

Introduction to the tokamak operation (GOLEM specific) - Level 1

Vojtěch Svoboda
on behalf of the tokamak GOLEM team
for the MEPhI, Moscow

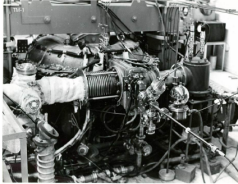
May 20, 2020

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- 3 The Tokamak GOLEM (remote) operation
- 4 Appendix

The GOLEM tokamak for education - historical background

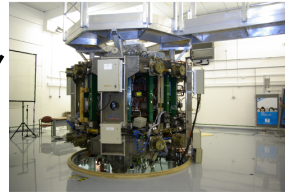
Kurchatov Institute near Moscow,
Soviet Union
1960: **TM1-MH**



1974



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



2006



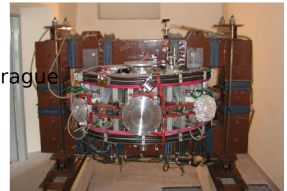
Institute of Plasma Physics
Czech republic
CASTOR **COMPASS**



2008



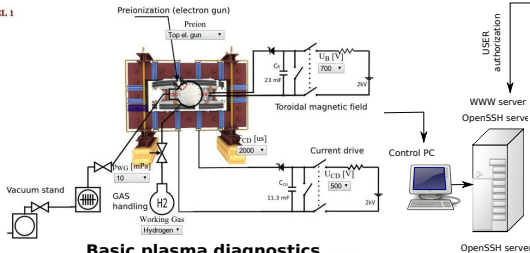
Czech Technical University Prague
Czech republic
GOLEM



The global schematic overview of the GOLEM experiment

LEVEL 1

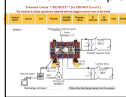
Tokamak technology setup



**Virtual control room
(remote participation)**

WWW control interface

HTML & PHP scripts



SSH control interface

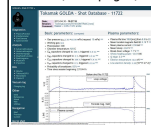
WINDOWS via putty



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

Data presentation

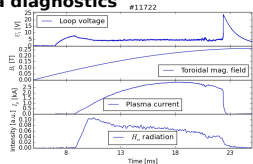
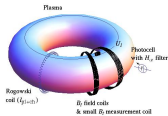
HTML (www pages)



Data handling

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

Basic plasma diagnostics



- Everything via `http://golem.fjfi.cvut.cz/MEPhI`
 - This presentation
 - Control rooms
 - Contact: Vojtech Svoboda,
+420 737673903,
svoboda@fjfi.cvut.cz
 - Chat:
tokamak.golem@gmail.com or
skype: tokamak.golem

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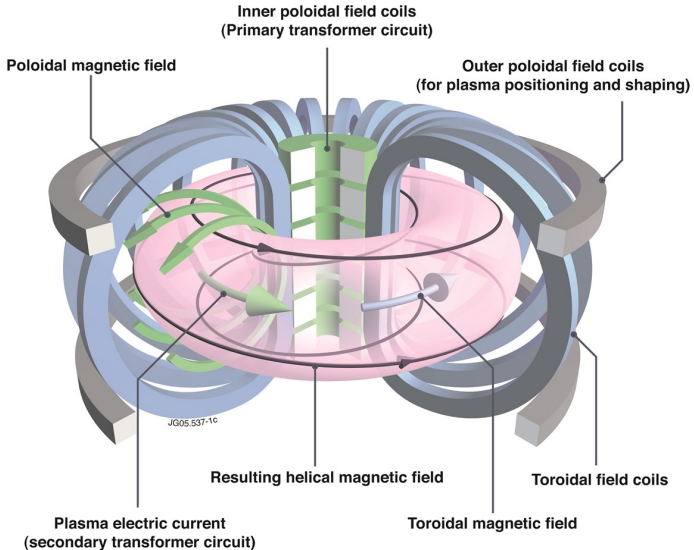
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4 Appendix

Tokamak magnetic confinement concept



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

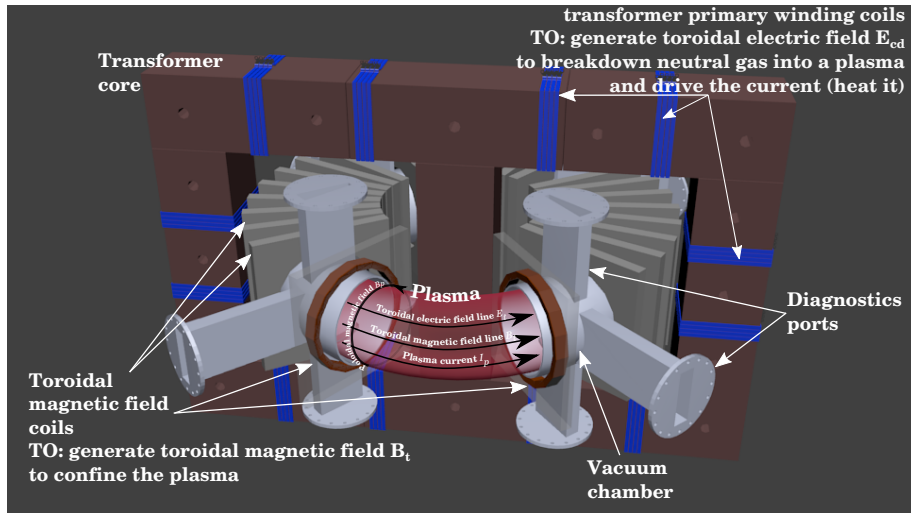


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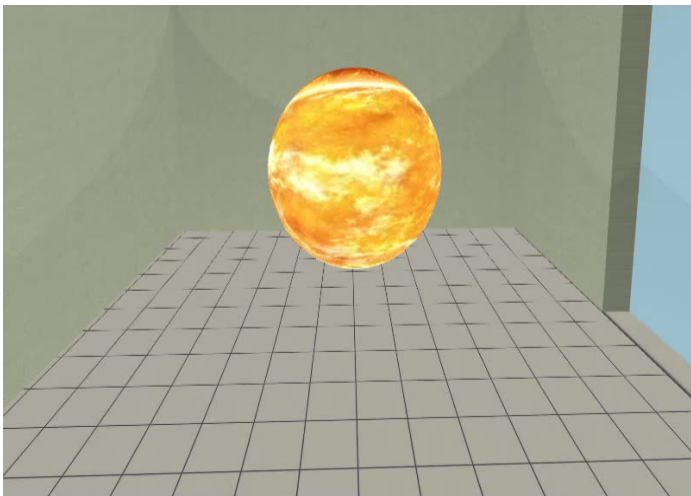
2 The Tokamak (GOLEM)

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

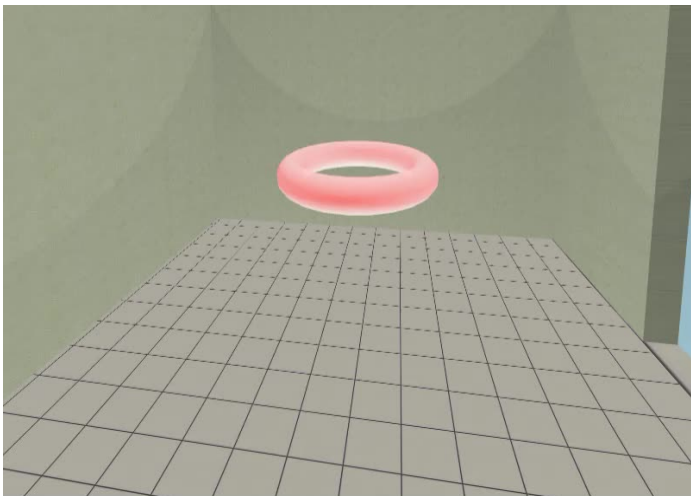
3 The Tokamak GOLEM (remote) operation

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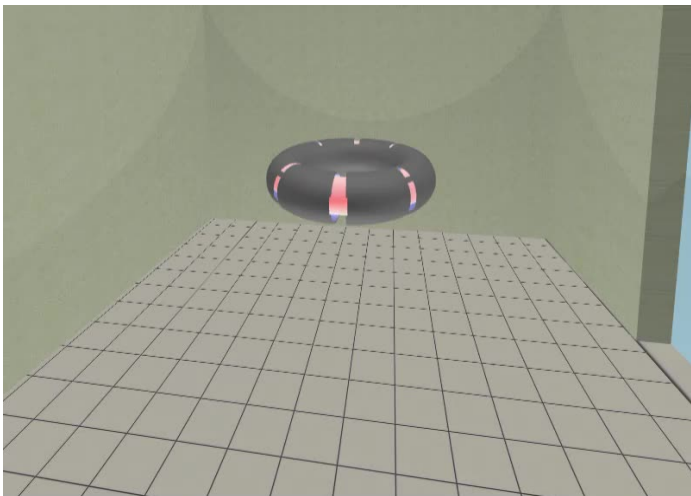
Our goal: the technology to create a μ Sun on the Earth



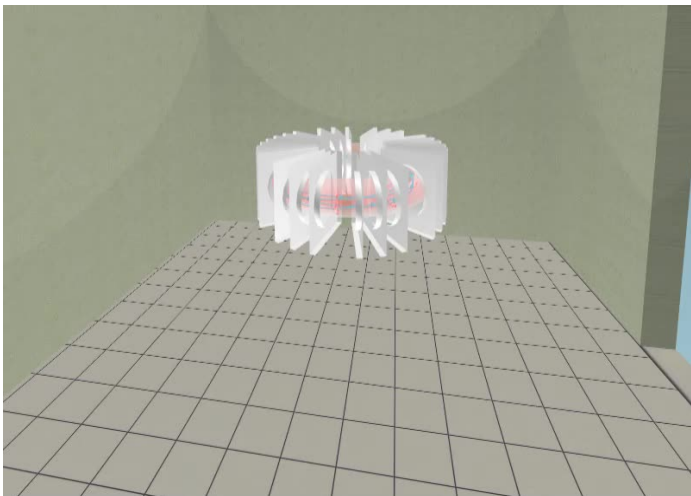
Magnetic confinement requires toroidal geometry



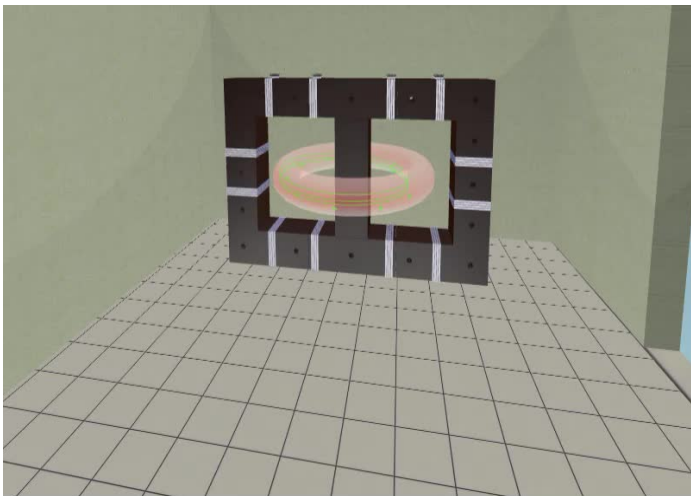
A chamber contains the thermonuclear reaction



Toroidal magnetic field coils confine the plasma



A transformer action creates and heats the plasma



The final technology altogether

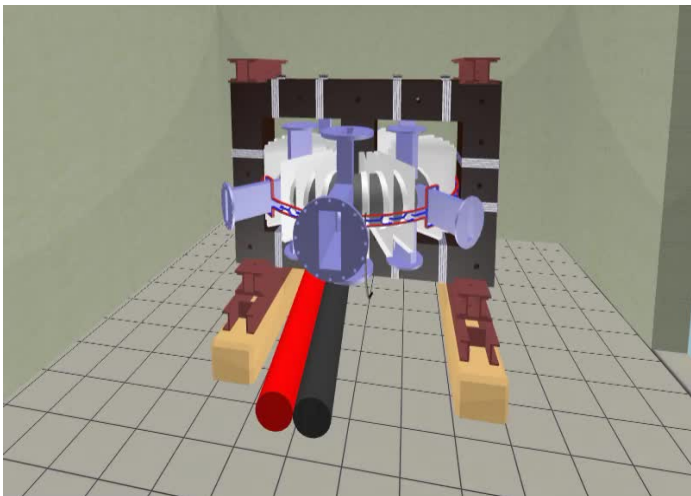


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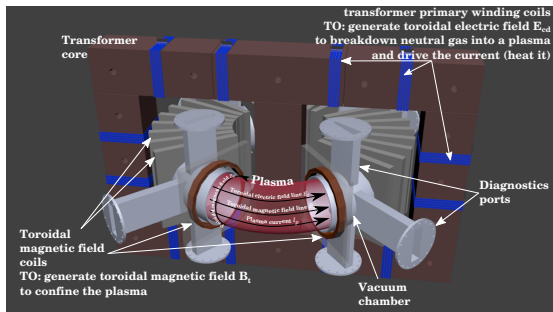
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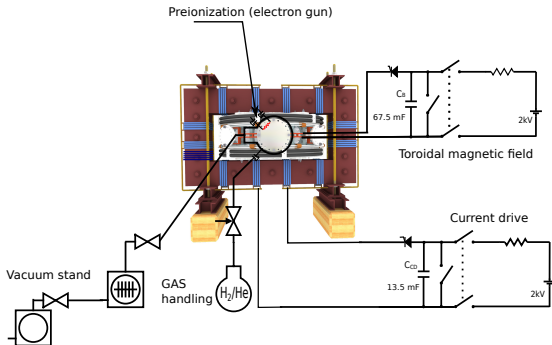
Plasma in Tokamak (GOLEM) - the least to do

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



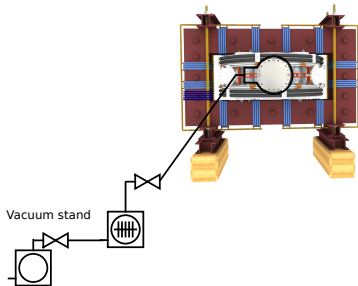
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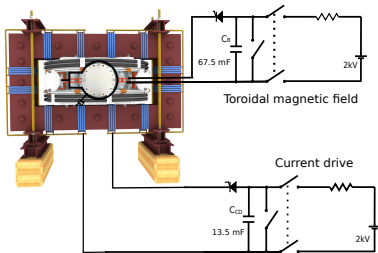
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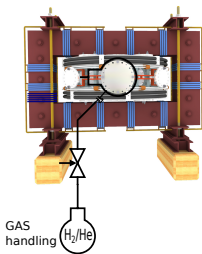
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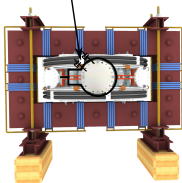


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Plasma in Tokamak (GOLEM) - the least to do

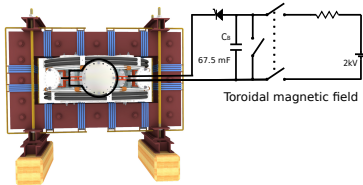
Preionization (electron gun)



To do:

- session start phase:
 - Evacuate the chamber
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 - **Preionization**
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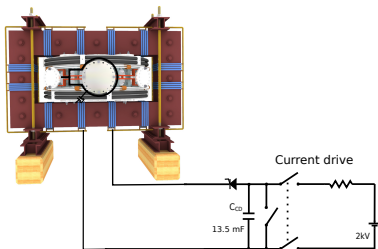
Plasma in Tokamak (GOLEM) - the least to do



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Plasma in Tokamak (GOLEM) - the least to do



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 - Diagnostics
- post-discharge phase

Tokamak GOLEM - schematic experimental setup

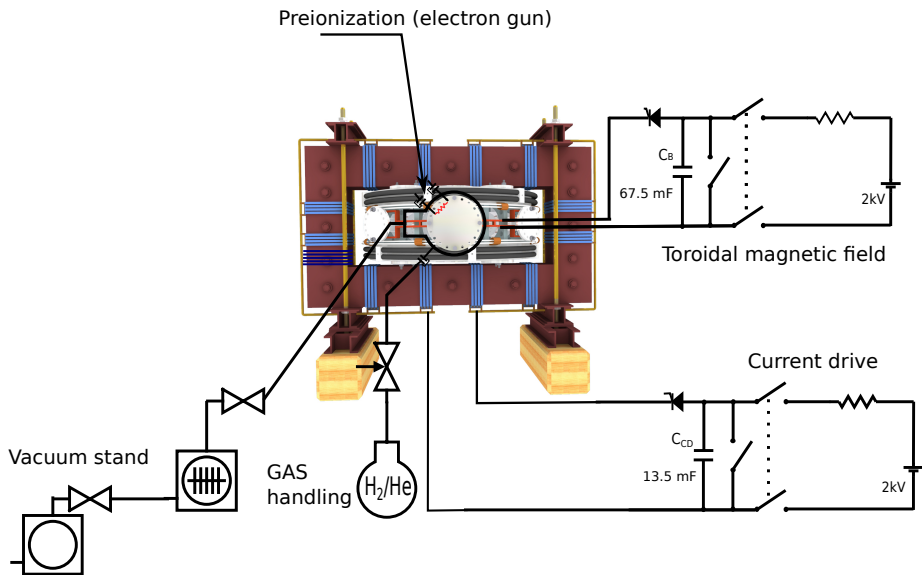


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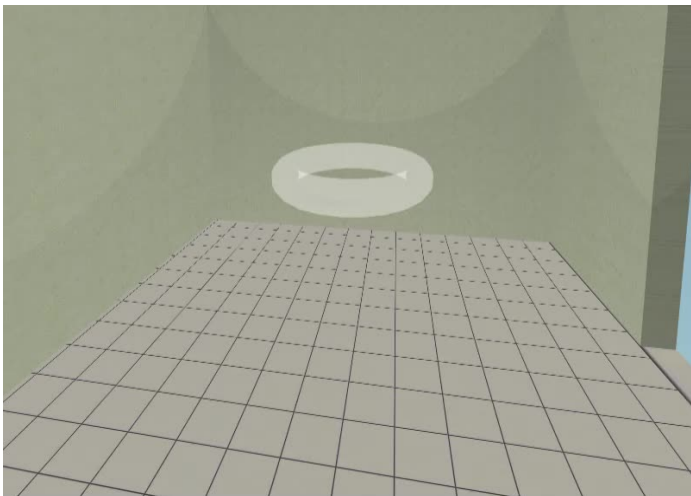
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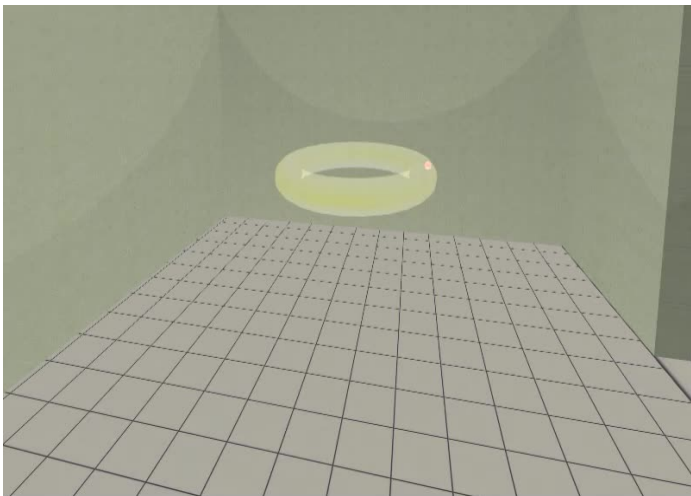
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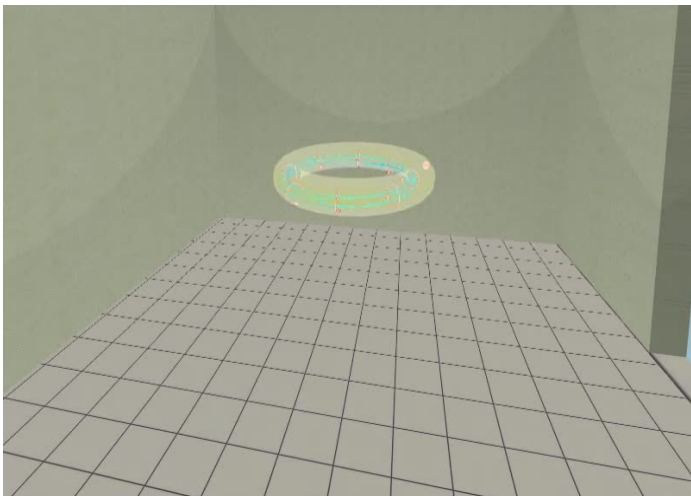
Introduce the working gas (Hydrogen x Helium)



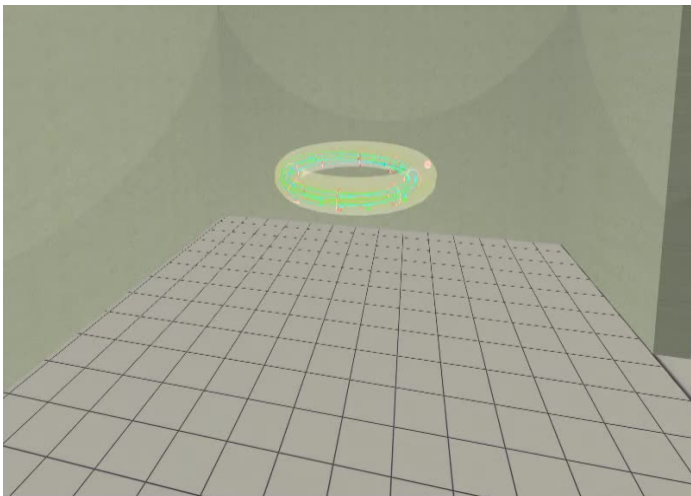
Switch on the preionization



Introduce the magnetic field



Introduce the electric field



Plasma ..

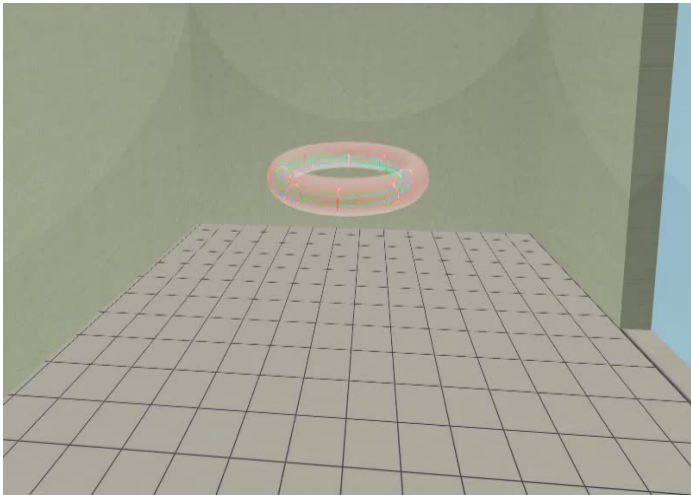


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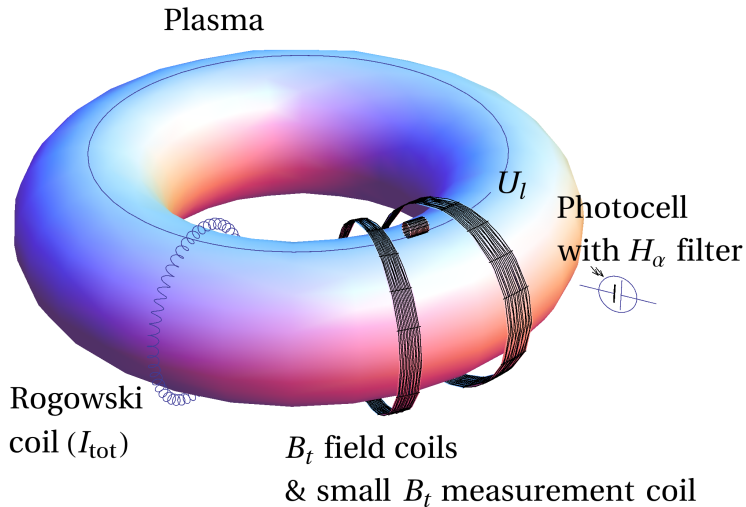
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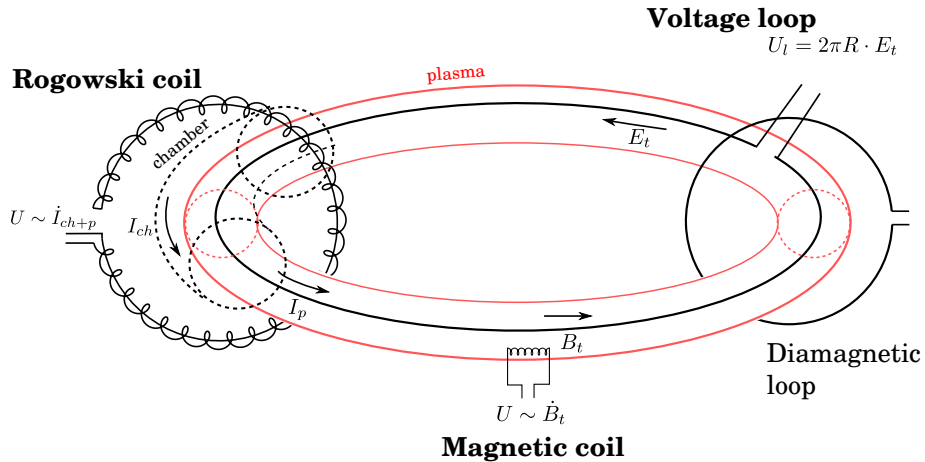
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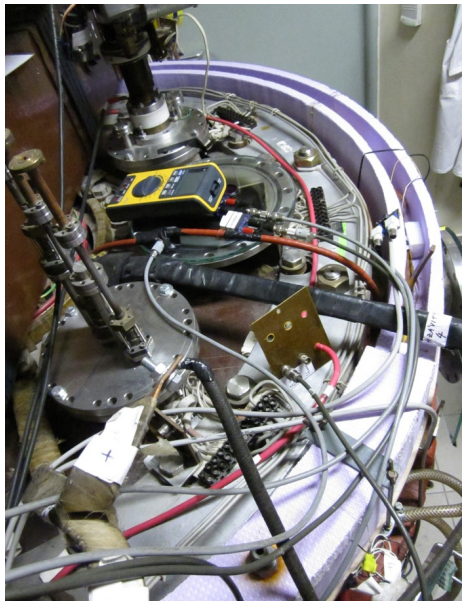
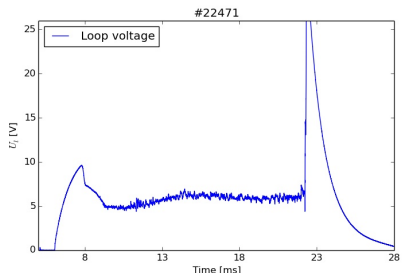
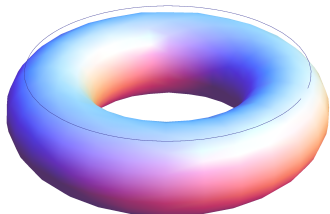
The GOLEM tokamak - basic diagnostics



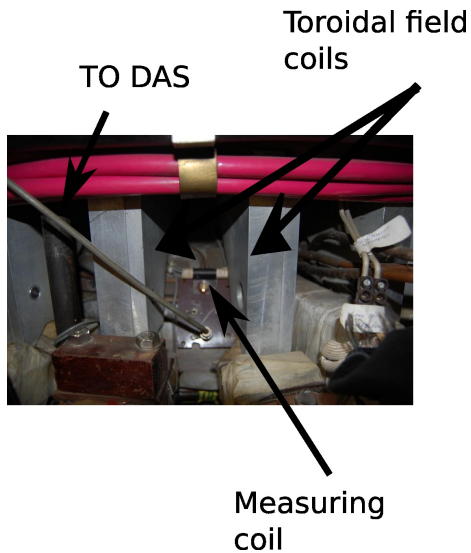
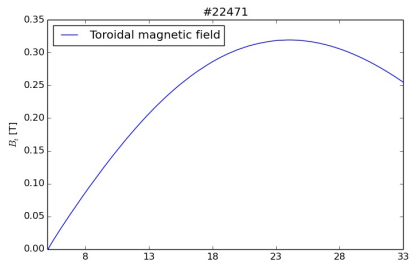
Schematic of electromagnetic diagnostics



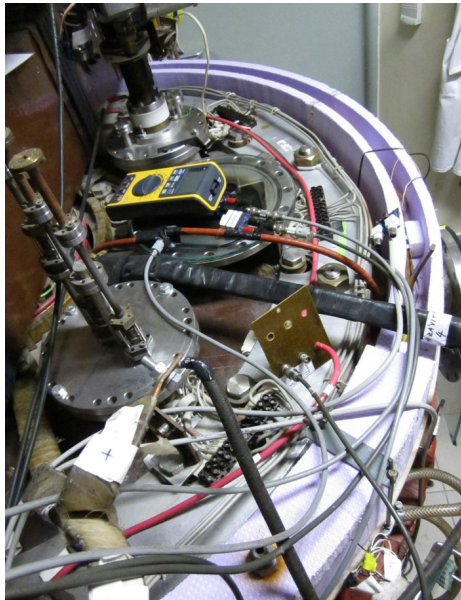
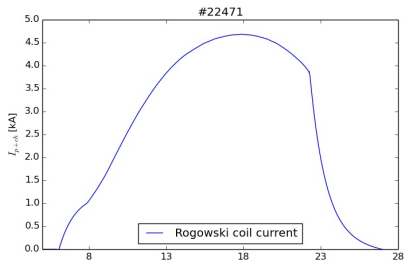
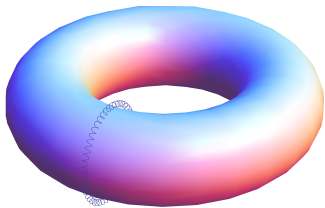
Loop voltage U_l @ the GOLEM tokamak



Toroidal magnetic field B_t @ the tokamak GOLEM



Total current I_{ch+p}



"Typical", well executed discharge @ GOLEM

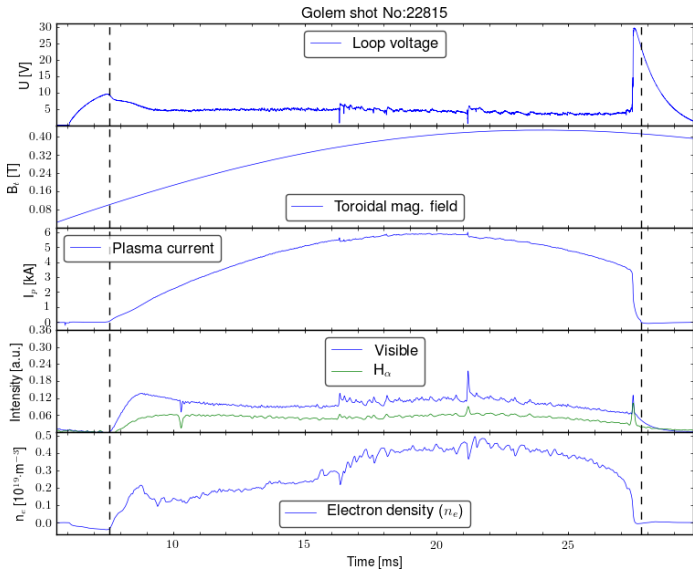


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Control room: Introduction

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 H_1/H_2

C_s 23 mF

C_{cp} 11.3 mF

2kV

2kV

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

Control room: Working gas

GOLEM Remote PREIONIZATION **Control room** Live Results

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_{gas} : 38 mPa

Hydrogen Helium

Next Set recommended value

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

Control room: Preionization

GOLEM remote PREIONIZATION Control room Live Results

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

67.5 mF

13.5 mF

230V

230V

ionization method

Steady gas No ionization

[Next](#)

3D model rendering method [Static image \(left\)](#) [Interactive X3DOM \(shown\)](#)

Control room: Magnetic field B_t

GOLEM interface: Introduction, Preionization, **Magnetic field**, Electric field, Submit

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

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 $U_{C_1} = 600$ V

Next Set recommended value

The 3D rendering shows a complex, multi-segmented toroidal structure. The segments are colored in blue and red, representing the magnetic field coils. A central vertical axis is visible, and the entire structure is set against a grid floor and a light-colored background.

Control room: Current drive E_{cd}

GOLEM Interface Introduction Control room Live Results ↑ The Torion 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

Toroidal magnetic field

Toroidal electric field

13.5 mF

2kV

GAS handling

Time delay of electric field start after the magnetic field starts t_d : 0 micro seconds

Capacitor voltage U_c : 400 V

Next Set recommended value

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

Control room: ... and Submit

The screenshot displays the GOLEM control room interface. At the top, a navigation bar includes 'GOLEM', 'Introduction', 'Control room', 'Live', and 'Results'. On the right, it shows the user 'The Torino Politecnico, Italy Group 1', 'Access: Level 2', and a 'Help' icon.

The main content area is divided into two sections. The left section contains a submission form with tabs for 'Introduction', 'Working gas', 'Preionization', 'Magnetic field', and 'Electric field'. The 'Submit' tab is active. The form includes a text area for a comment, a 'Submit' button, and instructions: 'Click the Submit button to send your configuration into the queue.' Below this, it states: 'After submission you can switch 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.' At the bottom of the form are two buttons: 'Watch the discharge Live!' and 'Go back to Introduction'.

The right section shows a 3D model rendering method with options for 'Static image (fast)' and 'Interactive X3DOM (slower)'. The 3D model depicts a tokamak device with a central plasma column, surrounded by complex magnetic field structures and support systems, all rendered in a stylized, blocky 3D style.

Shot homepage

GOLEM » Shot #22471 »



Diagnostics

- ✓ Interferometer
- ✓ Spectrometer
- ✗ FastCamera
- ✓ HXR

Analysis

- ✓ ShotHomepage

DAS

- ✓ TektronixDPO
- ✓ NIstandard
- ✓ Papouch_St
- ✓ Papouch_Ko
- ✓ Nloctopus

Vacuum log

Other

- Data
- References
- About
- Wiki
- Utilities

Navigation

- Next
- Previous

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 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 B_t : 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}

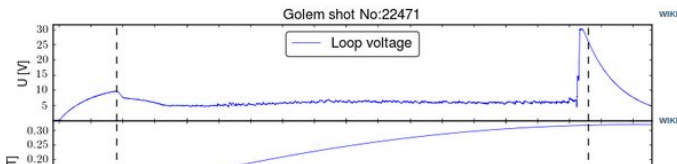


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GOLEM basic Data Acquisition System (DAS)

- $U_I, U_{B_t}, U_{I_{p+ch}}, I_{rad}$
- $\Delta t = 1\mu s / f = 1MHz$.
- Integration time = 40 ms, thus DAS produces 6 columns x 40000 rows data file.
- Discharge is triggered at 5th millisecond 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 or specific diagnostics have the format:

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

An overview of available data with identifiers, units, description, etc. for each discharge is at

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

Matlab

```
1 ShotNo=22471;
2 baseURL='http://golem.fjfi.cvut.cz/utils/data/';
3 identifier='loop_voltage';
4 %Create a path to data
5 dataURL=strcat(baseURL,int2str(ShotNo),'/',identifier);
6 % Write data from GOLEM server to a local file
7 urlwrite(dataURL,identifier);
8 % Load data
9 data = load(identifier, '\t');
10 % Plot and save the graph
11 plot(data(:,1)*1000, data(:,2), '.');
12 xlabel('Time [ms]')
13 ylabel('U_1 [V]')
14 saveas(gcf, 'plot', 'jpeg');
15 exit;
```

Jupyter (python)

```
1 import numpy as np
2 import matplotlib.pyplot as plt
3
4 shot_no = 22471
5 identifier = "loop_voltage"
6 # create data cache in the 'golem_cache' folder
7 ds = np.DataSource('golem_cache')
8 #Create a path to data and download and open the file
9 base_url = "http://golem.fjfi.cvut.cz/utils/data/"
10 data_file = ds.open(base_url+str(shot_no)+'/'+identifier)
11 #Load data from the file and plot to screen and to disk
12 data = np.loadtxt(data_file)
13 plt.plot(data[:,0], data[:,1]) #1. column vs 2. column
14 plt.savefig('graph.jpg')
15 plt.show()
```

Gnuplot

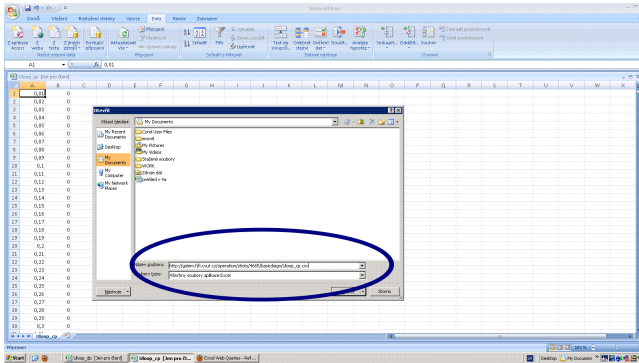
```
1 set macros;
2 ShotNo = "22471";
3 baseURL = "http://golem.fjfi.cvut.cz/utils/data/";
4 identifier = "loop_voltage";
5 #Create a path to data
6 DataURL= "@baseURL@ShotNo/@identifier";
7 #Write data from GOLEM server to a local file
8 !wget -q @DataURL;
9 #Plot the graph from a local file
10 set datafile separator "\t";
11 plotstyle = "with lines linestyle -1"
12 plot 'loop_voltage' using 1:2 @plotstyle;
13 exit;
14
15 # command line execution:
16 # gnuplot Uloop.gp -persist
```

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/utills/data/<#ShotNo>/<identifier>`

Spreadsheets (Excel and others)

are not recommended, only tolerated.

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- 2 The Tokamak (GOLEM)
- 3 The Tokamak GOLEM (remote) operation
- 4 Appendix**

References I

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