The GOLEM tokamak: 10 years of the Fusion education service

Vojtech Svoboda
on behalf of the tokamak GOLEM team
for **Seminar @ ASDEX Upgrade**, Garching

October 20, 2019

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Faculty of Nuclear Sciences and Physical Engineering Czech Technical University in Prague

FNSPE main building in Prague

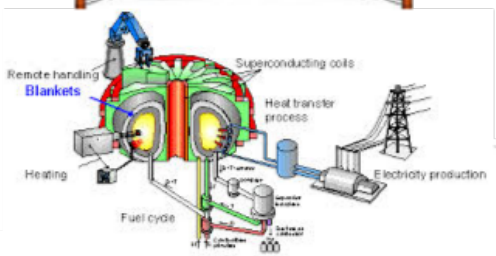
FNSPE insignia

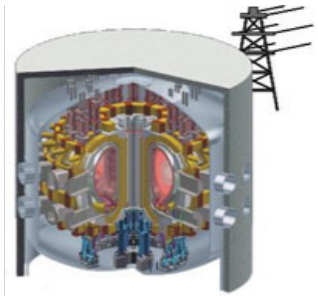
CTU ceremony hall

- CTU founded in 1707 by the emperor Joseph I.
- CTU approximately 2200 staff members, 16000 undergraduate students, 9000 graduate and PhD students. ($\approx$ 2500 foreign students).
- FNSPE established in 1955 with the mission to train new experts for the emerging Czechoslovak nuclear programme.
- FNSPE currently a centre of education and research specialised in boundary fields between modern science and their applications in technologies, medicine, economy, biology, ecology, and other fields.

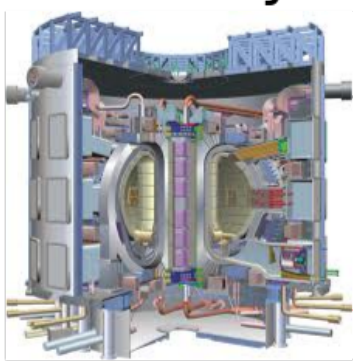
A Roadmap to the Fusion Power Plant

COMMERCIAL
POWER PLANT
???





DEMO (2044?-)
Mission: fusion electricity to the grid



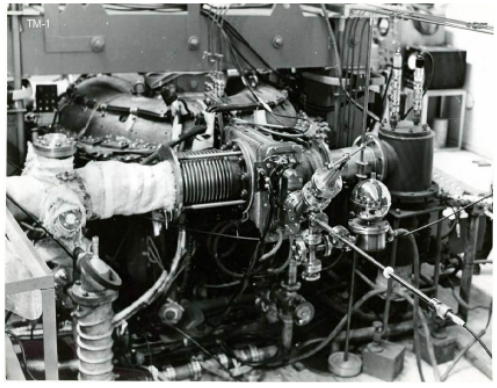
ITER (WORLD)
2025?-
Mission: ~ 400s 500 MW @ Q=10

JET (EU)
1984-present
World record (1997): ~ 2s 16 MW @ Q=0.67

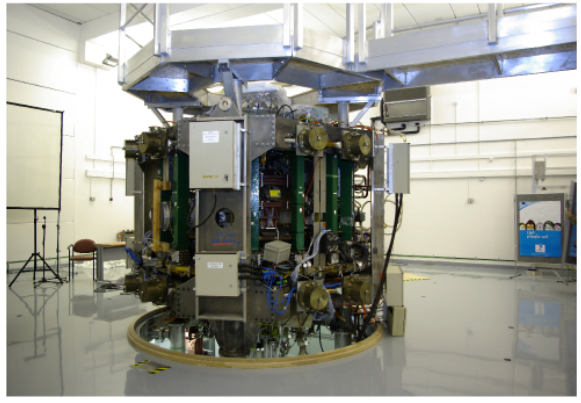
Education importance

The GOLEM tokamak for education - historical background

Kurchatov Institute near Moscow,
Soviet Union
1960: **TM1-MH**



Culham Centre for Fusion Energy
Great Britain
1989: **COMPASS-D**



1974

2006

Institute of Plasma Physics
Czech republic
CASTOR **COMPASS**

2008

Czech Technical University Prague
Czech republic
GOLEM

Tokamak GOLEM @ Wikipedia ..

File Edit View Go Bookmarks Tools Settings Window Help

https://en.wikipedia.org/wiki/Tokamak

home Kalendář Produkce Forecast Slovník Rano

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Tokamak

From Wikipedia, the free encyclopedia

This article is about the fusion reaction device. For other uses, see Tokamak (disambiguation).

A **tokamak** (Russian: **токамак**) is a device that uses a powerful magnetic field to confine plasma in the shape of a torus. Achieving a stable plasma equilibrium requires magnetic field lines that move around the torus in a helical shape. Such a helical field can be generated by adding a toroidal field

it decays into a proton and electron with the emission of energy. When the time comes to actually try to make electricity from a tokamak-based reactor, some of the neutrons produced in the fusion process would be absorbed by a liquid metal blanket and their kinetic energy would be used in heat-transfer processes to ultimately turn a generator.

Experimental tokamaks [edit]

Currently in operation [edit]

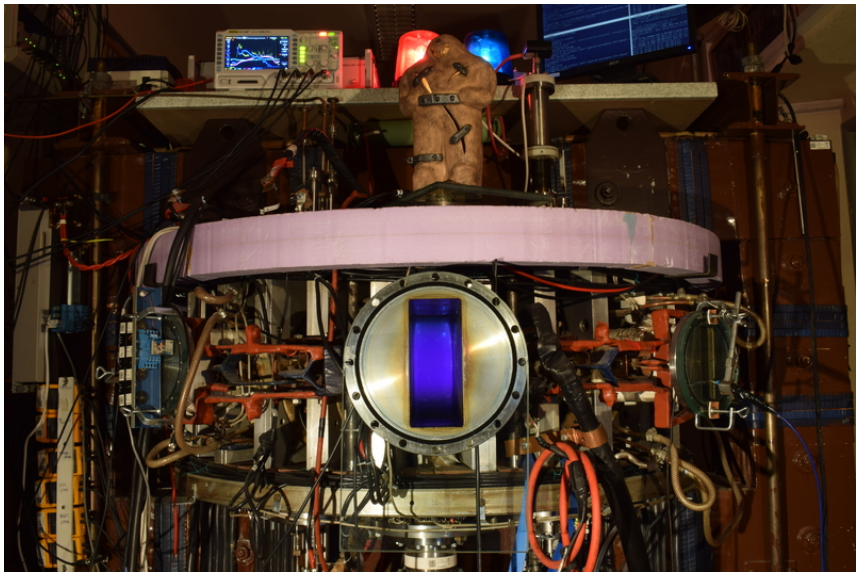
(in chronological order of start of operations)


Alcator C-Mod

- 1960s: TM1-MH (since 1977 Castor; since 2007 Golem[12]) in Prague, Czech Republic. In operation in Kurchatov Institute since early 1960s but renamed to Castor in 1977 and moved to IPP CAS,[13] Prague; in 2007 moved to FNSPE, Czech Technical University in Prague and renamed to Golem.[14]
- 1975: T-10, in Kurchatov Institute, Moscow, Russia (formerly Soviet Union); 2 MW
- 1983: Joint European Torus (JET), in Culham, United Kingdom
- 1985: JT-60, in Naka, Ibaraki Prefecture, Japan; (Currently undergoing upgrade to Super, Advanced model)
- 1987: STOR-M, University of Saskatchewan; Canada; first demonstration of alternating current in a tokamak.
- 1988: Tore Supra,[15] at the CEA, Cadarache, France
- 1989: Aditya, at Institute for Plasma Research (IPR) in Gujarat, India
- 1980s: DIII-D,[16] in San Diego, USA; operated by General Atomics since the late 1980s
- 1989: COMPASS,[13] in Prague, Czech Republic; in operation since 2008, previously operated from 1989 to 1999 in Culham, United Kingdom
- 1990: FTU, in Frascati, Italy
- 1991: Tokamak ISTTOK,[17] at the Instituto de Plasmas e Fusão Nuclear, Lisbon, Portugal;
- 1991: ASDEX Upgrade, in Garching, Germany

The GOLEM tokamak basic characteristics

The grandfather of all tokamaks (ITER newsline 06/18)



- Vessel major radius $R_0 = 0.4$ m
- Vessel minor radius $r_0 = 0.1$ m
- Plasma minor radius: $a \approx 0.06$ m
- Maximum toroidal magnetic field $B_t^{max} < 0.5$ T
- Maximum plasma current $I_p^{max} < 8$ kA
- Typical electron density: $< n_e > \approx 0.2 - 3 \times 10^{19}$ m^{-3}
- Effective ion charge: $Z_{eff} \approx 2.5$
- Maximum electron temperature $T_e^{max} < 100$ eV
- Maximum ion temperature $T_i^{max} < 50$ eV

GOLEM

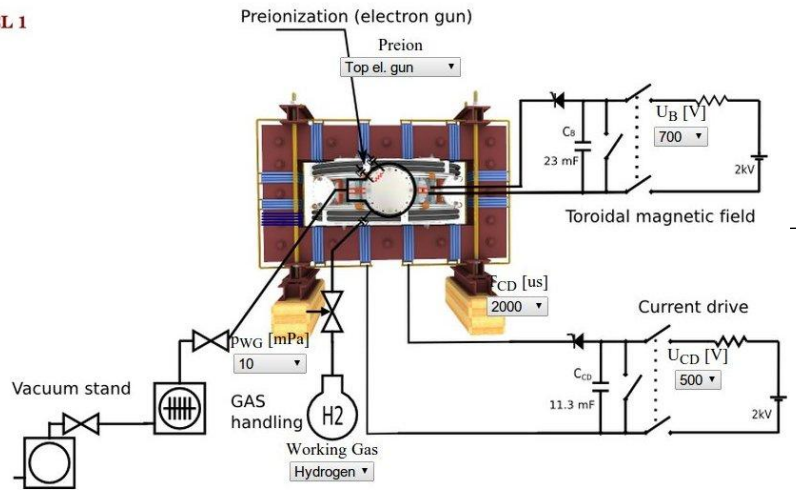
... somewhere, in the ancient cellars of Prague,

there is hidden indeed "infernal" power. Yet it is the very power of celestial stars themselves. Calmly dormant, awaiting mankind to discover the magic key, to use this power for their benefit...

At the end of the 16th century, in the times when the Czech lands were ruled by Emperor Rudolf II, in Prague, there were Rabbi Judah Loew, well known alchemist, thinker, scholar, writer and inventor of the legendary GOLEM - a clay creature inspired with the Universe power that pursued his master's command after being brought to life with a shem, . Golem is not perceived as a symbol of evil, but rather as a symbol of power which might be useful but is very challenging to handle. To learn more of the Golem legend, see e.g. Wikipedia/Golem.

The global schematic overview of the GOLEM experiment

Tokamak technology setup



internet

USER authorization

WWW server

OpenSSH serve

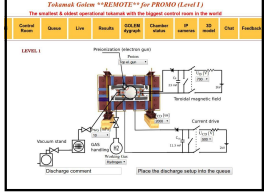
Control PC

OpenSSH server

Virtual control room (remote participation)

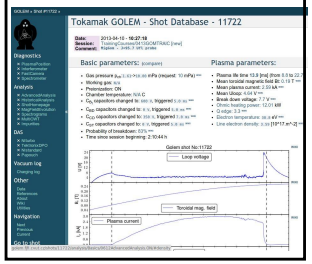
WWW control interface

HTML & PHP scripts



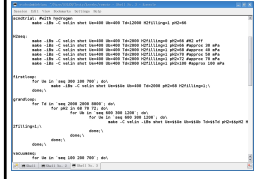
Data presentation

HTML (www pages)



SSH control interface

WINDOWS via putty

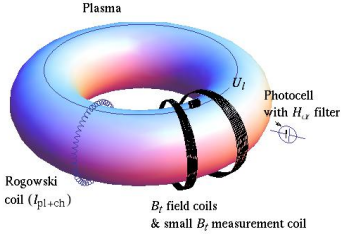


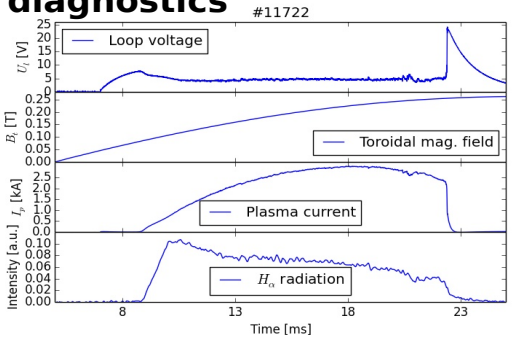
LINUX via ssh
or ssh+X tunnel
(advanced mode)

Data handling

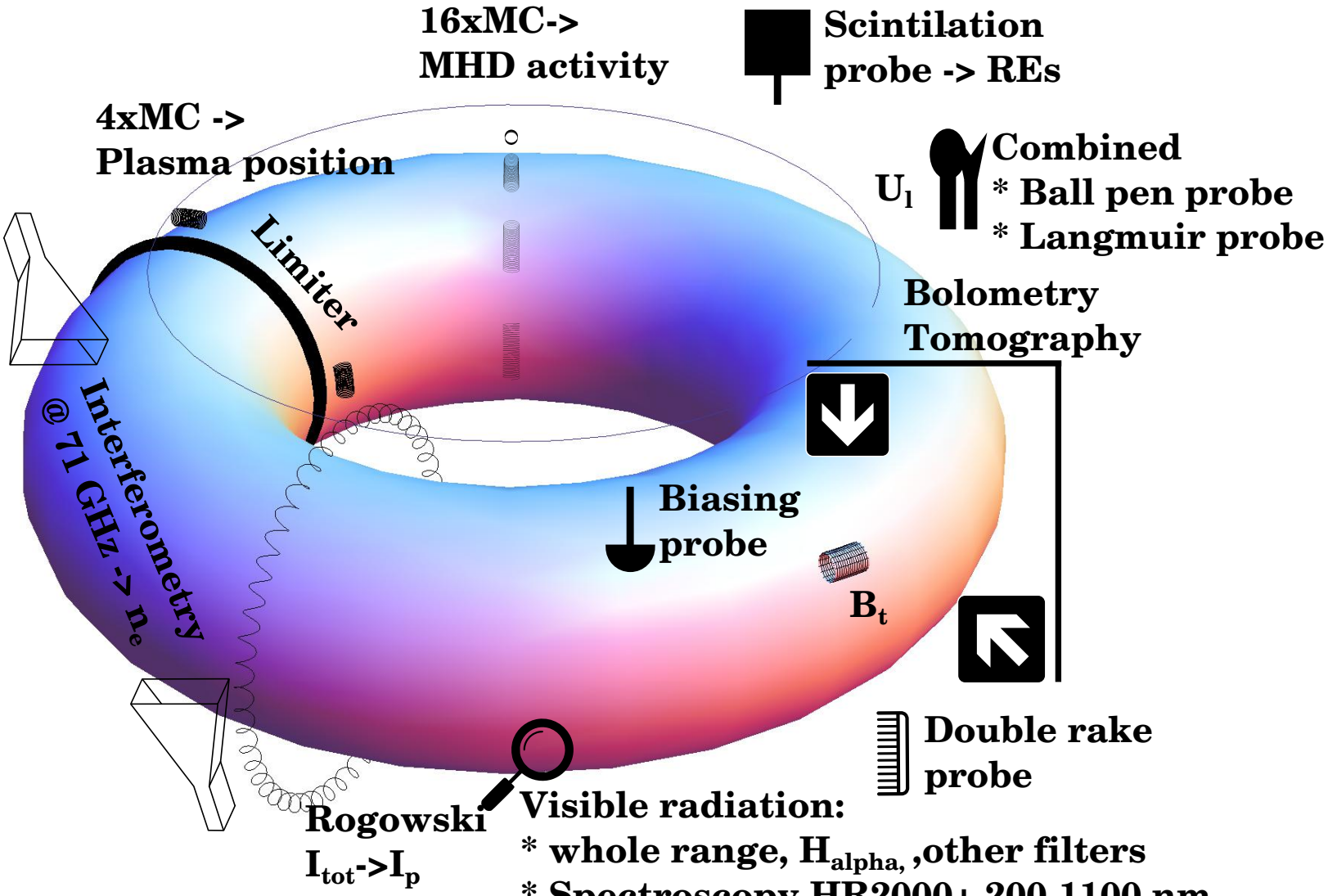
*wget
*gnuplot
*idl
*mathematica
*matlab
*etc...

Basic plasma diagnostics

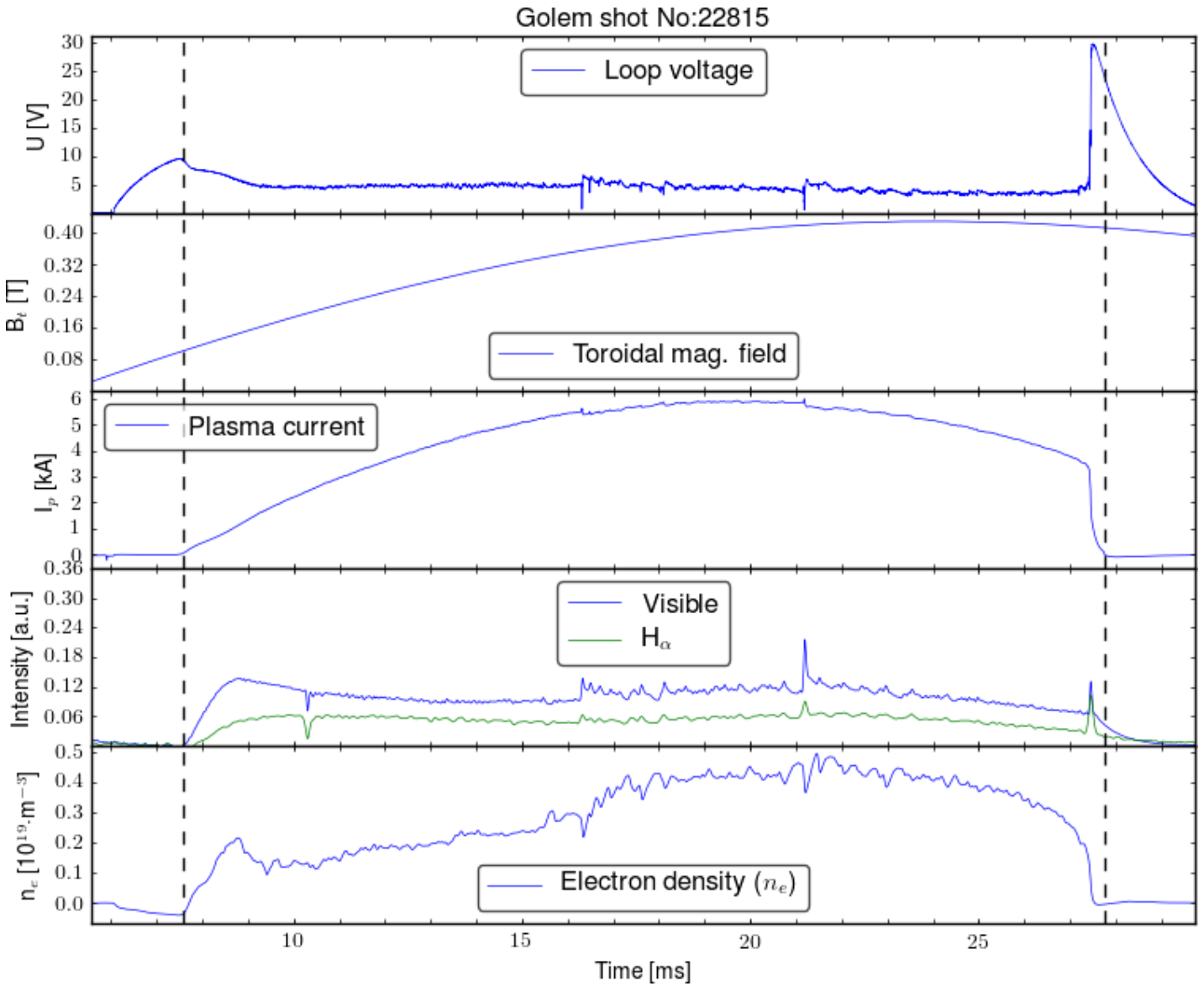




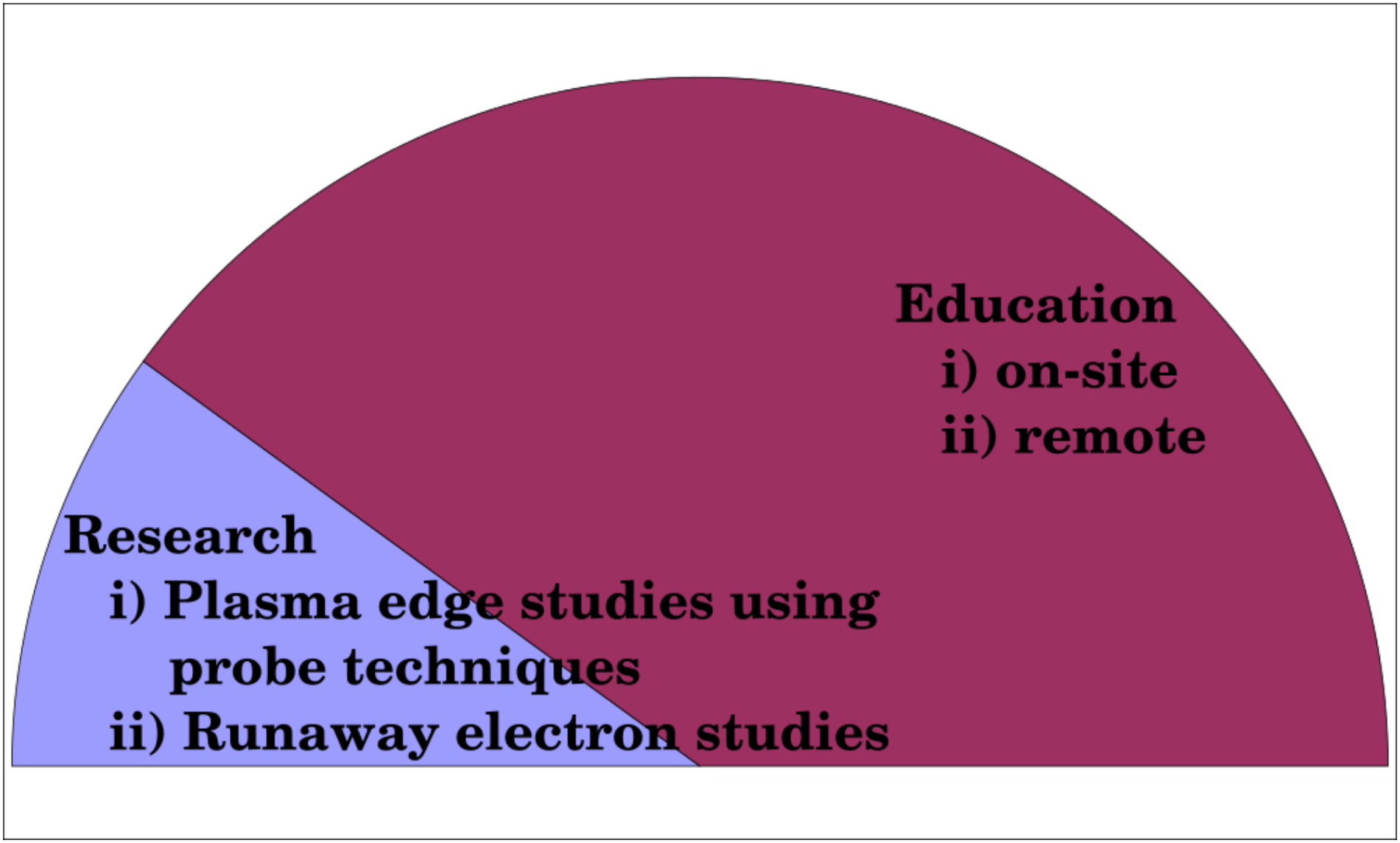
The GOLEM tokamak - standard diagnostics



”Typical”, well executed discharge @ GOLEM



The GOLEM tokamak mission



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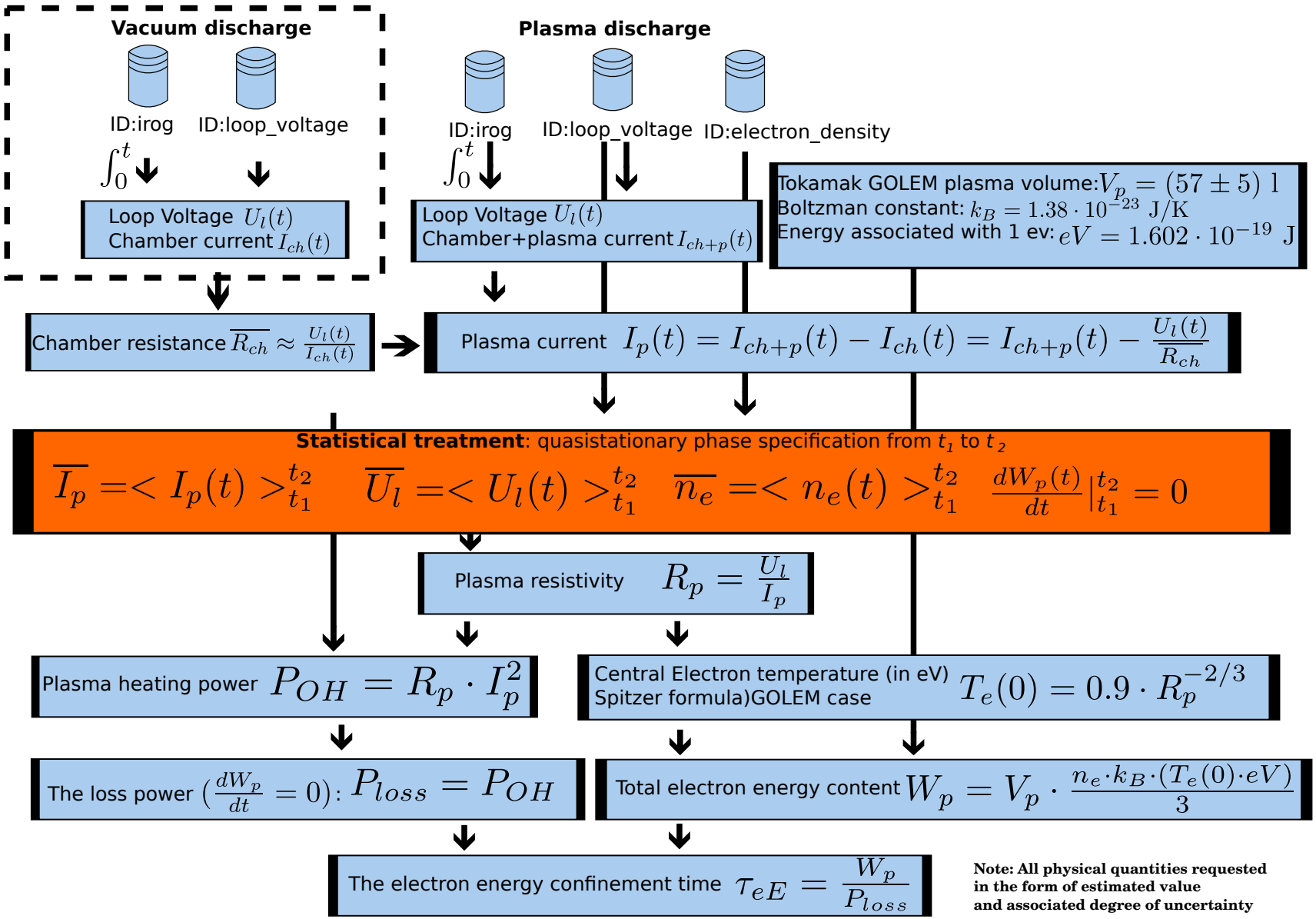
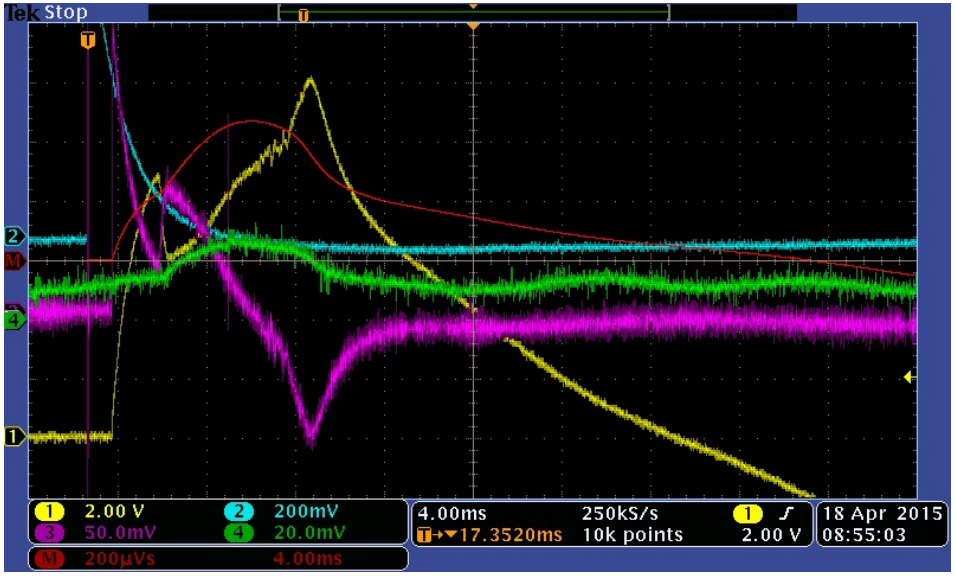
Towards Electron energy confinement time τ_E

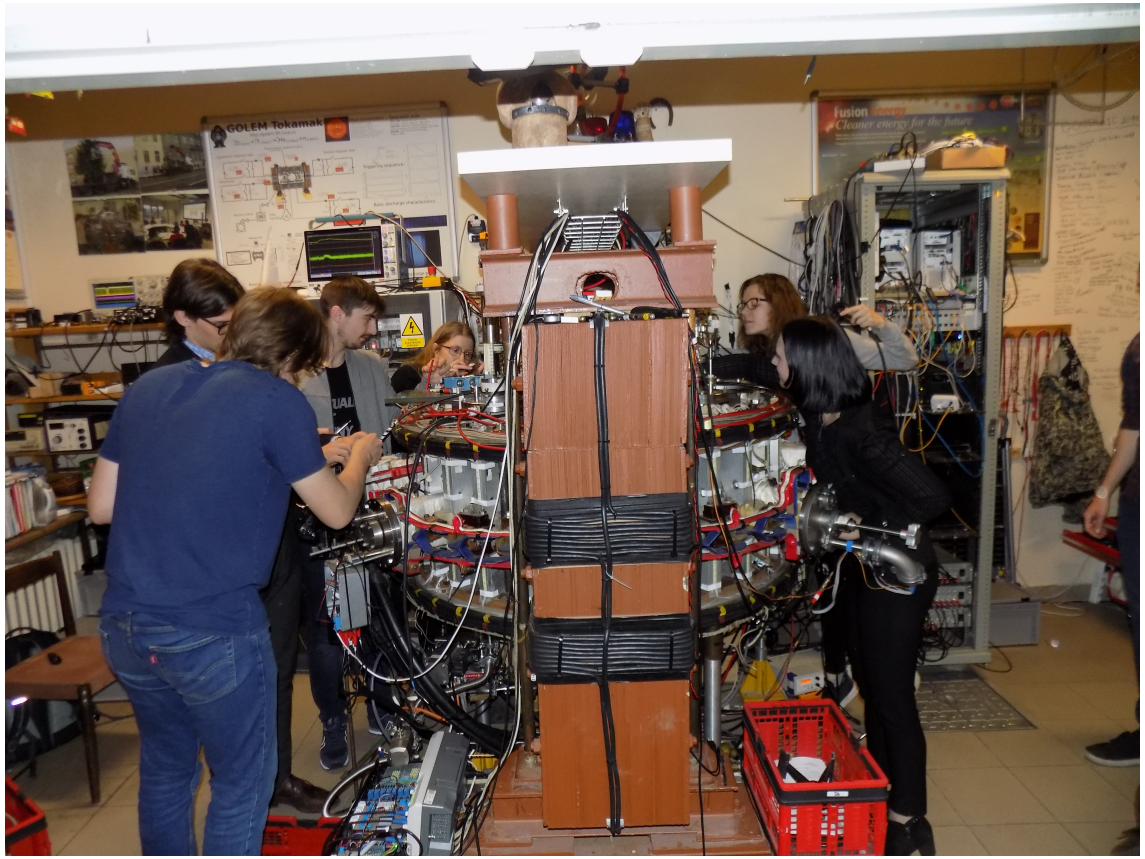


Note: All physical quantities requested in the form of estimated value and associated degree of uncertainty

Hands on the GOLEM tokamak

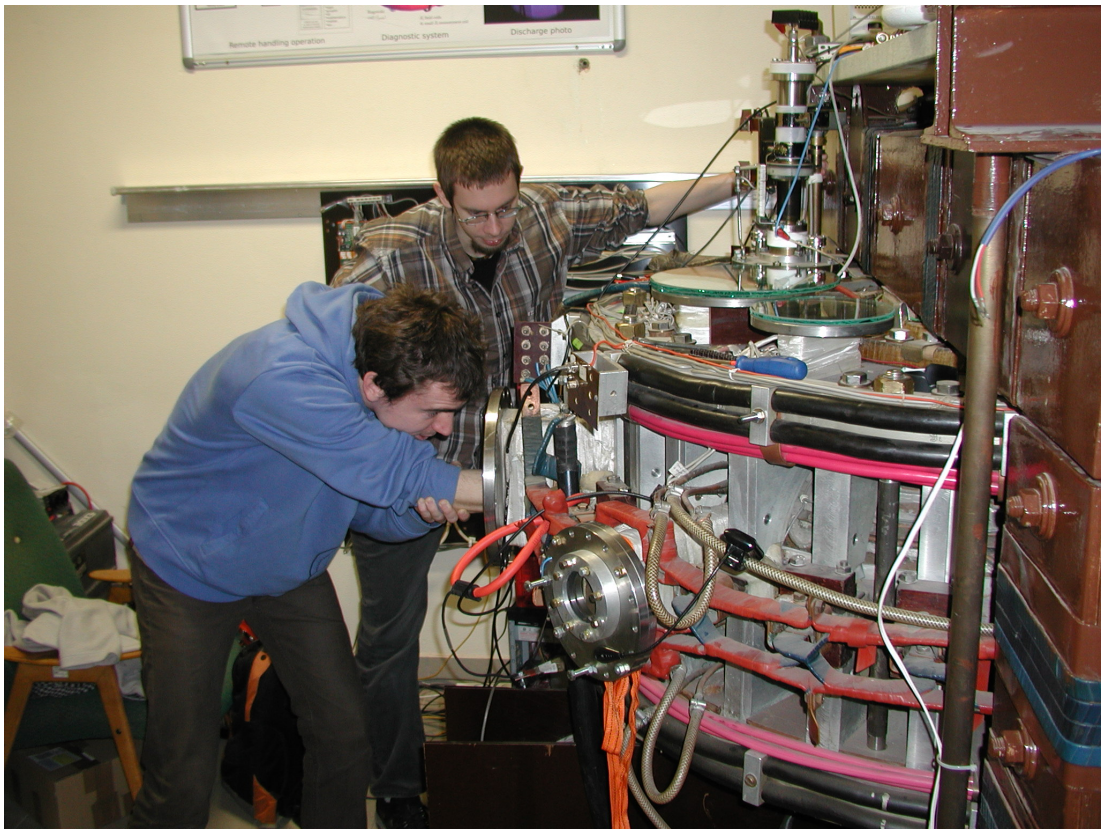


Hands on the GOLEM tokamak



- Laboratory Practice for Basic course of Physics 2015-19 (CT University Bachelor level).
- Advanced plasma training course 2014-19 (CT University Master level).
- Week of scientists 2013-19 (Czech republic High school level).
- International Golem Training Course 2013,2019 (Master and PhD level).

Bachelor & Master thesis made @ tokamak GOLEM



- **Bachelor thesis:** Magnetic field configurations and their measurement, Interactive model, Plasma flow velocity measurements using Mach probe arrays, Virtual model, Bolometric measurements, Breakdown studies, Vertical plasma stabilization.
- **Master thesis:** Microwave interferometry, Remote operation of the vertical plasma stabilization, Measurements of magnetic fields.

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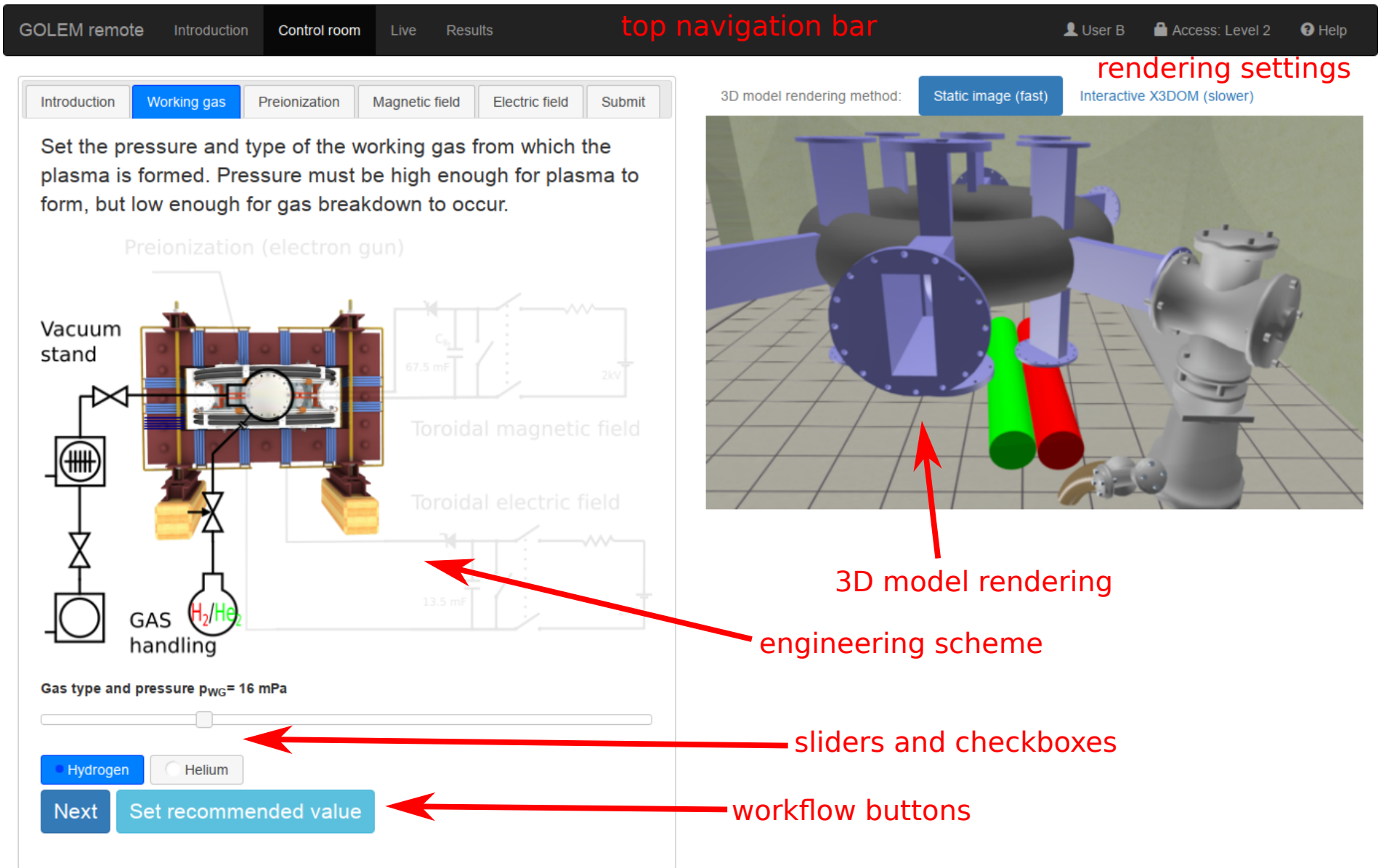
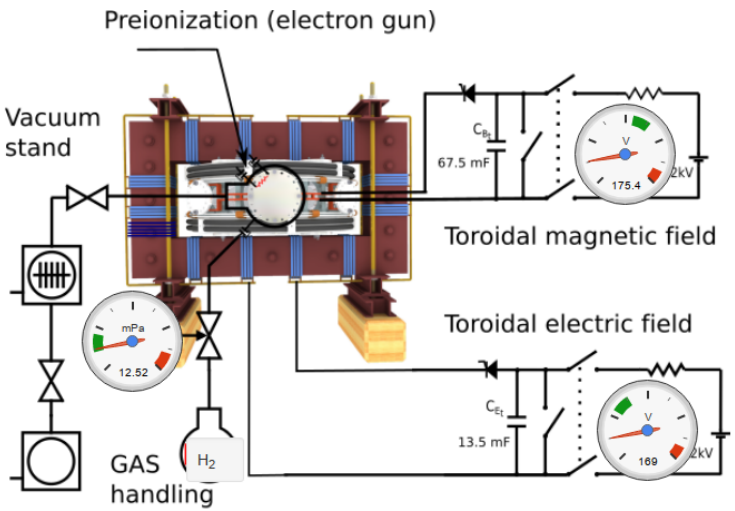
Remote control interface of the GOLEM tokamak



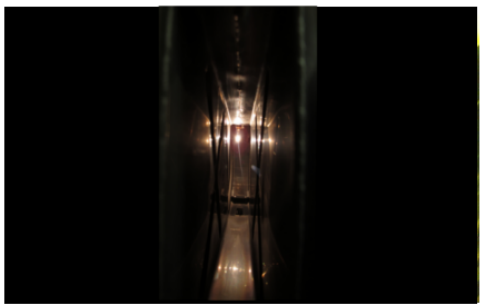
Live real-time view of the experiment

GOLEM remote | Introduction | Control room | **Live** | Results | User B | Access: Level 2 | Help



Charging capacitors, setting working gas pressure

Tokamak chamber camera



Room camera

Discharge request queue

Status	User	Comment	U_{B_t} [V]	U_{E_t} [V]	gas [mPa]
In progress	User A	plasma reference	800	450	16 (H)
Waiting	User A	higher pressure	800	450	20 (H)
Waiting	User B	strong E field	600	500	16 (H)

Shot homepage

GOLEM » Shot #22471 »

Tokamak GOLEM - Shot Database - 22471

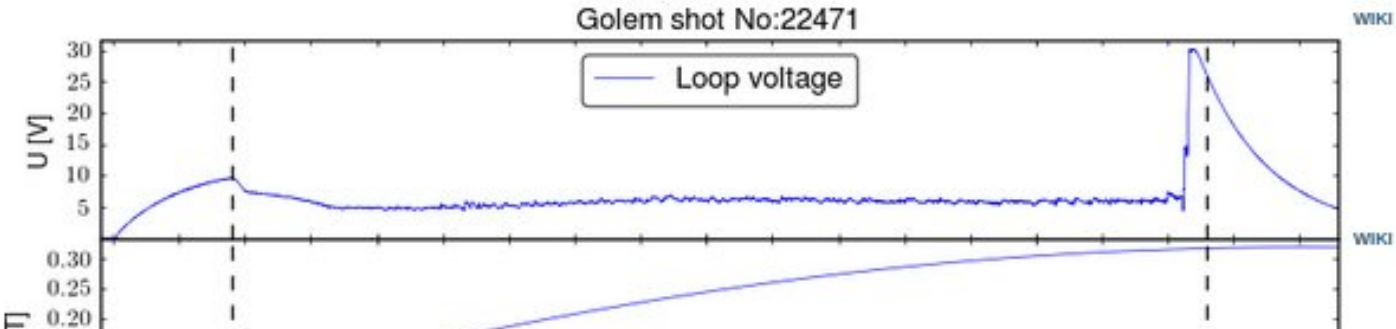
Date: 2016-09-29 - **14:33:57**
Session: TrainingCourses/Universities/Uni_Belgrade.rs/2016/
Comment: `Standard discharge`

Basic parameters: (compare)

- Gas pressure p_{ch}: `0.42`->`20.39` mPa (request: 20 mPa) WIKI
- Working gas: `H`
- Preionization: Upper el. gun
- Chamber temperature: 27.20 C
- C_{B_t} capacitors charged to: `800 V`, triggered `5.0 ms` WIKI
- C_{BD} capacitors charged to: `0 V`, triggered `5.0 ms` WIKI
- C_{CD} capacitors charged to: `400 V`, triggered `6.0 ms` WIKI
- C_{ST} capacitors charged to: `0 V`, triggered `5.0 ms` WIKI
- Probability of breakdown: 85% WIKI
- Time since session beginning: 0:07:50 h

Plasma parameters:

- Plasma life time **14.8** [ms] (from 7.8 to 22.6)
- Mean toroidal magnetic field Bt: 0.23 T WIKI
- Mean plasma current: 3.60 kA WIKI
- Mean Uloop: 5.92 V WIKI
- Break down voltage: 9.6 V WIKI
- Ohmic heating power: 21.33 kW
- Q edge: 2.9 WIKI
- Electron temperature: `41.1` eV WIKI
- Line electron density: `5.52` [10^17.m^-2] WIKI



Diagnostics
- ✓ Interferometer
- ✓ Spectrometer
- ✕ FastCamera
- ✓ HXR

Analysis
- ✓ ShotHomepage

DAS
- ✓ TektronixDPO
- ✓ NIstandard
- ✓ Papouch_St
- ✓ Papouch_Ko
- ✓ NIoctopus

Vacuum log

Other
- Data
- References
- About
- Wiki
- Utilities

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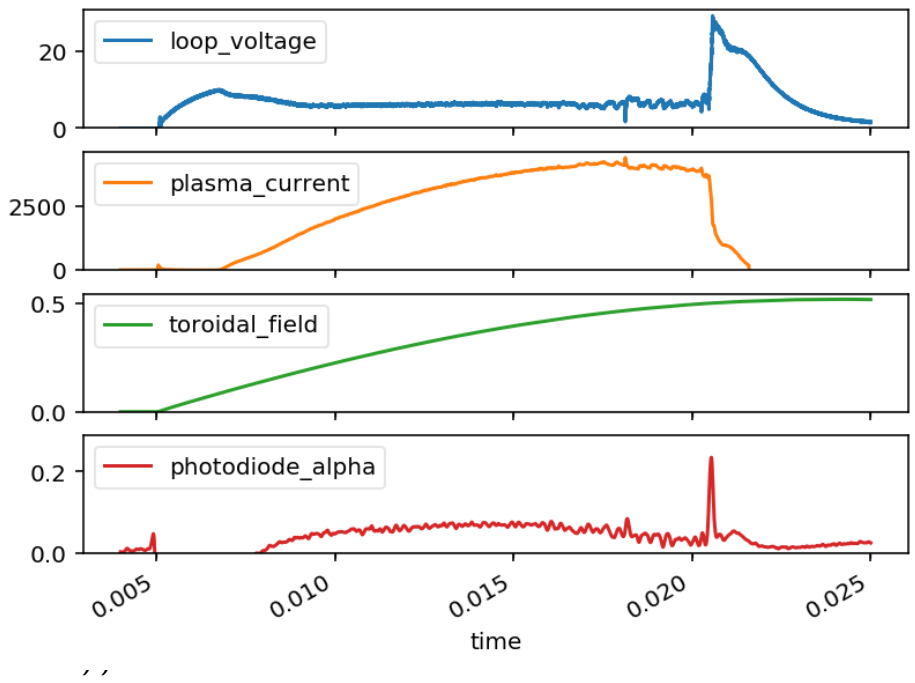
Remote data access (using a few high level functions)

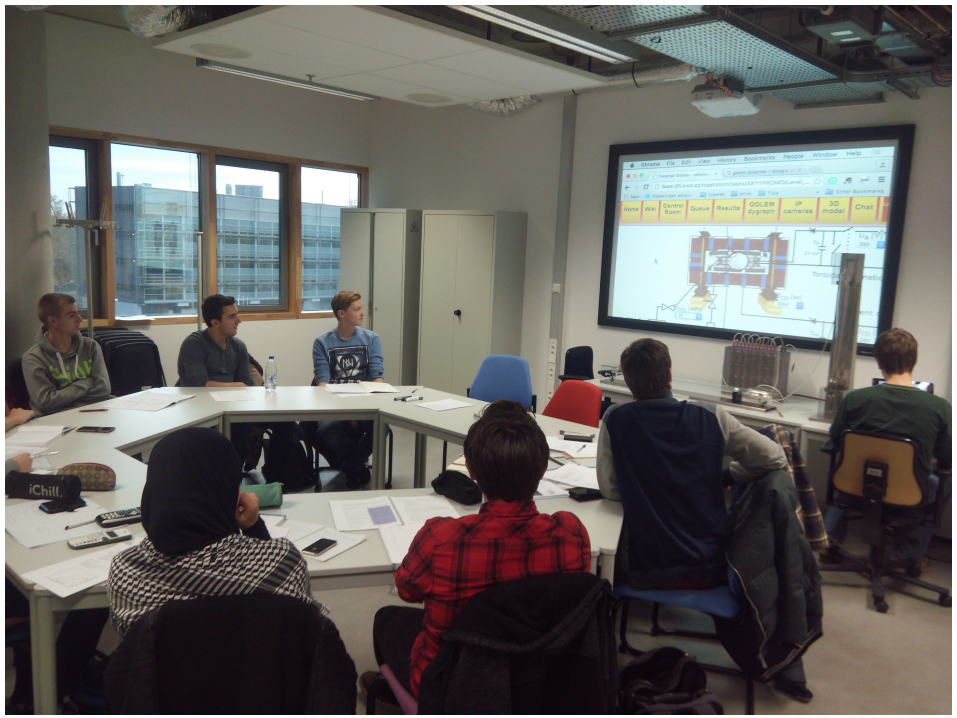
```
import pandas as pd
import matplotlib.pyplot as plt
URL = 'http://golem.fjfi.cvut.cz/utils/data/{}/
# function for reading 1D y(t) signals
def read_signal1d(shot_number, signal_id):
    url = URL.format(shot_number, signal_id)
    return pd.read_table(url,names=['time',sign
                         index_col='time')
# read the specified signals
shot_no = 29395
U_l = read_signal1d(shot_no, 'loop_voltage')
I_p = read_signal1d(shot_no, 'plasma_current')
P_OH = U_l*I_p
# vectorized, time-aligned operation
B_t = read_signal1d(shot_no, 'toroidal_field')
H_a = read_signal1d(shot_no, 'photodiode_alpha'
# combine into a data frame table
df = pd.concat([U_l, I_p, B_t, H_a], axis='colu
# plot the data table in subplots from 4 to 25
df.loc[4e-3:25e-3].plot(subplots=True, ylim=(0,
plt.show()
# display the figure in a window
```



Available topics

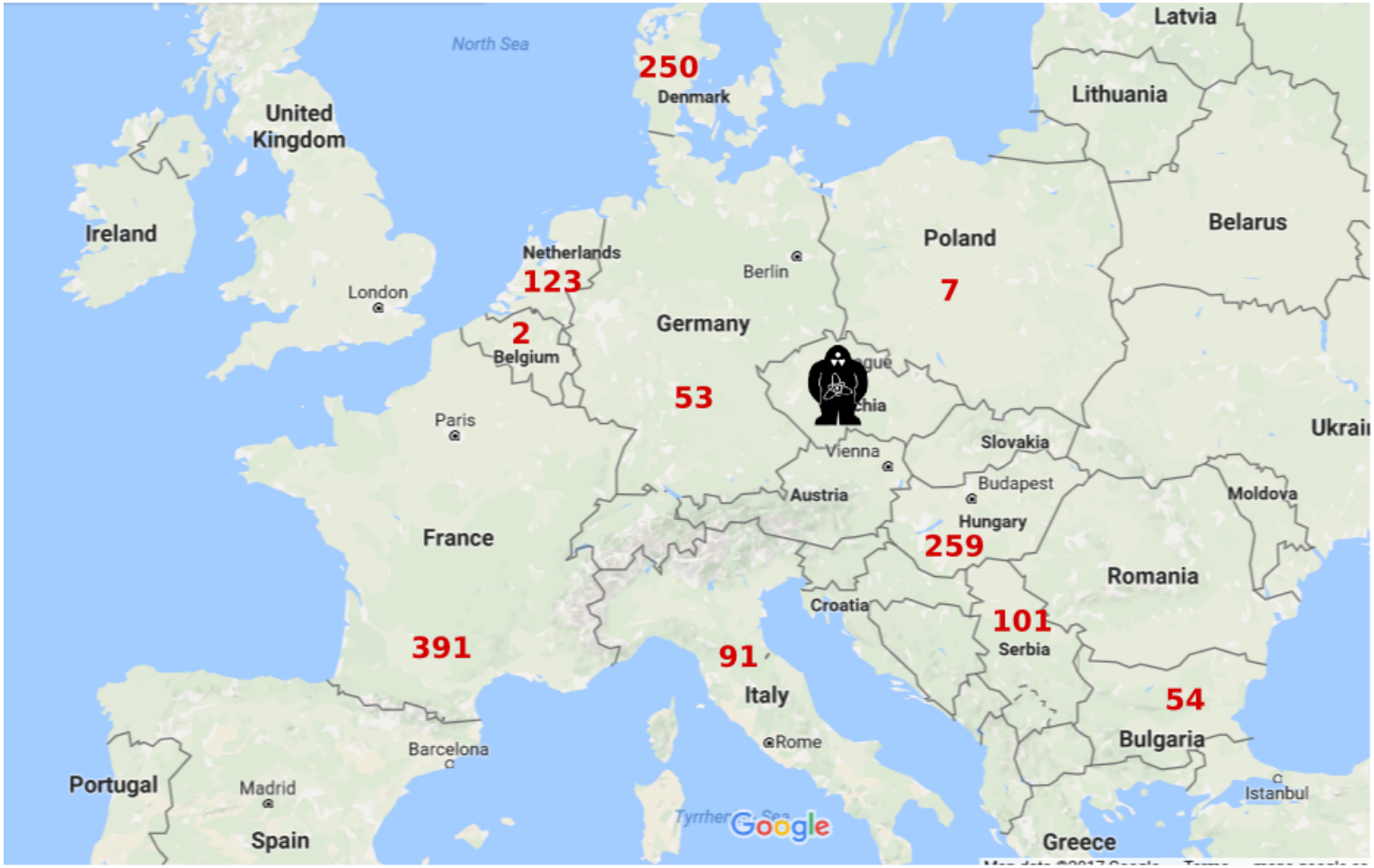
- Level 0 "a game/playground"
- Level 1 "basic"
  - Breakdown studies
  - Energy confinement time τ_E
  - $\mathbf{q} = \mathbf{2}$ disruptions
- Level 2 "data mining"
  - Neo-Alcator confinement scaling law
  - Machine learning
- Level 3 "advanced"
  - Isotopic studies

Remote control 2009-2019 inventory



- Demonstrations: Ghent University 09; Bochum University 13; Garching 13; Lemvig High School 14; Instituto Tecnologico Costa Rica 10; Armidale University 17.
- Training courses: French Training Course & EM 12-14,16-19; Bangkok 16-19; TU Eindhoven 11,15-19;TU Kobehaven 14,15,18;Grenoble TU 15, University of Belgrade 15-18; BUTE Budapest 10,12-18; University of Padova 14,16,18; TU Torino 16-18, St. Peterburg University 18-19. Kharkov University 19
- Workshops Kiten: 14,16,18; Observatorium Valasske Mezirici 14; Islamabad 14.

Remote discharges over the Czech borders (up to 2017)



+ IN ~ 10, + PK ~ 70, + OTHERS ~ 100

Σ(09/12-02/17)~1500

Fee: postcard from the venue of remote measurements

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One particular student from history 2008

Acknowledgement

Financial support highly appreciated:

CTU RVO68407700, SGS 17/138/OHK4/2T/14, GAČR GA18-02482S, EU funds CZ.02.1.01/0.0/0.0/16_019/0000778 and CZ.02.2.69/0.0/0.0/16_027/0008465, IAEA F13019, FUSENET and EUROFUSION.

Students, teachers, technicians (random order):

Vladimír Fuchs, Ondřej Grover, Jindřich Kocman, Tomáš Markovič, Michal Odstrčil, Tomáš Odstrčil, Gergo Pokol, Igor Jex, Gabriel Vondrášek, František Žácek, Lukáš Matěna, Jan Stockel, Jan Mlynář, Jaroslav Krbec, Radan Salomonovič, Vladimír Linhart, Kateřina Jiráková, Ondřej Ficker, Pravesh Dhyani, Juan Ignacio Monge-Colepicolo, Jaroslav Čeřovský, Bořek Leitl, Martin Himmel. Petr Švihra, Petr Mácha, Vojtěch Fišer, Filip Papoušek, Sergei Kulkov, Martin Imríšek.

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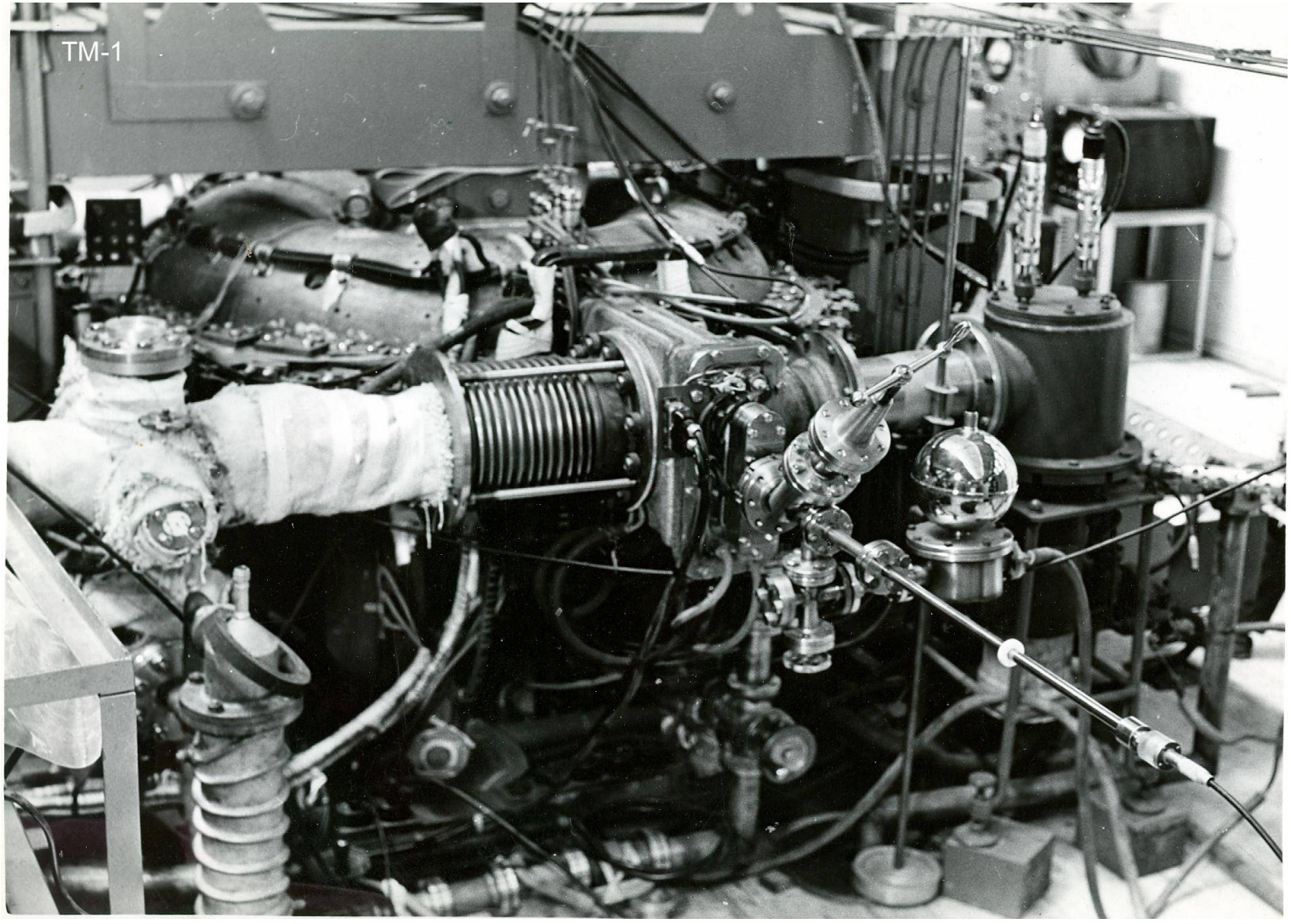
References I

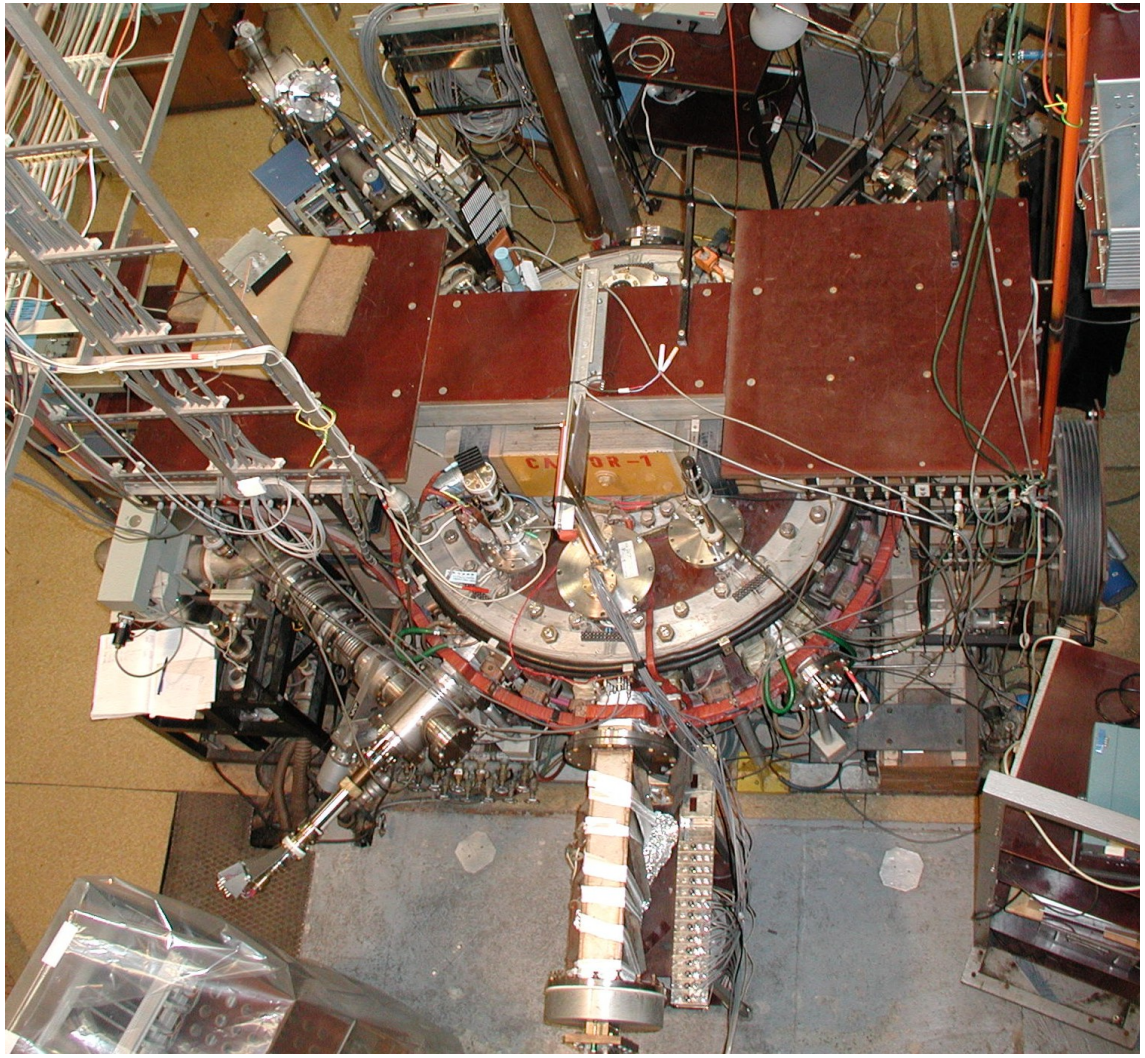
[1] V. Svoboda, B. Huang, J. Mlynar, G.I. Pokol, J. Stockel, and G Vondrasek. Multi-mode Remote Participation on the GOLEM Tokamak. *Fusion Engineering and Design*, 86(6-8):1310–1314, 2011.

[2] Tokamak GOLEM contributors. Tokamak GOLEM at the Czech Technical University in Prague. http://golem.fjfi.cvut.cz, 2007. [Online; accessed October 20, 2019].

XX/YY: TM-1



XX/YY: CASTOR

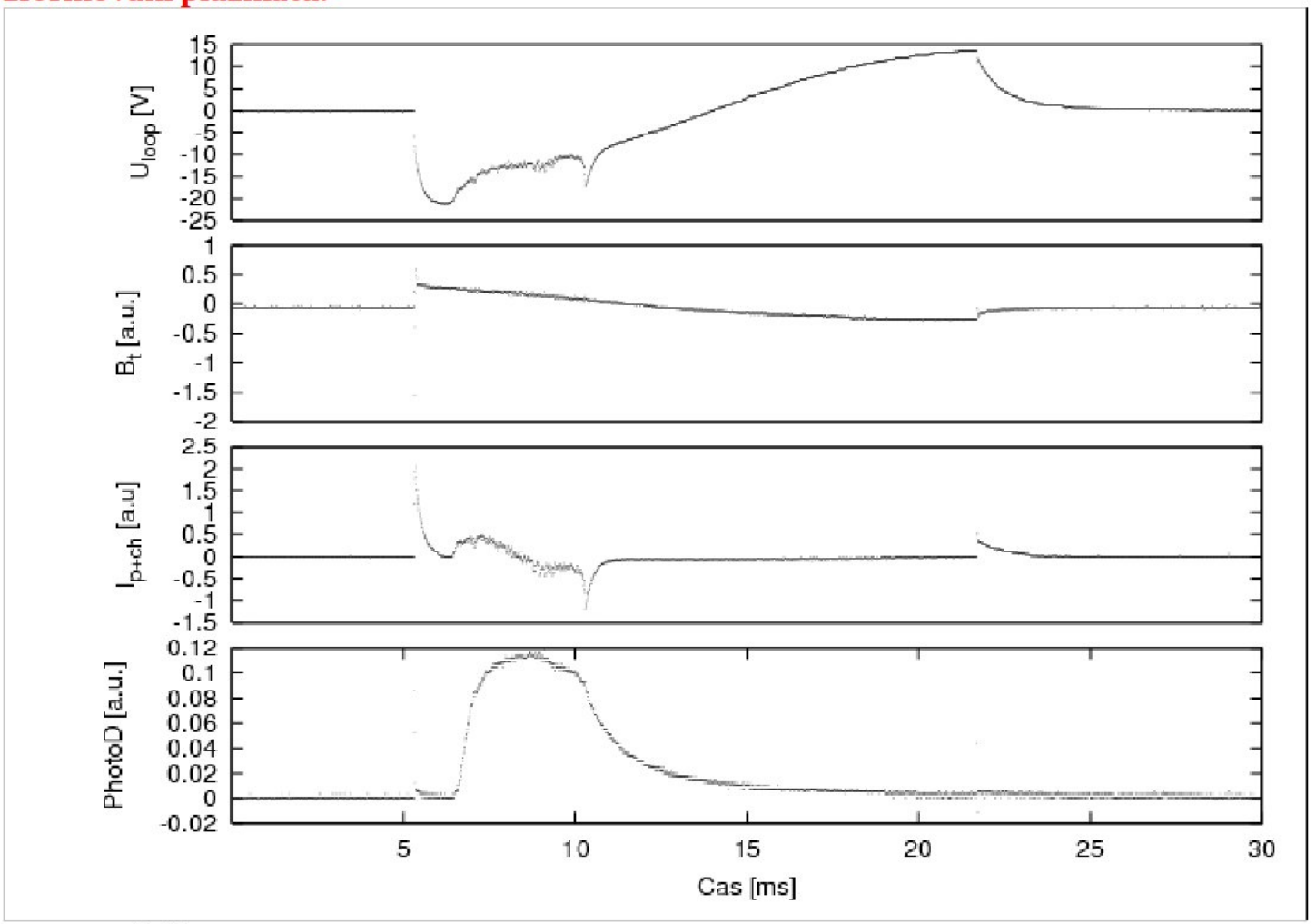


12/07: Last minutes at the IPP Prague

12/07: First minutes at the CTU Prague

07/09: First plasma in the tokamak GOLEM

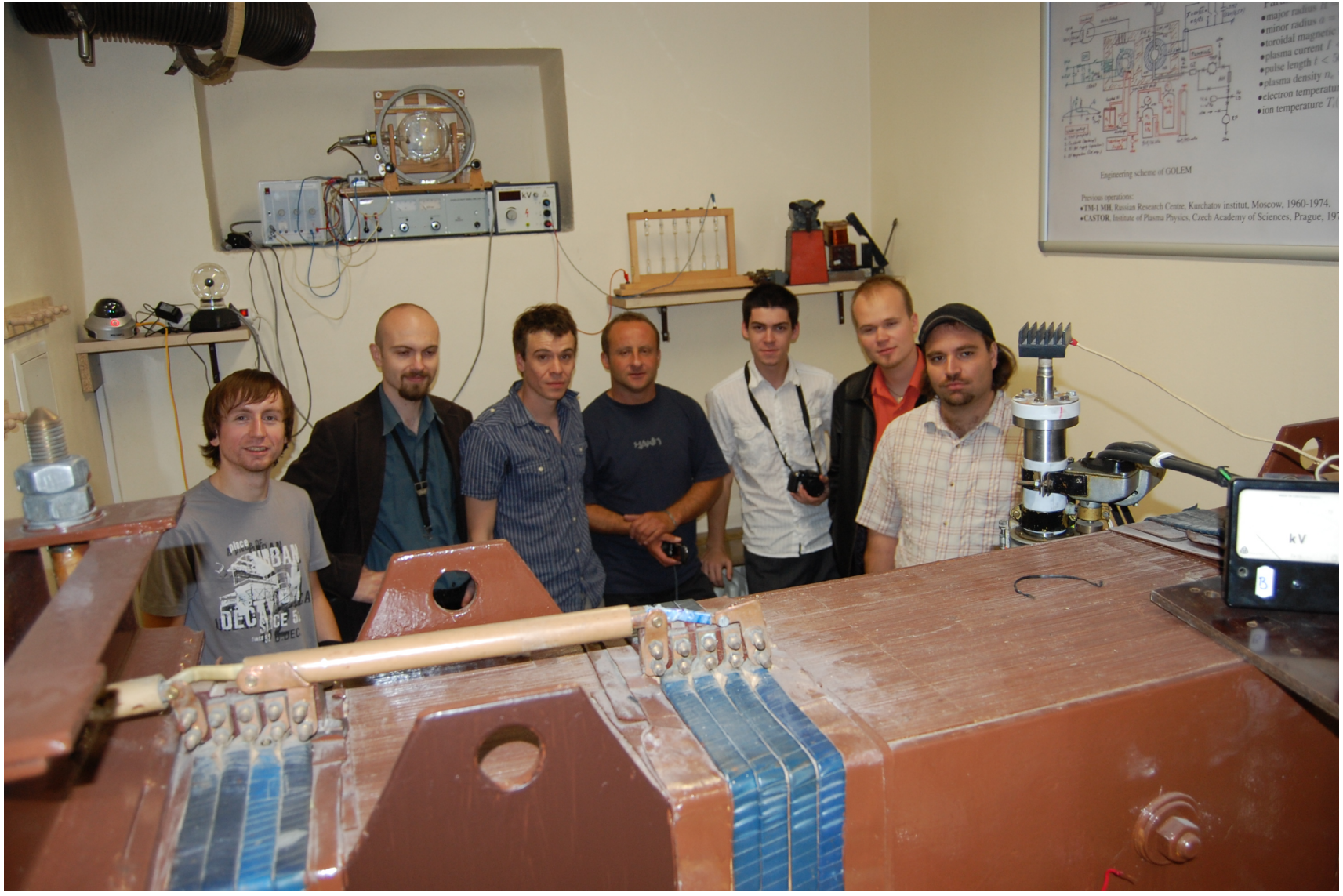
Časové průběhy signálů zřetelně ukazují, že došlo k průrazu neutrálního plynu a k zformování plazmatu.



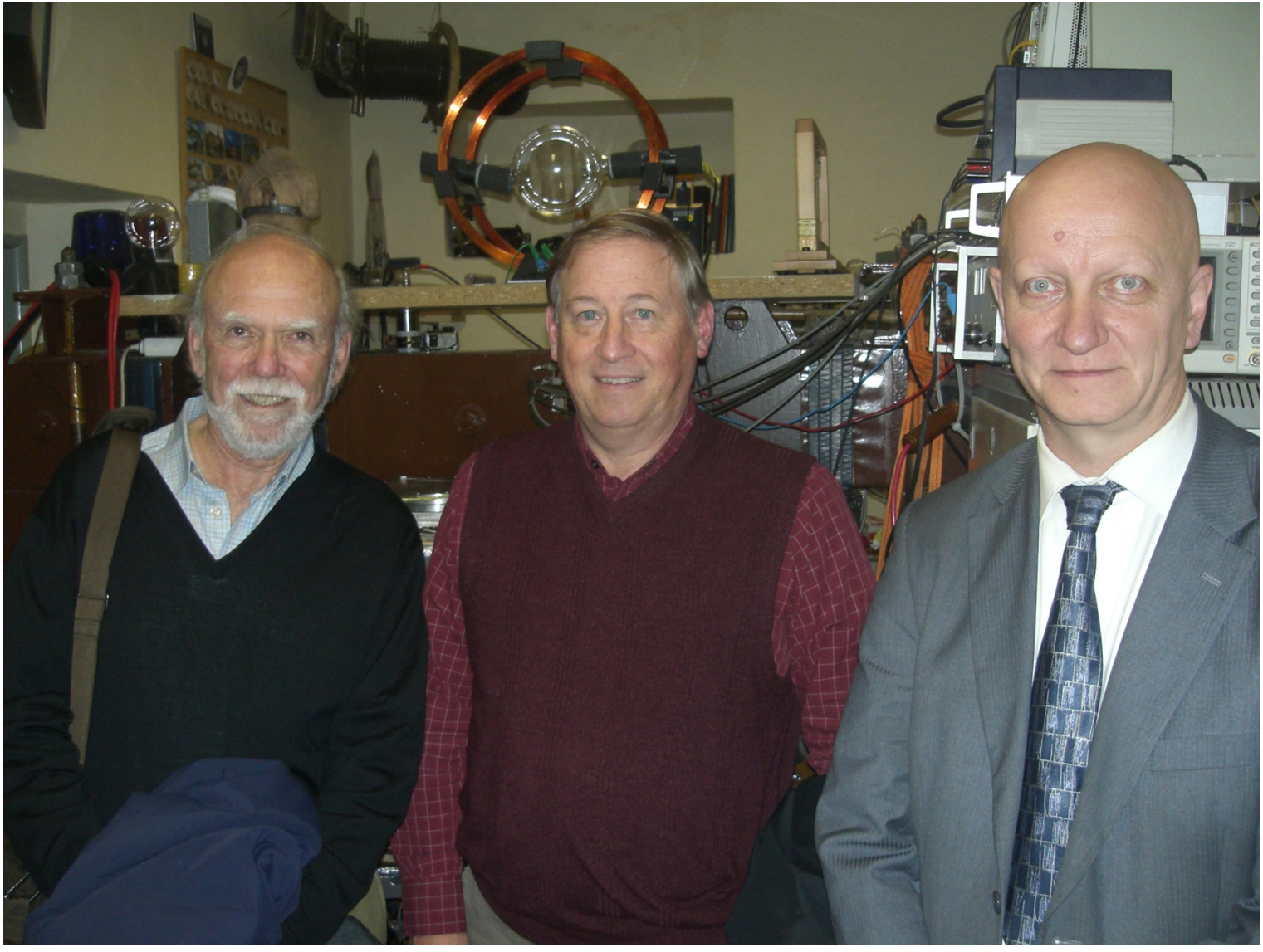
O tom svědčí:

1. Rychlý pokles napětí na závit v čase t = 6-7 ms a jeho malé fluktuace.které lze vidět až

09/09: Tokamak and tokamak

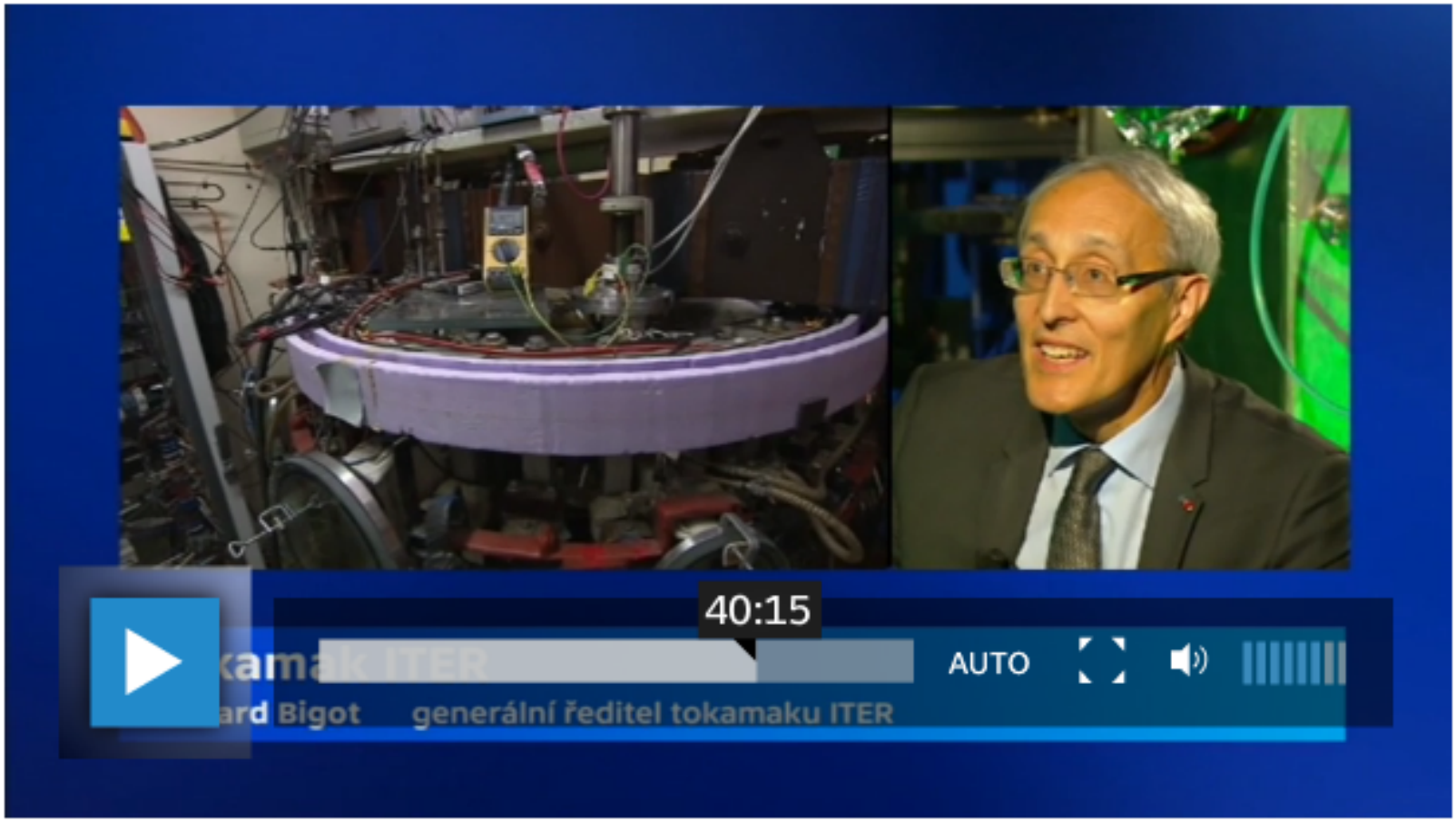


11/11: NP laureat at tokamak GOLEM



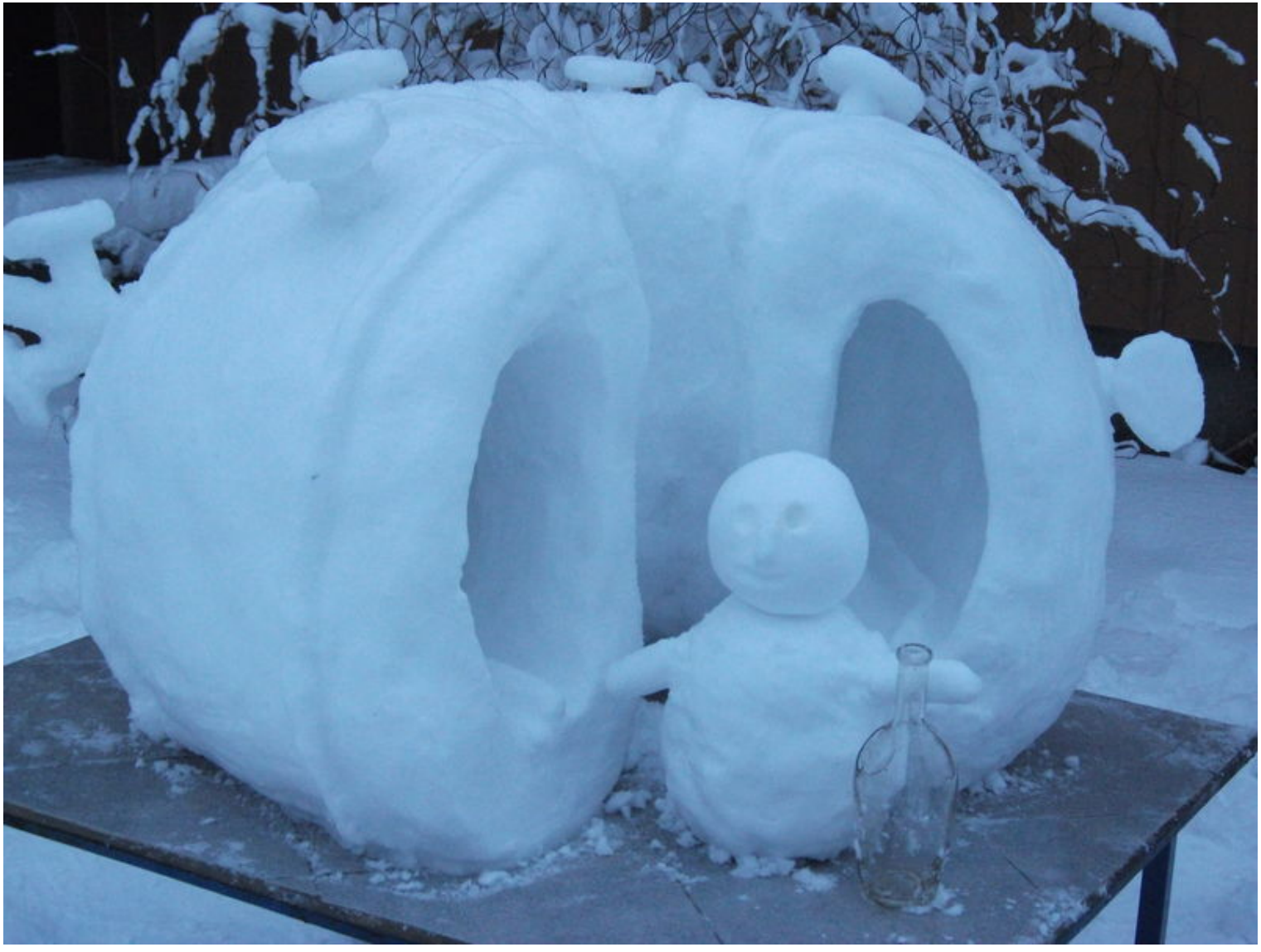
05/16: The youngest tokamak (GOLEM) operator, Adam (7 years).

0916: ITER DG, Mr. Bernard Bigot (Shot #22185)



Quotation from Czech Television Hydepark

2010: Tokamak GOLEM



2011: The tokamak COMPASS with NBI

2016: ITER segment

2017: First Spitzer Stellarator

Tokamak GOLEM

10/15: Trojan horse - #20000

GOLEM » Shot #20000 »

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Tokamak GOLEM - Shot Database - 20000

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Date: 2015-10-22 - **16:09:25**
Session: SessionPreparation
Comment: 20k

Congratulation, you have reached nuclear fusion.
The following explosion destroyed half of Prague and radioactive fallout contaminated whole Europe.
Have a nice day

Basic parameters: (compare)

- Gas pressure p_{ch}: 10.28->15.38 mPa (request: 5 mPa) WIKI
- Working gas: H
- Preionization: Upper el. gun
- Chamber temperature: 20.00 C
- C_{B_t} capacitors charged to: 1000 V, triggered 5.0 ms WIKI
- C_{BD} capacitors charged to: 0 V, triggered 5.0 ms WIKI
- C_{CD} capacitors charged to: 500 V, triggered 6.0 ms WIKI
- C_{ST} capacitors charged to: 0 V, triggered 5.0 ms WIKI
- Probability of breakdown: N/A WIKI
- Time since session beginning: 0:19:25 h

Plasma parameters:

- Plasma life time **8.7** [ms] (from 7.5 to 16.2)
- Mean toroidal magnetic field Bt: 0.22 T WIKI
- Mean plasma current: 1.42 kA WIKI
- Mean Uloop: 12.41 V WIKI
- Break down voltage: 10.5 V WIKI
- Ohmic heating power: 17.59 kW
- Q edge: 6.9 WIKI
- Electron temperature: 13.5 eV WIKI
- Line electron density: N/A [10^17.m^-2] WIKI