

Introduction to the tokamak GOLEM operation Practical guide

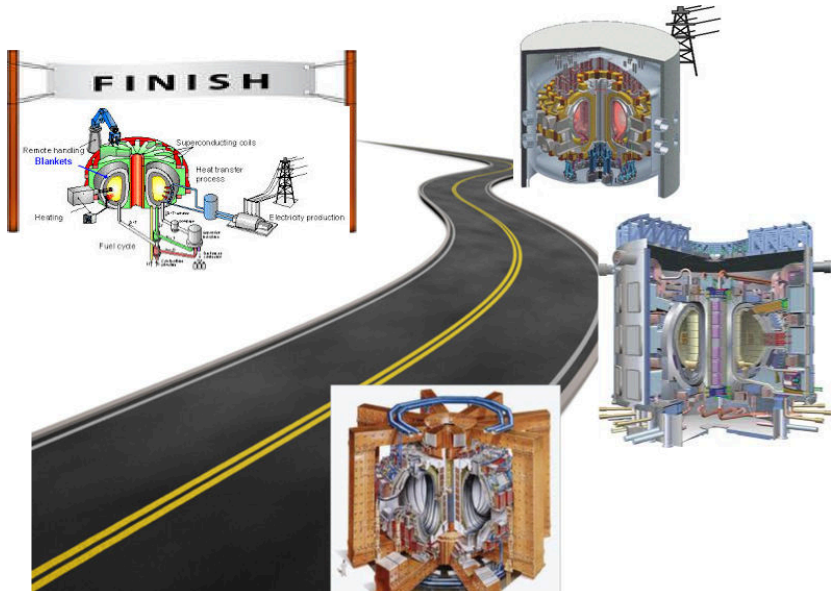
Vojtěch Svoboda
on behalf of the tokamak GOLEM team
for SAFE seminar Singapore 2024

October 16, 2024

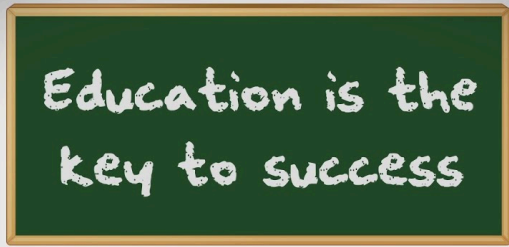
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- 2 The Tokamak (GOLEM)
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- 4 The Electron energy confinement time calculation (rough estimation)
- 5 Conclusion
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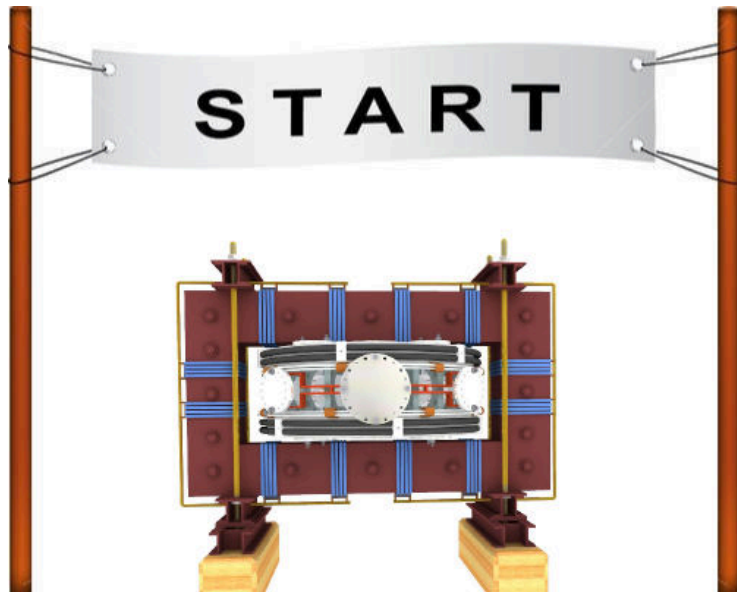
Milestones to Fusion Power Plant



Education importance

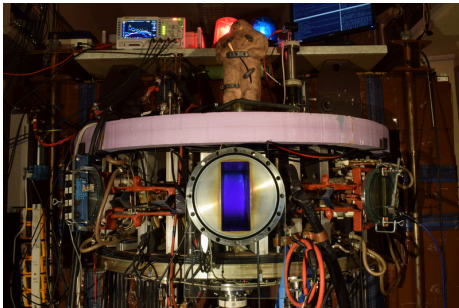


Let's start with the tokamak GOLEM - *the smallest tokamak in the World with the biggest controll room*



The GOLEM tokamak basic characteristics

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



- Vessel major radius: $R_0 = 0.4$ m
- Vessel minor radius: $r_0 = 0.1$ m
- Maximum plasma current:
 $I_p^{\max} < 8$ kA
- Maximum toroidal magnetic field: $B_t^{\max} < 0.5$ T
- Typical electron density:
 $\langle n_e \rangle \in (0.2, 3) \cdot 10^{19} \text{ m}^{-3}$
- Maximum electron temperature:
 $T_e^{\max} < 80$ eV
- Maximum discharge duration:
 $\tau_p^{\max} < 25$ ms

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 curve 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](#)]

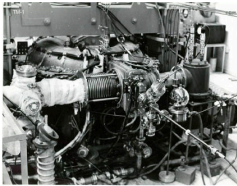
Currently in operation [[edit](#)]

(in chronological order of start of operations)

- 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: ADEX Upgrade, in Garching, Germany

The GOLEM tokamak for education - historical background

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



1974

Institute of Plasma Physics
Czech republic

CASTOR

COMPASS

2008

Czech Technical University Prague
Czech republic
GOLEM



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



2006



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...

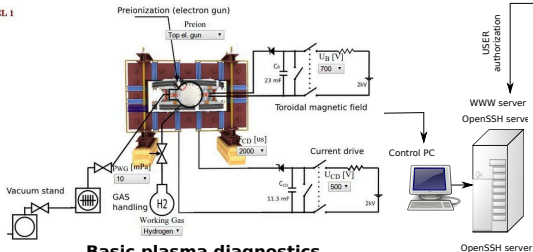


At the end of the 16th century, in the times when the Czech lands were ruled by Emperor Rudolf II, in Prague, there were Rabbi Judah Loew, well known alchemist, thinker, scholar, writer and inventor of the legendary GOLEM - a clay creature inspired with the Universe power that pursued his master's command 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. [1].

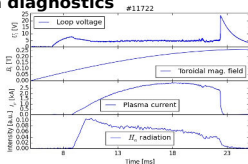
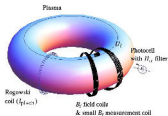
The global schematic overview of the GOLEM experiment

LEVEL 1

Tokamak technology setup



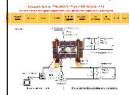
Basic plasma diagnostics



Virtual control room (remote participation)

WWW control interface

HTML & PHP scripts



SSH control interface

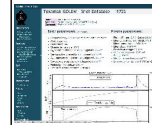
WINDOWS via putty



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

Data presentation

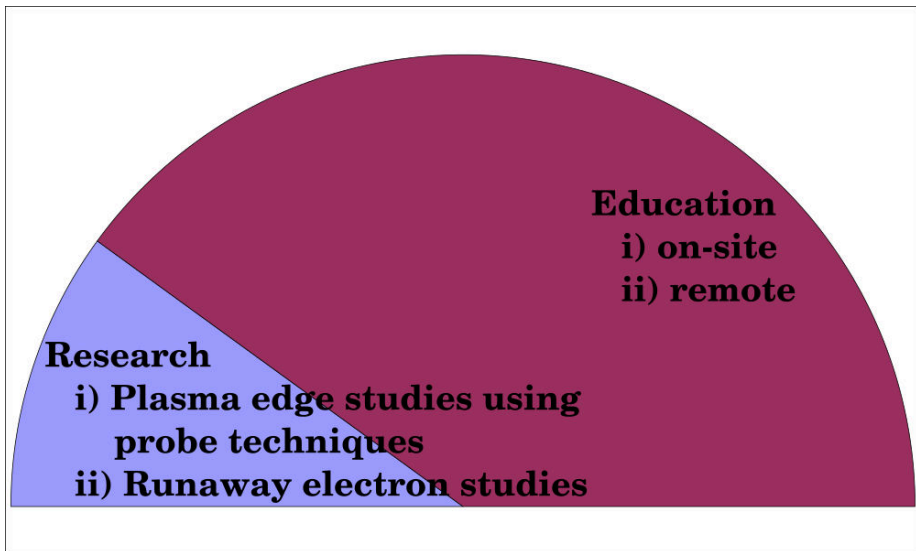
HTML (www pages)



Data handling

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

The GOLEM tokamak mission



Production

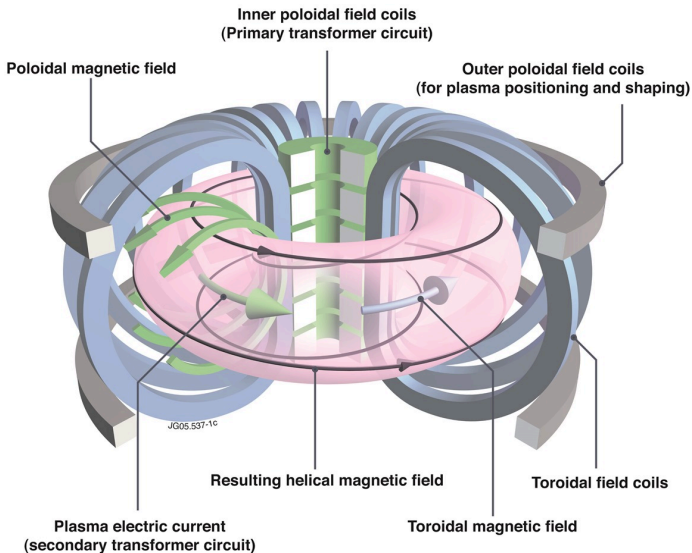
- Everything via <http://golem.fjfi.cvut.cz/SAFE>
 - This presentation
 - Control rooms
 - Contact: Vojtech Svoboda,
+420 737673903,
vojtech.svoboda@fjfi.cvut.cz
 - Videoconference:
<https://meet.google.com/hnv-qjhu-xvi>



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Tokamak magnetic confinement concept



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

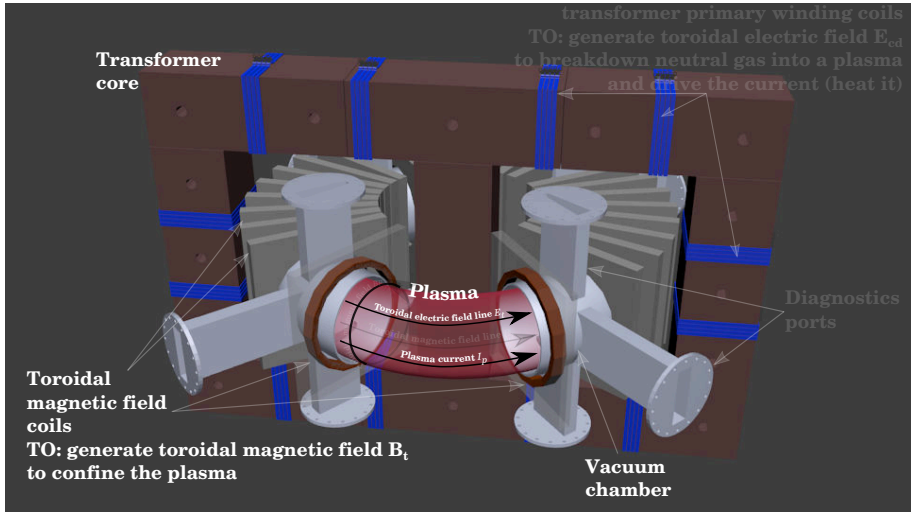


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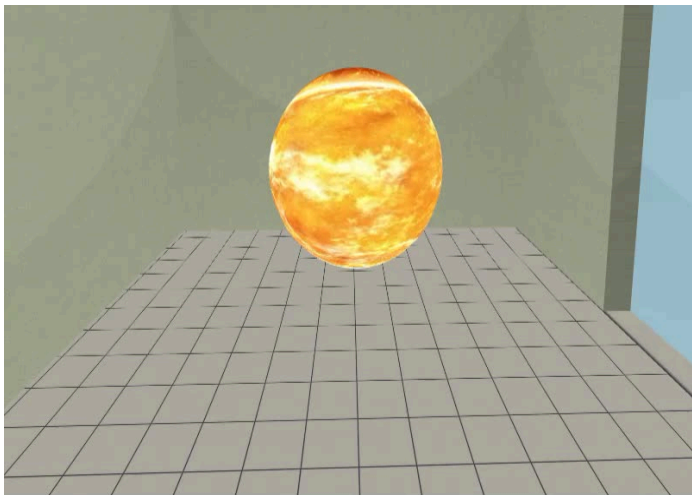
- The GOLEM tokamak concept
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- The scenario to make the (GOLEM) tokamak discharge
- The scenario to discharge virtually
- The GOLEM tokamak basic diagnostics

3 The Tokamak GOLEM (remote) operation

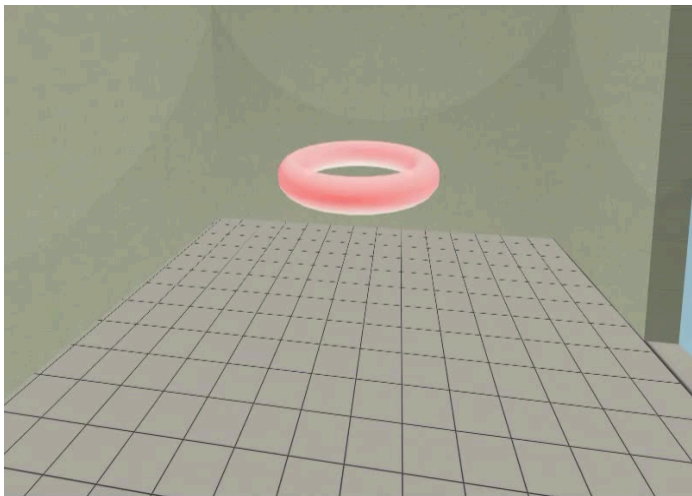
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5 Conclusion

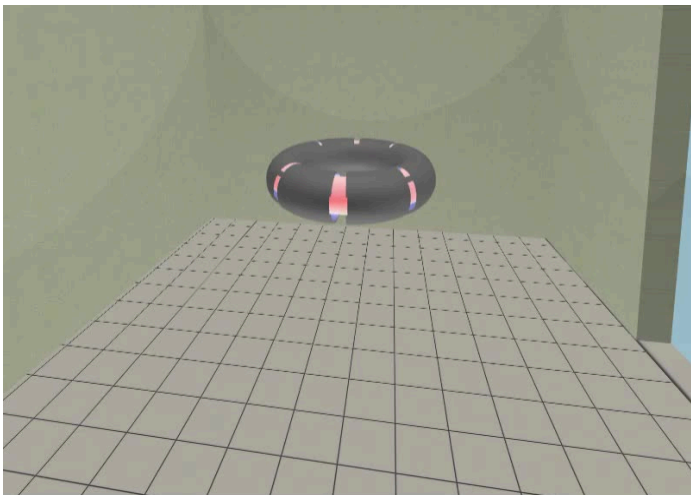
Our goal: the technology to create a μ Sun on the Earth



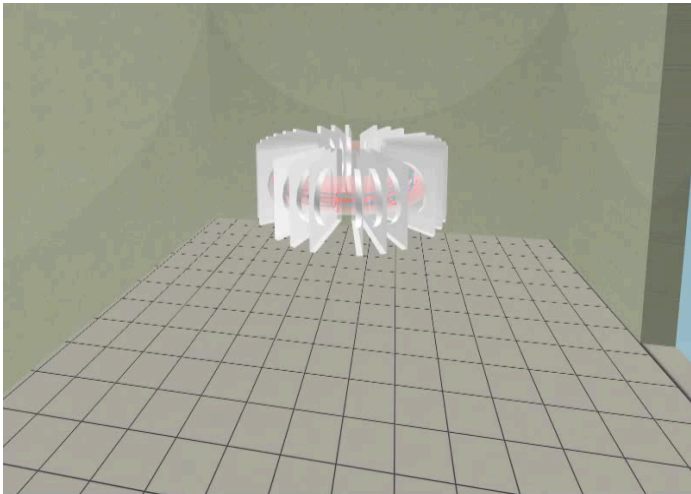
Magnetic confinement requires toroidal geometry



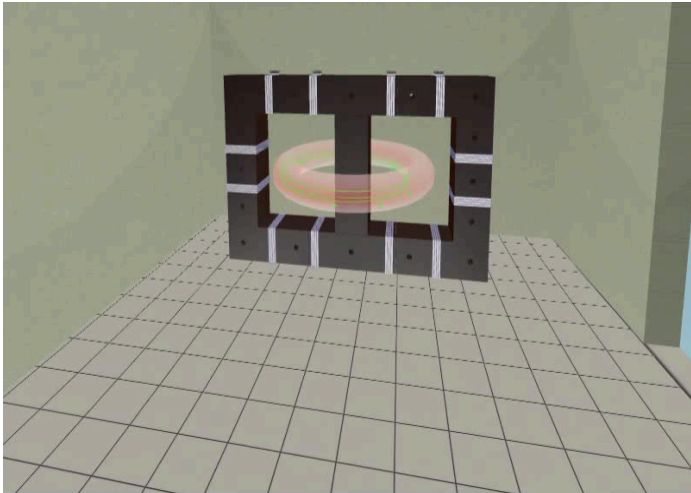
A chamber contains the thermonuclear reaction



Toroidal magnetic field coils confine the plasma



A transformer action creates and heats the plasma



The final technology altogether

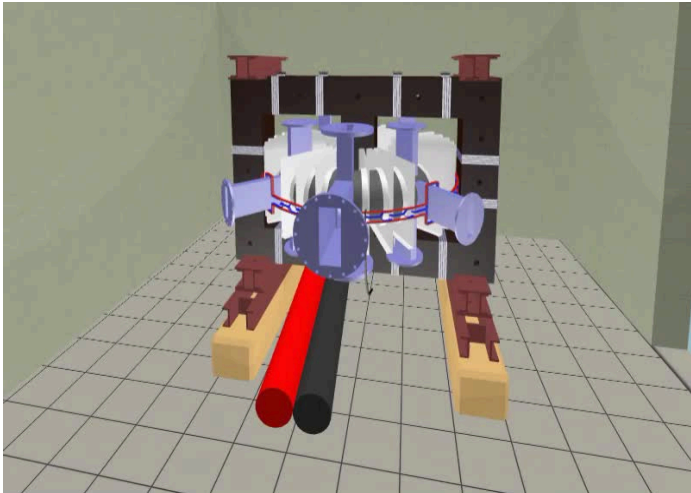


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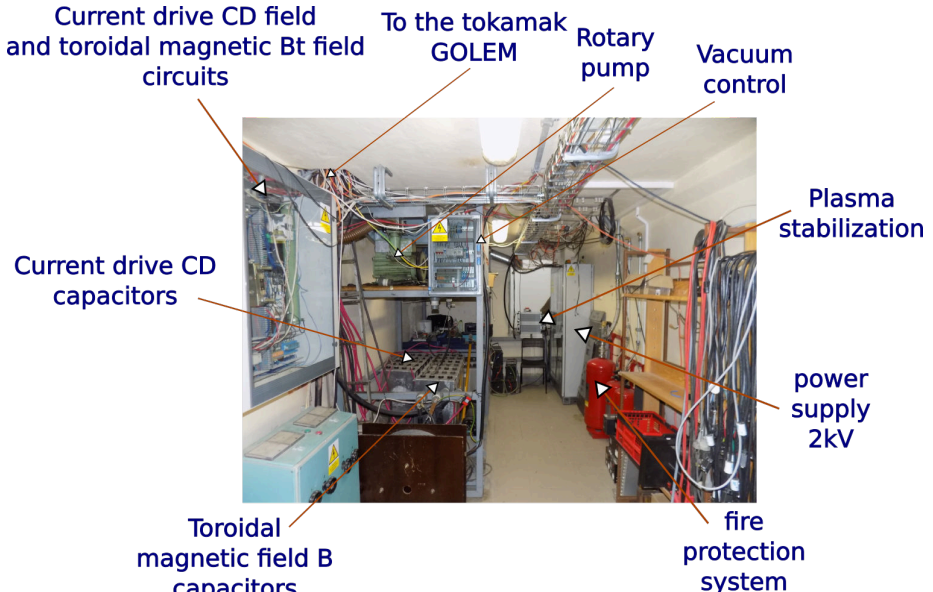
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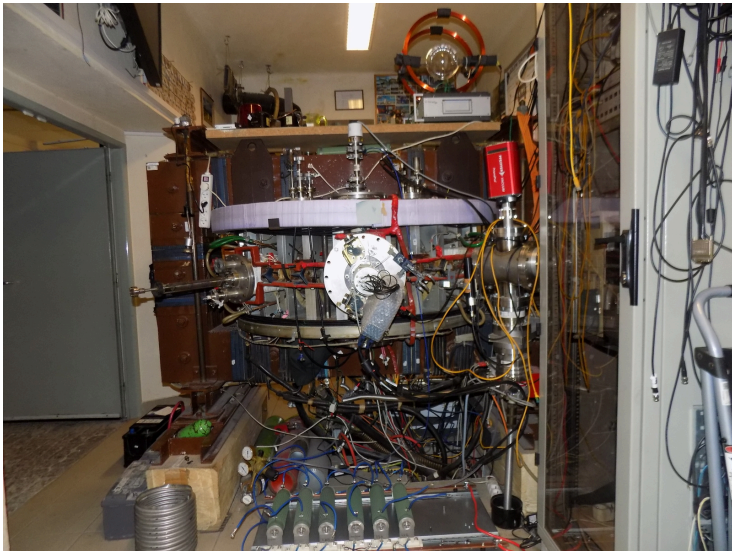
Infrastructure room (below tokamak) 10/16



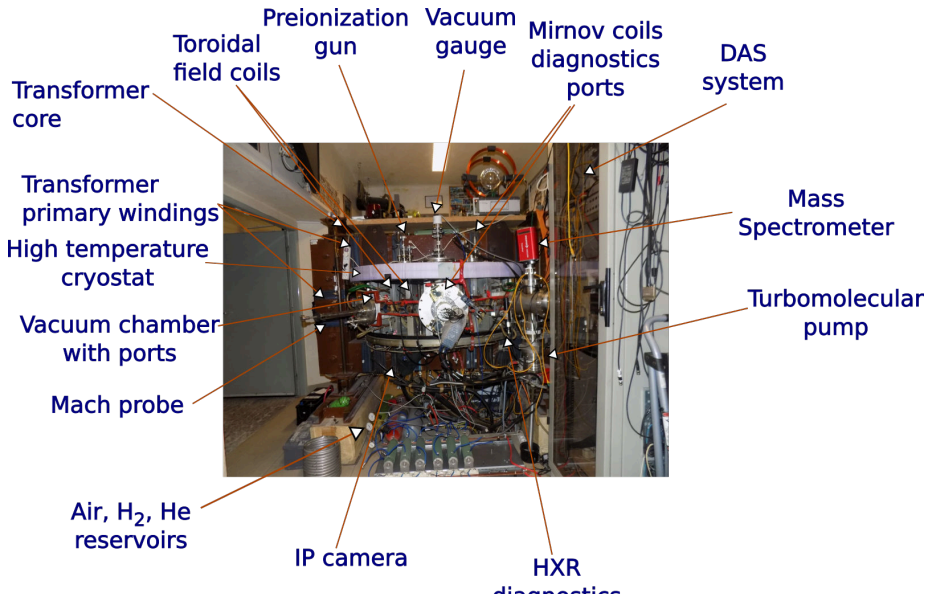
Infrastructure room (below tokamak) 10/16



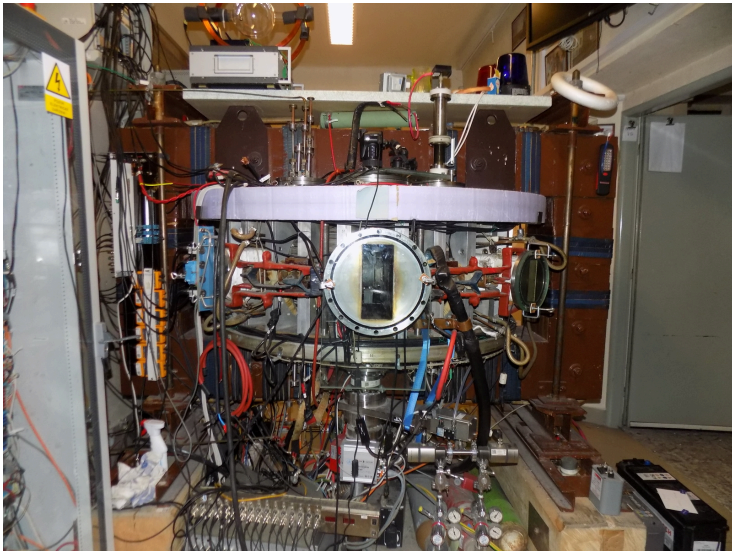
Tokamak room (North) 10/16



Tokamak room (North) 10/16



Tokamak room (South) 10/16



Tokamak room (South) 10/16

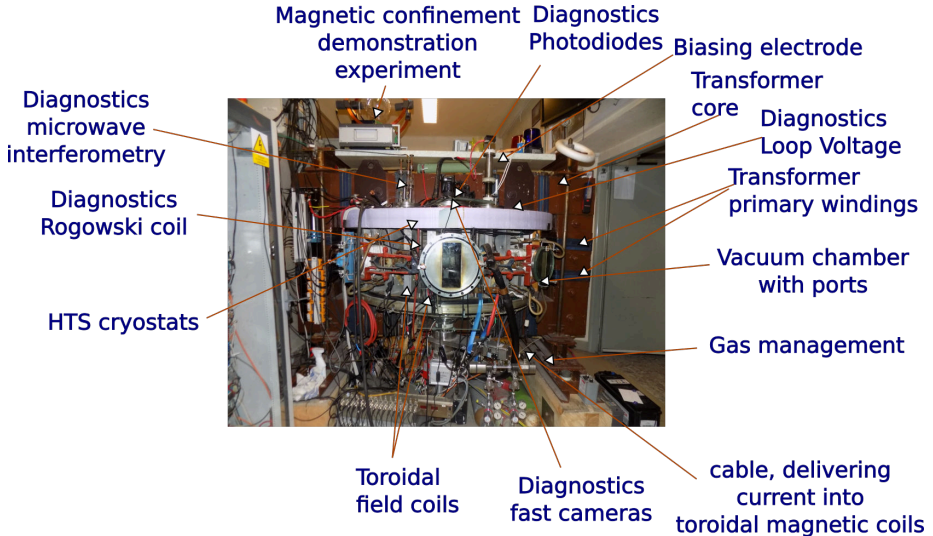


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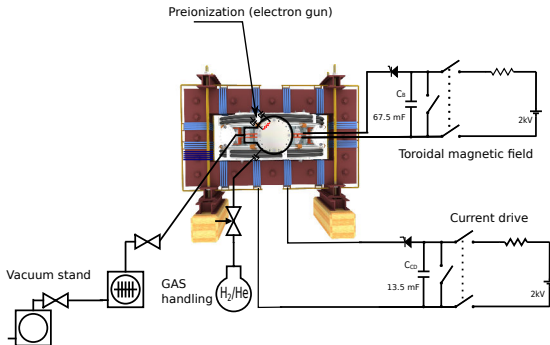
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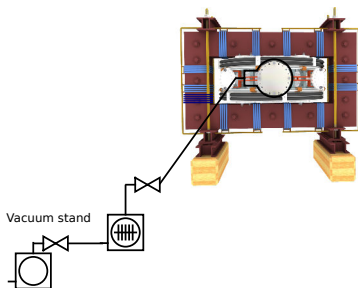
Plasma in Tokamak (GOLEM) - the least to do

To do:

- session start phase:
 - Evacuate the chamber
- pre-discharge phase
 - Charge the capacitors
 - Fill in the working gas
 - Preionization
- discharge phase
 - Toroidal magnetic field to confine plasma
 - Toroidal electric field to breakdown neutral gas into plasma
 - Toroidal electric field to heat the plasma
 - Plasma positioning
 - Diagnostics
- post-discharge phase



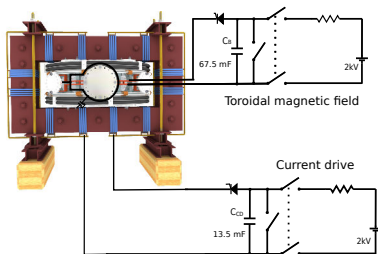
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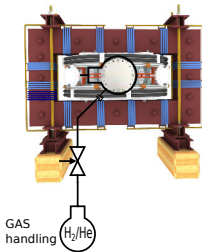
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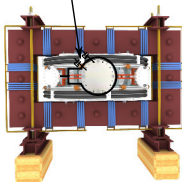


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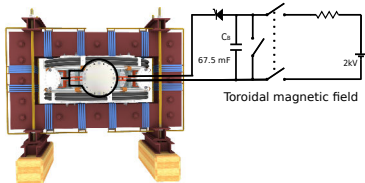
Preionization (electron gun)



To do:

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 - **Preionization**
- discharge phase
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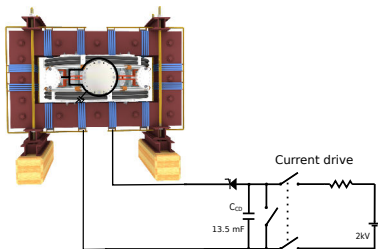
Plasma in Tokamak (GOLEM) - the least to do



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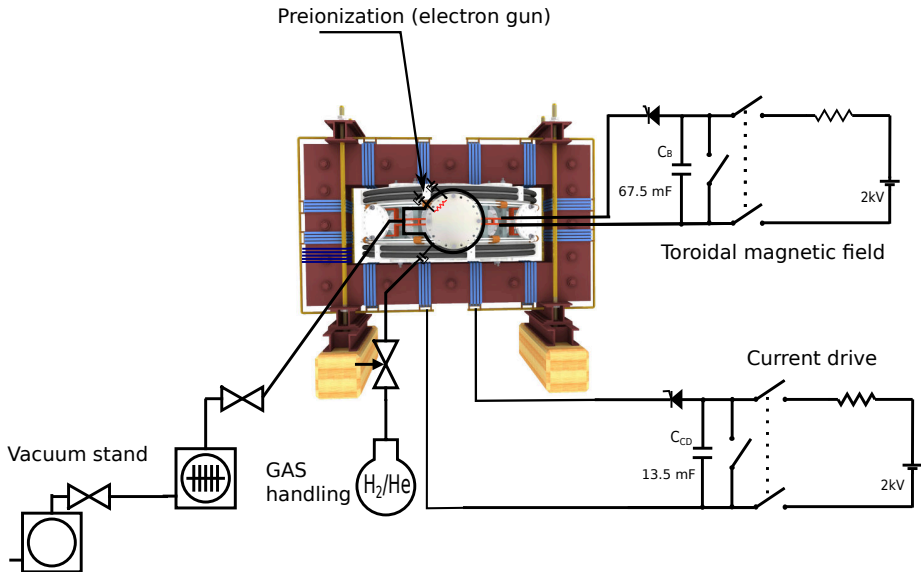
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Tokamak GOLEM - schematic experimental setup



Remote control interface of the GOLEM tokamak

GOLEM remote Introduction Control room Live Results top navigation bar User B Access: Level 2 Help

Introduction Working gas Preionization Magnetic field Electric field Submit rendering settings

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.

Preionization (electron gun)

Vacuum stand

Toroidal magnetic field

Toroidal electric field

GAS handling

Gas type and pressure $p_{WG} = 16 \text{ mPa}$

Hydrogen Helium

Next Set recommended value

3D model rendering method: Static image (fast) Interactive X3DOM (slower)

3D model rendering

engineering scheme

sliders and checkboxes

workflow buttons

The image shows a web-based remote control interface for the GOLEM tokamak. The interface has a dark blue header with navigation links: 'GOLEM remote', 'Introduction', 'Control room', 'Live', and 'Results'. A 'top navigation bar' is highlighted in red. Below the header, there's a 'Working gas' tab selected, with other tabs like 'Introduction', 'Preionization', 'Magnetic field', 'Electric field', and 'Submit'. The main content area displays instructions for setting the working gas pressure and type. It includes a schematic diagram of the tokamak system with labels for 'Preionization (electron gun)', 'Vacuum stand', 'Toroidal magnetic field', 'Toroidal electric field', and 'GAS handling'. A 3D model rendering of the system is shown on the right, with a '3D model rendering method' dropdown set to 'Static image (fast)'. Red arrows point to various UI elements: '3D model rendering' points to the 3D model, 'engineering scheme' points to the schematic diagram, 'sliders and checkboxes' points to the gas type and pressure controls, and 'workflow buttons' points to the 'Next' and 'Set recommended value' buttons. The 'Preionization (electron gun)' section is also visible.

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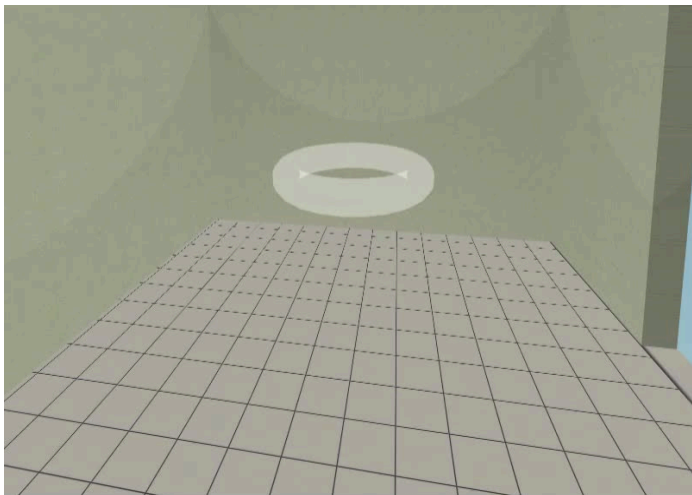
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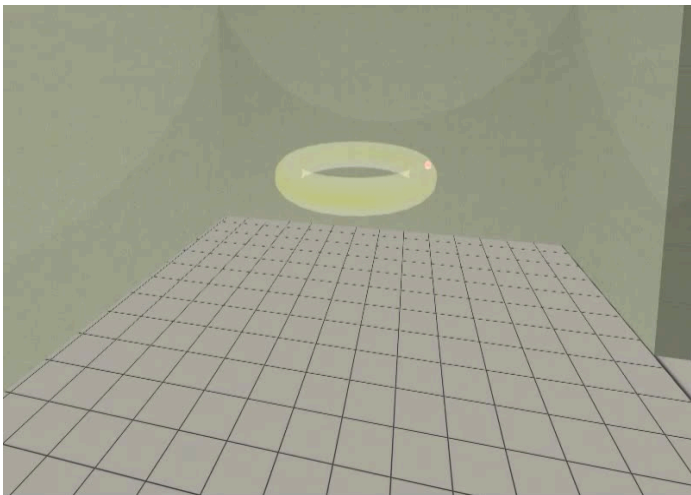
4 The Electron energy confinement time calculation (rough estimation)

5 Conclusion

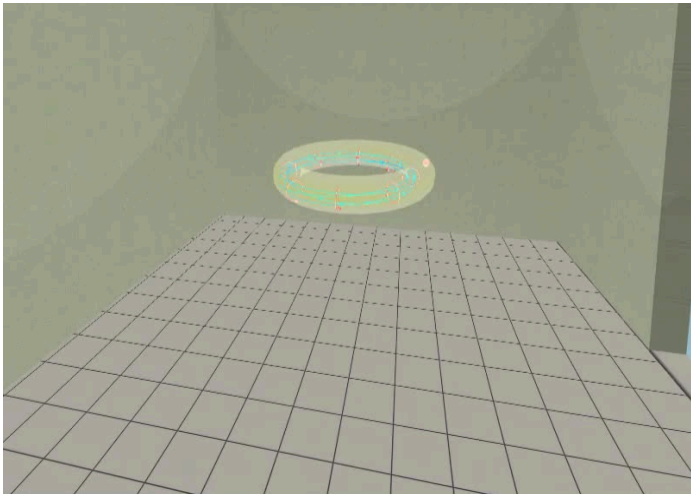
Introduce the working gas (Hydrogen x Helium)



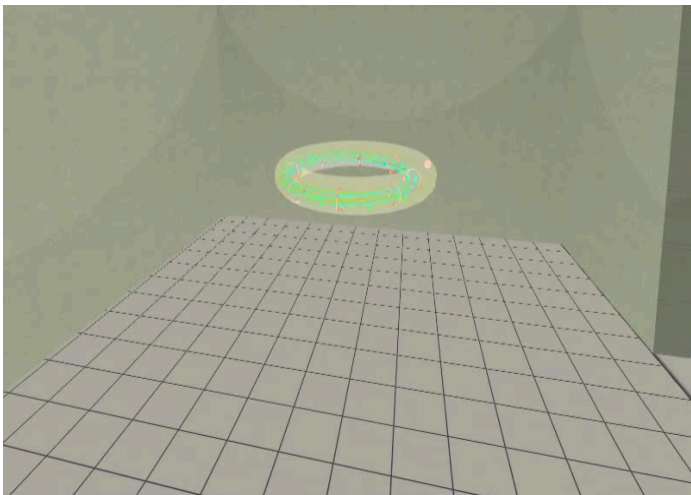
Switch on the preionization



Introduce the magnetic field



Introduce the electric field



Plasma ..

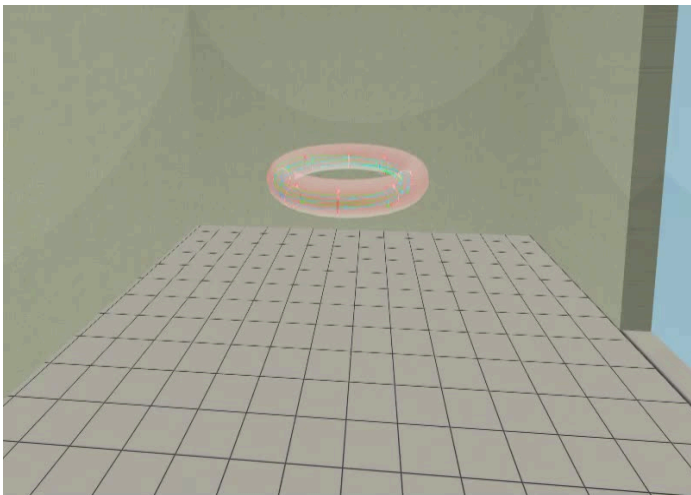


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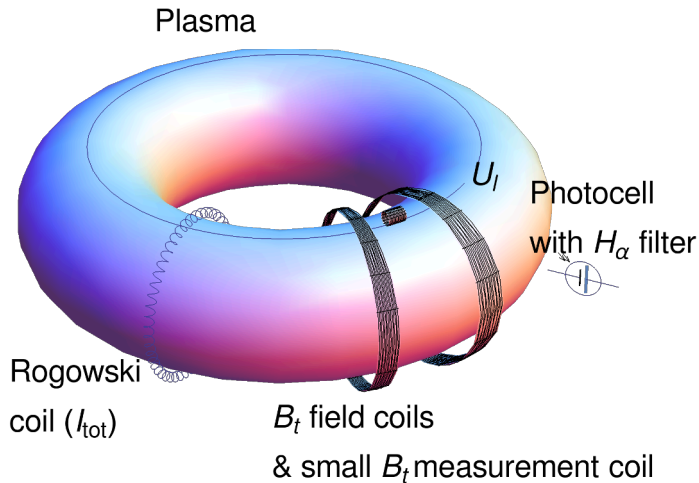
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The GOLEM tokamak - basic diagnostics



Hands on the GOLEM tokamak - equipment



Basic diagnostics - numerical processing, shot homepage

GOLEM - Shot #39187



Diagnostics

- BasicDiagnostics
- DoubleBaseProbe
- FastCameras
- HXRprobes
- Interferometry
- LimiterMimovCoils
- MHDring_TM
- Radiometer
- TimepixDetector
- TunnelProbe

Other

- Wiki
- Showroom

Navigation

- Next
- Previous
- Current

Tokamak GOLEM - Shot Database - #39187

The date of discharge execution

The session mission

The session ID

The discharge comment

22-05-18 17:55:04

GOLEM II -> EDU (MHD + biasing)

39183

Vert & Rad Stab
[copy] ; Driftent.sh --discharge --UBT 1200 --TBT 0 --Ucd 450 --Tcd 350 --preionization 1 --gas H --pressure 10 --diagnostics.limitermimovcoils "vacuum_shot=39109" --discharge.preionization "main_switch='on',powsup_heater=80,powsup_accel=100" --discharge.position_stabilization "main_switch='on',radial_switch='on',vertical_waveform='3000,0,9000,-20;18000,0,20000,0,30000,0',vertical_switch='on',radial_waveform='2000,0,3000,0,8000,-20;18000,0,19000,0,25000,0'" --ScanDefinition "39184 39185" --comment "Vert & Rad Stab"

Technological parameters

- Working Gas: $P_{discharge}^{before} = 1,66$ mPa; $P_{discharge}^{post} = 10,40$ mPa ($P_{WG}^{request} = 10$ mPa @ $\lambda_{WG}^{request} = H$)
- Toroidal magnetic field: $U_{B_t}^{request} = 1200$ V @ $I_{B_t}^{request} = 0,0$ us
- Current drive field: $U_{B_{cd}}^{request} = 450$ V @ $I_{B_{cd}}^{request} = 350,0$ us

Plasma:

- Plasma: yes or no: ☐
- Time parameters: $\Delta t_p = 15,08$ ms (from: $t_{start} = 2,49$ ms, to: $t_{end} = 17,57$ ms)

Plasma parameters:

- Loop voltage: $\overline{U}_{loop} = 8,02$ V; $max_{rc[discharge]} \overline{U}_{loop} = 9,89$ V; $U_{breakdown} = 10,83$ V
- Toroidal magnetic field: $\overline{B}_t = 0,40$ T; $max_{rc[discharge]} \overline{B}_t = 0,57$ T
- Plasma current: $I_p = 9,67$ kA; $max_{rc} I_p = 9,67$ kA; $R_{plasma} = 11,86$ m

GOLEM - Shot #39187



Diagnostics

- BasicDiagnostics
- DoubleBaseProbe
- FastCameras
- HXRprobes
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Other

- Wiki
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Navigation

- Next
- Previous
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On stage diagnostics

Data flow

measurement

digitization

analysis

Name

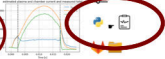
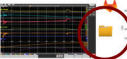
Experiment setup

Data acquisition system

Raw data

Analysis results

Basic Diagnostics



Basic diagnostics - numerical processing, raw data

GOLEM - Shot #39187 - <http://golem.fjfi.cvut.cz/shots/39187/Devices/Oscilloscopes/TektrMSO56-a/> autoreload: previous | next | current

Diagnostics

- BasicDiagnostics
- ShoukRateProbe
- FastCameras
- Stifences
- Interferometry
- LuminanceCells
- Measuring_TM
- Radometer
- TimepixDetector
- TunnelProbe

Other

- golem
- golemrcv

Navigation

- Next
- Previous
- Current

On stage diagnostics

Data flow: measurement → digitization → analysis →

Name Experiment setup Data acquisition system Raw data Analysis results

Basic Diagnostics

self probe not active part

Index of /shots/39187/Devices/Oscilloscopes/TektrMSO56-a

Name	Last modified	Size	Description
Parent Directory	-	-	-
BasicDiagnostics.sh	2022-05-18 17:58	3.2K	
ScreenshotAll.png	2022-05-18 17:58	184K	
TektrMSO56_ALL.csv	2022-05-18 17:58	3.9M	
Universals.sh	2022-05-18 17:58	1.2K	
das.jpg	2022-05-18 17:58	13K	
ls-all	2022-05-18 17:58	2.4K	
rawdata.jpg	2022-05-18 17:58	13K	

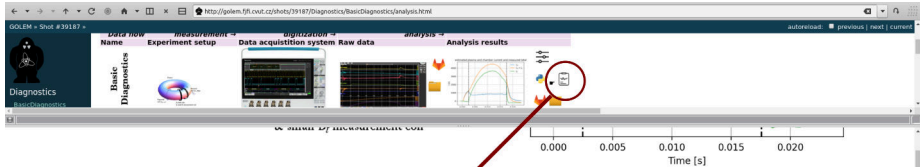
Apache/2.4.38 (Debian) Server at golem.fjfi.cvut.cz Port 80

Basic diagnostics - numerical processing, Jupyter-notebook@GitLab Download & play

The screenshot shows a web browser displaying a GitLab repository page for 'Tokamak GOLEM Basic diagnostics'. The top navigation bar includes tabs for 'Data flow', 'Measurement', 'Data acquisition system', 'Raw data', 'Analysis', and 'Analysis results'. The 'Analysis results' tab is active, showing a plot of 'Analysis results' with a red circle and a red arrow pointing to the notebook title. The notebook title is 'Tokamak GOLEM Basic diagnostics'. Below the title, there is a 'Procedure' section with a link '(This notebook to download)' and a 'Prerequisites: function definitions' section. The 'Load libraries' section contains the following code:

```
%matplotlib inline
import os
import numpy as np
import matplotlib.pyplot as plt
from scipy import constants, integrate, signal, interpolate
import sqlalchemy # high-level library for SQL in Python
import pandas as pd
import subprocess
```

Basic diagnostics - numerical processing, Jupyter-notebook applied on the Discharge



GOLEM - Shot #39187 +

http://golem.tyfl.cwt.cz/shots/39187/Diagnostics/BasicDiagnostics/analysis.html

autoreload previous next current

Diagnosics

BasicDiagnostics

Data flow Measurement Digitization Raw data Analysis Analysis results

Name Experiment setup Data acquisition system Raw data Analysis results

BasicDiagnostics

Time [s]

0.000 0.005 0.010 0.015 0.020

Procedure ([This notebook to download](#))

[bash wrapper](#), [Error log](#)

Prerequisites: function definitions

Load libraries

```
In [1]: %matplotlib inline
import os
import numpy as np
import matplotlib.pyplot as plt
from scipy import constants, integrate, signal, interpolate
import sqlalchemy # high-level library for SQL in Python
import pandas as pd
import subprocess
```

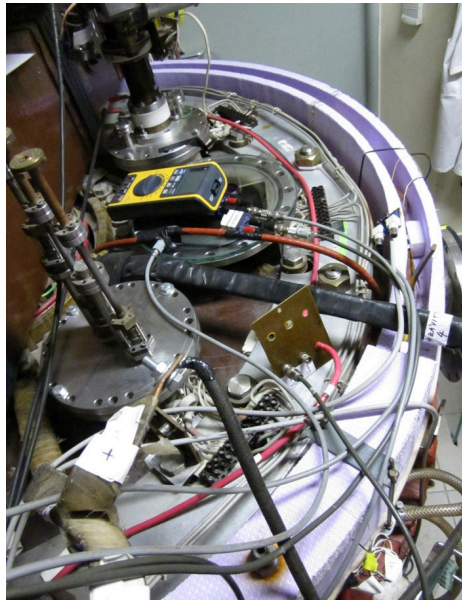
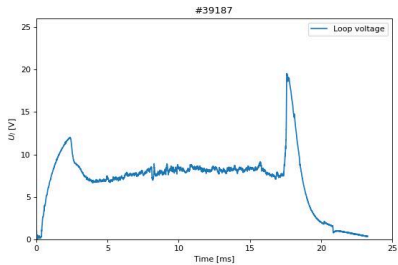
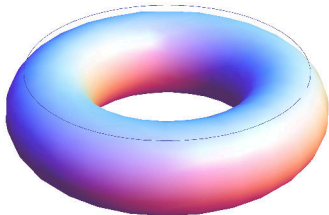
For interactive web figures

```
In [2]: import holoviews as hv
hv.extension('bokeh')
import hvplot.pandas
```

For conditional rich-text boxes

```
In [3]: from IPython.display import Markdown
```


Loop voltage U_l @ the GOLEM tokamak



Basic diagnostics - numerical processing, U_{loop}

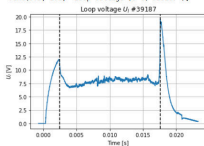
```
t_scale = 1e-3 if in_seconds else 1
if is_plasma:
    for t in (t_plasma_start, t_plasma_end):
        plt.axvline(t=t_scale, color='k', linestyle='--')
```

U_l management

Check the data availability

```
In [11]: loop_voltage = read_signal(shot_no, 'U Loop')
polarity_CD = read_parameter(shot_no, 'CD_orientation')
if polarity_CD != 'CW': # T000 hardcoded for now!
    loop_voltage *= -1 # make positive
loop_voltage = correct_inf(loop_voltage)
loop_voltage.loc[t_CD == 0]
ax = loop_voltage.plot(grid=True)
show_plasma_limits()
ax.set(xlabel='Time [s]', ylabel='SU l$ [V]', title='Loop voltage $U_l$ #{}'.format(shot_no));
```

```
Out[11]: [Text(0.5, 0, 'Time [s]'),
Text(0, 0.5, 'SU l$ [V]'),
Text(0.5, 1.0, 'Loop voltage $U_l$ #39187')]
```



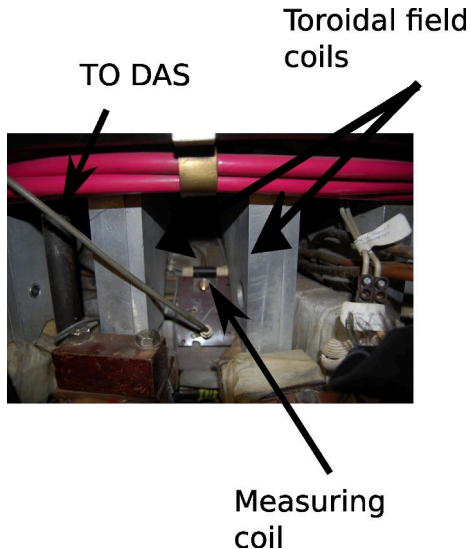
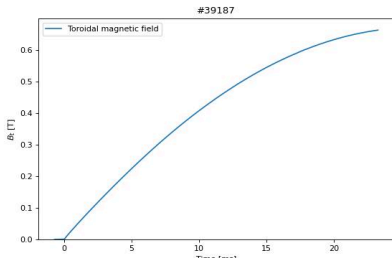
B_t calculation

Check the data availability

It is as magnetic measurement, so the raw data only give $\frac{dB_t}{dt}$

```
In [12]: dBt = read_signal(shot_no, 'U BtCoil')
polarity_Bt = read_parameter(shot_no, 'Bt_orientation')
if polarity_Bt != 'CW': # T000 hardcoded for now!
    dBt *= -1 # make positive
dBt = correct_inf(dBt)
dBt -= dBt.loc[offset_s1].mean()
ax = dBt.plot(grid=True)
show_plasma_limits()
ax.set(xlabel='Time [s]', ylabel='dBt [V]', title='BtCoil_raw signal #{}'.format(shot_no));
```

Toroidal magnetic field B_t @ the tokamak GOLEM



Basic diagnostics - numerical processing, B_t

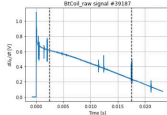
B_t calculation

Check the data availability

It is as magnetic measurement, so the raw data only give $\frac{dB_t}{dt}$

```
In [12]: dBt = read_signal(shot_no, 'BtCoil')
polarity_Bt = read_parameter(shot_no, 'Bt_orientation')
if polarity_Bt != 'CW':
    dBt *= -1 # make positive # 1000 hardcoded for now!
dBt = correct_inf(dBt)
dBt = dBt.loc[offset_sl].mean()
ax = dBt.plot(grid=True)
show_plasma_limits()
ax.set(xlabel='Time [s]', ylabel='dBt (B t)/dt [V]', title='BtCoil_raw signal #{}'.format(shot_no));
```

```
Out[12]: [Text(0.5, 0, 'Time [s]'),
Text(0, 0.5, 'dBt (B t)/dt [V]'),
Text(0.5, 1.8, 'BtCoil_raw signal #39187')]
```

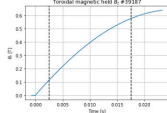


Integration (it is a magnetic diagnostic) & calibration

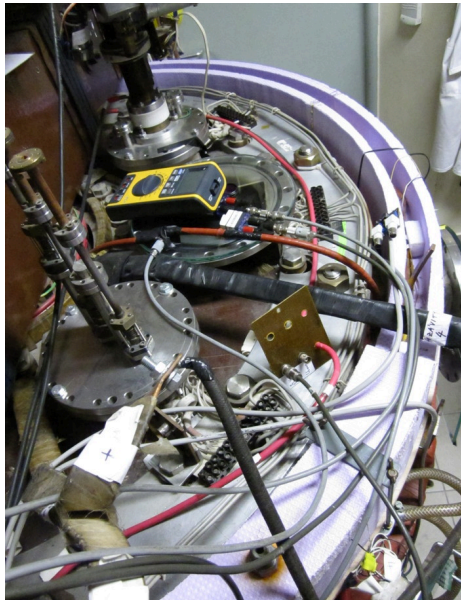
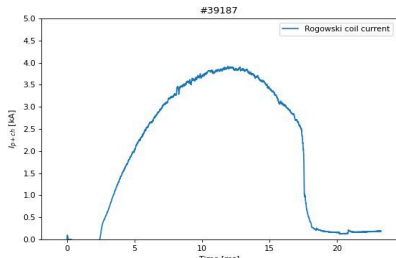
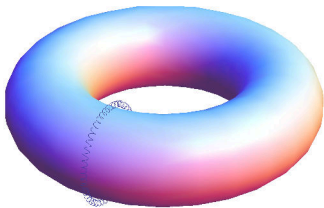
```
In [13]: K_BtCoil = float(read_parameter(shot_no, 'SystemParameters/K_BtCoil')) # Get BtCoil calibration factor
print('BtCoil calibration factor K_BtCoil= {} T/(Vs)'.format(K_BtCoil))
BtCoil calibration factor K_BtCoil=70.42 T/(Vs)
```

```
In [14]: Bt = pd.Series(integrate.cumtrapz(dBt, dBt.index, initial=0) * K_BtCoil,
index=dBt.index, name='Bt')
ax = Bt.plot(grid=True)
show_plasma_limits()
ax.set(xlabel='Time [s]', ylabel='Bt [T]', title='Toroidal magnetic field Bt ts #{}'.format(shot_no));
```

```
Out[14]: [Text(0.5, 0, 'Time [s]'),
Text(0, 0.5, 'Bt [T]'),
Text(0.5, 1.8, 'Toroidal magnetic field Bt ts #39187')]
```



Total current I_{ch+p}



Basic diagnostics - numerical processing, U_{ch+p}

http://ipdem.fjfi.cvut.cz/shots/39187/Diagnostics/BasicDiagnostics/analysis.html

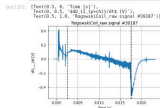
Chamber (+ Plasma) current I_{p+ch} calculation

The Rogowski coil around the chamber measures the total current contained within its boundaries. Therefore, if there is plasma, it measures the sum of the plasma and chamber currents, so a narrow discharge it measures only the chamber current.

Check the data availability

Because it is a magnetic measurement, the raw data only gives $\frac{dI_{p+ch}}{dt}$

```
In [131]: dIpch = read_signal(shot_no, 'U_RogCoil') # 3000 hardcoded for now!
if polarity_03 == 'SR':
    dIpch *= -1 # new positive
dIpch = correct_int(dIpch)
dIpch = dIpch - dIpch[0] # subtract offset
dIpch[0] = 0
ax = dIpch.plot(grid=True)
show_figure(figsize=(10, 10))
ax.set_xlabel('Time [s]', ylabel='dIpch [A/s]', title='RogowskiCoil raw signal #39187')
```

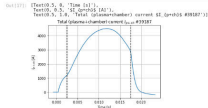


Integration (it is a magnetic diagnostic) & calibration

```
In [136]: R_RogowskiCoil = float(read_parameter(shot_no, 'SystemParameters/R_RogowskiCoil')) # der RogowskiCoil calibration factor
print('RogowskiCoil calibration factor: R_RogowskiCoil [A/Vs]', format(R_RogowskiCoil))

RogowskiCoil_calibration_factor = R_RogowskiCoil*338898.8 A/Vs

In [137]: Spch = pd.Series(integrate.contourgridspch, x=Spch.index, initial=0) * R_RogowskiCoil,
integrated_chamber_index_name='Spch'
ax = Spch.plot(grid=True)
show_figure(figsize=(10, 10))
ax.set_xlabel('Time [s]', ylabel='Spch [A]', title='Total (plasma+chamber) current dIpch [A/s] #39187')
```



Chamber current I_{ch} calculation

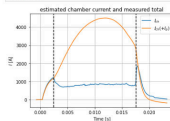
```
In [138]: R_chamber = float(read_parameter(shot_no, 'SystemParameters/R_chamber')) # der Chamber resistivity
print('Chamber resistivity R_chamber [Ohm]', format(R_chamber))

Chamber resistivity R_chamber=0.0071 Ohm

In [139]: L_chamber = float(read_parameter(shot_no, 'SystemParameters/L_chamber')) # der Chamber inductance
print('Chamber inductance L_chamber [H]', format(L_chamber))

Chamber inductance L_chamber=1e-06 H
```

```
In [121]: var = ax[1].twinx()
ax = I.plot()
ax.legend()
show_figure(figsize=(10, 10))
ax.set_xlabel('Time [s]', ylabel='Spch [A]', title='estimated chamber current and measured total')
plt.grid()
```



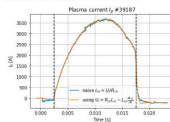
Plasma current I_p calculation

If there is plasma, the plasma current can be estimated as the difference between the total measured current and the estimated chamber current $I_p = I_{p+ch} - I_{ch}$

```
In [121]: if is_plasma:
    Ip_naive = Ipch - loop_voltage/R_chamber # creates a new Series
    Ip = Ipch - I_ch
    Ip.name = 'Ip'
    Ip_naive.plot(grid=True, label='naive $I_{ch}$', title='Plasma current $I_p$')
    ax = Ip.plot(grid=True, label='using $I_{ch} = R_{ch} \cdot I_{ch}$', title='Plasma current $I_p$')
    show_figure(figsize=(10, 10))
    ax.set_xlabel('Time [s]', ylabel='Spch [A]', title='Plasma current $I_p$')
else:
    Ip = Ipch * 0 # no current
    heading
```

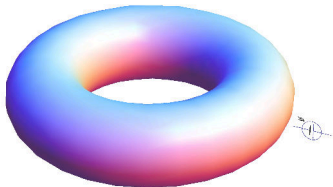
Out[121]: Plasma detected

plasma lifetime of 15.1 ms, from 2.5 ms to 17.6 ms

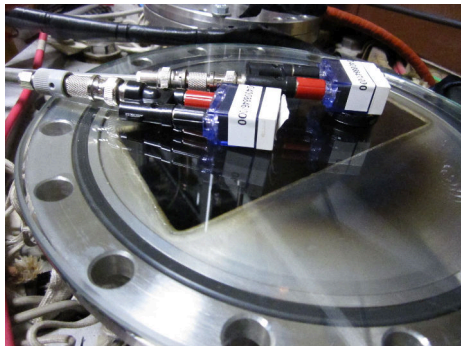
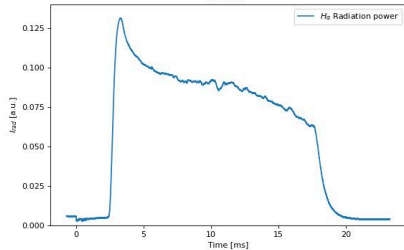


```
In [131]: fig = plt.figure(dpi=200)
for i in I.ch.rename('$I_{ch}$'), Ipch.rename('$I_{ch}+I_{p}$'), Ip.rename('$I_p$'):
    ax = I.plot()
```

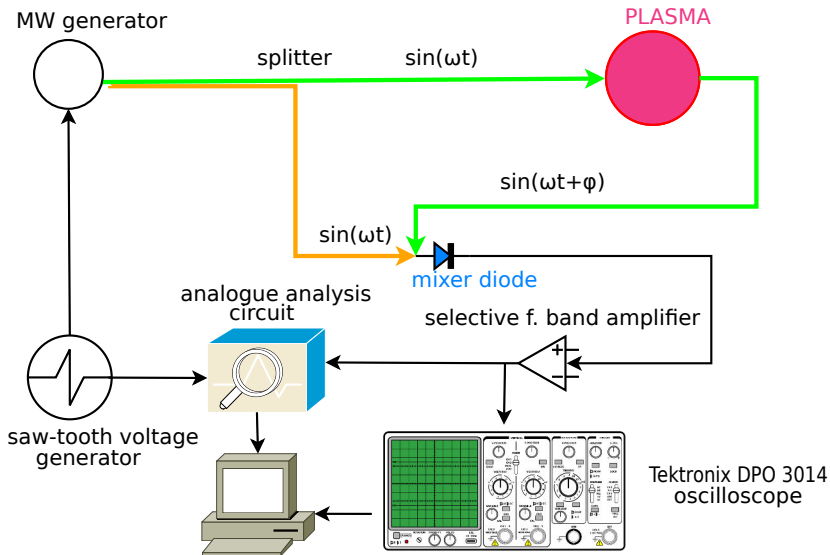
Visible radiation



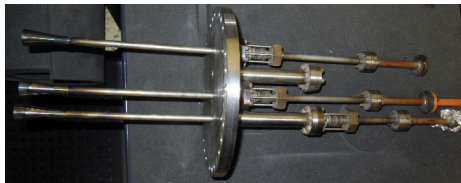
#39187



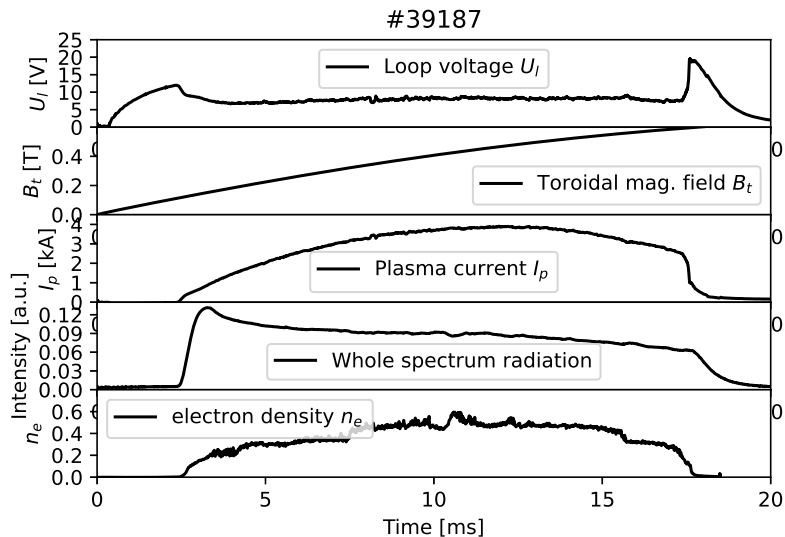
Electron density n_e interferometry measurement scheme



The GOLEM tokamak interferometry HW



Finally "Typical", well executed discharge @ GOLEM



Shot homepage (≈ 2 minutes after discharge execution)

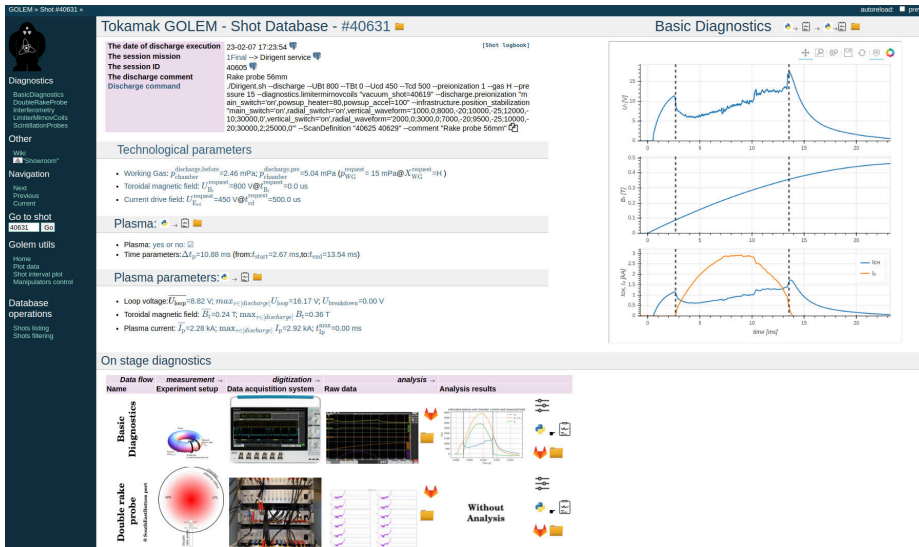


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- 3 The Tokamak GOLEM (remote) operation
- 4 The Electron energy confinement time calculation (rough estimation)
- 5 Conclusion
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 - Control room
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Remote control interface of the GOLEM tokamak

GOLEM remote Introduction **Control room** Live Results top navigation bar

User B Access: Level 2 Help

rendering settings

3D model rendering method: Static image (fast) Interactive X3DOM (slower)

Introduction **Working gas** Preionization Magnetic field Electric field Submit

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.

Preionization (electron gun)

Vacuum stand

Toroidal magnetic field

Toroidal electric field

GAS handling

Gas type and pressure $p_{WG} = 16 \text{ mPa}$

Hydrogen Helium

Next Set recommended value

3D model rendering

engineering scheme

sliders and checkboxes

workflow buttons

The screenshot displays the 'GOLEM remote' interface, specifically the 'Control room' tab. The top navigation bar includes 'GOLEM remote', 'Introduction', 'Control room' (active), 'Live', and 'Results'. A 'top navigation bar' label points to this area. Below the navigation bar, the 'rendering settings' section shows the '3D model rendering method' set to 'Static image (fast)'. The '3D model rendering' label points to the 3D model view on the right, which shows a tokamak structure with a red arrow pointing to it. The 'engineering scheme' label points to the diagram on the left, which shows the 'Preionization (electron gun)' and 'GAS handling' components. The 'sliders and checkboxes' label points to the 'Gas type and pressure' section, which includes a slider for pressure and checkboxes for 'Hydrogen' and 'Helium'. The 'workflow buttons' label points to the 'Next' and 'Set recommended value' buttons at the bottom of the interface.

Control room: Introduction

GOLEM remote

Introduction

Control room

Live

Results

Prague

Access: Level 1

Help

Introduction

Working gas

Preionization

Magnetic field

Current drive

Submit

This web interface will walk you through the process of configuring a discharge in the GOLEM tokamak. All settable values are perfectly safe. Proceed through each step by setting the desired values and then clicking the [Next](#) button. You can always go to a specific step by clicking its tab.

Preionization (electron gun)

Vacuum stand

Preionization (electron gun)

Toroidal magnetic field

Current drive

GAS handling

H_2/He

C_{23} 23 mF

$C_{11.3}$ 11.3 mF

2kV

2kV

[Next](#)

3D model rendering method:

Static image (fast)

Interactive X3DOM (slower)

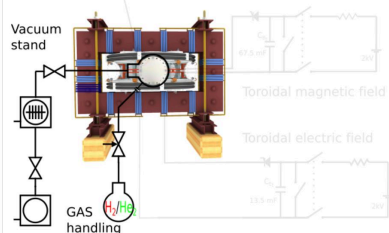
Control room: Working gas

GOLEM remote Introduction Control room Live Results

Navigation: Introduction Working gas Preionization Magnetic field Electric field Submit

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.

Preionization (electron gun)



Vacuum stand

GAS handling

Toroidal magnetic field

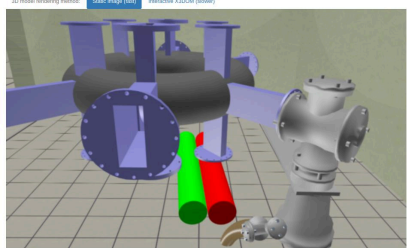
Toroidal electric field

Gas type and pressure $p_{\text{gas}} = 18 \text{ mPa}$

Hydrogen Helium

Next Set recommended value

3D model rendering method: Static image (file) Interactive X3DOM (browser)



Control room: Preionization

GOLEM remote Introduction Control room Live Results

Master Access: Level 2 Help

Introduction Working gas Preionization Magnetic field Electric field Submit

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 (electron gun)

Vacuum stand

GAS handling

Toroidal magnetic field

Toroidal electric field

Ionization method

☒ Electron gun ☐ No ionization

Next

3D model rendering method: [Static image \(best\)](#) [Interactive X3DOM \(slower\)](#)

Control room: Magnetic field B_t

GOLEM remote Introduction Control room Live Results

Press F11 to exit full screen 3D model rendering method Static image (best) Interactive X3DOM (slower)

Introduction Working gas Preionization **Magnetic field** Electric field Submit

Set the voltage on the capacitors to be discharged into the toroidal field coils. The higher the voltage, the larger the magnetic field confining the plasma.

Preionization (electron gun)

Vacuum stand

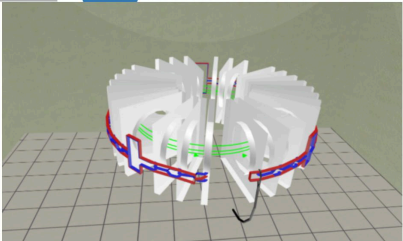
Toroidal magnetic field

Toroidal electric field

GAS handling

Capacitor voltage $U_{C_2} = 600 \text{ V}$

Next Set recommended value



The diagram illustrates the experimental setup for the GOLEM remote control room. It features a central vacuum stand containing a preionization (electron gun) and a toroidal magnetic field. The setup is connected to a gas handling system and a capacitor bank. The capacitor bank is shown with two capacitors, C_1 (67.5 mF) and C_2 (13.5 mF), and a 2kV voltage source. The toroidal magnetic field is represented by a series of coils, and the toroidal electric field is shown as a series of segments. A 3D visualization of the toroidal magnetic field structure is provided on the right, showing the complex arrangement of coils and the resulting field lines. The interface includes a navigation bar with tabs for Introduction, Working gas, Preionization, Magnetic field, Electric field, and Submit. A status bar at the top shows the current level (Level 2) and a help icon. A capacitor voltage slider is set to 600 V, with a 'Next' button and a 'Set recommended value' button.

Control room: Current drive E_{cd}

GOLEM remote

Introduction

Control room

Live

Results

View Tutorials

Politecnico, Italy Group 1

Access: Level 2

Help

Introduction

Working gas

Preionization

Magnetic field

Electric field

Submit

Set the voltage on the capacitors 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.

Preionization (electron gun)

Vacuum stand

67.5 mF

2kV

Toroidal magnetic field

Toroidal electric field

13.5 mF

2kV

GAS handling

Time delay of electric field start after the magnetic field starts t_{cd} : 0 micro seconds

Capacitor voltage U_{cd} : 400 V

Next Set recommended value

3D model rendering method

Static image (best)

Interactive X3DOM (slower)

Control room: ... and Submit

GOLEM remote

Introduction

Control room

Live

Results

Yin Yunus Politecnico, Ray Group 1

Access: Level 2

Help

Introduction

Working gas

Precorization

Magnetic field

Electric field

Submit

Write a comment describing your discharge configuration, i.e. the scientific aim of your experiment. Or just leave a friendly message.

Comment

Click the Submit button to send your configuration into the queue: [Submit](#)

After submission you can watch the discharge Live or go back to the Introduction tab and start again. Or you can go to specific control tabs and reconfigure the discharge and then submit another discharge request.

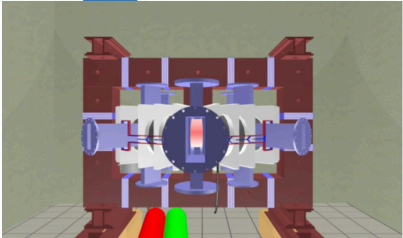
[Watch the discharge Live!](#)

[Go back to Introduction](#)

3D model rendering method

Static image (best)

Interactive X3DOM (slower)

A 3D model of a complex industrial or scientific apparatus, likely a discharge chamber. It features a central cylindrical component with a glowing red interior, surrounded by various pipes, valves, and structural supports. The model is rendered in a 3D perspective view, showing its intricate design and components.

Shot homepage (≈ 2 minutes after discharge execution)

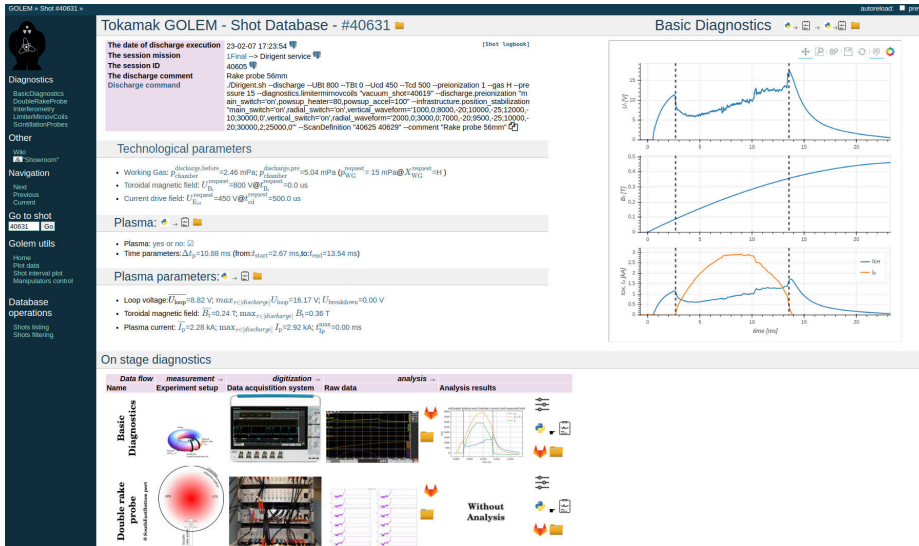


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GOLEM **basic** Data Acquisition System (DAS)

- $U_I, U_{B_t}, U_{I_{p+ch}}, I_{rad}$
- $\Delta t = 1\mu s / f = 1MHz$.
- Integration time = 40 ms, thus DAS produces 6 columns x 40000 rows data file.
- Discharge is triggered at 5th milisecond after DAS to have a zero status identification.



Data file example, DAS $\Delta t = 1\mu s / f = 1MHz$ (neutral gas into plasma breakdown focused)

t	$\approx U_I$	$\approx U_{\frac{dB_T}{dt}}$	$\approx U_{\frac{d(I_{p+ch})}{dt}}$	$\approx I_{rad}$
:	:	:	:	:
:	:	:	:	:
first	$\approx$	7405	lines ..	
:	:	:	:	:
:	:	:	:	:
0.007383	1.53931	0.390015	0.048828	0.001831
0.007384	1.53686	0.395508	0.067749	0.00061
0.007385	1.54053	0.391235	0.079956	0.00061
0.007386	1.53686	0.38147	0.072632	0
0.007387	1.54297	0.397949	0.059204	0.00061
0.007388	1.54053	0.384521	0.05249	0.00061
0.007389	1.54053	0.39856	0.068359	0.001221
0.00739	1.54053	0.393677	0.082397	0.001221
0.007391	1.53809	0.38208	0.072632	0.001221
0.007392	1.54297	0.400391	0.056763	0.00061
0.007393	1.54419	0.383911	0.053101	0.00061
0.007394	1.53931	0.397339	0.068359	0.001221
0.007395	1.54297	0.391846	0.084229	0.00061
0.007396	1.54541	0.394897	0.074463	0.00061
0.007397	1.54297	0.388184	0.056763	0.001221
0.007398	1.54297	0.391846	0.056763	0.00061
0.007399	1.54297	0.394287	0.06897	0.00061
:	:	:	:	:
:	:	:	:	:
next	$\approx$	32500	lines ..	
:	:	:	:	:
:	:	:	:	:

Data access

All the recorded data and the settings for each discharge (shot) are available at the GOLEM website. The root directory for the files is:

`http://golem.fjfi.cvut.cz/shots/<#ShotNo>/`

The most recent discharge has the web page:

`http://golem.fjfi.cvut.cz/shots/0`

Particular data from DAS specified with <DASname> and <DASchannelidentifier> have the format:

`http:
//golem.fjfi.cvut.cz/<#ShotNo>/<DASname>/<DASchannelidentifier>`

Jupyter (python)

```
import numpy as np
import matplotlib.pyplot as plt

shot_no = 39187
identifier = "U_loop.csv"
DAS='Diagnostics/BasicDiagnostics/Results/'
# create data cache in the 'golem_cache' folder
ds = np.DataSource('golem_cache')
#Create a path to data and download and open the file
base_url = "http://golem.fjfi.cvut.cz/shots/"
data_file = ds.open(base_url + str(shot_no)+ '/' +DAS +identifier)
#Load data from the file and plot to screen and to disk
data = np.loadtxt(data_file,delimiter=",")
plt.title('#'+str(shot_no))
plt.plot(data[:,0]*1000, data[:,1]) #1. column vs 2. column
plt.xlabel('Time [ms]');plt.ylabel('$U_1$ [V]');
plt.savefig('graph.jpg')
plt.show()

#Run it: save it as script.py and run "python script.py" or execute in a
```

Matlab

```
ShotNo=39187
baseUrl='http://golem.fjfi.cvut.cz/shots/';
diagnPATH='/Diagnostics/BasicDiagnostics/Results/U_loop.csv';
%Create a path to data
dataURL=strcat(baseUrl,int2str(ShotNo),diagnPATH);
% Write data from GOLEM server to a local file
urlwrite(dataURL,'LoopVoltage');
% Load data
data = load('LoopVoltage', '\t');
% Plot and save the graph
f = figure('visible', 'off');
hold on
plot(data(:,1)*1000, data(:,2), '.');
xlabel('Time [ms]')
ylabel('U_1 [V]')
hold off
print -djpeg plot.jpg
close(f)
exit;
```

Octave

```
ShotNo=39187
baseURL='http://golem.fjfi.cvut.cz/shots/';
diagnPATH='/Diagnostics/BasicDiagnostics/Results/U_loop.csv';
%Create a path to data
dataURL=strcat(baseURL,int2str(ShotNo),diagnPATH);
% Write data from GOLEM server to a local file
urlwrite(dataURL,'U_Loop.csv');
% Load data
data = load('U_Loop.csv', '\t');
% Plot and save the graph
plot(data(:,1)*1000, data(:,2), '.');
xlabel('time [ms]')
ylabel('U_{loop} [V]')
saveas(gcf, 'plot', 'jpg');
exit;
```

Gnuplot

```
identifier = 'U_loop.csv' ;  
ShotNo = '39187'  
# Create a path to the data  
DAS='Diagnostics/BasicDiagnostics/Results/'  
baseURL='http://golem.fjfi.cvut.cz/shots/'  
DataURL= baseURL.ShotNo.'/'.DAS.identifier  
set datafile separator ',';  
set title "Uloop for #".ShotNo;  
! wget -q @DataURL ;# Write data from GOLEM erver to a local file  
# Plot the graph from a local file  
set xrange [0:0.02];set xlabel 'Time [s]';set ylabel 'U_1 [V]'  
set terminal jpeg; plot identifier u 1:2 w l t 'Uloop'
```

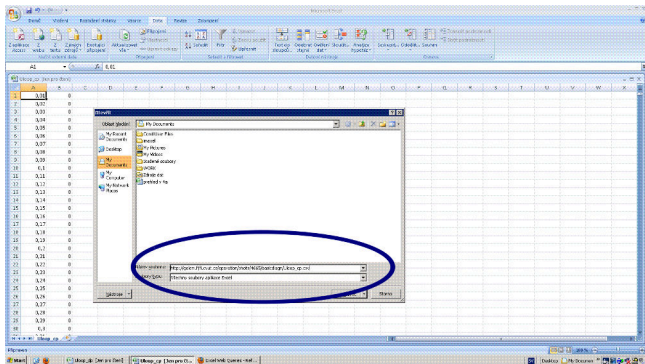
```
shot_no=39187;\nsignal_id="Diagnostics/BasicDiagnostics/Results/U_loop.csv";\
```

GNU Wget

GNU Wget is a free software package for retrieving files using HTTP, HTTPS and FTP, the most widely-used Internet protocols. It is a non-interactive commandline tool, so it may easily be called from scripts, cron jobs, terminals without X-Windows support, etc.

- Runs on most UNIX-like operating systems as well as Microsoft Windows.
- Homepage: <http://www.gnu.org/software/wget/>
- Basic usage:
 - To get U_l : `wget http://golem.fjfi.cvut.cz/utis/data/<#ShotNo>/loop_voltage`
 - To get whole shot: `wget -r -nH -cut-dirs=3 -no-parent -l2 -Pshot http://golem.fjfi.cvut.cz/shots/<#ShotNo>`

Excel



File→Open→

<http://golem.fjfi.cvut.cz/utis/data/<#ShotNo>/<identifier>>

Spreadsheets (Excel and others)

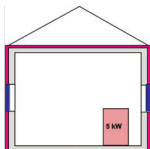
are not recommended, only tolerated.

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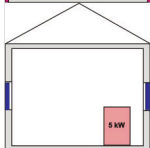
- 1 Introduction
- 2 The Tokamak (GOLEM)
- 3 The Tokamak GOLEM (remote) operation
- 4 The Electron energy confinement time calculation (rough estimation)**
- 5 Conclusion
- 6 Appendix

Energy balance of the house

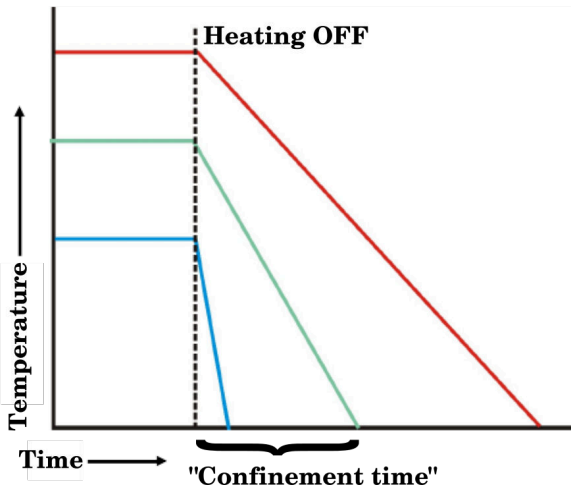
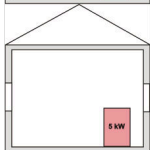
**Closed
windows
& insulation**



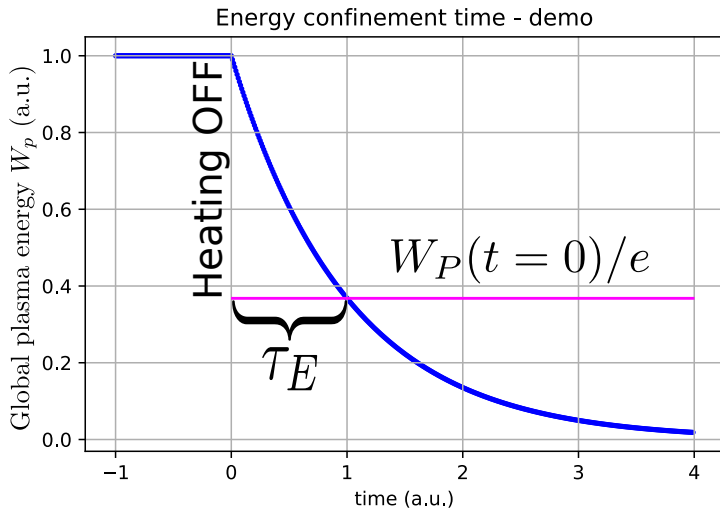
**Closed
windows**



**Open
windows**



Energy balance of the tokamak



Energy confinement time

Under the assumption of a simplified power balance, the heating power P_H is partially absorbed in the plasma and leads to an increase of the plasma energy W_p and the rest is lost as the loss power P_{Loss}

$$P_H = \frac{dW_p}{dt} + P_{Loss}$$

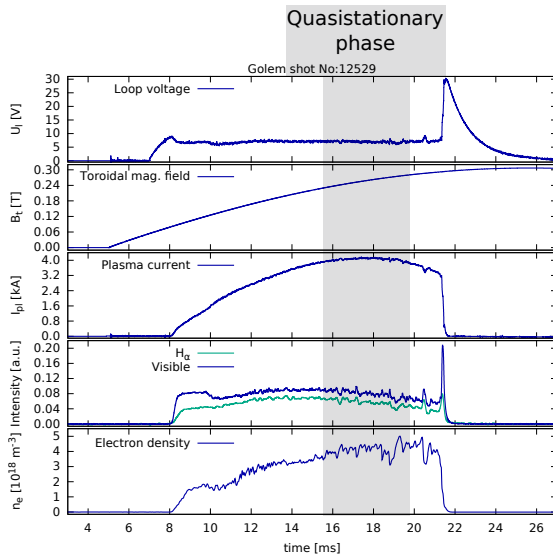
The energy confinement time is defined as the characteristic time scale of the exponential decay of the plasma energy W_p due to the loss power P_{Loss} :

$$\tau_E = \frac{W_p}{P_{Loss}} = \frac{W_p}{P_H - dW_p/dt}$$

Choosing the quasistationary phase of the plasma discharge, where $\frac{dW_p}{dt} = 0$ gives:

$$\tau_E(t) = \frac{W_p(t)}{P_H(t)}$$

The discharge - quasistationary phase



Plasma heating power

On the GOLEM tokamak the only heating mechanism of the plasma is ohmic heating P_{OH} resulting from the plasma current I_p flowing in a conductor with finite resistivity R_p . The time dependence of the ohmic heating power can be calculated as:

$$P_H(t) = P_{OH}(t) = R_p(t) \cdot I_p^2(t)$$

Plasma Energy

The global plasma energy content W_p can be simply calculated from the temperature estimation $T_e(0, t)$, average density n_e and plasma volume V_p , based on the ideal gas law, taking into account the assumed

$T_e(r, t) = T_e(0, t) \left(1 - \frac{r^2}{a^2}\right)^2$ temperature profile:

$$W_p(t) = V_p \frac{n_e k_B T_e(0, t)}{3}.$$

The information that the magnetic field reduces the degrees of freedom of the particles to two has been used to derive this formula.

- $V_p \approx 80 \text{ l}$

Central Electron Temperature estimation (Spitzer Formula)

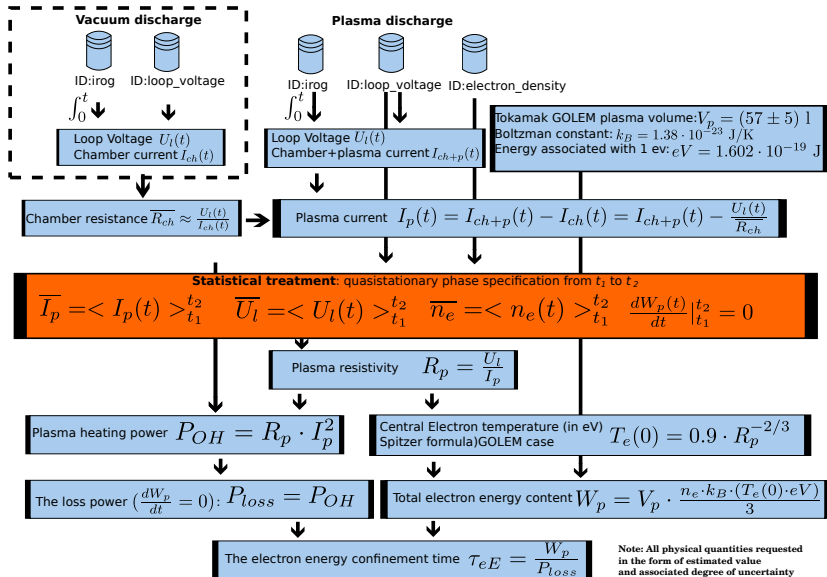
The time evolution of the central electron temperature $T_e(0, t)$ is calculated from equation based on Spitzer's resistivity formula (see eg. [2],[3]):

$$T_e(0, t) = \left(\frac{R_0}{a^2} \frac{8Z_{eff.}}{1544} \frac{1}{R_p(t)} \right)^{2/3}, [eV; m, \Omega]$$

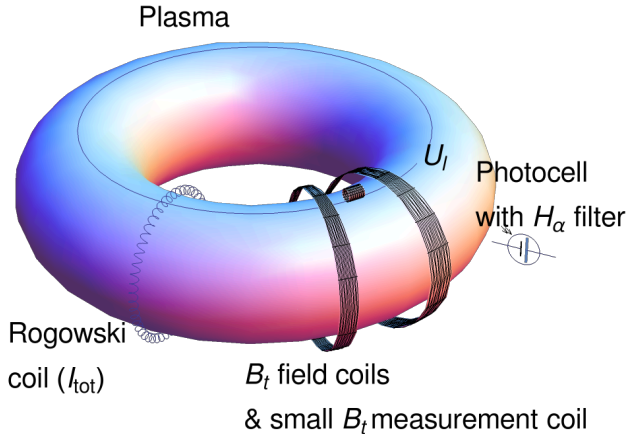
For particular case of the GOLEM tokamak it says:

$$T_e(0, t) = 0.9 \cdot \left(\frac{I_p(t)}{U_I(t)} \right)^{2/3}, [eV; A, V]$$

Towards Electron energy confinement time τ_E



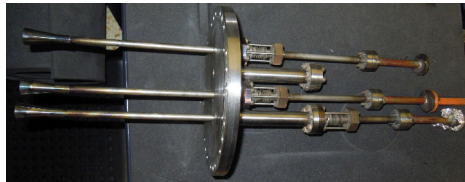
The GOLEM tokamak - standard diagnostics



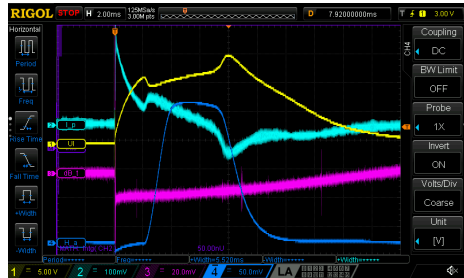
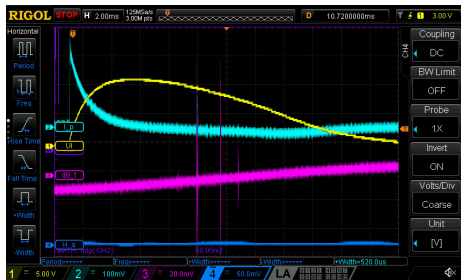
Hands on the GOLEM tokamak - equipment



The GOLEM tokamak interferometry HW



Vacuum x Plasma discharge @ Oscilloscope



Vacuum x Plasma shot

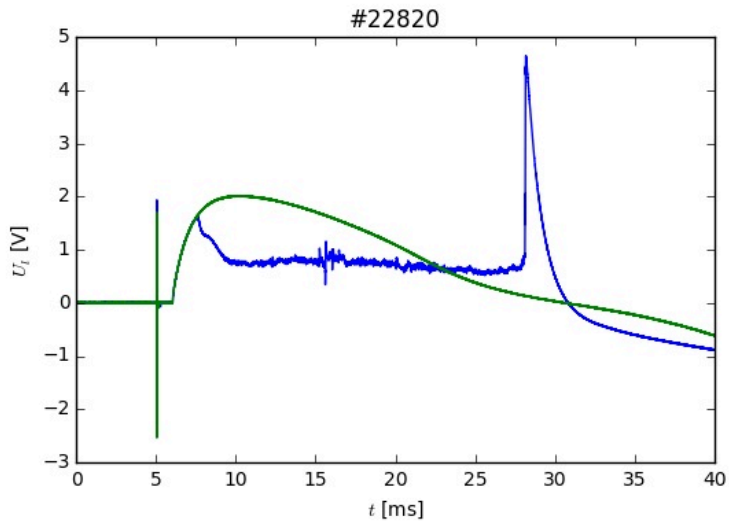


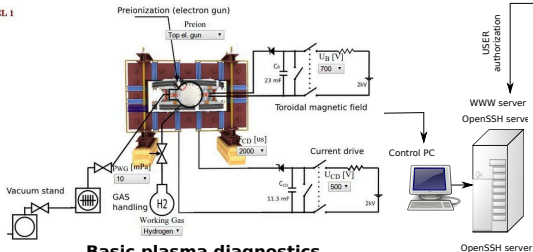
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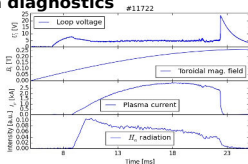
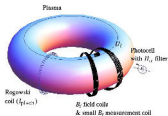
The global schematic overview of the GOLEM experiment

LEVEL 1

Tokamak technology setup



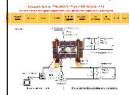
Basic plasma diagnostics



Virtual control room (remote participation)

WWW control interface

HTML & PHP scripts



SSH control interface

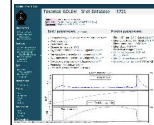
WINDOWS via putty



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

Data presentation

HTML (www pages)



Data handling

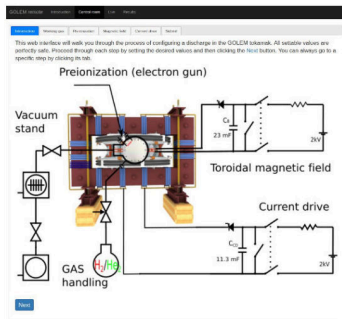
- *wget
- *gnuplot
- *idl
- *mathematica
- *matlab
- *etc...

Production

- Everything via <http://golem.fjfi.cvut.cz/SAFE>
 - This presentation
 - Control rooms
 - Contact: Vojtech Svoboda,
+420 737673903,
vojtech.svoboda@fjfi.cvut.cz
 - Videoconference:
<https://meet.google.com/hnv-qjhu-xvi>



Recommended values for the GOLEM tokamak operation



- Preionization: Top electron gunn
- Gas: Hydrogen. A Working gas pressure: p_{WG} [mPa] $< 0, 40 >$ mPa
- A voltage to charge the Current drive field E_t capacitor: U_{E_t} [V] $< 400, 700 >$ V
- A voltage to charge the Toroidal magnetic field B_t capacitor: U_{B_t} [V] $< 600, 1200 >$ V
- Time delay of the E_t trigger with respect to the B_t trigger: T_{CD} [μ s] $< 0, 10000 >$ μ s

Fee: postcard from the venue of remote measurements



Acknowledgement

Financial support highly appreciated:

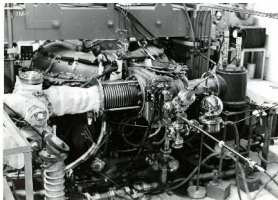
CTU RVO68407700, SGS 17/138/OHK4/2T/14, GAČR GA18-02482S, EU funds CZ.02.1.01/0.0/0.0/16_019/0000778 and CZ.02.2.69/0.0/0.0/16_027/0008465, IAEA F13019, FUSENET and EUROFUSION.

Students, teachers, technicians (random order):

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Thank you for your attention

Tokamak TM1
@Kurchatov Institute near Moscow
~1960-1977



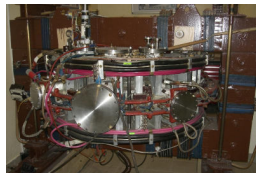
SCIENCE

Tokamak CASTOR
@Institute of Plasma Physics, Prague
1977-2007



**SCIENCE
& education**

Tokamak GOLEM
@Czech Technical University, Prague
2007-



**EDUCATION
& science**

... with the biggest
control room
in the world ..

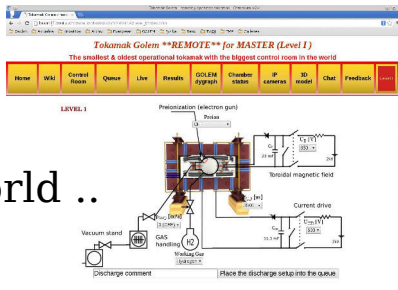


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References I

-  **Wikipedia contributors.** Golem — Wikipedia, the free encyclopedia. <https://en.wikipedia.org/w/index.php?title=Golem>, 2020. [Online; accessed 29-March-2020].
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-  **J. Wesson.** *Tokamaks*, volume 118 of *International Series of Monographs on Physics*. Oxford University Press Inc., New York, Third Edition, 2004.
-  **Tokamak GOLEM contributors.** Tokamak GOLEM at the Czech Technical University in Prague. <http://golem.fjfi.cvut.cz>, 2007. [Online; accessed October 16, 2024].