Innovation on ITER neutron diagnostics towards DEMO

M. Sasao

Advanced Diagnostics for Burning Plasmas

Out lines

- Introduction
- Neutron diagnostics on ITER
- Fusion output measurement and the calibration strategy for it
- Neutron diagnostics for physics understandings
- Summary

This presentation was prepared on the basis of discussion among the ITPA-daignostics Neutron working group.

Introduction
- Fusion Reaction Rates

Three terms constitute an actual reaction rate in a plasma of an unit volume, the thermo-nuclear term,

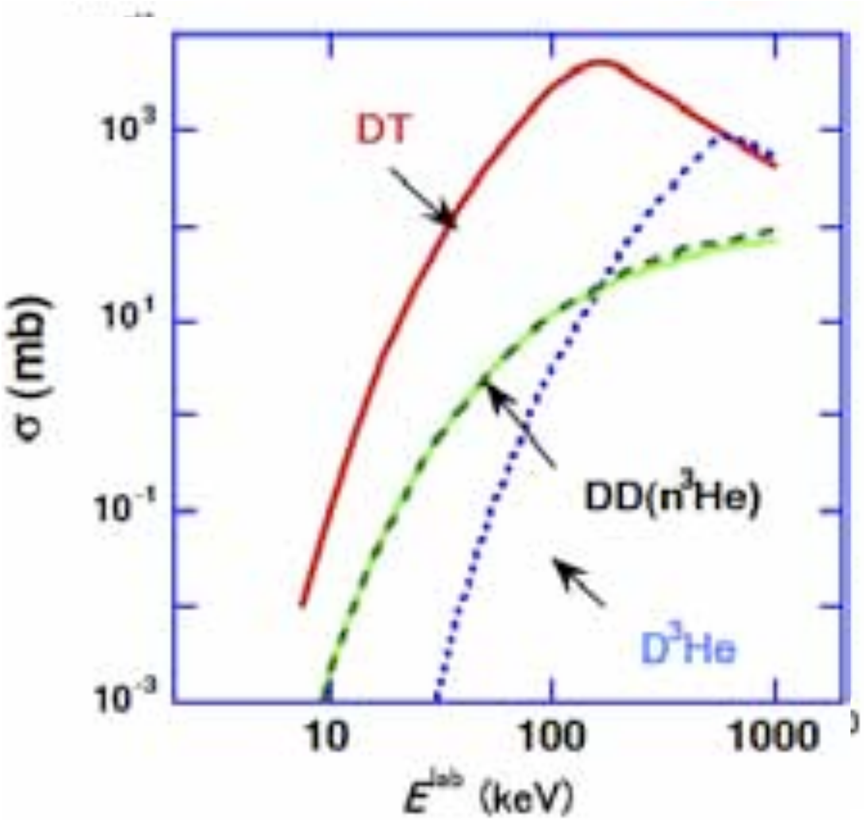
the beam thermal term and the beam-beam term.

$$Y_{\text{total}} = Y_{\text{th}} + Y_{\text{b-th}} + Y_{\text{b-b}}$$

$$\begin{cases} Y_{th} = n_j n_i \langle \sigma v \rangle_{Ti} & j \neq i \\ Y_{th} = \frac{1}{2} n_i^2 \langle \sigma v \rangle_{Ti} & j = i \end{cases}$$

$$Y_{b-th} = n_b n_i \langle \sigma v \rangle_{b-th}$$

$$Y_{b-b} = \tfrac{1}{2} n_b^{\ 2} \langle \sigma v \rangle_{b-b}$$



Fusion cross sections as a function of the energy of the reacting particles(a) and fusion reactivities for Maxwellian ion distributions as a function of T_i (b).

Introduction
- Role of neutron measurement -present

•In many magnetic-confinement fusion devices to date, where tritium is **not** introduced, but the plasma contains energetic deuterons, the dominate term is the beam-thermal DD term, $Y_{b\text{-}t.}$

•The measurement of fusion reactivities in the present devices does provide the information of energetic-ion behaviors, not directly provide the THERMO-NUCLEAR fusion output.

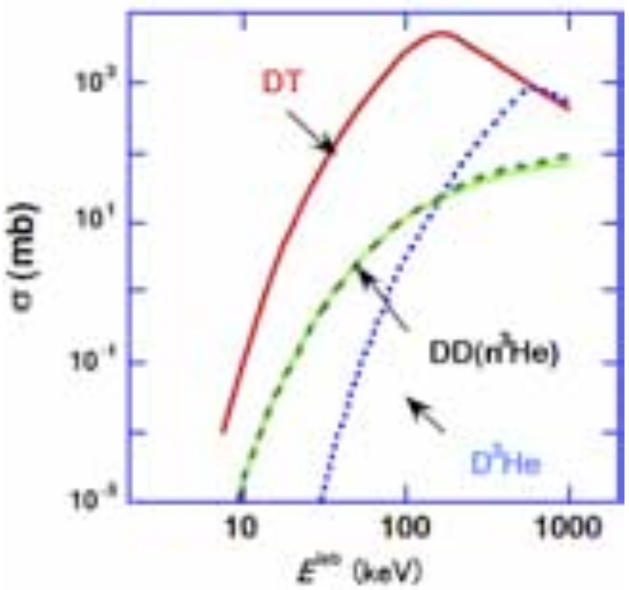
•Tritons produced through

d + d => t (1 MeV) + p (3 MeV)

undergo

d + t => n (14 MeV) + α (3.6 MeV),

and confinement of energetic-ion can be simulated (triton burn-up)



$$Y_{b-th} = n_b n_i \langle \sigma v \rangle_{b-th}$$

Introduction
- Role of neutron measurement -ITER

•In ITER, both thermal, Y_{th} ,, and the beam-thermal term, $Y_{b\text{-}t.}$ contirubute, but the thermal reaction is dominant in self heating phase .

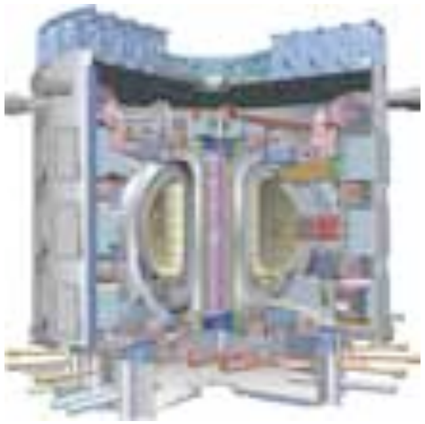
$Y_{b\text{-}t.}$: External beam Heating phase

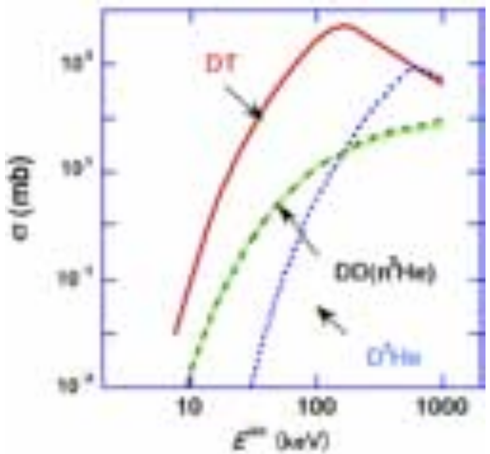
30MW NBI, 10^{20} Plasma ~ 3 x 10^{16} n/m^3

$Y_{th.}$:

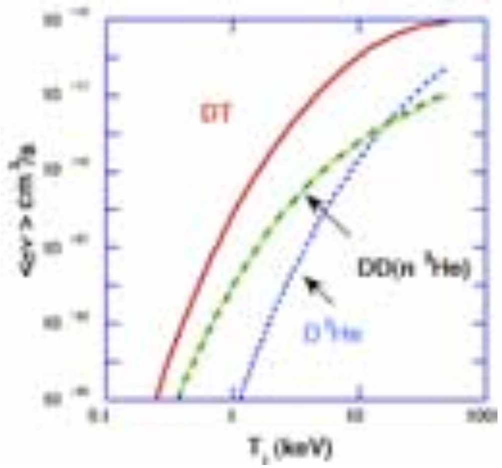
Ti=10keV, 10^{20} Plasma ~ 3 x 10^{17} n/m^3

Ti=20keV, 10^{20} Plasma ~ 10^{18} n/m^3





major radius	6.2	m
minor radius	2.0	m
volume	840	m^3
plasma current	15.0	MA
on-axis toroidal field	5.3	T
fusion power	500	MW
burn flat top	>400	s
energy multiplication	>10	

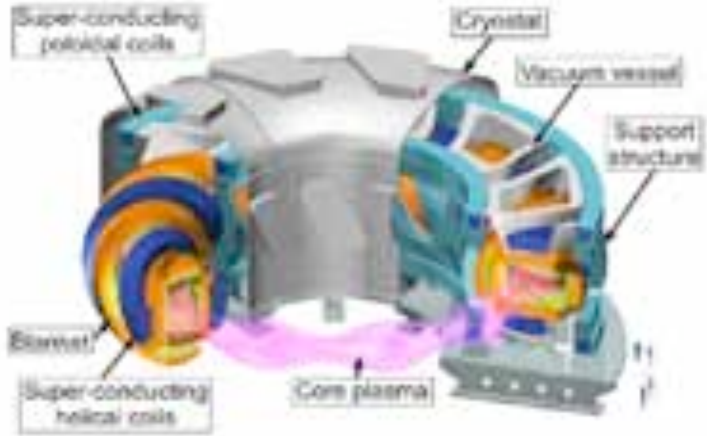


Introduction
- Role of neutron measurement DEMO

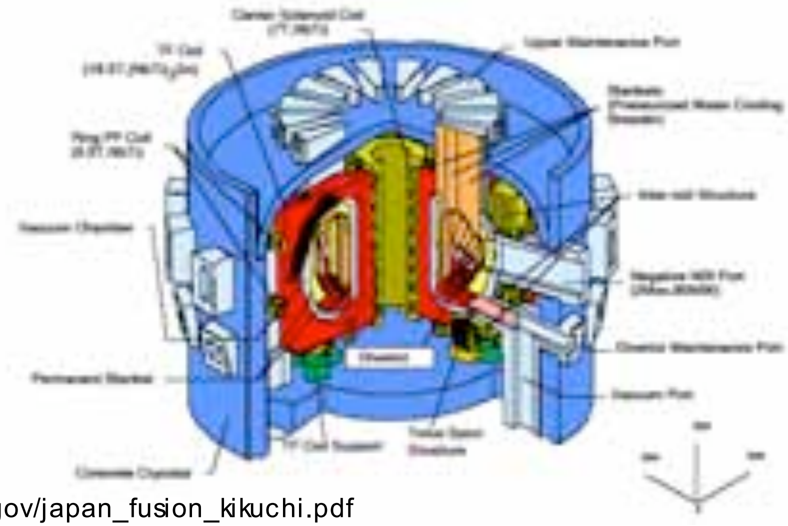
Only the thermal reaction contributes to the neutron emission.

$$P_{output} \sim 2 \sim 3\ \mathrm{GW}$$

$$P_{output}/P_{ext} \sim 50 \sim \infty$$



Nucl. Fusion **47** (2007) 1411–1417



http://fire.pppl.gov/japan_fusion_kikuchi.pdf

		Design Value
Plasma Current	I_p	12MA
Toroidal Field Coil	B_t	9T
Major Radius	R	7m
Aspect Ratio	A	4.1
Elongation	κ_{95}	1.85
Normalized Beta	β_N	3.5
Fusion Output	P_f	3GW
Current Drive Power	P_{CD}	60MW
Net Electric Output Power	P_e	1.08GW
Fusion Gain	Q	50
Averaged Neutron Wall Load	P_{nw}	$3\mathrm{MW/m^2}$

Introduction

- Information from Neutron Diagnostics on ITER

Fusion Output (Total reaction rate), Neutron fluence on the First Wall

Emissivity Profile, Profile changes

Energetic Particle Behavior, redistribution

Ion temperature, Ion temperature profile, Profile change

Energy Spread

Energetic Particle Behavior, Slowing down process

Ion temperature

Super Energetic Neutrons

Alpha Knock-on

Y_{DT}/Y_{DD} ratio

n_T/n_D ratio

Nuetron Diagnostics on ITER
- systems

Fusion Output (Total reaction rate), Neutron fluence on the First Wall

Neutron Flux monitors, activation systems

Emissivity Profile, Profile changes

Radial Neutron Camera, Vertical Neutron Camera

Energy Spread

Compact neutron spectrometers in Radial Neutron Camera,

Compact neutron spectrometers in Vertical Neutron Camera

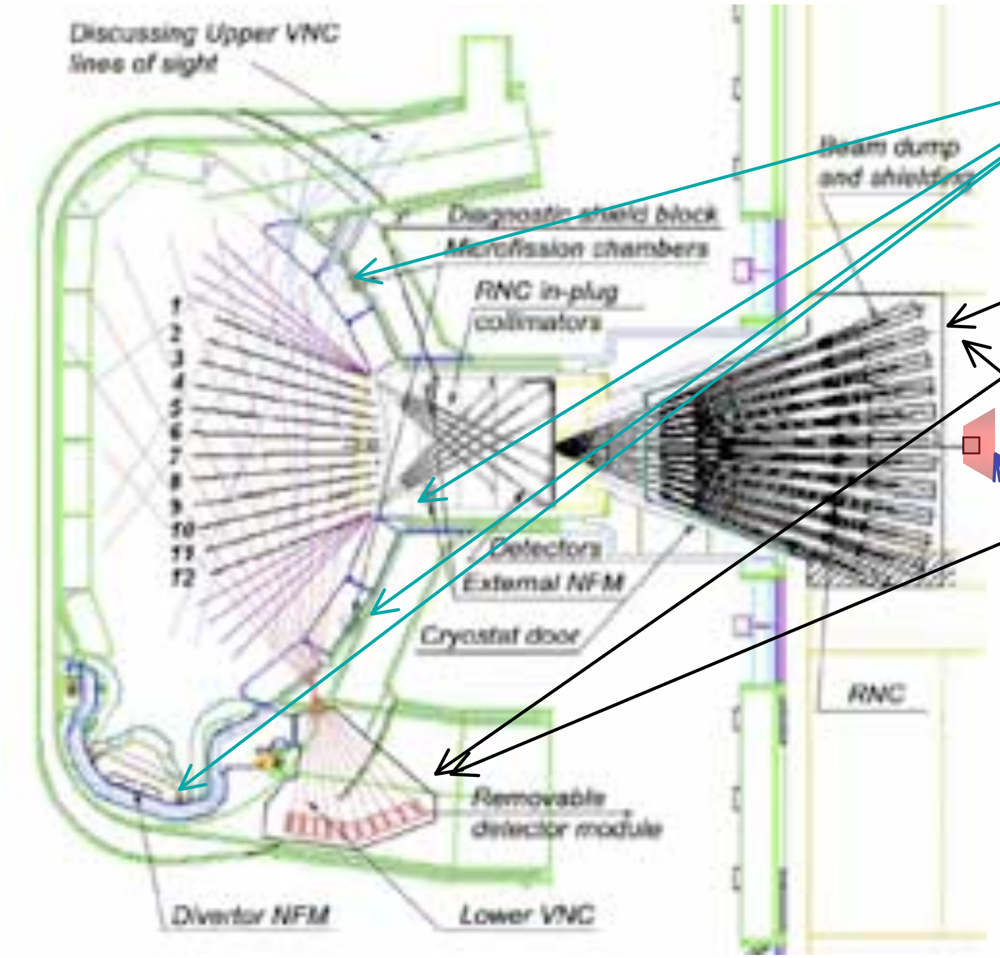
Super Energetic Neutrons

High Resolution Neutron Spectrometer

Y_{DT}/Y_{DD} ratio

Medium Resolution Neutron Spectrometer

Neutron Diagnostics on ITER
- systems



Neutron Flux monitors,
Activation systems

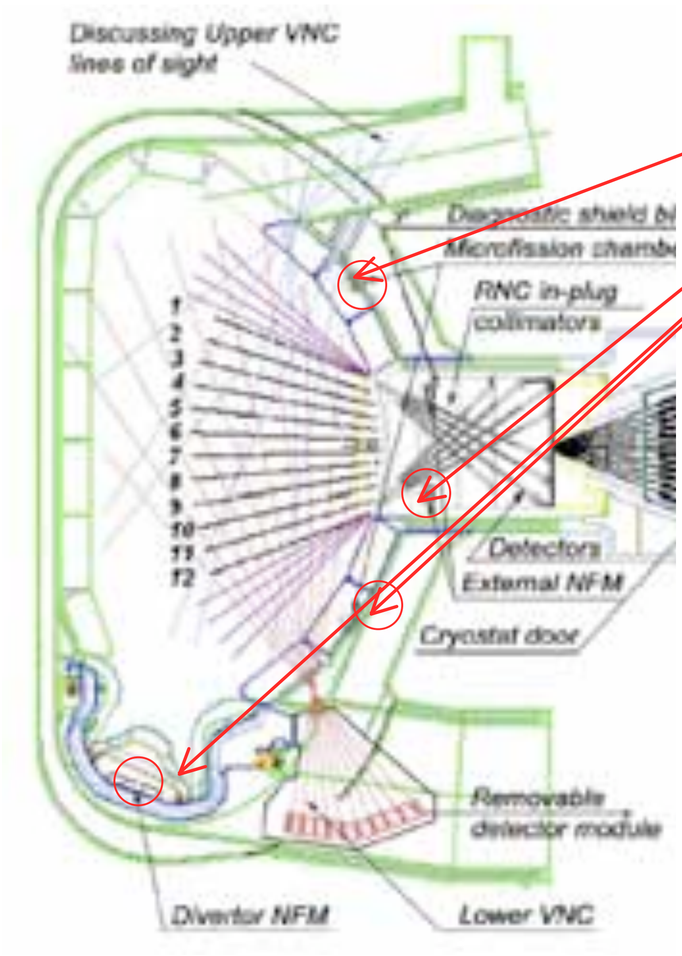
Radial Neutron Camera,
Vertical Neutron Camera

Compact neutron spectrometers in RNC,VNC

High Resolution Neutron Spectrometer

Medium Resolution Neutron Spectrometer

Fusion output measurement
- reliability and accuracy

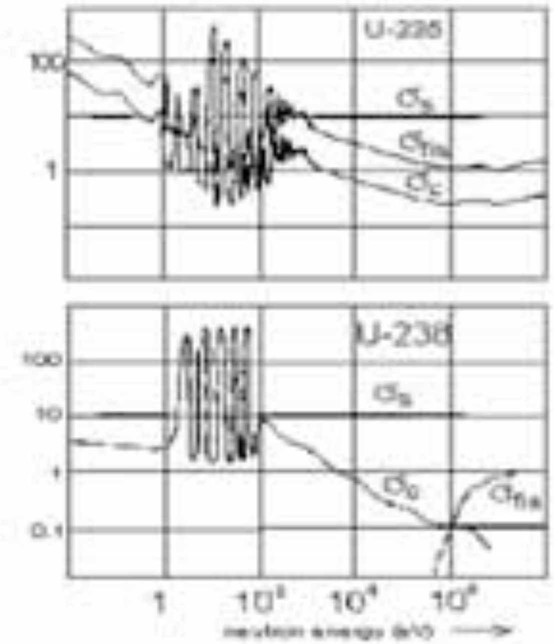


10% accuracy is required

Neutron Flux monitors

Detectors are sensitive to low energy neutrons (1/v dependence).

Blanket modules and shield modules function as a neutron energy degrader and a moderator.



http://www.ricin.com/nuke/gifs/cross.gif

Out lines

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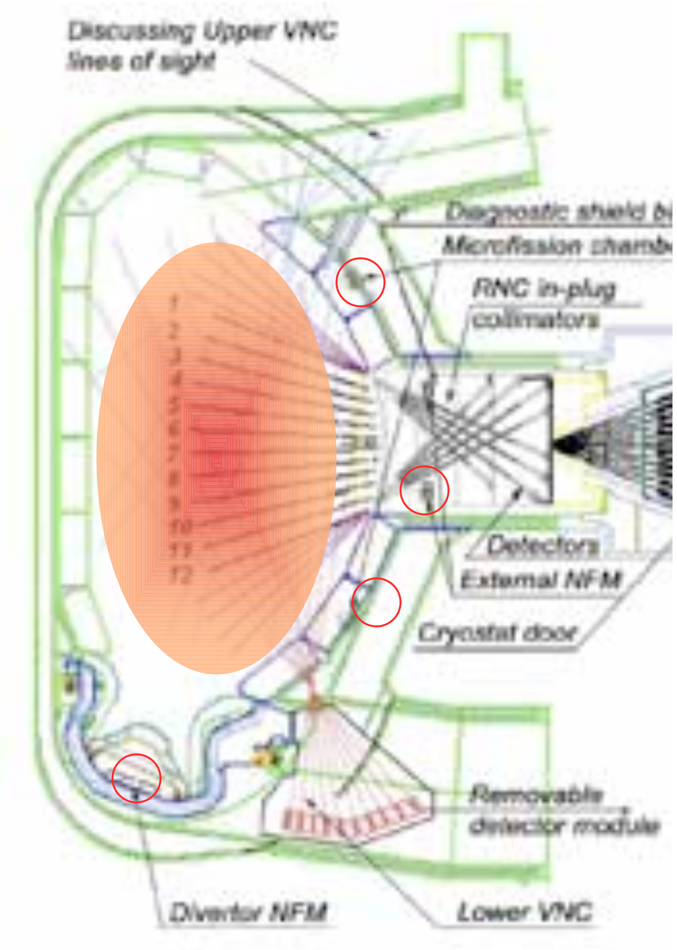
- Neutron diagnostics on ITER
- Fusion output measurement and the calibration strategy for it
- Neutron diagnostics for physics understandings
- Summary

Innovation on Fusion output measurement
- an extended source



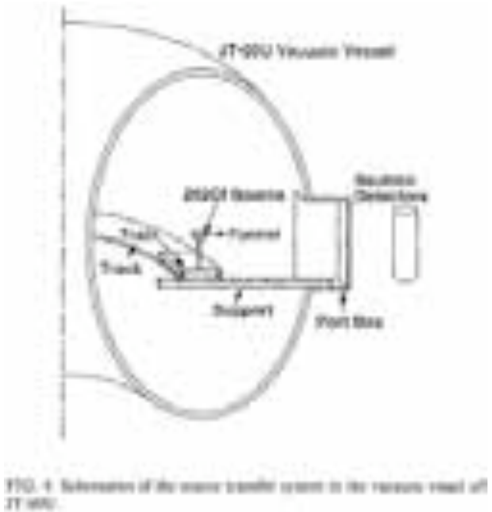
Neutron source is a volume source, extended into a donut shape.

$$C_n(\vec{X}_D) = \int Y(\vec{r})\,\eta(\vec{r},\vec{X}_D)\,d\vec{r}$$

$$C_n(\vec{X}_D) \qquad Y(\vec{r}) \qquad \eta(\vec{r},\vec{X}_D)$$

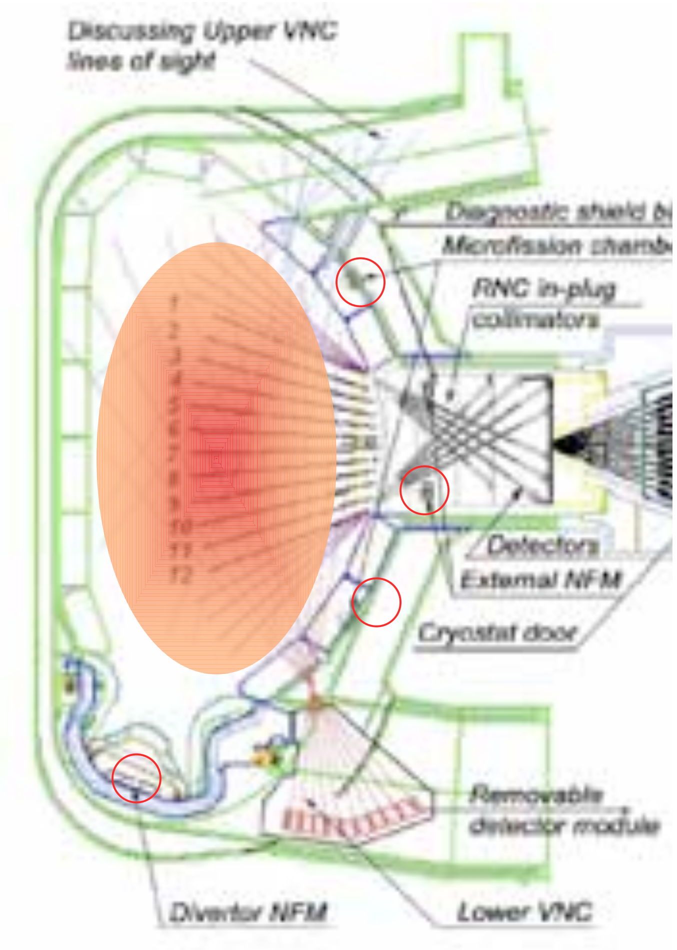
They are energy dependent.

Calibration using
a radio isotope (^{252} Cf) ,
DT/DD generators is needed.



T. Nishitani
Rev. Sci. Instrum. 63, 5270 (1992).

Innovation on Fusion output measurement
- should be supported by



Calibration

MCNP calculation is needed because of the difference in

the neutron energy distribution /

self-shadow effect.

Connection of measurement by many detectors/electronics

Activation systems

foils

water circulation - DEMO relevant

coolant temperature change

- DEMO relevant

Profile measurement

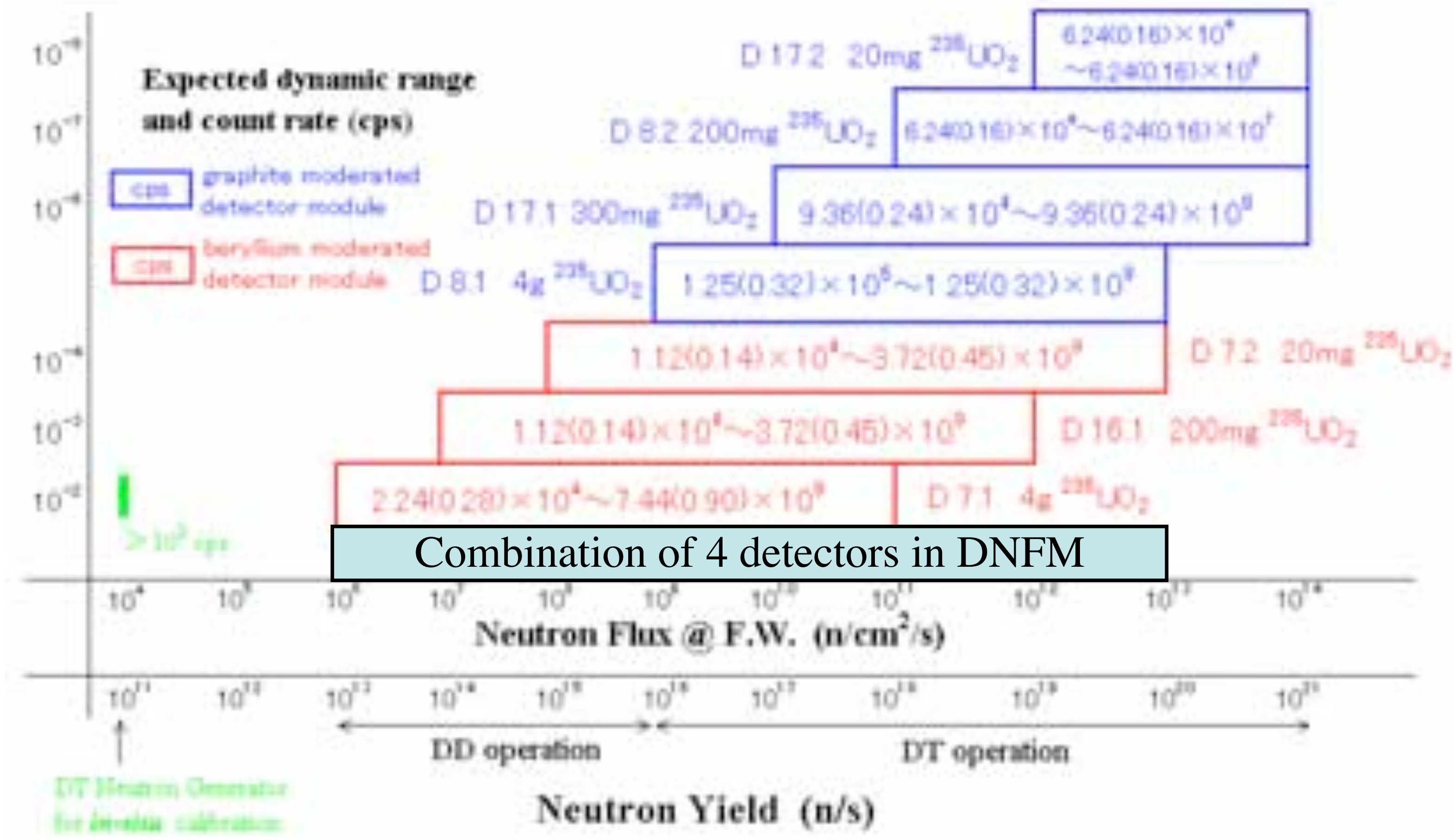
Profile changes

$Y_n(x)$ is not a function of Ψ .

Innovation on Fusion output measurement

- The dynamic range over 12 orders is required

Combination of 2 MCF's

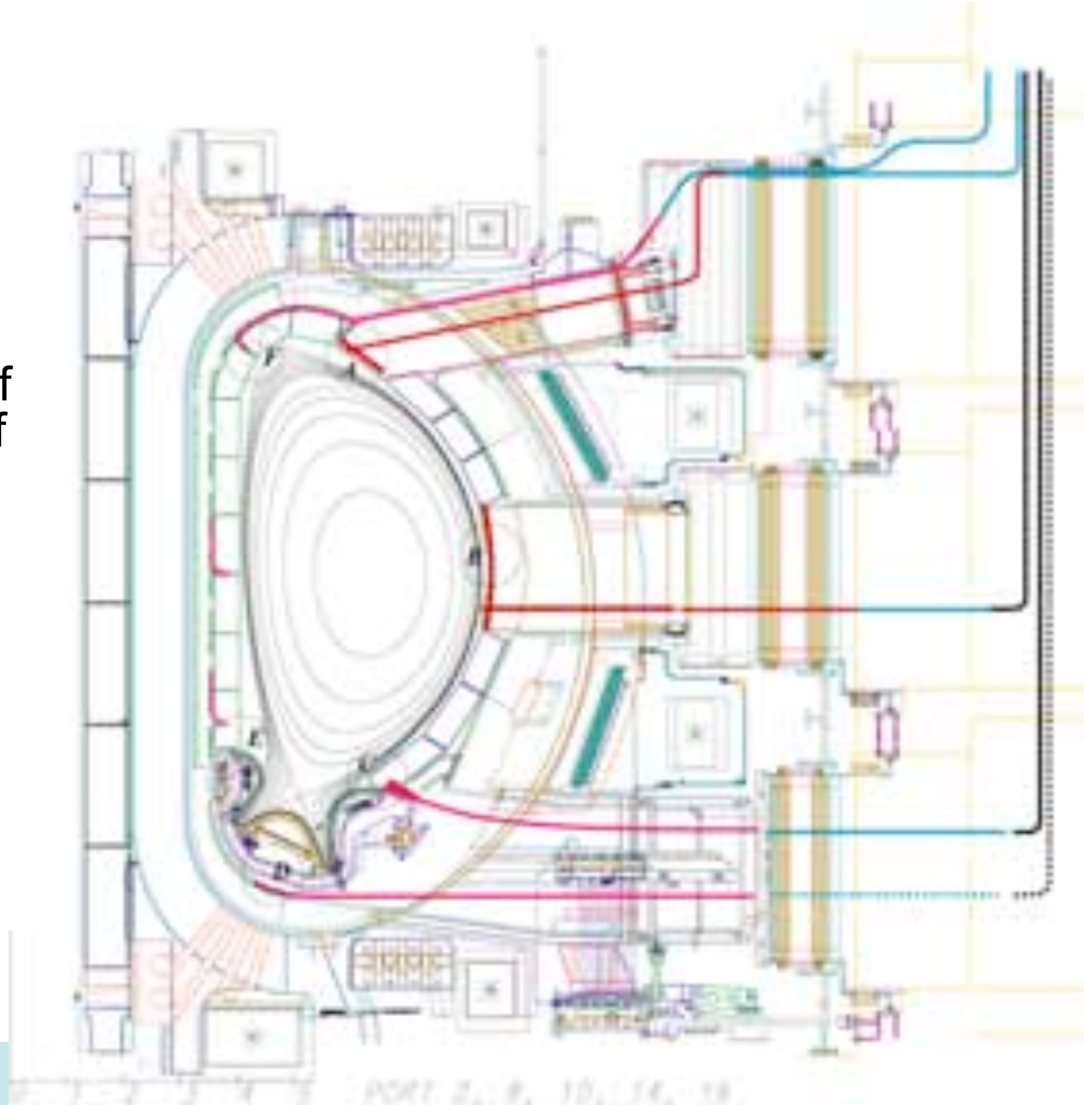


Foil activation

Irradiation Station & Transfer Line are under being designed.

Several irradiation positions are needed to guarantee the accuracy against the change of the plasma axis position,that of the neutron emission, etc..

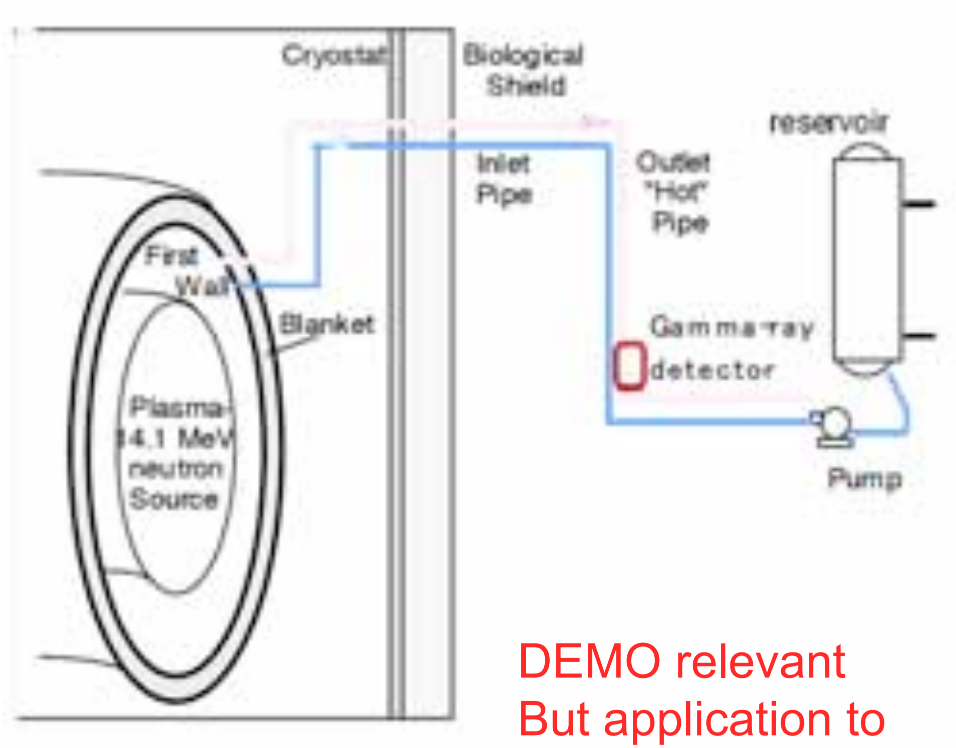
A Upper port plug
B Equatorial port plug
C Lower outboard VV wall
D Under Diverter Dome
E Lower inboard VV
F Upper inboard VV wall,
G Center inboard VV



Water Activation Systems

A neutron activation system with flowing water using the 16O(*n*,*p*)16N reaction

6.13 MeV gamma rays
the temporal resolution
would be less than the ITER requirement of 100 ms including turbulent diffusion effects for the flow
velocity of 10 m/s. With a flow velocity of 10 m/s, this system can measure the fusion power from
50 kW to 1 GW of the ITER operation by using two gamma-ray detectors;



DEMO relevant
But application to ITER is not decided yet

T. Nishitani
Rev. Sci. Instrum. 74, 1735 (2003).

Calorimetric measurements in ITER

J.C. Vallet & C.Portafaix

(EFDA-Euratom-CEA contract n° 03-1111)

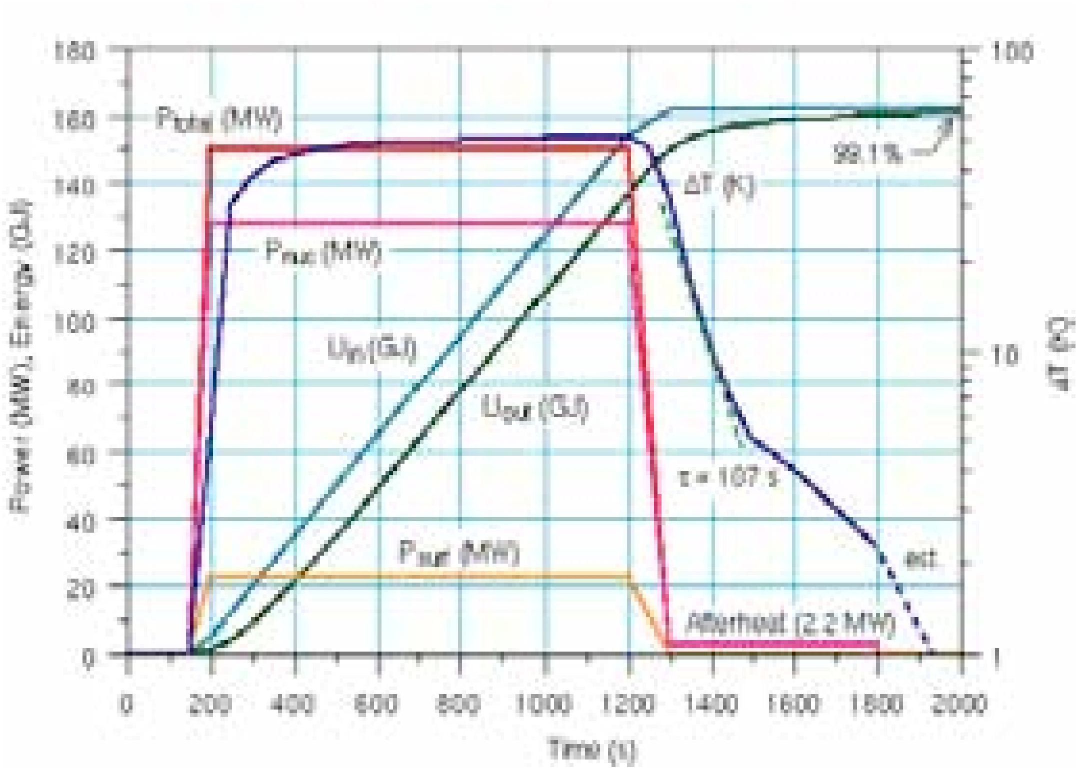


Fig. 3. Waveforms for one PFW/IBB HTS circuit with reference 1.5 GW pulse

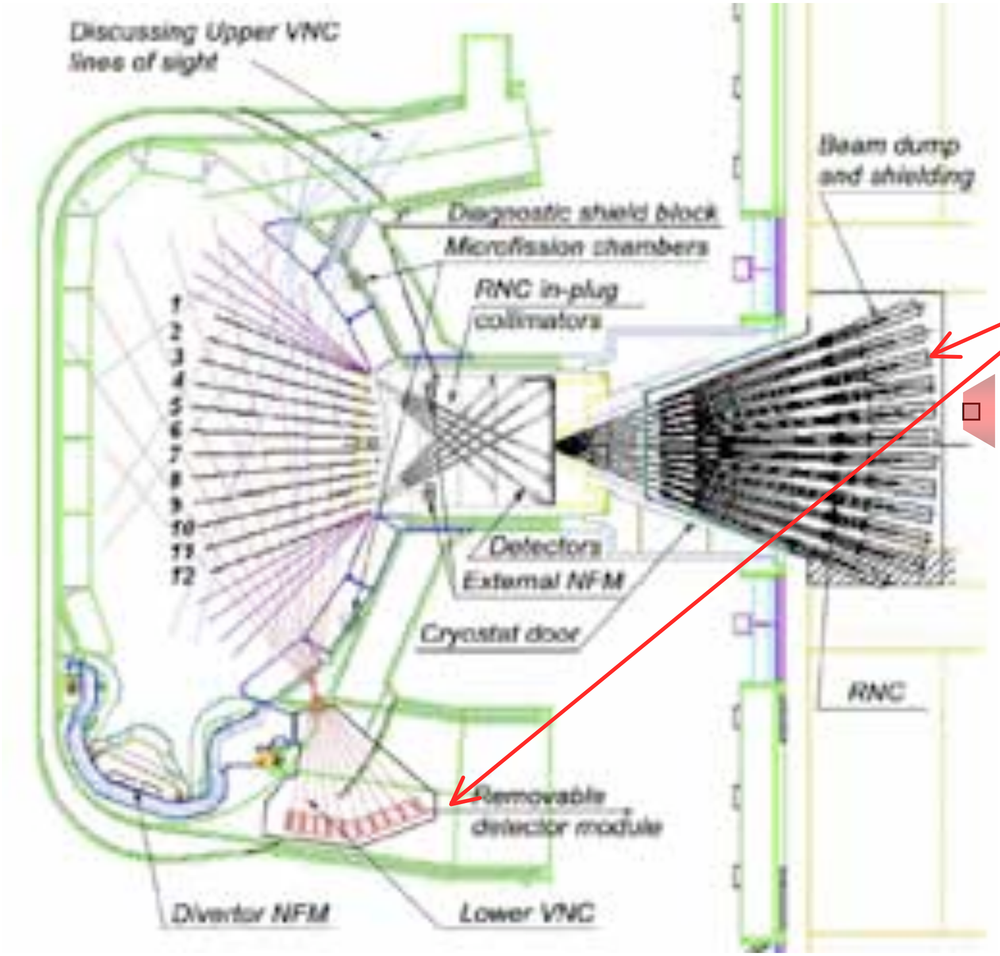
Fusion Power Measurement by Cooling Water Calorimetry

John Wesley; S 19 RI 8 97-07-10 F1

DEMO relevant
But application to ITER is not decided yet

- The modelling provides t_C=30s for the FW and t_C=60s for the BS

Innovation on
- Profile measurement systems



Accurate fusion output can not be obtained without neutron emission profile measurement.

Neutron Camera consist from

Multi channel collimator + detectors not sensitive to low energy neutrons and gamma's.

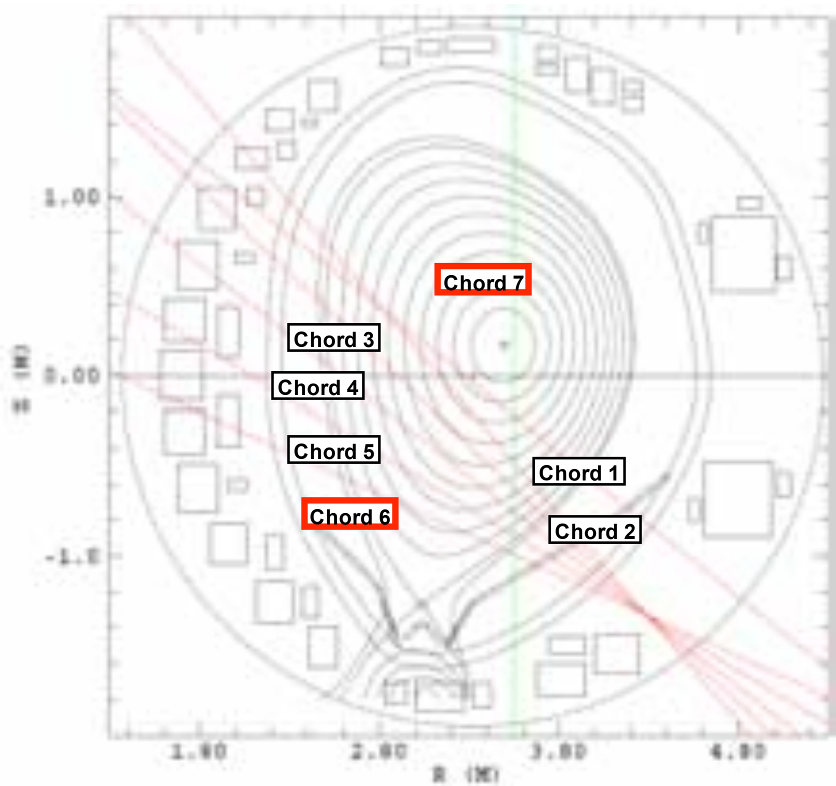
Some schintillator can discriminate neutrons from gamma's.

Fast electronics is needed.

.
Radial Neutron Camera,
Vertical Neutron Camera

Neutron emission profile measurement in JT-60U

- Measure the line-integrated neutron emission
  - ⇒ infer energetic ion profile
- 7 channel collimator array viewing a poloidal cross section



- Detector

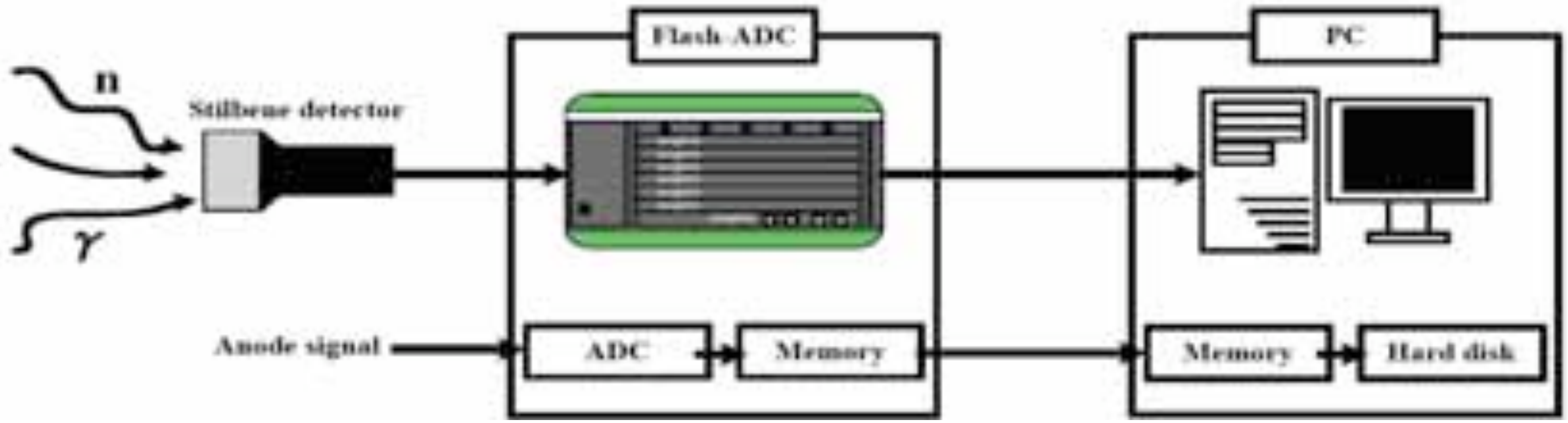
Stilben crystal neutron detector

***n-γ* discrimination** is necessary

DSP-system and fast discrimination software were developed. (K. Ishii, ITC18-P238)

Digital Signal Processors system

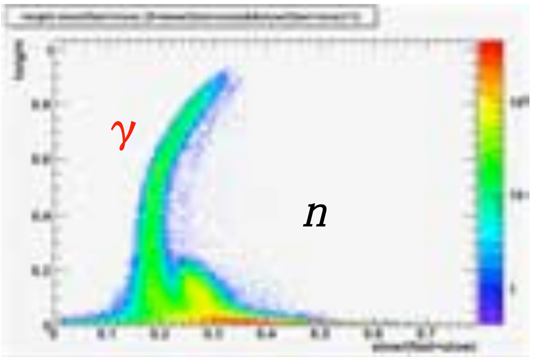
In the DSP system, output pulses from an anode of a photo multiplier tube (PMT) on a detector are recorded as continuous waveform using a fast flash analog-to-digital converter (flash ADC) [2,4,5].



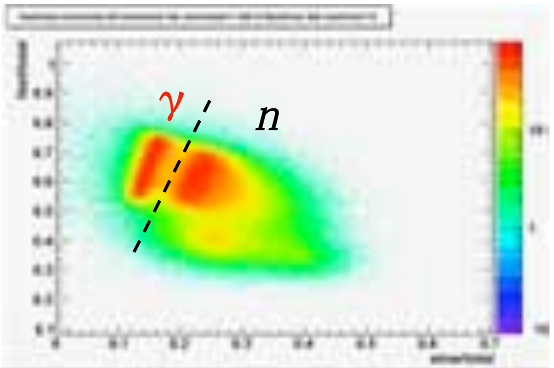
[3] M. Ishikawa, T. Itoga, T. Okuji, et al., Rev. Sci. Instrum.**77**, 10E706 (2006).
[5] T. Itoga, M. Ishikawa, M. Baba, et al., Radiat. Prot. Dosim. **126**, 380 (2007).
[6] K. Shinohara, T. Okuji, M. Ishikawa, et al., Rev. Sci. Instrum. **79**, 10E509 (2008).

Fast logics of Neutron-gamma discrimination

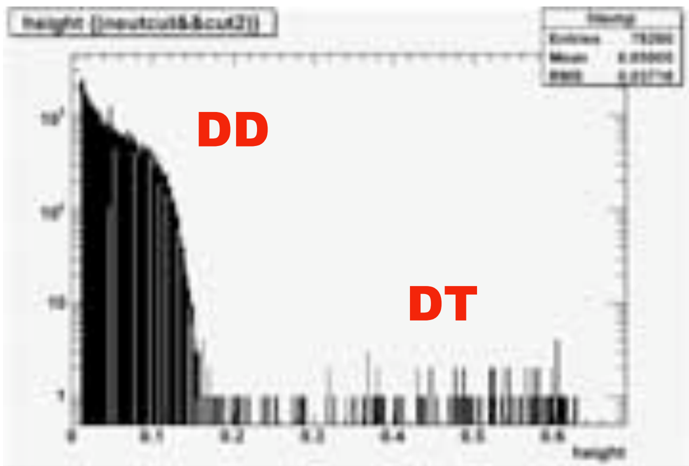
A new pulse-shape analysis method is developed and applied to all stilbene detectors. Figure shows a 2D map in fast-slow space normalized with total. Neutrons are discriminated from γ-rays clearly.This system enables routine measurement of DD neutron emission rate with time resolution of ms range, and also routine measurement of triton burn-up simultaneously.



Conventional
n-gamma discriminarion



New
n-gamma discriminarion



An example of Neutron spectra measured on one of channels, 50 ms.
JT-60U

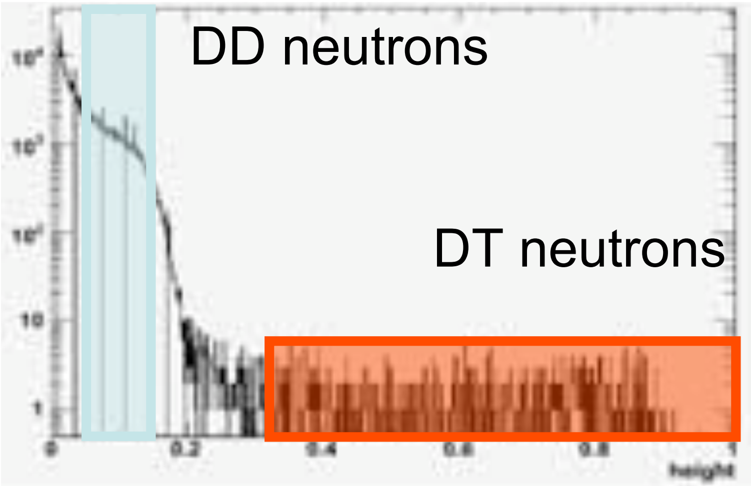
K. Ishii, ITC18-P238

Pulse Height Analysis

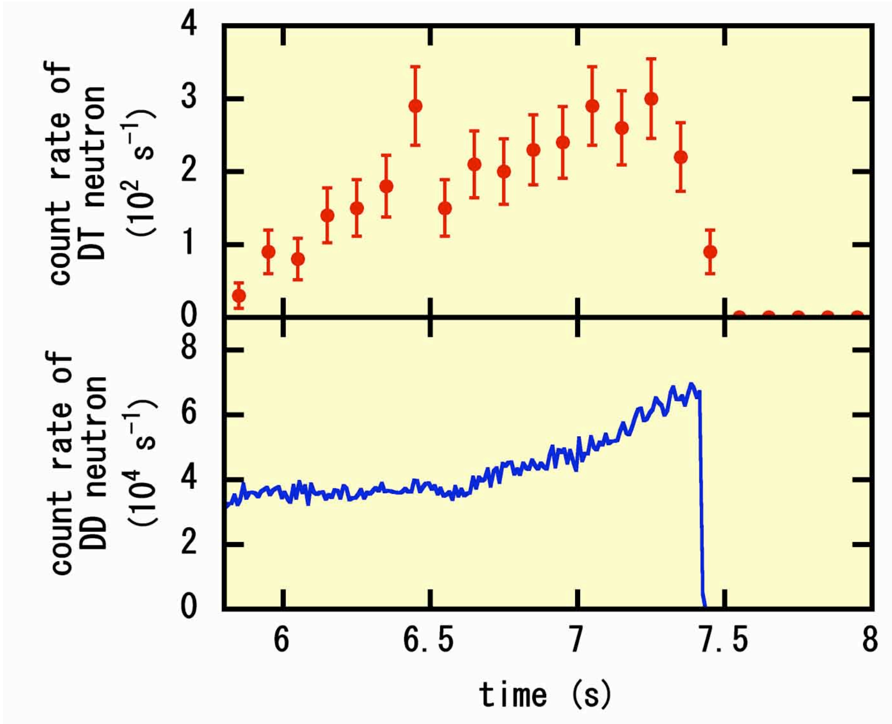
- Pulse height distribution is obtained to discriminate neutron events from *g* –ray events using both of conventional and new 2D map
- DT neutrons is measured as well as DD neutrons in the DD plasma

Define two regions for DD and DT neutrons

The time evolution of neutron emission rate is obtained



E49786 Chord 7



K. Ishii, ITC18-P238

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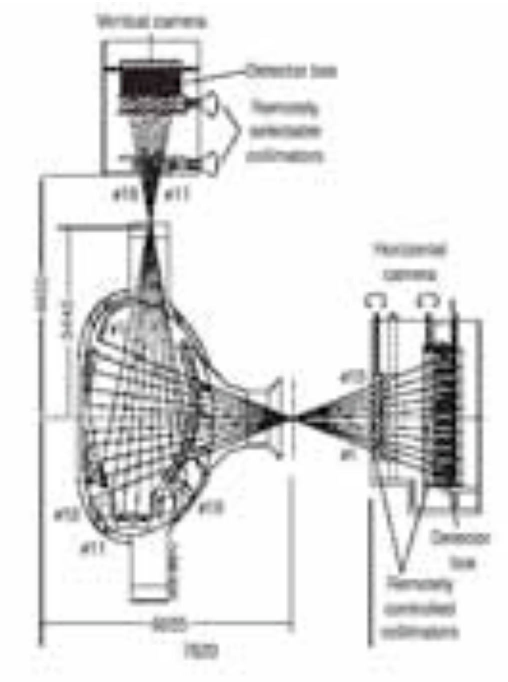
Neutron diagnostics for physics understandings

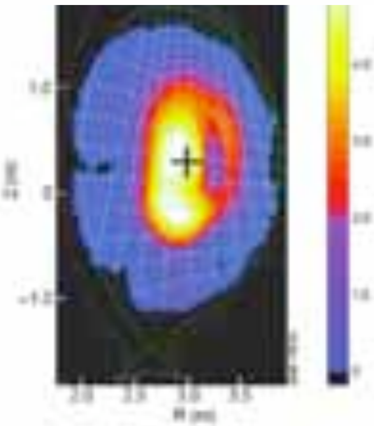
It was proven that measurement of Y_n, and neutron/gamma profile ($Y_n(\psi)$), secondary nuclear reaction products (triton burn-up) are useful to understand physics on heating scenario's, and energetic particle resonant behaviors - fishbone instabilities, ALE, TAE, etc., on PBX, TFTR and DIII-D, TFTR, JET, JT-60U, etc. Information on re-distribution was obtained by the profile measurement.



These physics studies might be difficult on ITER, because the heat source is alpha particles.

Confined and lost alpha particle diagnostics are expected to take over the role.

However, information on bulk ion behaviors can be studied both by change of emission profiles and ion temperature profiles.



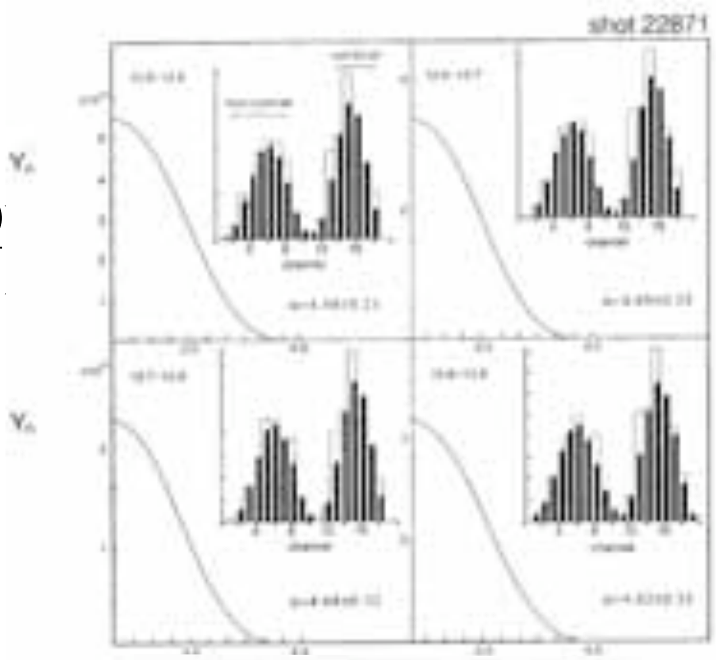
Bulk ion behaviors and ion diffusivity have been studied on JET by neutron emissivity profiles

The local ion power balance of this region can be expressed as

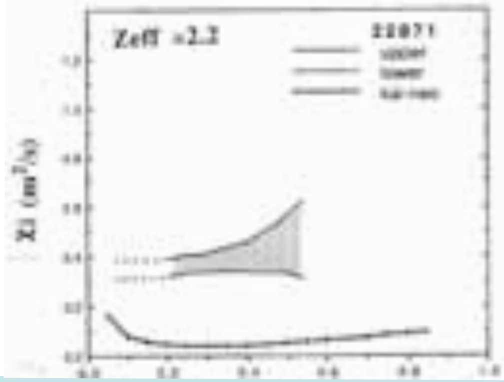
$$\frac{dW_i}{dt} = Q_{ei} - Q_{cond} \approx \frac{3}{2}\frac{n_e\left(T_e - T_i\right)}{\tau_{ei}} + \frac{1}{r}\frac{\partial}{\partial t}\left(rn_i(r)\chi_i(r)\frac{\partial T_i(r)}{\partial r}\right.$$

$$Y_n(\rho) = n_d(\rho)n_t(\rho)T_i^{\beta}(\rho)$$

$$Y_n(\rho) = Y_0(\rho)\left(1-\rho^2\right)^{\alpha}$$



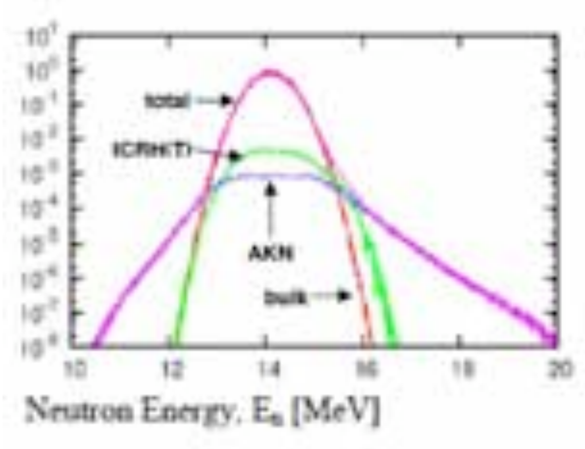
This is the equation to obtain χ_i (r).
Absolute values of n_d *(r)*, T_e *(r)*, T_i *(r)*, Y_n *(r)* 's are reducible.
Only the neutron emission decay constant and the profile factor of T_i *(r)* , *α* are main factors to determine the χ_i *(r)*.



M. Sasao, et al., Plasma Physics and Control.Fusion, 36(1994)p1-8

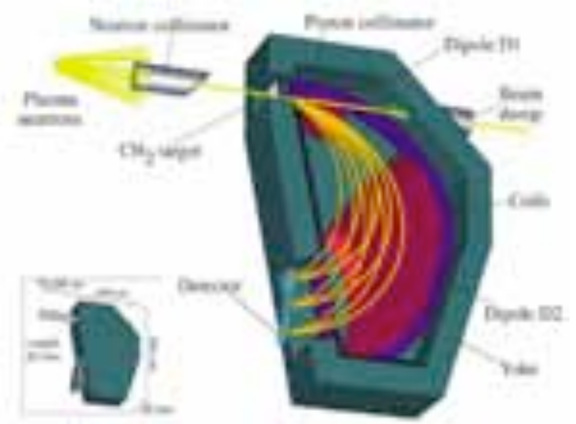
Alpha Knock-on effect on the neutron Spectrum

The population of fast confined α-particles can give rise to alpha knock-on neutron (AKN) emission in DT plasmas in the high energy tail of the spectrum, produced by supra-thermal knock on ions.



A large magnetic spectrometer

Was developed for the measurement on JET-DT campaign.

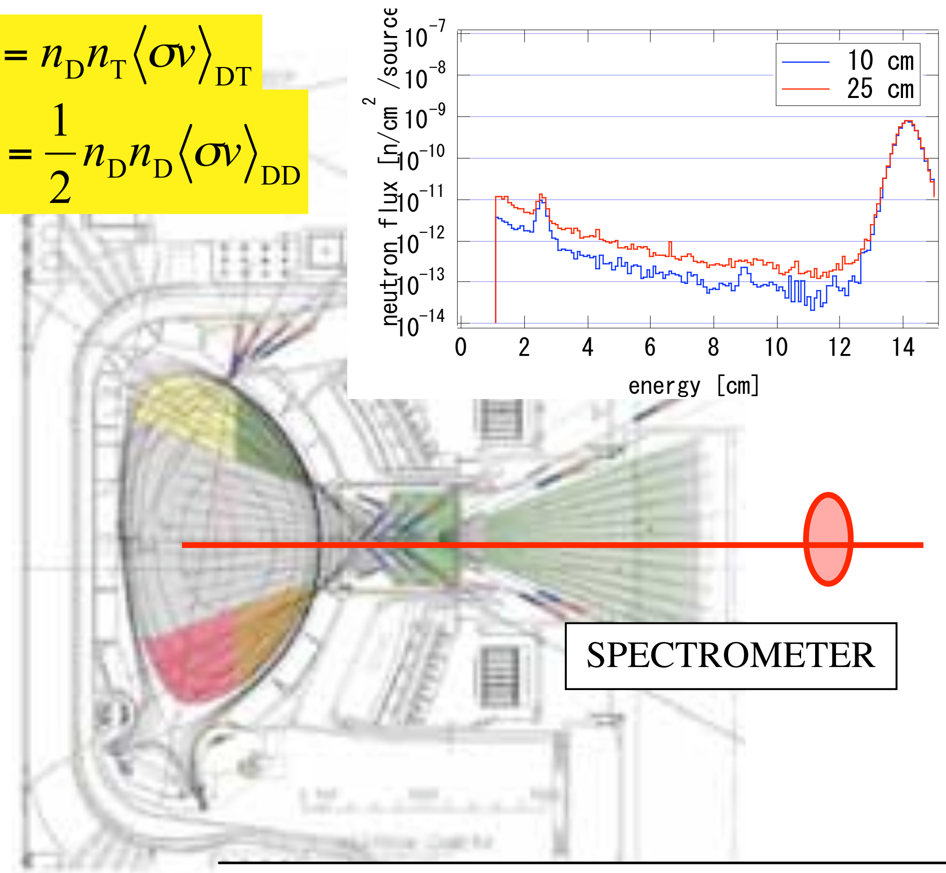


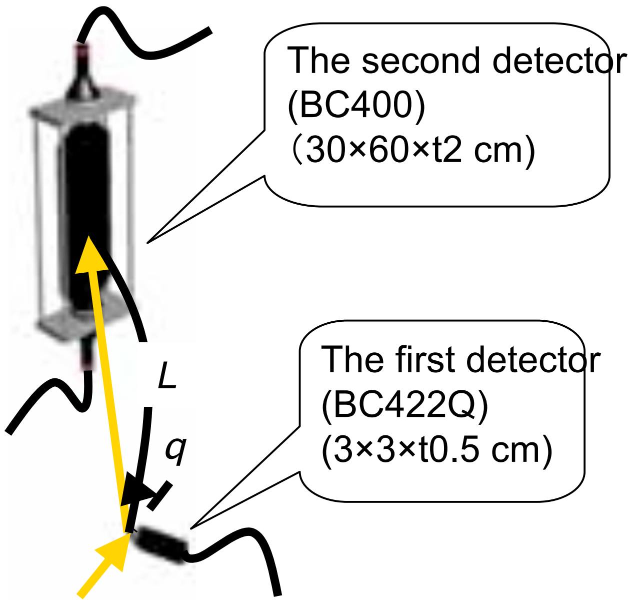
M. Sasao, et al., Fusion Technology and Science, Special Issue on diagnostics, Chapter 9 (2008, Feb.)

TOF spectrometer for the ITER - DD/DT neutron ratio measurement - high efficiency, high cps

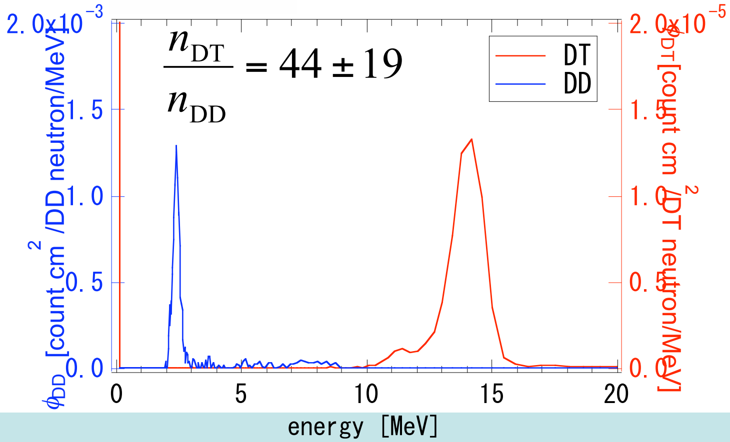
$$S_{DT} = n_D n_T \langle \sigma v \rangle_{DT}$$

$$S_{DD} = \frac{1}{2} n_D n_D \langle \sigma v \rangle_{DD}$$





[count cm²/neutron]	efficiency (resolution)
DT	3.5×10^{-5} ($\Delta E/E$ =10.6 %)
DD	3.9×10^{-4} ($\Delta E/E$ =11.3%)



Summary

- Neutron measurement is one of the major diagnostic methods on ITER, and it will be one of few plasma measurement tools on DEMO. Its principal role on ITER is to allow evaluation of fusion output. indicating how close the ITER plasma approaches the ultimate goal of a self-sustained nuclear fusion reactor.
- Accuracy (10%) and relaibility is demanded.
- Calibration experiment using ratio-isotopes, DD/DT neutron generators is needed, combined with MCNP calculation, foil-activations,and profile measurement.
- Connection of several detectors of different sensitivity is needed.
- In addition, neutron diagnostics supply a variety of both spatially and time-resolved information to facilitate our understanding of physics, especially with regard to the behaviours of energetic particle (heating phase), the ion temperature, the fuel isotope ratio (n_T/n_D), α-particle confinement, and so on.
- The time-resolved neutron emission profile is essential to study the ion transport of ITER plasma.