FACULTY OF NUCLEAR SCIENCES AND PHYSICAL ENGINEERING CTU IN PRAGUE

TOKAMAK GOLEM FOR FUSION EDUCATION – CHAPTER 17: PLASMA CURRENT STABILIZATION, BAYESIAN OPTIMIZATION, RUNAWAY ELECTRONS AND NN-BASED VISUAL TOMOGRAPHY

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H=High school B=BSc M=MSc P=PhD PD=PostDoc

INTRODUCTION

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

GOLEM tokamak:

- **World's oldest operational tokamak**: $R = 0.4\,\mathrm{m}$, $a = 0.085\,\mathrm{m}$, $B_t < 0.8\,\mathrm{T}$, $I_p < 16\,\mathrm{kA}$
- **Remote-control interface**: students worldwide perform plasma experiments hands-on
- Subject of high-school projects and Bachelor's/Master's theses; **part of** the basic physics **curriculum**
- **Diagnostics testing bed**

Fig. 1: Geographic distribution of GOLEM remote operation sessions.

ARDUINO-BASED PHYSICAL CONTROL PANEL

- Prototype of Arduino-based panel
- Manual control knobs, automatically produces discharge command
- Enables **youngest visitors** to initiate a plasma discharge under supervision

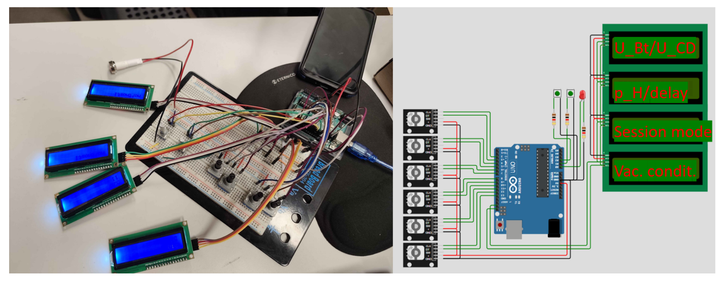

Fig. 6: Arduino control panel prototype for GOLEM.

PLASMA CURRENT STABILIZATION AND FLAT-TOP

- Auxiliary primary winding + AE TECHRON amplifiers enable active control
- Flat-top of ∼**13 ms at 4 kA** achieved (shot #50170)
- Reproducibility is sensitive to vessel conditioning
- Model-based control under development
  - $\mathbf{RI} + \mathbf{L}\dot{\mathbf{I}} + \mathbf{u} = 0$
  - $\mathbf{I} = (I_{\mathrm{CD}}, I_{\mathrm{aux}}, I_{\mathrm{ch}}, I_{\mathrm{p}})^{\top}$
  - $\mathbf{u} = (U_{\mathrm{CD}}, -U_{\mathrm{aux}}(t), 0, 0)^{\top}$
    - capacitor discharge $\dot{U}_{\mathrm{CD}}(t) - \frac{I_{\mathrm{CD}}(t)}{C_{\mathrm{CD}}} = 0$ and controllable U_{aux}

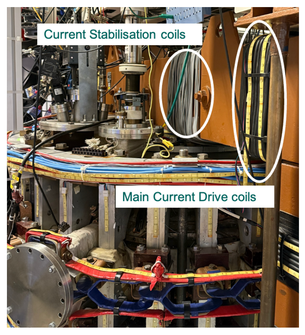

Fig. 2: Stabilisation coils in GOLEM.

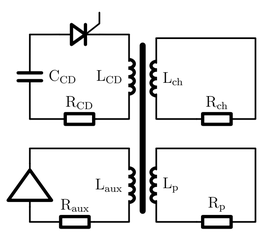

Fig. 3: Scheme of GOLEM current drive circuit.

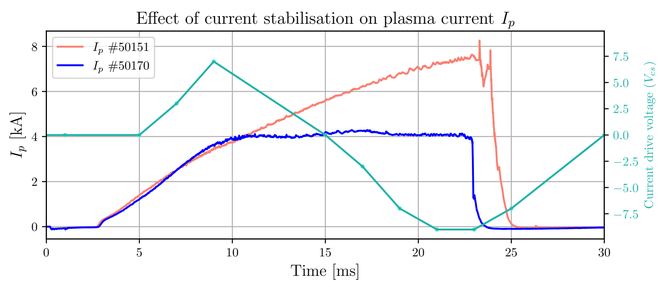

Fig. 4: Flat-top: shot #50170 (∼13 ms, 4 kA) vs. reference.

RUNAWAY ELECTRON STUDIES

- **Modelling and Inversion of HXR intensities** using Geant4-based forward modelling and tomographic methods [3]
  - RE strike-point localization demonstrated (using 5 scintillation detectors)
  - RE pitch-angle reconstruction requires $\gtrsim$15 detectors and RE energy dependent modelling.
- **MHD-modulated RE losses**: Timepix3 measurements combined with wavelet-based analysis of Mirnov coil signals
  - significant time–frequency coherence between RE activity and magnetic fluctuations observed

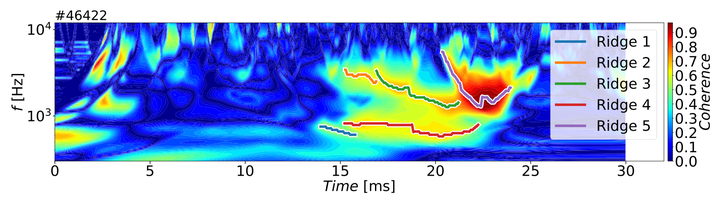

Fig. 7: Time–frequency coherence between Mirnov coil and Timepix3 signals.

- Developments and testing of **Direct Detection of Runaway Electrons** (DDRE) probe
  - Three scintillation pins behind collimator
  - **Sensitivity to** selected regions of the **(E, α) phase space**
  - Effective **discrimination between HXR background and RE signals confirmed**

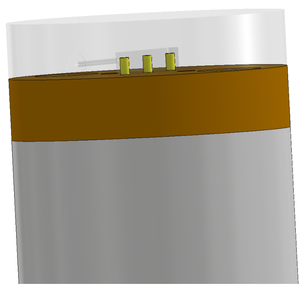

Fig. 8: CAD model of the DDRE probe.

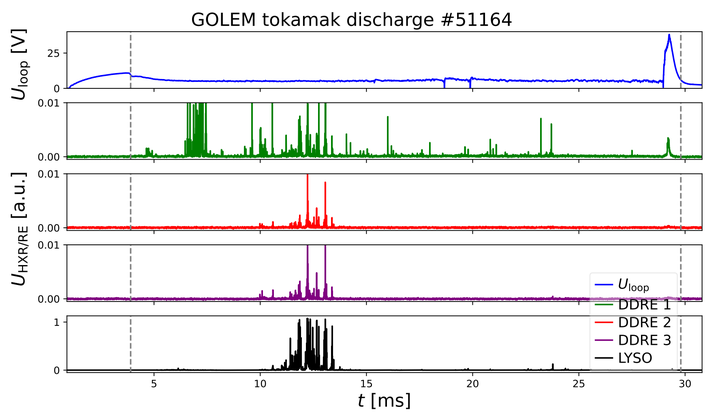

Fig. 9: DDRE response compared with external LYSO detector.

BAYESIAN OPTIMIZATION OF DISCHARGE PARAMETERS

- Extended Bayesian optimisation (*Optuna library* [2]) tested for radial and vertical position control waveforms-step function in 5-10 time nodes
  - Optimisation space too large → limited success
- Original scheme modified with **4 main input parameters** modified by adding **3 waveform scaling parameters** - current, radial and vertical position stabilisation
  - Stable results → **longer discharges** within the explored domain
  - **Stable currents** during the discharges achieved
- In future, this approach will be combined with other control approaches

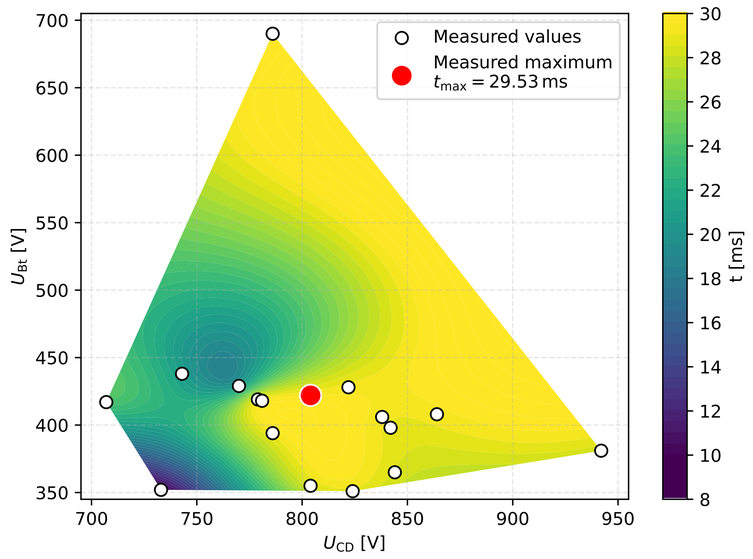

Fig. 5: Discharge duration (colour bar) vs. U_{bt} and U_{cd} over Bayesian iterations.

NN-BASED VISIBLE TOMOGRAPHY AND MIRNOV COILS

- Ongoing work investigates possible relationships between **neural network–based visible camera tomography** [4] and **plasma position** inferred from Mirnov coil measurements at a different toroidal location.
- A 3D visualization of the GOLEM tokamak provides a common geometric framework for comparing camera tomography and Mirnov coil diagnostics during plasma evolution.

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[4] Abbasi et al., Artificial Neural Network-Based Tomography Reconstruction of Plasma Radiation Distribution at GOLEM Tokamak. J Fusion Energ 43, 64 (2024).

EUROPEAN UNION European Structural and Investment Funds OP Research, Development and Education

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