Misure di ioni veloci mediante la spettroscopia di neutroni e raggi gamma nei plasmi termonucleari ad alte prestazioni: risultati recenti e prospettive future

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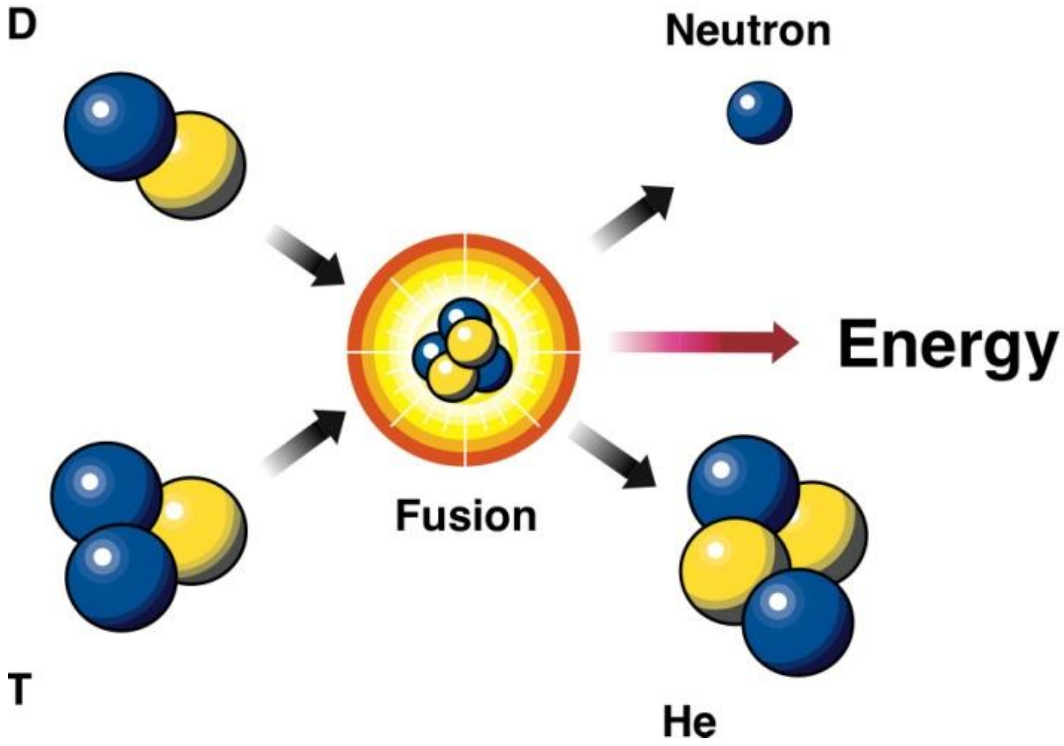
Outline

- **Fast ion diagnostics in large scale tokamaks**
- **Neutron and gamma-ray spectroscopy measurements in thermonuclear plasmas**
- **Towards a nuclear diagnostics based tomography of the fast ion phase space with compact detectors**

Thermonuclear fusion

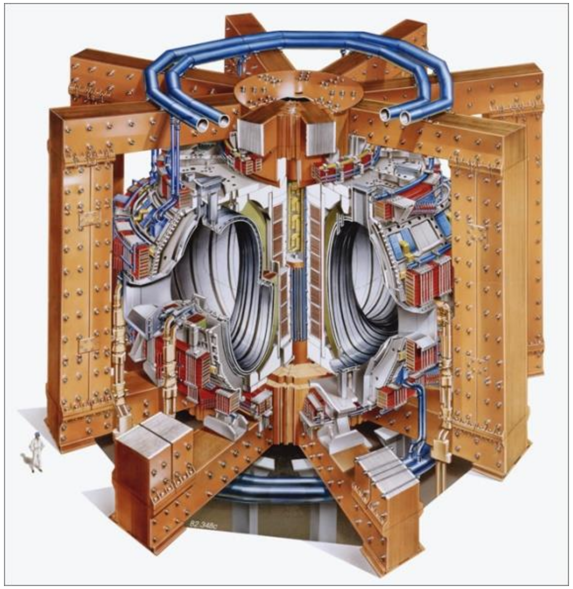


$$D + T \rightarrow \alpha + n + 17.6\ \mathrm{MeV}$$

How do we measure distribution function of the fuel ions and fusion products?

Requirements:

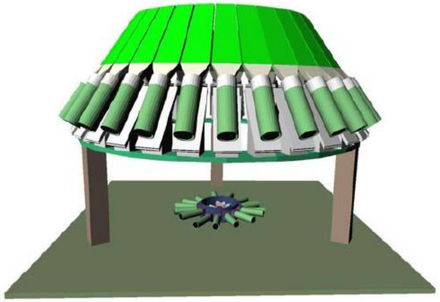
- **Temperature:** **100 million degrees**
- **Pressure:** **8 atm**
- **Confinement time:** **1 s**

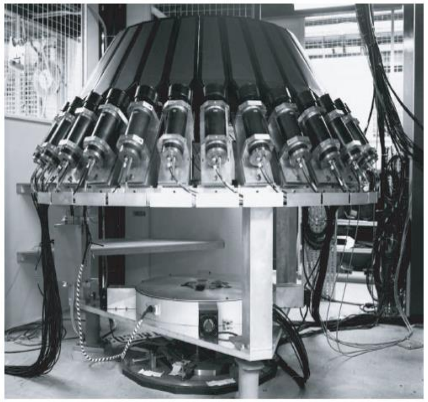


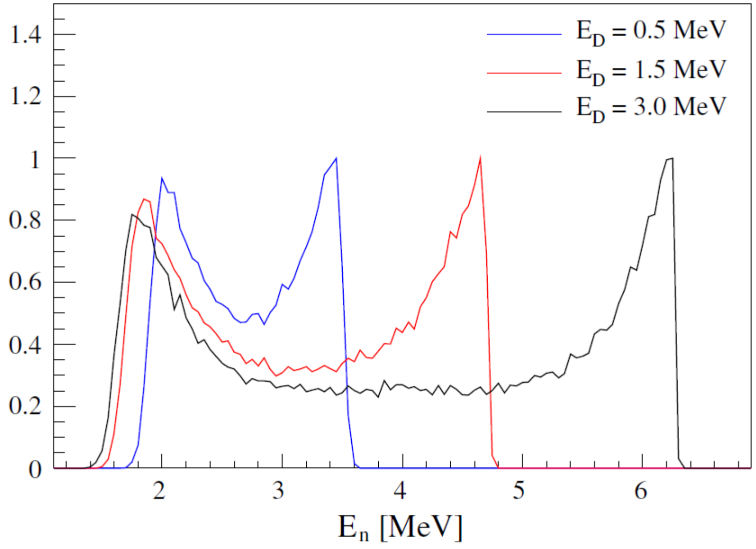
Plasma nuclear physics

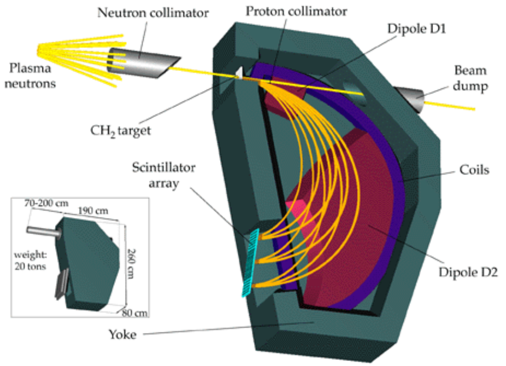
Instrumentation and techniques developed for fundamental **nuclear physics** studies have been adapted and applied for **plasma diagnostic purposes**

The **neutron spectrum** changes depending on the **fuel ion** energy distribution









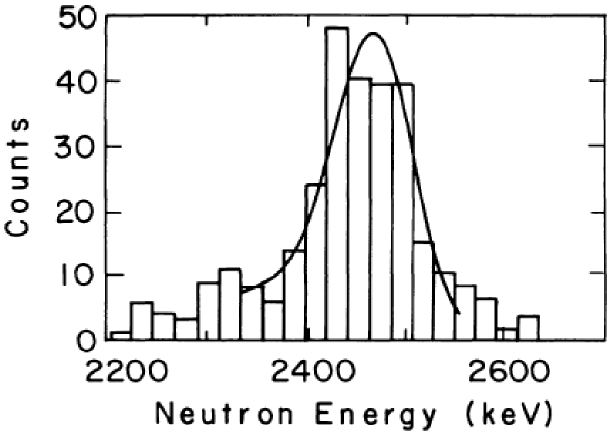
Dedicated instrumentation has been developed based on the **time of flight** or **magnetic proton recoil** technique

M. Gatu Johnson, NIM A 591 (2008) 417

A. Sundén, at al, NIM A 610 (2009)682

From early measurements to high sensitivity spectrometers

From the proof of principle: temperature determination from the spectral width



Fisher et al. Phys. Rev. A 28 (1983) 3121

$$w \propto T^{1/2}$$

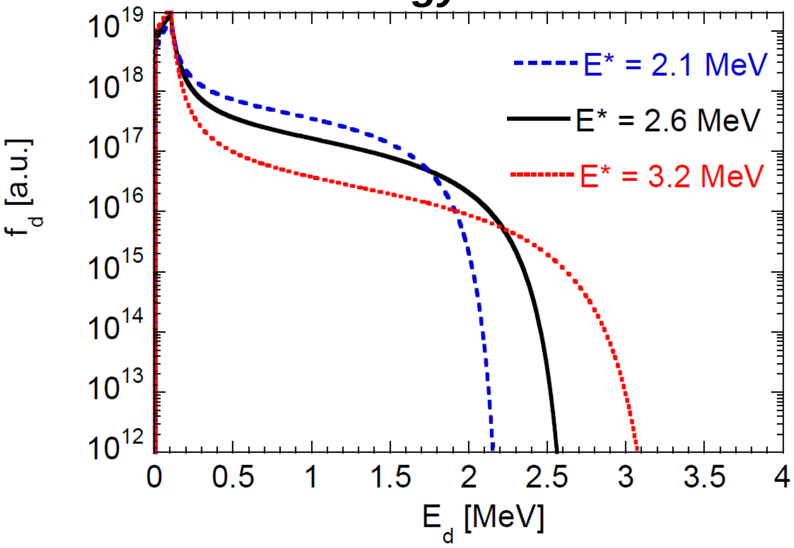
Ohmic plasmas (no auxiliary heating)

^{3}He detector

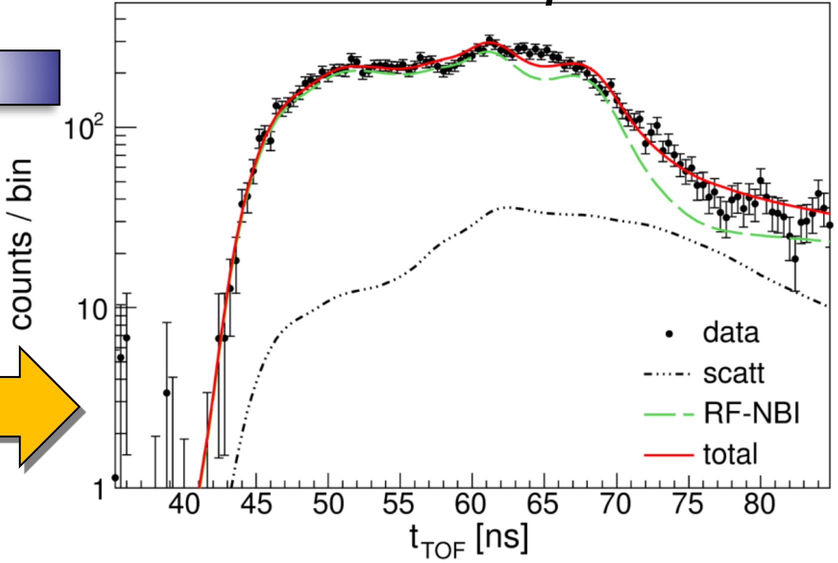
Sum of 169 discharges

To contemporary measurements: full determination of the fuel ion energy distribution

Fuel ion energy distribution



JET # 86459 ***Neutron spectrum***

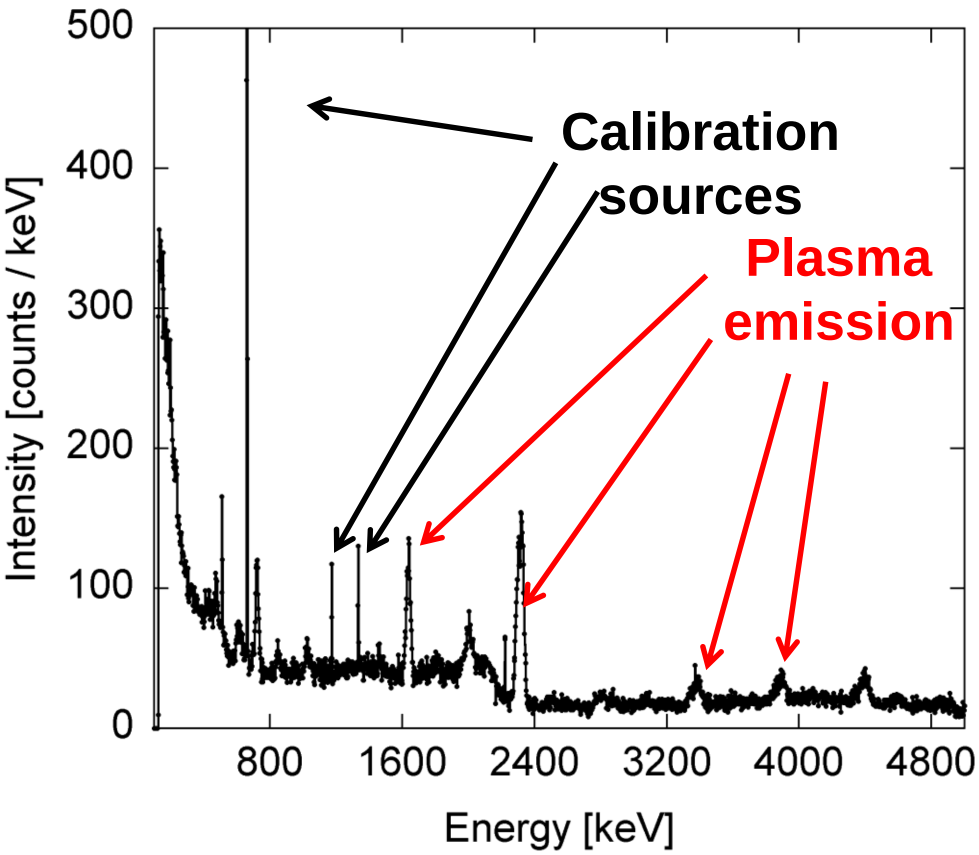


J. Eriksson, M. Nocente et al. submitted to Nucl. Fusion

Measuring the Doppler broadening of the plasma γ-ray peaks

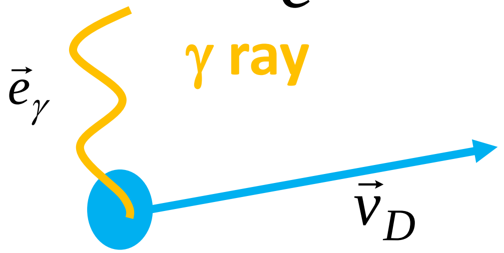
Fusion products and **suprathermal ions** from auxiliary heating systems can be measured by naturally occurring nuclear reactions with plasma impurities

Eg. ^{3}He + ^{12}C → ^{14}N* + p ^{14}N*→ ^{14}N + γ (1.63 MeV)



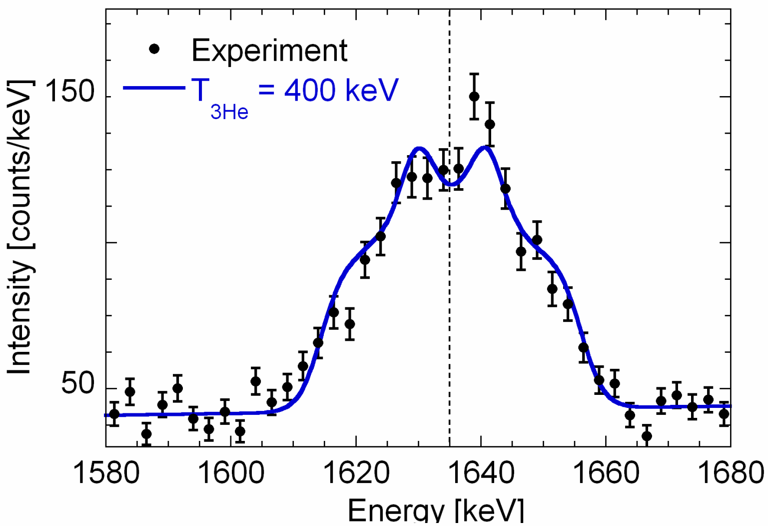
Advanced gamma-ray spectrometers traditionally used in nuclear physics have been adapted to measure the **γ-ray Doppler broadening** induced by the fast ion energy distribution

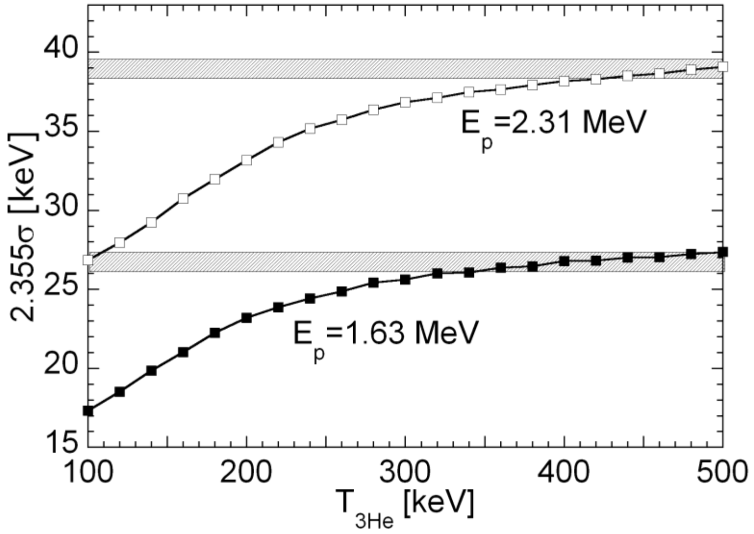
$$E_{\gamma} = E_{\gamma 0}\left(1 + \frac{1}{c}\vec{v}_{12C} \cdot \vec{e}_{\gamma}\right)$$

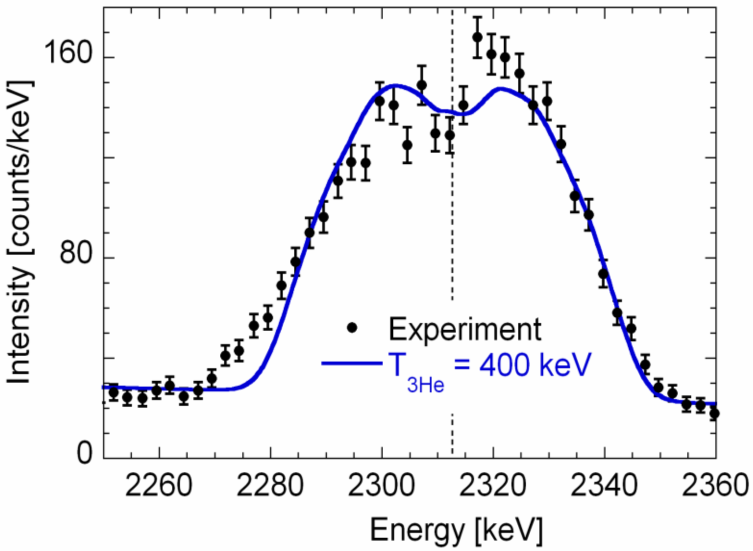


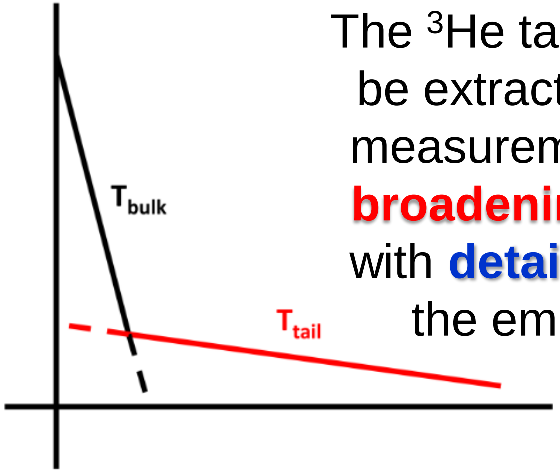
High energy resolution gamma-ray spectroscopy measurements in thermonuclear plasmas

High purity Germanium detector – ^{3}He tail temperature determination





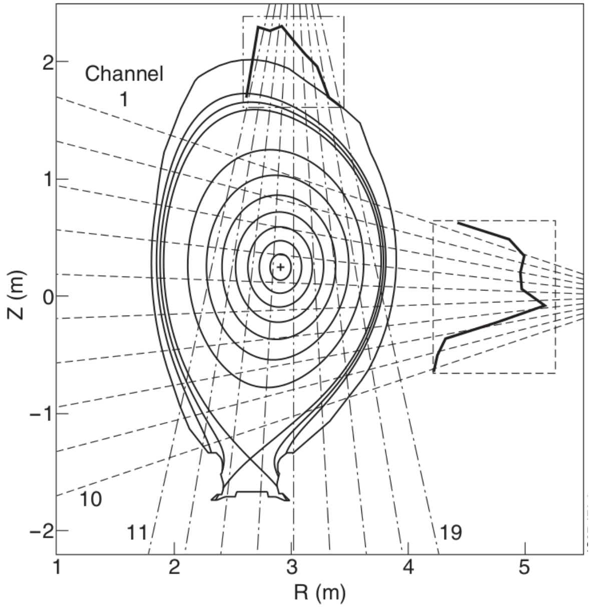




The ^{3}He tail temperature can be extracted by combining measurements of the **peak broadening and intensity** with **detailed modelling** of the emission process

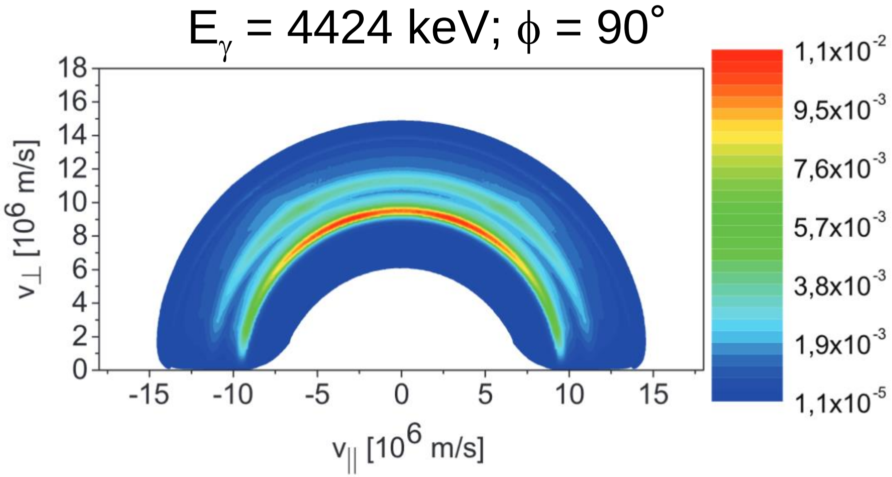
M. Tardocchi, M. Nocente et al. PRL 107 (2011) 205002

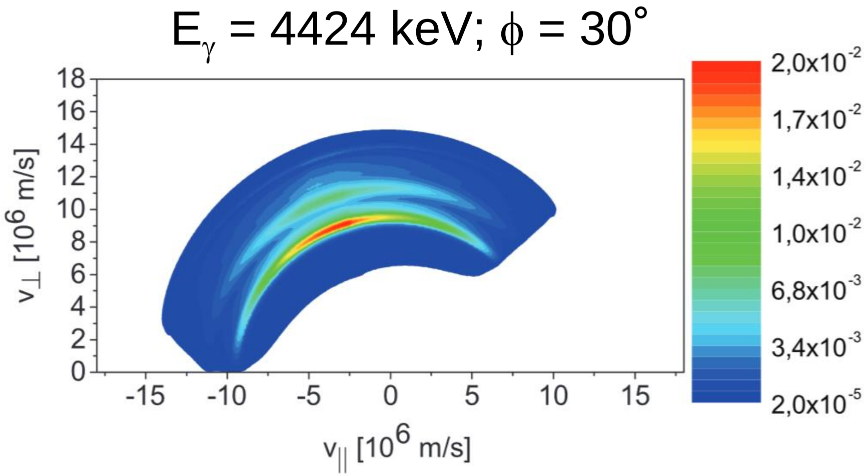
A future route: phase space tomography with compact neutron and gamma-ray detectors



Compact detectors are needed to reconstruct the **spatial profile** of neutron and gamma-ray emission from measurements along **multiple collimated sightlines**.

Adding **spectroscopy capabilities** to multi-sightline measurements opens up to a **velocity space tomography**, given the different **weight in the fast ion phase space** of measurements at different angles w.r.t. the magnetic field


E_γ = 4424 keV; ϕ = 90°


E_γ = 4424 keV; ϕ = 30°

M. Salewski, M. Nocente et al. Nucl. Fusion 55 (2015) 093029

$$\alpha + {}^{9}\mathrm{Be} \rightarrow n + {}^{12}\mathrm{C}^* \qquad {}^{12}\mathrm{C}^* \rightarrow {}^{12}\mathrm{C} + \gamma$$

Compact detector R&D for plasma nuclear physics

Single Crystal Diamond detectors

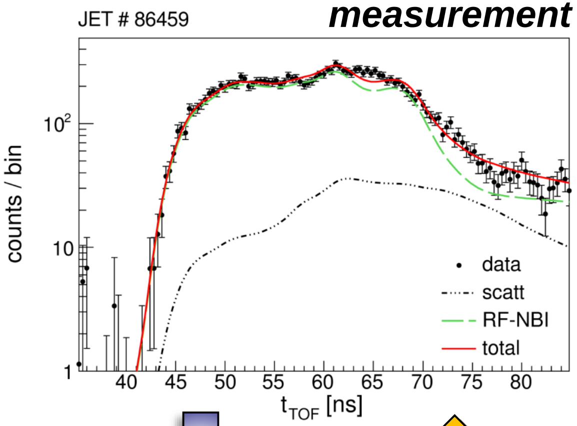
for neutron measurements along multiple sightlines

- ✓ **Magnetic field insensitivity**
- ✓ **Radiation hardness**
- ✓ **Good energy resolution**

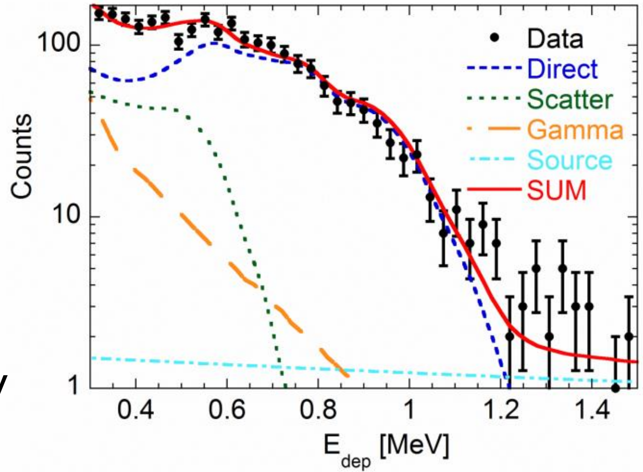
based on nuclear reactions between neutrons and ^{12}C nuclei of the device

Already used for neutron and charged particle measurements in **nuclear accelerator** and **spallation source** experiments

Time of flight measurement

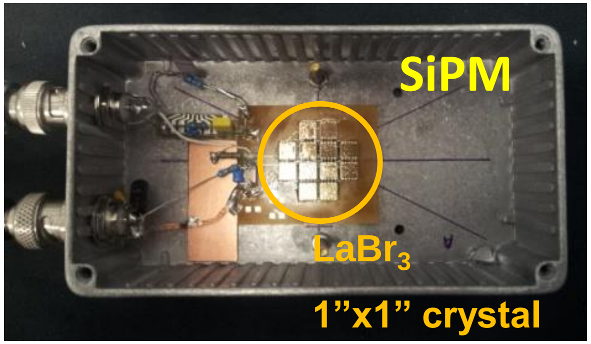


Diamond measurement



M. Nocente et al. accepted for publication on Rev. Sci. Instrum.

Compact γ-ray detectors based on $LaBr_3(Ce)$ + Silicon Photo Multipliers



M. Nocente et al. Rev. Sci. Instrum. 85 (2014) 11E108

Since few years, SiPMs have been widely used for light read-out in PET applications (E_γ=511 keV).

A system based on **$LaBr_3(Ce)$ + SiPM** is being explored for measurements in the E_γ > 1 MeV range at high energy resolution and MHz counting rates

Conclusions

- **Neutron and gamma-ray emission** from a thermonuclear plasma is a rich source of information on **supra-thermal ions**

- Neutron and gamma-ray spectroscopy measurements of the **energetic ion energy distribution** have been demonstrated by **applying nuclear physics instrumentation to plasma measurements**

- Undergoing developments in the technology of **compact detectors** can open up to a **fast ion phase space tomography** by **spectroscopy measurements along multiple sight-lines**

Backup slides

Diagnostics on mid-size and large scale machines

On **midsize machines** two types of techniques are employed

a) Active diagnostics

(based on light emission, microwave scattering etc.)

b) Passive diagnostics

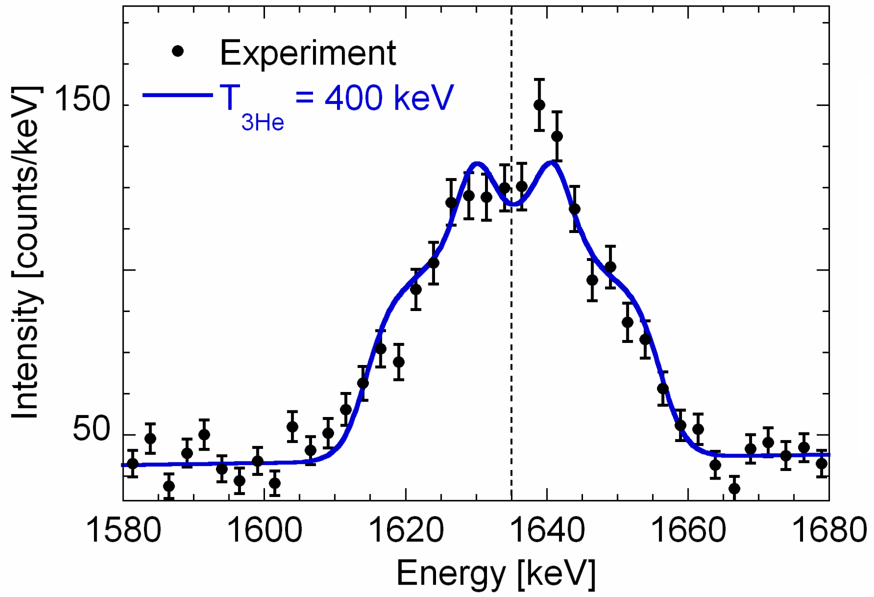
(based on direct measurements of neutrals and charged particles at the edge)

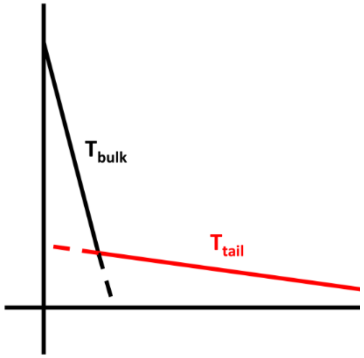
On **large scale, reactor relevant** machines the same techniques may not be feasible (high edge temperatures and radiation fluxes)

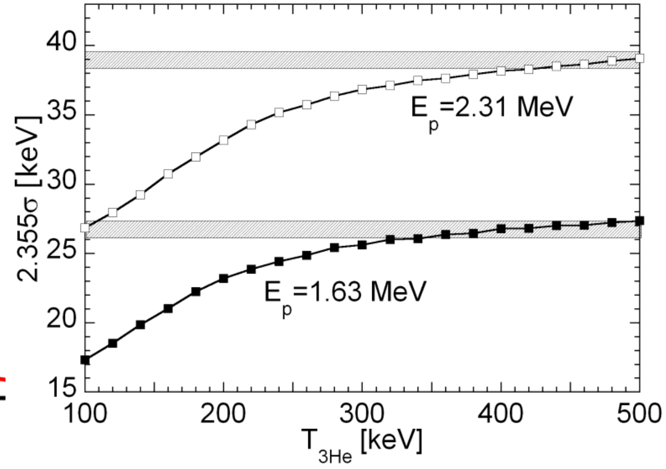
Indirect diagnostics based on the plasma intrinsic nuclear emission must be explored

Combining high energy resolution and MHz counting rate capability

High purity Germanium detector – ^{3}He tail temperature determination

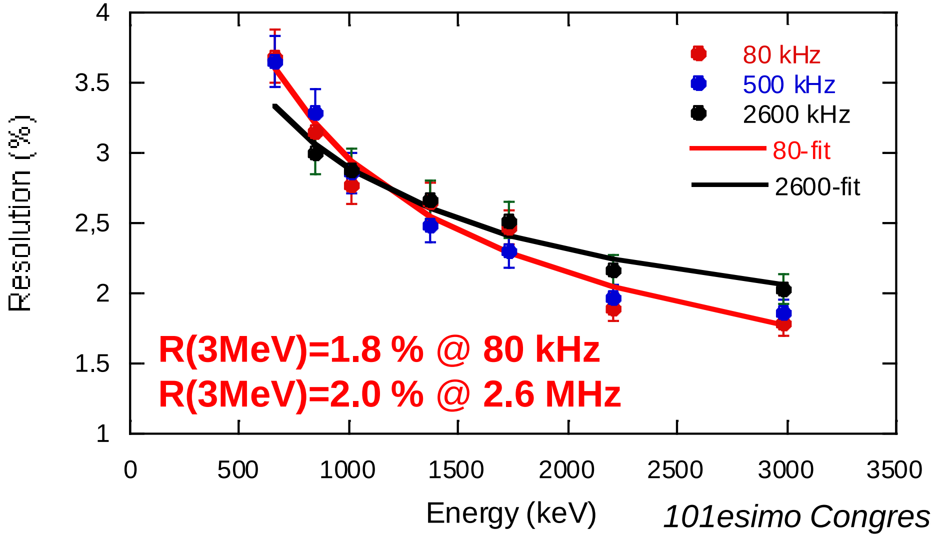






M. Tardocchi, M. Nocente et al. PRL 107 (2011) 205002

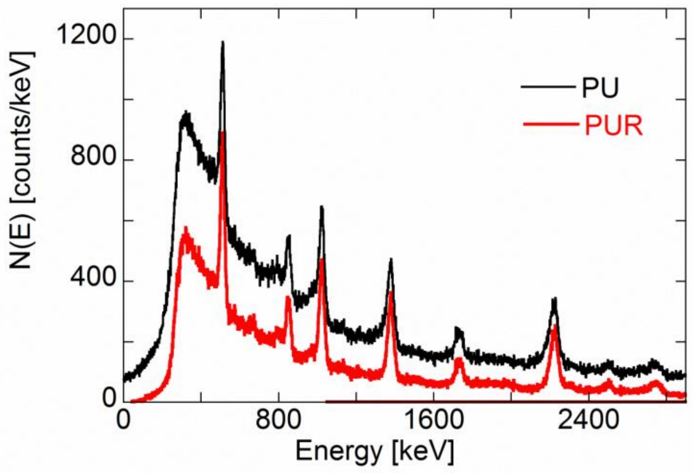
LaBr$_3$(Ce) for spectroscopy measurements at MHz counting rates



R(3MeV)=1.8 % @ 80 kHz

R(3MeV)=2.0 % @ 2.6 MHz

Rate = 2.6 MHz



M. Nocente et al. IEEE Trans. Nucl. Sci. 60 (2013) 1408