Tokamak GOLEM for fusion education – chapter 17: plasma current stabilization, Bayesian optimization, runaway electrons and NN-based visual tomography

M. Tunkl[1,3,*], S. Abbasi[1], B. Boczek[1], J. Buryanec[1], O. Ficker[1,2], G.I. Pokol[1,5],
P. Pilař[1], L. Lobko[1,3], Š. Malec[1], T. Oktábcová[4], J. Paz-Peñuelas Oliván[1],
K.P. Gómez Romero[1], V. Svoboda[1], K.J. Wijsman[1]

[1]*Faculty of Nuclear Sciences and Physical Engineering, CTU in Prague, Czechia*
[2]*Institute of Plasma Physics, Czech Academy of Sciences, Prague, Czechia*
[3]*Department of Applied Physics, Ghent University, Belgium*
[4]*Gymnasium Na Zatlance 11, Prague, Czechia*
[5]*Department of Nuclear Techniques, Budapest University of Technology and Economics, Hungary*
[*]*Corresponding author: tunklmar@cvut.cz*

Introduction This contribution presents current student projects carried out at the GOLEM tokamak, operated at the Czech Technical University in Prague (CTU). It is the second of two contributions on this topic.

Plasma current stabilization and flat-top The current drive of the GOLEM tokamak is based on an iron core carrying the magnetic flux generated by a solenoid powered by a capacitor discharge. This naturally leads to a non-uniform plasma-current waveform, which is not ideal for plasma experiments.

The recent installation of an auxiliary primary winding powered by an AE TECHRON amplifier (Fig. **??**) enables finer control of the plasma current. Experiments targeting flat-top operation in hydrogen discharges achieved a 13 ms flat-top at 4 kA (Fig. **??**). Reproducibility remains sensitive to vessel conditioning. Further efforts are directed towards an automated stabilization system based on numerical simulations.

The system of differential equations describing the GOLEM tokamak and its plasma current drive is given system of equations:

$$\mathbf{R}\,\mathbf{I}(t)+\mathbf{L}\,\dot{\mathbf{I}}(t)+\mathbf{u}(t)=\mathbf{0}, \tag{1}$$

$$\mathbf{I}(t)=\begin{bmatrix} I_{\mathrm{CD}}(t) & I_{\mathrm{aux}}(t) & I_{\mathrm{ch}}(t) & I_{\mathrm{p}}(t)\end{bmatrix}^{\top}, \tag{2}$$

$$\mathbf{u}(t)=\begin{bmatrix} U_{\mathrm{C}}(t) & -U_{\mathrm{aux}}(t) & 0 & 0\end{bmatrix}^{\top} \tag{3}$$

$$\mathbf{R}=\mathrm{diag}\big(R_{\mathrm{CD}},R_{\mathrm{aux}},R_{\mathrm{ch}},R_{\mathrm{p}}\big), \tag{4}$$

$$\dot{U}_{\mathrm{C}}(t) - \frac{I_{\mathrm{CD}}(t)}{C_{\mathrm{CD}}} = 0. \tag{5}$$

where the current vector $\mathbf{I}$ is composed of the capacitor-driven current I_{CD}, auxiliary winding current I_{aux}, chamber current I_{ch}, and plasma current I_{p}. The corresponding resistance matrix $\mathbf{R}$ has the diagonal form while the inductance matrix $\mathbf{L}$ contains both the self-inductances on the diagonal and the mutual inductances as off-diagonal entries. The source vector $\mathbf{u}(t)$ represents the capacitor bank voltage $U_{\mathrm{CD}}(t)$ and the voltage $U_{\mathrm{aux}}(t)$ supplied by the AE TECHRON amplifier. The capacitance of the current drive capacitor bank is $C_{\mathrm{CD}} = 13.5\,\mathrm{mF}$. Based on this model, the current I_{aux} required to drive the auxiliary primary winding in order to achieve a plasma-current flat-top can be determined; however, the implementation of this approach is still in progress.

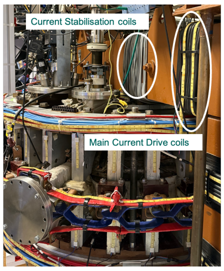

Figure 1: Stabilization coils on GOLEM.

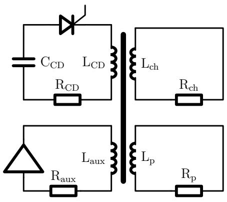

Figure 2: Scheme of GOLEM current drive circuit.

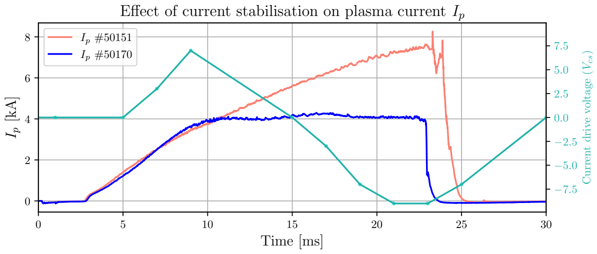

Figure 3: Best flat-top result (shot #50170): ∼13 ms at 4 kA compared to an unstabilized discharge.

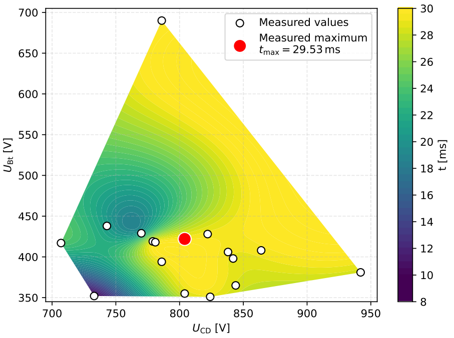

Figure 4: Domain for the optimization of the GOLEM discharge length (color coded) in the two most important discharge preset parameters: voltage on the capacitor bank for TF coils U_{Bt} and primary windings U_{CD}.

Bayesian optimization of discharge parameters Building on previous work [?] aimed at maximizing discharge duration, the optimization framework was extended to include waveforms for current and position stabilization (radial, vertical) systems.

An initial approach based on step-function waveform optimization led to an excessive number of parameters. A simplified strategy was therefore adopted, in which the optimizer selected key operational parameters as in the previous version - including magnetic-field-coil voltages, discharge timing, and gas pressure. On top of these scaling coefficients for predefined stabilization waveforms were added.

In total, this resulted in 7 input parameters. Compared with earlier campaigns, the updated approach achieved more stable and longer plasma discharges with plasma current reaching quazi-flattops, maximum discharge duration achieved was 29.53 ms (Fig. **??**). The optimiser was in full control of the tokamak with no human interference in the batch of discharges. The results demonstrate the capability of probabilistic optimization methods to efficiently explore complex operational parameter spaces in real plasma physics experimental environments.

Arduino-based physical control panel An Arduino-based control panel is under development (Fig. **??**) to automate discharge initiation and simplify operation. It allows even inexperienced users to initiate discharges under supervision. The prototype includes manual controls for key parameters and digital readouts for verification.

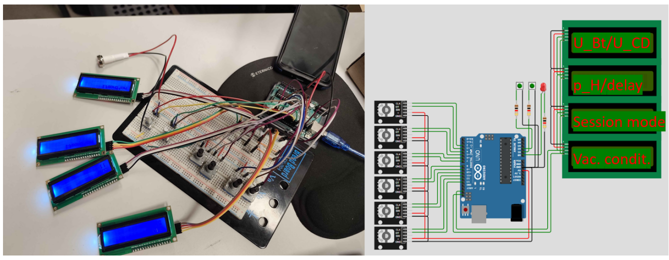

Figure 5: Arduino control panel prototype for GOLEM.

Runaway Electron Studies cobine diagnostic development, forward modelling and signal analysis to better understand RE losses.

Hard X-ray (HXR) emission produced during RE impacts on the limiter was modelled using Geant4, and RE parameters were reconstructed using a tomographic approach based on HXR measurements. Strike-point localization has been demonstrated with five scintillation detectors; however, reliable inference of pitch-angle requires broader coverage ($\gtrsim$15 detectors) and extension of the model to full energy dependence [**?**]. Development of both the detector system and forward model is ongoing.

High-resolution Timepix3 measurements were combined with wavelet-based time–frequency analysis of Mirnov coil signals. Significant coherence in selected regions indicates modulation of RE losses by MHD activity (Fig. **??**).

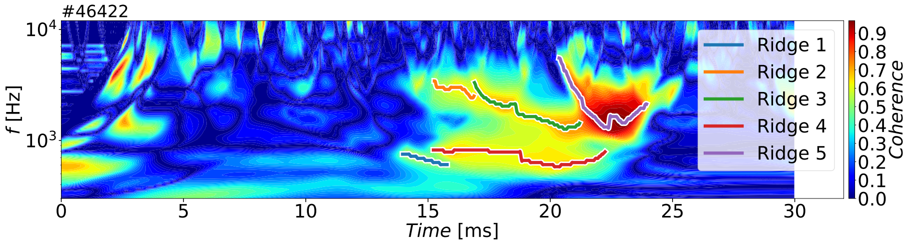

Figure 6: Minimum wavelet coherence between Mirnov coil signals and RE activity observed by Timepix3.

A novel DDRE (Direct Detection of Runaway Electrons) scintillation probe is being developed and tested. It consists of three miniature scintillators behind a collimator (Fig. **??**), enabling sensitivity to selected regions of (E, α) phase space. Initial results demonstrate clear discrimination between HXR background and direct RE impacts: HXR produces comparable signals in all channels, whereas RE impacts dominate in the first detector (Fig. **??**). Current work focuses on improving light collection efficiency for energy-resolved measurements.

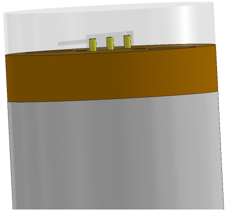

Figure 7: CAD model of DDRE probe.

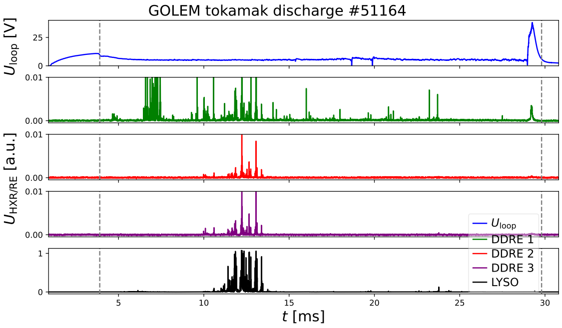

Figure 8: Signals from DDRE probe compared with external LYSO scintillation detector.

NN-based visible camera tomography and Mirnov coil measurements Ongoing research investigates the complementarity of neural-network-based visible-light tomography [**?**] and Mirnov coil diagnostics. Time-resolved analysis methods are being developed to compare the evolution of reconstructed plasma radiation distributions with plasma position and motion inferred from magnetic measurements at a different toroidal location across multiple plasma discharges.

Acknowledgements This work was supported by the Grant Agency of the Czech Technical University in Prague, Grant No. SGS24/144/OHK4/3T/14 and SGS25/160/OHK4/3T/14.

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 - EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

References

[1] S. Malec et al., Tokamak GOLEM for fusion education – chapter 16, EPS Conference, 2025.

[2] T. Akiba et al., Optuna: A Next-generation Hyperparameter Optimization Framework, Proc. 25th ACM SIGKDD Int. Conf. on Knowledge Discovery and Data Mining, 2623–2631 (2019), doi:10.48550/arXiv.1907.10902.

[3] M. Tunkl et al., Modelling and inversion of bremsstrahlung from runaway electrons on the GOLEM tokamak. (Accepted), PPCF, 2026, doi:10.1088/1361-6587/ae7e23.

[4] S. Abbasi et al., Artificial Neural Network-Based Tomography Reconstruction of Plasma Radiation Distribution at GOLEM Tokamak. J Fusion Energ **43**, 64 (2024), doi:10.1007/s10894-024-00458-z.