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

M. Nocente\textsuperscript{1,2}, G. Gorini\textsuperscript{1,2} and M. Tardocchi\textsuperscript{2}

\textsuperscript{1}Dipartimento di Fisica, Università degli Studi di Milano-Bicocca, Milano
\textsuperscript{2}Istituto di Fisica del Plasma, CNR, Milano
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

\[ \text{D} + \text{T} \rightarrow \alpha + \text{n} + 17.6 \text{ MeV} \]

**Requirements:**

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

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


\[ W \propto T^{1/2} \]

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**

- \( E^*=2.1 \text{ MeV} \)
- \( E^*=2.6 \text{ MeV} \)
- \( E^*=3.2 \text{ MeV} \)

---

**Neutron spectrum**

J. Eriksson, M. Nocente et al. submitted to Nucl. Fusion
Measuring the Doppler broadening of the plasma $\gamma$-ray peaks

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

Eg. $^3\text{He} + ^{12}\text{C} \rightarrow ^{14}\text{N}^* + p$ $^{14}\text{N}^* \rightarrow ^{14}\text{N} + \gamma (1.63 \text{ MeV})$

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

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

101esimo Congresso della Società Italiana di Fisica, 22 Settembre 2015
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

101esimo Congresso della Società Italiana di Fisica, 22 Settembre 2015
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.

\[ E_\gamma = 4424 \text{ keV}; \phi = 90^\circ \]

\[ E_\gamma = 4424 \text{ keV}; \phi = 30^\circ \]

\[ \alpha + {}^9\text{Be} \rightarrow n + {}^{12}\text{C}^* \]

\[ {}^{12}\text{C}^* \rightarrow {}^{12}\text{C} + \gamma \]

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

Compact $\gamma$-ray detectors based on $\text{LaBr}_3(\text{Ce}) +$ Silicon Photo Multipliers

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

A system based on $\text{LaBr}_3(\text{Ce}) + \text{SiPM}$ is being explored for measurements in the $E_\gamma > 1$ MeV range at high energy resolution and MHz counting rates


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

- Experiment
  $T_{^3\text{He}} = 400$ keV

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

- $R(3\text{MeV}) = 1.8\%$ @ 80 kHz
  $R(3\text{MeV}) = 2.0\%$ @ 2.6 MHz

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

Rate = 2.6 MHz