Tokamak GOLEM for fusion education – chapter 16: Bayesian discharge optimization, Artificial Neural Network tomography, runaway electrons, lithium evaporator

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Introduction This contribution is devoted to current student's projects at the GOLEM tokamak at CTU in Prague with support of the Institute of Plasma Physics (IPP CAS) which were conducted during 2024. This is the second part of two contributionson this subject.

Bayesian discharge optimization Thanks to the robust and simple Golem discharge setup via single multi-argument command entered to the control server, it was possible to implement a Bayesian optimizer to directly run the tokamak and optimize selected parameters of the discharge. Such connection of autonomous software control with complicated plasma confinement device is unique even on the global scale. In the first approach, the discharge duration, which is a function of many parameters on Golem due to the use of a capacitor bank, iron core, occurrence of relatively strong error fields and varying vacuum conditions, was optimized. Using variation of four main initial setup parameters: voltage on the capacitor bank of toroidal filed circuit, primary windings, mutual delay of triggering of these two circuits and gas pressure in the chamber before the discharge, the optimizer found a stable maximum – reaching record length for the given configuration. The optimization was based on results of 100 discharges from recent campaigns and roughly

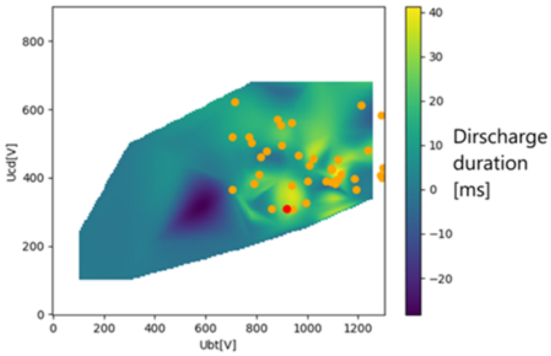

Fig. 1: Domain for the optimization of the Golem discharge length (color bar) in the two most important discharge preset parameters: voltage on the capacitor bank for TF coils (x-axis) and primary windings (y-axis). The background colormap is reconstructed using the 100 recent pulses, the orange dots are parameters selected by the optimizer and the red dot is the located optimum with - record length in given configuration without active position stabilisation: 26.29 ms.

30 iterations when the machine was directly controlled by the optimizer, see Fig. 1. The results were further improved when feed-forward stabilization was utilized.

Runaway Electron Loss Localization Preliminary results indicate that deliberate detector placement, combined with Monte Carlo radiation modeling, enables the localization of runaway electron (RE) losses based on the distribution of hard X-ray (HXR) signals. Three LYSO scintillation probes were arranged to detect HXR radiation from REs (see Fig. 2). By comparing the relative signal strengths between the probes (Fig. 3), the position of RE interactions could be estimated. This initial test is a first step toward the goal of determining RE pitch angles from the angular distribution of HXR emission of RE losses.

Golem in Augmented reality Using the free Google AR API, simplified CAD models of some Golem tokamak components can be viewed via your mobile camera. Use the QR code (requires Google Chrome – copy the link if another browser opens – Android only, page in Czech). Iso-surfaces of magnetic fields from some coil systems are shown as well, calculated in 2D by FEMM and converted to 3D via Python. Since this format is not ideal for field visualization, alternatives are being explored.

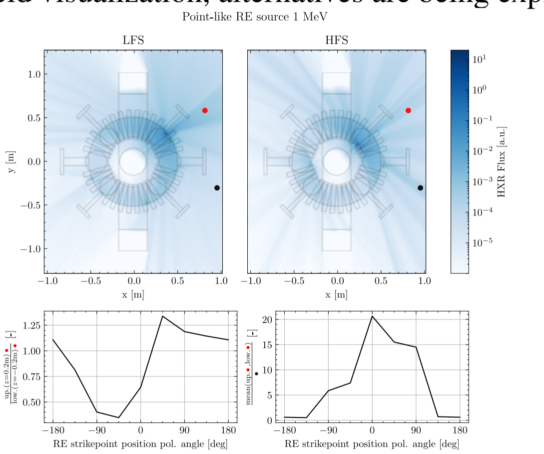

Fig. 2: Upper left: runaway beam hitting the limiter from low field side (LFS), upper right: RE on high field side (HFS). Lower: Dependence between RE strike-point position and ratios between two detectors.

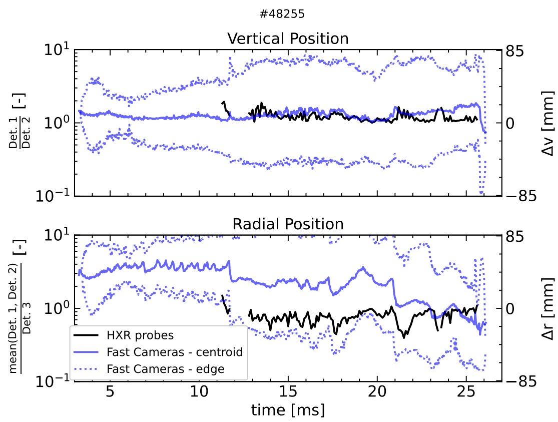

Fig. 3: Time evolution of ratios between two HXR probes corresponds to shift in plasma position.

Lithium evaporator For the purposes of experimental campaigns utilizing Lithium an evaporator system is currently being developed. The simple design features a stainless steel (or Boron-Nitride-Carbide) cup mounted on a manipulator arm, with holes for a heating element and thermocouple. Lithium flux is provided by evaporation [1], regulated by the heater-thermocouple system. The geometry of the cup allows Li wetting via capillary forces strong enough to retain it [2]. Recent tests confirm viability of the design for GOLEM, though some components need upgrades. While Li evaporation was observed, the power output of the heating cartridge was insufficient to reach the ~ 350 °C needed for proper wetting [2].

Design of an In-Vessel Probe for RE Detection The design of an in-vessel probe for direct runaway electron (RE) measurement is being finalized. The probe will use three small YAP:Ce scintillation pins (0.8 mm diameter, Ti-coated) arranged in a line (CRYTUR crystals). The pins will be enclosed in a molybdenum cover serving as both collimator and absorber. The modular probe design enables testing various collimators and scintillation coatings. The collimator allows pitch angle measurements, while the probe's geometry permits radial and angular adjustments via a manipulator. Scintillation light will be transmitted through optical fibres to a SiPM located outside the chamber and recorded by an oscilloscope.

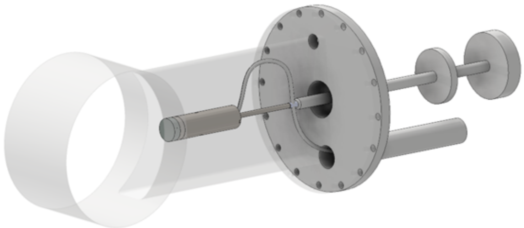

Fig. 4: Probe mounted on manipulator.

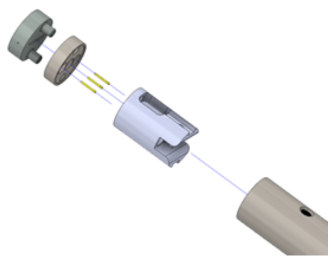

Fig. 5: Detail of the probe – flexible design. Interchangeable collimator, pins holder, scintillation pins, optical fibre mount and manipulator mount.

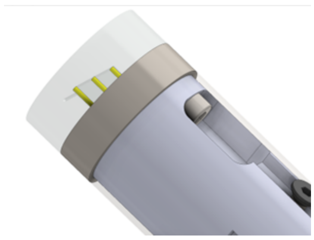

Fig. 6: Detail of the probe head – Mo cover as collimator with scintillation pins (yellow) inside.

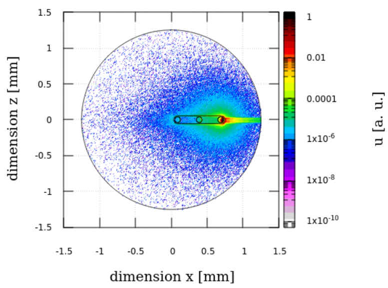

Fig. 7: FLUKA simulation of 1 MeV RE beam penetrating the probe (top view).

GOLEM-PUC-Chile collaboration A remote experimental campaign with PUC-Chile students included 5 sessions and 102 plasma discharges at GOLEM. The focus was UV/visible spectrometry (Ocean Optics HR2000+ES, $t_{res} = 2$ ms) for monitoring emission lines of main gases (H/He) and impurities (e.g. Fe, N). Key parameters: $I_{p,max} < 11$ kA, $B_{p,max} < 0.56$ T, gas pressure $p_{WG} = 5$ – 22 mPa, and plasma position control. This enabled hands-on tokamak training and analysis of plasma–wall interaction and conditioning. Hydrogen plasmas with control lasted longer than uncontrolled ones (28 vs. 11 ms), showing reduced impurity emission. Helium discharges had lower $I_{p,max}$, shorter duration (< 10 ms), and richer impurity spectra. Further analysis will assess effects of gas species and magnetic setup on plasma stability and impurity influx.

Timepix3-Based Diagnostics of Runaway Electron Losses The Timepix3 detector was used to study hard X-ray (HXR) emission from runaway electrons (REs). With its 256×256 pixel array, it provides high spatial, energy, and temporal resolution, including 1.56 ns time-of-arrival (TOA) precision and a hit rate of up to 40 Mhits/s/cm^2. The detector was positioned with a clear view through the beryllium window in the equatorial plane of the tokamak (Fig. 8), it enabled correlation with magnetic signals from Mirnov coils, offering complementary insights into RE dynamics and MHD activity. Wavelet coherence analysis of Timepix3 and Mirnov coil signals (see Fig. 9) suggests that RE losses are closely related to MHD events. Evidence also indicates energy-dependent coupling of REs to specific MHD modes, to be explored in future studies.

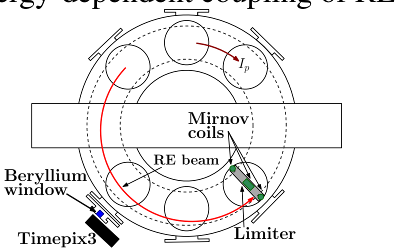

Fig. 8: Schematic representation of the experimental arrangement of Timepix3 detector at Beryllium window and Mirnov coils behind the limiter.

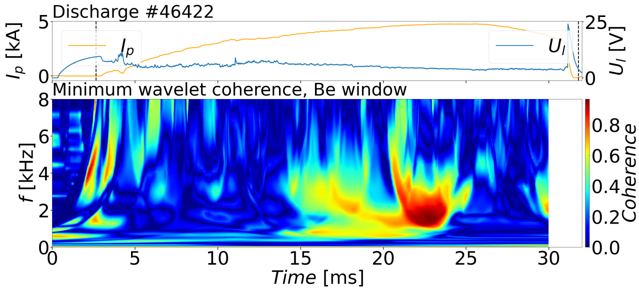

Fig. 9: The minimum wavelet coherence highlights the correlation between hard X-ray (HXR) emission and MHD activity.

Artificial Neural Network tomography Training dataset optimization was performed to enhance an Artificial Neural Network (ANN)-based model for tomographic reconstruction of visible plasma radiation at the GOLEM tokamak. The training data include emissivity phantoms with synthetic measurements from two visible cameras. The neural network consists of 2560 input neurons, one hidden layer, and 1600 output neurons, trained with a fixed learning rate and dropout regularization. Model performance is evaluated under data quality changes: noise simulates measurement uncertainty, dropped pixels represent reduced spatial resolution, and random gaps mimic missing sensor data. As shown in Fig. 10 (left to right: original sample, prediction without distortion, and predictions with noise, drop-pixel, and gaps), model accuracy is sensitive to these distortions. [3].

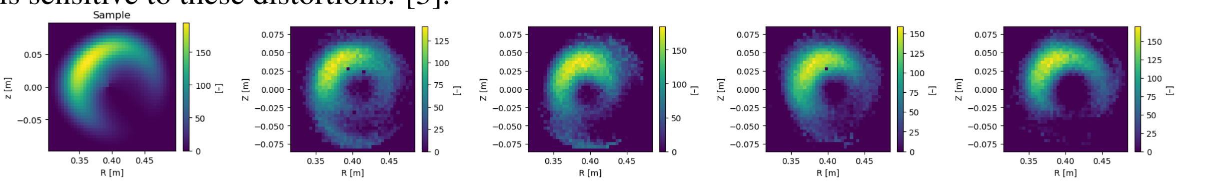

Fig. 10: From left to right: the original sample, the model prediction without distortion, and predictions with noise, dropped pixels, and random gaps.

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References

[1] C. B. Alcock et al., *Canadian Metallurgical Quarterly*, Vol. 23, No.3, pp. 309-313, 1984

[2] P. Fiflis et al., *Fusion Engineering and Design 89* (2014) 2827–2832

[3] S. Abbasi, J. Mlynar, J. Chlum, O. Ficker, V. Svoboda, and J. Brotankova, *Artificial Neural Network-Based Tomography Reconstruction of Plasma Radiation Distribution at GOLEM Tokamak*, Journal of Fusion Energy, vol. 43, no. 2, p. 64, 2024.