Remote experiments at the GOLEM tokamak - Level 1

Ondřej Grover
on behalf of the GOLEM tokamak team
for the **Cadarache Winter event** training session

February 19, 2019

Resources and contact

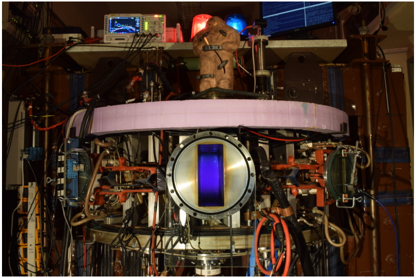
- Everything via `http://golem.fjfi.cvut.cz/Cadarache`
  - This presentation
  - Control room
  - Data analysis tutorials
  - Contact: Ondřej Grover ondrej.grover@gmail.com

Table of Contents

Table of Contents

The GOLEM tokamak basic characteristics

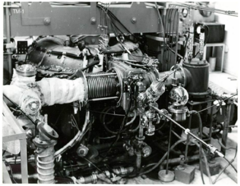
The grandfather of all tokamaks (ITER newsline 06/18)



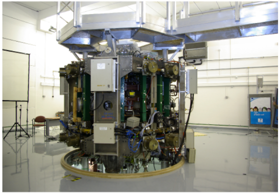
- Vessel major radius: $R_0 = 0.4$ m
- Vessel minor radius: $r_0 = 0.1$ m
- Plasma minor radius: $a \approx 0.06$ m
- Toroidal magnetic field: $B_t < 0.5$ T
- Plasma current: $I_p < 8$ kA
- Electron density: $n_e \approx 0.2 - 3 \ \times 10^{19}$ m^{-3}
- Effective ion charge: $Z_{eff} \approx 2.5$
- 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**



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



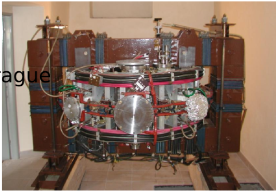
1974

2006

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

2008

Czech Technical University Prague
Czech republic
GOLEM



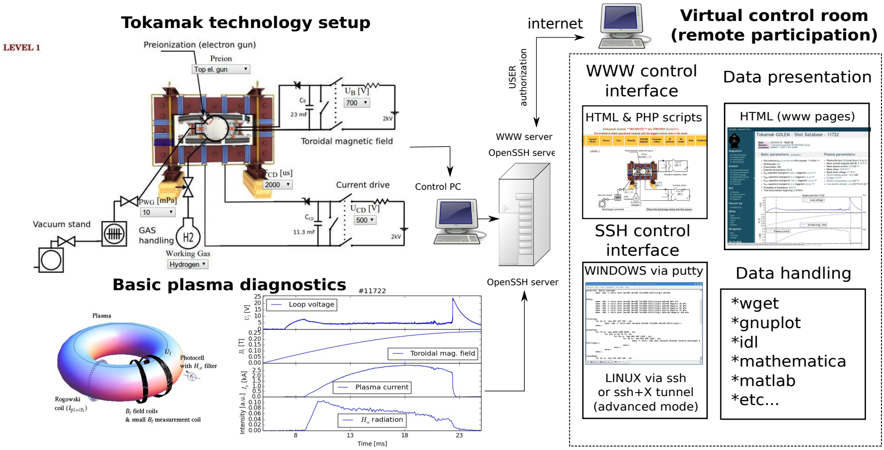
GOLEM

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

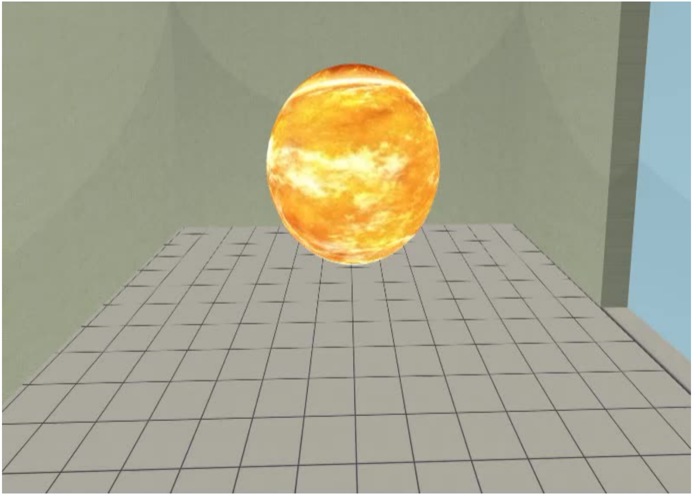
there is hidden indeed "infernal" power. Yet it is the very power of celestial stars themselves. Calmly dormant, awaiting mankind to discover the magic key, to use this power for their benefit...

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

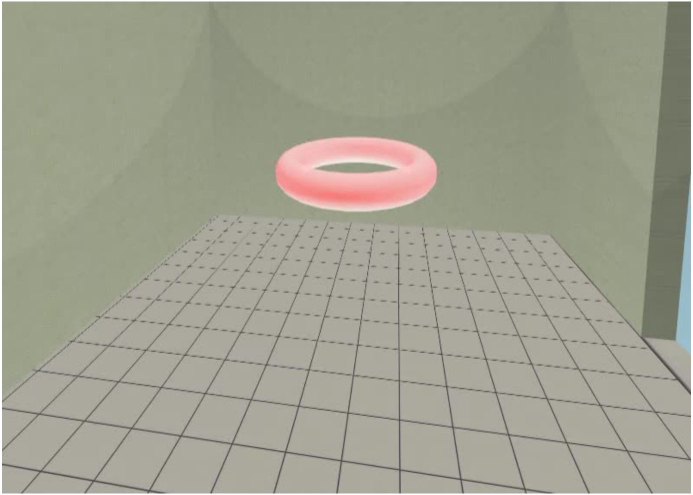
The global schematic overview of the GOLEM experiment



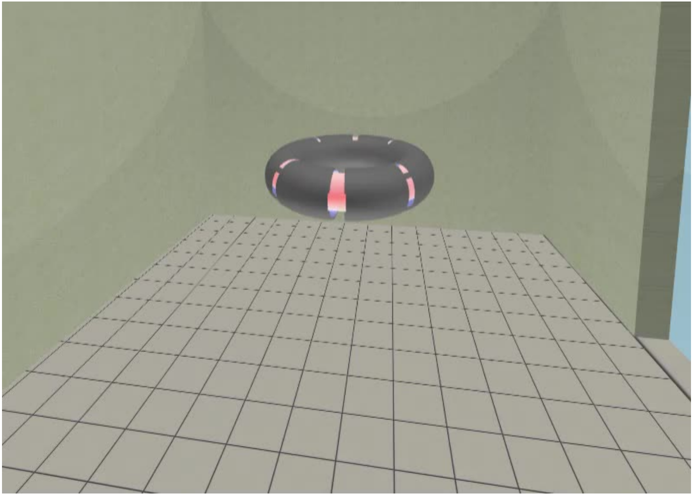
Our goal: the technology to create a μSun on the Earth



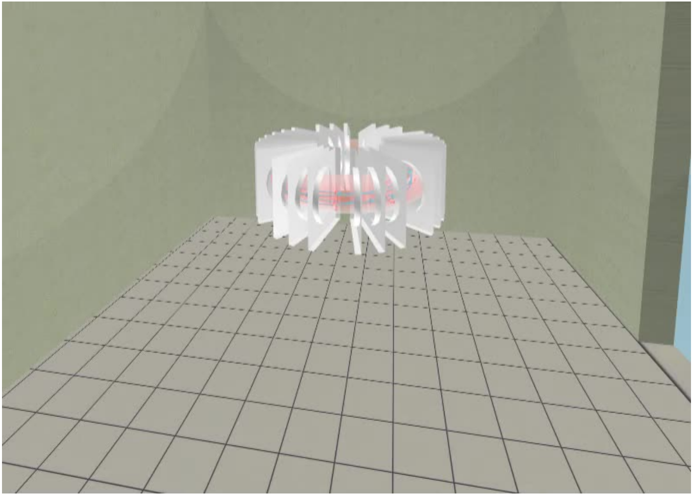
Magnetic confinement requires toroidal geometry



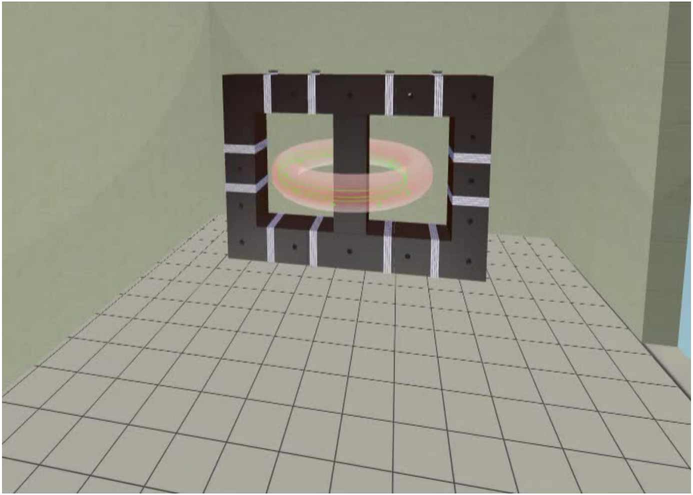
A chamber contains the thermonuclear reaction



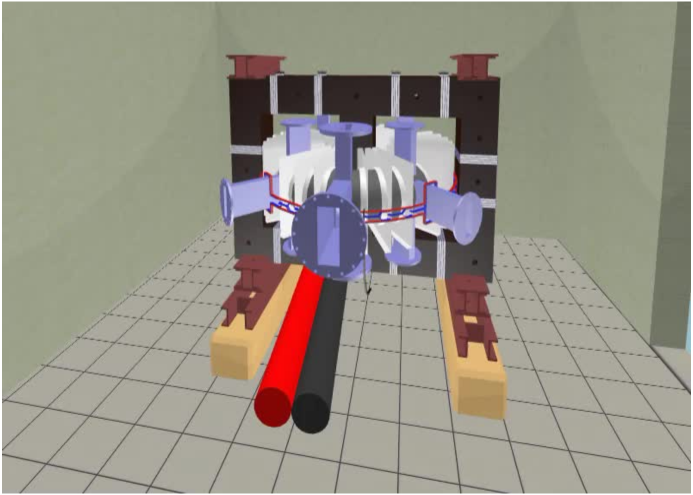
Toroidal magnetic field coils confine the plasma



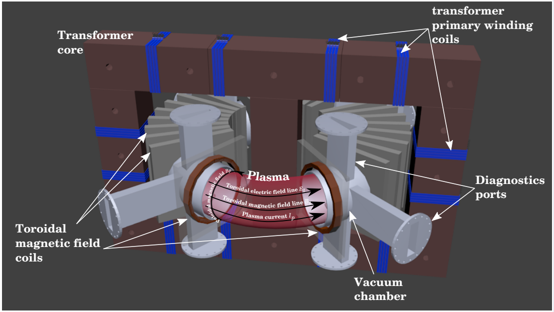
A transformer action creates and heats the plasma



The final technology altogether



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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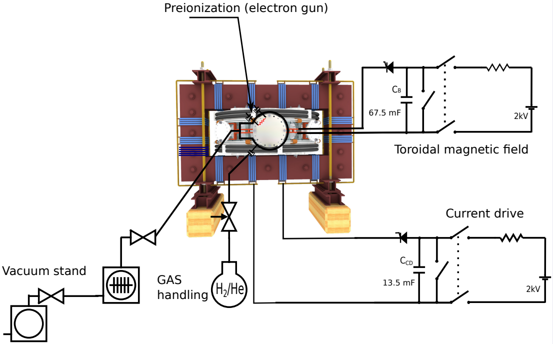

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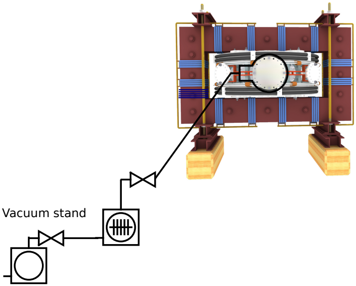

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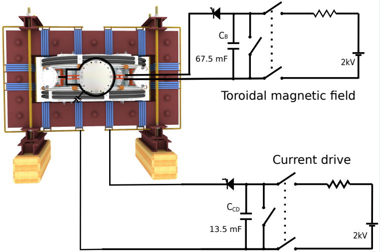

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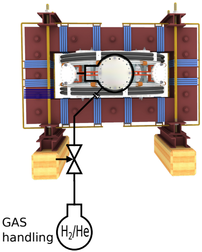

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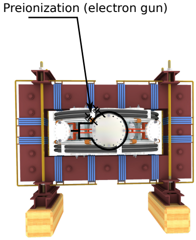

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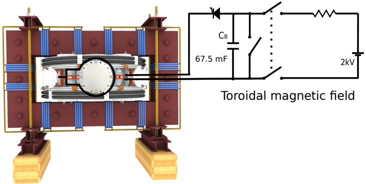

Toroidal magnetic field

To do:

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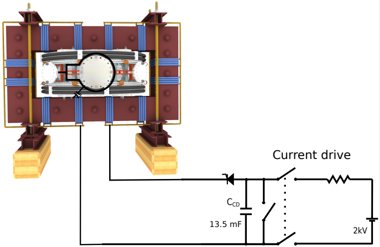

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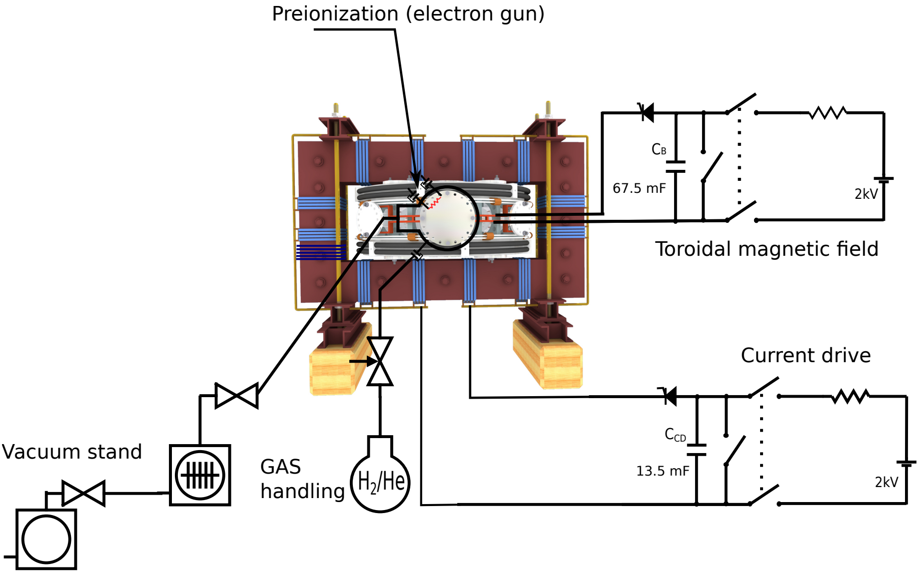
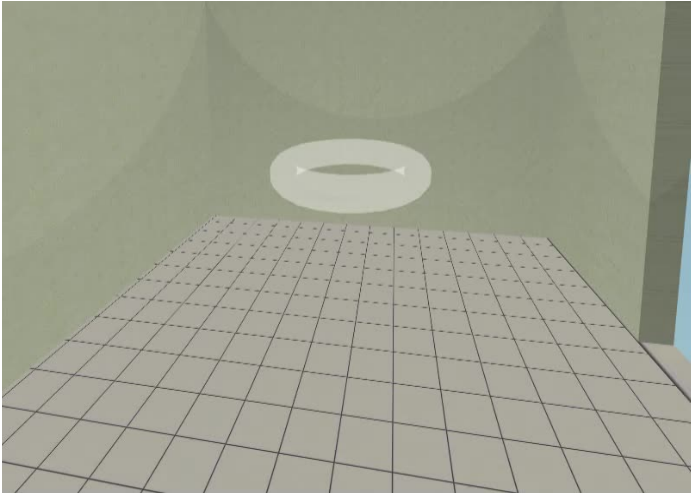
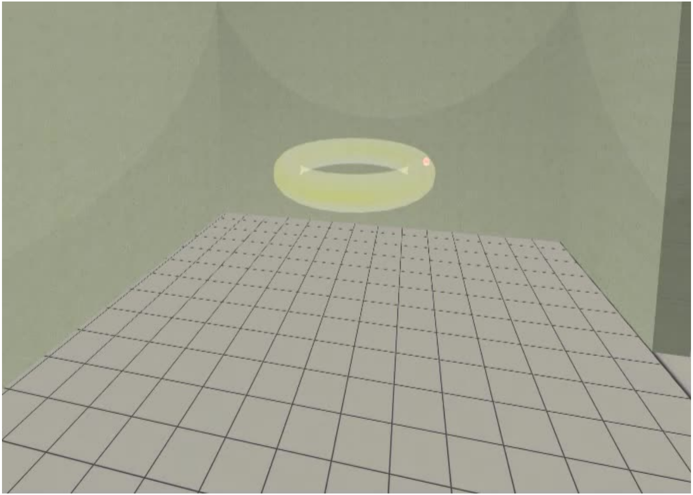
Tokamak GOLEM - schematic experimental setup



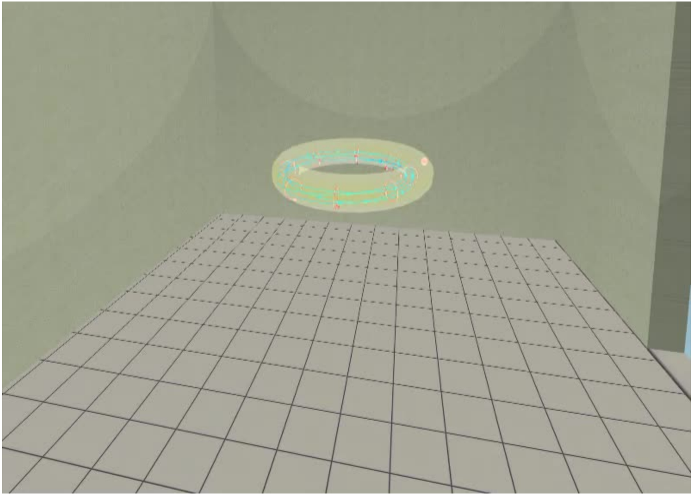
Introduce the working gas (Hydrogen x Helium)



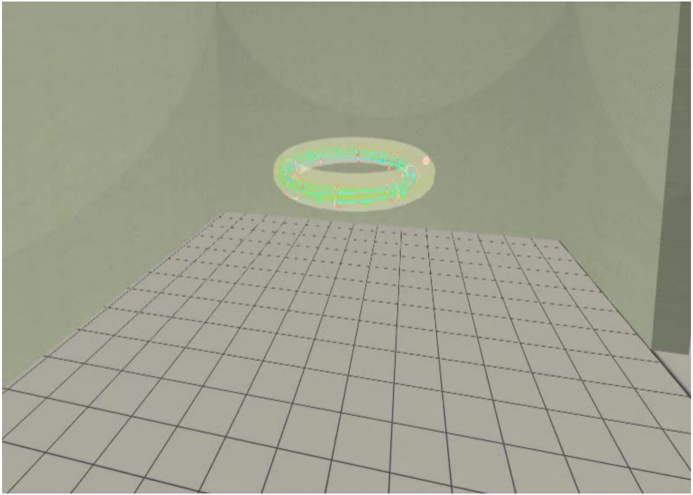
Switch on the preionization



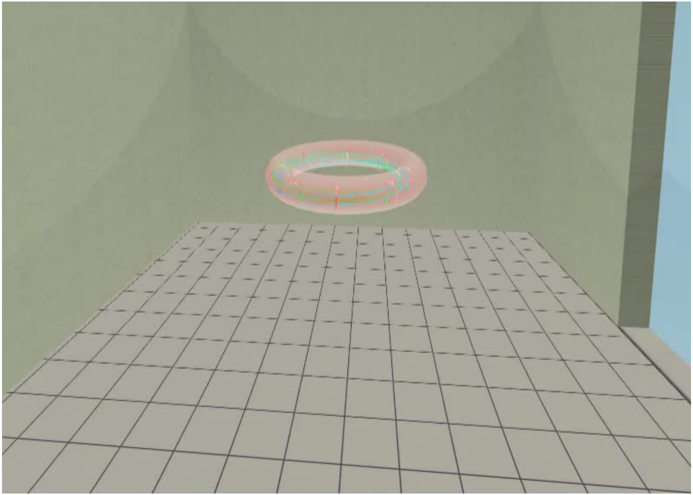
Introduce the magnetic field



Introduce the electric field



Plasma ..



Infrastructure room (below tokamak) 10/16

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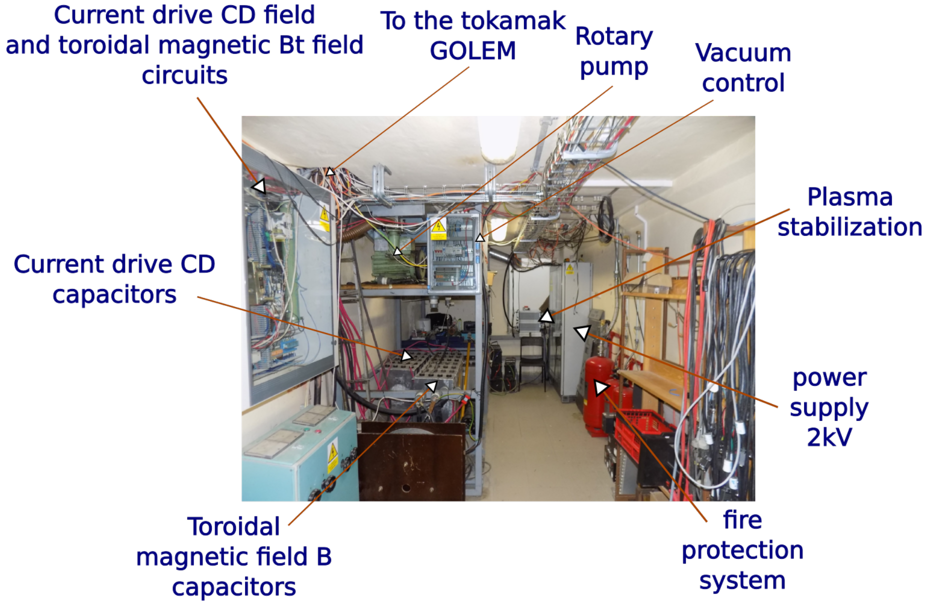
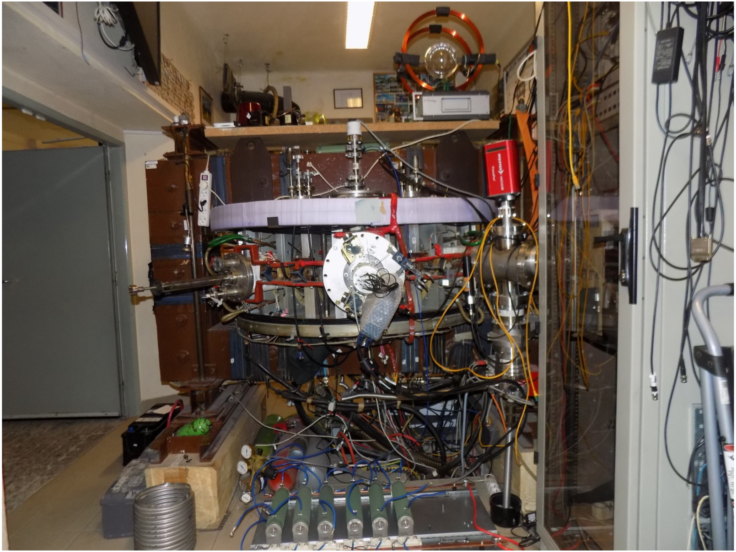
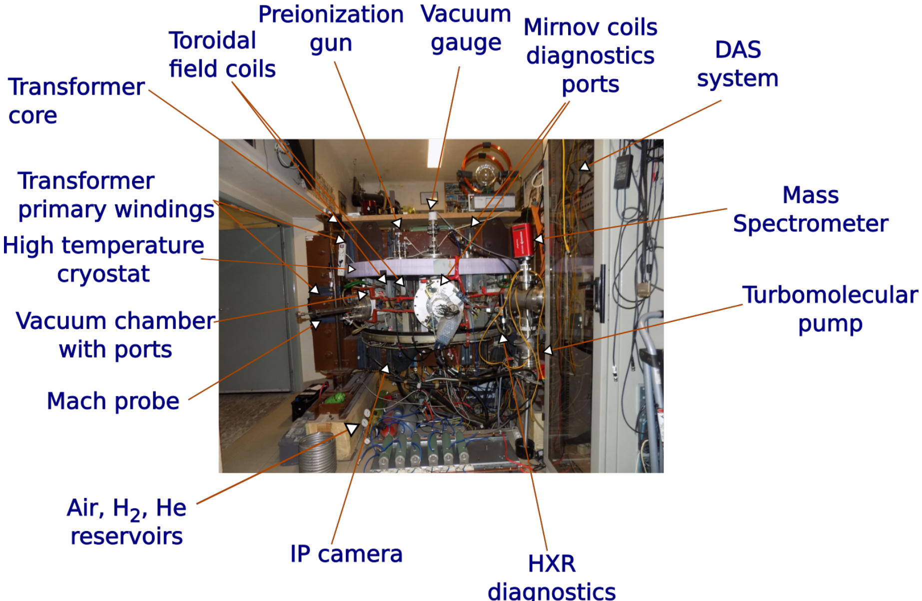


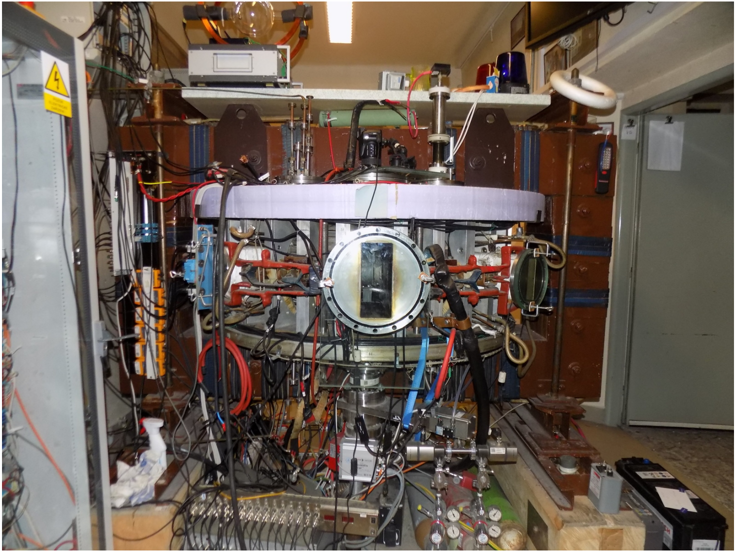
Tokamak room (North) 10/16



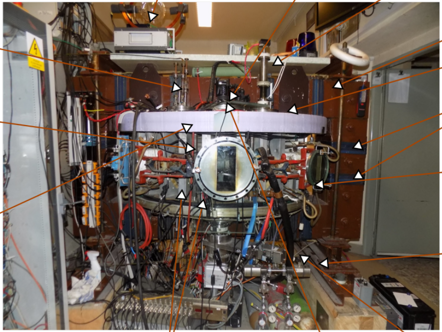
Tokamak room (North) 10/16



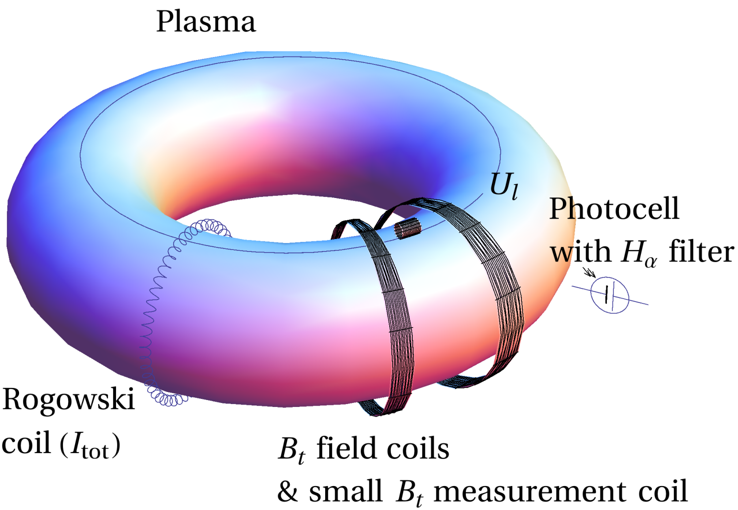
Tokamak room (South) 10/16



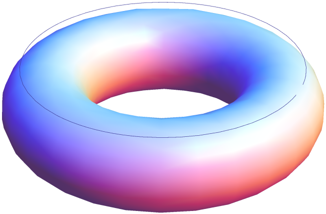
Tokamak room (South) 10/16

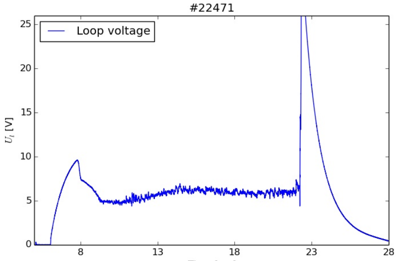


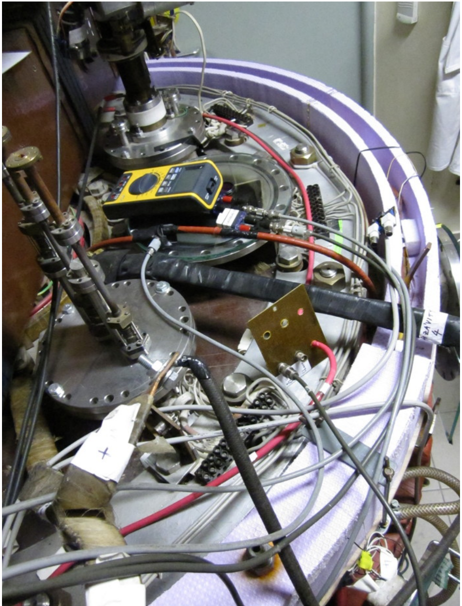
The GOLEM tokamak - basic diagnostics



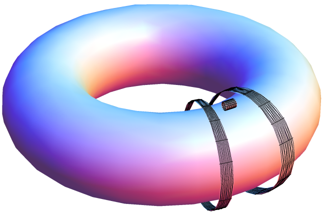
Loop voltage U_l @ the GOLEM tokamak

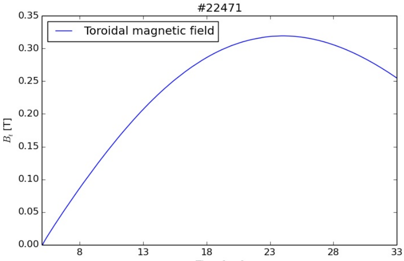


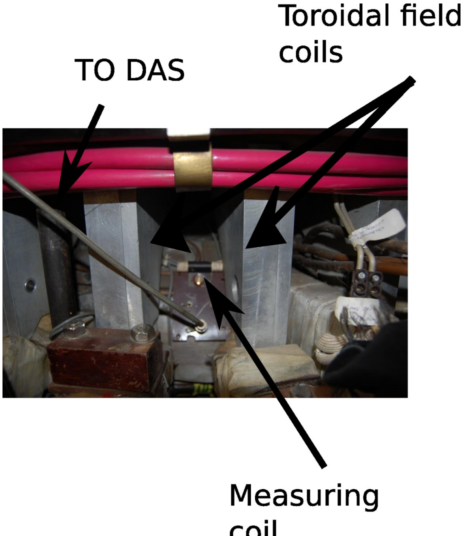




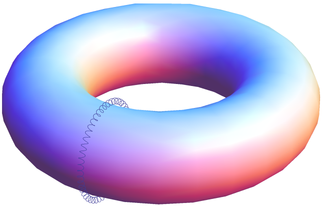
Toroidal magnetic field B_t @ the tokamak GOLEM

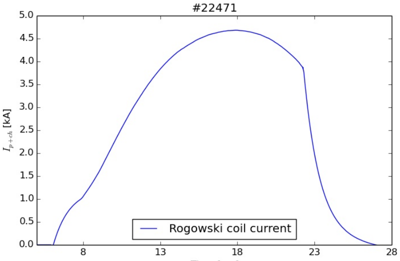


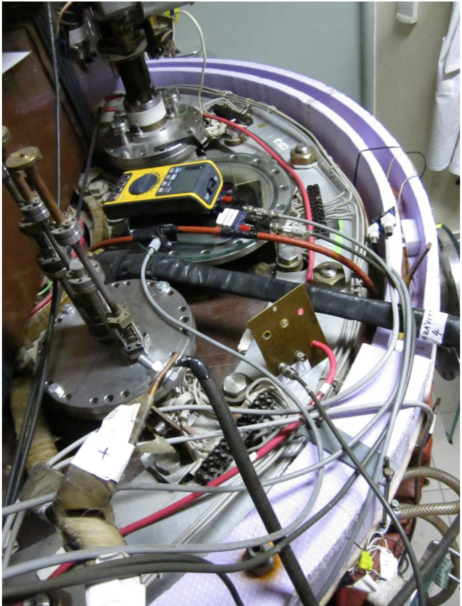




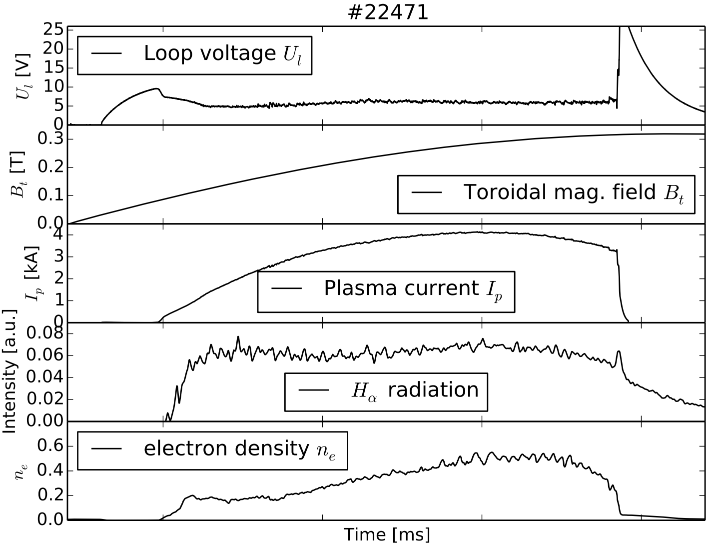
Total current I_{ch+p}



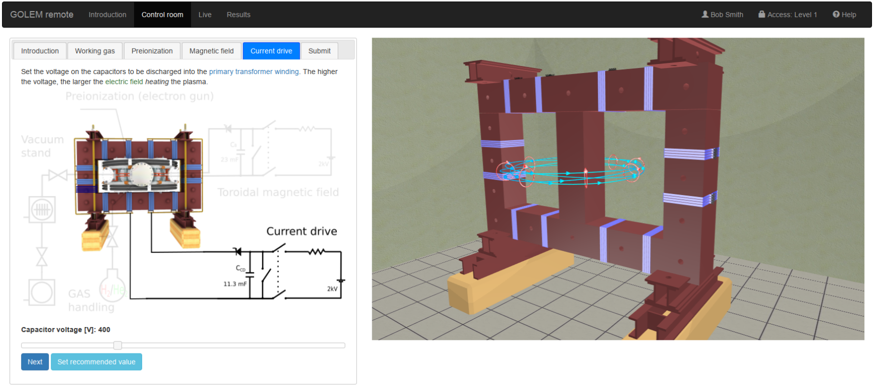




Basic diagnostics traces at the GOLEM tokamak



Remote operation web app - Control room



Shot homepage

GOLEM » Shot #22471 »

Diagnostics

- ✓ Interferometer
- ✓ Spectrometer
- × FastCamera
- ✓ HXR

Analysis

- ✓ ShotHomepage

DAS

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

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_t} capacitors charged to: 800 V, triggered 5.0 ms WIKI
- C_{BD} capacitors charged to: 0 V, triggered 5.0 ms WIKI
- C_{CD} capacitors charged to: 400 V, triggered 6.0 ms WIKI
- C_{ST} capacitors charged to: 0 V, triggered 5.0 ms WIKI
- Probability of breakdown: 85% WIKI
- Time since session beginning: 0:07:50 h

Plasma parameters:

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

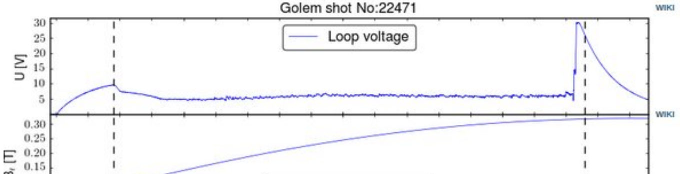


Table of Contents

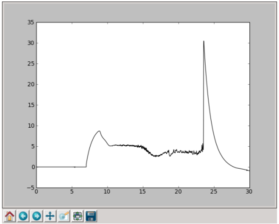
GOLEM **basic** Data Acquisition System (DAS)

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

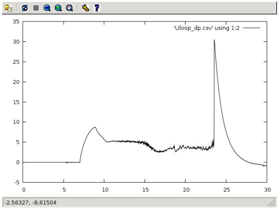
Data file example, DAS $\Delta t = 1\mu s/f = 1MHz$ (neutral gas into plasma breakdown focused)

t	$\approx U_l$	$\approx U_{\frac{dB_T}{dt}}$	$\approx U_{\frac{d(I_{p+ch})}{dt}}$	$\approx I_{rad}$
:	:	:	:	:
:	:	:	:	:
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 ..	
:	:	:	:	:
:	:	:	:	:

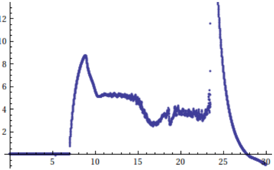
Plot #4665 U_l graph



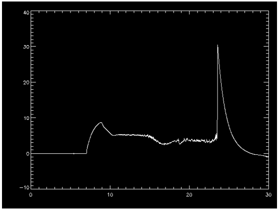
python



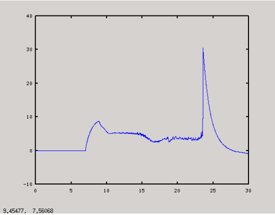
gnuplot



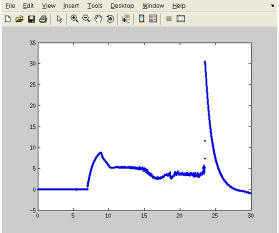
mathematica



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/utils/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/utils/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('U_l [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.DataSource('golem_cache')
#Create a path to data and download and open the file
base_url = "http://golem.fjfi.cvut.cz/utils/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

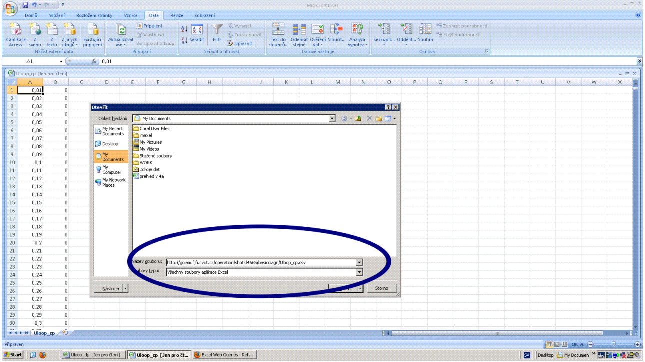
```
set macros;
ShotNo = "22471";
baseURL = "http://golem.fjfi.cvut.cz/utils/data/";
identifier = "loop_voltage";
#Create a path to data
DataURL= "@baseURL@ShotNo/@identifier";
#Write data from GOLEM server to a local file
!wget -q @DataURL;
#Plot the graph from a local file
set datafile separator "\t";
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/utils/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



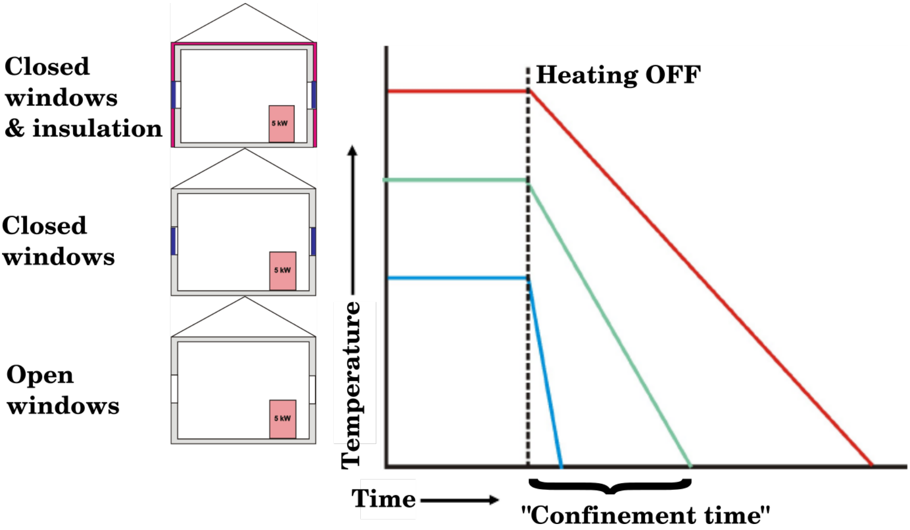
File→Open→
`http://golem.fjfi.cvut.cz/utils/data/<#ShotNo>/<identifier>`

Spredsheets (Excel and others)

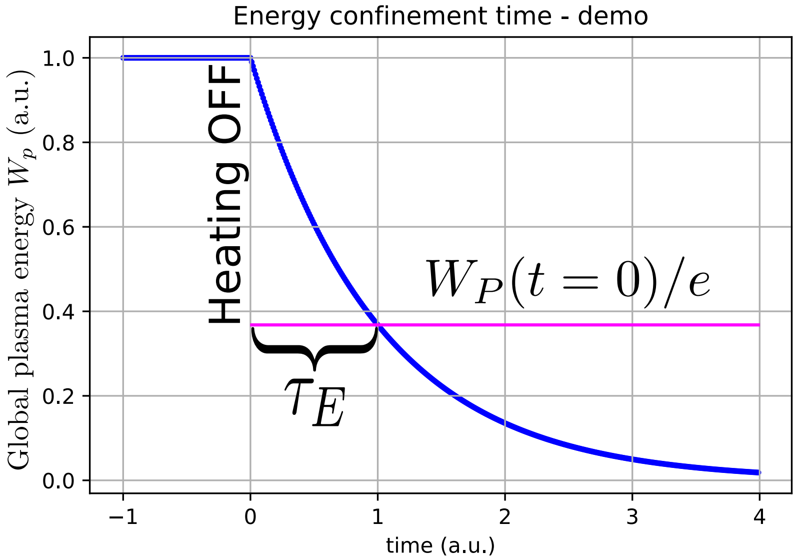
are not recommended, only tolerated.

Table of Contents

Energy balance of the house



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

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

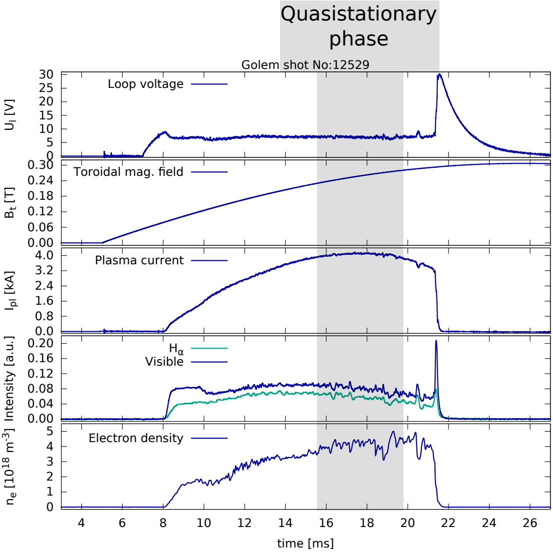
The energy confinement time is defined as the characteristic time scale of the exponential decay of the plasma energy W_p due to the loss power P_L:

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

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

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

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.

- $V_p \approx 80$ l

Central Electron Temperature estimation (Spitzer Formula)

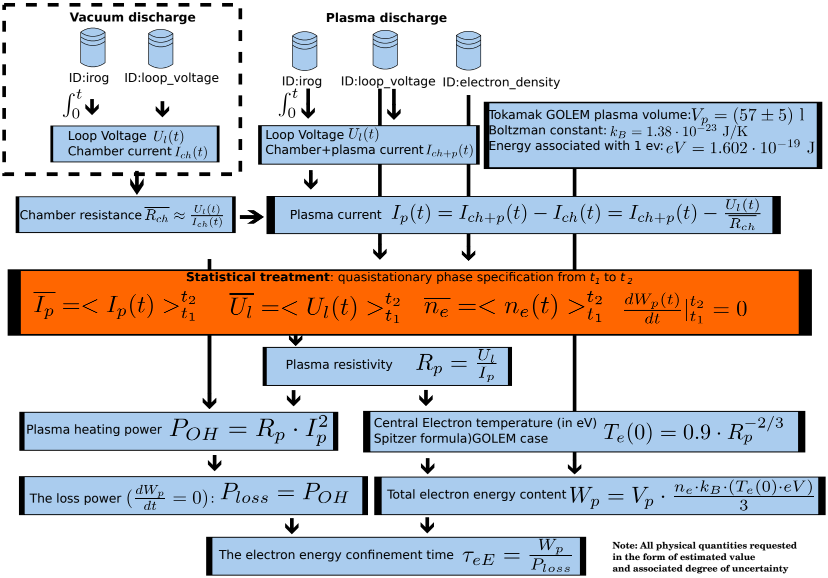
The time evolution of the central electron temperature $T_e(0,t)$ is calculated from equation based on Spitzer's resistivity formula (see eg. [1],[2]):

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

For particular case of the GOLEM tokamak it says:

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

Towards Electron energy confinement time τ_E



Suggested experimental aims

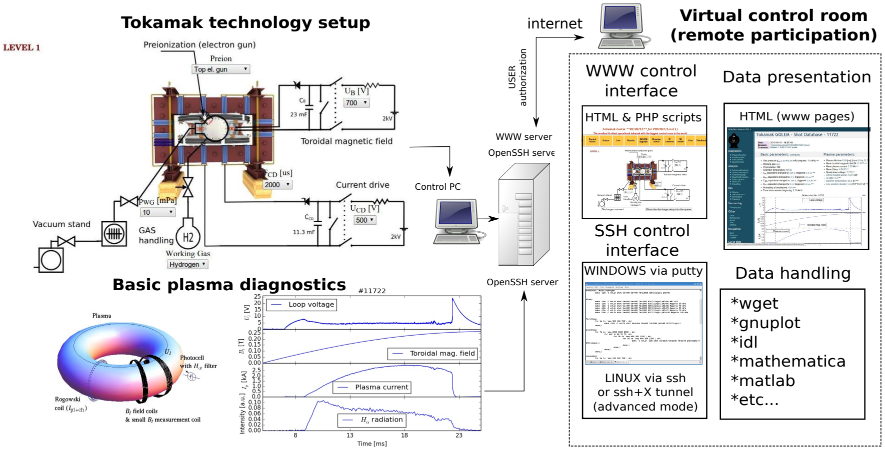
Plasma parameters worth optimizing: plasma duration, breakdown U_{loop}, central T_e, n_e, $W_p = VT_e n_e$, τ_E

Suggested method of optimization of a given plasma parameter:

1. analyze dependence of the plasma parameter on others (preferably machine parameters like I_p, B_t) in formulas and the physics background
2. select engineering parameters most likely to influence the chosen parameter
3. choose a set or several sets of points in the configuration space (U_{CD}, U_{Bt}, p_{WG}, ...) where only 1 parameter is varied at once
4. analyze the trends in the results from this set of discharges
5. choose a smaller region in the configuration space according to the discovered trends and use your empirical insight (and luck) to further optimize the parameter

Table of Contents

The global schematic overview of the GOLEM experiment



Resources and contact

- Everything via `http://golem.fjfi.cvut.cz/Cadarache`
  - This presentation
  - Control room
  - Data analysis tutorials
  - Contact: Ondřej Grover
    ondrej.grover@gmail.com

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Students, teachers, technicians (random order):

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References I

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