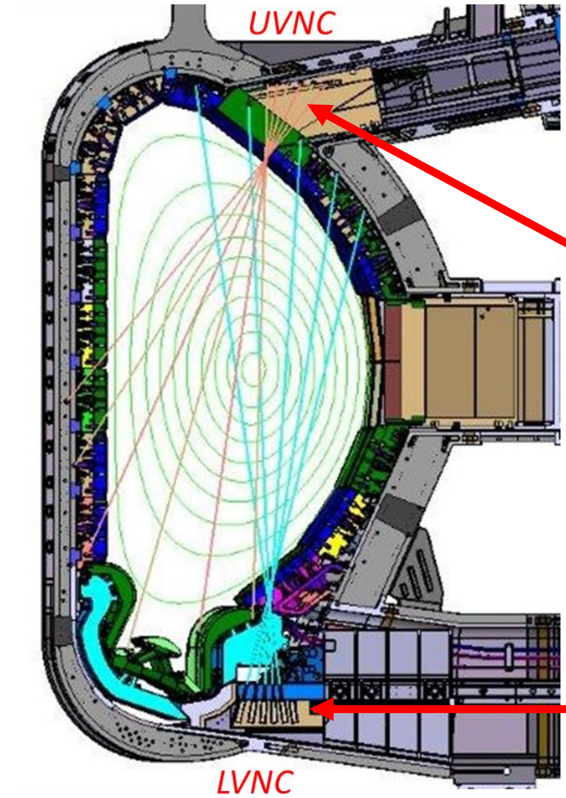
Calibration strategy of the ITER Vertical Neutron Camera

G. Nemtsev, R. Rodionov, R. Khafizov, P. Revyakin, Y. Kashchuk

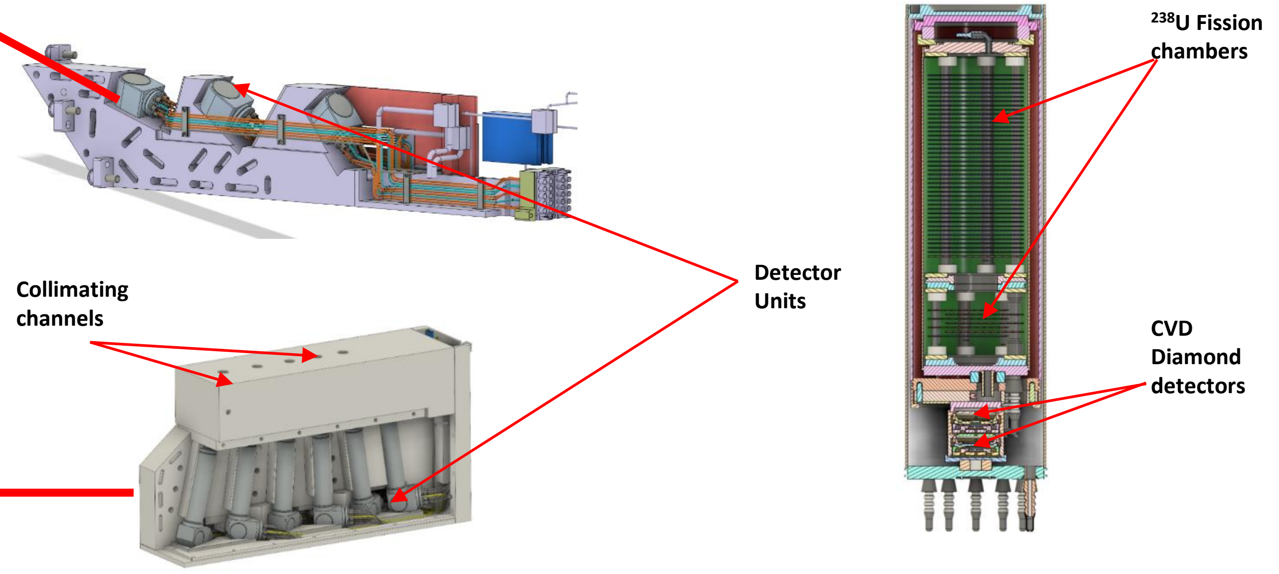
Overview of ITER Vertical Neutron Camera



The VNC provides time- and space-resolved measurements of the neutron emissivity and neutron flux, fusion power density and alpha-source density profile and other parameters

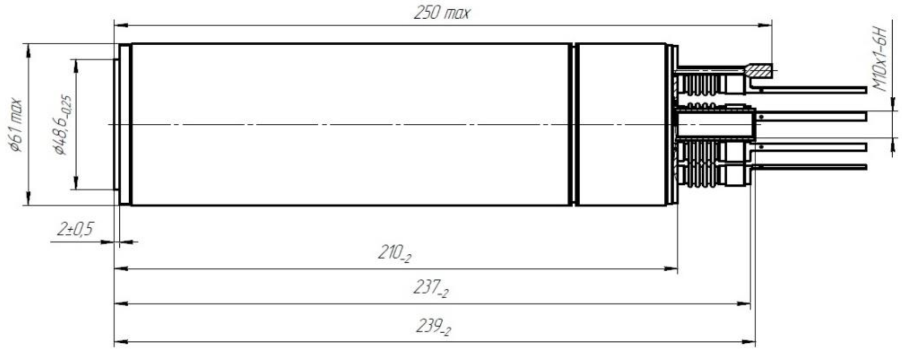
Upper VNC – 6 Lines of sight

Lower VNC – 5 Lines of sight

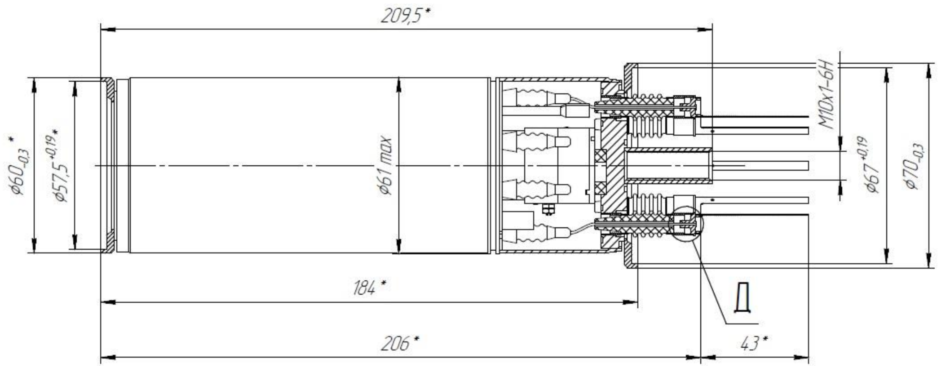


VNC detector parameters

LVNC detector unit



UVNC detector unit



Each detector unit has two fission chamber based on ^{238}U and two diamond detectors

Latest configuration of VNC detectors

LVNC detector unit

- ^{238}U Fission chamber – 1 g
- ^{238}U Fission chamber – 0.1 g
- CVD diamond detector matrix (4 detectors 4,5x4,5x0.5 mm^3)
- Small CVD diamond detector 4,5x4,5x0.1 mm^3

UVNC detector unit

- ^{238}U Fission chamber – 0.7 g
- ^{238}U Fission chamber – 0.045 g
- CVD diamond detector matrix (4 detectors 4,5x4,5x0.5 mm^3)
- Small CVD diamond detector 4,5x4,5x0.1 mm^3

*Fission chambers are designed to operate for both **DD** and **DT** neutron measurements. Diamond detectors are designed only for **DT** neutron measurements.*

Planned FAT measurements

Test 1: Check of Electrical Continuity

The following criteria shall be verified to declare that the test has been successfully passed:

- Insulator resistance are higher than specified limit values;
- leak currents under HV applied are lower then specified limit values;
- The measured values of resistance and capacitance are within the required limits

Test 2: to verify the operation of the VNC system

To verify the operation of the VNC system after Cassete body/UPP/Diagnostic Rack assembly, to confirm that the received signals correspond to known and to verify system performance.

The main criterion of success is obtaining the required signal of detectors. The test has passed successfully, if we will see the required nanosecond pulse signal on each diamond detectors.
The amplitude of pulses after preamplification is 0 to 2 V, and their duration-at-base goes up to 50 ns.

These tests are planned to be performed at every assembly stage: UVNC/LVNC detector units assembled in detector module, detector module integrated to Port-Plug/Diagnostic Rack, VNC system tested at PPTF

Characterization of VNC detector measurements

- Measurement of Fission chamber sensitivity to 2.5 MeV neutrons
- Measurement of Fission chamber sensitivity to 14 MeV neutrons
- Measurement of Diamond detector sensitivity to 14 MeV neutrons
- Measurement of Diamond detector energy resolution
- Operation of VNC detectors at high temperature
- Long term stability study

Measurement of Fission chamber sensitivity to 14 MeV neutrons

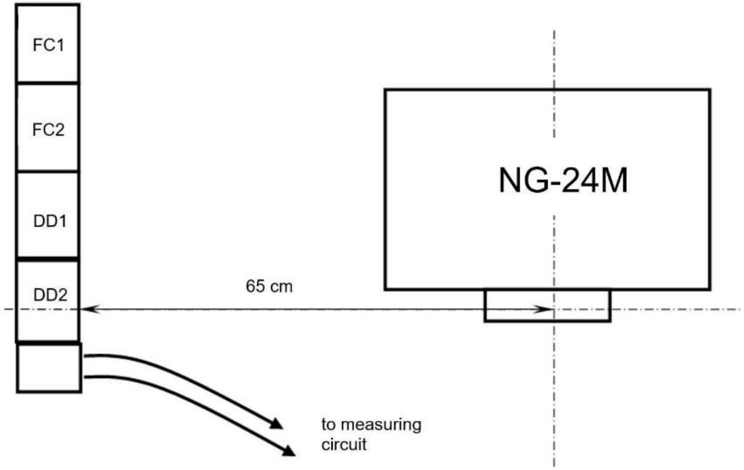
Objectives

- To measure sensitivity of Fission chambers to 14 MeV neutrons.

As a result of the tests the following should be measured:

- Response spectrum
- Sensitivity

Procedure description



VNC detector unit is installed so that the tested Fission Chamber is located at a point with the measured neutron flux density at an angle of 90 degrees relative to the axis of the generator in the target plane at a distance of 650 mm from the center of the target. The pulse analyzer is started to measure. The NG 24M neutron generator is output to the intensity level ($1 \cdot 10^{10}$ neutron/s). The measurement of the amplitude spectrum is carried out for 400 s.

Measurement of Fission chamber sensitivity to 14 MeV neutrons

Environmental parameters

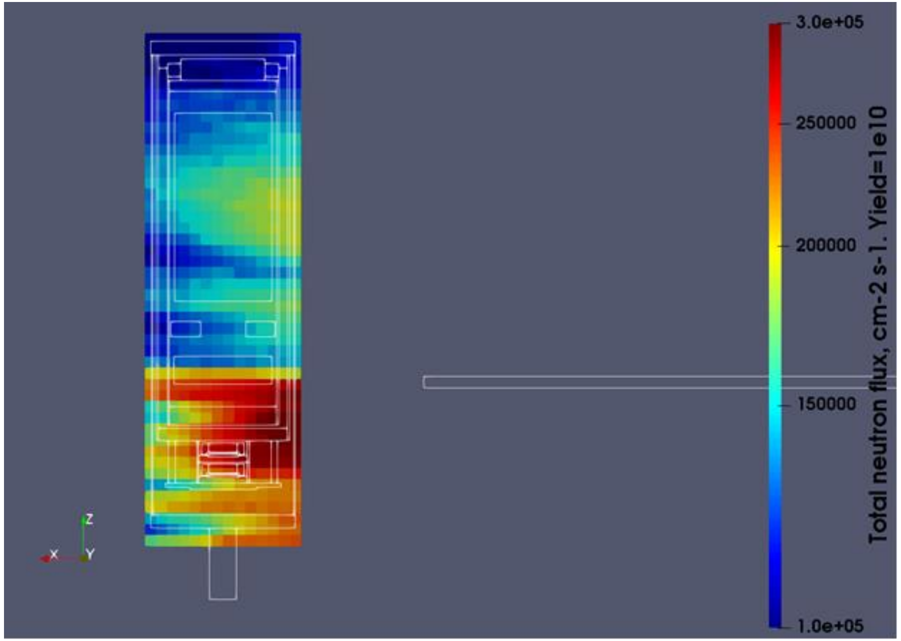
All kinds of tests carried out in normal climatic conditions (temperature - (20 ± 5) °C, relative humidity - (45...80) %, atmospheric pressure (630 ... 800) mmHg (84 ... 106.7) kPa).

Test equipment

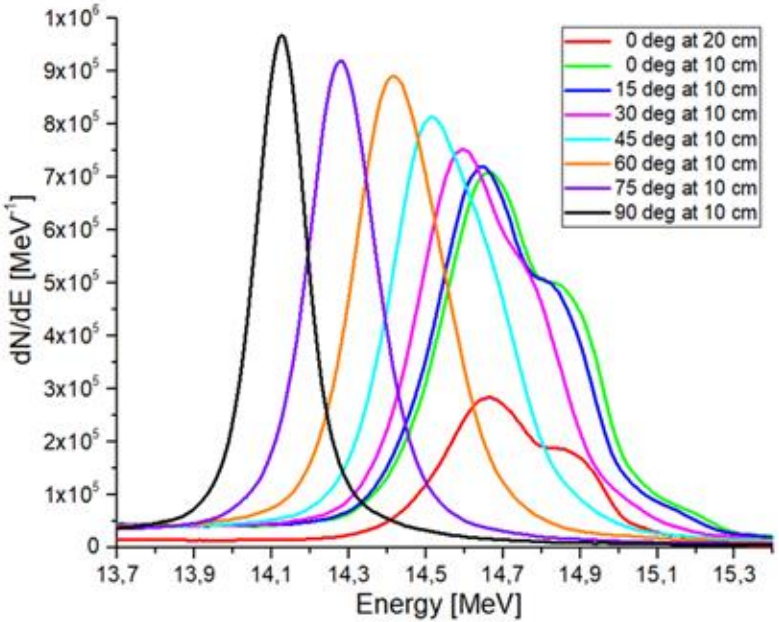
- Neutron generator NG-24M
- Dosimetric system SRK-AT2327
- Preamp CanBerra 2004
- Shape amplifier Ortec 673
- Ortec 926 pulse analyzer
- Keithley-6517B electrometer

Measurement of Fission chamber sensitivity to 14 MeV neutrons

Calibration source(s) description



Calculation of the neutron flux density at the detector irradiation point, yield of Neutron generator NG-24 is 10^{10} n/s



Measured neutron spectra with Diamond detector at different angles of neutron generator.

Measurement of Fission chamber sensitivity to 14 MeV neutrons

Duration

1 working day per fission chamber

Criteria of success:

- the sensitivity of Fission Chamber to 14.1 MeV is at least 10^{-4} cm^2
- the error in determining the sensitivity of Fission Chamber does not exceed 5%

Measurement of Fission chamber sensitivity to 2.5 MeV neutrons

Objectives

- To measure sensitivity of Fission chambers to 2.5 MeV neutrons.

As a result of the tests the following should be measured:

- Response spectrum
- Sensitivity

Measurement of Fission chamber sensitivity to 2.5 MeV neutrons

Procedure description

VNC detector unit is installed so that the tested Fission Chamber is located at a point with the measured neutron flux density at an angle of 90 degrees relative to the axis of the generator in the target plane at a distance of 200 mm from the center of the target. The pulse analyzer is started to measure. The ING 07D neutron generator is output to the intensity level ($1 \cdot 10^7$ neutron/s). The measurement of the amplitude spectrum is carried out for 1000 s.

Measurement of Fission chamber sensitivity to 2.5 MeV neutrons

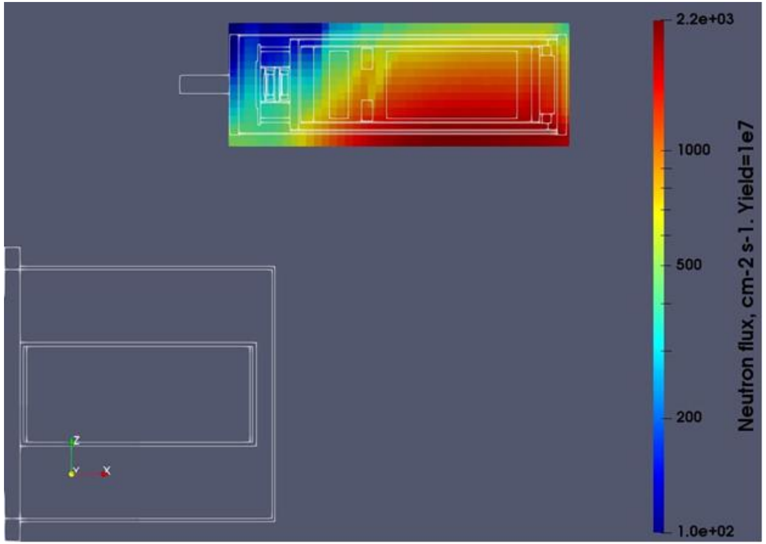
Environmental parameters

All kinds of tests carried out in normal climatic conditions (temperature - (20 ± 5) °C, relative humidity - (45...80) %, atmospheric pressure (630 ... 800) mmHg (84 ... 106.7) kPa).

Test equipment

- Neutron generator ING-07D
- Dosimetric system SRK-AT2327
- Preamp CanBerra 2004
- Shape amplifier Ortec 673
- Ortec 926 pulse analyzer
- Keithley-6517B electrometer

Calibration source(s) description



Calculation of the neutron flux density at the detector irradiation point, yield of Neutron generator ING-07D is 10^7 n/s

Measurement of Fission chamber sensitivity to 2.5 MeV neutrons

Duration

1 working day per fission chamber

Criteria of success:

- the sensitivity of Fission Chamber to 2.5 MeV is at least 10^{-4} cm^2
- the error in determining the sensitivity of Fission Chamber does not exceed 10%

Measurement of Diamond detector sensitivity and energy resolution to 14 MeV neutrons

Objectives

- To measure sensitivity of Diamond Detector to 14 MeV neutrons.

As a result of the tests the following should be measured:

- *Response spectrum*
- *the position of the peak corresponding to the (n, α) reaction on carbon*
- *the width of the peak corresponding to (n, α) reaction on carbon*
- *sensitivity to 14 MeV neutrons*

Measurement of Diamond detector sensitivity and energy resolution to 14 MeV neutrons

Duration

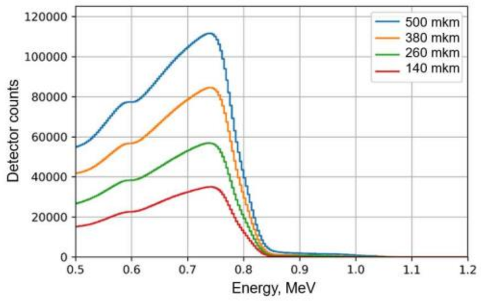
1 working day per detector

Criteria of success:

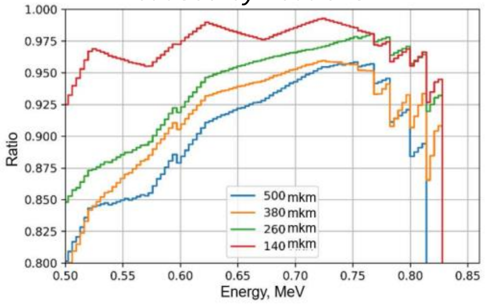
- the energy resolution of diamond detectors to 14 MeV neutrons is determined with an error of no more than 10%;
- leak current at the operating voltage of the detector offset does not exceed 100 pA
- the sensitivity of diamond detectors to neutrons with an energy of 14.1 MeV is at least 2×10^{-6} cm^2;

Diamond detectors in DD phase (sensitivity to gamma radiation)

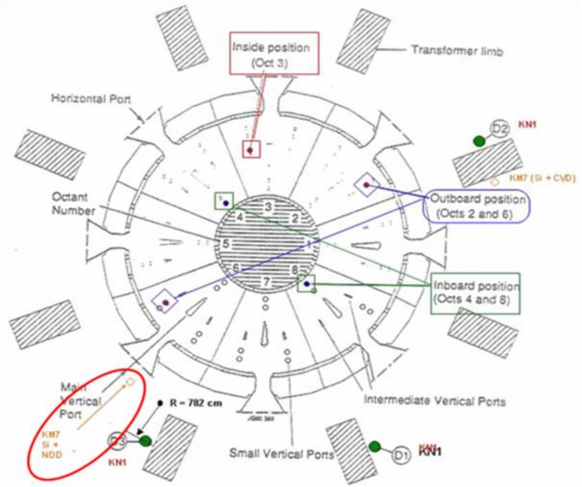
Calculated response spectra for diamond detectors with different thickness under irradiation by DD neutron generator ING07D



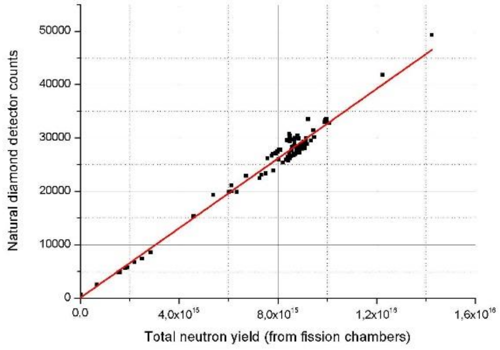
Ratio between total counts and counts caused by neutrons



*JET experience**



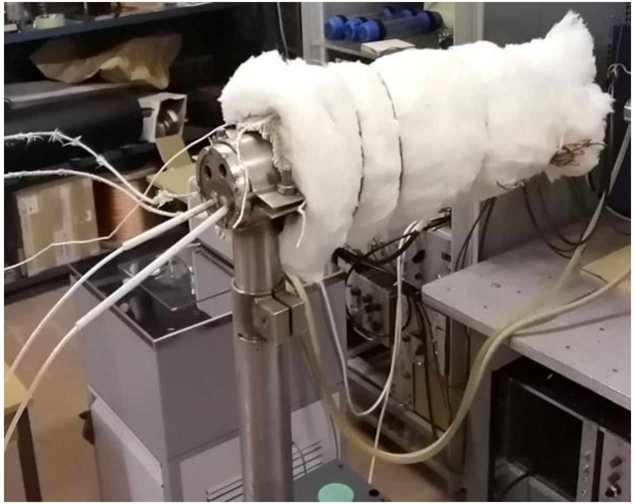
Location of the detector on JET, Main Horizontal Port, octant 6 (marked with red circle)



Counts of diamond detector thickness 180 nm vs counts of fission chamber

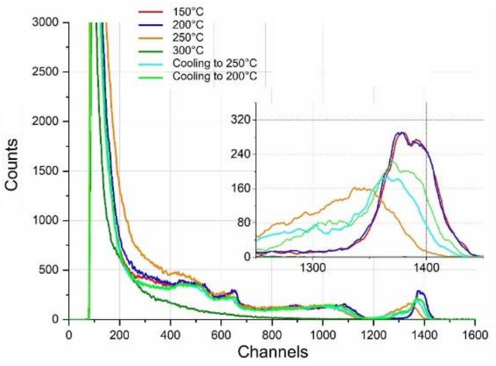
**Diagnostic of fusion neutrons on JET tokamak using diamond detector*
G. Nemtsev, et al AIP Conference Proceedings, Volume 1612, Issue 1, p.93-96

High temperature tests

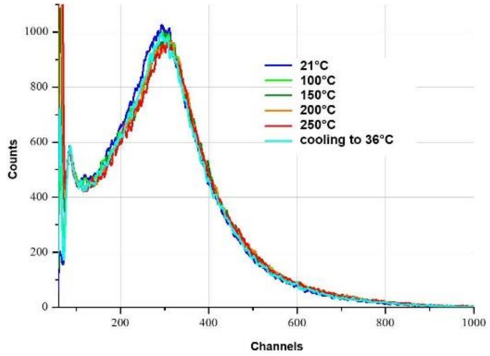


UVNC detector unit with heating element and thermal insulation installed in front of Neutron Generator

Diamond detector response under different temperature and 14 MeV neutron irradiation



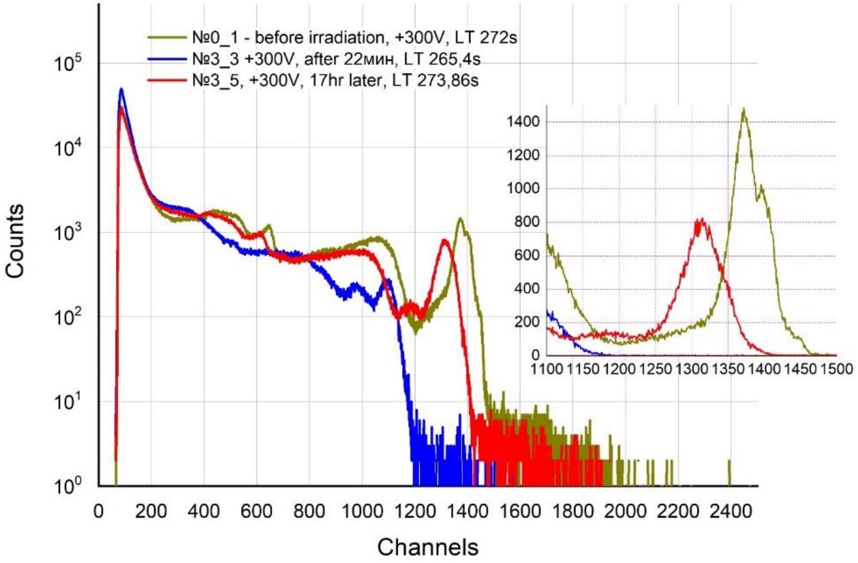
Fission chamber response under different temperature and 14 MeV neutron irradiation



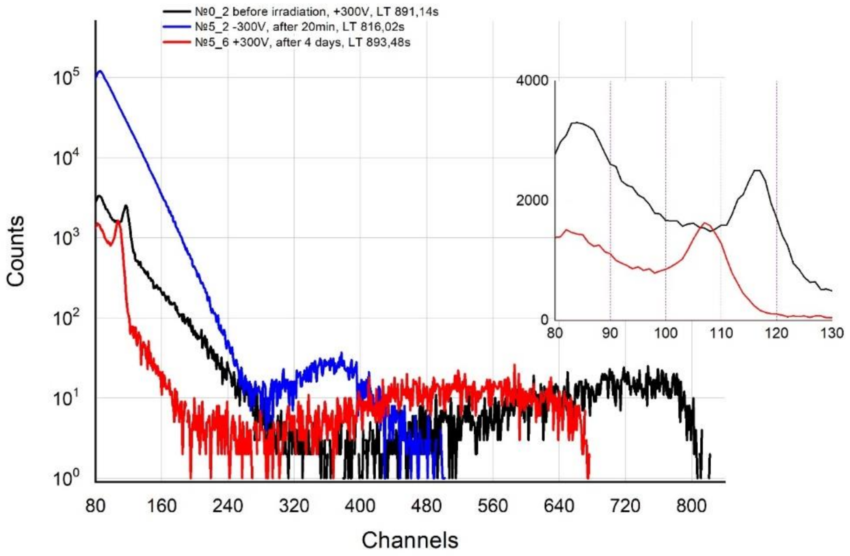
There is no temperature effects on Fission Chambers. Diamond detectors change their response at temperature higher than 200 C. Operation temperature in VNC is not exceeding 100 C, detectors are cooled. Additional tests are not planned.

Long term stability

Study of diamond detector radiation hardness, thick diamond plate 4,5x4,5x0,5 mm^3



Irradiation with fluence 10^{14} n/cm^2



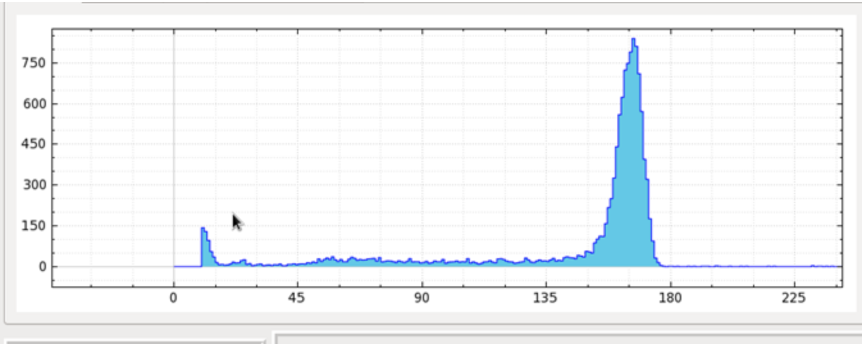
Diamond embedded source, fluence 10^{14}

Thermocycling test

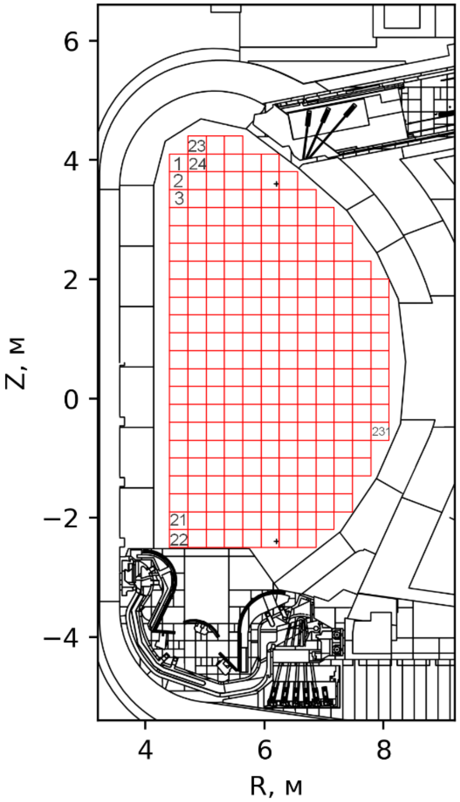
Diamond detector successfully passed 500 cycles of thermal loads. Thermal Load from 70 ° up to 250 °C, heating rate 60° per hour, approximately duration 1 day per cycle

Diamond detectors after 500 cycles of Thermal Load on air

Spectrum from embedded sources ^{241}Am and ^{137}Cs after 500 cycles of Thermal Load



VNC profile measurement



Neutron source is represented as an array of pixels in the plasma poloidal cross-section

Pixel size - 10×10 cm^2

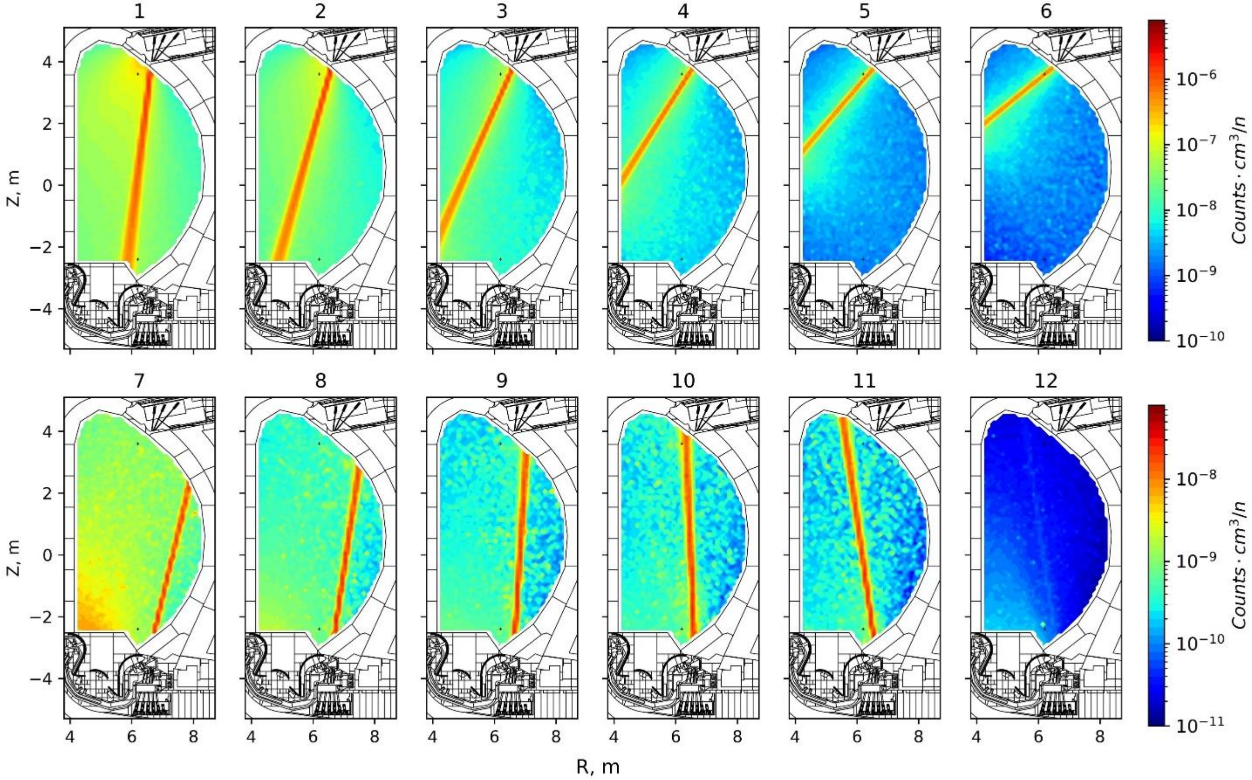
$$N_i = \sum_j G_{ij} f_j$$

G_{ij} - Detector contribution matrix

f_j - Neutron emissivity of the *j-th* pixel, n/cm^{3}s

N_i - *i-th* detector count rate

DT neutron contribution matrix for fission chambers



1. *R. Rodionov et al. Calculation of DD and DT neutron contribution matrix for ITER vertical neutron camera detectors. Fus. Eng. Des. Vol. 173, (2021), 112874*

Neutron source profile reconstruction

Maximum likelihood estimation method is an effective approach to solve plasma tomography problems[1]

$$\bar{N}_i = \sum_j G_{ij} f_j$$

N_i - neutron detector measurements (have Poisson distribution)

Likelihood function

$$L(\boldsymbol{N}|\boldsymbol{f}) = \prod_i \frac{(\bar{N}_i)^{N_i}}{N_i} e^{-\bar{N}_i}$$

$$\boldsymbol{f}_{ML} = arg\max_{\boldsymbol{f}} L(\boldsymbol{N}|\boldsymbol{f})$$ - The solution - reconstructed neutron source profile.

EM-algorithm[2,3]:

$$f_i^{(k+1)} = \frac{f_i^{(k)}}{s_i} \sum_j \frac{N_j}{z_j} G_{ji} \qquad z_j = \sum_m G_{jm} f_m^{(k)} \qquad s_i = \sum_j G_{ji}$$

Prior information – neutron source intensity is believed to be constant along magnetic surfaces[1]

$$f_i^{smooth} = \sum_j w_{ij} f_j$$

w_{ij} - smoothing operator which is applied in every iteration of EM-algorithm

1. *T. Craciunescu, et.al. Nuclear Instruments and Methods in Physics Research A 595 (2008), 623 - 630*
2. *L.A. Shepp and Y. Vardi. IEEE Transactions on Medical Imaging, vol. MI-1, No. 2, 1982*
3. *K. Lange, R. Carson. Journal of Computer Assisted Tomography, 8(2), 1984, 306 – 316*

Neutron source profile reconstruction: mixed neutron fields

$$\mathbf{N_{DD}} = \mathbf{G_{DT}^{DD}}\,\mathbf{F_{DT}} + 0 \cdot \mathbf{F_{DD}}$$

$$\mathbf{N_{FC}} = \mathbf{G_{DT}^{FC}}\,\mathbf{F_{DT}} + \mathbf{G_{DD}^{FC}}\,\mathbf{F_{DD}}$$

$$\Rightarrow$$

$$\begin{bmatrix}\mathbf{N_{DD}}\\ \mathbf{N_{FC}}\end{bmatrix} = \begin{bmatrix}\mathbf{G_{DT}^{DD}} & 0\\ \mathbf{G_{DT}^{FC}} & \mathbf{G_{DD}^{FC}}\end{bmatrix}\begin{bmatrix}\mathbf{F_{DT}}\\ \mathbf{F_{DD}}\end{bmatrix}$$

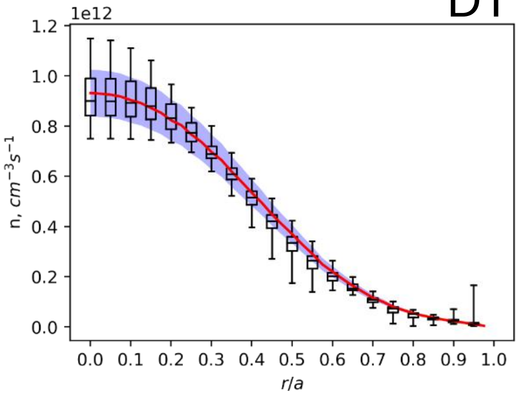
Calculation approach

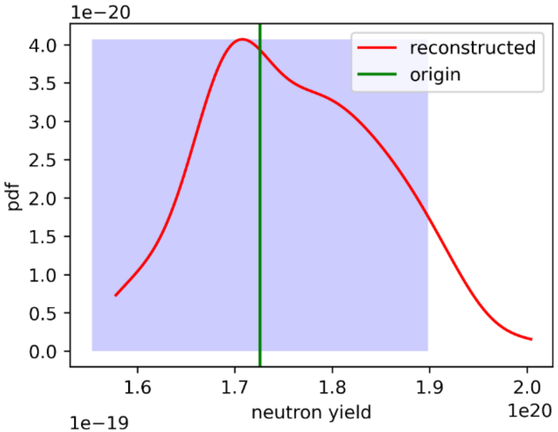
1. Use “exact” contribution matrix and neutron source profiles to generate detector measurements (expected values).
2. Generate variation of the magnetic surfaces for the given plasma scenario
3. Generate random detector measurements from Poisson distribution with expected values computed in p.1
4. For magnetic surfaces from p. 2 create smoothing operator.
5. Generate random value of δ to create random contribution matrix, which will be used to reconstruct neutron source profile.
6. Apply EM-algorithm to reconstruct DD and DT neutron source profile using data obtained in pp. 3-5.
7. Calculate total neutron yield of DD and DT neutrons.

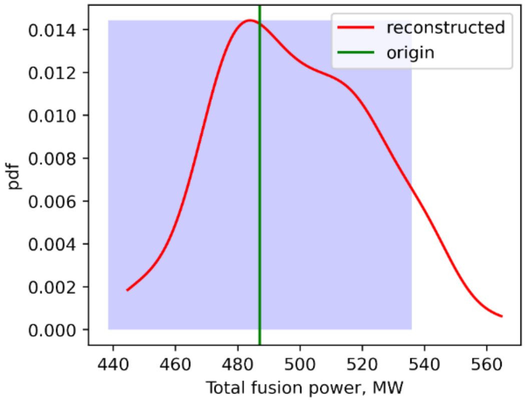
By repeating steps 2 – 7 N times we obtain distributions of reconstructed neutron profiles.

Scenario DT-15MA Peaked Q=10 (487 MW), 1 ms

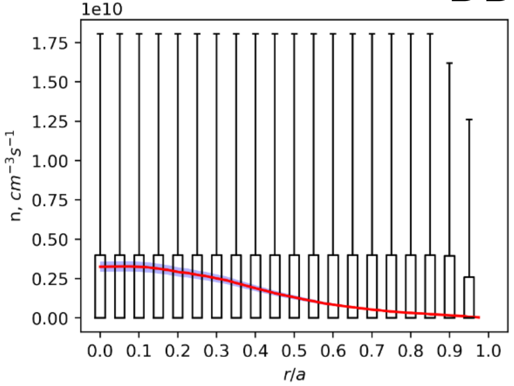
DT

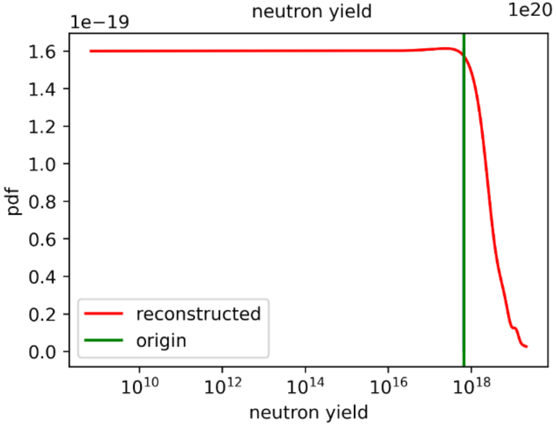


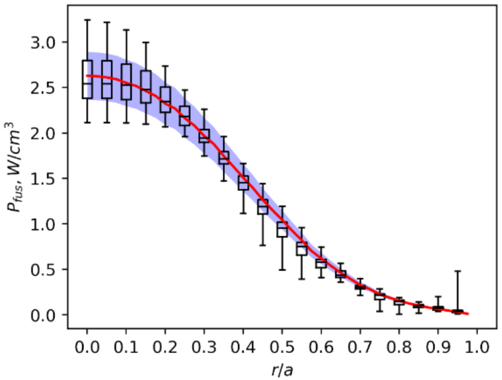




DD

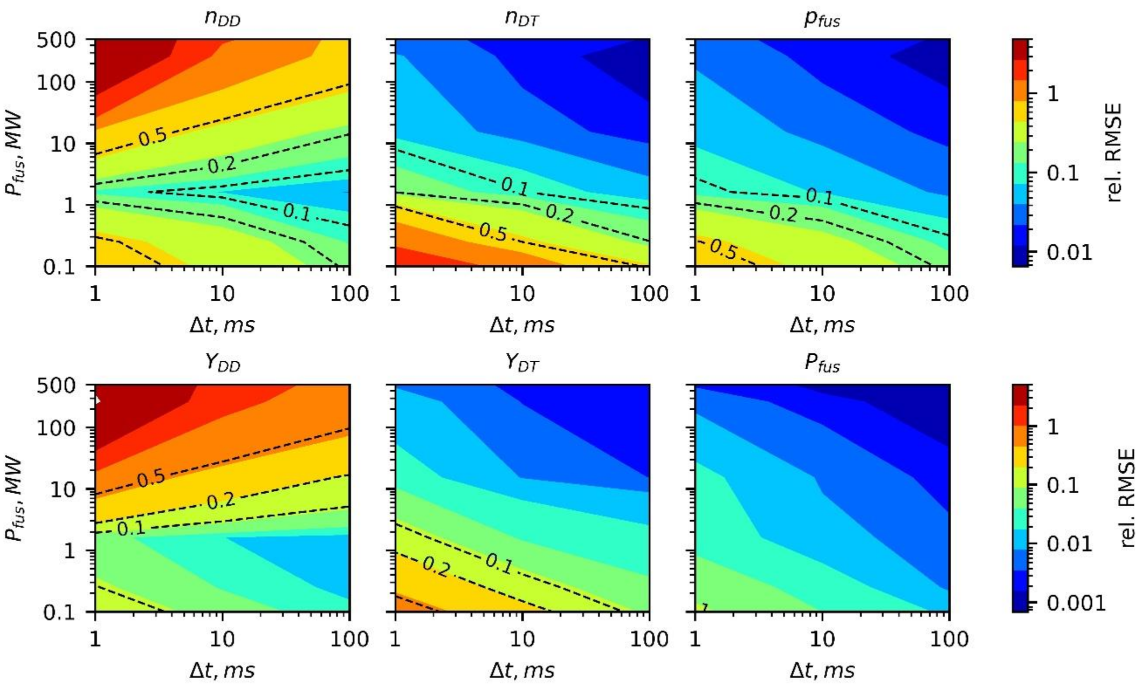






Distribution of reconstruction errors

Only statistical measurement errors of detectors



Average profile reconstruction error:

- DD neutrons
- DT neutrons
- Fusion Power density

Error in integral values:

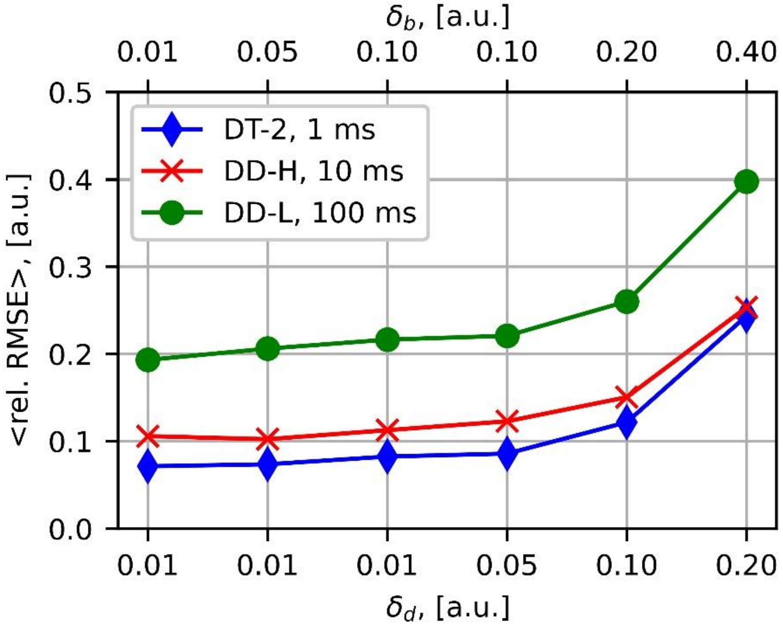
- DD neutron yield
- DT neutron yield
- Fusion Power

Errors of contribution matrix

$$\mathbf{G_r} = \mathbf{G_d}(1 + \delta_d) + \mathbf{G_b}(1 + \delta_b)$$

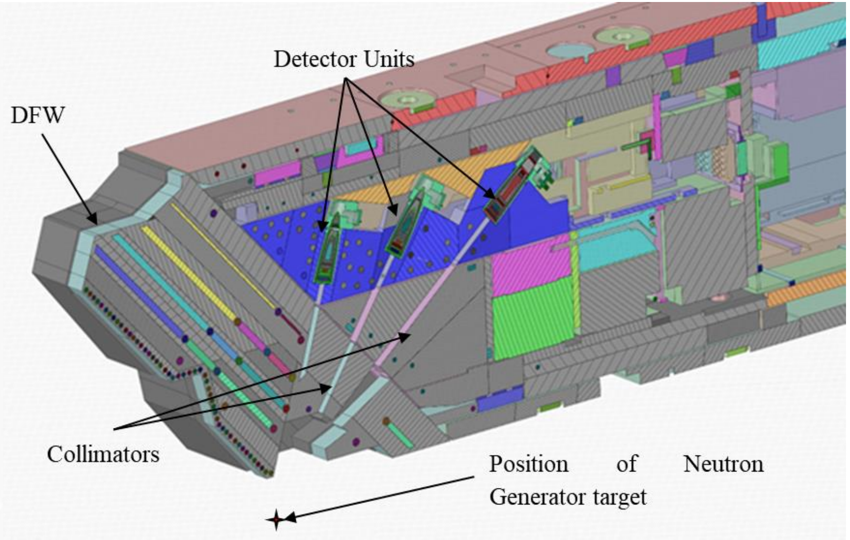
$\mathbf{G_d}$ - contribution matrix of direct neutrons
$\mathbf{G_b}$ - contribution matrix of background neutrons
$\mathbf{G_r}$ - disturbed contribution matrix used for tomographic reconstruction
δ_d and δ_b - relative errors $\mathbf{G_d}$ and $\mathbf{G_b}$

Average error in reconstruction of fusion power profile



Proposal for in-vessel calibration

Systematical error of VNC contribution matrix can be corrected during in-vessel calibration with DT neutron generator



Detector count rate at the yield of Neutron Generator - 10^{11} n/s

Collimator #	1	3	5
Fission Chamber, 700 mg	1292,81	885,11	5,65
45 mg	131,81	89,57	0,67

Conclusions

- *Preliminary characterization plan for VNC detectors is developed. It includes measurement of Fission Chamber sensitivity to 2.5 MeV and 14 MeV neutrons, measurements of Diamond detector energy resolution and sensitivity to 14 MeV neutrons*

- *Diamond detectors are characterized only for **DT** neutron measurements. It is planed to cross calibrate them with Fission Chambers during DD phase.*

- *Diamond detectors have limitation on radiation hardness. In the most channels they can operate only partial ITER life time*

- *There is no considerable temperature effect on measurement of VNC detectors.*

- *Approach with DD and DT neutron contribution matrix is proposed to consider the impact of background neutrons and to reconstruct the neutron emissivity profile.*

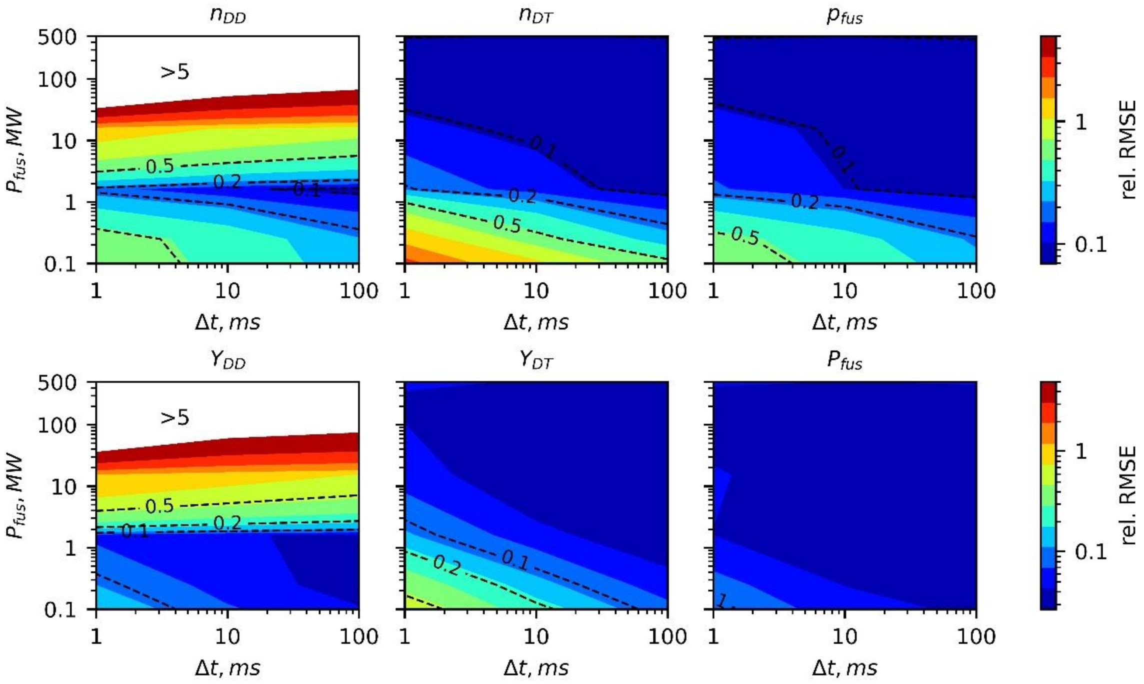
- *Sensitivity of the profile reconstruction to the statistical errors of measurements, errors of magnetic surface shapes and errors of contribution matrix is calculated.*

- *Strategy of VNC in-vessel calibration is proposed.*

Thank you

Distribution of reconstruction errors

All errors are included (statistical, shape of magnetic surfaces, accuracy of calculation of source functions)



Average profile reconstruction error:

- DD neutrons
- DT neutrons
- Fusion Power density

Error in integral values:

- DD neutron yield
- DT neutron yield
- Fusion Power