Other applications of IFMIF/DONES: Material irradiations at high neutron fluences and high energies

IFMIF/ELAMAT Town Meeting, Rzeszów, Poland, April 14-15, 2016

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This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Background/motivation

IFMIF Intense Neutron Source

International Fusion Material Irradiation Facility

- Conceived as intense neutron source for the high fluence irradiation and qualification of materials considered for future fusion power reactors.
- Key issue: To provide a neutron flux density ≈ 10^{14} -10^{15} $cm^{-2}s^{-1}$ with “first-wall-like” fast neutron spectrum and continuous irradiation scheme at elevated temperature levels.
- Accelerator based IFMIF neutron source can provide such conditions in a small irradiation volume with two deuteron beams (125 mA, 40 MeV) impinging on a liquid Lithium target.
- Material specimens placed in carefully designed and optimised irradiation assembly called High Flux Test Module (HFTM) backed with further modules for irradiation at lower flux levels.
- Lithium target and Test Modules are arranged in the Test Cell room with a typical dimension of 4x4x3 m^3

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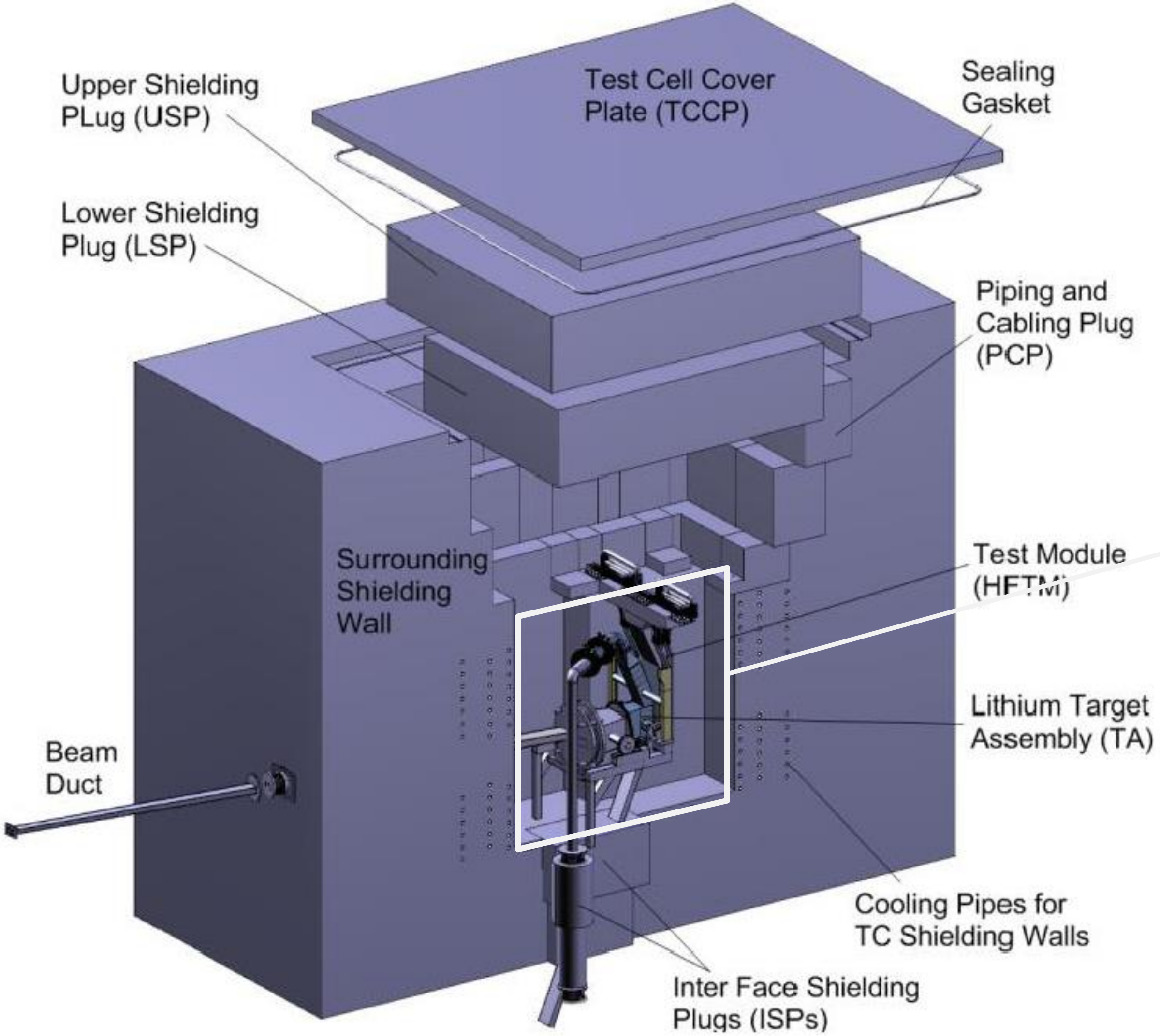
IFMIF/DONES Neutron Source

Demo Oriented Neutron Source

- Under development within the Early Neutron Source (ENS) project of EUROfusion’s Power Plant Physics and Technology (PPPT) programme.
- Projected as intermediate irradiation test facility with a reduced performance goal aiming at the provision of irradiation data required for the construction of DEMO within time schedule assumed in the European fusion roadmap.
- Utilizes one full IFMIF accelerator with a deuteron beam (125 mA, 40 MeV) producing half the neutron intensity of IFMIF.
- This approach allows upgrading DONES at a later stage to the full IFMIF performance with a second accelerator.
- Lithium target, Test Cell and HFTM of DONES and IFMIF are identical while other irradiation modules are not considered in DONES.
- Absence of other irradiation modules in the full size Test Cell of DONES allows utilizing the available radiation field for other irradiation purposes.

IFMIF/DONES Test Cell Configuration



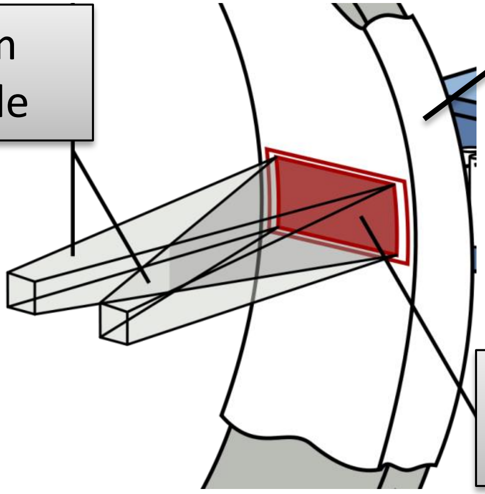
Lithium target, Test Cell, HFTM identical but no other irradiation modules in DONES

Test Cell inner dimensions: 4x4x2.8 m^3

Computational Tools & Models

McDeLicious Monte Carlo Code

- Developed at FZK/KIT to represent the d-Li neutron and gamma source term properly in Monte Carlo transport calculations for IFMIF
  - Deuteron beam configuration, orientation and profile
  - Deuteron slowing down in Lithium
- Enhancement to MCNP5 with tabulated double-differential d + ^{6,7}Li cross-section data up to 50 MeV



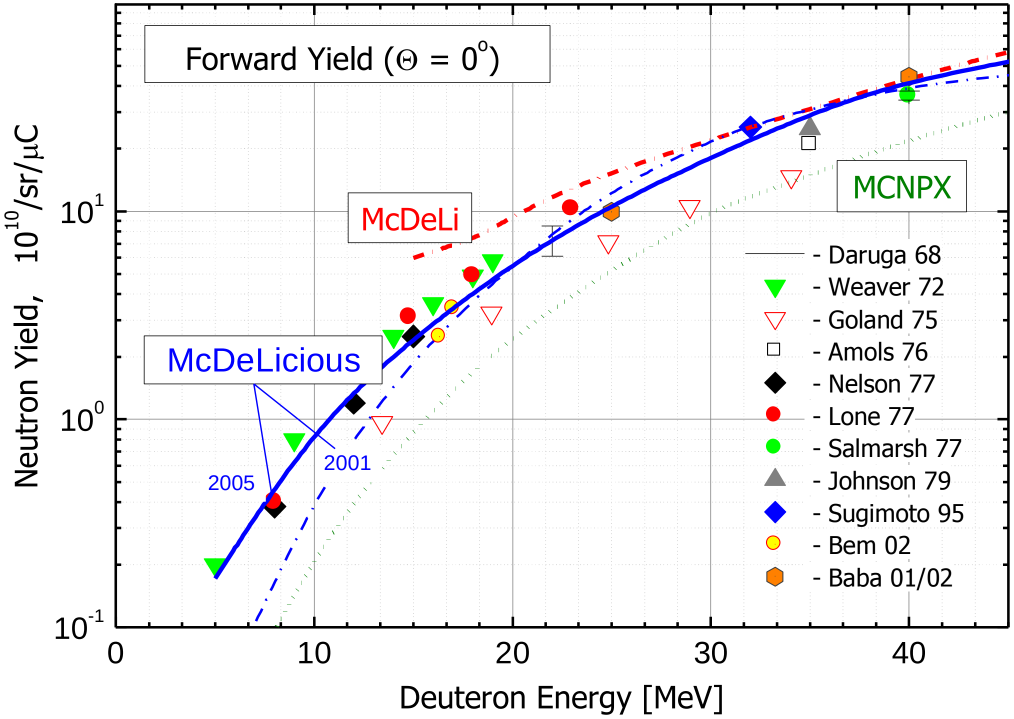
Liquid lithium target
25-mm thickness

Two deuteron beam
9 deg. Incident angle

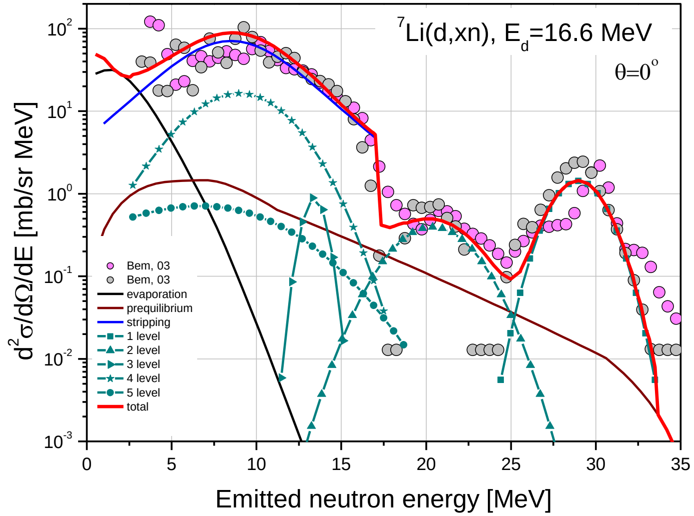
Beam footprint
20-cm width, 5-cm height

McDeLicious Monte Carlo Code

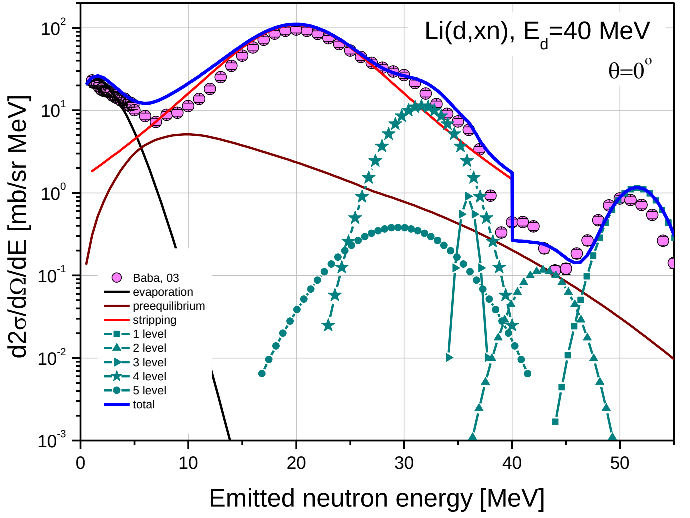
Thick Li-target Neutron Yields: McDeLicious prediction vs. measured data



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



M. Hagiwara et al., FST 48(2005)1320

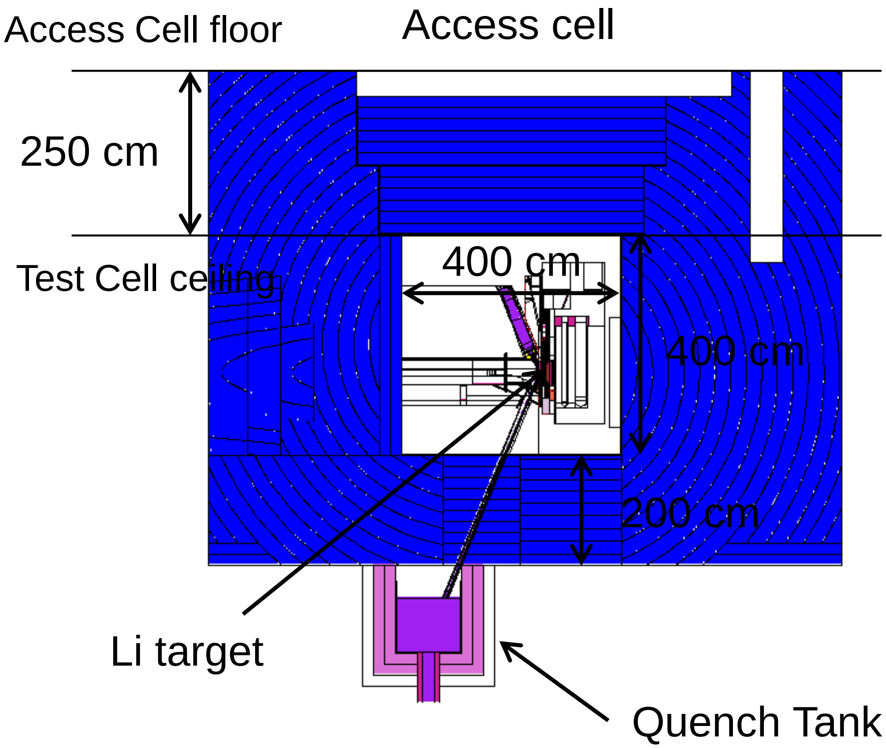


IFMIF/DONES neutronics calculations

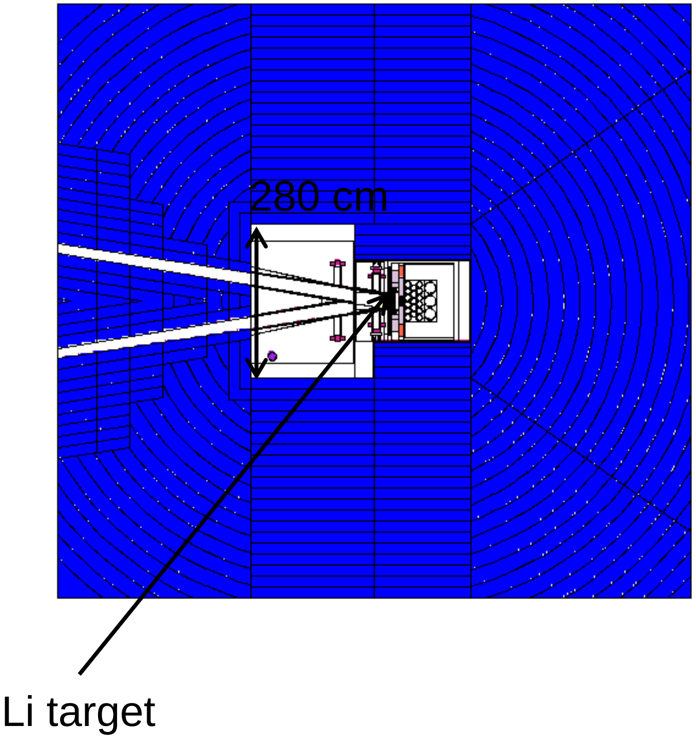
- Monte Carlo calculations using McDeLicious code with FENDL-3.0 neutron cross-section data extending up to 150 MeV
- Detailed 3D IFMIF/DONES model, processed from CAD geometry, including Li Target Assembly, deuteron beam ducts, Test Cell with Cover/Walls, Test Modules, Li pipes and Quench Tank
- Nuclide inventory calculations using FISPACT code with FENDL-3.0 activation cross-section data

IFMIF Test Cell calculation model

Vertical cut

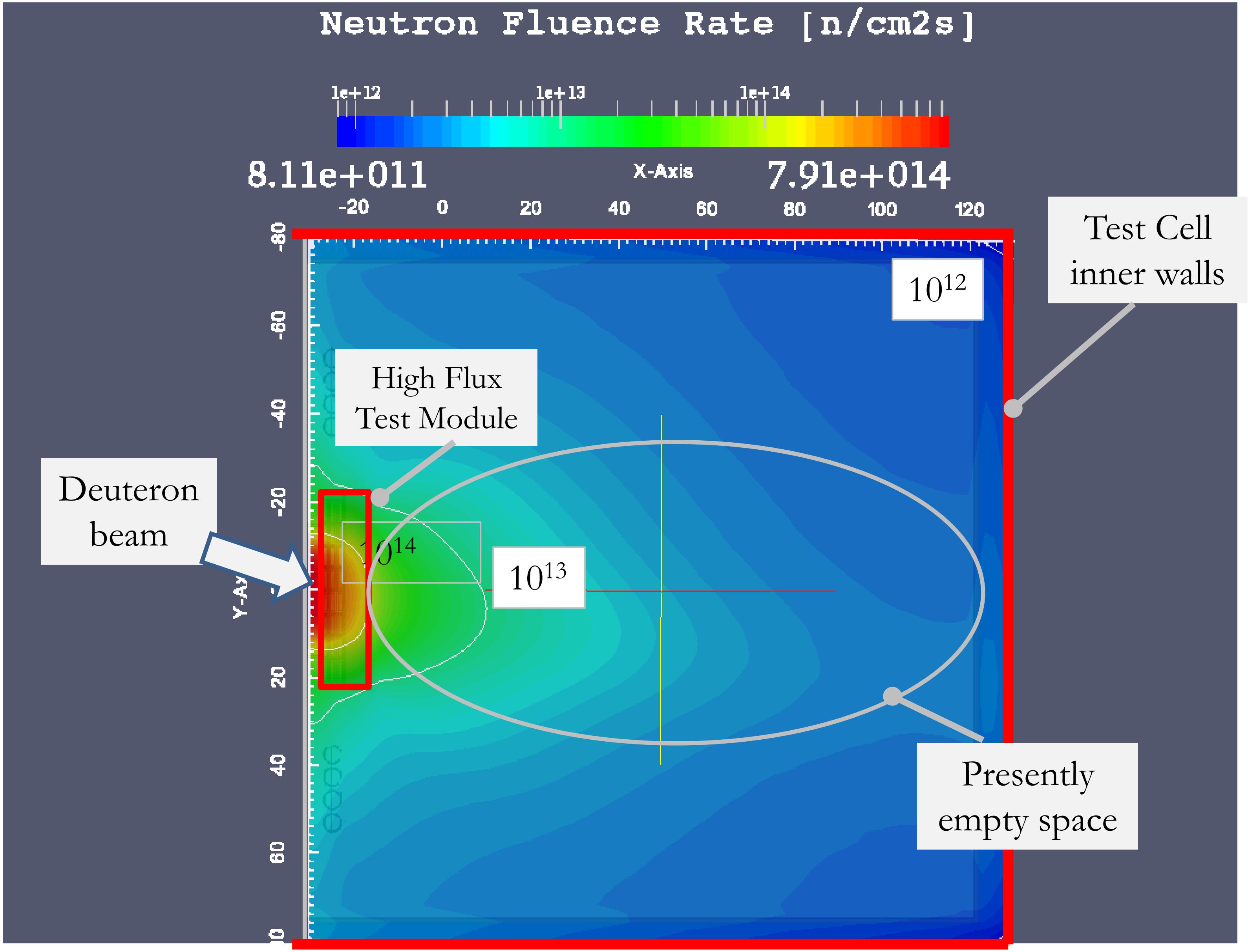


Horizontal cut



Radiation Fields

DONES Test Cell – Neutron flux map



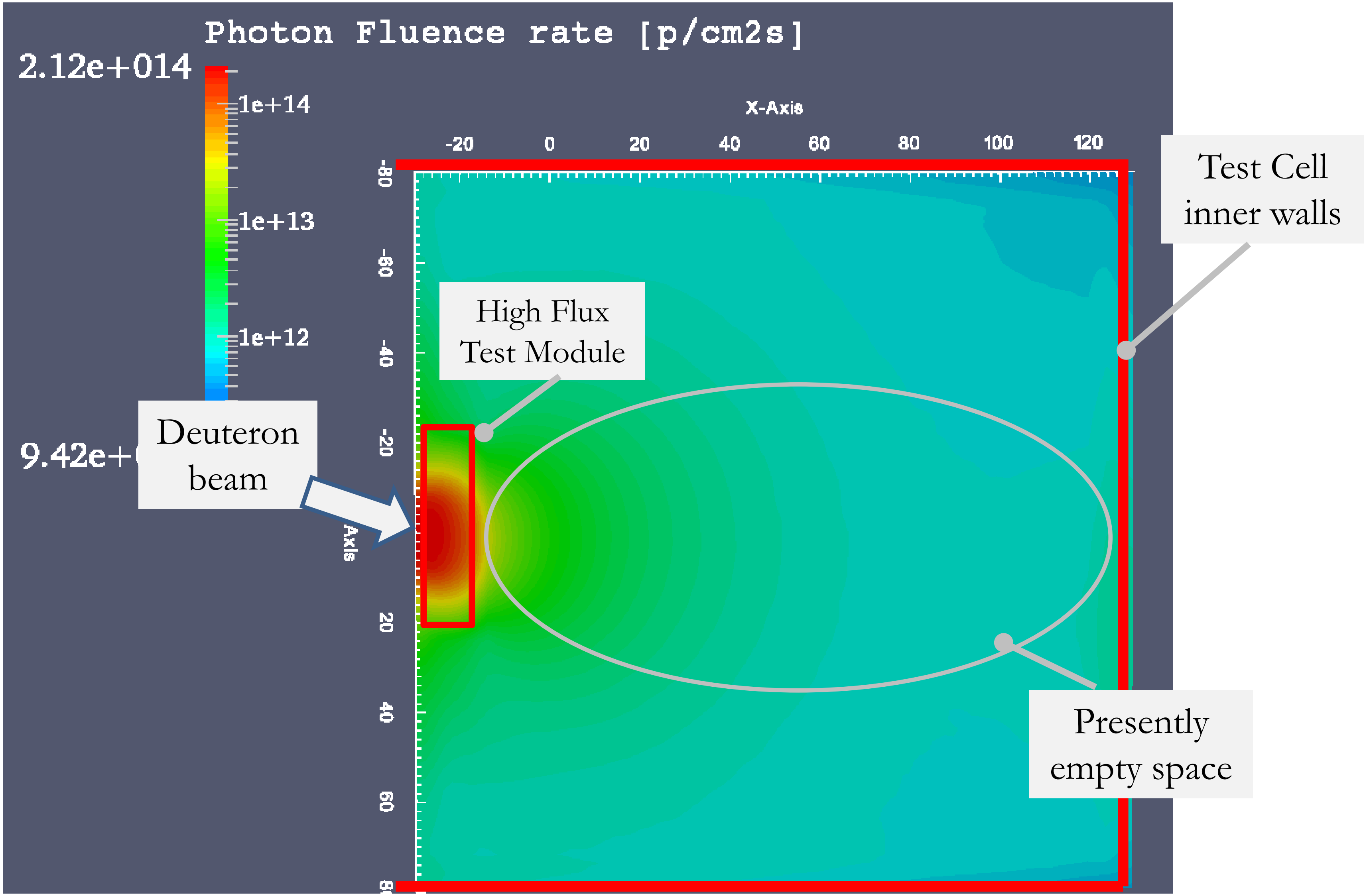
Test Cell inner walls

High Flux Test Module

Deuteron beam

Presently empty space

DONES Test Cell – Photon flux map



Test Cell inner walls

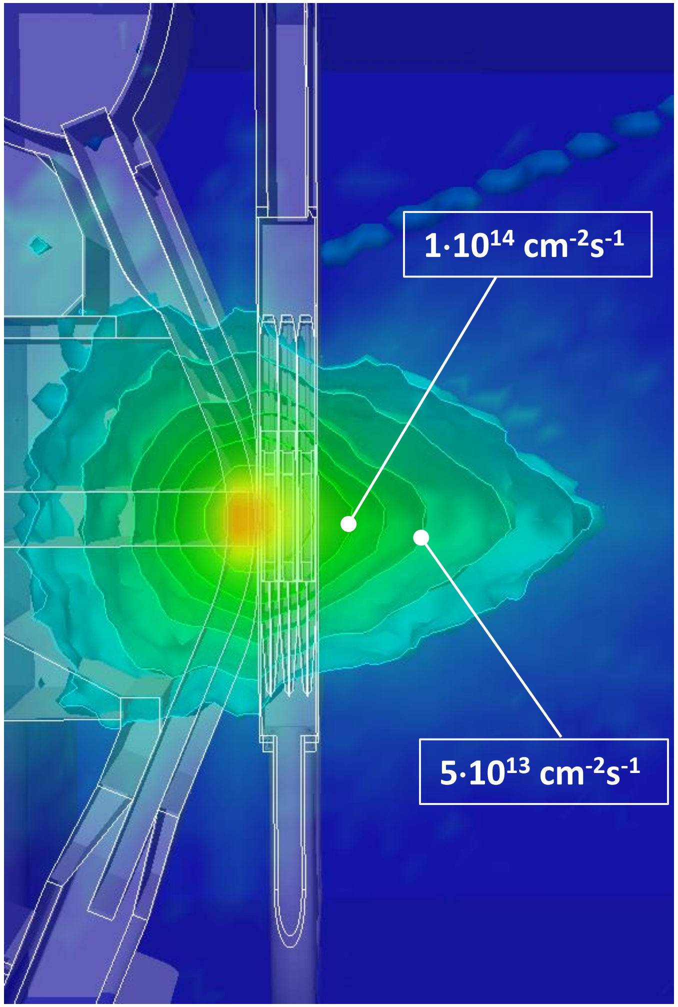
High Flux Test Module

Deuteron beam

Presently empty space

ENS/DONES Neutron Flux Distribution

Vertical cut



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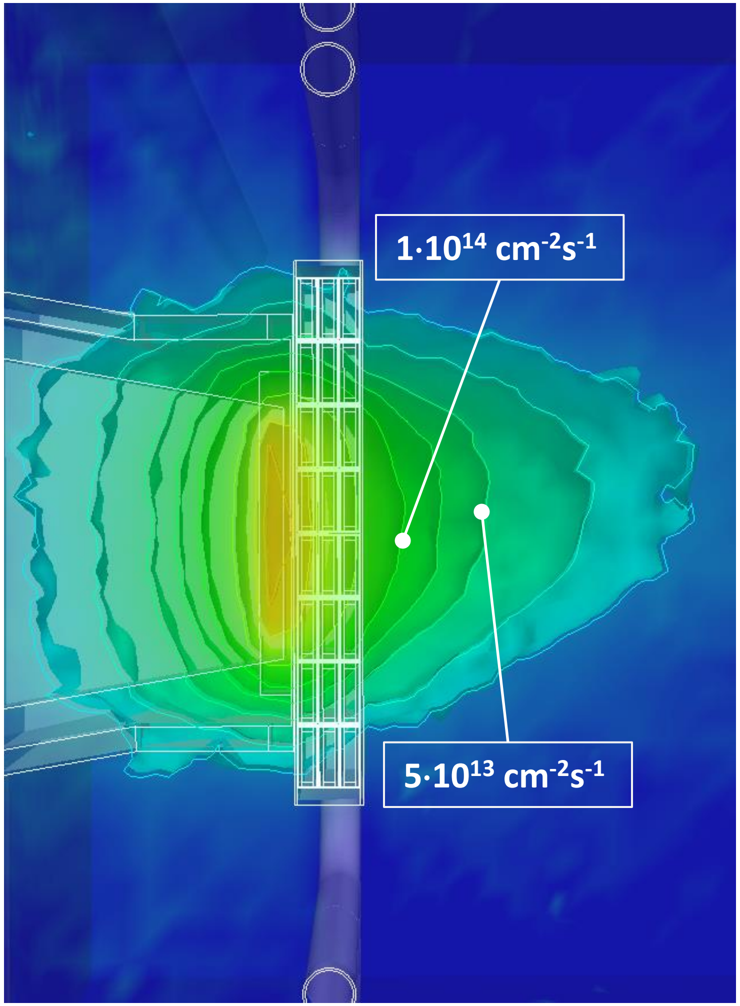
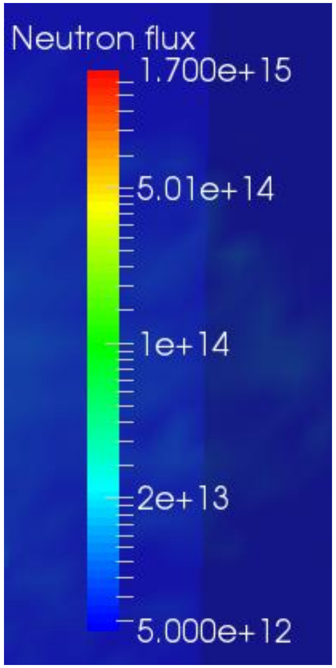


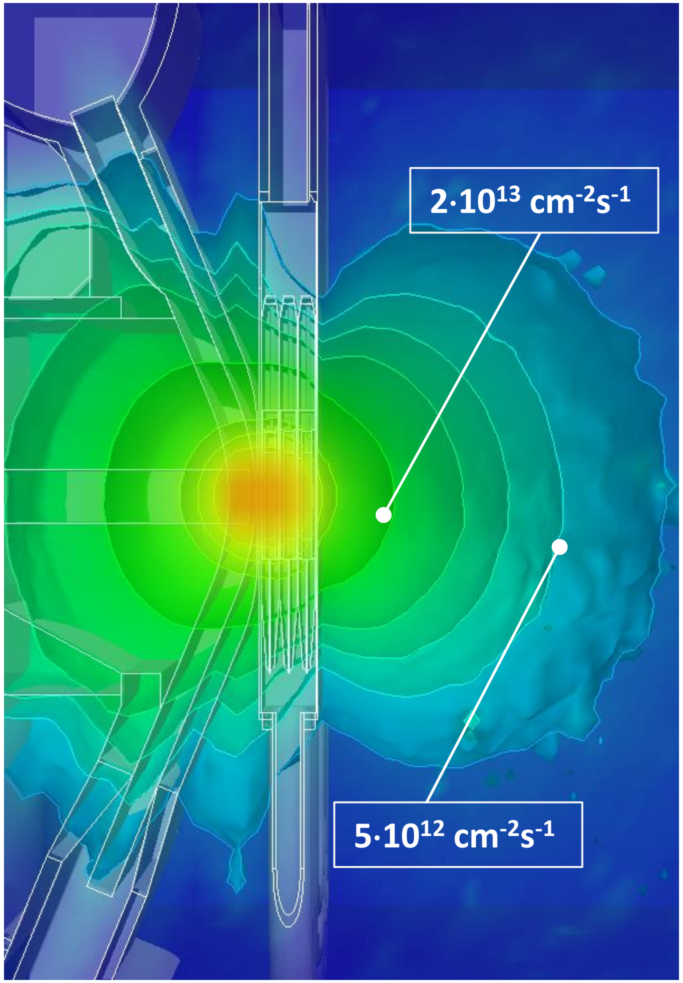
DONES

One deuteron beam,
125 mA, 40 MeV



ENS/DONES Gamma Flux Distribution

Vertical cut



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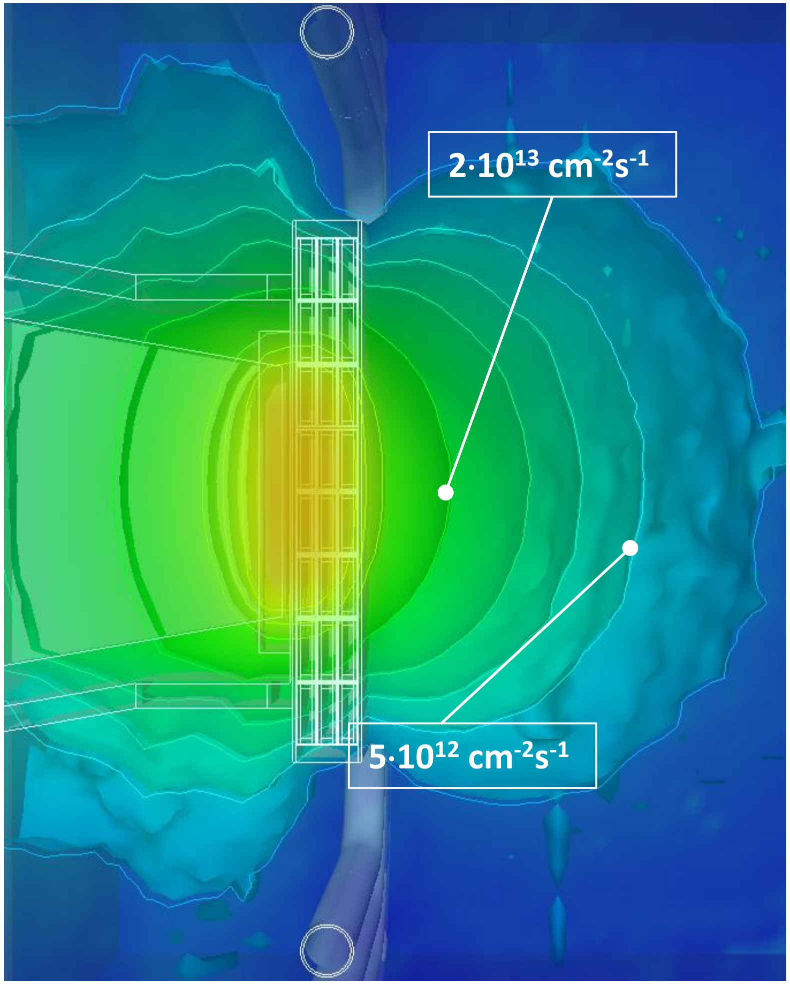

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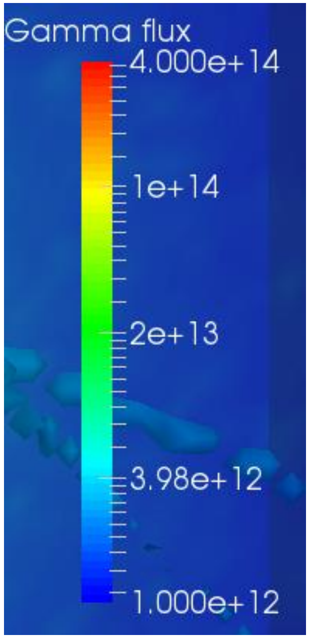
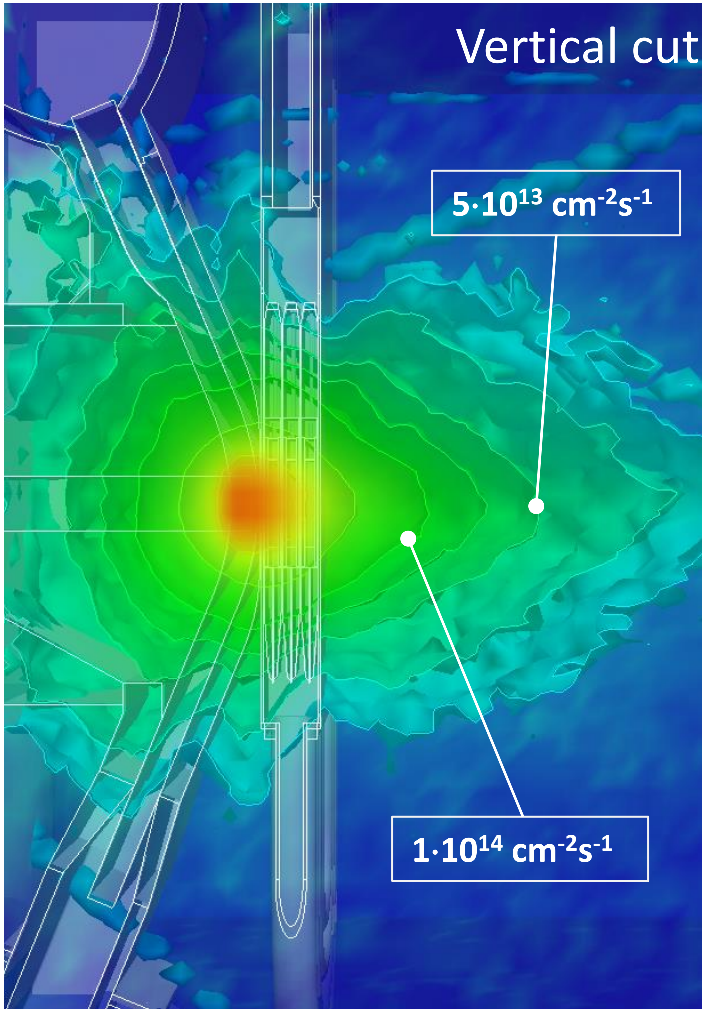


IFMIF vs. DONES: Neutron Flux Distribution

IFMIF

Two deuteron beams, 2 x 125 mA, 40 MeV



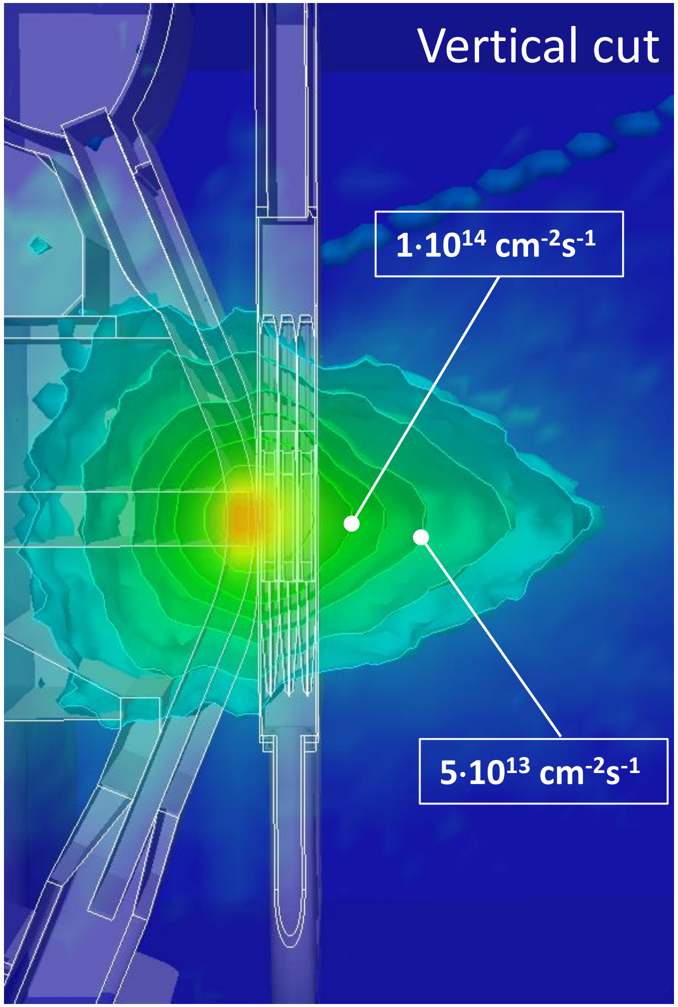
Vertical cut

$5\cdot10^{13}$ cm^{-2}s^{-1}

$1\cdot10^{14}$ cm^{-2}s^{-1}

DONES

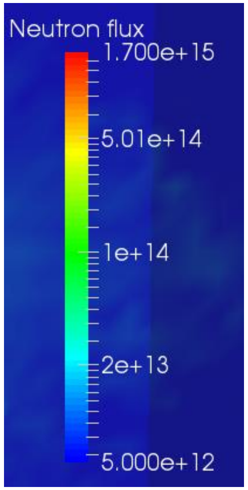
One deuteron beam, 125 mA, 40 MeV



Vertical cut

$1\cdot10^{14}$ cm^{-2}s^{-1}

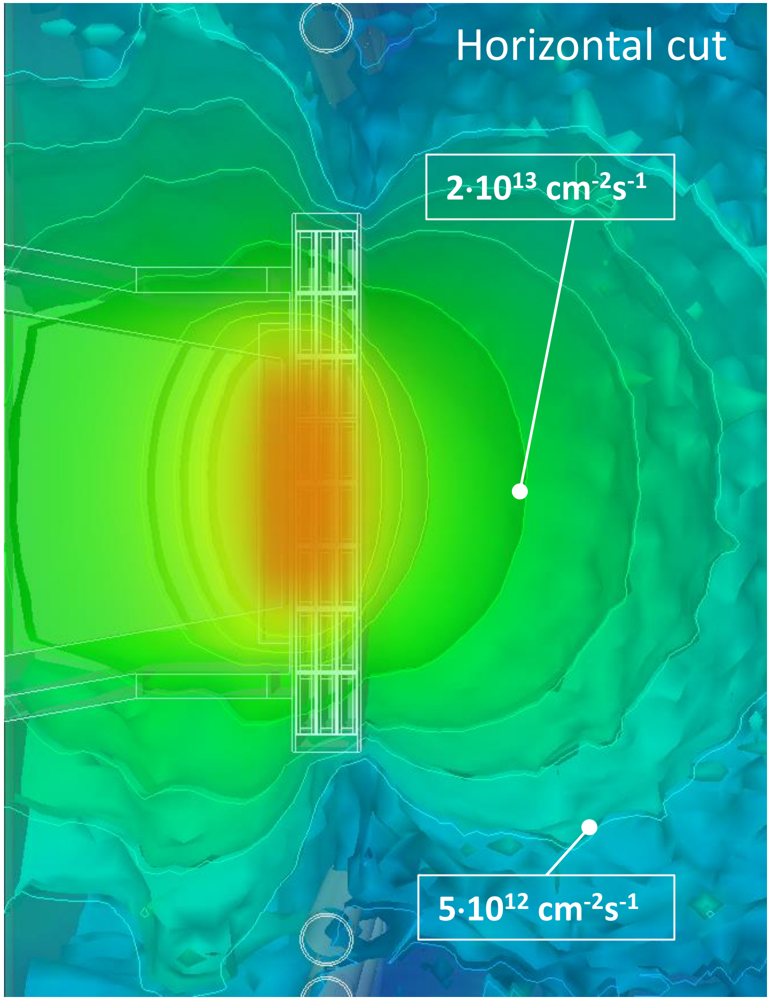
$5\cdot10^{13}$ cm^{-2}s^{-1}



IFMIF vs. DONES: Gamma Flux Distribution

IFMIF

Two deuteron beams, 2 x 125 mA, 40 MeV



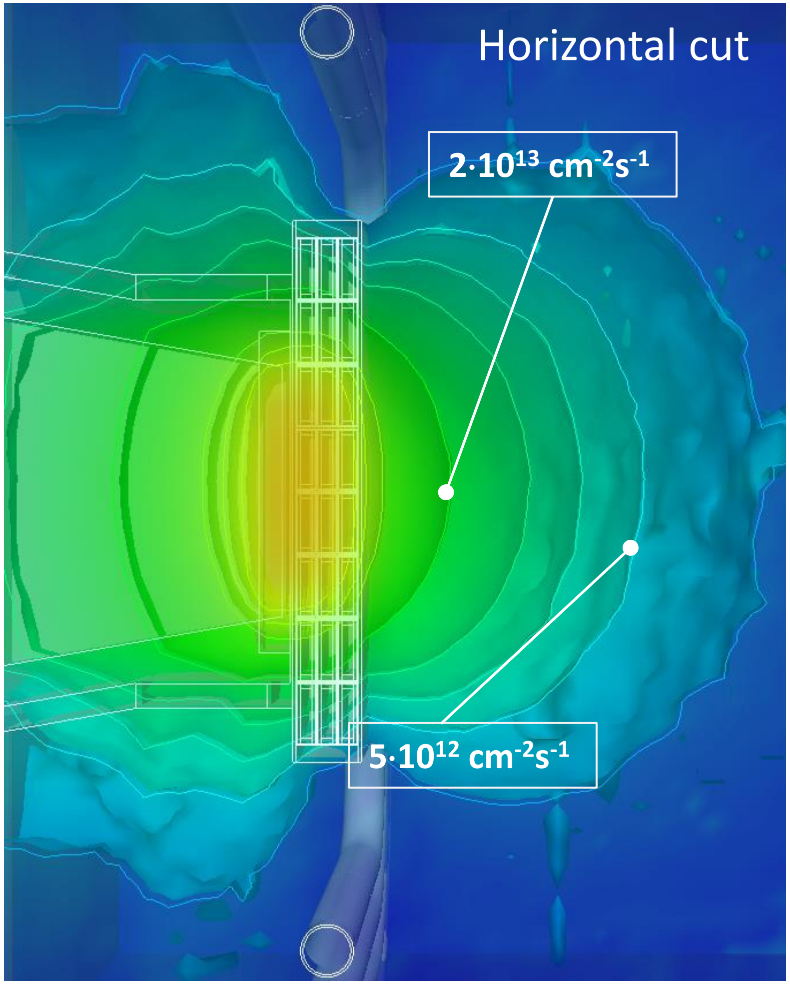
Horizontal cut

$2{\cdot}10^{13}$ $cm^{-2}s^{-1}$

$5{\cdot}10^{12}$ $cm^{-2}s^{-1}$

DONES

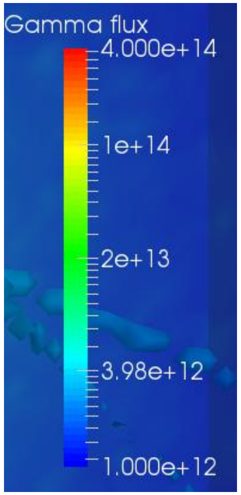
One deuteron beam, 125 mA, 40 MeV



Horizontal cut

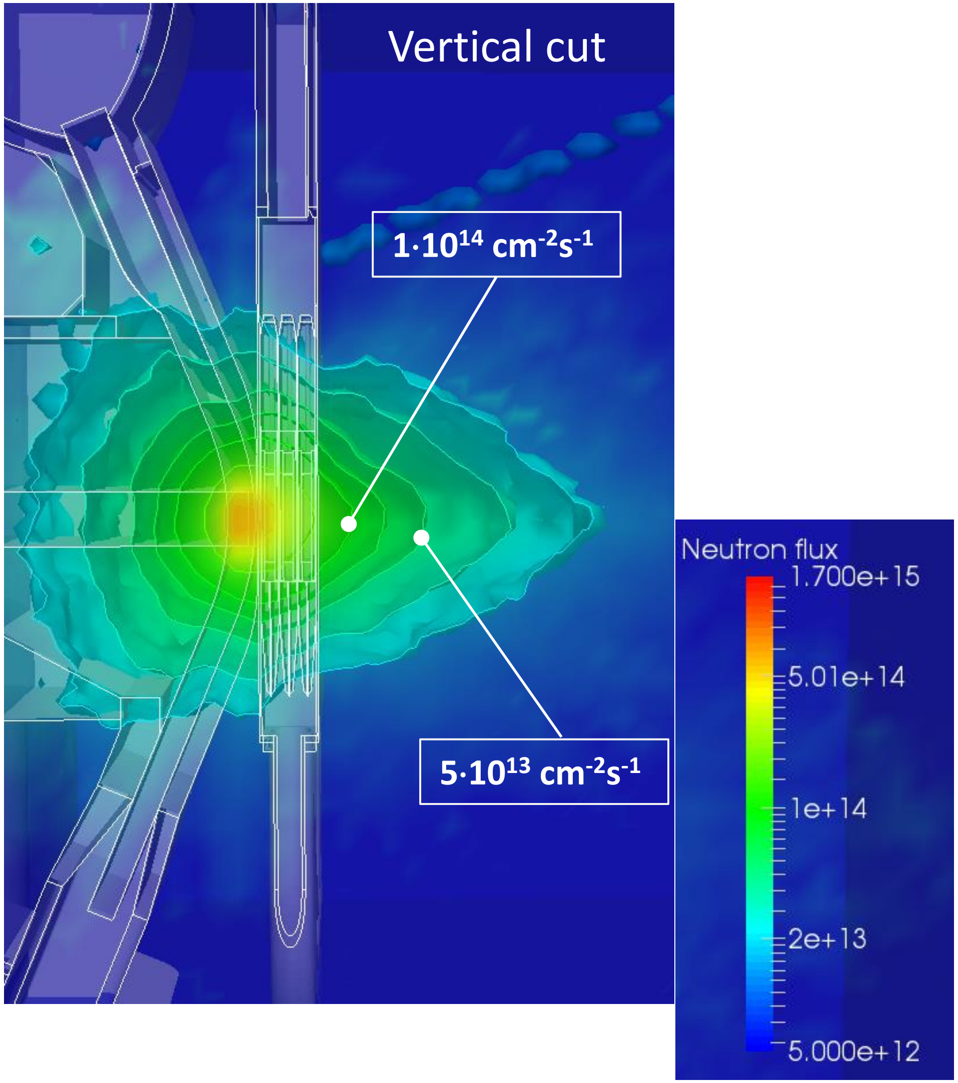
$2{\cdot}10^{13}$ $cm^{-2}s^{-1}$

$5{\cdot}10^{12}$ $cm^{-2}s^{-1}$



DONES: Effect of HFTM on Neutron Flux Distribution

HFTM present

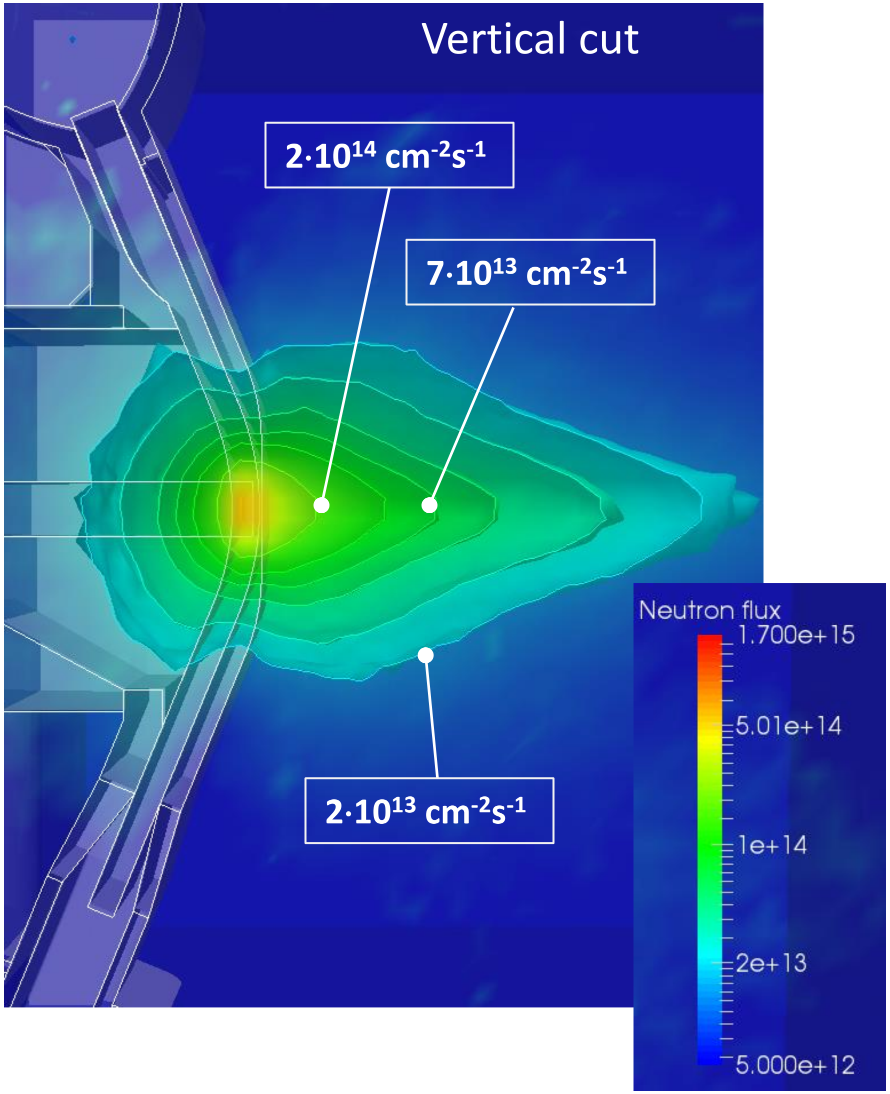


Vertical cut

$1 \cdot 10^{14}$ cm^{-2}s^{-1}

$5 \cdot 10^{13}$ cm^{-2}s^{-1}

HFTM removed



Vertical cut

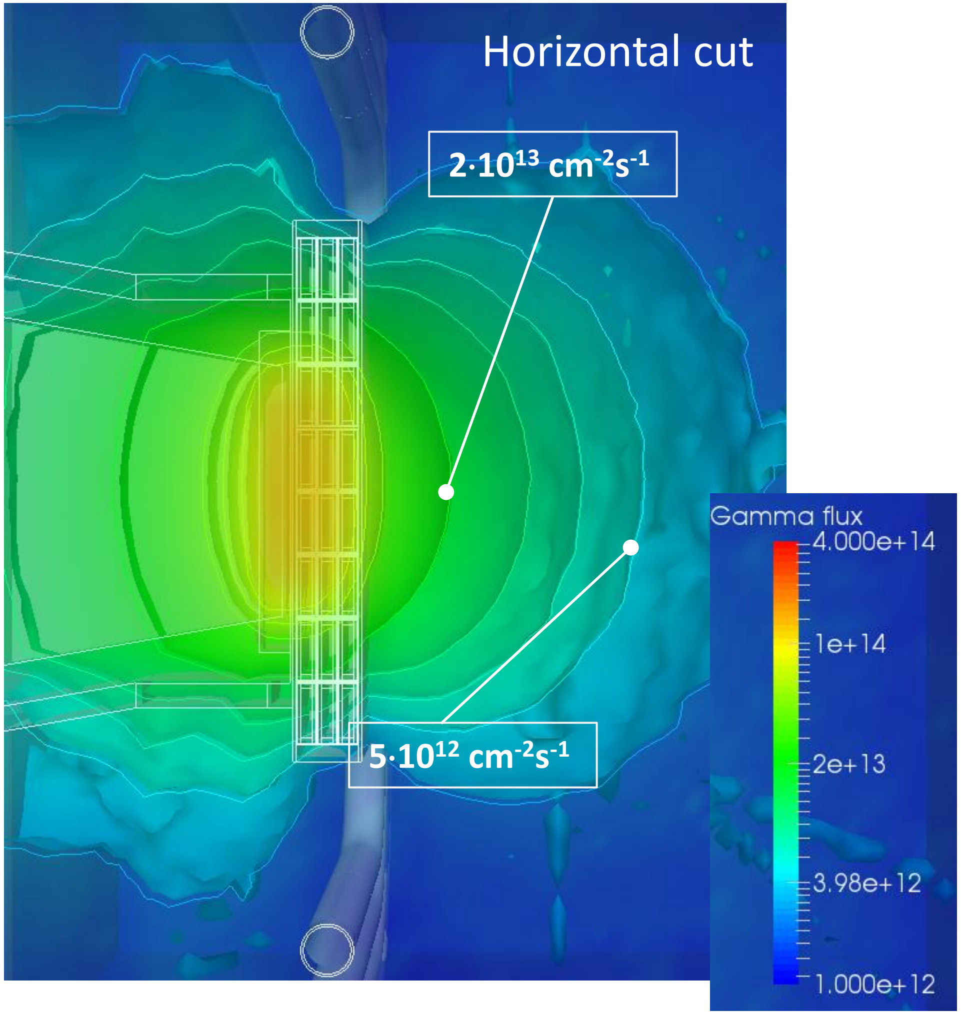
$2 \cdot 10^{14}$ cm^{-2}s^{-1}

$7 \cdot 10^{13}$ cm^{-2}s^{-1}

$2 \cdot 10^{13}$ cm^{-2}s^{-1}

DONES: Effect of HFTM on Gamma Flux Distribution

HFTM present

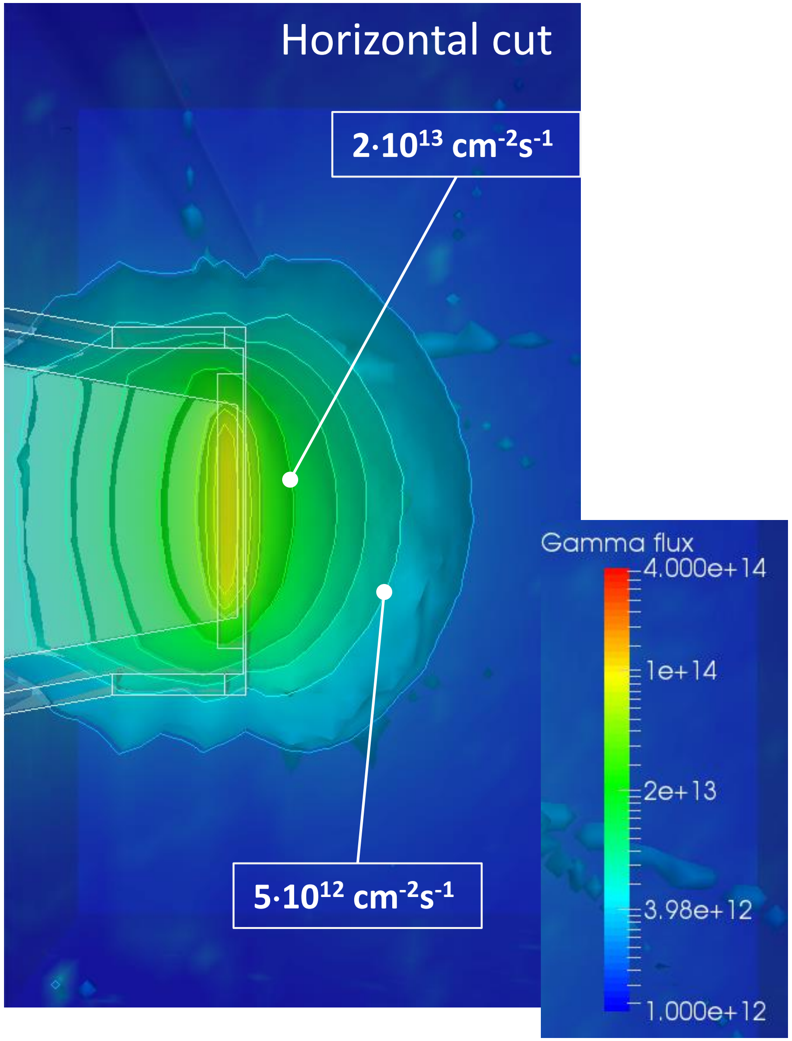


Horizontal cut

$2\cdot10^{13}$ $cm^{-2}s^{-1}$

$5\cdot10^{12}$ $cm^{-2}s^{-1}$

HFTM removed



Horizontal cut

$2\cdot10^{13}$ $cm^{-2}s^{-1}$

$5\cdot10^{12}$ $cm^{-2}s^{-1}$

Irradiation Simulations

IFMIF/DONES other applications

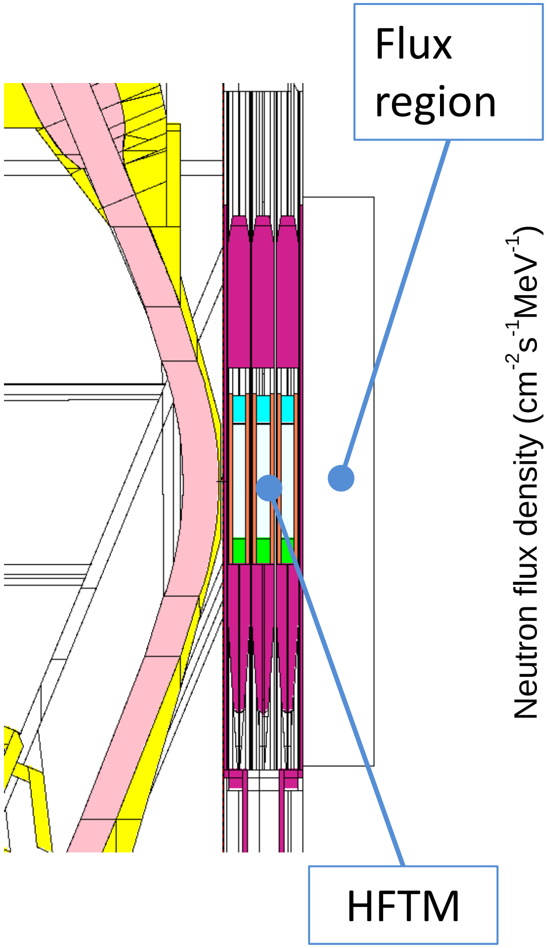
“Other applications”

⇒ Other than fusion material irradiations

- Many potential other applications —> subject of this workshop
- Guideline of this presentation:
  - Take benefit of IFMIF/DONES’ unique feature to produce continuously high neutron fluences at high neutron energies.
  - Utilize irradiation possibilities for isotope production (medical radionuclides, isotope doping, …)
  - High transmutation rates achievable for high-energy threshold reactions
  - No other facilities can provide such irradiation conditions
  - No strong interference with HFTM irradiation—> no significant impact on DONES’ primary mission

DONES Neutron Flux Spectrum

Flux region behind HFTM with HFTM in place and HFTM removed

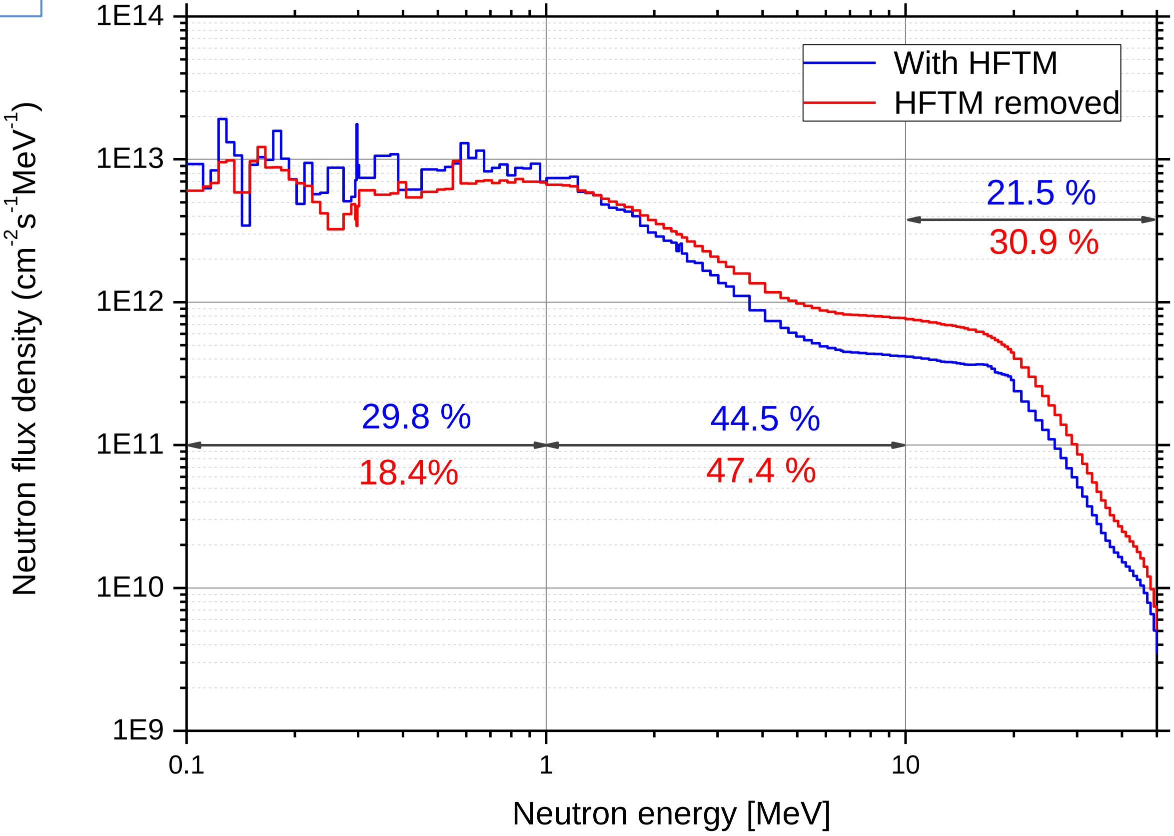


HFTM in place

ϕ_{tot} = 2.57 10^{13} $cm^{-2}s^{-1}$

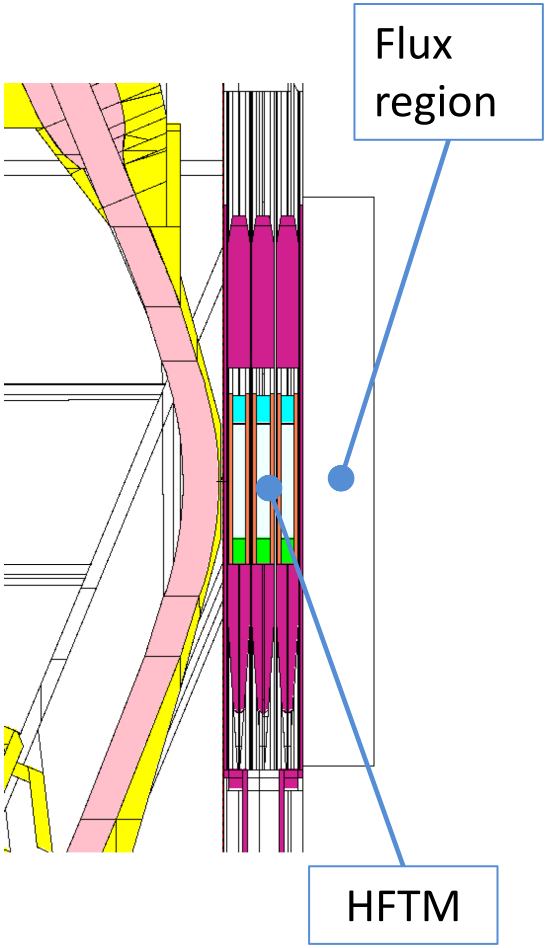
HFTM removed

ϕ_{tot} = 3.12 10^{13} $cm^{-2}s^{-1}$



DONES Photon Flux Spectrum

Flux region behind HFTM with HFTM in place and HFTM removed



Flux region

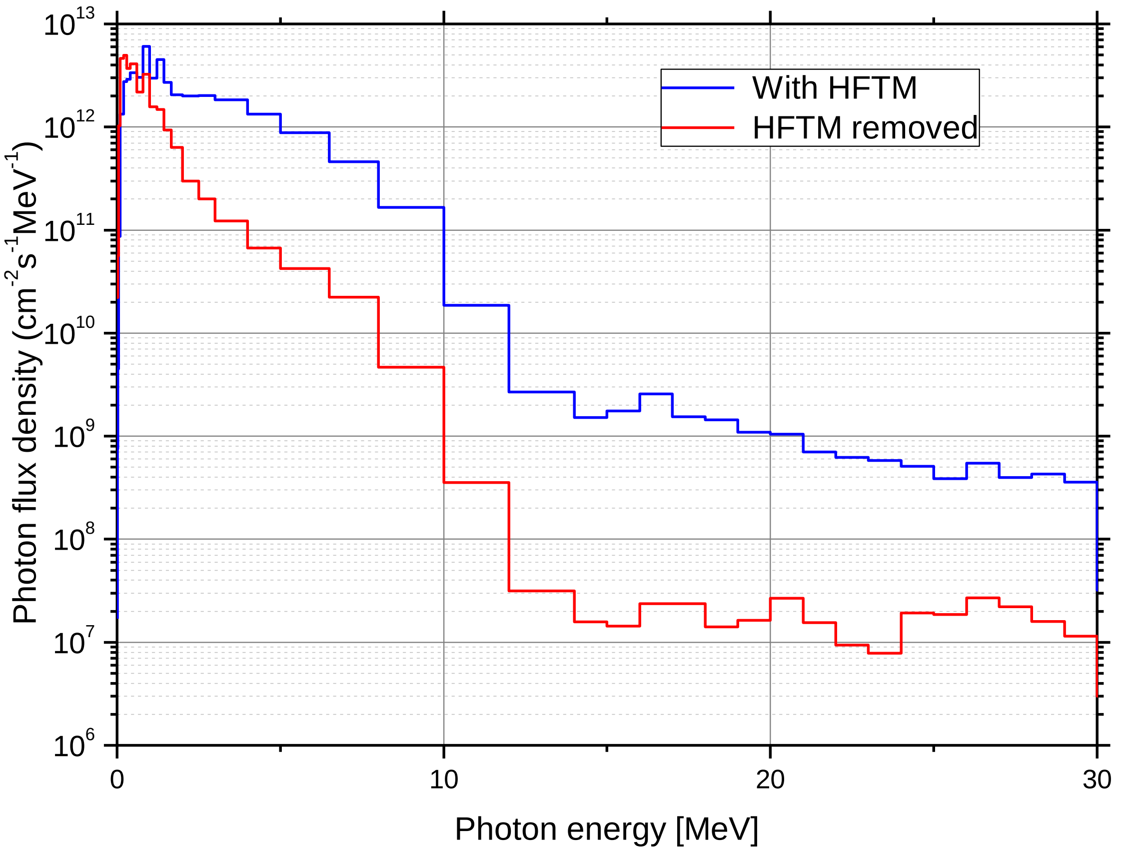
HFTM

HFTM in place

ϕ_{tot} = 1.06 10^{13} $cm^{-2}s^{-1}$

HFTM removed

ϕ_{tot} = 4.93 10^{12} $cm^{-2}s^{-1}$



Mo-99 production in DONES

- Medical radioisotope ^{99m}Tc formed by β-decay of ^{99}Mo ($T_{1/2}$ = 66 h)
- Can be produced by high flux irradiations in IFMIF/DONES

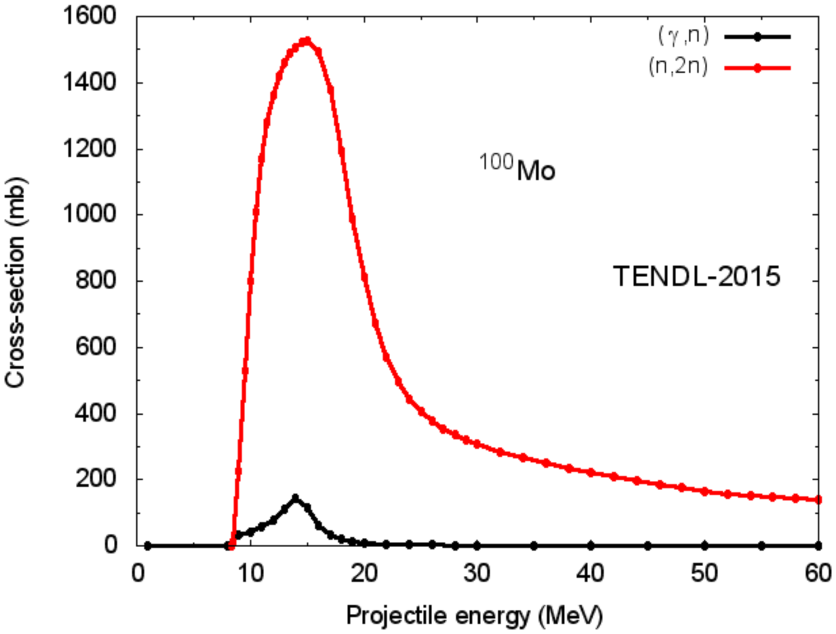
Possible reaction paths in IFMIF/DONES:

- ^{98}Mo (n, γ)^{99}Mo ⇒ requires soft spectrum
- ^{100}Mo(n,2n)^{99}Mo ⇒ high energy neutrons
- ^{100}Mo (γ,n)^{99}Mo ⇒ high energy gammas

Natural Mo isotope abundancies:

^{98}Mo	24.19 at %
^{100}Mo	9.67 at %

- Neutron flux level in DONES ~ 10^{13} - 10^{14} cm^{-2}s^{-1}
- Gamma flux level in DONES ~ 10^{12} - 10^{13} cm^{-2}s^{-1}



Mo-99 production in DONES

Irradiation of 1g Mo_{nat} in flux region behind HFTM over 1 fpy(*)

Neutron flux: $\phi_{tot} = 2.57\ 10^{13}\ cm^{-2}s^{-1}$

	Mass (g/g Mo)	Activity (Bq/g Mo)
Mo-99	2.598E-07	4.619E+09
Tc-99m	2.086E-08	4.068E+09

Reaction pathways:

	Contribution [%]
Mo-98(n,γ)Mo-99	27.6
Mo-100(n,2n)Mo-99	71.3

Photon flux:

$\phi_{tot} = 1.06\ 10^{13}\ cm^{-2}s^{-1}$

Reaction rate ratio

$$\frac{\text{Mo-100 (g,n) Mo-99}}{\text{Mo-100 (n,2n)Mo-99}}$$

$\approx$ 2.5E-3 $\Rightarrow$ < 1 %

No significant Mo-99 production via photon induced reactions

(*) *1 fpy = 1 full power year*

Er-169 production in DONES

Irradiation of 1g Er_{nat} in flux region behind HFTM over 1 fpy

Neutron flux: $\phi_{tot} = 2.57\ 10^{13}\ cm^{-2}s^{-1}$

	Mass (g/g Er_{nat})	Activity (Bq/g Er_{nat})
Er-169	2.06E-6	6.27E+09

Natural Er isotope abundances:

^{168}Er 26.98 at %
^{170}Er 14.9 at %

Reaction pathways:

	Contribution [%]
Er-168(n,γ)Er-169	35
Er-170 (n,2n)Er-169	65

Isotope doping in DONES

Irradiation of 1g Si_{nat} in flux region behind HFTM over 1 fpy

Natural Si isotope abundancies:

^{28}Si 92.22 at %
^{29}Si 4.685 at %
^{30}Si 3.092 at %

Neutron flux: $\phi_{tot} = 2.57\ 10^{13}\ cm^{-2}s^{-1}$

	Atoms (g/g Si_{nat})	Mass (g/g Si_{nat})	appm
P-31	2.44E+15	1.25E-7	11.4

Produced via Si-30(n,γ)Si-31 reaction

Desired doping level is about 1 P atom per billion Si atoms, i. e. 10^{-3} appm

Conclusions

- IFMIF/DONES well suited for high fluence material irradiations
- Unique irradiation facility providing
  - High neutron (and photon) flux densities
  - High energy neutrons (and photons) – up to 50 MeV
- Available space in Test Cell can be utilized for “other” irradiation purposes, e. g. isotope production for medical and industrial applications.
- No strong interference/impact on irradiation of fusion materials in High Flux Test Module