Italian National Agency for New Technologies, Energy and Sustainable Economic Development

This work has 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.

Real-Time Measurement of Relevant Nuclear and Radiation Quantities in Fusion Experiments

Technical Meeting on Synergies between Nuclear Fusion Technology Developments and Advanced Nuclear Fission Technologies

IAEA, Vienna, 6-10 June 2022

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Outline

Premise

- Rad. Det. working conditions and measurements in Fission and Fusion Environments

Part 1: Neutron Measurements

- TBM Mock-up Diamond detector and exp. setup
- Measurement of T production at JET

Part 2: Dose Rate Measurements

- Shutdown Dose Rate Measurements at JET
- Benchmark of SDR prediction tools

Concluding Remarks

Fission and Fusion Environments

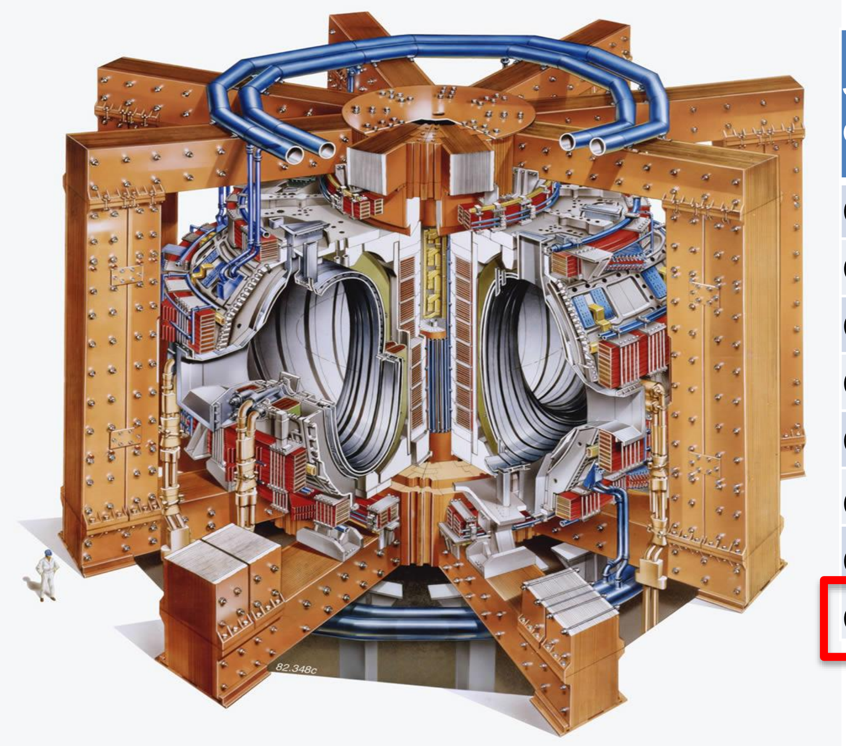
Harsh working conditions for rad. detectors:

- Intense neutron and gamma radiation fields;
- High temperature;
- Intense magnetic and electromagnetic fields in tokamak.

Measurements of relevance in both fields:

- Neutron flux, energy spectra and derived quantities;
- Dose rate due to the neutron activation.

Last Deuterium-Tritium campaign at JET



JET campaign	start date	end date	Total N yield	Max N yield per pulse
C36a (DD)	04/01/2016	27/06/2016	7.63E+18	5.01E+16
C36b (DD)	10/10/2016	15/11/2016	1.13E+19	1.26E+17
C38a (DD)	03/06/2019	20/12/2020	3.69E+19	1.47E+17
C38b (DD)	17/02/2020	23/03/2020	1.49E+19	2.14E+17
C38c (DD)	06/07/2020	26/09/2020	1.66E+19	1.92E+17
C39T (TT)	07/12/2020	18/12/2020	6.08E+15	1.60E+15
C40 (TT)	04/01/2021	31/07/ 2021	8.52E+18	1.46E+17
C41 (DT)	08/08/2021	21/12/ 2021	8.48E+20	2.09E+19

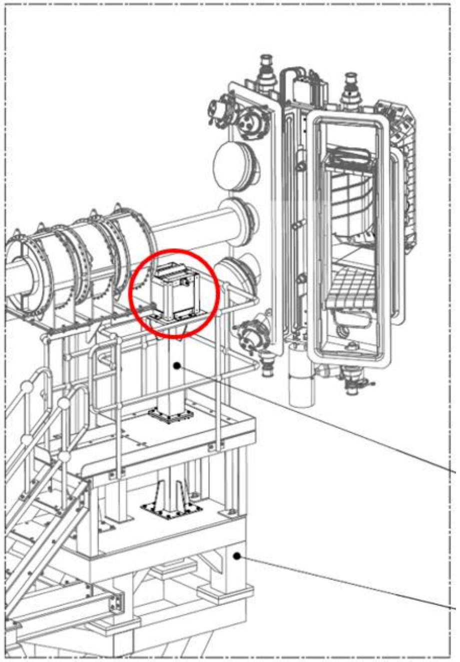
Successful JET DT campaign in 2021

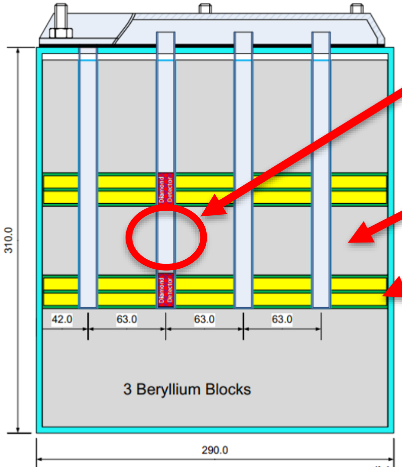
- Record sustained fusion power of 10.3 MW averaged over 5 seconds doubling the previous record (JET, 1997)
- 8.5 x 10^{20} DT neutrons
- Max daily yield rate 1.04 10^{20} DT on 21 December

Part 1
Neutron Measurements

TBM Mock-up at JET

- **Tritium breeding blanket** is a key component in a fusion reactor (**DEMO**);
- **Test Blanket Modules** (TBMs) in **ITER** will provide the first experimental data to validate the predictions on tritium production and recovery;
- **Mock-up of HCPB TBM** (Helium Cooled Pebble Bed) featuring all the relevant nuclear details to reproduce as close as possible the neutron energy spectra occurring in the TBM in ITER.





Detector (online measurement of T production rate)

Filled with Be

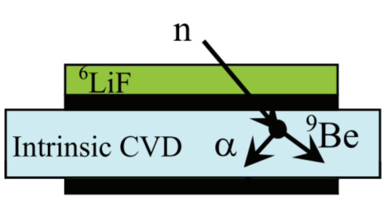
Li_2CO_3 powder simulating the Li_4SiO_4 breeder ceramics of the TBM

300 D x 290 L x 310 H mm^3

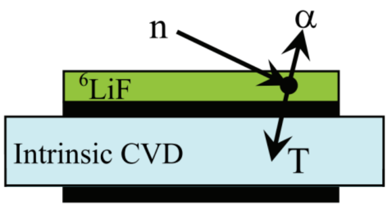
TBM mock-up installed at JET to take advantage of the high neutron emission expected during DTE2 campaign

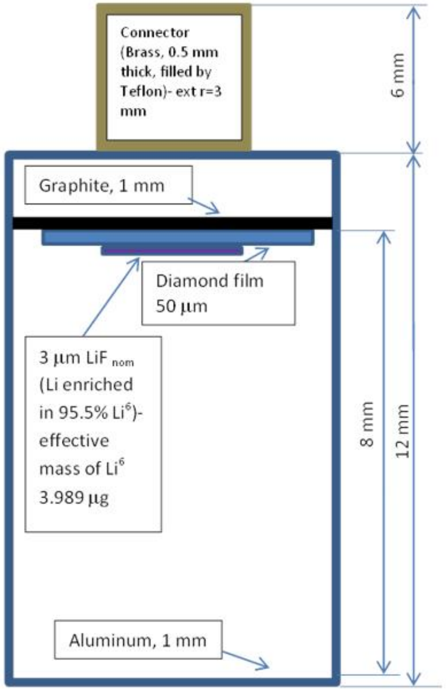
TBM Mock-up Diamond Detector (TBMD)

Fast neutrons



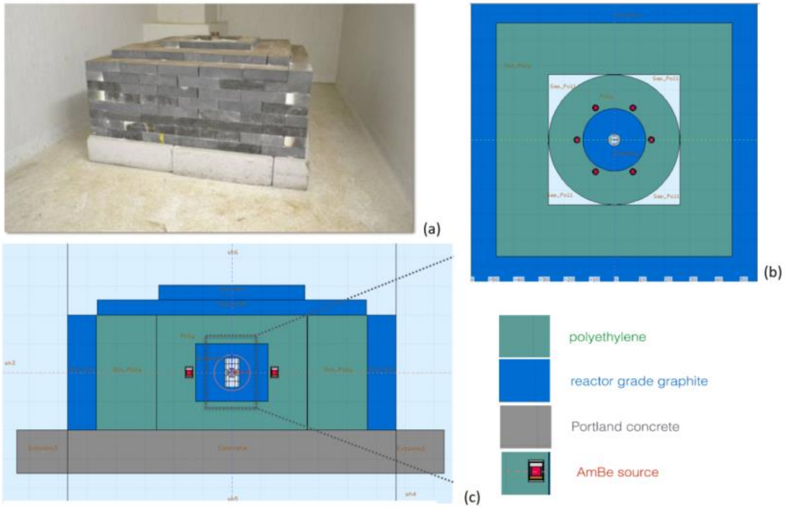
Thermal neutrons





- Single Crystal Diamond (SCD)
- 50 µm thick, surface of 4.3x4.3 mm^2
- 3 µm LiF converting layer (95 % enriched ^{6}Li) on top of the upper electrode
- 14-MeV neutrons detected through **^{12}C(n,α)^{9}Be**, $E_n > 6.1$ MeV
- Thermal neutrons detected through **^{6}Li(n,α)T** (T@2.73 MeV, α@2.07MeV)
- Calibrated to assess TBM performance (T production inside TBM mock-up)

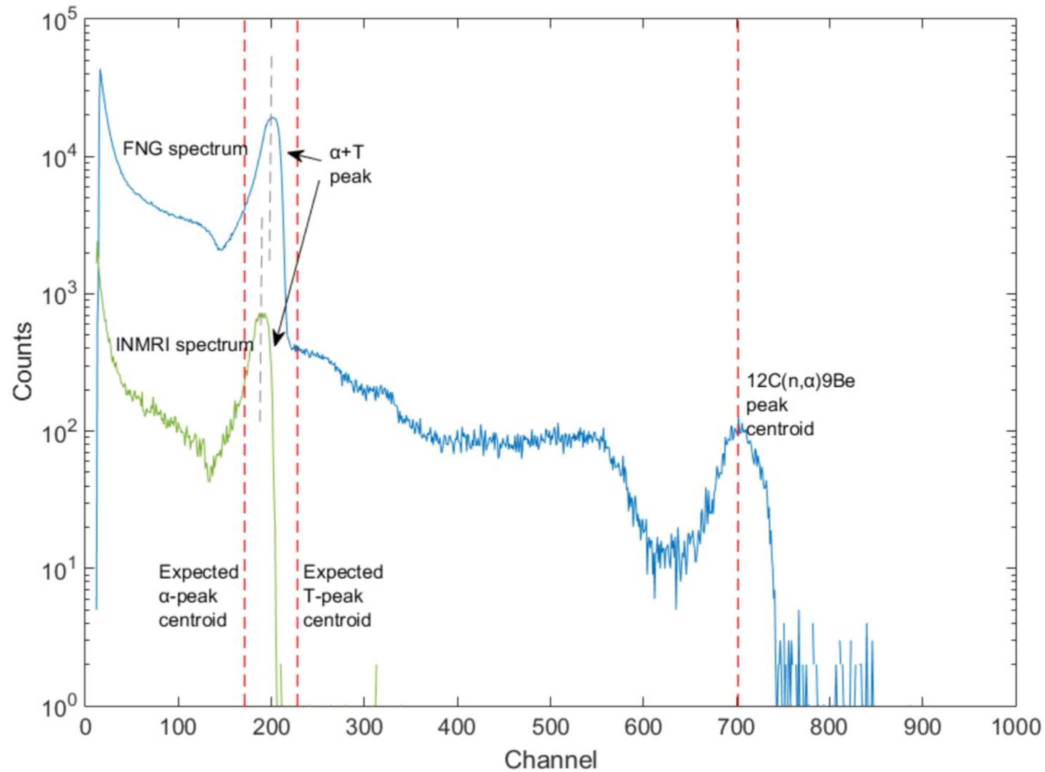
TBMD: Calibration at ENEA-INMRI (T production)



ENEA-INMRI thermal neutron flux density standard: picture (a), horizontal (b) and vertical (c) cross sections.

Table 4.2 Characteristic limits of the measurement

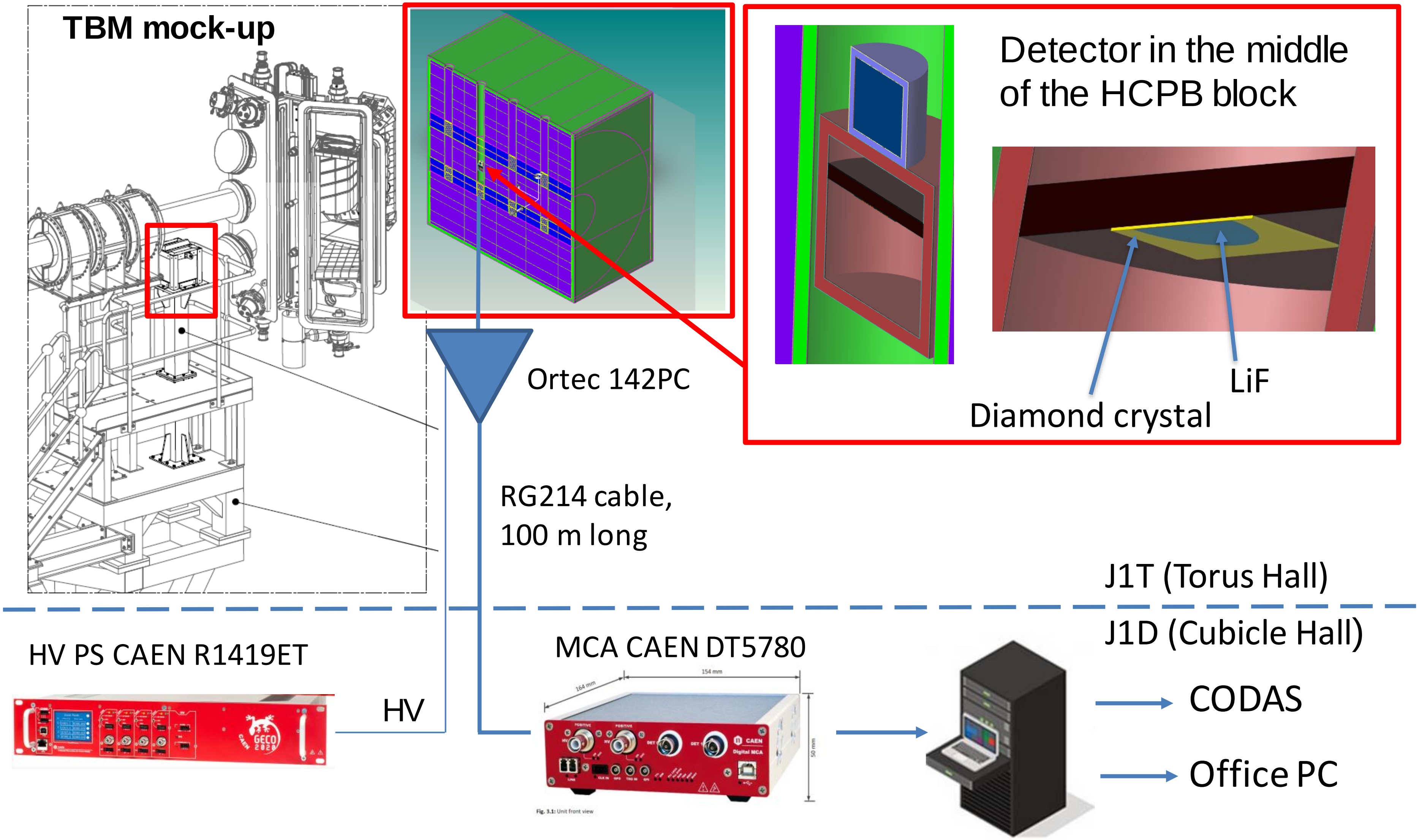
Quantity	Symbol	Value
Primary measurement result (i.e., ROI net counts)	y	17670
Standard Uncertainty associated with y	u(y)	188
Decision threshold	y^*	219
Detection limit	$y^\#$	440
Lower limit of the confidence level (95%)	$y^<$	17302
Upper limit of the confidence level (95%)	$y^>$	18038
Best estimate of the measurand	$\hat{y}$	17670
Standard uncertainty associated with $\hat{y}$	$u(\hat{y})$	188



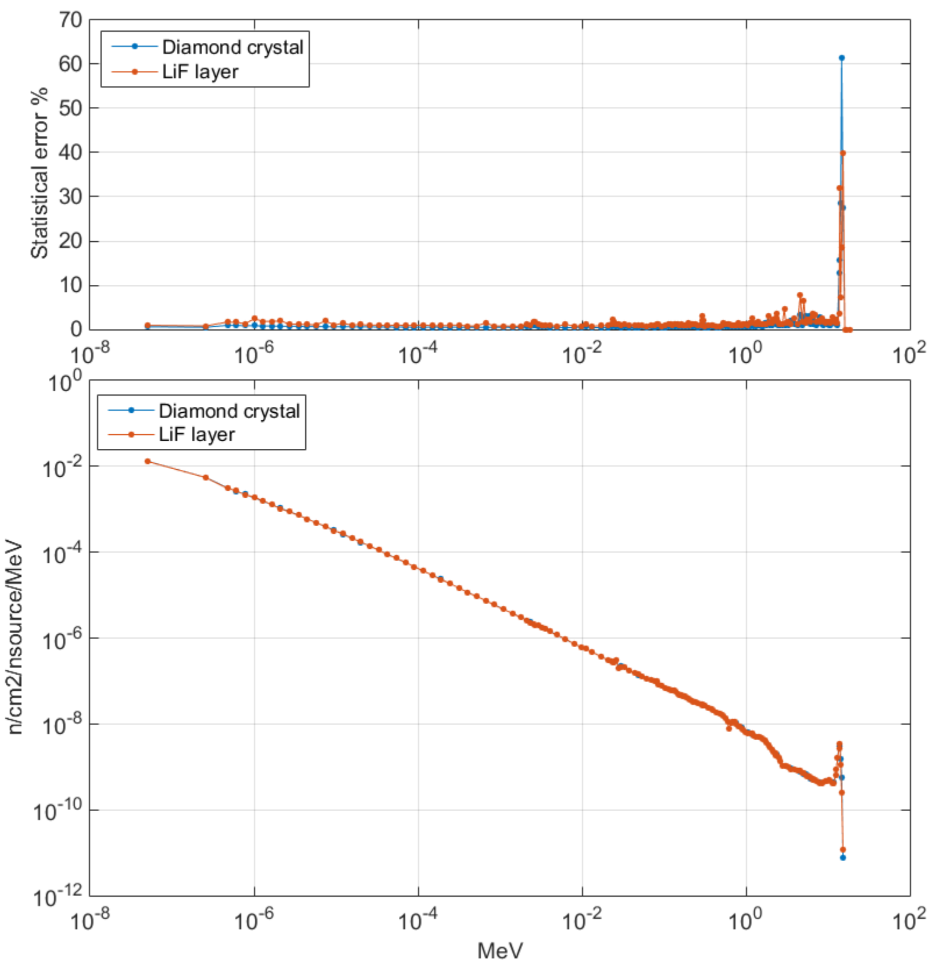
$$R_{Li6} = <\sigma\varphi> = \frac{cps\ M_{Li6}}{N_{Av}\ m_{Li6}\ \varepsilon\ k} = K_{cal}\ cps$$

Kcal=(2.504±0.039)x10^{-18}, i.e., 1 count per second (cps) corresponds to Kcal reactions ^{6}Li(n,T)α per atom of Li^6 in the converting layer

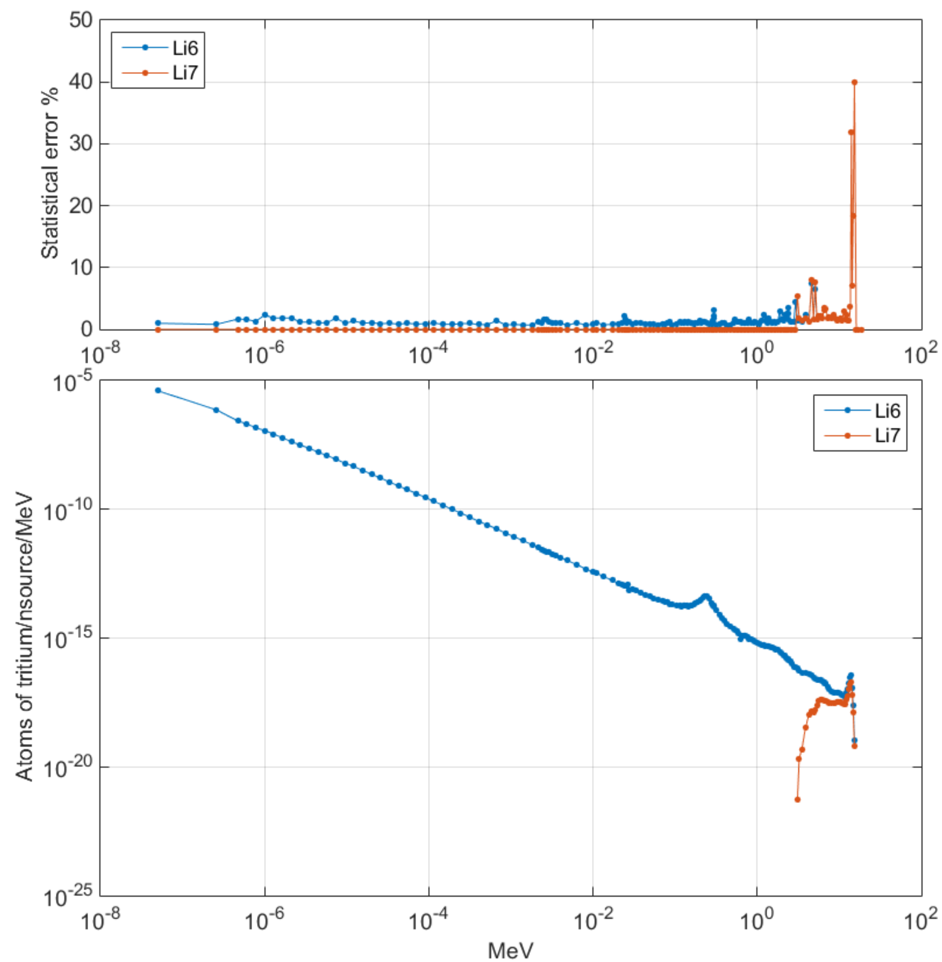
TBMD: Setup of Experiment



TBMD: MCNP Calculations

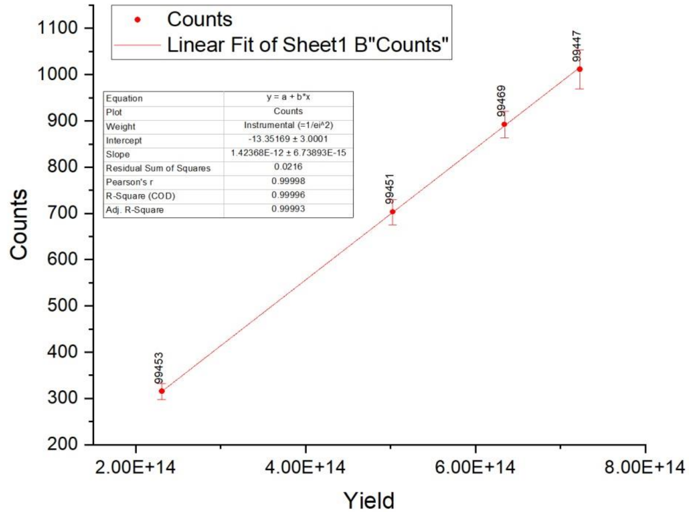


Neutron Flux



T production

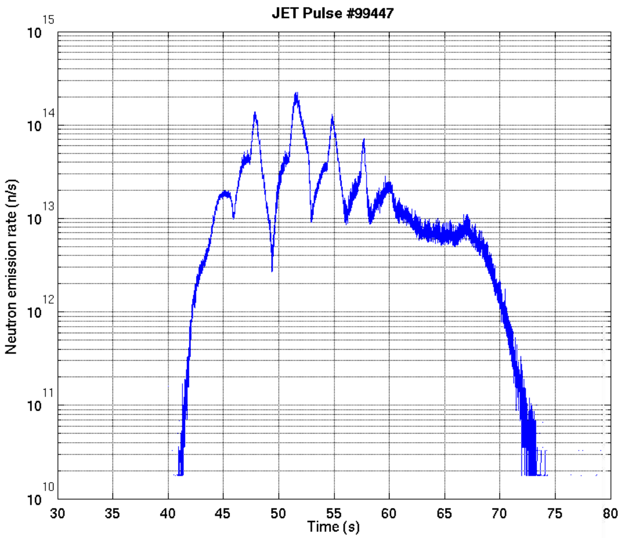
TBMD: Calculation/Measurement (C/E)

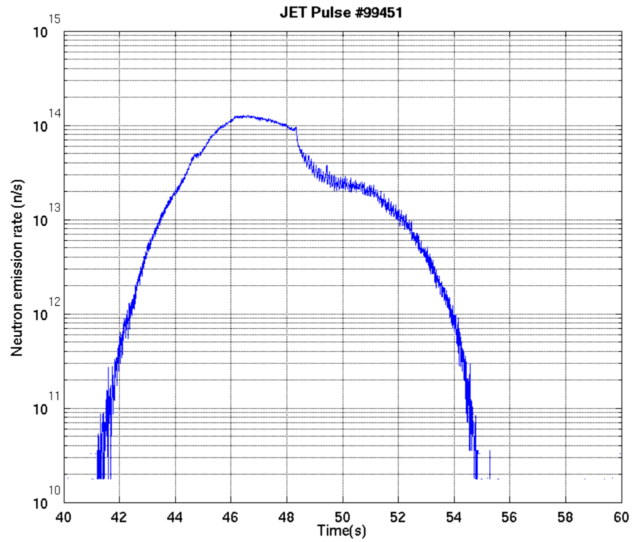


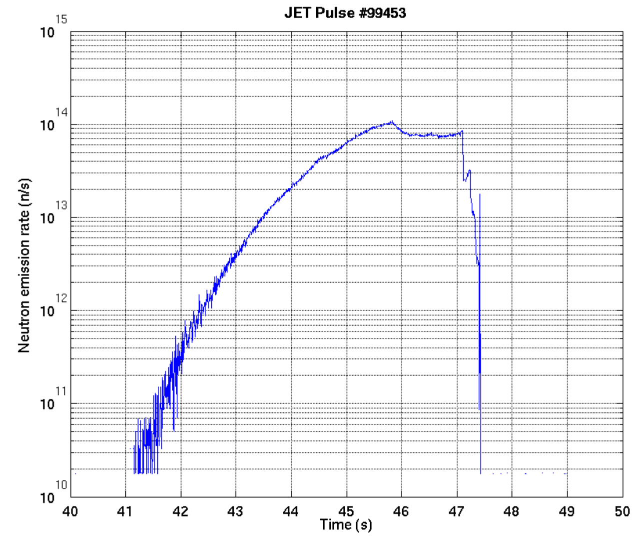
- As far as neutron yield rate <1E15 n/s, a **constant detection efficiency is observed;**
- **Tritium production (MCNP output):** $(1.083\pm0.005)\times10^{-12}$ T/n_{source} due to ^{6}Li; $(4.81\pm0.23)\times10^{-17}$ T/n_{source} due to ^{7}Li

		MCNP calculation		TBMD measurements		
Pulse number	**Neutron yield**	**T/neutron source in Li6**	**T/neutron source in Li7**	**T/neutron source in Li6**	**C/E for Li6**	**Note**
99447	7.23E+14	**1.083E-12**	4.81E-17	**1.40E-12**	**0.77 (±0.03)**	
99451	5.03E+14	**1.083E-12**	4.81E-17	**1.40E-12**	**0.77 (±0.03)**	
99453	2.31E+14	**1.083E-12**	4.81E-17	**1.36E-12**	**0.79 (±0.05)**	below detection limit

TBMD: Calculation/Measurement (C/E)







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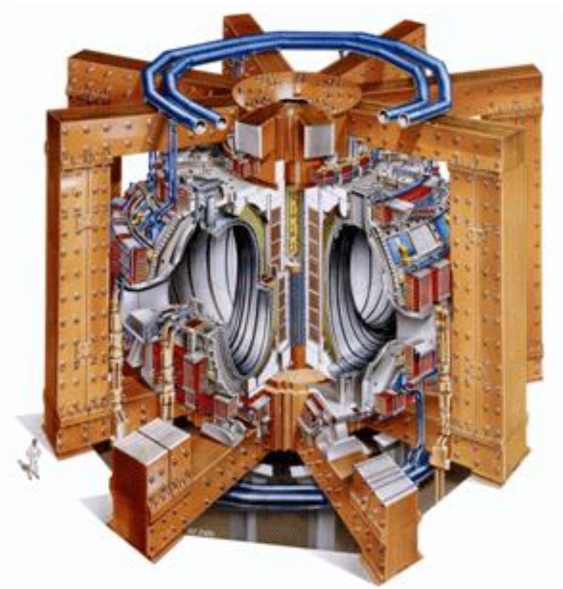
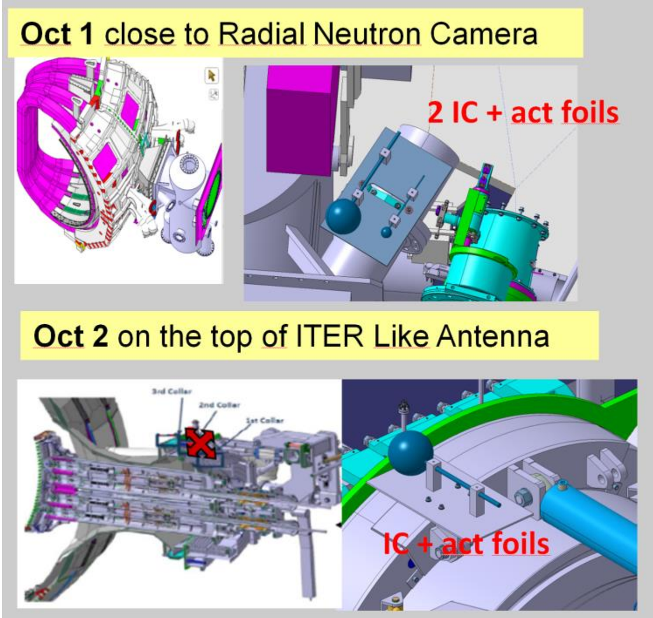
Part 2
Dose Rate Measurements

Shutdown Dose Rate (SDR) Measurements at JET

SDR **due to neutron activation** is of primary importance for **planning tokamak operation in respect of dose limits to external radiation exposure**.

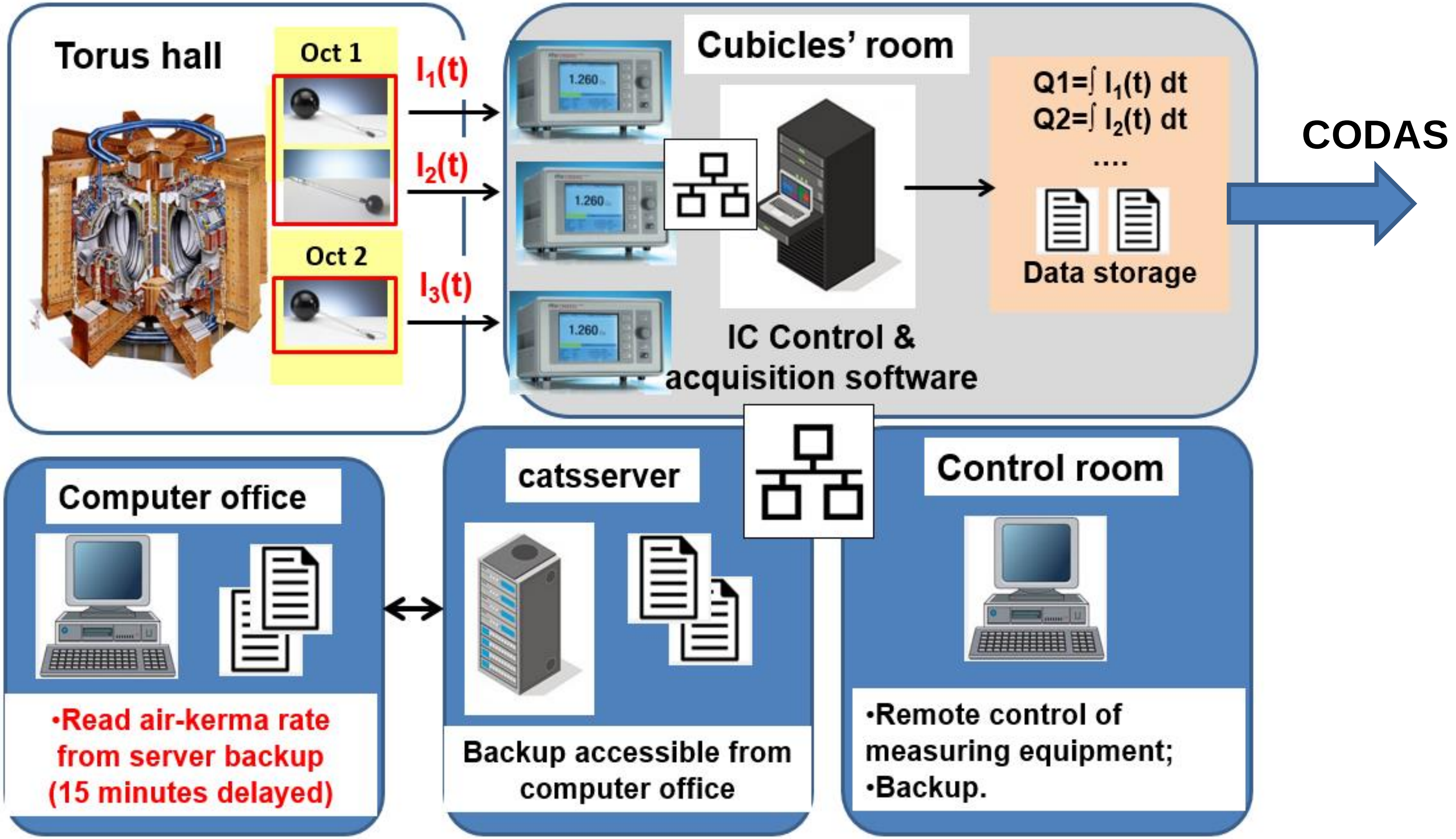
Considering its ITER-relevance, **SDR experiment at JET** is a unique opportunity **to validate the numerical tools for ITER nuclear analysis.**





3 active gamma dosimeters based on spherical air-vented ionization chambers (ICs) have been installed in ex-vessel positions close to the horizontal ports of the tokamak in **Octants 1 and 2.**

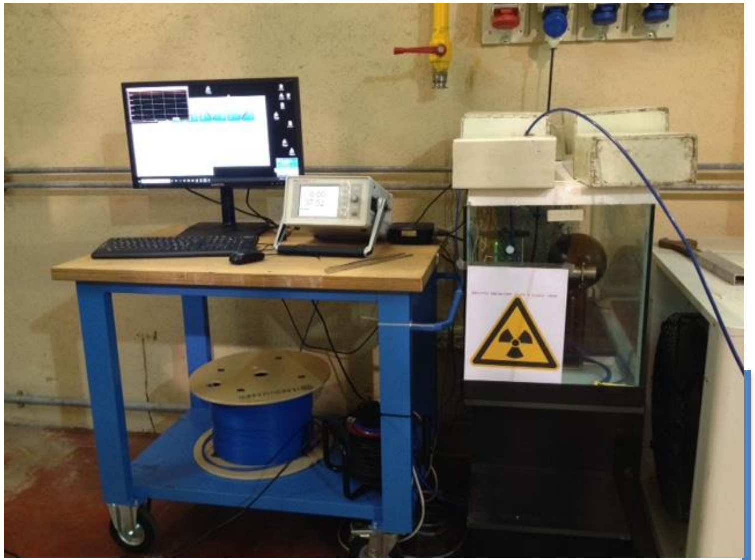
SDR at JET: Layout of Detection System



SDR at JET: Influence quantitites

Precise and widely recognized code of practices [1,2] apply in the **evaluation of influence quantities affecting dosimetric measurements** and in the mitigation of their effects to a negligible level.

- **Air temperature and pressure (k_{TP})**
- **Humidity (k_h)**
- **Ion recombination (k_{sat})**
- **Stability (k_{stab})**
- **Linearity (k_{lin})**
- **Leakage current (k_{leak})**
- **Direction of radiation field (k_{rot})**
- **O2 content in air**



N2 tank

[1] International Atomic Energy Agency (IAEA), Absorbed Dose Determination in External Beam Radiotherapy: An International Code of Practice for Dosimetry based on Standards of Absorbed Dose to Water, Technical Reports Series No. 398, IAEA, Vienna (2000).

[2] American Association of Physicists in Medicine (AAPM), AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon and electron beams. Med. Phys. 26 (9), September 1999, 1847-1870.

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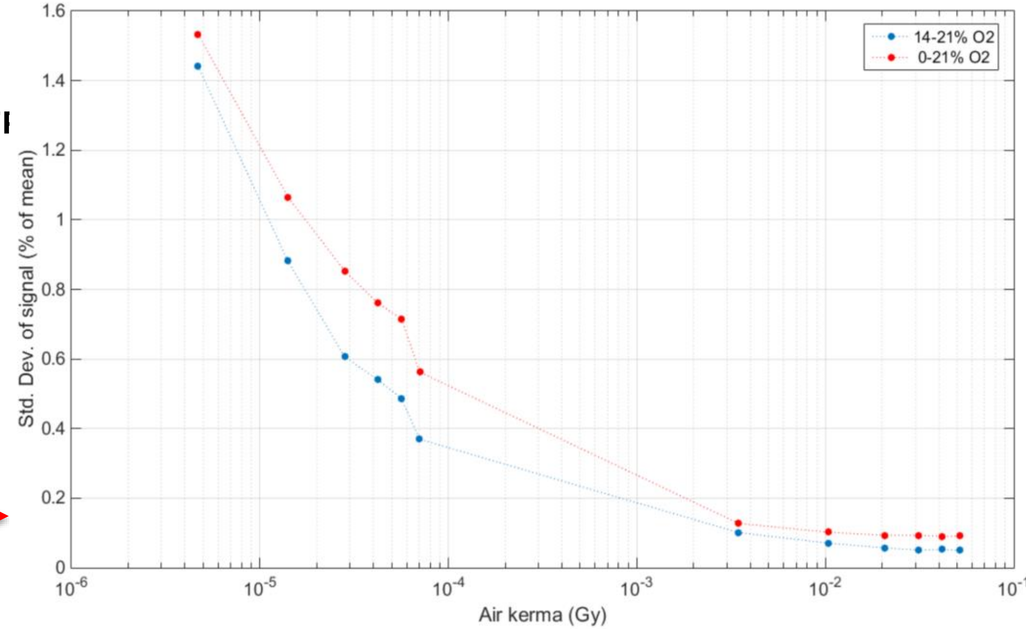
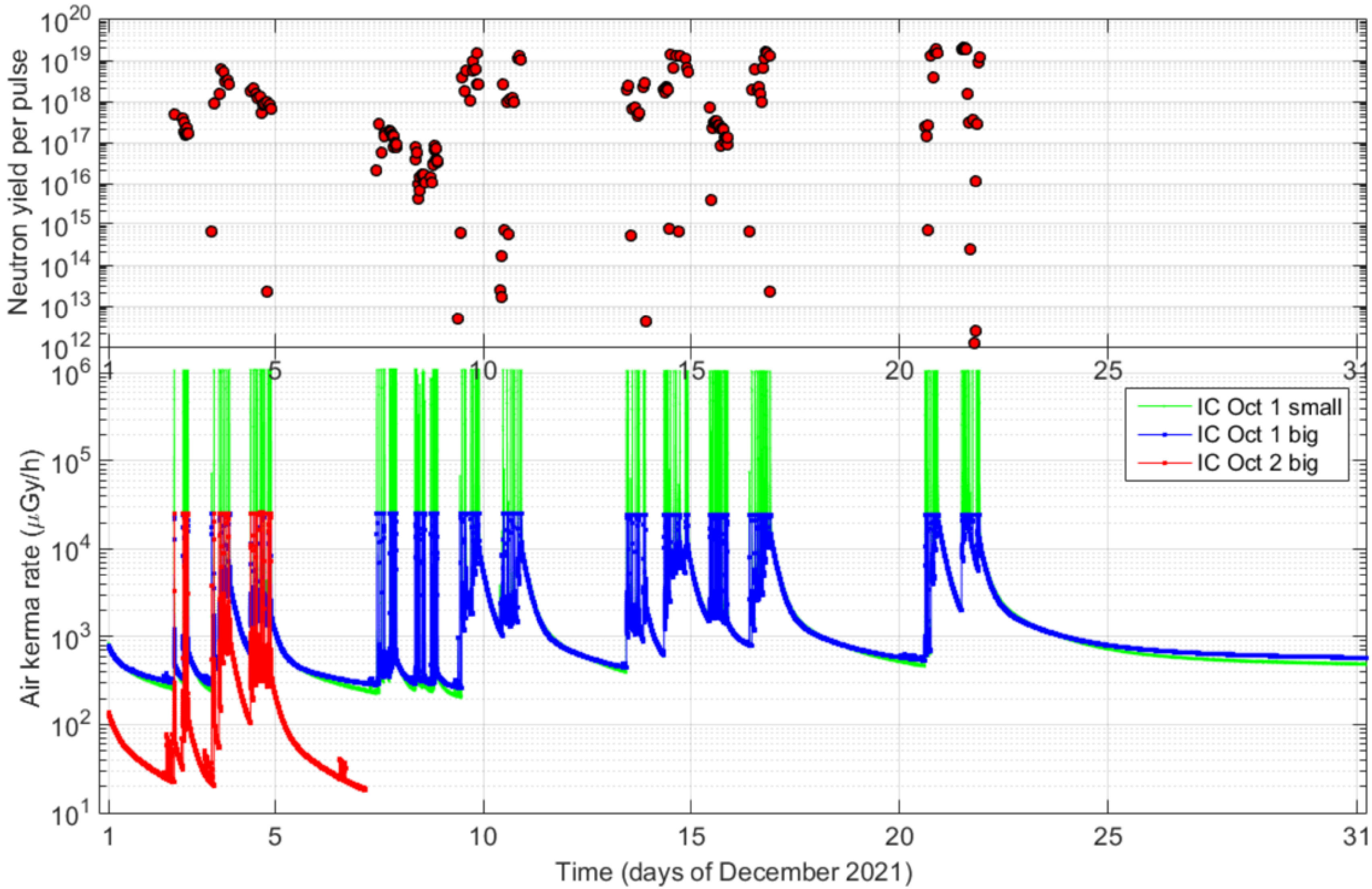
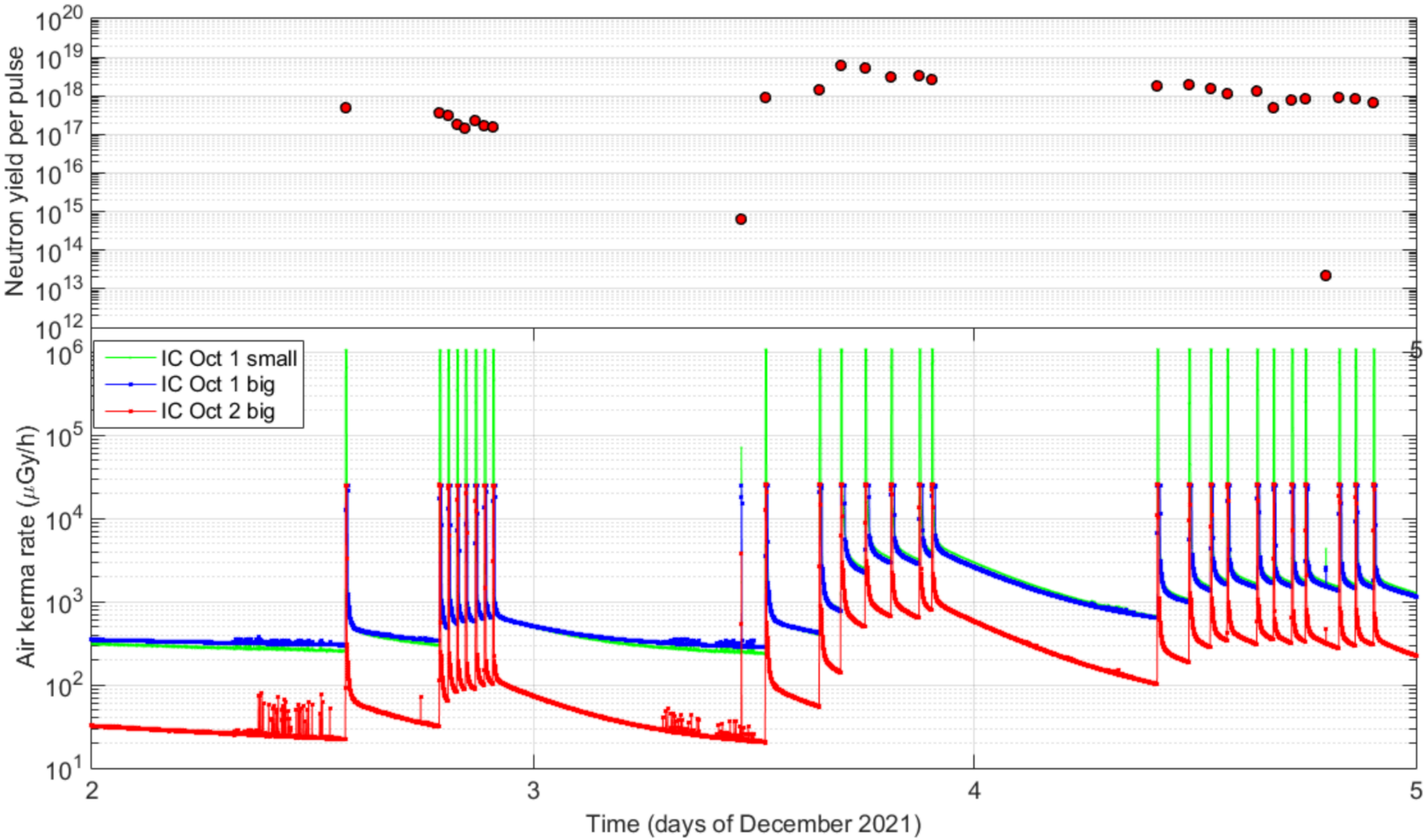


The influence of O2% is < 1.6%
(to be accounted in the uncertainty budget)

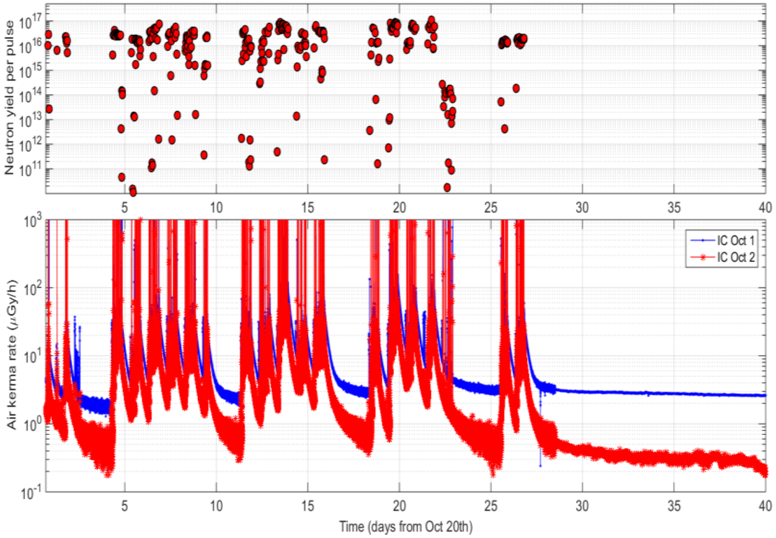
SDR at JET: December 2021



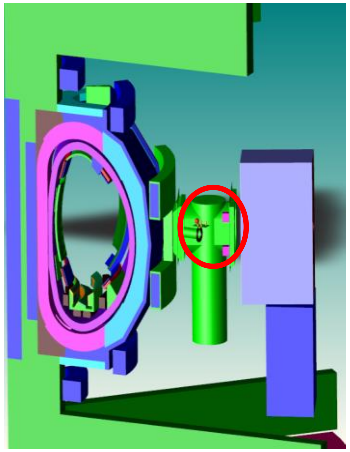
SDR at JET: 2-5 December 2021



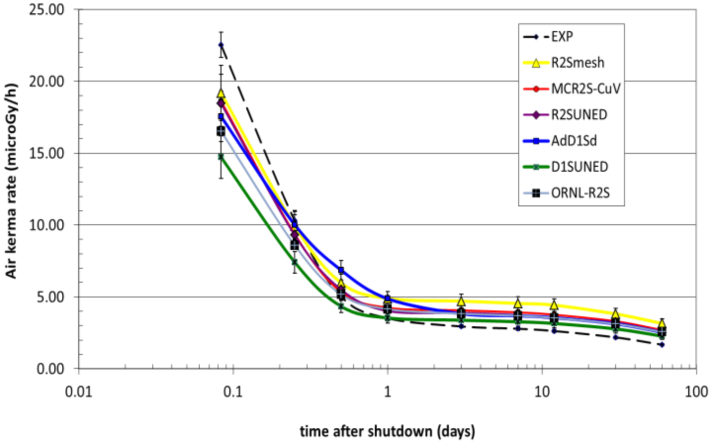
SDR at JET: Benchmark results SDR 2016



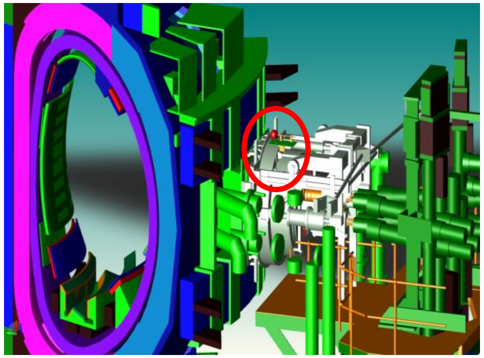
Octant 1



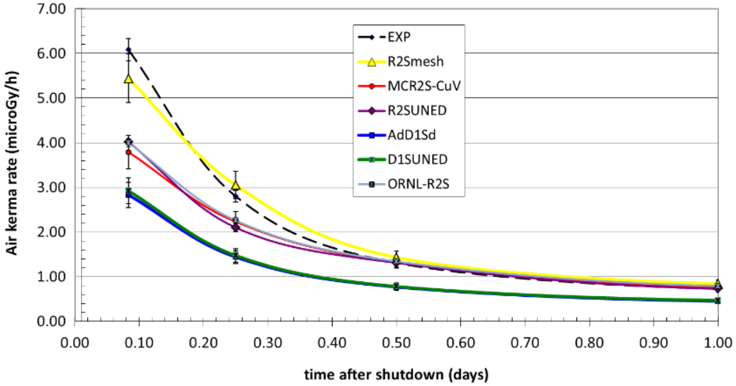
SDR vs. time after shutdown



Octant 2



SDR vs. time after shutdown



- Agreement within **±20%** at 2 hrs;
- Underestimation up to **30%** for D1S tools;
- R2S tools: incorrect treatment of $Cu^{63}(n,\gamma)Cu^{64}$ reaction.

R. Villari, TOFE 2020

Concluding Remarks

Neutron-related Measurements

- Diamond detector installed at JET inside TBM mock-up to **measure tritium production**;
- **C/E=0.77** above the detection limit determined during calibration at ENEA-INMRI;
- More robust configuration to be thought in the future for high temperature, i.e. mineral insulating cables under testing at JET.

Dose Rate Measurements

- Detection system installed in Torus Hall, controlled from remote through dedicated pieces of software;
- Large set of data provided for code benchmarking of SDR tools employed for ITER since 2016;
- DTE2 measurements: range OCT 1) ~100-10 mGy/h, OCT 2) ~4-1mGy/h, **relevant for both ITER port interspaces and port cells. Analysis in progress.**

Thank you for your attention!

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Spare Slides

Harsh Working Conditions in Fiss. Fus. Env.

- Detectors for measuring nuclear performance and radiation quantities of relevance in **fission and fusion environments** have in common the requirement of **withstanding harsh working conditions** dictated by **intense neutron and gamma radiation fields**.
- **High temperature** constitutes a further harsh element in some locations of the machine where it is necessary to perform some on-line measurements.
- Fusion environments are usually characterized also by **intense magnetic fields** for plasma confinement and **intense electromagnetic fields** from heating systems delivering power to the plasma, which can act as relevant source of noise and interference in the detection process.

Measurements of Relevance in Fiss. Fus. Env.

- Online measurement of **neutron flux, energy spectra and derived quantities** are of primary importance in fission and fusion reactors.
- The purpose ranges from **power monitoring** and **detection of abnormal functioning** to **diagnostics** to improve the understanding of reactor physics and evaluate performance of some components in demonstration and prototype reactors.
- From **radioprotection standpoint**, the measurement of **dose rate due to the neutron activation** is of common interest in both fields. In fusion, the measurement of dose rate is also important for the **refinement of some computational tools for dose rate prediction**.

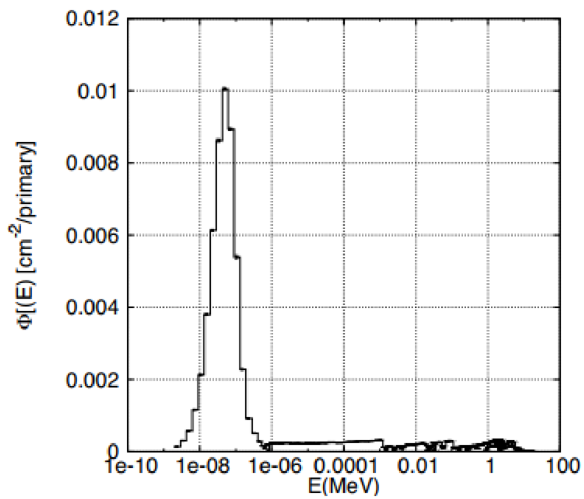
Thermal Standard Neutron field

Last measurement campaign: 03/2014 (multiple activation foil method):

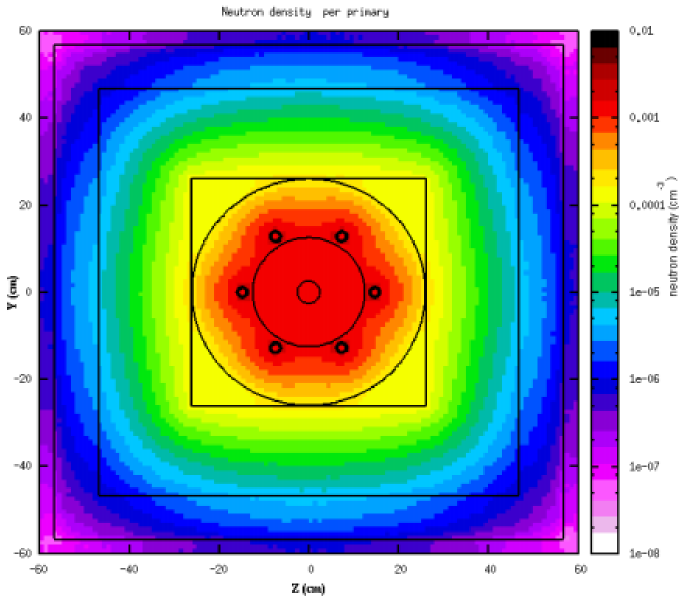
Thermal flux measured in the cavity [cm^-2 s^-1]:	Spatial uniformity over a volume 4 cm high and 2 cm in diameter:	Cadmium Ratio:
1.15E+4 +/-1%	+/-0.2%	8.0 +/-2%

MC predictions (by Fluka code) are well in agreement with measurements (within 7%).

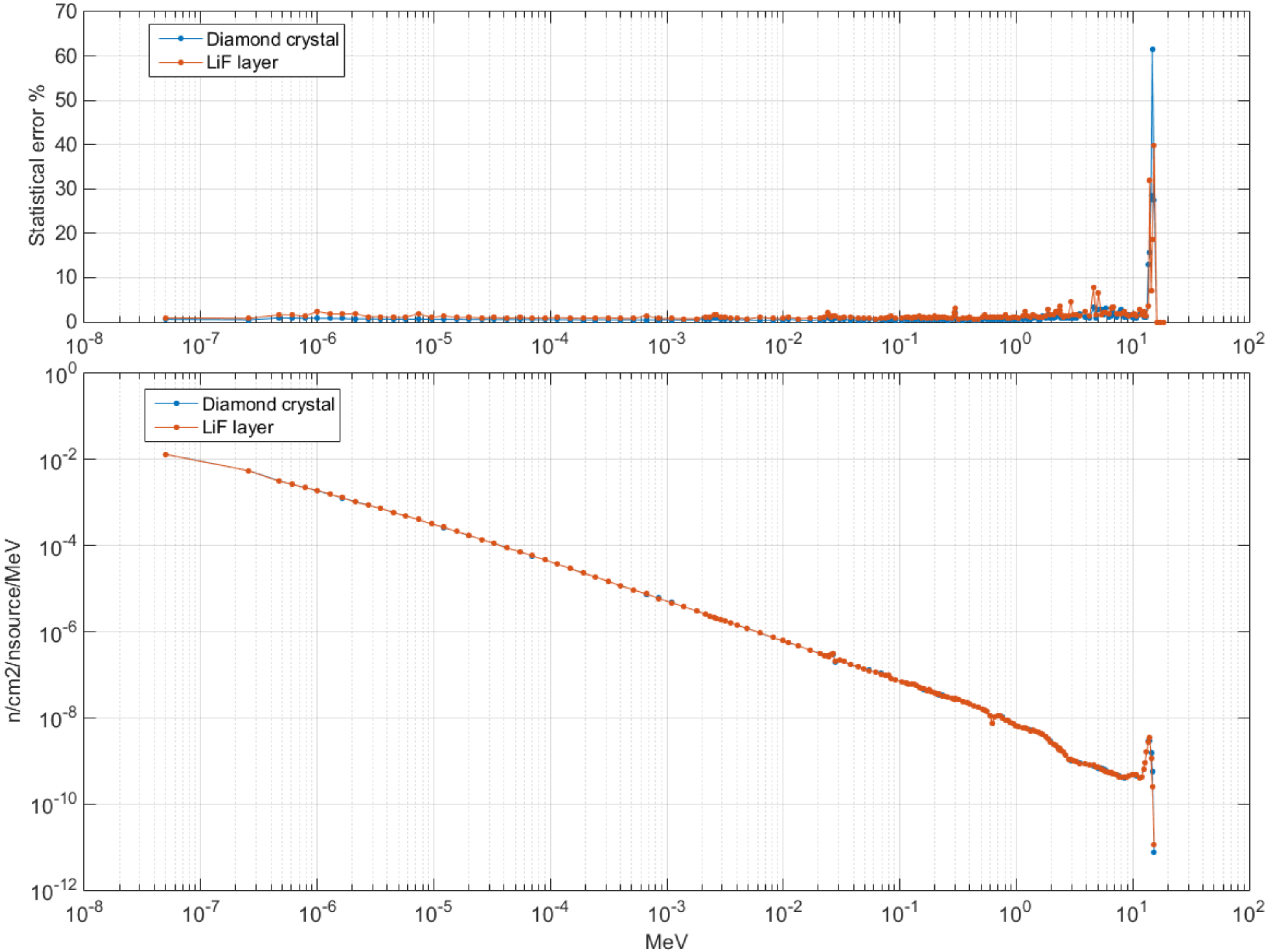
Neutron Energy spectrum in the cavity



Neutron density in the thermal standard



TBMD: MCNP Response Prediction



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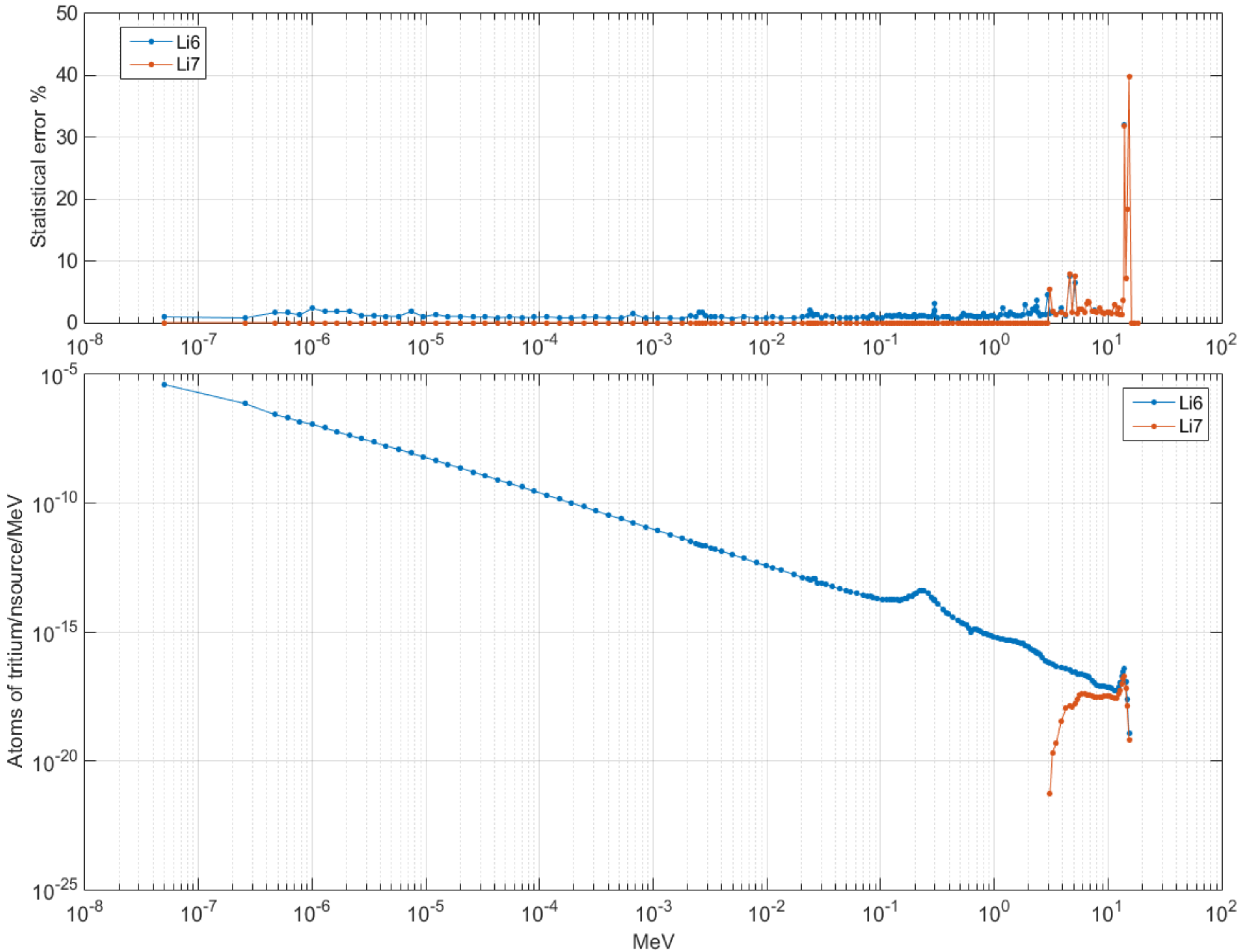
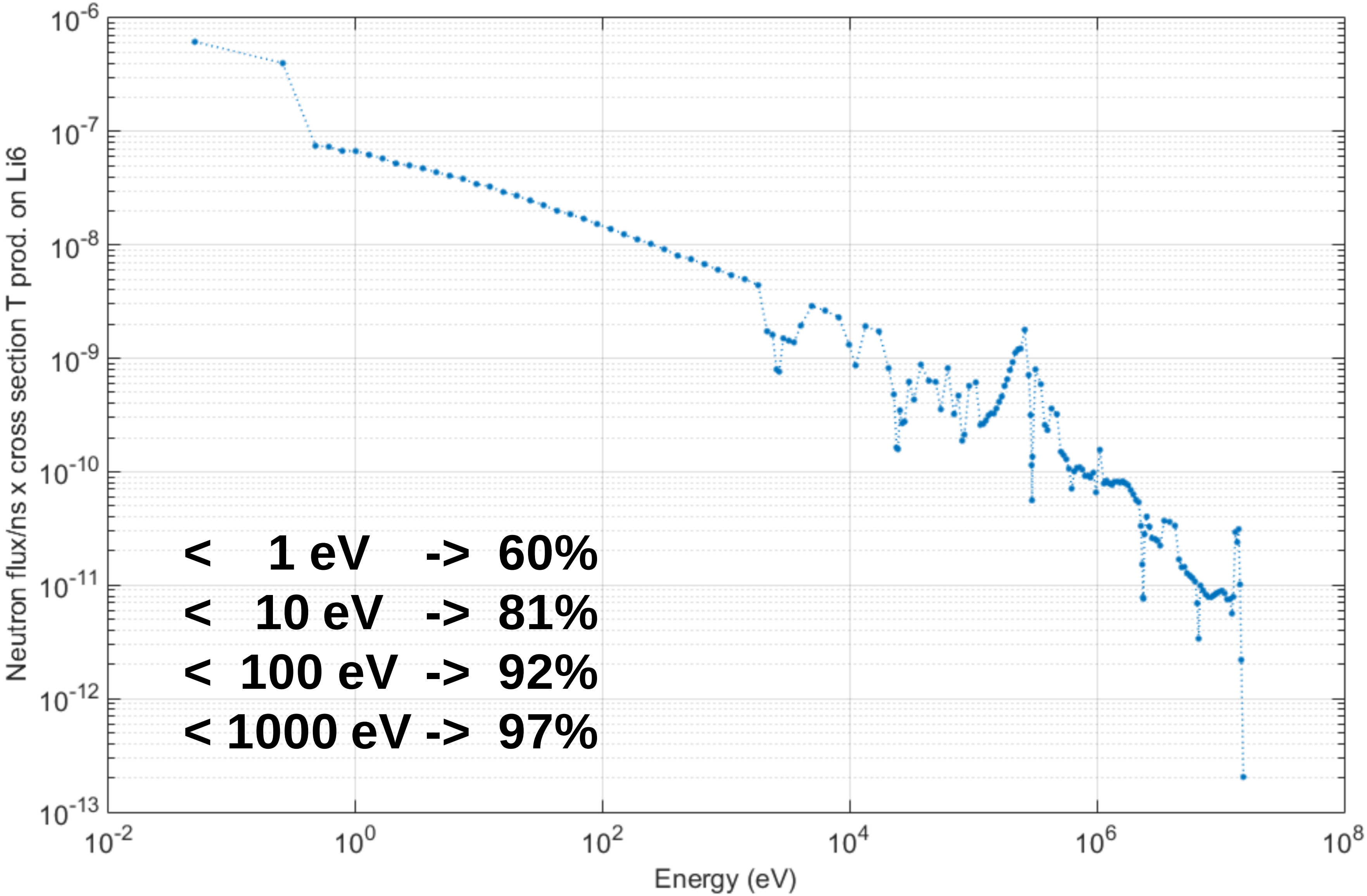
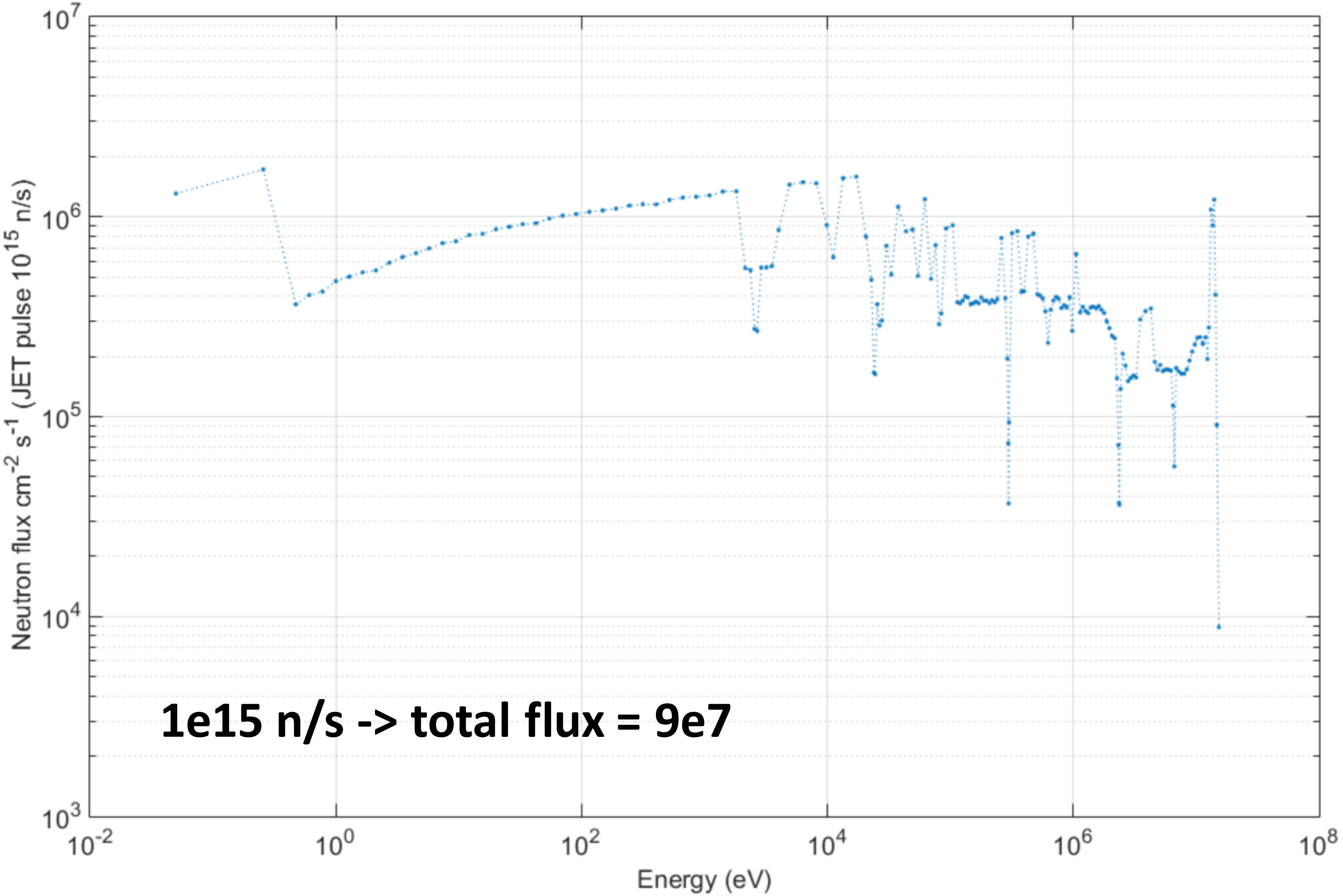


n flux/ns x T prod cross section



< 1 eV -> 60%
< 10 eV -> 81%
< 100 eV -> 92%
< 1000 eV -> 97%

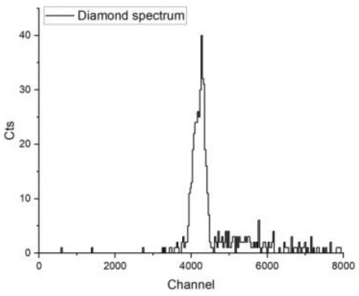
n flux in SCD for 1E15 n/s pulse

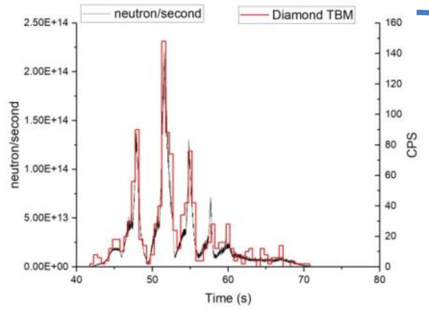


1e15 n/s -> total flux = 9e7

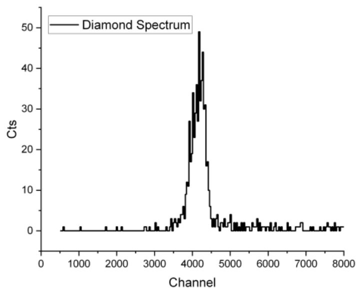
TBM mock-up diamond: Saturation at high cps

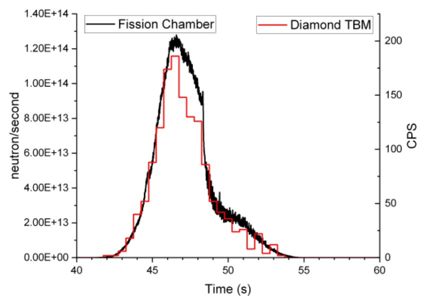
Pulse 99447



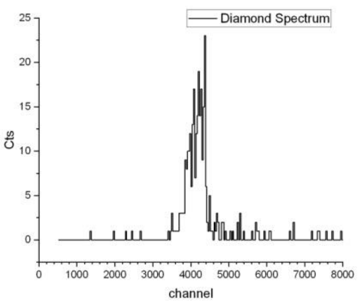


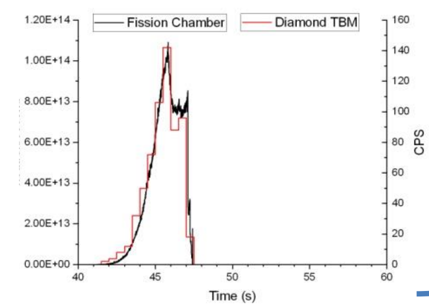
Pulse 99451





Pulse 99453



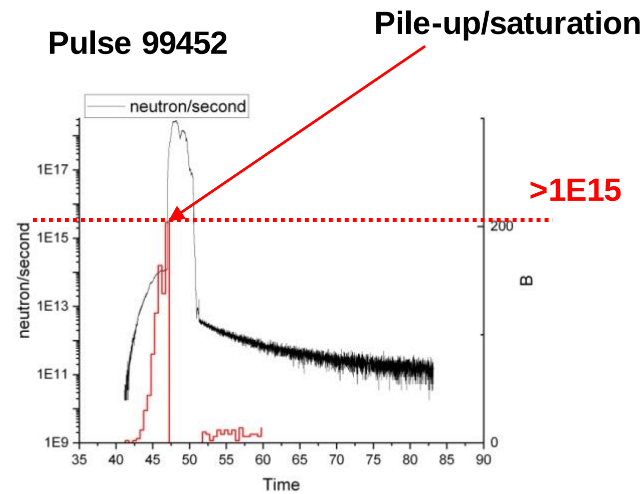


JET yield rate

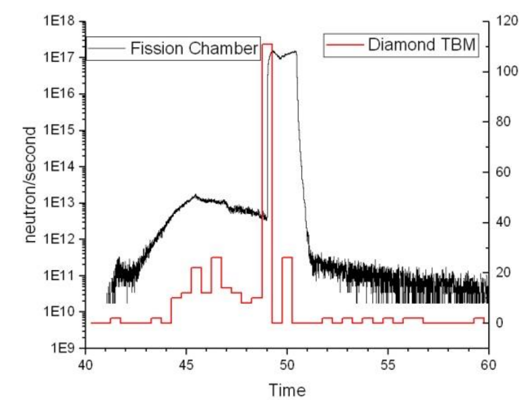
<1E15 n/s

>1E15 n/s

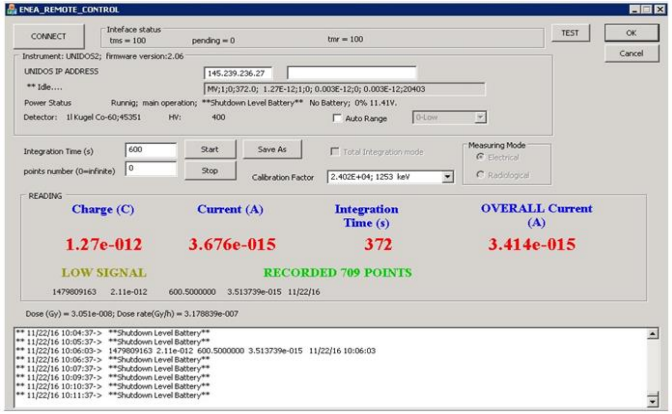
Pulse 99452



Pulse 99454

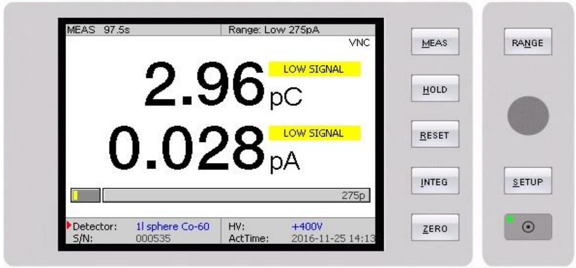


SDR at JET: Software



(a)

- Main parameters of the ongoing measurement;
- Electrometer's IP address
- Start/stop meas.
- Save data
- Set Integration time

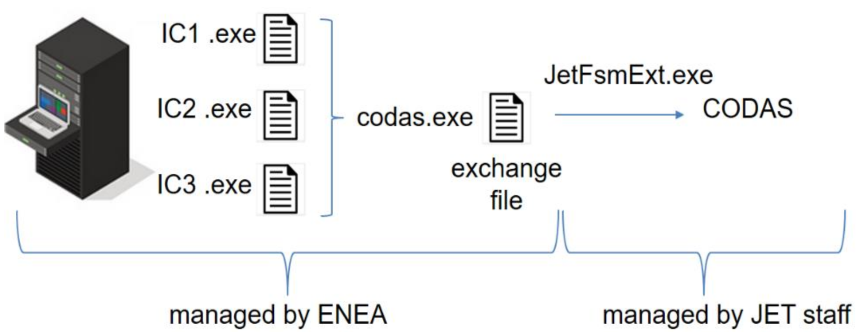


(b)

Virtual front panel of the electrometer which allows the same operations of the real one, including the high voltage settings, measuring range (low, medium and high signal), etc

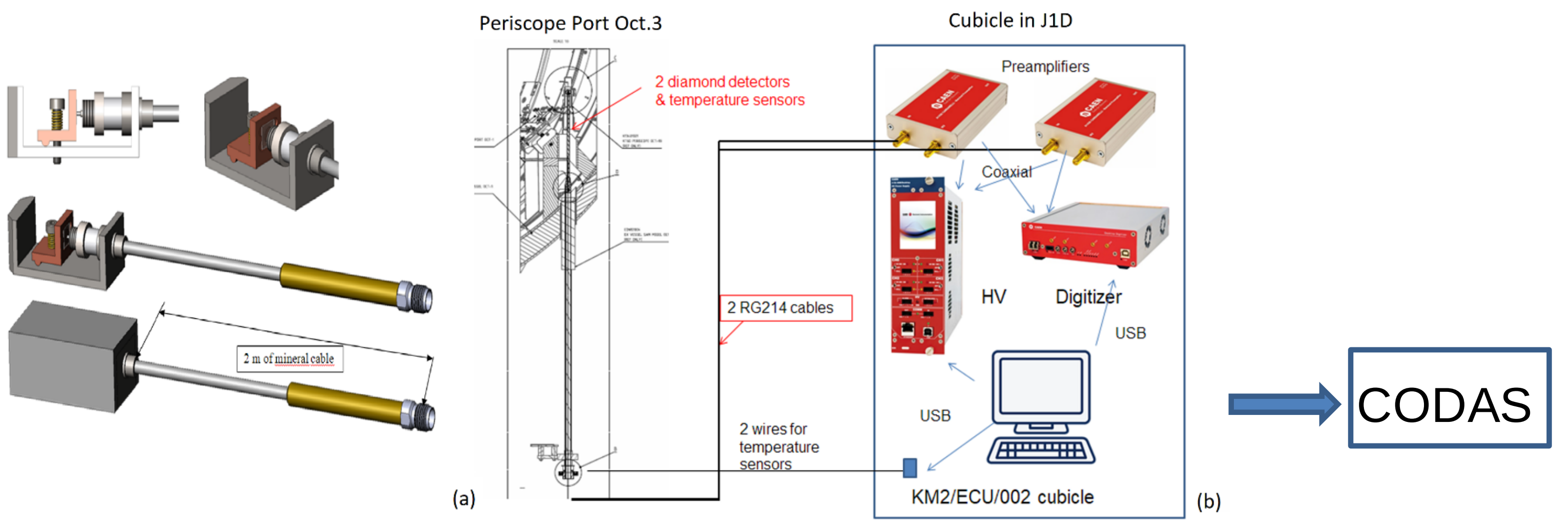
Mimic of ion chamber readings in the JET CODAS system (DE/codas/kn5a-stat)

Interface with CODAS



Main Achievements: Diamonds in vertical port

Setup of Experiment



- ➢ Two diamond detectors at approx. 200°C:
- 500 μm thick, sensitive to fast neutrons through reaction **$^{12}C(n,\alpha)^{9}Be$ (> 6.1 MeV)**
- 300 μm thick covered with a layer of ^{6}LiF, also sensitive to <6.1 MeV neutrons through reaction **$^{6}Li(n,\alpha)T$**;
- ➢ Both detectors **are cased** as shown in Fig. and featured **with mineral cables with electric insulation suitable for high temperature** (aluminium oxide);
- ➢ They are connected to the cubicle KM2/ECU/002 in J1D through coaxial cables type RG214, about 100 meters long, **standard screen from electromagnetic interference**, i.e., a double screen of silvered copper.

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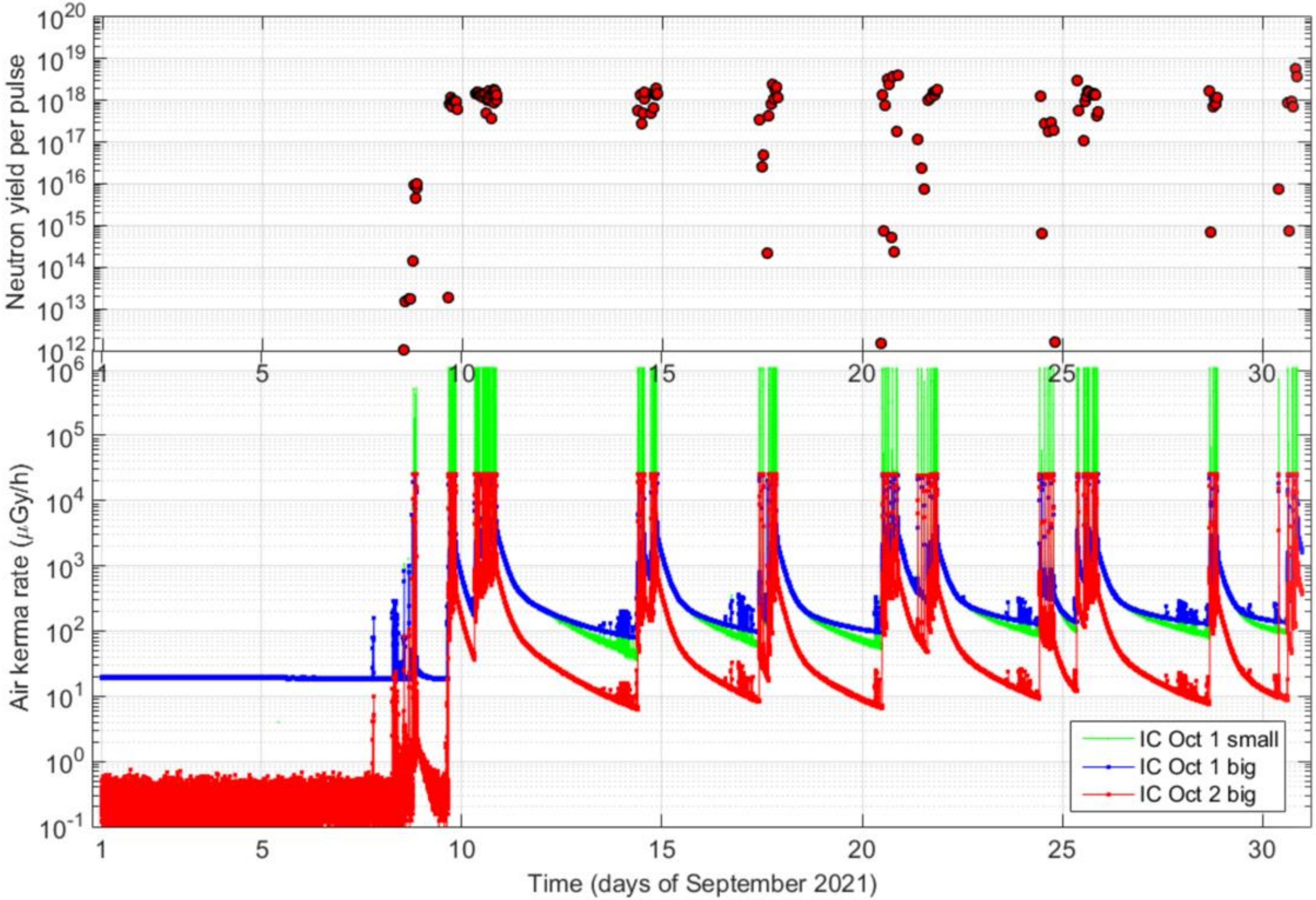
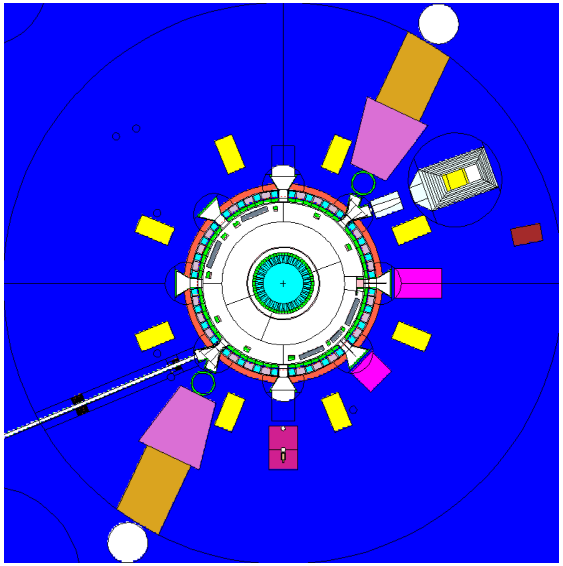
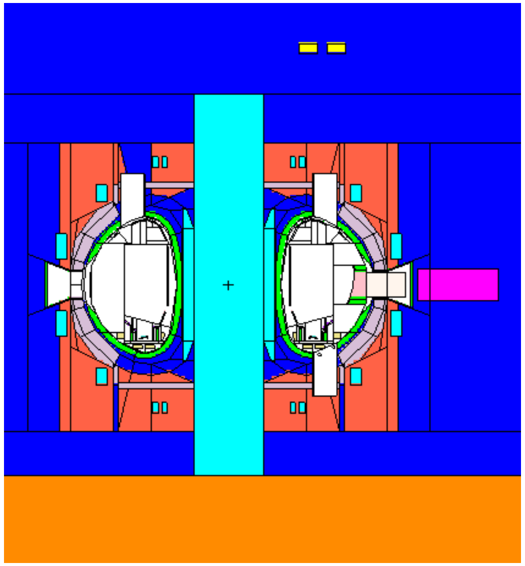
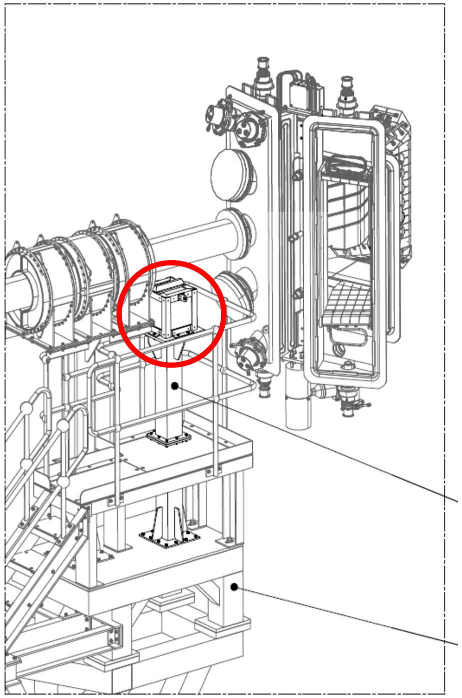


- Model implemented in UU MCNP JET model
- Position obtained from drawings



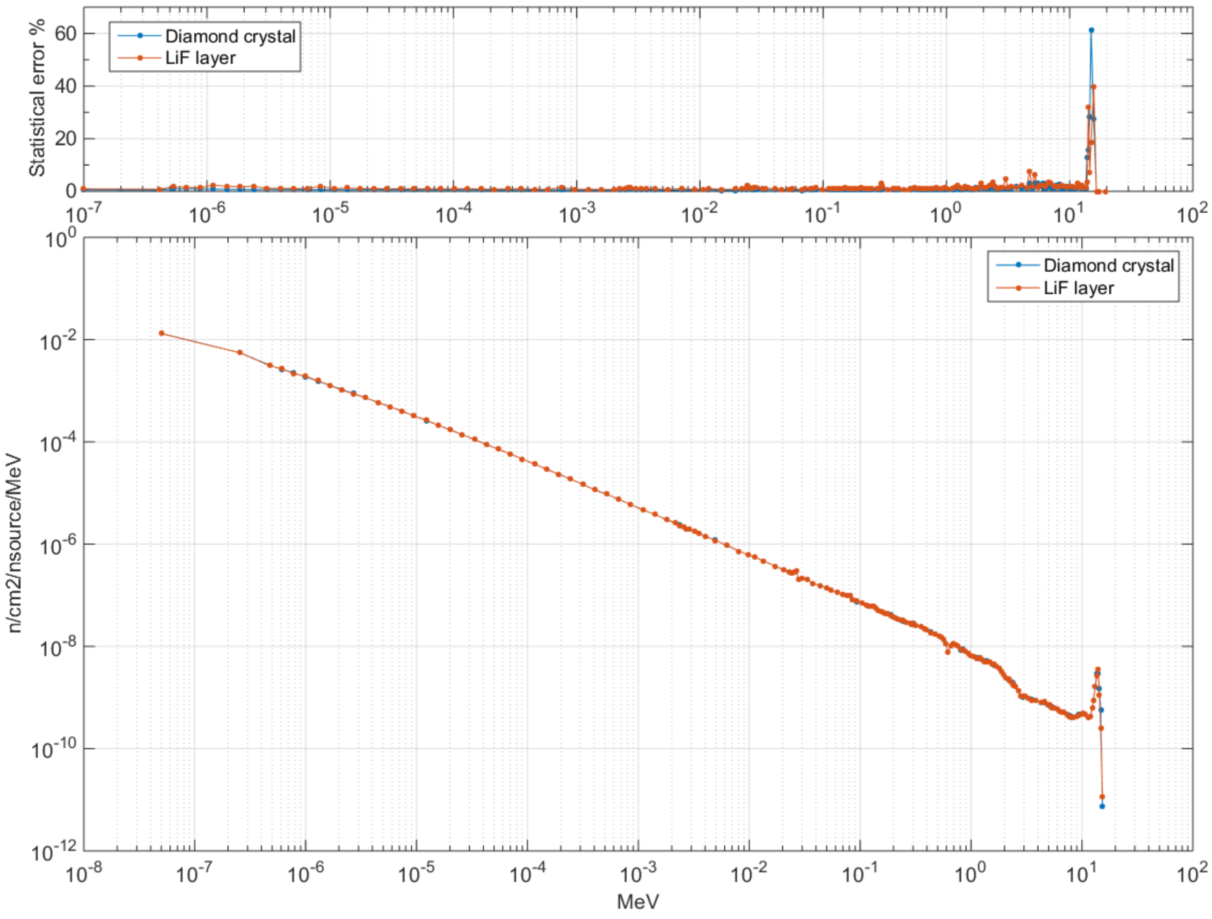


Original JET model



Drawing with position of TBM

Flusso x sezione d'urto è significativo non il solo flusso !!



Total neutron fluence
Dia $(9.0929\pm0.0336)\times10^{-8}$ $n/cm^2/n_{source}$
LiF $(9.0618\pm0.0435)\times10^{-8}$ $n/cm^2/n_{source}$

- E>0.1 MeV ~37% of the total
- E<1 eV is ~ 4.7%
- E> 5.7 MeV. 8.2%

No significant differences between the two spectra.