

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

Vojtěch Svoboda
on behalf of the tokamak GOLEM team
for the Torino politecnico, Italy

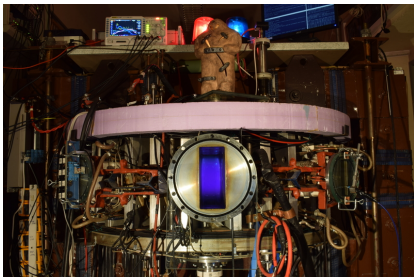
December 18, 2018

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The GOLEM tokamak basic characteristics

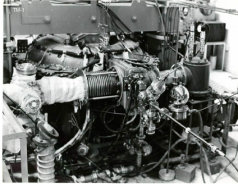
The grandfather of all tokamaks (ITER newslines 06/18)



- Vessel major radius: $R_0 = 0.4$ m
- Vessel minor radius: $r_0 = 0.1$ m
- Plasma minor radius: $a \approx 0.06$ m
- Toroidal magnetic field: $B_t < 0.5$ T
- Plasma current: $I_p < 8$ kA
- Electron density:
 $n_e \approx 0.2 - 3 \times 10^{19} \text{ m}^{-3}$
- Effective ion charge: $Z_{eff} \approx 2.5$
- Electron temperature: $T_e < 100$ eV
- Ion temperature: $T_i < 50$ eV
- Discharge duration: $\tau_p < 25$ ms
- (Electron) energy confinement time:
 $\tau_e \approx 50$ us

The GOLEM tokamak for education - historical background

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



1974

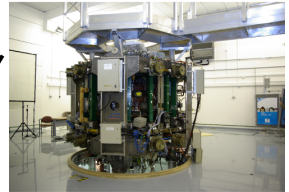


Institute of Plasma Physics
Czech republic
CASTOR **COMPASS**

2006



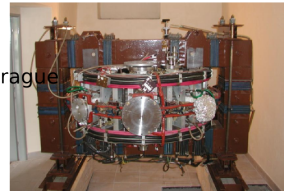
Culham Centre for Fusion Energy
Great Britain
1989: **COMPASS-D**



2008



Czech Technical University Prague
Czech republic
GOLEM



GOLEM

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

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

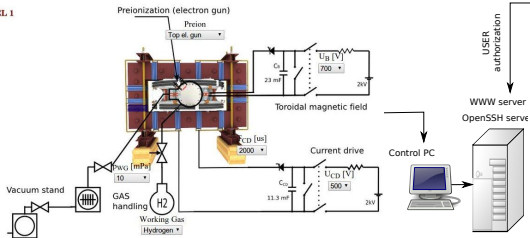


At the end of the 16th century, in the times when the Czech lands were ruled by Emperor Rudolf II, in Prague, there were Rabbi Judah Loew, well known alchemist, thinker, scholar, writer and inventor of the legendary GOLEM - a clay creature inspired with the Universe power that pursued his master's command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

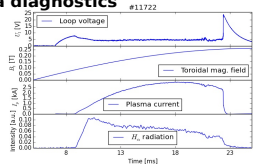
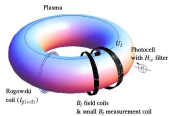
The global schematic overview of the GOLEM experiment

LEVEL 1

Tokamak technology setup



Basic plasma diagnostics

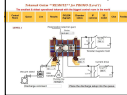


internet

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)



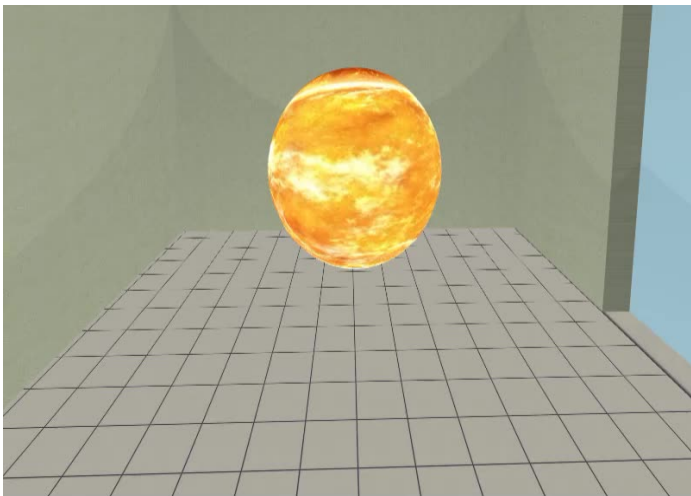
Data handling

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

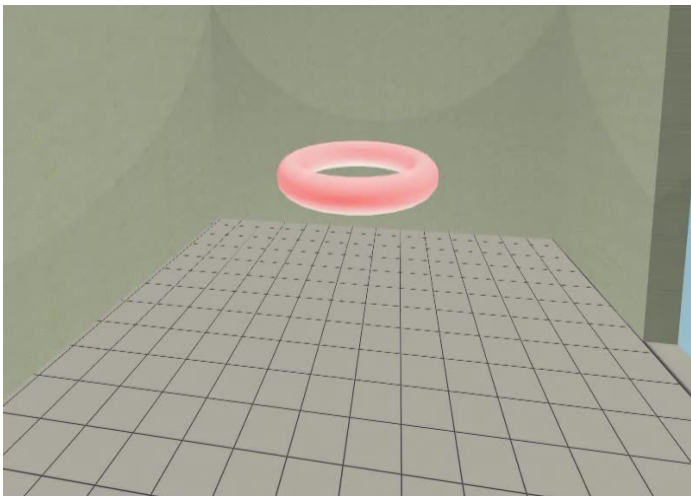
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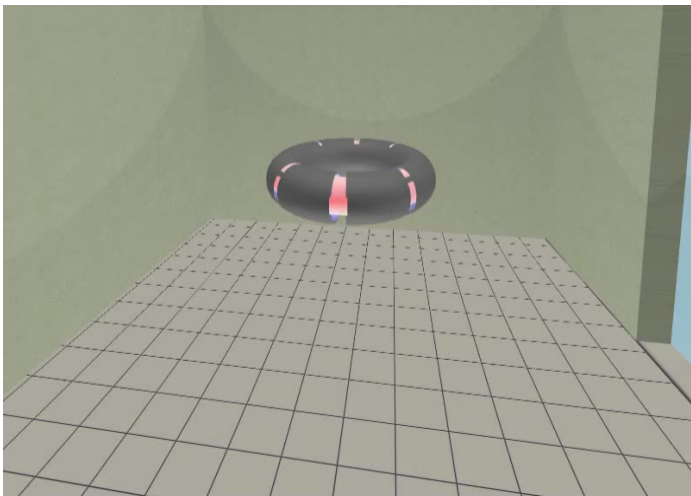
Our goal: the technology to create a μ Sun on the Earth



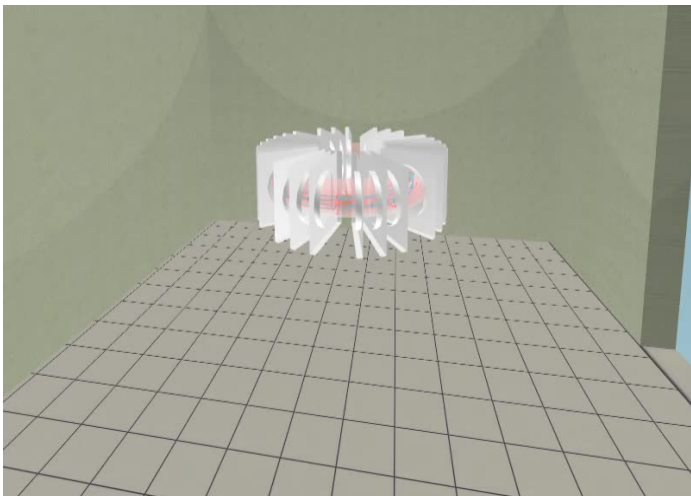
Magnetic confinement requires toroidal geometry



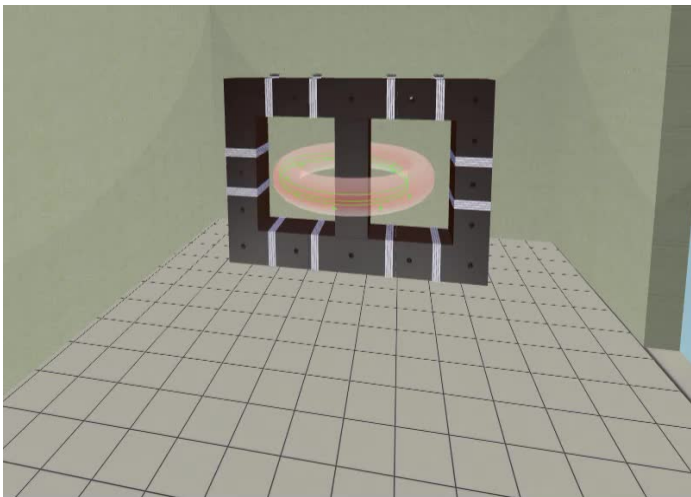
A chamber contains the thermonuclear reaction



Toroidal magnetic field coils confine the plasma



A transformer action creates and heats the plasma



The final technology altogether

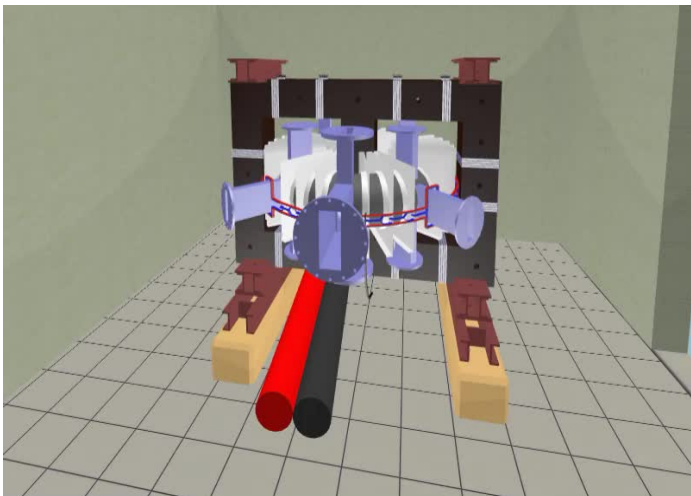
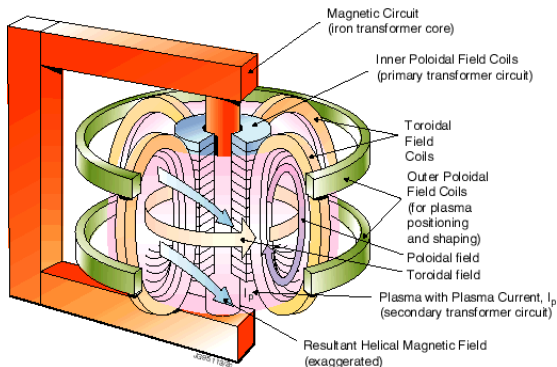


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Plasma in Tokamak (GOLEM) - the least to do



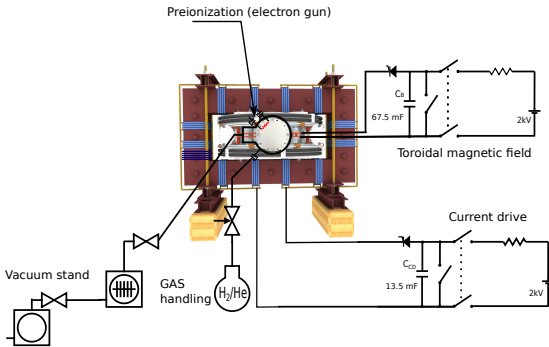
To do:

- 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

Plasma in Tokamak (GOLEM) - the least to do

To do:

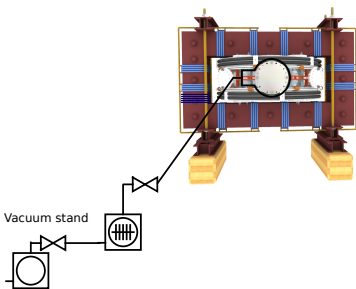
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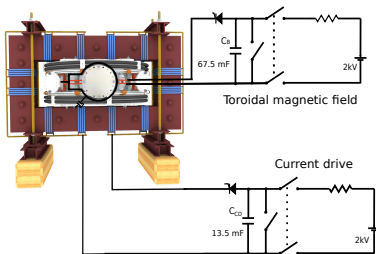
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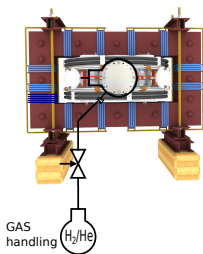
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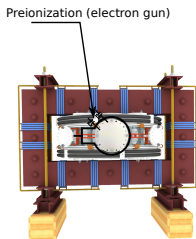
Plasma in Tokamak (GOLEM) - the least to do



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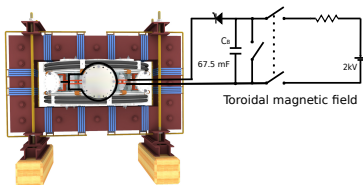
Plasma in Tokamak (GOLEM) - the least to do



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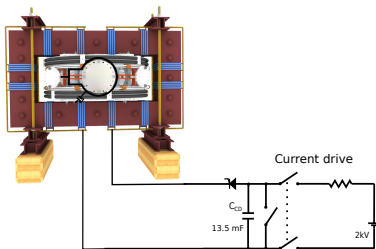
Plasma in Tokamak (GOLEM) - the least to do



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Plasma in Tokamak (GOLEM) - the least to do



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 - **Toroidal electric field to heat the plasma**
 - Plasma positioning
 - Diagnostics
- post-discharge phase

Tokamak GOLEM - schematic experimental setup

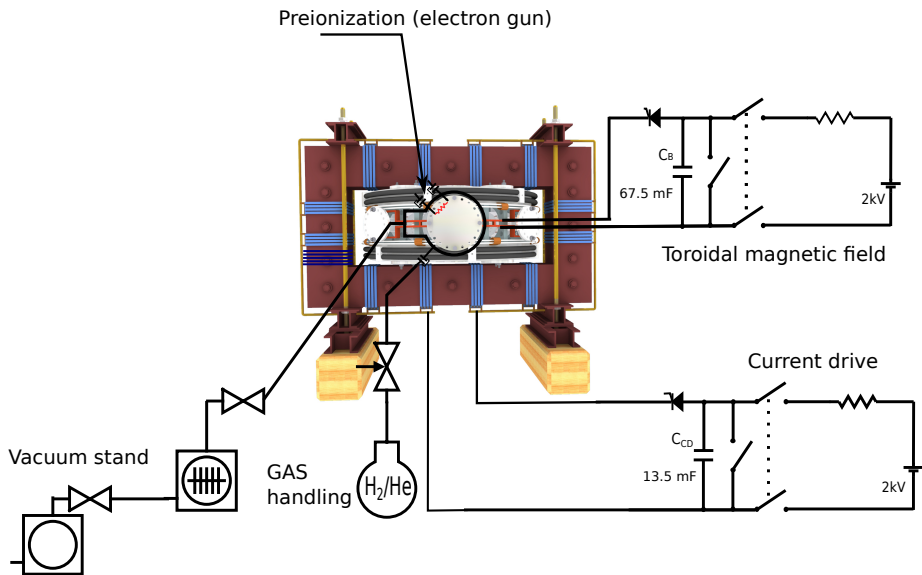
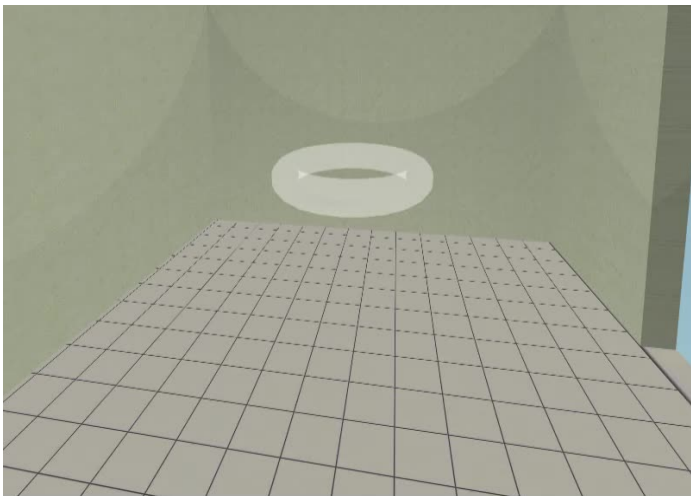


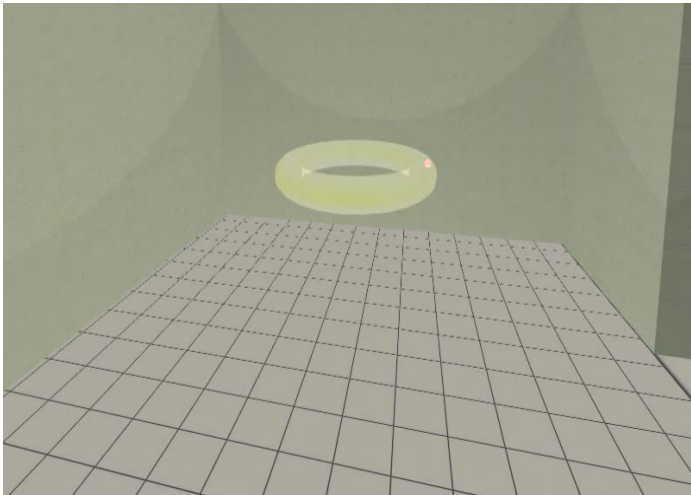
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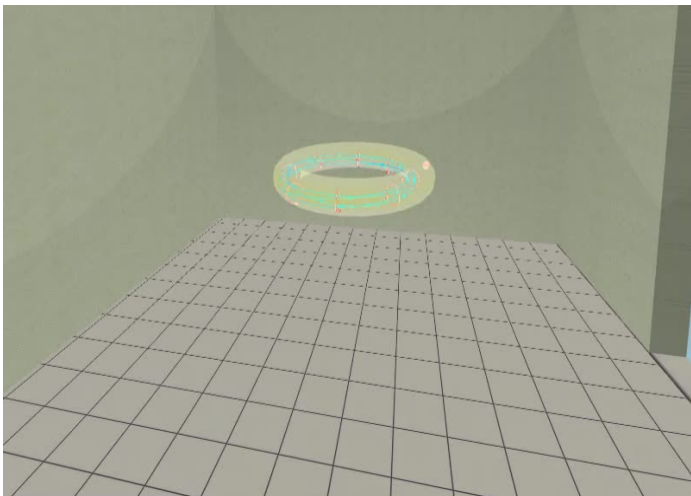
Introduce the working gas (Hydrogen x Helium)



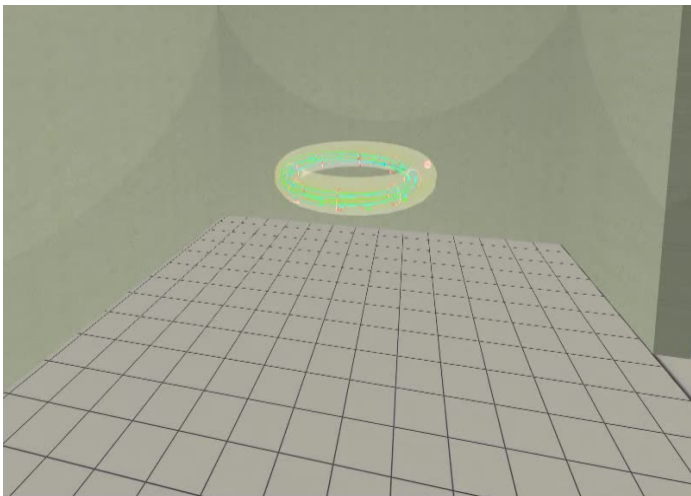
Switch on the preionization



Introduce the magnetic field



Introduce the electric field



Plasma ..

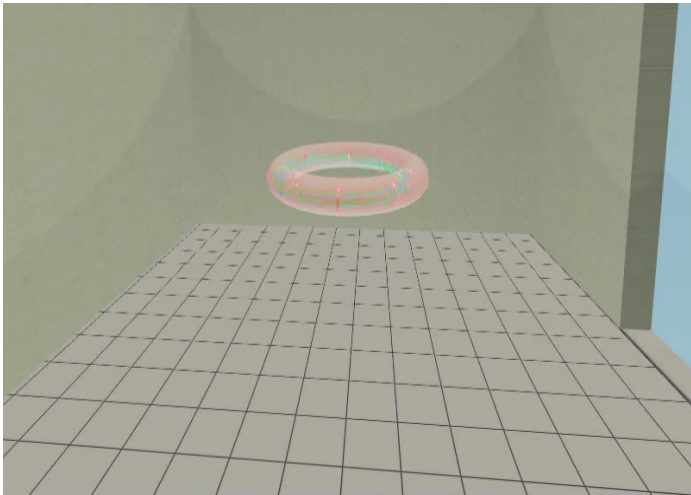


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Infrastructure room (below tokamak) 10/16



Infrastructure room (below tokamak) 10/16

Current drive CD field
and toroidal magnetic Bt field
circuits

To the tokamak
GOLEM

Rotary
pump

Vacuum
control



Current drive CD
capacitors

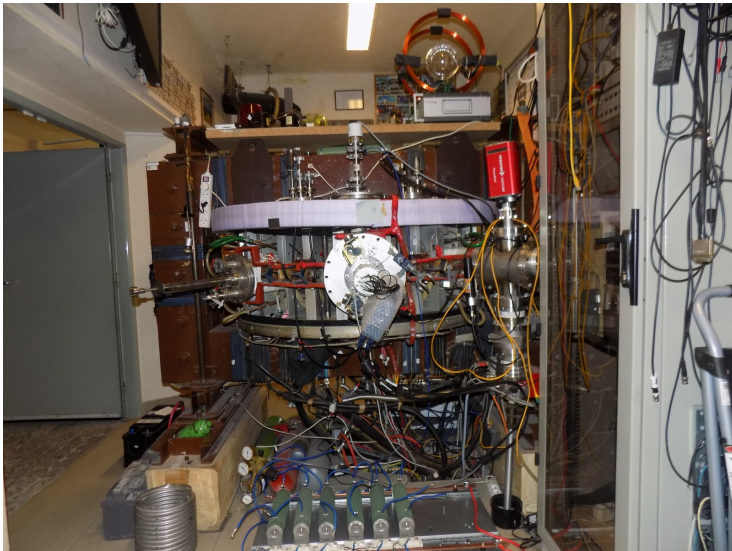
Plasma
stabilization

power
supply
2kV

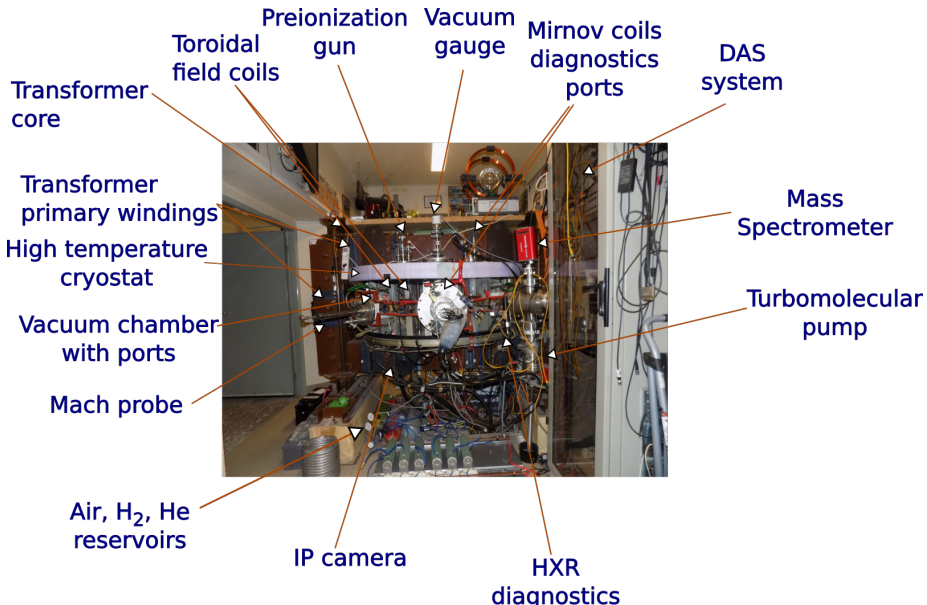
Toroidal
magnetic field B
capacitors

fire
protection
system

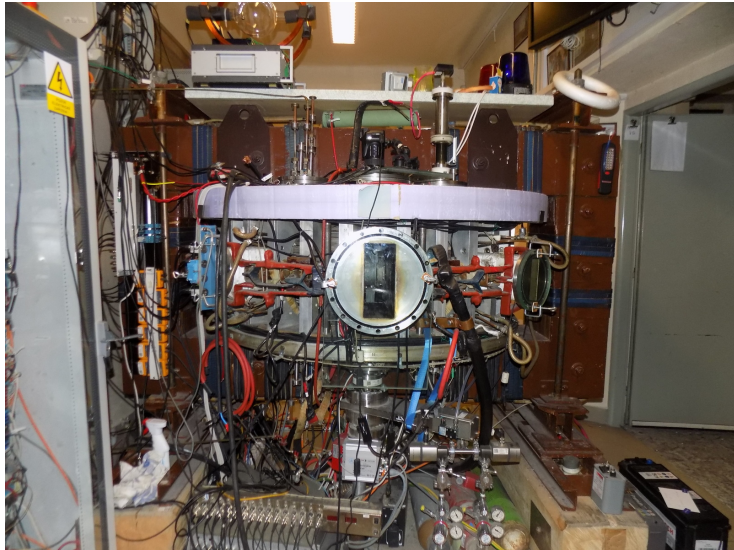
Tokamak room (North) 10/16



Tokamak room (North) 10/16



Tokamak room (South) 10/16



Tokamak room (South) 10/16

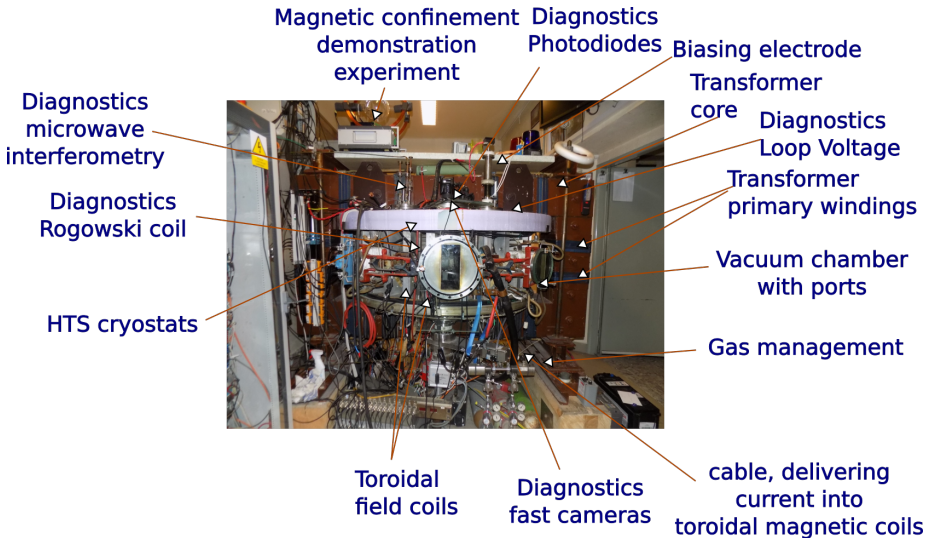
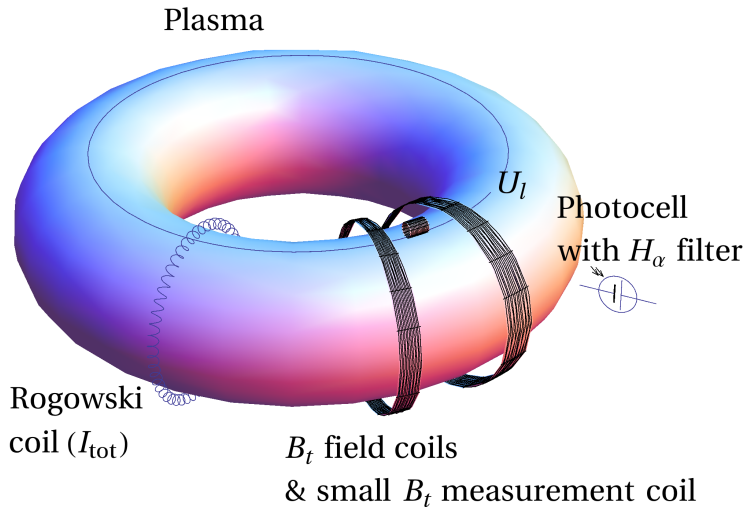


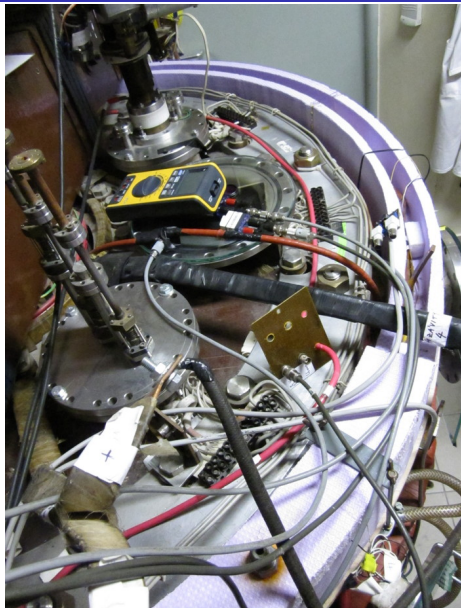
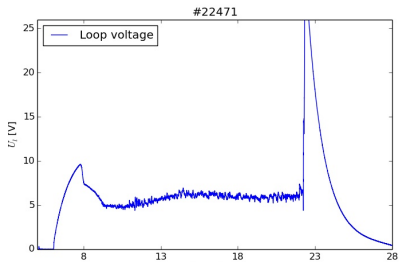
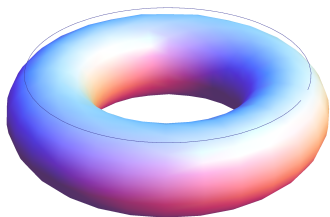
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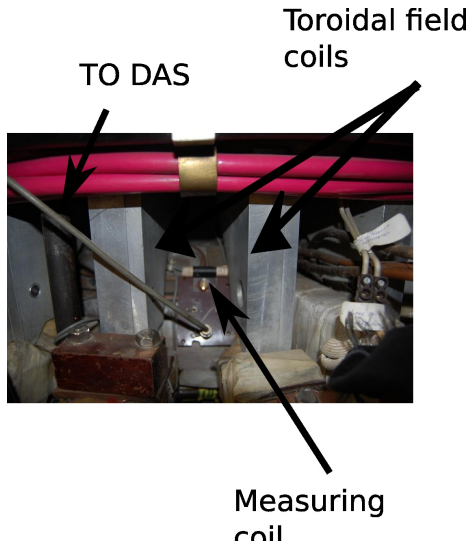
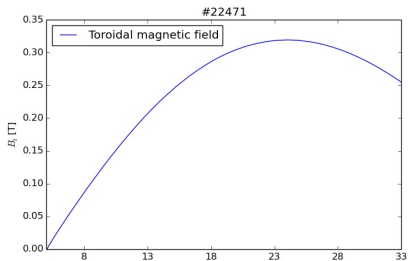
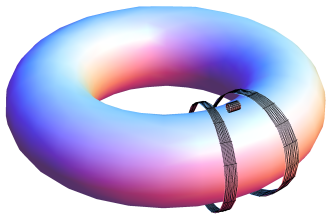
The GOLEM tokamak - basic diagnostics



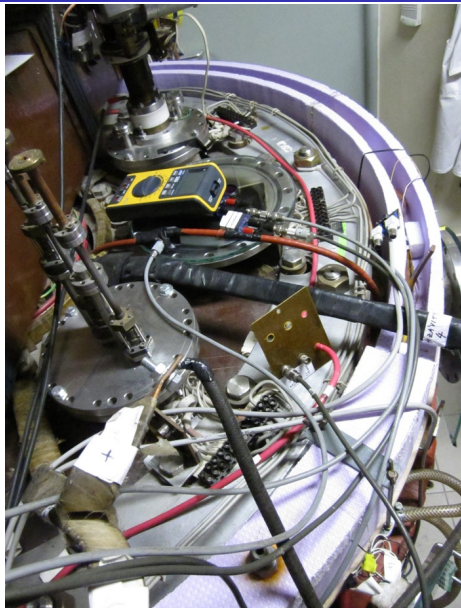
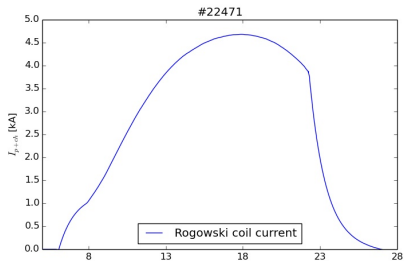
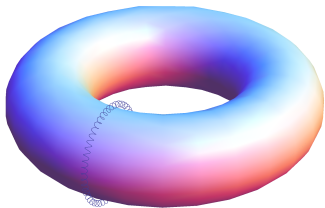
Loop voltage U_l



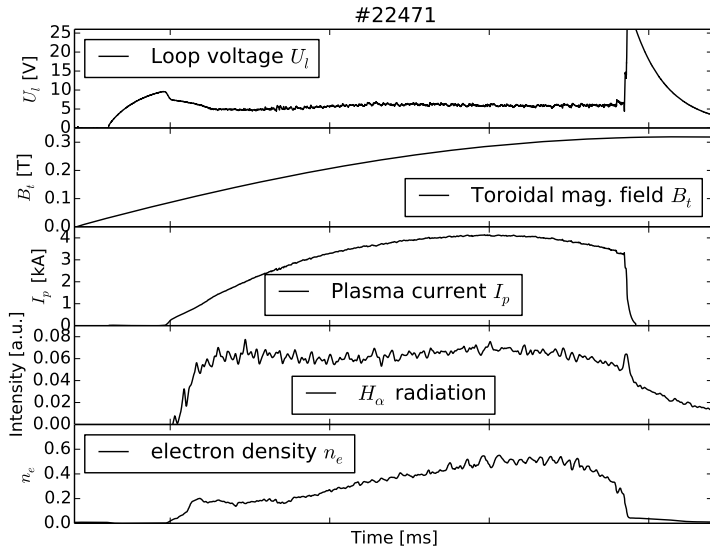
Toroidal magnetic field B_t



Total current I_{ch+p}



Basic diagnostics traces at the GOLEM tokamak



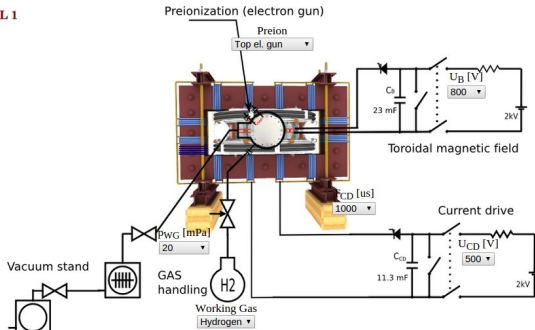
Remote operation

Tokamak Golem ****REMOTE**** for PROMO (Level I)

The smallest & oldest operational tokamak with the biggest control room in the world



LEVEL 1



Default discharge setup

Place the discharge setup into the queue

Note: We use cookies to record last set parameters in your browser to simplify parameter scans.

Anybody to test it?



Diagnostics

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

Analysis

- ✓ ShotHomepage

DAS

- ✓ TektronixDPO
- ✓ Nlstandard
- ✓ Papouch_St
- ✓ Papouch_Ko
- ✓ Nlcoctopus

Vacuum log

Other

- Data
- References
- About
- Wiki
- Utilities

Navigation

- Next
- Previous
- Current

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_1} 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](#)

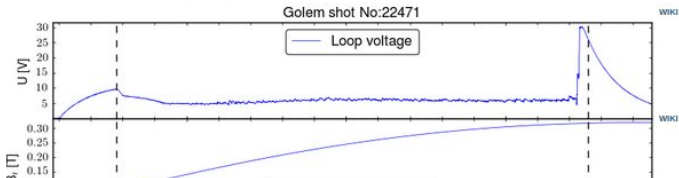


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GOLEM basic Data Acquisition System (DAS)

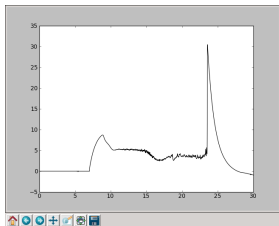
- $U_I, U_{B_t}, U_{I_{p+ch}}, I_{rad}$
- $\Delta t = 1\mu s / f = 1MHz$.
- Integration time = 40 ms, thus DAS produces 6 columns x 40000 rows data file.
- Discharge is triggered at 5th millisecond after DAS to have a zero status identification.



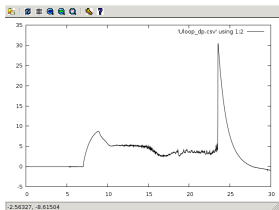
Data file example, DAS $\Delta t = 1\mu s / f = 1MHz$ (neutral gas into plasma breakdown focused)

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 ..	:
:	:	:	:	:
:	:	:	:	:

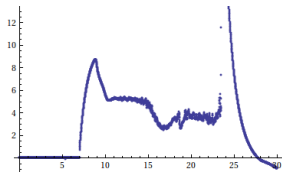
Plot #4665 U_l graph



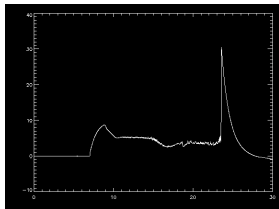
python



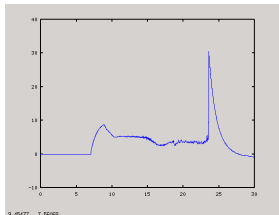
gnuplot



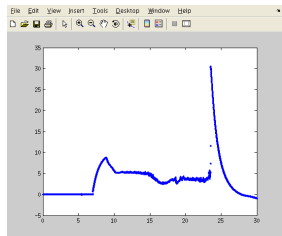
mathematica



idl



octave



matlab

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

```
ShotNo=22471;
baseURL='http://golem.fjfi.cvut.cz/utis/data/';
identifier='loop_voltage';
%Create a path to data
dataURL=strcat(baseURL,int2str(ShotNo), '/', identifier);
% Write data from GOLEM server to a local file
urlwrite(dataURL, identifier);
% Load data
data = load(identifier, '\t');
% Plot and save the graph
plot(data(:,1)*1000, data(:,2), '.');
xlabel('Time [ms]')
ylabel('UL [V]')
saveas(gcf, 'plot', 'jpeg');
exit;
```

Jupyter (python)

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

shot_no = 22471
identifier = "loop_voltage"
# create data cache in the 'golem_cache' folder
ds = np.DataStore('golem_cache')
#Create a path to data and download and open the file
base_url = "http://golem.fjfi.cvut.cz/utis/data/"
data_file = ds.open(base_url+str(shot_no)+'/'+identifier)
#Load data from the file and plot to screen and to disk
data = np.loadtxt(data_file)
plt.plot(data[:,0], data[:,1]) #1. column vs 2. column
plt.savefig('graph.jpg')
plt.show()
```

Gnuplot

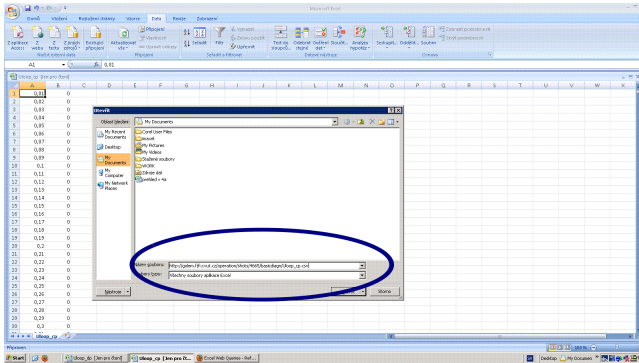
```
set macros;  
ShotNo = "22471";  
baseURL = "http://golem.fjfi.cvut.cz/utils/data/";  
identifier = "loop_voltage";  
#Create a path to data  
DataURL= "@baseURL@ShotNo/@identifier";  
#Write data from GOLEM server to a local file  
!wget -q @DataURL;  
#Plot the graph from a local file  
set datafile separator "\t";  
plotstyle = "with_lines_linestyle_-1"  
plot 'loop_voltage' using 1:2 @plotstyle;  
exit;  
  
# command line execution:  
# 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/utils/data/<#ShotNo>/<identifier>`

Spreadsheets (Excel and others)

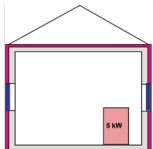
are not recommended, only tolerated.

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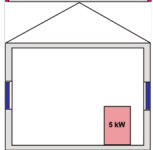
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- 8 The Electron energy confinement time calculation**
- 9 Conclusion
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Energy balance of the house

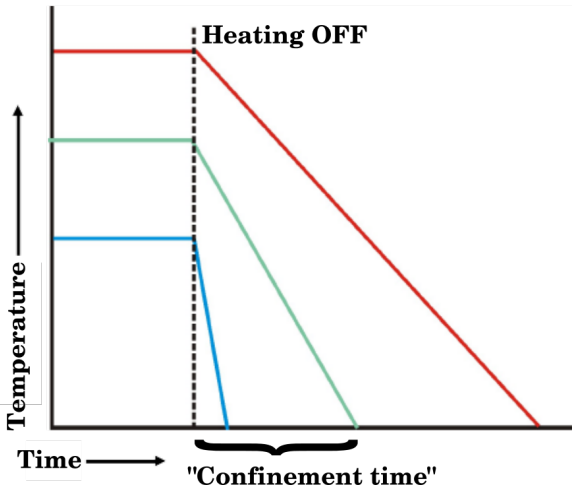
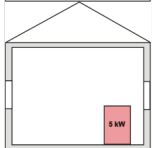
Closed windows & insulation



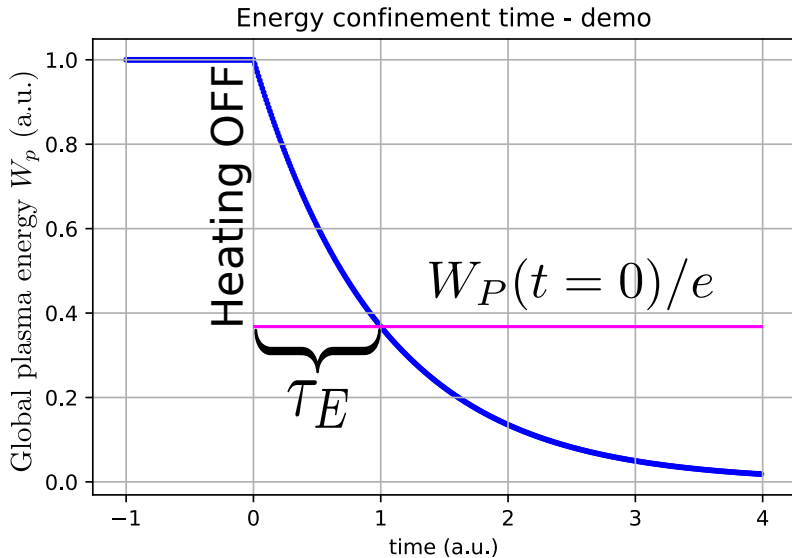
Closed windows



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_L

$$P_H = \frac{dW_p}{dt} + P_L$$

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_L :

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

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

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

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)

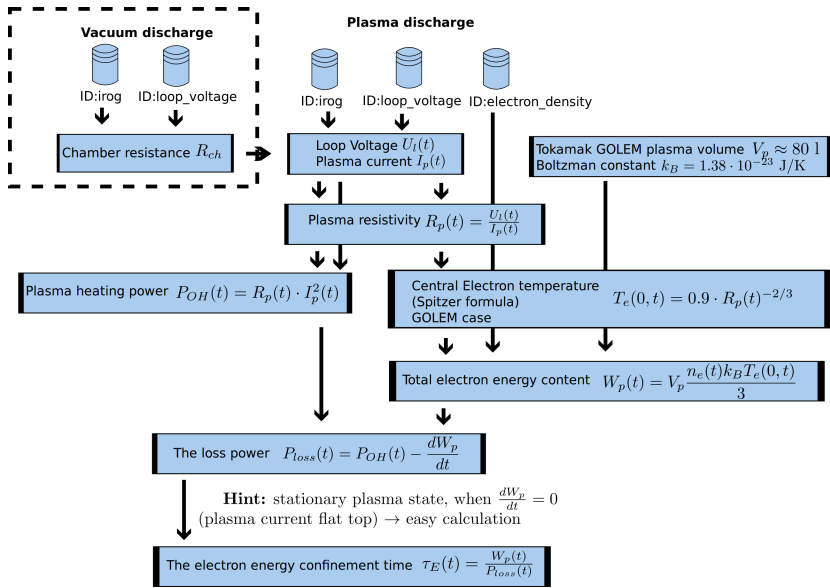
The time evolution of the central electron temperature $T_e(0, t)$ is calculated from equation based on Spitzer's resistivity formula (see eg. [1],[2]):

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

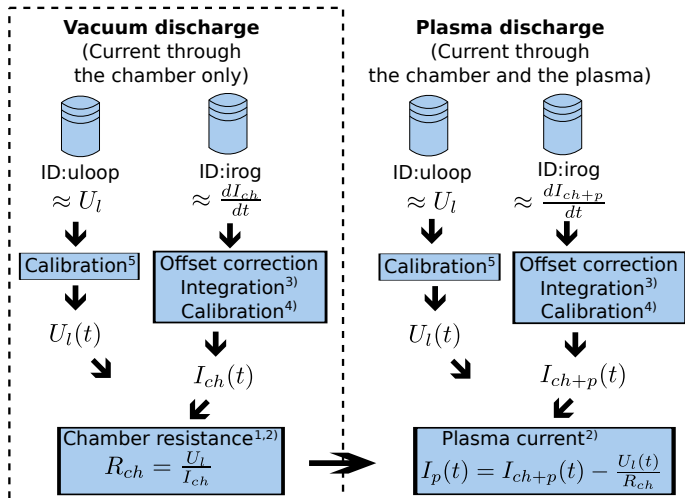
For particular case of the GOLEM tokamak it says:

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

Towards Electron energy confinement time τ_E



Towards Plasma current I_p



1) With some statistical effort. 2) Do it in the stationary phase, i.e. current constant, to avoid inductive phenomena. 3) 1 us step. 4) Rogowski Coil calibration constant = $5.3 \cdot 10^6$ A/Vs 5) Uloop calibration constant = 5.5

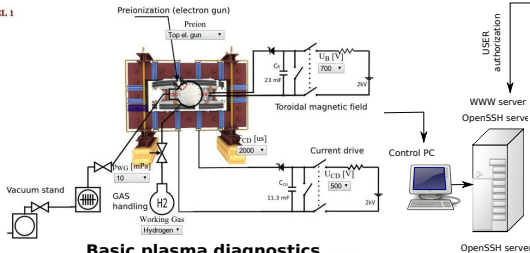
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The global schematic overview of the GOLEM experiment

LEVEL 1

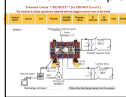
Tokamak technology setup



**Virtual control room
(remote participation)**

WWW control interface

HTML & PHP scripts



SSH control interface

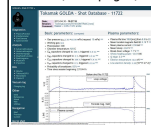
WINDOWS via putty



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

Data presentation

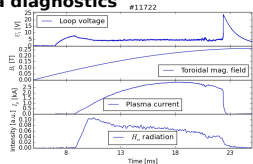
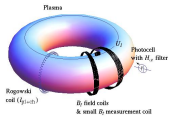
HTML (www pages)



Data handling

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

Basic plasma diagnostics

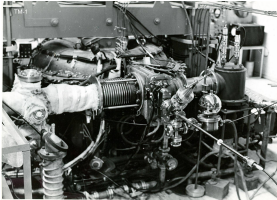


- Everything via <http://golem.fjfi.cvut.cz/Torino>
 - This presentation
 - Control rooms
 - Contact: Vojtech Svoboda,
+420 737673903,
svoboda@fjfi.cvut.cz
 - Chat:
tokamak.golem@gmail.com or
skype: tokamak.golem



Thank you for your attention

Tokamak TM1
@Kurchatov Institute near Moscow
~1960-1977



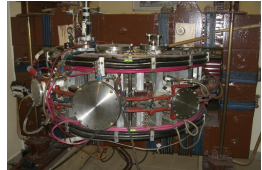
SCIENCE

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 ..

Tokamak Golem **REMOTE for MASTER (Level 1)**
The earliest & oldest operational tokamak with the biggest control room in the world

Home WB1 Control Room Queue Live Results GOLEM diagram Chamber status IP camera 3D model Chat Feedback Logout

LEVEL 1

Preionization (electron gun)
Preion. Press

Toroidal magnetic field
 $T_0 [V]$ 0000

Current drive
 $C_0 [A]$ 0000

Vacuum stand
GAS handling
Working Gas
Discharge comment

Place the discharge setup into the queue

Acknowledgement

Financial support highly appreciated:

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Students, teachers, technicians (random order):

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References I



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