

Introduction to tokamak operation (GOLEM specific) - Level 1

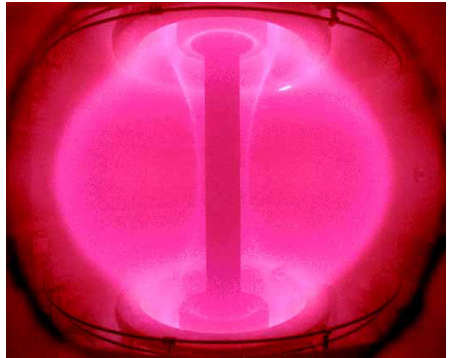
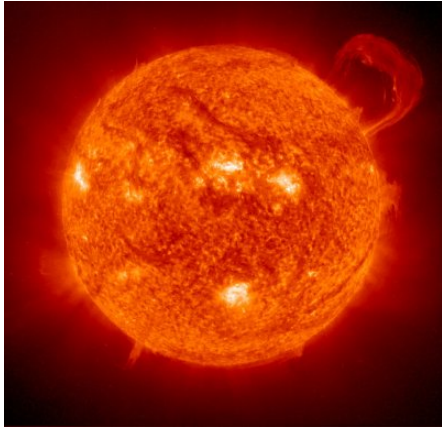
Vojtěch Svoboda
on behalf of the tokamak GOLEM team
for Hot shots, 3th edition

April 27, 2017

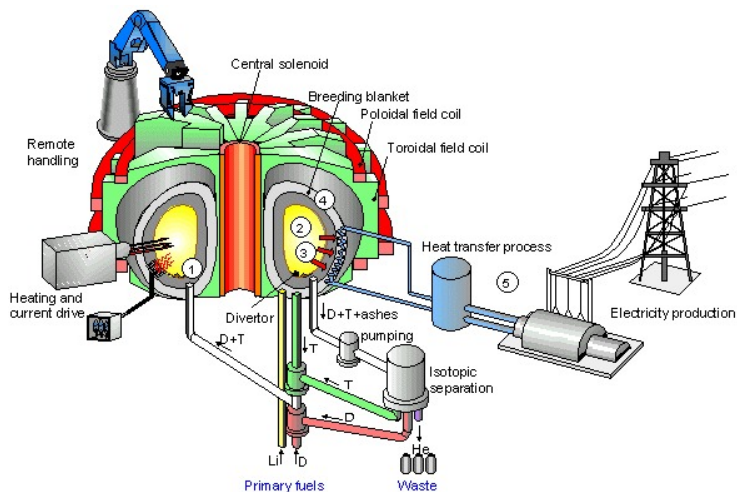
Table of Contents

- 1 Starter
- 2 The tokamak GOLEM - introduction
- 3 The tokamak (GOLEM) concept
- 4 The scenario to make the tokamak (GOLEM) discharge
- 5 The Tokamak GOLEM - engineering scheme
- 6 Tokamak GOLEM - basic diagnostics
- 7 Tokamak GOLEM - operation
- 8 Data handling @ the Tokamak GOLEM
- 9 Conclusion
- 10 Appendix

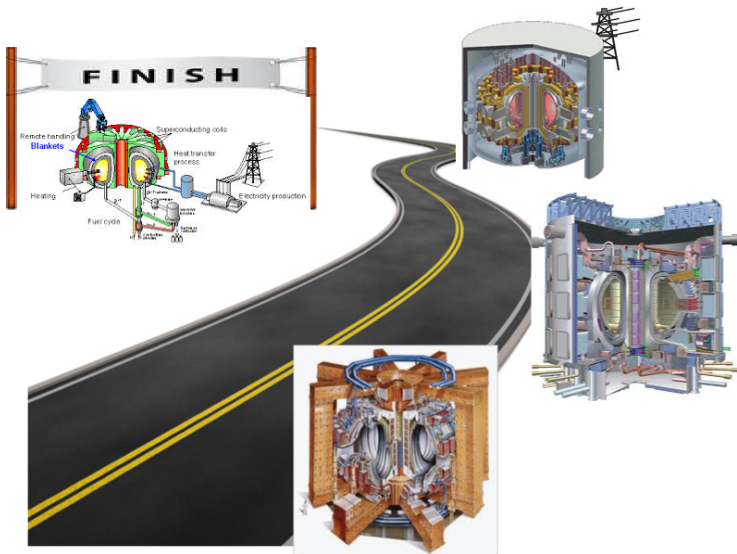
Foreword



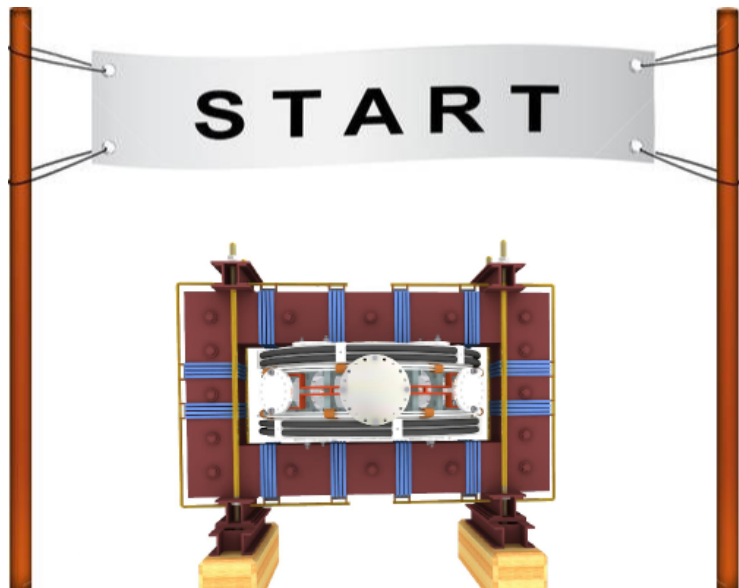
Our mission



Milestones to the Fusion Power Plant



Let's start with the tokamak GOLEM



Notice/Warning/Alert

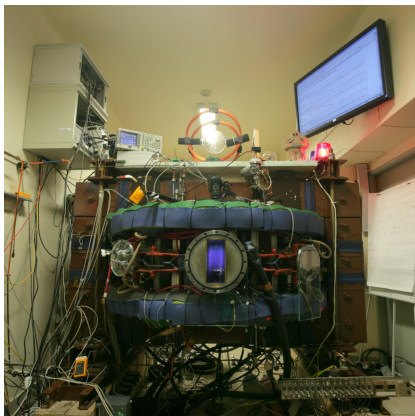
Everything simplified

... for educational purposes ..

Table of Contents

- 1 Starter
- 2 The tokamak GOLEM - introduction**
- 3 The tokamak (GOLEM) concept
- 4 The scenario to make the tokamak (GOLEM) discharge
- 5 The Tokamak GOLEM - engineering scheme
- 6 Tokamak GOLEM - basic diagnostics
- 7 Tokamak GOLEM - operation
- 8 Data handling @ the Tokamak GOLEM
- 9 Conclusion
- 10 Appendix

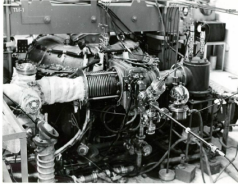
Basic characteristics



- Vessel major radius: $R_0 = 0.4$ m
- Vessel minor radius: $r_0 = 0.1$ m
- Minor radius $r_0 = 0.1$ m
- Plasma radius $a = 0.085$ m
- Toroidal magnetic field $B_t < 0.5$ T
- Plasma current $I_p < 8$ kA
- Plasma density
 $n \approx 0.2 - 3 \times 10^{19}/\text{m}^{-3}$
- Electron temperature $T_e < 100$ eV
- Ion temperature $T_i < 50$ eV
- Length of the discharge $\tau < 20$ ms

Tokamak GOLEM for education - historical background

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



1974

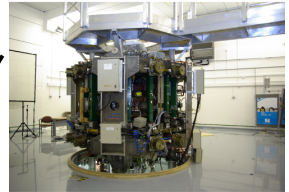


Institute of Plasma Physics
Czech republic
CASTOR **COMPASS**

2006



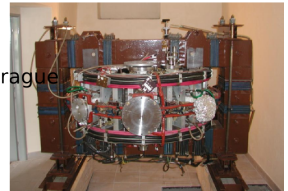
Culham Centre for Fusion Energy
Great Britain
1989: **COMPASS-D**



2008



Czech Technical University Prague
Czech republic
GOLEM



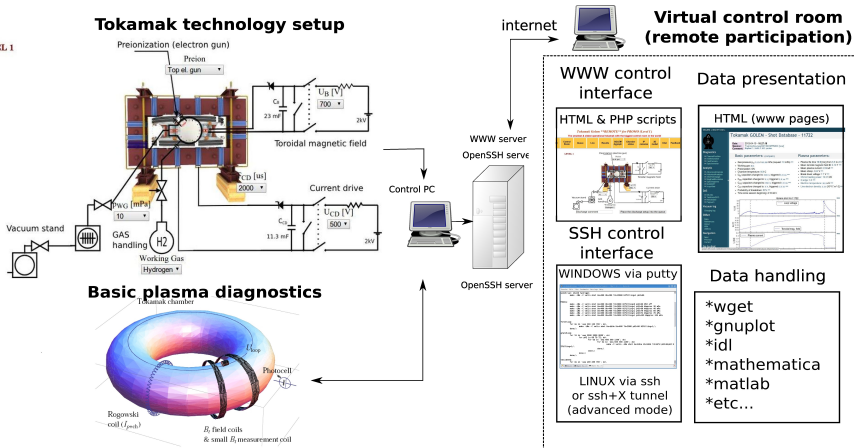
GOLEM



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



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

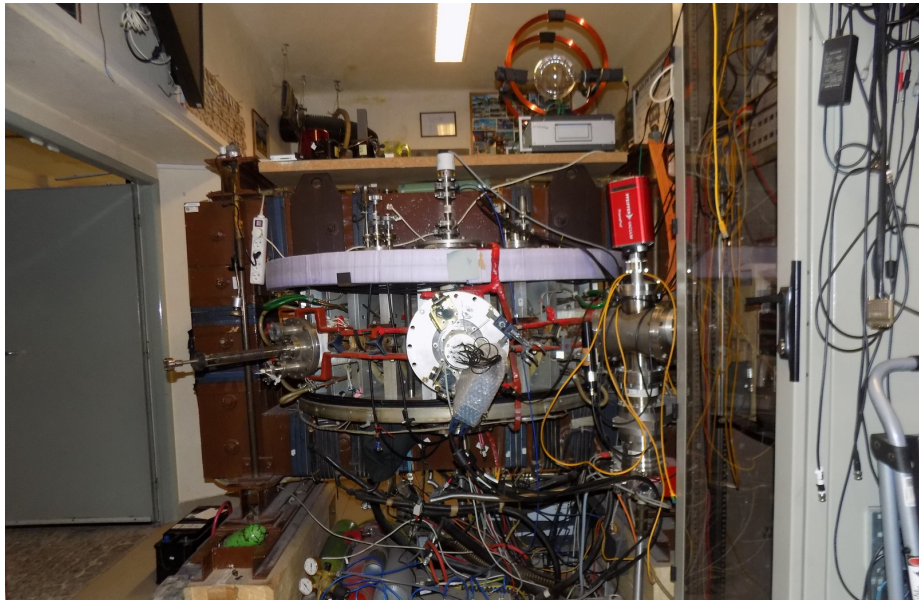
Plasma
stabilization

power
supply
2kV

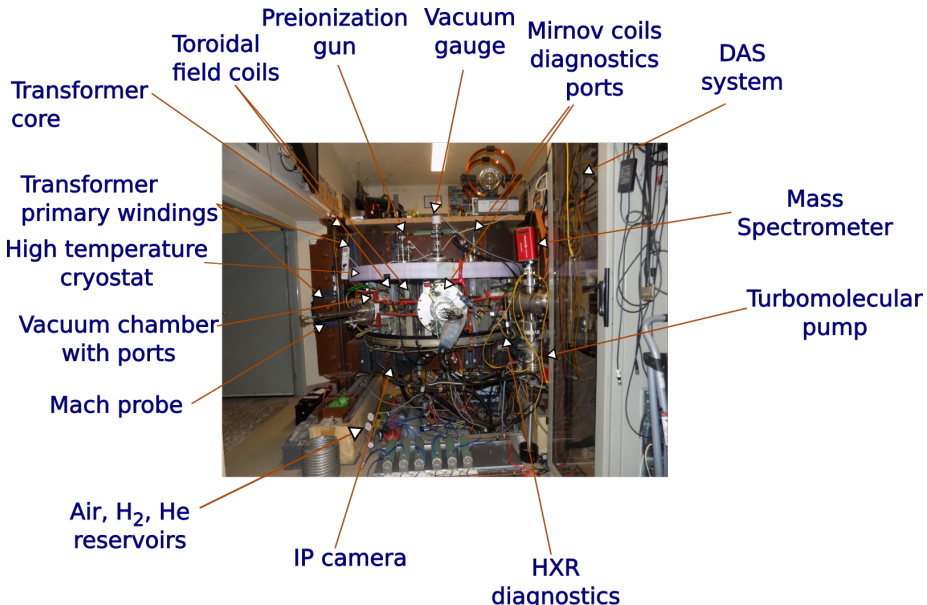
Toroidal
magnetic field B
capacitors

fire
protection
system

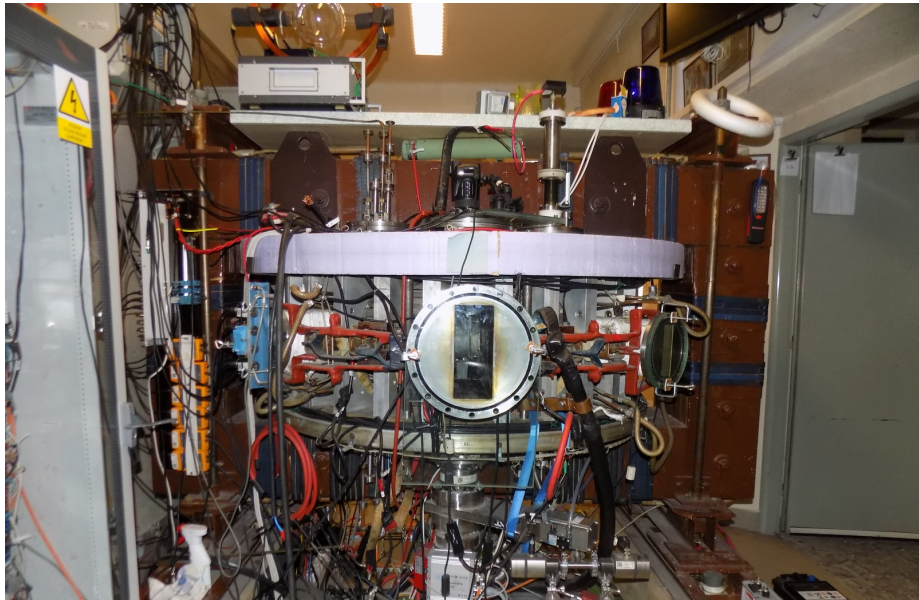
Tokamak room (North) 10/16



Tokamak room (North) 10/16



Tokamak room (South) 10/16



Tokamak room (South) 10/16

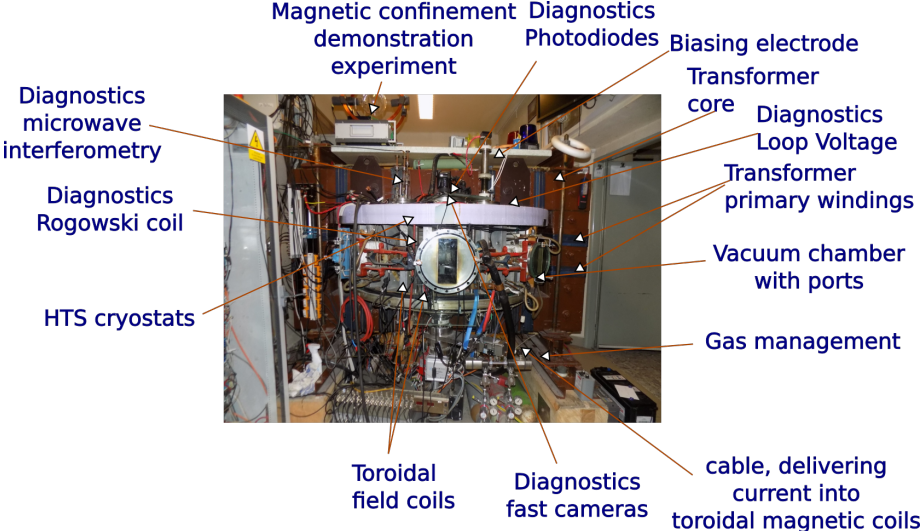
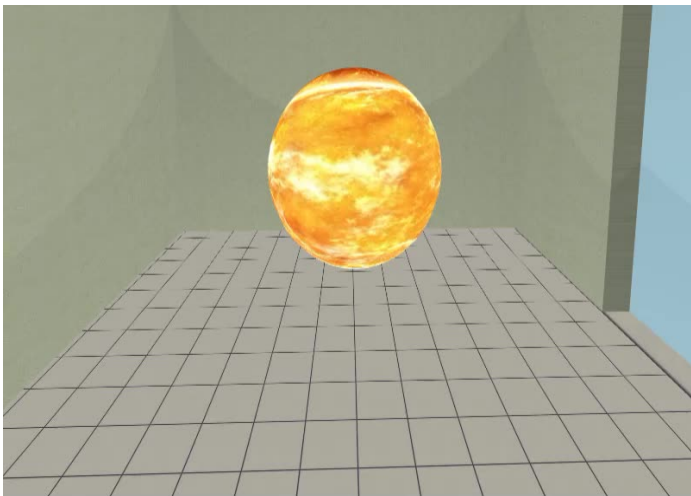


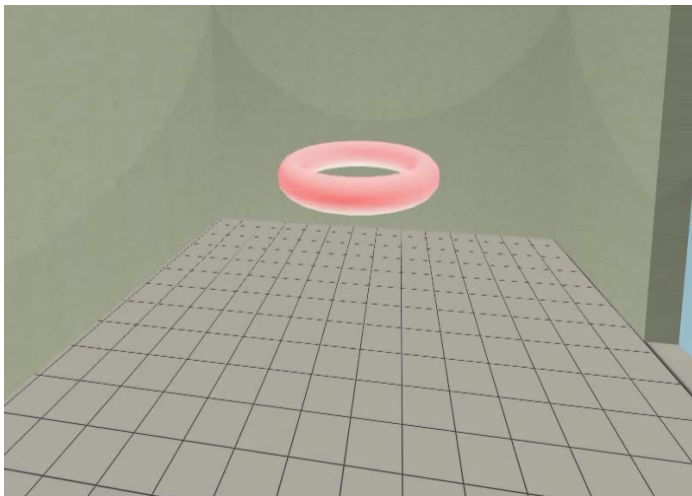
Table of Contents

- 1 Starter
- 2 The tokamak GOLEM - introduction
- 3 The tokamak (GOLEM) concept**
- 4 The scenario to make the tokamak (GOLEM) discharge
- 5 The Tokamak GOLEM - engineering scheme
- 6 Tokamak GOLEM - basic diagnostics
- 7 Tokamak GOLEM - operation
- 8 Data handling @ the Tokamak GOLEM
- 9 Conclusion
- 10 Appendix

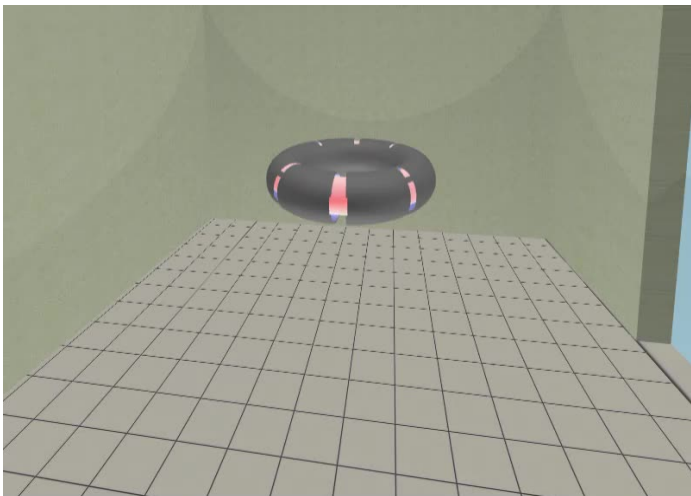
The technology to conquer: make a μ Sun on the Earth



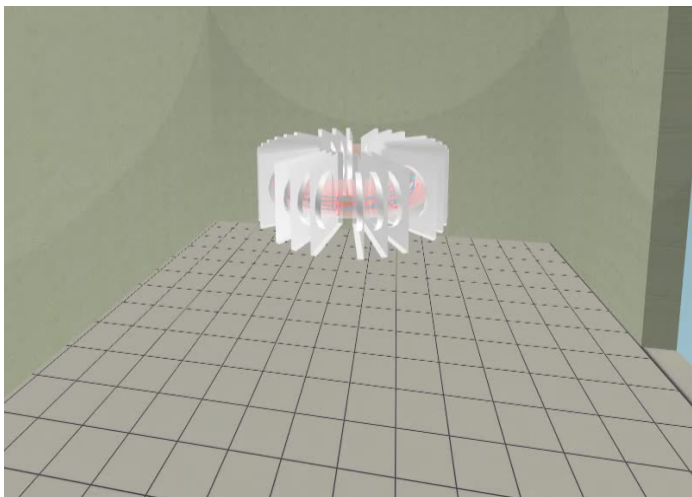
Magnetic confinement requires the toroidal geometry



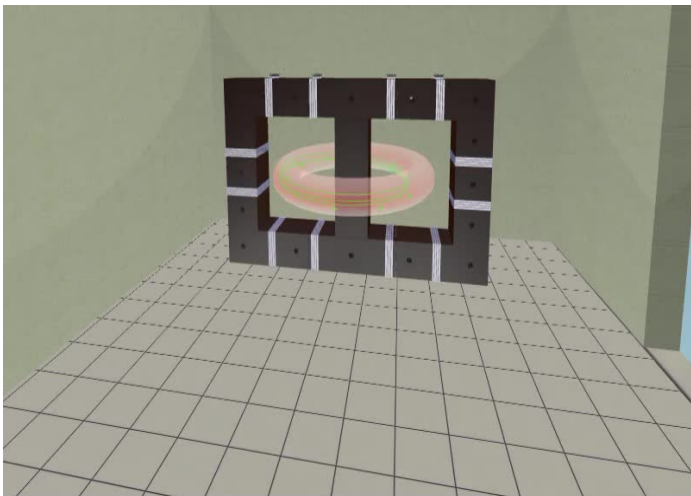
The thermonuclear reaction takes place in the chamber



Toroidal magnetic field coils secure the plasma confinement



Transformer secures the plasma creation and heating



The final technology altogether

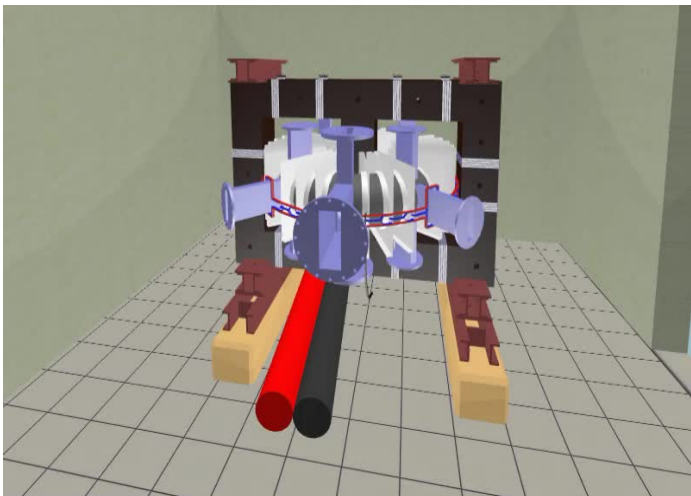
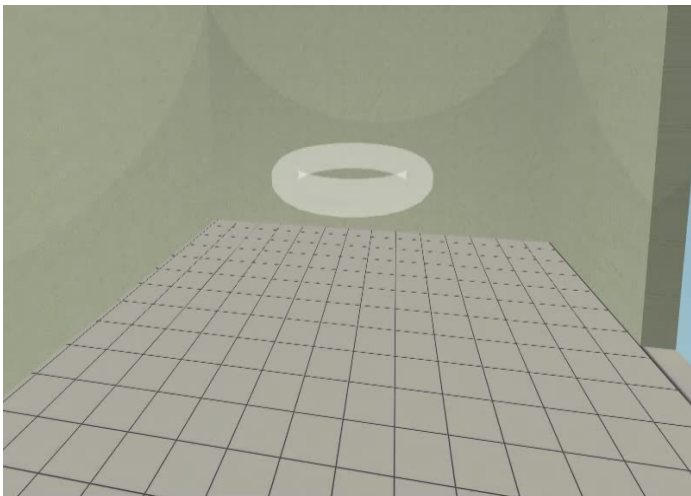


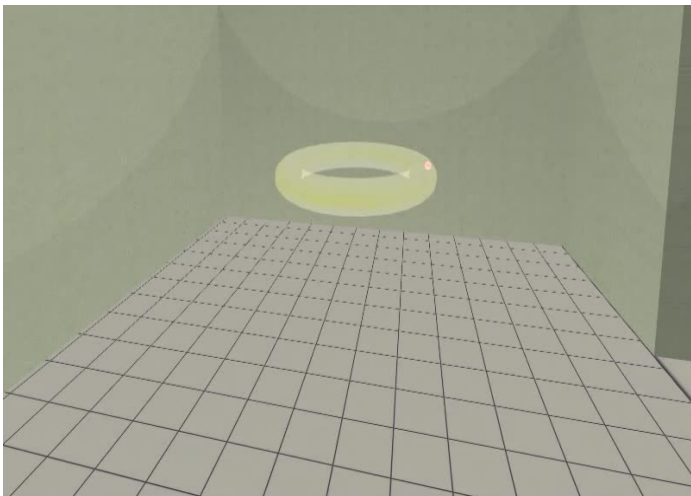
Table of Contents

- 1 Starter
- 2 The tokamak GOLEM - introduction
- 3 The tokamak (GOLEM) concept
- 4 The scenario to make the tokamak (GOLEM) discharge**
- 5 The Tokamak GOLEM - engineering scheme
- 6 Tokamak GOLEM - basic diagnostics
- 7 Tokamak GOLEM - operation
- 8 Data handling @ the Tokamak GOLEM
- 9 Conclusion
- 10 Appendix

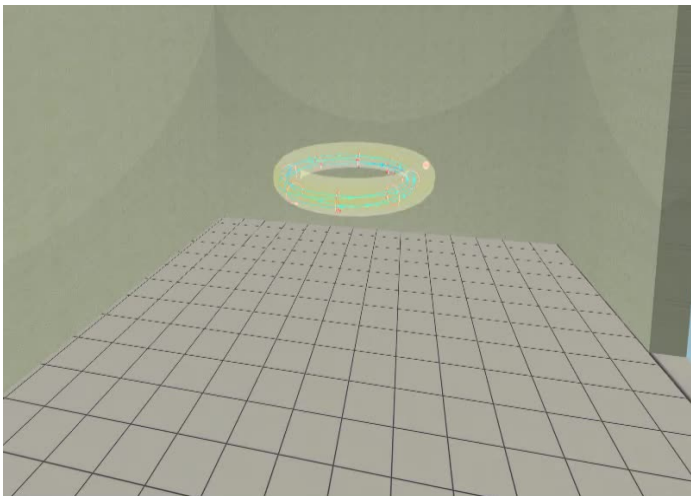
Introduce the working gas (Hydrogen x Helium)



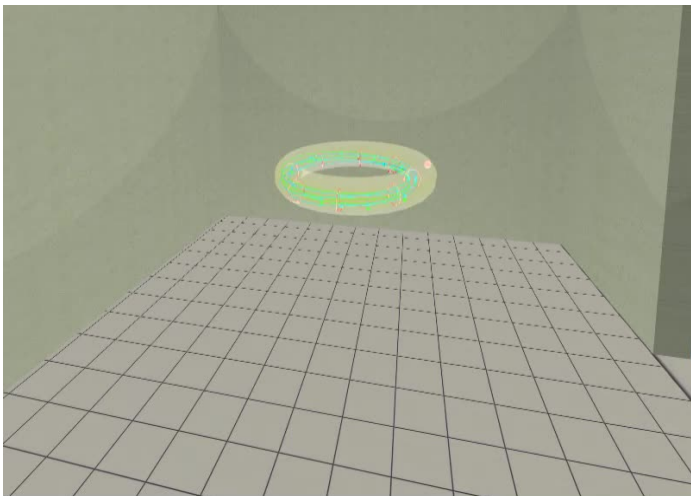
Switch on the preionization



Introduce the magnetic field



Introduce the electric field



Plasma ..

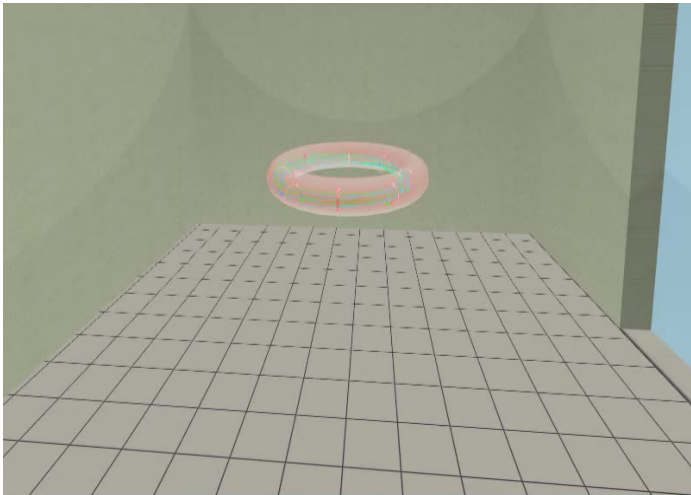
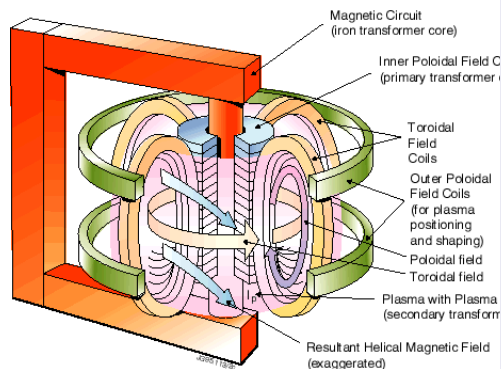


Table of Contents

- 1 Starter
- 2 The tokamak GOLEM - introduction
- 3 The tokamak (GOLEM) concept
- 4 The scenario to make the tokamak (GOLEM) discharge
- 5 The Tokamak GOLEM - engineering scheme**
- 6 Tokamak GOLEM - basic diagnostics
- 7 Tokamak GOLEM - operation
- 8 Data handling @ the Tokamak GOLEM
- 9 Conclusion
- 10 Appendix

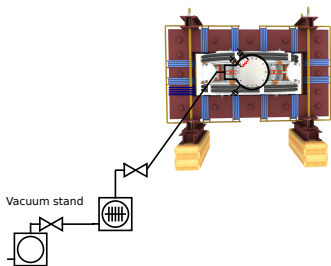
Plasma in Tokamak (GOLEM) - the least to do



To do:

- session 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

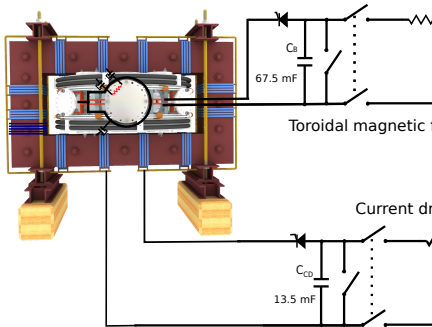
Plasma in Tokamak (GOLEM) - the least to do



To do:

- session 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

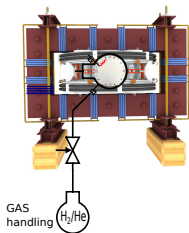
Plasma in Tokamak (GOLEM) - the least to do



To do:

- session 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

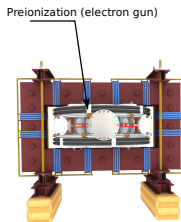
Plasma in Tokamak (GOLEM) - the least to do



To do:

- session 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

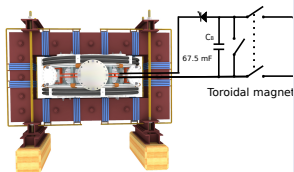
Plasma in Tokamak (GOLEM) - the least to do



To do:

- session 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

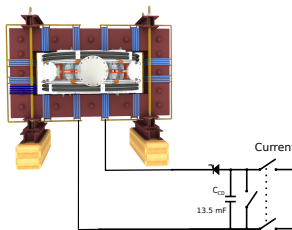
Plasma in Tokamak (GOLEM) - the least to do



To do:

- session 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



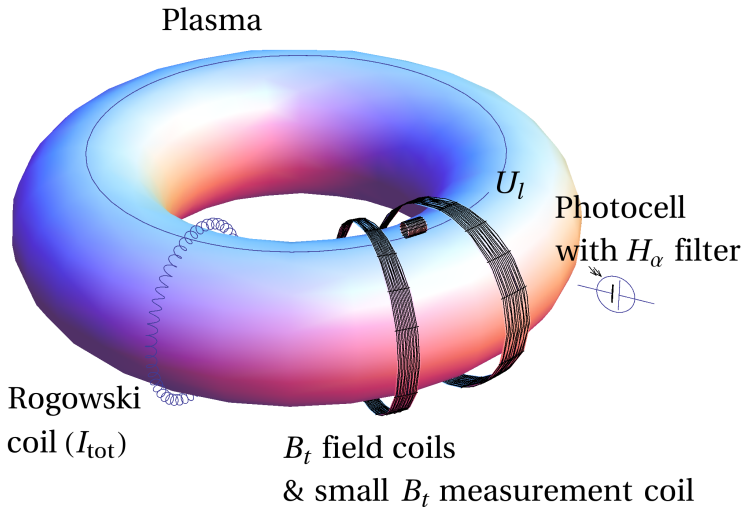
To do:

- session 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

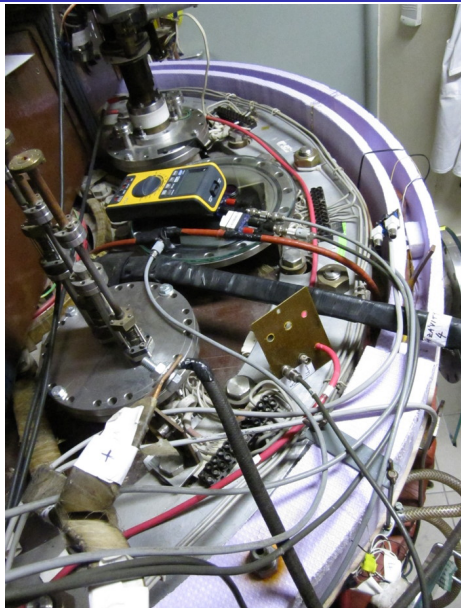
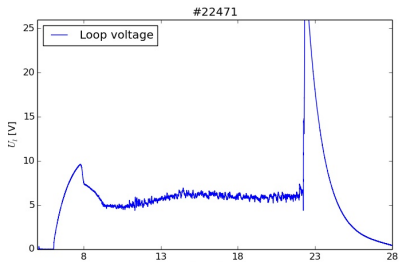
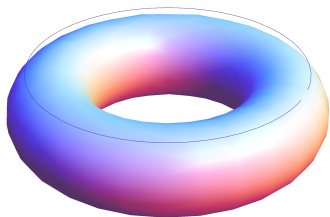
Table of Contents

- 1 Starter
- 2 The tokamak GOLEM - introduction
- 3 The tokamak (GOLEM) concept
- 4 The scenario to make the tokamak (GOLEM) discharge
- 5 The Tokamak GOLEM - engineering scheme
- 6 Tokamak GOLEM - basic diagnostics**
- 7 Tokamak GOLEM - operation
- 8 Data handling @ the Tokamak GOLEM
- 9 Conclusion
- 10 Appendix

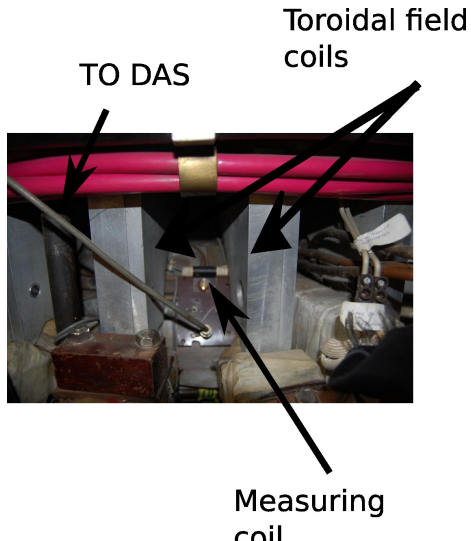
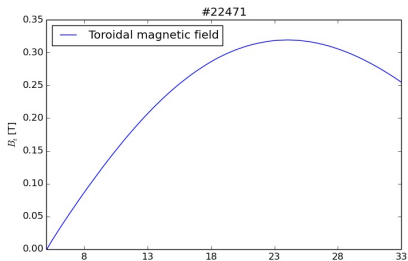
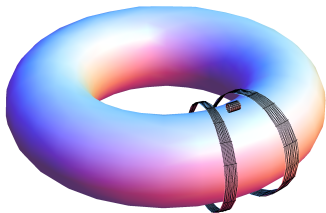
Tokamak GOLEM - basic diagnostics



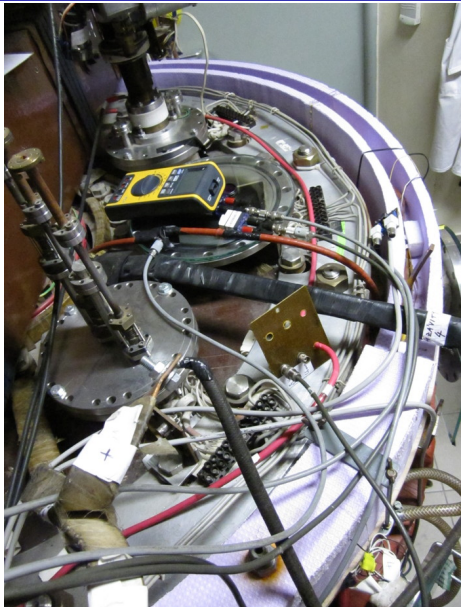
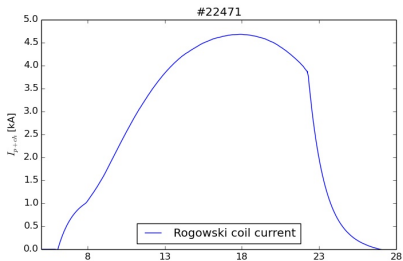
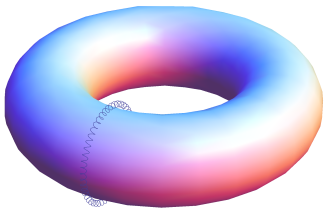
Loop voltage U_l



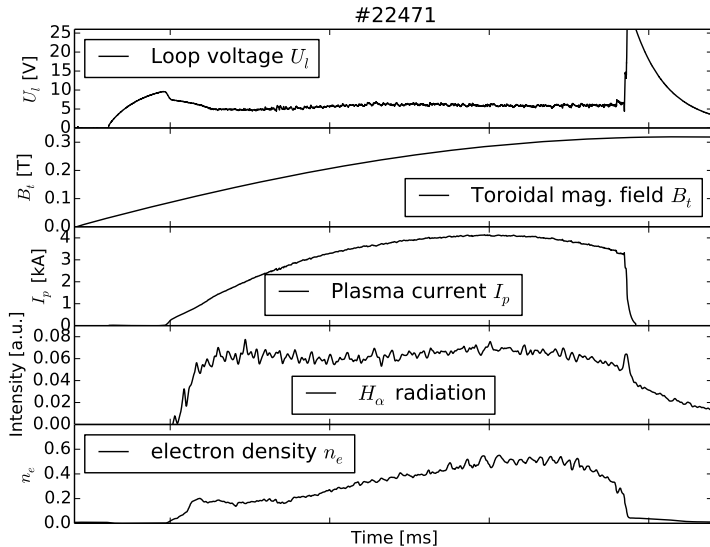
Toroidal magnetic field B_t



Total current I_{ch+p}



Basic diagnostics @ tokamak GOLEM



Plasma x vacuum discharge

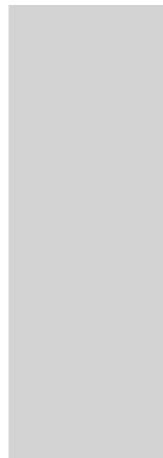
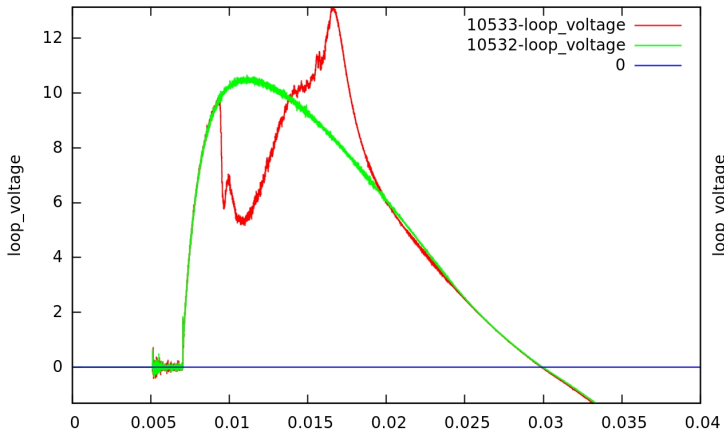


Table of Contents

- 1 Starter
- 2 The tokamak GOLEM - introduction
- 3 The tokamak (GOLEM) concept
- 4 The scenario to make the tokamak (GOLEM) discharge
- 5 The Tokamak GOLEM - engineering scheme
- 6 Tokamak GOLEM - basic diagnostics
- 7 Tokamak GOLEM - operation**
- 8 Data handling @ the Tokamak GOLEM
- 9 Conclusion
- 10 Appendix

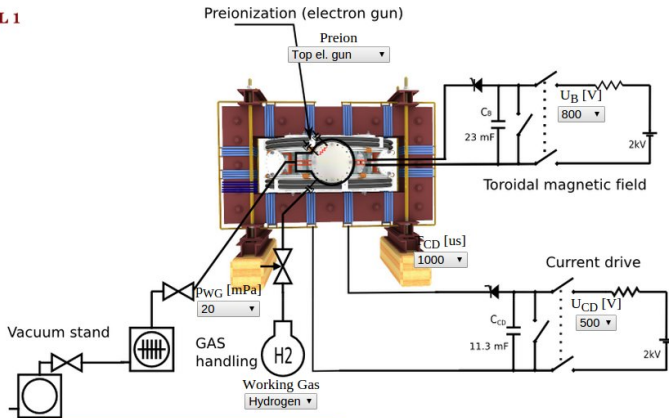
Remote operation

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

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



LEVEL 1





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](#)

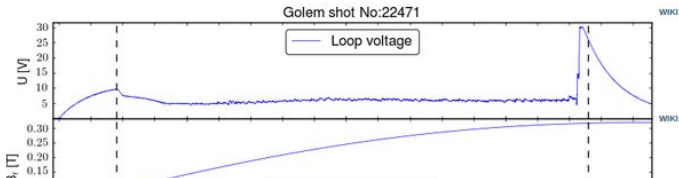


Table of Contents

- 1 Starter
- 2 The tokamak GOLEM - introduction
- 3 The tokamak (GOLEM) concept
- 4 The scenario to make the tokamak (GOLEM) discharge
- 5 The Tokamak GOLEM - engineering scheme
- 6 Tokamak GOLEM - basic diagnostics
- 7 Tokamak GOLEM - operation
- 8 Data handling @ the Tokamak GOLEM**
- 9 Conclusion
- 10 Appendix

GOLEM basic Data Acquisition System (DAS)

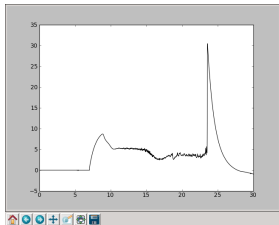
- $U_I, U_{B_t}, U_{I_{p+ch}}, I_{rad}$
- $\Delta t = 1\mu s / f = 1MHz$.
- Integration time = 40 ms, thus DAS produces 6 columns x 40000 rows data file.
- Discharge is triggered at 5th millisecond after DAS to have a zero status identification.



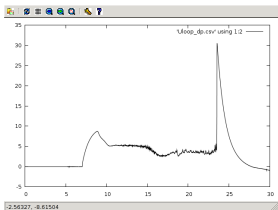
Data file example, DAS $\Delta t = 1\mu s / f = 1MHz$ (neutral gas into plasma breakdown focused)

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

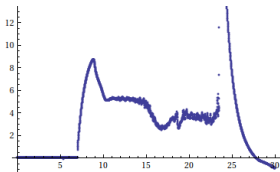
Plot 4665 U_l graph



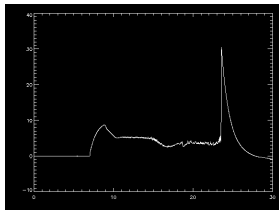
python



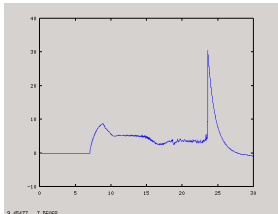
gnuplot



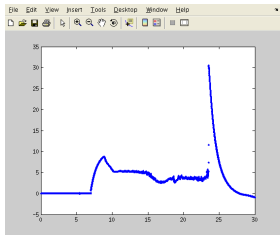
mathematica



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/utis/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/utills/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)

```
# coding: utf-8
```

```
# In[ ]:
```

```
import matplotlib.pyplot as plt
from numpy import loadtxt
from urllib import urlopen
```

```
baseURL = "http://golem.fjfi.cvut.cz/utils/data/"
```

```
ShotNo = 22639
```

```
identifier = "loop_voltage"
```

```
#Create a path to data
```

```
dataURL = urlopen(baseURL+ str(ShotNo) + '/' + identifier)
```

```
#Load data from GOLEM server
```

```
data=loadtxt(dataURL, delimiter='\t')
```

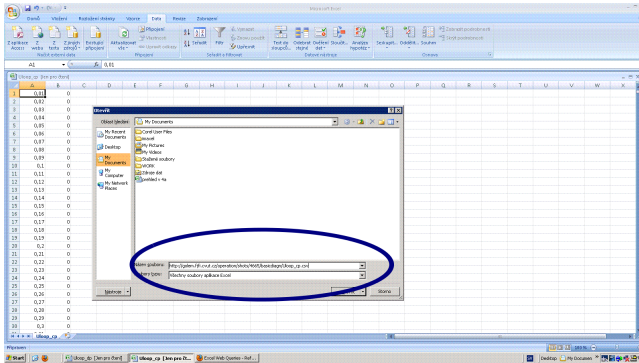
```
#Plot the graph
```

```
plt.plot(data[:,0], data[:,1], 'k-')
```


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>`

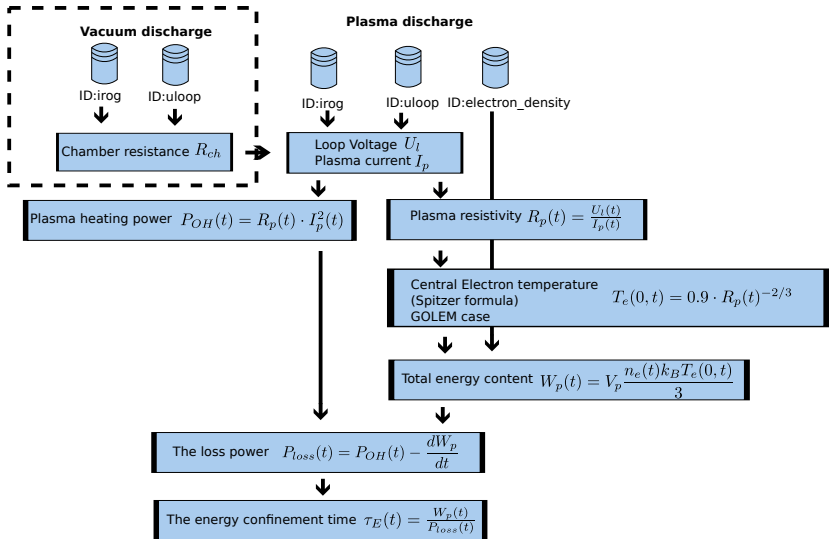
Spreadsheets (Excel and others)

are not recommended, only tolerated.

Table of Contents

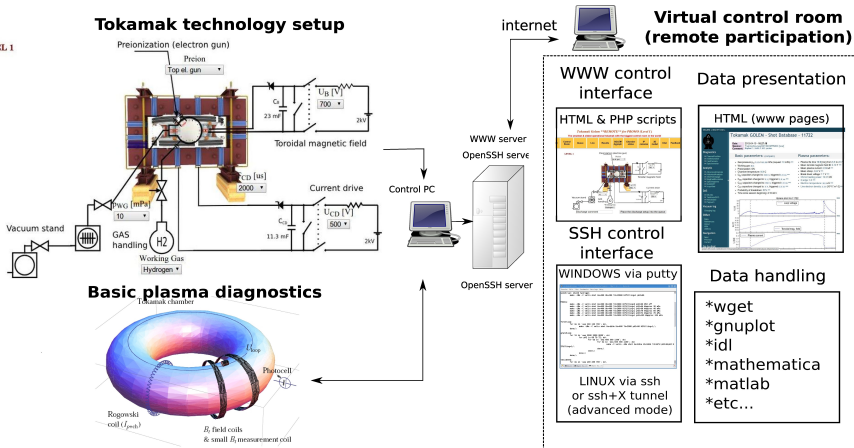
- 1 Starter
- 2 The tokamak GOLEM - introduction
- 3 The tokamak (GOLEM) concept
- 4 The scenario to make the tokamak (GOLEM) discharge
- 5 The Tokamak GOLEM - engineering scheme
- 6 Tokamak GOLEM - basic diagnostics
- 7 Tokamak GOLEM - operation
- 8 Data handling @ the Tokamak GOLEM
- 9 Conclusion**
- 10 Appendix

Towards Energy confinement time τ_E



The global schematic overview of the GOLEM experiment

LEVEL 1



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.




Winter school of Plasma Physics - Marianska 2016 (Toroidal field coil 4 ITER, cooling test)



Table of Contents

- 1 Starter
- 2 The tokamak GOLEM - introduction
- 3 The tokamak (GOLEM) concept
- 4 The scenario to make the tokamak (GOLEM) discharge
- 5 The Tokamak GOLEM - engineering scheme
- 6 Tokamak GOLEM - basic diagnostics
- 7 Tokamak GOLEM - operation
- 8 Data handling @ the Tokamak GOLEM
- 9 Conclusion
- 10 Appendix

References I

-  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.
-  Brotankova, J.
Study of high temperature plasma in tokamak-like experimental devices.
PhD. thesis 2009.
-  Tokamak GOLEM team.
Tokamak GOLEM at the Czech Technical University in Prague.
<http://golem.fjfi.cvut.cz>, 2007.

References II



J. Wesson.

Tokamaks, volume 118 of *International Series of Monographs on Physics*.

Oxford University Press Inc., New York, Third Edition, 2004.

Physical Quantities @ the tokamak GOLEM

Loop Voltage: U_l [V]

Total (plasma+chamber) current: I_{p+ch} [A]

Chamber current: I_{ch} [A]

Plasma current: I_p [A]

Plasma resistivity: R_p [Ω]

Plasma heating power: P_{OH} [W]

Total plasma energy content: W_p [J]

Chamber resistivity: R_{ch} [Ω]

Electron temperature: T_e [eV]

Energy confinement time: τ_E [s]

Plasma volume: $V_p = 0,057$ [m^3]

Rogowski coil calibration constant: $K_{Rogowski} = 5.3 \cdot 10^6$ [A/Vs]

Loop Voltage calibration constant: $K_{LoopVoltage} = 5.5$ [-]

Boltzmann constant : $k_B = 1.38064852 \cdot 10^{-23}$ [J/K]