# Remote experiments at the GOLEM tokamak - Level 1

Ondřej Grover
on behalf of the GOLEM tokamak team
for the **Fusion Master gathering** training session

February 26, 2018

# 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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- The GOLEM tokamak discharge scenario
- Photographic tour of the GOLEM tokamak
- Basic (GOLEM) tokamak diagnostics

2 Remote experiments at the GOLEM tokamak
- Data handling at the GOLEM tokamak
- Electron energy confinement time calculation

3 Conclusion

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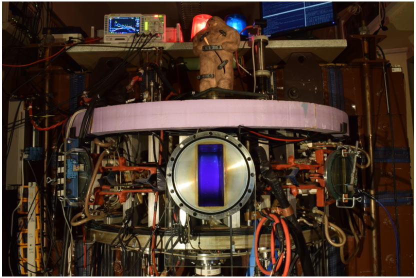
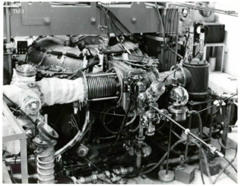
# Tokamak GOLEM basic characteristics



- Vessel major radius: $R_0 = 0.4$ m
- Vessel minor radius: $r_0 = 0.1$ m
- Plasma minor radius: $a = 0.06$ m
- Toroidal magnetic field: $B_t < 0.5$ T
- Plasma Current: $I_p = 8$ kA
- Electron density: $n_e \approx 0.2 - 3 \ \times 10^{19} \ m^{-3}$
- Electron temperature: $T_e = 100$ eV
- Ion temperature: $T_i = 50$ eV
- Discharge duration: $\tau_p = 25$ ms

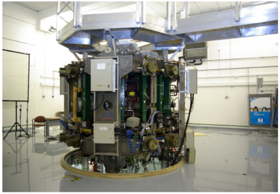
# Tokamak GOLEM for education - historical background

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



1974

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

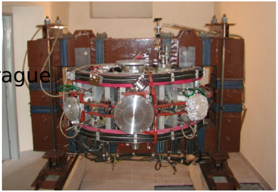


2006

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

2008

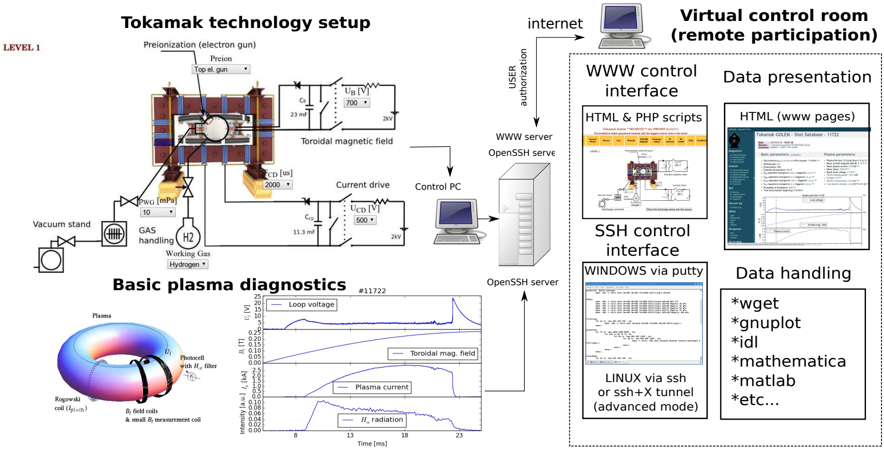
Czech Technical University Prague
Czech republic
**GOLEM**



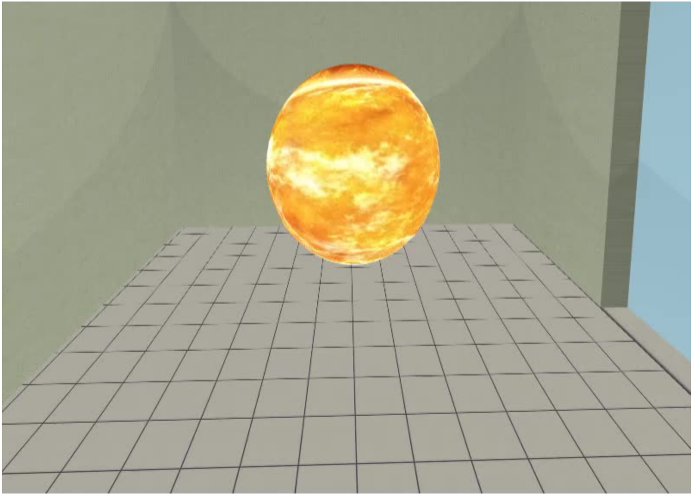
# GOLEM

The new location of the tokamak is just next to the old Prague Jewish cemetery where Rabi Loew (Golem builder) is burried, and that is why it was renamed GOLEM (and also for the symbol of potential power you get if you know the magic). Interestingly, here in Prague, where the Golem legend originated, 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.

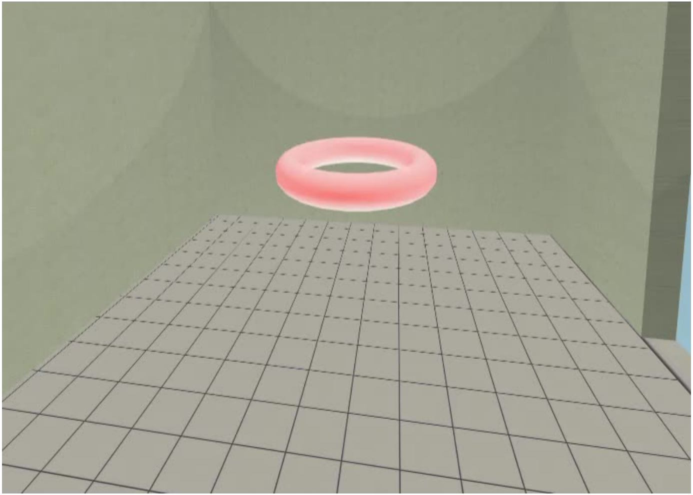
# The global schematic overview of the GOLEM experiment



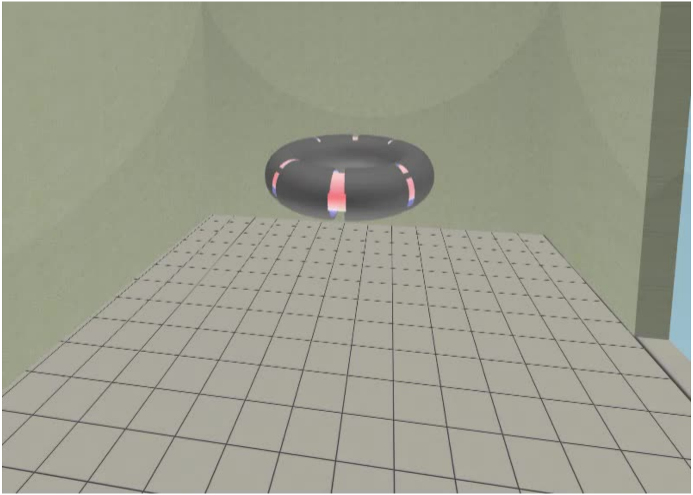
# Our goal: technology to create a $\mu$Sun on Earth



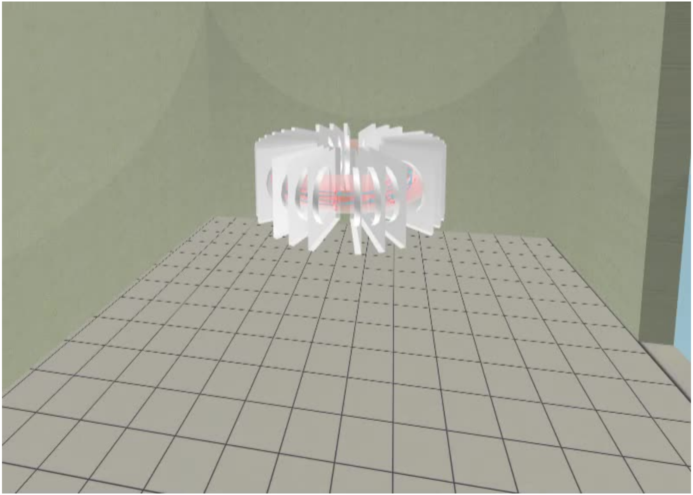
# Magnetic confinement requires toroidal geometry



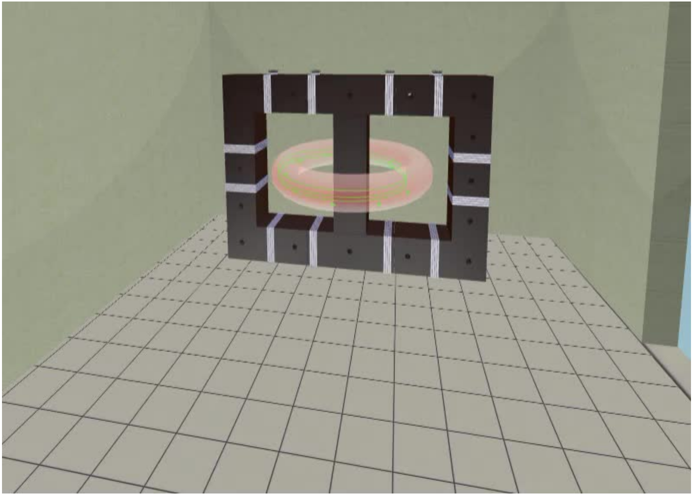
# A chamber contains the thermonuclear reaction



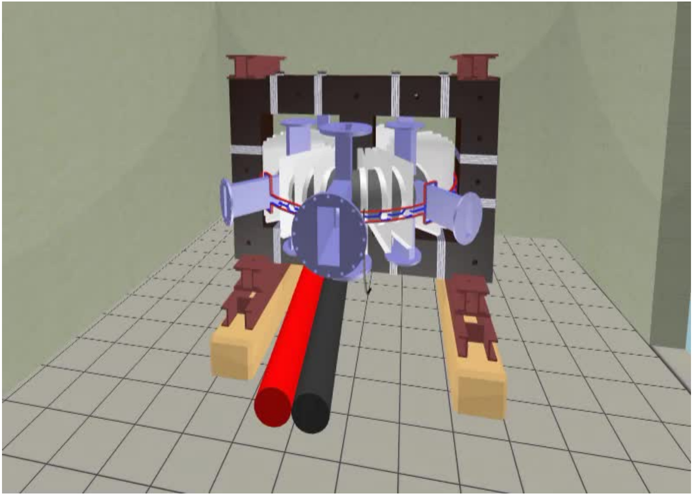
# Toroidal magnetic field coils confine the plasma



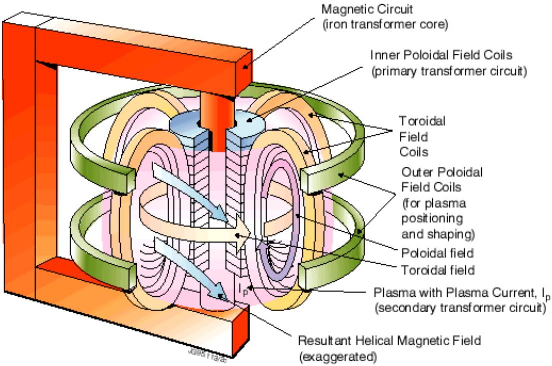
# A transformer creates and heats the plasma



# 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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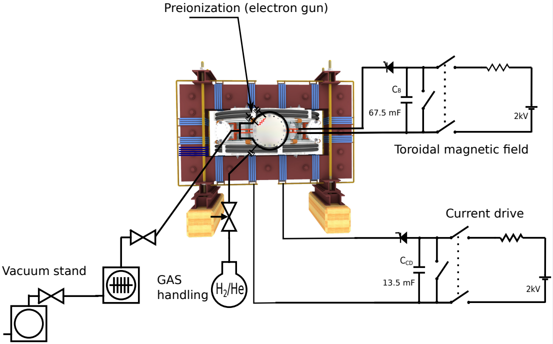


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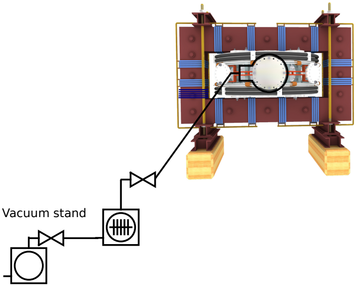


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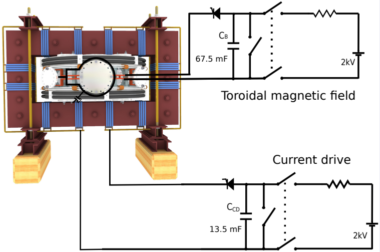


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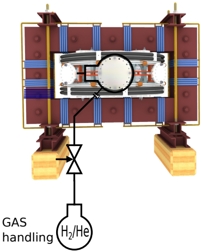


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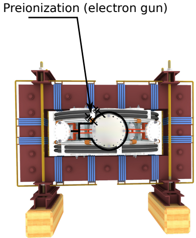


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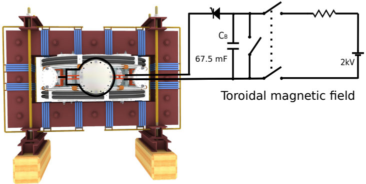


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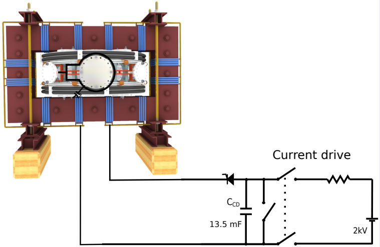


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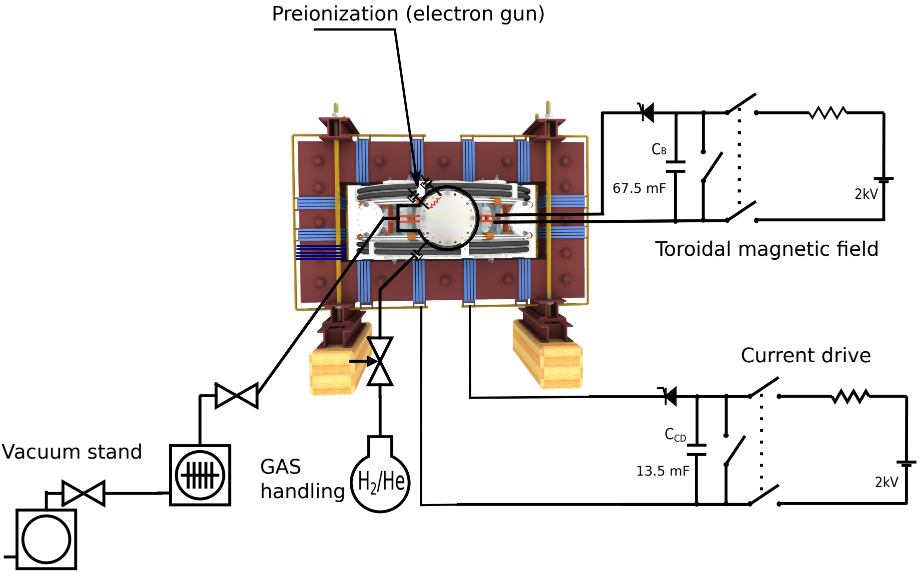
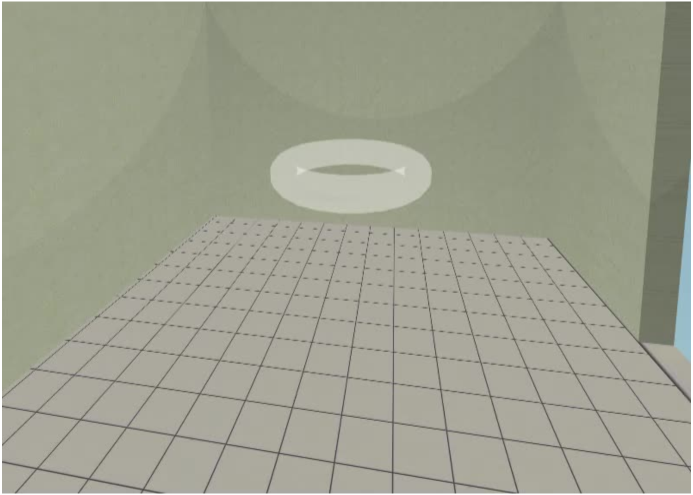
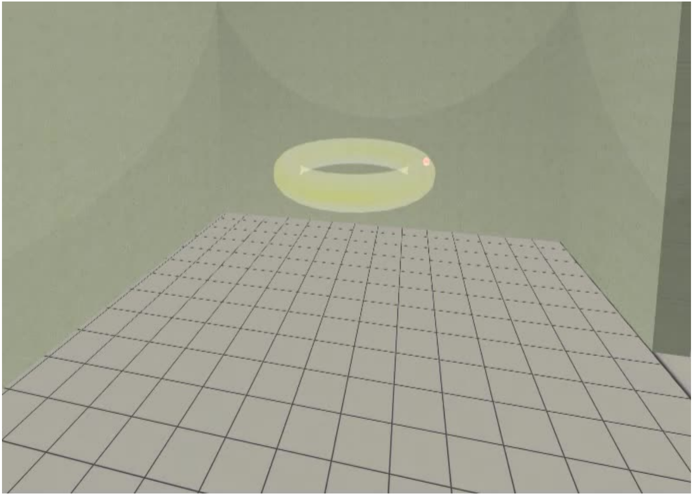
# Tokamak GOLEM - schematic experimental setup



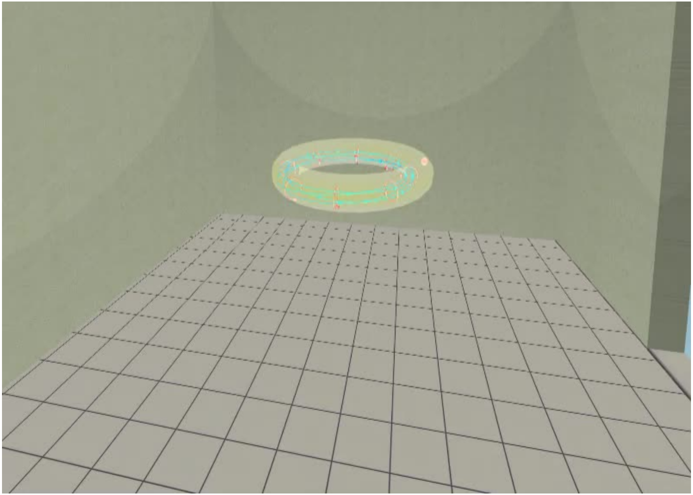
# Introduce the working gas (Hydrogen x Helium)



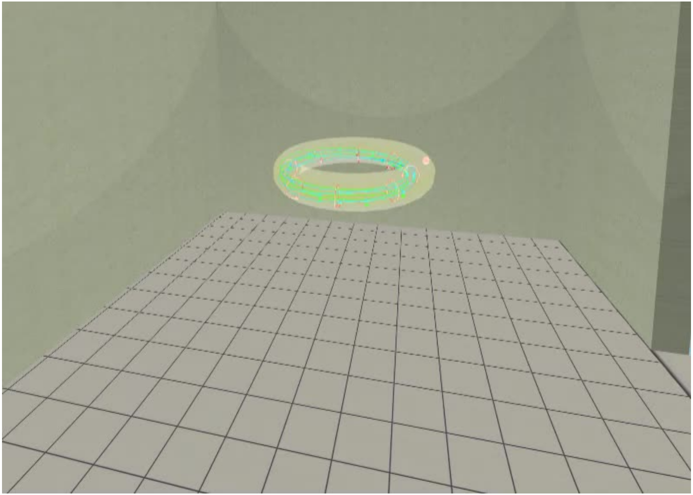
# Switch on the preionization



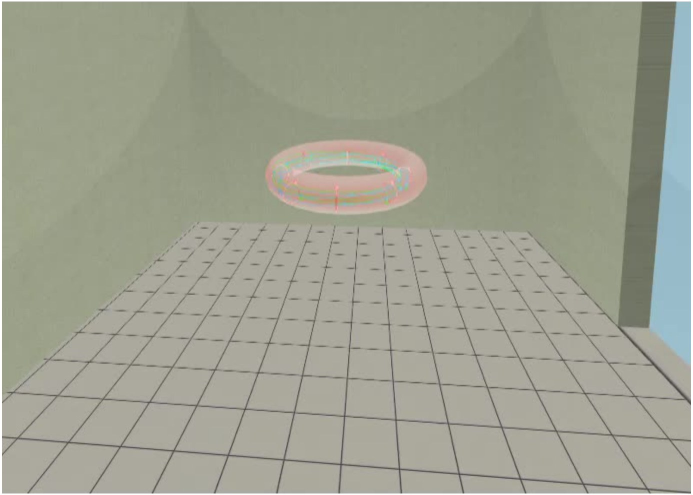
# Introduce the magnetic field



# Introduce the electric field



# Plasma ..



# Infrastructure room (below tokamak) 10/16

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Current drive CD field
and toroidal magnetic Bt field
circuits

To the tokamak
GOLEM

Rotary
pump

Vacuum
control

Plasma
stabilization

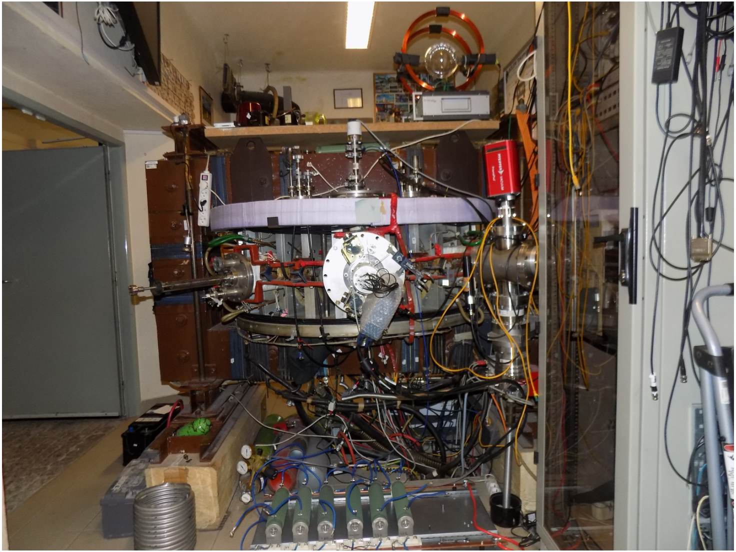
Current drive CD
capacitors

power
supply
2kV

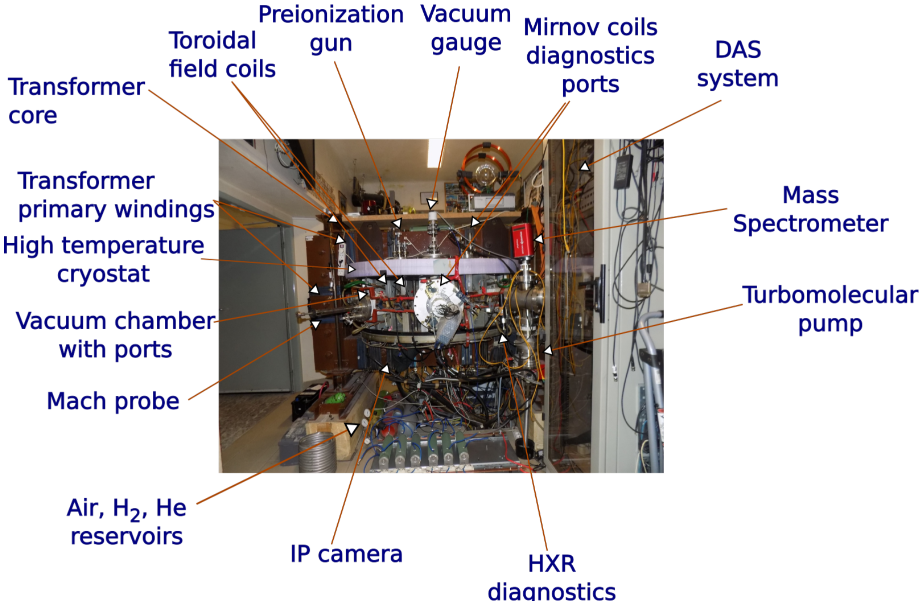
Toroidal
magnetic field B
capacitors

fire
protection
system

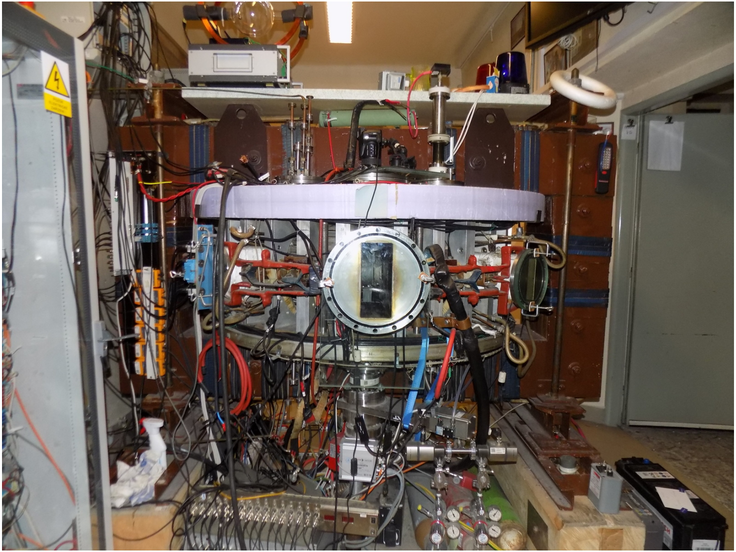
# Tokamak room (North) 10/16



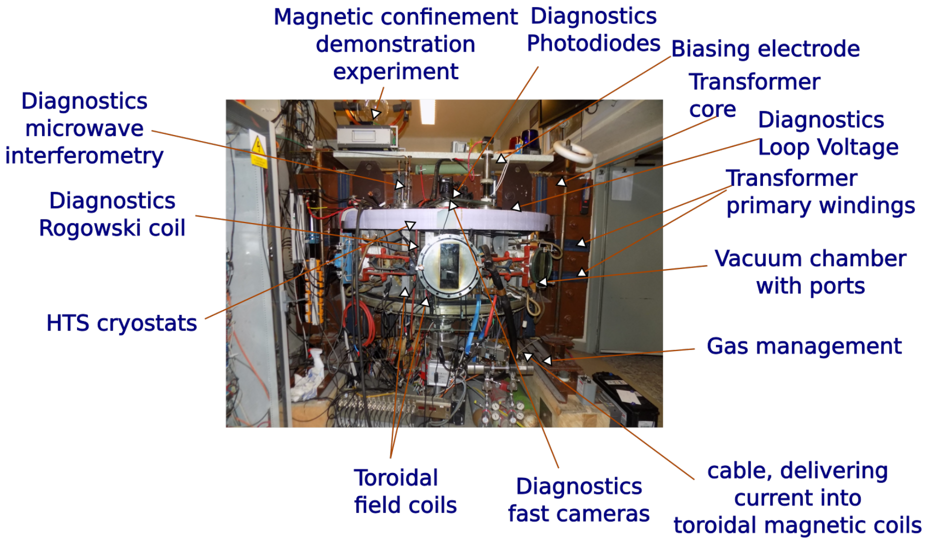
# Tokamak room (North) 10/16



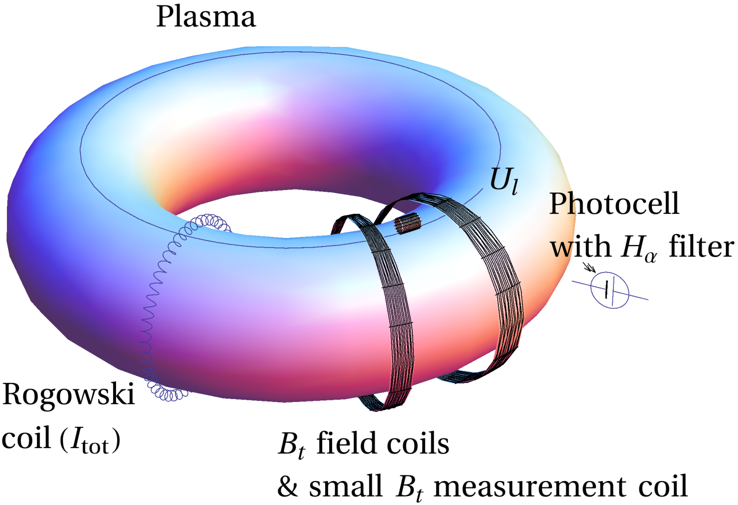
# Tokamak room (South) 10/16



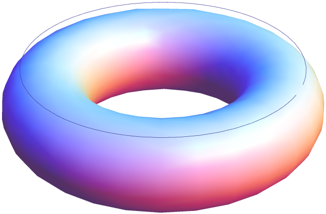
# Tokamak room (South) 10/16

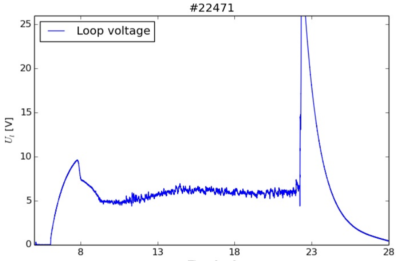


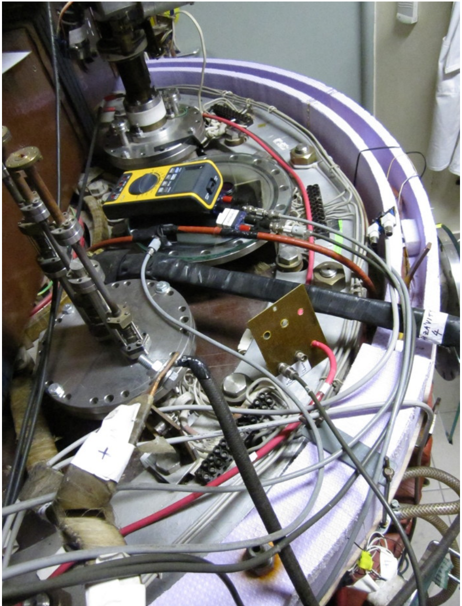
# Tokamak GOLEM - basic diagnostics



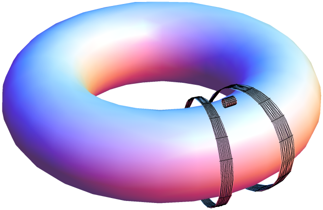
# Loop voltage $U_l$

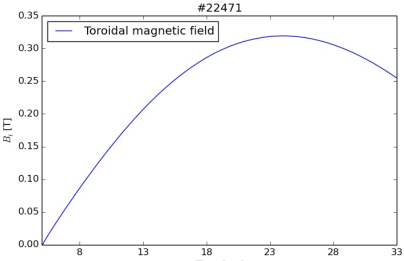


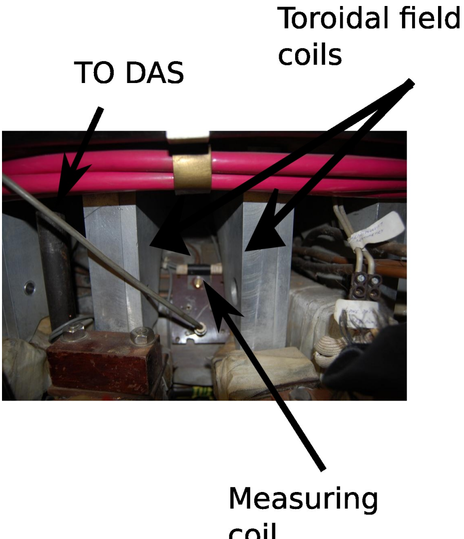


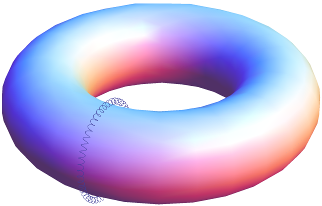
# Toroidal magnetic field $B_t$

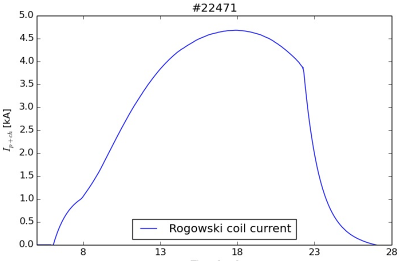


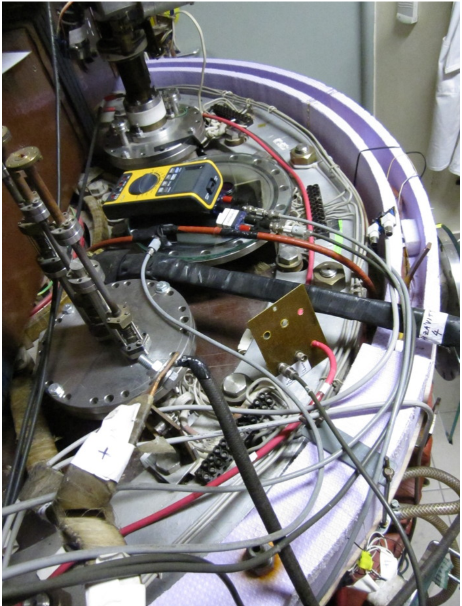


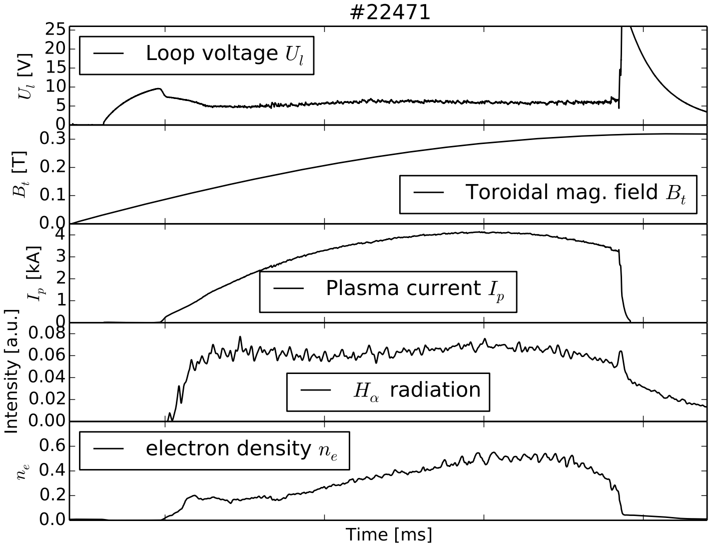
# Total current $I_{ch+p}$





# Basic diagnostics traces at the GOLEM tokamak



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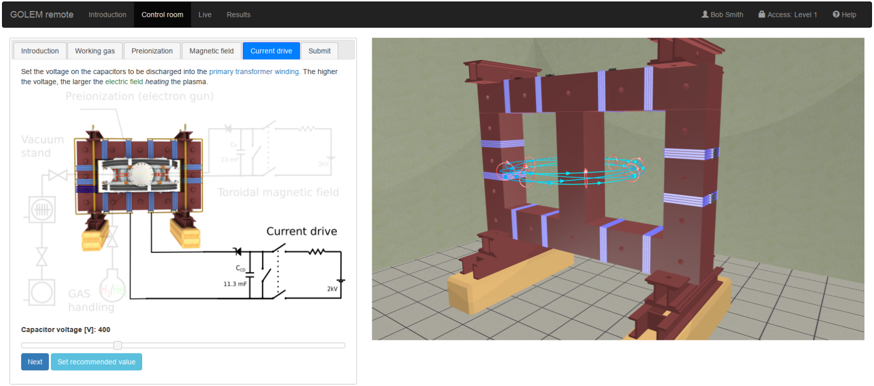
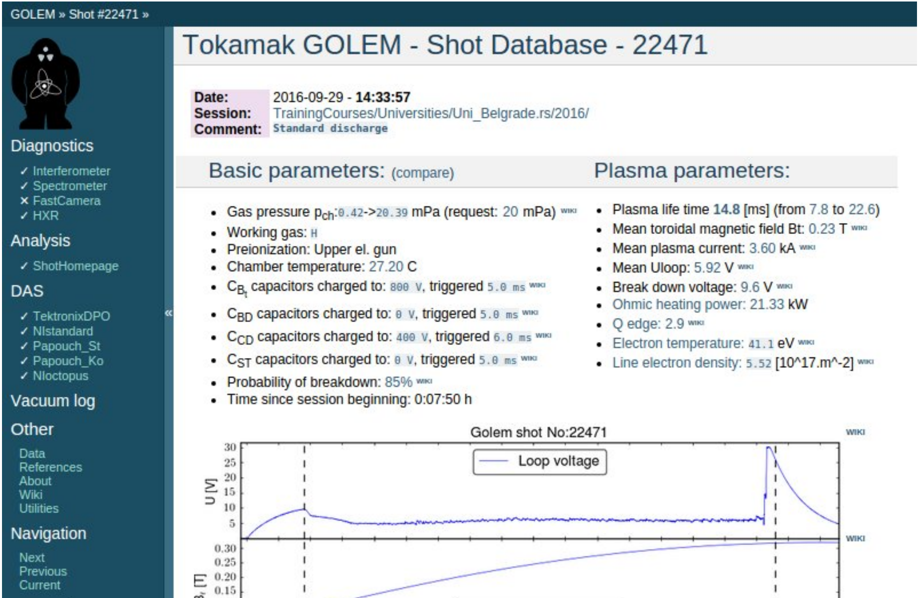
# Remote operation web app - Control room



# Shot homepage



# 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 | ≈ | 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 |
| : | : | : | : | : |
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| next | ≈ | 32500 | lines .. | |
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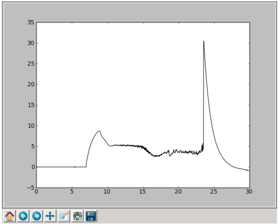
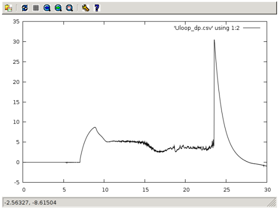
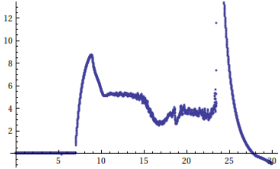
# Plot #4665 $U_l$ graph



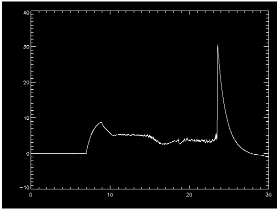
python



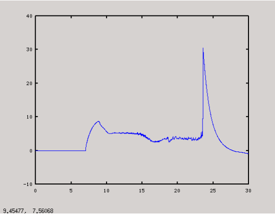

gnuplot



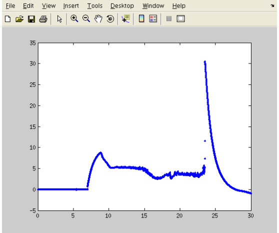
mathematica



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.DataStore('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

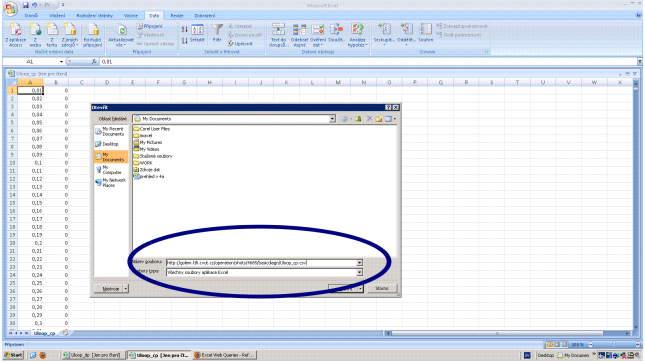
```
set macros;
ShotNo = "22471";
baseURL = "http://golem.fjfi.cvut.cz/utils/data/";
identifier = "loop_voltage";
#Create a path to data
DataURL= "@baseURL@ShotNo/@identifier";
#Write data from GOLEM server to a local file
!wget -q  @DataURL;
#Plot the graph from a local file
set datafile separator "\t";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

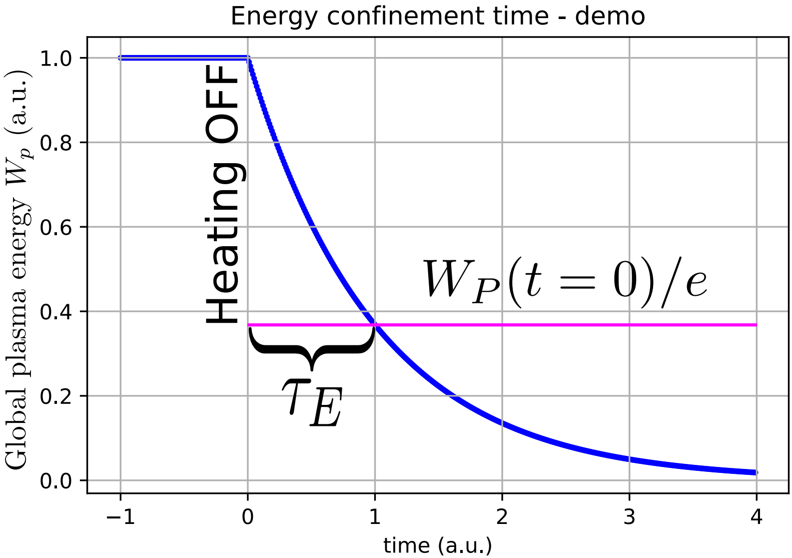



File→Open→
`http://golem.fjfi.cvut.cz/utils/data/<#ShotNo>/<identifier>`

## Spredsheets (Excel and others)

are not recommended, only tolerated.

# Energy confinement time - intro



# 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.

- $V_p \approx 80$ l

# Central Electron Temperature estimation (Spitzer Formula)

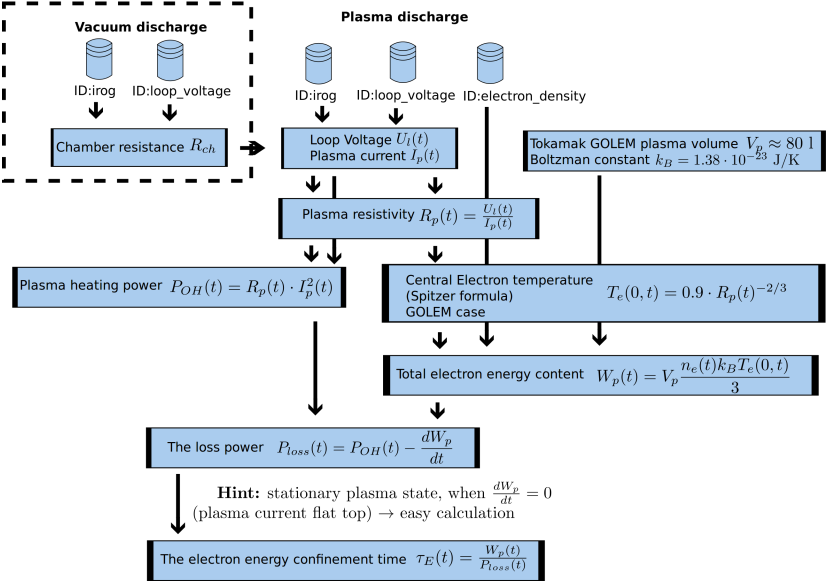
The time evolution of the central electron temperature $T_e(0,t)$ is calculated from equation based on Spitzer's resistivity formula (see eg. [1],[2]):

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

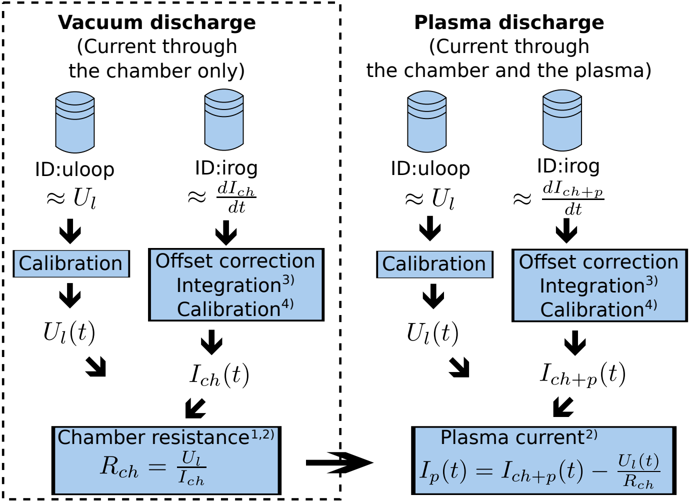
For particular case of the GOLEM tokamak it says:

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

# Towards Electron energy confinement time $\tau_E$



# 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 . $10^6$ A/Vs (see config.py)

# Suggested experimental aims

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

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 ($U_{CD}$, $U_{Bt}$, $p_{WG}$, $\dots$) 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

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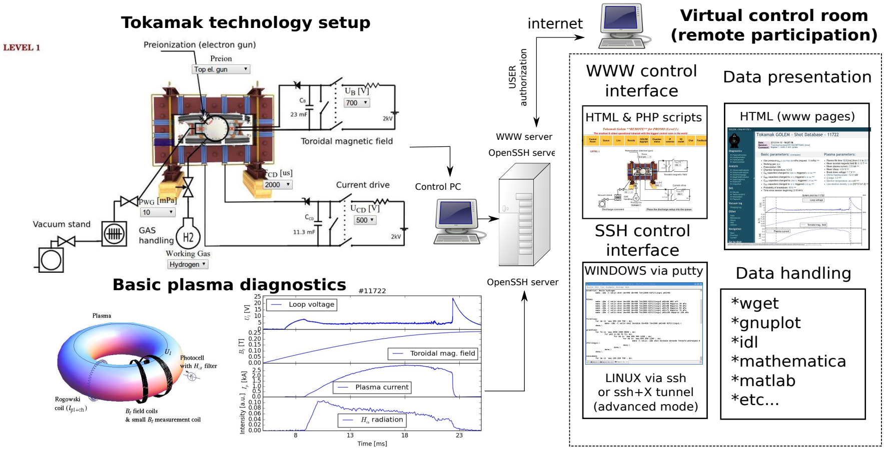
# The global schematic overview of the GOLEM experiment



# 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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# References I


Brotankova, J.
Study of high temperature plasma in tokamak-like experimental devices.
PhD. thesis 2009.

J. Wesson.
*Tokamaks*, volume 118 of *International Series of Monographs on Physics*.
Oxford University Press Inc., New York, Third Edition, 2004.

V. Svoboda, B. Huang, J. Mlynar, G.I. Pokol, J. Stockel, and G Vondrasek.
Multi-mode Remote Participation on the GOLEM Tokamak.
*Fusion Engineering and Design*, 86(6-8):1310–1314, 2011.

# References II

Tokamak GOLEM team.
Tokamak GOLEM at the Czech Technical University in Prague.
http://golem.fjfi.cvut.cz, 2007.