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Tritium production in the blanket of a demonstration thermonuclear plant using nuclear raw materials

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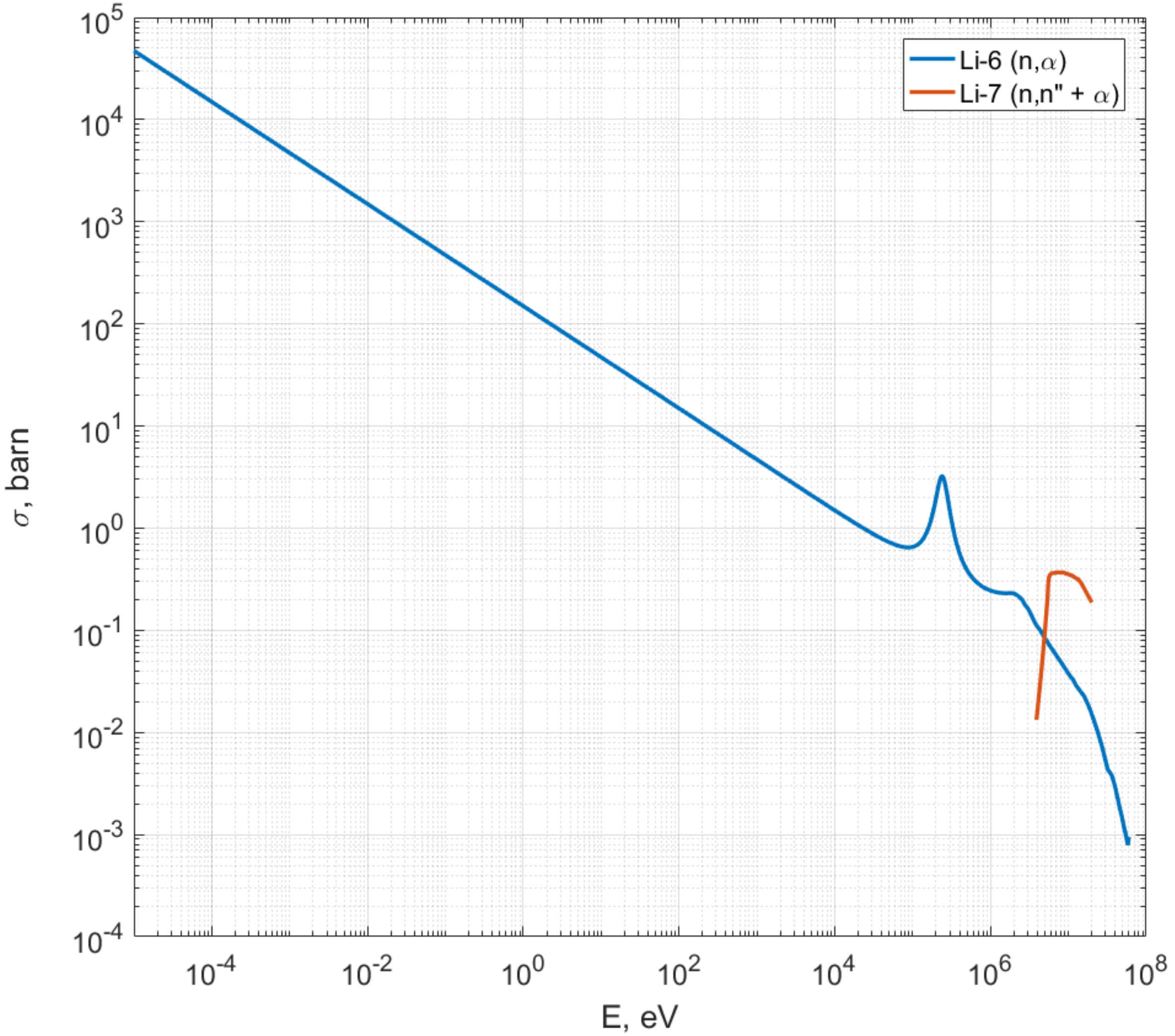
Vienna, 2022

Introduction

- **The purpose of this study**: is to define the potential of the fusion neutron source with a low fusion power (40 MW) for tritium breeding necessary for the first loadings of DEMO scale fusion power plants.
- **Research goals**:
  - To develop a detailed 3D model of the hybrid reactor DEMO-FNS* for neutronics calculations
  - To define tritium breeding ratio (TBR) for a prospective design options of the DEMO-FNS blanket
  - To show an upper and lower limits for tritium breeding rate using a simplified 2D DEMO-FNS model

* Yu.S. Shpanskiy and the DEMO-FNS Project Team. Progress in the Design of the DEMO-FNS Hybrid Facility. Nucl. Fusion 2019, 59, 076014,

Tritium breeding by lithium irradiation

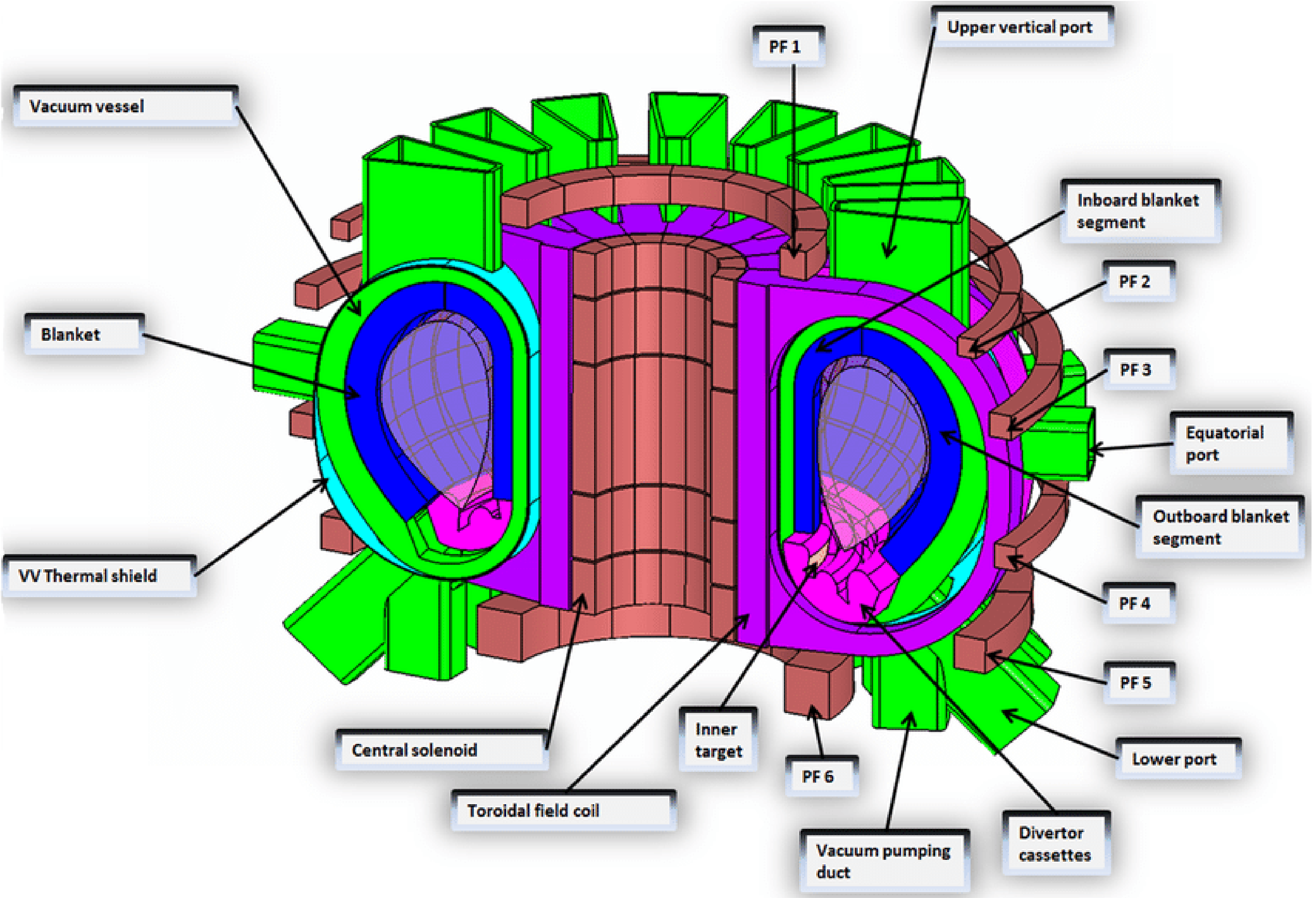


$$^{6}\mathrm{Li} + \mathrm{n} \rightarrow {}^{3}\mathrm{T} + {}^{4}\mathrm{He} + 4.79\ \mathrm{MeV}$$

$$^{7}\mathrm{Li} + \mathrm{n} \rightarrow {}^{3}\mathrm{T} + {}^{4}\mathrm{He} + \mathrm{n} - 2.47\ \mathrm{MeV}$$

- The most effective T breeding is provided with ^{6}Li (abundance 7.6%)
- 1 GWt fusion reactor consumes ~**54.1 kg of tritium annually**

Fusion reactor DEMO



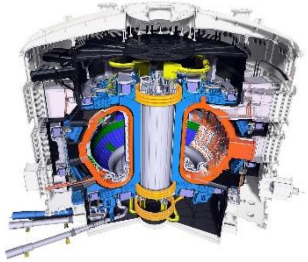
- Fusion power – 1 GWt
- Tritium consumption – 54 kg/y
- Initial tritium loading – 5 kg
- Tritium breeding ratio (TBR) – 1.05-1.15

Tassone A. Study on liquid metal magnetohydrodynamic flows and numerical application to a water-cooled blanket for fusion reactors. 2019

Applications of FNS

- **«Pure» thermonuclear fusion**

D, T
Li

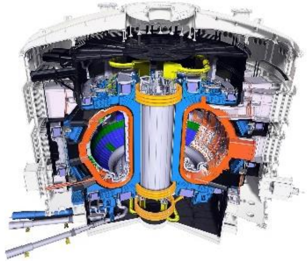


Neutrons

Heat/Electricity
Tritium

- **Hybrid burner reactor with TRU**

D, T
Li
MA

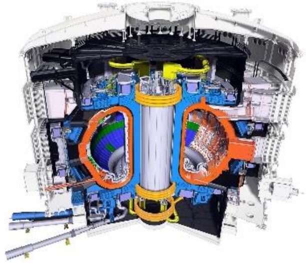


Neutrons

Heat/Electricity
Tritium
Fission neutron
Fission products

- **Hybrid breeder reactor**

D, T
U-238
Th-232



Neutrons

Heat/Electricity
Pu-239, U-233

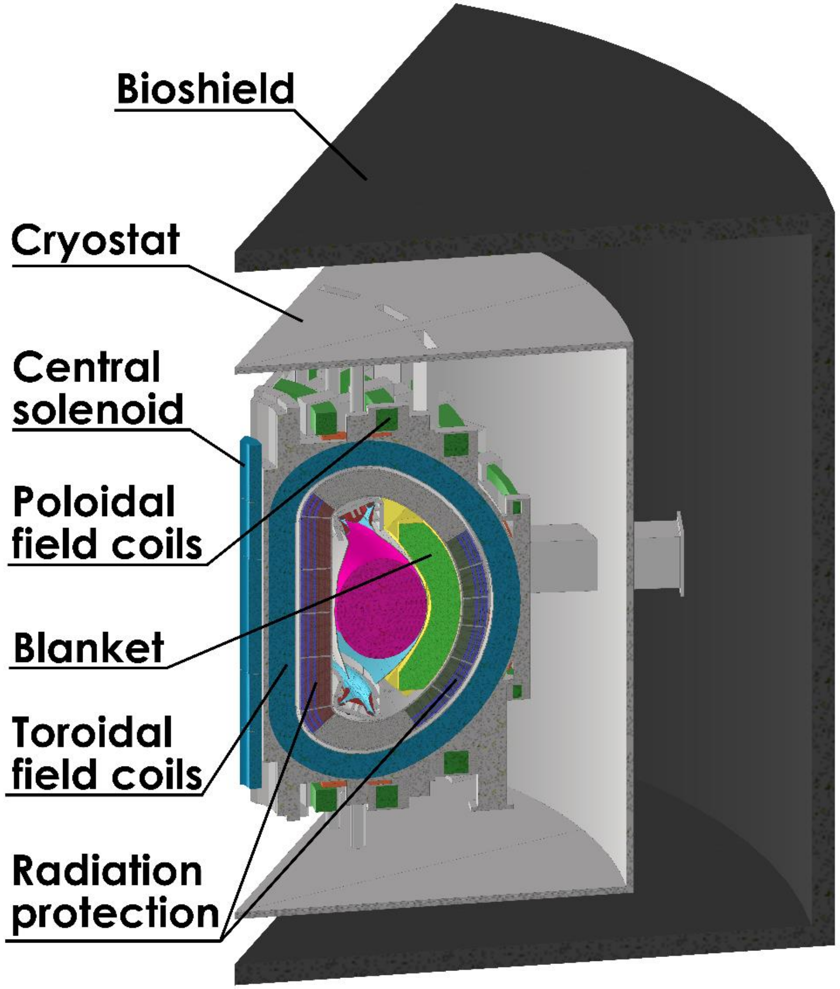
MA – minor actinides (Np, Am, Cm); TRU – transuranic; T – tritium; FNS – fusion neutron source

Neutron multiplication in fusion and fission systems

System	Neutrons per Fission, ν; Multiplication μ	Residue (Reaction Maintenance and Breeding Subtracted)	Leakage and Volumetric Losses	Free Neutrons Available for Extended Breeding
Critical nuclear reactor ^{235}U, thermal spectrum	ν 2.44	ν − 2 0.44	1.0	−0.56
Critical nuclear reactor ^{239}Pu, thermal/fast spectrum	ν 2.9/3.05	ν − 2 0.9/1.05	0.9	0/0.15
Fusion reactor D+T, Be/Pb – multiplier	μ 2/1.8	μ − 1 1/0.8	0.8	0.2/0
Hybrid reactor D+T and ^{238}U	ν 4.5	ν − 1 3.5	1.0	2.5
Hybrid reactor D+T and MA, $G = 2$	$\mu_s + 1$	μ_s		
$k_{eff} = 0.95$	39	38	12.8	25.2
$k_{eff} = 0.8$	9	8	3.0	5.0

Kuteev B. V., Goncharov P. R. Fusion–Fission Hybrid Systems: Yesterday, Today, and Tomorrow // Fusion science and technology. 2020. Vol. 76. № 7. P. 836–847.

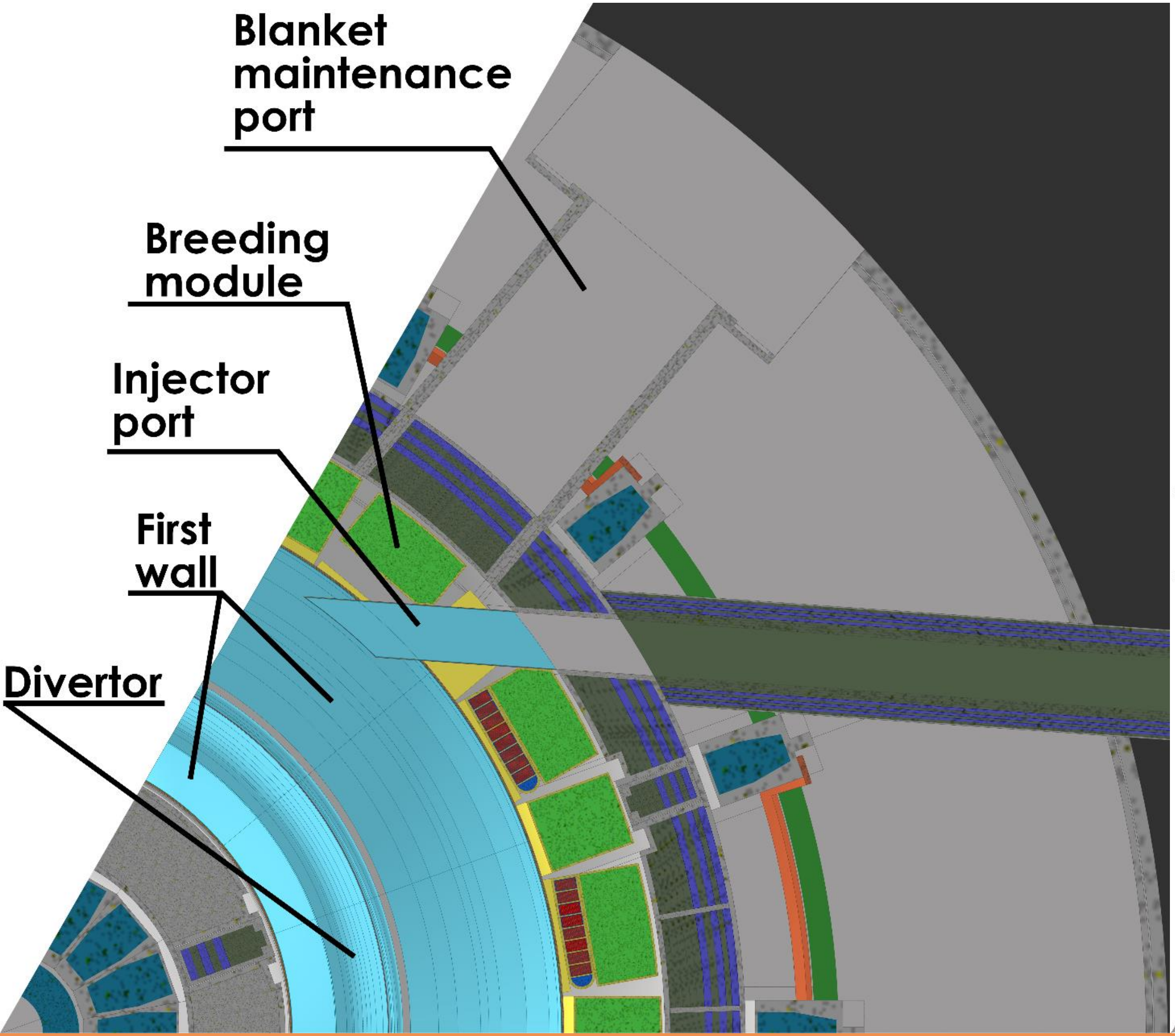
Detailed 3D model of DEMO-FNS hybrid reactor



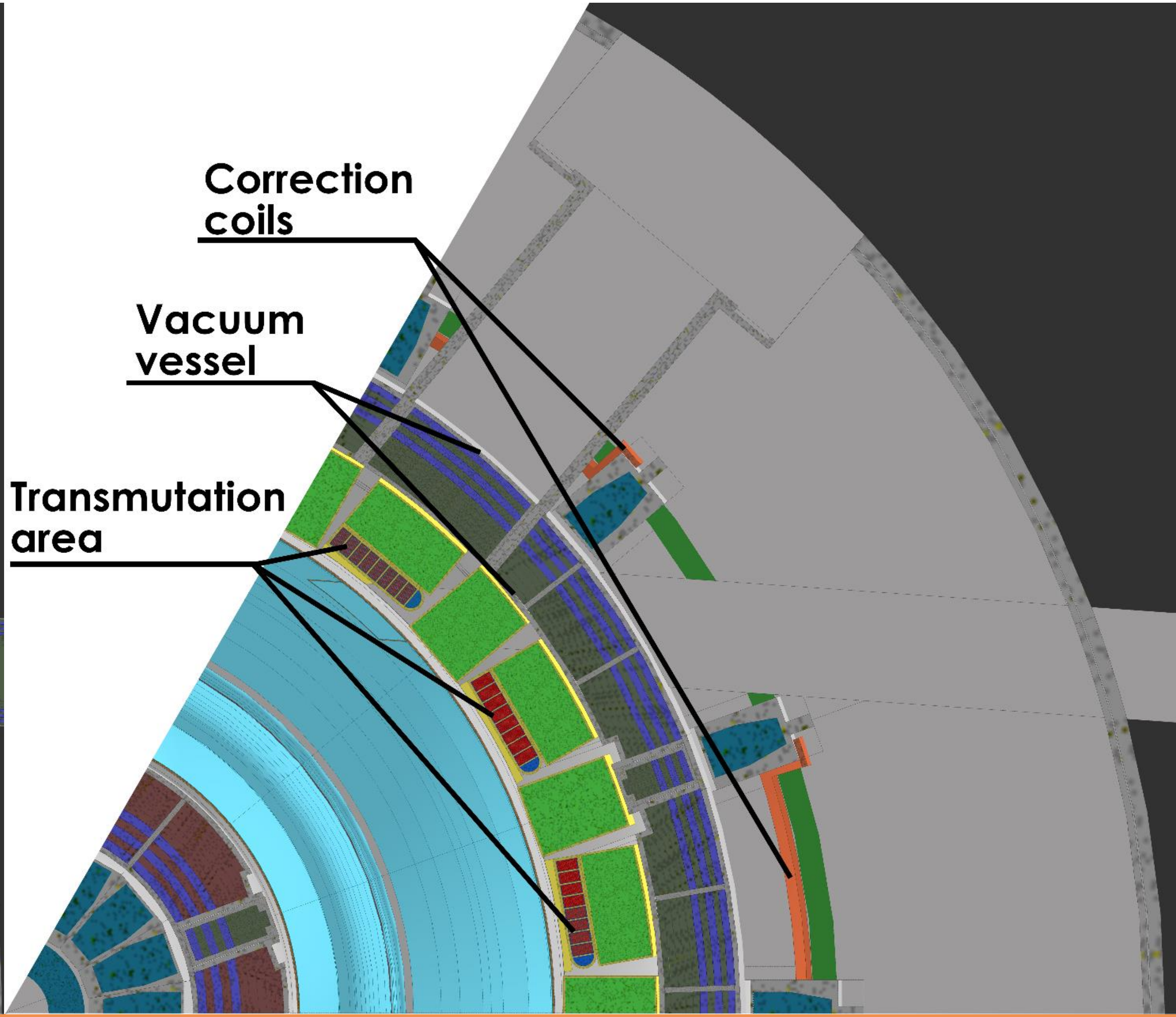
- Fusion power – 40 MW ($1.4\cdot10^{19}$ neutron/s)
- 1/6 fraction (60°) of whole reactor
- Mirror boundary conditions for neutron transport
- Blanket content (for 1/6):
  - 3 transmutation areas (TrA) with MA: 2 long, 1 short
  - 14 breeding modules (BM) filled with Li_4SiO_4
- Radiation shield: 70% steel and 30% borated water
- 5 years of irradiation
- Spectrum change during irradiation is not taken into account
- $k_{eff} = 0.95$
- Calculations are performed with SuperMC program*

* Y. Wu. Multi-functional Neutronics Calculation Methodology and Program for Nuclear Design and Radiation Safety Evaluation, Fusion Science and Technology 74(2018) 321-329;
Y. Wu, J. Song, H. Zheng, et al. CAD-Based Monte Carlo Program for Integrated Simulation of Nuclear System SuperMC, Annals of Nuclear Energy 82(2015) 161-168

Horizontal cut of DEMO-FNS model

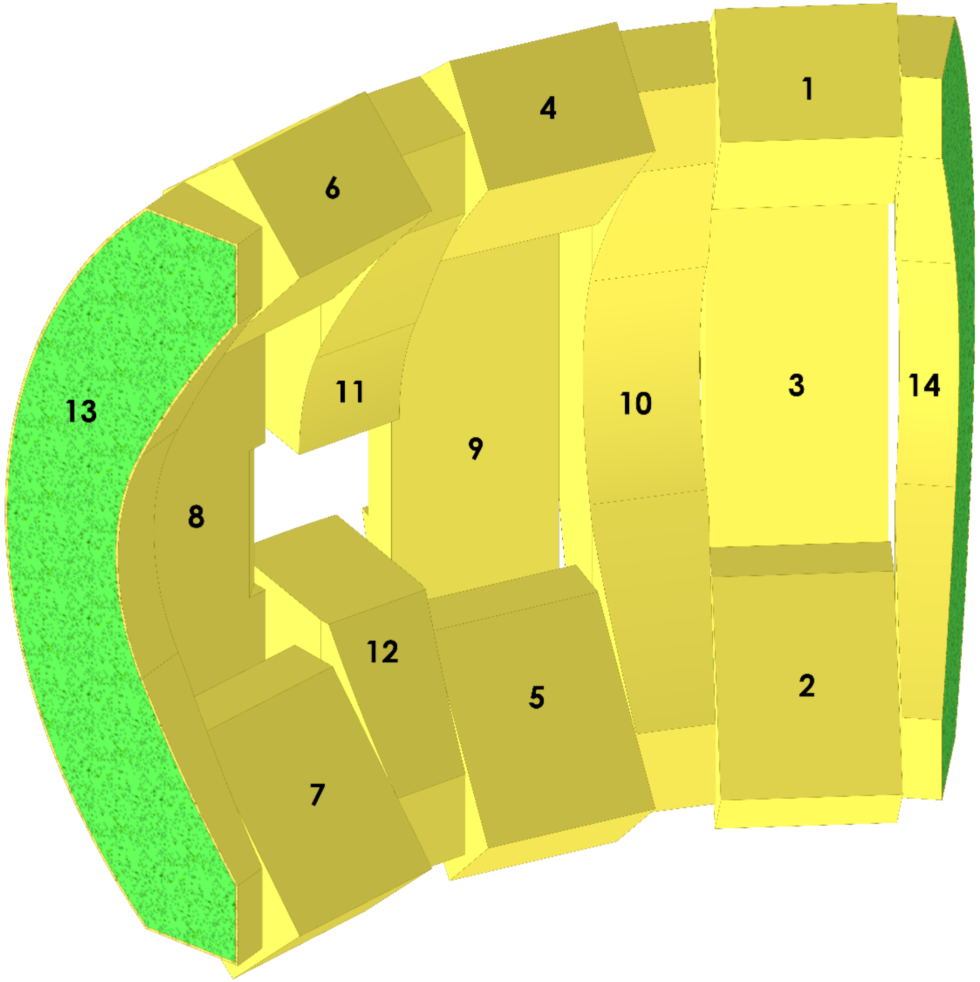


Equatorial cut (height 0 mm)



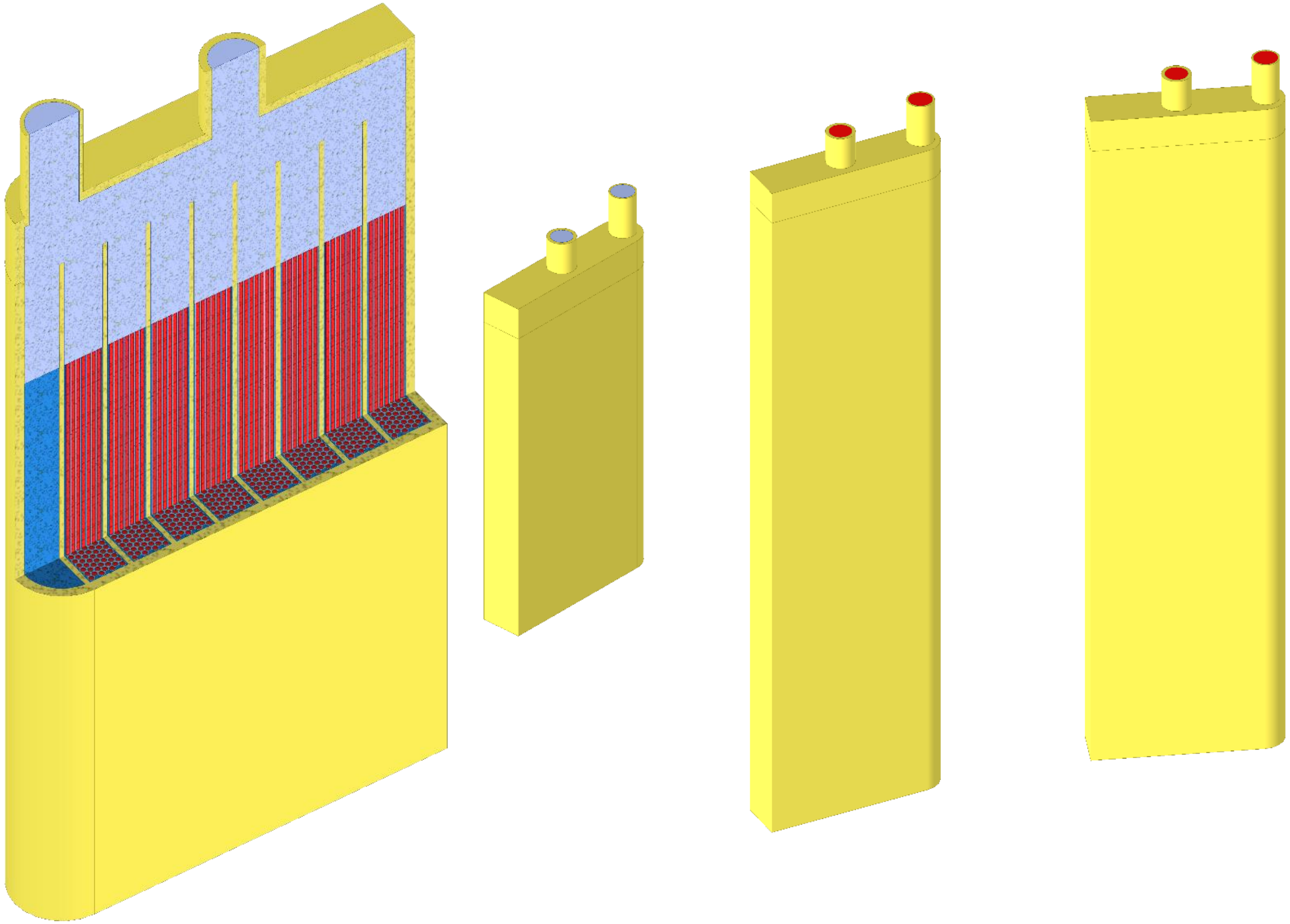
Height 500 mm

Tritium breeding modules



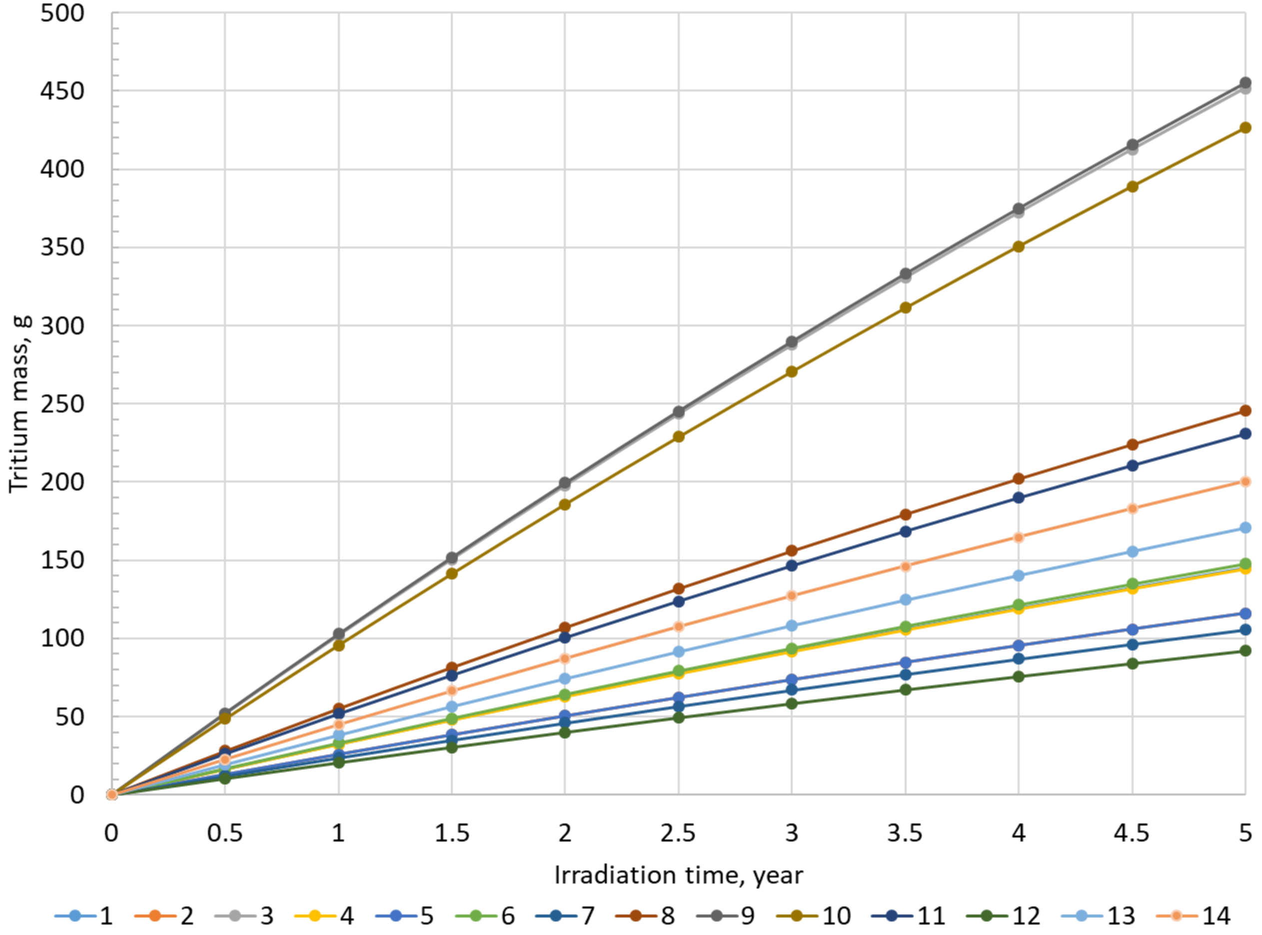
- Tritium breeding modules set in the sector:
  - 3 modules near vacuum vessel
  - 6 small modules (under and above TrA)
  - 3 large modules between TrA (10, 11+12, 13+14)
- BM filled with granules made of Li_4SiO_4 with material volume fraction ~48%
- Effective material density – 1.12 g/cm^3
- Lithium is enriched by ^{6}Li up to 90%
- Raw material volume: 9.5 m^3 for sector and 56.9 m^3 for whole blanket
- Mass: 10.6 t for sector and 63.5 t for whole blanket

Transmutation assemblies (TrA) for neutron multiplication



- TrA comprises rods with metallic fuel made of MA and Zr (4% mass)
- Fuel density – 15 g/cm^3
- Long rods - 2300 mm, short – 925 mm
- Diameter of the fuel rod – 10 mm
- Rod cladding material – steel ЭК-181
- Step of the triangular lattice – 12.7 mm
- Coolant – mixture of steam and water (6.5 MPa)
- Fuel loading (MA+Zr) for sector ~ 4.37 t, for whole blanket ~ 26.24 t

Tritium mass change over time for each breeding module

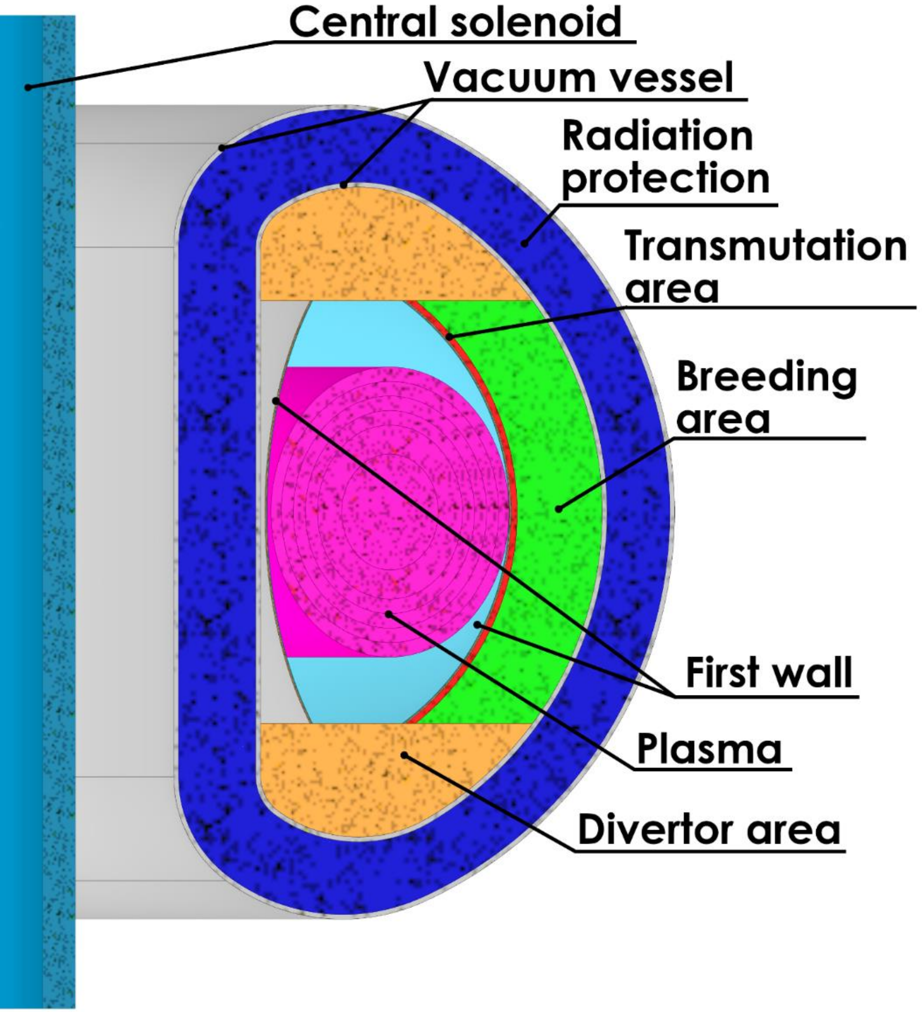


No. of module	Module loading Li_4SiO_4, kg	Mass of tritium (over a year), g	Breeding effectiveness, g/t
1	591.613	32.55	55.019
2	591.613	25.98	43.919
3	821.378	102.05	124.242
4	591.613	32.37	54.709
5	591.613	25.98	43.919
6	591.613	33.13	56.005
7	591.613	23.63	39.947
8	818.355	55.10	67.330
9	814.415	102.80	126.226
10	1635.337	95.67	58.500
11	809.166	51.77	63.975
12	493.593	20.63	41.802
13	817.648	38.22	46.740
14	817.680	44.92	54.932
Sector	10577.252	684.80	64.743
Whole reactor	63463.514	4108.80	

Tritium breeding analysis

- The most effective tritium breeding is expected in modules 9, 3 and 8
  - They are located after TrA – most part of fission neutrons are absorbed by them
  - BM №8 is located after small TrA, thus it has less breeding effectiveness compared to BM 9 and 3
- The least effective tritium breeding in modules, located at the bottom and top of the blanket (2, 5, 7, 12)
  - Modules 7 and 12 are obscured by injector port
- Annual tritium build up – 4.1 kg/year
- Tritium Breeding Ratio (TBR) – 1.86
  - Surplus amount of tritium 1.9 kg/year
- Considerable neutron leakage is the reason of such low result for TBR
  - Transmutation assemblies' surface faced to the plasma takes only 20% of the outboard first wall surface

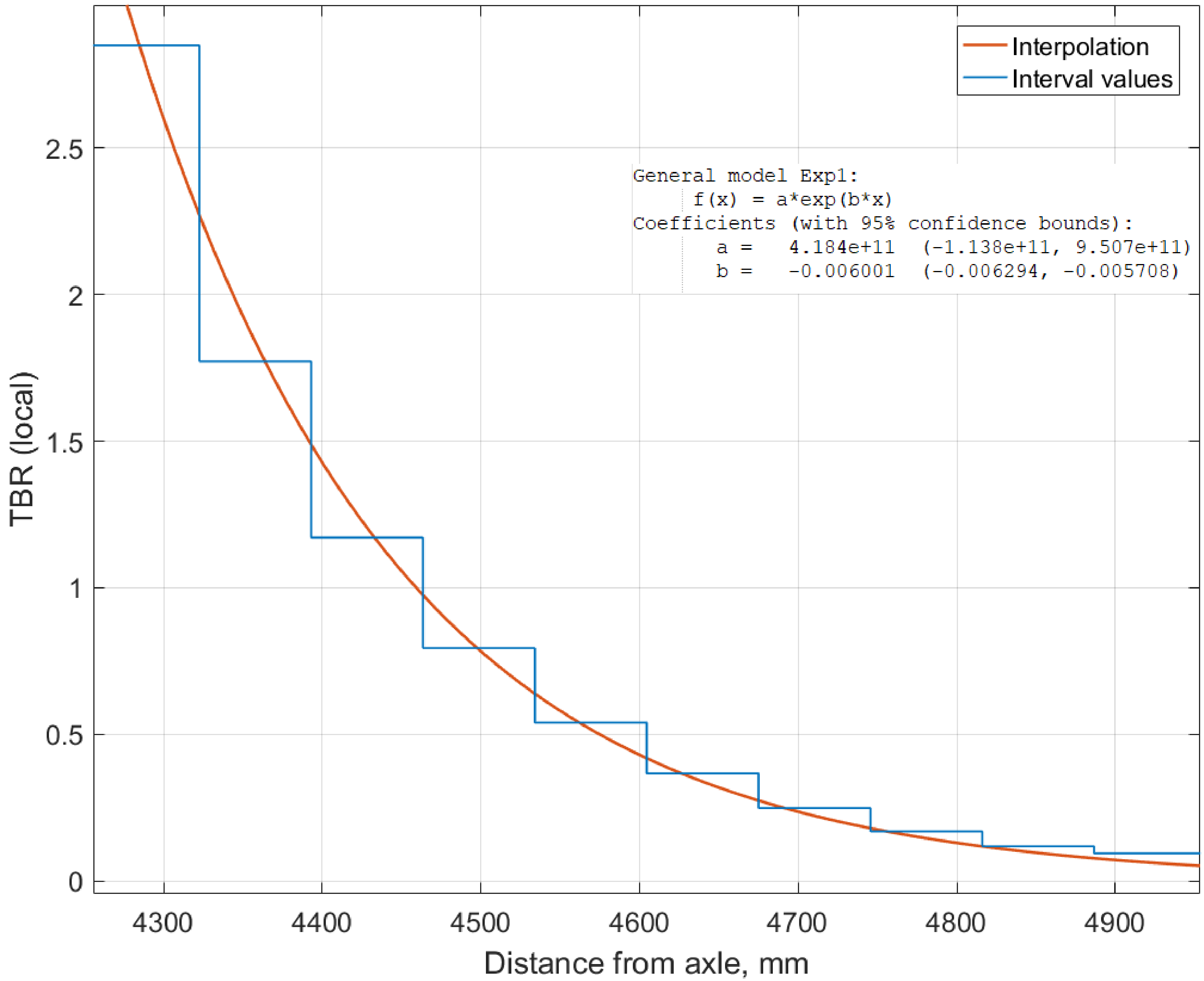
2D simplified model of DEMO-FNS hybrid reactor



- Symmetrical in the toroidal direction
- Fusion power – 40 MW ($1.4 \cdot 10^{19}$ neutron/s)
- Radiation shield (homogeneous): 70% steel plus 30% borated water
- Blanket: MA (47 mm, 70 t), Li_4SiO_4 (705 mm, 83 t)
- $k_{eff} = 0.95$
- **TBR = 8.11** (total: 17.9 kg/y, free: 15.6 kg/y)
- Without MA **TBR = 0.56**
- With Be layer instead of MA **TBR = 0.78**

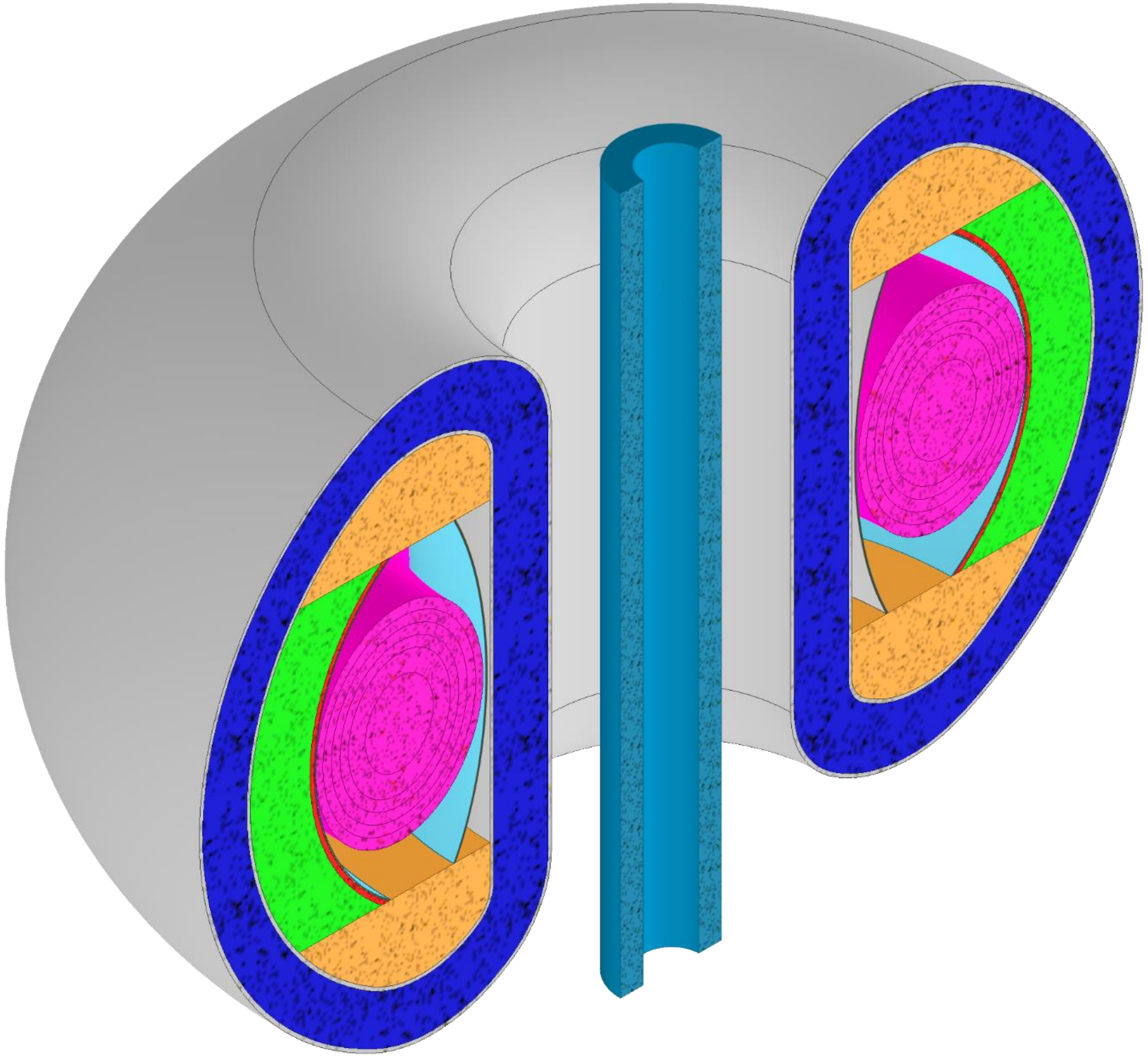
Li is enriched by ^{6}Li up to 90%

Breeding rate change with distance from axle

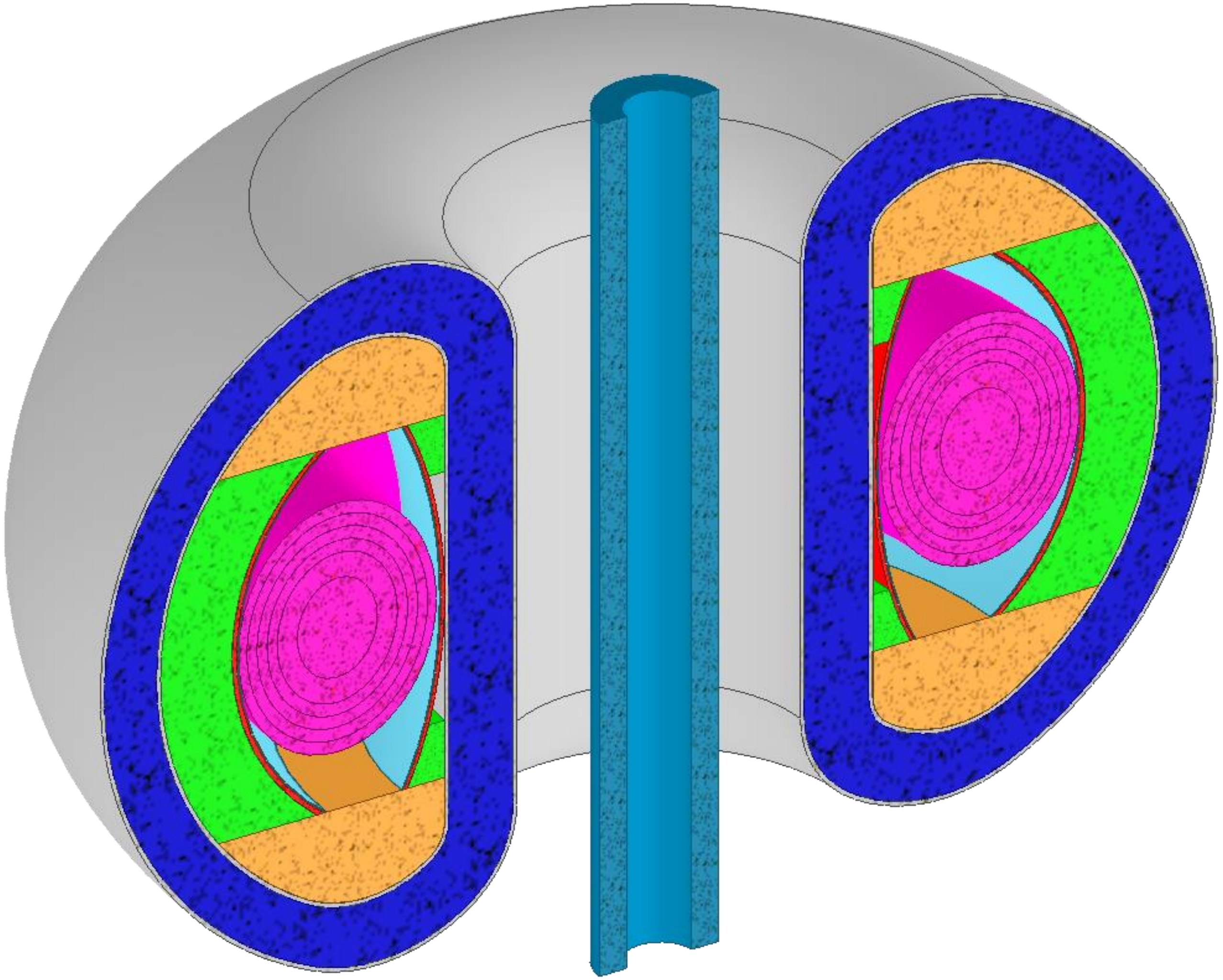


- Local tritium breeding ratio drops exponentially with layer thickness
- No need to use the whole blanket volume to reach such total TBR values

Optimization – adding materials on the inboard area



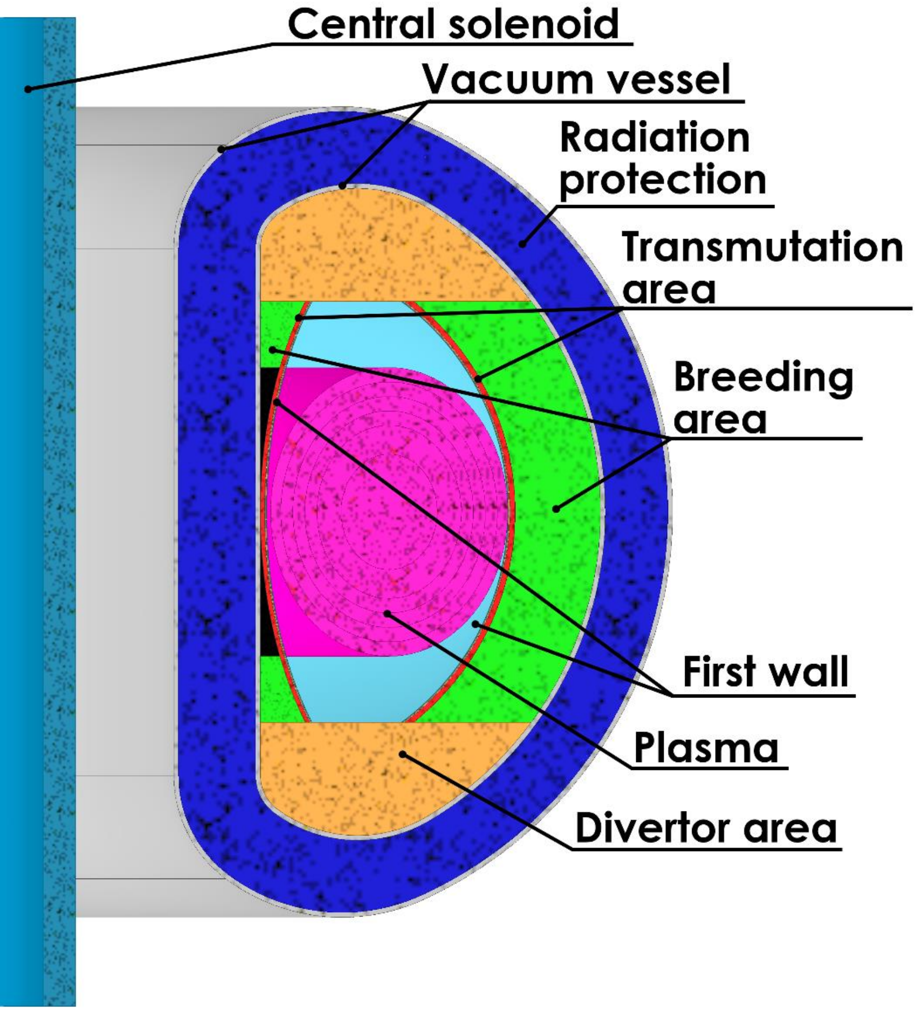
MA + Li_4SiO_4 only on outboard



MA + Li_4SiO_4 on outboard and inboard

This improvement leads to reducing neutron leakage. Otherwise fast neutron losses are significant

2D simplified model with additional materials on the inboard area



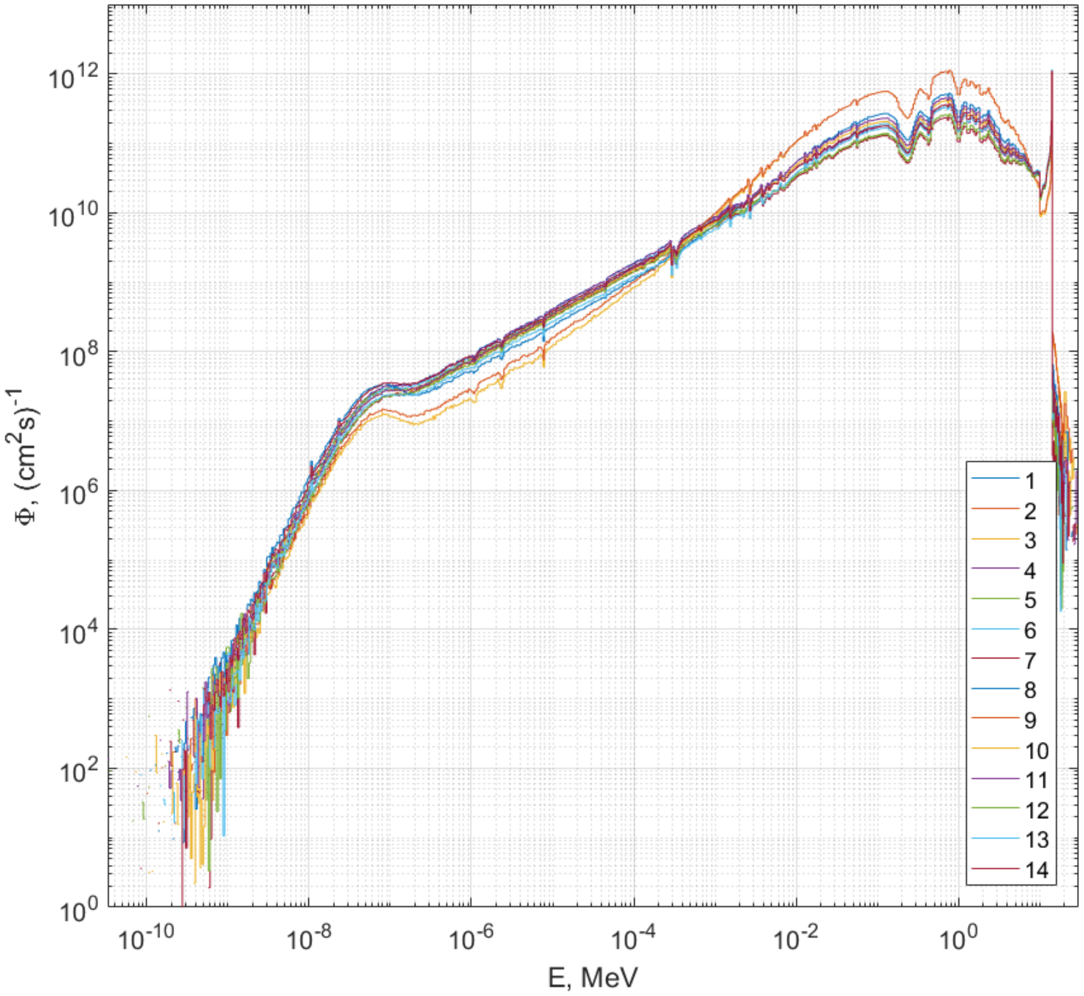
- Blanket:
  - Outboard: MA (43 mm, 64 t), Li_4SiO_4 (709 mm, 84 t)
  - Inboard: MA (34 mm, 25 t), Li_4SiO_4 (4.6 t)
- k_{eff} = 0.95 (inboard + outboard)
- **TBR = 12.0** (total: 26.5 kg/y, free: 24.3 kg/y)
  - Small inboard area (5% of total Li loading) gives 22% of tritium
- This amount of free tritium is substantial for first loading and fuel cycle of DEMO reactor

Conclusion

- A new detailed model of tokamak hybrid reactor for neutron calculations is developed and used for TBR calculations (with SuperMC program)
  - It is shown that realistic geometry of the tokamak device dramatically affects tritium breeding results
- TBR for the detailed DEMO-FNS model with vertical zones providing neutron multiplication via MA fission is 1.86
  - Surplus production rate of tritium available for the first loading of fusion reactors is 1.89 kg/year. This low result is defined by very ineffective use of the primary plasma produced neutron flux, although for research tasks this is appropriate
- It is required to optimize the blanket structure to increase tritium breeding
- Using of appropriately distributed fissile materials (like MA) in the blanket being placed close to outer and inner sides of the first wall might provide a significant growth of TBR (up to 12 for 2D simplified model)

Thanks for attention!

Volume averaged neutron spectra for each breeding module



- Spectra in 7 and 9 BM differ the most
- 9 is module near vacuum vessel, 7 – small module under short TrA
- Fraction of neutrons with energy higher than 1 MeV in 7 BD is 1.2 times higher than in 9 BD
- Integral neutron flux in 9 BM is 3.7 higher than in 7 BD