Tokamak GOLEM for fusion education – chapter 16: plasma edge, transport barrier, spectroscopy, tomography, fast ion temperature, electric probes, MHD instability

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Introduction This paper is devoted to current students' projects at the GOLEM tokamak at the CTU in Prague with support of the Institute of Plasma Physics in Prague (IPP CAS), which were conducted during 2024. This device uniquely features a full remote-control system which extends its reach worldwide. This is the first part of two contributions on this subject. Transport barrier and spectroscopy related part of the work in this article was realized in the frame of summer and winter schools (SUMTRAIC and EMTRAIC) held at the IPP Prague [1].

Transport barrier In recent experiments on the GOLEM tokamak (circular plasma cross-section), spontaneous formation of a transport barrier (TB) was observed in He plasmas [2]. To investigate this phenomenon, plasma potential and electron temperature (T_e) profiles were measured using a combined Langmuir and Ball-pen probe in both H and He plasmas. Extensive scans in Ohmic heating power (P_h) and working gas pressure (p) were performed. The main aim was to study the scaling of the T_e gradient and its dependence on different plasma parameters as well as the shearing rate ω. It was found that the ratio of the T_e gradient after / before the TB formation increases gradually with both P_h and p in He plasmas as $\frac{(\nabla T_\mathrm{e}^\mathrm{max})^\mathrm{after}}{(\nabla T_\mathrm{e}^\mathrm{max})^\mathrm{before}} \propto P_\mathrm{h}^{0.67} \cdot p_\mathrm{He}^{0.92}$, see Fig. 1 (left). Fig. 1 (right) shows that correlation between the normalized T_e gradient and the shearing rate becomes stronger with increasing p. These findings enhance our understanding of TB formation and may guide future experiments in other circular tokamaks.

Spectroscopy As part of the SUMTRAIC and EMTRAIC 2024 events, several compact HR2000+ spectrometers from Ocean Optics equipped with different diffraction gratings measured the emission from the GOLEM tokamak plasma in the near ultraviolet (through visible light) to near infrared spectral region to investigate the previously observed color change in He discharges, associated with the formation of an edge transport barrier [2]. To correctly identify the

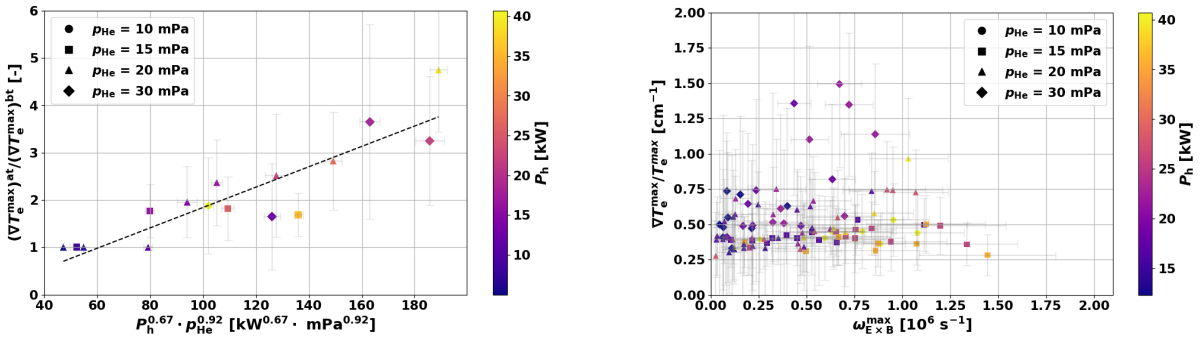

Fig. 1: (left) Scaling law for the ∇T_e ratio as a function of power input and pressure. (right) Dependency of the T_e inverse decay length on the T_e sheering rate

observed spectral peaks under GOLEM-specific conditions, the spectral axis was re-calibrated in 2024 using two spectral calibration sources from Ocean Optics, see example in Fig. 2 (left). A non-negligible shift of the spectral axis was found for the $\text{Halpha}_{\text{IPP}}$ spectrometer .

Detailed analysis of the measured spectra revealed many low-Z impurity spectral lines of lower ionization states (H I, C II, N II, O I), whose intensity increases with time, while intensity of the main gas (He I) lines decreases, indicating a strong inflow of these impurities during the discharge, see Fig. 2 (right). Surprisingly, several chlorine emission lines in the green and blue spectral region (470 - 550 nm) were identified, revealing erosion of the in-vessel diagnostics cables. Moreover, although the probe measurements indicate T_e up to 10 eV in the edge plasma and basic diagnostics estimates 40 eV in the core (Spitzer conductivity estimate), the spectroscopic measurements do not confirm the presence of any expected higher ionization states with ionization energy higher than 20 eV (He II lines are not visible in the entire spectrum and even the identification of the C III triplet at 465 nm is highly speculative, as it clearly overlaps with several N II and probably also O II lines).

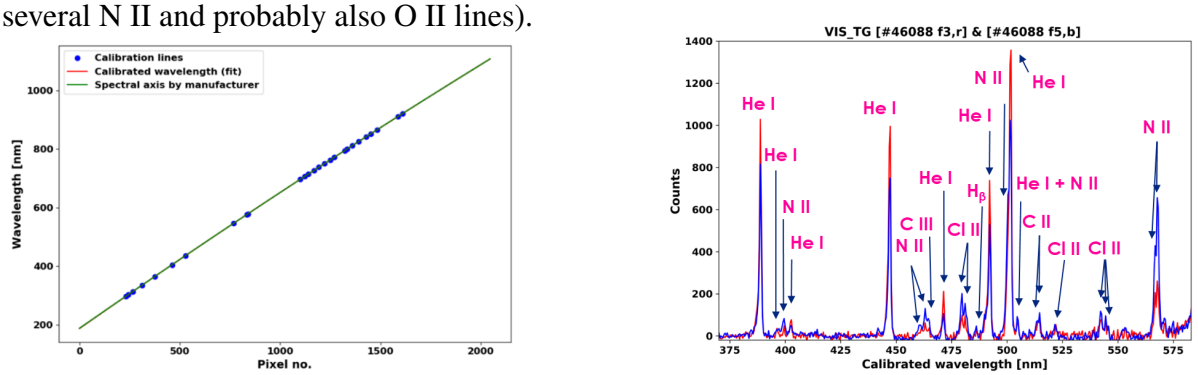

Fig. 2: (left) Spectral calibration of the VIS_{TG} spectrometer – good agreement of manufacturer's λ axis with the GOLEM calibration. Calibration curve is fitted using a cubic polynomial. (right) Shorter wavelength part of the measured spectrum by the VIS_{TG} spectrometer. Initial discharge phase (red) compared with its later phase (blue) $\rightarrow$ clear difference between the main gas (He) and present impurities (H, C, N, Cl) behaviour in time.

Tomography Figure 3 shows the tomographic reconstruction of visible plasma radiation at $t = 4.7$ ms from shot 46979 during the EMTRAIC 2024 event ($t = 1.82$ ms start of the discharge). Reconstruction of radiation tomography images was performed based on Mini-

mum Fisher Regularization (MFR) [3], showing the red, green and blue channels from left to right. The reconstructions highlight wavelength-dependent emissivity variations: the red channel shows a pronounced edge brightness near the plasma boundary, indicating a sharp gradient.

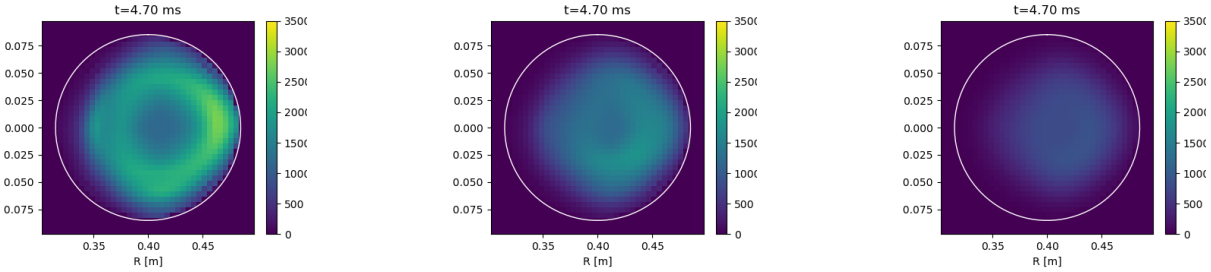

Fig. 3: The tomography reconstruction of visible radiation of shot 46979 at $t = 4.7$ ms

Fast ion temperature Ion temperature (T_i) was measured with a temporal resolution of $5\,\mu$s (fastest in fusion research) in He plasmas using a fast swept ball-pen probe [4, 5]. This temporal resolution falls below the typical timescales of turbulent structures ($\sim 10\,\mu$s), enabling direct analysis of their dynamic evolution. A novel technique was applied analysing the full IV-characteristic of Ball-pen probes with T_i as a fitting parameter. Time evolutions of T_i were obtained across various discharges at different radial probe positions, see example Fig. 4 (left). The resulting histograms of T_i, see Fig. 4 (right), exhibit a characteristic distribution with a pronounced high-temperature tail and a large number of low values, corresponding to positive skewness and high kurtosis — features typical of turbulent plasmas [6]. The motivation for these measurements is to further study turbulent behaviour of T_i and enable future studies of T_i radial profiles in the presence of the transport barrier [2]. By overcoming previous limitations in temporal resolution, this approach provides an unprecedented tool for diagnosing ion temperature fluctuations in magnetically confined fusion devices.

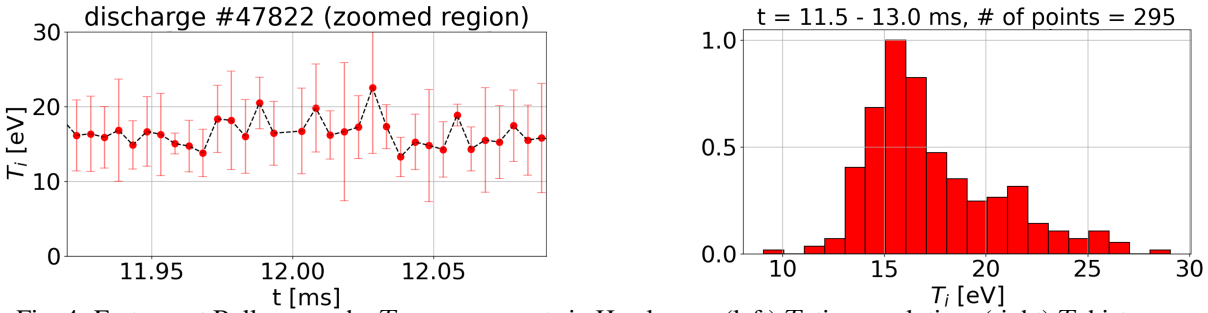

Fig. 4: Fast swept Ball-pen probe T_i measurements in He plasma: (left) T_i time evolution. (right) T_i histogram.

Electric probes A newly designed combined electric probe-head consisting of two Ball-pen and two Langmuir probes has been recently installed and is currently undergoing calibration, see IV-characteristic example in Fig. 5 (left). The new dual probe-head design newly allows simultaneous voltage-sweeping & I_{sat} or U_{fl} measurements. It is intended to be used e.g. for transport barrier studies [2] and fast (up to 100 kHz) T_i measurements [4].

New probe electronics system is also being developed for simpler operation, improved data acquisition and easy setup change between I_{sat}^{+}, U_{fl}, U_{bias} and U_{sweep} modes, see Fig. 5 (right).

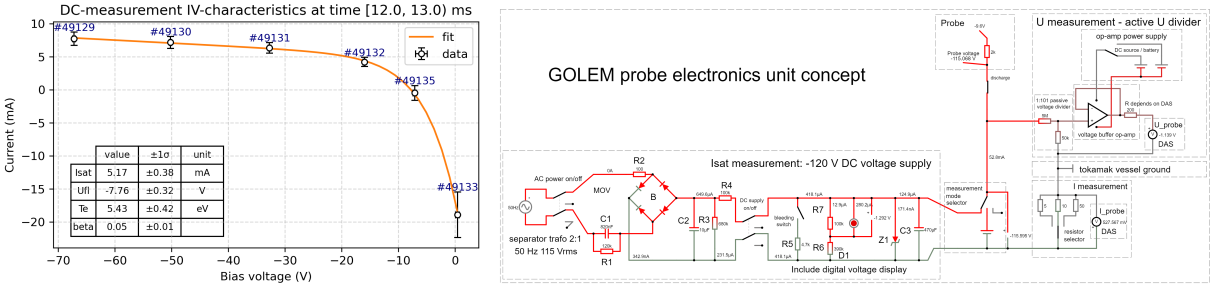

Fig. 5: (left) Lamgmuir probe IV-characteristic fit. (right) Design concept of a new electric probe electronics unit.

MHD instability studies are one of the key topics of tokamak plasma research. One such instability investigated on the GOLEM tokamak is magnetic islands. Interactions between magnetic islands and error fields can trigger mode locking – stopping the rotation of the plasma – and can potentially lead to disruptions.

It can be identified from the power spectrum of the Mirnov coils, since the rotation of a magnetic island produces harmonic oscillation in the poloidal magnetic field. To streamline magnetic island identification, a modular Python-based data visualization interface is being developed. This tool significantly accelerates island detection and cataloging. One implemented feature is Pearson correlation analysis of Mirnov coil signals, which enables determination of magnetic islands' poloidal structure.

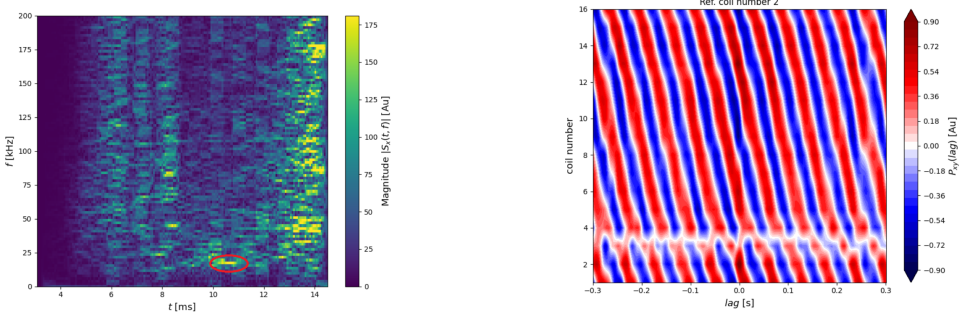

Fig. 6: (left) Mirnov coil spectrogram. (right) Pearson correlation of two Mirnov coils from shot 47240.

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