Gamma ray spectroscopy measurements of fast ions on ASDEX Upgrade

M. Nocente[1,2], M. Garcia-Munoz[3], G. Gorini[1,2], M. Tardocchi[2], A. Weller[3], S. Akaslompolo[4], R. Bilato[3], V. Bobkov[3], C. Cazzaniga[1], B. Geiger[3], G. Grosso[2], A. Herrmann[3], V. Kiptily[5], M. Maraschek[3], R. McDermott[3], J.M. Noterdaeme[3], Y. Podoba[3], G. Tardini[3] and the ASDEX Upgrade Team

Max-Planck-Institut für Plasmaphysik, EURATOM Association, Garching, Germany

[1] Dipartimento di Fisica "G. Occhialini", Universita' degli Studi di Milano Bicocca, Milan, Italy
[2] Istituto di Fisica del Plasma, EURATOM-ENEA-CNR Association, Milan, Italy
[3] Max-Planck-Institut für Plasmaphysik, EURATOM Association, Garching, Germany
[4] Aalto University School of Science, EURATOM-TEKES Association, Helsinki, Finland
[5] Culham Centre for Fusion Energy, Culham, UK

INTRODUCTION

Gamma ray spectroscopy is a proposed diagnostic technique to measure the energy distribution of **confined fast ions in the MeV range** on ITER [1]. In today experiments, it is used at JET, where the installation of **high resolution spectrometers** has enhanced the **quality of the measurements** and contributed to a better **understanding of the nuclear physics** behind γ-ray emission [2]. Unlike JET, **ASDEX Upgrade** (AUG) is a **midsize tokamak**, with lower plasma current and magnetic fields. However its **large set of fast ion diagnostics** has recently provided experimental results in the field of **energetic particle studies**, with the characterization of losses induced by several fast particle driven MHD modes [3]. The unique possibility to **combine information from different diagnostics** makes AUG an interesting machine also for γ-ray spectroscopy observations. In this work we report the **first γ-ray measurements of fast ions on AUG**.

DEVELOPMENT OF GAMMA RAY EMISSION SCENARIOS

Protons and **deuterons** can be accelerated on AUG by means of Ion Cyclotron Resonance Heating (ICRH). Two different scenarios can be considered

- **Deuteron acceleration**
  - ✓ 2nd harmonic heating on a perpendicularly injected D beam (E_{beam} = 62 keV) in D plasmas
  - ✓ Observe γ-ray emission from d+^{14}N reactions
    - ➢ **Advantage**: quite high cross section
    - ➢ **Disadvantage**: E_d > 400 keV required; Confinement of d ions only up to 800 keV
- **Proton acceleration**
  - ✓ Minority heating on hydrogen impurities
  - ✓ Observe γ-ray emission from proton capture on boron and deuterium (d + p --> ^{3}He + γ)
    - ➢ **Advantage:** high confinement energies (E_p > 1.5 MeV)
    - ➢ **Disadvantage:** much lower cross section (≈ 1 / 100 than d+^{14}N)

A **high efficiency LaBr$_3$(Ce) scintillator** [4] developed for high rates was used for the measurements.

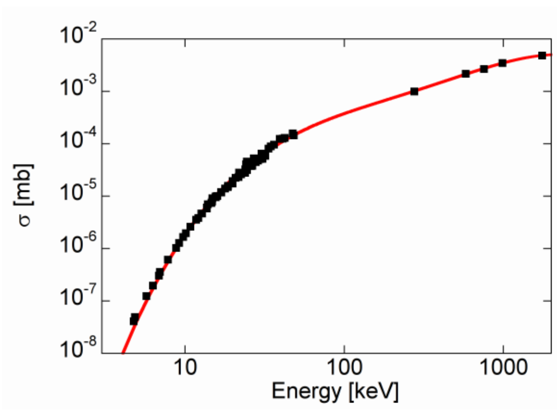

***Figure 1**. Cross section of the d(p,γ)^{3}He reaction as a function of the proton energy in the laboratory frame with data taken from the EXFOR database. The solid line is the result of the fit to the experimental data.*

EXPERIMENTAL RESULTS

- **Deuteron acceleration**
  - ✓ Although ICRH and d beam synergy was assessed with NPA measurements, **no γ-ray emission was observed**.
  - ✓ In most discharges n_e could not be kept low enough ($n_e < 6\cdot10^{19}$ m^{-2}). **Very few** signatures of fast ion driven **MHD activity** and associated **losses** were detected.
- **Proton acceleration**
  - ✓ **γ-ray emission was observed** in two identical discharges (#26615 and #26616) with significant **fast ion driven MHD activity.**
  - ✓ An **excess of events** that could be ascribed to **proton capture on boron** was detected for E_γ = 9-12 MeV. A clear **peak from the d(p,γ)^{3}He reaction** was measured at **E_γ=5.5 MeV**. The γ **count rate increased with time**. A **proton tail temperature** in the range **70 - 100 keV** could be inferred from NPA and γ-ray measurements..
  - ✓ **Toroidal Alfvén Eigenmodes** (TAEs) were detected on Mirnov coils (n=3-6). Associated **losses** in a **broad energy range** were manifested on **the fast ion loss detector** (FILD) for **E_p > 400 keV**.

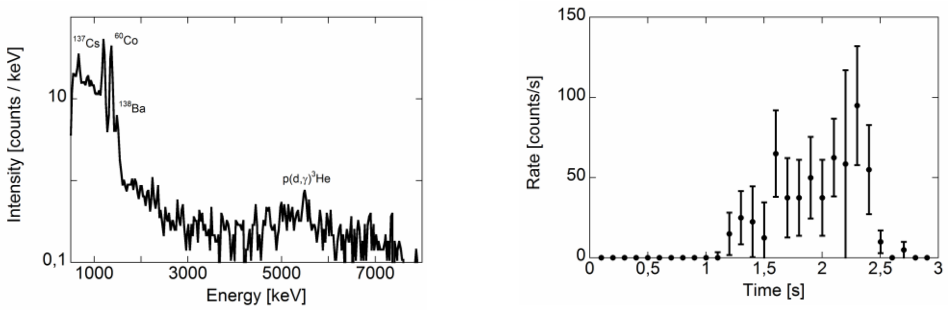

***Figure 2.** (Left) Sum of γ ray spectra for discharges #26615 and #26616 integrated for 1 s during ICRH showing the 5.5 MeV peak from the d(p,γ)^{3}He reaction. (Right) Measured E_γ=5.5 MeV count rate as a function of time averaged between the two discharges.*

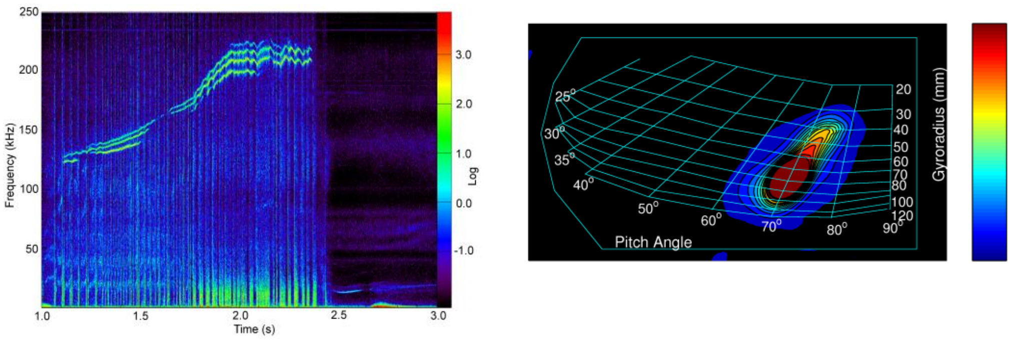

***Figure 3.** (Left) Frequency spectrogram from Mirnov coils showing characteristic frequencies of TAEs driven by fast protons and (Right) FILD data at 1.5 s for shot #26615.*

DISCUSSION

- γ-ray emission from the d(p,γ)^{3}He reaction can be interpreted in terms of the **differential reactivity $y_\gamma(E_p)$**=$f(E_p)v\sigma(E_p)$ that expresses the γ-ray emission intensity as a function of the proton energy E_p.
- For proton tail temperatures in the range 70-100 keV, y_γ has a **peak** between **E_p=120 keV** and **E_p=180 keV**. Most of **γ-ray emission** involves protons with **E_p < 400 keV**.
- The increasing γ-ray emission rate as function of time suggests that **protons with E_p < 400 keV are well confined** and **not affected by MHD activity**, in **agreement** with the absence of proton losses in this energy range as detected by the **FILD**.
- Calculations of **particle-mode resonance curves** reveals that **many energies may resonate with the observed TAEs**, justifying the broad energy range of losses observed on the FILD. Interactions with **E_p<400 keV** protons involves **negative harmonics** (p < 0) of the **bounce frequency**.
- As the γ-ray emission rate increased with time (and no losses were observed on the FILD for E_p < 400 keV), **resonances with p < 0 did not significantly affect confinement**
- Further measurements on AUG shall benefit from an **overlap** between the **region responsible for γ-ray emission** and **that affected by losses** (E_p > 400 keV). This can be partially achieved with a **proton tail temperature of 150 keV**.

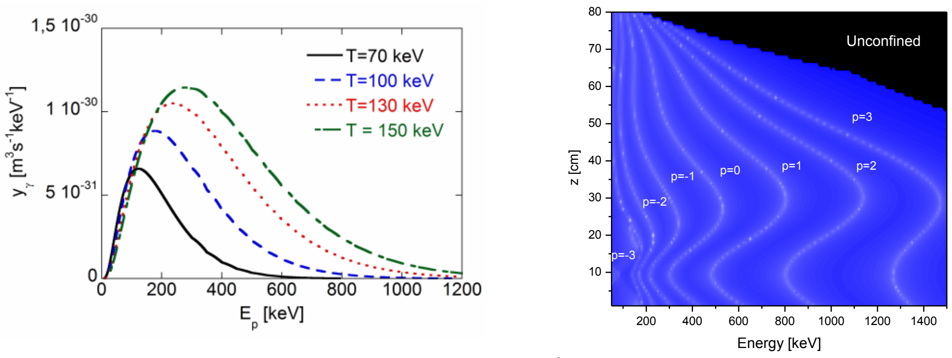

***Figure 4.** (Left) Differential reactivity of the d(p,γ)^{3}He reaction calculated for different tail temperatures as a function of the proton energy. (Right) Calculated resonances in phase space between protons having their turning points on the magnetic axis and TAEs with toroidal mode number n = 4 and bounce harmonics p=-3 to 3.*

CONCLUSIONS

- **First γ-ray spectroscopy measurements** of fast ions on **ASDEX Upgrade** were carried out
- Scenarios relying on the **acceleration of protons and deuterons** were designed. Different heating strategies and γ emitting reactions were developed.
- **No γ-ray emission** was observed in scenarios with **deuteron** acceleration
- **γ-ray emission** from proton **capture on boron** and **deuterium** was observed in scenarios with **proton** acceleration. **Tail temperatures** in the range **70-100 keV** were assessed. **TAEs** on Mirnov coils and associated **losses** on the FILD were detected throughout the discharge
- **γ-ray emission** was mostly due to protons with **E_p < 400 keV**. The observed **increasing count rate assessed the confinement of E_p < 400 keV** protons that could resonate with the TAEs through **negative harmonics of the bounce frequency**.
- An **overlap** between the **region responsible for γ-ray emission** and **that affected by losses** shall be partially achieved in future measurements with a **proton tail temperature of 150 keV**.

ACKNOWLEDGEMENT

This work was supported by EURATOM and carried out within the framework of EFDA. The views and opinions expressed herein do not necessarily reflect those of the European Commission. The computing resources of CSC - IT centre for science were used in the data-analysis

[1] V. Kiptily *et al.*, Plasma Phys. Control. Fusion 48, R59 (2006)
[2] M. Tardocchi *et al.*, "Spectral broadening of characteristic γ-ray emission peaks from ^{12}C(^{3}He,pγ)^{14}N reactions in fusion plasmas", submitted to Phys. Rev. Letters
[3] M. Garcia-Munoz *et al.*, Phys. Rev. Letters 104, 185002 (2010)
[4] M. Nocente *et al.*, Rev. Sci. Instrum. 81, 10D321 (2010)