

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

Vojtěch Svoboda
on behalf of the tokamak GOLEM team
for the Technical University of Eindhoven

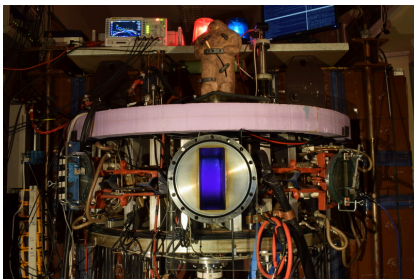
January 14, 2020

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


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
- Plasma minor radius: $a \approx 0.06$ m
- Maximum toroidal magnetic field $B_t^{max} < 0.5$ T
- Maximum plasma current $I_p^{max} < 8$ kA
- Typical electron density:
 $\langle n_e \rangle \approx 0.2 - 3 \times 10^{19} \text{ m}^{-3}$
- Effective ion charge: $Z_{eff} \approx 2.5$
- Maximum electron temperature $T_e^{max} < 100$ eV
- Maximum ion temperature $T_i^{max} < 50$ eV

Tokamak GOLEM @ Wikipedia ..



WIKIPEDIA
The Free Encyclopedia

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Article **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: TM1-MH (since 1977 Castor; since 2007 Golem^[12]) in [Prague, Czech Republic](#). In operation in [Kurchatov Institute](#) since early 1960s but renamed to Castor in 1977 and moved to IPP CAS,^[13] Prague; in 2007 moved to FNSPE, [Czech Technical University in Prague](#) and renamed to Golem.^[14]
- 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,^[15] at the CEA, [Cadarache, France](#)
- 1989: Aditya, at [Institute for Plasma Research \(IPR\) in Gujarat, India](#)
- 1980s: DIII-D,^[16] in [San Diego, USA](#); operated by [General Atomics](#) since the late 1980s
- 1989: COMPASS,^[13] 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 ISTOK,^[17] at the Instituto de Plasmas e Fusão Nuclear, [Lisbon, Portugal](#);
- 1991: ASDEX Upgrade, in [Garching, Germany](#)


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Read

Talk

View history

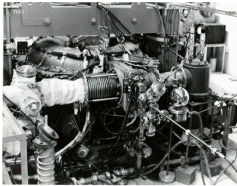
Search



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

2008

Czech Technical University Prague
Czech republic
GOLEM



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

2006



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...

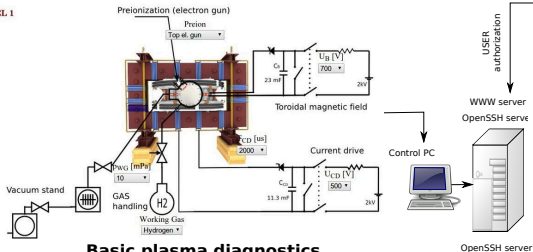


At the end of the 16th century, in the times when the Czech lands were ruled by Emperor Rudolf II, in Prague, there were Rabbi Judah Loew, well known alchemist, thinker, scholar, writer and inventor of the legendary GOLEM - a clay creature inspired with the Universe power that pursued his master's command 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. [Wikipedia/Golem](https://en.wikipedia.org/wiki/Golem).

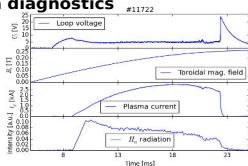
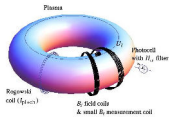
The global schematic overview of the GOLEM experiment

LEVEL 1

Tokamak technology setup



Basic plasma diagnostics

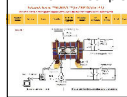


internet

**Virtual control room
(remote participation)**

WWW control interface

HTML & PHP scripts



SSH control interface

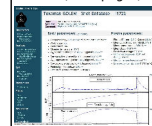
WINDOWS via putty



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

Data presentation

HTML (www pages)



Data handling

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

Production

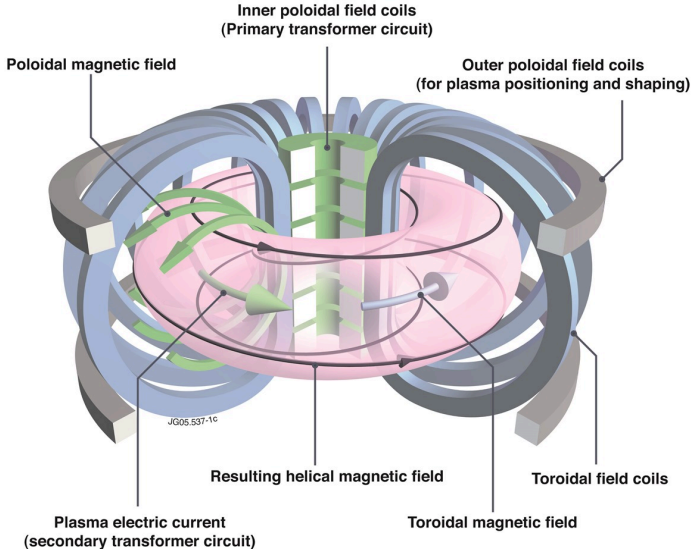
- Everything via <http://golem.fjfi.cvut.cz/Eindhoven>
 - This presentation
 - Control rooms
 - Contact: Vojtech Svoboda,
+420 737673903,
svoboda@fjfi.cvut.cz
 - Chat:
tokamak.golem@gmail.com or
skype: tokamak.golem



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Tokamak magnetic confinement concept



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

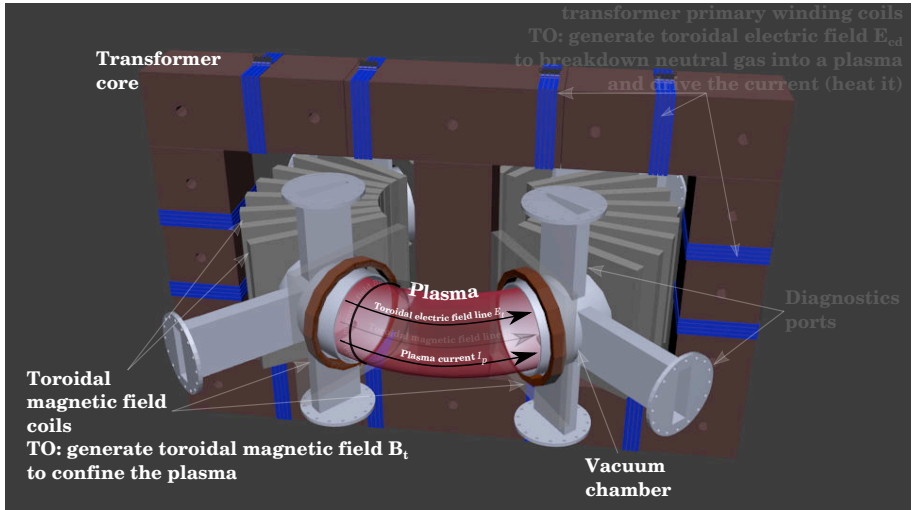


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- The GOLEM tokamak basic diagnostics
- The GOLEM tokamak - guide tour

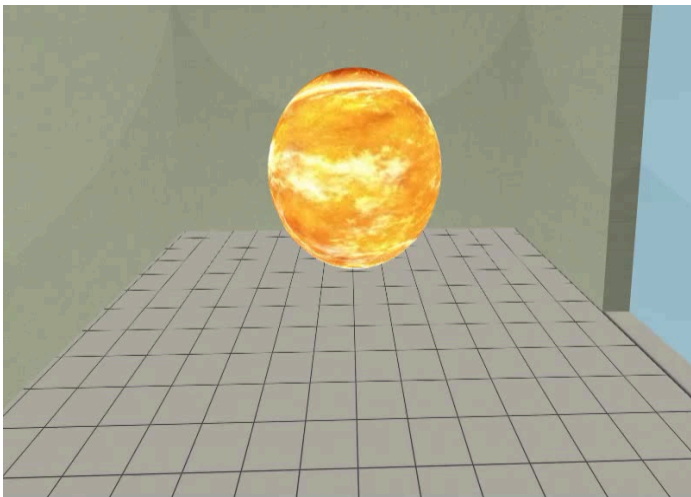
3 The Tokamak GOLEM (remote) operation

4 The Electron energy confinement time calculation (rough estimation)

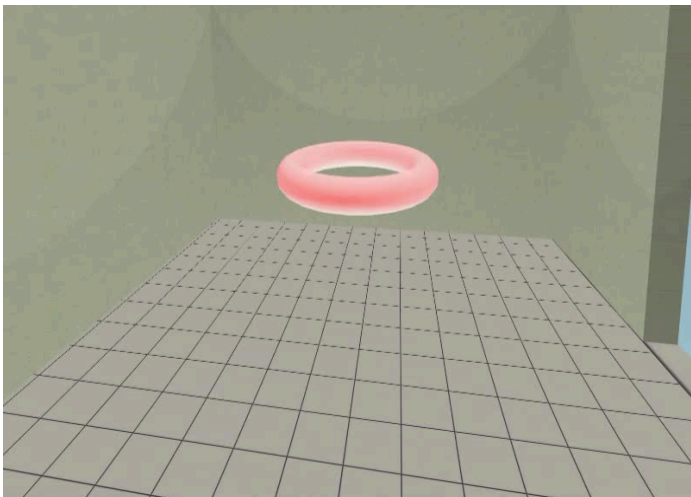
5 Conclusion

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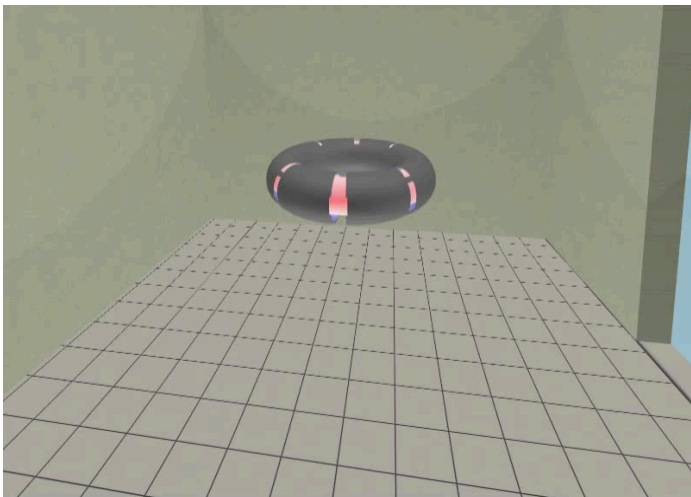
Our goal: the technology to create a μ Sun on the Earth



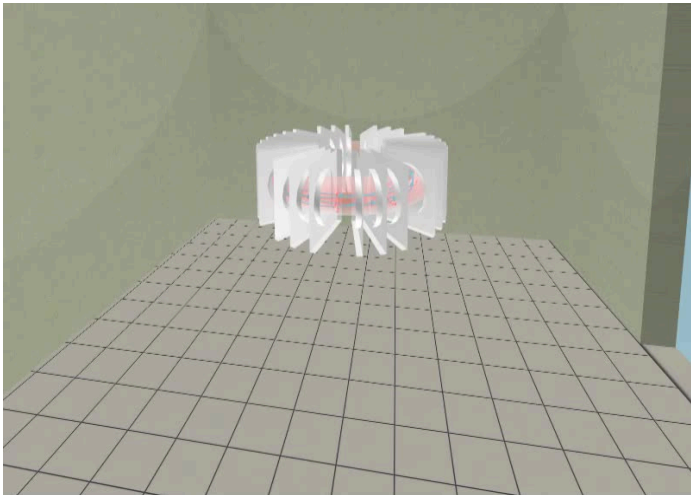
Magnetic confinement requires toroidal geometry



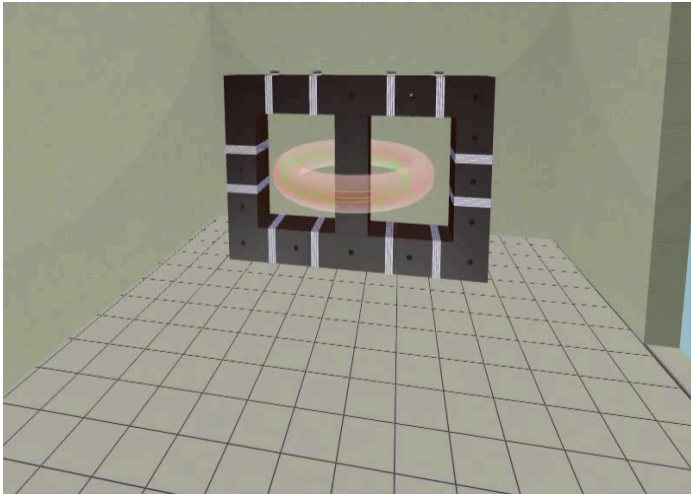
A chamber contains the thermonuclear reaction



Toroidal magnetic field coils confine the plasma



A transformer action creates and heats the plasma



The final technology altogether

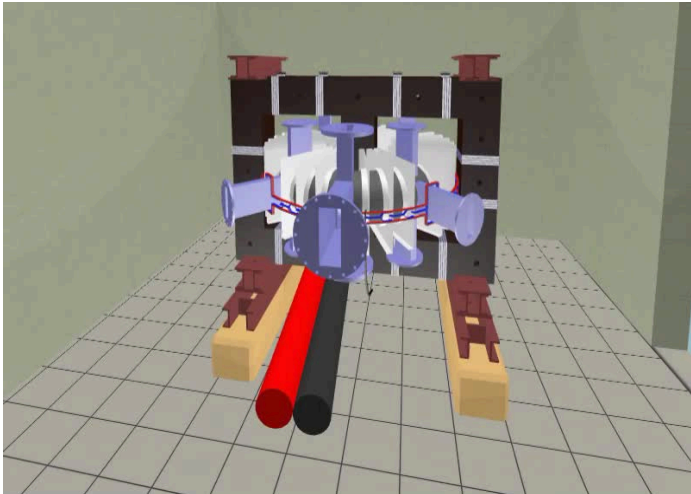


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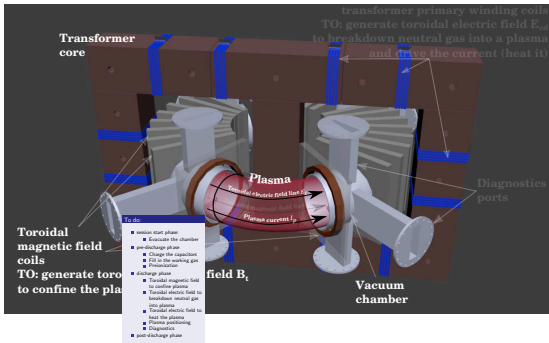
3 The Tokamak GOLEM (remote) operation

4 The Electron energy confinement time calculation (rough estimation)

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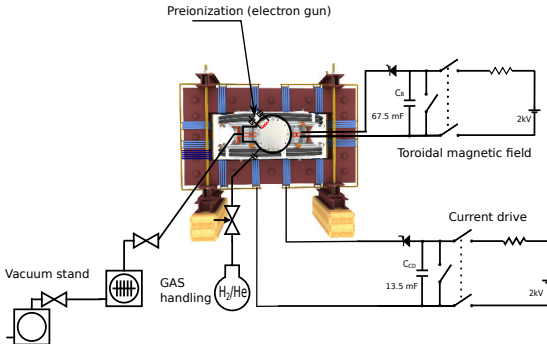
Plasma in Tokamak (GOLEM) - the least to do



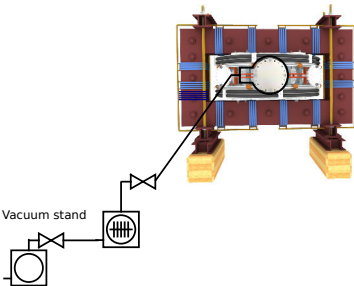
Plasma in Tokamak (GOLEM) - the least to do

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



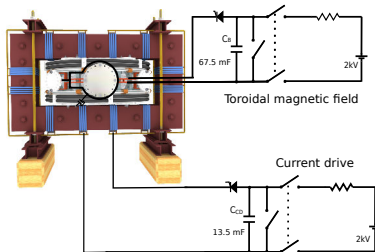
Plasma in Tokamak (GOLEM) - the least to do



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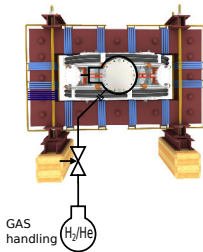
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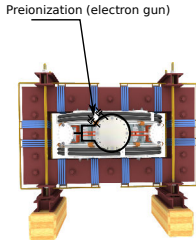
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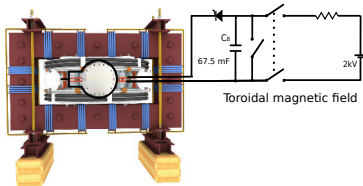
Plasma in Tokamak (GOLEM) - the least to do



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- post-discharge phase

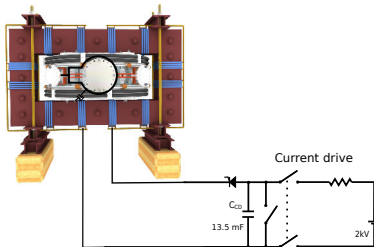
Plasma in Tokamak (GOLEM) - the least to do



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Plasma in Tokamak (GOLEM) - the least to do



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- discharge phase
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 - **Toroidal electric field to heat the plasma**
 - Plasma positioning
 - Diagnostics
- post-discharge phase

Tokamak GOLEM - schematic experimental setup

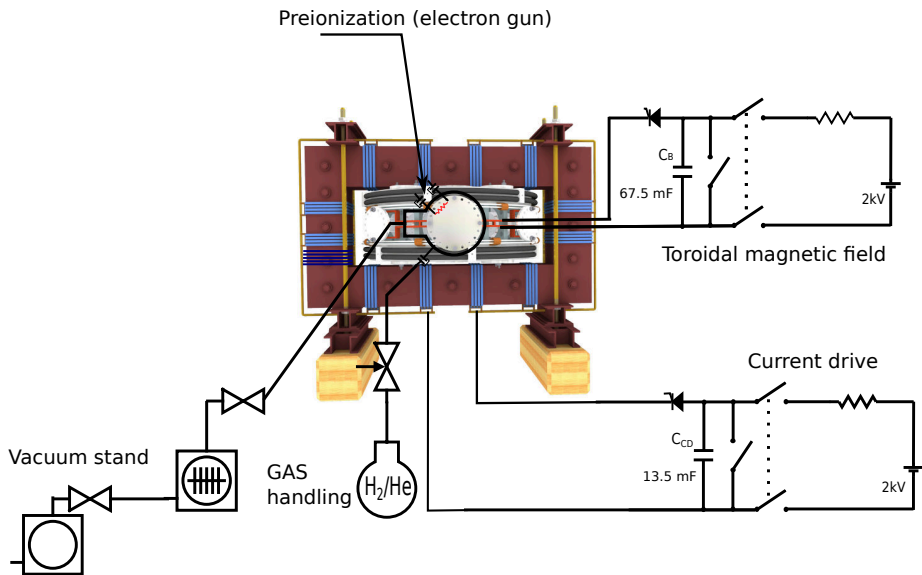


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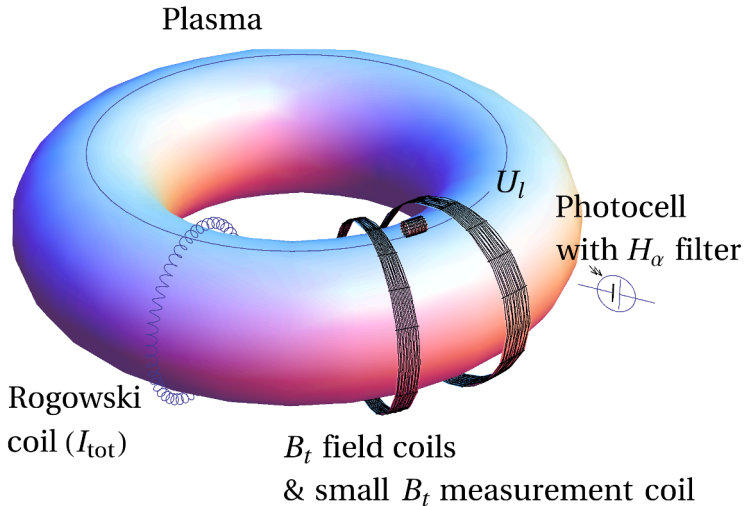
3 The Tokamak GOLEM (remote) operation

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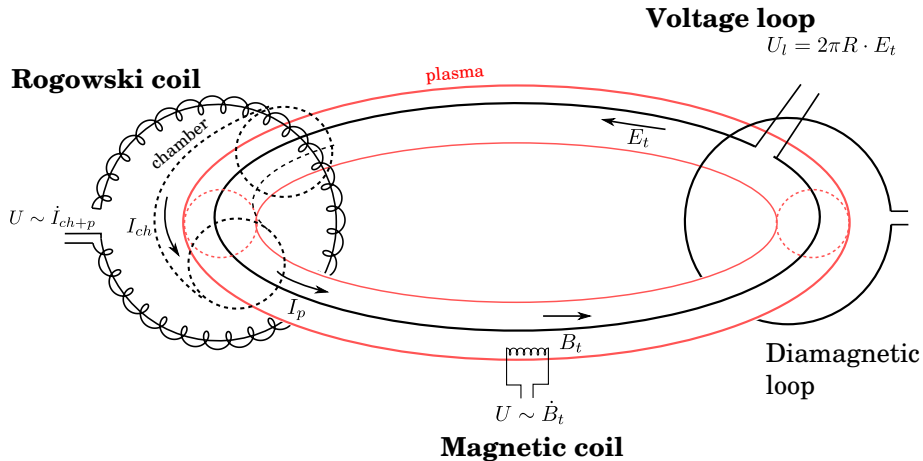
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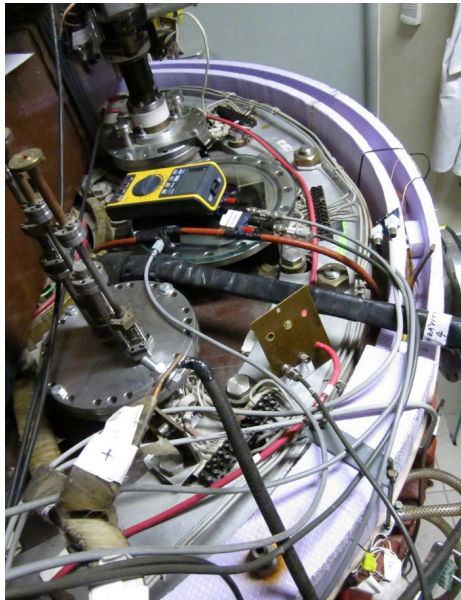
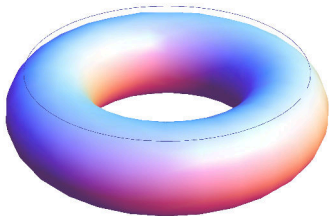
The GOLEM tokamak - basic diagnostics



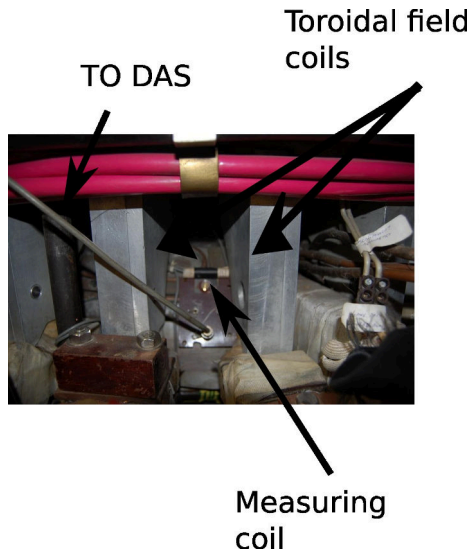
Schematic of electromagnetic diagnostics



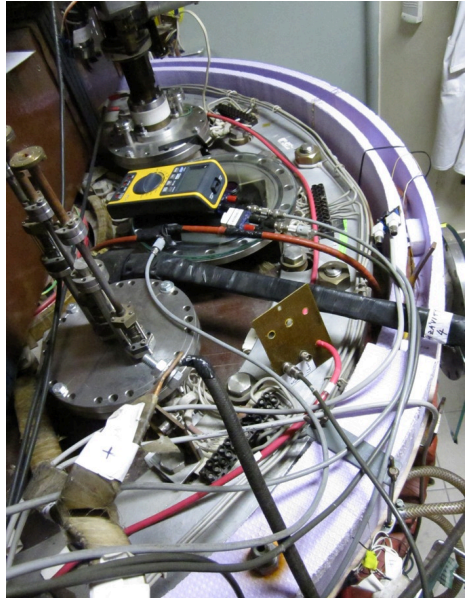
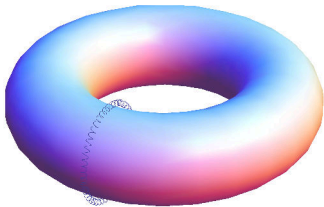
Loop voltage U_l @ the GOLEM tokamak



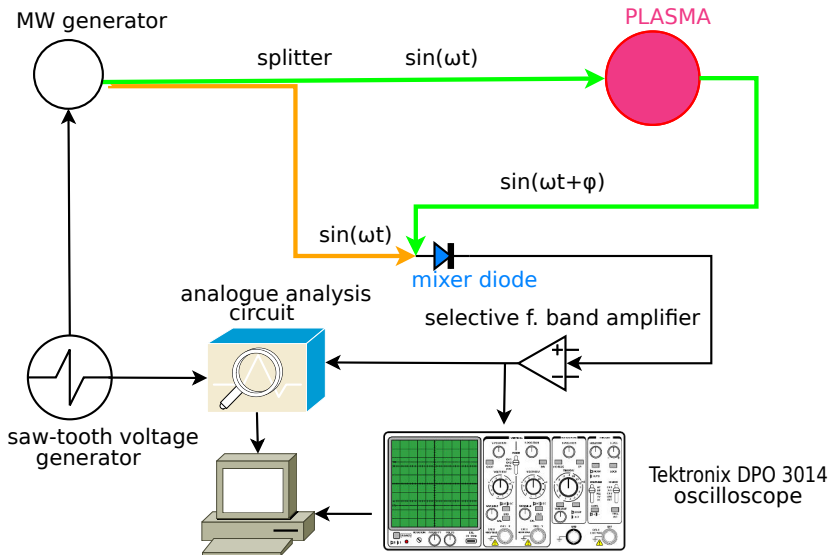
Toroidal magnetic field B_t @ the tokamak GOLEM



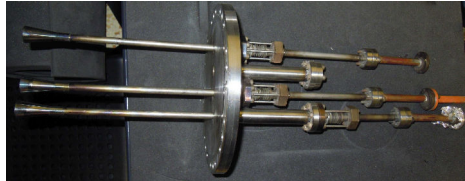
Total current I_{ch+p}



Electron density n_e interferometry measurement scheme



The GOLEM tokamak interferometry HW



"Typical", well executed discharge @ GOLEM

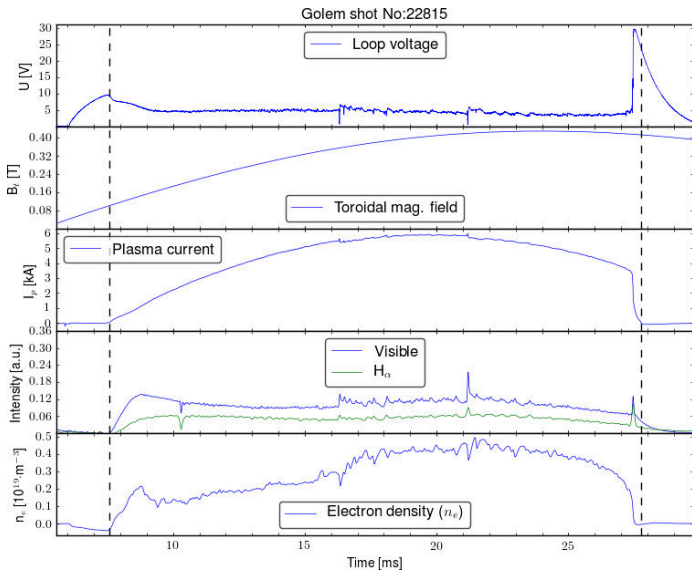


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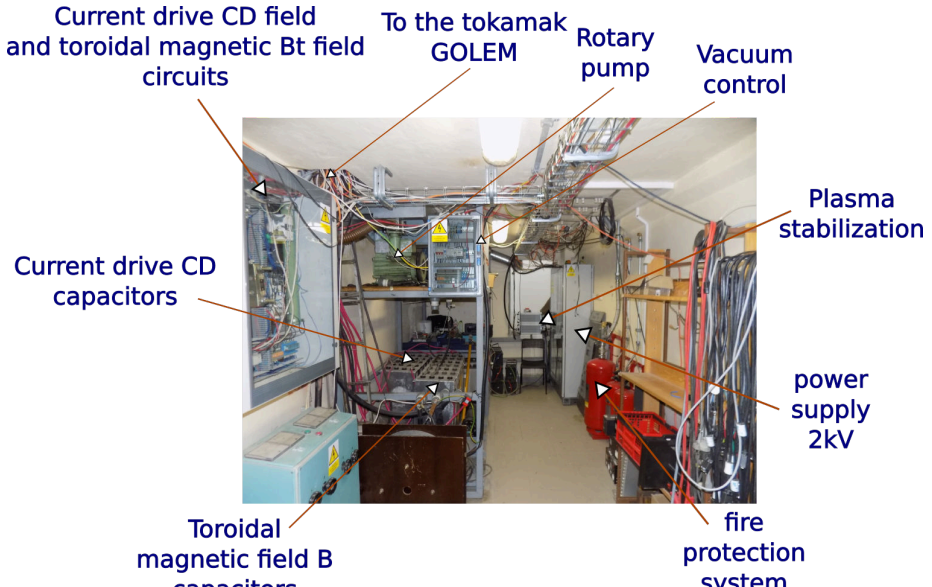
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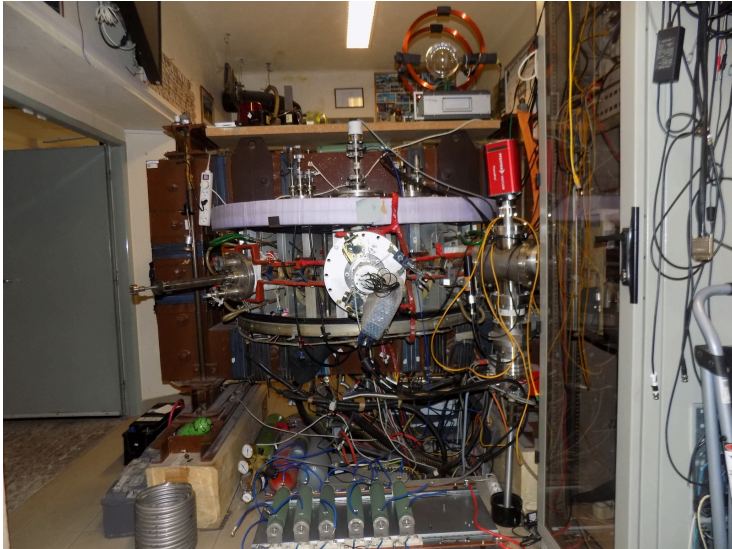
Infrastructure room (below tokamak) 10/16



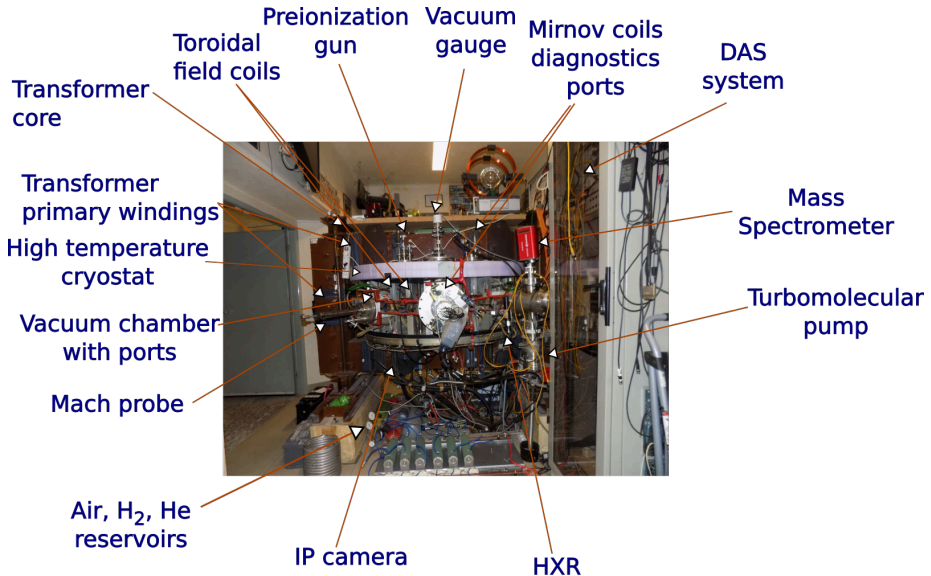
Infrastructure room (below tokamak) 10/16



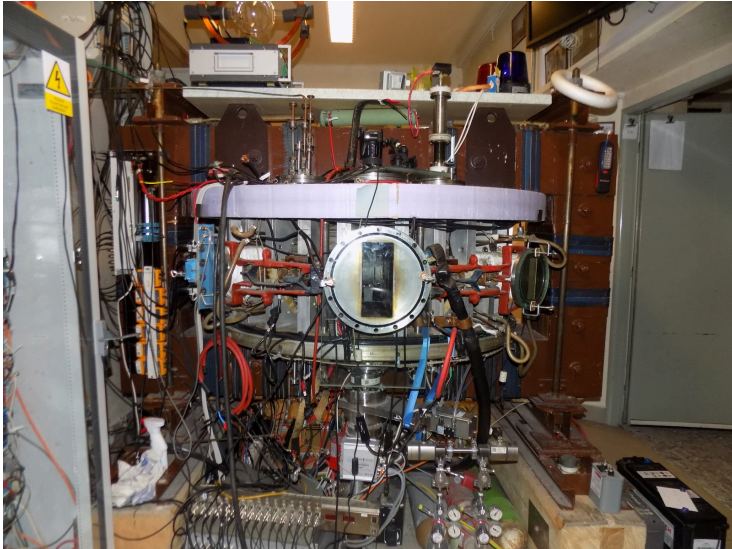
Tokamak room (North) 10/16



Tokamak room (North) 10/16



Tokamak room (South) 10/16



Tokamak room (South) 10/16

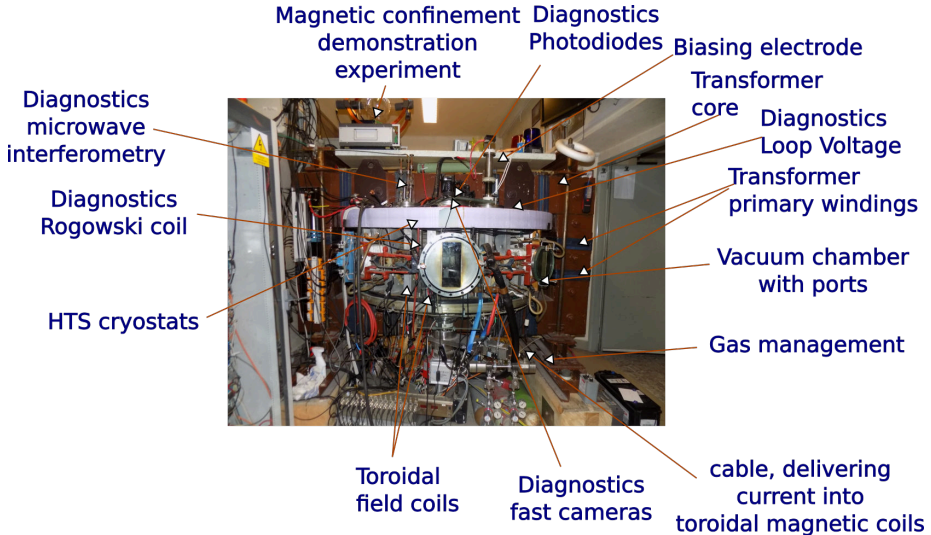


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Control room: Introduction

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

Toroidal magnetic field

Current drive

GAS handling H_2/Hg

C_s 23 mF

C_p 11.3 mF

2kV

2kV

[Next](#)

3D model rendering method:

Static image (fast)

Interactive X3DOM (slower)

Control room: Working gas

GOLEM remote Introduction **Control room** Live Results

Model Access Level 1 Help

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/Hg

Toroidal magnetic field 67.5 mT

Toroidal electric field 13.5 mV

Gas type and pressure $p_{\text{gas}} = 36 \text{ mPa}$

Hydrogen Helium

Next Set recommended value

3D model rendering method **Static image (left)** Interactive X3DOM (below)

Control room: Preionization

GOLEM remote Introduction **Control room** Live Results

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

The neutral working gas must be first 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

Ionization method

☒ Electron gun ☐ No ionization

[Next](#)

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

Control room: Magnetic field B_t

GOLEM remote Introduction Control room Live Results

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

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

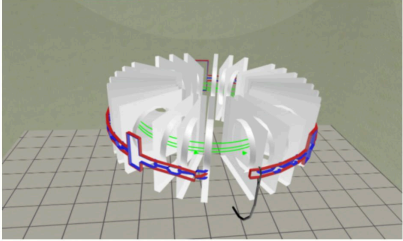
Toroidal magnetic field

Toroidal electric field

GAS handling

Capacitor voltage $U_{C0} = 600 \text{ V}$

Next Set recommended value



The image shows a 3D rendering of the toroidal magnetic field coils. The coils are arranged in a complex, multi-layered structure, with green lines indicating the magnetic field lines. The rendering is shown in a 3D perspective view, with a grid floor and a grey background.

Control room: Current drive E_{cd}

GOLEM remoteIntroductionControl roomLiveResults

the Torneo Politecnico, Italy Group 1Access Level 2Help

IntroductionWorking gasPreionizationMagnetic fieldElectric fieldSubmit

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

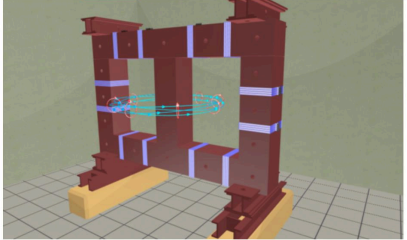
GAS handling

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

Capacitor voltage U_{cd} : 400 V

NextSet recommended value

3D model rendering method:Static image (first)Interactive X3DOM (below)



Control room: ... and Submit

GOLEM remote

Introduction

Control room

Live

Results

the Torino Politecnico, Italy Group 1

Access Level 2

Help

Introduction

Working gas

Precorization

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.

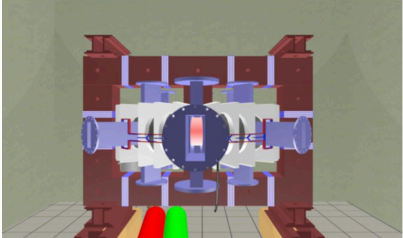
Comment

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

After submission you can switch 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 \(fast\)](#) [Interactive X3DOM \(slow\)](#)



Shot homepage

GOLEM » Shot #22471 »



Diagnostics

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

Analysis

- ✓ ShotHomepage

DAS

- ✓ TektronixDPO
- ✓ Nlstandard
- ✓ Papouch_St
- ✓ Papouch_Ko
- ✓ Nlloctopus

Vacuum log

Other

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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](#)

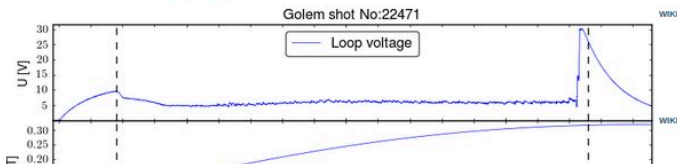


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GOLEM basic Data Acquisition System (DAS)

- $U_I, U_{B_t}, U_{I_{p+ch}}, I_{rad}$
- $\Delta t = 1\mu s / f = 1MHz$.
- 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 or specific diagnostics have the format:

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

An overview of available data with identifiers, units, description, etc. for each discharge is at

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

Matlab

```
ShotNo=22471;
baseURL='http://golem.fjfi.cvut.cz/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 numpy as np
import matplotlib.pyplot as plt

shot_no = 22471
identifier = "loop_voltage"
# create data cache in the 'golem_cache' folder
ds = np.DataSource('golem_cache')
#Create a path to data and download and open the file
base_url = "http://golem.fjfi.cvut.cz/utis/data/"
data_file = ds.open(base_url+str(shot_no)+'/'+identifier)
#Load data from the file and plot to screen and to disk
data = np.loadtxt(data_file)
plt.plot(data[:,0], data[:,1]) #1. column vs 2. column
plt.savefig('graph.jpg')
plt.show()
```

Gnuplot

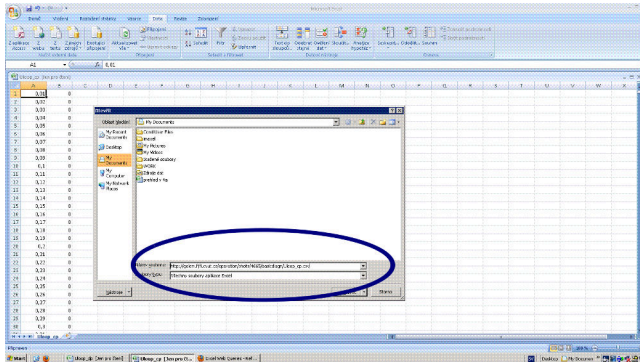
```
set macros;  
ShotNo = "22471";  
baseURL = "http://golem.fjfi.cvut.cz/utils/data/";  
identifier = "loop_voltage";  
#Create a path to data  
DataURL= "@baseURL@ShotNo/@identifier";  
#Write data from GOLEM server to a local file  
!wget -q @DataURL;  
#Plot the graph from a local file  
set datafile separator "\t";  
plotstyle = "with_lines_linestyle_-1"  
plot 'loop_voltage' using 1:2 @plotstyle;  
exit;  
  
# command line execution:  
# gnuplot Uloop.gp -persist
```

GNU Wget

GNU Wget is a free software package for retrieving files using HTTP, HTTPS and FTP, the most widely-used Internet protocols. It is a non-interactive commandline tool, so it may easily be called from scripts, cron jobs, terminals without X-Windows support, etc.

- Runs on most UNIX-like operating systems as well as Microsoft Windows.
- Homepage: <http://www.gnu.org/software/wget/>
- Basic usage:
 - To get U_l : `wget http://golem.fjfi.cvut.cz/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/utis/data/<#ShotNo>/<identifier>>

Spreadsheets (Excel and others)

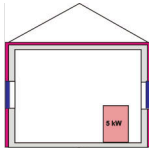
are not recommended, only tolerated.

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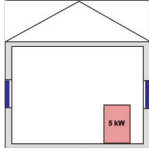
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Energy balance of the house

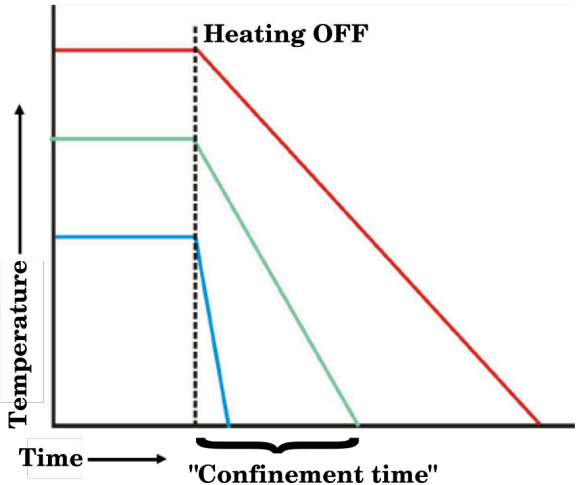
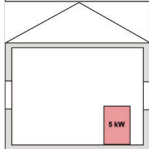
**Closed
windows
& insulation**



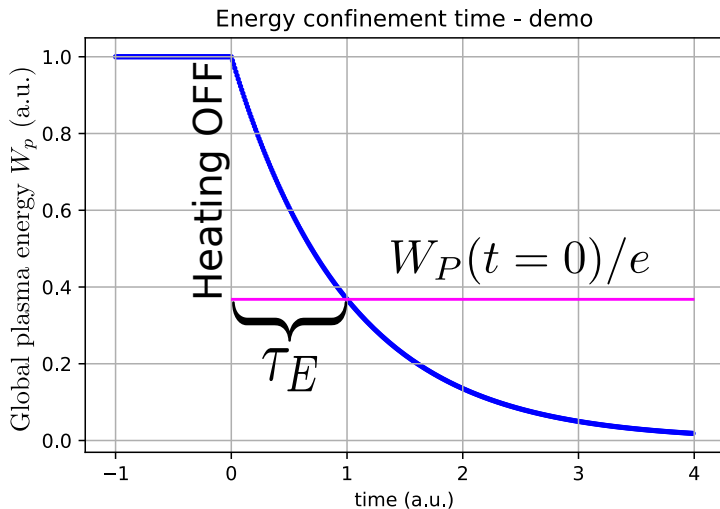
**Closed
windows**



**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

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

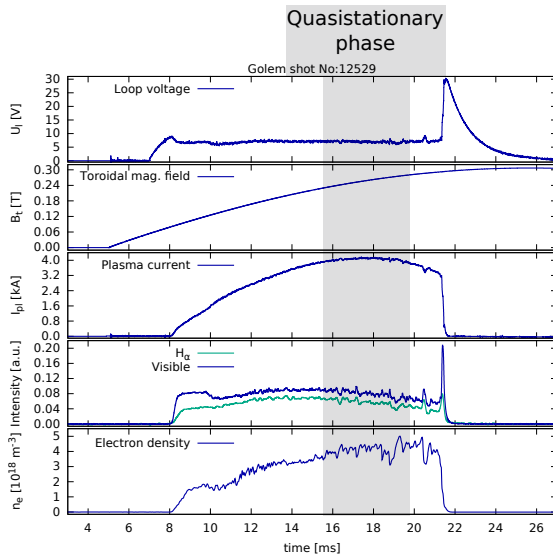
The energy confinement time is defined as the characteristic time scale of the exponential decay of the plasma energy W_p due to the loss power P_L :

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

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)

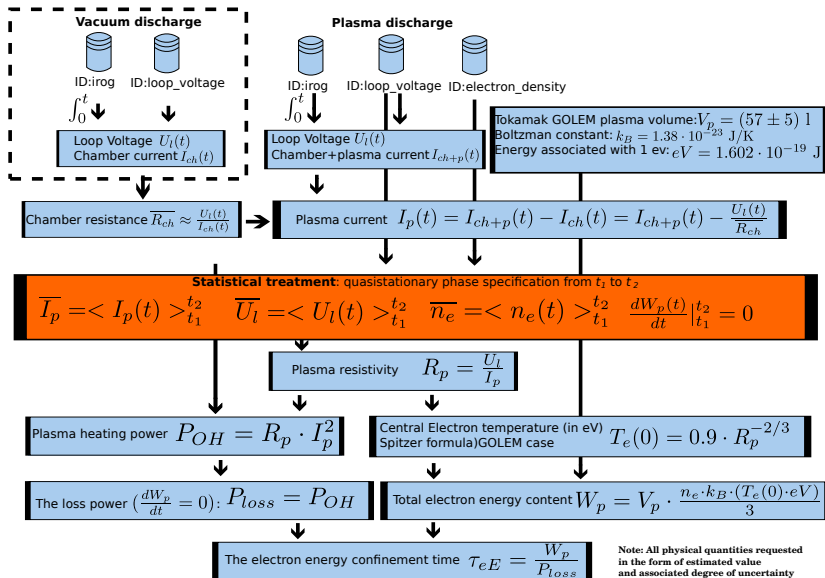
The time evolution of the central electron temperature $T_e(0, t)$ is calculated from equation based on Spitzer's resistivity formula (see eg. [2],[1]):

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

For particular case of the GOLEM tokamak it says:

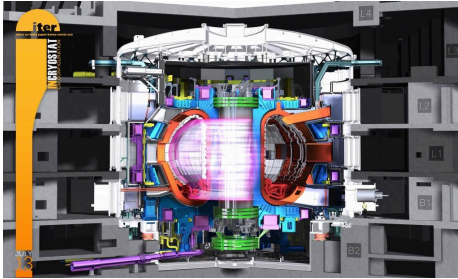
$$T_e(0, t) = 0.9 \cdot \left(\frac{I_p(t)}{U_I(t)} \right)^{2/3}, [eV; A, V]$$

Towards Electron energy confinement time τ_E



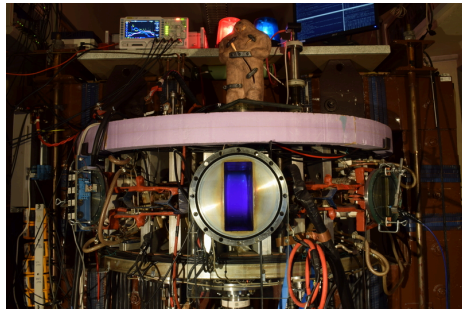
The competition

The ITER: 3.6 s



credit:[3]

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



credit:[4]

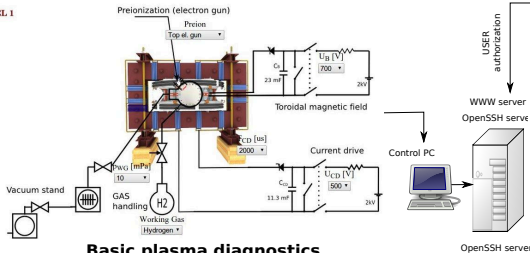
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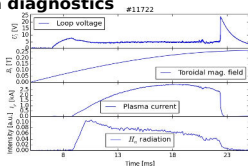
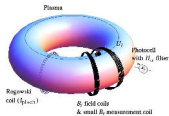
The global schematic overview of the GOLEM experiment

LEVEL 1

Tokamak technology setup



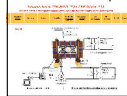
Basic plasma diagnostics



Virtual control room (remote participation)

WWW control interface

HTML & PHP scripts



SSH control interface

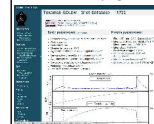
WINDOWS via putty



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

Data presentation

HTML (www pages)



Data handling

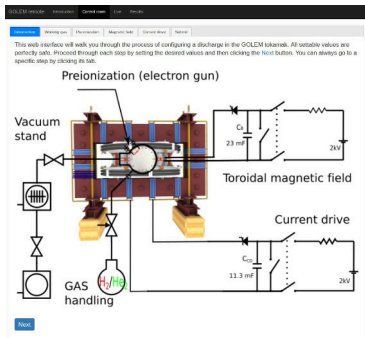
- *wget
- *gnuplot
- *idl
- *mathematica
- *matlab
- *etc...

Production

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



Recommended values for the GOLEM tokamak operation



- Preionization: Top electron gunn
- 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} [μ s] $< 0, 10000 >$ μ s

Acknowledgement

Financial support highly appreciated:

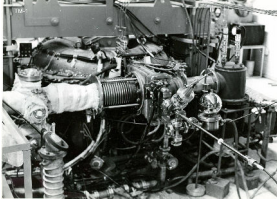
CTU RVO68407700, SGS 17/138/OHK4/2T/14, GAČR GA18-02482S, EU funds CZ.02.1.01/0.0/0.0/16_019/0000778 and CZ.02.2.69/0.0/0.0/16_027/0008465, IAEA F13019, FUSENET and EUROFUSION.

Students, teachers, technicians (random order):

Vladimír Fuchs, Ondřej Grover, Jindřich Kocman, Tomáš Markovič, Michal Odstrčil, Tomáš Odstrčil, Gergo Pokol, Igor Jex, Gabriel Vondrášek, František Žáček, Lukáš Matěna, Jan Stockel, Jan Mlynář, Jaroslav Krbec, Radan Salomonovič, Vladimír Linhart, Kateřina Jiráková, Ondřej Ficker, Pravesh Dhyani, Juan Ignacio Monge-Colepicolo, Jaroslav Čěrovský, Bořek Leitl, Martin Himmel. Petr Švihra, Petr Mácha, Vojtěch Fišer, Filip Papoušek, Sergei Kulkov, Martin Imříšek.

Thank you for your attention

Tokamak TM1
@Kurchatov Institute near Moscow
~1960-1977



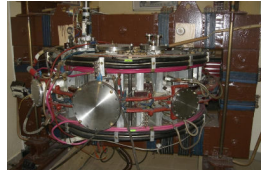
SCIENCE

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 ..

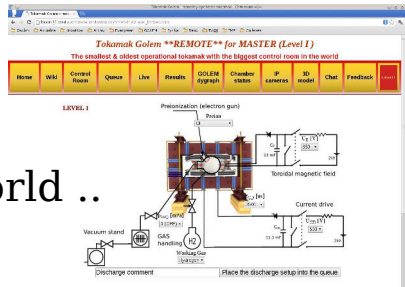







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References I

-  J. Wesson. *Tokamaks*, volume 118 of *International Series of Monographs on Physics*. Oxford University Press Inc., New York, Third Edition, 2004.
-  Brotankova, J. Study of high temperature plasma in tokamak-like experimental devices. PhD. thesis 2009.
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-  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.