

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

Vojtěch Svoboda

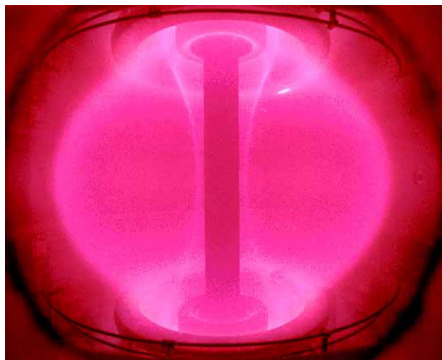
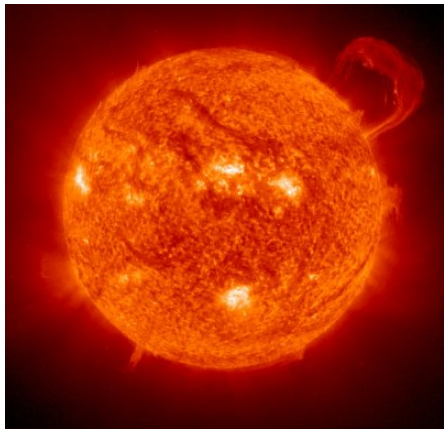
on behalf of the tokamak GOLEM team

for the Dec, the 12th event @ Torino politecnico, 2nd edition

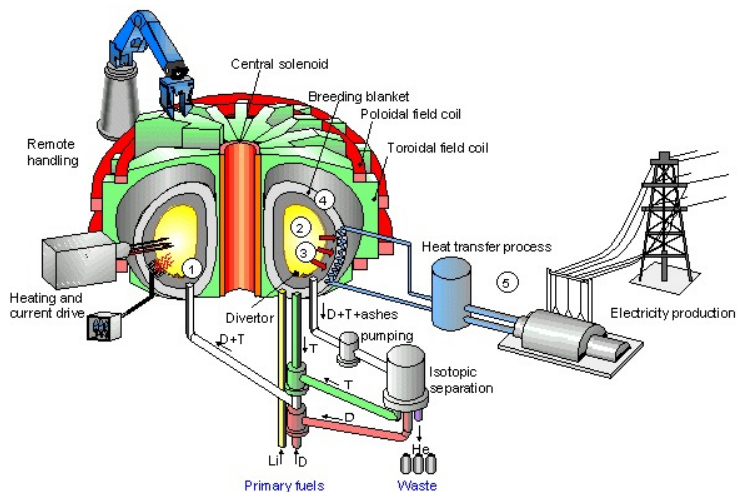
<http://golem.fjfi.cvut.cz/torino> OR <http://goo.gl/diBCy8>

January 26, 2018

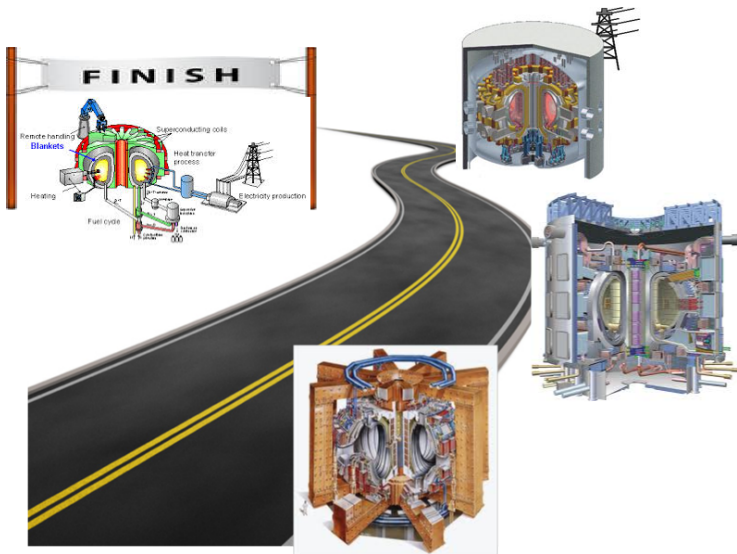
Foreword



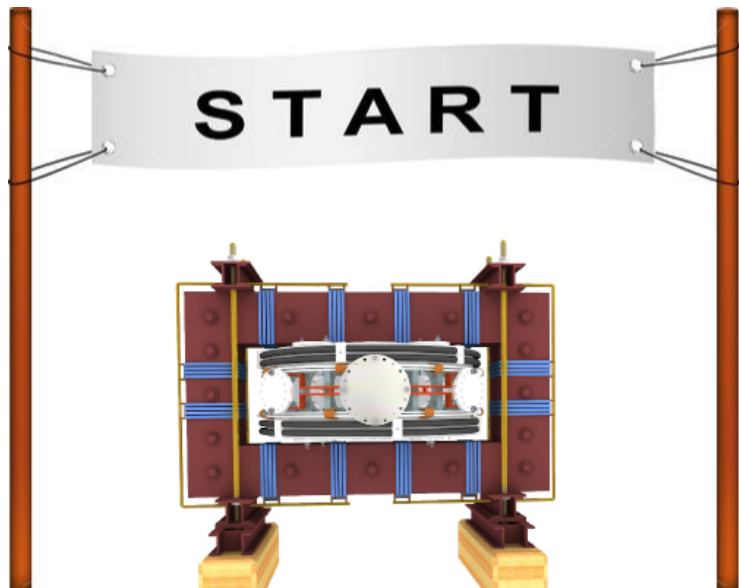
Our mission



Milestones to the Fusion Power Plant



Let's start with the tokamak GOLEM



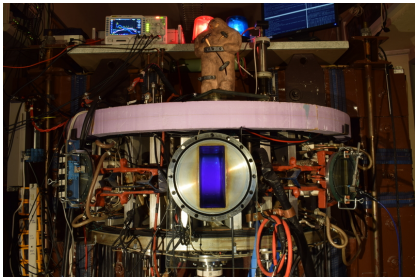
Notice/Warning/Alert

Everything simplified

... for educational purposes ..

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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:
 $n_e \approx 0.2 - 3 \times 10^{19} \text{ m}^{-3}$
- 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

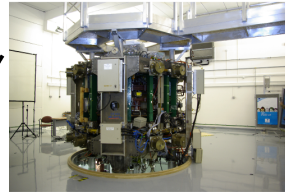


Institute of Plasma Physics
Czech republic
CASTOR **COMPASS**

2006



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



2008



Czech Technical University Prague
Czech republic
GOLEM



GOLEM

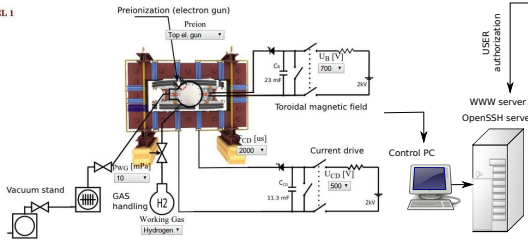


The new location of the tokamak is just next to the old Prague Jewish cemetery where Rabi Loew (Golem builder) is buried, and that is why it was renamed GOLEM (and also for the symbol of potential power you get if you know the magic). Interestingly, here in Prague, where the Golem legend originated,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

LEVEL 1

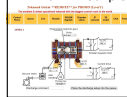
Tokamak technology setup



Virtual control room (remote participation)

WWW control interface

HTML & PHP scripts



SSH control interface

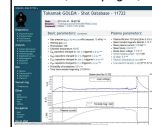
WINDOWS via putty



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

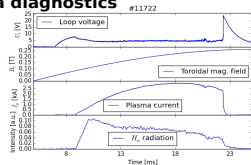
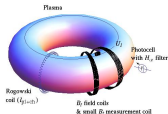
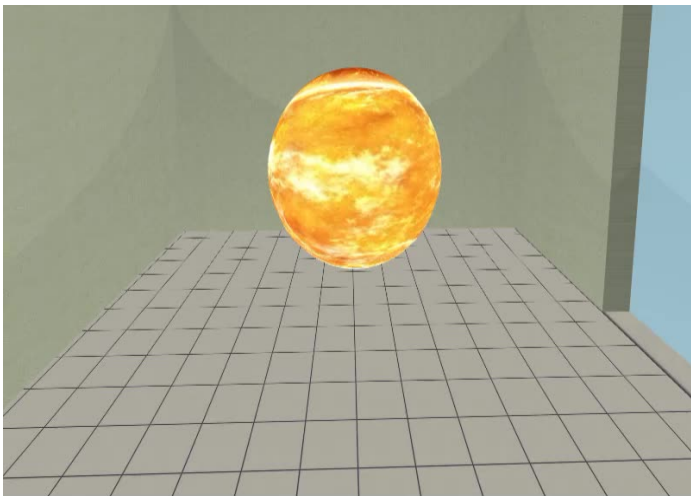
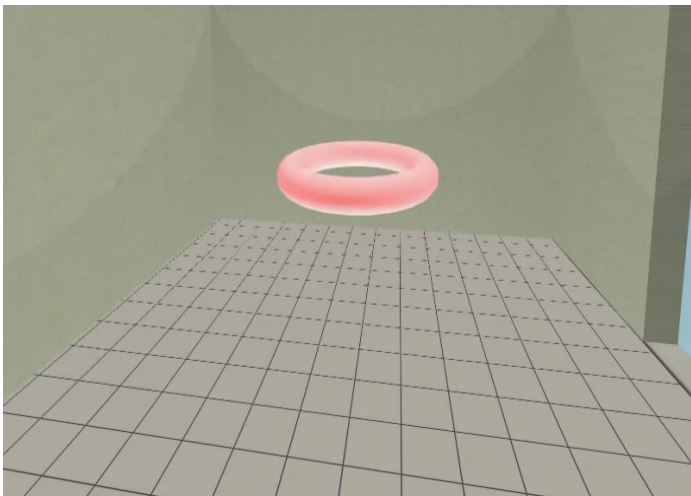


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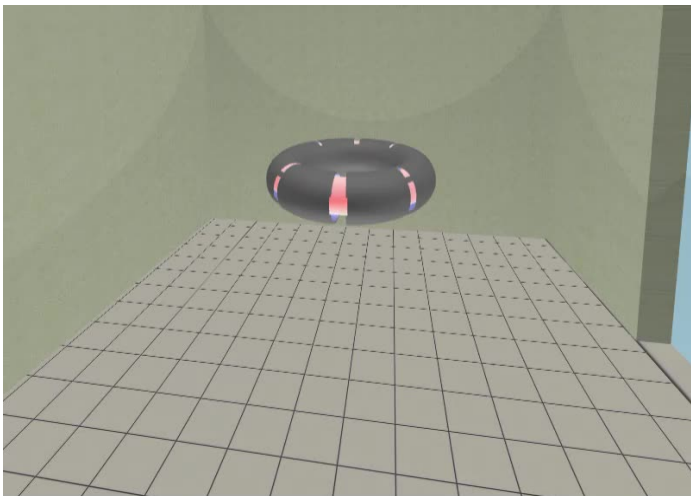
The technology to conquer: make a μ Sun on the Earth



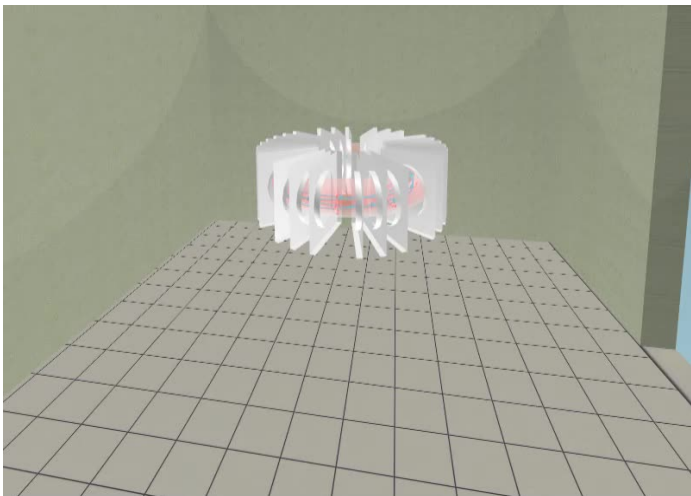
Magnetic confinement requires the toroidal geometry



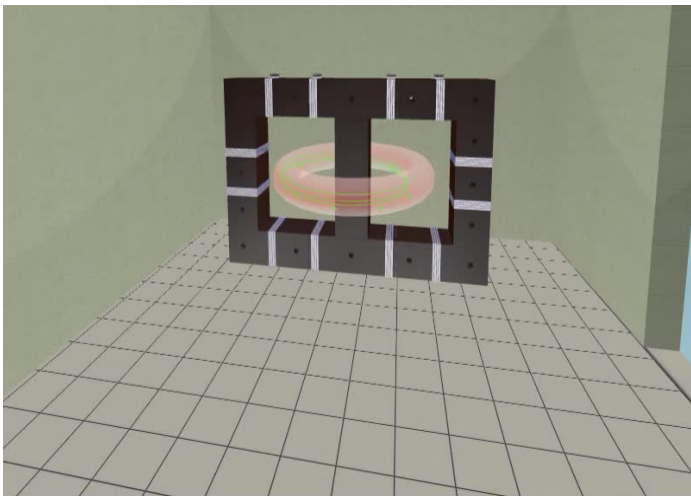
The thermonuclear reaction takes place in the chamber



Toroidal magnetic field coils secure the plasma confinement



Transformer secures the plasma creation and heating



The final technology altogether

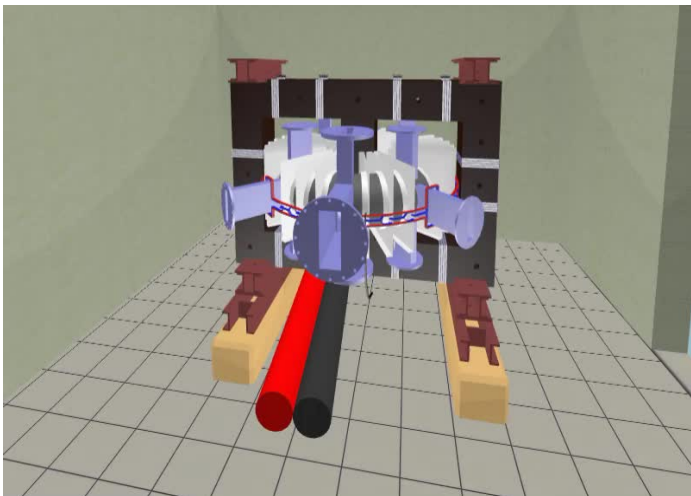
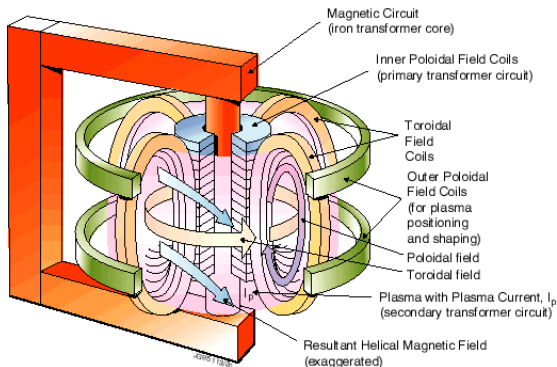


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Plasma in Tokamak (GOLEM) - the least to do



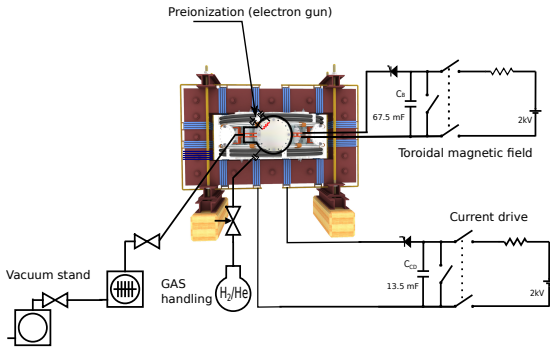
To do:

- 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:

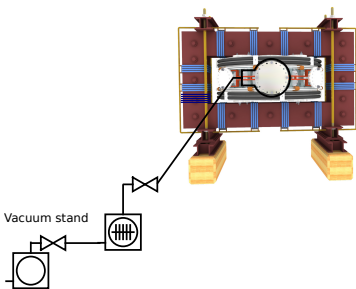
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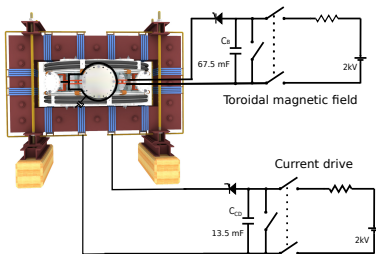
Plasma in Tokamak (GOLEM) - the least to do

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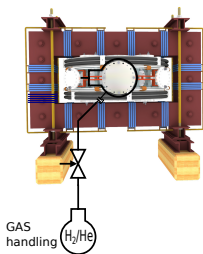
Plasma in Tokamak (GOLEM) - the least to do



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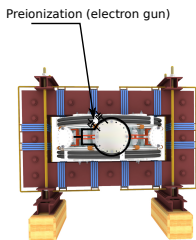
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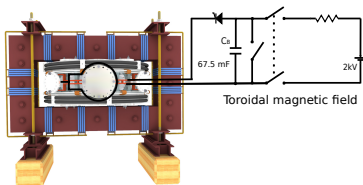
Plasma in Tokamak (GOLEM) - the least to do



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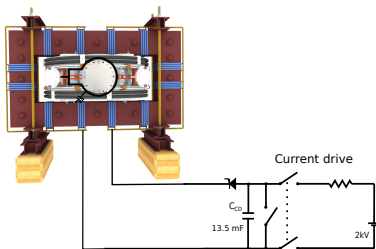
Plasma in Tokamak (GOLEM) - the least to do



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Tokamak GOLEM - schematic experimental setup

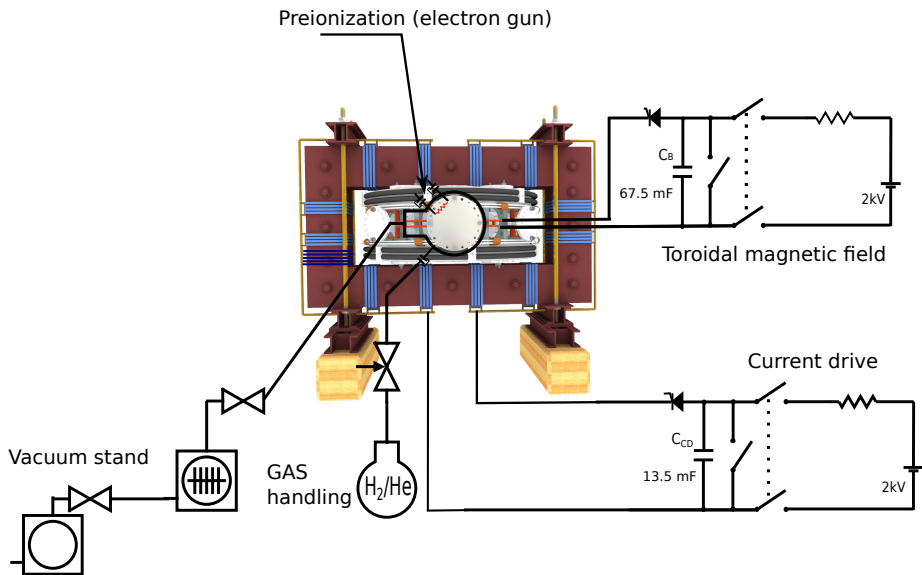
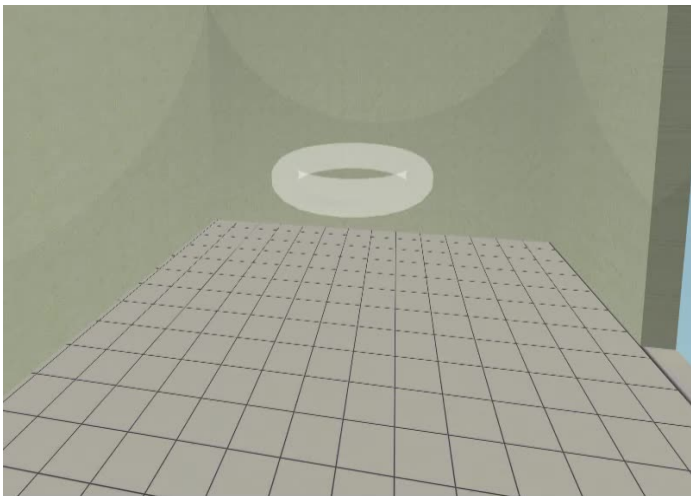
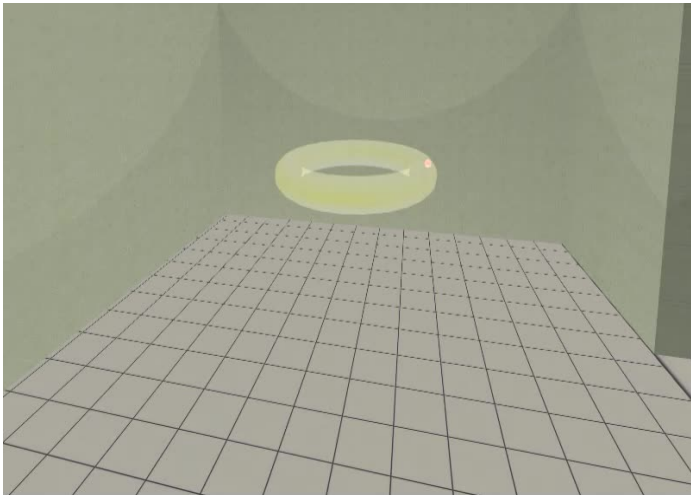


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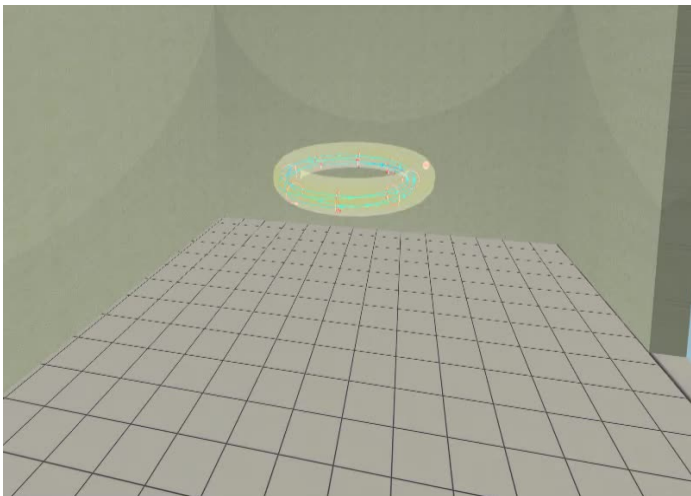
Introduce the working gas (Hydrogen x Helium)



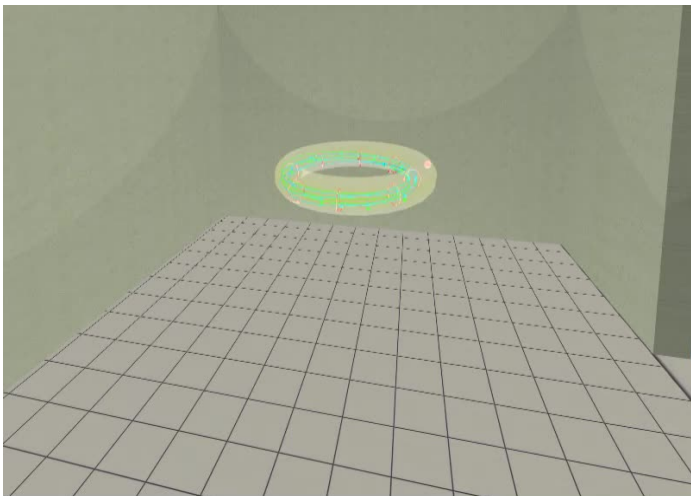
Switch on the preionization



Introduce the magnetic field



Introduce the electric field



Plasma ..

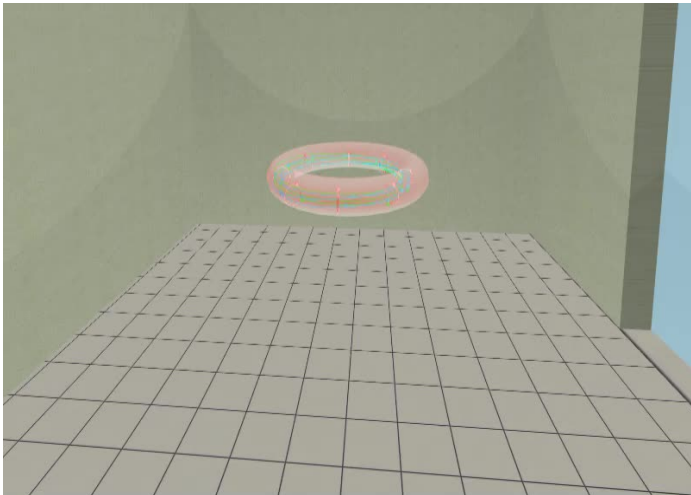


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Infrastructure room (below tokamak) 10/16



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

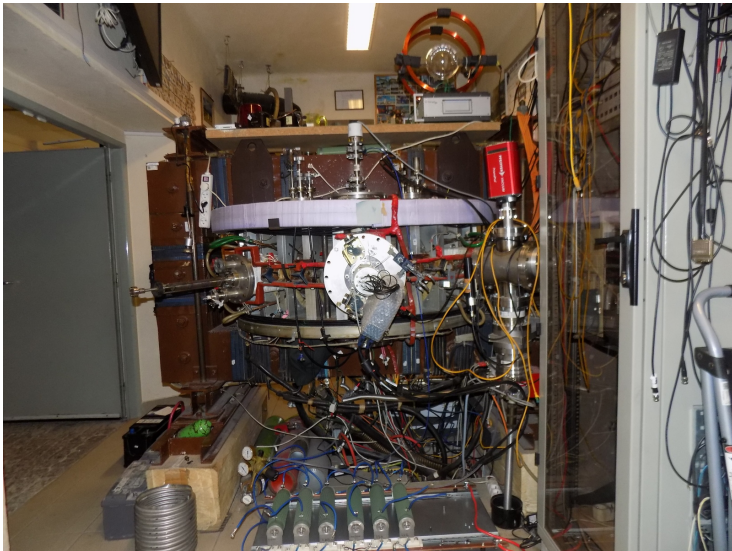
Plasma
stabilization

power
supply
2kV

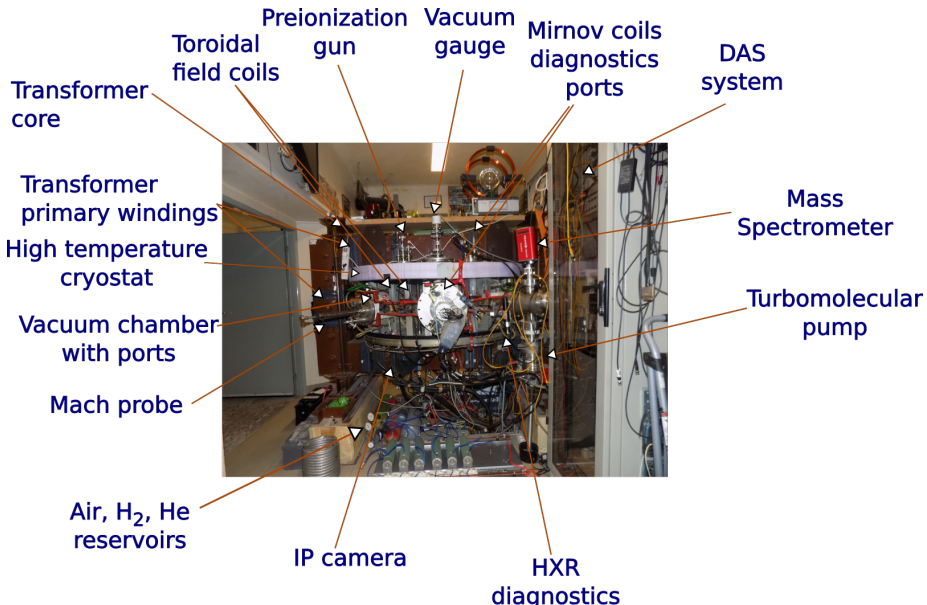
Toroidal
magnetic field B
capacitors

fire
protection
system

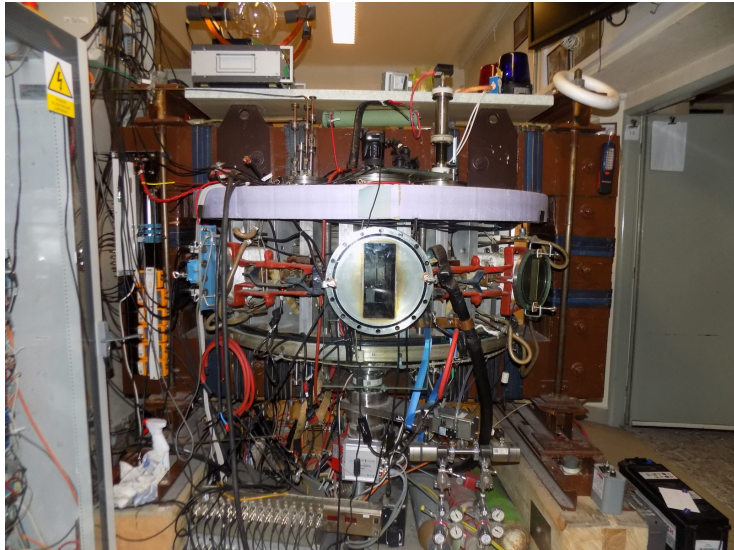
Tokamak room (North) 10/16



Tokamak room (North) 10/16



Tokamak room (South) 10/16



Tokamak room (South) 10/16

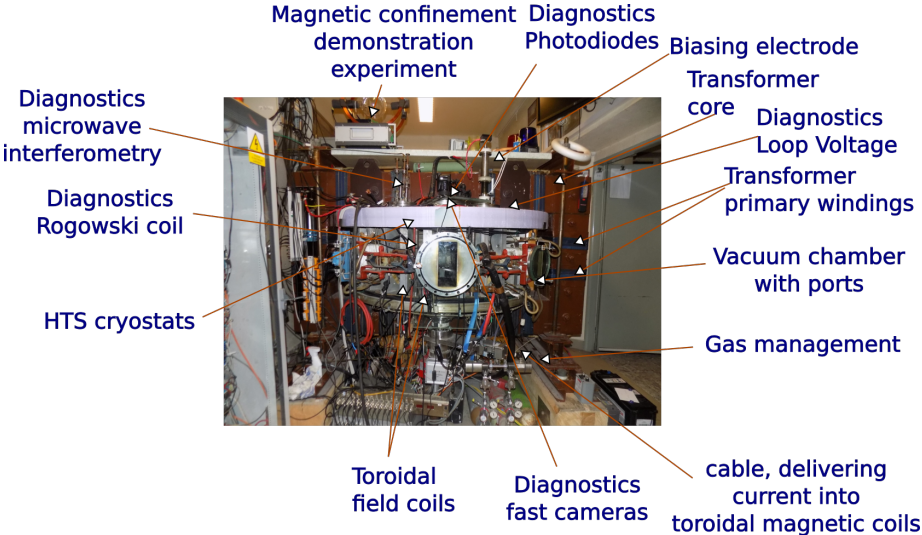
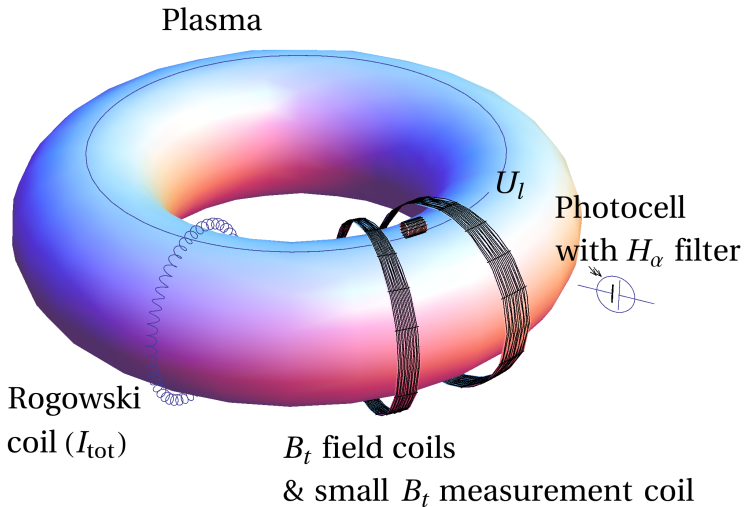
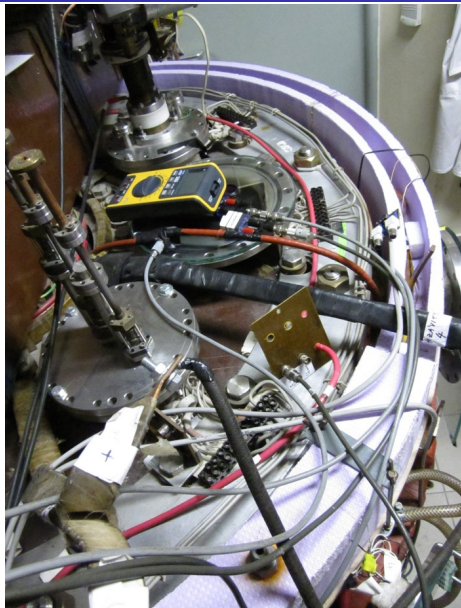
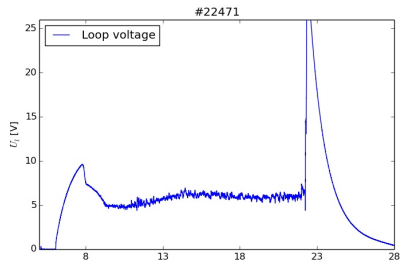
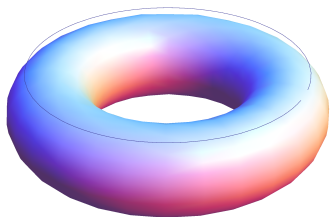


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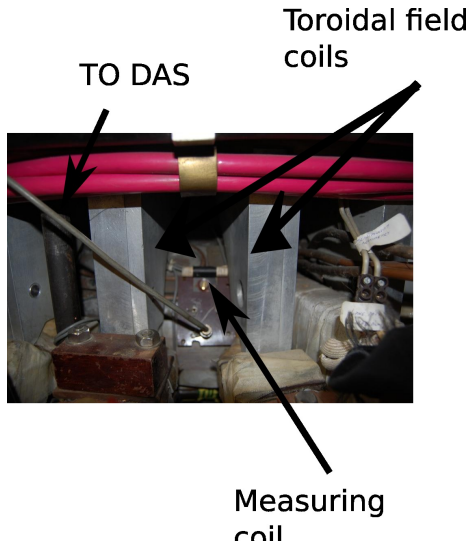
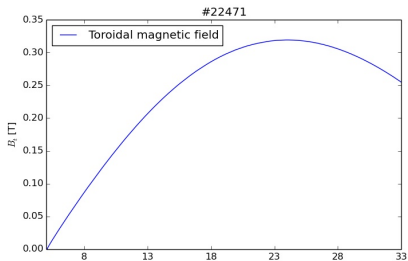
Tokamak GOLEM - basic diagnostics



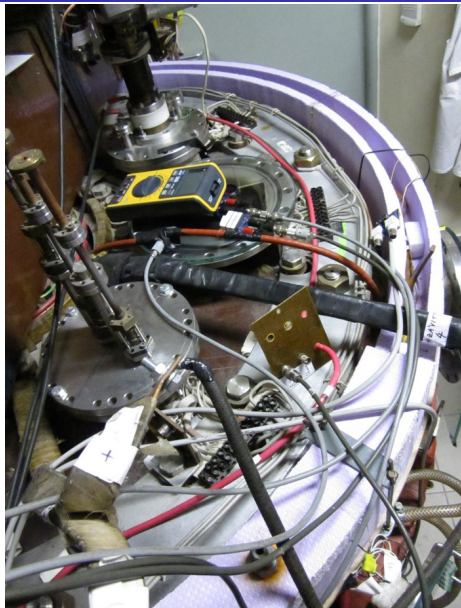
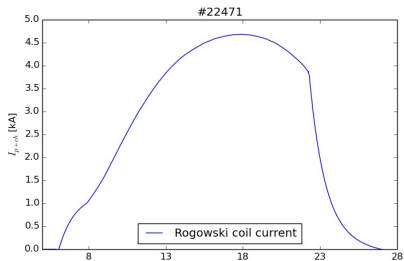
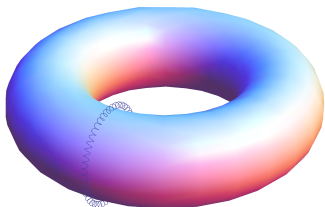
Loop voltage U_l



Toroidal magnetic field B_t



Total current I_{ch+p}



Basic diagnostics @ tokamak GOLEM

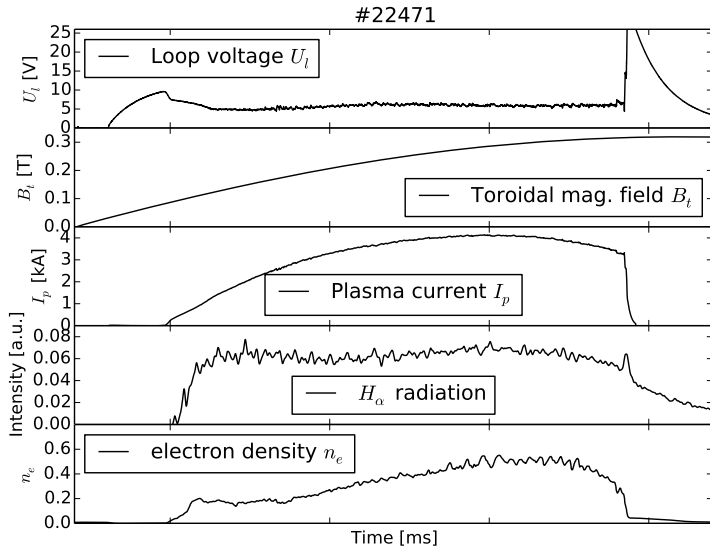


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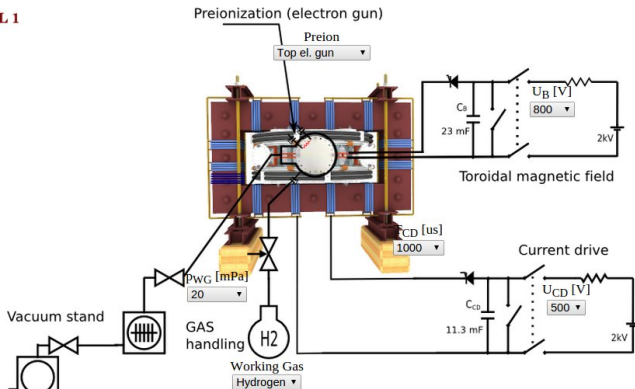
Remote operation

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.



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 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](#)

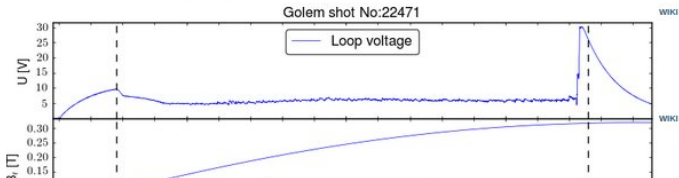


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GOLEM basic Data Acquisition System (DAS)

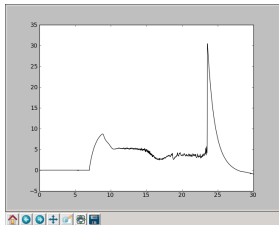
- $U_I, U_{B_t}, U_{I_{p+ch}}, I_{rad}$
- $\Delta t = 1\mu s / f = 1MHz$.
- Integration time = 40 ms, thus DAS produces 6 columns x 40000 rows data file.
- Discharge is triggered at 5th millisecond after DAS to have a zero status identification.



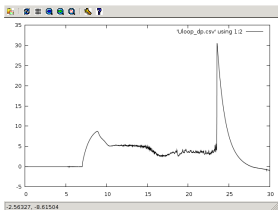
Data file example, DAS $\Delta t = 1\mu s / f = 1MHz$ (neutral gas into plasma breakdown focused)

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

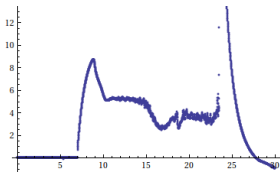
Plot #4665 U_l graph



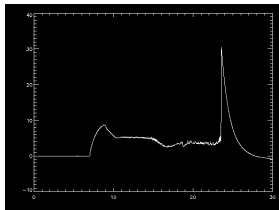
python



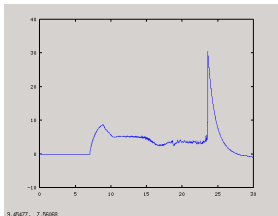
gnuplot



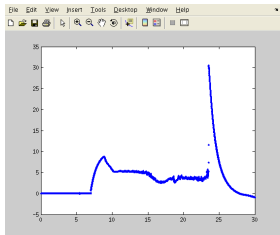
mathematica



idl



octave



matlab

Data access

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

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

Actually last 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>.
```

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>`

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 matplotlib.pyplot as plt
import numpy as np
#from urllib import urlopen #python 2.7
from urllib.request import urlopen #python 3.0

ShotNo = 22471
diagnSPEC = "loop_voltage"

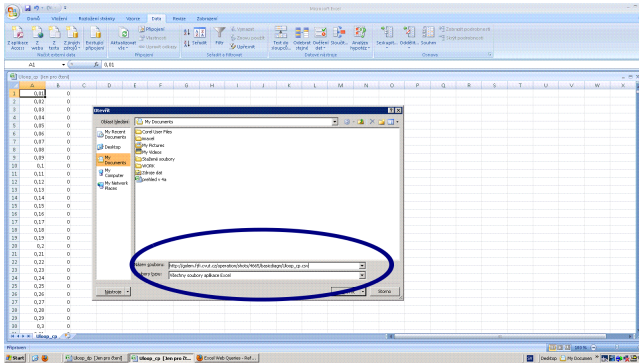
#Create a path to data
baseURL = "http://golem.fjfi.cvut.cz/Utils/data/"
dataURL = urlopen(baseURL+str(ShotNo)+'/'+diagnSPEC)

#Load data from GOLEM server and plot to screen and to disk
uloop=np.load(dataURL)
plt.plot(uloop['data'])
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
```

Excel



File→Open→

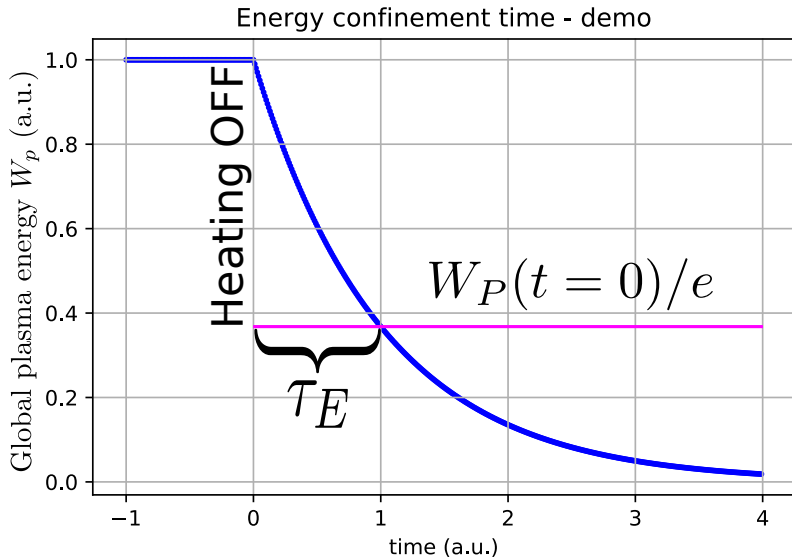
`http://golem.fjfi.cvut.cz/utills/data/<#ShotNo>/<identifier>`

Spreadsheets (Excel and others)

are not recommended, only tolerated.

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Energy confinement time - intro



(Electron) energy confinement time at the tokamak GOLEM

The energy confinement time is defined as a function of the global plasma energy content W_p , and the applied total heating power P :

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

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

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

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:

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

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)

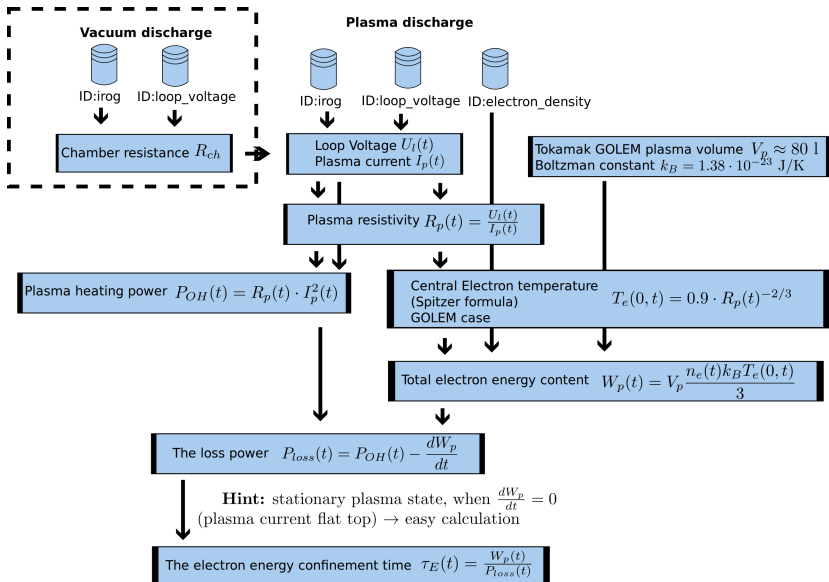
The time evolution of the central electron temperature $T_e(0, t)$ is calculated from equation based on Spitzer's resistivity formula (see eg. [?],[?]):

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

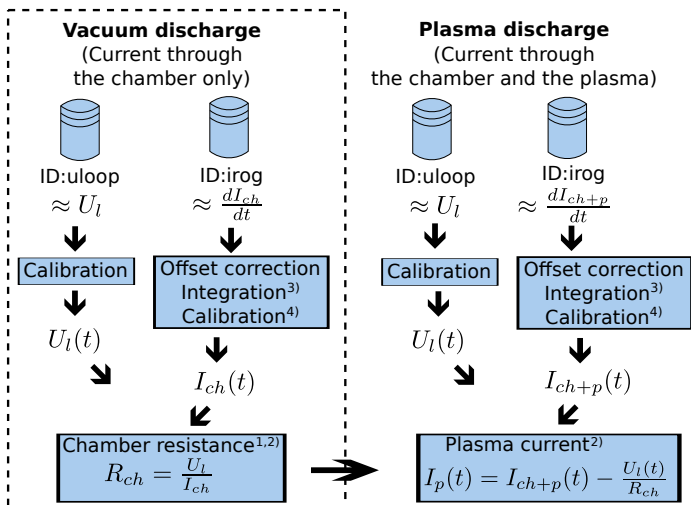
For particular case of the GOLEM tokamak it says:

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

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.

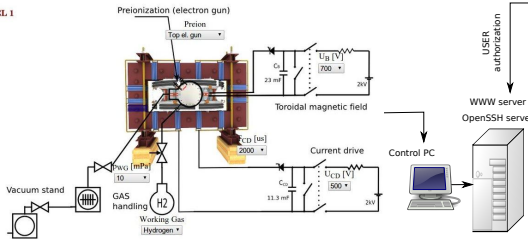
3) 1 us step 4) Rogowski Coil calibration constant = $5.3 \cdot 10^6$ A/Vs (see config.py)

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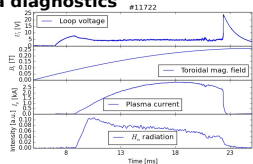
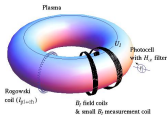
The global schematic overview of the GOLEM experiment

LEVEL 1

Tokamak technology setup



Basic plasma diagnostics



internet

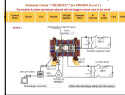
**Virtual control room
(remote participation)**

WWW control interface

Data presentation

HTML & PHP scripts

HTML (www pages)



SSH control interface

WINDOWS via putty

Data handling



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

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

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

Acknowledgement

Acknowledgement

The financial support by FUSENET, MSM 6840770039, MSM 6840770014 and A1581 is acknowledged.

Special thanks to the GOLEM team (students, teachers, technicians)

Edita Bromova, Vladimir Fuchs, Ondrej Grover, Igor Jex, Jindrich Kocman, Jaroslav Krbec, Borek Leitl, Tomas Markovic, Lukas Matena, Michal Odstrcil, Tomas Odstrcil, Ondrej Pluhar, Gergo Pokol, Jan Stockel, Tereza Ruzickova, Gabriel Vondrasek, Ondrej Vrba, Frantisek Zacek and Jiri Zara.

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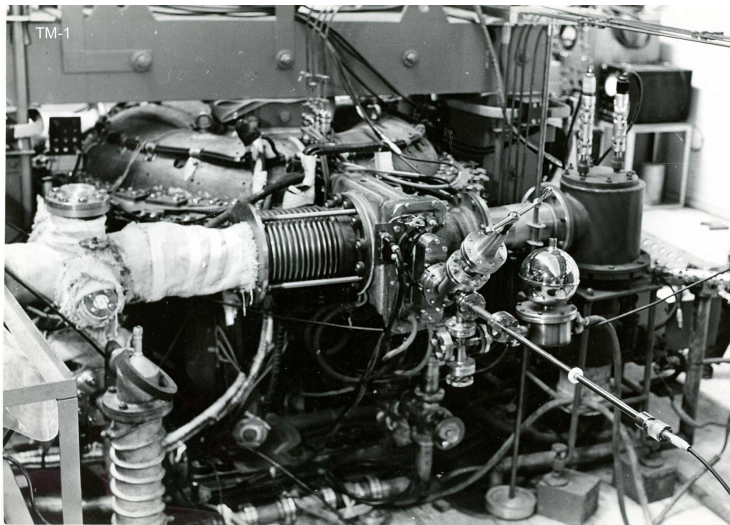
References I

Just for the case ...

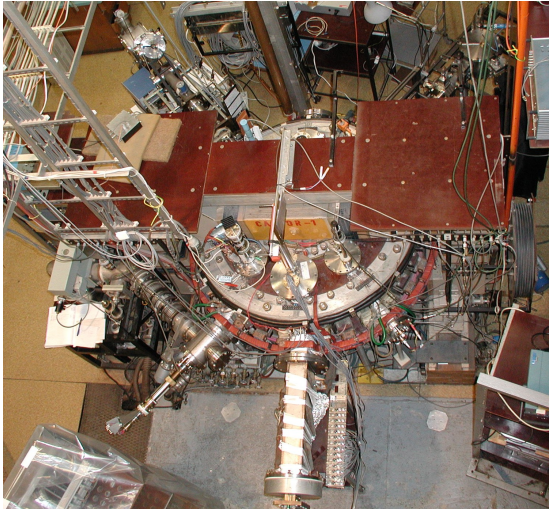
Few moments

from the tokamak GOLEM history

XX/YY: TM-1



XX/YY: CASTOR



12/07: Last minutes at the IPP Prague

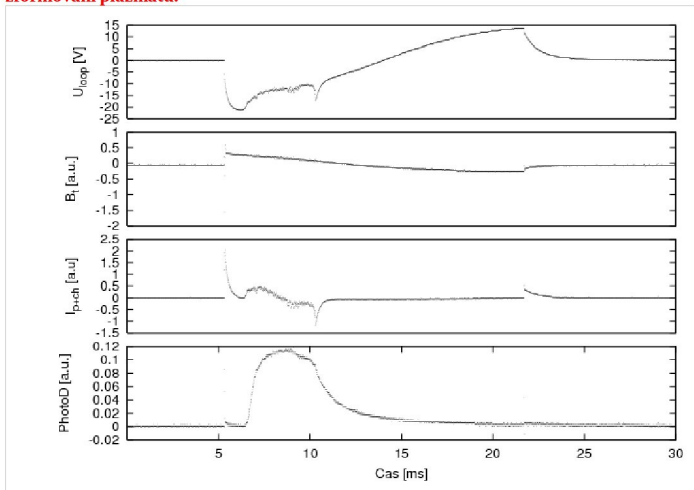


12/07: First minutes at the CTU Prague



07/09: First plasma in the tokamak GOLEM

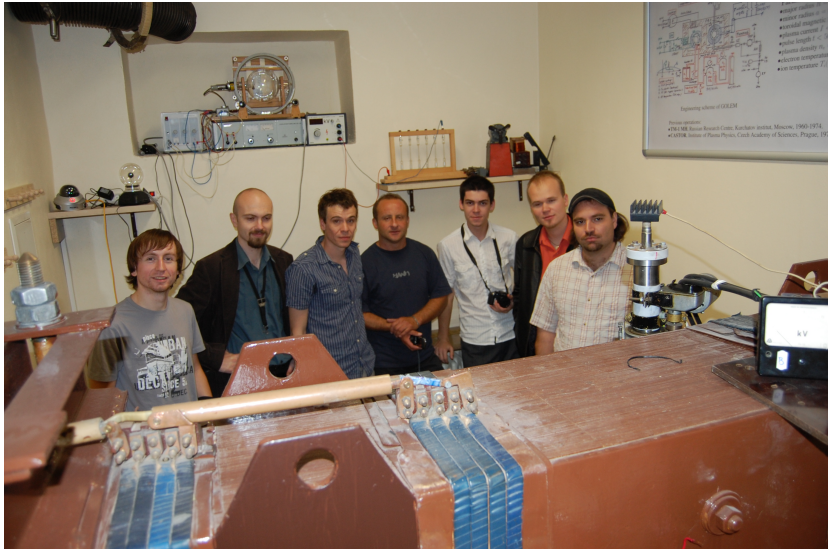
Časové průběhy signálů zřetelně ukazují, že došlo k průrazu neutrálního plynu a k zformování plazmatu.



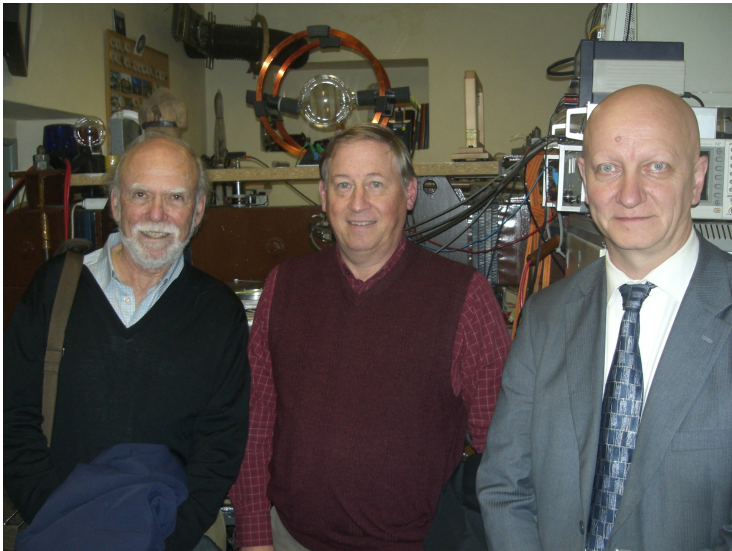
O tom svědčí:

1. Rychlý pokles napětí na závit v čase $t = 6-7$ ms a jeho malé fluktuace, které lze vidět až

09/09: Tokamak and tokamak



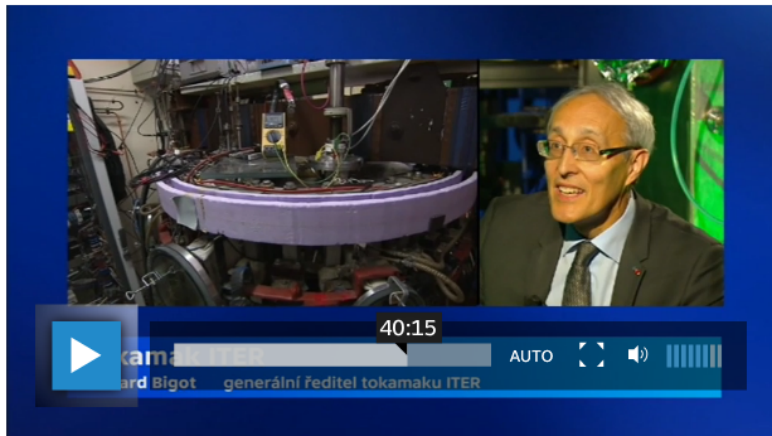
11/11: NP laureat at tokamak GOLEM



05/16: The youngest tokamak (GOLEM) operator, Adam (7 years).



0916: ITER DG, Mr. Bernard Bigot (Shot #22185)



Quotation from Czech Television Hydepark

I am very pleased with the GOLEM ...

2010: Tokamak GOLEM



2011: The tokamak COMPASS with NBI



2016: ITER segment



2017: First Spitzer Stellarator



11/17: GOLEM tokamak "mapping"

Tokamak GOLEM



12/16: Trojan horse - shift


golem.fjfi.cvut.cz/shots/22816/

GOLEM » Shot #22816 »

Tokamak GOLEM - Shot Database - 22816

Date: 2016-12-02 - 13:39:42
Session: SessionPreparation/2016
Comment: JarCer - B scan for HXR U_B=1100, U_cd=500

Congratulation, you have reached nuclear fusion.
The following explosion destroyed half of Prague and radioactive fallout contaminated whole Europe.
Have a nice day



Basic parameters: (compare)

- Gas pressure p_{CH_4} : 0.16 -> 27.98 mPa (request: 28 mPa) ^{W01}
- Working gas: H
- Preionization: Upper el. gun
- Chamber temperature: 23.60 C
- C_A capacitors charged to: 1100 V, triggered 5.0 ns ^{W01}
- C_{AD} capacitors charged to: 0 V, triggered 5.0 ns ^{W01}
- C_{CD} capacitors charged to: 500 V, triggered 6.0 ns ^{W01}
- C_{ST} capacitors charged to: 0 V, triggered 5.0 ns ^{W01}
- Level of noise (dB) in room: 0.005 V
- Probability of breakdown: 90% ^{W01}
- Time since session beginning: 1:04:47 h

Plasma parameters:

- Plasma life time 20.0 [ms] (from 7.3 to 27.3)
- Mean toroidal magnetic field Bt: 0.33 T ^{W01}
- Mean plasma current: 5.63 kA ^{W01}
- Mean Uloop: 5.26 V ^{W01}
- Break down voltage: 9.9 V ^{W01}
- Ohmic heating power: 29.65 kW
- Q edge: 2.7 ^{W01}
- Electron temperature: 59.9 eV ^{W01}
- Line electron density: 5.58 [10¹⁷ m⁻²] ^{W01}

Go to shot 22816 Go

Other: Data, References, About, Wiki, Utilities

Navigation: Next, Previous, Current

Golem shot No:22816 W01