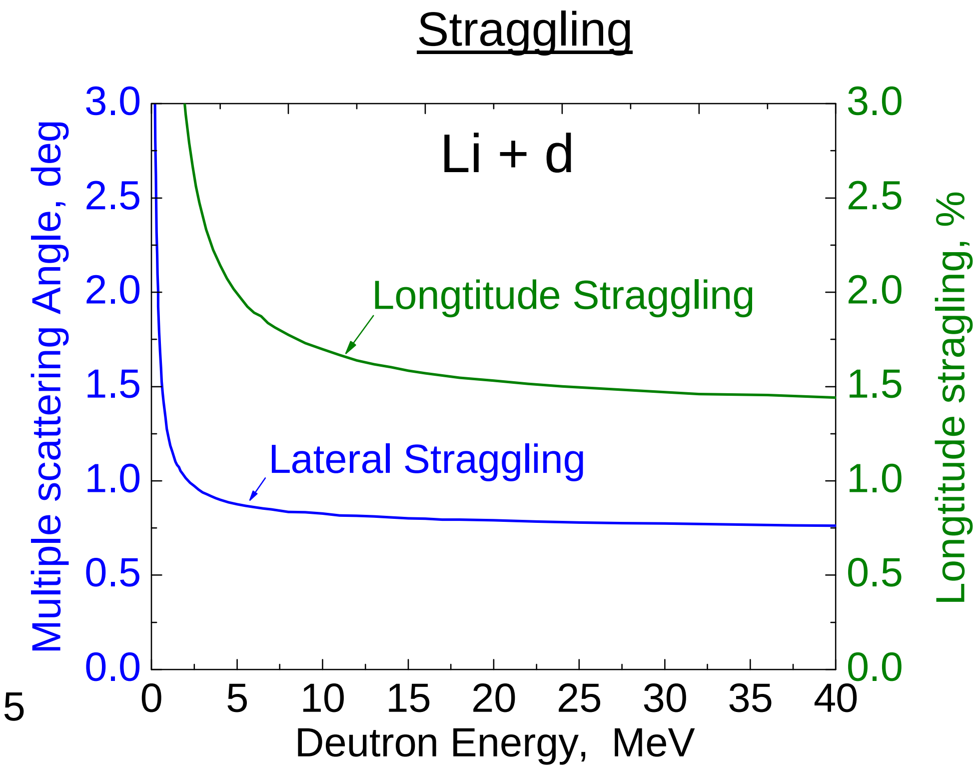
Deuteron slowing down and energy deposition in Li-jet



- *Deuteron track length reach 2.1 cm;*
- *Peak Energy Deposition is 150 kW/cc at the depth of 2.0 cm (at the end of d-track)*
  (without incident deuteron energy smearing - 1000 kW/cc !)
- *Average energy deposition in Li jet = (40 MeV x 250 mA=10,000 kW)/(20x5x2 cc) =50 kW/cc*

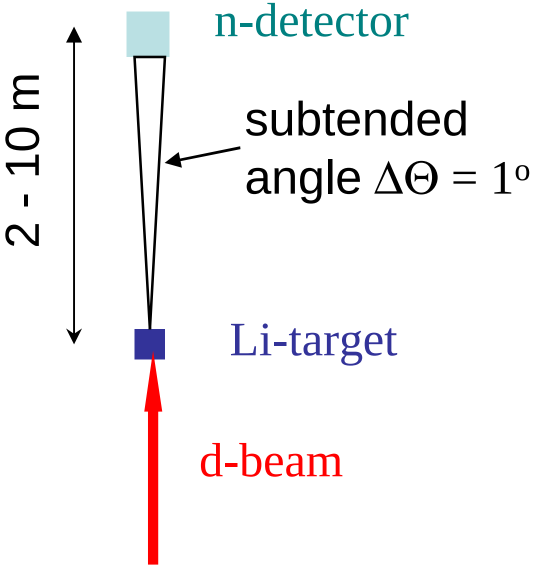
Deuteron collisions and Neutron productions probabilities in Li-jet



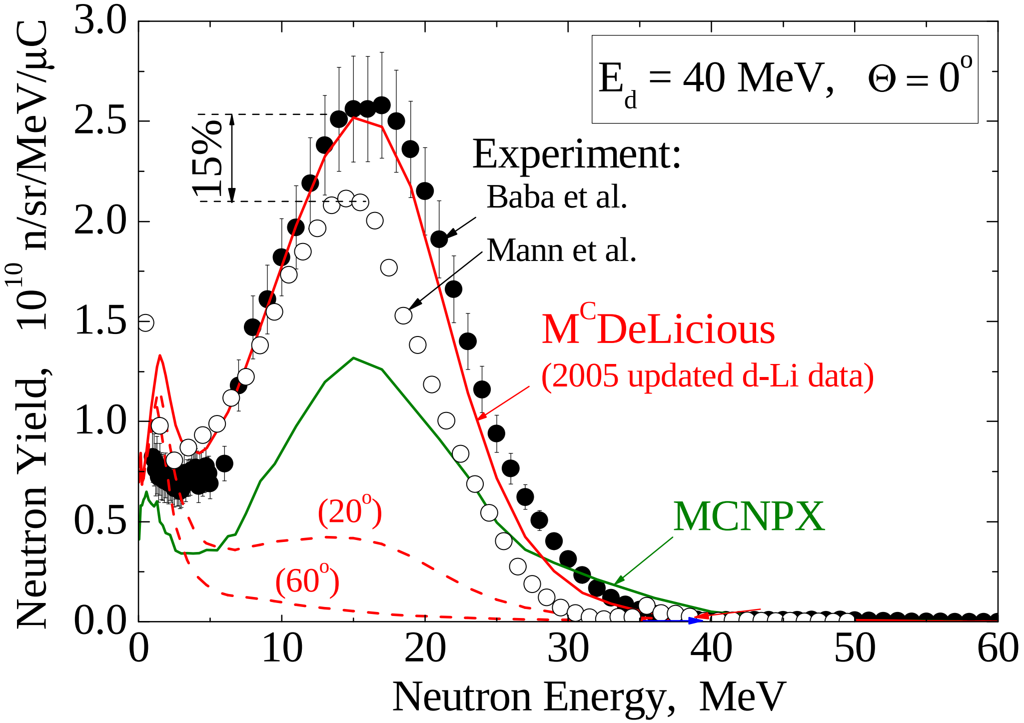


- *First deuteron collision in Li-jet dominates*
- *Second collisions - most probably are an elastic scattering which conserves incident deuteron direction within 1º and energy*
- *Every 100 deuterons with 40 MeV produce in Li-jet: 7.2 neutrons and 1.2 gammas*

D-Li Neutron Spectra: thick target measurements in laboratory do show a 14 MeV peak !



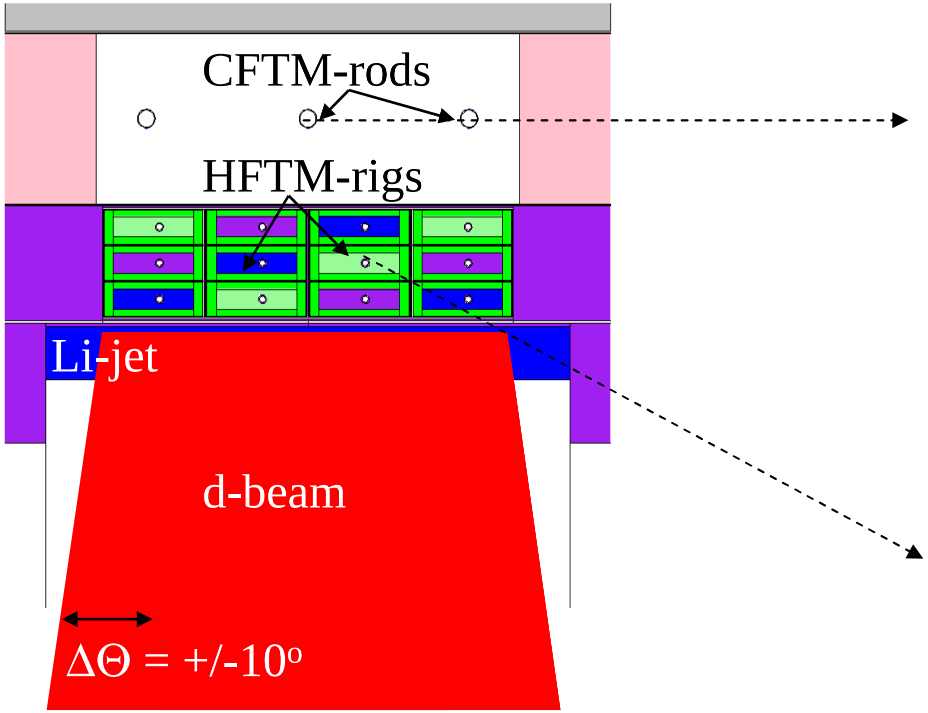
Neutron Spectra at well defined angles:



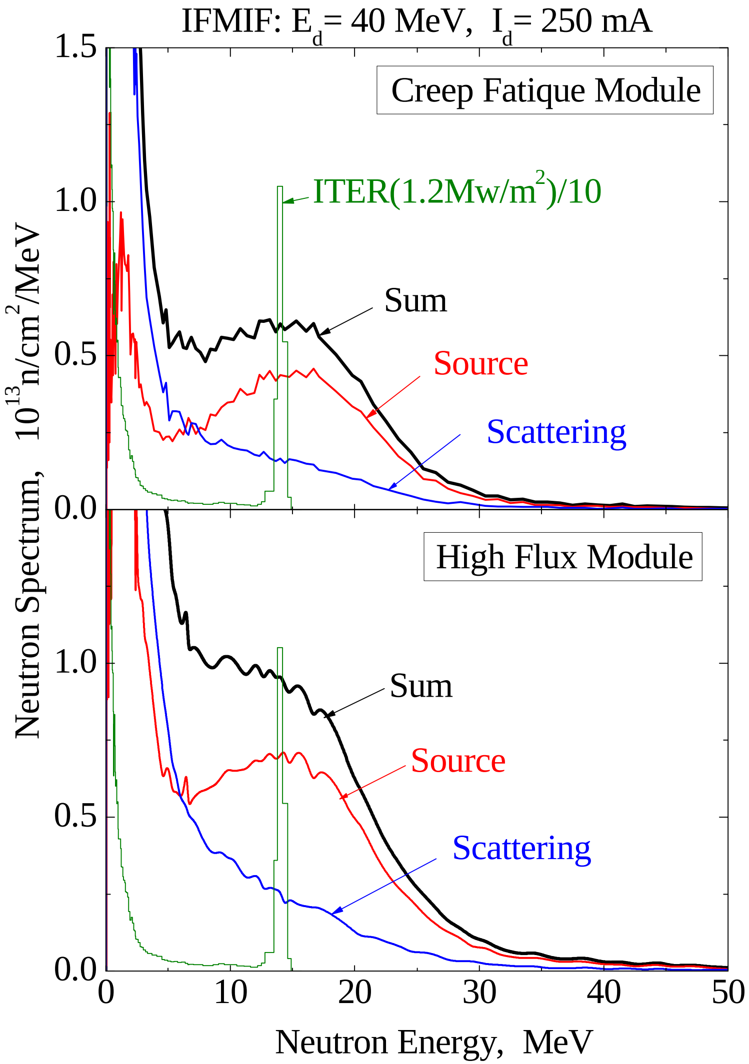
Peak at energy 15 MeV is clearly visible in well fine angle geometry. This peak is reproduced by 2005 updated d-Li evaluation within 10%

Does IFMIF neutron spectra have 14 MeV peak (?)

IFMIF fragment:



Neutron Spectra at Atom point



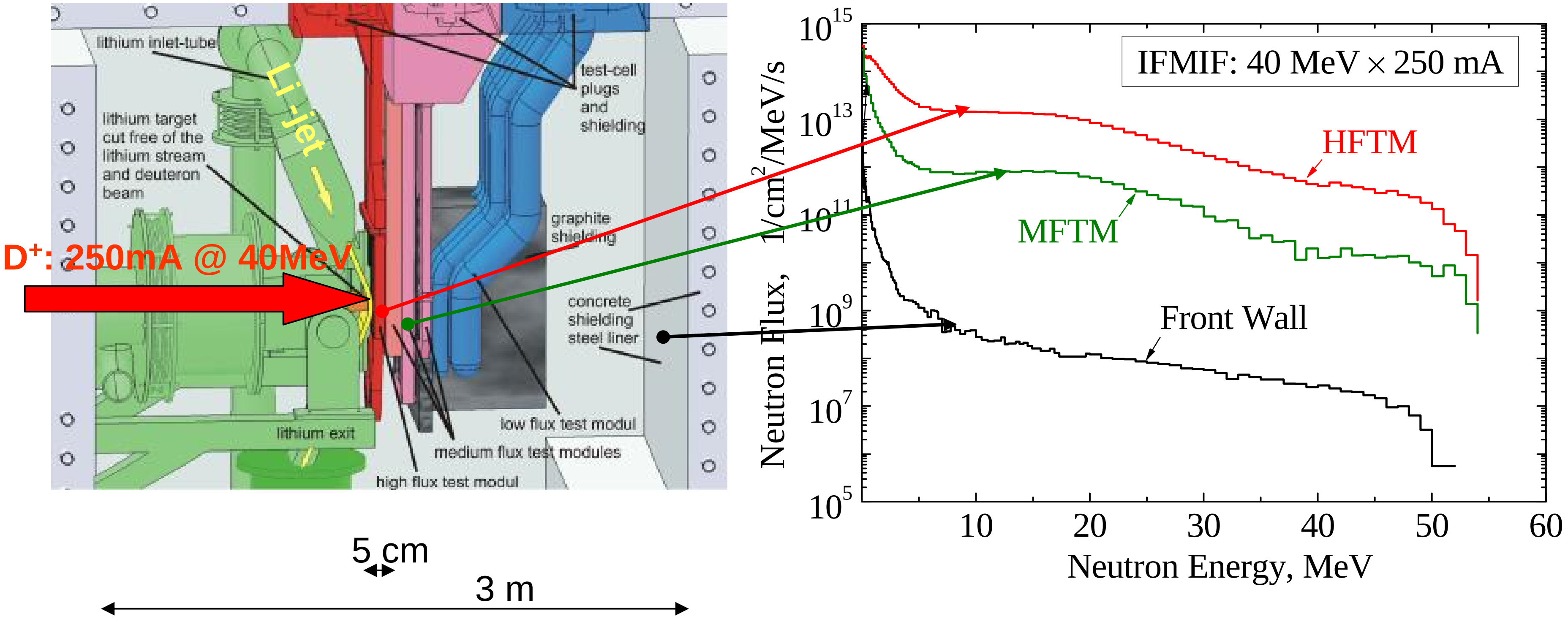
Angular smearing and multiple scattering smooth a 14 MeV neutron peak in HFTM, resulting to the shape without local extremes

S.P. Simakov et al. Fus.Eng.Des.82(2007)2510

Neutron spectra inside the Test Cell

IFMIF test cell design

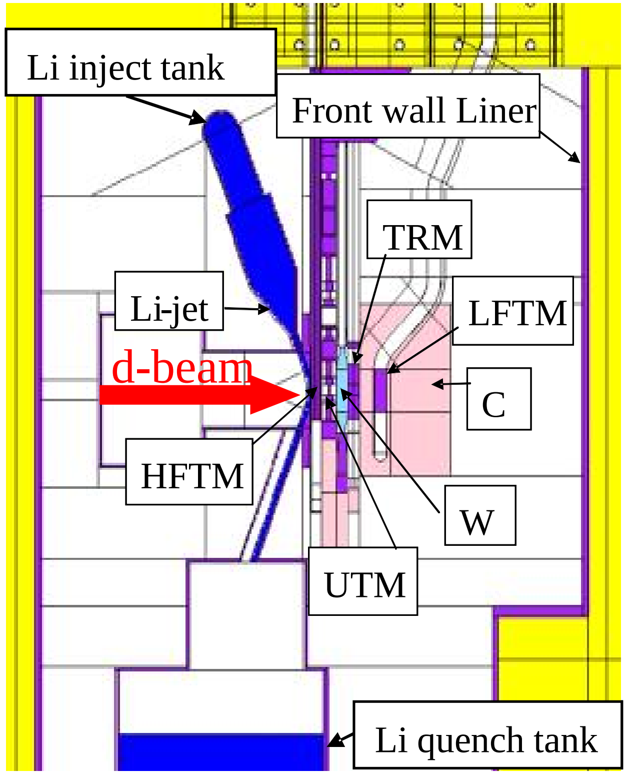
Calculated neutron spectra at different spots



Neutronics calculations do predict smoothed (no peaks) energy distribution all over the IFMIF test cell

Li-jet nuclear responses: Tritium and Be-7 Inventories

Test Cell & Li -loop



^{3}H and ^{7}Be production rates in Li-loop sub-systems (calculated by the McDeLicious code)

Loop component	Mass, kg	Reaction	Inventory	Rate, g/fpy
Li jet	1	d + Li	**^{7}Be**	**1.5**
		d + Li	^{3}H	6.0
		n + Li	^{3}H	0.4
Li injection tank	18	n + Li	^{3}H	0.2
Li quench tank	1200	n + Li	^{3}H	1.0
Li drain tubes	3	n + Li	^{3}H	0.1
Total			**^{3}H**	**7.7**

D-Li collision in jet is a main source of Tritium and Be-7 inventories in the Li-Loop

S.P. Simakov et al., JNM 329-333(2004)213

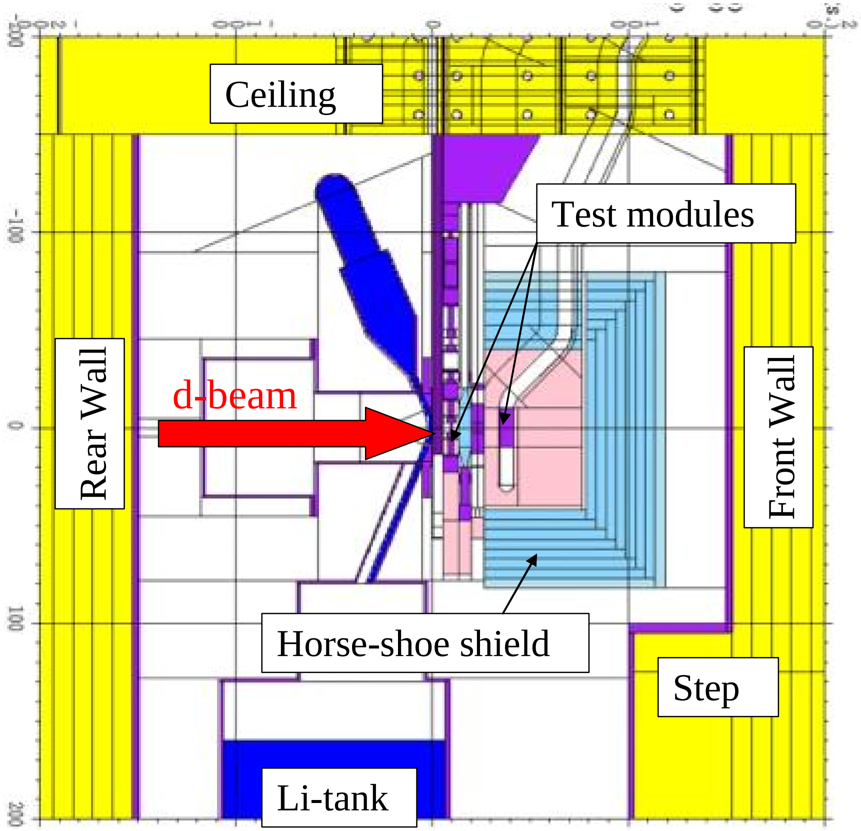
MCNP geometry model
for the IFMIF test cell
/latest version - md34/

developed by F. Wasastjerna
VTT Processes, Helsinki, Finland

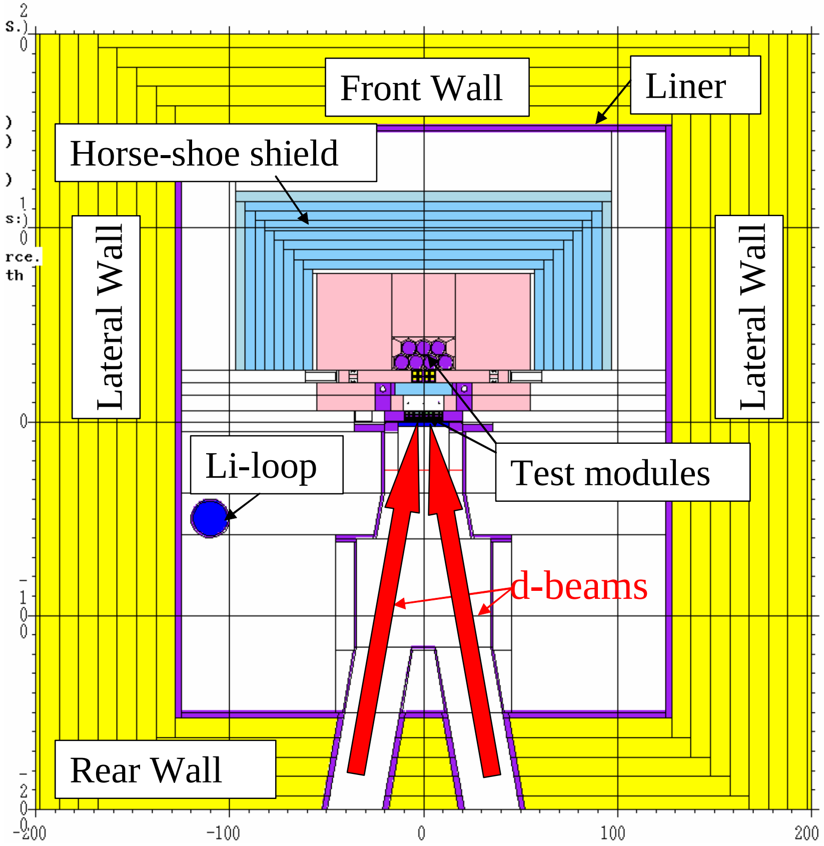
F. Wasastjerna, Ann. of Nucl. Energy 35(2008)438–445

MCNP geometry Model

Test Cell /Vertical cut/

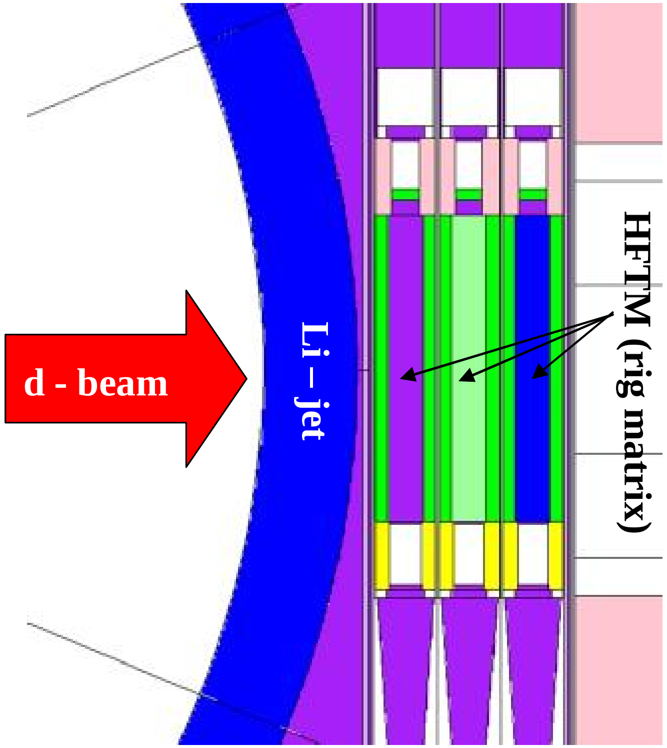


Test Cell /Horizontal cut/

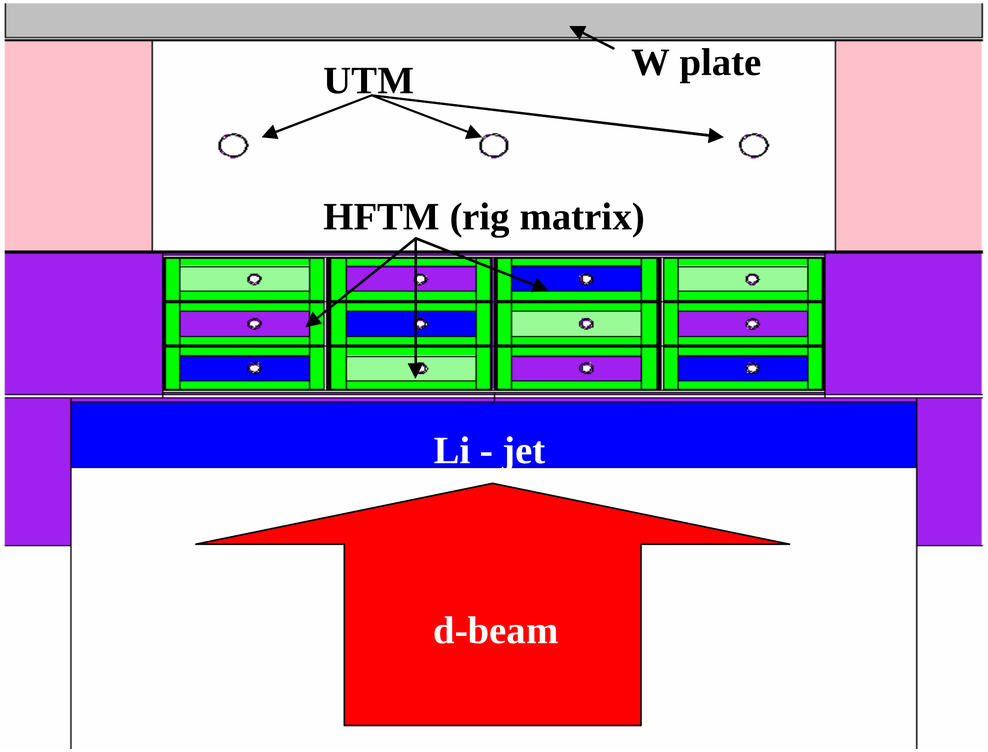


MCNP geometry Model (continued)

HFTM /Vertical cut/

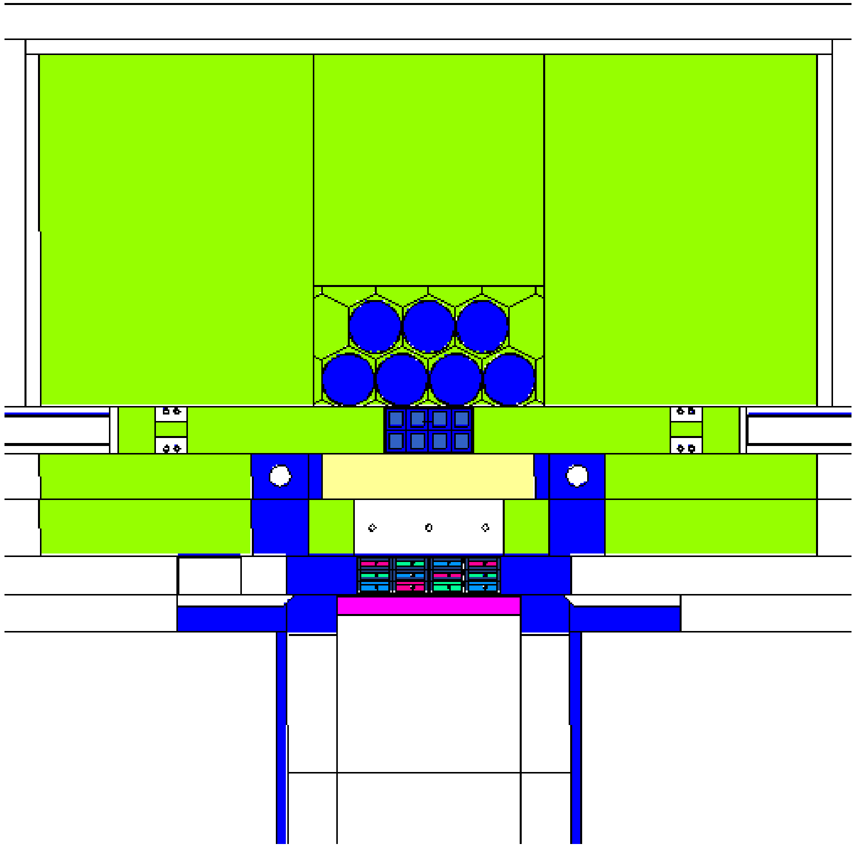


HFTM, MFTM, LFTM /Horizontal cut/

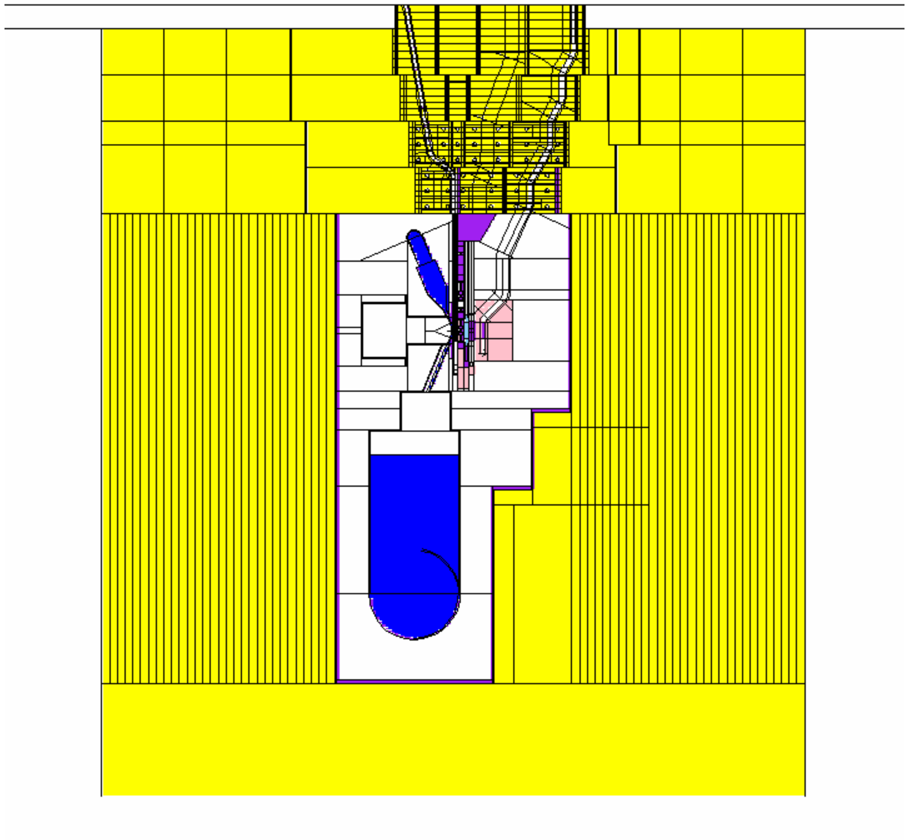


MCNP geometry Model (continued)

HFTM, MFTM, LFTM /Horizontal cut/



Test Cell and Walls /Vertical cut/



Evaluated cross sections data

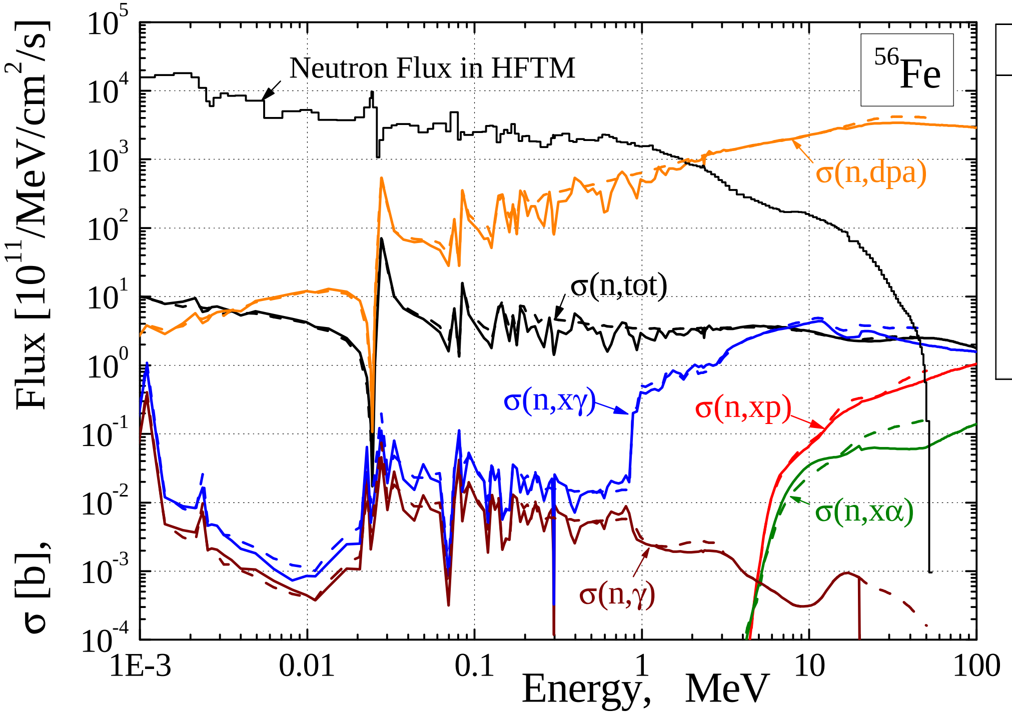
for neutron transport and
nuclear responses calculations
in the IFMIF

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

- IFMIF project
  - ^{1}H, ^{56}Fe, ^{23}Na, ^{39}K, ^{28}Si, ^{12}C, ^{52}Cr, ^{51}V, ^{6,7}Li, ^{9}Be (INPE/FZK)
  - $^{180,182\text{-}184,186}$W, ^{181}Ta (EFF/JEFF)
- LANL 150 MeV data files (ENDF/B-VI.6 or B-VII)
  - ^{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
  - $^{40,42\text{-}44,46,48}$Ca, ^{45}Sc, $^{46\text{-}50}$Ti, $^{54,56\text{-},58}$Fe, $^{70,72\text{-}74,76}$Ge, $^{204,206\text{-}208}$Pb, ^{209}Bi
- JENDL-HE data file
  - ^{1}H, ^{12,13}C, ^{14}N, ^{16}O, $^{24\text{-}26}$Mg, ^{27}Al, $^{28\text{-}30}$Si, ^{39,41}K, $^{40,42\text{-}\ 46,48}$Ca, $^{46\text{-}50}$Ti,^{51}V, $^{50,52\text{-}54}$Cr, ^{55}Mn, $^{54,56\text{-}58}$Fe, ^{59}Co, $^{58,60\text{-}62,64}$Ni, ^{63,65}Cu, $^{64,66\text{-}68,70}$Zn,$^{90\text{-}\ 92,94,96}$Zr, ^{93}Nb, $^{180,182\text{-}184,186}$W, $^{196,198\text{-}202,204}$Hg
- Few other evaluations
  - KAERI (^{12}C, ^{27}Al, ^{56}Fe, ^{208}Pb), BNL (^{12}C, ^{56}Fe,^{208}Pb, ^{209}Bi), IPPE ($^{232\text{-}238}$U, ^{237,239}Np, $^{236\text{-}244}$Pu)

Transport cross sections and nuclear responses

Evaluated neutron cross sections
(LANL – solid, INPE/FZK – dash)



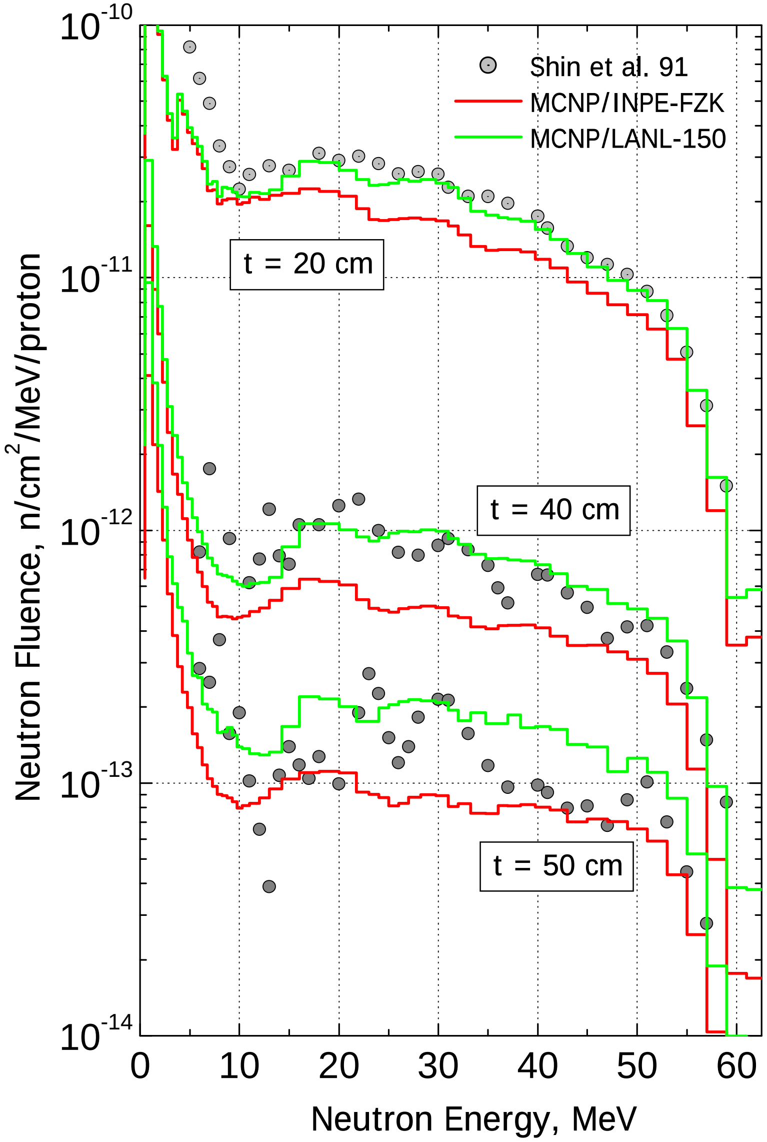
Responses in HFTM/IFMIF vs. Libraries
(uncertainties due to XS data)

Parameter	LANL	INPE	Differ.
dpa-rate, 1/fpy	31.1	33.6	8 %
Heating, W/cm3	16.9	19.7	16 %
H-production, appm/fpy	1602	1767	10 %
He-production, appm/fpy	345	396	13 %
n-flux, 10^{14}/cm2/s	7.05	7.43	5 %
γ-flux, 10^{14} /cm2/s	3.38	3.59	6 %

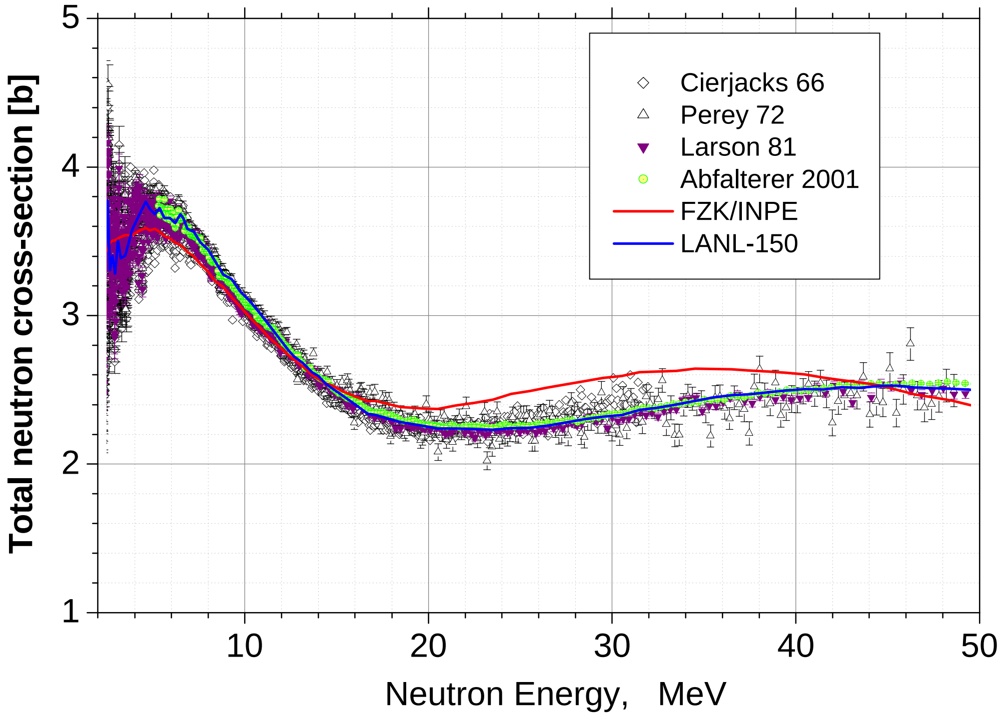
Expected uncertainties of IFMIF nuclear responses due to the transport cross sections data amounts at least (5 - 15)%

Iron Transmission Benchmark Experiment

Fe slabs (20, 40 50 cm) irradiated with source neutrons produced by 65 MeV protons on Cu target /TIARA, Shin et al./

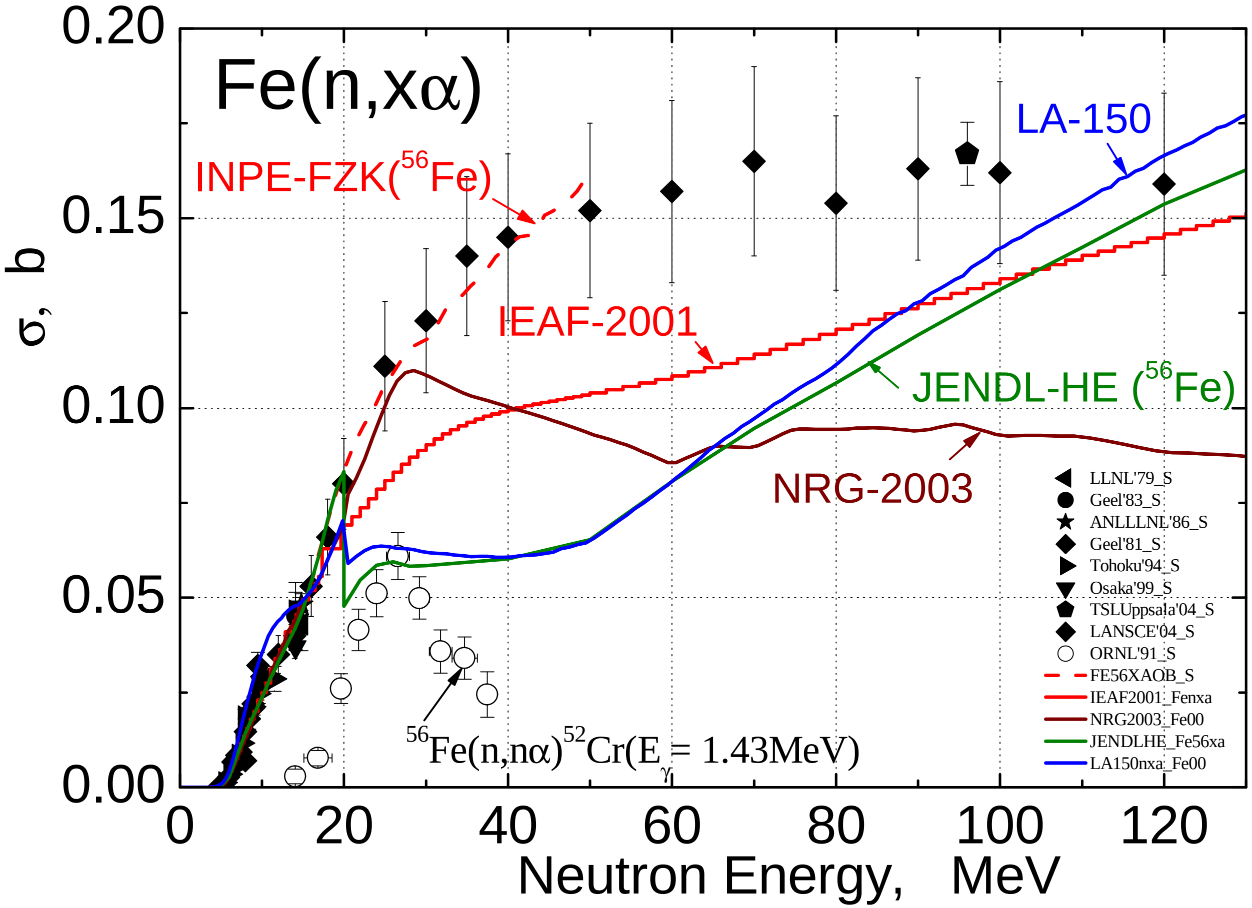


Fe(nat) total neutron cross-section



LA-150 looks more preferable than INPE-FZK

Gas (He) production cross-sections in Iron



INPE-FZK looks more preferable than LA-150 (?!)

Transport and nuclear response cross sections files for IFMIF

High Energy Files (up to 150 MeV)

LA-150 library (extension = 24c), xsdir = iedirLA

n + 1-H-1, H-2
n + 4-Be-9
n + 6-C-nat
n + 8-O-16
n + 13-Al-27
n + 14-Si-28, Si-29, Si-30
n + 20-Ca-nat
n + 24-Cr-50, Cr-52, Cr-53, Cr-54
n + 26-Fe-54, Fe-56, Fe-57
n + 28-Ni-58, Ni-60, Ni-61, Ni-62, Ni-64
n + 29-Cu-63, Cu-65
n + 74-w-182, W-183, W-184, W-186

Fusion Energy Files (up to 20 MeV)

JENDL-FF library (extension = 41c)

n + 22-Ti-46, Ti-47, Ti-48, Ti-49, Ti-50

(better to replace by JEFF-3.1, < 200 MeV

ENDF/B-VI library (extension = 60c)

n + 16-S-32

(better to replace by ENDF/B-VII, < 20 MeV)

IFMIF Energy domain Files (up to 50 MeV)

INPE/FZK library (extension = 95c)

n + 3-Li-6, Li-7	from file wq_Li6 and wq_Li7 (xsdir_wq_Li6_Li7)
n + 11-Na-23	from file iexs2 (bin) or iexs1 (ASCII, xsdir =iedir1)
n + 19-K-39	…
n + 23-V-51	…

McDeLicious:

programming details

McDeLicious Logic Structure

1. Main subroutine **source_lib-05.F90** does following:

for the First sampling history

- calls subroutine **load**(filename,..) which uploads in memory the ACE files with d-^{6}Li and d-^{7}Li cross sections

- reads beam parameters from the McDelicious input file such as number of beams, declination angle, d-beam spatial profile parameters, deuteron incident energy, Li-jet density, entrance surface and target cell

- calls subroutine **yield_Ed**(..) which calculates deuteron range in Li media, total neutron yield and prepares the tables for deuteron track sampling

McDeLicious Logic Structure (continued)

for All others sampling histories

- calls subroutine **yz_sample(…)** and samples deuteron direction and entrance point on the surface of Li target

- calls subroutine **sample_Ed(…),** which samples d-track length to collision and calculates this point (X,Y,Z), deuteron energy E_d and neutron weight W_n there

- samples whether isotope ^{6}Li or ^{7}Li a deuteron collides with

- subroutine **sample_EnAng (…)** – samples neutron emission Energy E_n , polar Θ_n and azimuth φ_n Angles using tables from d-Li ACE file

- submits to MCNP parameters of generated neutron:
  $\{X,Y,Z\}, \{cos_X, cos_Y, cos_Z\}, E_n, W_n, T_n=0$

2. Files **load_sample-05.F90** and **beam.F90** collect subroutines and functions mentioned above: *load, yield_Ed, sample_Ed, sample_EnAng, dedx, f_average, yz_sample, gausdev*

McDeLicious subroutines allocation and compilation with MCNP5 ones to get executable for *mpi* parallelism

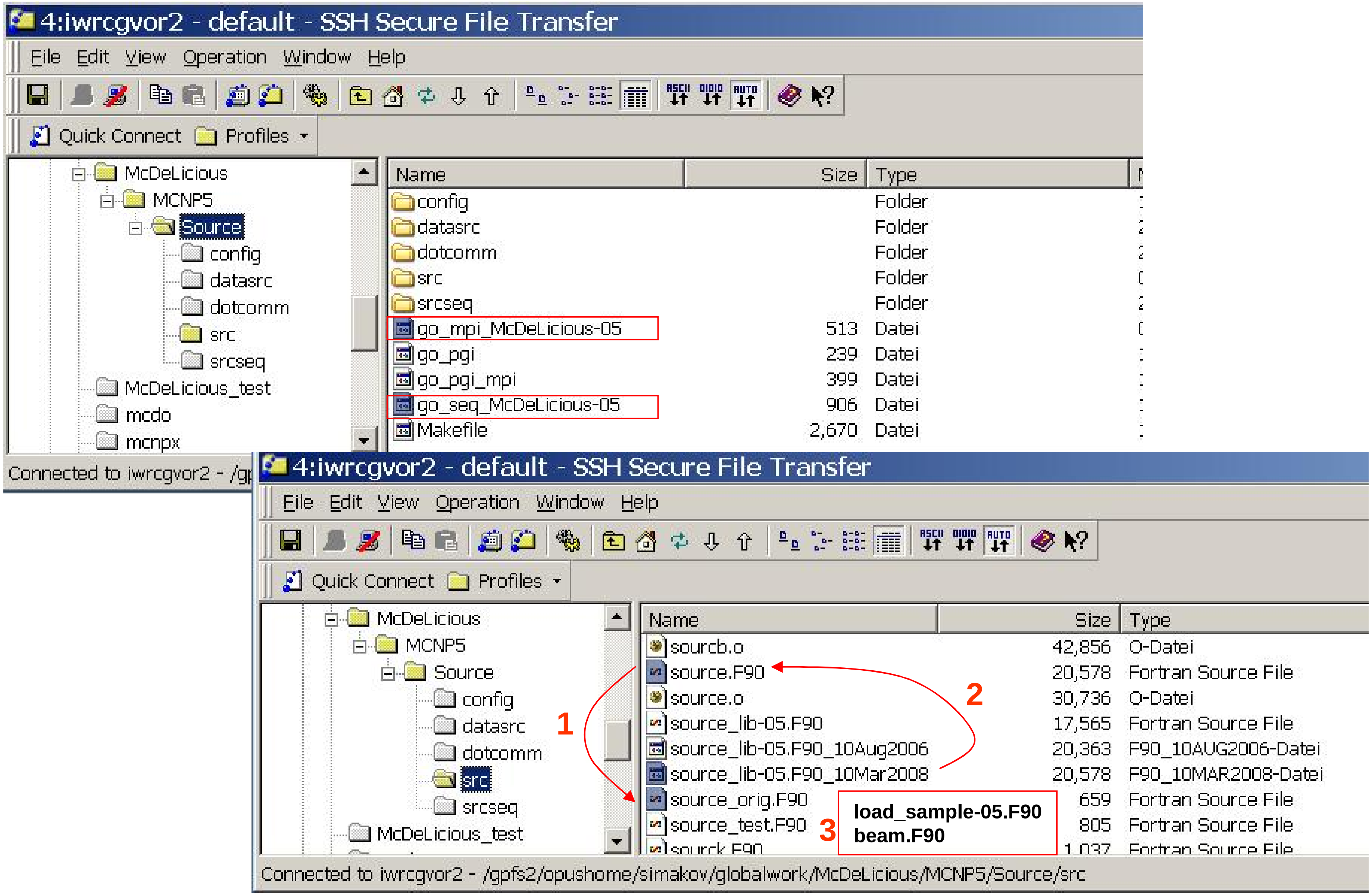
- Subroutine **source_lib-05.F90** should replace
  MCNP dummy subroutine **source.F90** in directory MCNP5/Source/src;
  files **load_lib-05.F90** and **beam.F90** should be allocated there too

- System dependent script for MCNP5 compilation **go_pgi_mpi**
  (after slight modification - **go_mpi_McDeLicious-05)**
  should be available in directory MCNP5/Source
  and has to be executed

- After successful compilation an executable file **mcnp5.mpi** will be produced
  which should be renamed to **McDeLicious-05**
  and moved in your working or bin directory

- To run McDelicious code one needs specific ACE files :
  d_li6_056.ace_up50 and **d_li7_056.ace_up50**
  - which are the d-^{6,7}Li evaluation processed by NJOY code

McDeLicious subroutines allocation in MCNP5 directories



Name	Size	Type
config		Folder
datasrc		Folder
dotcomm		Folder
src		Folder
srcseq		Folder
go_mpi_McDeLicious-05	513	Datei
go_pgi	239	Datei
go_pgi_mpi	399	Datei
go_seq_McDeLicious-05	906	Datei
Makefile	2,670	Datei

Connected to iwrcgvor2 - /gp

Name	Size	Type
sourcb.o	42,856	O-Datei
source.F90	20,578	Fortran Source File
source.o	30,736	O-Datei
source_lib-05.F90	17,565	Fortran Source File
source_lib-05.F90_10Aug2006	20,363	F90_10AUG2006-Datei
source_lib-05.F90_10Mar2008	20,578	F90_10MAR2008-Datei
source_orig.F90	659	Fortran Source File
source_test.F90	805	Fortran Source File
sourck.F90	1,037	Fortran Source File

load_sample-05.F90
beam.F90

Connected to iwrcgvor2 - /gpfs2/opushome/simakov/globalwork/McDeLicious/MCNP5/Source/src

McDeLicious Input File Structure

MCNP cards

message:Datapath=~/directory_for_data
xsdir=xsdir_file_for_cross_sections

empty line
Cell cards
empty line
Surface cards
empty line
Materials

IFMIF Test Cell geometry
and materials cards
(around lines 8000 lines)

Sp901
….
SP916

D-Li source specification cards
(see next slide)

MCNP cards

Tally cards
F6n,p cell_number
….

Responses specification cards
(see next slide)

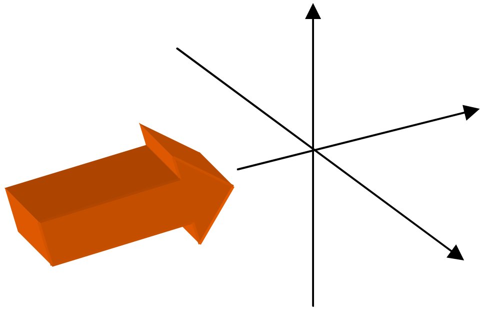
mode n,p
phys:p j 1
cut:n 1j 5.0E-7
nps 1.E+7

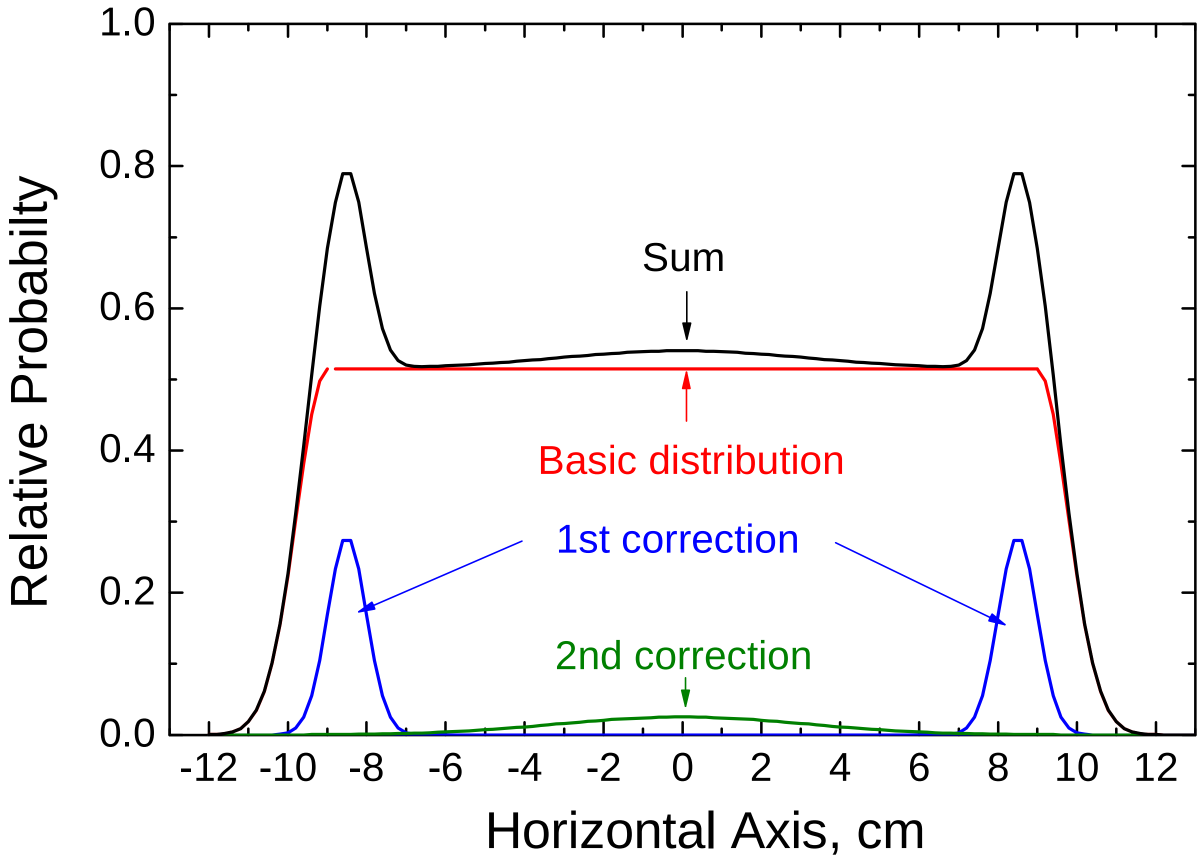
Problem specification cards

McDeLicious Input File: D-Li Source Specification

```
c  ------------------------------------------------------------ ------------------------------------------
c    two 40MeV d-beams declined in Horizontal plane by 10deg, 20x5cm2 Footprint
c  ------------------------------------------------------------ -----------------------------------------
c  beams     #1              # 2
SI901 L        1                 1                  $ target number
SI902 L        1                 1                  $ beams current (only relative value has meaning)
SI903 L       40                40                  $ beams energy Ed [MeV]
c             cos(x)   cos(y)   cos(z)      cos(x)  cos(y)    cos(z) for beam orientation
SI904 L 0.173648  0.  0.984808    -0.173648  0.  0.984808 $ beams 10deg in Horiz.
SI905 L   1 0 0             1 0 0                   $ beam orientation vector: along X-axis
c           Xo     σ    m   Xo     σ    m      for  beam spatial profile for 20 x 5 cm**2
SI906 L 9.0  0.6  1.00  9.0   0.6  1            $ basic  horizontal parameters
SI907 L 2.0  0.6  1.00  2 .0  0.6  1            $ basic      vertical parameters
SI908 L 8.5 0.25 0.35  8.5  0.25 0.35           $ first     horizontal correction
SI909 L 0     0     0      0     0      0          $ first         vertical correction
SI910 L 0   10     0.2    0   10   0.2          $ second horizontal correction
SI911 L 0    0      0      0     0      0          $ second     vertical correction
c          x    y     z         x      y    z       for beam centre coordinates
SI912 L 0    0 -2.68      0      0 -2.68          $ beam spot centre [cm] on Li-jet surface
SI913 L 2001                                        $ program cell number for Li-jet
SI914 L 0 0 1                                       $ target surface normal: along Z-axis
SI915 L 0.512    2.50                               $ target density [g/cm**3], thickness [cm]
SI916 L 0.075   0.925                               $ Li-6 and Li-7 relative Abundance
```

One d-beam spatial profile presentation





$$p(x) = m * \exp(-(x - x_0)^2 / 2s\ ) / \sqrt{2ps}$$ (+ Heaviside function for basic profile)

	Horizontal			Vertical		
	m	X_0, cm	σ, cm^2	m	X_0, cm	σ, cm^2
Basic	1.00	±9.0	0.60	1.0	±2.0	0.6
1st correction	0.35	±8.5	0.25	-	-	-
2nd correction	0.20	0.0	10.0	-	-	-

P. Wilson, Report FZKA 6218, 1999

Tallies and its normalization

Overal normalization

- All McDeLicious results (talleis) are normalized per one incident deteuron

Specific Tally normalization:

- Flux Tally (F4, F5) for Neutron and Photon [1/cm^2/s]:

I [mA] * 1.E-3 / (e$^-$=1.60218E-19) = 6.2415E+15 * I [mA] = 1.56045E+18 (I=250 mA)

- Heating Tally (F6:n,p) by neutrons and photons [W/g]:

I [mA] * 1.E-3 (MeV/J=1.60218E-13)/(e=1.602177E-19 C)= I [mA] *1.E+3 =2.5E+5 (I=250mA)

- Heating in material M using mean flux in Cell estimated by tally F4 [W/g]:

```
F4:n   cell
FM4    I [mA] * 1.E+3 *atom/gramm_denisity   M   -1  -4
F4:p   cell
FM4    I [mA] * 1.E+3 *atom/gramm_denisity   M   -5  -6
```

Tallies and its normalization (continued)

Displacement Damage Rate caused by neutrons in materials

$$Damage\_Rate[dpa/fpy] = F[n/cm^2/s] \times s_{dpa}[b] \times 1.E-24[cm^2/b] \times 3.1557E+7[s/fpy]$$

where:

F [n/cm^2/s] - neutron flux = F4[n/cm^2]* I [mA] * 1.E-3 / (e-=1.602177E-19 C)

$s_{dpa}[b] = 0.8 \times DE[b*MeV]/(2 \times E_d[eV])$ - displacement cross section

DE [MeV*b] - damage energy (available in MT=444)

E_d [eV] – threshold energy to displace atom in lattice (e.g., 40 eV for Fe)

Finally:

$$Damage\_Rate[dpa/fpy] = (78785.2/Ed \times I[mA]) \times F4[n/cm^2]$$

Example: dpa/fpy in Iron (material M) which fills the Cell;
d-beam current I = 250 mA

```
F4:n Cell
FM4 4.9241E+5   M   444
```

Tallies and its normalization (continued)

Gas production rate = gas atoms per 1 target atom over time unit

$$Gas\_Production\,[appm/\,fpy] =$$

$$= F[n/cm^2/s]\times s_{\,gas}[b]\times 1.E-24[cm^2/b]\times 3.1557E+7[s/\,fpy]\times 1.E+6[appm]$$

where:

F   [n/cm2/s] - neutron flux = F4[n/cm2]* I [mA] * 1.E-3 / (e-=1.602177E-19 C)

σ_{gas} [b]   - gas production cross-section MT=203 (H) or MT=207(He)

Finally:

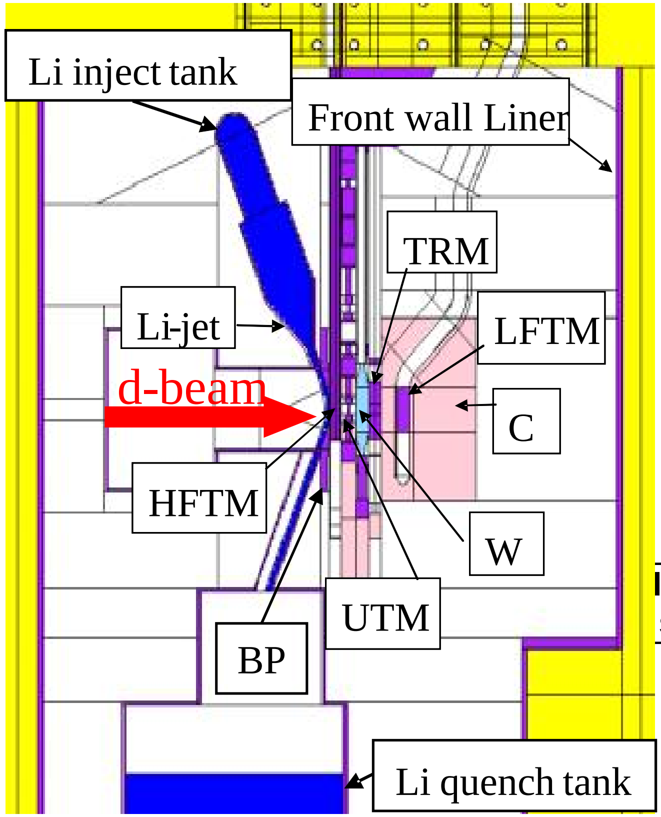
$$Gas\_Production[\ appm/\,fpy\ ] = (\,0.19696\times I[mA])\times F4[\ n/cm^2\ ]$$

Example: He [appm/fpy] in Iron (material M) which fills the Cell;
d-beam current I = 250 mA

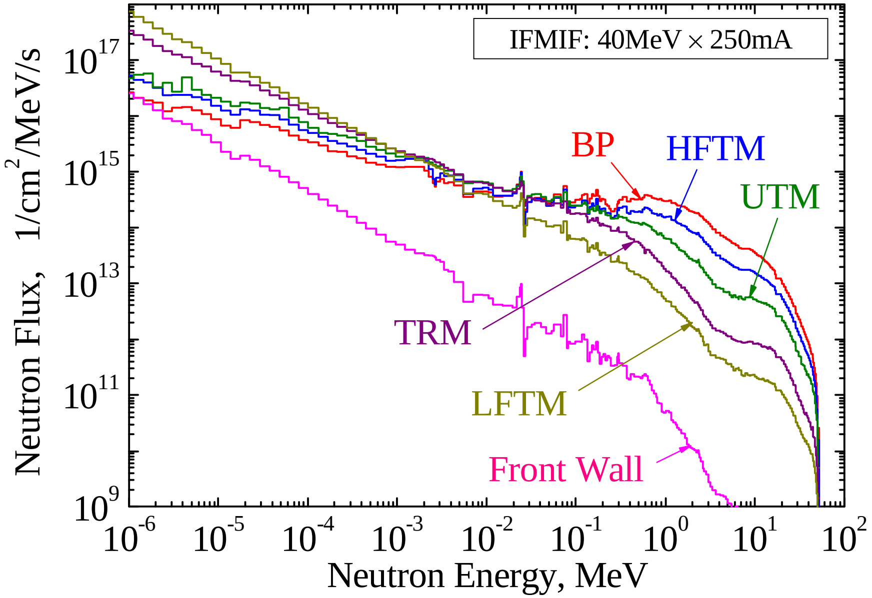
F4:n Cell
FM4 49.241   M   207

Nuclear Responses in the IFMIF sub-systems

Test Cell global model



Neutron energy fluxes in the IFMIF



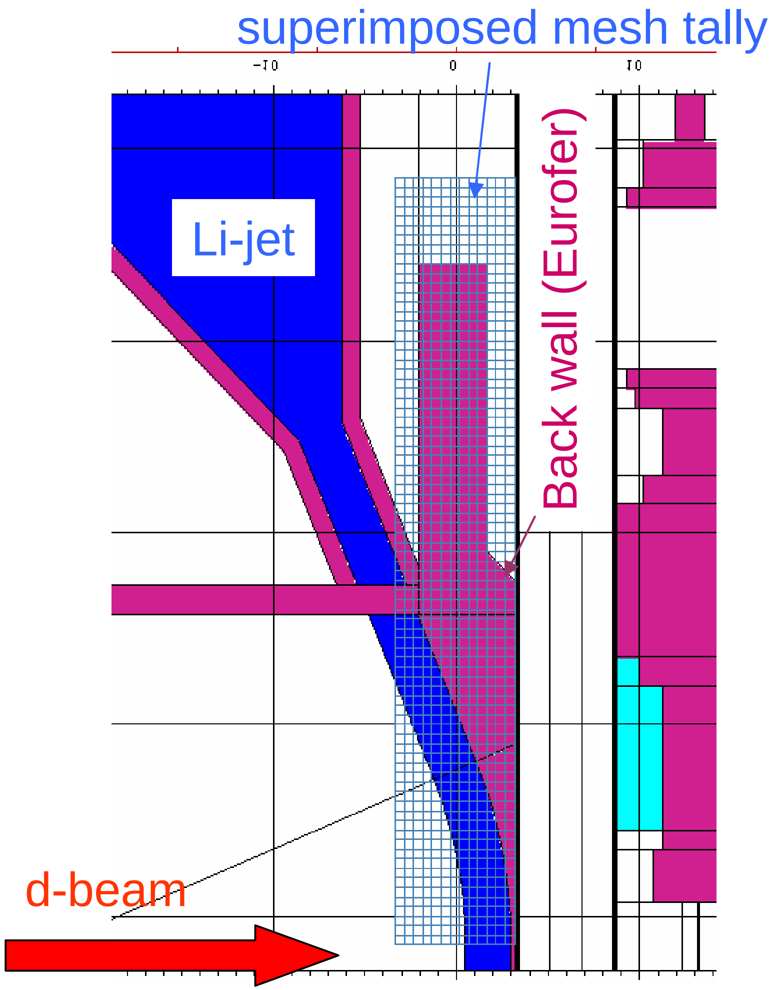
Neutron fluxes & dpa in the IFMIF components

IFMIF test cell sub-system	Neutron Flux, 10^{14} n/cm^2/s	Damage (Element), dpa/fpy
Li-jet back Plate (BP)	15.0	66 (Fe)
High Flux Test Module (HFTM)	7.3	20 - 55 (Fe)
Univers. Test Machine (UTM)	3.5	11 (Fe)
Tungsten Moderator (W)	2.0	1.1 (W)
Tritium Release module (TRM)	1.1	2.4 (Fe), 3.5 (Be)
Low Flux Test Module (LFTM)	0.61	0.65 (Fe)
Front wall steel liner	0.01	0.004 (Fe)

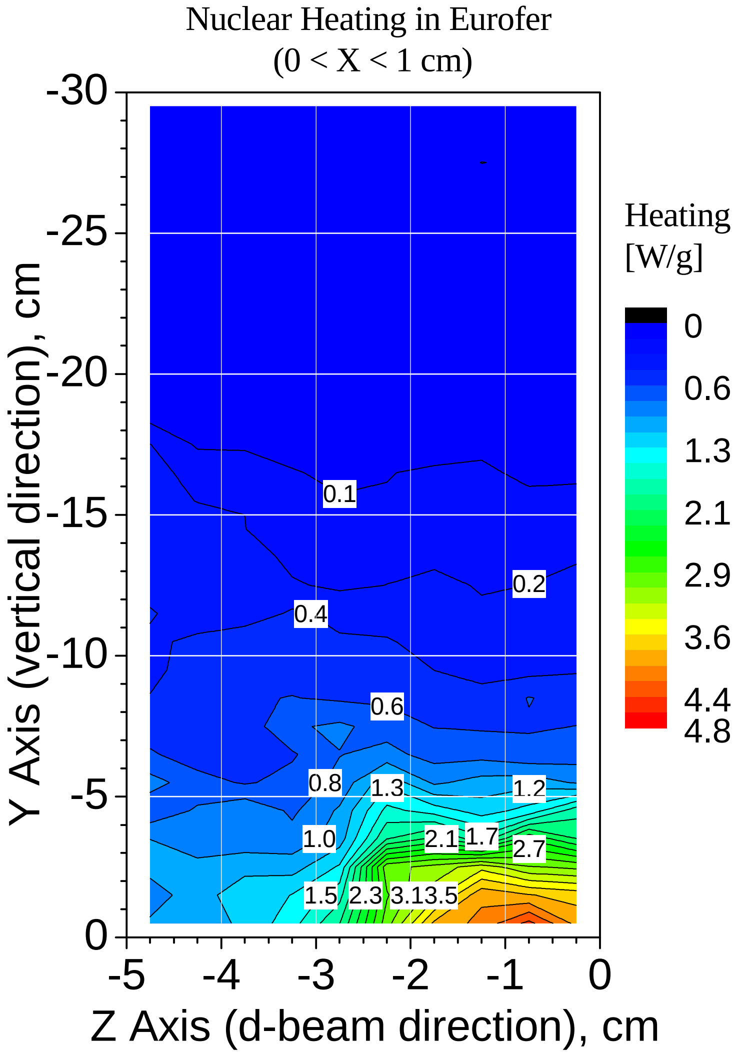
S.P. Simakov et al. Fus.Eng.Des.75-79(2005)813

Nuclear Responses in the IFMIF sub-systems /F4 mesh tallies capabilities/

Model fragment of Li-jet backed by Wall



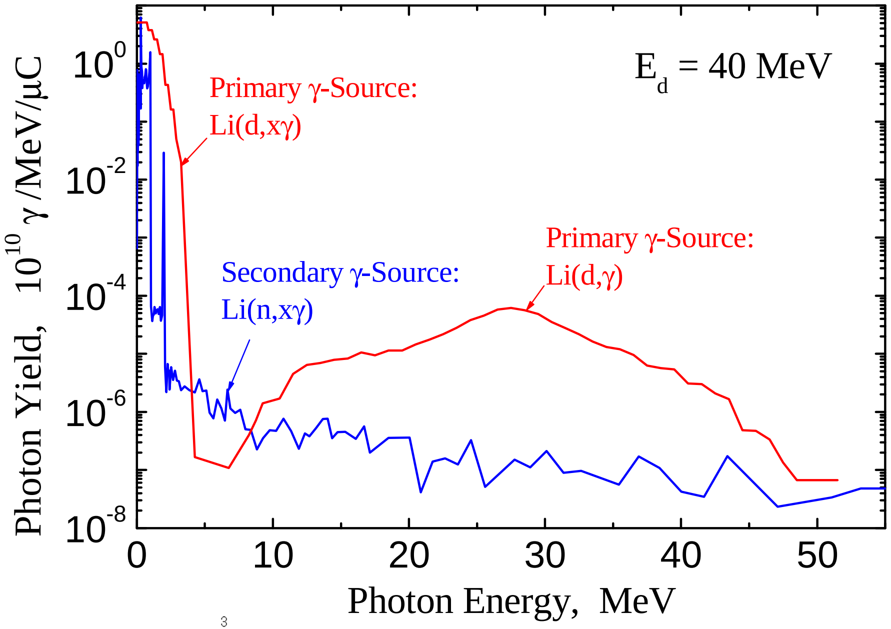
Nuclear Heating in Eurofer from F4 mesh tally



IFMIF neutronics, McDeLicious code
Test Cell geometry model:

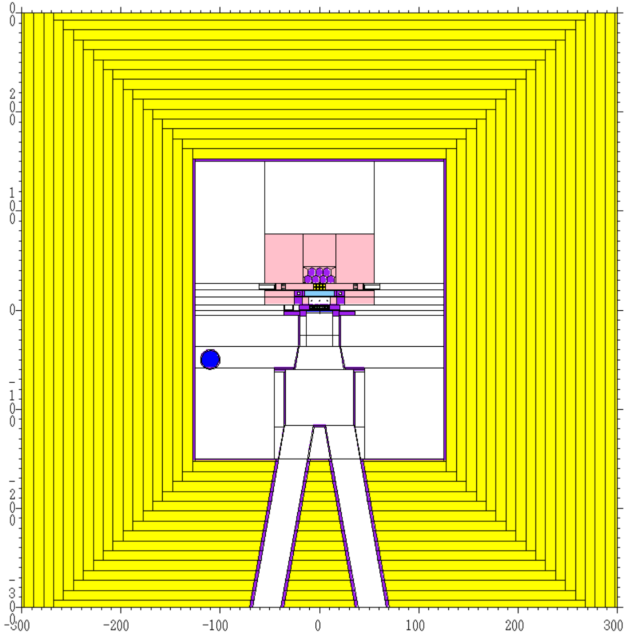
further developments

McDeLicious further development



Direct Gamma-source:

inclusion of Li(d,xg) photons to account their contribution to the responses



Variance reduction:

biasing of d-Li source angular distribution to improve statistics for backward directions and for streaming through the shield

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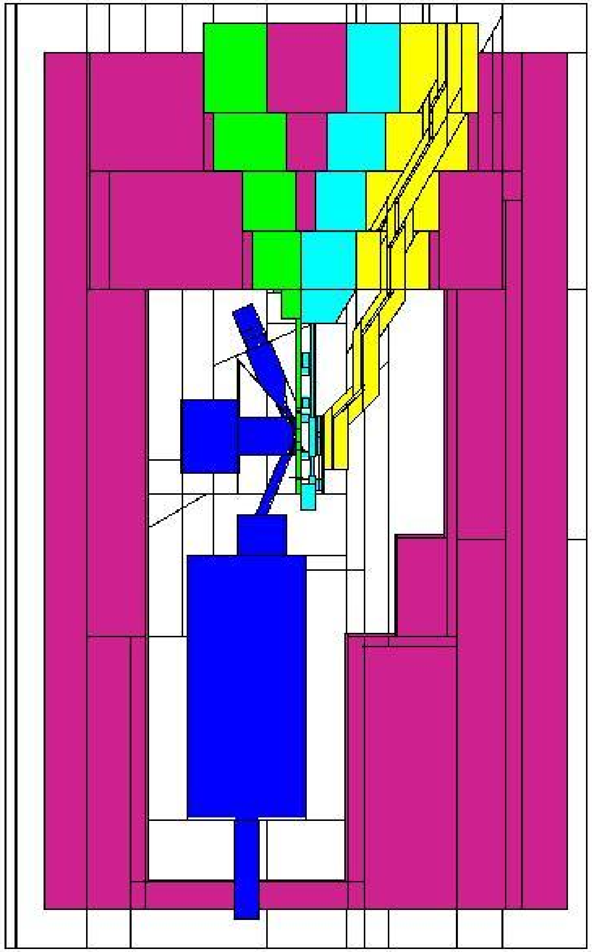
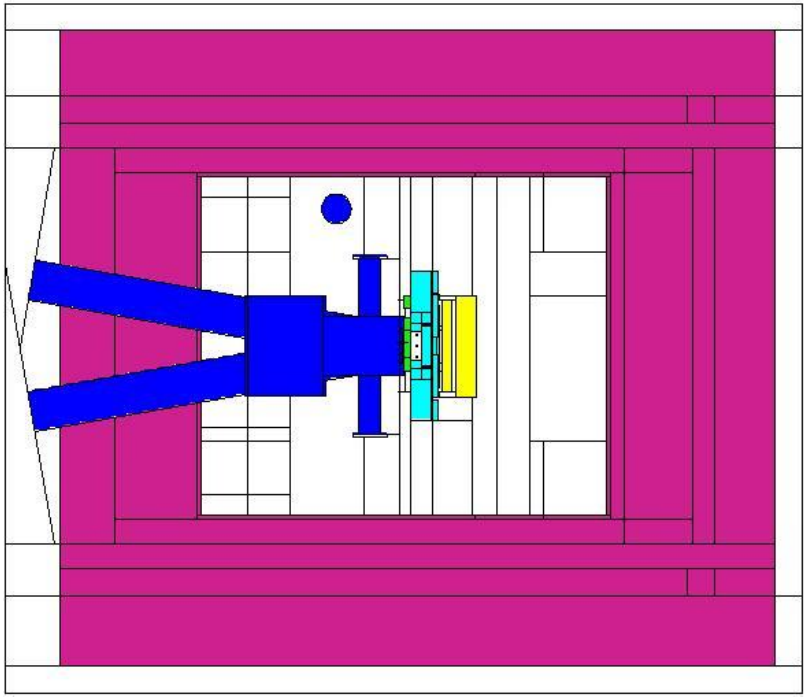
IFMIF Test Cell MCNP Model converted by McCAD from CAD

Vertical cut of test cell



Horizontal cut at target mid-plane level



H. Tsige-Tamirat et al. Fus. Eng.Des.,82(2007)1956