Tokamak GOLEM for fusion education - chapter 7

R. Duban[1], O. Ficker[1,3], O. Grover[1], K. Jirakova[1], B.Leitl[1], M. Matusu[1], T. Okonechnikova[2], J. Stockel[1,3], V. Svoboda[1], G. Vondrasek[1]

[1] *Faculty of Nuclear Sciences and Physical Engineering CTU in Prague, Prague, Czech Rep.*

[2] *Faculty of Electrical Engineering CTU in Prague, Prague, Czech Rep.*

[3] *Institute of Plasma Physics AS CR, v.v.i., Assoc EUROATOM-IPP.CR, Prague, Czech Rep.*

As the oldest operational tokamak in the world, tokamak GOLEM at FNSPE CTU in Prague, Czech Republic serves primarily to educate students of the faculty in tokamak physics and related fields. This contribution covers various student projects of the last year.

Tokamak GOLEM presentation based on X3DOM technology

A 3D virtual model of GOLEM and its infrastructure has been integrated into the GOLEM web page using X3DOM technology. The web interface implements interactive functions which control the virtual world, allowing to learn about the tokamak independently of platform. For example, it is possible to construct the tokamak part by part while displaying information about the chosen part. The result of the project is a web application that introduces the tokamak to students of FNSPE.

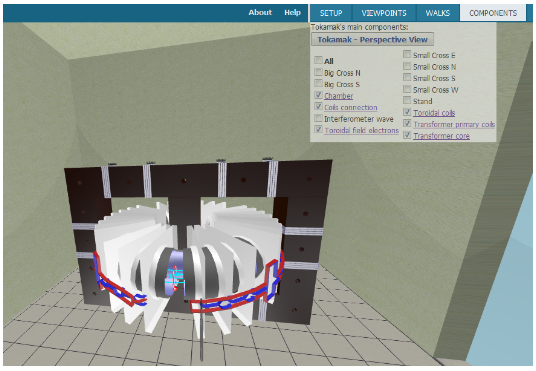

Figure 1: *Demonstration of an interactive option - tokamak construction.*

Periodic runaway electron losses caused by magnetic perturbations

Following the recent observation of runaway electron (RE) losses induced by MHD instabilities in different machines (e.g. FTU [2], COMPASS [1]), we tried to achieve similar results in the short discharges and low parameter plasma of tokamak GOLEM. From the wide variety of instabilities that can perturb RE orbits, magnetic islands are the most suitable regarding both their frequency and detection options. Furthermore, magnetic islands have already been observed on GOLEM using a 16-Mirnov coil ring [3]. For our experiments we used coils of this ring together with a scintillation

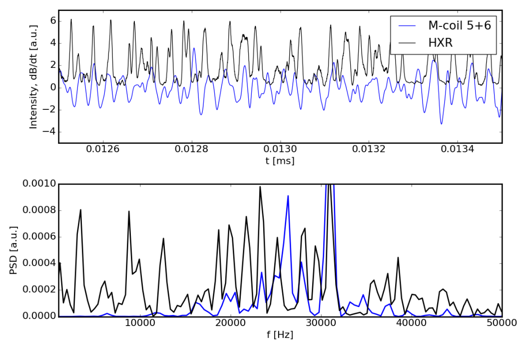

Figure 2: *Convolved signal of neighbouring Mirnov coils compared to smoothed HXR signal in the time range where strong correlation is expected (top), power spectral density of these signals (bottom). Discharge #21501.*

detector which observes the fast evolution of RE-limiter interaction. In the signal from these detectors, periodic clusters of HXR photon peaks were observed (Fig. 2 top) which may occur due to the influence of the islands on RE losses. The signals are quite noisy and have a different nature (HXR - bunches of peaks with exponential decay, and Mirnov coil - sinusoidal signal with a complicated spectrum). However, the frequency spectrum of these signals is very similar, namely in the region of 15-30 kHz. This gives the first evidence that the oscillations of both signals are interconnected and it shows that the phenomenon is worth deeper investigation.

Enhancement of MHD statistical method's studies by coherence of $B_{\theta per}$ coils

Following previous MHD studies [3] at the tokamak GOLEM, a new statistical method of spectral coherence was tested. In signal processing, coherence is defined as

$$C_{xy} = \frac{\mid S_{xy} \mid^2}{S_{xx}S_{yy}},$$

where S_{xy} stands for the cross-spectral density of compared signals and S_{xx}, S_{yy} for power spectral density. The coherence method describes the similarity of the complex frequency spectra of two signals. As it analyses signals similarity, both clear and weak events present in wide phase shift scale may be displayed next to each other. Spectral coherence shows events taking place at higher frequencies as well which calls for further investigation.

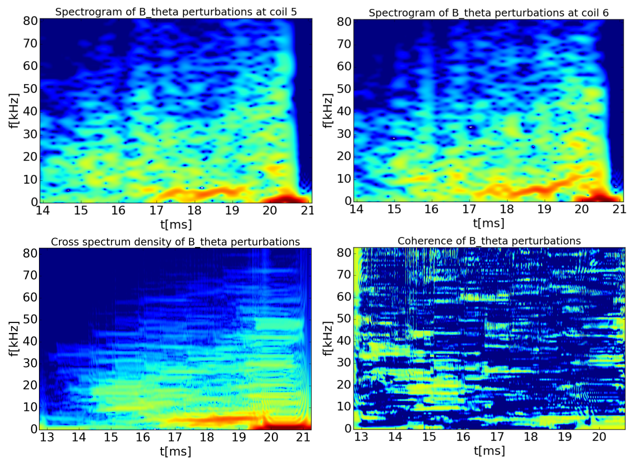

Figure 3: *Spectrograms of perturbation of B_θ measured at coils 5 and 6, their cross-spectrum time evolution S_{xy} and their spectral coherence. Discharge #10579.*

Reynolds stress profile measurements using a 2D array of Langmuir probes

The radial profile of Reynolds stress $\langle v_r v_\theta \rangle$ was measured using a 2D Langmuir probe array in H a He discharges. The array consists of two probe rakes with 2x8 pins in the radial direction separated radially and poloidally by 2.5 mm. The stress is assumed to be caused by electrostatic turbulence with velocities given by the $\vec{E} \times \vec{B}$ drifts. The electric field was estimated as spatial differences of floating potentials measured by the Langmuir probes (T_e fluctuations were neglected). The ergodic average

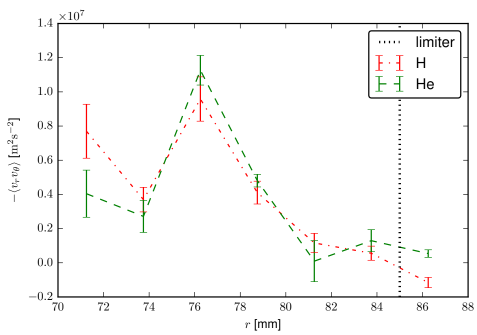

Figure 4: *Radial profiles of Reynolds stress measured with a 2D Langmuir rake probe array (8x2 pins) in H and He discharges.*

was taken over ~ 3 ms stationary parts of each discharge. Results from 11 H and 5 He discharges were statistically processed. All discharges exhibited a peak in the profile ~ 1 cm inside the limiter, suggesting possible generation of a shear flow layer by the Reynolds force $\nabla_r \langle v_r v_\theta \rangle$. In He discharges the gradients around the peak were slightly steeper. The measured profiles suggested the presence of peaks further inwards, but these were not investigated due to the risk of severe perturbation of the plasma profile by the probe head.

Edge plasma fluctuations analysis using a rake probe of Langmuir pins

Using measurements on shot-to-shot basis, the radial profile of ion saturated current I_{sat} in H and He plasma was obtained and the probability distribution function (PDF) of its fluctuations was described by its moments (see Fig. 7). The results for hydrogen are similar to those obtained on other tokamaks, e.g. COMPASS in Prague [4]. Positive skewness is found in the SOL, dropping to zero after the LCFS is crossed. This hints at the presence of turbulent structures possibly generated by interchange instability inside the LCFS. The PDF in hydrogen and helium is mostly similar. However, skewness does not fall to zero in helium plasma, but rather remains at a positive value of ~ 1. The same applies to the profile of kurtosis, though the difference is not as evident there. It's possible that the "blob birth zone" is located deeper in the plasma in case of helium, but it may also be that turbulence properties, affected by Larmor radius size, are different.

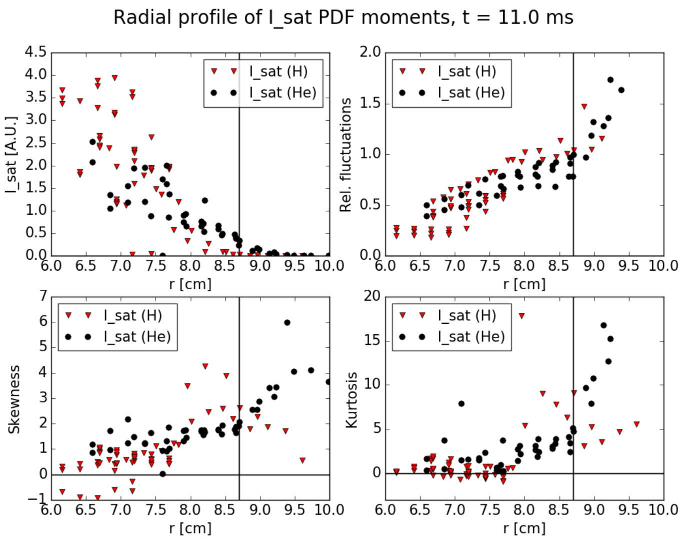

Figure 5: *Radial profile of I_{sat} fluctuations PDF in hydrogen and helium plasma.*

Mach number measurement using single a Mach probe on rotatable manipulator

The rotatable Mach probe is located on the outer midplane on adjustable radius. Parallel (toroidal) and perpendicular (poloidal) Mach numbers $M_\parallel$ and $M_\perp$ (flow is parallel/perpendicular to the magnetic fieldlines) can be measured using equation, [5]

$$\ln \frac{I_{sat}(\varphi)}{I_{sat}(\varphi + \pi)} = 2.4 \left(M_\parallel - \frac{M_\perp}{\tan \varphi} \right).$$

Because of the short discharges on the tokamak GOLEM ≈ 8 ms, sinusoidal magnetic field, plasma movement upwards and decreasing separatrix radius, velocity shear layer (E_r=0) changes in time, which has significant effect on the flow via $E_r \times B$ drift.

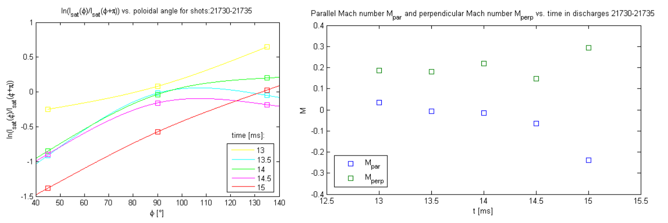

Figure 6: *(a) Ratio of Ion saturation currents on Mach probe angle. (90°-flow is perpendicular to the electrode surface); (b) Perpendicular $M_\perp$ and parallel $M_\|$ Mach numbers in time.*

The opposite field configurations results in opposite $E \times B$ drift in the SOL. In the normal field configuration (E-ACW, B-CW), particles are accelerated opposite the main flow, therefore $M_\|$ ($\varphi = 90°$) is decreasing in time. $M_\|$ and $M_\perp$ has different dependence on E_r, [5]. Position of the velocity shear layer in time on the outer midplane is not known, but its character suggest decreasing E_r on outer midplane, as probe distance from separatrix increases in time.

Testing AXUV module for plasma radiation studies

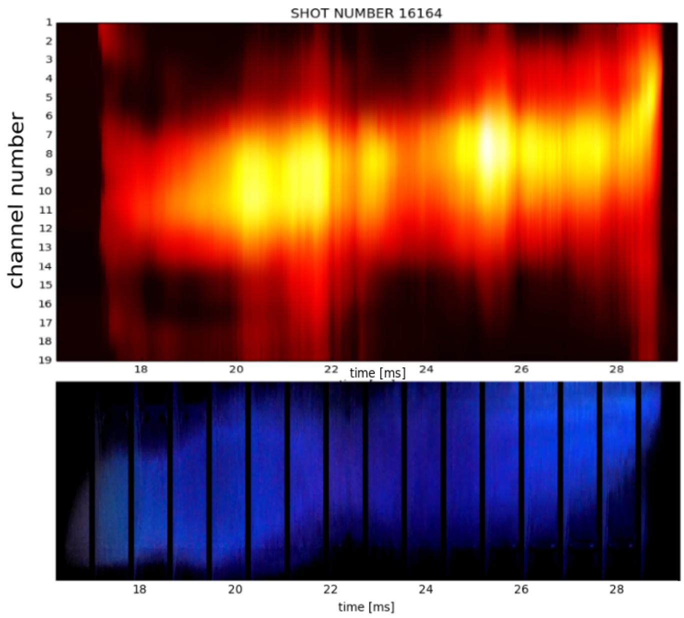

Figure 7: *Smoothed signal from AXUV array (hot scale) compared to signal from fast camera (blue).*

Testing AXUV (Absolute eXeme Ultra Violet) module was put into operation for plasma radiation studies on tokamak GOLEM. The module consists of 20 AXUV fast photodiods placed behind a pinhole. The spatialy calibrated detector was placed on tokamak LFS port and tested for the estimation of vertical position of low temperature plasma $T_e \sim 30$ eV. The signal was compared to a fast camera signal. The next step is to use two new AXUV20EL modules for determination of plasma position in the poloidal cross-section and studies of plasma radiation behaviour during a discharge in μs resolution.

Acknowledgement: This work was supported by the Grant Agency of the Czech Technical University in Prague, grant No. SGS15/164/OHK4/2T/14.

References

[1] O. Ficker et al., FuseNET PhD event, Prague, 2015
[2] F. Causa et al. , 42nd EPS Conference on Plasma Physics, Lisbon, 2015
[3] T. Markovic, Master thesis, CTU Prague, 2012
[4] K. Jirakova et al., Week of Doctoral Students 2016 (poster contribution), Prague, 2016
[5] K. Dyabilin, Czech. J. Phys. 50/S3 , Prague, 2000