

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

Vojtěch Svoboda  
on behalf of the tokamak GOLEM team  
for the Torino Politecnico, Italy

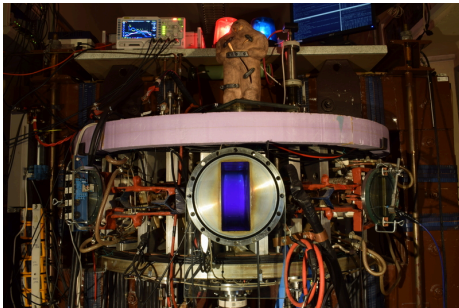
November 25, 2021

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- 3 The Tokamak GOLEM (remote) operation
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# The GOLEM tokamak basic characteristics

*The grandfather of all tokamaks (ITER newslines 06/18)*



- Vessel major radius:  $R_0 = 0.4$  m
- Vessel minor radius:  $r_0 = 0.1$  m
- Maximum plasma current:  
 $I_p^{\max} < 8$  kA
- Maximum toroidal magnetic field:  $B_t^{\max} < 0.5$  T
- Typical electron density:  
 $\langle n_e \rangle \in (0.2, 3) \cdot 10^{19} \text{ m}^{-3}$
- Maximum electron temperature:  
 $T_e^{\max} < 80$  eV
- Maximum discharge duration:  
 $\tau_p^{\max} < 25$  ms


# Tokamak GOLEM @ Wikipedia ..

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## Tokamak

From Wikipedia, the free encyclopedia

*This article is about the fusion reaction device. For other uses, see [Tokamak \(disambiguation\)](#).*

A **tokamak** (Russian: **токамак**) is a device that uses a powerful magnetic field to confine plasma in the shape of a torus. Achieving a stable plasma equilibrium requires magnetic field lines that move around the torus in a helical shape. Such a helical field can be generated by adding a toroidal field


it decays into a proton and electron with the emission of energy. When the time comes to actually try to make electricity from a tokamak-based reactor, some of the neutrons produced in the fusion process would be absorbed by a liquid metal blanket and their kinetic energy would be used in heat-transfer processes to ultimately turn a generator.

### Experimental tokamaks [ edit ]

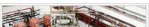
#### Currently in operation [ edit ]

(in chronological order of start of operations)

- 1960s: TМ1-MH (since 1977 Castor; since 2007 Golem<sup>[12]</sup>) in Prague, Czech Republic. In operation in Kurchatov Institute since early 1960s but renamed to Castor in 1977 and moved to IPP CAS,<sup>[13]</sup> Prague; in 2007 moved to FNSPE, Czech Technical University in Prague and renamed to Golem.<sup>[14]</sup>
- 1975: T-10, in Kurchatov Institute, Moscow, Russia (formerly Soviet Union); 2 MW
- 1983: Joint European Torus (JET), in Culham, United Kingdom
- 1985: JT-60, in Naka, Ibaraki Prefecture, Japan; (Currently undergoing upgrade to Super, Advanced model)
- 1987: STOR-M, University of Saskatchewan; Canada; first demonstration of alternating current in a tokamak.
- 1988: Tore Supra,<sup>[15]</sup> at the CEA, Cadarache, France
- 1989: Aditya, at Institute for Plasma Research (IPR) in Gujarat, India
- 1980s: DIII-D,<sup>[16]</sup> in San Diego, USA; operated by General Atomics since the late 1980s
- 1989: COMPASS,<sup>[13]</sup> in Prague, Czech Republic; in operation since 2008, previously operated from 1989 to 1999 in Culham, United Kingdom
- 1990: FTU, in Frascati, Italy
- 1991: Tokamak ISTTOK,<sup>[17]</sup> at the Instituto de Plasmas e Fusão Nuclear, Lisbon, Portugal;
- 1991: ASDEX Upgrade, in Garching, Germany

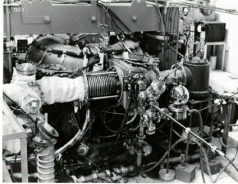


Alcator C-Mod



# The GOLEM tokamak 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

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

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

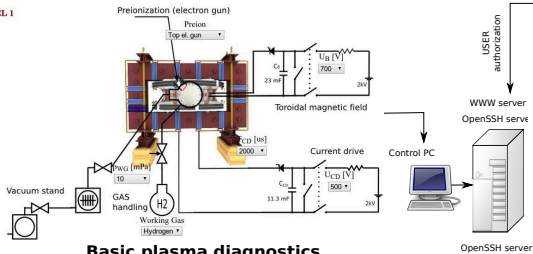


At the end of the 16th century, in the times when the Czech lands were ruled by Emperor Rudolf II, in Prague, there were Rabbi Judah Loew, well known alchemist, thinker, scholar, writer and inventor of the legendary GOLEM - a clay creature inspired with the Universe power that pursued his master's command after being brought to life with a shem, . Golem is not perceived as a symbol of evil, but rather as a symbol of power which might be useful but is very challenging to handle. To learn more of the Golem legend, see e.g. [1].

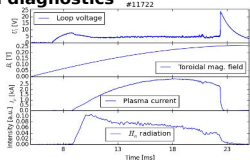
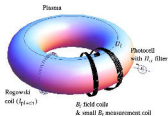
# The global schematic overview of the GOLEM experiment

LEVEL 1

## Tokamak technology setup



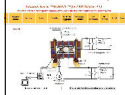
## Basic plasma diagnostics



## Virtual control room (remote participation)

### WWW control interface

#### HTML & PHP scripts



### SSH control interface

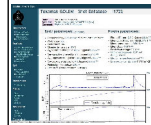
#### WINDOWS via putty



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

### Data presentation

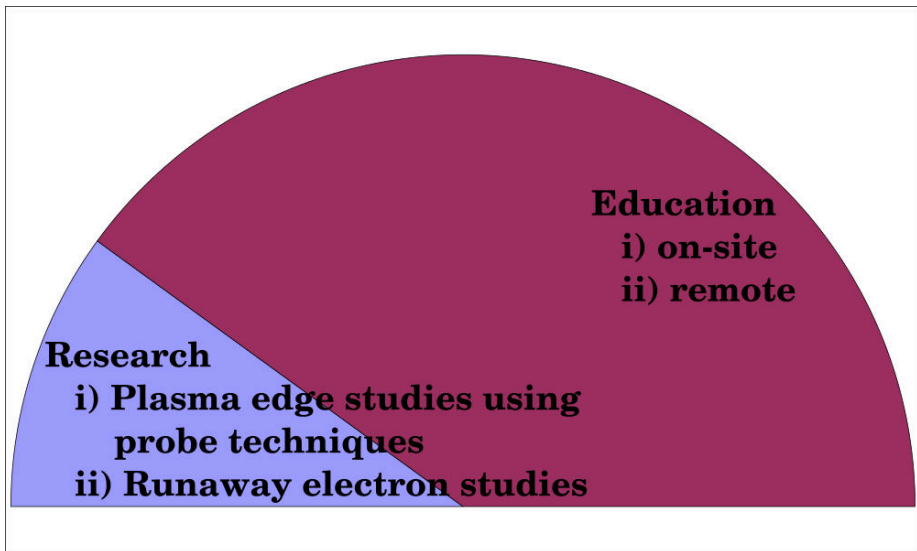
#### HTML (www pages)



### Data handling

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

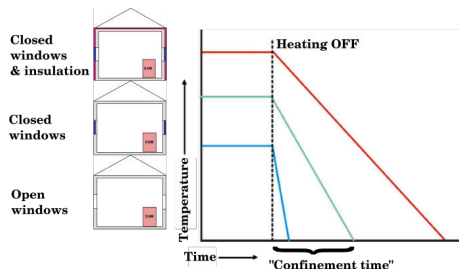
# The GOLEM tokamak mission



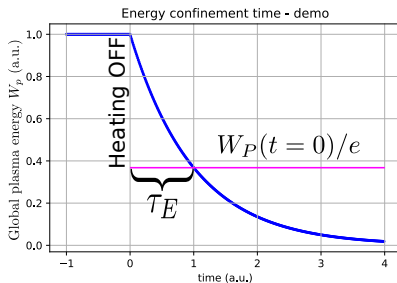


# Towards ... Energy confinement time

## House



## Tokamak



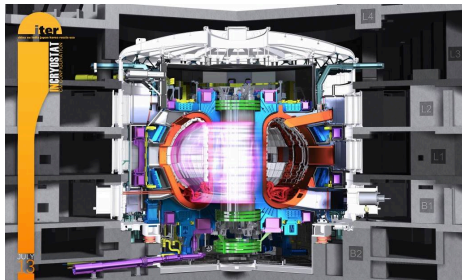
- The confinement time:  $\tau_E = \frac{W}{P_{\text{loss}}}$
- Energy density:  $W = 3nk_B T$
- Reactions per volume per time of fusion reactions is:  
 $f = n_d n_t \langle \sigma v \rangle = \frac{1}{4} n^2 \langle \sigma v \rangle$
- Fusion heating  $fE_{\text{ch}}$ , where  $E_{\text{ch}} = 3.5 \text{ MeV}$  should exceeds the losses:  
 $fE_{\text{ch}} \geq P_{\text{loss}}$

$$n\tau_E \geq L \equiv \frac{12}{E_{\text{ch}}} \frac{k_B T}{\langle \sigma v \rangle} \geq 1.5 \cdot 10^{20} \frac{\text{s}}{\text{m}^3}$$

(DT reaction@minimum  $\approx 26 \text{ keV}$ )

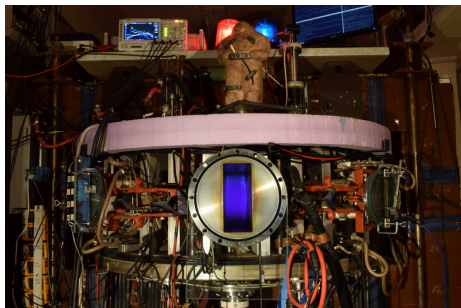
# The competition

The ITER: 3.6 s



credit:[3]

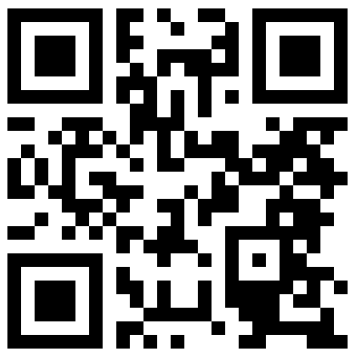
The GOLEM: ??? s or ms or us ??



credit:[4]

# Production

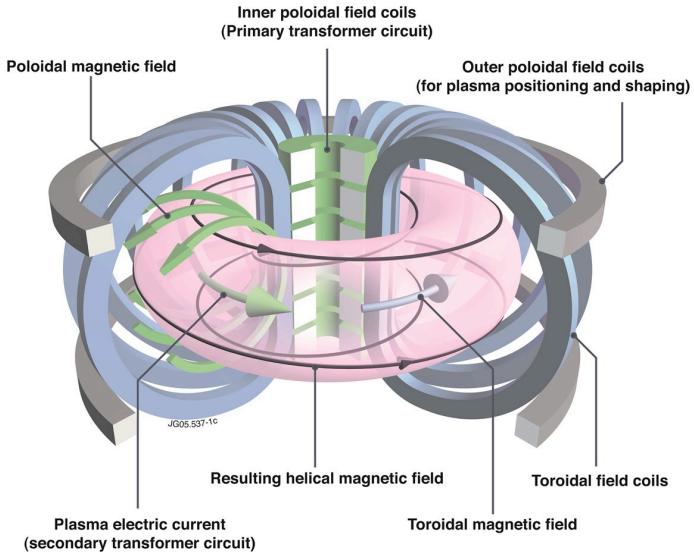
- Everything via <http://golem.fjfi.cvut.cz/Torino>
  - This presentation
  - Control rooms
  - Contact: Vojtech Svoboda,  
+420 737673903,  
[svoboda@fjfi.cvut.cz](mailto:svoboda@fjfi.cvut.cz)
  - Chat:  
[tokamak.golem@gmail.com](mailto:tokamak.golem@gmail.com) or  
skype: tokamak.golem



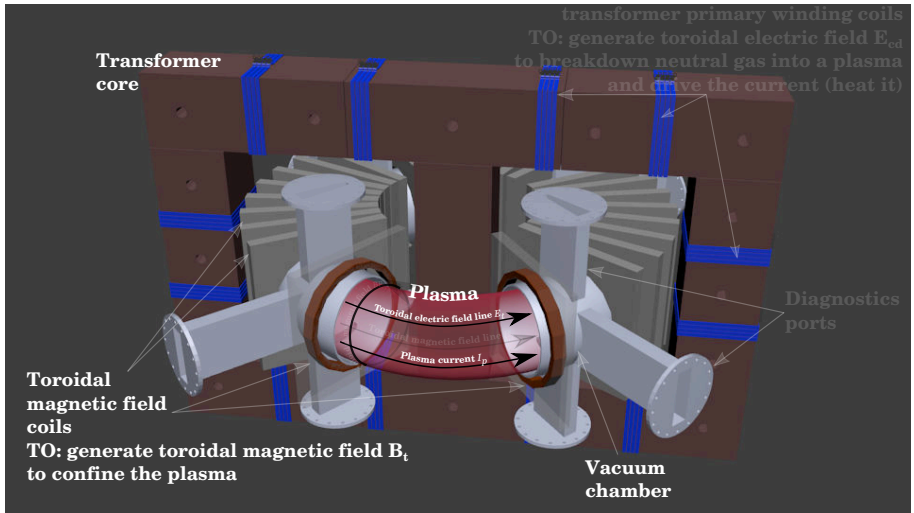
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# Tokamak magnetic confinement concept



# Tokamak (GOLEM) basic concept to confine and heat the plasma



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- The GOLEM tokamak - guide tour

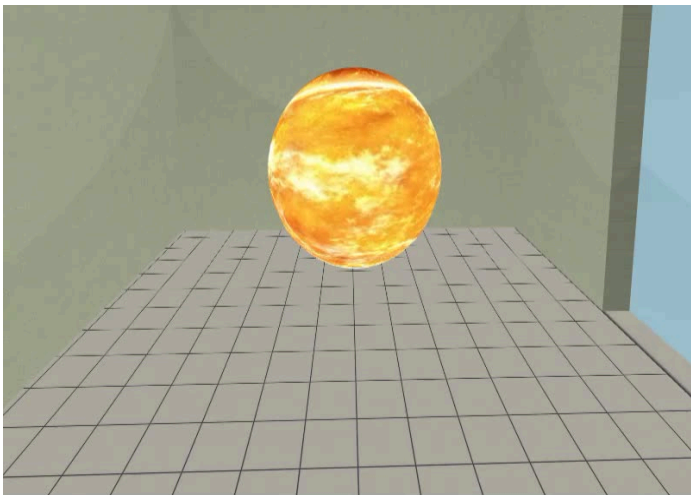
## 3 The Tokamak GOLEM (remote) operation

## 4 The Electron energy confinement time calculation (rough estimation)

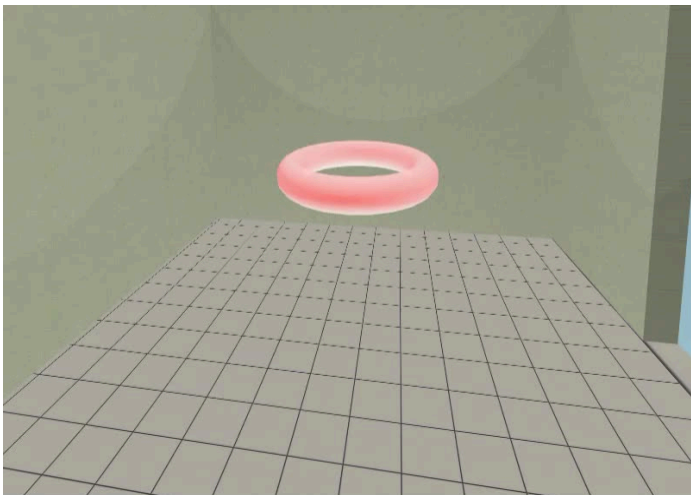
## 5 Conclusion



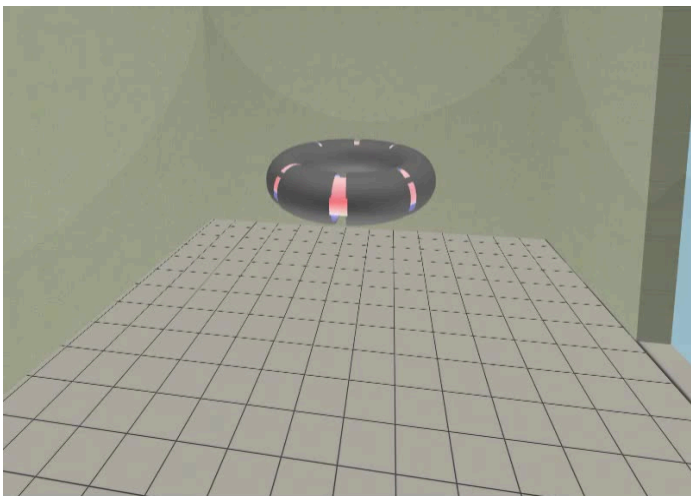
Our goal: the technology to create a  $\mu$ Sun on the Earth



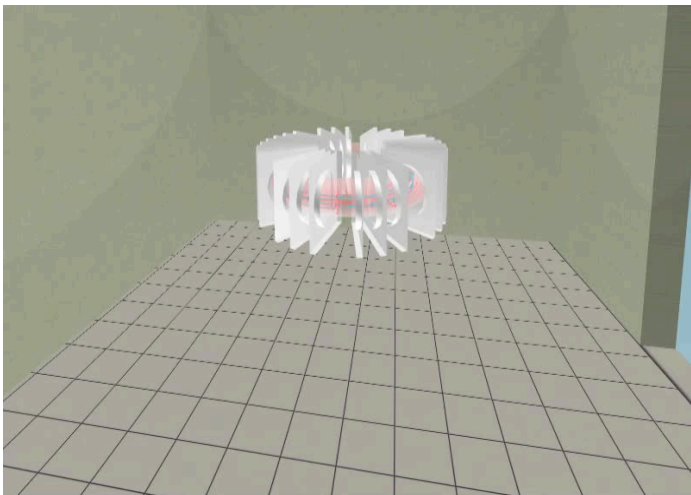
# Magnetic confinement requires toroidal geometry



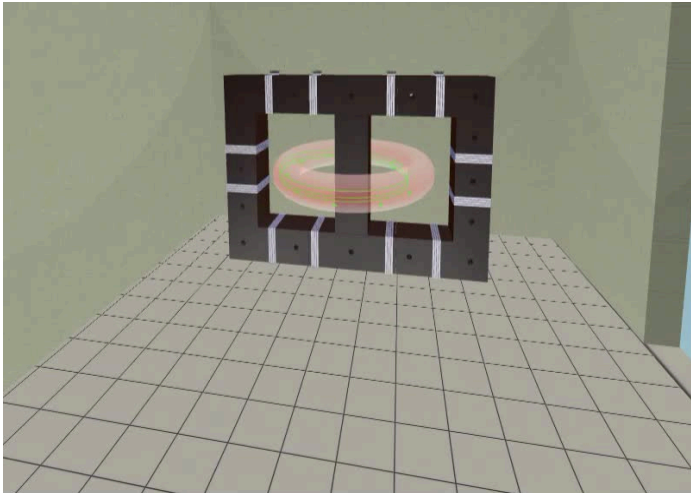
A chamber contains the thermonuclear reaction



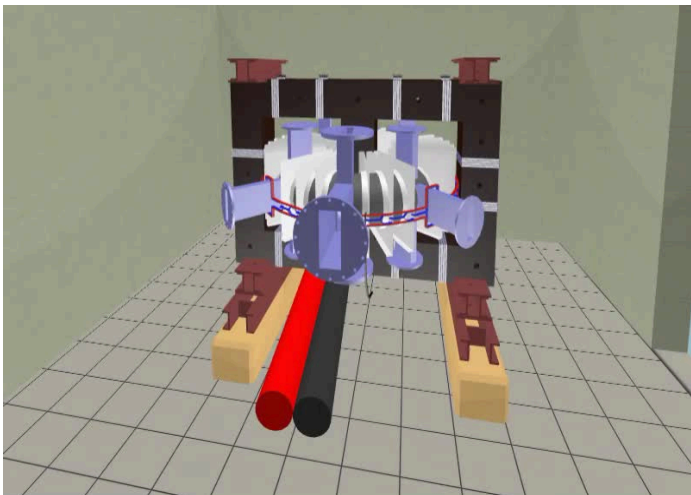
Toroidal magnetic field coils confine the plasma



A transformer action creates and heats the plasma



# The final technology altogether



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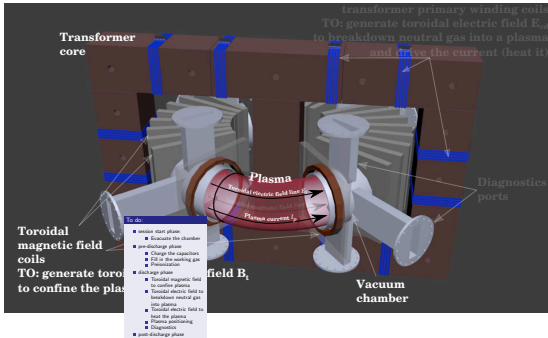
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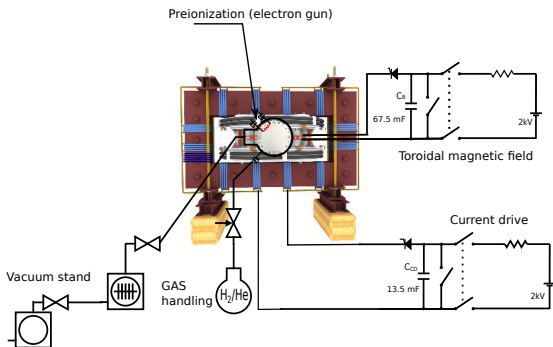
## 5 Conclusion

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





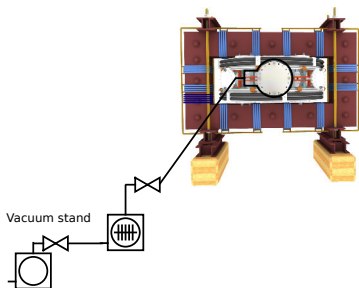
# Plasma in Tokamak (GOLEM) - the least to do



## 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

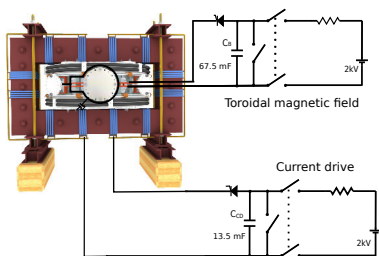
# Plasma in Tokamak (GOLEM) - the least to do



## To do:

- session start phase:
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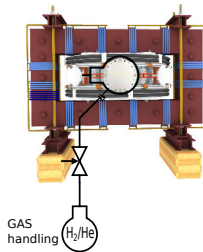
# Plasma in Tokamak (GOLEM) - the least to do



## To do:

- session start phase:
  - Evacuate the chamber
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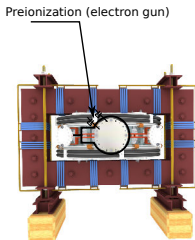
# Plasma in Tokamak (GOLEM) - the least to do



## To do:

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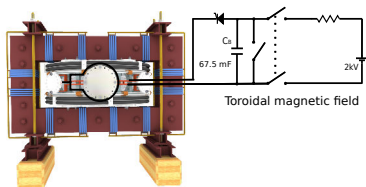
# Plasma in Tokamak (GOLEM) - the least to do



## To do:

- session start phase:
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  - Fill in the working gas
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  - Toroidal magnetic field to confine plasma
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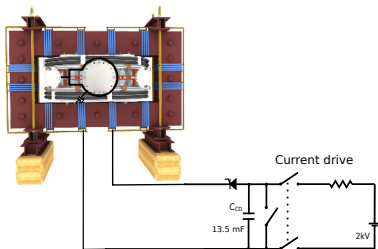
# Plasma in Tokamak (GOLEM) - the least to do



## To do:

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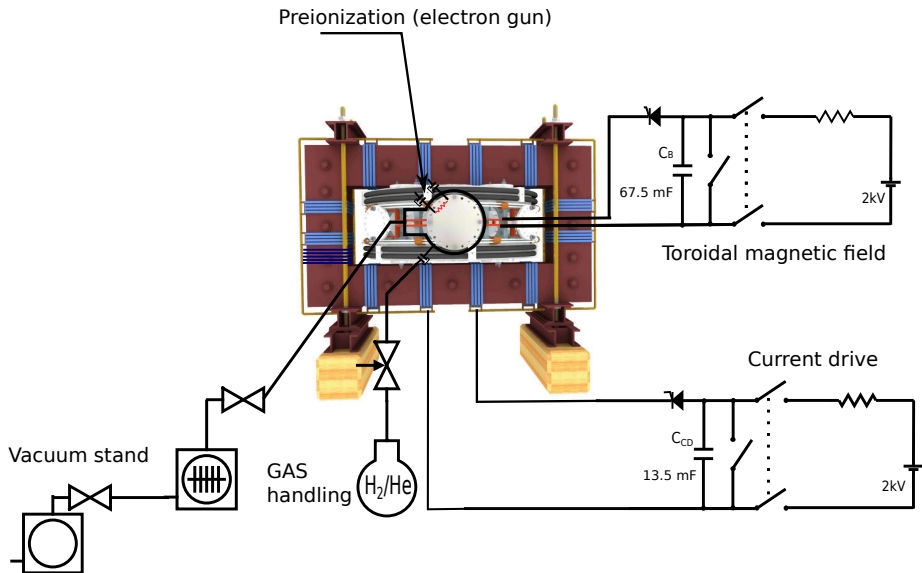
# Plasma in Tokamak (GOLEM) - the least to do



## To do:

- session start phase:
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  - Fill in the working gas
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  - **Toroidal electric field to heat the plasma**
  - Plasma positioning
  - Diagnostics
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# Tokamak GOLEM - schematic experimental setup





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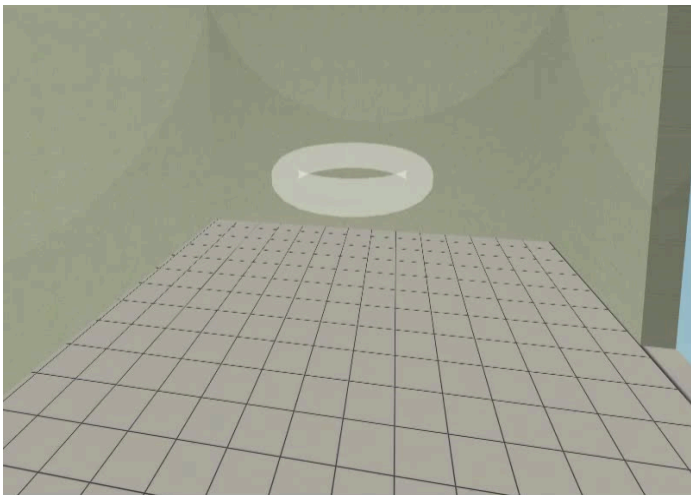
- The GOLEM tokamak concept
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## 3 The Tokamak GOLEM (remote) operation

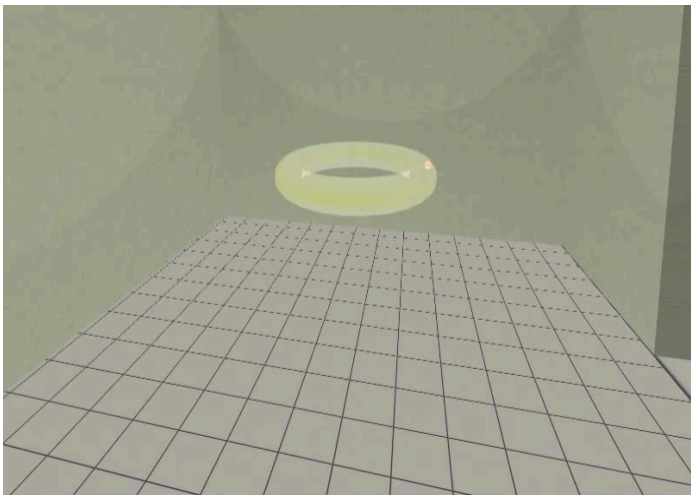
## 4 The Electron energy confinement time calculation (rough estimation)

## 5 Conclusion

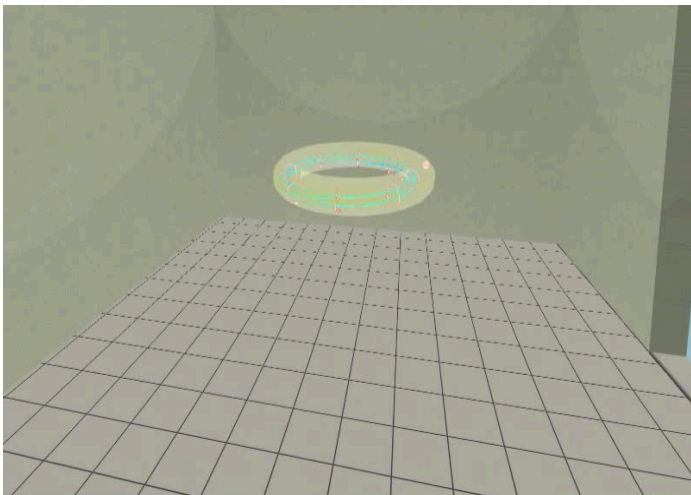
Introduce the working gas (Hydrogen x Helium)



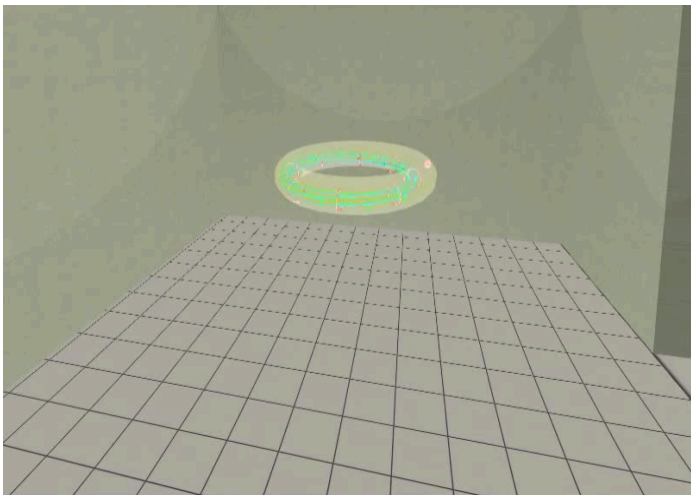
Switch on the preionization



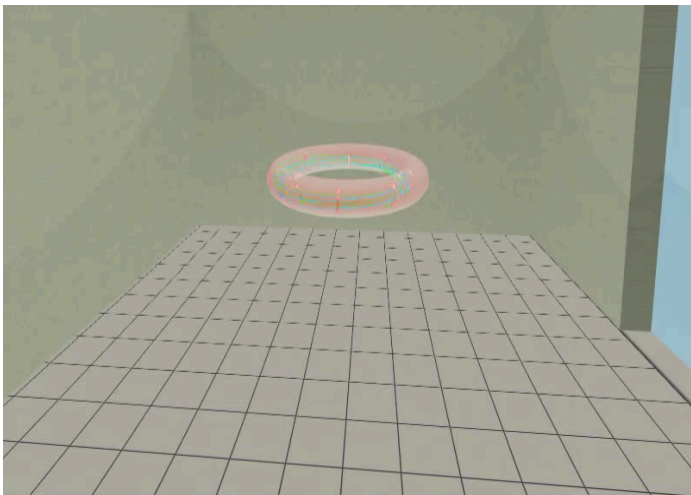
# Introduce the magnetic field



# Introduce the electric field



# Plasma ..



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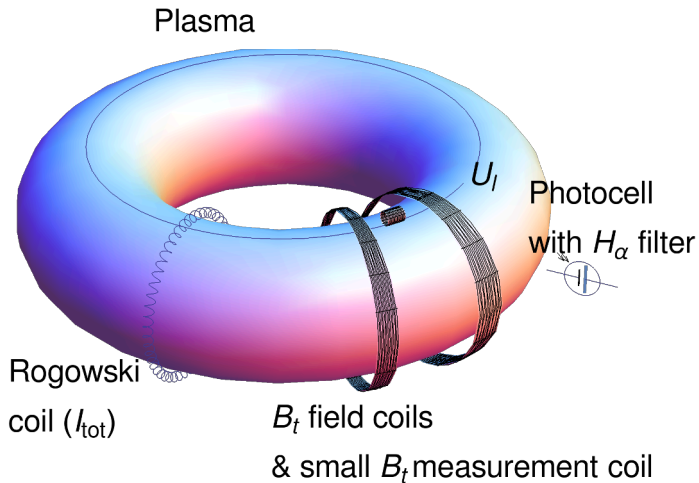
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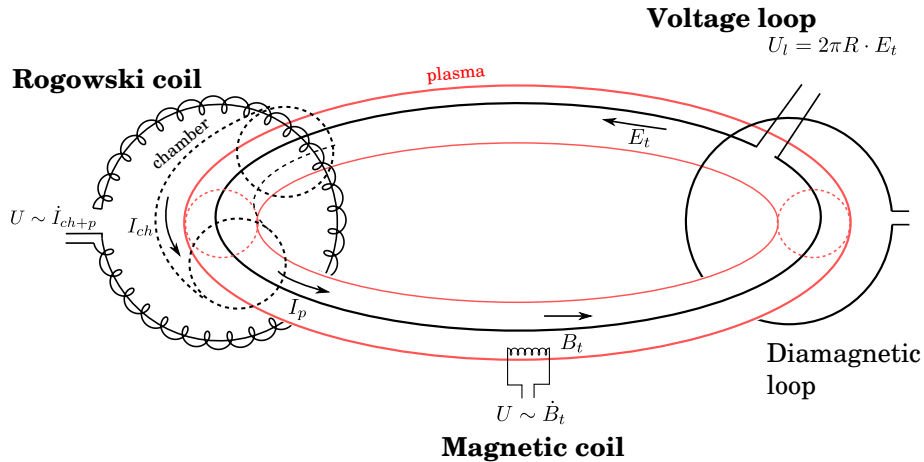
## 5 Conclusion

# The GOLEM tokamak - basic diagnostics

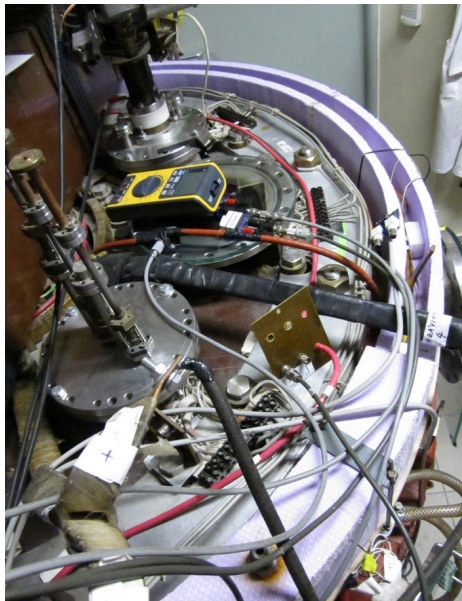
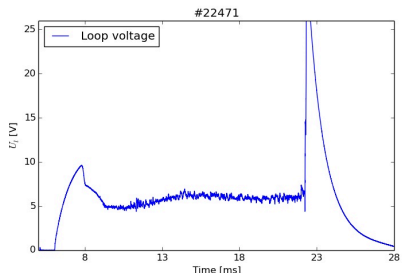
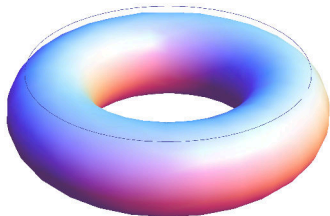




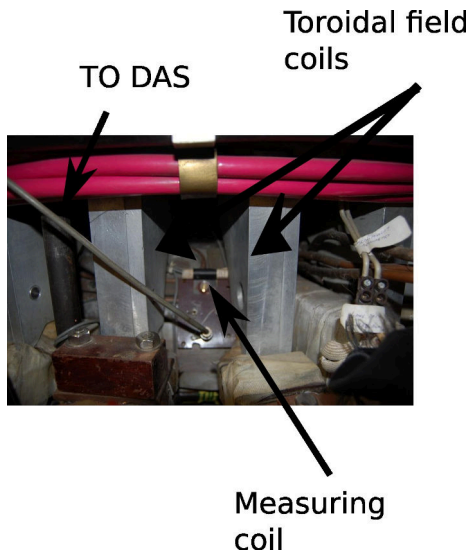
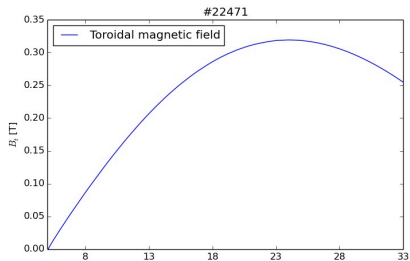
# Schematic of electromagnetic diagnostics



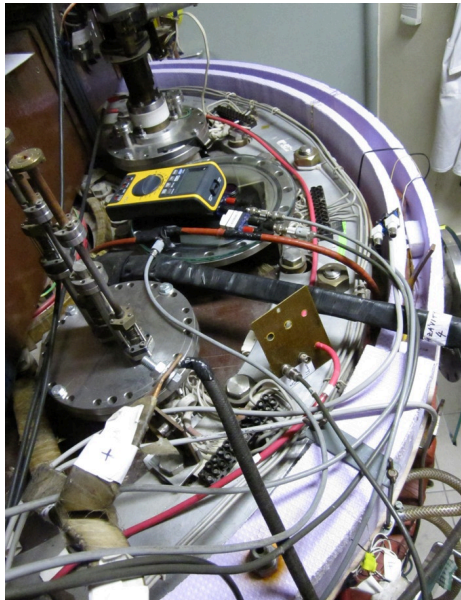
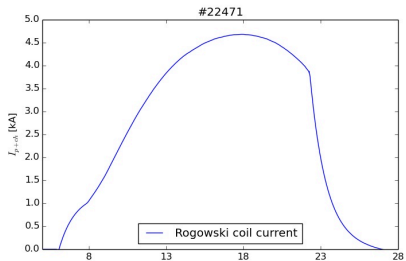
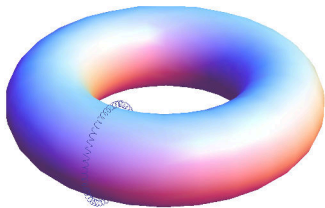
# Loop voltage $U_l$ @ the GOLEM tokamak



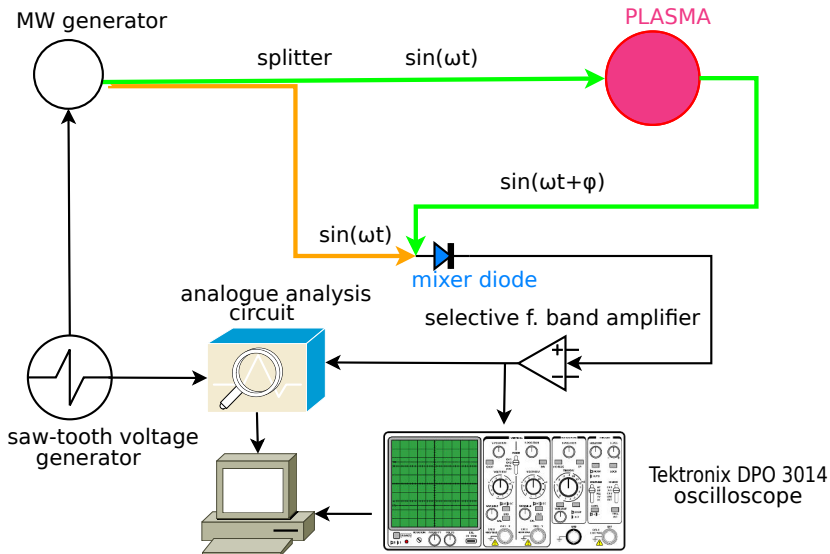
# Toroidal magnetic field $B_t$ @ the tokamak GOLEM



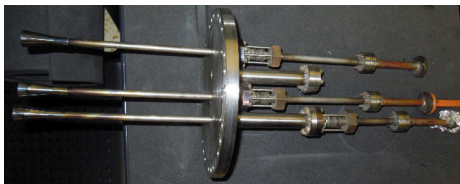
# Total current $I_{ch+p}$



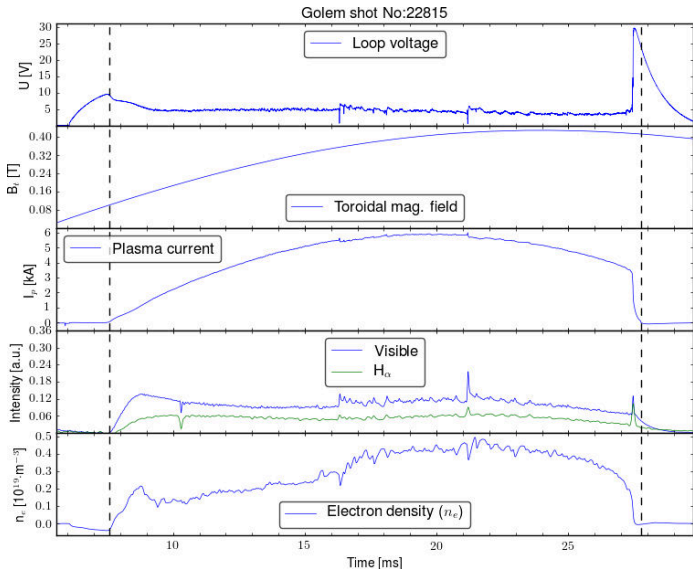
# Electron density $n_e$ interferometry measurement scheme



# The GOLEM tokamak interferometry HW



# "Typical", well executed discharge @ GOLEM



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## 5 Conclusion



# 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

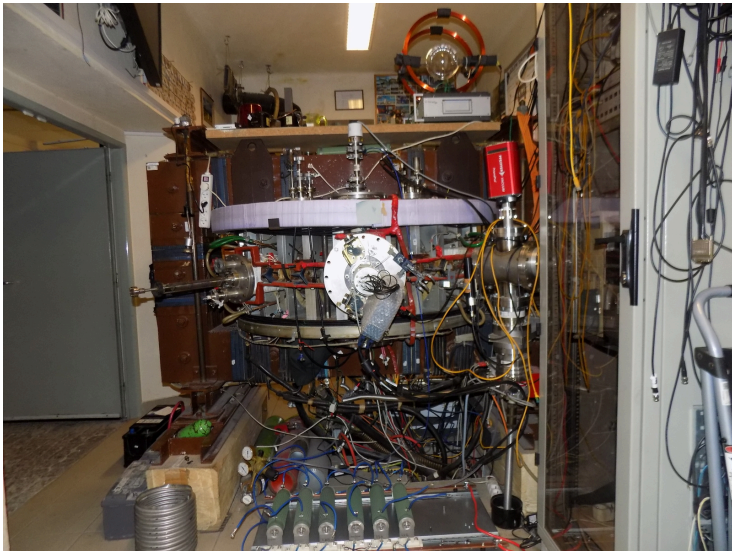
power  
supply  
2kV

Toroidal  
magnetic field B  
capacitors

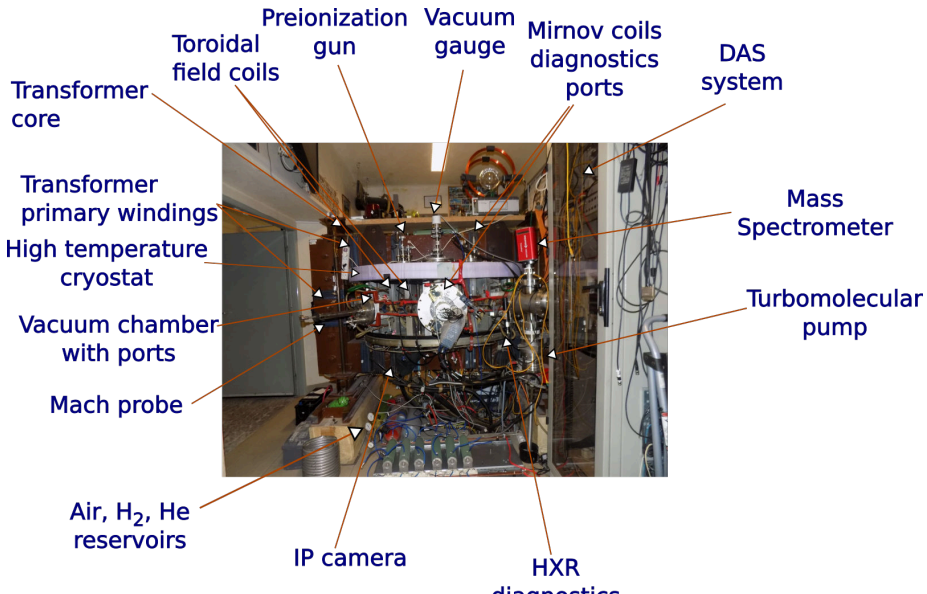
fire  
protection  
system



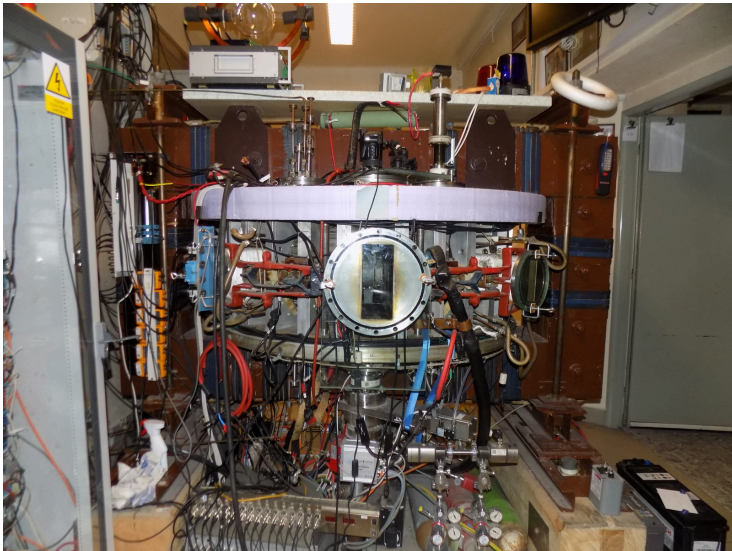
# Tokamak room (North) 10/16



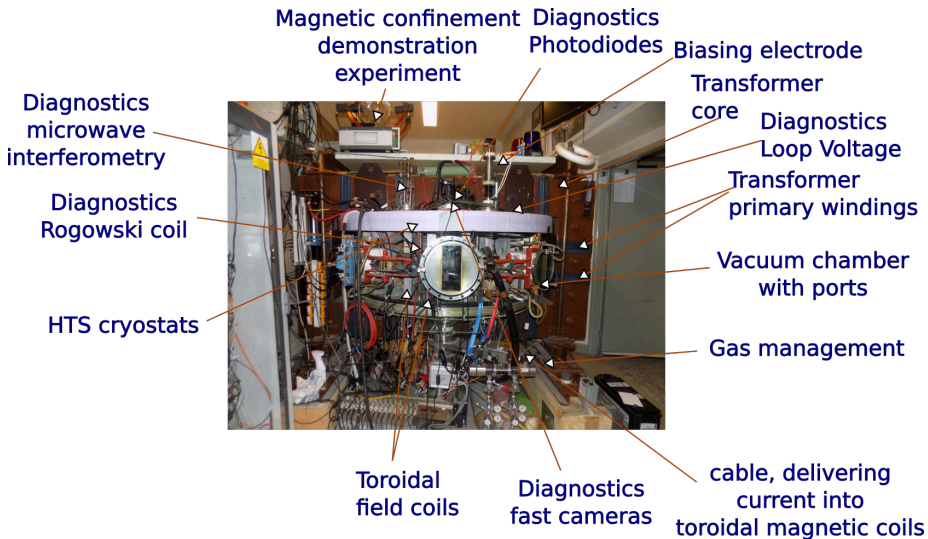
# Tokamak room (North) 10/16



# Tokamak room (South) 10/16



# Tokamak room (South) 10/16



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# Control room: Introduction

GOLEM remote Introduction **Control room** Live Results

Prague Access: Level 1 Help

Introduction Working gas Preionization Magnetic field Current drive Submit

This web interface will walk you through the process of configuring a discharge in the GOLEM tokamak. All settable values are perfectly safe. Proceed through each step by setting the desired values and then clicking the [Next](#) button. You can always go to a specific step by clicking its tab.

**Preionization (electron gun)**

Vacuum stand

Preionization (electron gun)

Toroidal magnetic field

Current drive

GAS handling  $H_2/He$

23 mF  $C_p$

11.3 mF  $C_p$

2kV

2kV

Next

3D model rendering method: **Static image (fast)** Interactive X3DOM (slower)

# Control room: Working gas

GOLEM remote Introduction Control room Live Results

Introduction Working gas Preionization Magnetic field Electric field Submit

Set the pressure and type of the working gas from which the plasma is formed. Pressure must be high enough for plasma to form, but low enough for gas breakdown to occur.

### Preionization (electron gun)

Vacuum stand

GAS handling  $H_2/H_8$

Toroidal magnetic field

Toroidal electric field

Gas type and pressure  $p_{gas}$ : 38 mPa

Hydrogen Helium

Next Set recommended value

3D model rendering method Static image (best) Interactive X3DOM (preview)

# Control room: Preionization

GOLEM remote Introduction Control room Live Results

Introduction Working gas Preionization Magnetic field Electric field Submit

The neutral working gas must first be ionized in order to break down into a plasma. Using the electron gun will locally ionize the gas. Without any ionization, no plasma can form.

### Preionization (electron gun)

Vacuum stand

GAS handling

Toroidal magnetic field

Toroidal electric field

67.5 mF

13.5 mF

20V

20V

ionization method

Electron gun  No ionization

Next

3D model rendering method Static image (best) Interactive X3DOM (viewer)

# Control room: Magnetic field $B_t$

GOLEM version: Introduction Control room Live Results

Press F11 to exit full screen  
3D model rendering method: Static image (best) Interactive X3DOM (viewer)

Introduction Working gas Preionization **Magnetic field** Electric field Submit

Set the voltage on the capacitors to be discharged into the toroidal field coils. The higher the voltage, the larger the magnetic field confining the plasma.

Preionization (electron gun)

Vacuum stand

Toroidal magnetic field

Toroidal electric field

GAS handling

Capacitor voltage  $U_{C_1} = 600$  V

Next Set recommended value

# Control room: Current drive $E_{cd}$

GOLEM remote Introduction Control room Live Results

the Torneo Politecnico, Italy Group 1 Access: Level 2 Help

Introduction Working gas Preionization Magnetic field **Electric field** Submit

Set the voltage on the capacitors to be discharged into the [primary transformer winding](#). The higher the voltage, the larger the electric field creating and heating the plasma. The electric field capacitors are discharged after a configurable delay with respect to the magnetic field capacitors.

Preionization (electron gun)

Vacuum stand

Toroidal magnetic field

Toroidal electric field

GAS handling

Time delay of electric field start after the magnetic field starts  $t_{cd}$ : 0 micro seconds

Capacitor voltage  $U_{cd}$ : 400 V

Next Set recommended value

3D model rendering method Static image (best) Interactive X3DOM (viewer)

# Control room: ... and Submit

GOLEM remote Introduction Control room Live Results

the Torneo Politecnico, Italy Group 1 Access: Level 2 Help

Introduction Working gas Preionization Magnetic field Electric field **Submit**

Write a comment describing your discharge configuration, i.e. the scientific aim of your experiment. Or just leave a friendly message.

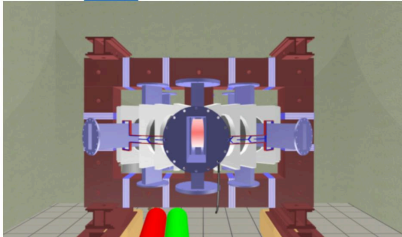
Comment

Click the Submit button to send your configuration into the queue. **Submit**

After submission you can watch the discharge Live or go back to the Introduction tab and start again. Or you can go to specific control tabs and reconfigure the discharge and then submit another discharge request.

[Watch the discharge Live!](#) [Go back to Introduction](#)

3D model rendering method: [Static image \(best\)](#) [Interactive X3DOM \(slower\)](#)



# Shot homepage

GOLEM » Shot #22471 »



## Diagnostics

- ✓ Interferometer
- ✓ Spectrometer
- ✗ FastCamera
- ✓ HXR

## Analysis

- ✓ ShotHomepage

## DAS

- ✓ TektronixDPO
- ✓ Nistandard
- ✓ Papouch\_St
- ✓ Papouch\_Ko
- ✓ Nloctopus

## Vacuum log

## Other

- Data
- References
- About
- Wiki
- Utilities

## Navigation

- Next
- Previous
- Current

# Tokamak GOLEM - Shot Database - 22471

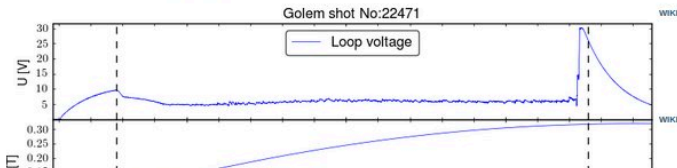
**Date:** 2016-09-29 - 14:33:57  
**Session:** TrainingCourses/Universities/Uni\_Belgrade.rs/2016/  
**Comment:** Standard discharge

## 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 ..	:
:	:	:	:	:
:	:	:	:	:

# 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 specified with <DASname> and <DASchannelidentifier> have the format:

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

# Jupyter (python)

```
1 import numpy as np
2 import matplotlib.pyplot as plt
3
4 shot_no = 33993
5 identifier = "LoopVoltageCoil_raw.csv"
6 DAS='DASs/StandardDAS/'
7 # create data cache in the 'golem_cache' folder
8 ds = np.DataSource('golem_cache')
9 #Create a path to data and download and open the file
10 base_url = "http://golem.fjfi.cvut.cz/shots/"
11 data_file = ds.open(base_url + str(shot_no)+ '/' +DAS +identifier)
12 #Load data from the file and plot to screen and to disk
13 data = np.loadtxt(data_file,delimiter=",")
14 plt.plot(data[:,0], data[:,1]) #1. column vs 2. column
15 plt.xlabel('Time [ms]');plt.ylabel('$U_1$ [V]');
16 plt.savefig('graph.jpg')
17 plt.show()
18
19 #Run it: save it as script.py and run "python script.py" or execute in a
    ceel in a Jupyter Notebook
```

# Matlab

```
1 ShotNo=33993
2 baseURL='http://golem.fjfi.cvut.cz/shots/';
3 diagnPATH='/DASs/StandardDAS/LoopVoltageCoil_raw.csv';
4 %Create a path to data
5 dataURL=strcat(baseURL,int2str(ShotNo),diagnPATH);
6 % Write data from GOLEM server to a local file
7 urlwrite(dataURL,'LoopVoltage');
8 % Load data
9 data = load('LoopVoltage', '\t');
10 % Plot and save the graph
11 f = figure('visible', 'off');
12 hold on
13 plot(data(:,1)*1000, data(:,2), '.');
14 xlabel('Time [ms]')
15 ylabel('U_1 [V]')
16 hold off
17 print -djpeg plot.jpg
18 close(f)
19 exit;
```

# Octave

```
1 ShotNo=33993
2 baseURL='http://golem.fjfi.cvut.cz/shots/';
3 diagnPATH='/DASs/StandardDAS/LoopVoltageCoil_raw.csv';
4 %Create a path to data
5 dataURL=strcat(baseURL,int2str(ShotNo),diagnPATH);
6 % Write data from GOLEM server to a local file
7 urlwrite(dataURL,'LoopVoltageCoil_raw.csv');
8 % Load data
9 data = load('LoopVoltageCoil_raw.csv', '\t');
10 % Plot and save the graph
11 plot(data(:,1), data(:,2), '.');
12 xlabel('time [ms]')
13 ylabel('U_loop [V]')
14 saveas(gcf, 'plot', 'jpg');
15 exit;
```

# Gnuplot

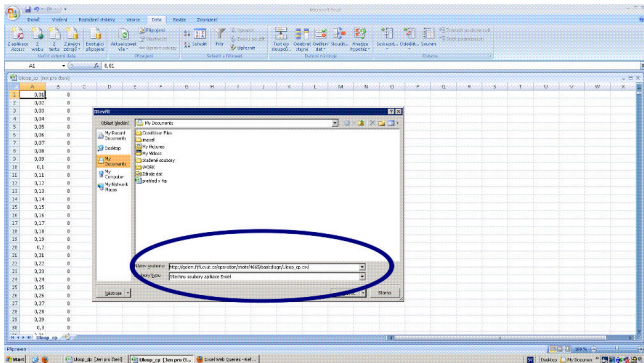
```
1 identifier = 'LoopVoltageCoil_raw.csv' ;
2 ShotNo = '33993'
3 # Create a path to the data
4 DAS='DASs/StandardDAS/'
5 baseURL='http://golem.fjfi.cvut.cz/shots/'
6 DataURL= baseURL.ShotNo.'/'.DAS.identifier
7 set datafile separator ',';
8 set title "Uloop for #".ShotNo;
9 # Write data from GOLEM erver to a local file
10 ! wget -q @DataURL ;
11 # Plot the graph from a local file
12 set xrange [0:0.02];set xlabel 'Time [s]';set ylabel 'U_1 [V]'
13 plot identifier u 1:2 w l t 'Uloop'
```

# 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>`

# Excel



File→Open→

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

Spreadsheets (Excel and others)

are not recommended, only tolerated.

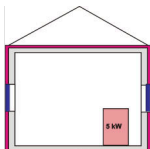


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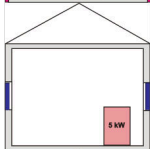
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# Energy balance of the house

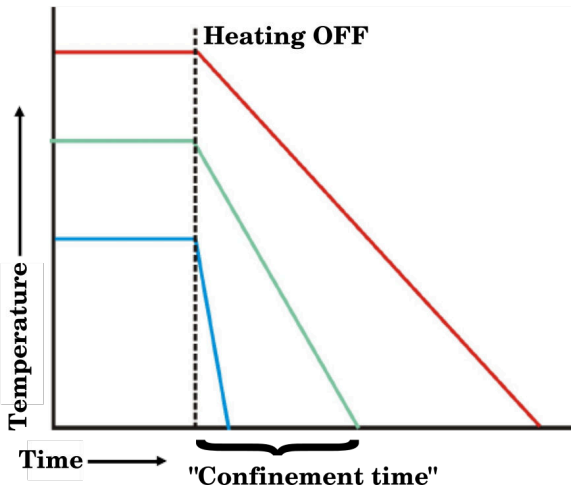
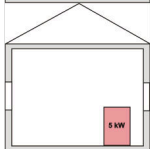
**Closed windows & insulation**



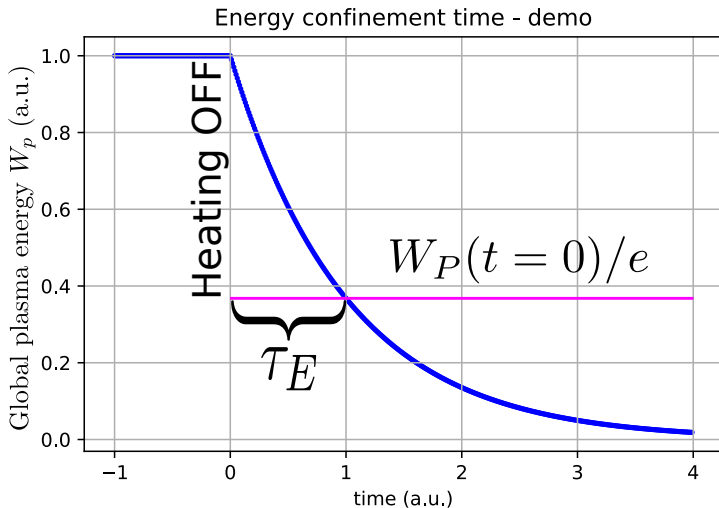
**Closed windows**



**Open windows**



# Energy balance of the tokamak



## Energy confinement time

Under the assumption of a simplified power balance, the heating power  $P_H$  is partially absorbed in the plasma and leads to an increase of the plasma energy  $W_p$  and the rest is lost as the loss power  $P_L$

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

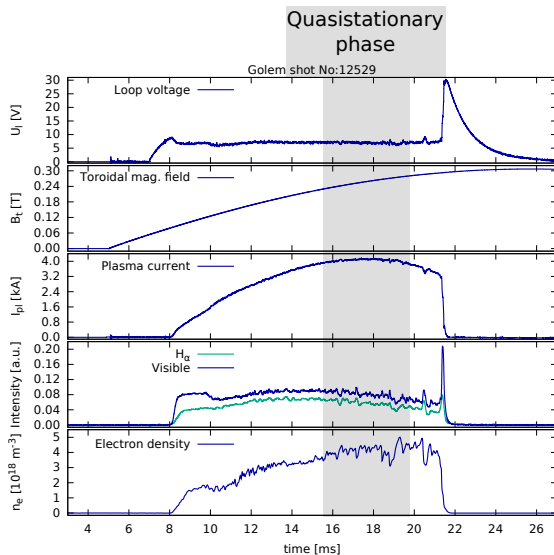
The energy confinement time is defined as the characteristic time scale of the exponential decay of the plasma energy  $W_p$  due to the loss power  $P_L$ :

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

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

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

# The discharge - quasistationary phase



## Plasma heating power

On the GOLEM tokamak the only heating mechanism of the plasma is ohmic heating  $P_{OH}$  resulting from the plasma current  $I_p$  flowing in a conductor with finite resistivity  $R_p$ . The time dependence of the ohmic heating power can be calculated as:

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

# Plasma Energy

The global plasma energy content  $W_p$  can be simply calculated from the temperature estimation  $T_e(0, t)$ , average density  $n_e$  and plasma volume  $V_p$ , based on the ideal gas law, taking into account the assumed

$T_e(r, t) = T_e(0, t) \left(1 - \frac{r^2}{a^2}\right)^2$  temperature profile:

$$W_p(t) = V_p \frac{n_e k_B T_e(0, t)}{3}.$$

The information that the magnetic field reduces the degrees of freedom of the particles to two has been used to derive this formula.

- $V_p \approx 80 \text{ l}$

# 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. [6],[5]):

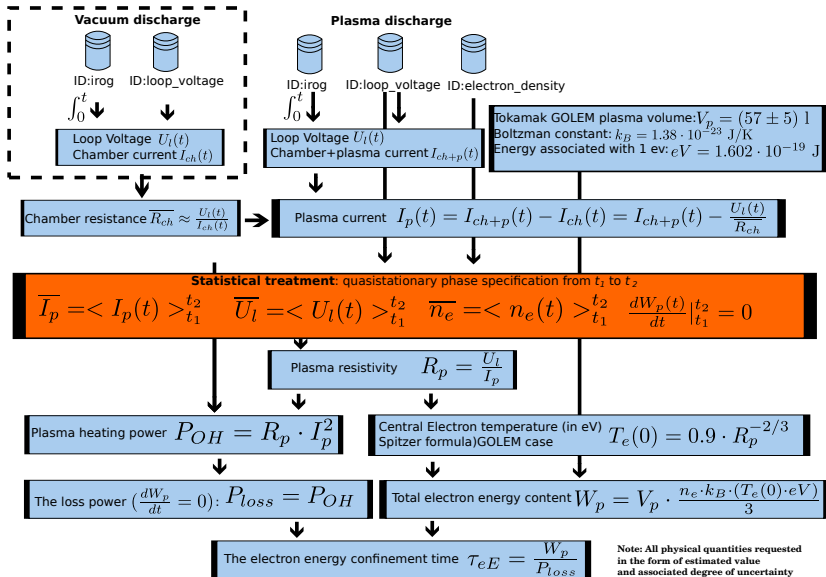
$$T_e(0, t) = \left( \frac{R_0}{a^2} \frac{8Z_{eff.}}{1544} \frac{1}{R_p(t)} \right)^{2/3}, [eV; m, \Omega]$$

For particular case of the GOLEM tokamak it says:

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



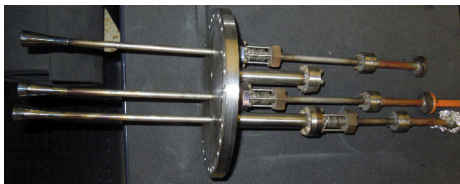
# Towards Electron energy confinement time $\tau_{eE}$



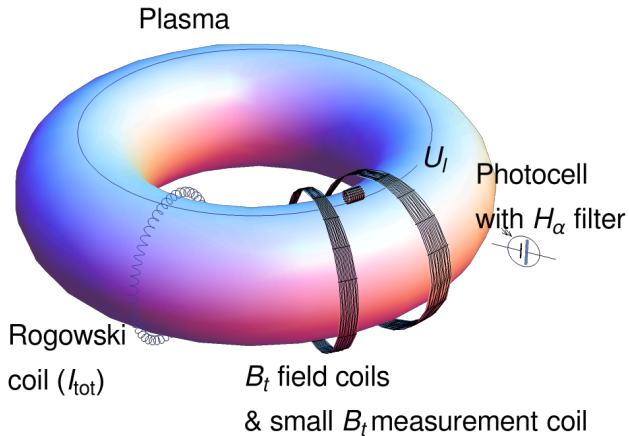
# Hands on the GOLEM tokamak - equipment



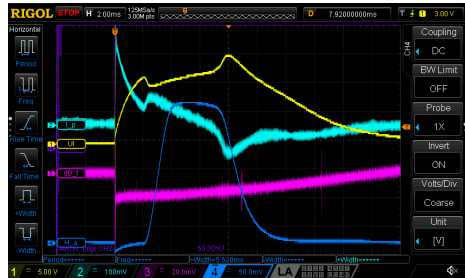
# The GOLEM tokamak interferometry HW



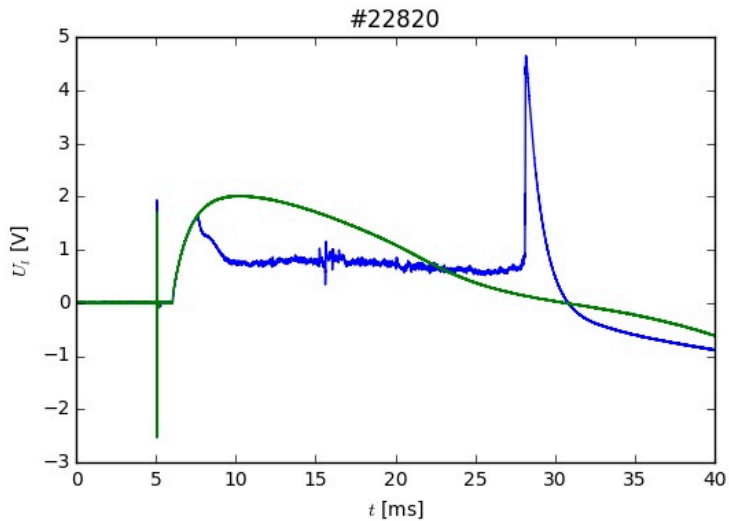
# The GOLEM tokamak - standard diagnostics



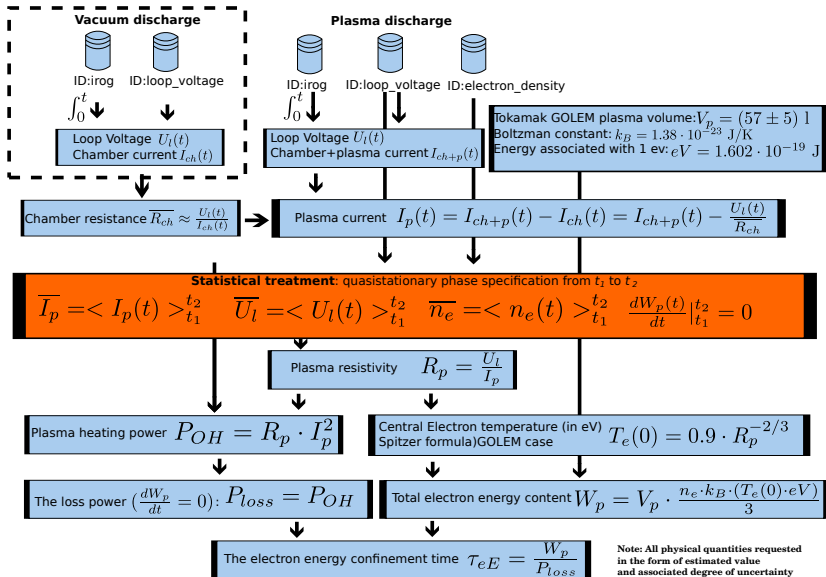
# Vacuum x Plasma discharge @ Oscilloscope



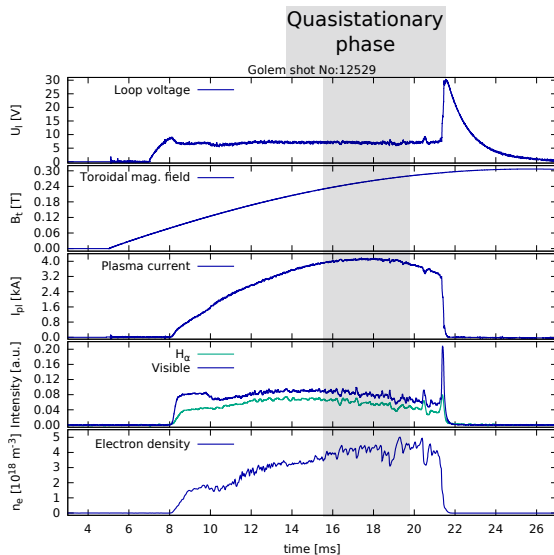
# Vacuum x Plasma shot



# Towards Electron energy confinement time $\tau_{eE}$



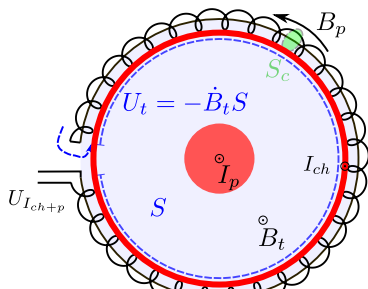
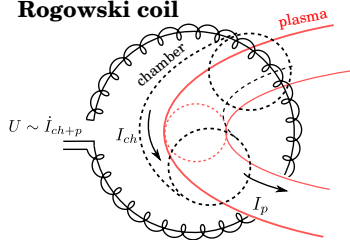
# The discharge - quasistationary phase





# Rogowski coil for the (chamber & plasma) current $I_{ch+p}$ measurements

## Rogowski coil



- Ampere's Law:  $\nabla \times \mathbf{B} = \mu_0 \mathbf{j}$   
(neglecting  $\dot{\mathbf{D}}$ )
- current through (const) surface  $S$ :  
 $\int \mathbf{j} \cdot d\mathbf{S} = I_{ch+p}$
- (const) poloidal field along surface border  $l$ :  $\int \nabla \times \mathbf{B} \cdot d\mathbf{S} = \oint B_p dl = I B_p$
- voltage induced:  $U_{I_{ch+p}} + U_t - U_t = -N \dot{B}_p S_c = -\mu_0 \frac{N S_c}{l} \dot{I}_{ch+p}$
- The wire of the coil is back-wound to omit a strong toroidal magnetic field  $B_t$  signal.

# Magnetic measurements generally I

- Raw signals (analog  $U_r(t)$  or, respectively, its discretized digital  $U_i$  counterpart form ) must be specially maintained:
  - corrected for the DC bias  $U_{offset}$  of the measurement circuit,
  - integrated (pure diagnostics signal voltage  $U_d(t)$  is induced by the time derivative of the appropriate magnetic flux),
  - multiplied by calibration factors  $C_d$  ( $C_{Bt}$ ,  $C_{RC}$ ).
- We can express the basic relationship  $U_r(t) = U_d(t) + U_{offset}$
- The measured signal  $U_d(t)$  is proportional to the time derivative of the original physical quantity  $D(t)$  signal (it is a magnetic measurement):

$$U_d(t) \propto \frac{dD(t)}{dt}, \text{ or } U_d(t) = C_d \frac{dD(t)}{dt}$$

Where the linearity coefficient  $C_d$  is called a calibration factor.

## Magnetic measurements generally II

- To determine the desired physical quantity  $D(t)$ , we just have to perform an integration over time:

$$D(t) = \frac{1}{C_d} \int_0^t U_d(t') dt' = \frac{1}{C_d} \int_0^t (U_r(t) - U_{offset}) dt'$$

- In reality, the measurement is not continuous. The system performs a series of measurements  $U_i$  separated by with time step  $\Delta t = 1 \text{ us}$ .
- In practice, we replace the integral by a sum:

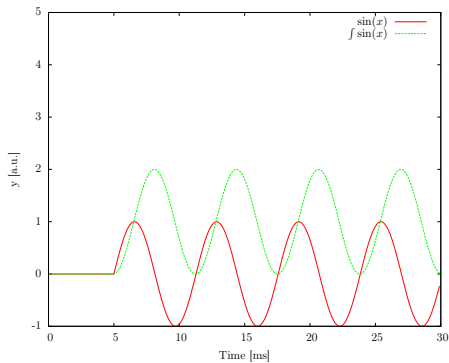
$$D_i = \frac{1}{C_d} \sum_{j=0}^{t/\Delta t} (U_i(t_j) - U_{offset}) \Delta t$$

$$D_i = \frac{1}{C_d} \left( \sum_{j=0}^{t/\Delta t} U_i(t_j) \right) - U_{offset} t$$

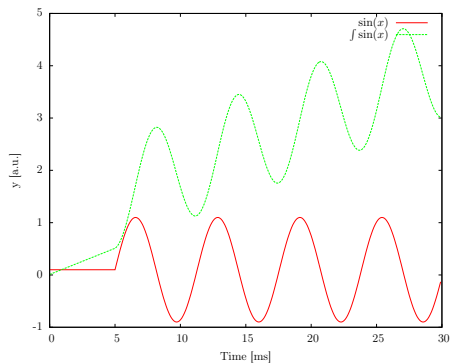
- The offset  $U_{offset}$  can be specified from the beginning of the data series before switching on the real experiment.

# Magnetic measurement demo - game with $U_{offset}$

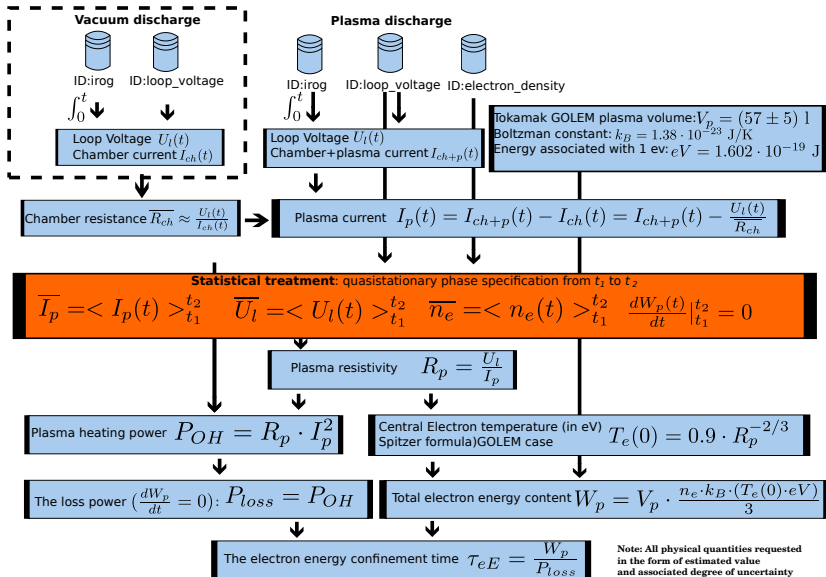
Without  $U_{offset}$



With  $U_{offset}$



# Towards Electron energy confinement time $\tau_E$



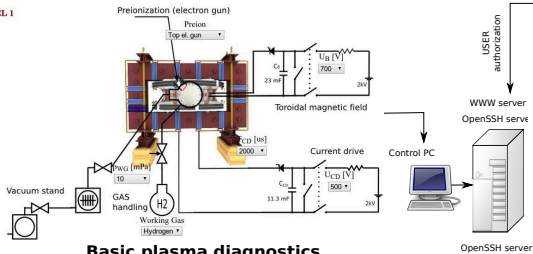
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- 5 Conclusion**
- 6 Appendix

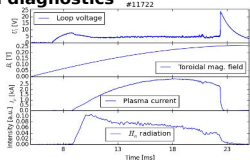
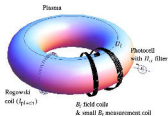
# The global schematic overview of the GOLEM experiment

LEVEL 1

## Tokamak technology setup



## Basic plasma diagnostics



internet

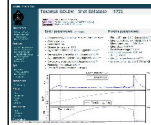
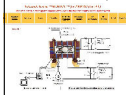
Virtual control room  
(remote participation)

WWW control interface

Data presentation

HTML & PHP scripts

HTML (www pages)



SSH control interface

WINDOWS via putty

Data handling



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

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

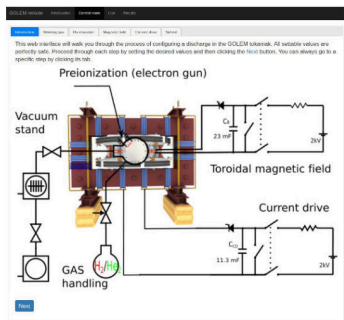
# Production

- Everything via <http://golem.fjfi.cvut.cz/Torino>
  - This presentation
  - Control rooms
  - Contact: Vojtech Svoboda,  
+420 737673903,  
[svoboda@fjfi.cvut.cz](mailto:svoboda@fjfi.cvut.cz)
  - Chat:  
[tokamak.golem@gmail.com](mailto:tokamak.golem@gmail.com) or  
skype: tokamak.golem





# Recommended values for the GOLEM tokamak operation



- Preionization: Top electron gun
- Gas: Hydrogen. A Working gas pressure:  $p_{WG}$  [mPa]  $< 0, 40 >$  mPa
- A voltage to charge the Current drive field  $E_t$  capacitor:  $U_{E_t}$  [V]  $< 400, 700 >$  V
- A voltage to charge the Toroidal magnetic field  $B_t$  capacitor:  $U_{B_t}$  [V]  $< 600, 1200 >$  V
- Time delay of the  $E_t$  trigger with respect to the  $B_t$  trigger:  $T_{CD}$  [ $\mu$ s]  $< 0, 10000 >$   $\mu$ s

# Fee: postcard from the venue of remote measurements



# Acknowledgement

## Financial support highly appreciated:

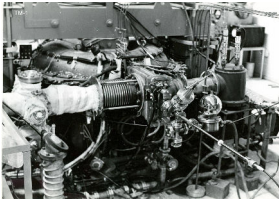
CTU RVO68407700, SGS 17/138/OHK4/2T/14, GAČR GA18-02482S, EU funds CZ.02.1.01/0.0/0.0/16\_019/0000778 and CZ.02.2.69/0.0/0.0/16\_027/0008465, IAEA F13019, FUSENET and EUROFUSION.

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# Thank you for your attention

**Tokamak TM1**  
@Kurchatov Institute near Moscow  
~1960-1977



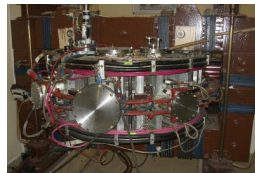
**SCIENCE**

**Tokamak CASTOR**  
@Institute of Plasma Physics, Prague  
1977-2007



**SCIENCE**  
& education

**Tokamak GOLEM**  
@Czech Technical University, Prague  
2007-



**EDUCATION**  
& science

... with the biggest  
control room  
in the world ..

**Tokamak Golem **\*\*REMOTE\*\*** for MASTER (Level 1)**

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

Home	Wiki	Control Room	Queue	Live	Results	GOLEM Diagram	Chamber status	IP cameras	3D model	Chat	Feedback	Stop
------	------	--------------	-------	------	---------	---------------	----------------	------------	----------	------	----------	------

**LEVEL 1**

Preionization (electron gun)  
Proton  
Toroidal magnetic field  
Current drive  
Vacuum island  
GAS handling  
Working Gas  
Discharge comment  
Place the discharge setup into the queue.

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- 2 The Tokamak (GOLEM)
- 3 The Tokamak GOLEM (remote) operation
- 4 The Electron energy confinement time calculation (rough estimation)
- 5 Conclusion
- 6 Appendix**

# References I

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