Evaluating the Fusion Power Accuracy using Synthetic Measurement Simulations

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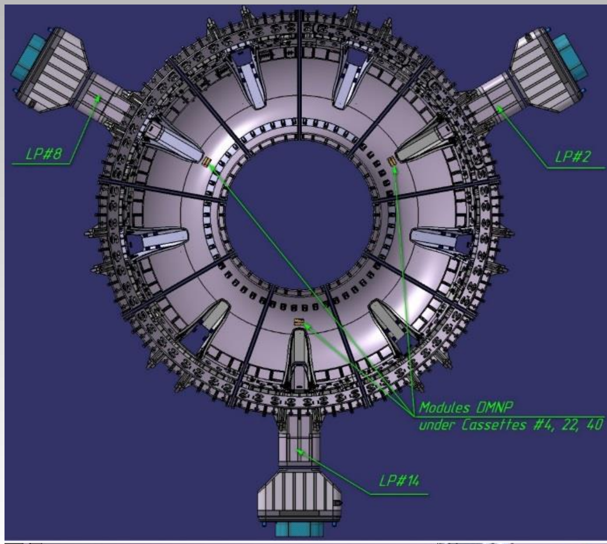
Outlook

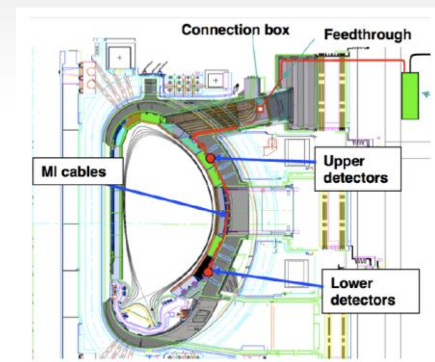
- Introduction
  - DNFM, NFM, MFC description
  - ITER plasma scenarios
- Separate measurements simulation
  - DNFM
  - NFM
  - MFC
- Systematic uncertainty estimation
- Integrated measurements by DNFM & NFM & MFC

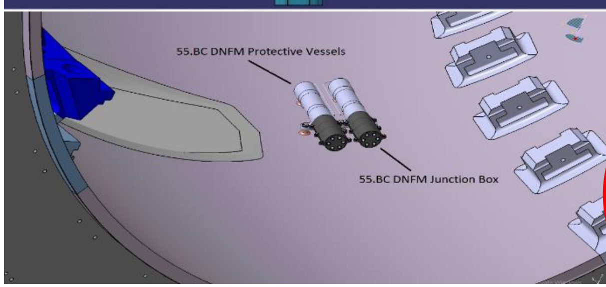
Diagnostic tools description

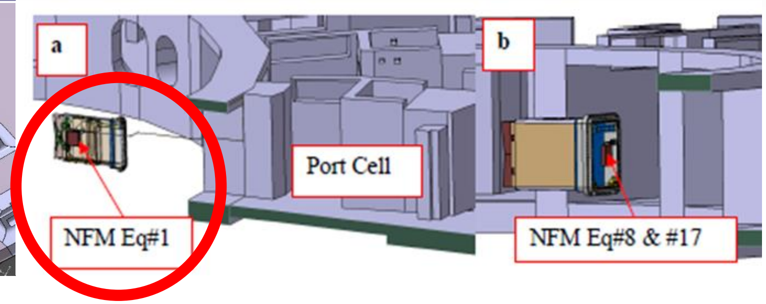


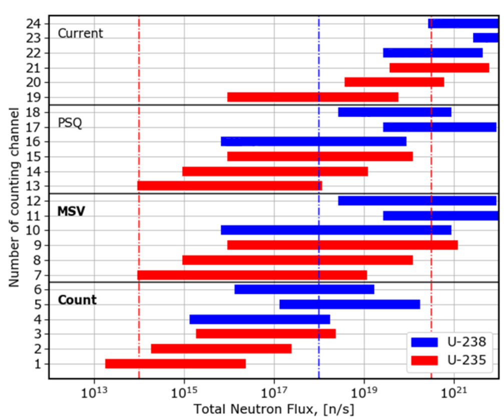
Value	Range	Accuracy
Total Neutron Flux (Neutron Yield), [n/s]	$10^{14} - 10^{18}$ (DD)	20%
	$10^{18} - 3{,}2 \cdot 10^{20}$ (DT)	10%
Fusion power, [MW]	0,1 – 3	20%
	3 – 900	10%

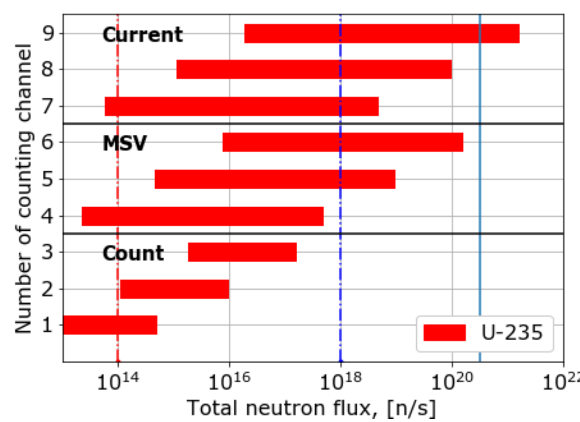
Time resolution 1 or 10 ms

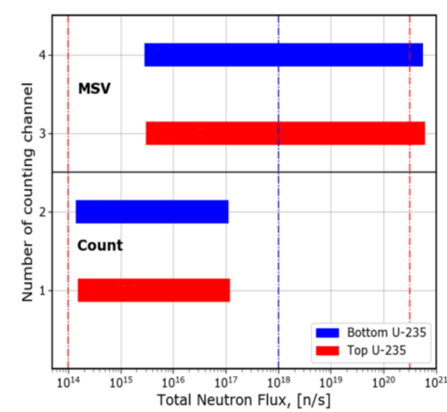








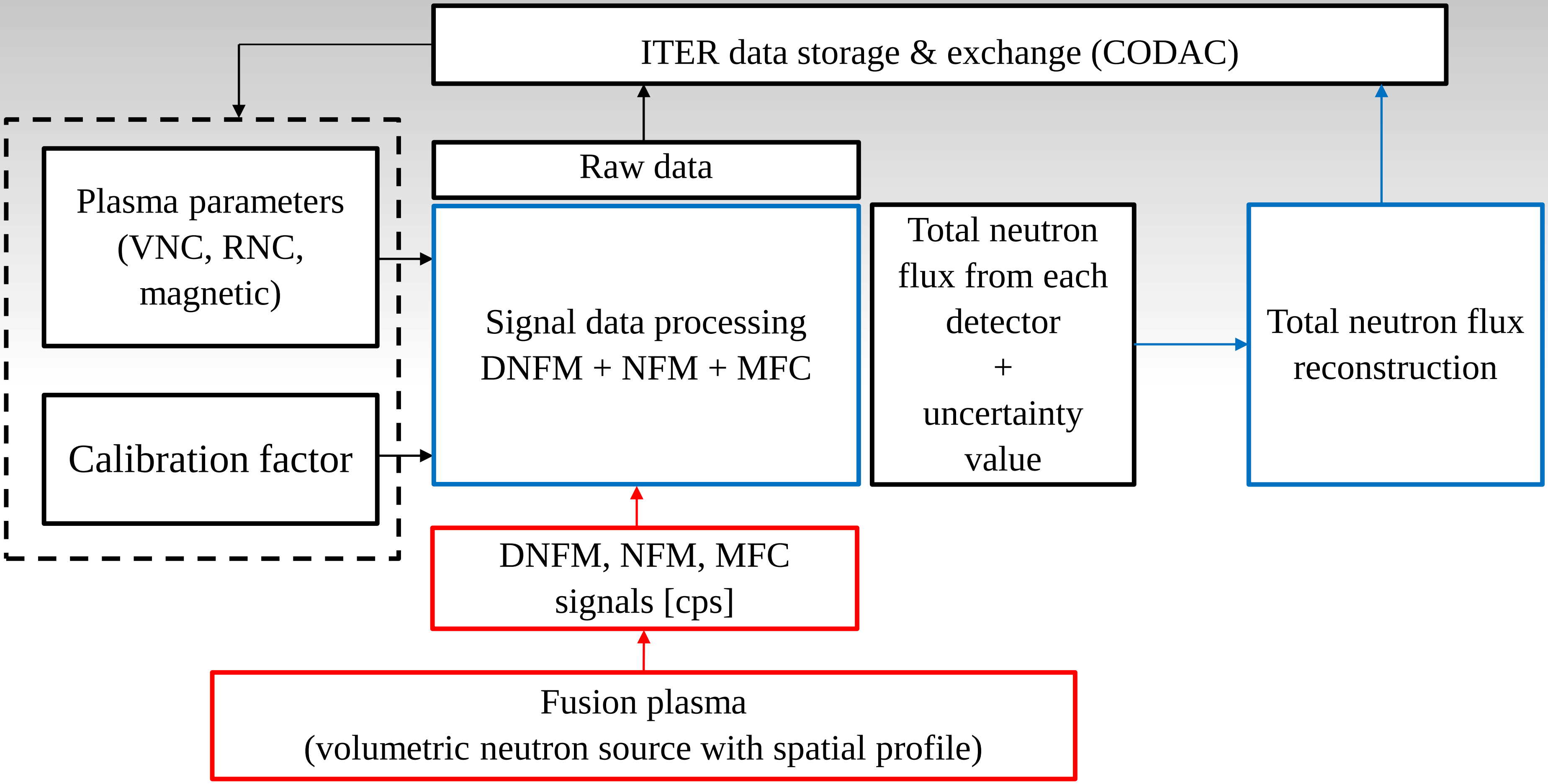




Our goals

- Diagnostic design validation
- Data processing algorithms development
- Measurements uncertainty sources and its value
- Minimization of the total measurement uncertainty value

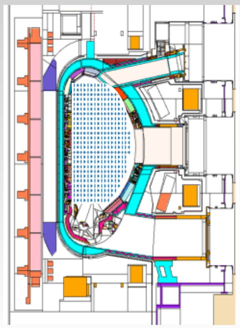
Total neutron flux reconstruction breakdown scheme

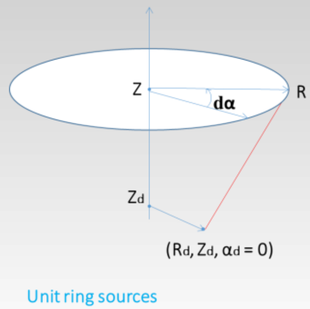


Legend: Data from outside | Source of initial signals | Processing of monitors data

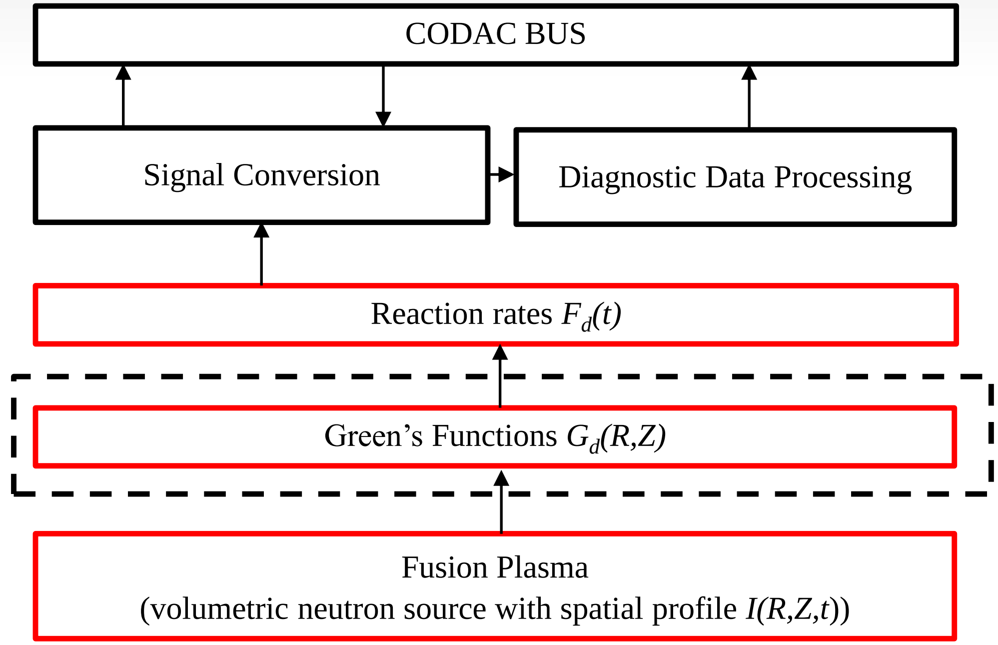
Diagnostics reaction rate simulation

$$F_d(X) = \hat{H}_d I(X_0) = \int G_d(X, X_0) I(X_0) dX_0 \qquad G_d(X, X_0) = \hat{H}_d \cdot \delta(X_0)$$



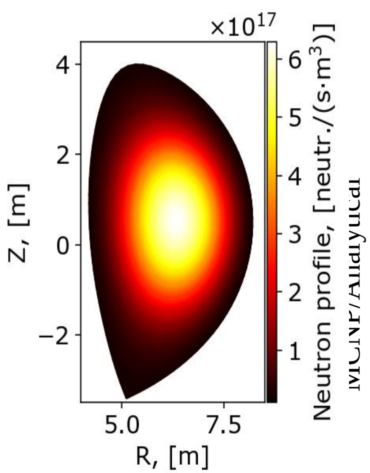


$$F_d(t) = 2\pi \iint G_d(R, Z) I(R, Z, t) R dR dZ$$



Neutron sources

$I(R, Z, t)$



$\{G_d^{ij}\} = \{G_d(R_i, Z_j)\}$

$G_d(R, Z) = \mathbf{RBF}\ (\{G_d(R_i, Z_j)\})$

$$\phi(r) = \sqrt{1 + (\varepsilon r)^2} \qquad \Phi\boldsymbol{\lambda} = \boldsymbol{f}$$

$$\mathbf{RBF}: s(\boldsymbol{X}) = \sum \lambda_i \phi(\|\boldsymbol{X} - \boldsymbol{X}_i\|)$$

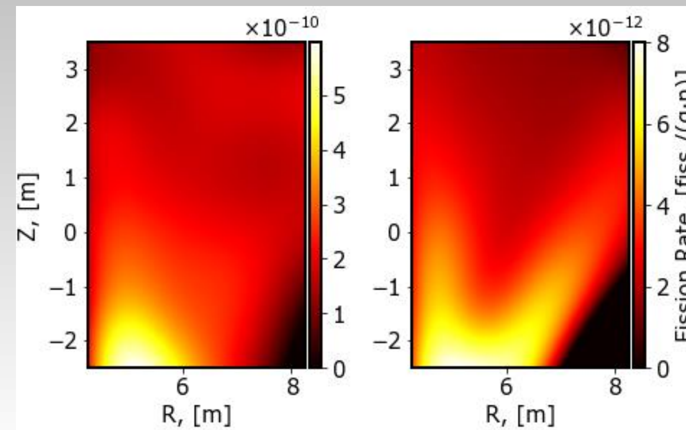
A. O. Kovalev, A. R. Polevoi, et.al. –
Simulations of Fusion power measurements by Monitors of Neutron flux in evolving ITER Plasma –
Journal of Fusion Energy, ISSN 0164-0313, DOI 10.1007/s10894-020-00232-x, 2020

Green's function accuracy check

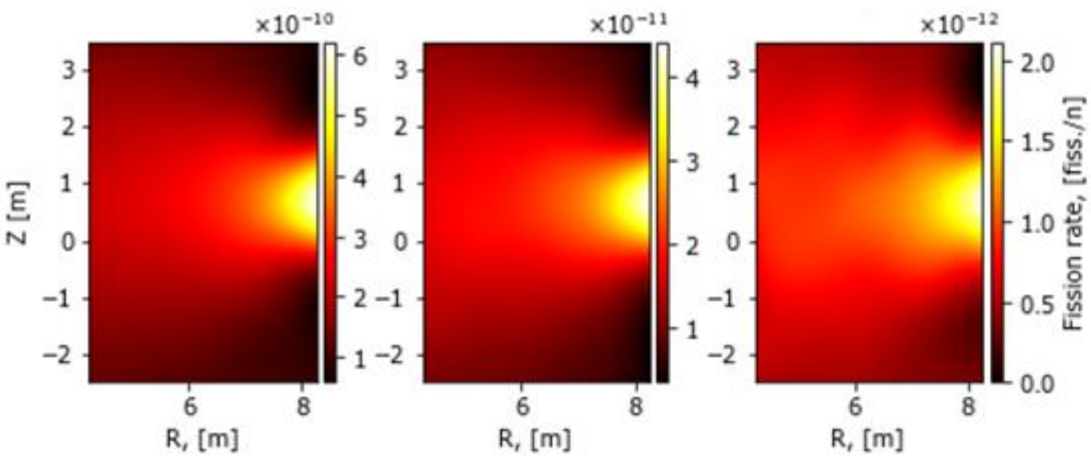
For example:
DNFM Green's function validation results

Uranium isotope	Uranium mass, [mg]	Rel. dev. from the standard DD neutron source, [%]	Rel. dev. from the standard DT neutron source, [%]
U-235	500	2.5	7.7
	50	4.1	2.6
	5	8.5	1.2
U-238	500	-2.1	-0.45
	5	-2.1	-0.51
	50	-0.6	-0.51

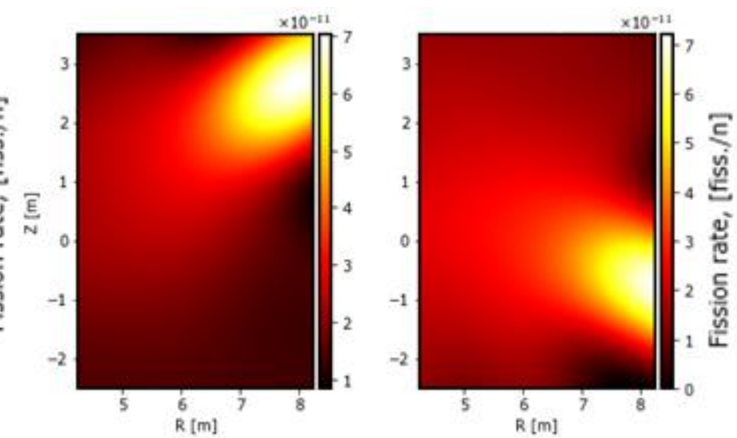
DNFM



NFM

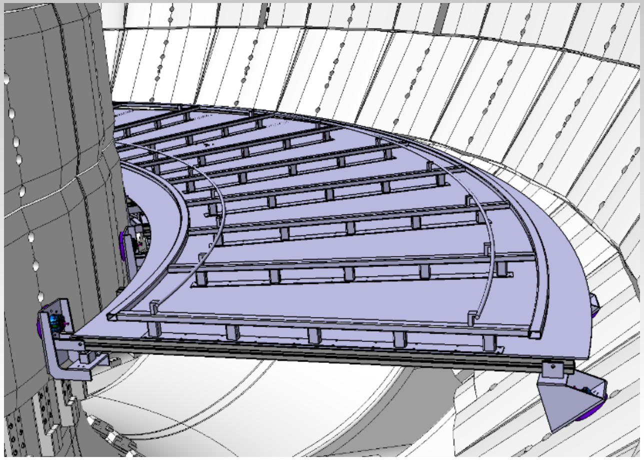


MFC



Calibration strategy

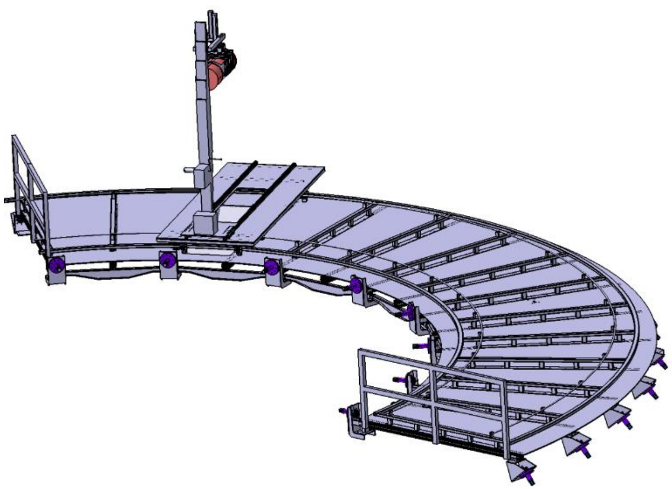
Measurement = Neutron yield *Detector response function*ITER Calibration factor

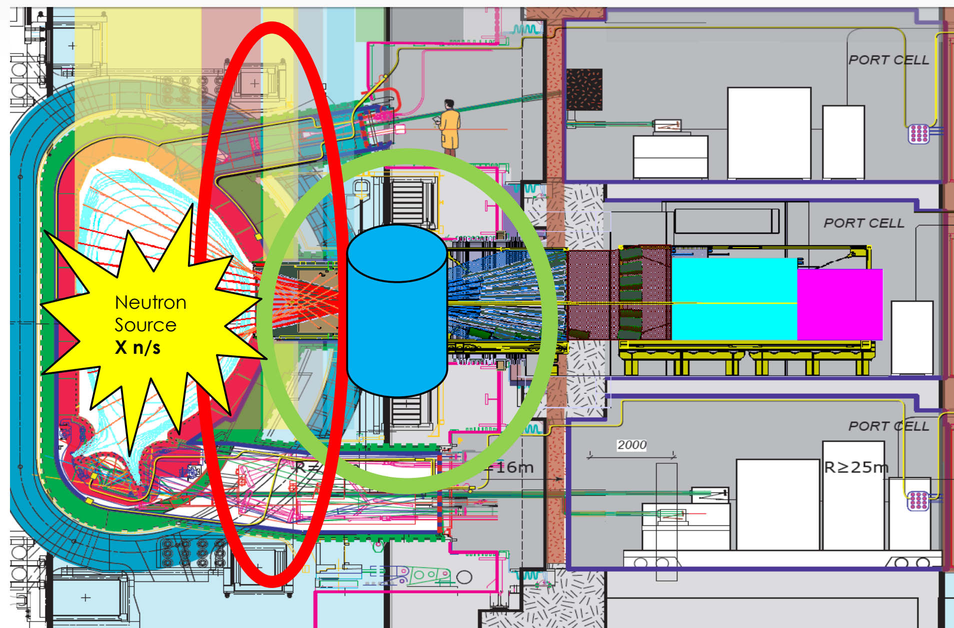


C [cps]

Requirement
<10%

P_{fus}

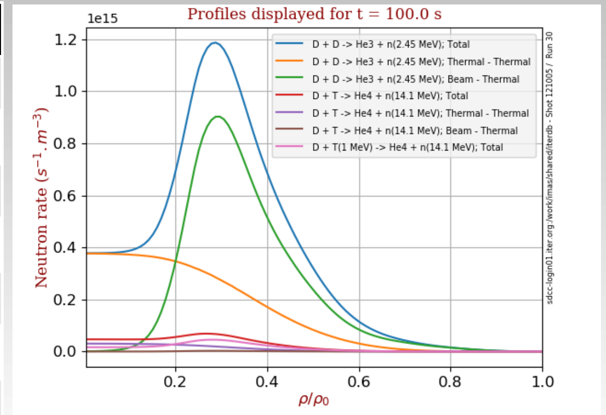


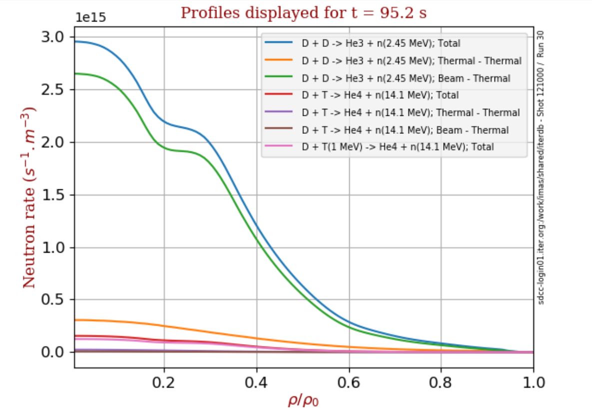


ITER org.: L. Bertalot, A. Saxena, V.A. Krasilnikov, et. al

ITER DD scenarios (from IMAS database)

#	Pulse	Ip, [MA]	B0, [T]	Fuelling	Confinement	Workflow
1	121000	7.5	2.65	D	H-mode	ASTRA
2	121001	7.5	2.65	D	H-mode	ASTRA
3	121002	7.5	2.65	D	H-mode	ASTRA
4	121003	7.5	2.65	D	H-mode	ASTRA
5	121004	15.0	5.3	D	L-mode	ASTRA
6	121005	15.0	5.3	D	L-mode	ASTRA
7	121006	15.0	5.3	D	H-mode	ASTRA
8	121007	15.0	5.3	D	H-mode	ASTRA
9	121008	15.0	5.3	D	H-mode	ASTRA
10	121009	7.5	2.65	D	Ohmic	ASTRA
11	121010	7.5	2.65	D	Ohmic	ASTRA
12	121011	7.5	2.65	D	Ohmic	ASTRA
13	121012	3.5	2.65	D	Ohmic	ASTRA
14	121013	3.0	2.65	D	Ohmic	ASTRA





DD plasma as a source of neutrons is of research interest for several reasons e.g.:

- Multichannel neutron production (DD beam-thermal; DD thermal-thermal; DT beam-thermal; DT thermal-thermal; D+T(1 MeV) reaction, where T was born in DD reaction)
- Wide variety of neutron emission profile peaking factor

ITER org.: M. Schneider, A.R. Polevoi

Algorithm and assumptions

The analysis is done for DD and DT ITER scenarios stored in the IMAS database

Assumptions:

For 500 MW ITER DT baseline scenario at flat-top with 50:50 DT mix the ratio of Total neutron fluxes from DD and DT reactions Y_n^{DD}/Y_n^{DT} << 1

For DD plasma scenarios from the IMAS DB Y_n^{DD}/Y_n^{DT} ~10 – 20 >> 1

Thus, the simulations of DD plasma parameters measurements are performed under the assumption that Y_n^{DT} is negligibly small compared to the value of Y_n^{DD}

Algorithm:

Value	Equation	Additional information
Count rate	$C, \Delta C$	MSV and Current modes outputs are considered in the units equivalent to cps
Calibration factor	K_{Y^0}	From in-vessel calibration & simulation
Total Neutron Flux	$Y_n(t) = K_{Y^0} \cdot C(t)$, $\Delta Y_n(t)$	+ Weighted average method
Fusion power	$P_f(t) = k \cdot Y_n(t)$	k, [eV/n] – reaction energy release per one neutron

Calibration factors for DD plasma (DNFM)

True values

- $C_{tot} \approx FR_{tot} = FR_{DD} + FR_{DT}$
- $Y_{tot} = Y_n^{DD} + Y_n^{DT}$
- $P_{tot} = k^{DD} Y_n^{DD} + k^{DT} Y_n^{DT}$

Measured values if we distinguish DT & DD

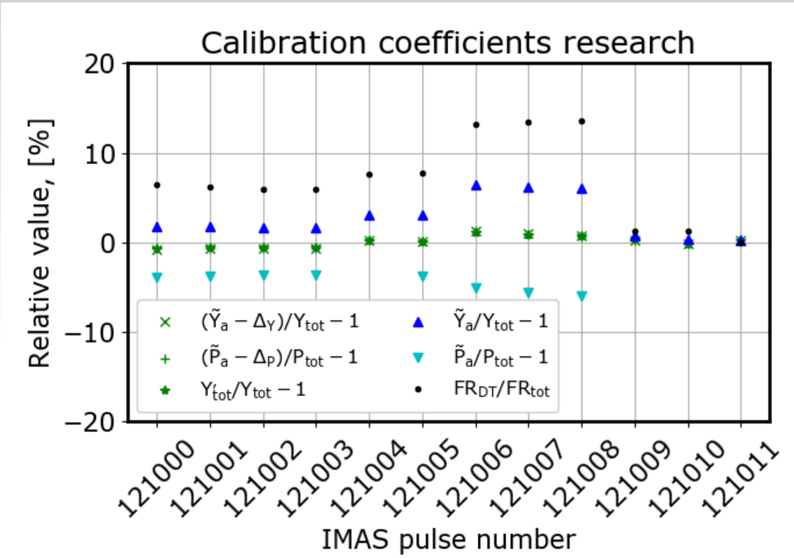
- $Y'_{tot} = K_{Y0}^{DD} FR_{DD} + K_{Y0}^{DT} FR_{DT}$
- $P'_{tot} = k^{DD} K_{Y0}^{DD} FR_{DD} + k^{DT} K_{Y0}^{DT} FR_{DT}$

Measured values with our assumptions

- $\widetilde{Y_a} = K_{Y0}^{DD} FR_{tot} = K_{Y0}^{DD} (FR_{DD} + FR_{DT})$
- $\widetilde{P_a} = k^{DD} \widetilde{Y_a} = k^{DD} K_{Y0}^{DD} (FR_{DD} + FR_{DT})$

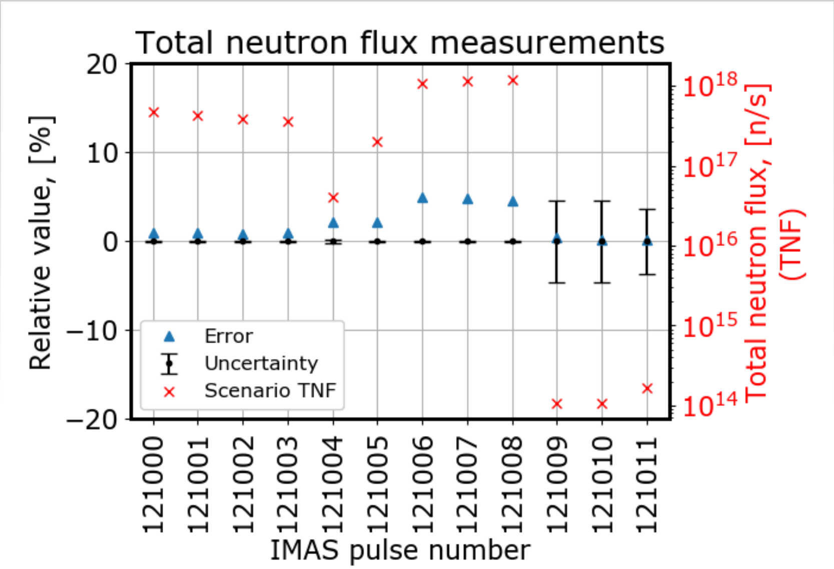
Error of measurements with our assumptions

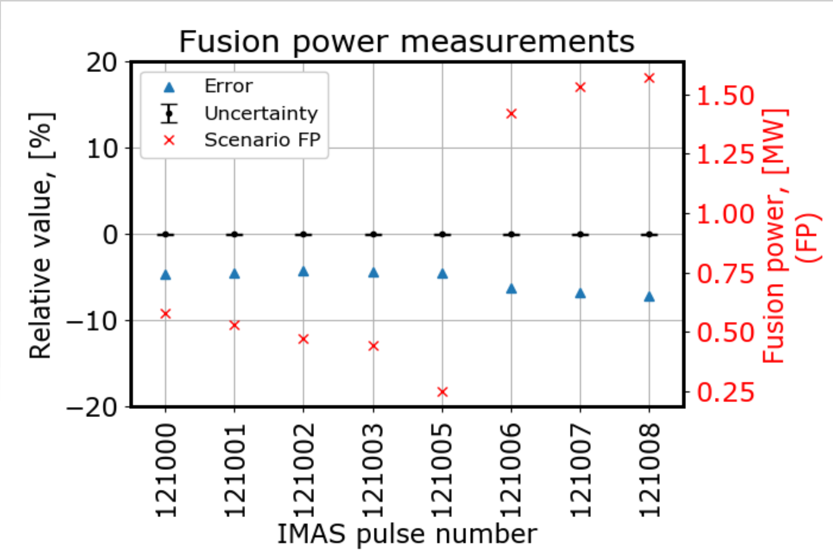
- $\Delta_Y = \widetilde{Y_a} - Y'_{tot} = \left(\frac{K_{Y0}^{DD}}{K_{Y0}^{DT}} - 1 \right) Y'_{DT}$
- $\Delta_P = \widetilde{P_a} - P'_{tot} = \left(\frac{k^{DD} K_{Y0}^{DD}}{k^{DT} K_{Y0}^{DT}} - 1 \right) P'_{DT}$



$K_{Y0}^{DD} / K_{Y0}^{DT}$	~1,6
$k^{DD} K_{Y0}^{DD} / k^{DT} K_{Y0}^{DT}$	~0,7

DNFM measurements simulation for DD plasma

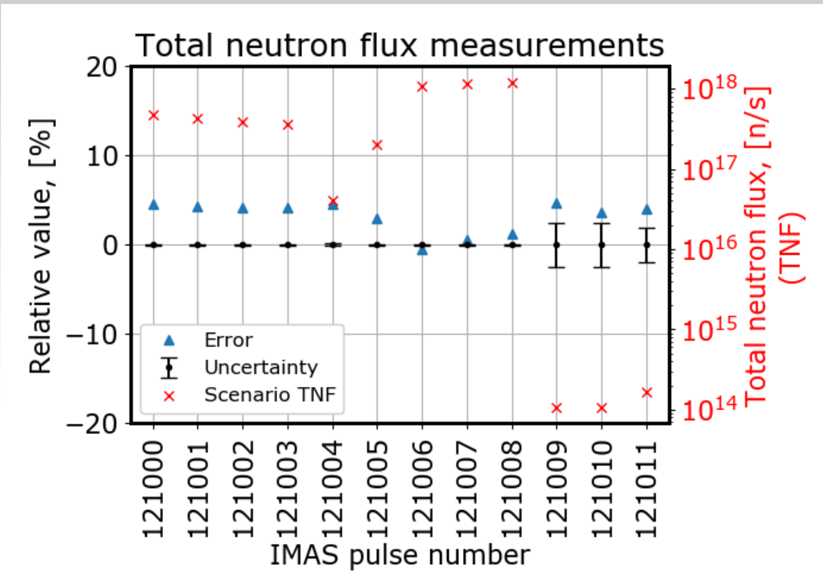


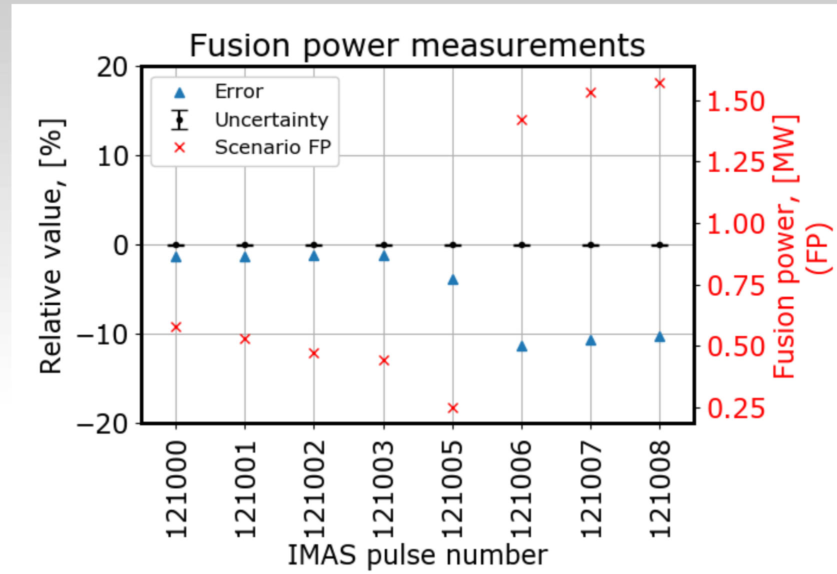


The red crosses on a plots are the values of Total neutron flux or Fusion power (right Y-axis) for each IMAS pulse number (X-axis).
The blue triangles are the measurements error value linked with the provided assumptions

$$Rel.error = \frac{Measured\ value}{True\ value} - 1 \qquad Rel.uncertainty = \frac{Abs.uncertainty}{Measured\ value}$$

NFM measurements simulation for DD plasma





The red crosses on a plots are the values of Total neutron flux or Fusion power (right Y-axis) for each IMAS pulse number (X-axis).
The blue triangles are the measurements error value linked with the provided assumptions

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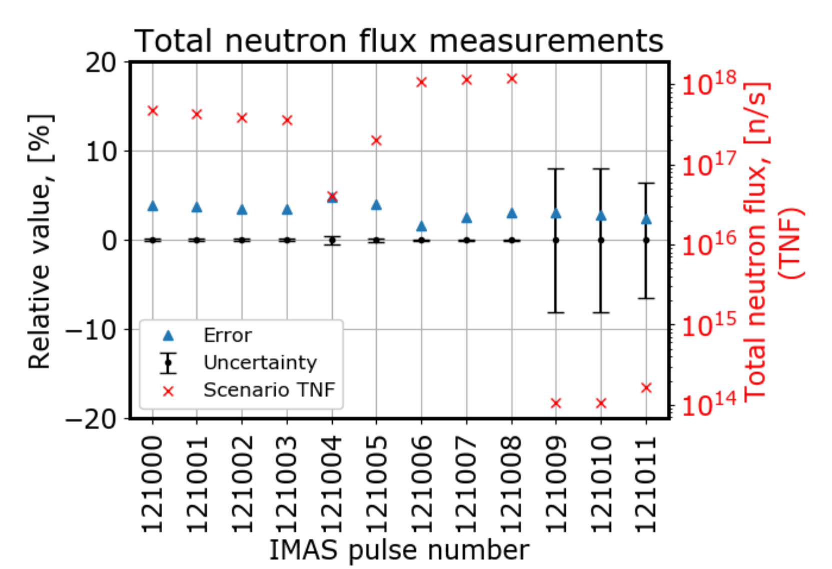
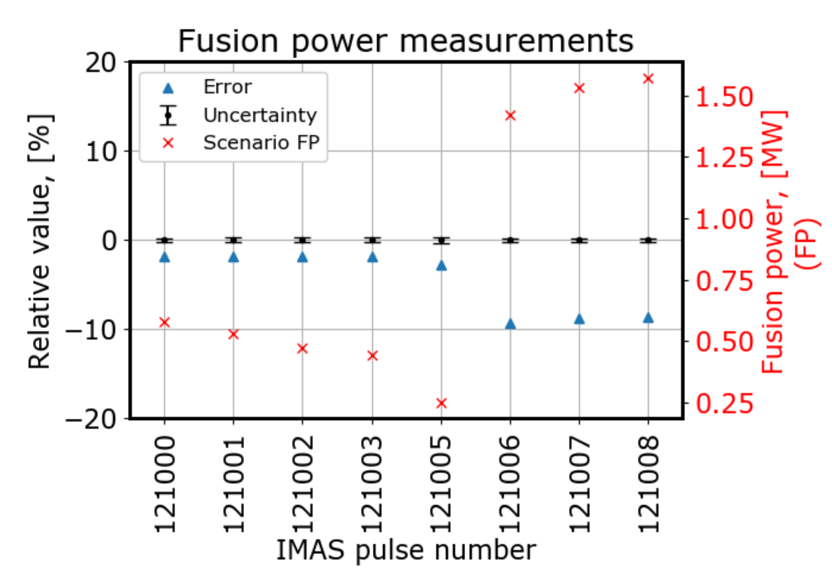
MFC measurements simulation for DD plasma





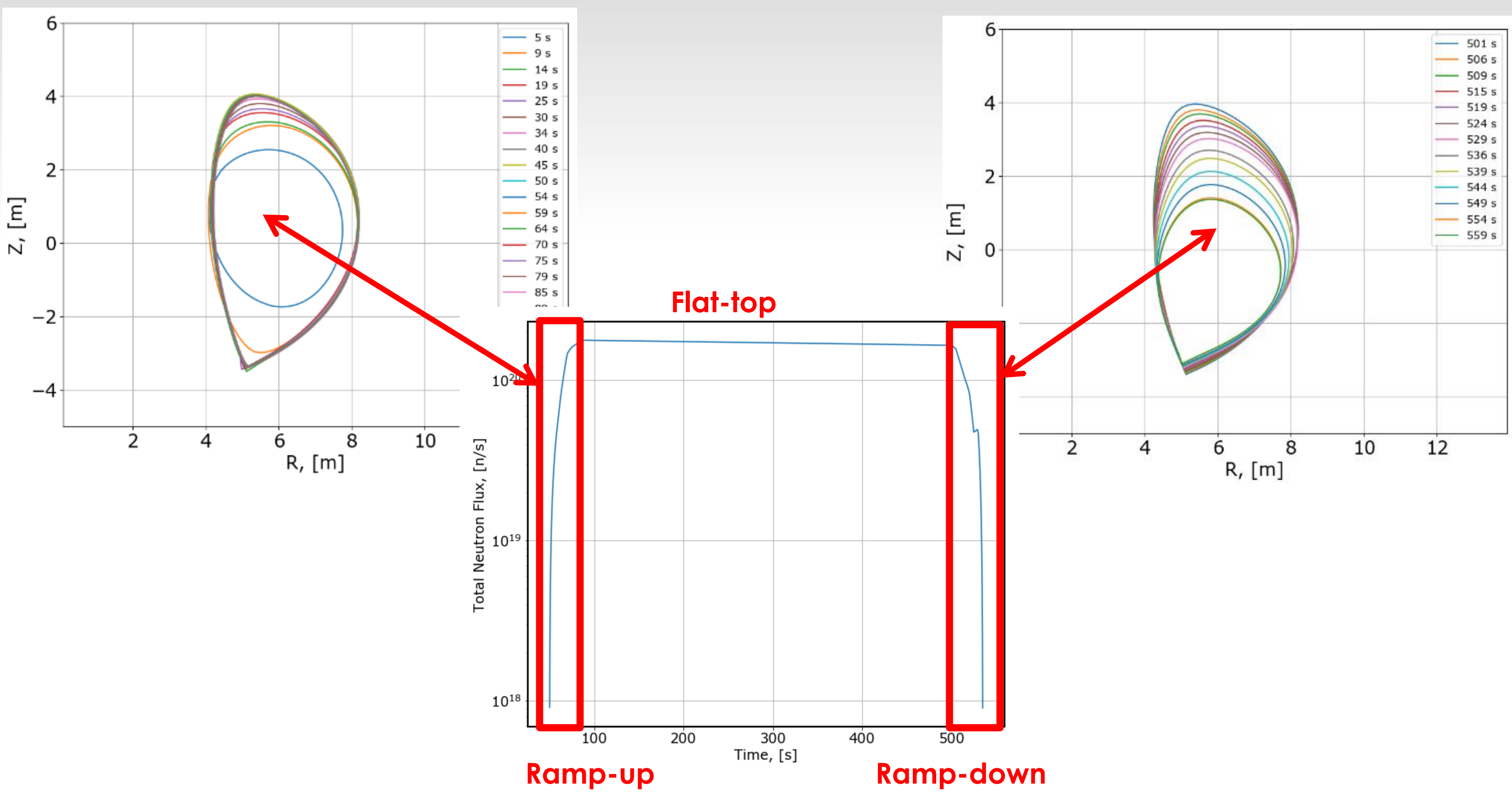
The red crosses on a plots are the values of Total neutron flux or Fusion power (right Y-axis) for each IMAS pulse number (X-axis).
The blue triangles are the measurements error value linked with the provided assumptions

$$Rel.error = \frac{Measured\ value}{True\ value} - 1 \qquad Rel.uncertainty = \frac{Abs.uncertainty}{Measured\ value}$$

ITER plasma baseline scenario

Plasma compound: D:T = 1:1
Max. Fusion power: 500 MW
Current: 15 MA
Fusion energy gain factor Q: 10
Max. Ion temperature: 25 keV

Neutron source properties:
1) DT neutrons
2) Toroidally symmetric
3) On a given magnetic surface, the plasma parameters are constant



A.R. Polevoi et al., "**Assessment of neutron emission from DD to DT operation of ITER**," *42th EPS Conference on Plasma Physics*, (2015).

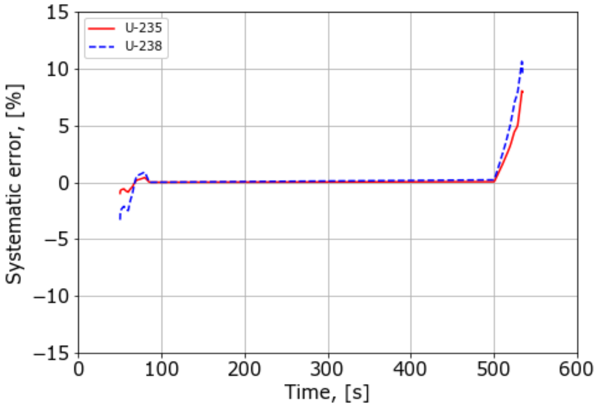
Systematic error (on each FC)

$Y_n(t)$ - *real*

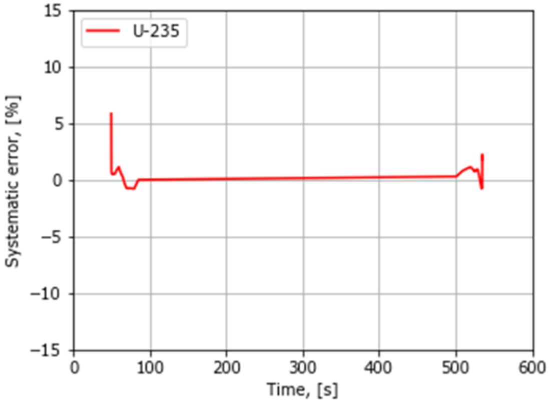
$\widetilde{Y_n}^i(t) = K_{Y_0}^i \cdot C^i(t)$- *measured*

Systematic rel. error = $(\widetilde{Y_n}^i(t) - Y_n(t))/Y_n(t)$

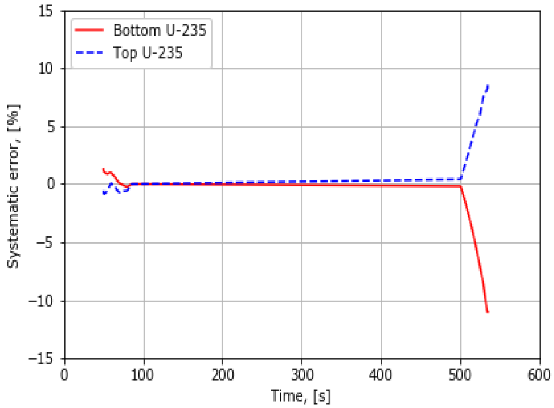
DNFM



NFM



MFC

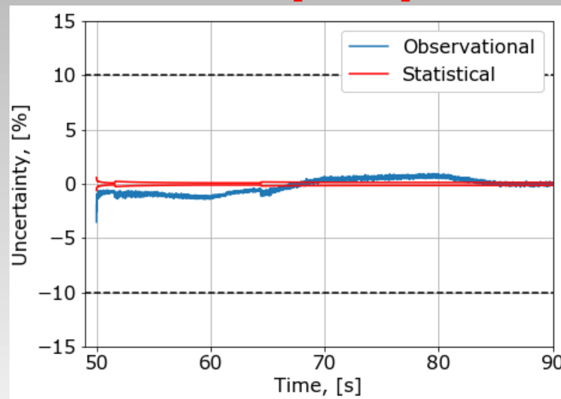


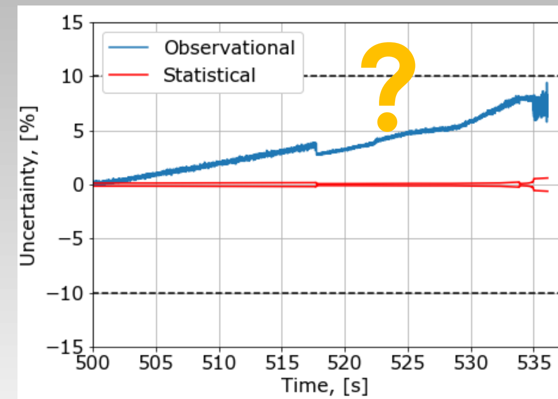
(stat. noise is not included)

Separate measurements simulation

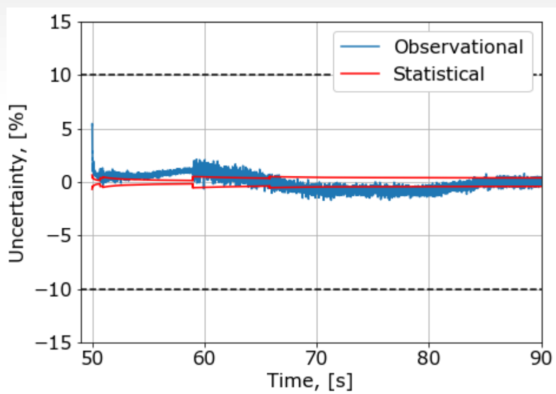
Ramp-up | **Ramp-down**

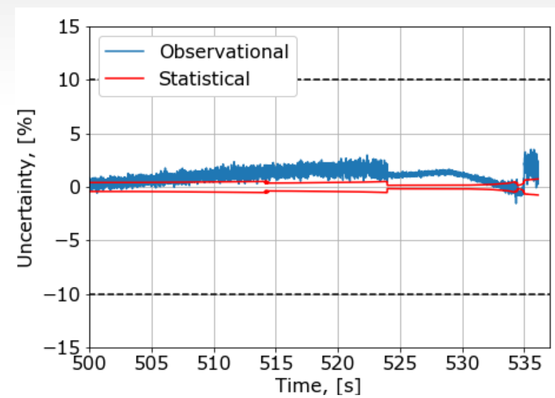
DNFM



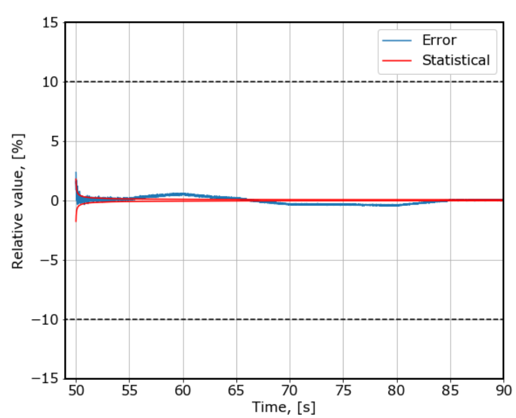


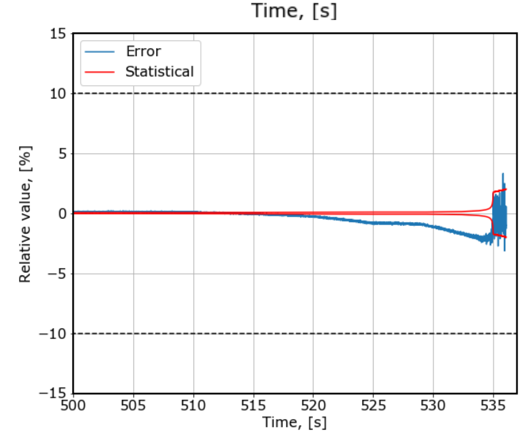
NFM





MFC



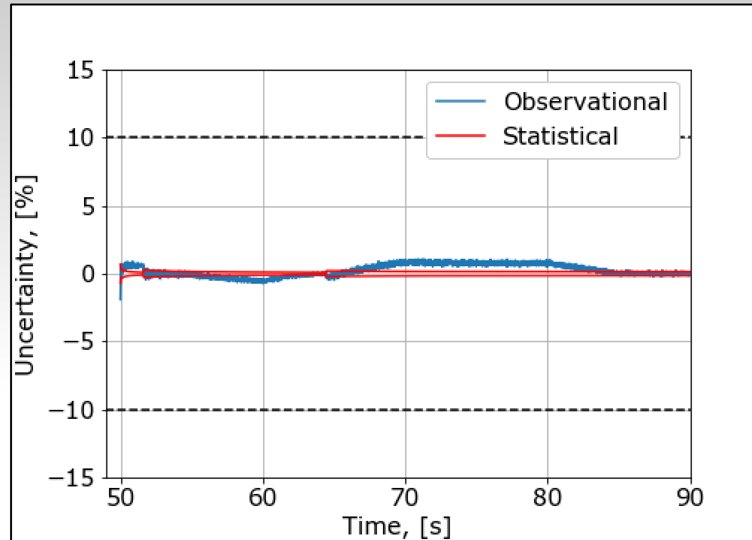


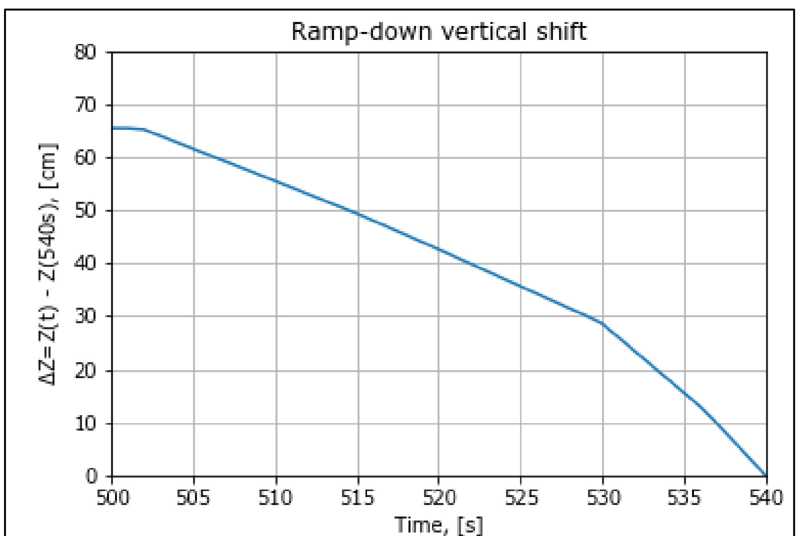
Plasma position correction for DNFM

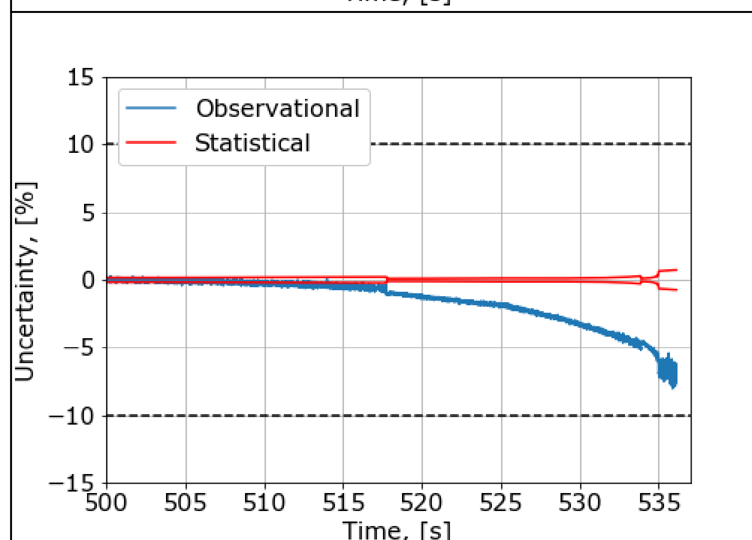
FC#	Ratio $K_V = K_{Y_0}/K^r(R_0,Z_0)$, [a.u.]
1	0.90
2	0.87
3	0.92
4	0.79
5	0.78
6	0.79

$$K^r(R,Z) = \boldsymbol{interp\_lin\_2D}\left(\left\{\frac{Y^r}{C^r}(R_i,Z_j)\right\}\right)$$

$$K_Y(t) \equiv K_V \cdot K^r\big(R(t),Z(t)\big)$$







Systematic uncertainty estimation

1) Estimate dependence of measurements from plasma position

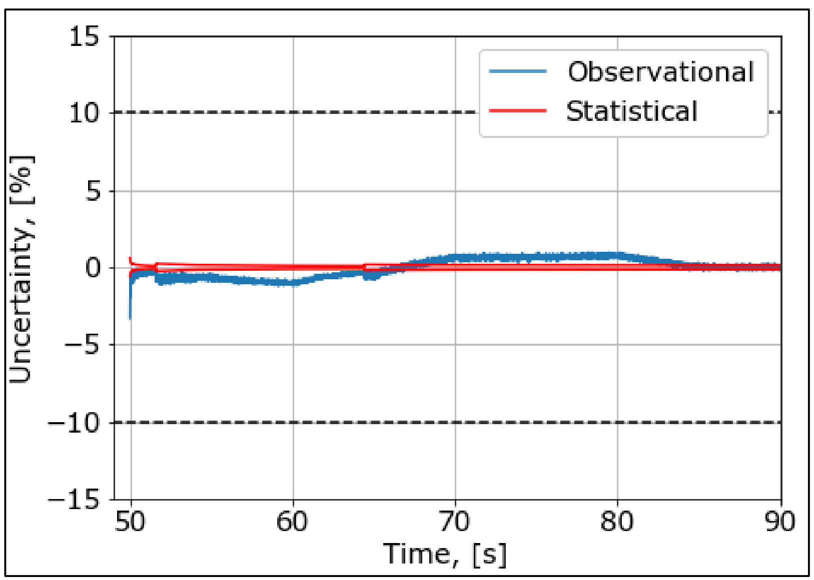
$$K_Y(t) \equiv K_V \frac{\left(K^r(R,Z) + K^r(R_0,Z_0)\right)}{2}$$

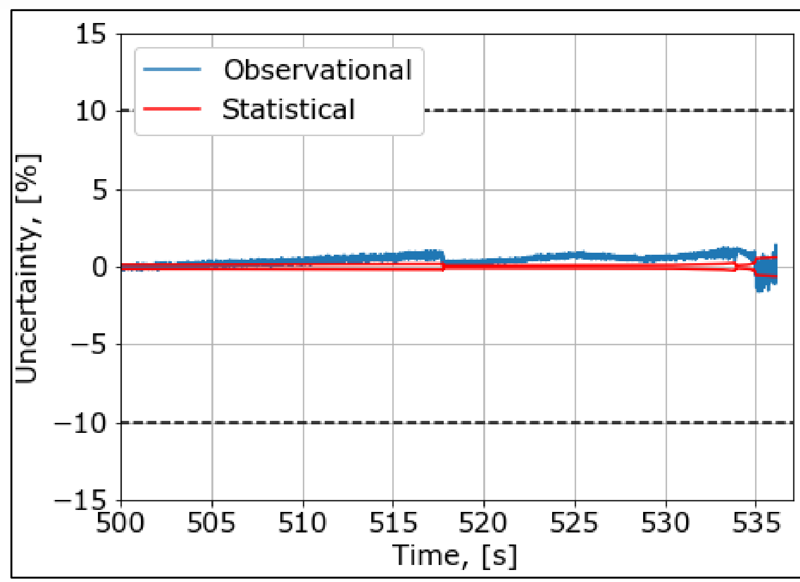
2) Estimate systematic error

$$\varepsilon_{Sys}(t) = \frac{K_Y(t) - K_Y^0}{K_Y^0}$$

DNFM

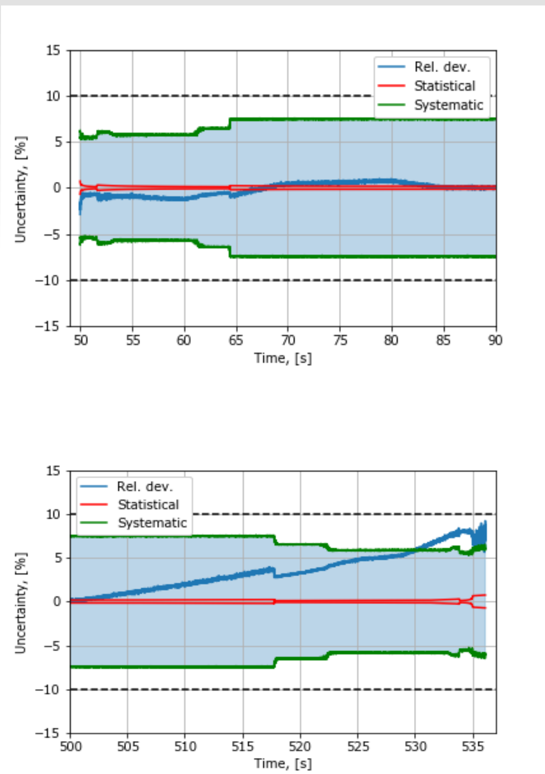
(corrected using (1))



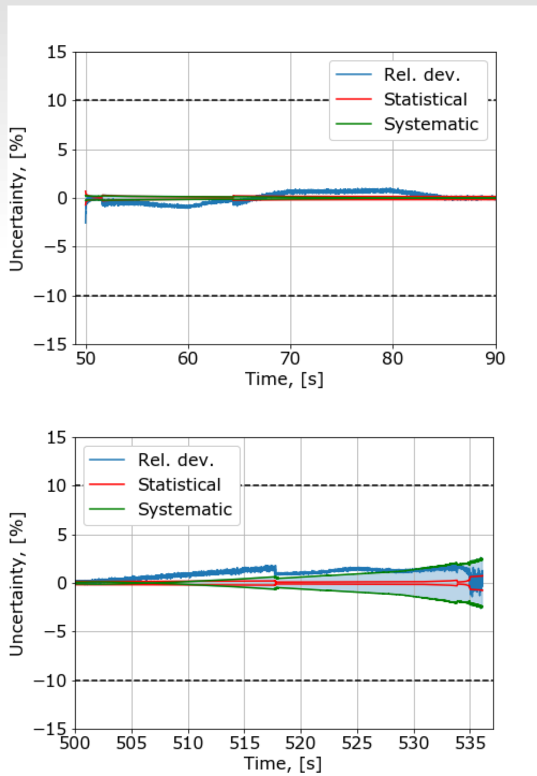


Systematic error analysis

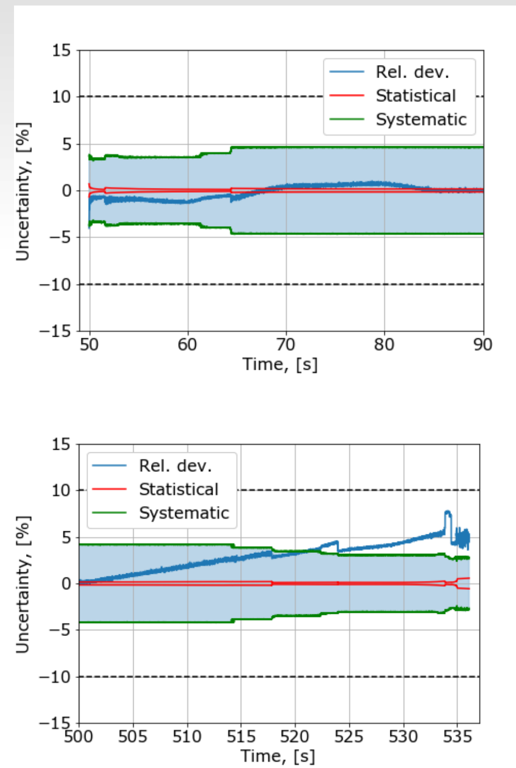
Method#	Description	Systematic error
1	Single DNFM	Tabulated
2	DNFM with the plasma position correction	Estimated
3	DNFM + NFM	Tabulated for NFM and DNFM
4	Method #2 + NFM	Estimated using plasma position value for DNFM and tabulated for NFM
5	DNFM + NFM + MFC	



Method #1



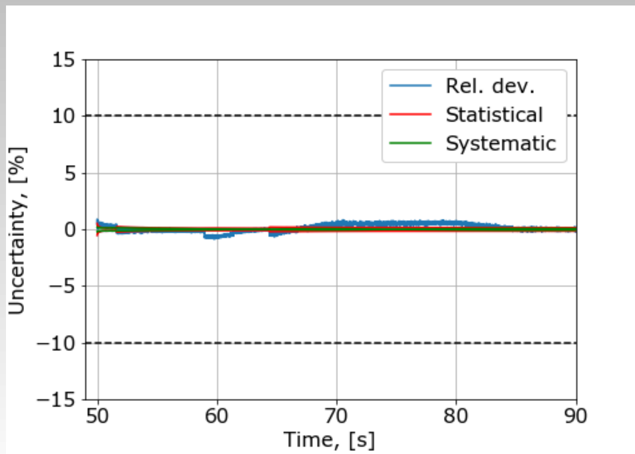
Method #2

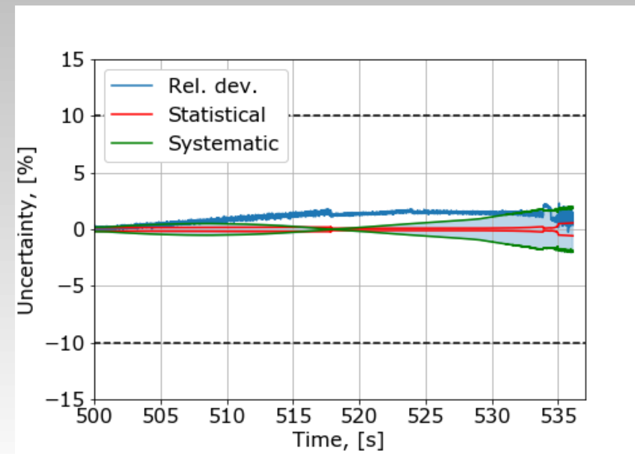


Method #3

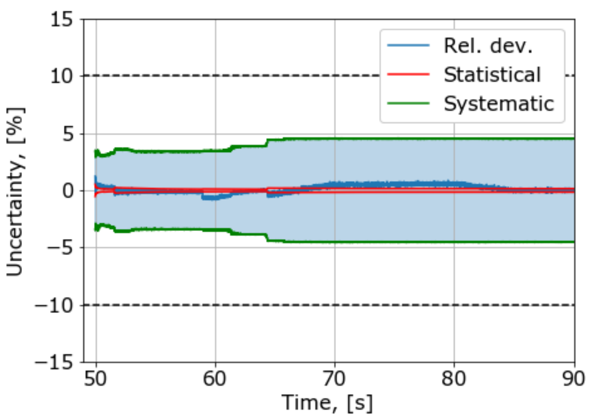
Systematic error analysis

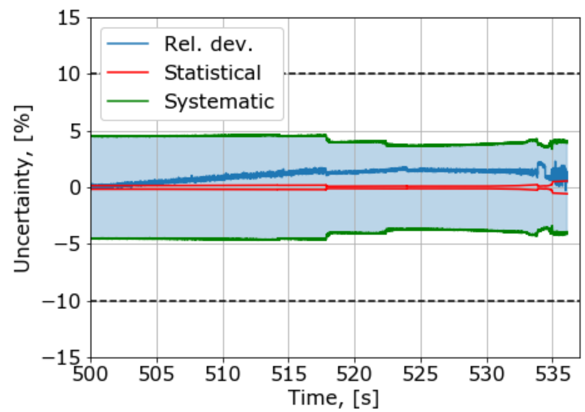
Method #4





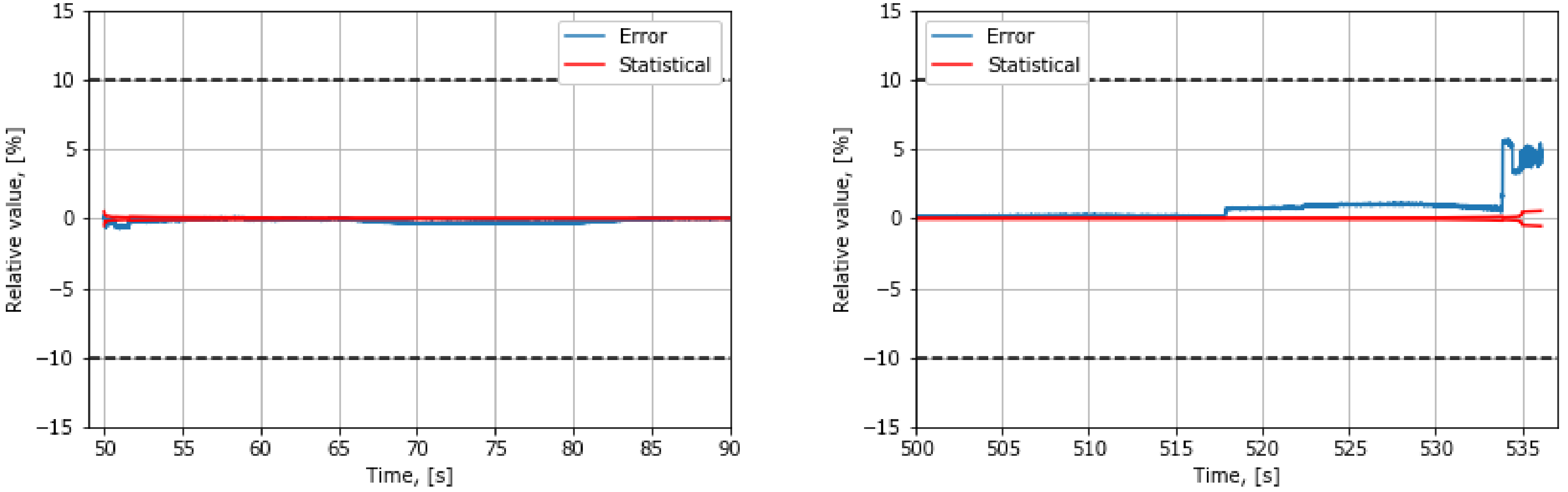
The total uncertainty value for Methods #1, 2 and 3 will not exceed the value 9.4%, 5.0% and 6.4% respectively, if worth calibration uncertainty level achieved: $\delta K_{Y_0} = 10\%$ *and confidence level 95 %*





Systematic error analysis

Method #5



Systematic error caused by neutron emission profile and plasma geometry changes reduced to minimal value

Best algorithm

Value	Equation	Additional information
Count rate (DNFM, NFM, MFC)	C	**3** modules DNFM x **6** FC x **4** measuring modes + **3** NFM FC x **3** measuring modes + **4** modules MFC x **2** measuring modes = **89** outputs
Calibration factor	K_Y^0	From in-vessel calibration
Plasma position correction (for DNFM)	$K_Y(t) = K_V \dfrac{\left(K^r\left(R(t), Z(t)\right) + K^r(R_0, Z_0)\right)}{2}$	K_V - ratio of C from ring and volumetric sources $K^r(R, Z)$ - interpolation of calibration results
Estimate systematic error (for DNFM)	$\sigma_{Sys}Y(t) = \varepsilon_{Sys}(t) \cdot K_Y(t) \cdot C(t)$ $\delta Y(t) = \sqrt{\delta_{Sys}^2 Y(t) + \delta_{St}^2 Y(t)}$ $\varepsilon_{Sys}(t) = \dfrac{K_Y(t) - K_Y^0}{K_Y^0}$	For each detector and measuring mode
Total neutron flux	$Y_n(t) = K_Y(t) \cdot C(t)$	+ Weighted average with NFM and MFC measurements
Fusion power	$P_f(t) = k_p \cdot Y_n(t)$	k_p, [eV/n] – reaction energy release per one neutron

Summary

- Method of Total neutron flux measurements was developed and tested on a DNFM, NFM EQ1 and MFC designs
- The systematic uncertainty caused by the neutron emission profile changes was automatically reduced using weighted averaging method of the detectors signal processing
- The use of plasma position information is recommended to minimize the systematic uncertainty and to evaluate systematic uncertainty
- DNFM, NFM and MFC designs satisfy Total neutron flux reconstruction accuracy requirements (with confidence level 95%)
  taking into account the fluctuations of the neutron emission profile, plasma equilibrium geometry, statistical and systematic uncertainties
- Method (#5) of integrated measurements by ITER neutron monitors proposed and can be used by IO team on Total neutron flux and Fusion power reconstruction.
- The integration of diagnostics will ensure the best accuracy of Total neutron flux and Fusion power measurements.

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Questions?

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