INSTITUTE OF PLASMA PHYSICS OF THE CZECH ACADEMY OF SCIENCES

TOKAMAK GOLEM: HISTORY, PRESENCE, ACHIEVEMENTS

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OUTLINE

History

- TM-1
- CASTOR
- GOLEM

GOLEM in current days

- Basic overview
- Diagnostic
- Database

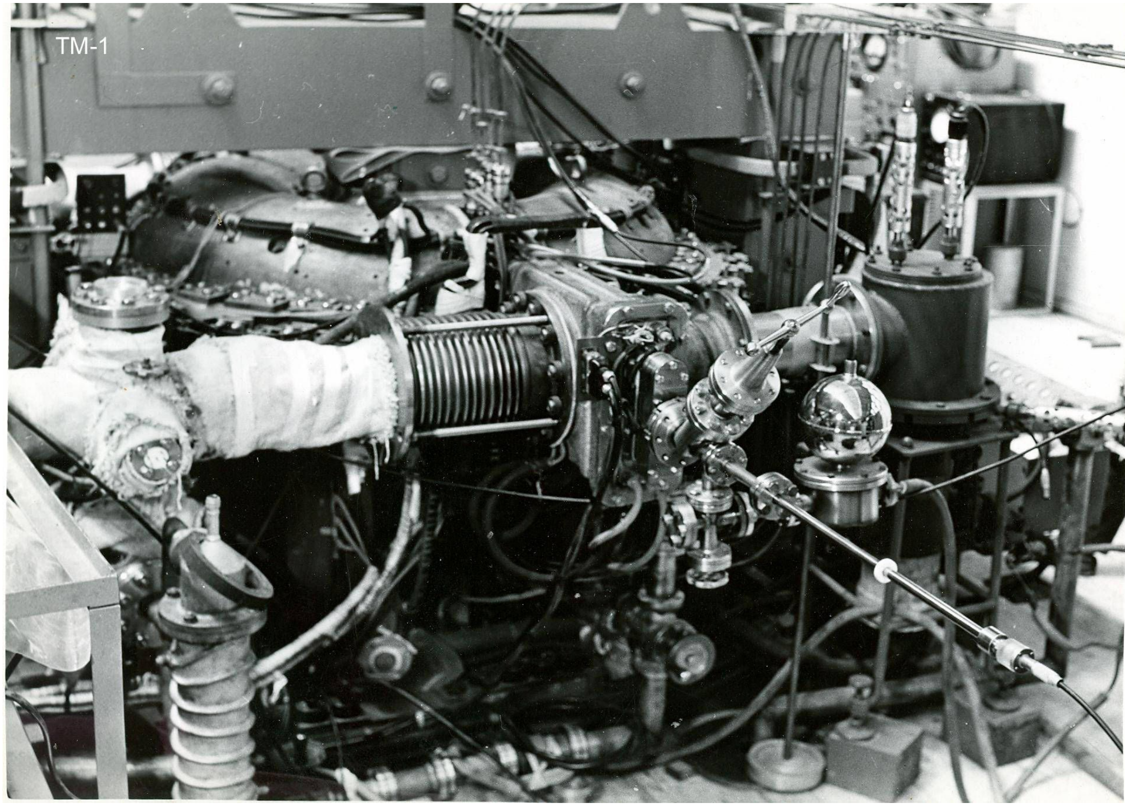
GOLEM achievements

- Interesting papers
- Student works

TM-1

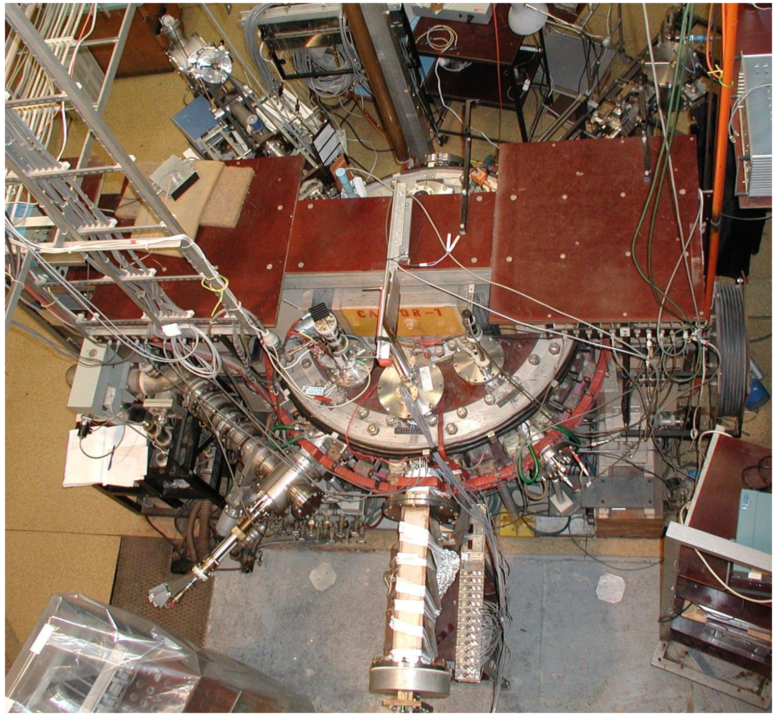
- Constructed in 1960 in the Soviet Union at the Kurchatov Institute in Moscow.
- It was the third tokamak constructed in history (after T-1 and T-2 tokamaks).
- **Named as TM-1** (tokamak malyj - a small tokamak).
- One of the first functional experimental **small-size** tokamak designed for controlled thermonuclear fusion research.
- In russia served for **radiofrequency wave interaction studies.**

- Influential group of theorists in czech republic studying RF current drive => TM-1 was **donated to our Institute** in **1975**, operating **under name TM-1 MH** (microwave heating).
- The primary goal after moved to our institute was to study microwave heating of plasma.



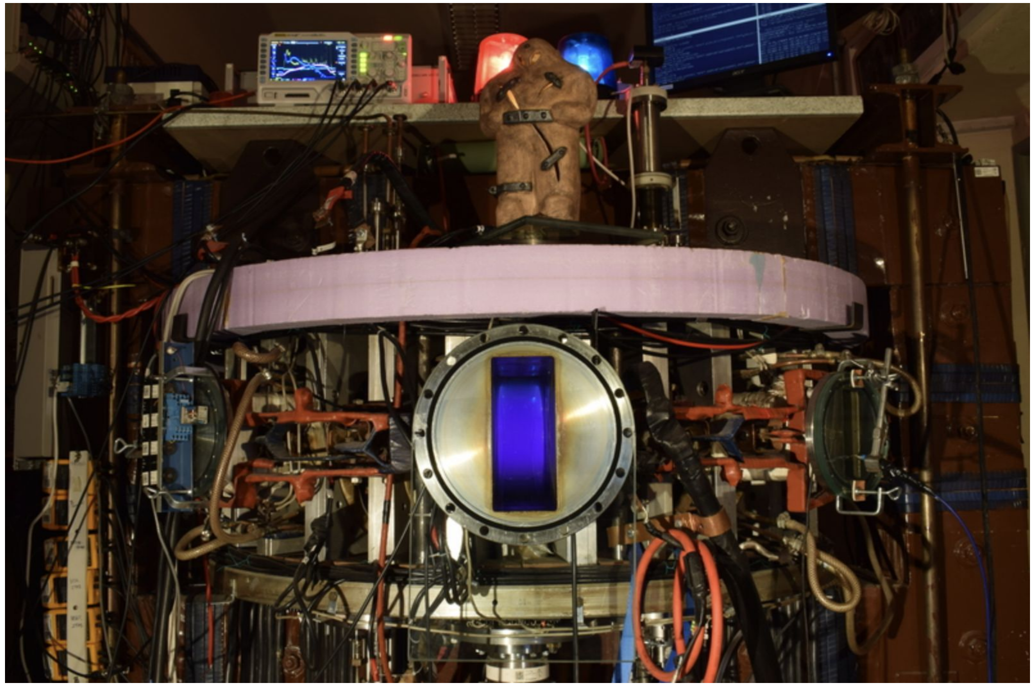
CASTOR

- **TM-1 MH** was completely refurbished (new vacuum vessel, new diagnostics ports, feedback system, etc) and renamed to **CASTOR** (**C**zech **A**cademy of **S**ciences **TOR**us) **in 1984.**
- Main research focused on edge turbulence and lower hybrid current drive.
- The research was undertaken until the end of 2006, when CASTOR was replaced by COMPASS tokamak.



Major radius	R = 0.4 m
Minor radius	a = 0.085 m
Toroidal magnetic field	B_t = 1.5 T
Plasma current	I_p< 25 kA
Line averaged density	n_e = $(0.2\text{-}3.0)\times10^{19}$ m^{-3}
Electron temperature	T_e < 200 eV
Discharge duration	t < 50 ms

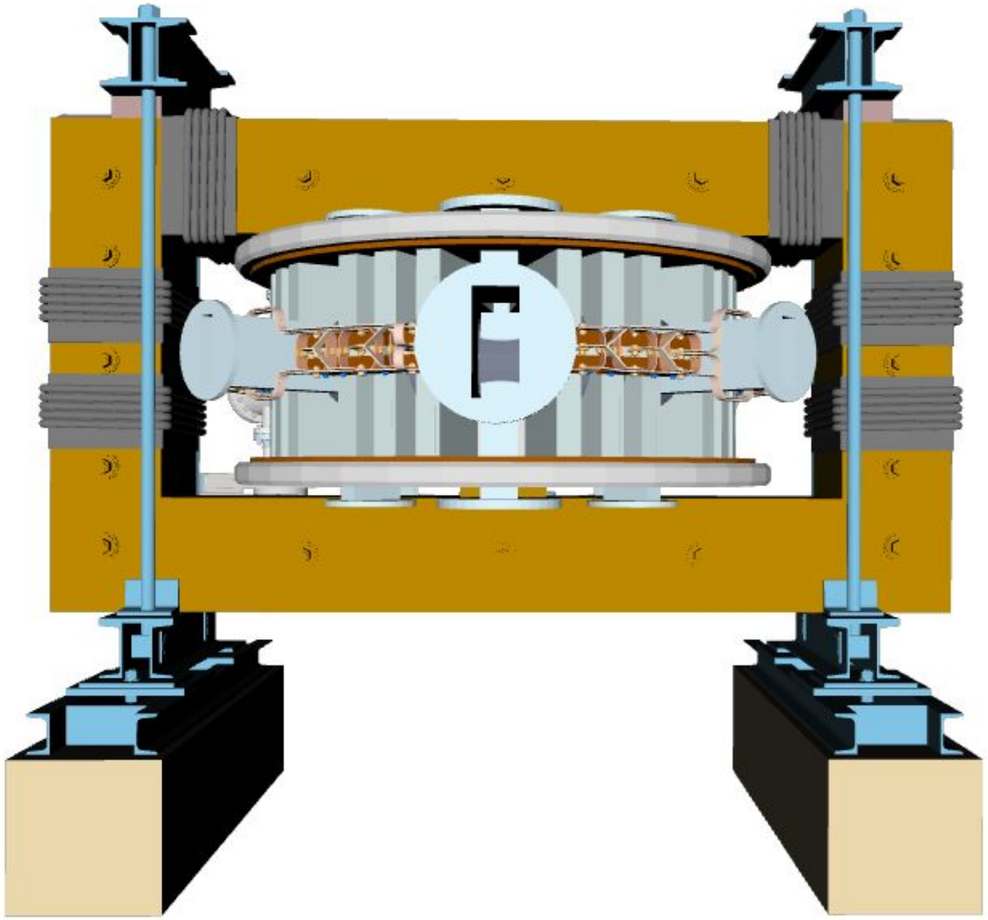
- **CASTOR** was moved to Technical University in Prague in 2007.
- The origin of the name **GOLEM** is because of the near distance to the old Prague Jewish cemetery, where Rabi Loew (Golem builder) is buried.
- Servers both as the educational and scientific device.



Major radius	R = 0.4 m
Minor radius	a = 0.085 m
Toroidal magnetic field	$B_t = 0.5$ T
Plasma current	$I_p < 8$ kA
Line averaged density	$n_e = (0.2\text{-}3.0) \times 10^{19}\ m^{-3}$
Electron temperature	$T_e < 100$ eV
Discharge duration	t < 25 ms

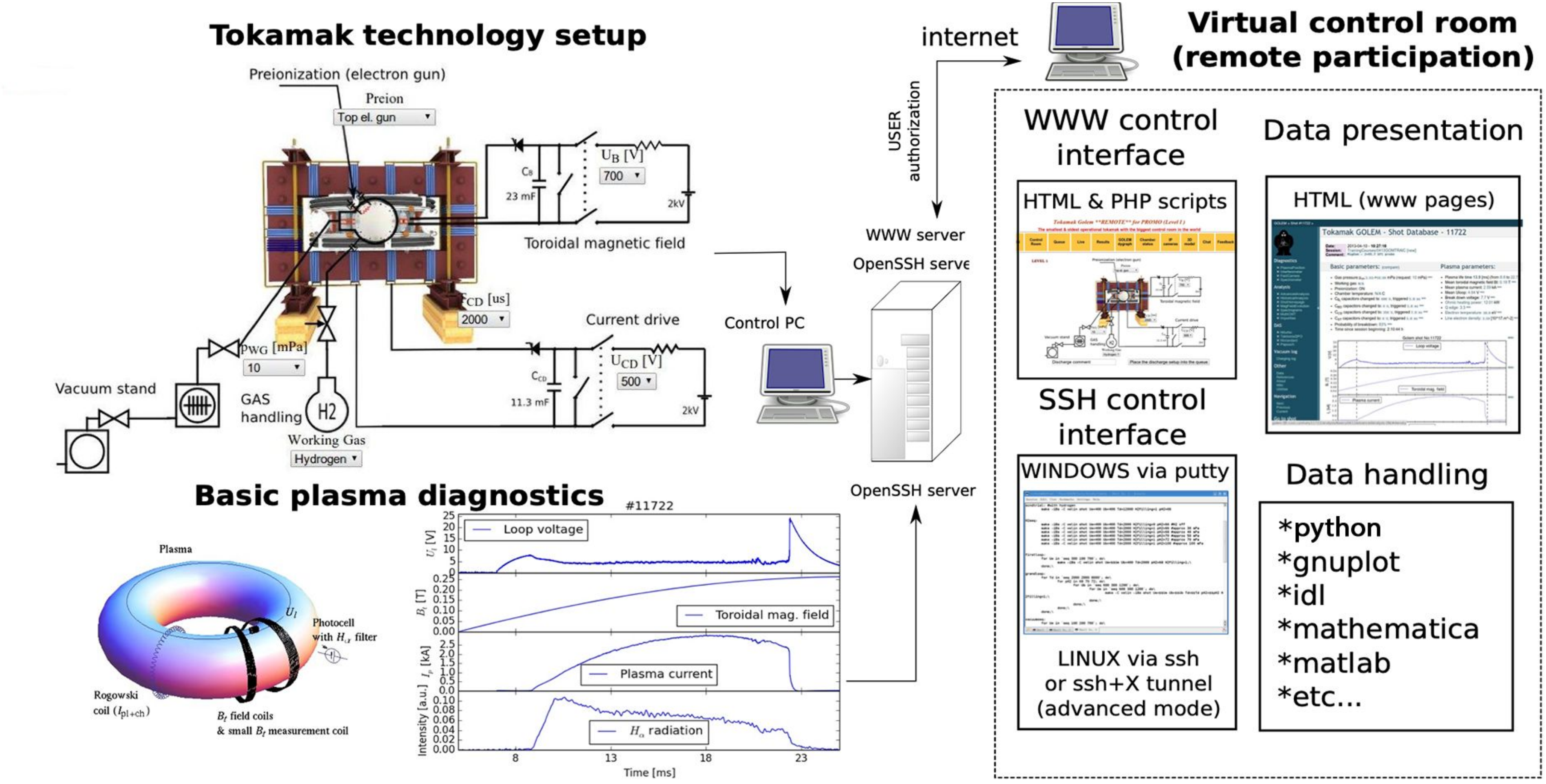
TOKAMAK GOLEM

- The oldest still operating tokamak in the world.
- **Circular plasma cross-section**
- **Partial moon-shaped poloidal limiter**
- Non-axisymmetric transformer iron core for current drive.
- Various working gases (H, D, He, Ar).
- Serves for both educational and scientific purposes:
  - Golem activities ratio: 20% Research, 80% Education
- Topic of many Bachelor a Diploma thesis.
- **Main focus:**
  - Runaway studies
  - Plasma edge studies using advanced probes



Realistic CAD model of tokamak GOLEM

GOLEM BASIC DIAGRAM



GOLEM REMOTE CONTROL

- **GOLEM** is unique because of its possibility of **fully remote control.**
- Control system is **based** on **Linux bash** command language.
- Two options available:
  - Use user-friendly web GUI (limited options)
  - SSH connection (full control over tokamak)
- This allows fully remote experiments (remote trainings, etc).

```
./Dirigent.sh --discharge --operation.discharge "style='standard',vacuum_shot='44738'" --infrastructure.bt_ecd
"U_Bt=950,t_Bt=0,O_Bt='CW',U_cd=650,t_cd=0,O_cd='CW'" --infrastructure.preionization
"S_device='HotCathode',SW_main='on',U_heater=100,U_accel=100" --infrastructure.workinggas
"S_mode='U_v',S_gas='He',p_H=15,U_v=44.0" --infrastructure.positionstabilization
"main_switch='on',radial_switch='on',radial_waveform='1000,0;2000,-5;5000,0;6000,-20;30000,0',vertical_switch='on',vertical_waveform='
1000,0;2000,-5;7000,-10;8000,-20;30000,0'" --diagnostics.langballpenprobe
"r_lp_tip='46',S_mode_lp='isat',R_lp_div_osc='10e3',R_lp_div_nosc='1e6',R_bpp_div_osc='10e3',R_bpp_div_nosc='1e6',U_lp='-90',R_lp_isat
='47'" --comment "He Isat scan r=46 mm"
```

- In total, there are **just few inputs:**
  - **Mandatory: calling main script**, **setting plasma current and toroidal magnetic field**, **preionization setup**, **working gas type and pressure**, **plasma stabilization**, **discharge comment.**
  - **Optional: other diagnostics** (combined probe head, but can be any).

```
./Dirigent.sh --discharge --operation.discharge "style='standard',vacuum_shot='44738'"
 --infrastructure.bt_ecd "U_Bt=950,t_Bt=0,O_Bt='CW',U_cd=650,t_cd=0,O_cd='CW'"
 --infrastructure.preionization "S_device='HotCathode',SW_main='on',U_heater=100,U_accel=100"
 --infrastructure.workinggas "S_mode='U_v',S_gas='He',p_H=15,U_v=44.0"
 --infrastructure.positionstabilization
"main_switch='on',radial_switch='on',radial_waveform='1000,0;2000,-5;5000,0;6000,-20;30000,0',vertical_switch='on',vertical_waveform='
1000,0;2000,-5;7000,-10;8000,-20;30000,0'"
 --diagnostics.langballpenprobe
"r_lp_tip='46',S_mode_lp='isat',R_lp_div_osc='10e3',R_lp_div_nosc='1e6',R_bpp_div_osc='10e3',R_bpp_div_nosc='1e6',U_lp='-90',R_lp_isat
='47'"
--comment "He Isat scan r=46 mm"
```

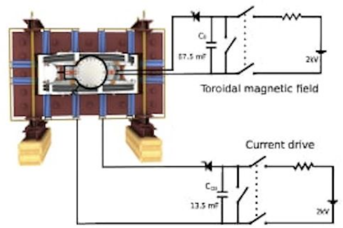
GOLEM REMOTE CONTROL

GOLEM remote | Introduction | Control Room | Live | Results | Test | Access: Level 2 | Help

Use | Session Master Discharge | as Template

Basic Diacharge Parameters (infrastructure.bt_ecd)

Hide Descriptions



Toroidal Field Capacitor

Voltage on the capacitors U_{B_t} to be discharged into the toroidal field coils.
The higher the voltage, the larger the magnetic field confining the plasma.

Current Drive Capacitor

Voltage on the capacitors U_{cd} to be discharged into the primary transformer winding.
The higher the voltage, the larger the electric field creating and heating the plasma. The electric field capacitors are discharged after a configurable delay with respect to the magnetic field capacitors.

Toroidal Field Capacitor: U_Bt = 500 V

Torodial Field Delay: t_Bt = 0 us

Current Drive Capacitor: U_cd = 350 V

Current Drive Delay: t_cd = 1000 us

Toroidal Field Orientation: O_Bt = CW | ACW

Current Orientaiton: O_cd = CW | ACW

Working Gas (infrastructure.workinggas)

Set the pressure and type of the working gas from which the plasma is formed. Pressure must be high enough for plasma to form, but low enough for gas breakdown to occur.

S_mode = U_v | p_wg | vacuum

Gas Type: S_gas = H | He

Gas Pressure: p_H = 10 mPa

U_v = 22.0 V

Preionization (infrastructure.preionization)

The neutral working gas must be first ionized in order to break down into a plasma.
Using the **electron gun** will locally ionize the gas. Without any ionization, no plasma can form.

Preionization device: S_device = HotCathode (Electron gun)

SW_main = on | off

U_heater = 100 V

U_accel = 80 V

Plazma Positon Stabilization (infrastructure.positionstabilization)

Stabilization master switch: main_switch = on | off

Radial stabilization switch: radial_switch = on | off

Radial Waveform: radial_waveform = 1000,0;2000,-5;5000,-10;9000,-2

Vertical Stabilization switch: vertical_switch = on | off

Vertical Waveform: vertical_waveform = 1000,0;2000,-5;7000,-10;8000,-2

Double Rake Probe (diagnostics.doublerakeprobe)

r_first_tip = 0 mm

X_mod = 111111111111

1. 2. 3. 4. 5. 6. 7. 8. 9. 10. 11. 12.

I_SilverBox = 0

Rake Probe (diagnostics.rakeprobe)

r_First_Tip = 100 mm

phi_First_Tip = 0 deg

X_mod = 111111111111

I_SilverBox = 12

1. 2. 3. 4. 5. 6. 7. 8. 9. 10. 11. 12.

r_manipulator = 60 mm

phi_manipulator = 0 deg

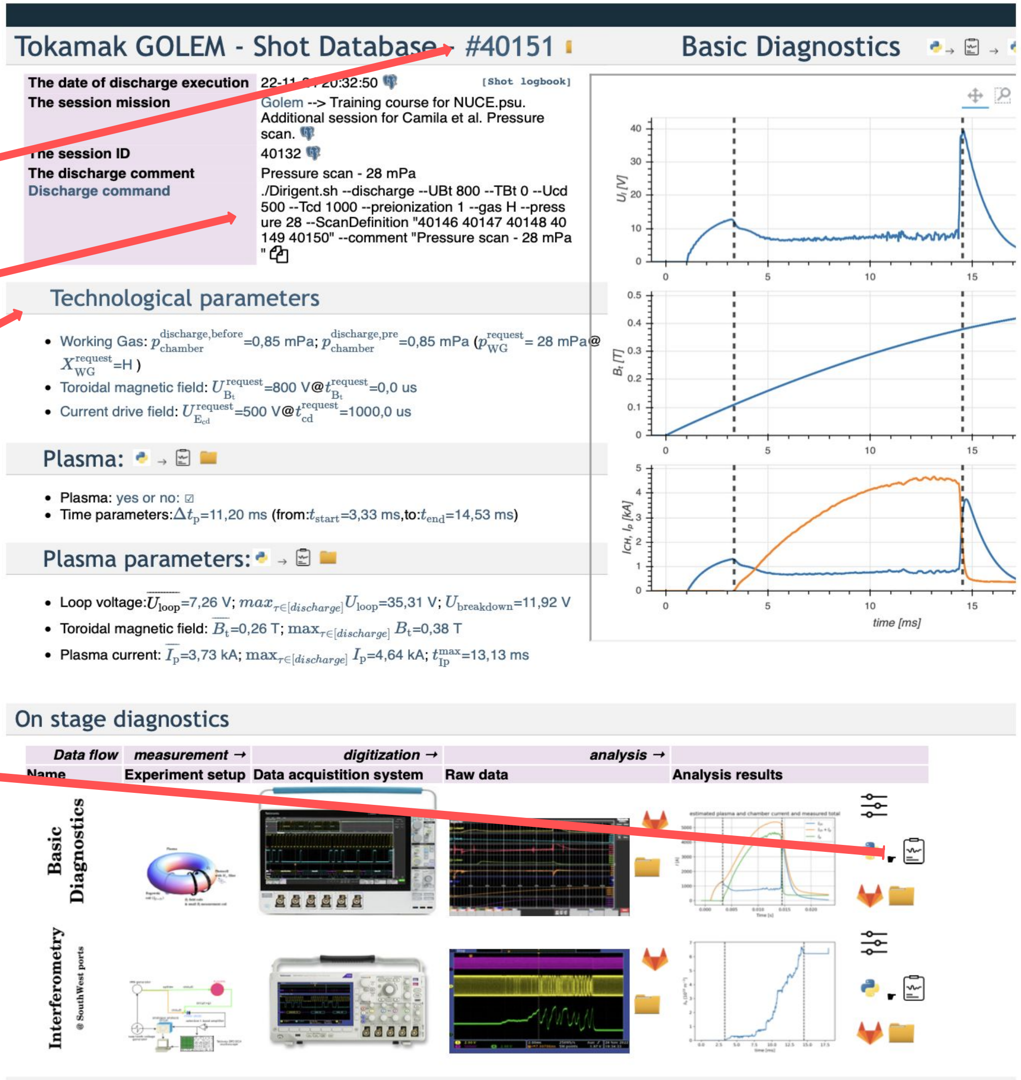
(comment)

comment =

Copy command to clipboard | Submit Discharge

SHOT HOMEPAGE

1. Discharge number
2. Discharge command
3. Technological parameters
4. Plasma parameters
5. Diagnostics
6. Data



http://golem.fjfi.cvut.cz/shots/45694/

SHOT HOMEPAGE

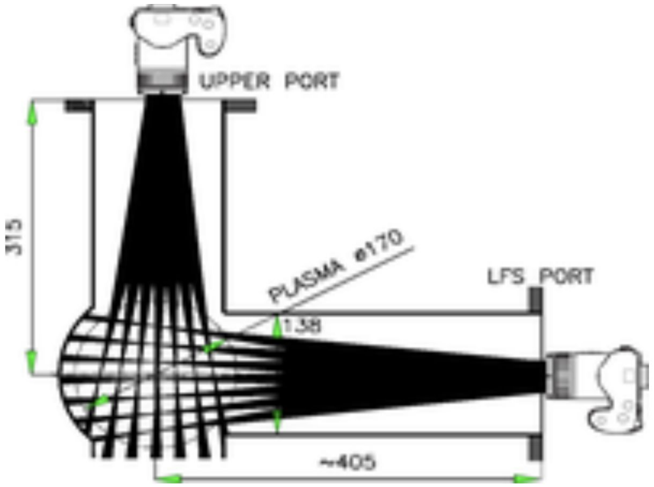
Index of /shotdir/44005/Diagnostics/BasicDiagnostics/Results

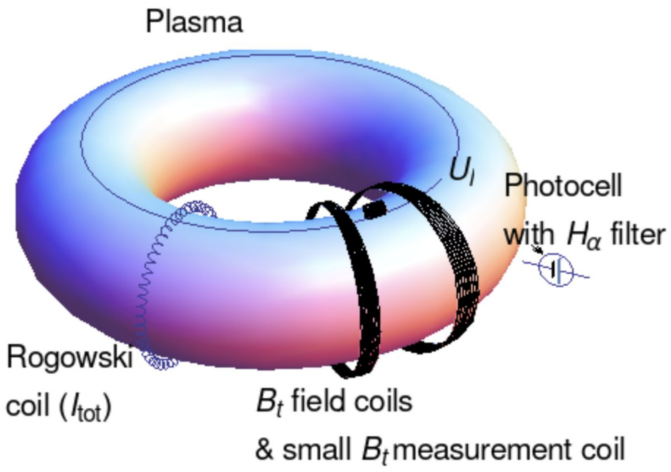
Name	Last modified	Size	Description
Parent Directory		-	
Bt.csv	2024-03-07 12:12	785K	
Bt_max	2024-03-07 12:12	5	
Bt_mean	2024-03-07 12:12	5	
Ich.csv	2024-03-07 12:12	747K	
Ich_max	2024-03-07 12:12	5	
Ich_mean	2024-03-07 12:12	5	
Ip.csv	2024-03-07 12:12	775K	
Ip_max	2024-03-07 12:12	5	
Ip_mean	2024-03-07 12:12	5	
U_loop.csv	2024-03-07 12:12	565K	
U_loop_max	2024-03-07 12:12	6	
U_loop_mean	2024-03-07 12:12	5	

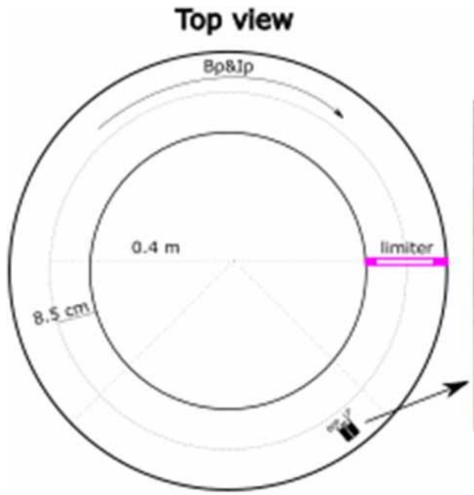
Apache/2.4.59 (Debian) Server at golem.fjfi.cvut.cz Port 80

BASIC DIAGNOSTICS

- Tokamak GOLEM is equipped with several diagnostics:
  - **Basic diagnostics** for main plasma parameters measurements (plasma current, loop voltage, fast cameras, …)
  - **Interferometry** for line-averaged density.
  - **Fast cameras** for global plasma view and tomography.
  - **Magnetic coils** (MHD ring equipped with 16 Mirnov coils).
  - **RE diagnostics** (scintillation detectors, strip detector, Timepix).
  - **Spectroscopy** (mainly compact spectrometers - both wide wavelength range and focused on specific lines).
  - **VARIOUS ELECTRIC PROBES:** used for electron temperature, plasma potential, and ion saturation current measurements.







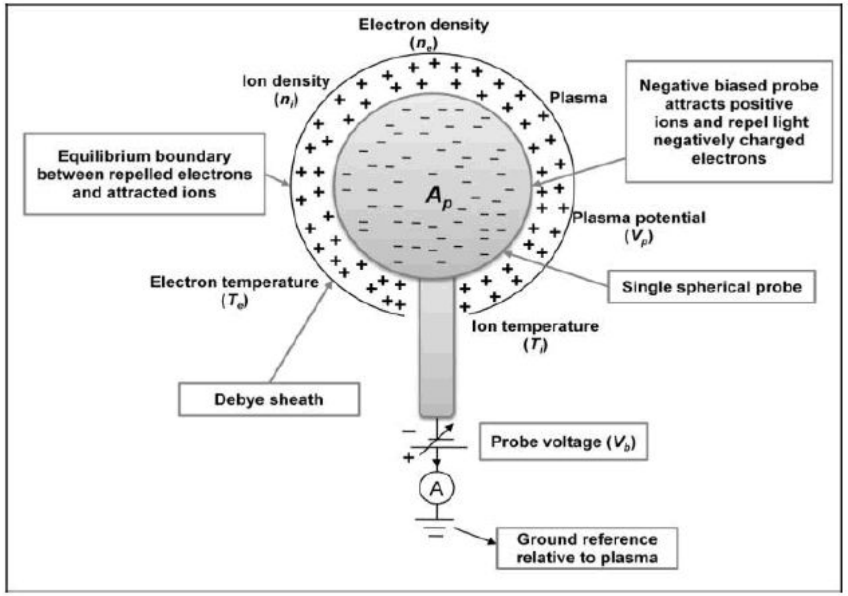
ELECTRIC PROBES I

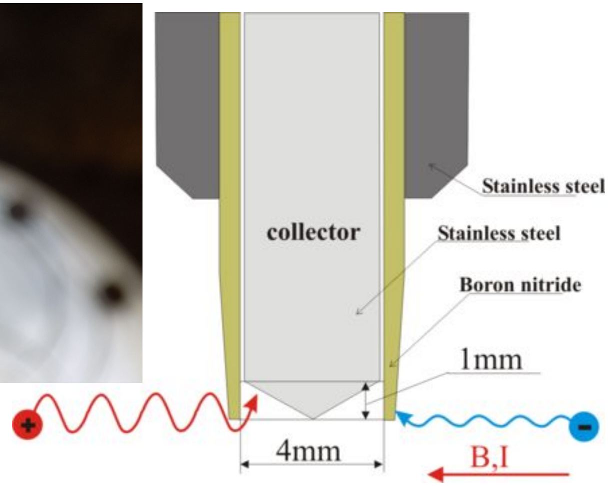
- **Langmuir probe:**
  - Simple conductive wire inserted into plasma.
  - Charge particles are attracted to the collector.
  - Measures floating potential $\mathbf{U_{fl}}$ / ion saturation current $\mathbf{I_{sat}}$
- **Ball-pen probe:**
  - Modified electric probe to measure plasma potential **ϕ** directly.
  - Electrons with smaller gyro radius are physically shielded => ion and electron currents are balanced [https://en.wikipedia.org/wiki/Ball-pen_probe] and factor R=0

$$\alpha = ln\left(\frac{A_e j_e^{sat}}{A_i j_i^{sat}}\right) = ln(R)$$

  - Combined with Langmuir probe => fast electron temperature $\mathbf{T_e}$ measurements based on:

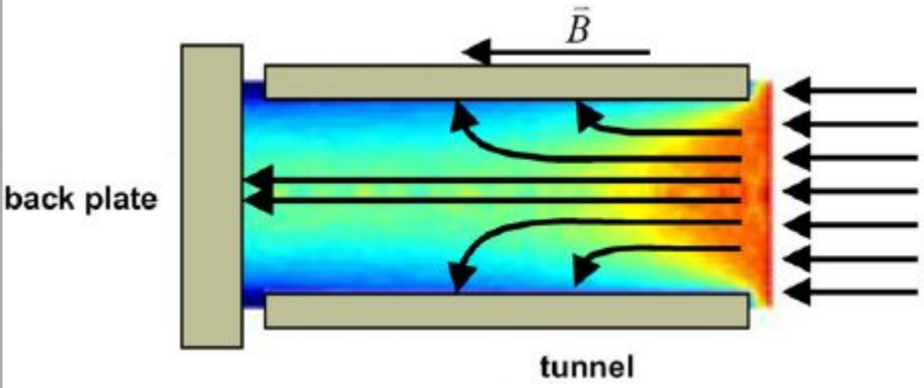
$$\mathbf{T_e = (\phi - U_{fl})/\alpha}$$





ELECTRIC PROBES II

- **Double rake probe:**
  - An array of Langmuir probes
  - Allows to measure radial profile of $\mathbf{U_{fl}}$ / $\mathbf{I_{sat}}$ within single discharge
- **Tunnel probe:**
  - Modified electric probe used for $\mathbf{I_{sat}}$ measurements.
  - Consists of tunnel and back-plate.
  - The electric field is located in the vicinity => no sheath expansion.
  - Plasma rotation / Mach number measurements.



TRANSPORT BARRIER ANALYSIS

LETTER • OPEN ACCESS

Spontaneous formation of a transport barrier in helium plasma in a tokamak with circular configuration

P. Macha[1,2,5], J. Adamek[2], J. Seidl[2], J. Stockel[2,4], V. Svoboda[1], G. Van Oost[3], L. Lobko[1] and J. Krbec[2]

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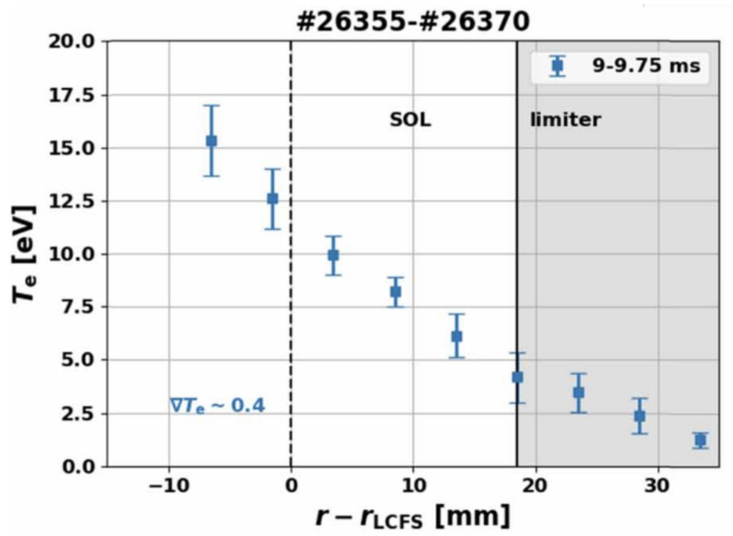
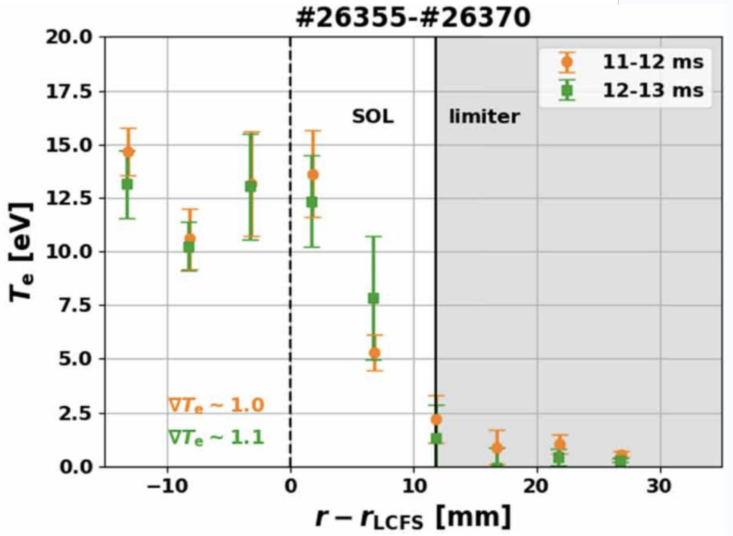
Nuclear Fusion, Volume 63, Number 10
Citation P. Macha *et al* 2023 *Nucl. Fusion* **63** 104003
DOI 10.1088/1741-4326/acf1af

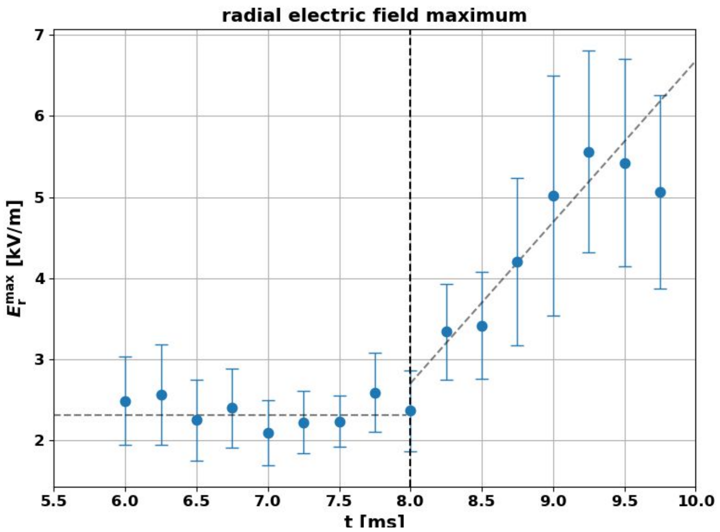


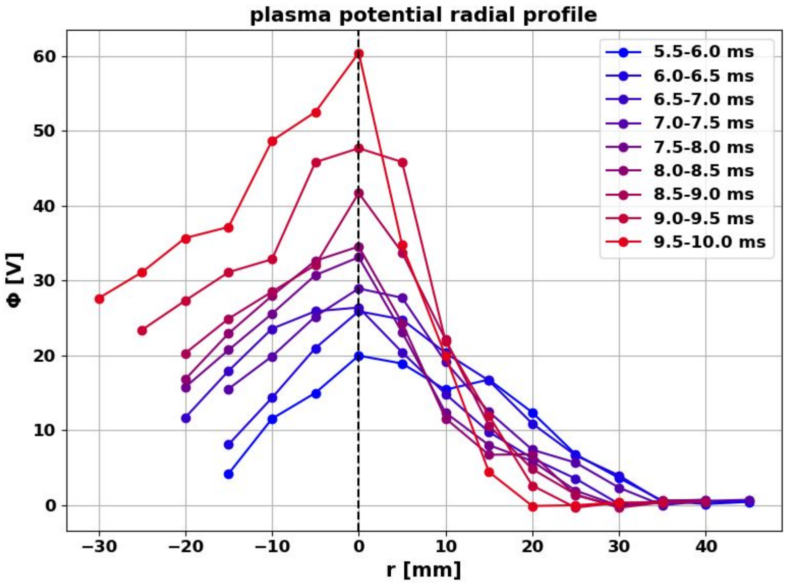
- **Steep gradient of electron temperature** was observed.
- **Gradually increasing radial electric** field and **velocity shear.**
- **P_{LH} power satisfied by L-H transition scaling laws.**
- **=> spontaneous formation of a transport barrier in helium plasma on GOLEM.**

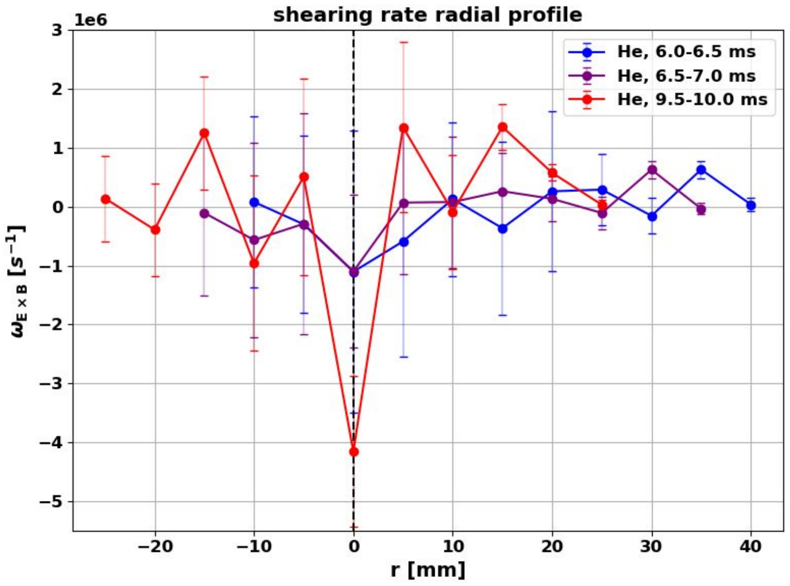


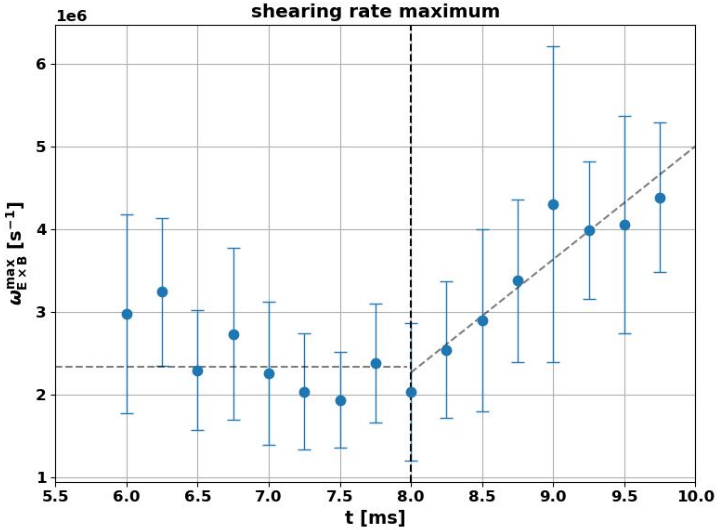
WHAT WAS ALREADY OBSERVED II

- We observed formation of **strong radial electric field** and **shearing rate.**
- All of this was **formed spontaneously** under specific discharge conditions (high ohmic heating and relatively low plasma density).
- The mechanism of the process is however still not known and could be explained.
- **Following experiments as one of the SUMTRAIC task.**









RUNAWAY ELECTRONS RESULTS

Journal of Instrumentation

PAPER

Progress in HXR diagnostics at GOLEM and COMPASS tokamaks

J. Cerovsky[3,1,2], O. Ficker[1,2], V. Svoboda[2], E. Macusova[1], J. Mlynar[1,2], J. Caloud[1,2], V. Weinzettl[1], M. Hron[1] and COMPASS team and EUROfusion MST1 team[4]

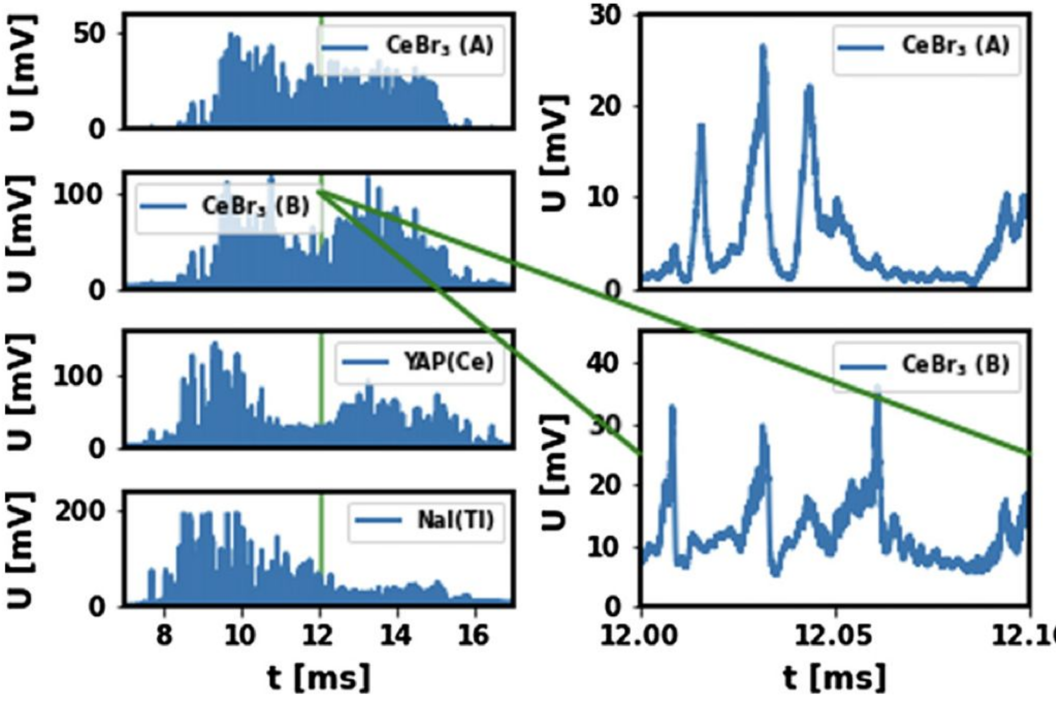
Published 10 January 2022 • © 2022 IOP Publishing Ltd and Sissa Medialab

Journal of Instrumentation, Volume 17, January 2022

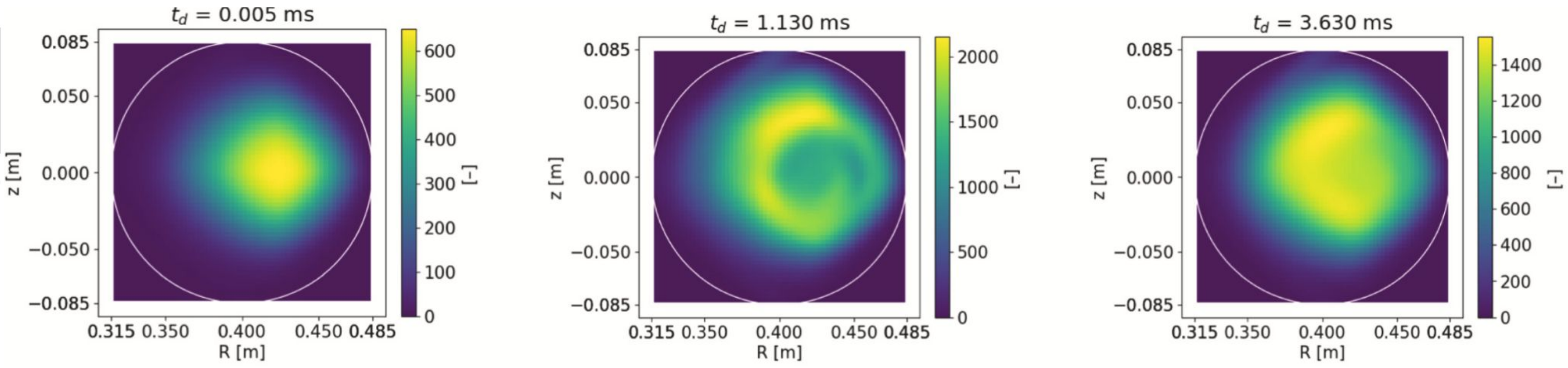
Citation J. Cerovsky *et al* 2022 *JINST* **17** C01033

DOI 10.1088/1748-0221/17/01/C01033

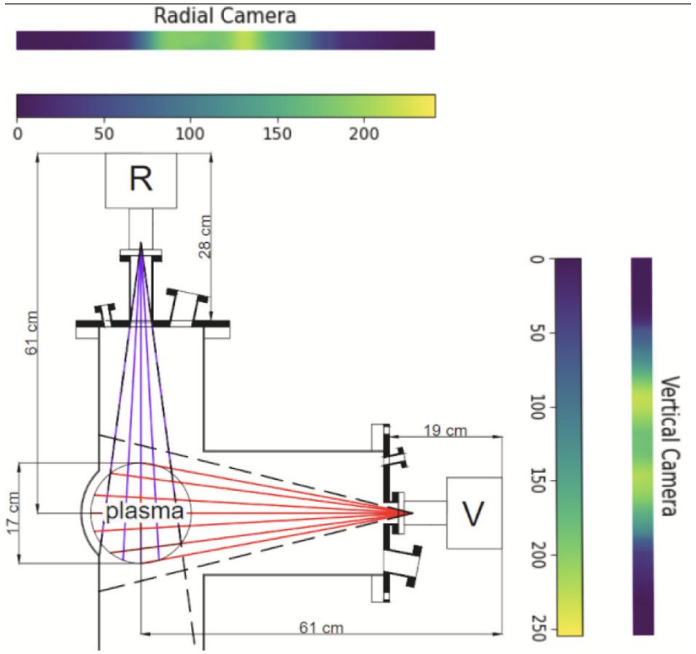
- **Low plasma density** (n_e ≈ 1018 m−3), **high toroidal electric field** (E_T ≈ 4-7 V/m) => **generation of runaway electrons.**
- Several scintillation detectors (NaI(Tl),YAP(Ce), and CeBr3) and Timepix + strip detectors were used on GOLEM.
- Acquired signals suffer from large number of multiple pile-up events.
- The development of collimator or additional shielding is necessary for future successful operation.



Evolution of signals from scintillation detectors during discharge #36649 at GOLEM tokamak.



- **The tomographic inversions** were performed on line integrated signal acquired **by the two visible cameras.**
- The **Minimum Fisher Regularization (MFR) algorithm** implementation from open source python package Tomotok **was used.**
- The results showed the expected hollow emissivity profile.
- There are however still several drawbacks, which needs to be solved (further validation of implementation, enhancing cameras FOV, camera relative calibration).



OTHER INTERESTING PAPERS

1. M Dimitrova et al. “**Plasma properties in the vicinity of the last closed flux surface in hydrogen and helium fusion plasma discharges**”. In: Plasma Physics and Controlled Fusion 66.7 (2024), p. 075022. doi: 10.1088/1361-6587/ad5377. url: https://dx.doi.org/ 10.1088/1361-6587/ad5377.
2. G. Sarancha et al. “**Remote Plasma Physics Research and Teaching by Example of Turbulence Study at the University-Scale Tokamak GOLEM**”. In: Fusion Science and Technology 79.4 (2023), pp. 432–445. doi: 10.1080/15361055.2022.2148842. eprint: https://doi.org/10.1080/15361055.2022.2148842. url: https://doi.org/10.1080/15361055.2022.2148842.
3. S. Kulkov et al. “**Detection of runaway electrons at the COMPASS tokamak using a Timepix3-based semiconductor detector**”. In: Journal of Instrumentation 17.02 (Feb. 2022), P02030. doi: 10.1088/1748-0221/17/02/p02030. url: https://doi.org/10. 1088/1748-0221/17/02/p02030.
4. G Sarancha et al. “**Magnetic turbulence and long-range correlation studies in the Golem tokamak**”. In: Journal of Physics: Conference Series 2055.1 (Oct. 2021), p. 012003. doi: 10.1088/1742-6596/2055/1/012003. url: https://doi.org/10.1088/1742-6596/2055/1/012003.
5. G.A. Sarancha et al. “**Hydrogen and helium discharges in the Golem tokamak**”. In: Problems Of Atomic Science And Technology, Ser. Thermonuclear Fusion 4 (2021), pp. 92–110. doi: 10.21517/0202-3822-2021-44-4-92-110. url: https://doi.org/10. 21517/0202-3822-2021-44-4-92-110.
6. J. Stockel et al. “**Operational Domain in Hydrogen Plasmas on the Golem Tokamak**”. In: Journal of Fusion Energy 38 (Mar. 2019), pp. 253–261. issn: 1572-9591. doi: 10.1007/s10894-019-00215-7.
7. O. Grover et al. “**Remote operation of the Golem tokamak for Fusion Education**”. In: Fusion Engineering and Design 112 (2016), pp. 1038–1044. issn: 0920-3796. doi: 10.1016/j.fusengdes.2016.05.009.
8. And many many other papers

STUDENTS THESIS

Diploma thesis:

1. S. Malec: **Compton camera** for detection of hard X-rays produced on the Golem tokamak
2. M. Tunkl: Development of a new **runaway electron diagnostics** method based on strip semiconductor detectors
3. D. Cipciar: **Ion and electron temperature study** in the edge plasma of the tokamak device
4. P. Macha: **Edge plasma studies** in tokamaks by the mean of **advanced electric probes**.
5. B. Leitl: **Tomografická rekonstrukce** profilu vyzařování plazmatu na tokamaku Golem
6. J. Kocman: **Řízení polohy** plazmatického prstence na tokamaku Golem
7. L. Matěna: **Microwave interferometry** on the tokamak Golem
8. Ondřej Ficker: Generation, losses and detection of **runaway electrons** in tokamaks
9. T. Markovič: **Measurements of magnetic fields** on the tokamak Golem

Bachelor thesis:

1. Jan Buryanec: **Stabilizace proudu plazmatem** na tokamaku Golem
2. J. Chlum: Implementation of **tomographic inversion** on the Golem tokamak
3. J. Malinak: **Electron temperature measurements** using rail probe on the tokamak Golem

Highschool works:

1. M. Pokorný: Měření a simulace polohy plazmatu na tokamaku GOLEM
2. A. Socha: Poloha zóny vytváření turbulentních struktur v okrajovém plazmatu tokamaku GOLEM
3. D. Kropáčková: Stabilizace plazmatu na tokamaku GOLEM

SUMMARY

- Tokamak GOLEM, build as TM-1 in russia, placed at IPP as CASTOR, now operating at CTU, is the oldest still operating tokamak in the world.
- Offers full remote control and data access.
- The focus is mostly on edge plasma studies and runaway electrons.
- Its main mission is education (80%) and science (20%).
  - Producing future fusion specialists every year.
  - Still capable of producing current fusion relevant research.
- Equipped with several basic and advanced diagnostic still offers opportunities for interesting work.
- 2 topics of SUMTRAIC 2024 focused on GOLEM.

EUROPEAN UNION
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