Karlsruhe Institute of Technology

TECHNISCHE UNIVERSITÄT DRESDEN

Neutronics experiments in support of the European fusion development program

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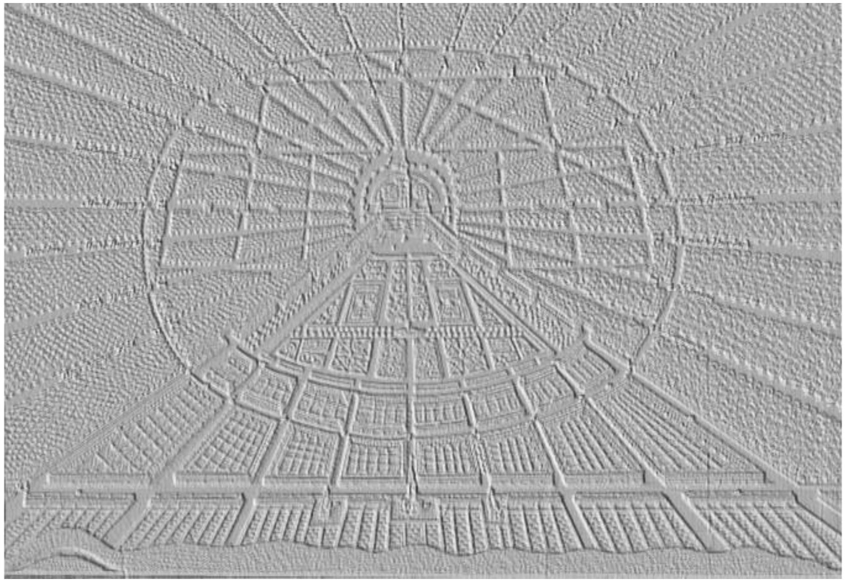
INSTITUTE FOR NEUTRON PHYSICS AND REACTOR TECHNOLOGY



Institute for Neutron Physics and Reactor Technology

Work Group **Neutronics and Nuclear Data**

Nuclear analyses	ITER, DEMO, IFMIF, ESS, NFS
Development of numerical tools and software	MCCAD, R2S, R2SMes …
Nuclear data	Evaluations, contributions to EAF / EFF / JEFF / FENDL …
Neutronics experiments	Benchmarks and mock-ups Activation, shut-down dose rates Development of nuclear instrumentation

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This presentation

Outline

- Basics of Tokamak fuel cycle
  (from the neutronics point of view)

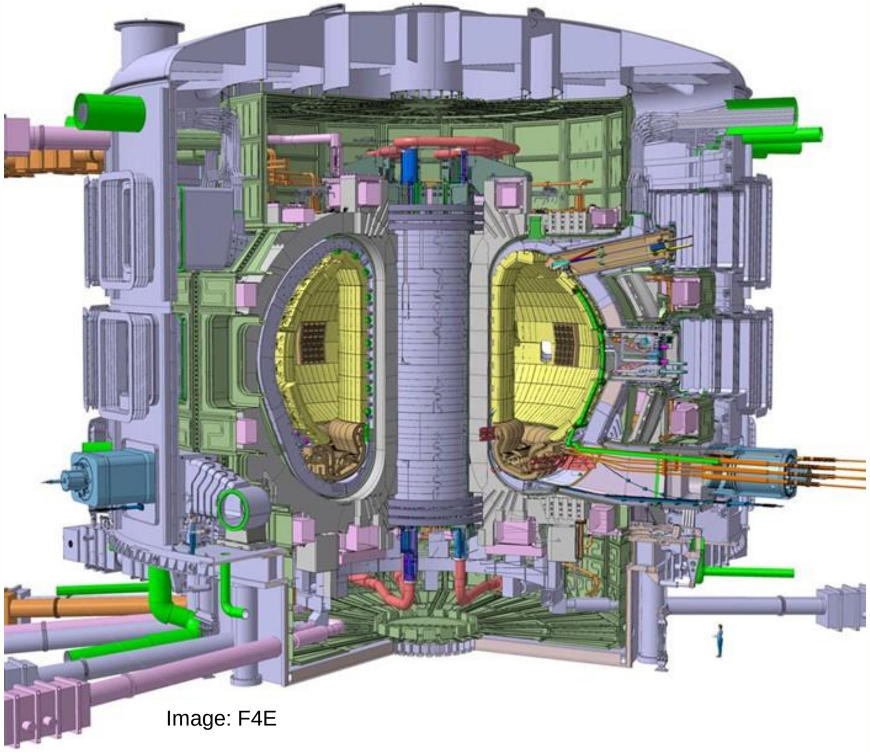
- Tritium breeding blanket neutronics experiment

  → DT Neutron generators
  → Example: Mock-up of the Helium-Cooled Lithium-Lead Test Blanket Module (HCLL TBM)

- Neutronics instrumentation for the ITER Test Blanket Modules

  → Self-powered neutron detector
  → Neutron activation system
  → Silicon carbide detector

Basic fuel cycle in a tokamak reactor



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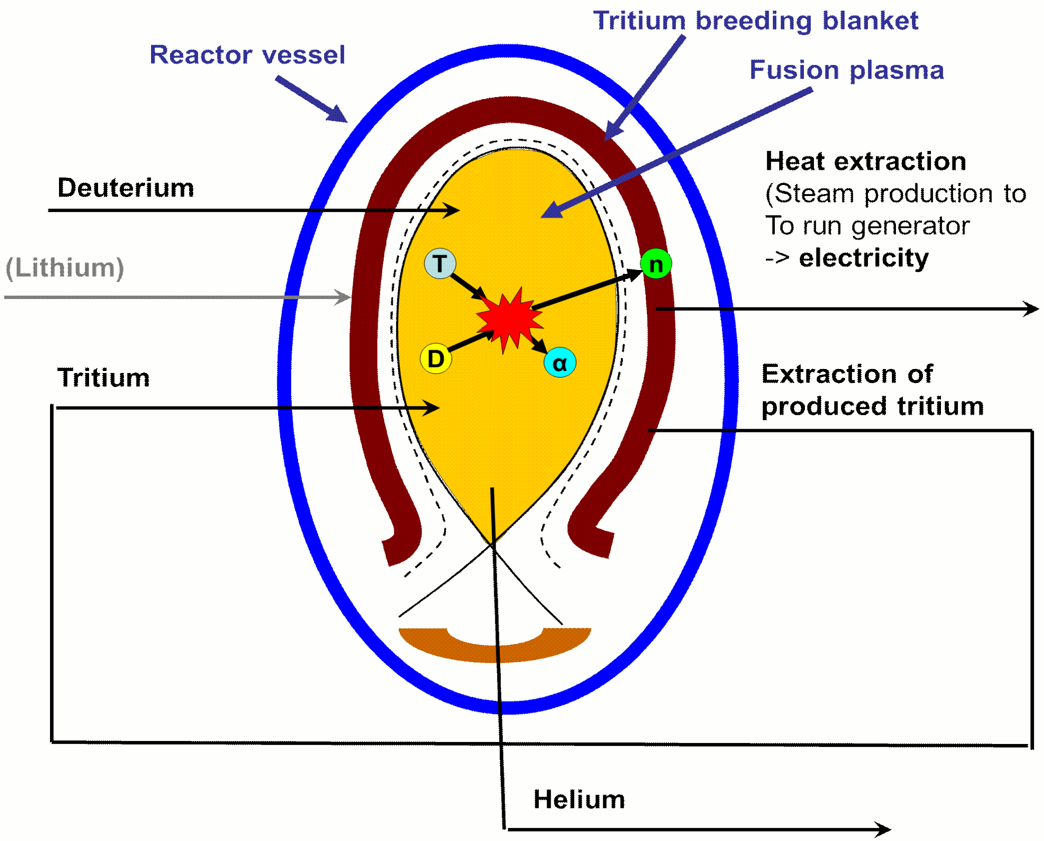
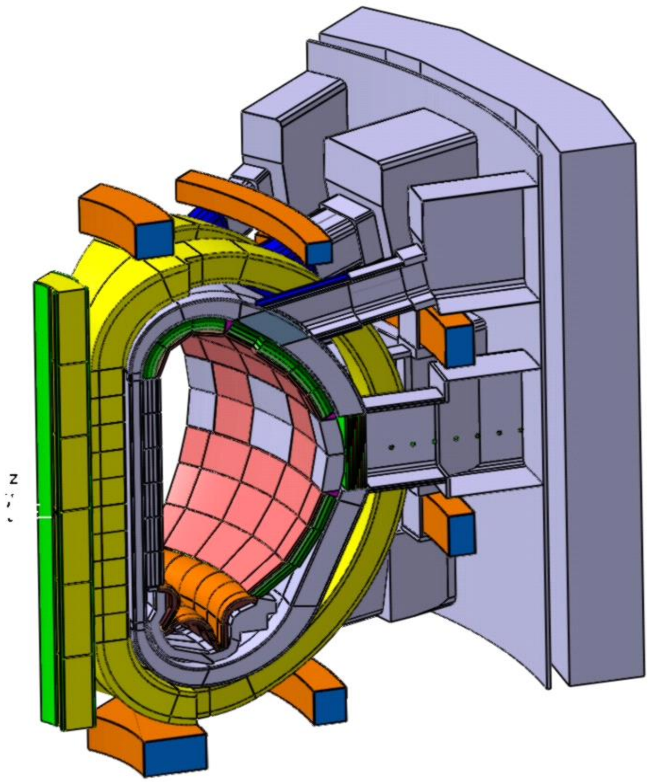


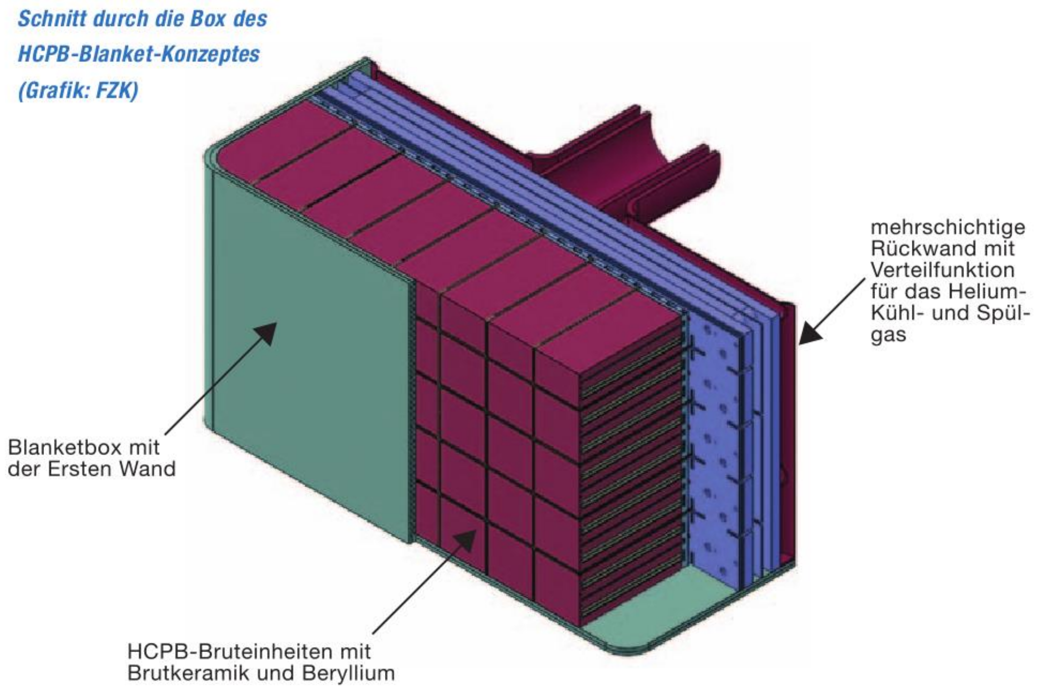
Fuel: **Lithium and Deuterium**

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

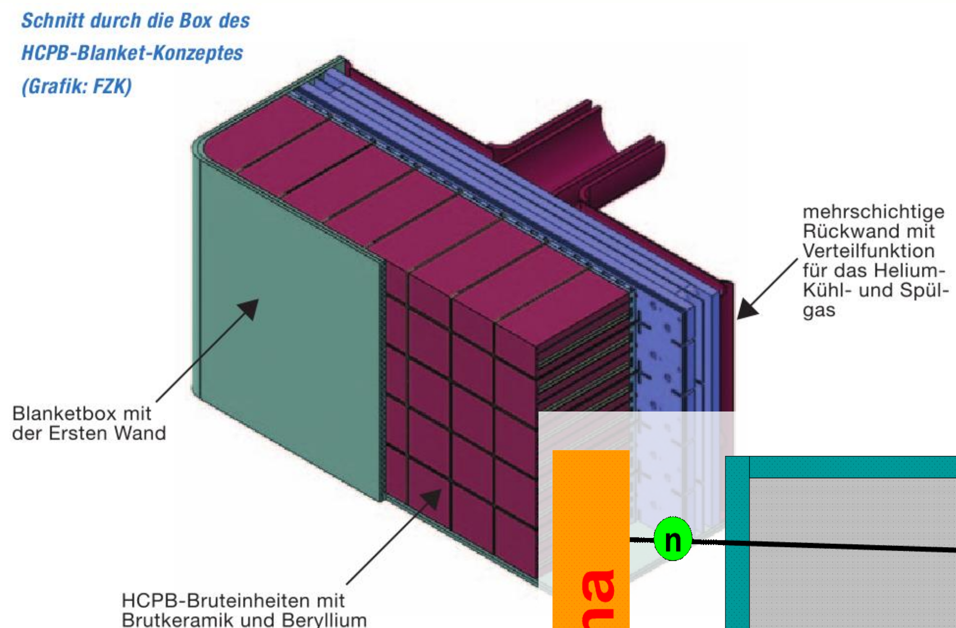




The fusion plasma is surrounded by a so called **breeding blanket,** which serves three main purposes:

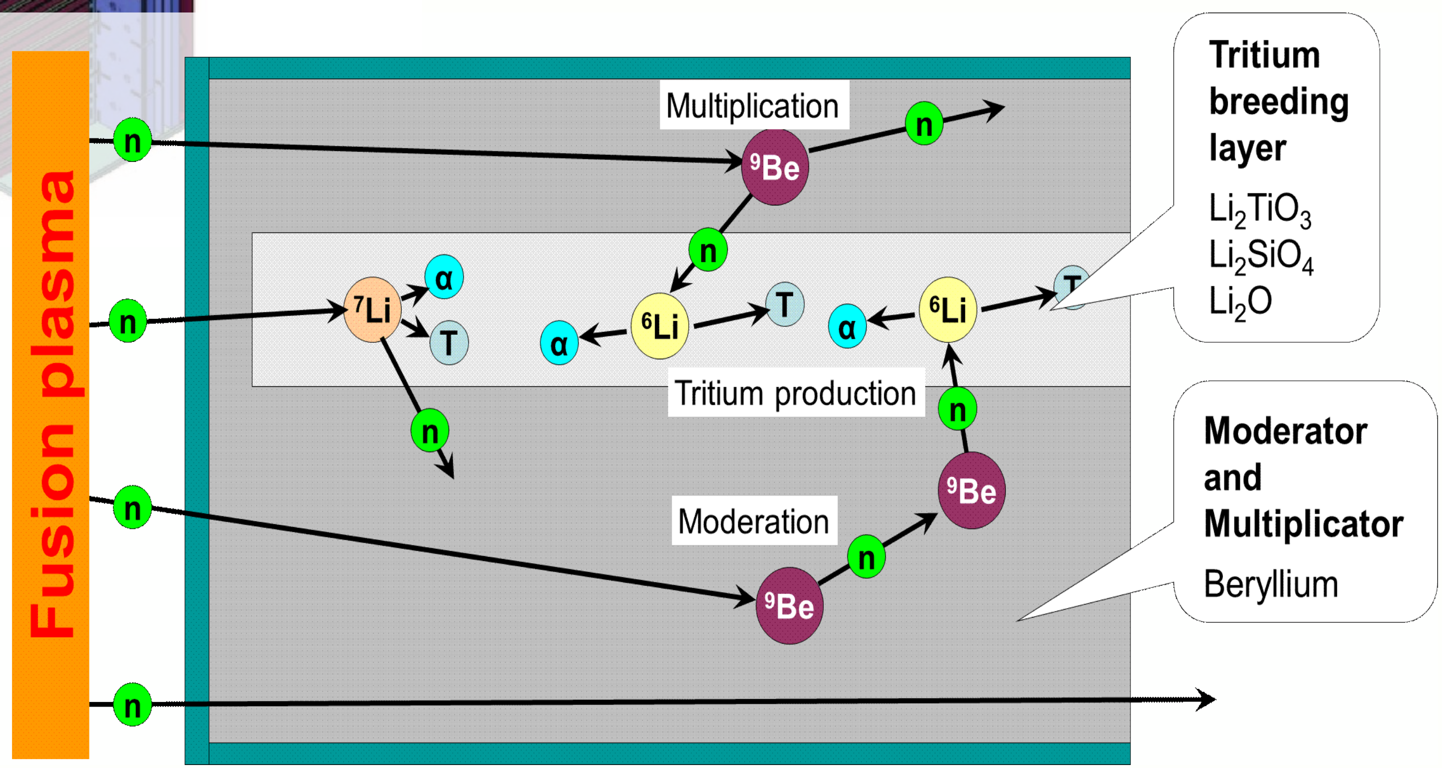
- *Tritium production (one of the two fuels of the reactor)*
- *Energy conversion (→ **Heat generation**)*
- *Shielding for field coils behind the blanket*

Basic fuel cycle in a tokamak reactor



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



Objective of breeding blanket neutronics experiments

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Important nuclear parameters for breeding blankets (fusion)

- 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)

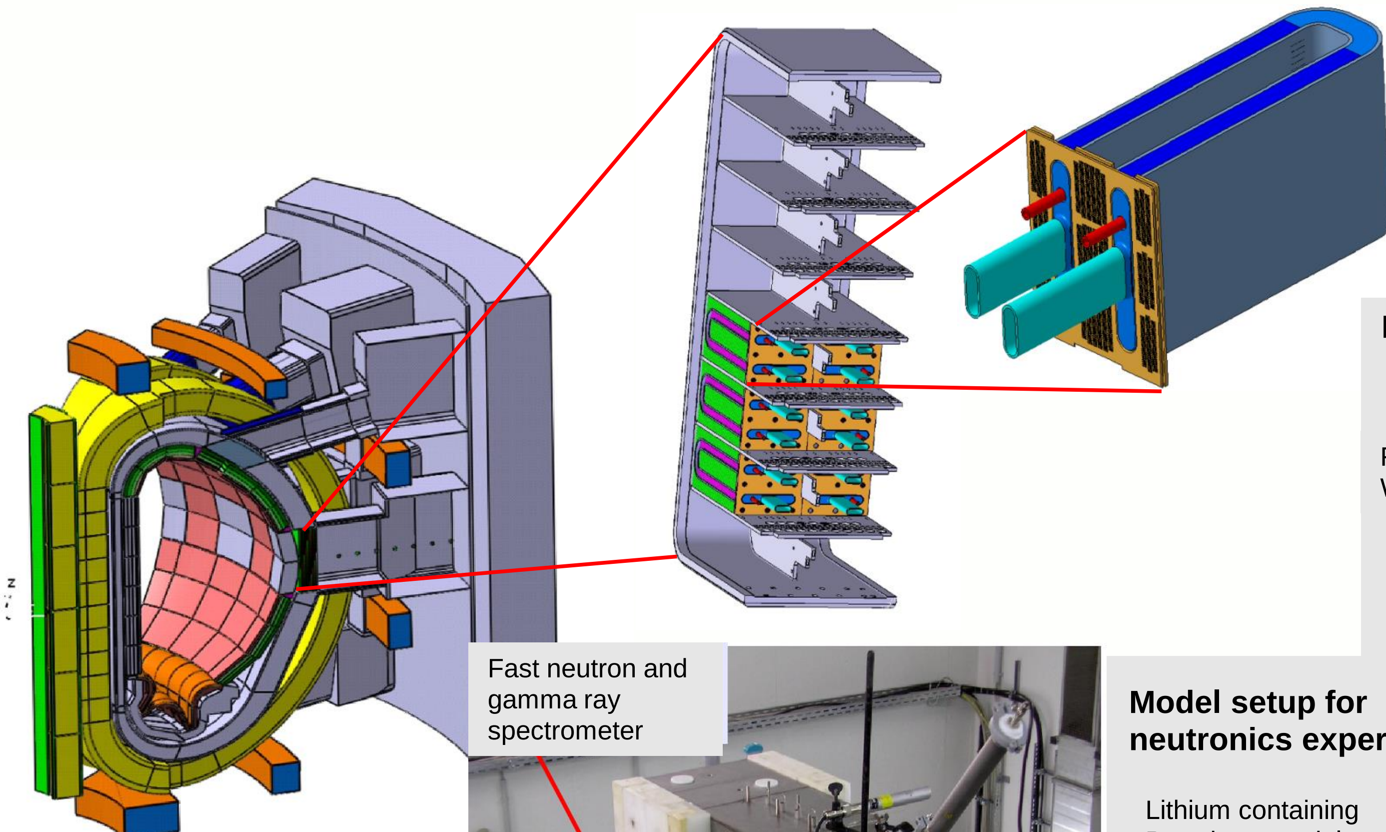
→

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

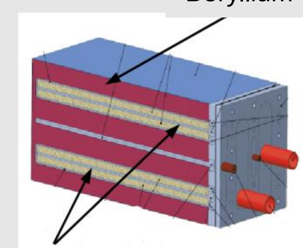
Proof of suitability and applicability of available transport codes and nuclear data for predicting such responses:

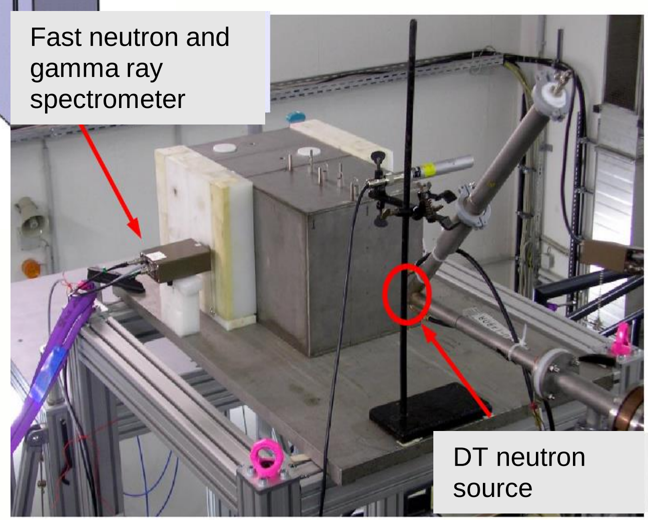
Calculation +/- Uncertainty
to be compared with
Experiment +/- Uncertainty

ITER Test Blanket Module mockup experiments with neutron generators

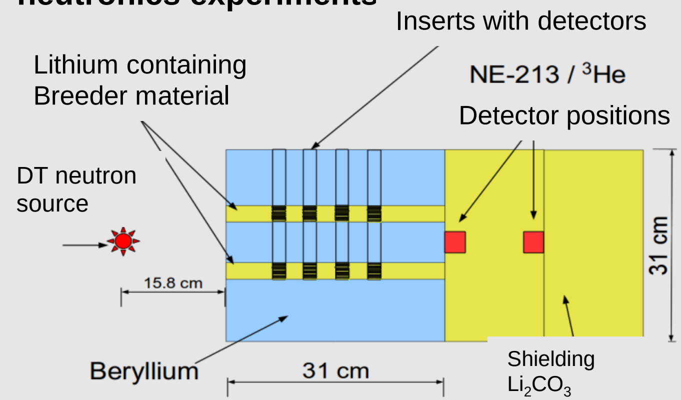


Breeder unit





Model setup for neutronics experiments

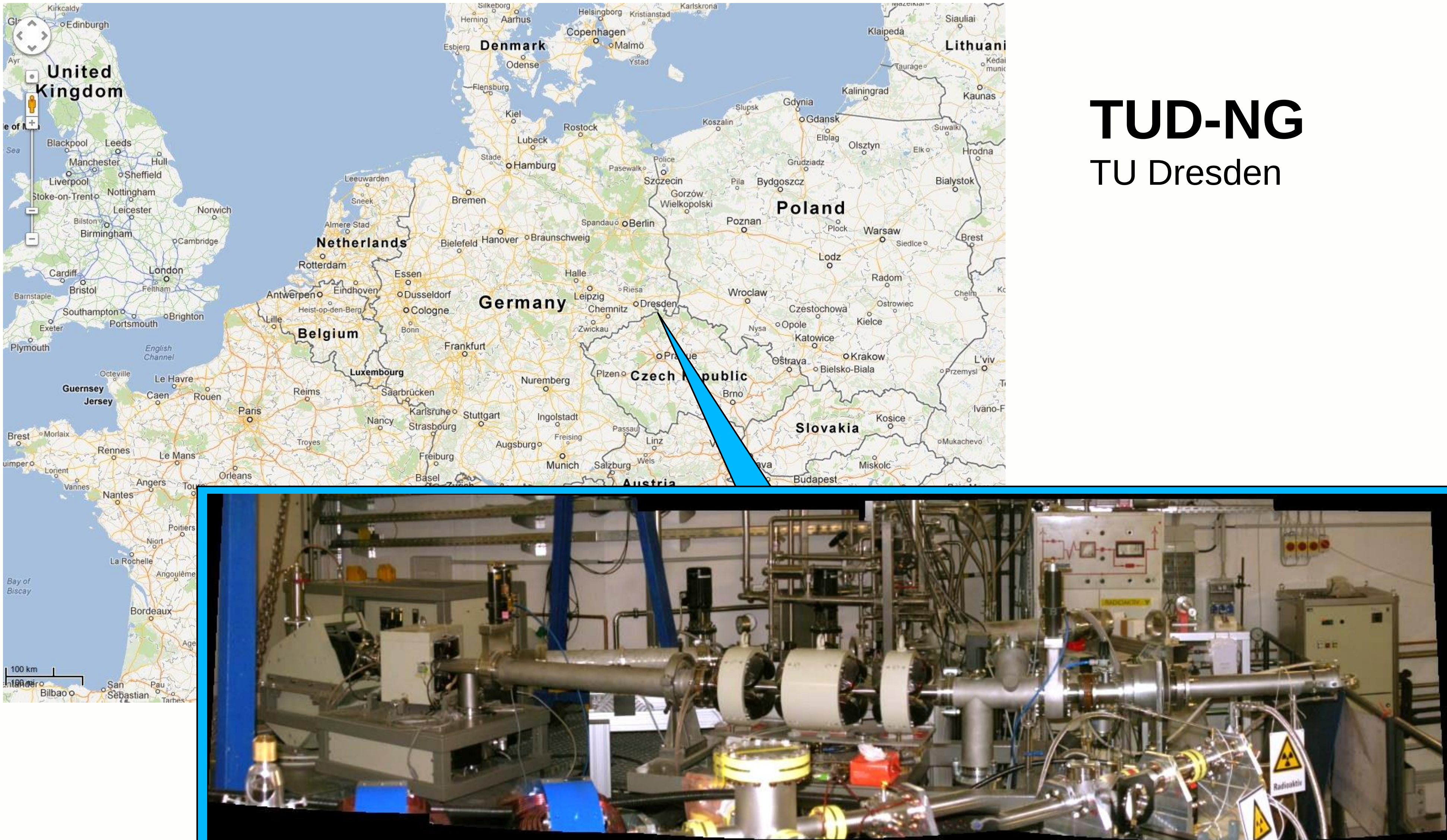


Example:
Helium Cooled Pebble Bed (HCPB) TBM

Neutron generator laboratories involved in the EU fusion neutronics experiments

FNG
ENEA Frascati

Neutron generator laboratories involved in the EU fusion neutronics experiments



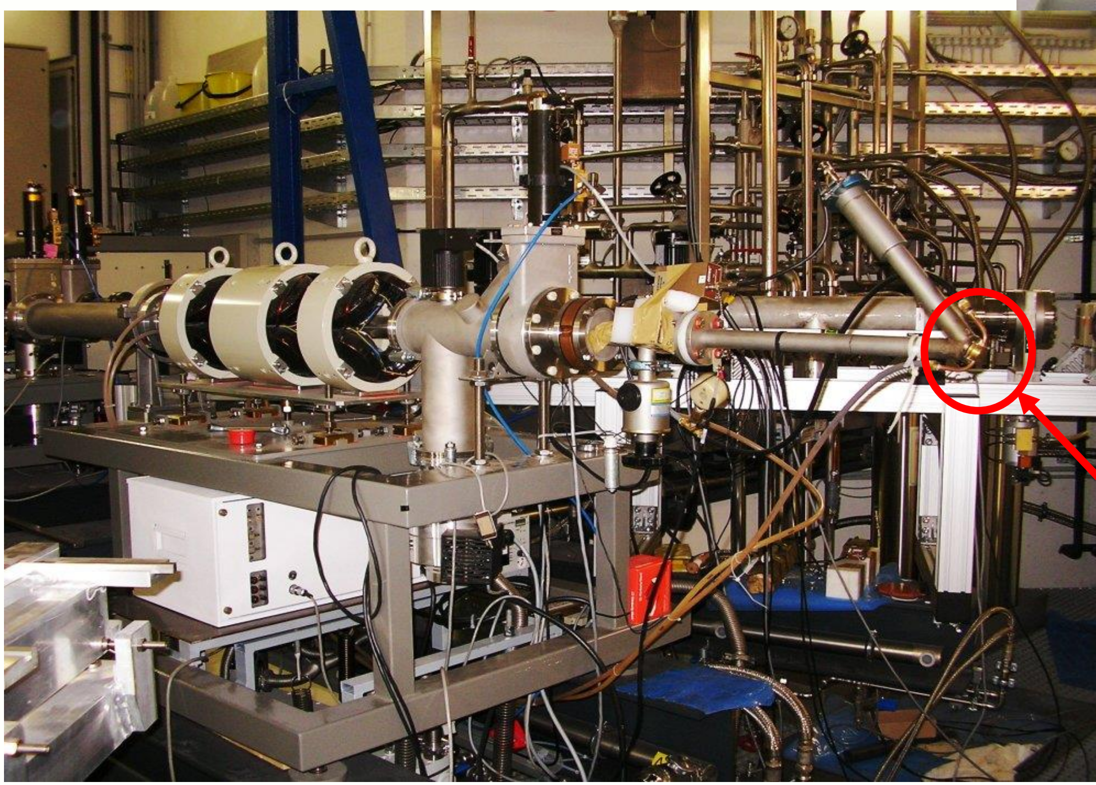
TUD-NG

TU Dresden

Technical University of Dresden Neutron Generator

Accelerator: 300 kV, 10 mA

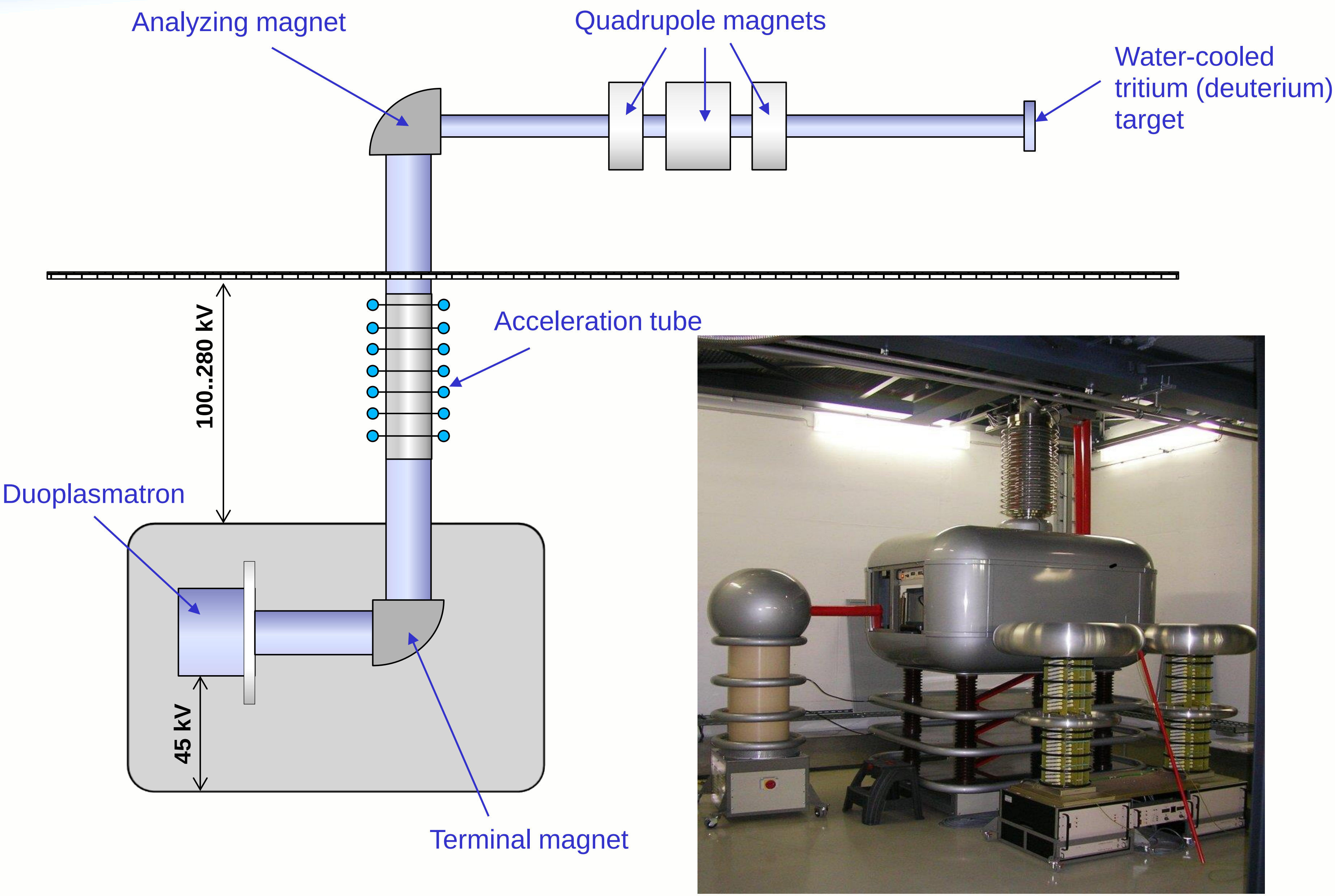
- up to 10^{12} n / s
- continuous or pulsed operation
 (accelerator prepared for ns pulsing)
- fixed and rotating T-Target



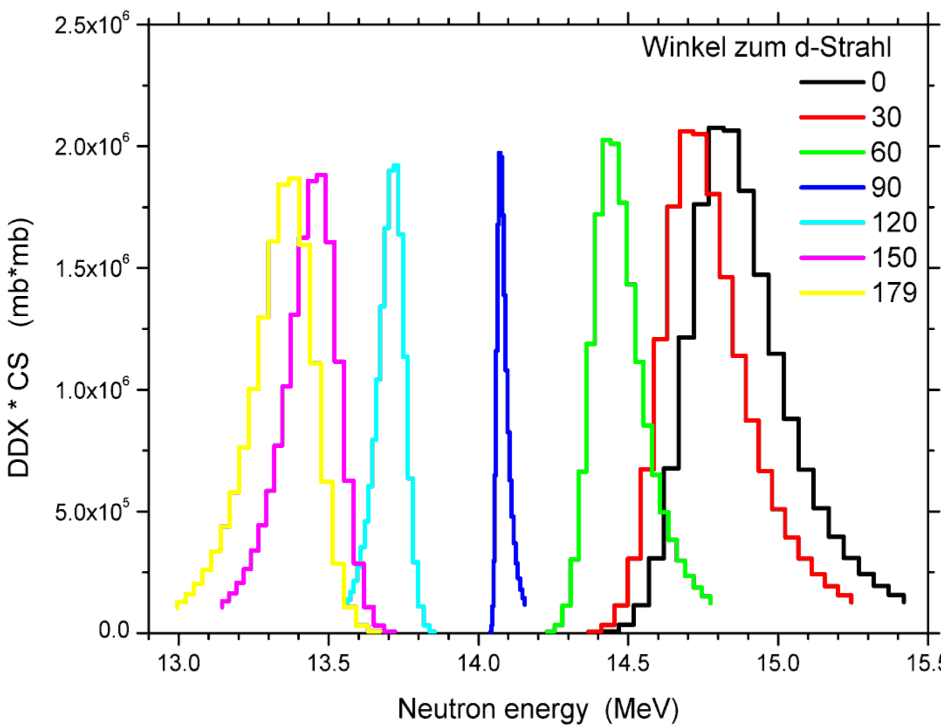
Targets:

Tritium: 3, 30, 250 Ci
Deuterium

Technical University of Dresden Neutron Generator



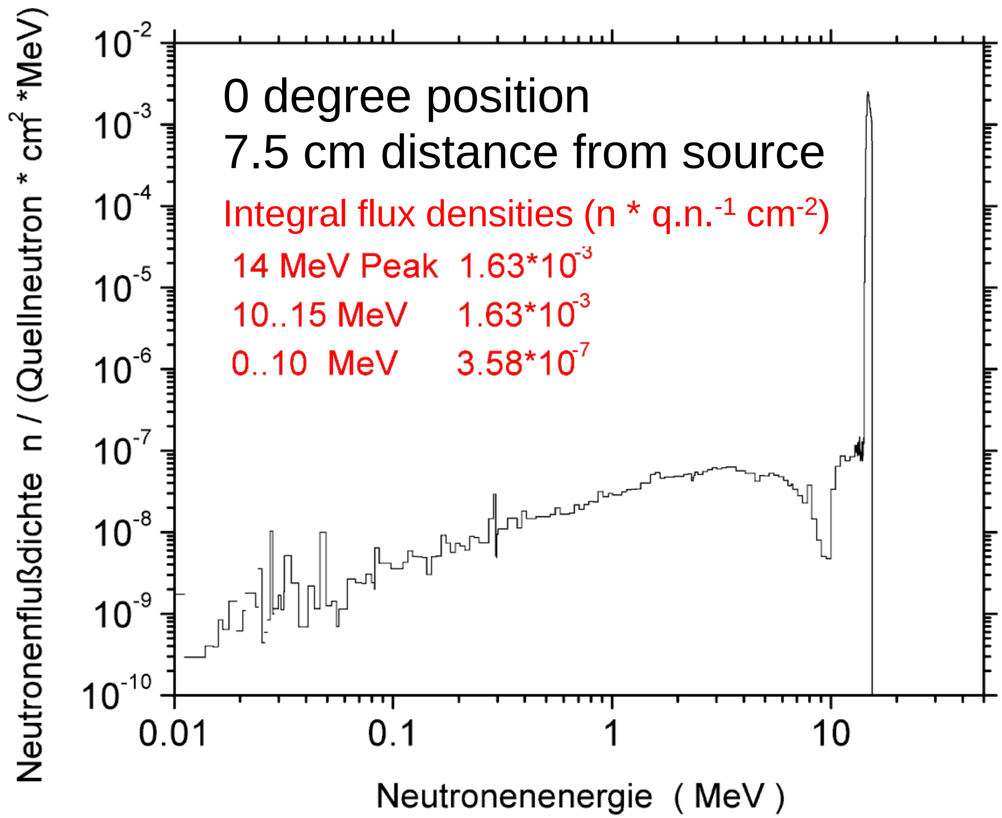
Technical University of Dresden Neutron Generator



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

Technical University of Dresden Neutron Generator
Overview of experimental activities

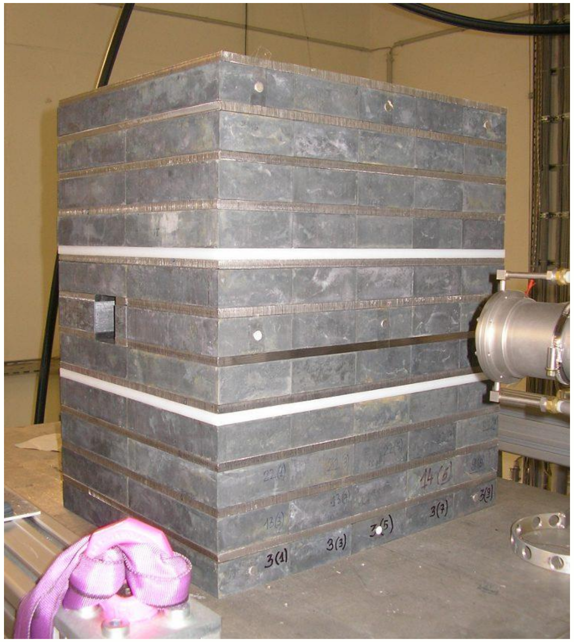
- Experiments related to the development of nuclear fusion power plants (previously EFDA-Tasks, currently mostly F4E-Grants)
  - Checking of activation data (EAF): Irradiation of materials relevant for fusion reactors and comparison with EASY calculations
  - **Testing of neutron transport data (FENDL, JEFF): Irradiation experiments of mock-ups of the European Test Blanket Modules for ITER**
  - **Development of instrumentation for future neutronics experiments with the TBM in ITER and for fusion reactor diagnostics**
- Activation experiments and cross section measurements for development of instrumentation for neutrinoless double beta decay experiments
- Measurement of cross sections around 14 MeV and at 2.5 MeV (for astrophysics, nuclear fusion and geology) Collaboration with Universities of Vienna and Heidelberg
- Experiments to determine soft error characteristics in electronics

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)

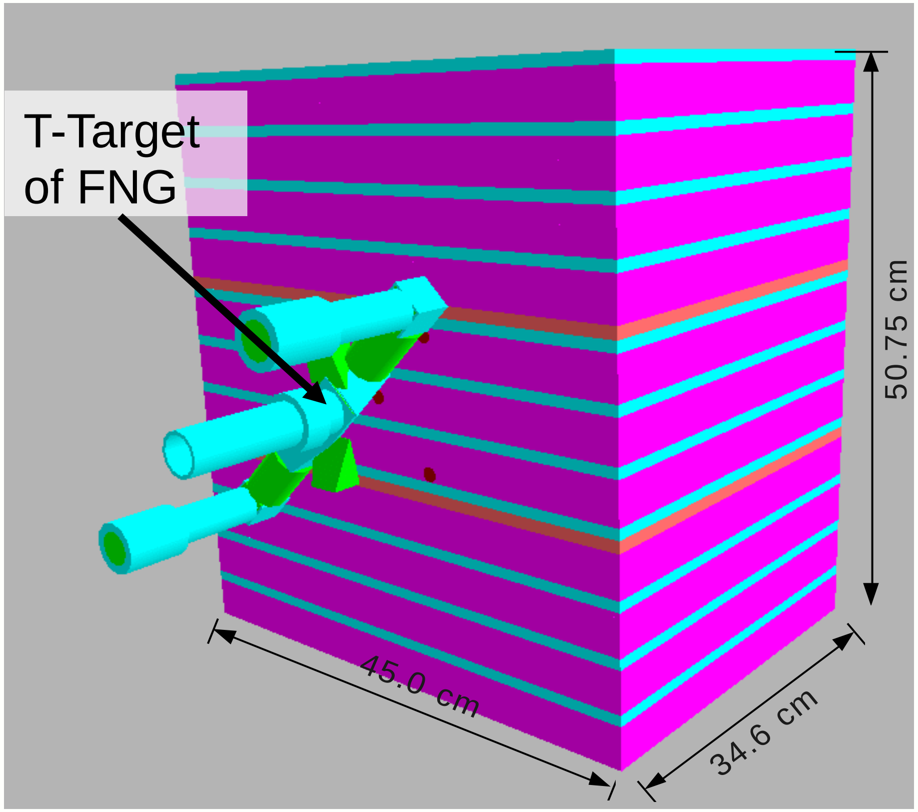
As part of this program, neutronics experiments have been performed to validate the predictions of Tritium Production Rate (TPR) in these concepts

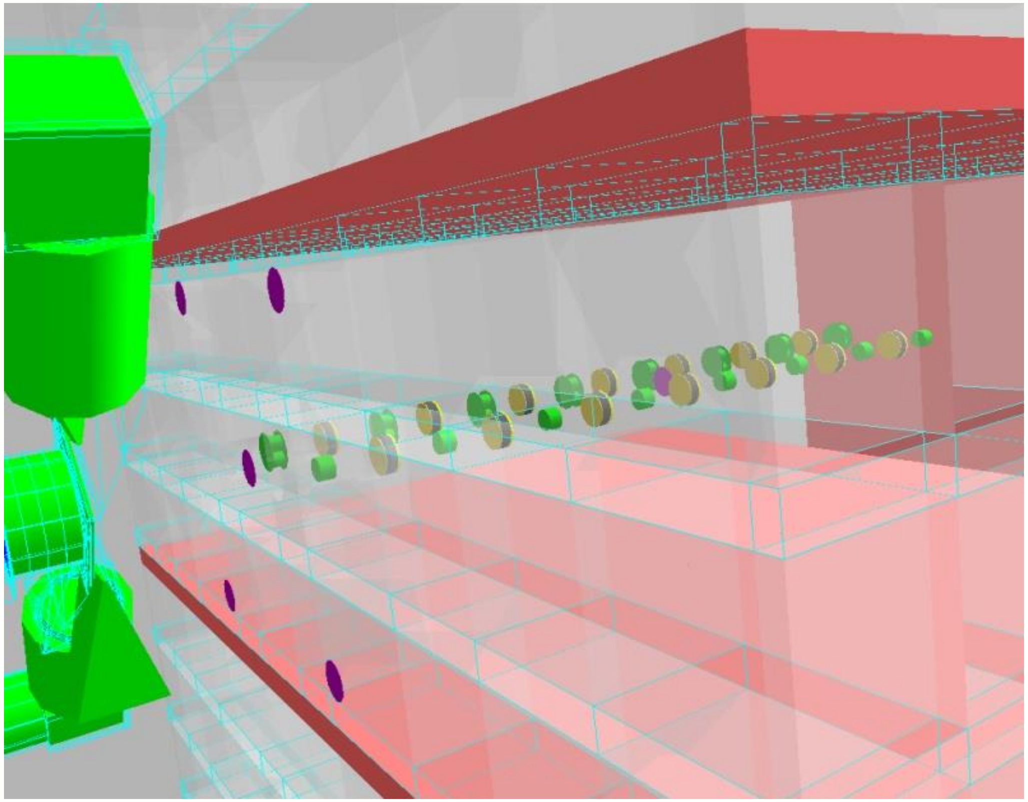


M. Angelone, P. Carconi, U. Fischer, D. Leichtle, A. Klix, I. Kodeli, K. Kondo,
L. Petrizzi, M. Pillon, W. Pohorecki, R. Villari

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)

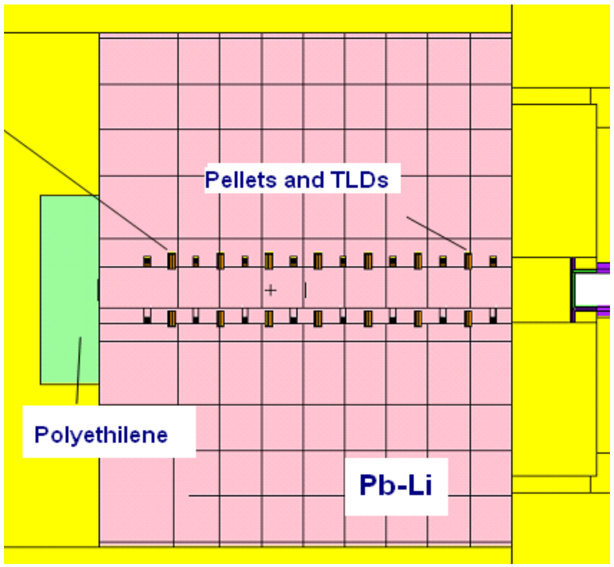


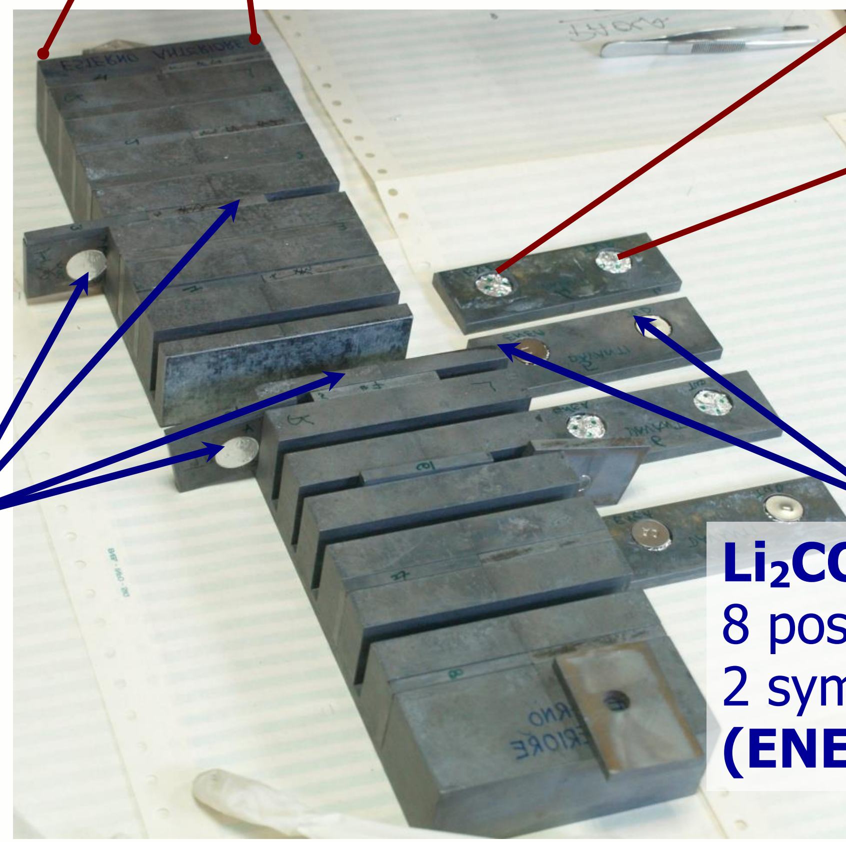


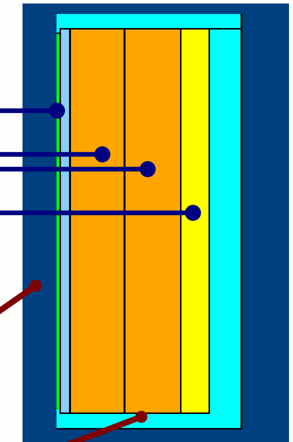
Mock-up consists of layers of LiPb (110 bricks, Li/PbLi: 0.615±0.016 wt%), Eurofer steel (Eurofer-97) and polyethylene
Detectors placed along the axis of the mock-up

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)







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)

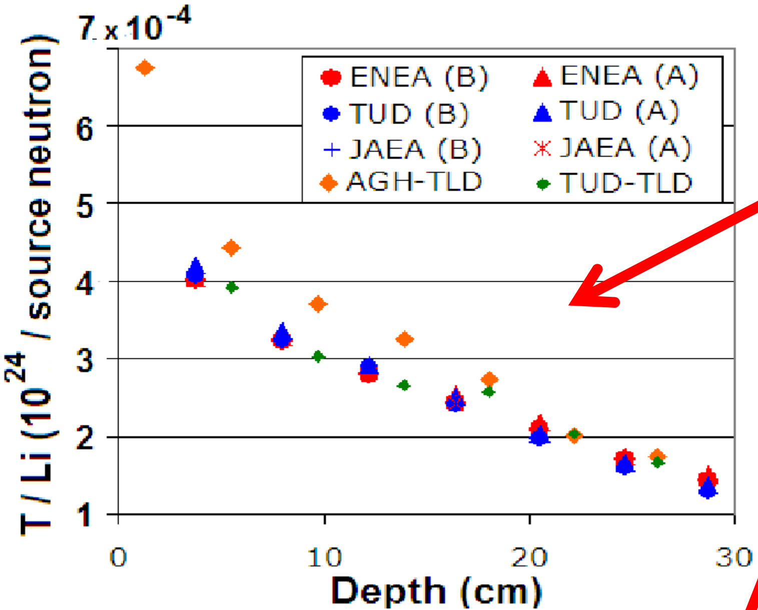
- **Li_2CO_3** pellets are dissolved in acids
  solution is mixed with liquid scintillator
  Tritium is measured by β-counting

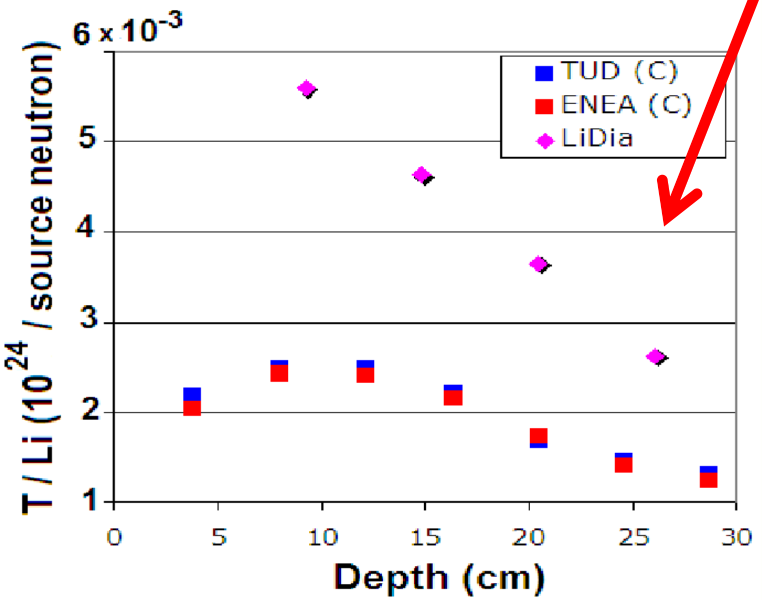
- Thermoluminescence detectors (**TLD**)
  Tritium production is measured in two ways:

  - 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

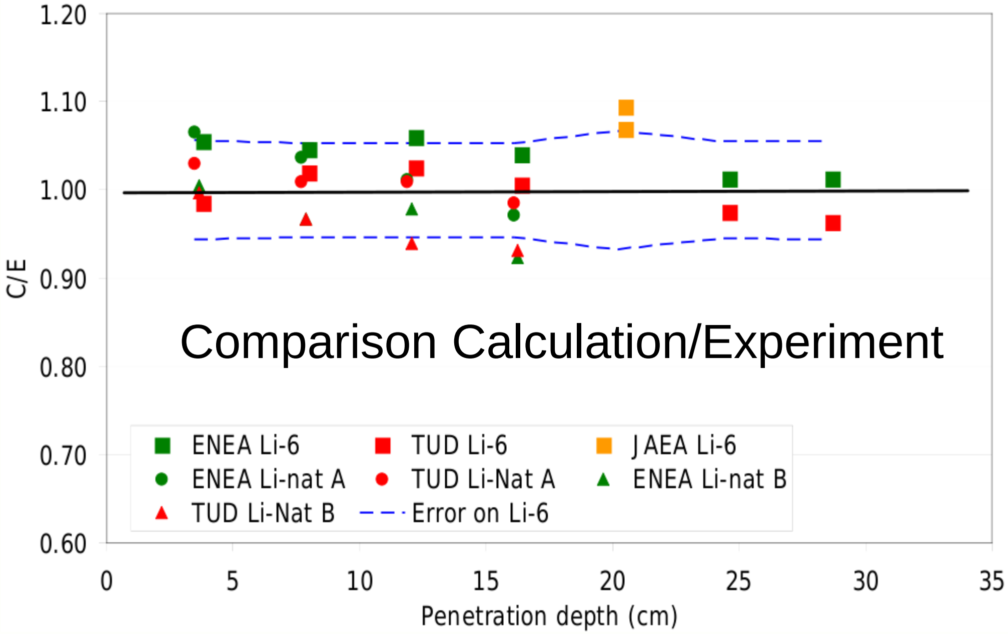




Tritium production rates along central axis of HCLL TBM mockup

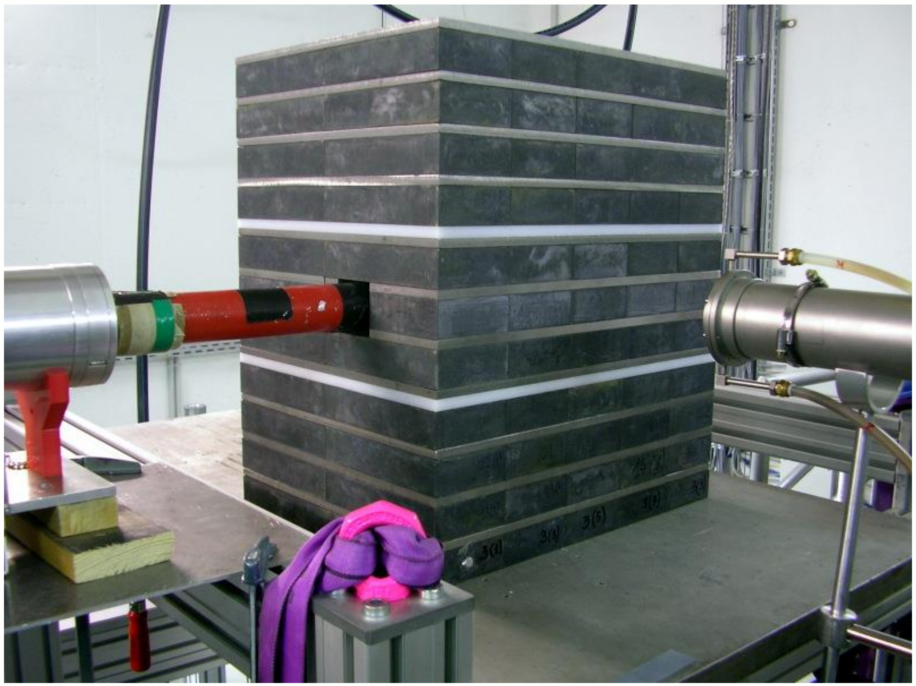
^{nat}Li-type detectors (Li_2CO_3 pellets, TLD)

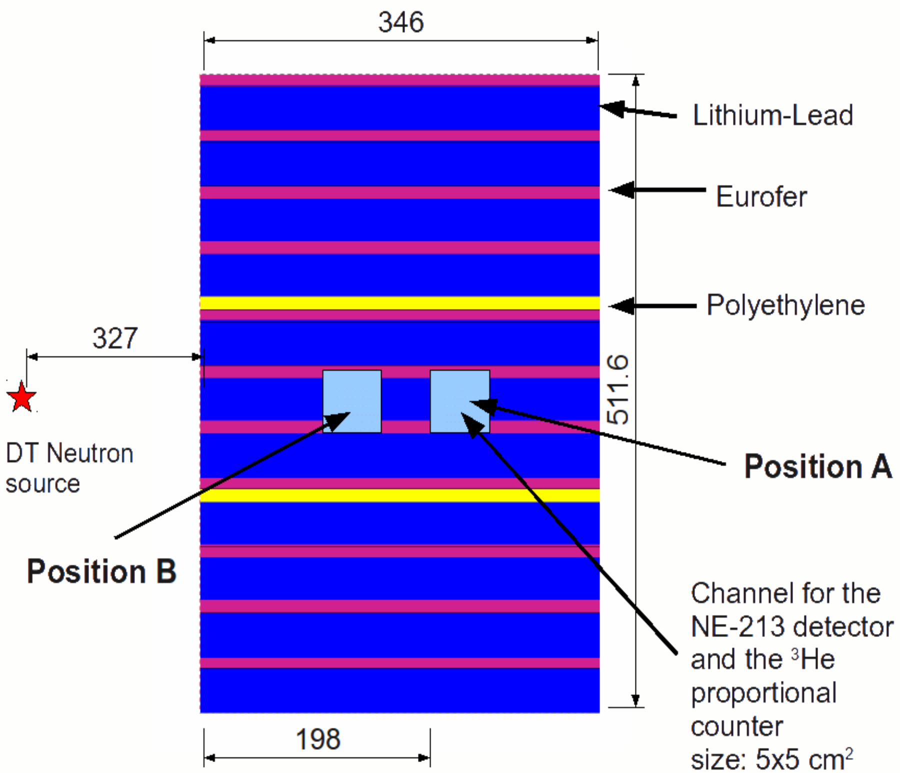
^{6}Li enriched detectors (Li_2CO_3 pellets, TLD, LiF covered diamond)
(There is negligible self-shielding in case of the diamond detector.)



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

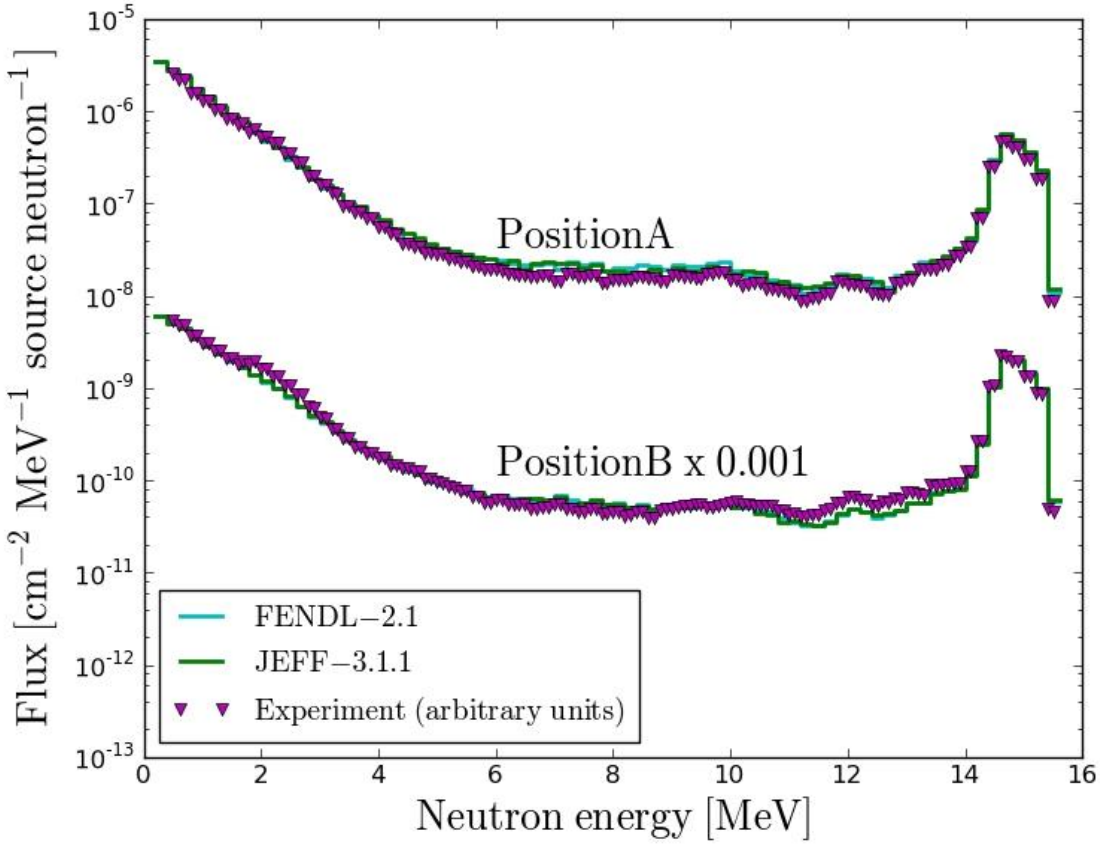


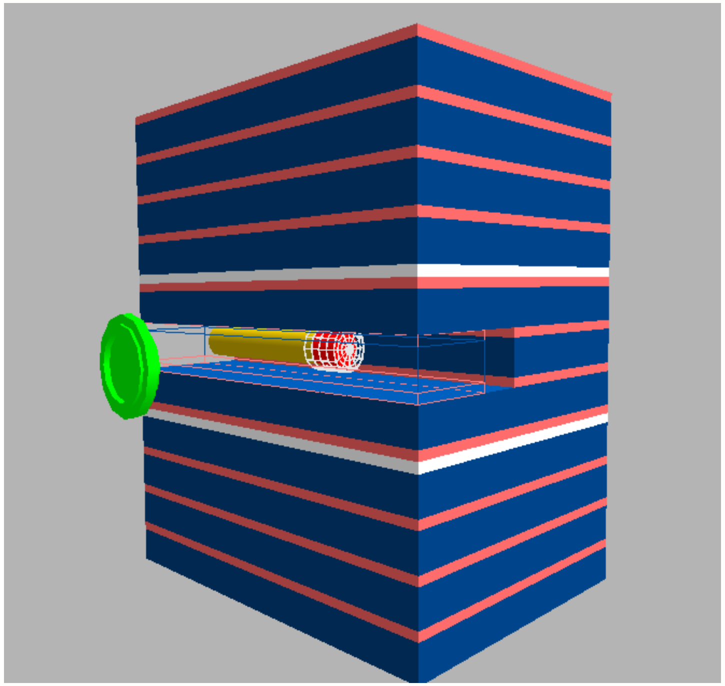


Left: NE-213 detector (1.5"x1.5 ")
Right: Ti-T target of neutron generator
Middle: Mock-up

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

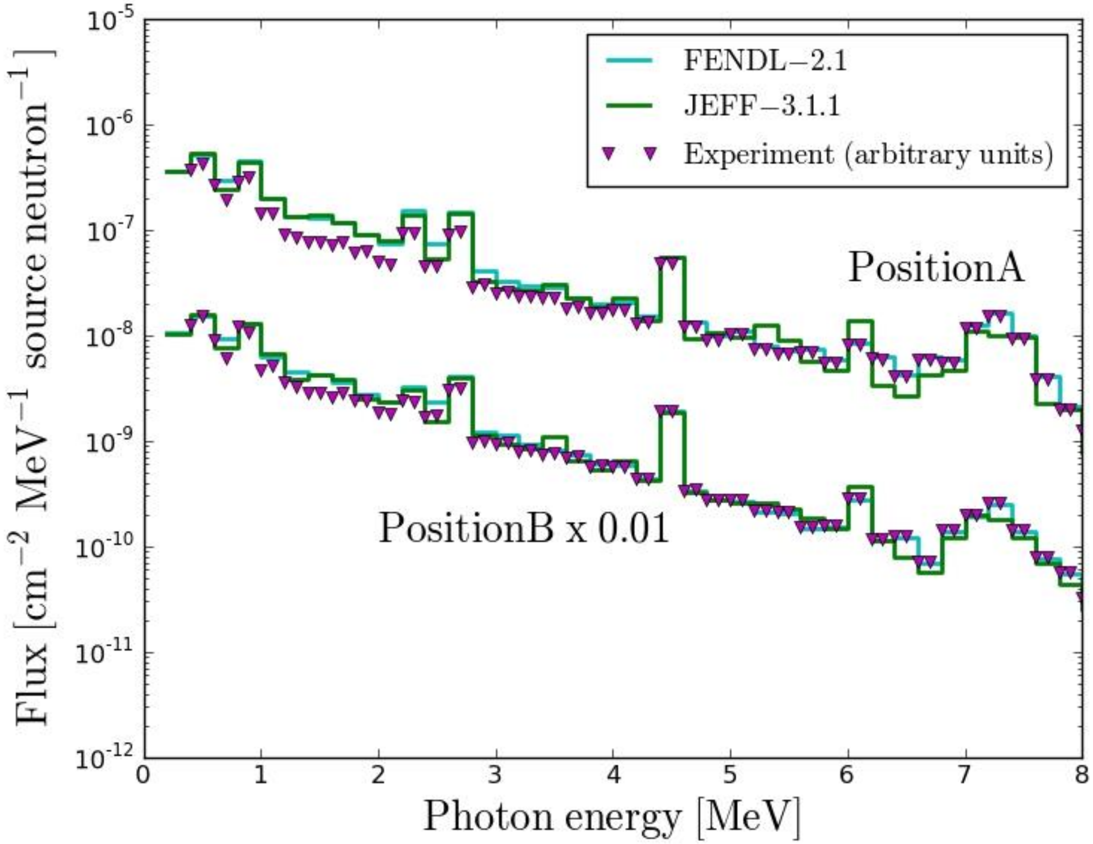
HCLL TBM mock-up experiment
Fast neutron flux spectra

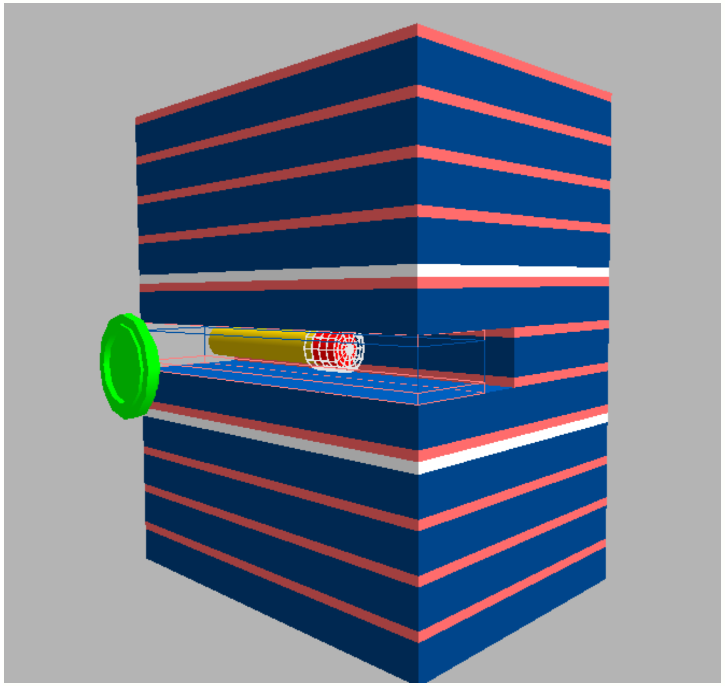




Pulse height spectra recorded with the NE-213 detector
Unfolding with MAXED code, response matrix (validated at PTB)
Calculations with MCNP5 and JEFF-3.1.1 and FENDL-2.1
Normalization of unfolded spectra by fitting 14 MeV peak height

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 Blankt Modules

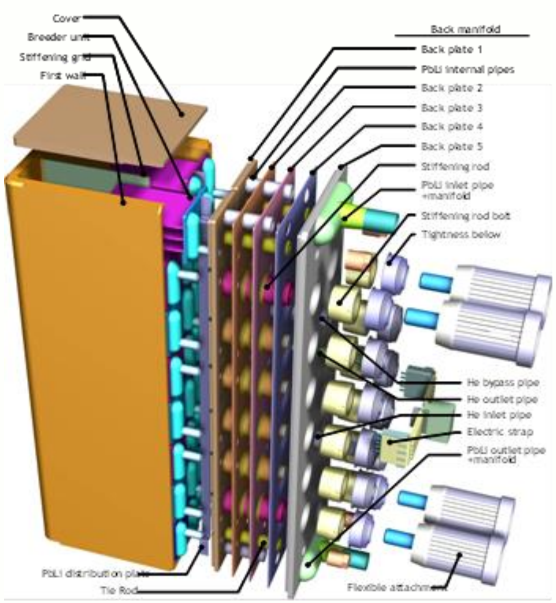
ITER TBM neutronics experiments are expected to ***fill the gap*** between today's experiments with DT neutron generators and the conditions in DEMO and power reactor breeding blankets

Local neutron flux measurements in the TBM should provide normalization for other parameters (also „non-neutronics“) with better accuracy as compared to interpolation from flux measurements outside the TBM
Particular importance for Tritium accountancy in TBS experiments!

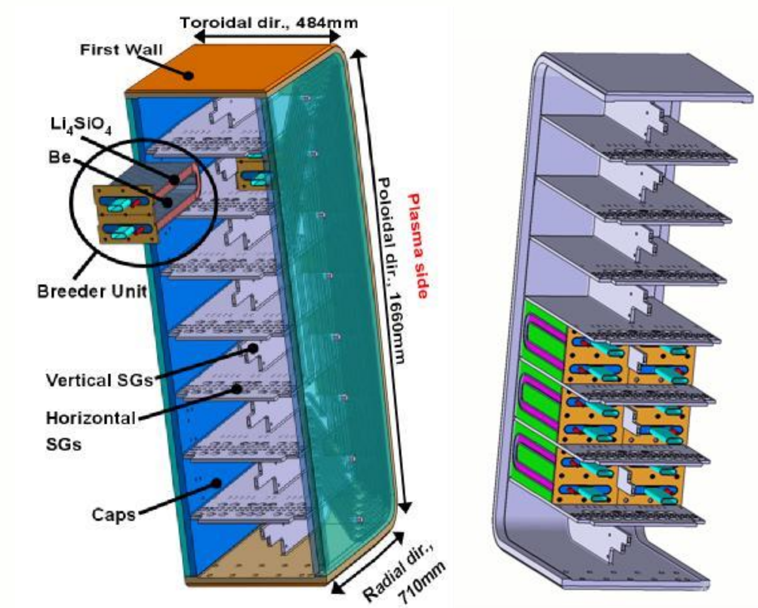
Local tritium production rate measurements in the TBM provide more information than integral tritium production measurements in the sweeping gas or liquid breeder for the whole breeding blanket

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).

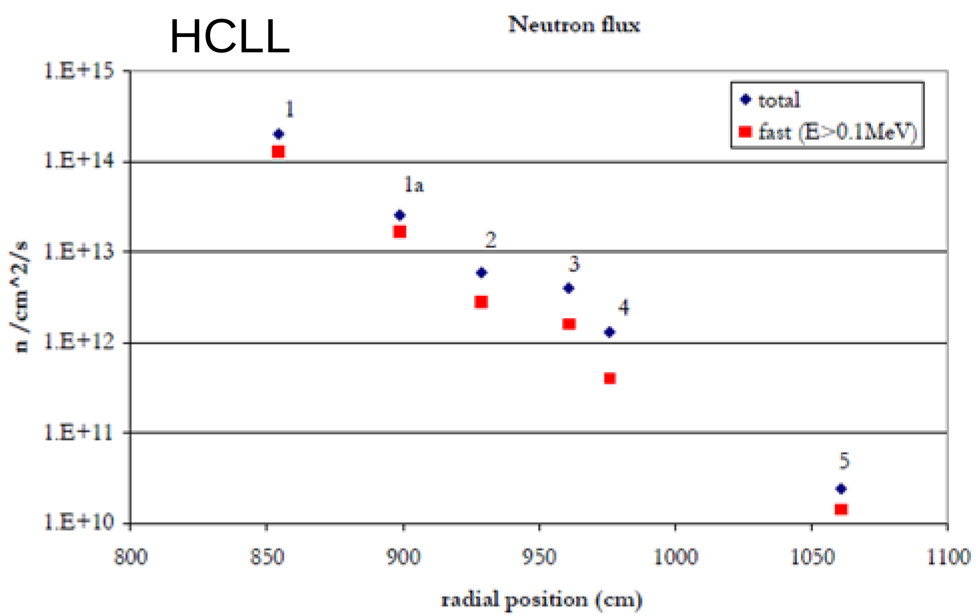


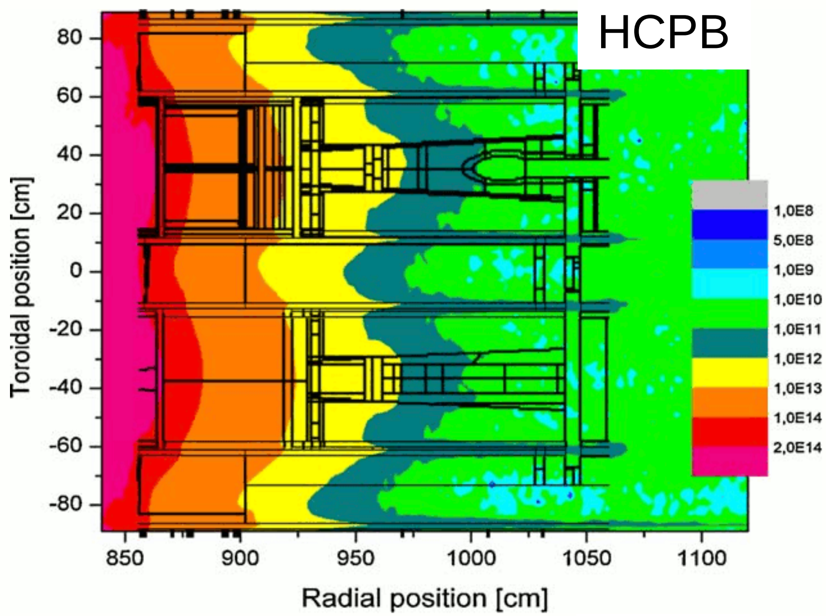
HCLL TBM

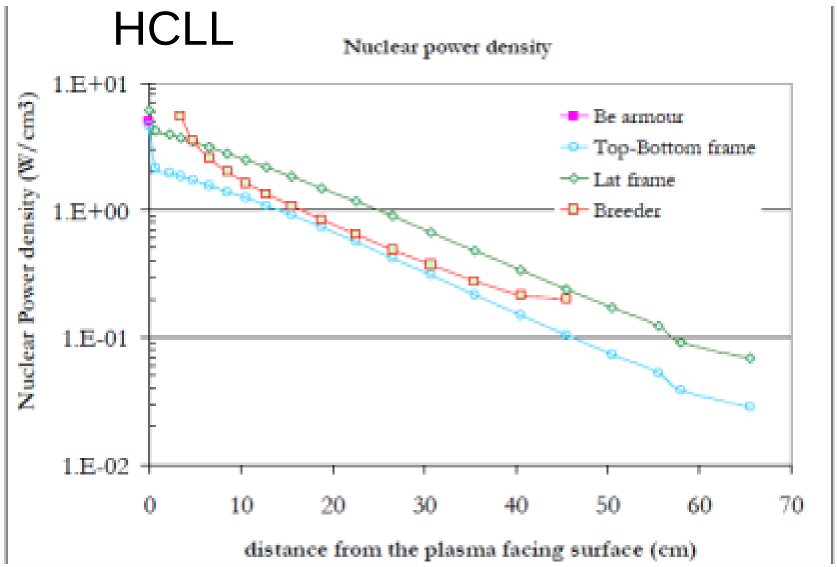


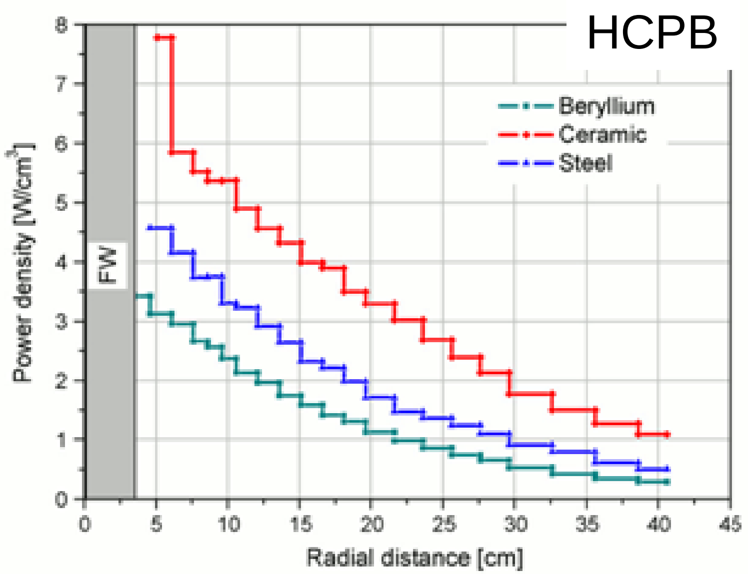
HCPB TBM

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

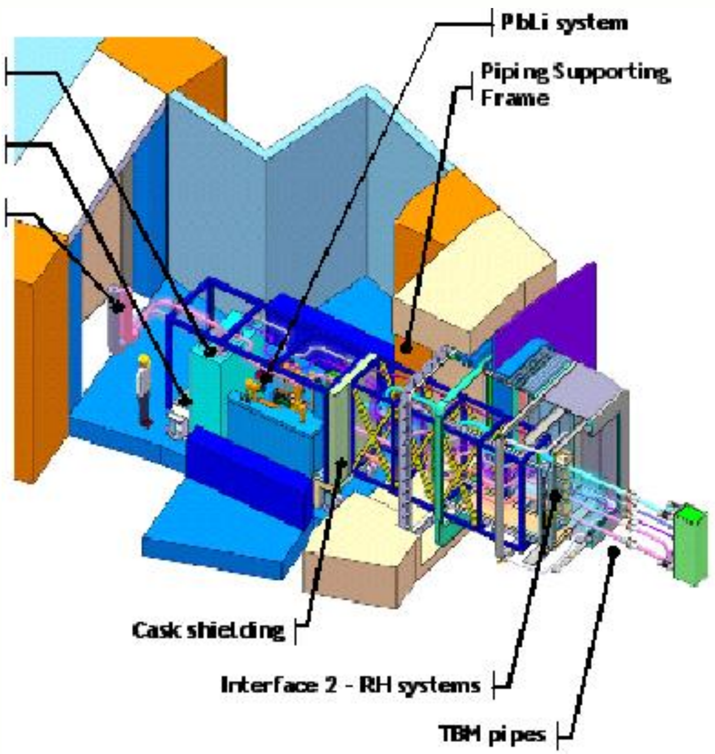








Neutronics instrumentation for the ITER TBM
- Conditions in the TBM -



R&D work within F4E Tasks (F4E-2008-GRT-09, GRT-056) and others

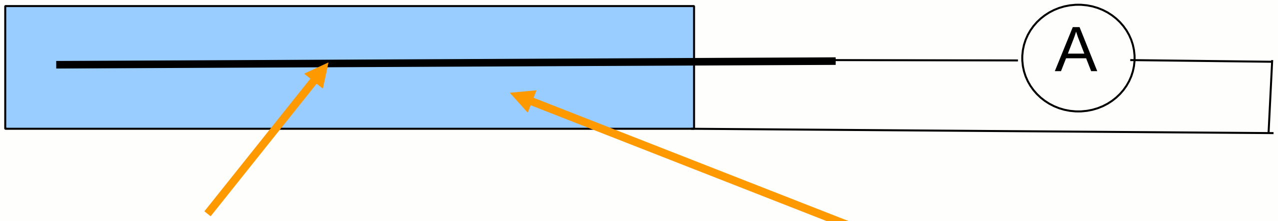
Conditions in the TBM terribly bad for detectors / diagnostics

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

Possible candidates: Neutron aktivation system, miniature fission chambers, diamond detectors, silicon carbide detectors, self-powered neutron detectors

Testing and qualification underway

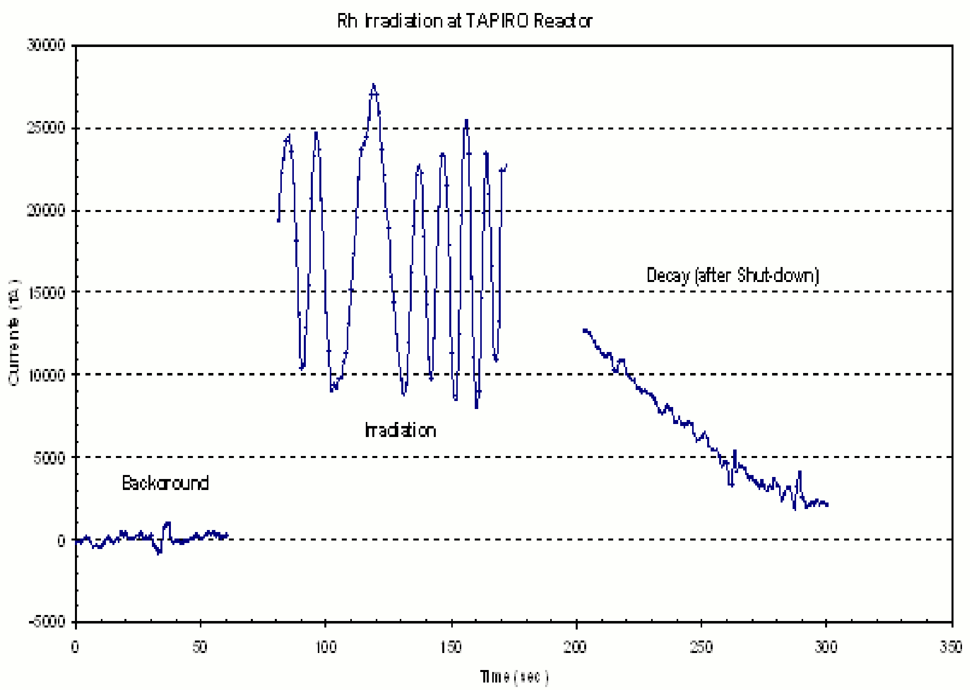
Self-powered neutron detectors (SPND)



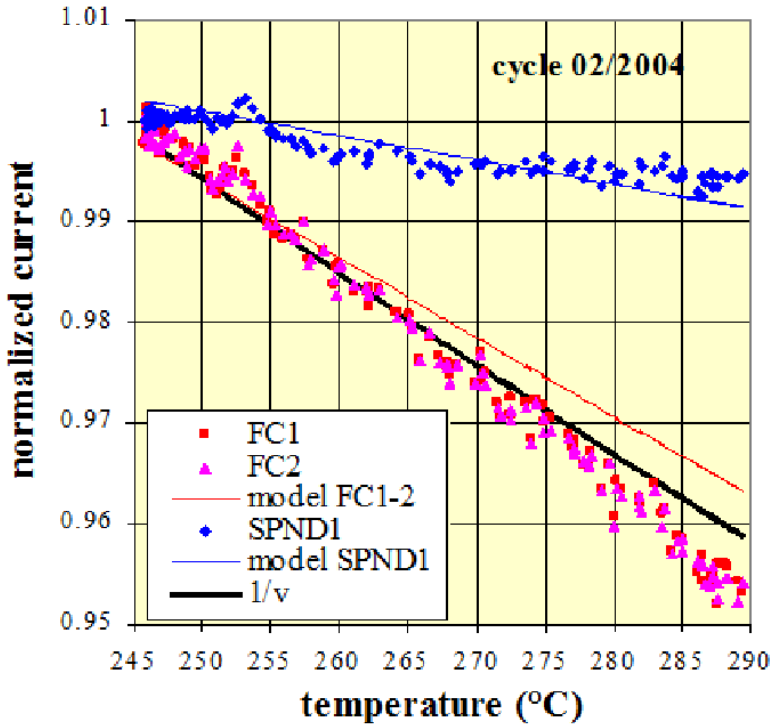
- central lead: Rh, Co and others, insulation MgO or Al_2O_3
- induced beta activity or Compton electrons -> small current
- may have a slow response time (half-life of beta activity)
- applied in fission reactors
- Conditions in fusion reactor may be incompatible due to strong EM fields

Work in collaboration with ENEA Frascati
First tests with commercial SPND (optimized for thermal neutrons!) done
Tests with materials for fast neutrons underway

Self-powered neutron detectors (SPND)



Response of the Rh SPND tested at TAPIRO of ENEA Cassacia. The oscillations are thought to be due to EM noise from a helium cooling pump



Temperature dependence of the signal of a Rh SPND.
(Ludo Vermeeren: ANIMMA2013 short course, Marseille, June 23, 2013)

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)

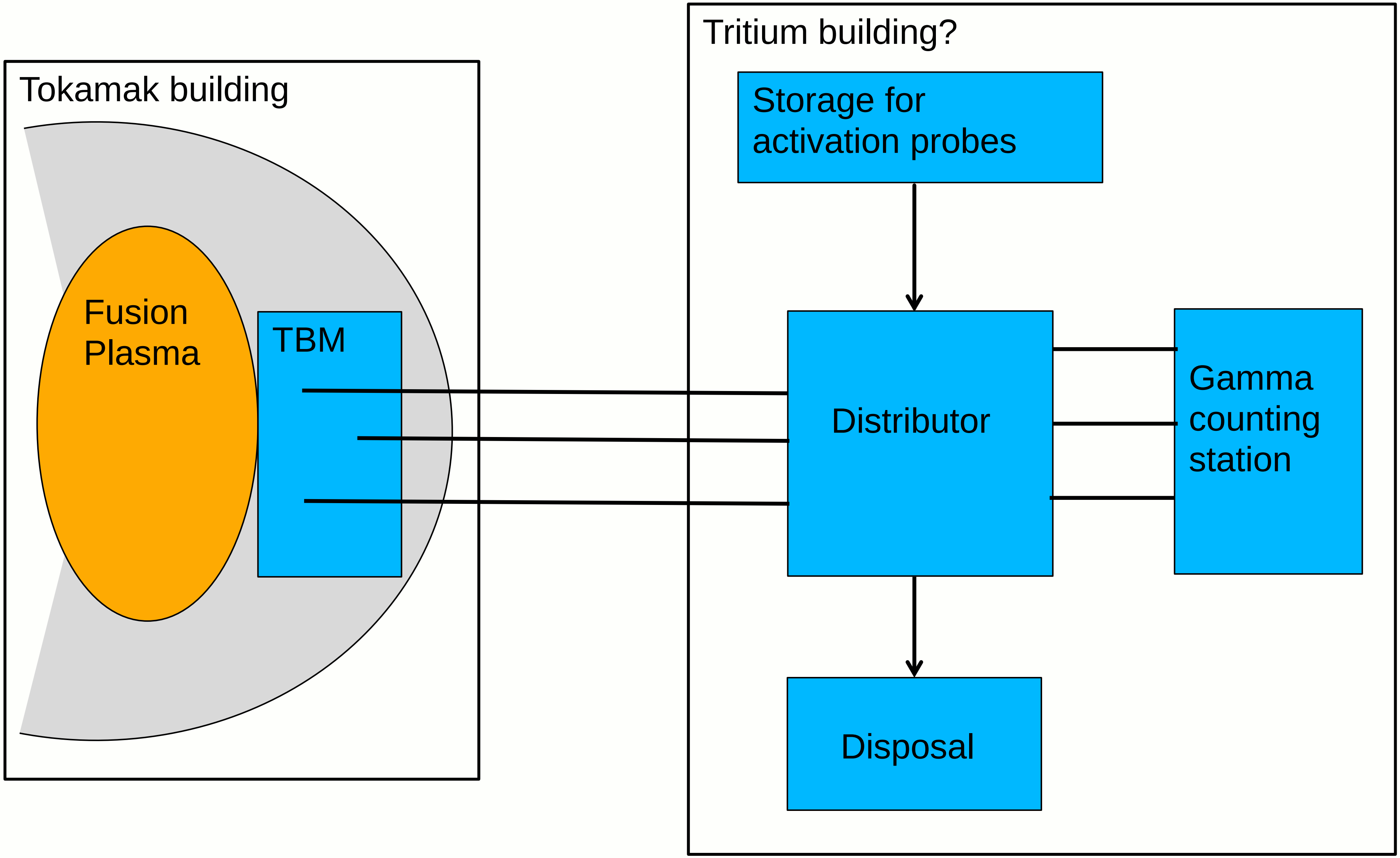
(may be MgO needs to be used as insulator!)

Results were presented at ISFNT 2013

Further work underway:

- ***Preparation of test detectors with proposed new emitter materials, testing in fast neutron fields***
- ***Testing in Tokamak EM field (ASDEX)***

Neutron Activation System

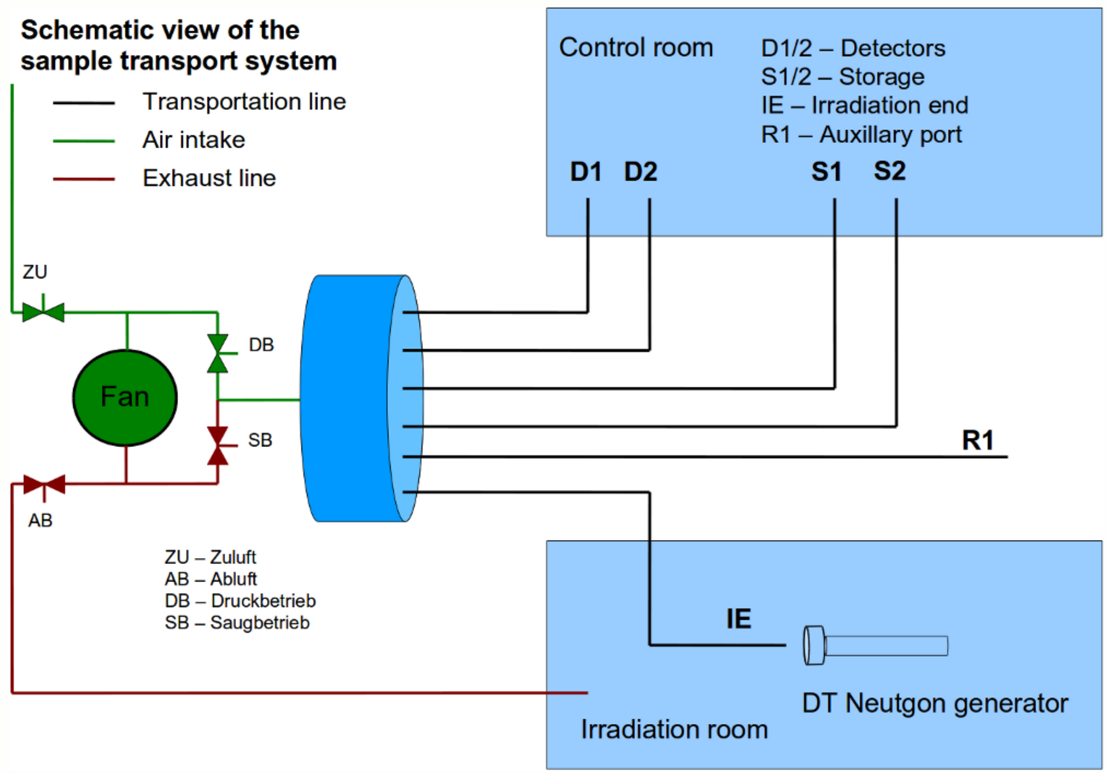


TBM Neutron Activation System
Neutronics test system at TUD-NG

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

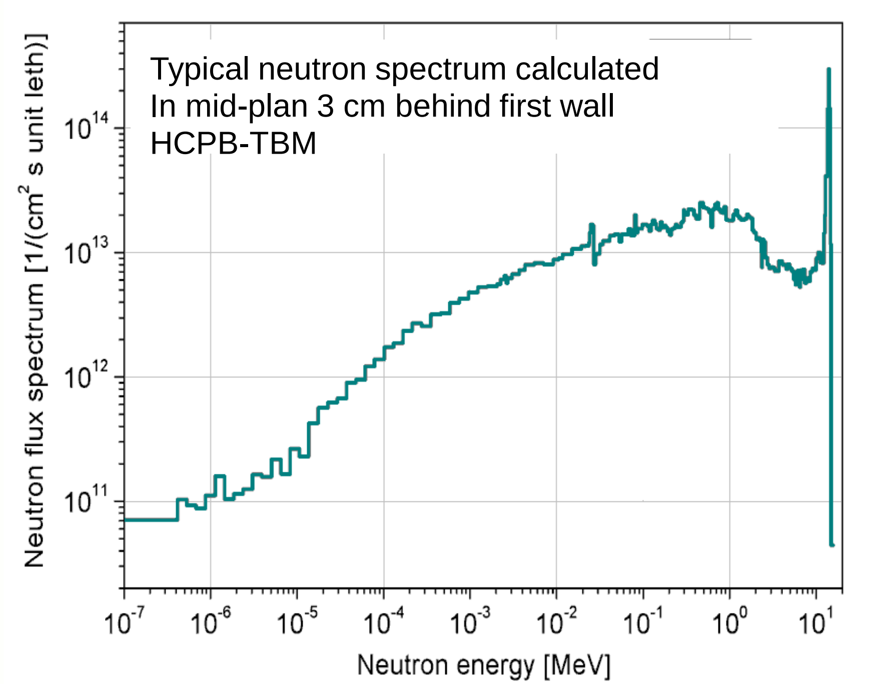
Spectral neutronen flux density

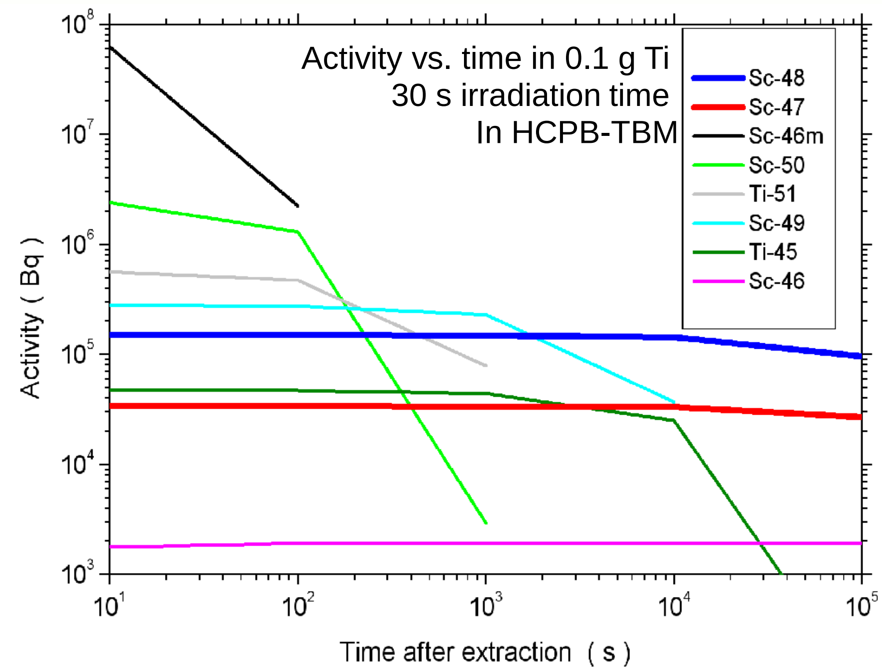
- Application of suitable (new) dosimetry reactions (short half-lives)
- Testing of suitable measurement regimes
- Testing of suitable gamma ray detectors (HPGe, CZT,...)
- Demonstration of an automated system



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

Neutron activation system for the TBM





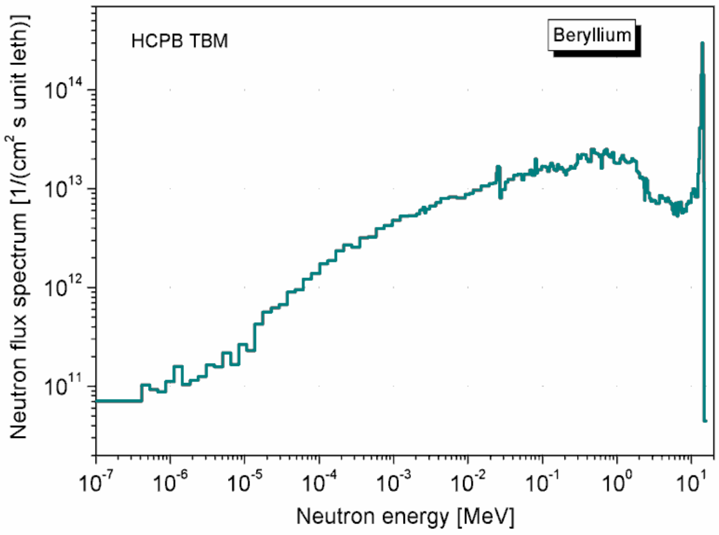
- Calculations with MCNP-5 and EASY-2007 show principal applicability of "traditional" dosimetry reactions
- Extension of this set of reactions to **short-living induced radio isotopes** underway

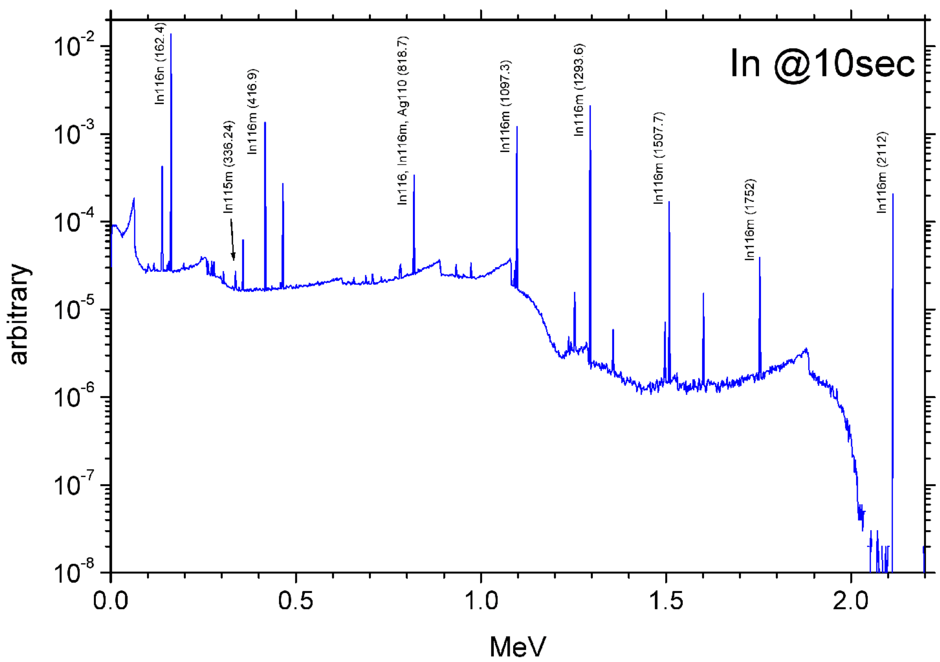
→ *Aim:* Reduction of necessary corrections of short time measurements
Methodology for recording of **time profiles** of neutron spectra (Dt ~ 10..30 s)

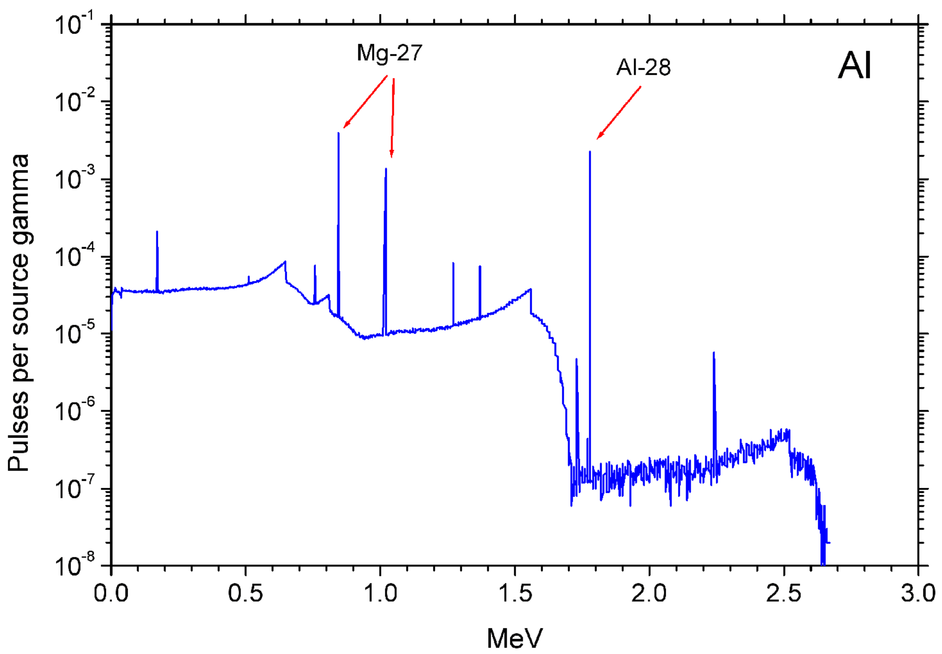
Short half-life compensates for on average smaller cross sections
in case of similar cross section: higher activity after extraction leads to higher sensitivity

Neutron activation system for short measurement cycles

- Half-lives between 30 sec and 600 sec, gamma line intensity more than 10 %
- Neutron spectrum calculation for selected position in TBM (MCNP5, FENDL-2.1; P. Pereslavtsev, KIT)
- Activation calculated for 0.1 g of each material (EASY-2007): 30 sec irradiation followed by 10 sec cooling time (allowing for sample transport to gamma-ray detector etc.)
- Calculation of pulse height spectra in HPGe detector from gamma-rays emitted by the activation foils (MCNP5, mcplib04, el03)



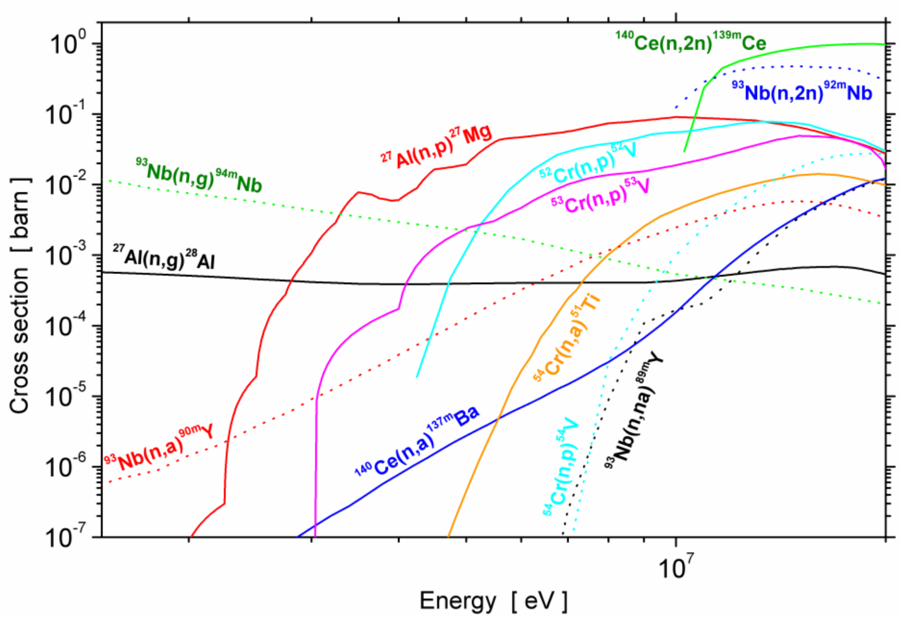


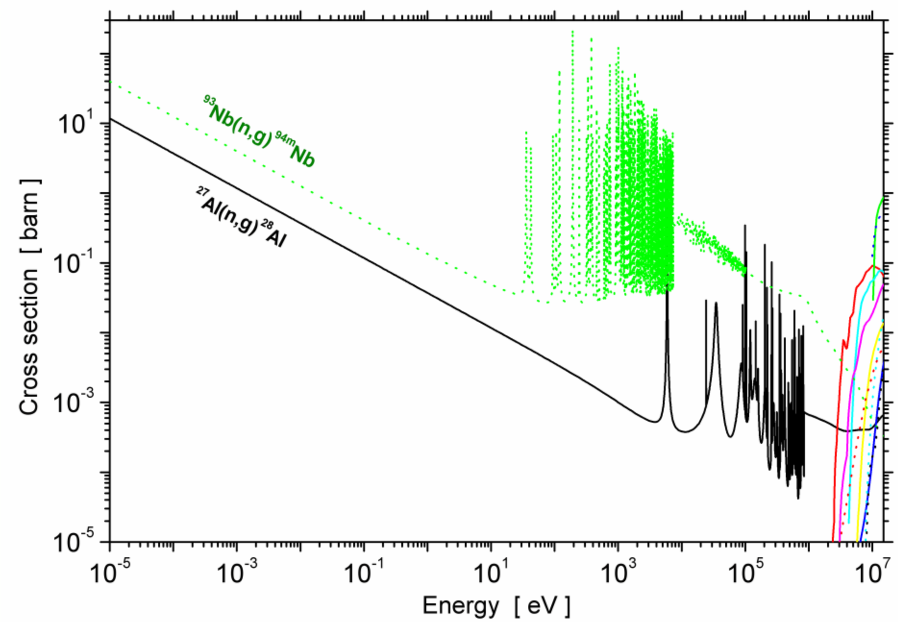


Neutron activation system for short measurement cycles

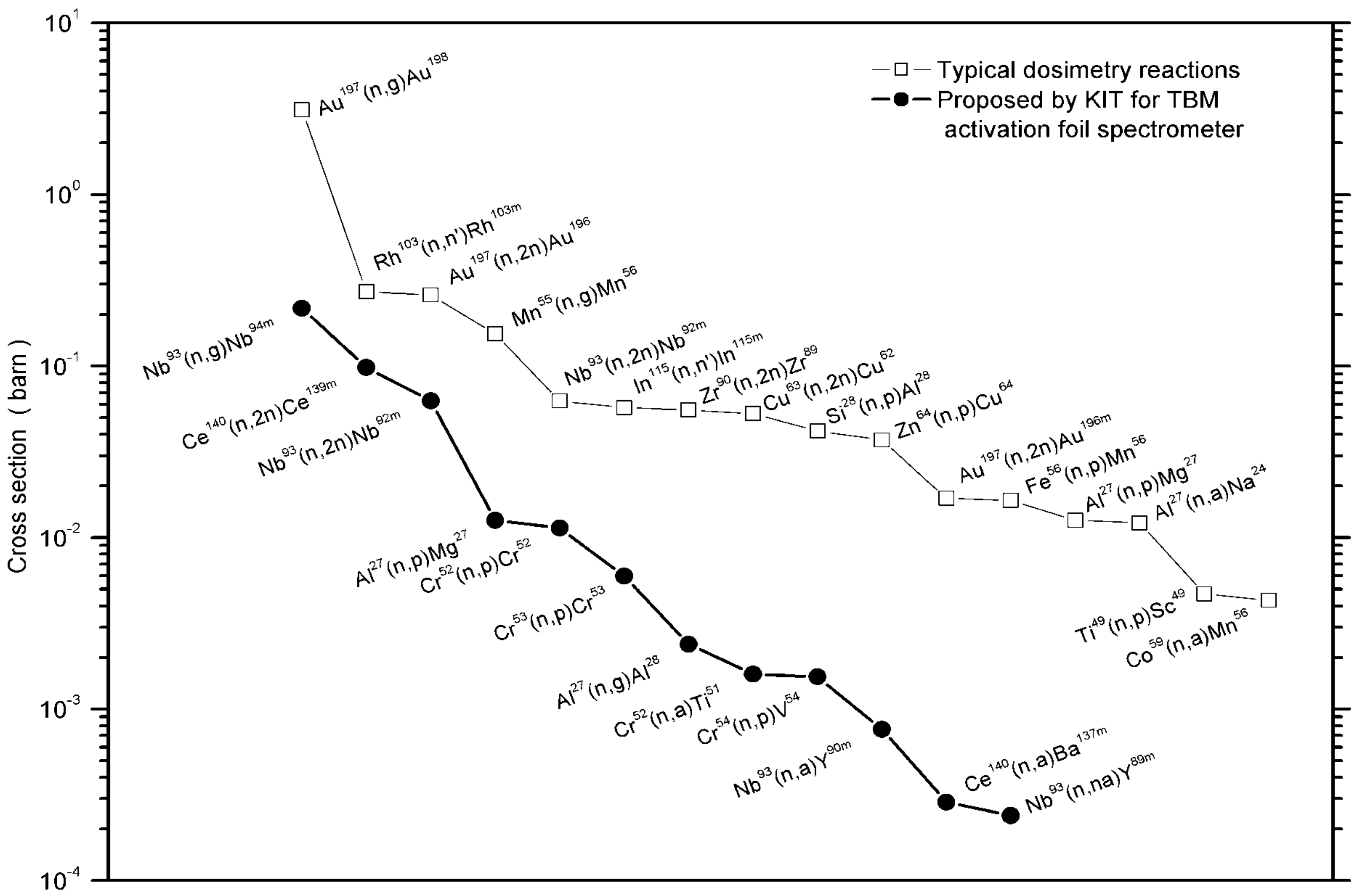
Dosimetry reaction	Half-life (sec)	Approx. threshold energy (MeV)	Gamma-ray energy / Intensity of gamma line
^{140}Ce (n,2n) ^{139m}Ce	56.1	10	754.2 / 0.9242
^{140}Ce (n, α) ^{137m}Ba	153.12	12	661.7 / 0.9007
^{27}Al (n,g) ^{28}Al	134.46	--	1778.7 / 1.00
^{27}Al (n,p) ^{27}Mg	567.48	4.5	843.7 / 0.718 1014.4 / 0.282
^{52}Cr (n,p) ^{52}V	224.7	5.5	1434.1 / 1.000
^{53}Cr (n,p) ^{53}V	97.2	6	1006.3 / 0.896 1289.5 / 0.1004
^{54}Cr (n,p) ^{54}V	49.8	11	834.8 / 0.971 989.1 / 0.801 2259.3 / 0.456
^{54}Cr (n,p) ^{51}Ti	348.0	8.2	320.1 / 0.942
^{93}Nb (n,g) ^{94m}Nb	375.6	--	41.0 / 7.3e-4 871.1 / 4.95e-3
^{93}Nb (n,a) ^{90m}Y	11484	6.9	202.5 / 0.9725 479.5 / 0.9074
^{93}Nb (n,nα) ^{89m}Y	15.663	12.5	909.0 / 0.9916
^{93}Nb (n,2n) ^{92m}Nb	876960	9.5	934.5 / 0.9904

Isotope		Abundance (%)	Melting temp. (°C)	Contributions to radio isotope	
Ce	136	0.19	795		
	138	0.25			
	140	88.48		n,2n → ^{139m}Ce; 99.99%	n,α → ^{137m}Ba; 100%
	142	11.08			
Al	27	100.0	660	n,γ → ^{28}Al; 100%	n,p → ^{27}Mg; 100%
Cr	50	4.35	1907		
	52	83.79		n,p → ^{52}V; 99.637%	
	53	9.50		n,p → ^{53}V; 99.863%	
	54	2.36		n,p → ^{54}V; 100%	n,α → ^{51}Ti; 100%
Nb	93	100.0	2468	n,γ → ^{94m}Nb; 100% n,nα → ^{89m}Y; 100%	n,α → ^{90m}Y; 100% n,2n → ^{92m}Nb; 100%

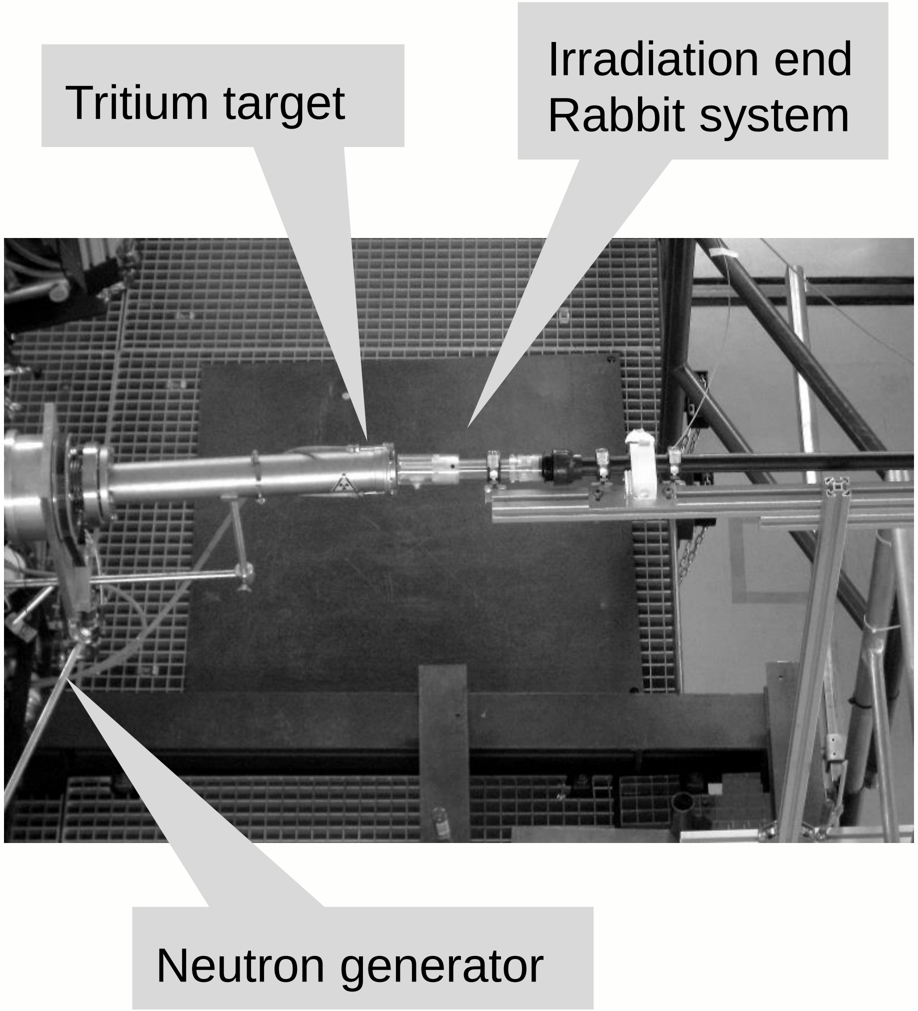


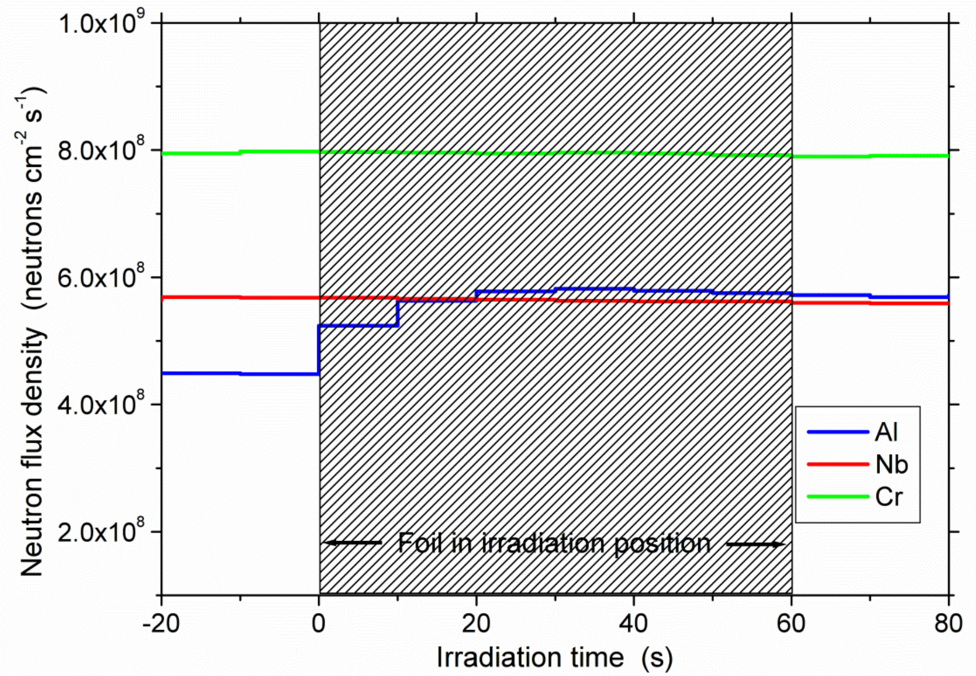


Neutron activation system for the TBM



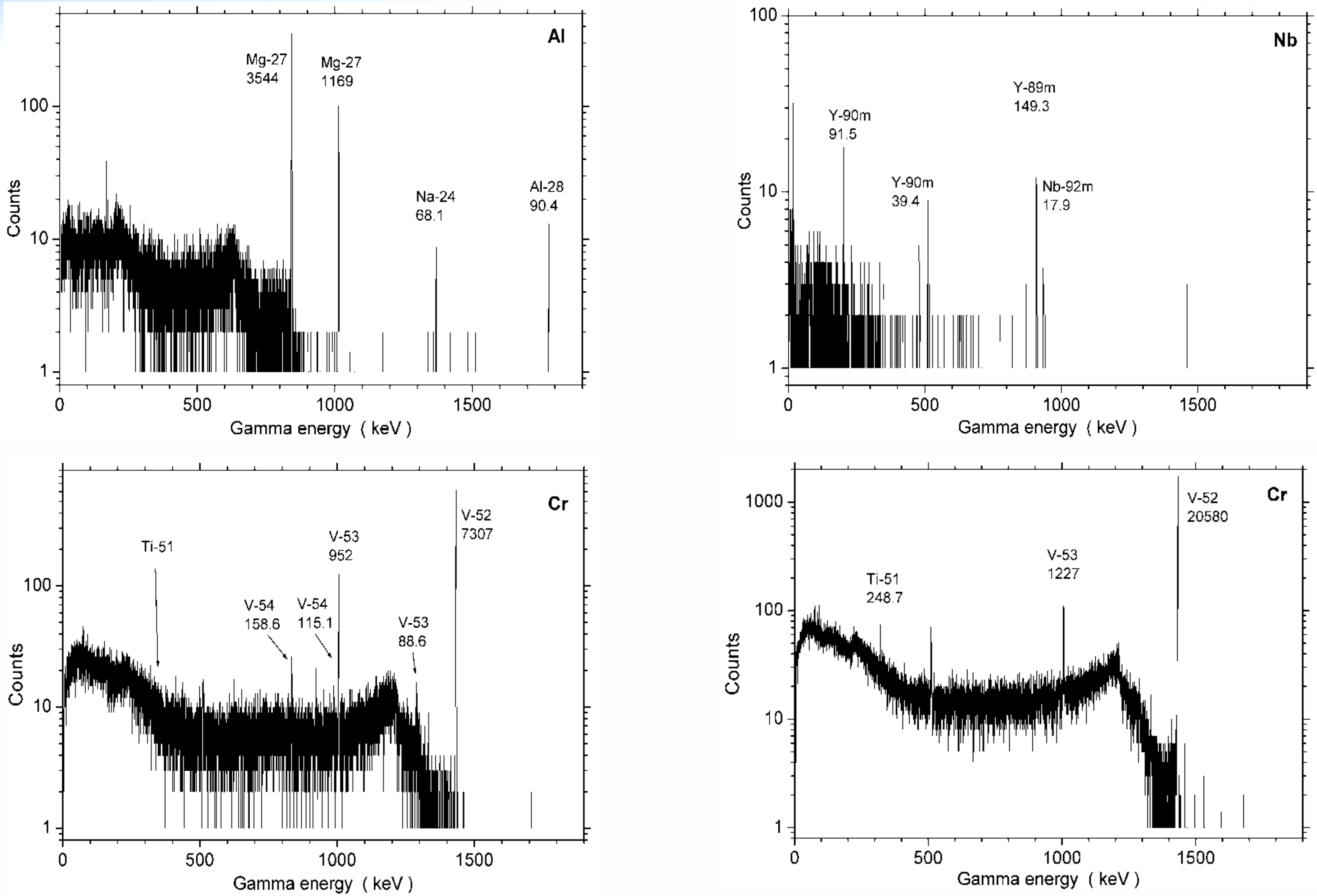
Neutron activation system for short measurement cycles





- Neutron flux density in sample position three to four orders of magnitude lower than in TBM
- Test foils 10 mm diameter, ~0.6 g
  Material purity >99.9%

TBM Neutron Activation System

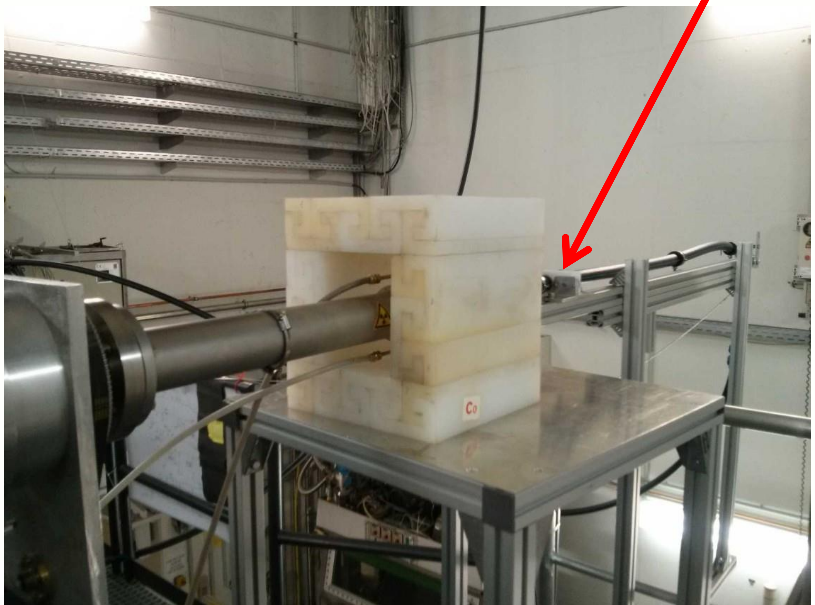


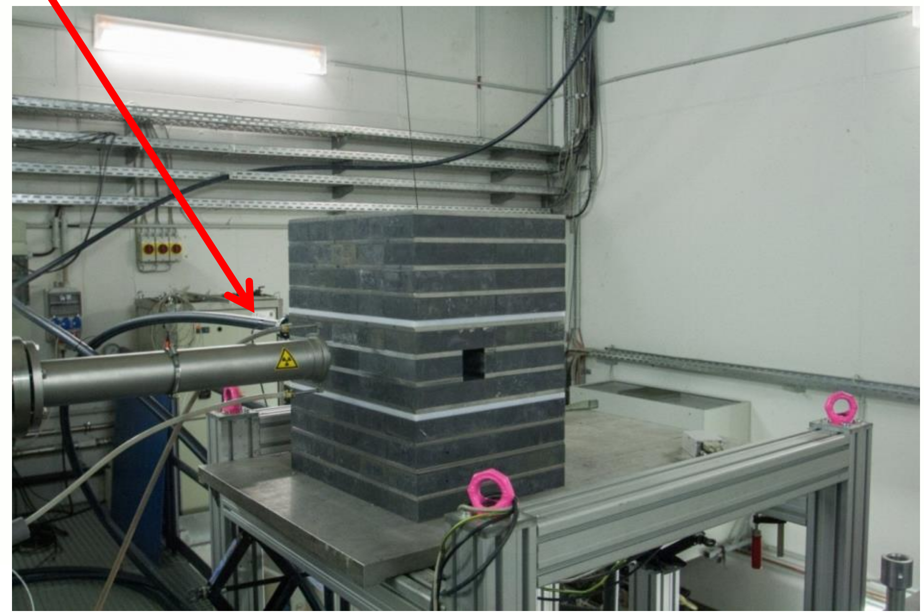
Irradiation time 60 s, fluence at sample position 3.39 - 4.77×10^{10} n/cm^2 , Transport time 16..23 s, measurement time (HPGe, 30%, ca. 5 cm distance); Second Cr spectrum: Measurement start 99 s after extraction for 300 s

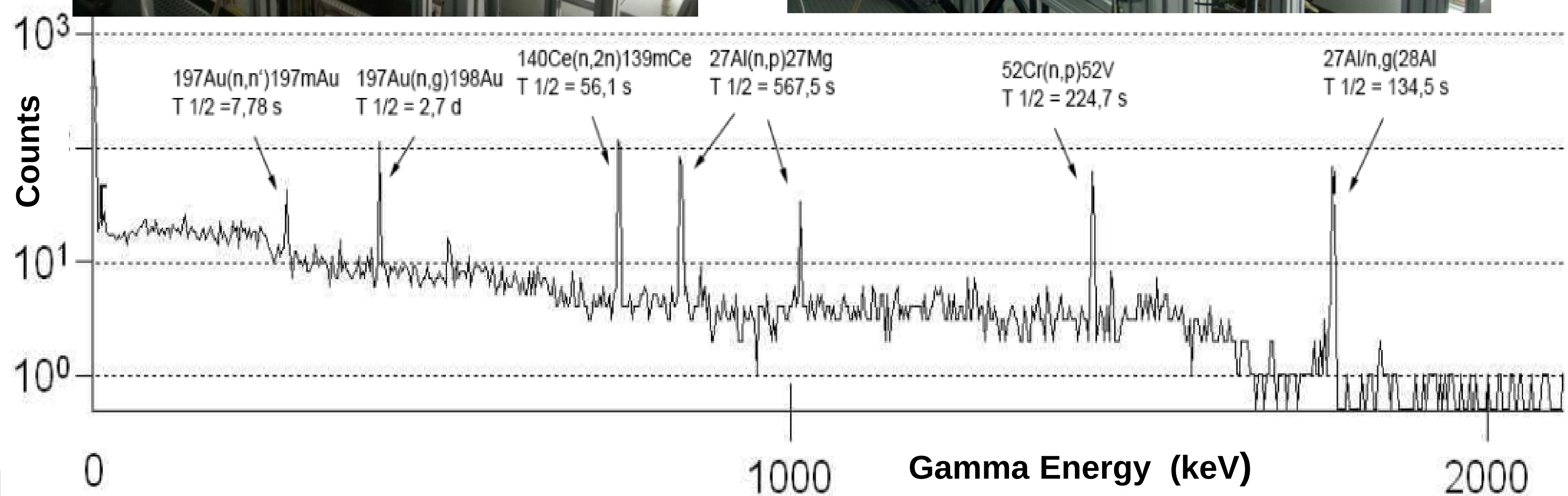
TBM Neutron Activation System

Rabbit transport tube

(M.S. thesis Tom Rücker)





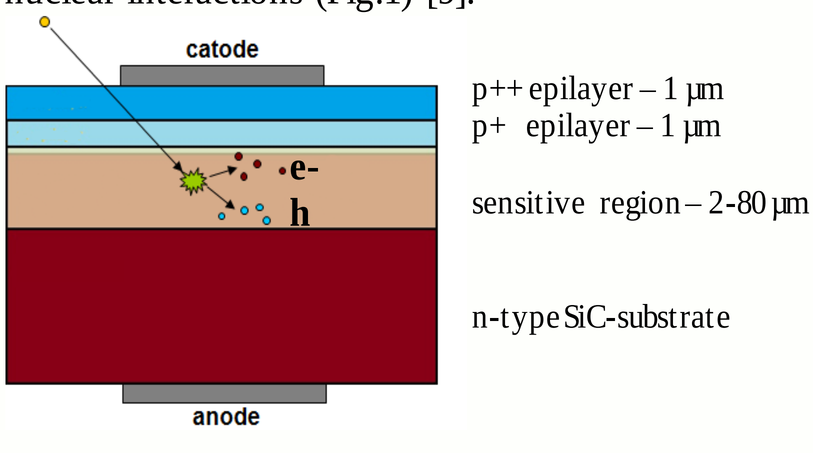


Silicon carbide detector

I_SMART (KIC-InnoEnergy); PhD thesis work Dora Szalkai

- 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
- I_SMART aims at developing a complete detection system
- Tests in thermal (BR1) and 14 MeV (TUD-NG) neutron fields and intense bremstrahlungs fields (CEA) done
- Tests at high temperature foreseen for early 2014
- Tritium production rate measurement possible utilizing Li containing deposits

nuclear interactions (Fig.1) [9].



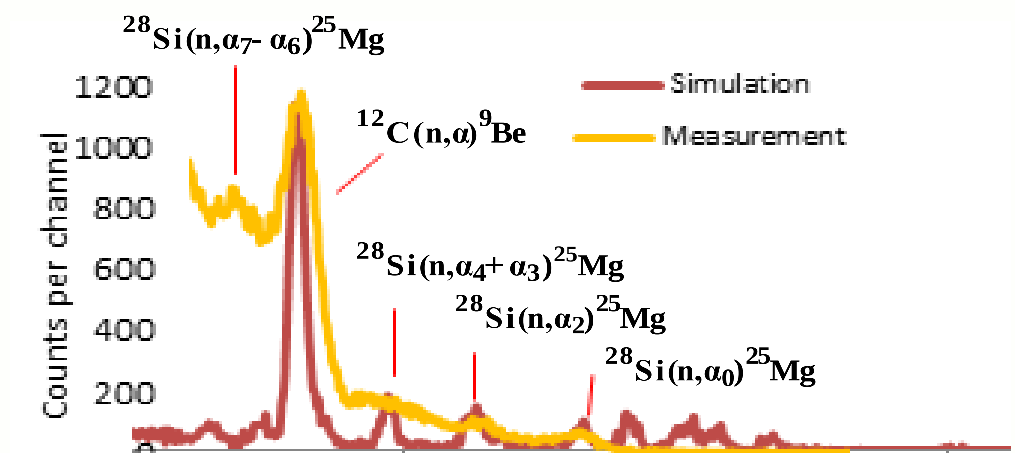
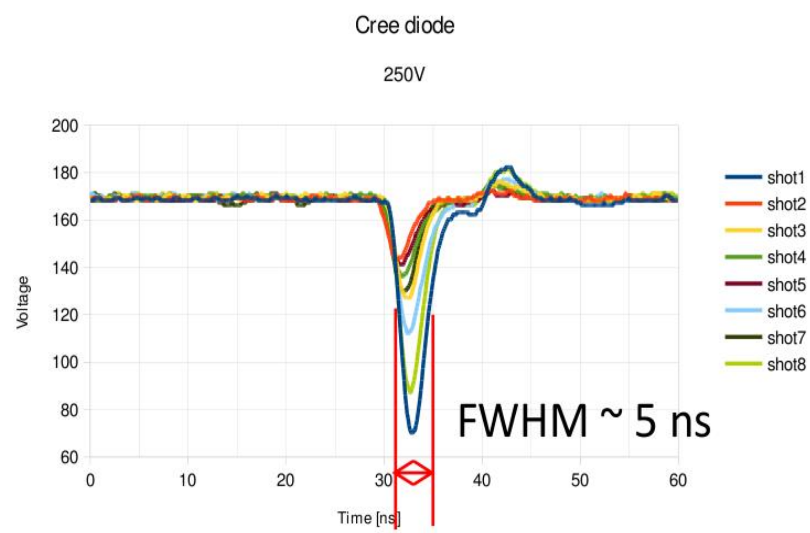


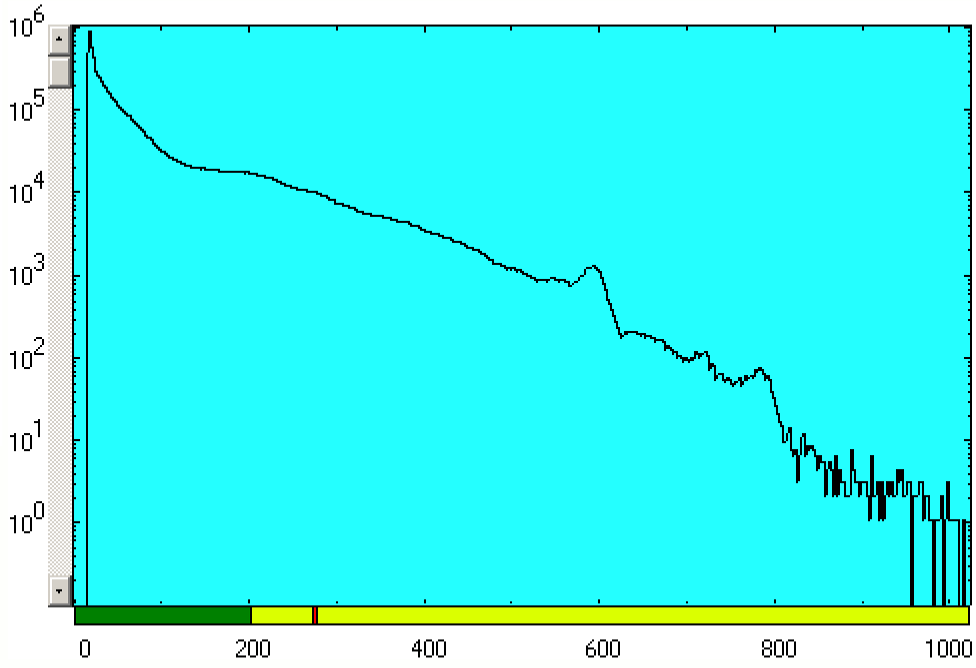
Fig.1. Diode construction and the operation scheme

Silicon carbide detector
I_SMART (KIC-InnoEnergy)

Collaboration between CEA, KIT, SCK*CEN, AMU, Univ. of Oslo, KTH, AGH and funded by KIC InnoEnergy with the aim to develop a detector system
Preparation of diodes with novel structures and testing started in 2012

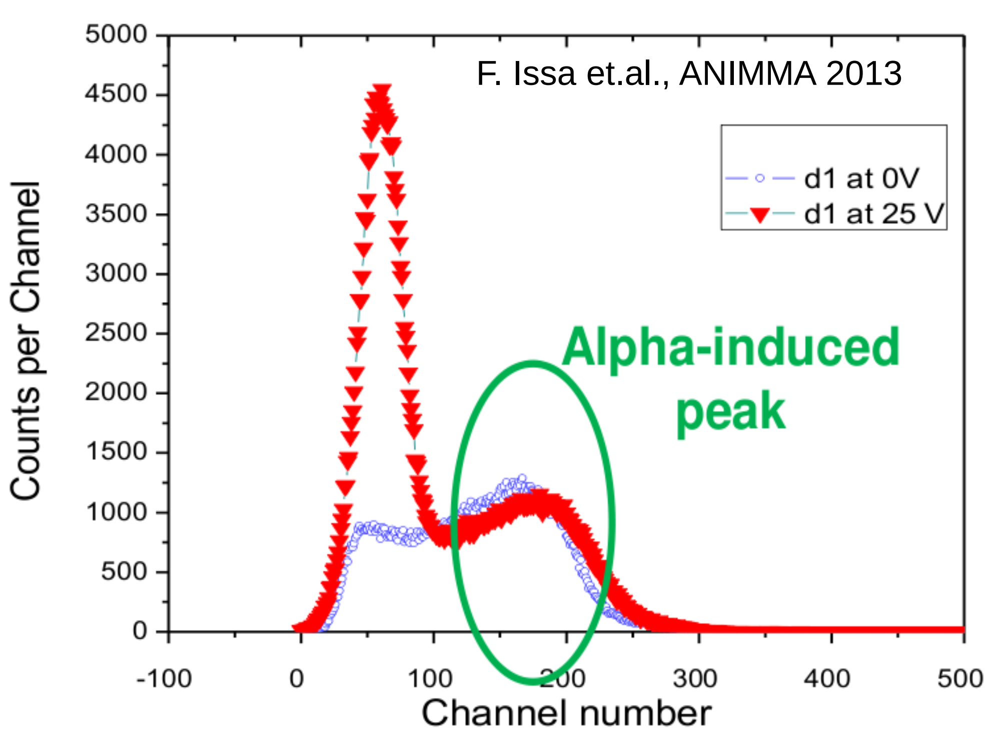
KIT focuses on application to TBM

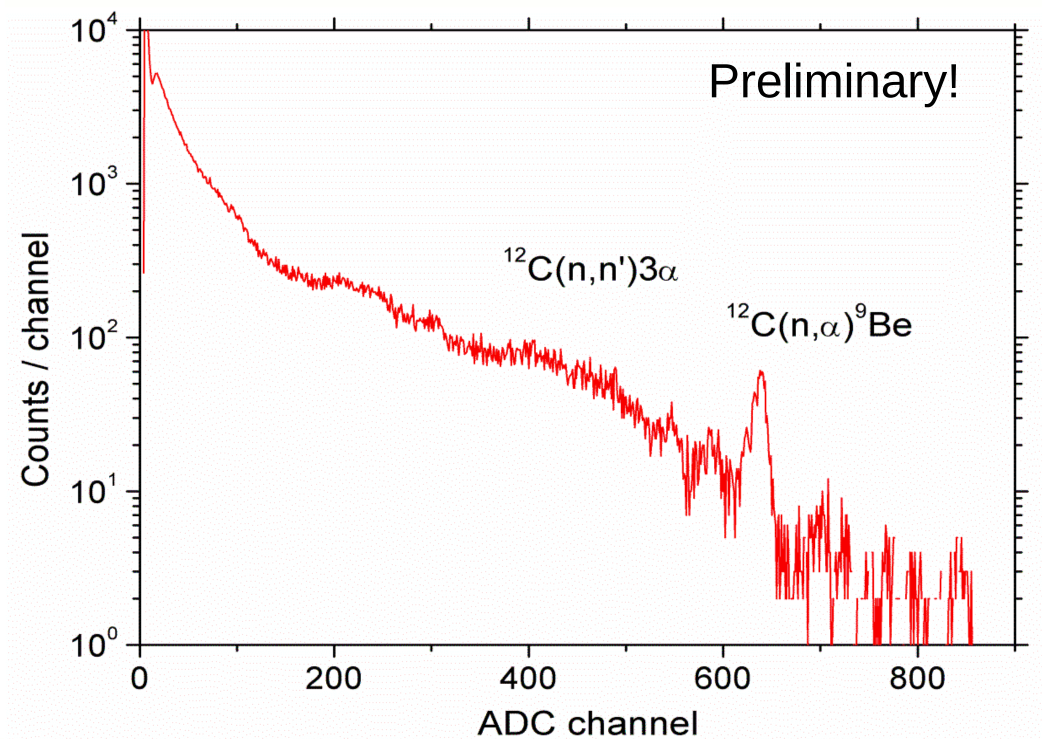




Typical signal from a commercial Schottky diode irradiated with 14 MeV neutrons and corresponding pulse height spectrum

Silicon carbide detector
I_SMART (KIC-InnoEnergy)





With boron implantation in thermal neutron field (BR1)

In DT neutron field (TUD-NG)

Summary

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

- Radiation transport codes 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

Thank you very much for your attention!

Disclaimer for parts of the work presented herein:
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