Neutronics aspects of fusion reactor research

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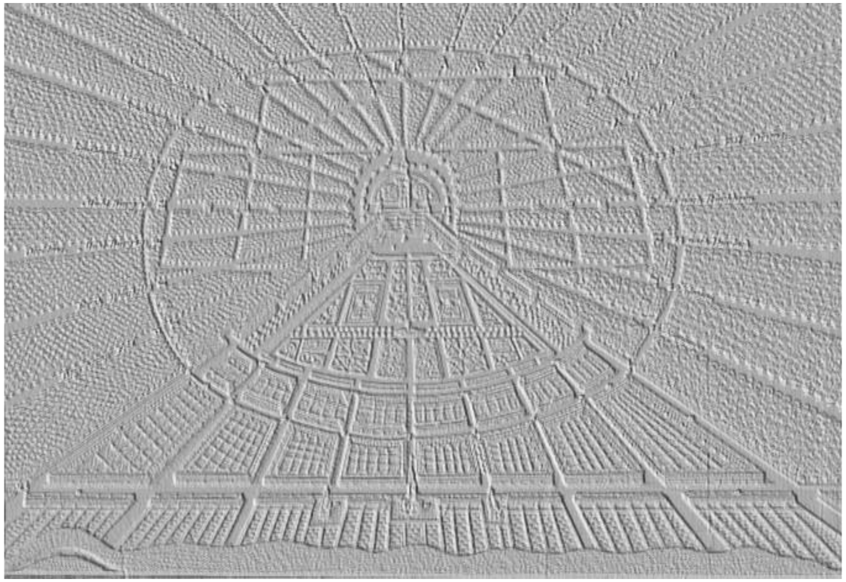

Thanks to

M. Angelone[1], P. Batistoni[1], U. Fischer[2], D. Gehre[3], B. Ghidersa[2], G. Kleizer[4], A. Lyoussi[5], L. Ottaviani[6], M. Pillon[1], P. Raj[2], Th. Reimann[2], I. Rovni[4], T. Rücker[7], D. Szalkai[2], K. Tian[2] and many others

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[2] Karlsruhe Institute of Technology, Karlsruhe, Germany
[3] Technische Universität Dresden, Dresden, Germany
[4] Budapest University of Technology and Economics, Budapest, Hungary
[5] CEA Cadarache, Cadarache, Frankreich
[6] Aix-Marseille University, Marseille, Frankreich
[7] University of Applied Sciences Zittau-Görlitz, Zittau, Germany

Outline

- Basics of fusion reactors
  (from the neutronics point of view)
  → Ignition of plasma
  → Fuel cycle
  → Breeding blanket
- (Some) Large experimental devices
- Tritium breeding blanket mock-up experiments
  → Example: Mock-up of the Helium-Cooled Lithium-Lead Test Blanket Module (HCLL TBM)
- Neutronics instrumentation for the ITER test blanket modules

Electric energy from nuclear fusion

Operating principle of a fusion power plant based on DT reaction similar to conventional and fission power plants: Generated heat converted into steam driving a generator which produces electricity.

Electric energy from fusion is of interest:

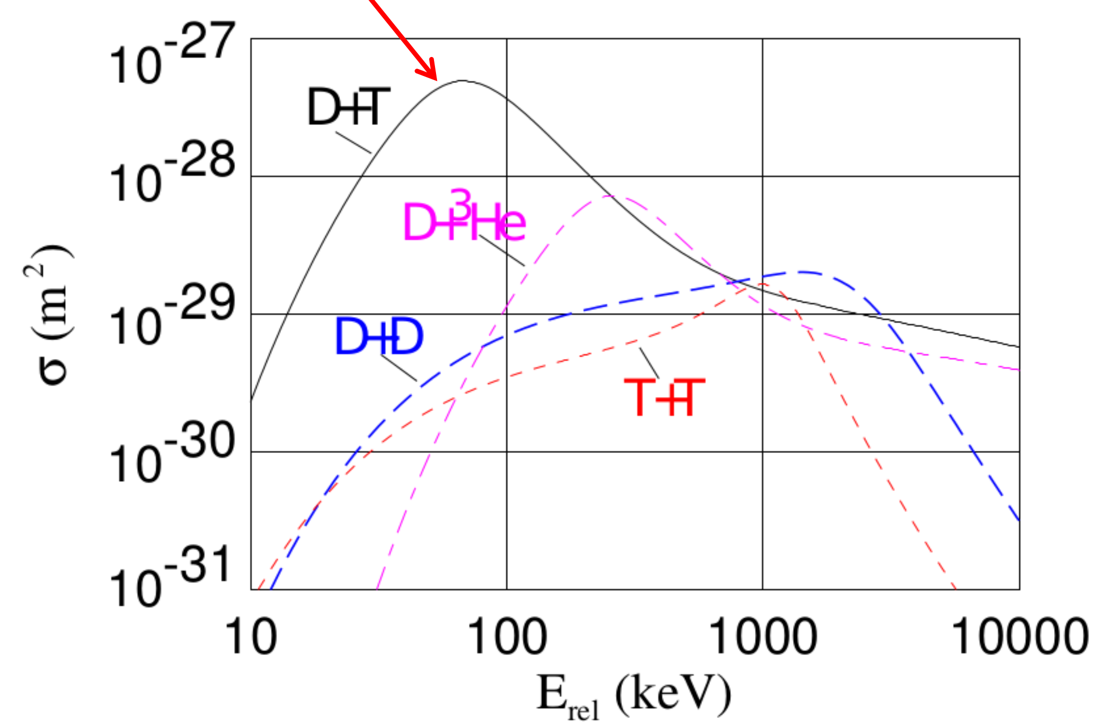
- Fuel available on Earth‘s surface for a long time (up to 3×10^7 y)
- No greenhouse gas emission
- No generation of a broad spectrum of long-living radioactive waste
- Energy in fusion reactor at any time so small that a „run-away“ cannot occur

Which fusion reactions?

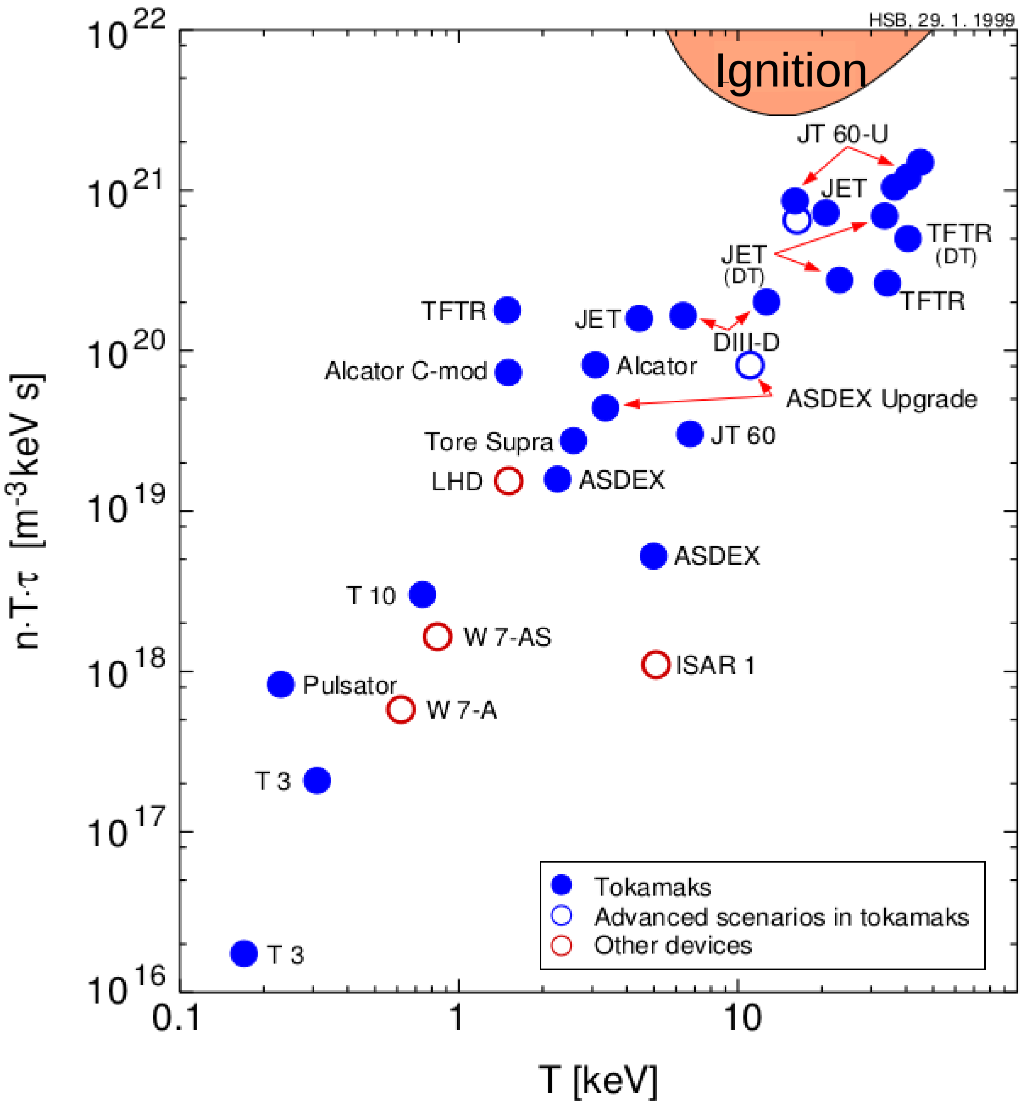
D + D	→	^{3}He + n	+3.3 MeV
D + D	→	T + p	+4.0 MeV
D + T	**→**	**^{4}He + n**	**+17.6 MeV**
T + T	→	^{4}He + 2n	+11.3 MeV
D + ^{3}He	→	^{4}He + p	+18.4 MeV

DT is attractive for its high reaction cross section

Note that D+^{3}He is not free of neutron emission (→material activation) due to „parasitic“ DD reactions with some DT contribution.



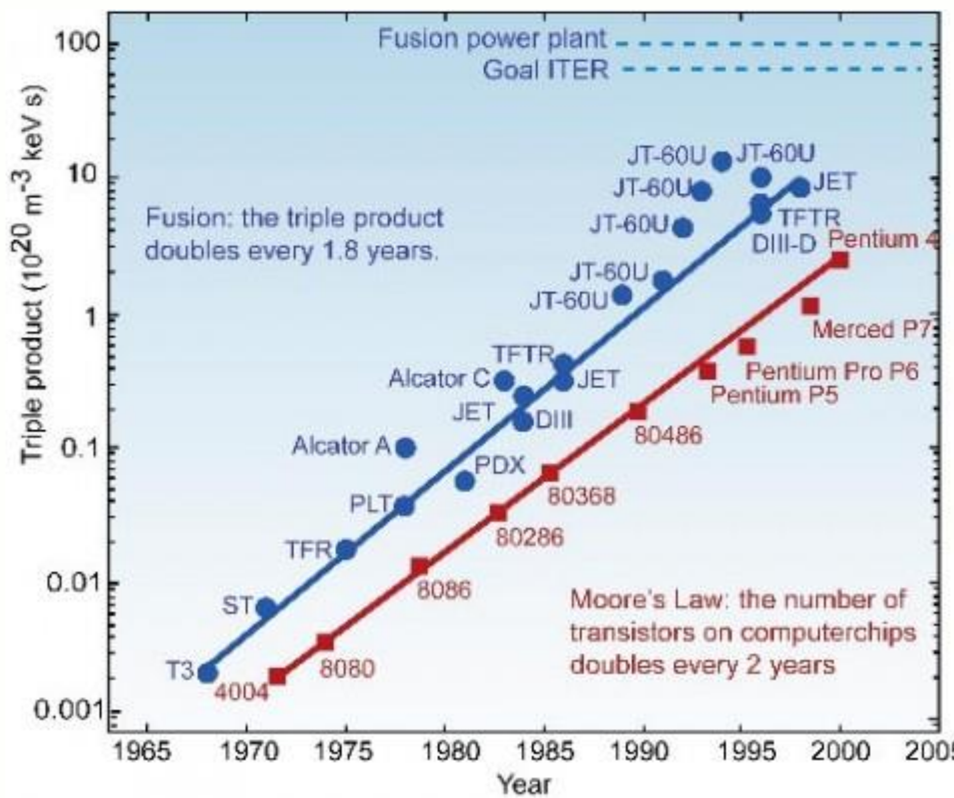
Ignition of the fusion plasma



Gain of fusion plasma

$$Q_{DT} = \frac{\Phi_{DT}}{\Phi_H} = \frac{n\tau\langle\sigma u\rangle E_{DT}}{12 k_b T}$$

Lawson criterion: $$n\tau \geq \frac{12 k_b T}{\langle\sigma u\rangle E_{DT}}$$



Picture source: http://www.fusenet.eu/node/42

Ignition: Fusion reaction continues without additional heating from outside

Where does the tritium come from?

In nature: Product of cosmic rays $^{14}N + n \rightarrow {}^{12}C + T$

Artificially: Byproduct in nuclear reactors applying D_2O (e.g. CANDU)
$D + n \rightarrow T$ ~2 kg/yr

This will **not be sufficient** to fuel fusion reactors based on DT (expected consumption ≈0.5 kg/day)

Tritium produced from lithium under neutron irradiation in the reactor:

- $^6Li + n \rightarrow T + \alpha$ +4.8 MeV
- $^7Li + n \rightarrow T + \alpha + n$ -2.8 MeV

Natural lithium: 7.5% ^6Li and 92.5% ^7Li

Sources of lithium:

- 10^{11} kg in landmass (sufficient for ~3×10^4 yr)
- 10^{14} kg in oceans (sufficient for ~ 3×10^4 yr)

Basic fuel cycle in a tokamak reactor

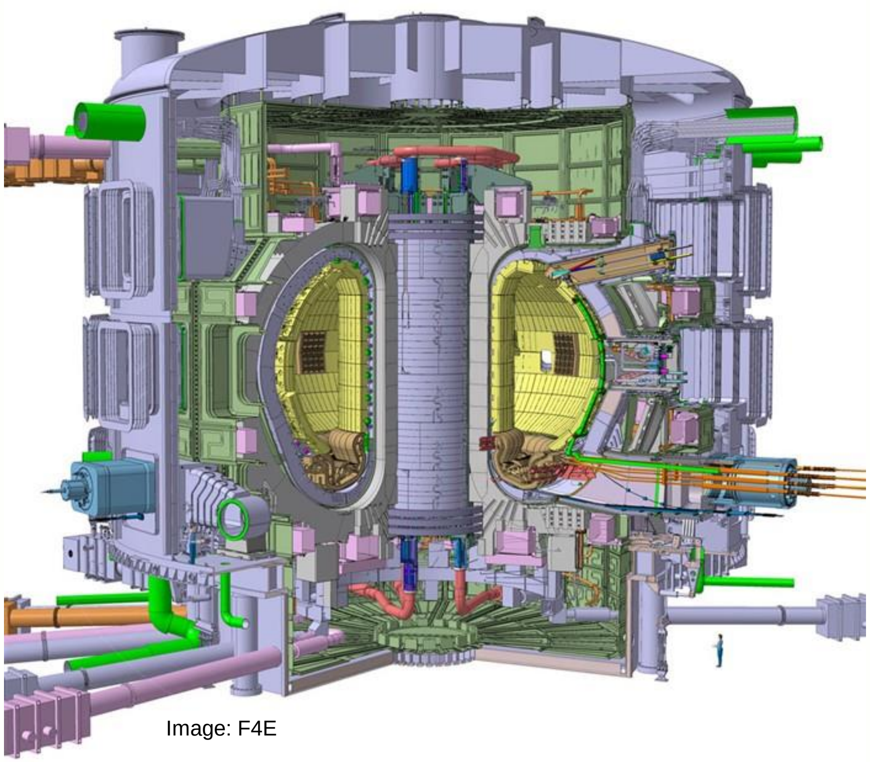
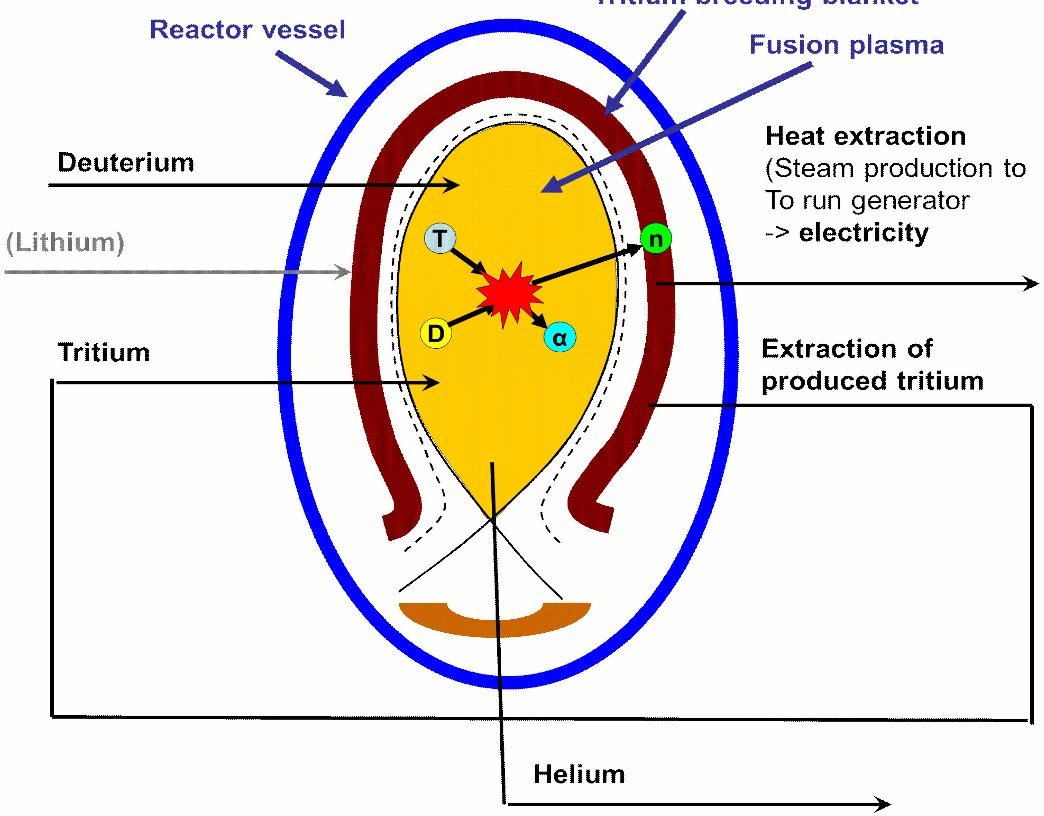


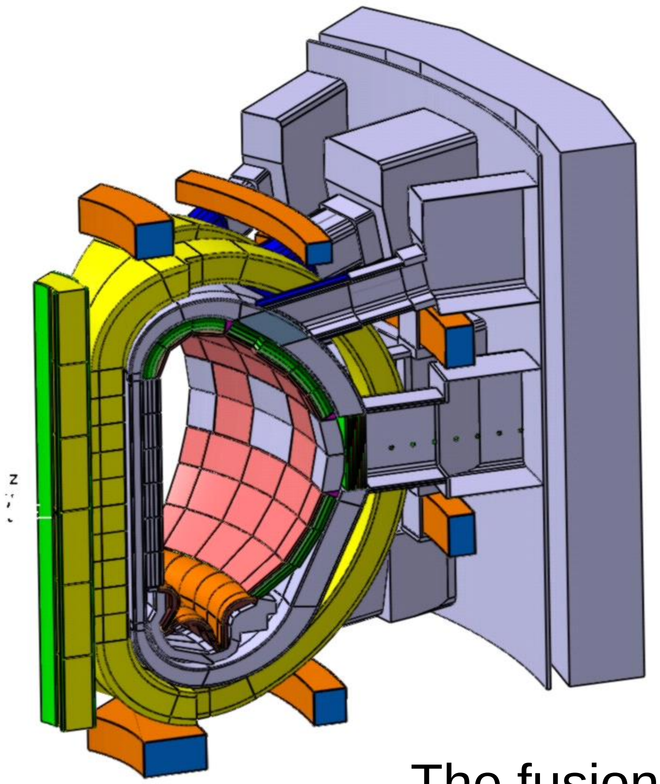
Image: F4E

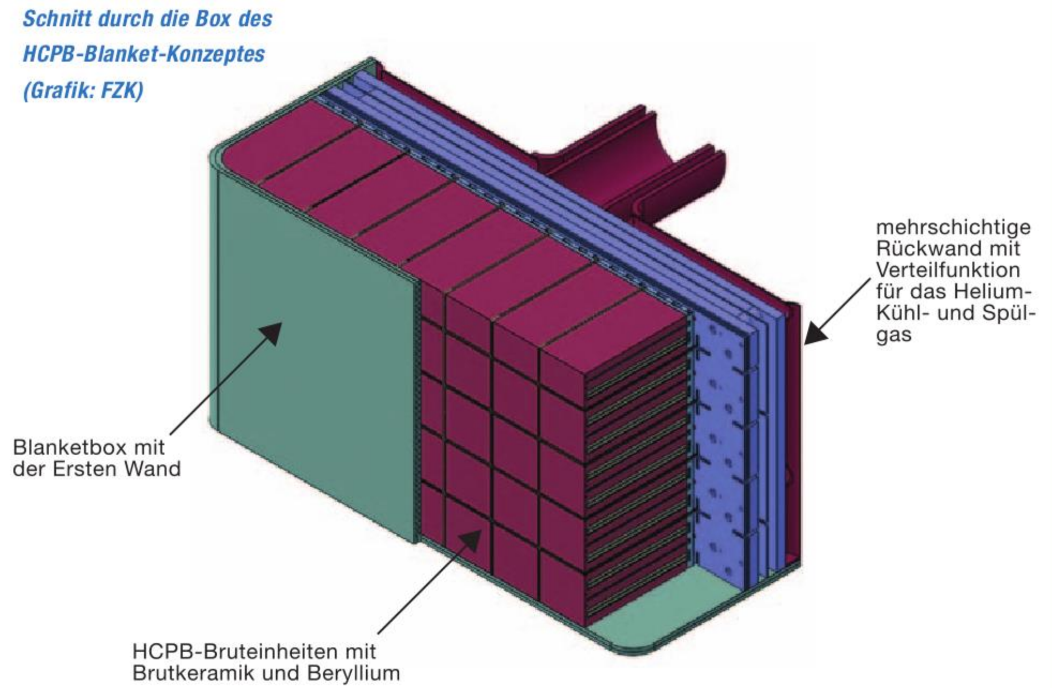


Fuel: **Lithium and Deuterium**

Tritium for DT reaction must be produced in the blanket
Tritium breeding ratio **must be larger than 1** plus some margin for losses in the tritium extraction and processing system
plus production of tritium for startup of further fusion power reactors

Basic fuel cycle in a tokamak reactor

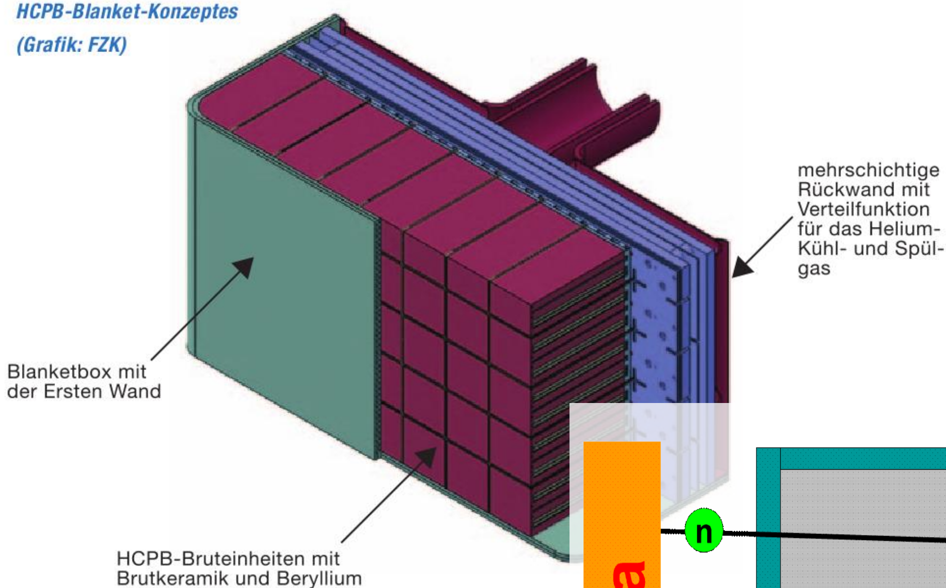




The fusion plasma is surrounded by a so called **breeding blanket,** which serves three main purposes:

- *Tritium production*
- *Energy conversion (→ **Heat generation**)*
- *Shielding for field coils behind the blanket*

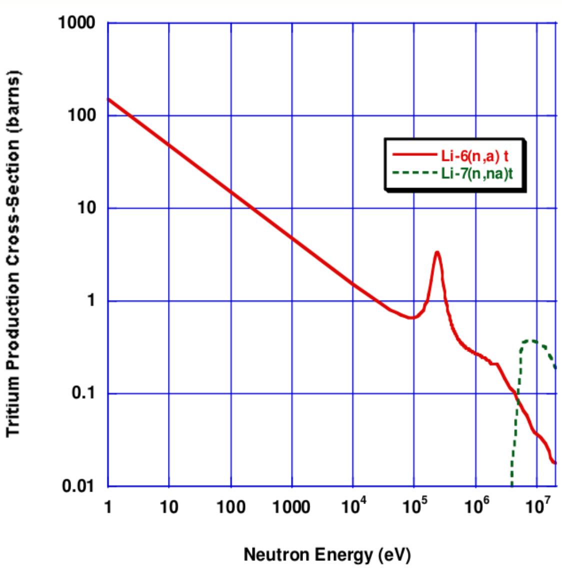
Basic fuel cycle in a tokamak reactor

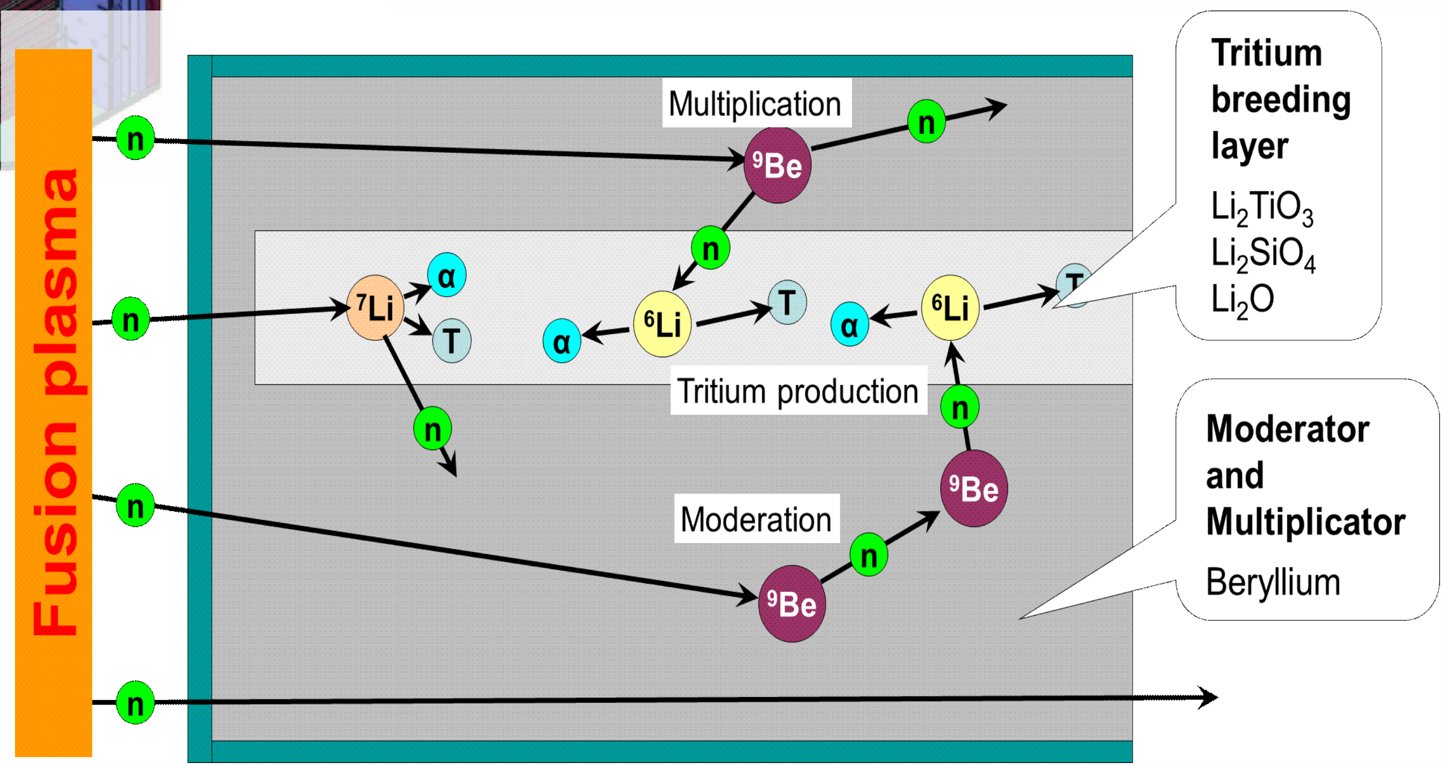


Schnitt durch die Box des HCPB-Blanket-Konzeptes (Grafik: FZK)

Important nuclear reactions in a typical solid-type breeding blanket

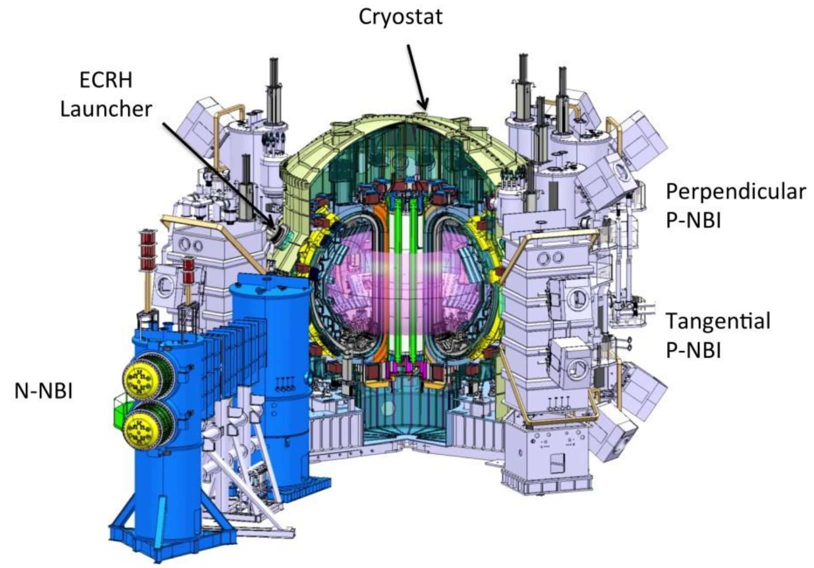
The produced tritium (ca. 570 g/day in the entire blanket) is removed with a sweeping gas



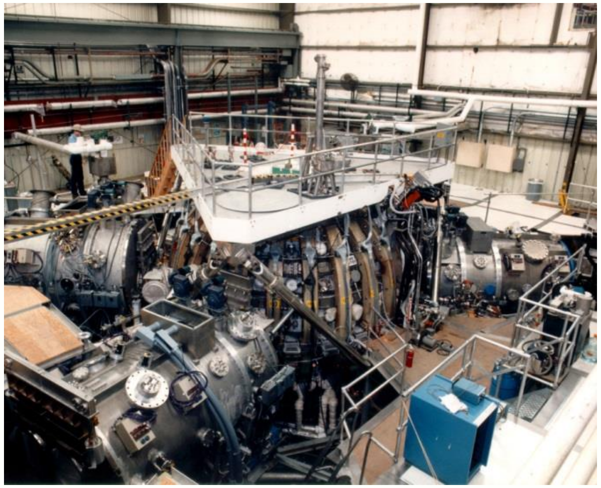


Some large tokamak reactors

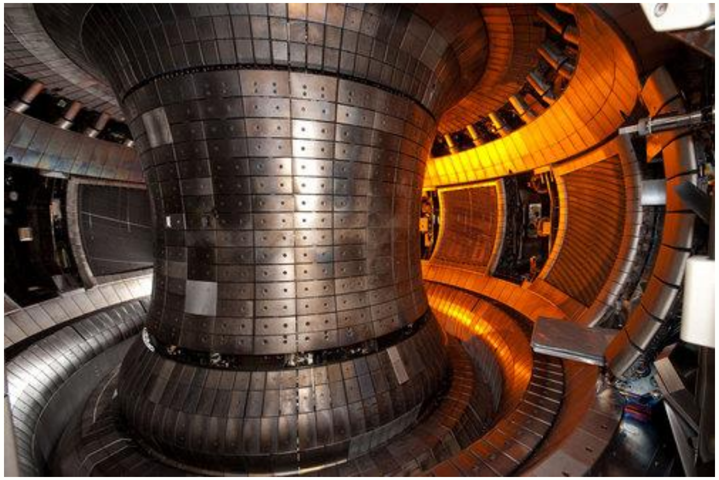
JET (Culham, UK)
Source:https://upload.wikimedia.org/wikipedia/en/8/80/JointEuropeanTorus_external.jpg



JT-60SA (Naka, Japan)
Source: http://www.jt60sa.org/pics/JT-60SA_cutaway3B.jpg



DIII-D (San Diego, CA)
Source: https://alltheworldstokamaks.files.wordpress.com/2012/07/diii-d.jpg



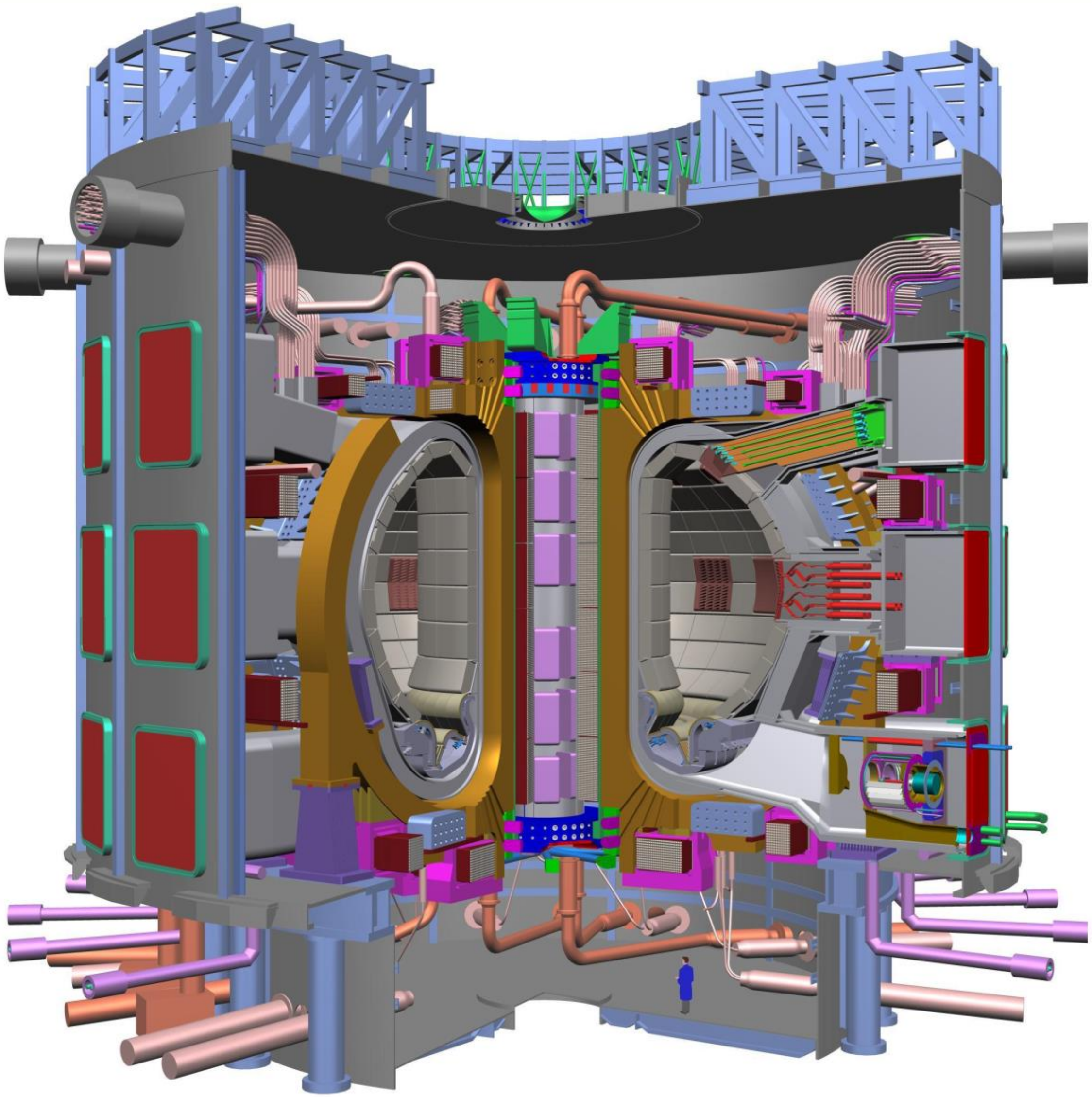
ASDEX Upgrade (Garching, Germany)
Source:https://pbs.twimg.com/profile_images/2548176563/hccmkozdpcbsgedefb9x.jpeg

ITER (The Way)

Construction site of ITER in Cadarache, Provence, France

Picture source: www.iter.org

ITER (The Way)



- Output power up to 500 MW
- Q=10 (burning plasma!)
- Pulse length 400-600 s
- Studies plasma and fusion reactor technology including the tritium breeding system
- Demonstrates safety of a fusion device

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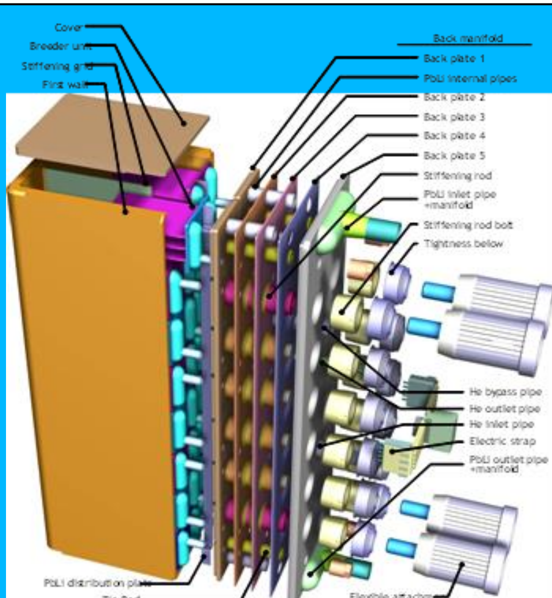
Golden, 27. September 2016
Institute of Neutron Physics
and Reactor Technology

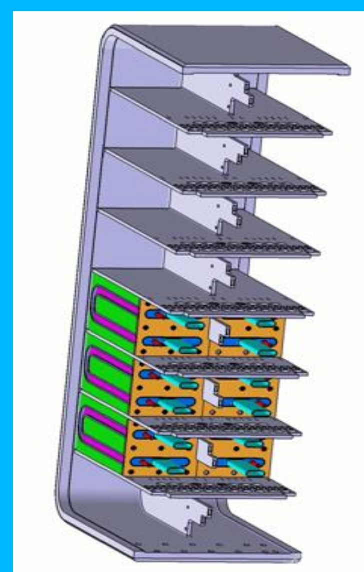
Breeding blanket concepts (EU)
to be tested in ITER

	Helium-Cooled Lithium-Lead (HCLL)	Helium-Cooled Pebble Bed (HCPB)
Tritium breeder	Liquid lithium lead	Li_4SiO_4 or Li_2TiO_3
Neutron multiplier	Liquid lithium lead	Beryllium
Coolant	Helium	Helium

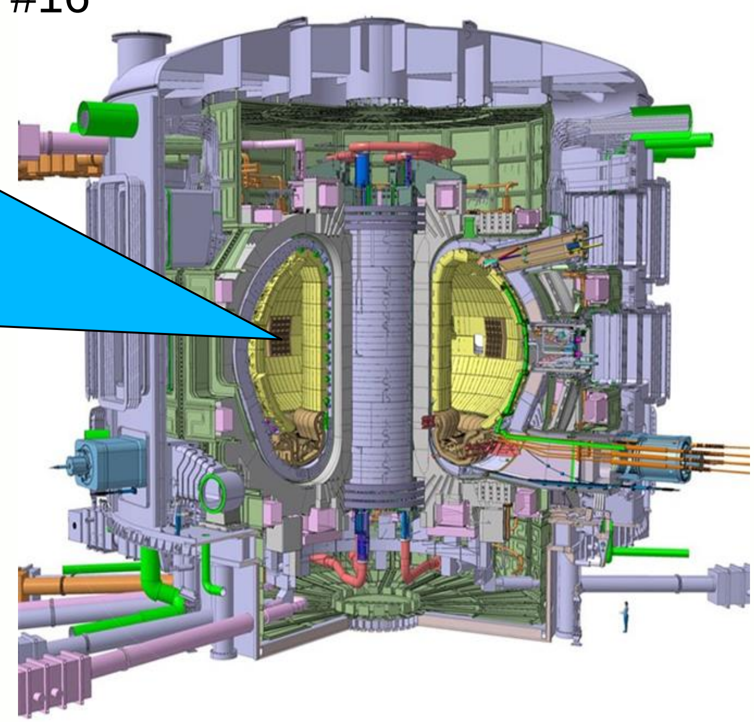
Test **B**lanket **M**odules will be inserted in equatorial port #16



HCLL TBM



HCPB TBM



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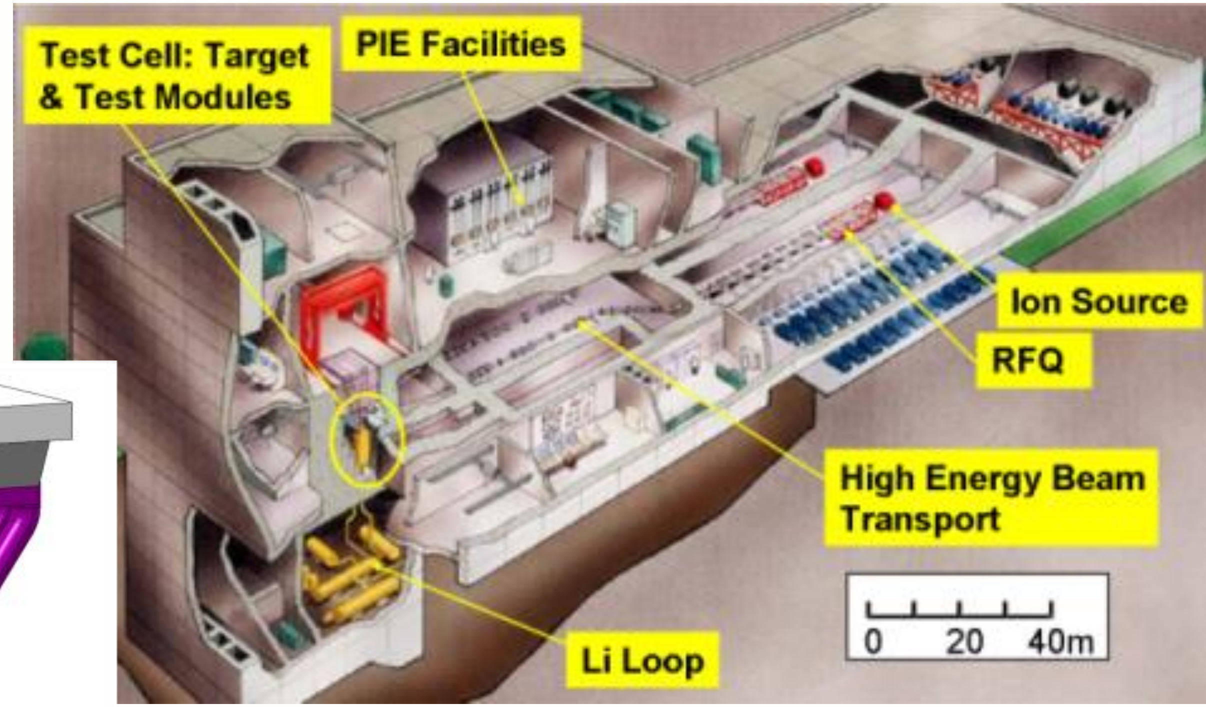
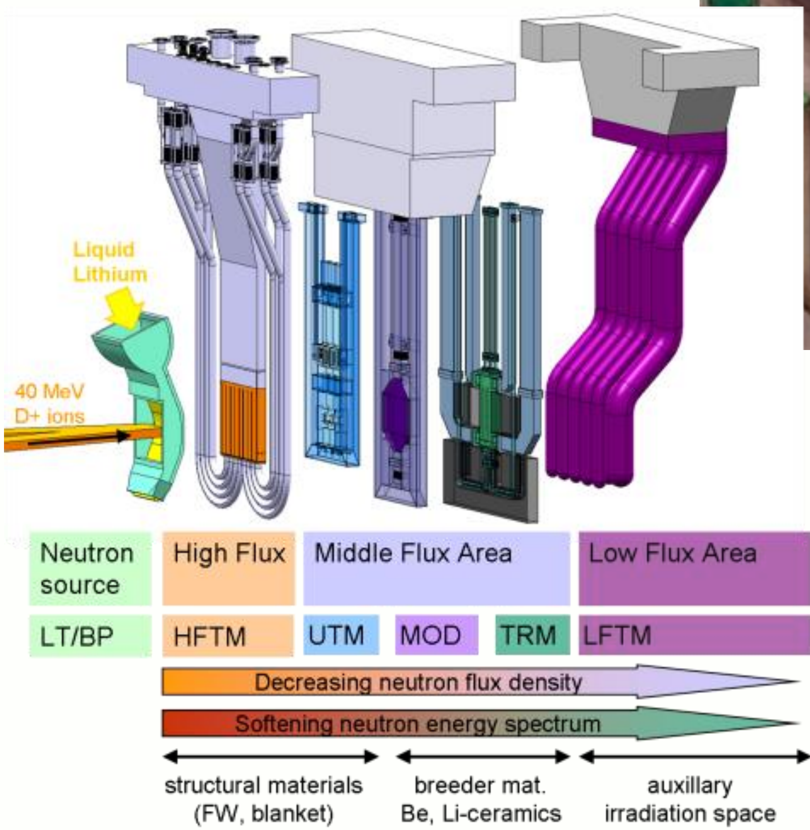
International Fusion Materials Irradiation Facility (IFMIF)

Main mission:

Material irradiation with fast neutrons to damage levels up to 55 dpa





Neutron source:
Deuterons with 40 MeV energy on Li beam current 2x125 mA

Engineering validation and engineering design activities completed.
To be built: Where? When?
Or Early Neutron Source instead?

Source of pictures: https://www.inr.kit.edu/english/124.php

Objective of neutronics experiments

Important nuclear parameters for fusion reactor blankets

- Tritium production rate / Tritium breeding ratio
- Nuclear heating
- Shielding capabilities
- Material activation
- Gas production
- others

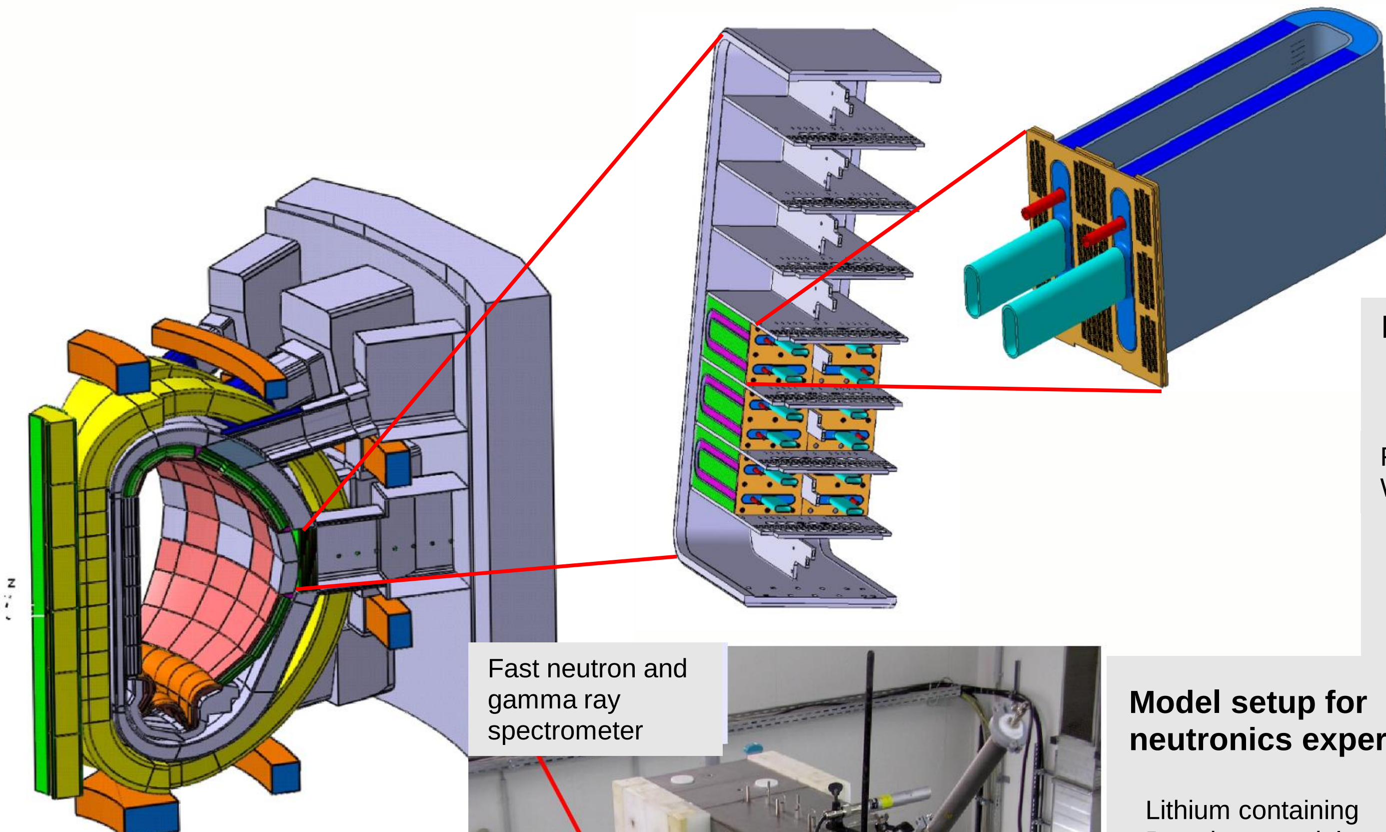
Neutronics calculations based on nuclear data libraries, radiation trans-port and inventory codes ⇄ Input for the physical design of the blanket (with iterations) →

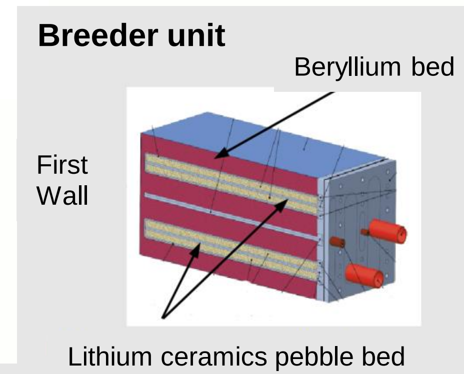
- Physical design
- System operation
- Licensing
- Maintenance
- Decommissioning
- others

Proof of suitability and applicability of available transport codes and nuclear data for predicting such responses:

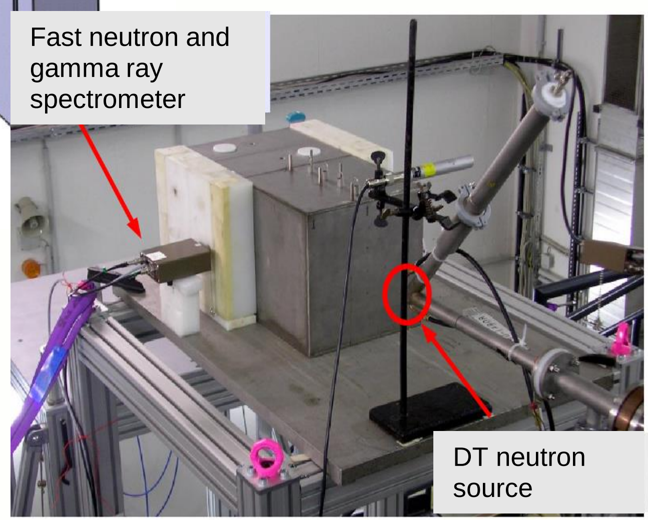
Calculation +/- Uncertainty
to be compared with
Experiment +/- Uncertainty

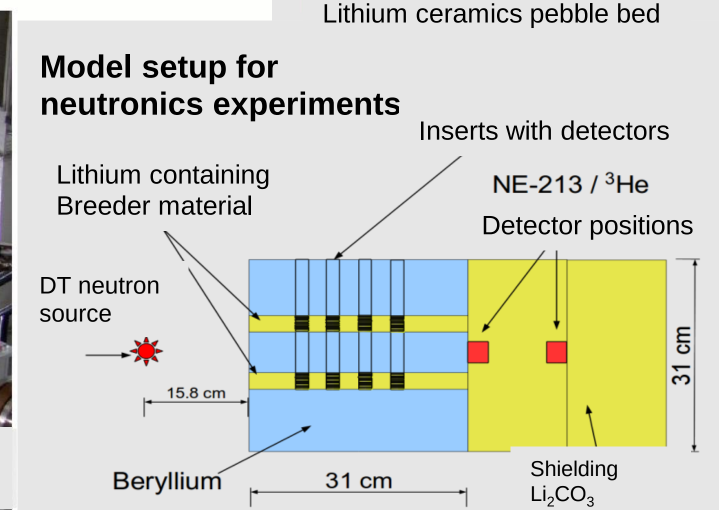
TBM mockup experiments with neutron generators



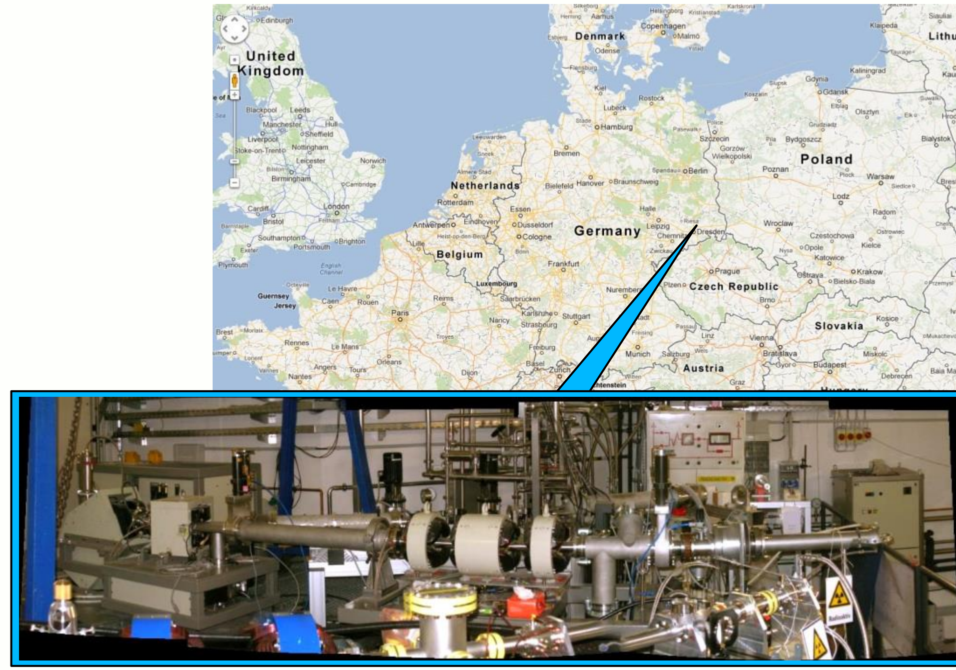


Example:
Helium Cooled Pebble Bed (HCPB) TBM





Neutron generator laboratories involved in the EU fusion neutronics experiments



Fusion Neutron Source

Japan Atomic Energy Agency (Tokaimura)

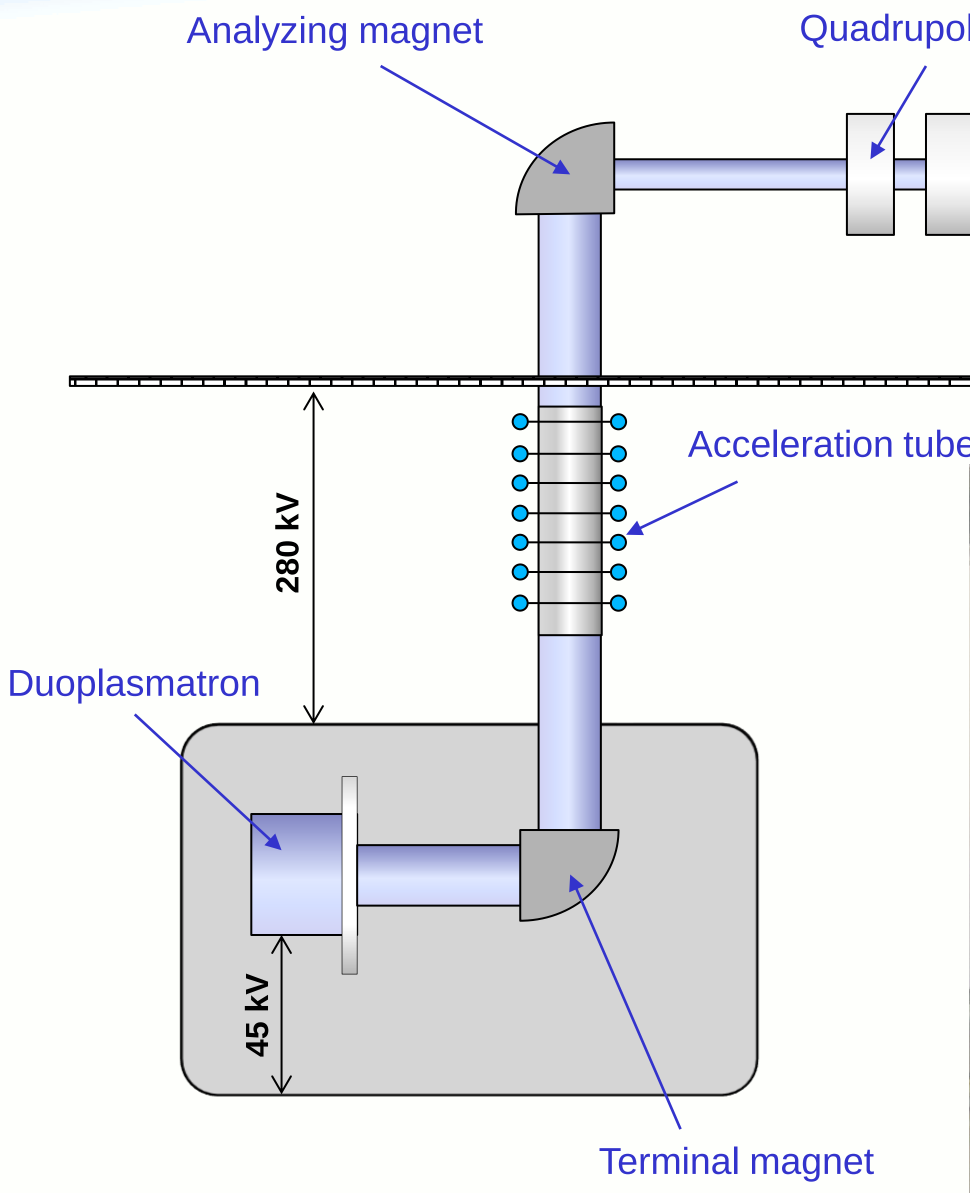
(through **IEA-NTFR** Implementing Agreement)

FNG, ENEA Frascati

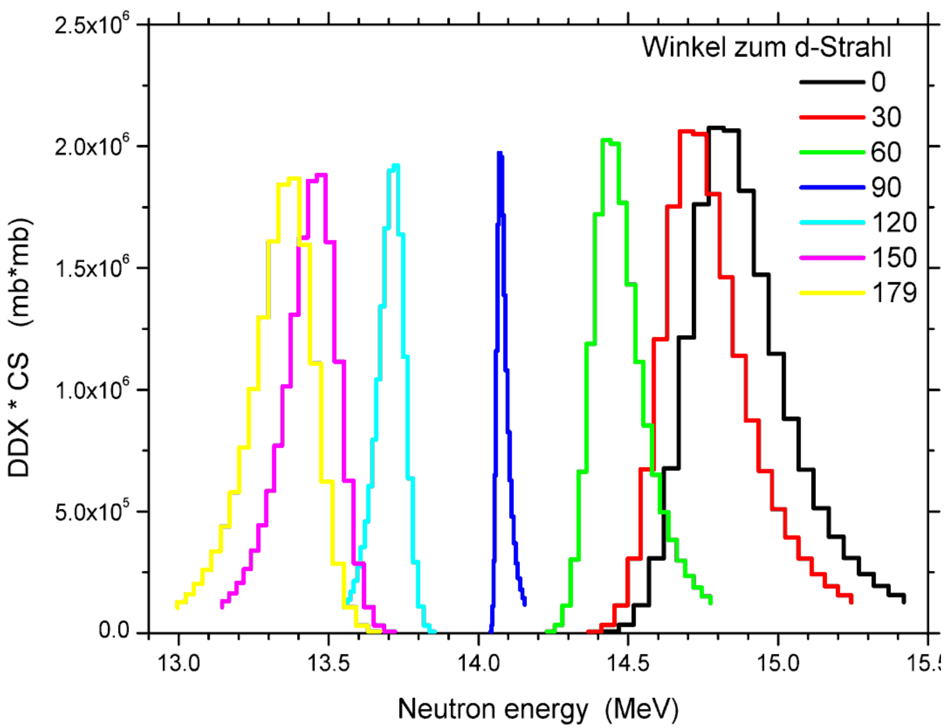
TUD-NG, TU Dresden

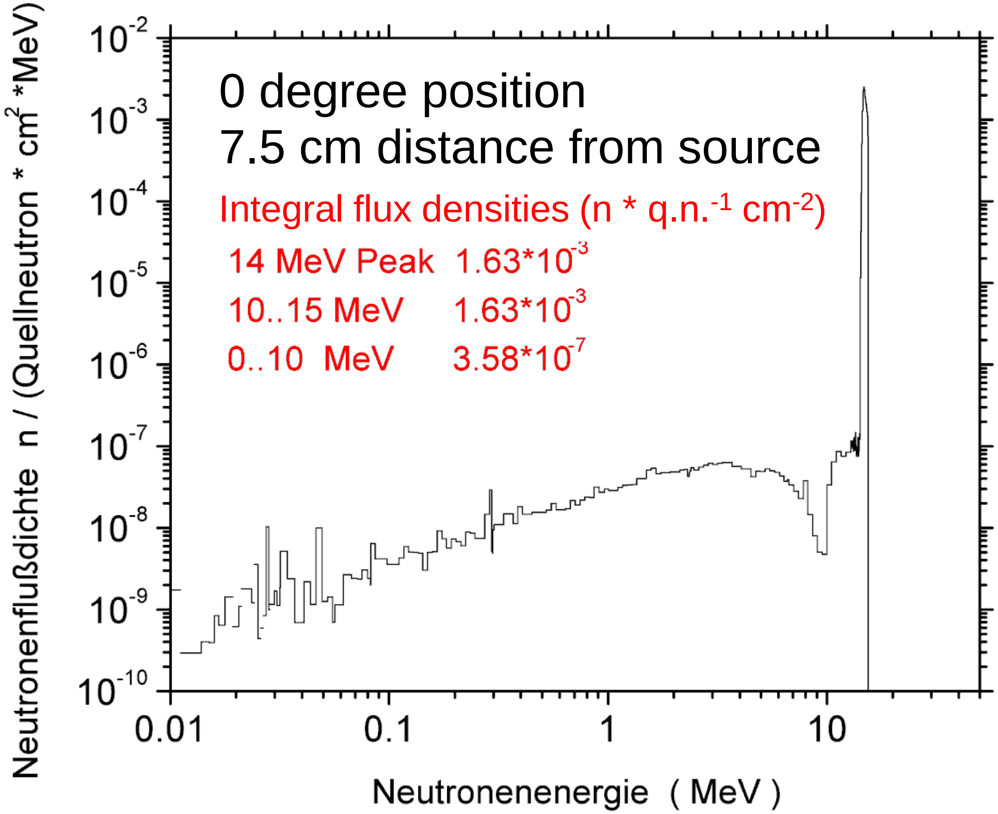
FNS, JAEA Tokaimura

Technical University of Dresden Neutron Generator



Technical University of Dresden Neutron Generator





Calculated spectrum of the DT neutron peak depending on angle to d-beam

Assuming thick target and 320 keV deuteron energy

-> reaction cross section measurement around 14 MeV

Calculated neutron spectrum

Neutron energy distribution from DROSG[1]

Transport through target assembly with MCNP[2] .

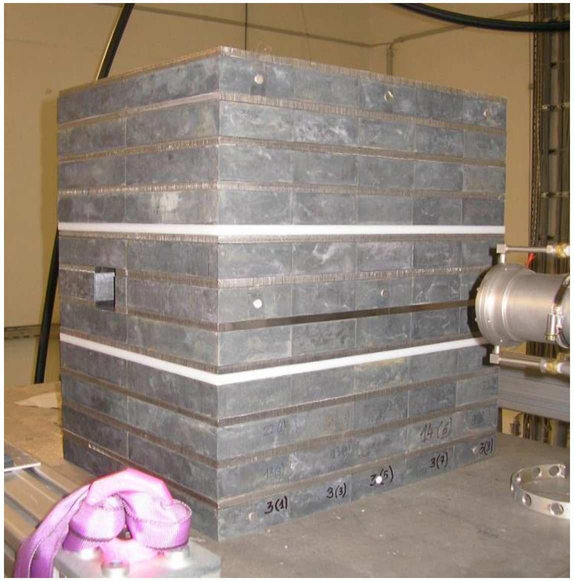
1) M.Drosg, DROSG-2000: Neutron Source Reactions, IAEA-NDS-87, IAEA Nuclear Data Section, May 2005
2) MCNP—A General Monte Carlo N-Particle Transport code, Version 5, Report LA-UR-03-1987, Los Alamos, 2003

Neutronics experiments with a mock-up of HCLL TBM

The EU is conducting a R&D program for developing Helium Cooled Lithium Lead (HCLL) and Helium Cooled Pebble Bed (HCPB) blankets

Both concepts will be tested in ITER (Test Blanket Module - TBM)

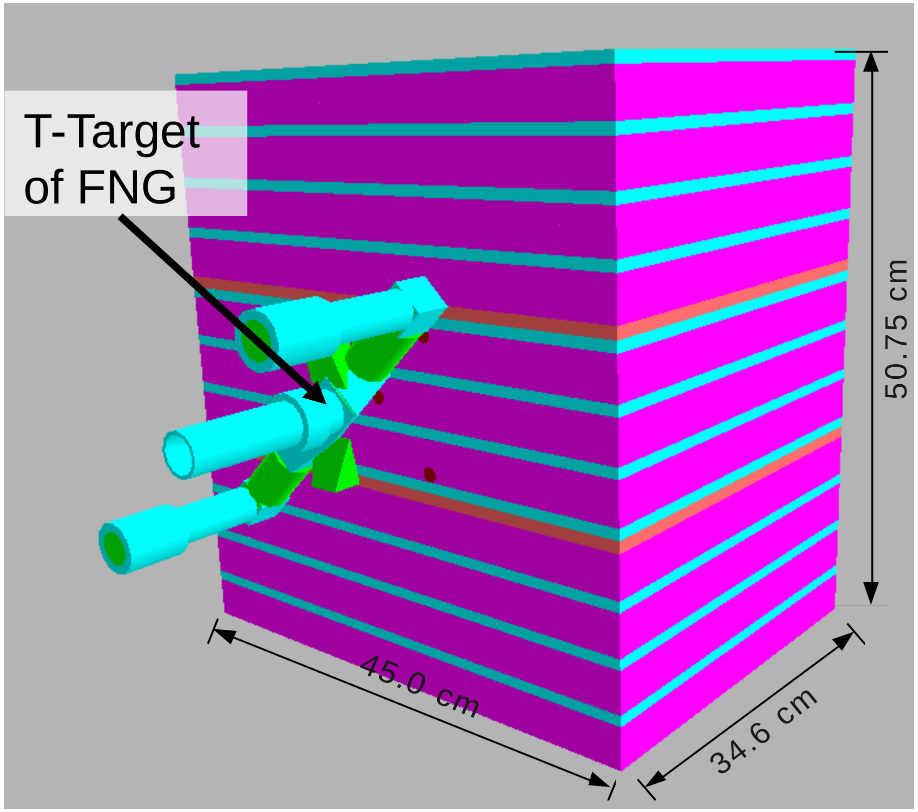
As part of this program, neutronics experiments have been performed to validate the predictions of Tritium Production Rate (TPR) in these concepts

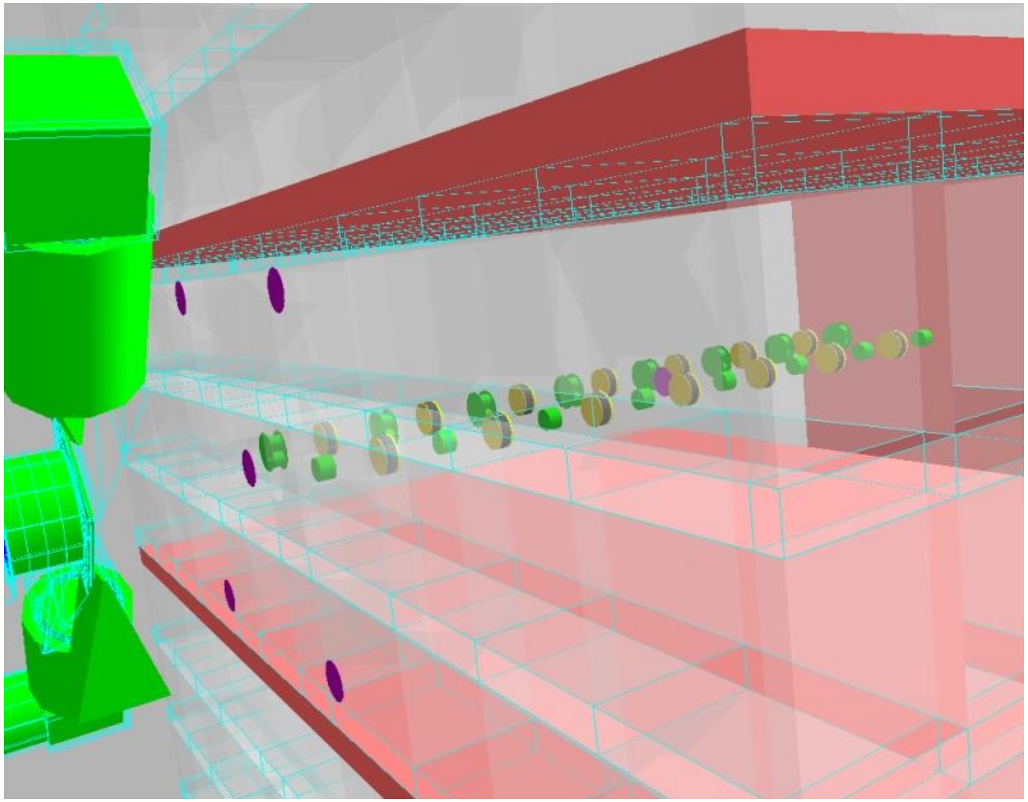


Measurement of tritium production rates, neutron and photon flux spectra

A collaboration between ENEA, TUD, FZK, AGH, JSI (EFDA-F4E) and with JAEA (IEA-NTFR Implementing Agreement)

HCLL TBM mock-up experiment
Tritium production rate (at FNG / ENEA Frascati)

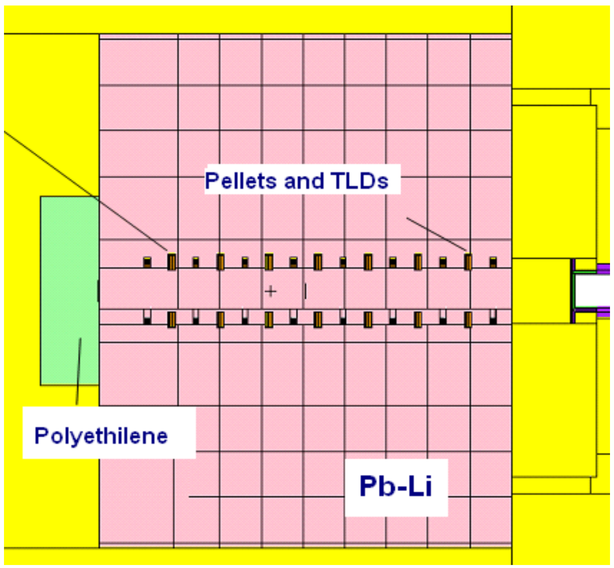


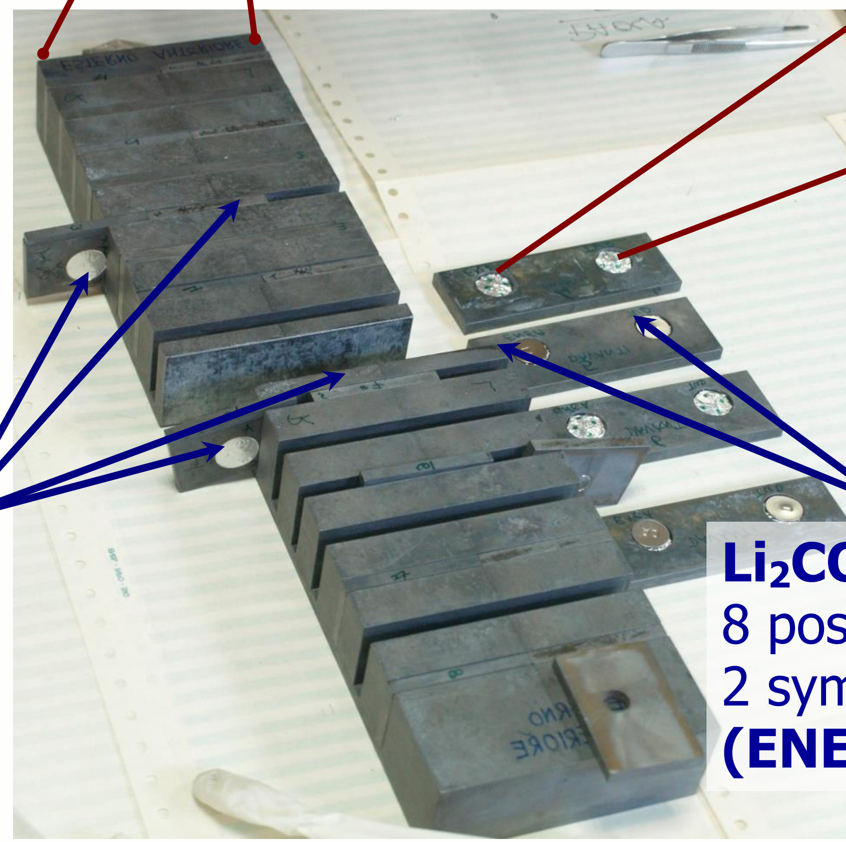


Mock-up consists of layers of LiPb (110 bricks, Li/PbLi: 0.615±0.016 wt%), Eurofer steel (Eurofer-97) and polyethylene
Detectors placed along the axis of the mock-up

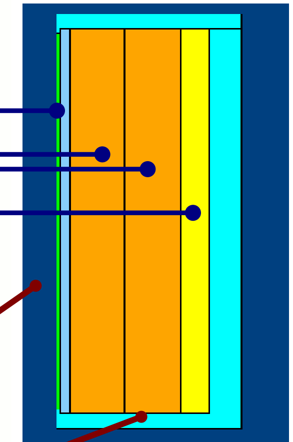
MCNP model: Detailed description of the neutron source and the detectors (Li_2CO_3 pellets and all LiF-TLD)

HCLL TBM mock-up experiment
Tritium production rate (at FNG / ENEA Frascati)





Stacks:
Ni activation foil
Li-nat (2mm)
95% Li-6 (1 mm)



Thermo-luminescent detectors TLDs (LiF)
8 positions in depth
in 2 symmetrical rows
(KIT & AGH)

Li_2CO_3 pellets
8 positions in depth
2 symmetrical rows
(ENEA, KIT, JAEA)

HCLL TBM mock-up experiment
Tritium production rate (at FNG / ENEA Frascati)

- **Li_2CO_3** pellets are dissolved in acids
  solution is mixed with liquid scintillator
  Tritium is measured by β-counting

- Thermoluminescence detectors (**TLD**)
  Tritium production is measured in two ways:

  - by thermoluminescence signal due to the dose from ^{6}Li(n,t)α and ^{7}Li(n,n′t)α reactions during irradiation

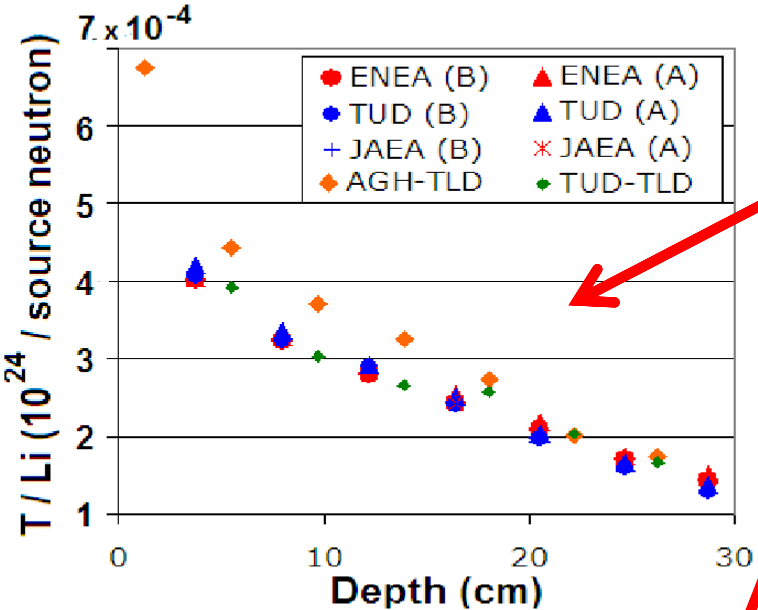
  - by thermoluminescence signal due to the dose from tritium decay after irradiation

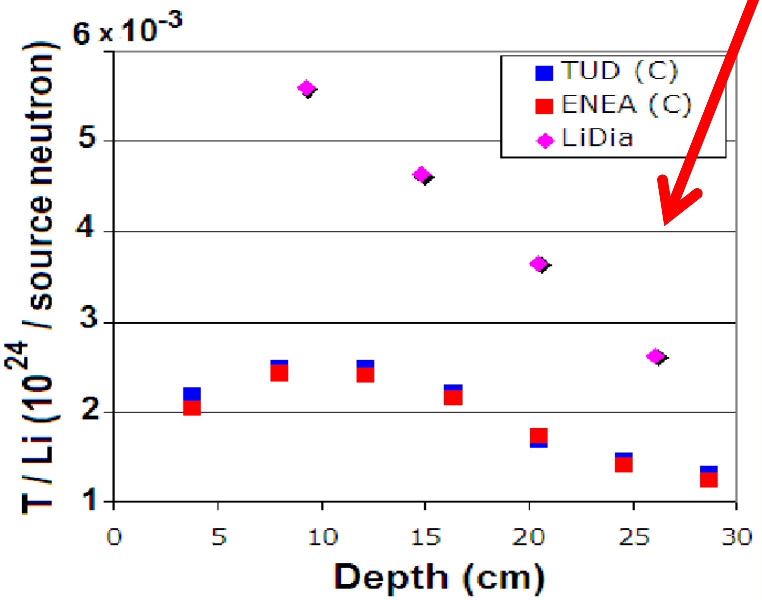
HCLL TBM mock-up experiment: **Tritium production rates**

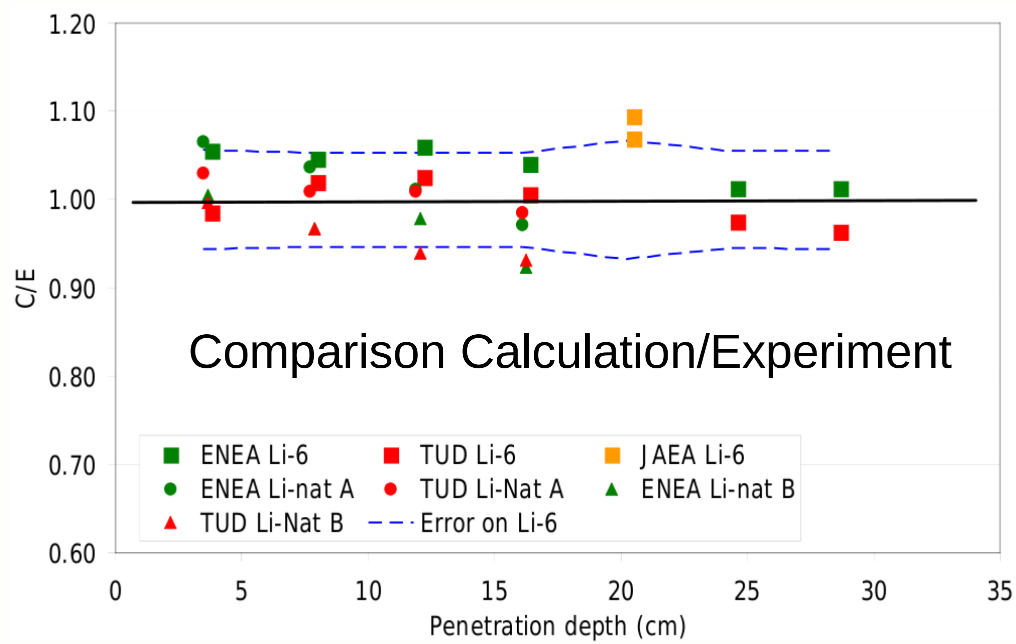
Tritium production rates along central axis of HCLL TBM mockup

^{nat}Li-type detectors (Li_2CO_3 pellets, TLD)

^{6}Li enriched detectors (Li_2CO_3 pellets, TLD, LiF covered diamond)
(There is negligible self-shielding in case of the diamond detector.)

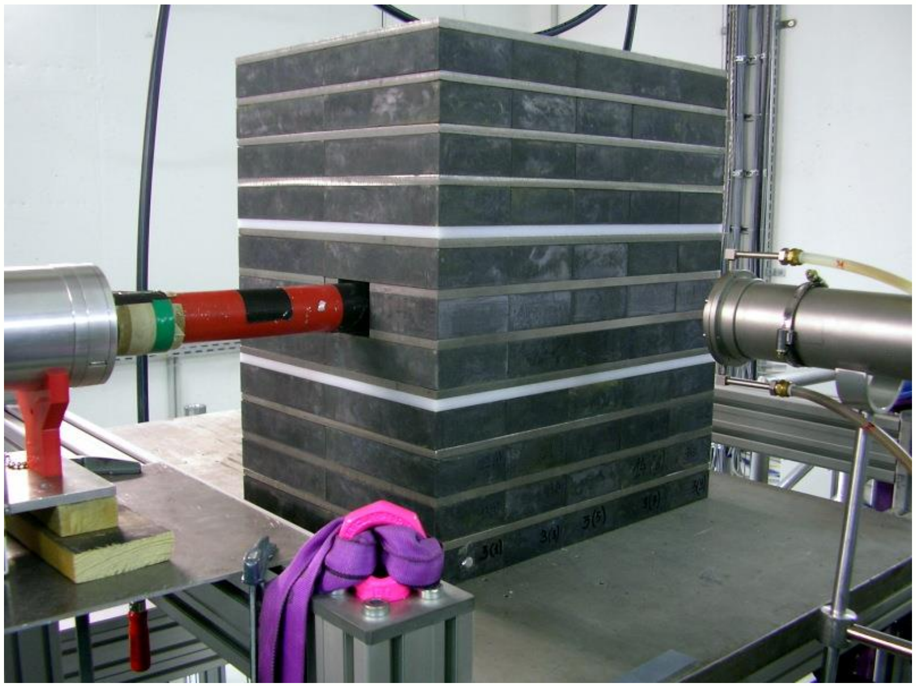


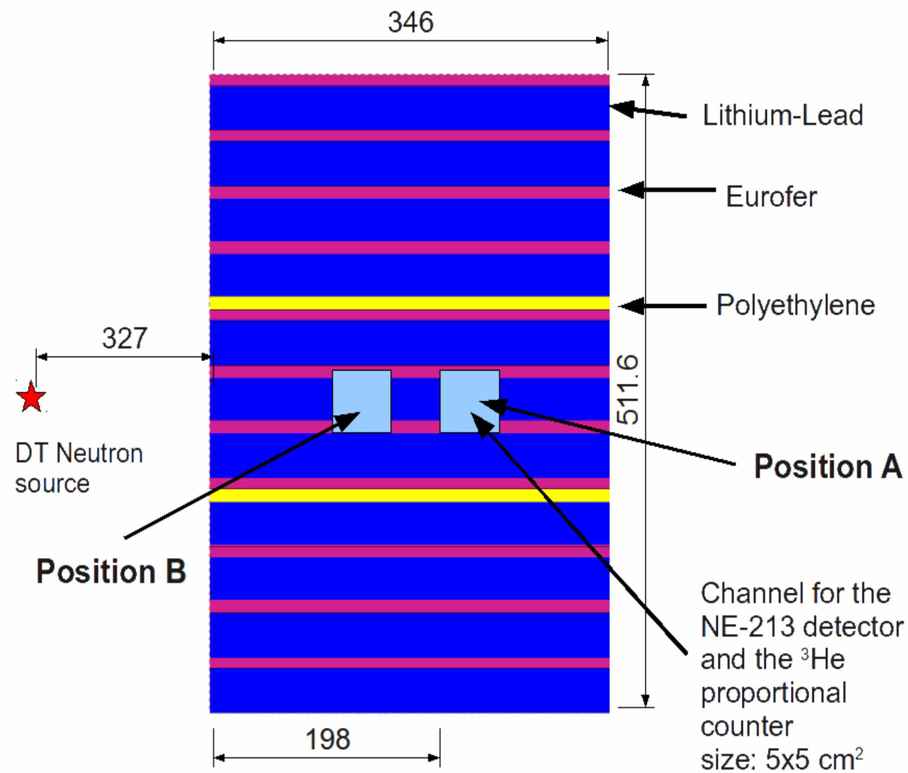




Diagrams from P.Batistoni et.el., *Final results on a neutronics experiment on a HCLL tritium breeder blanket mock-up*, 10th Intl. Symp. on Fusion Nuclear Technology, 11 – 16 Sept. 2011 - Portland (OR)

HCLL mock-up experiment:
Set-up for the measurement of fast neutron and gamma-ray fluxes at TUD-NG

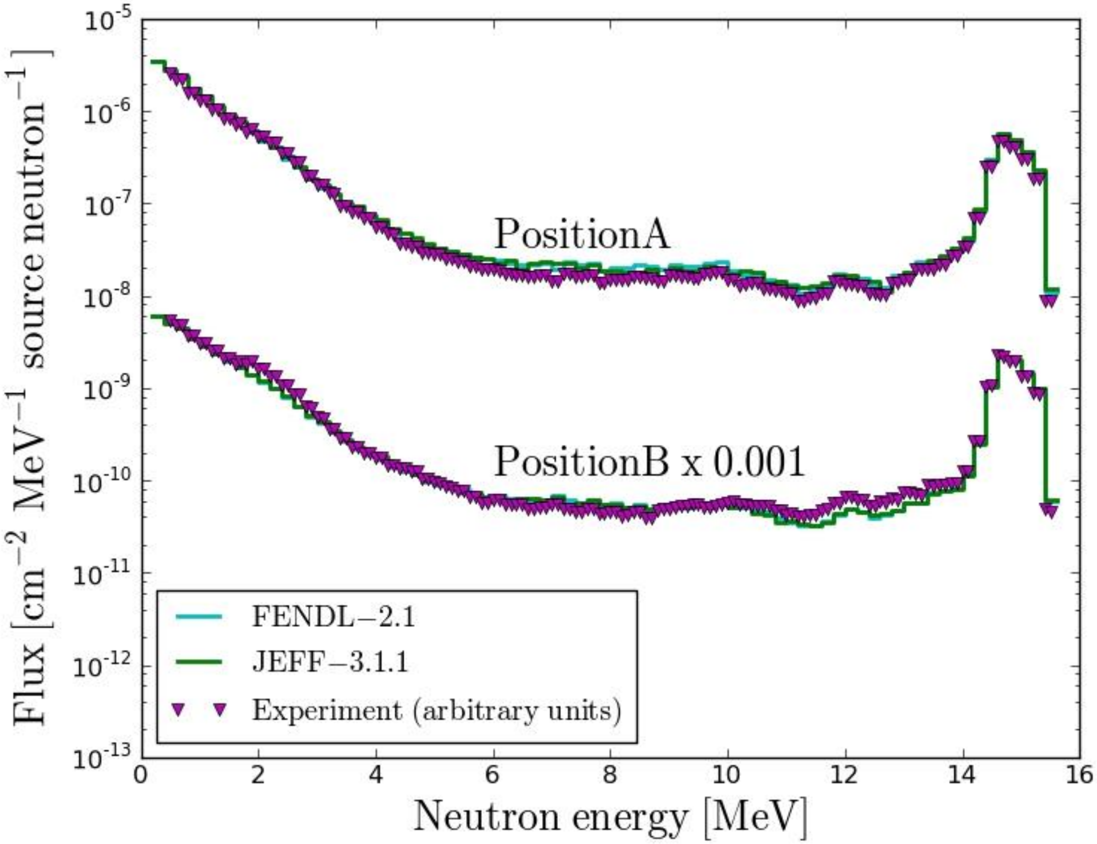


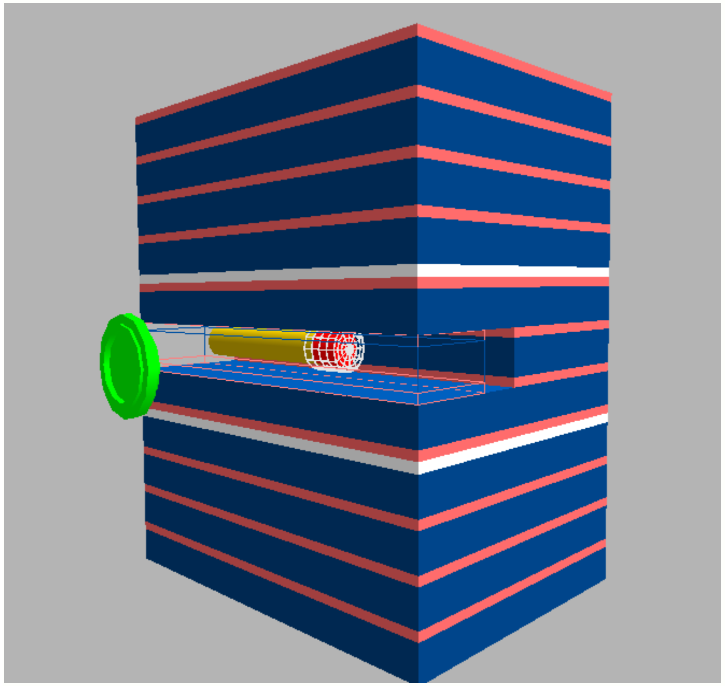


Left: NE-213 detector (1.5"x1.5 ")
Right: Ti-T target of neutron generator
Middle: Mock-up

Two measurement position have been used. Only one channel was present at a time.

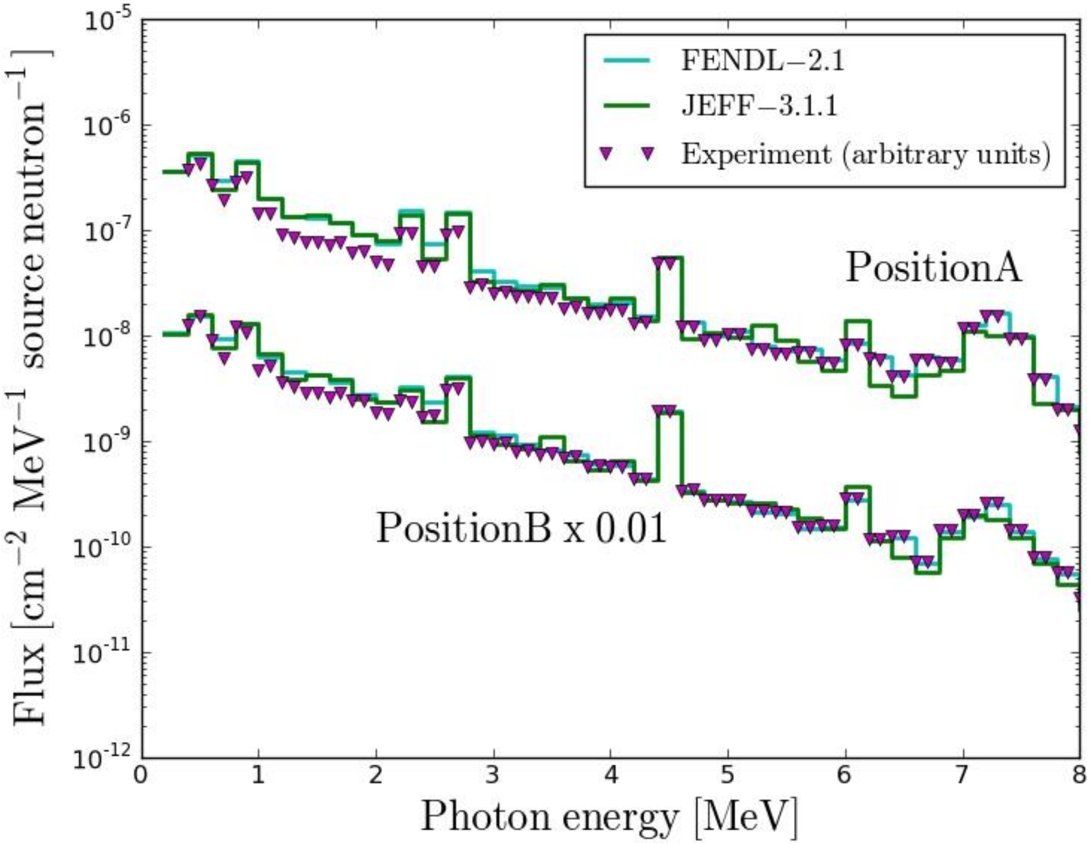
HCLL TBM mock-up experiment
Fast neutron flux spectra

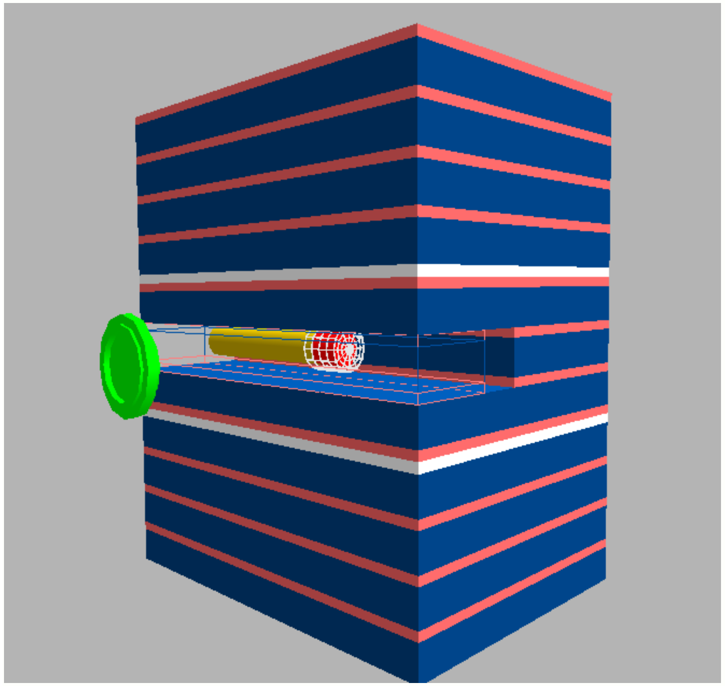




- Pulse height spectra recorded with the NE-213 detector
- Unfolding with MAXED code, response matrix (validated at PTB)
- Calculations with MCNP5 and JEFF-3.1.1 and FENDL-2.1
- Normalization of unfolded spectra by fitting 14 MeV peak height

HCLL TBM mock-up experiment
Gamma-ray flux spectra





- Pulse height spectra recorded with the NE-213 detector
- Unfolding with MAXED code and response matrix
- Calculations with MCNP5 and JEFF-3.1.1 and FENDL-2.1
- Normalization from neutron spectrum

Neutronics instrumentation for the ITER Test Blanket Modules

ITER TBM (neutronics) experiments are an important step on the way to DEMO and power reactor breeding blankets

Local neutron flux measurements:

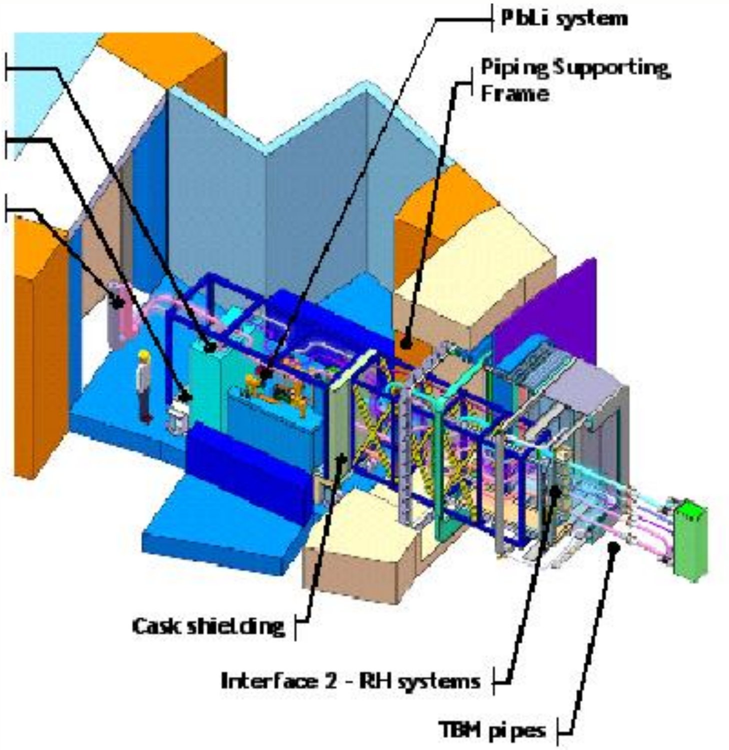
- normalization for other parameters (also „non-neutronics“) in the TBM
- better accuracy than interpolated flux values from measurements outside the TBM

Particular importance for Tritium accountancy!

ITER TBM neutronics experiments will allow to check

- **high-fidelity calculational tools**
- **Modelling of heterogeneous fusion reactor relevant complicated structures under fusion reactor relevant conditions**

Neutronics instrumentation for the ITER TBM
- Conditions in the TBM -



Conditions in the TBM terribly bad for any kind of detectors / diagnostics

- ***10^9~10^{14} n*cm^{-2}s^{-1}***
- **300..550 ºC**
- **Magnetic fields ~4 T**
- **difficult access**
- **little space**

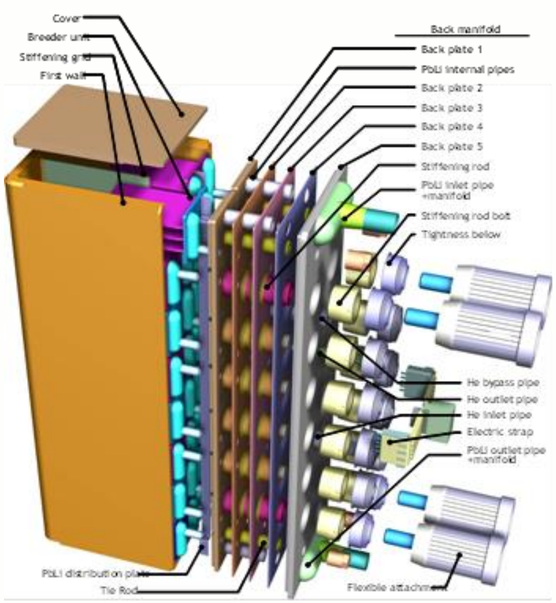
Possible candidates for neutron flux measurements:

Activation foils, miniature fission chambers, diamond detectors, silicon carbide detectors, self-powered neutron detectors

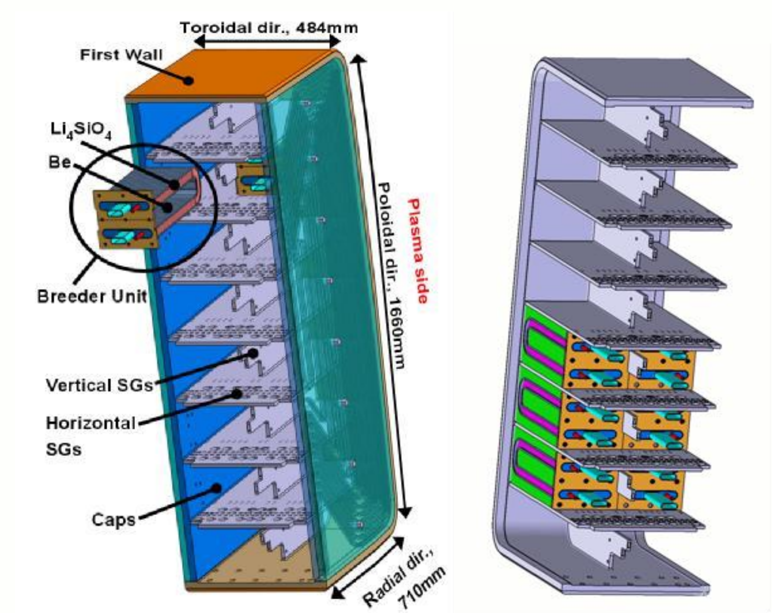
Testing and qualification underway

TBM nuclear instrumentation and research plan

EM-TBM: Electromagnetic TBM (plasma H-H phase);
NT-TBM: Neutronic TBM (plasma D-D and first period of the D-T low cycle phases);
TT-TBM: Thermo-mechanic & Tritium Control TBM (last period of the D-T low cycle and first period of the D-T high duty cycle phases);
IN-TBM: Integral TBM (last period of the high duty cycle D-T phase).

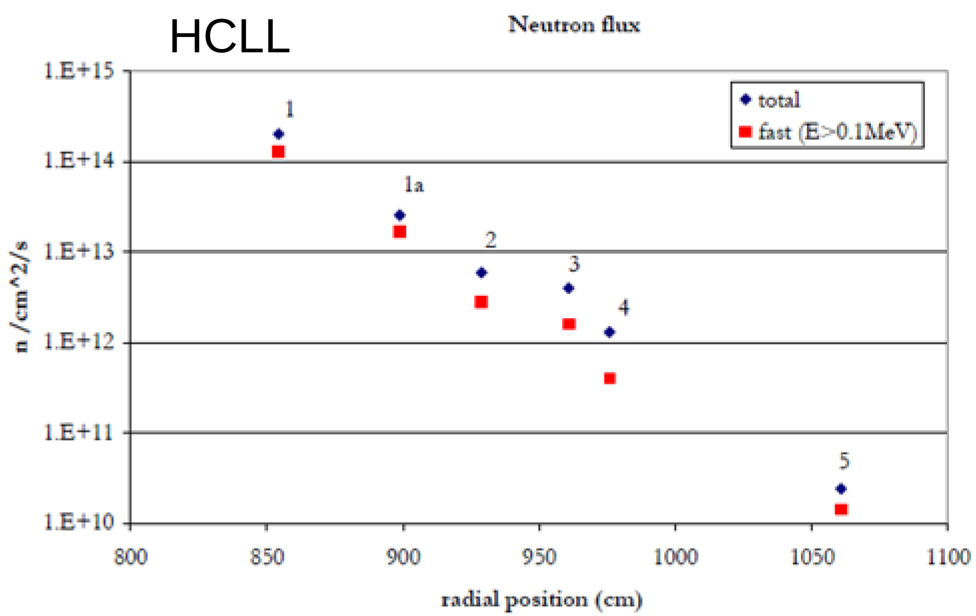


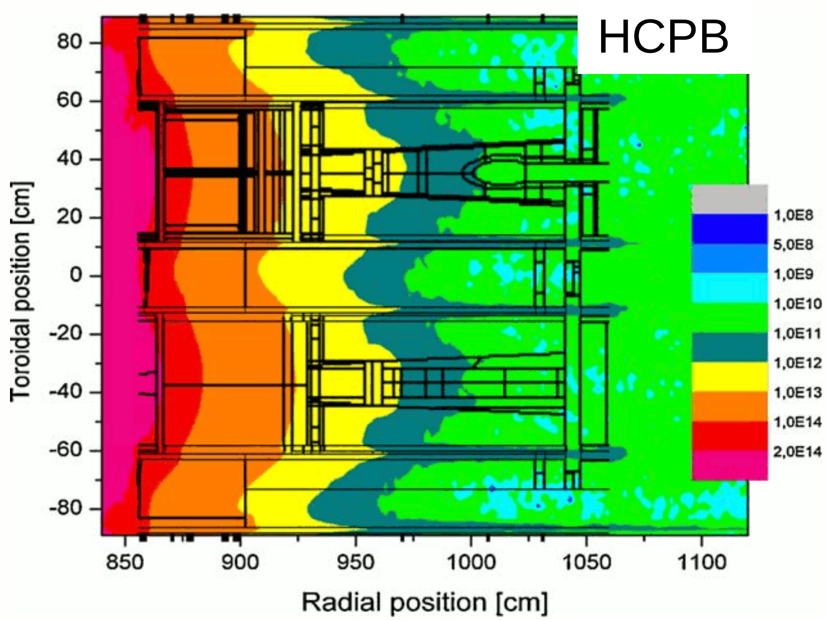
HCLL TBM

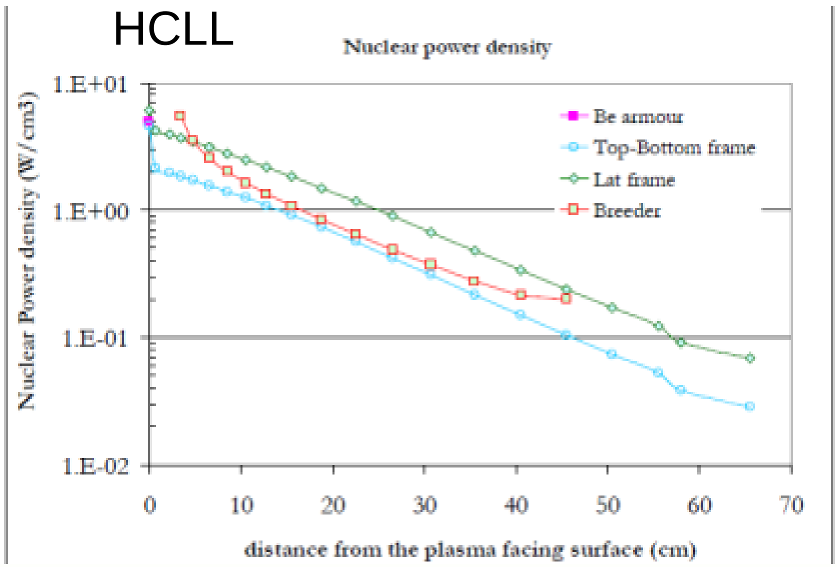


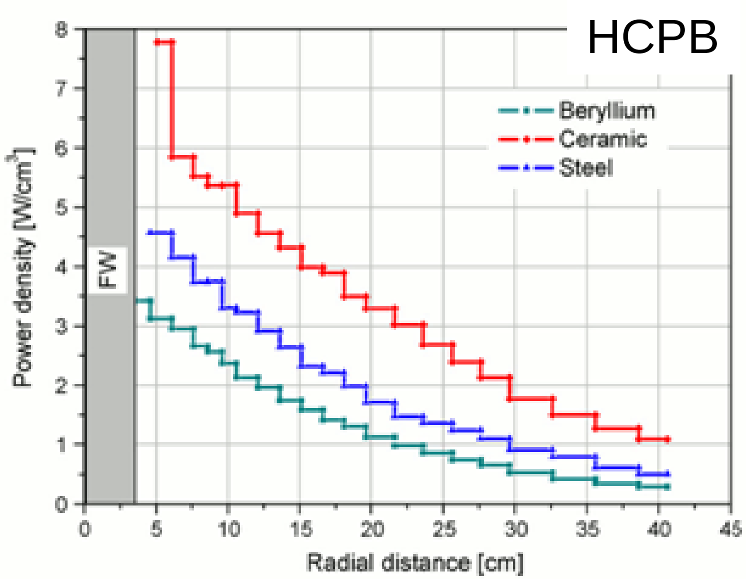
HCPB TBM

Neutronics instrumentation for the ITER TBM
- Conditions in the TBM at 500 MW fusion power -

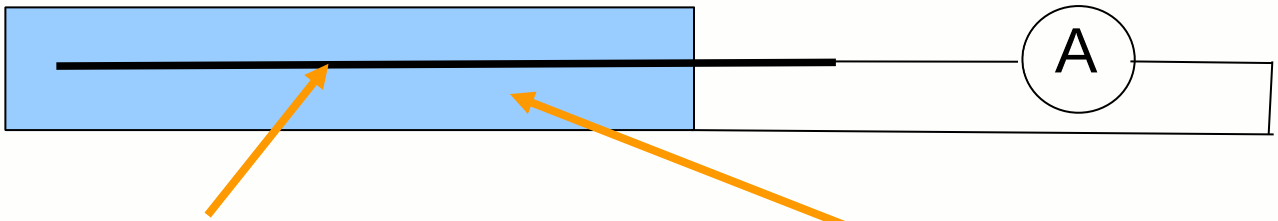








Self-powered neutron detectors (SPND)



- central lead (emitter): Rh, Co and others, insulation MgO or Al_2O_3
- induced beta activity or induced Compton electrons -> small current
- applied in fission reactors
- Conditions in fusion reactor may be incompatible due to strong EM fields

Work in collaboration with ENEA Frascati:

- Tests with commercially available SPND in fast neutron field of TAPIRO reactor (ENEA Casaccia) and FNG (ENEA Frascati)
- Calculations with inventory code system EASY and typical HCPB neutron spectrum and comparison with results from TAPIRO
- Search for candidate emitter materials for fast neutron fields and production of test detectors (beta emitters with high beta energy, short half-life, few or no parasitic induced beta activities)
- Tests with fast neutron sensitive materials underway

Self-powered neutron detectors (SPND)

	TBM steady-state HCLL (Bq/ccm)			
	(n,□)	(n,p)	(n,□)	(n,2n)
Li		1.17E+10		
Be			2.05E+11	
Na		2.88E+10	8.69E+10	
Al	1.53E+10	1.09E+11		
Si		2.84E+11		
		7.03E+09		
		1.62E+09	2.12E+09	
V	2.15E+11	4.98E+10		
Cr		1.20E+11		
		7.42E+09		
		5.08E+08	5.01E+08	
Mn		6.78E+10	3.87E+10	
Fe		2.24E+09		
		1.27E+11	9.44E+07	
Cu	1.31E+11			
Zn		3.23E+10		
		3.31E+09		
		3.03E+07	2.94E+07	
Rh	1.46E+13		1.20E+10	
Pd		7.93E+09		
		5.11E+09		
		8.20E+08		
Ag			6.59E+09	
	4.10E+12			4.47E+11
	1.53E+13		9.86E+08	
In	3.32E+11			

Candidate materials for fast neutron sensitive SPND were identified

Be, (Si), (Al), Cr, Fe, Cu,
Rh (thermal),
In (low melting point)
Al (with MgO as insulator)

(may be MgO needs to be used as insulator!)

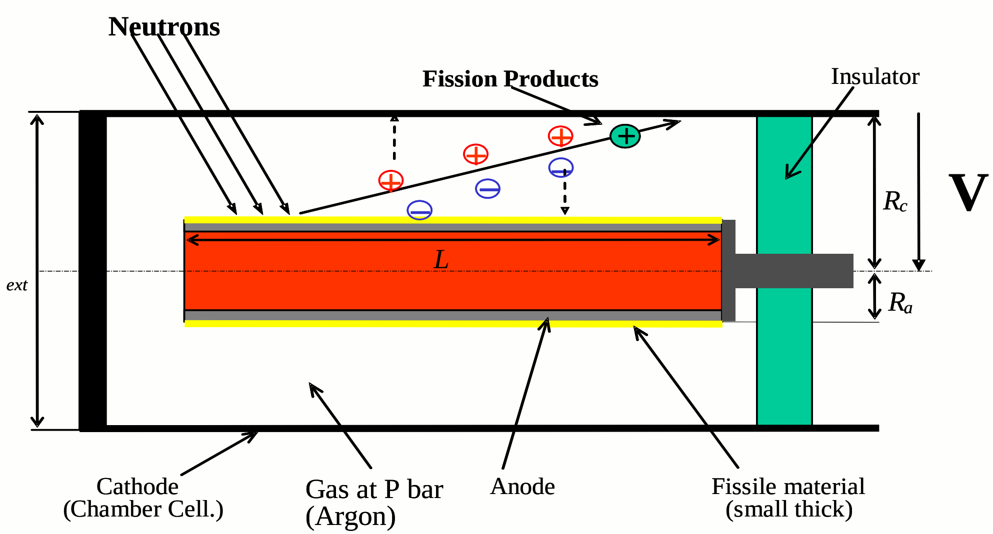
Results were presented at ISFNT 2013

Further work underway:

- ***Preparation of test detectors with proposed new emitter materials, testing in fast neutron fields (FNG, TUD-NG, TAPIRO) and γ fields (Calliope)***
- ***Testing in Tokamak EM field (ASDEX, FTU)***

Colorado School of Mines
Golden, 27. September 2016
Institute of Neutron Physics
and Reactor Technology

Neutronics instrumentation for the ITER TBM



Physical principal of Fission Chamber neutron detector

Miniature fission chamber

- Anode covered with fissile material
- Fission products generate el. charges
- Electrical signal (pulse, current) carries information on neutron flux density, reaction rates

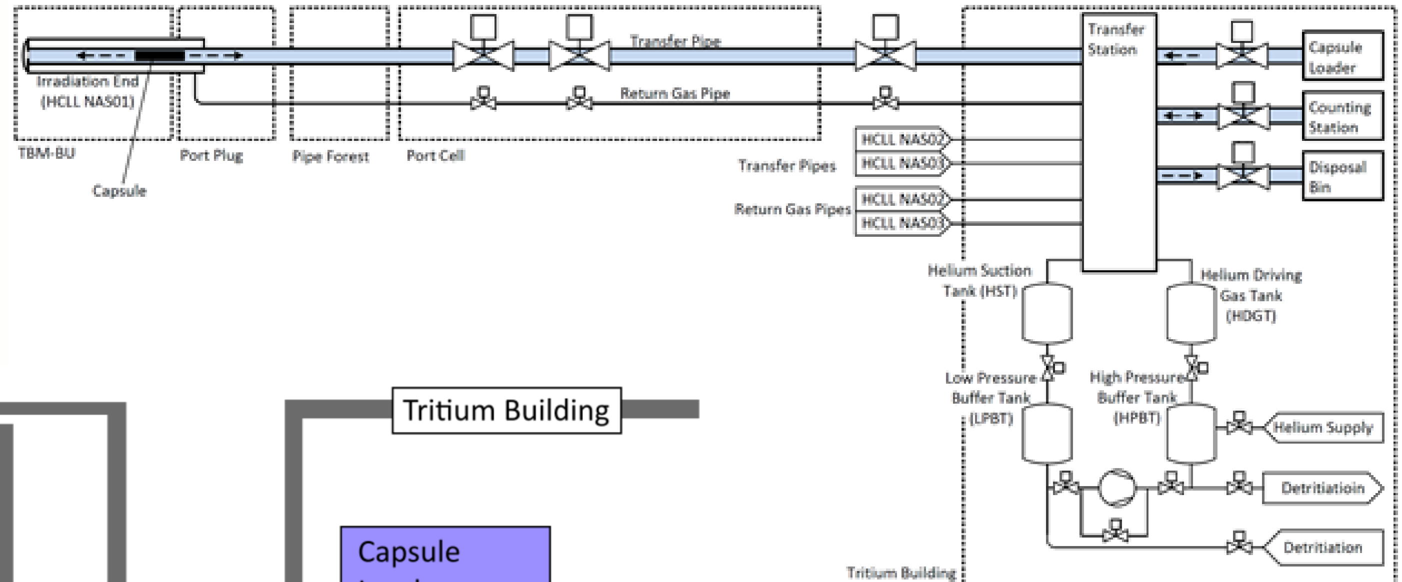
- Rare gas (no chemical changes under severe ionizing radiation, pressure usually less than 1 bar)

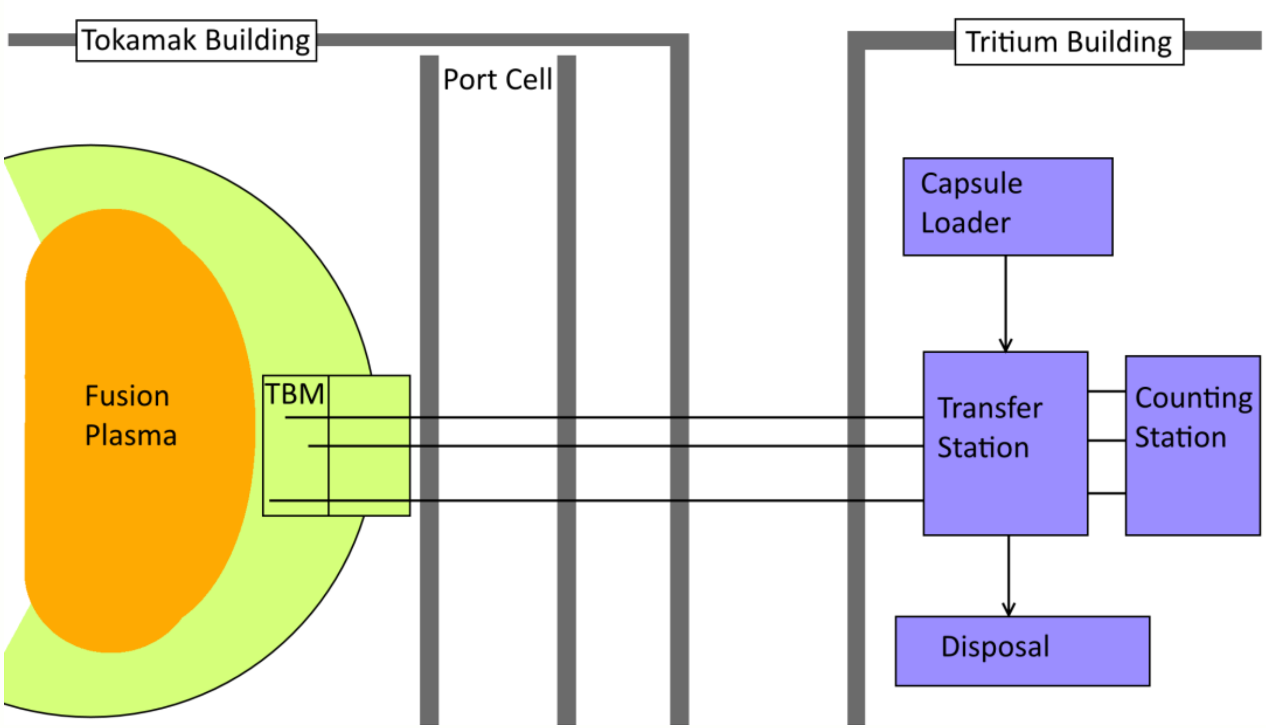
- Miniature fission chambers (CEA Cadarache) Diameter 1.5 mm, length 12 mm, 0.2 mg fissile material

tested at 350 °C and flux densities of 10^{14} n/cm^2/s, total flux 10^{21} n/cm^2

Neutronics instrumentation for the ITER TBM
TBM Neutron Activation System

Preliminary Process Flow Diagram





Layout of a TBM neutron activation system

Neutronics instrumentation for the ITER TBM
TBM Neutron Activation System

Neutronics part

- Selection of suitable activation materials
- Test measurements with neutron generator and pneumatic transport system
- Optimization of mass ratios and rabbit design
- Investigation of measurement uncertainties

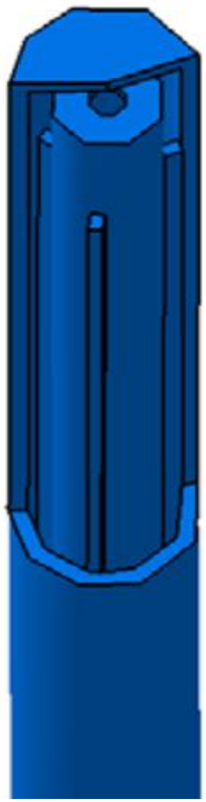
Mechanical part

Mechanical test system under construction at INR

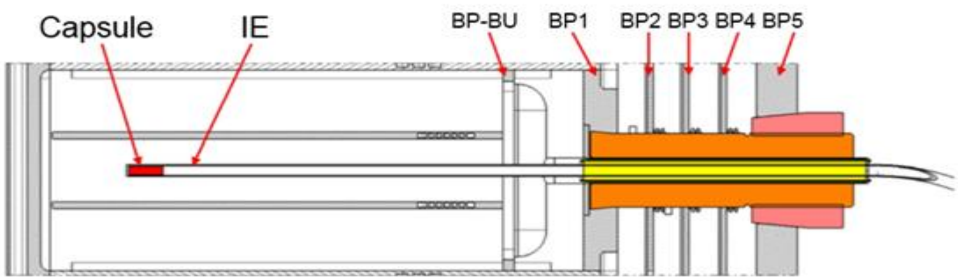
Preliminary engineering assessment within F4E Task Order OMF-331-02-01-02

- TBM-NAS similar to ITER NAS due to nature of problem to be solved
- Must be driven by He; N_2 etc. would be no option
- Expect three or four measurement positions in each TBM (HCLL and HCPB)

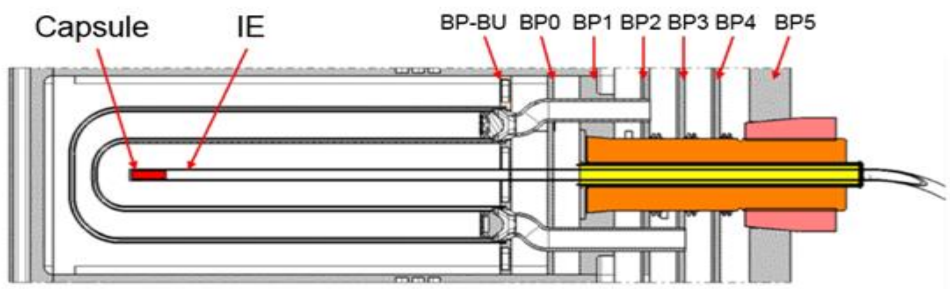
Neutronics instrumentation for the ITER TBM
TBM Neutron Activation System



Typical Design of the
Irradiation Ends (IE)



Position of one IE in HCLL TBM



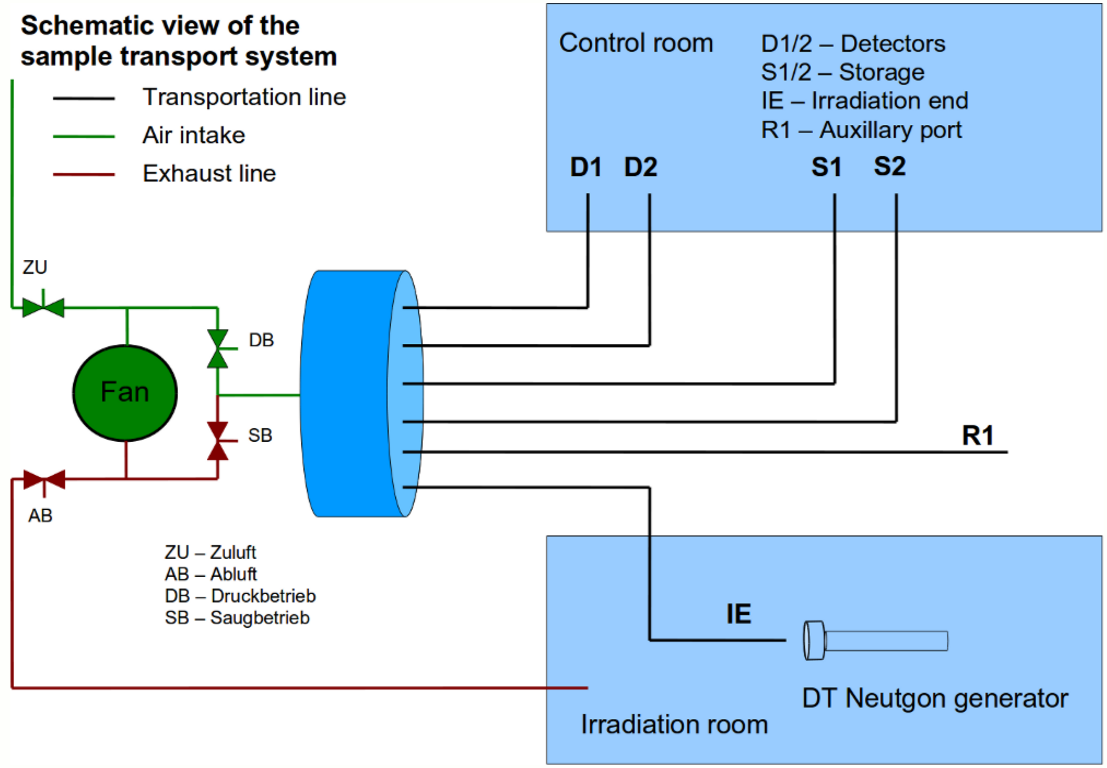
Position of one IE in HCPB TBM

Neutronics instrumentation for the ITER TBM
Neutron Activation System test system at TUD-NG

Pneumatic transport system (Rabbit system) for testing at TUD-NG designed in collaboration with Technical University of Dresden

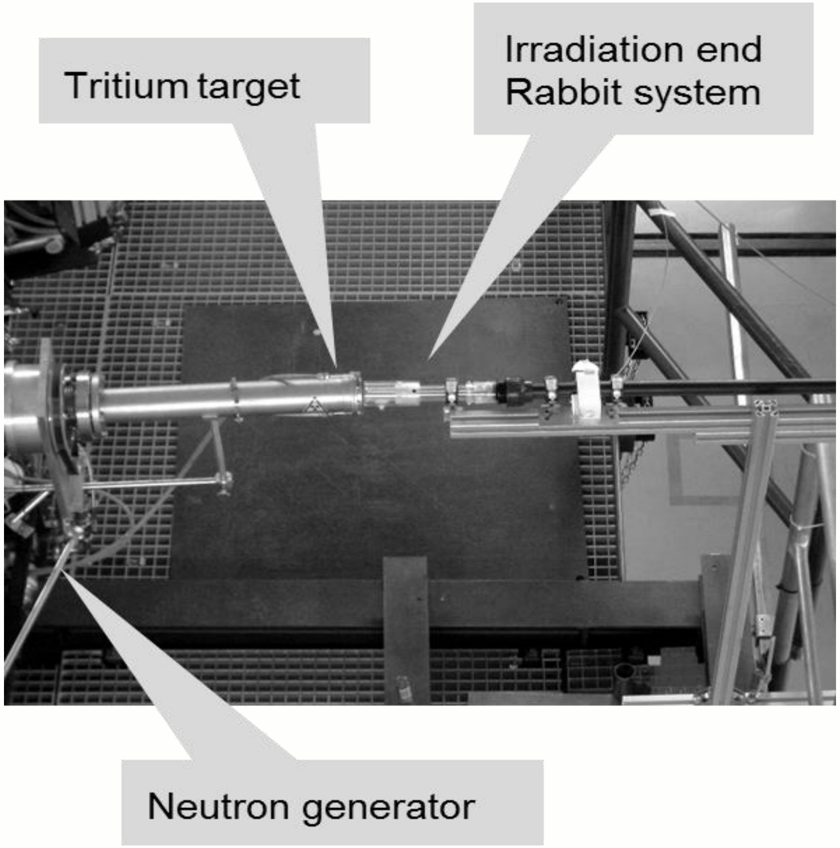
Spectral neutron flux density

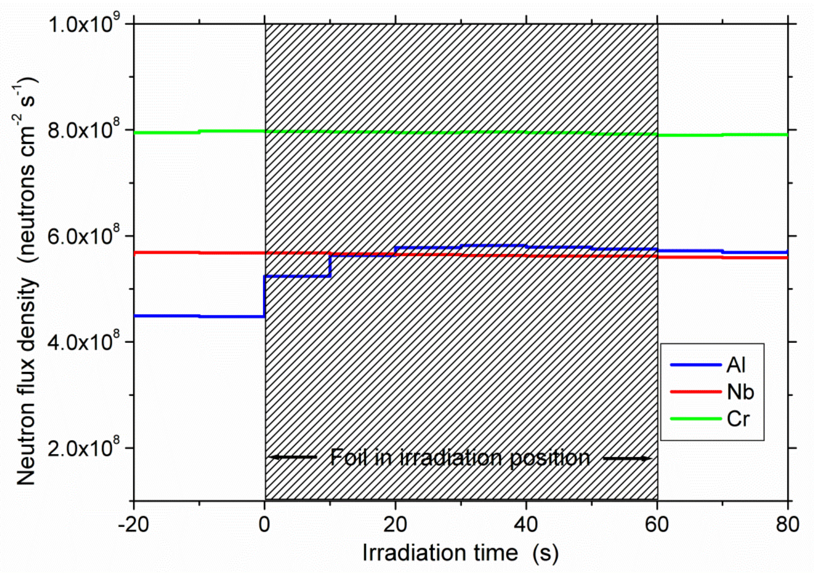
- Application of suitable (new) dosimetry reactions (short half-lives)
- Testing of suitable measurement regimes
- Testing of suitable gamma ray detectors (HPGe, CZT,...)
- Demonstration of an automated system

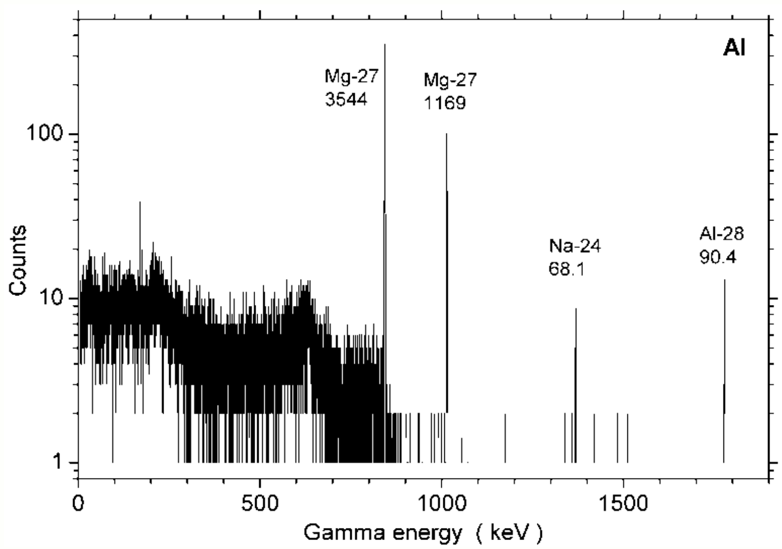


- Simulatneous gamma ray measurement of all materials in activation probe:
  - → Design (sintered, alloyed)
  - → Perhaps contaminated (tritium)

Neutronics instrumentation for the ITER TBM
Neutron Activation System test system at TUD-NG





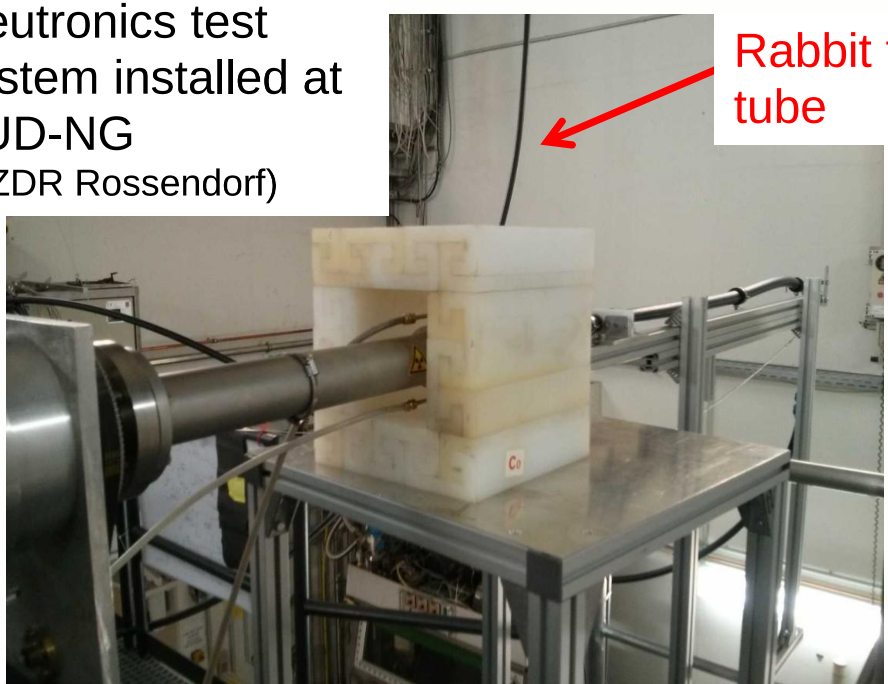


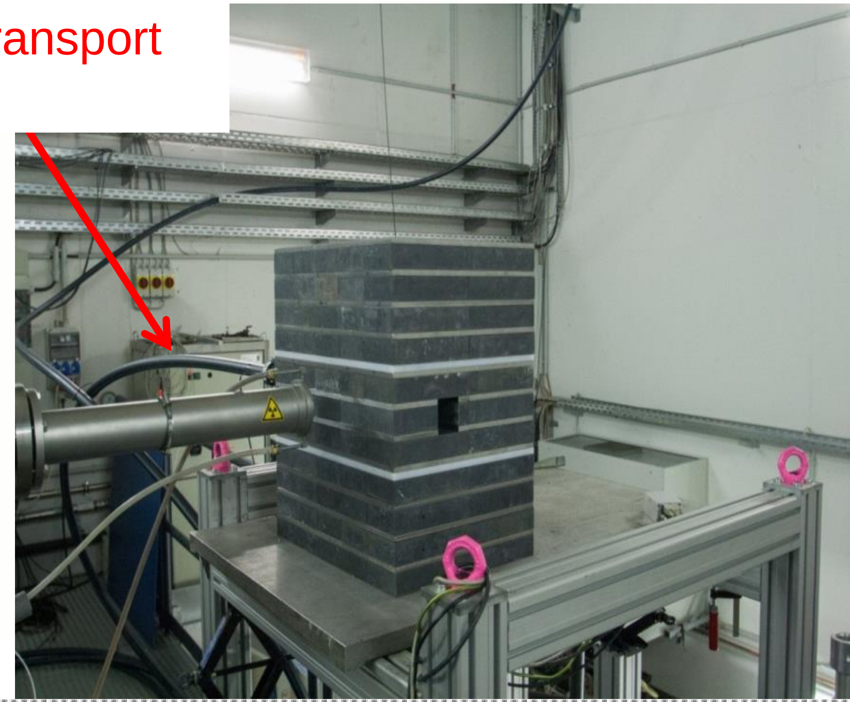
- Test foils 10 mm diameter, ~0.6 g, material purity >99.9%
- Irradiation time 60 s, fluence at sample position 3.39 - 4.77×10^{10} n/cm^2
- Transport time 16..23 s
- Gamma measurement HPGe, 30%, ca. 5 cm distance 60 to 600 sec

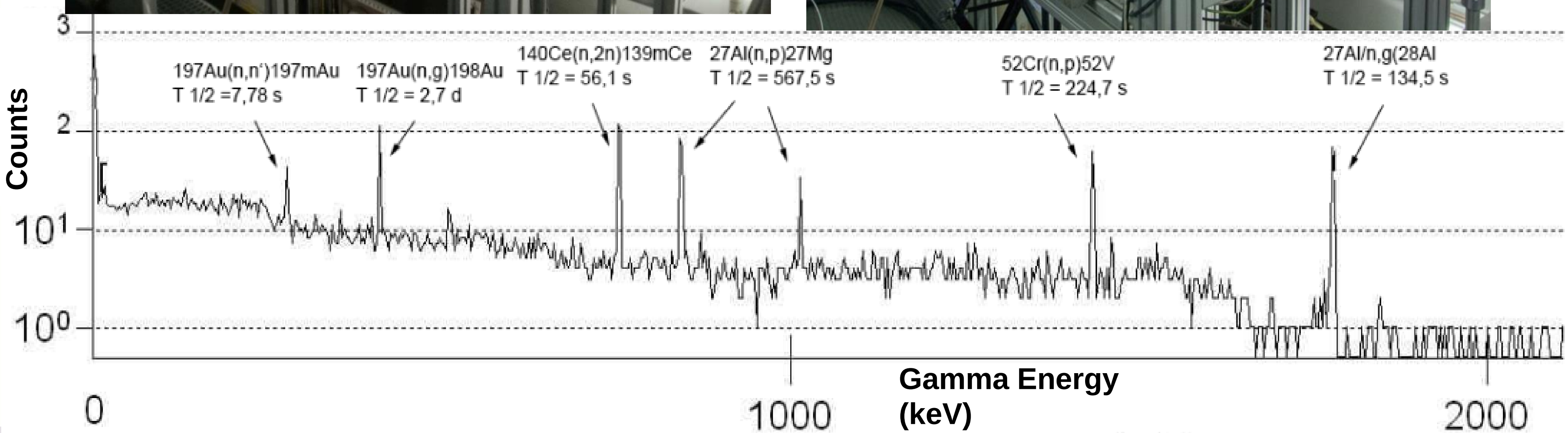
Neutronics instrumentation for the ITER TBM
Neutron Activation System test system at TUD-NG

Neutronics test system installed at TUD-NG
(HZDR Rossendorf)

Rabbit transport tube



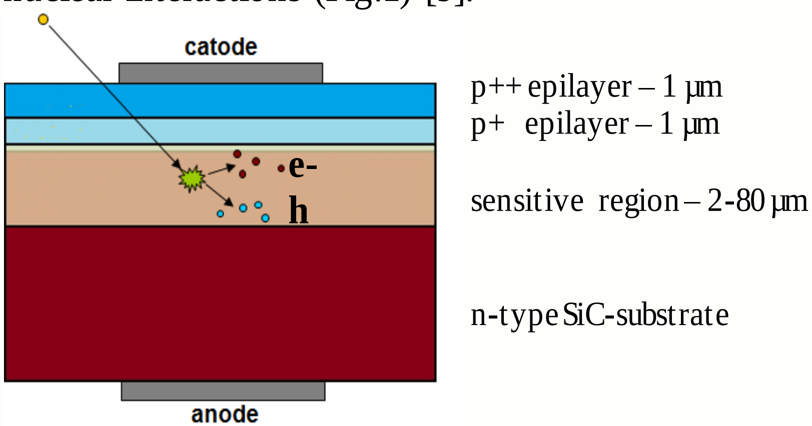




Neutronics instrumentation for the ITER TBM
Silicon carbide detector
I_SMART (KIC-InnoEnergy)

- Large band gap semiconductor detectors
- better radiation hardness than Si
- SiC electronics proven to operate at temperatures of several hundred °C
- R&D on SiC detectors has been done since many years

nuclear interactions (Fig.1) [9].



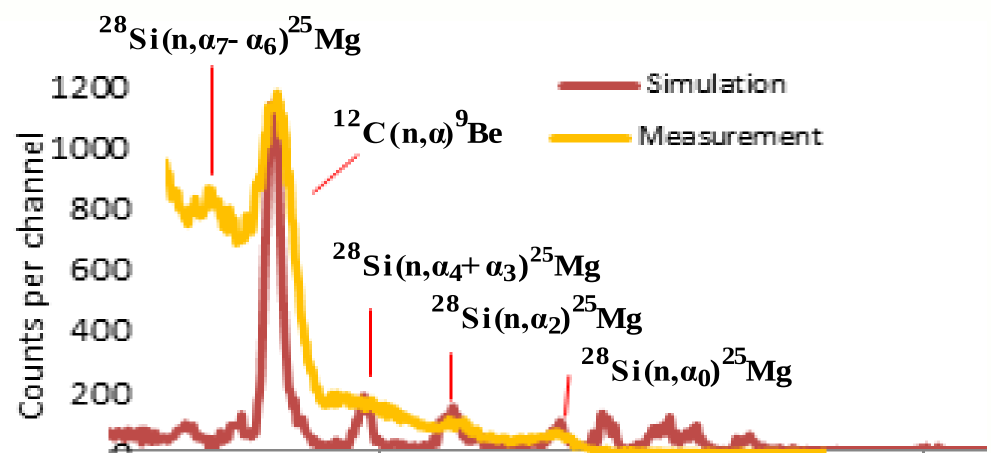
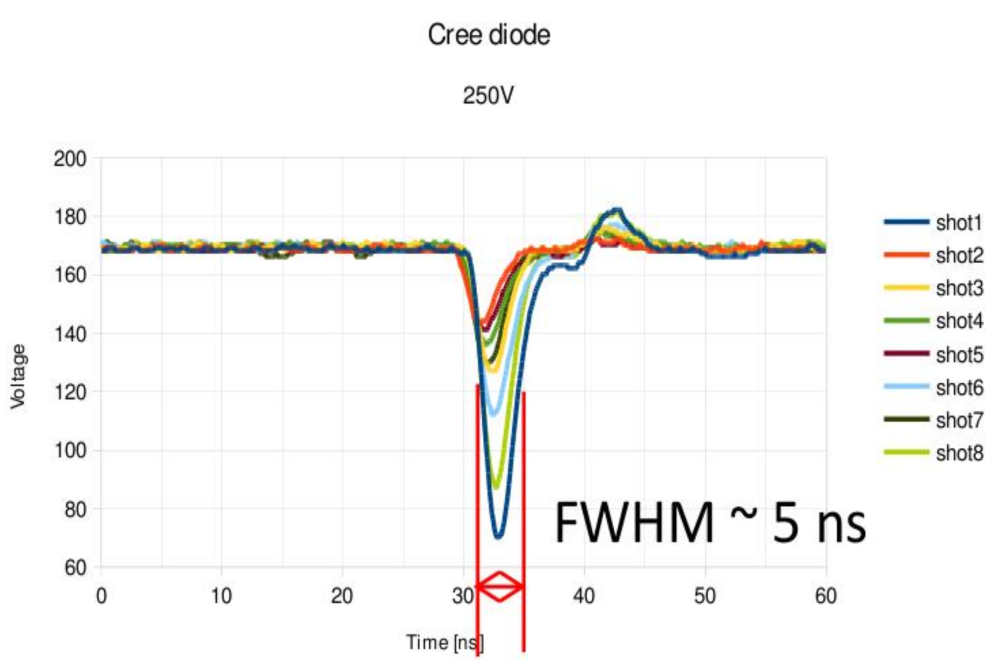
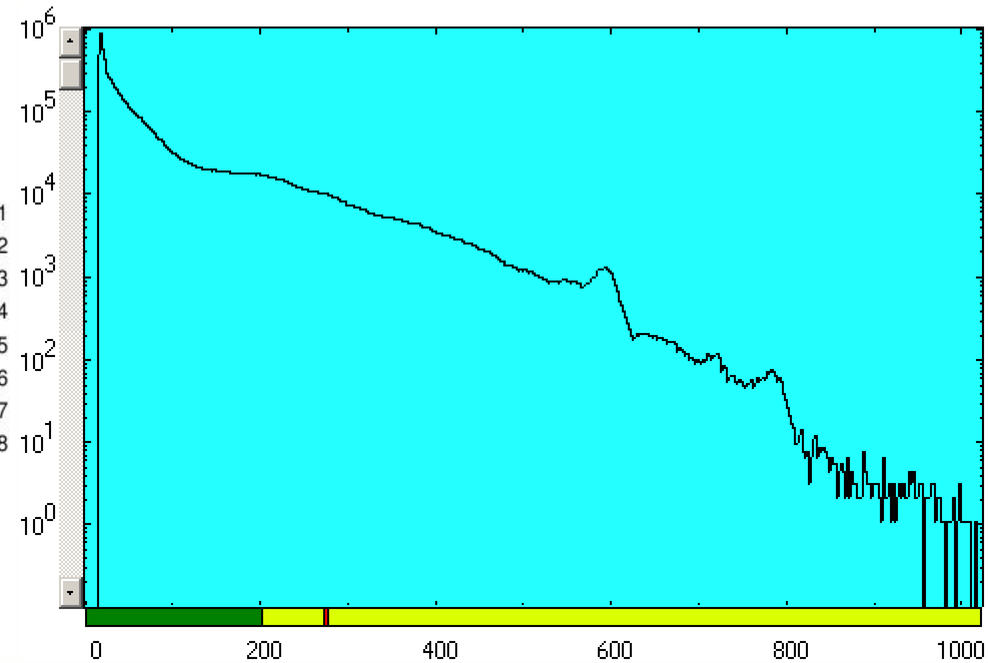


Fig.1. Diode construction and the operation scheme

Neutronics instrumentation for the ITER TBM
Silicon carbide detector





Typical signal from a commercial Schottky diode irradiated with 14 MeV neutrons and corresponding pulse height spectrum

Neutronics instrumentation for the ITER TBM
Silicon carbide detector

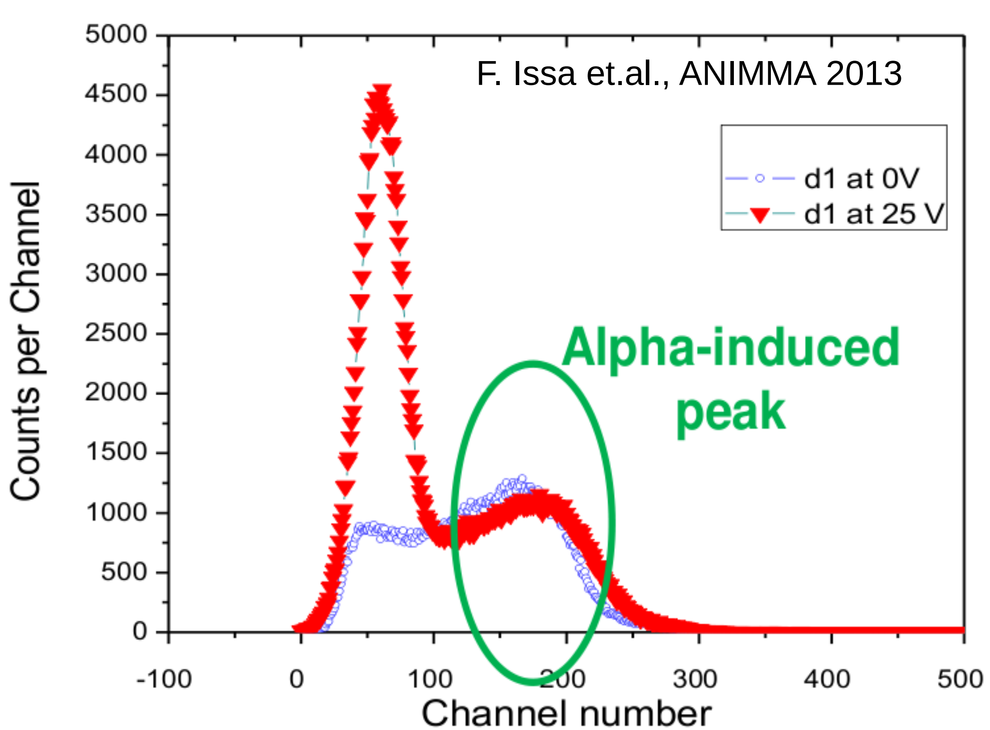
I_SMART (KIC-InnoEnergy)

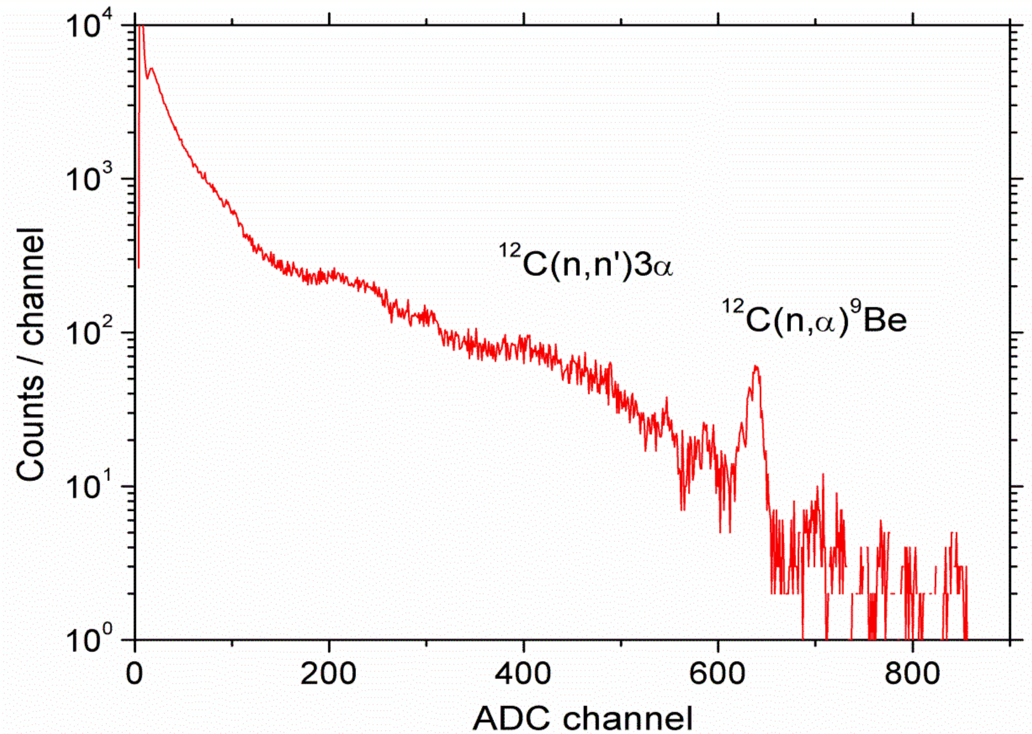
Collaboration between
CEA, KIT, SCK*CEN, AMU, Univ. of Oslo, KTH, AGH
funded by KIC InnoEnergy with the aim to develope a detector system

- I_SMART: detectors for fast neutrons (plain SiC) and thermal neutrons (boron conversion layer) developed
- Signal processing electronics based on SiC investigated
- Testing in thermal (BR1, SCK*CEN Mol) and 14 MeV (TUD-NG, TU Dresden) neutron fields and intense bremstrahlungs fields (CEA Cadarache)

KIT focused on application to ITER TBM

Neutronics instrumentation for the ITER TBM
Silicon carbide detector

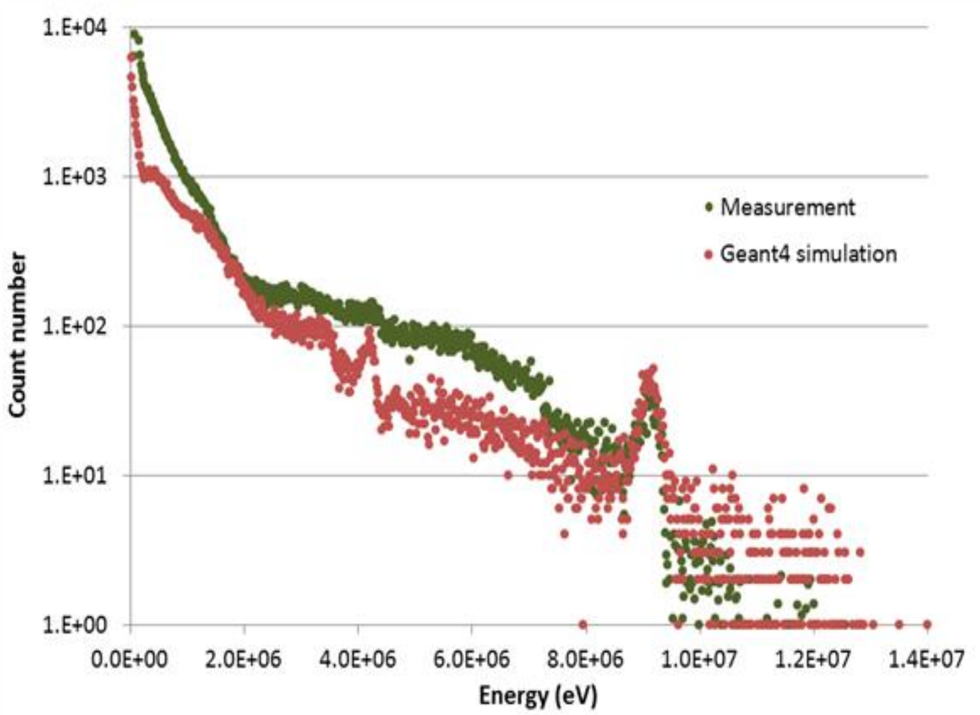




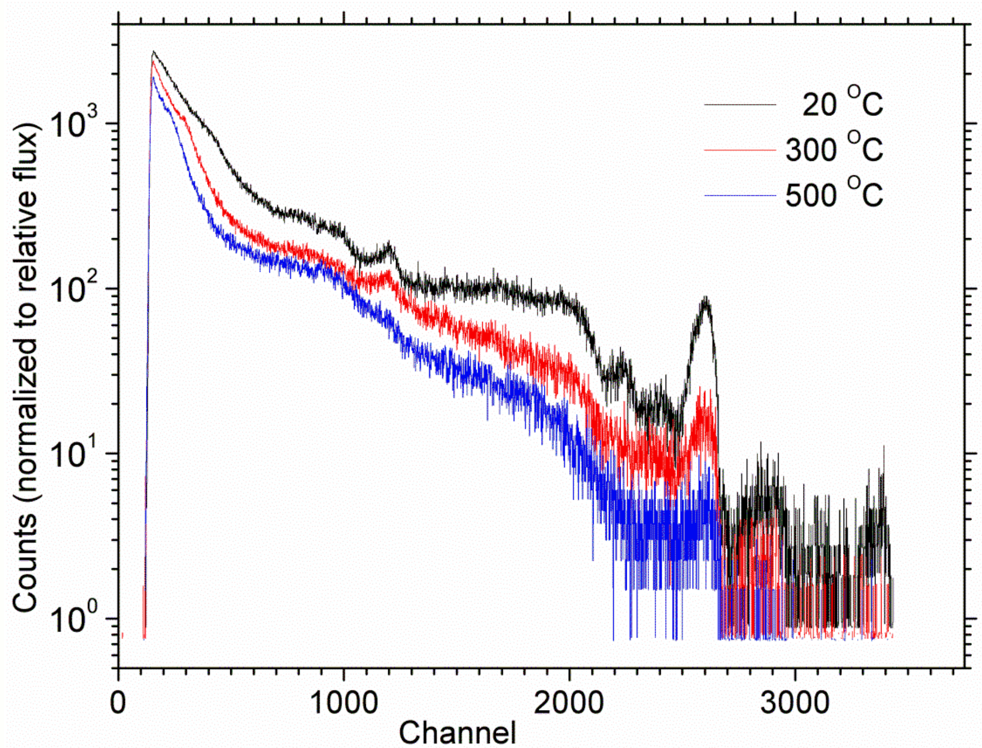
With boron implantation in thermal neutron field (BR1, room temperature)

In DT neutron field (TUD-NG, room temperature)

Neutronics instrumentation for the ITER TBM
Silicon carbide detector

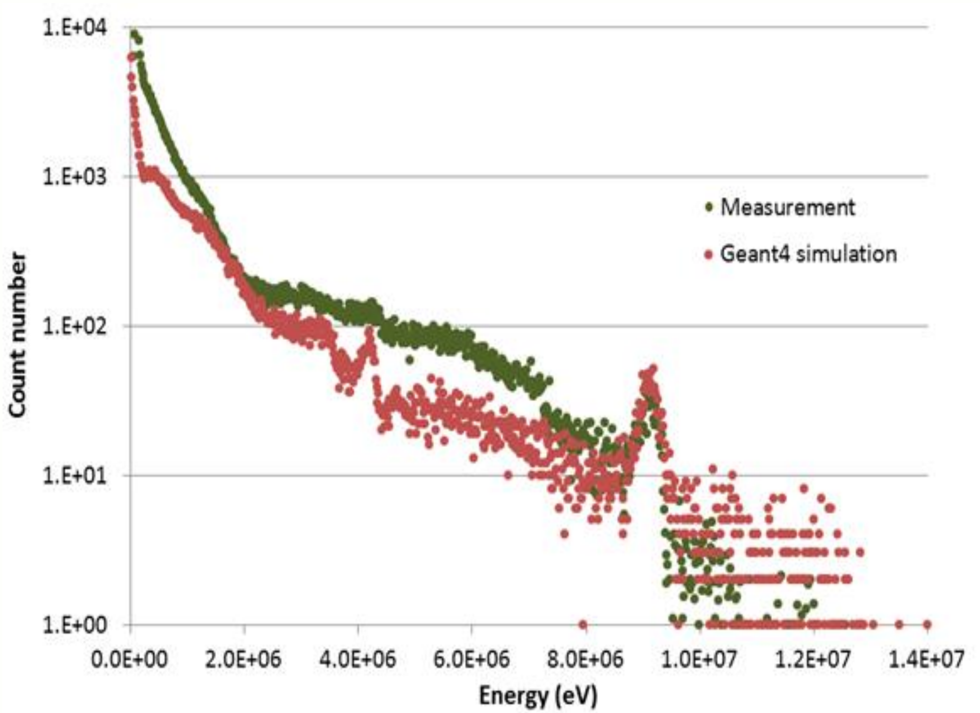


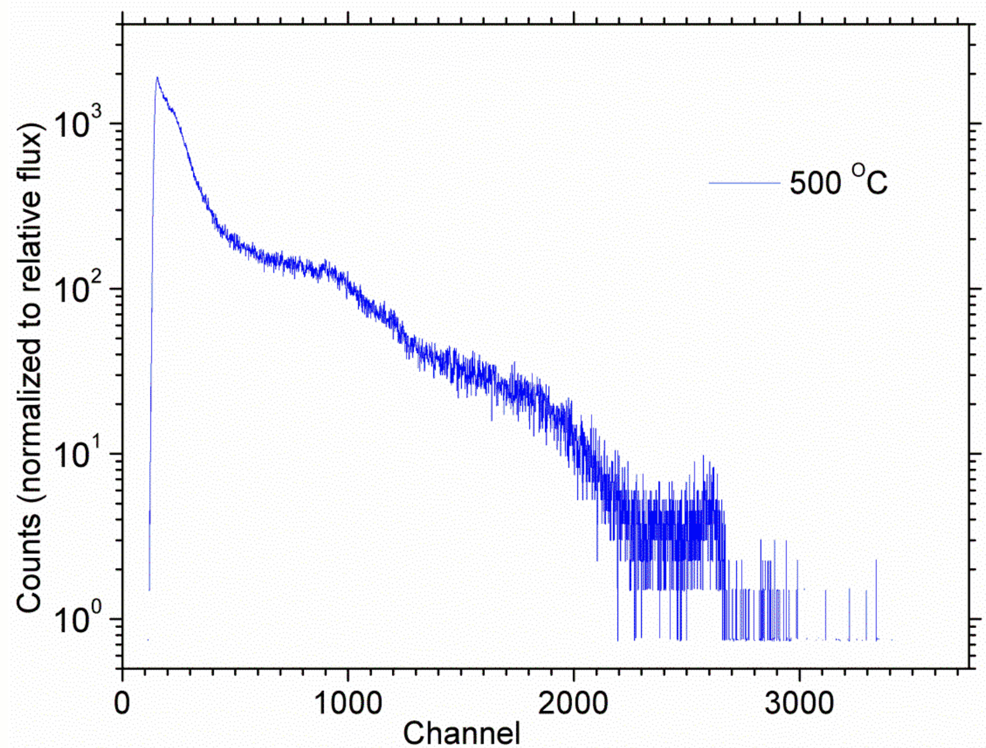
Measured and modeled (GEANT-4) pulse height spectrum under irradiation with 14 MeV neutrons



Measured pulse height spectra under irradiation with 14 MeV neutrons and at temperatures relevant for the ITER TBM

Neutronics instrumentation for the ITER TBM
Silicon carbide detector





Measured and modeled (GEANT-4) pulse height spectrum under irradiation with 14 MeV neutrons

Measured pulse height spectra under irradiation with 14 MeV neutrons and at temperatures relevant for the ITER TBM

Even at 500 °C spectroscopic behaviour is retained to some extend.

Neutronics instrumentation for the ITER TBM
Silicon carbide detector

Main results

- Tests with 4H-SiC diode detector with 14 MeV fast neutrons up to 500 °C.
- Stable operation up to 300°C with 4H-SiC detector on high bias voltages, with 14 MeV neutrons.
- Beyond 300°C up to 500°C operation on decreased bias voltage, with 14 MeV neutrons.
- Stable count rate per second on a certain temperature from room temperature up to 500 °C.

Summary

- A tritium breeding rate >1 plus some margin is essential for self-sustained operation of power fusion reactors

- Radiation transport codes (and coupling to other codes such as thermo hydraulics etc) and nuclear data are important tools for the design of fusion power reactors (tritium and gas production rate, heating, material activation and others) **require experimental testing and validation**

- currently: neutron generators (14 MeV neutrons), nuclear reactors (high flux densities, E<14 MeV) and other neutron sources, blanket mock-up experiments

- **ITER provides an experimental environment which would allow a more reliable extrapolation to a DEMO reactor**

- Neutron flux in the TBM is a basic parameter to which many other measurements in TBM experiments will be related (neutronics and non-neutronics) (→ Tritium accountancy)

- Development of measurement methodology and nuclear instrumentation which can sustain the harsh environment in a TBM underway

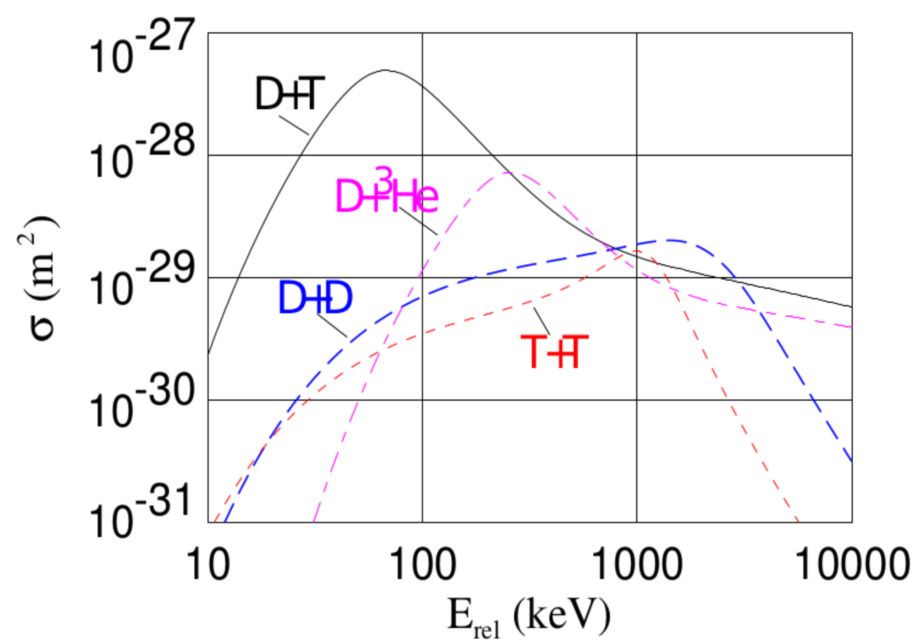
Legal matters

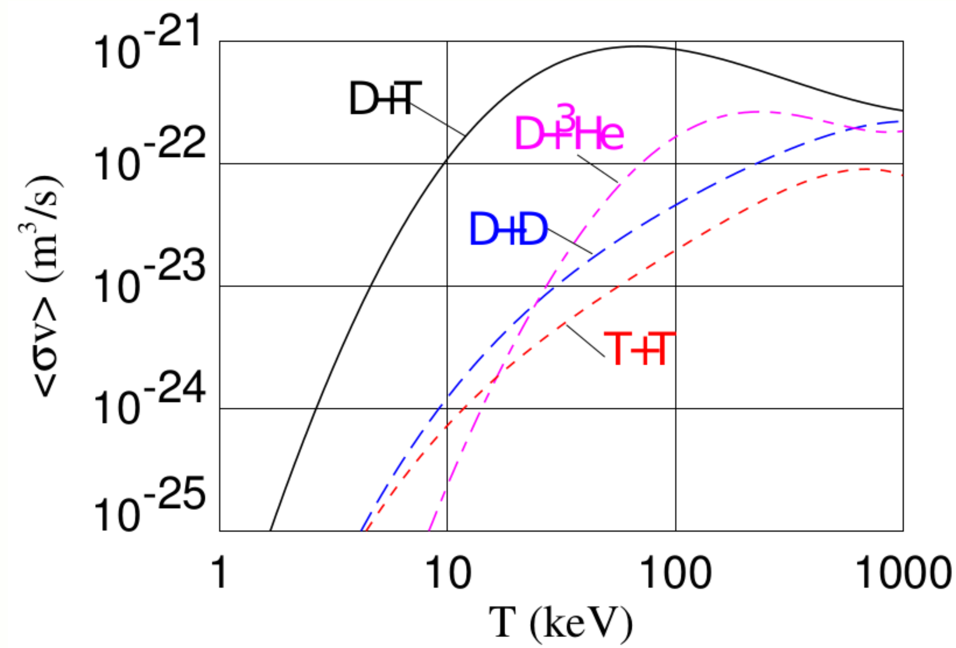
Parts of this work have been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Acknowledgement for parts of the work presented herein:
This work, supported by the European Communities under the contracts of Association with EURATOM, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Disclaimer for parts of the work presented herein:
This work, supported by the European Communities under the Contract of Association between EURATOM and Forschungszentrum Karlsruhe, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Ignition





Accelerator-based fusion device does not deliver net energy due to beam energy losses in Compton collisions

Substantial increase of reaction rates by supplying energy thermally + confinement

Reaction rate:

$$R = n_a n_b \langle \sigma u \rangle$$

$$\langle \sigma u \rangle = \frac{4}{\sqrt{2 m_r \pi} (kT)^{3/2}} \int dE_r E_r \sigma(E_r) e^{-\frac{E_r}{kT}}$$

Ignition

Plasma is cooled with a characteristic time τ due to losses (mainly Bremsstrahlung).

Heating: $\Phi_H = \frac{3nk_bT}{\tau}$

Fusion power density: $\Phi_{DT} = \frac{n^2}{4}\langle\sigma u\rangle \mathrm{E_{DT}}$ with E_{DT}=17.6 MeV

Q value or gain of a fusion plasma: $Q_{DT} = \frac{\Phi_{DT}}{\Phi_H} = \frac{n\tau\langle\sigma u\rangle \mathrm{E_{DT}}}{12k_bT}$

Breakeven: $Q_{DT} = 1$

A fusion reactor should do more than this, re-arranging the formula leads to the

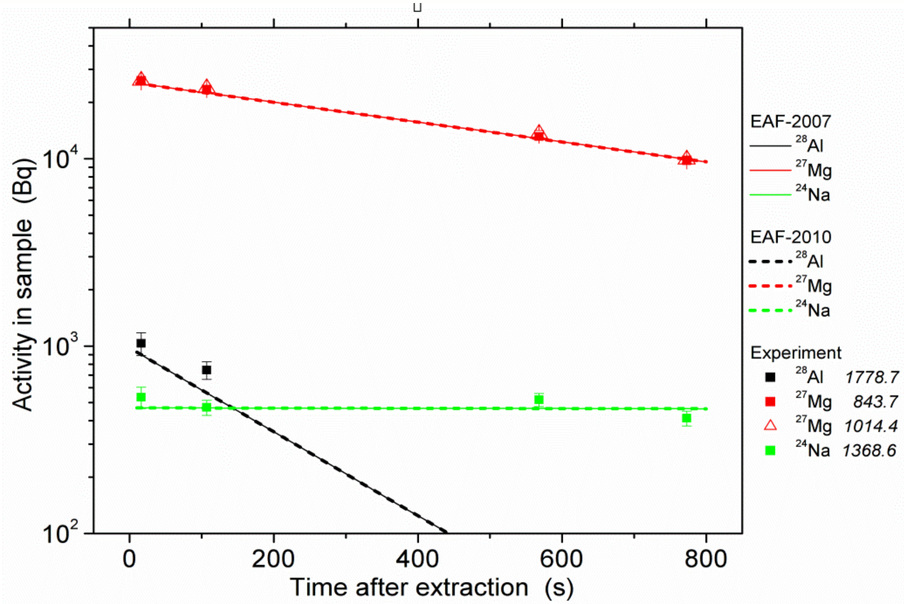
Lawson criterion: $\boldsymbol{n\tau \geq \frac{12k_bT}{\langle\sigma u\rangle \mathrm{E_{DT}}}}$

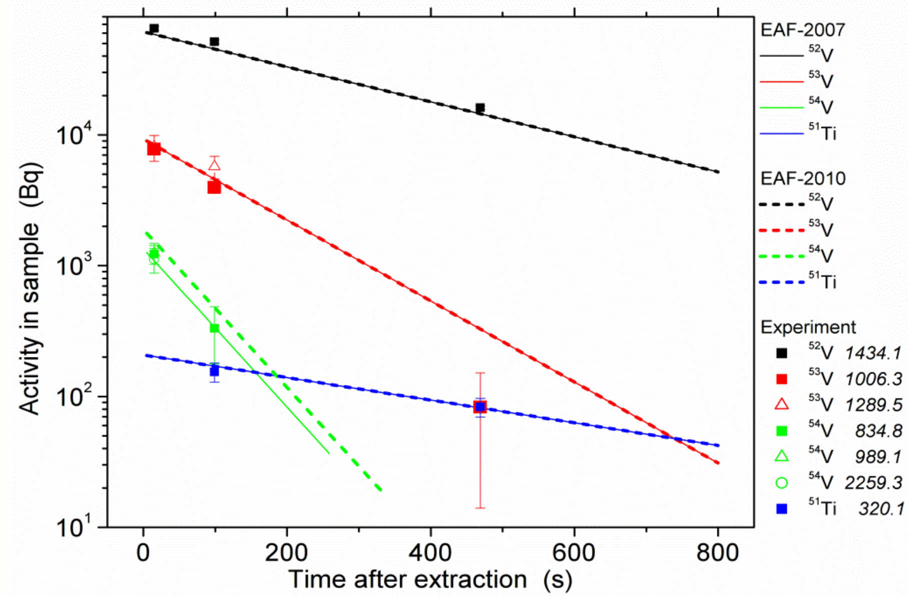
Triple product: $\boldsymbol{nT\tau}$

(accounts for pressure, must be compensated by magnetic field)

Typical target parameters: $n_e \approx 10^{20}$ m^{-3}, T = 15 keV, τ_E = 5 s

Neutronics instrumentation for the ITER TBM
Neutron Activation System test system at TUD-NG





- Gamma-ray measurement 60 to 600 s
- Most of isotopes of interest clearly seen even under much lower neutron flux density
- Measurement uncertainty between 5 and 30% under these conditions
- Comparison with inventory calculations with the FISPACT code and EAF-2007/2010 activation data libraries