Online experimentation at the GOLEM tokamak

Ondrej Grover, Vojtech Svoboda and Jan Stockel
on behalf of the tokamak GOLEM team
for **EXP.AT '19** Madeira

June 12, 2019

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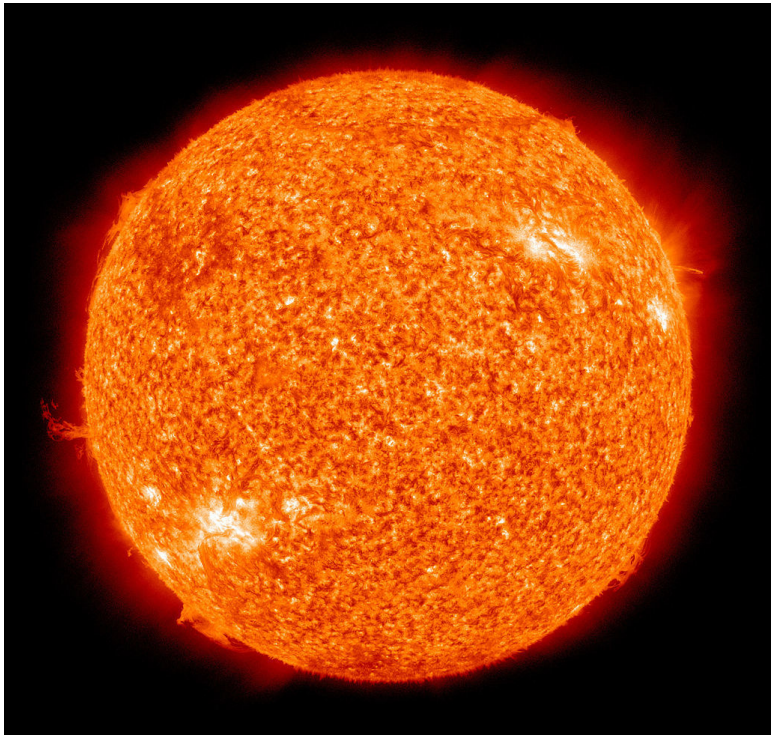
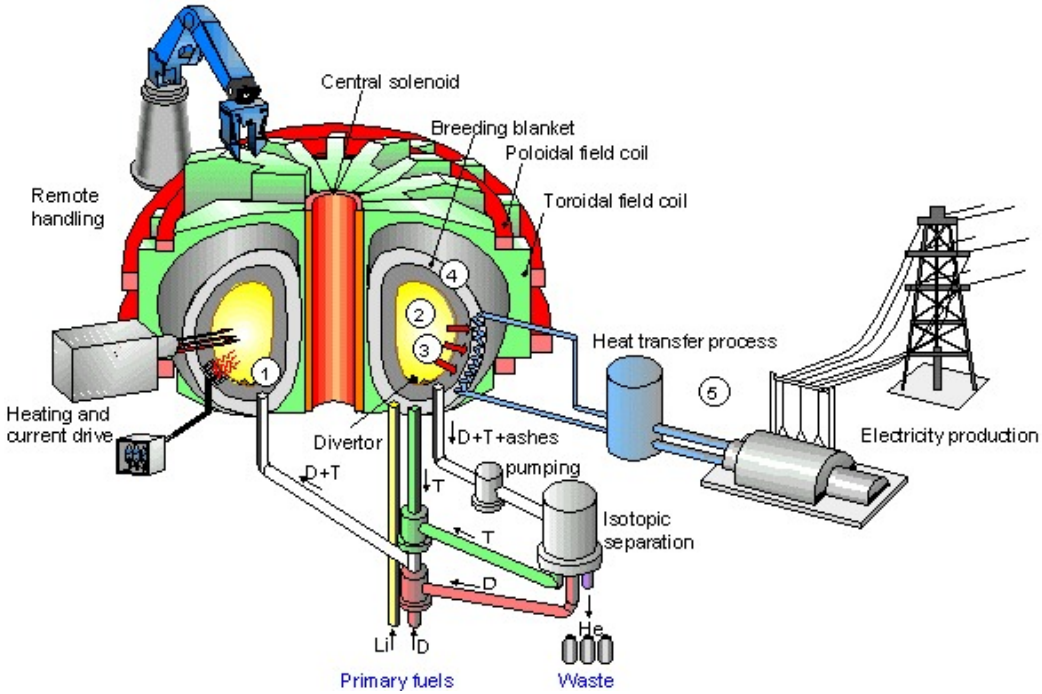
Tokamak mission:
to create μSun in the terrestrial conditions



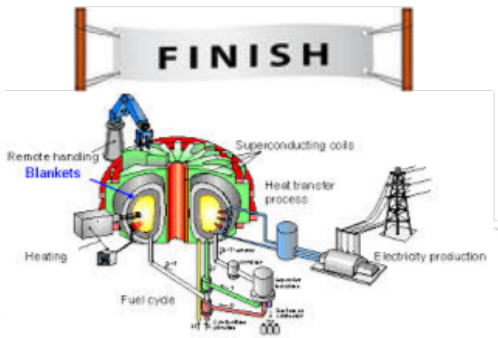


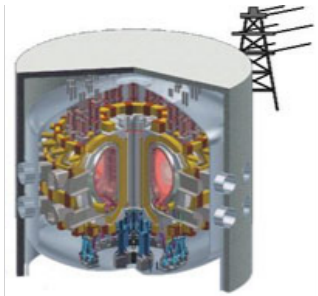
$$ {}^{2}_{1}\mathbf{D}_{(10\mathbf{keV})} + {}^{3}_{1}\mathbf{T}_{(10\mathbf{keV})} \Rightarrow {}^{4}_{2}\mathbf{He}_{(3.5\mathbf{MeV})} + \mathbf{n}_{(14.1\mathbf{MeV})} $$

The task: to heat (up to 100 million degrees) DT fuel and confine it (up to 30 years) in the high temperature plasma state of matter to produce He & fusion energy.

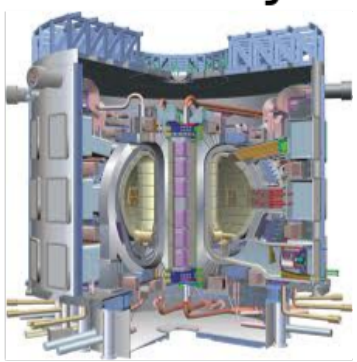
A Roadmap to the Fusion Power Plant

COMMERCIAL
POWER PLANT
???





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



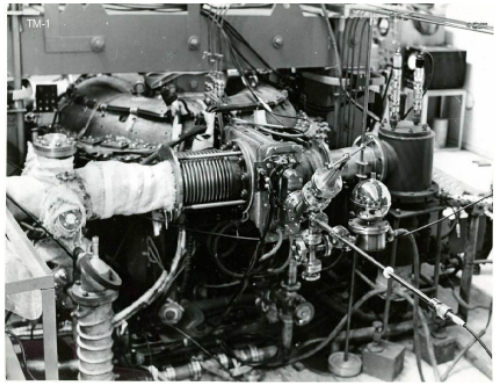
ITER (WORLD)
2025?-
Mission: ~ 400s 500 MW @ Q=10

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

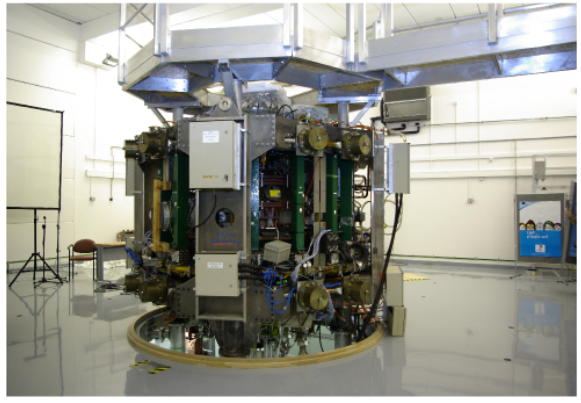
Education importance

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

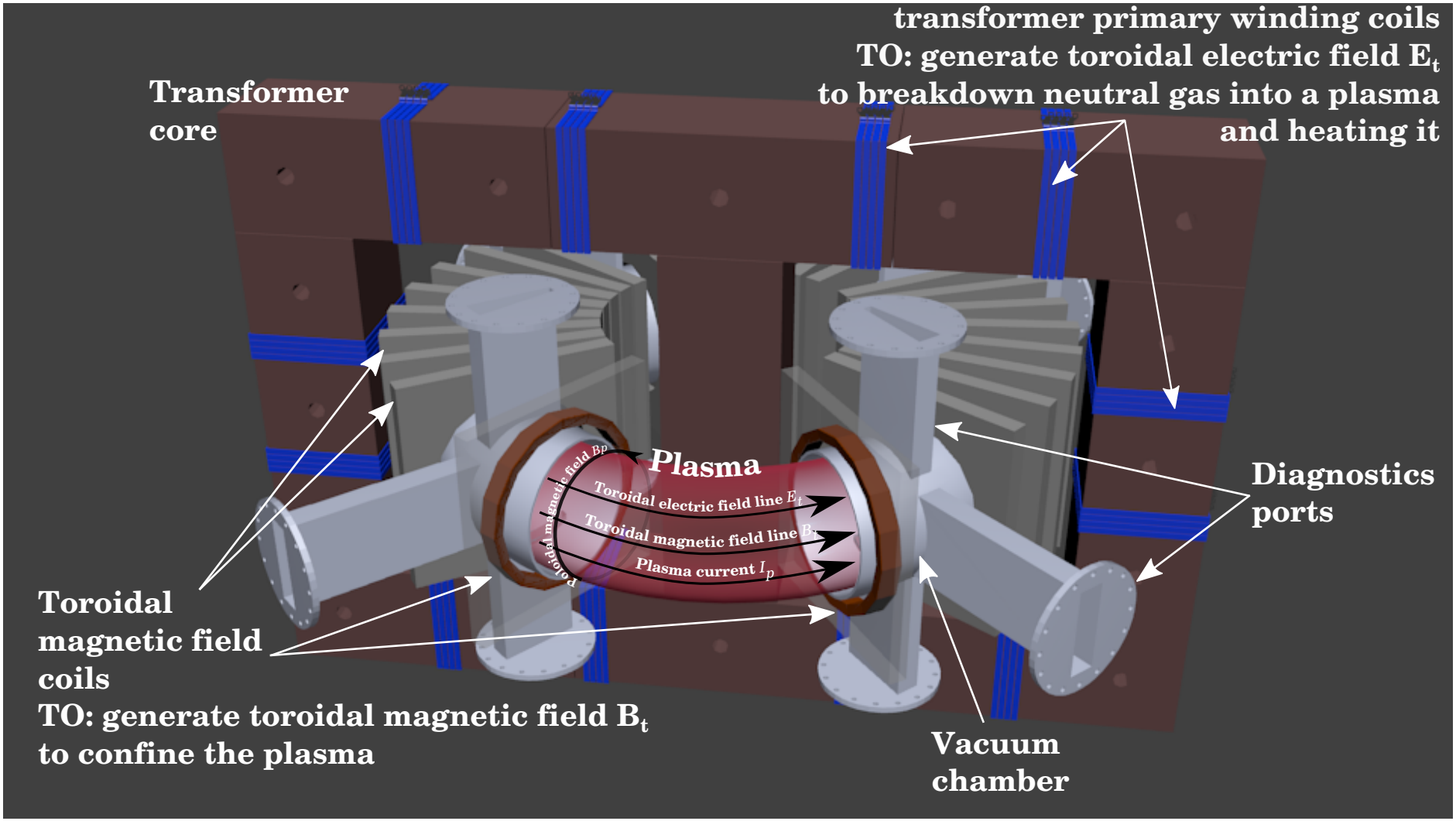
2006

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

2008

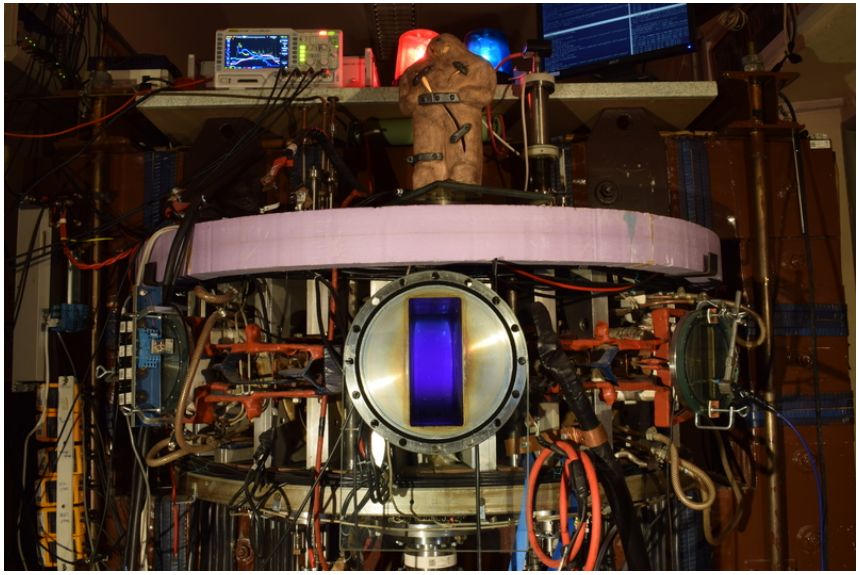
Czech Technical University Prague
Czech republic
GOLEM

Tokamak (GOLEM) basic concept to confine and heat the plasma



The GOLEM tokamak basic characteristics

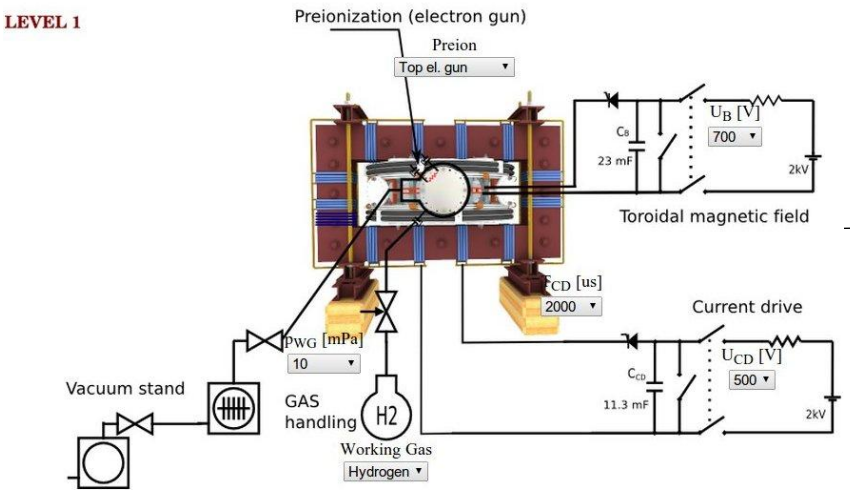
The grandfather of all tokamaks (ITER newsline 06/18)



- 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

The global schematic overview of the GOLEM experiment

Tokamak technology setup



internet

USER authorization

WWW server

OpenSSH serve

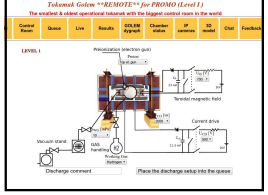
Control PC

OpenSSH server

Virtual control room (remote participation)

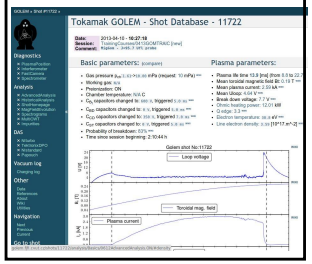
WWW control interface

HTML & PHP scripts



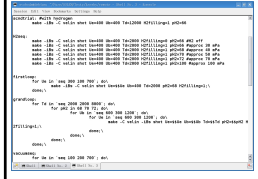
Data presentation

HTML (www pages)



SSH control interface

WINDOWS via putty

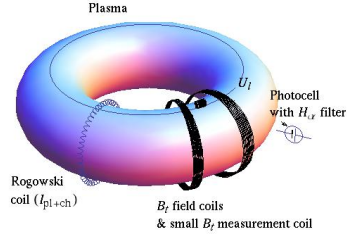


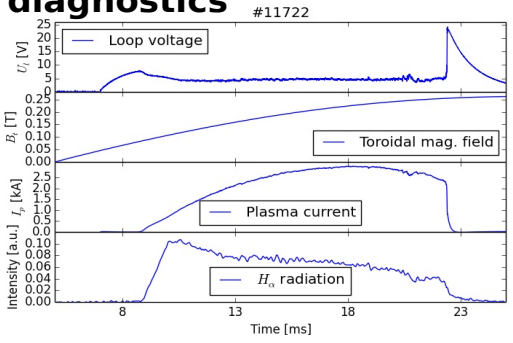
LINUX via ssh
or ssh+X tunnel
(advanced mode)

Data handling

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

Basic plasma diagnostics





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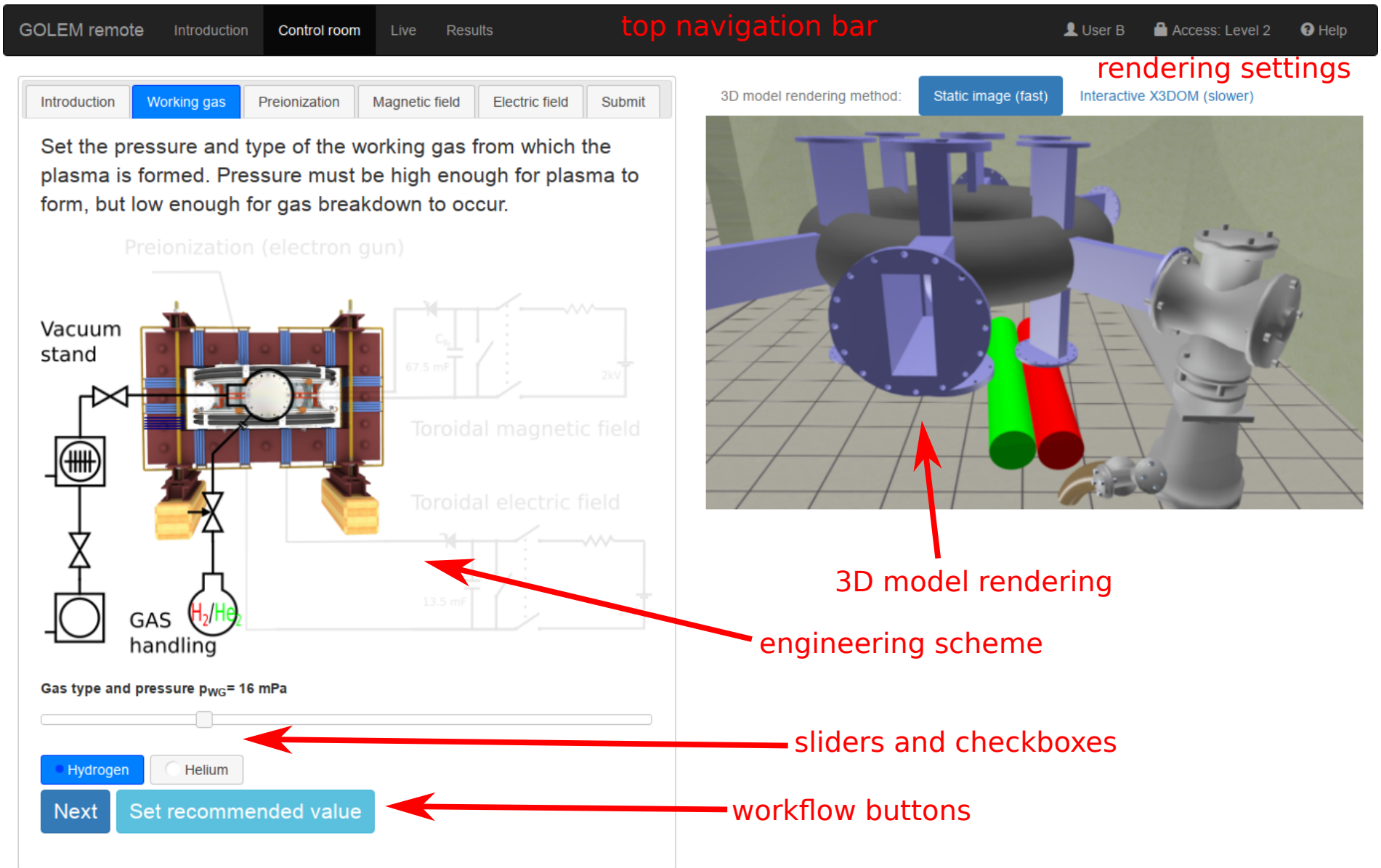
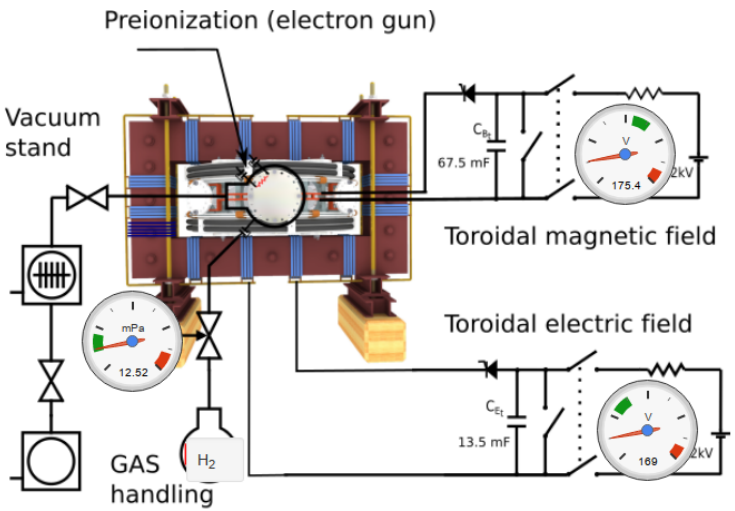
Remote control interface of the GOLEM tokamak



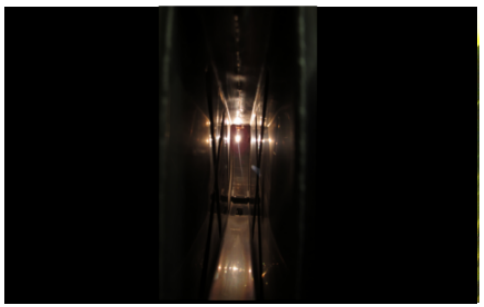
Live real-time view of the experiment

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

Diagnostics

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

Analysis

- ✓ ShotHomepage

DAS

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

Vacuum log

Other

Data
References
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Tokamak GOLEM - Shot Database - 22471

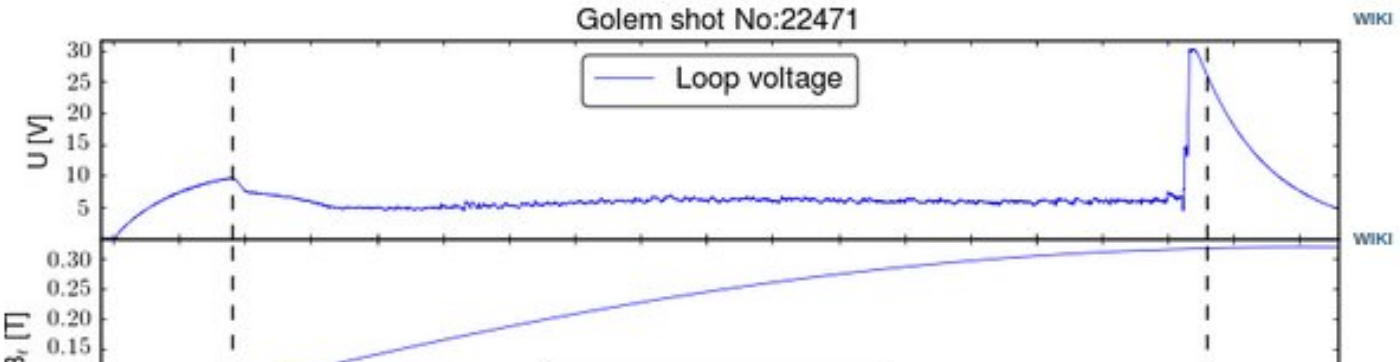
Date: 2016-09-29 - **14:33:57**
Session: TrainingCourses/Universities/Uni_Belgrade.rs/2016/
Comment: `Standard discharge`

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

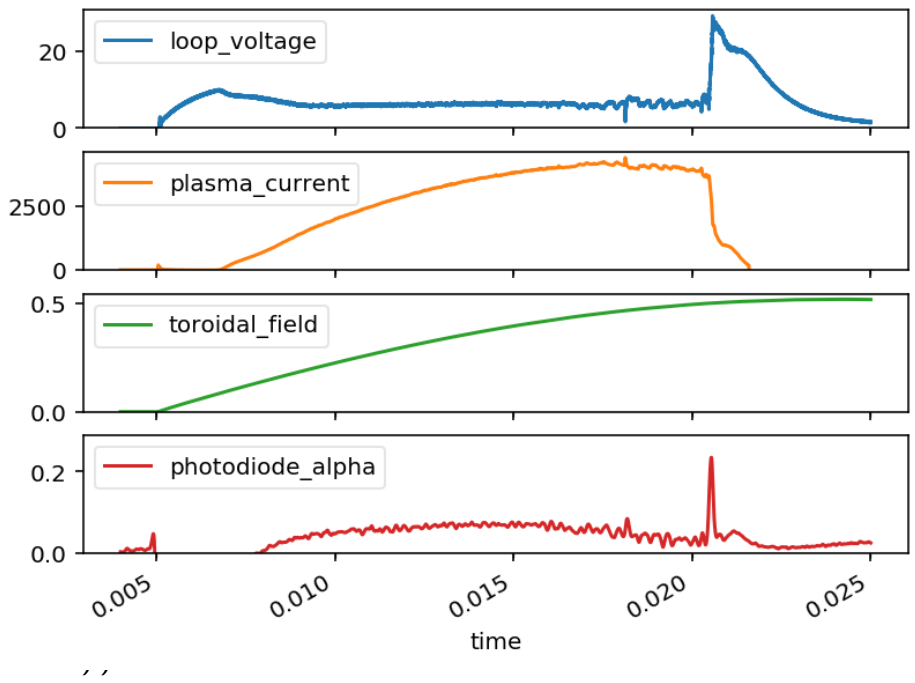
Plasma parameters:

- 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



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
```



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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

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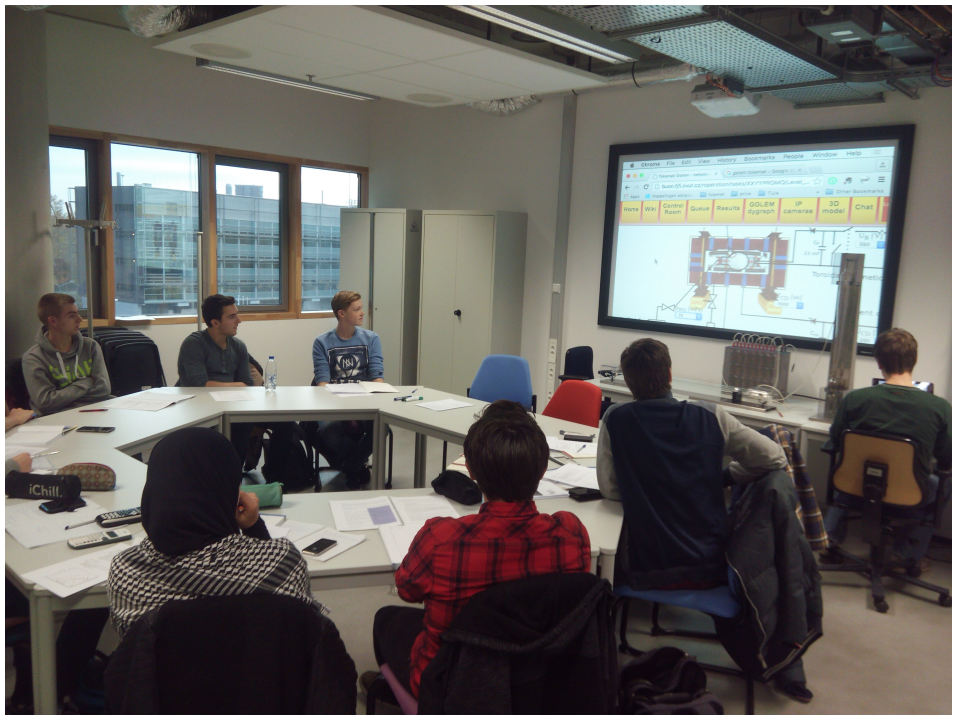
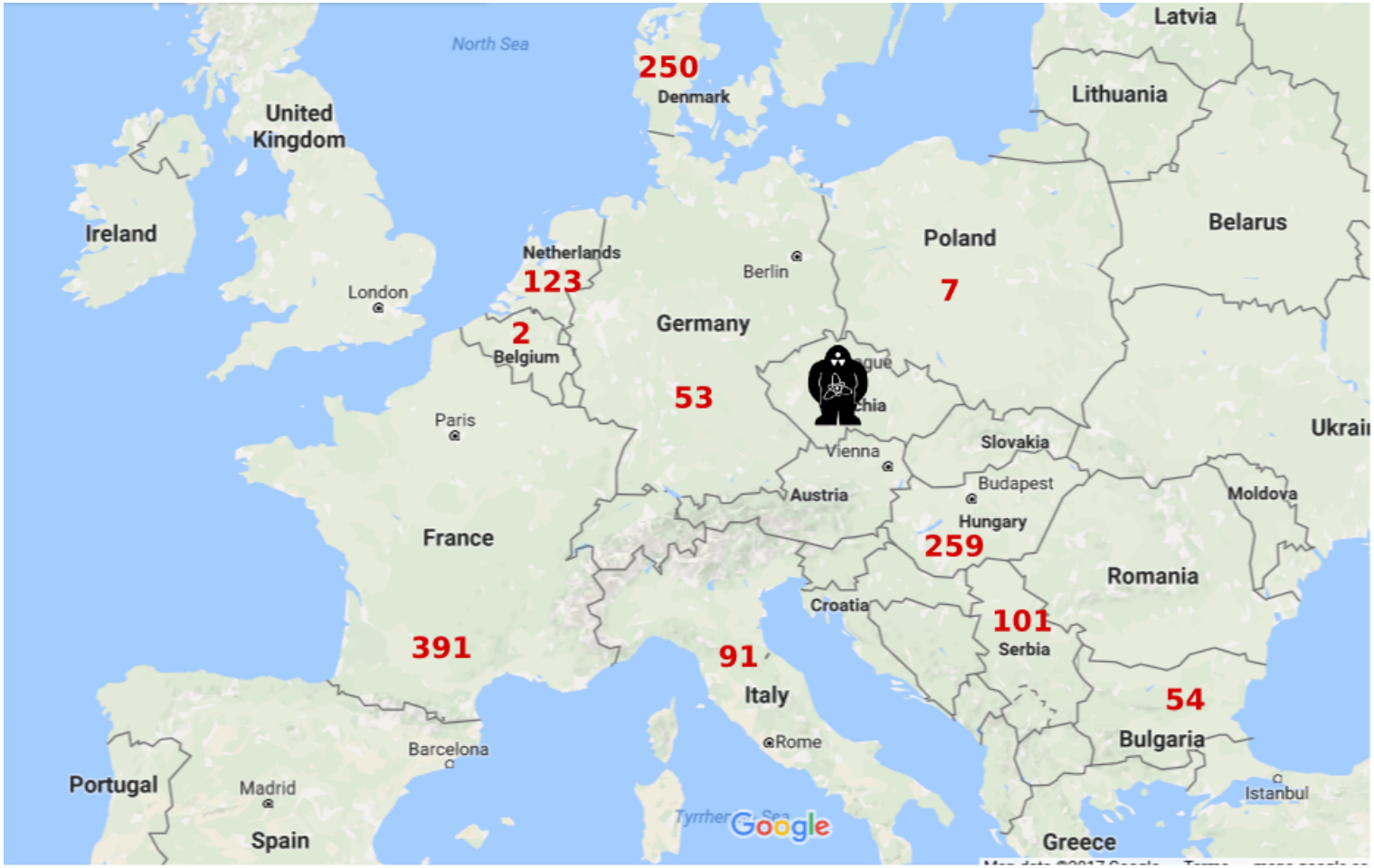
Remote control 2009-2019 inventory



- 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

Control room tomorrow open (Demo #65 @ UMa-R Room D 8:30-10:00)

Go to http://golem.fjfi.cvut.cz/expat19

... and enjoy discharges from Madeira ..
from any internet device (even from your mobile phones)

Tokamak GOLEM for Fusion education

You are welcome to exploit this facility

- Lectures, demonstrations at universities
- Spring/Summer/Autumn/Winter schools
- Training courses
- ... etc.
- ... even remote Bachelor and/or Diploma thesis

web:`http://golem.fjfi.cvut.cz`
mailto:svoboda@fjfi.cvut.cz

Fee: postcard from the venue of remote measurements

Acknowledgement

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