

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

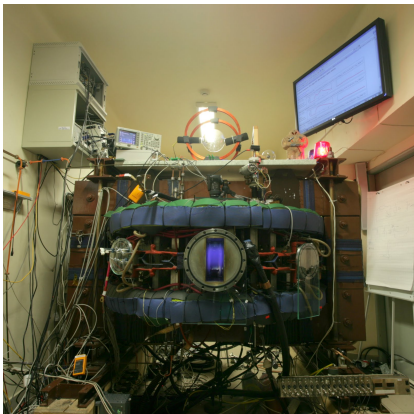
Vojtěch Svoboda  
on behalf of the tokamak GOLEM team  
for the Padova demonstration

December 2, 2016

# Outline

- 1 Introduction
- 2 Tokamak GOLEM - engineering scheme
- 3 Tokamak GOLEM - basic diagnostics
- 4 Tokamak GOLEM - operation
- 5 Data handling @ the Tokamak GOLEM
- 6 Estimation of main plasma parameters
- 7 Closings
- 8 Appendix

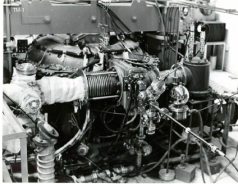
# Basic characteristics



- Major radius  $R_0 = 0.4$  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**



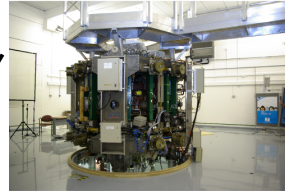
1974

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**



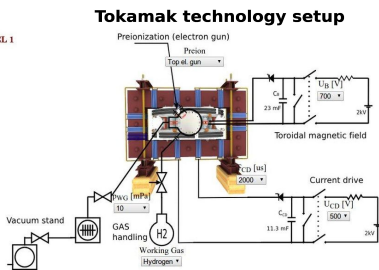
# GOLEM



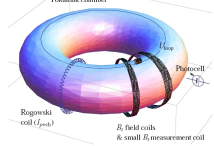
The new location of the tokamak is just next to the old Prague Jewish cemetery where Rabi Loew (Golem builder) is buried, and that is why it was renamed GOLEM (and also for the symbol of potential power you get if you know the magic). Interestingly, here in Prague, where the Golem legend originated,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

LEVEL 1



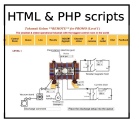
### Basic plasma diagnostics



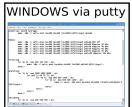
internet **Virtual control room (remote participation)**



### WWW control interface



### SSH control interface



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

### Data presentation



### Data handling

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

# 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

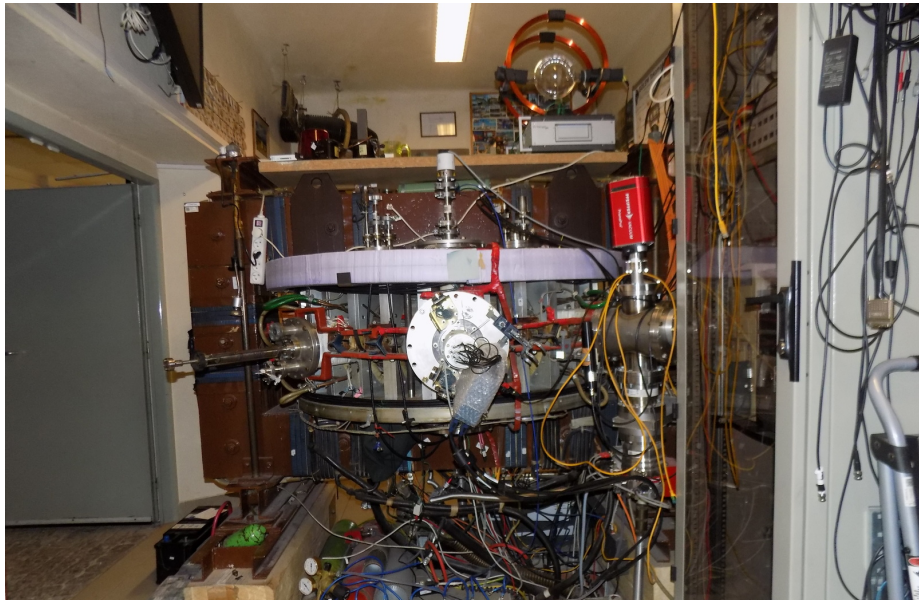
power  
supply  
2kV

Toroidal  
magnetic field B  
capacitors

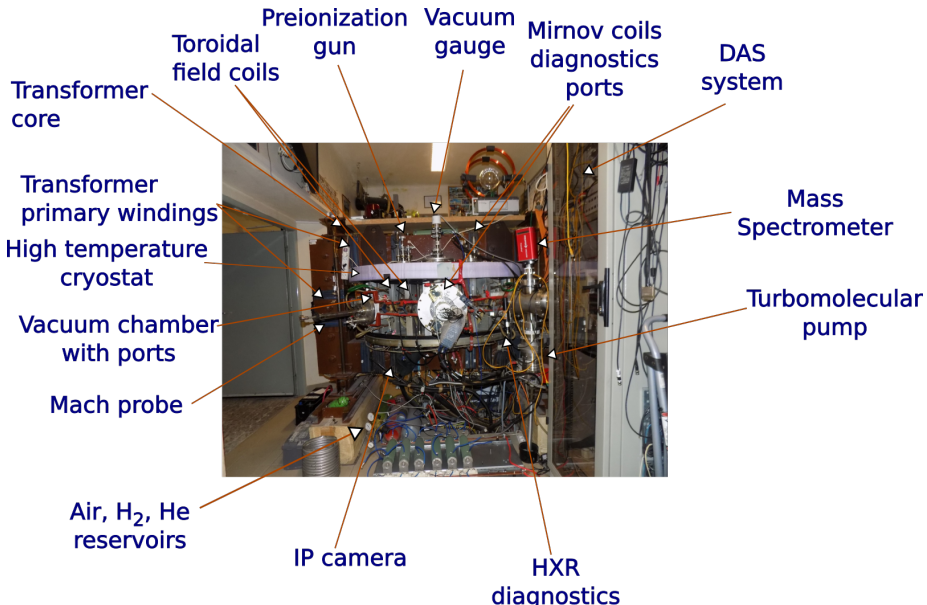
fire  
protection  
system



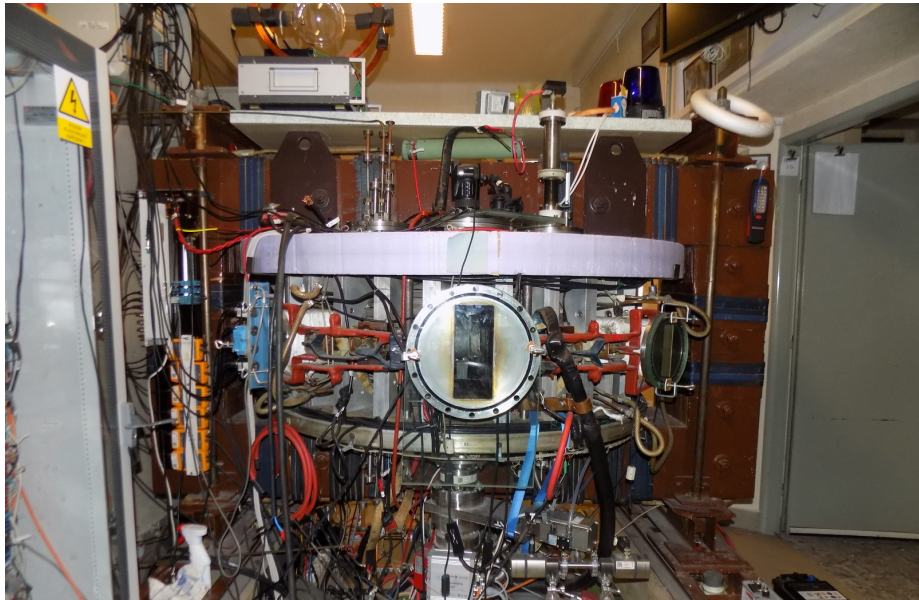
# Tokamak room (North) 10/16



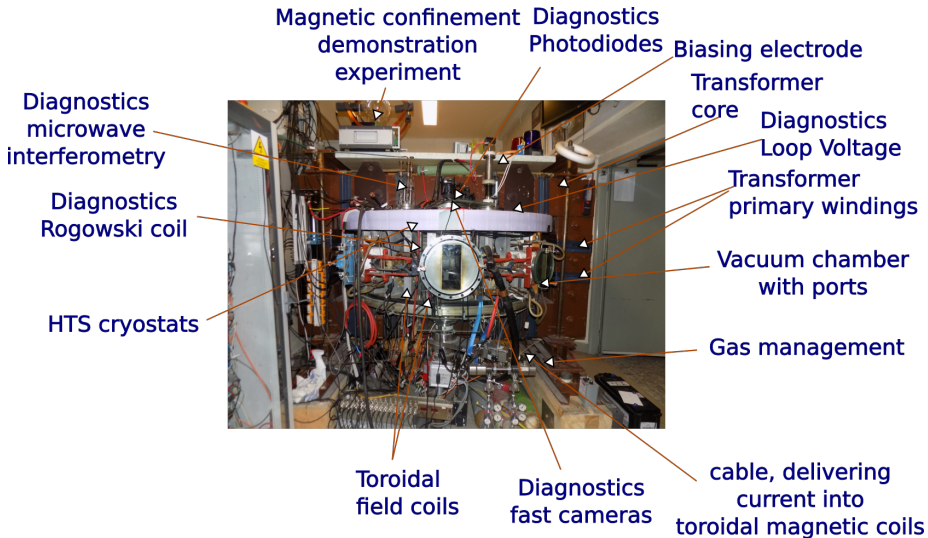
# Tokamak room (North) 10/16



# Tokamak room (South) 10/16



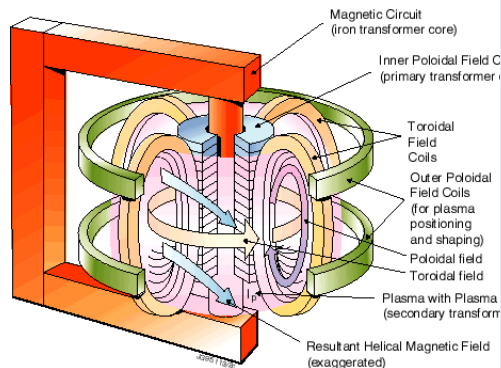
# Tokamak room (South) 10/16



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# Plasma in Tokamak (GOLEM) - the least to do

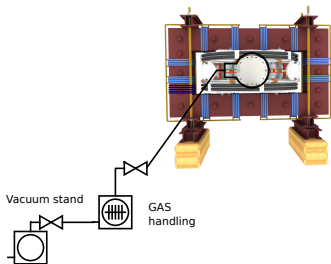


## To do:

- Evacuate the chamber
- Fill in the working gas
- Preionization
- 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

# Plasma in Tokamak (GOLEM) - the least to do

LEVEL 1

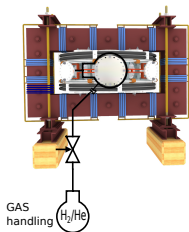


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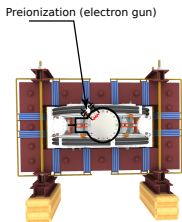
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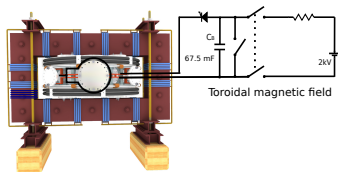


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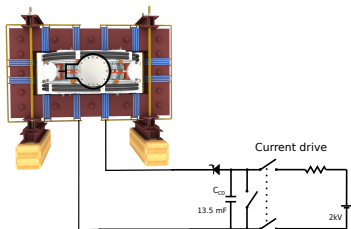


To do:

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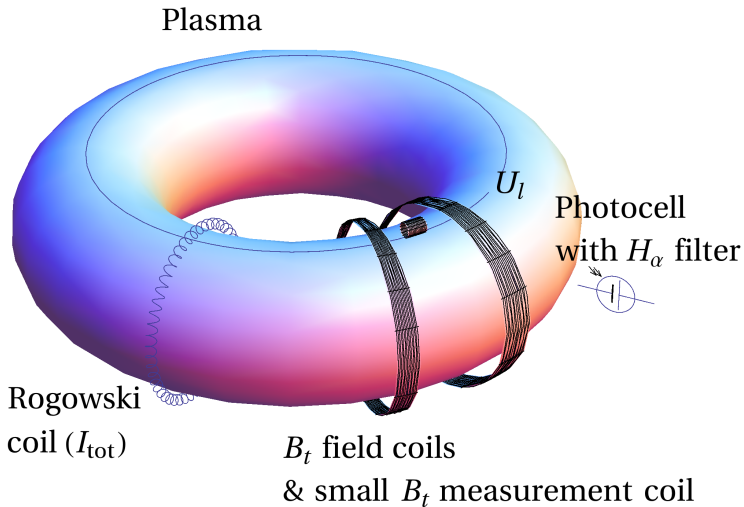
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- Evacuate the chamber
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- Toroidal magnetic field to confine plasma
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- **Toroidal electric field to heat the plasma**
- Plasma positioning
- Diagnostics

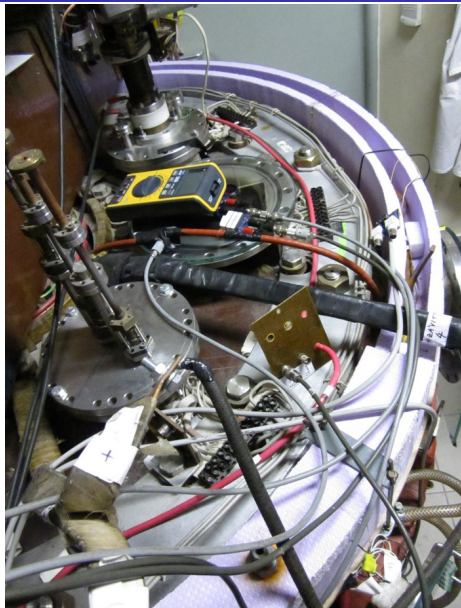
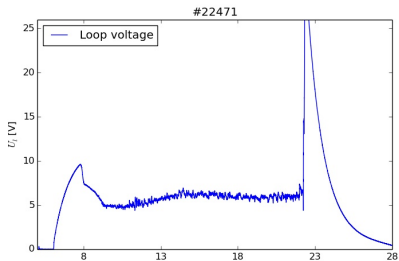
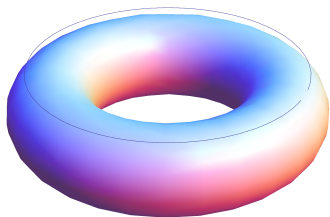
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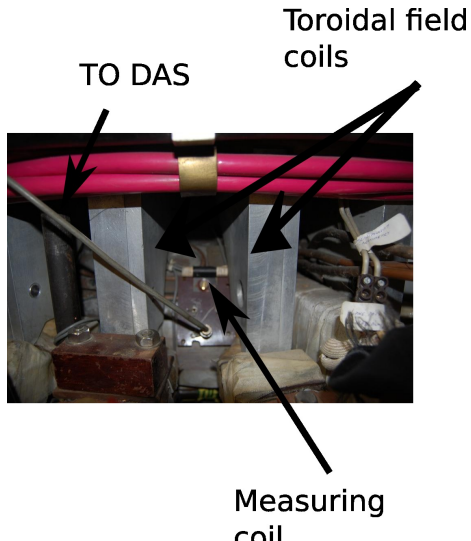
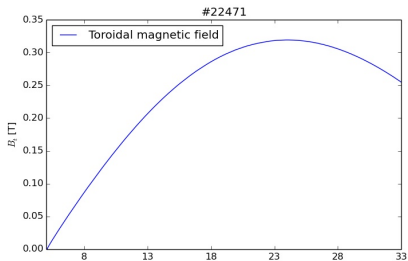
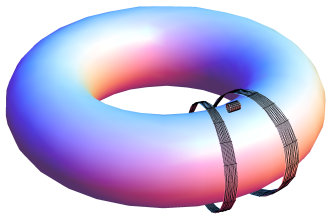
# Tokamak GOLEM - basic diagnostics



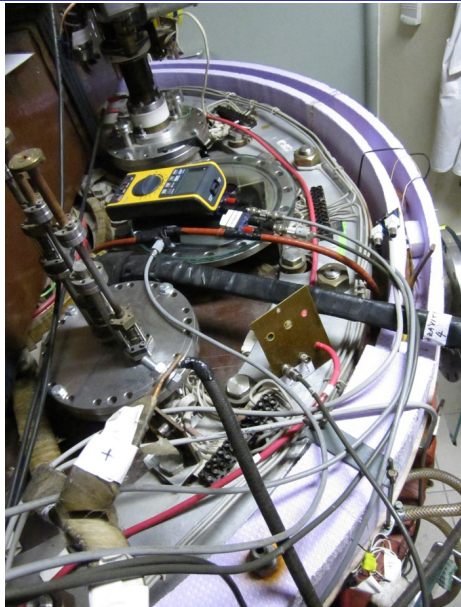
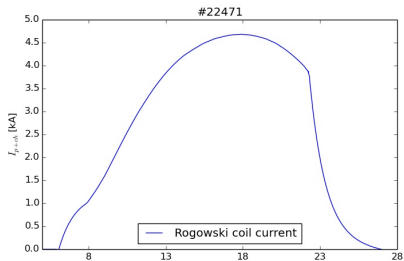
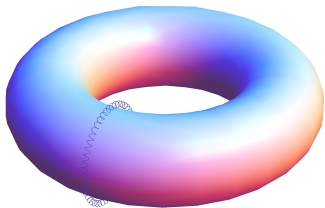
# Loop voltage $U_l$



# Toroidal magnetic field $B_t$

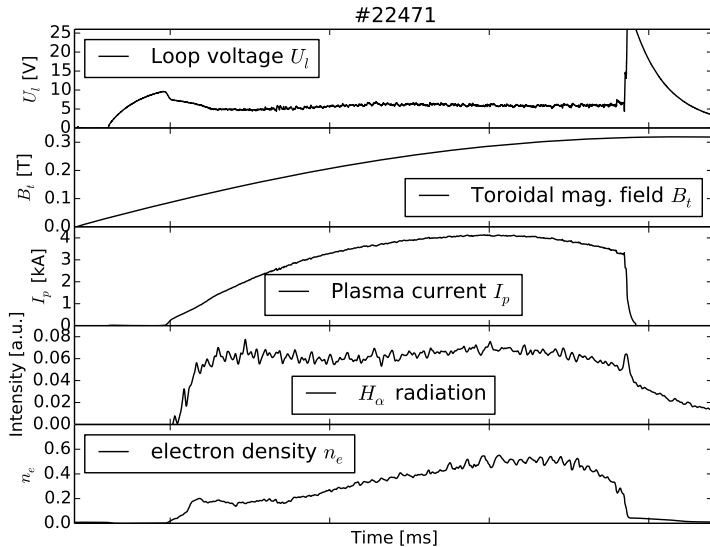


# Total current $I_{ch+p}$

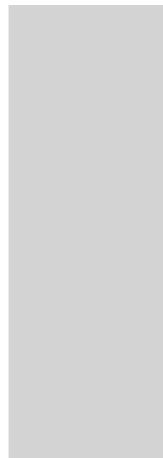
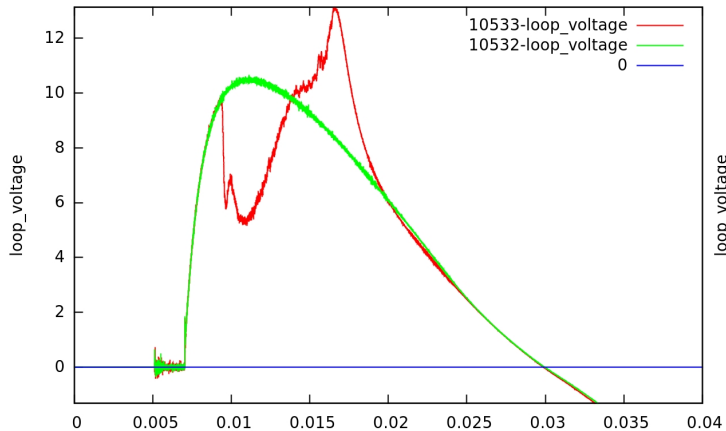




# Basic diagnostics @ tokamak GOLEM



# Plasma x vacuum discharge



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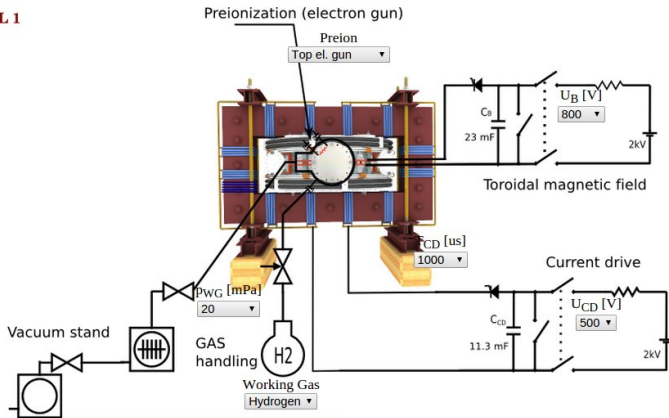
# Remote operation

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

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



LEVEL 1





## 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

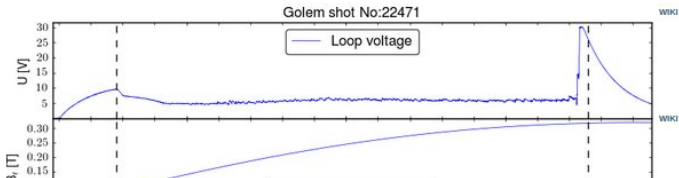
**Date:** 2016-09-29 - 14:33:57  
**Session:** TrainingCourses/Universities/Uni\_Belgrade.rs/2016/  
**Comment:** Standard discharge

## 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 [ $10^{17} \text{m}^{-2}$ ] [WIKI](#)



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# GOLEM basic Data Acquisition System (DAS)

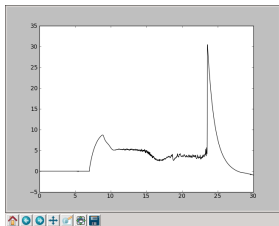
- $U_I, U_{B_t}, U_{I_{p+ch}}, I_{rad}$
- $\Delta t = 1\mu s / f = 1MHz$ .
- Integration time = 40 ms, thus DAS produces 6 columns x 40000 rows data file.
- Discharge is triggered at 5th millisecond after DAS to have a zero status identification.



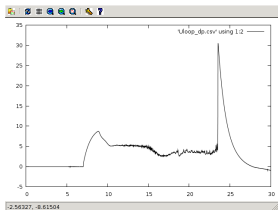
Data file example, DAS  $\Delta t = 1\mu s / f = 1MHz$  (neutral gas into plasma breakdown focused)

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

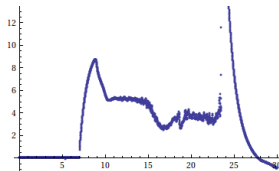
# Plot 4665 $U_l$ graph



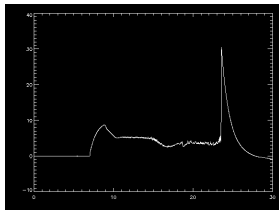
python



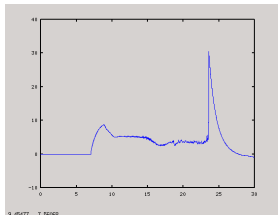
gnuplot



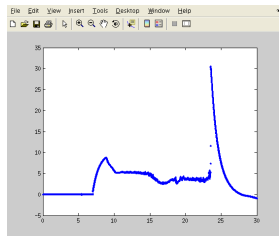
mathematica



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)

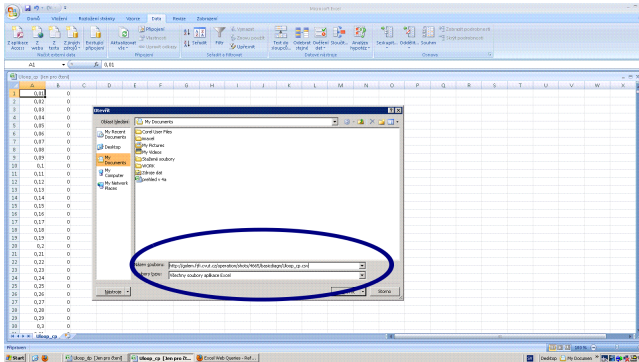
```
import matplotlib.pyplot as plt
from numpy import loadtxt
from urllib import urlopen

baseURL = "http://golem.fjfi.cvut.cz/Utils/data/"
ShotNo = 22471
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-')
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/utis/data/<#ShotNo>/<identifier>`

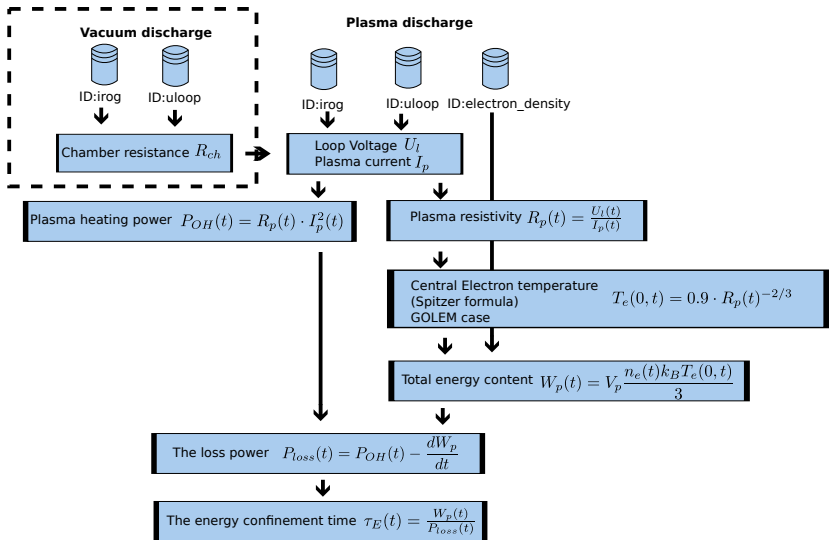
Spreadsheets (Excel and others)

are not recommended, only tolerated.

# Outline

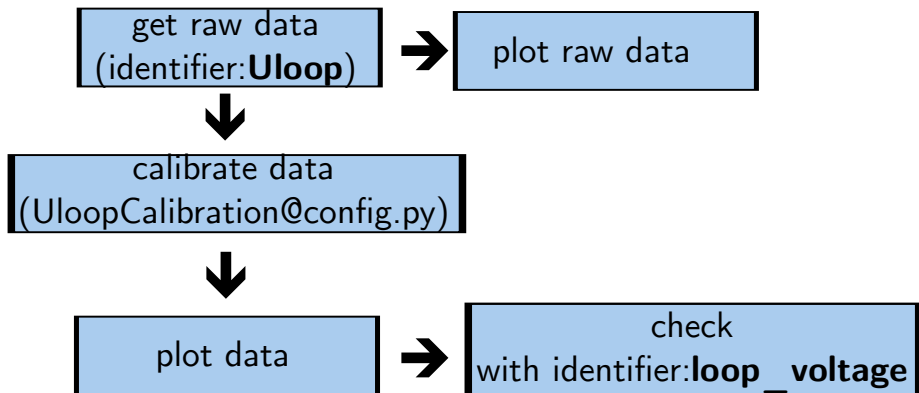
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# Towards Energy confinement time $\tau_E$

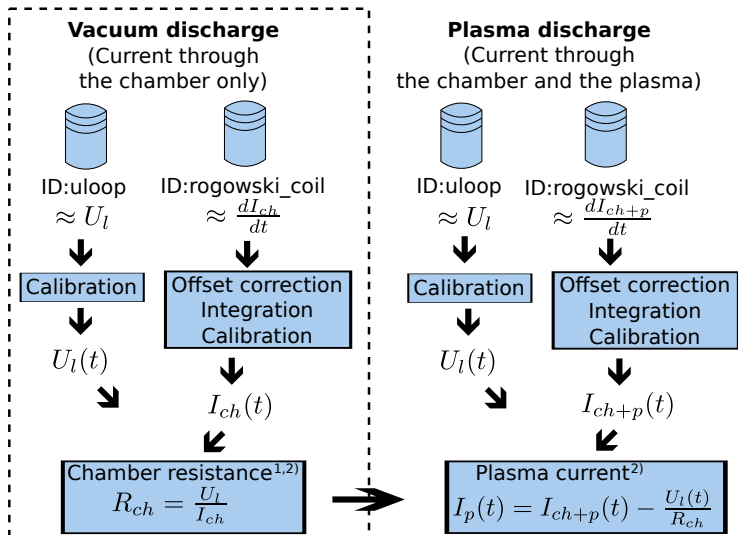




## Flowchart for $U_l$ generation



# Towards Plasma current $I_p$



1) With some statistical effort.

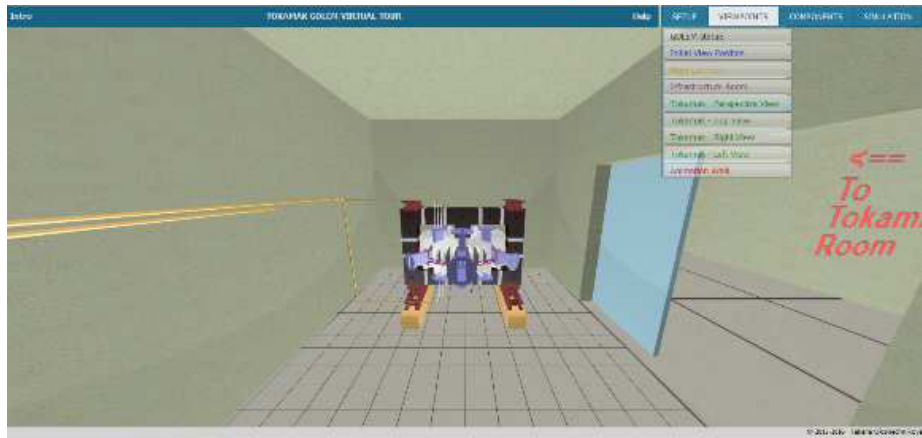
2) Do it in the stationary phase, i.e. current constant, to avoid inductive phenomena.

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- Everything via `http://golem.fjfi.cvut.cz/rshot`
  - Contact: Vojtech Svoboda, +420 737673903.
  - possible chat: `vojtech.svob@gmail.com`
  - skype: `tokamak.golem`.

# Tokamak GOLEM - virtual model



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



# Outline

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- 2 Tokamak GOLEM - engineering scheme
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- 4 Tokamak GOLEM - operation
- 5 Data handling @ the Tokamak GOLEM
- 6 Estimation of main plasma parameters
- 7 Closings
- 8 Appendix**



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# 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:  $R_p$  [ $\Omega$ ]

Plasma heating power:  $P_{OH}$  [W]

Total plasma energy content:  $W_p$  [J]

Chamber resistivity:  $R_{ch}$  [ $\Omega$ ]

Electron temperature:  $T_e$  [eV]

Energy confinement time:  $\tau_E$  [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]