

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

Vojtěch Svoboda
on behalf of the tokamak GOLEM team
for the Hands' on projects Cadarache Winter event 2021, France.

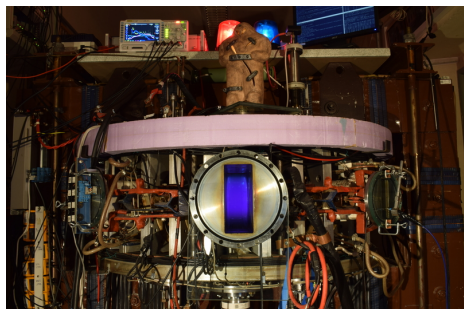
February 15, 2021

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- 2 The Tokamak (GOLEM)
- 3 The Tokamak GOLEM (remote) operation
- 4 Conclusion
- 5 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
- 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]

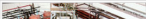
Currently in operation [edit]

(in chronological order of start of operations)

- 1960s: 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 ISTTOK,^[17] at the Instituto de Plasmas e Fusão Nuclear, Lisbon, Portugal;
- 1991: ASDEX Upgrade, in Garching, Germany

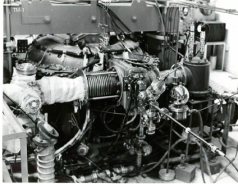


Alcator C-Mod



The GOLEM tokamak for education - historical background

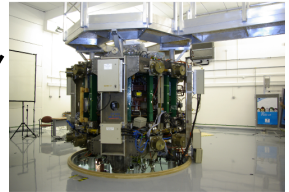
Kurchatov Institute near Moscow,
Soviet Union
1960: **TM1-MH**



1974



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



2006



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



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...

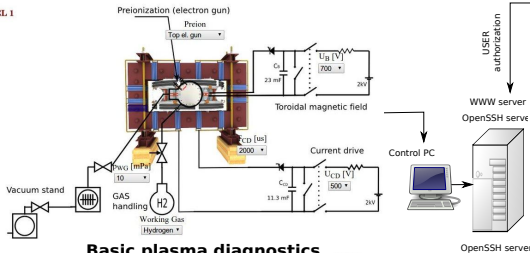


At the end of the 16th century, in the times when the Czech lands were ruled by Emperor Rudolf II, in Prague, there were Rabbi Judah Loew, well known alchemist, thinker, scholar, writer and inventor of the legendary GOLEM - a clay creature inspired with the Universe power that pursued his master's command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

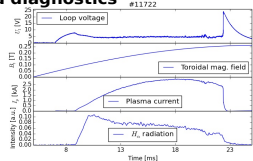
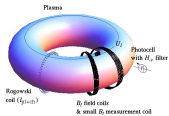
The global schematic overview of the GOLEM experiment

LEVEL 1

Tokamak technology setup



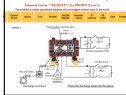
Basic plasma diagnostics



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

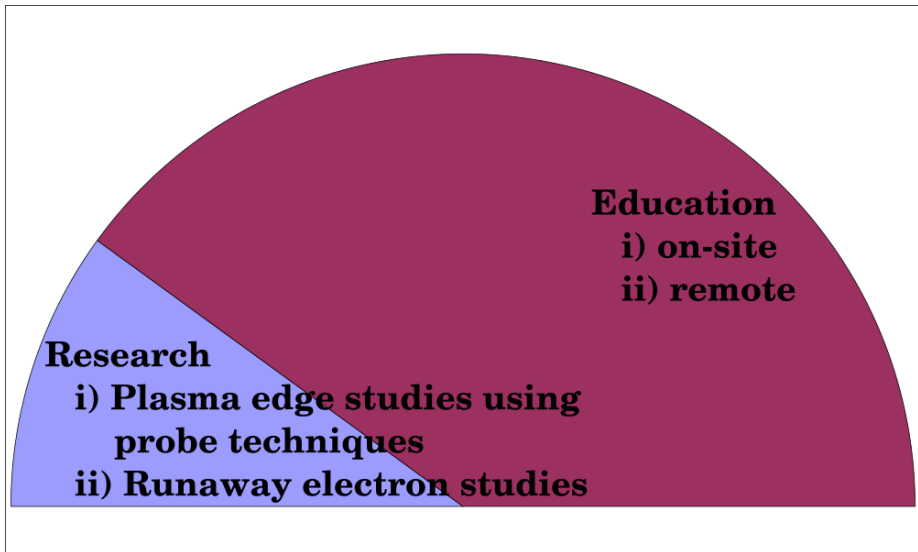
HTML (www pages)



Data handling

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

The GOLEM tokamak mission



Research

- i) Plasma edge studies using probe techniques**
- ii) Runaway electron studies**

Education

- i) on-site**
- ii) remote**

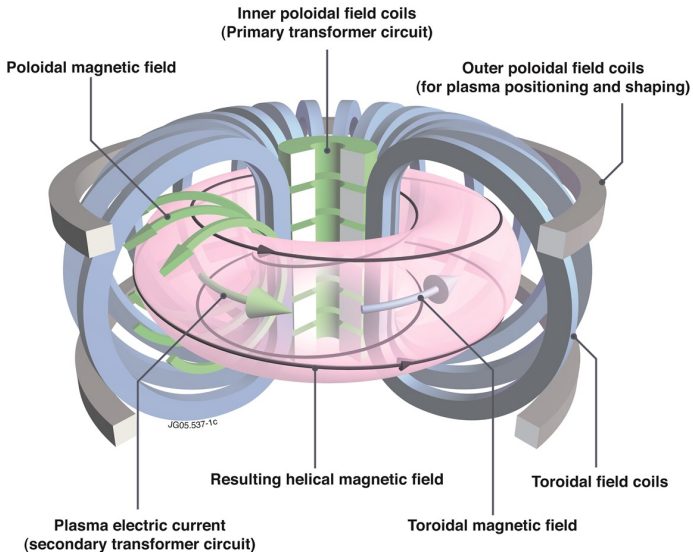
- Everything via <http://golem.fjfi.cvut.cz/Cadarache>
 - This presentation
 - Control rooms
 - Contact: Vojtech Svoboda,
+420 737673903,
svoboda@fjfi.cvut.cz
 - Chat:
tokamak.golem@gmail.com or
skype: tokamak.golem
 - Videoconference:
<https://meet.vpsfree.cz/golem>



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- 3 The Tokamak GOLEM (remote) operation
- 4 Conclusion
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Tokamak magnetic confinement concept



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

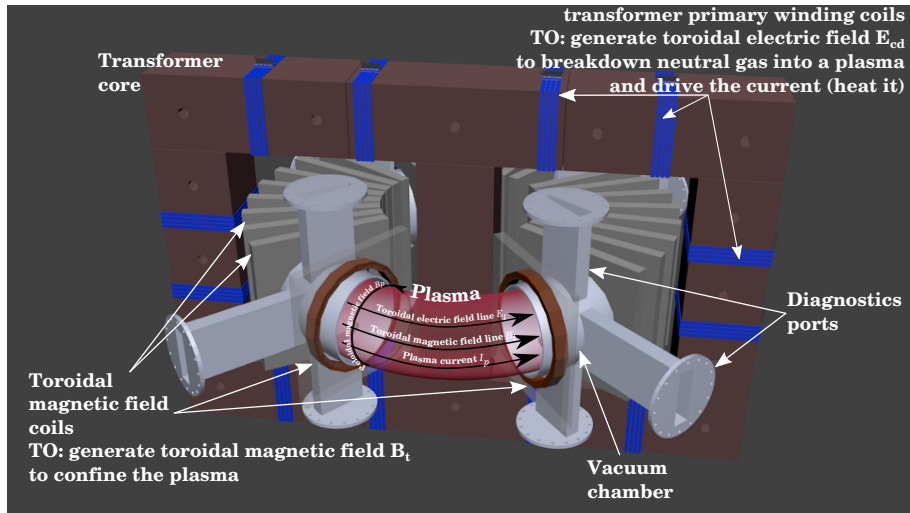


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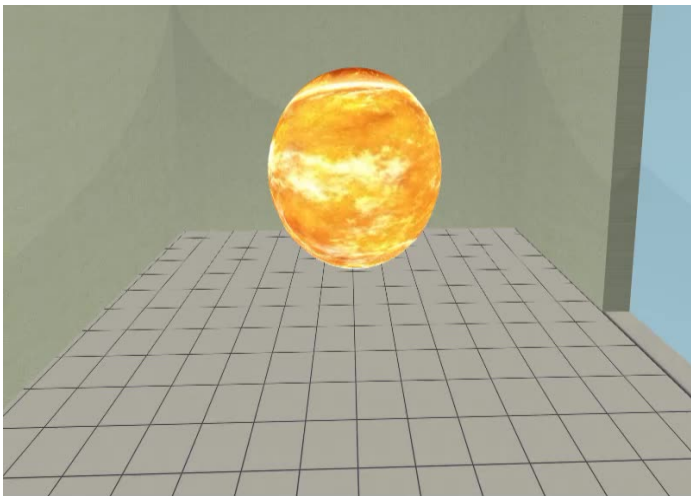
- The GOLEM tokamak concept
- The scenario to make the (GOLEM) tokamak discharge
- The scenario to discharge virtually
- The GOLEM tokamak basic diagnostics
- The GOLEM tokamak - guide tour

3 The Tokamak GOLEM (remote) operation

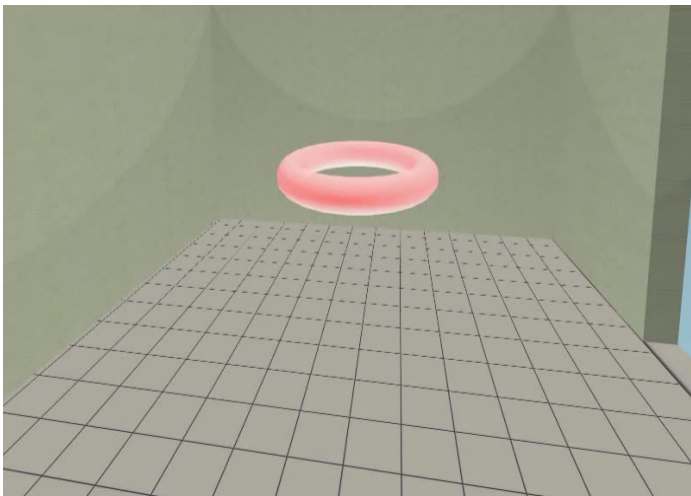
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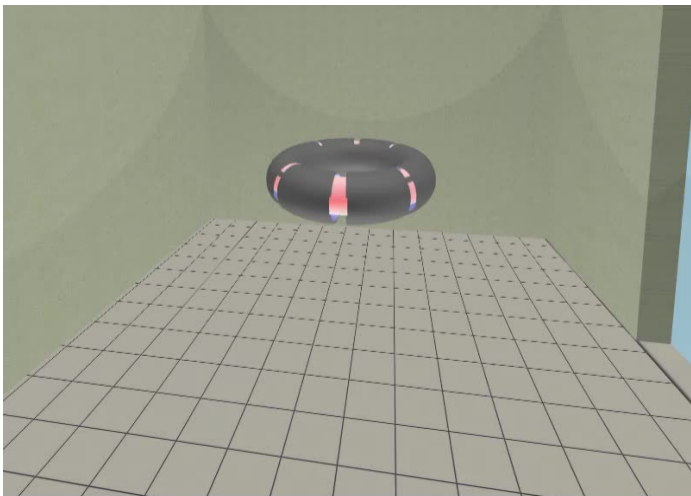
Our goal: the technology to create a μ Sun on the Earth



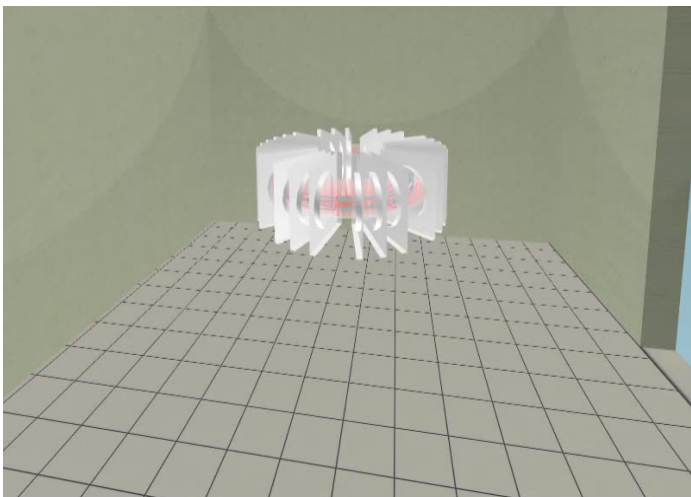
Magnetic confinement requires toroidal geometry



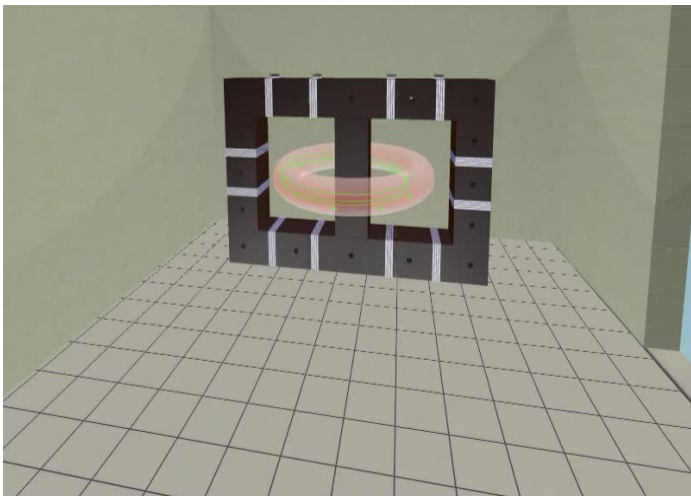
A chamber contains the thermonuclear reaction



Toroidal magnetic field coils confine the plasma



A transformer action creates and heats the plasma



The final technology altogether

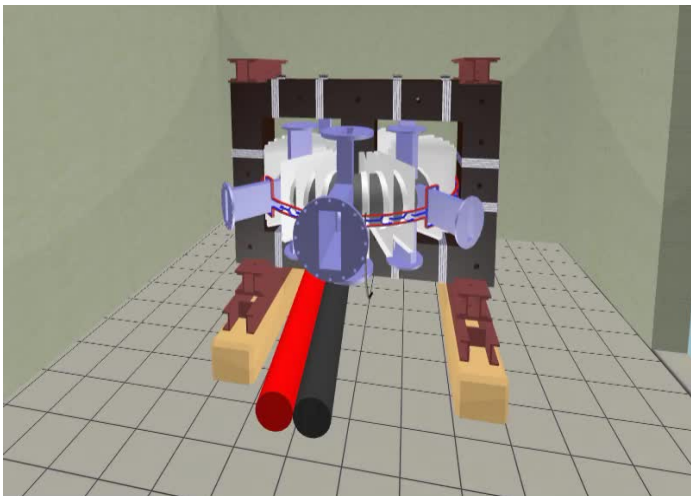


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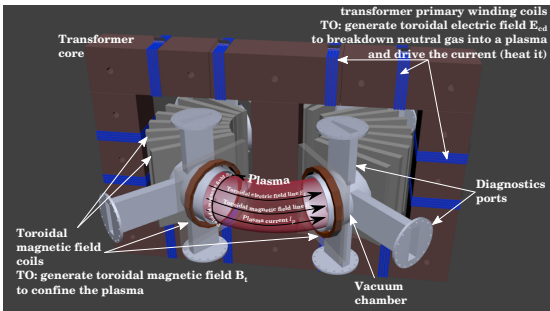
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Plasma in Tokamak (GOLEM) - the least to do

To do:

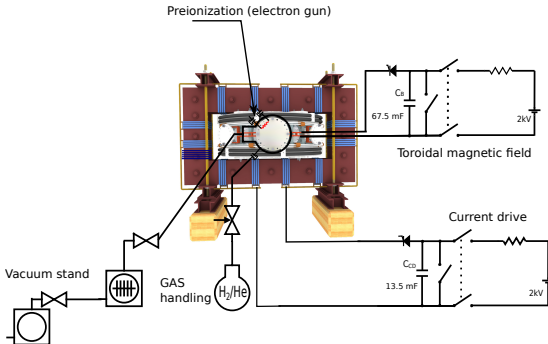
- session start phase:
 - Evacuate the chamber
- pre-discharge phase
 - Charge the capacitors
 - Fill in the working gas
 - Preionization
- discharge phase
 - Toroidal magnetic field to confine plasma
 - Toroidal electric field to breakdown neutral gas into plasma
 - Toroidal electric field to heat the plasma
 - Plasma positioning
 - Diagnostics
- post-discharge phase



Plasma in Tokamak (GOLEM) - the least to do

To do:

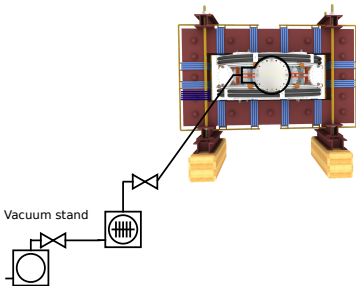
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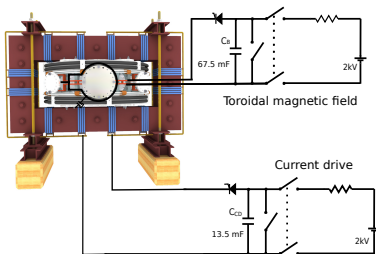
Plasma in Tokamak (GOLEM) - the least to do

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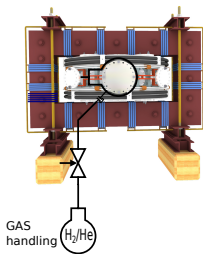
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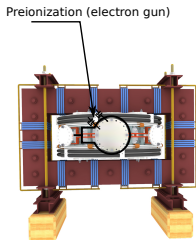
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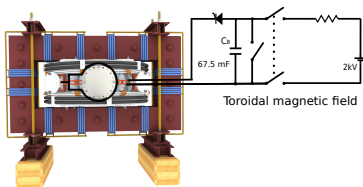
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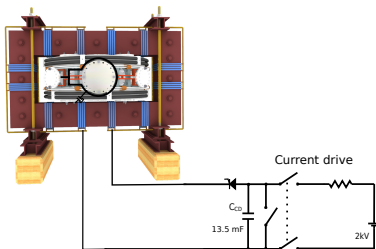
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Plasma in Tokamak (GOLEM) - the least to do



To do:

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 - **Toroidal electric field to breakdown neutral gas into plasma**
 - **Toroidal electric field to heat the plasma**
 - Plasma positioning
 - Diagnostics
- post-discharge phase

Tokamak GOLEM - schematic experimental setup

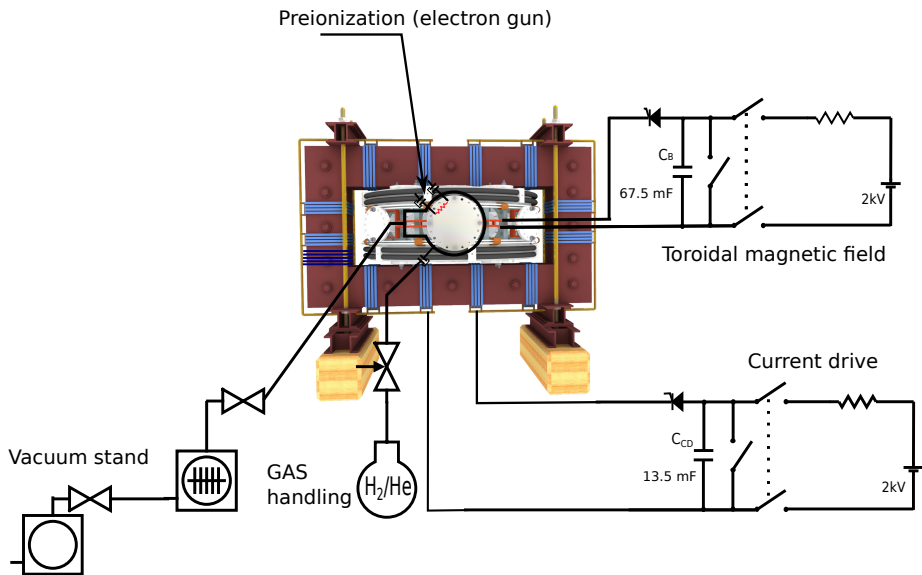


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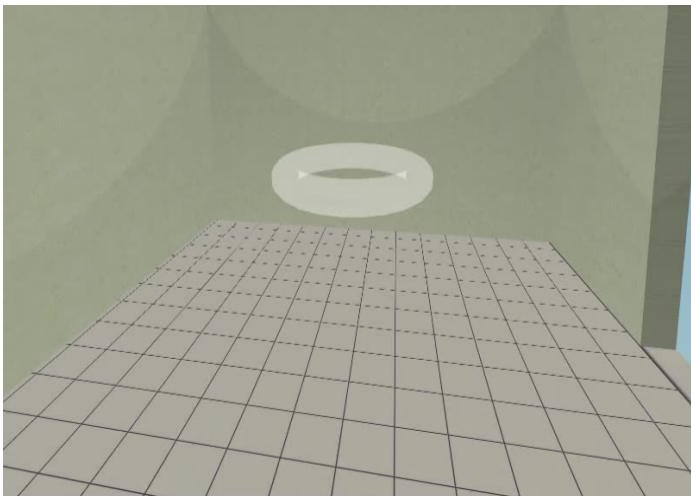
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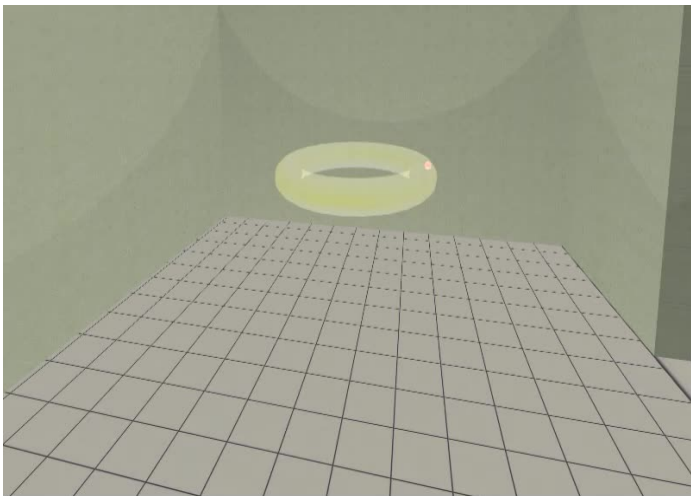
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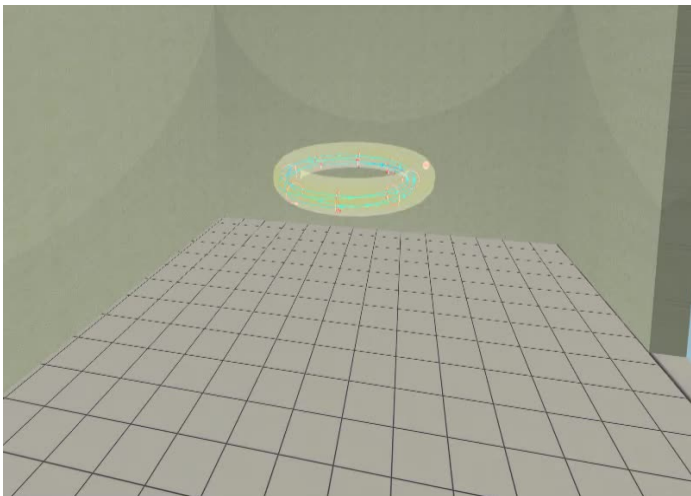
Introduce the working gas (Hydrogen x Helium)



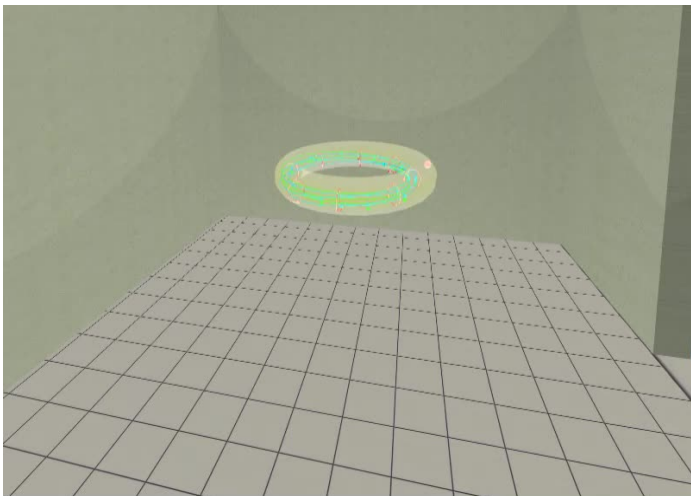
Switch on the preionization



Introduce the magnetic field



Introduce the electric field



Plasma ..

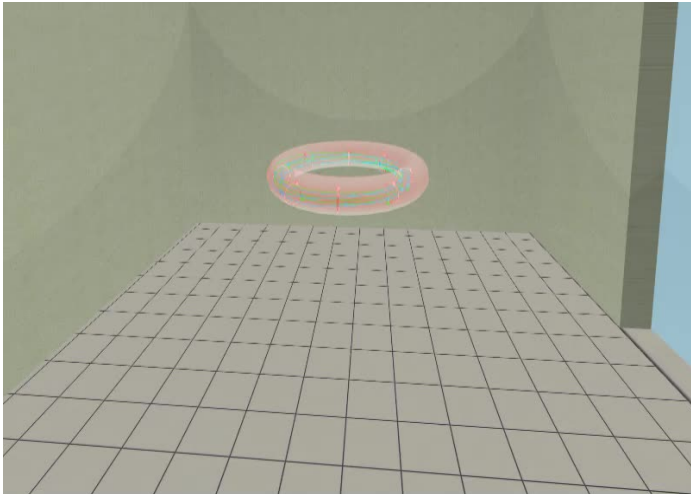


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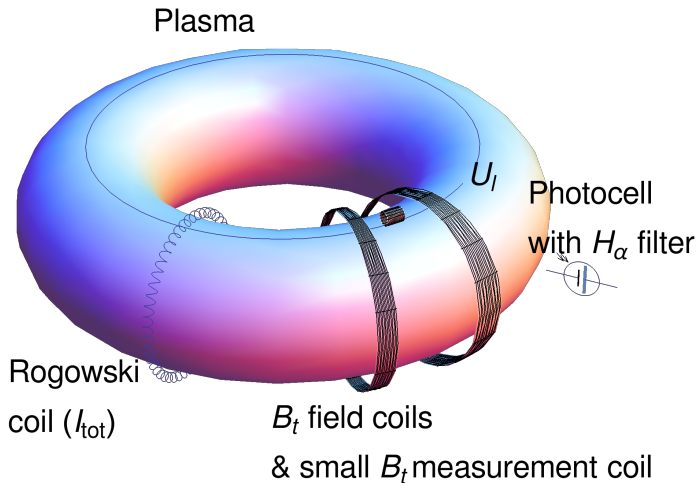
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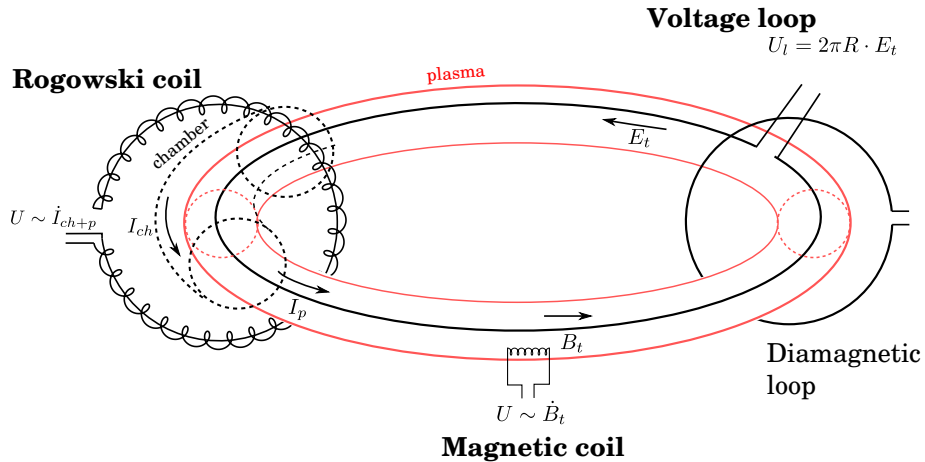
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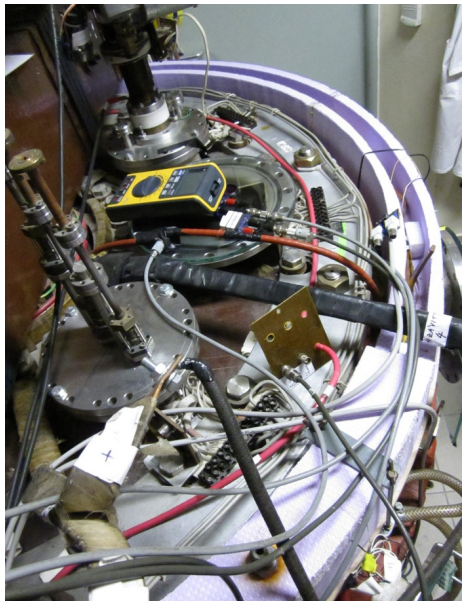
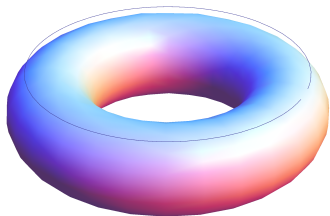
The GOLEM tokamak - basic diagnostics



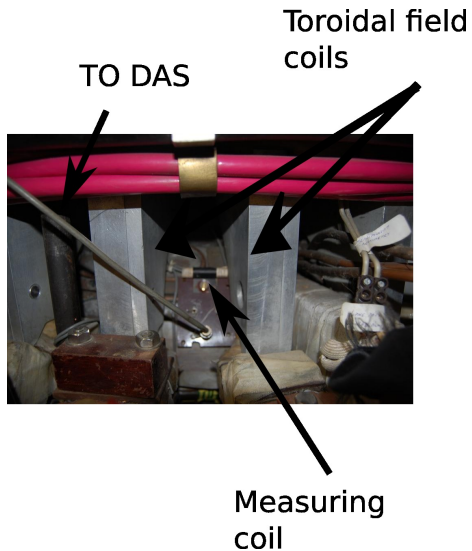
Schematic of electromagnetic diagnostics



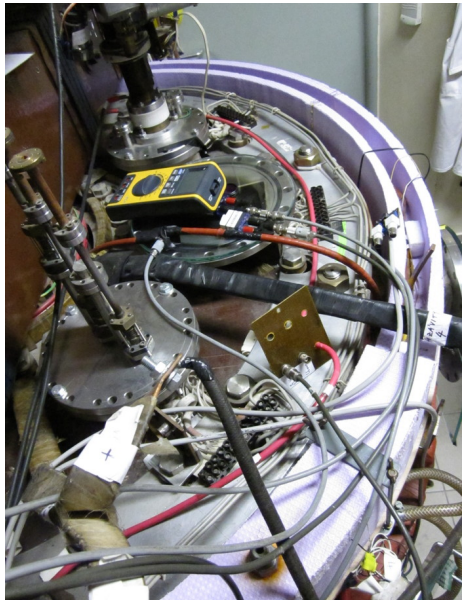
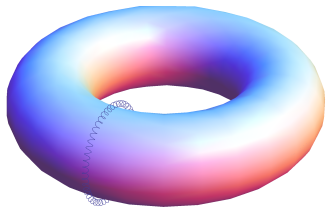
Loop voltage U_l @ the GOLEM tokamak



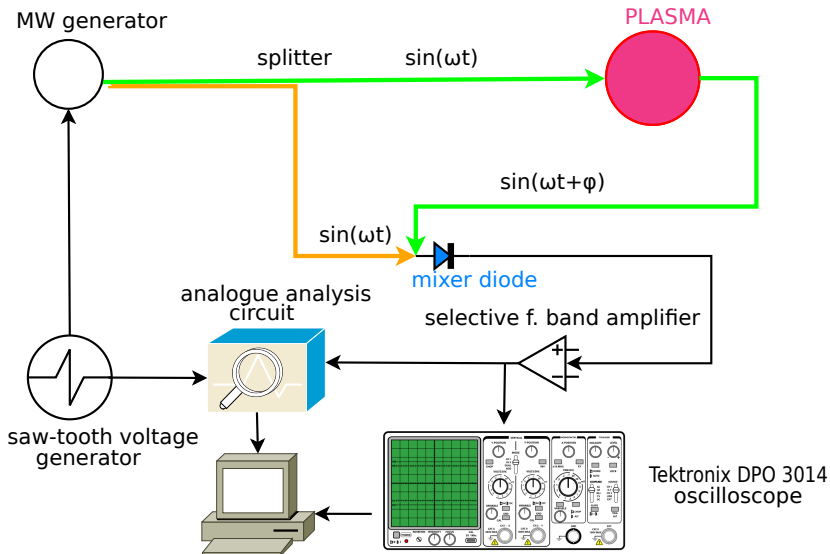
Toroidal magnetic field B_t @ the tokamak GOLEM



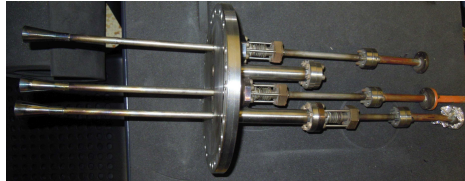
Total current I_{ch+p}



Electron density n_e interferometry measurement scheme



The GOLEM tokamak interferometry HW



"Typical", well executed discharge @ GOLEM

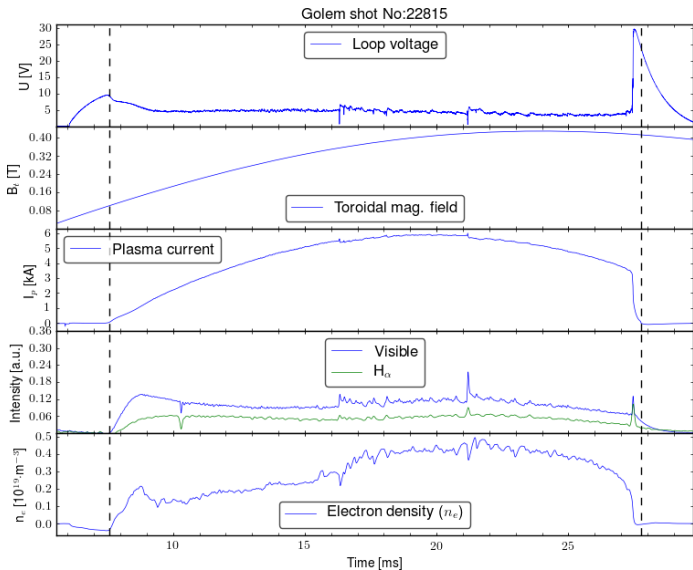


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Infrastructure room (below tokamak) 10/16



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

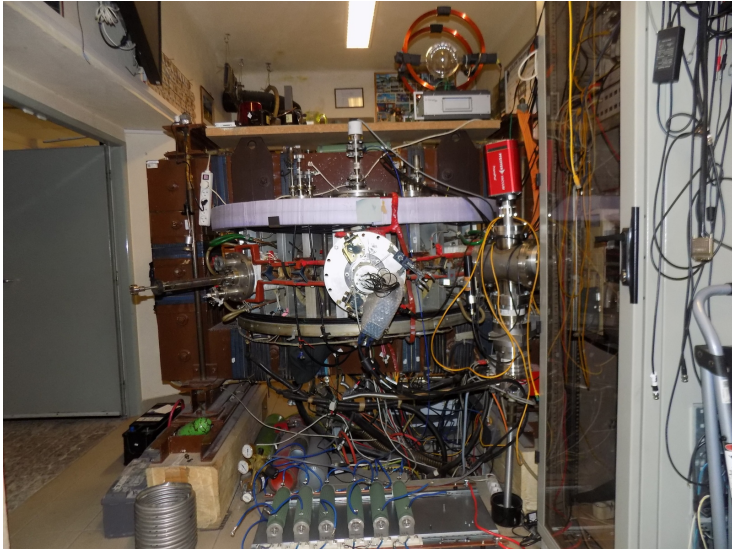
power
supply
2kV

Toroidal
magnetic field B
capacitors

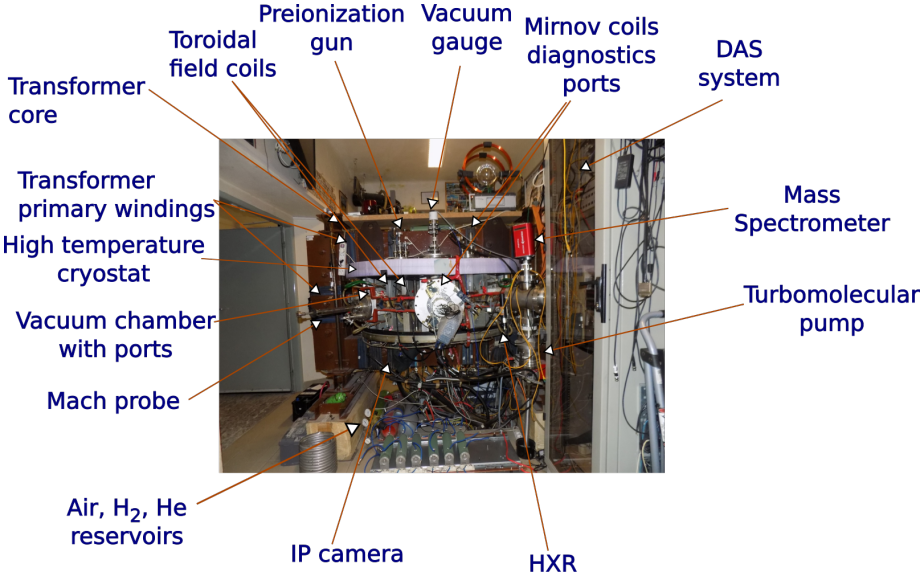
fire
protection
system



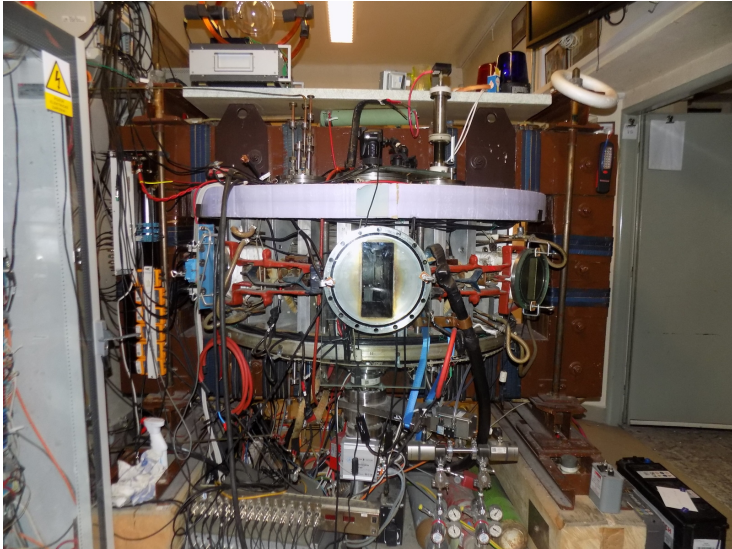
Tokamak room (North) 10/16



Tokamak room (North) 10/16



Tokamak room (South) 10/16



Tokamak room (South) 10/16

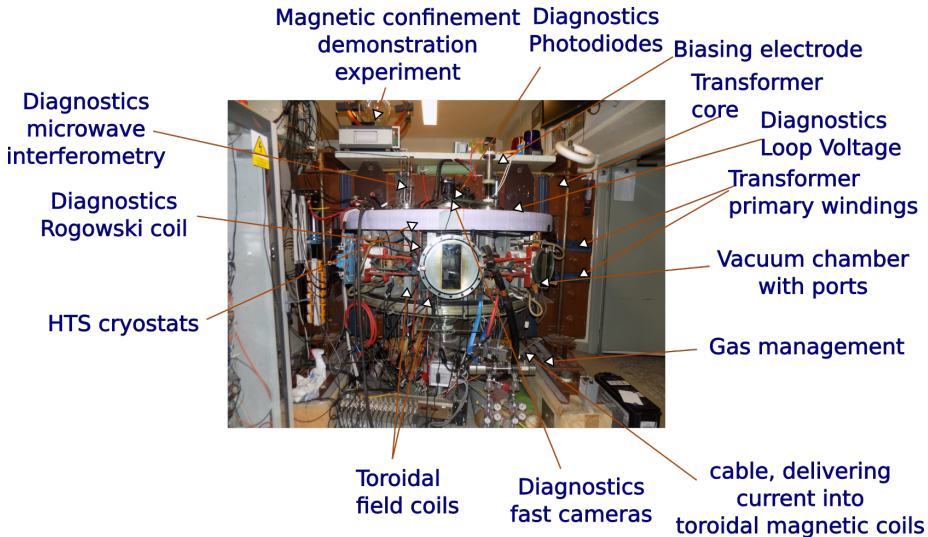


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 - Control room
 - Data handling @ the Tokamak GOLEM
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Control room: Introduction

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/H_3

23 mF C_p 2kV

11.3 mF C_{cp} 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_2^+

Toroidal magnetic field 67.5 mF

Toroidal electric field 13.5 mF

200V

200V

Gas type and pressure $p_{\text{gas}} = 38 \text{ mPa}$

Hydrogen Helium

Next Set recommended value

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

Control room: Preionization

GOLEM remote PREIONIZATION Control room Live Results

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

67.5 mF

13.5 mF

230V

230V

ionization method

Stick-in gas No ionization

[Next](#)

3D model rendering method [Static image \(fixed\)](#) [Interactive X3DOM \(viewer\)](#)

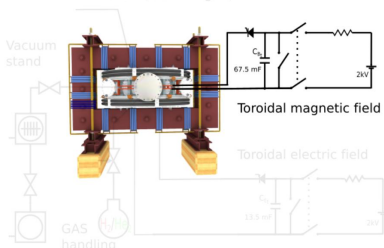
Control room: Magnetic field B_t

GOLEM interface: Introduction, Preionization, **Magnetic field**, Electric field, Submit

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

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

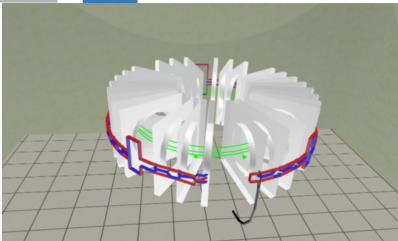
Toroidal magnetic field

Toroidal electric field

GAS handling

Capacitor voltage $U_{C_1} = 600 \text{ V}$

Next Set recommended value



Control room: Current drive E_{cd}

GOLEM Interface Introduction Control room Live Results

the Torion 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_d : 0 micro seconds

Capacitor voltage U_c : 400 V

Next Set recommended value

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

Control room: ... and Submit

GOLEM Interface 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.

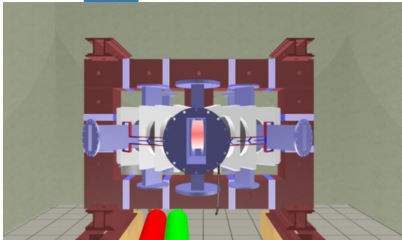
Comment

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

After submission you can 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 (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

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}

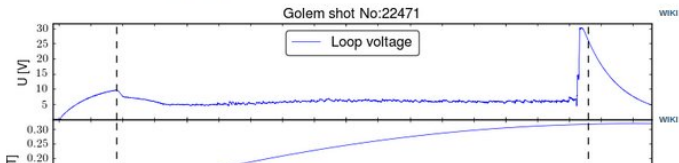


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- 2 The Tokamak (GOLEM)
- 3 The Tokamak GOLEM (remote) operation**
 - Control room
 - Data handling @ the Tokamak GOLEM
- 4 Conclusion
- 5 Appendix

GOLEM basic Data Acquisition System (DAS)

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



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

t	$\approx U_I$	$\approx U_{\frac{dB_T}{dt}}$	$\approx U_{\frac{d(I_{p+ch})}{dt}}$	$\approx I_{rad}$
:	:	:	:	:
:	:	:	:	:
first	\approx	7405	lines ..	:
:	:	:	:	:
:	:	:	:	:
0.007383	1.53931	0.390015	0.048828	0.001831
0.007384	1.53686	0.395508	0.067749	0.00061
0.007385	1.54053	0.391235	0.079956	0.00061
0.007386	1.53686	0.38147	0.072632	0
0.007387	1.54297	0.397949	0.059204	0.00061
0.007388	1.54053	0.384521	0.05249	0.00061
0.007389	1.54053	0.39856	0.068359	0.001221
0.00739	1.54053	0.393677	0.082397	0.001221
0.007391	1.53809	0.38208	0.072632	0.001221
0.007392	1.54297	0.400391	0.056763	0.00061
0.007393	1.54419	0.383911	0.053101	0.00061
0.007394	1.53931	0.397339	0.068359	0.001221
0.007395	1.54297	0.391846	0.084229	0.00061
0.007396	1.54541	0.394897	0.074463	0.00061
0.007397	1.54297	0.388184	0.056763	0.001221
0.007398	1.54297	0.391846	0.056763	0.00061
0.007399	1.54297	0.394287	0.06897	0.00061
:	:	:	:	:
:	:	:	:	:
next	\approx	32500	lines ..	:
:	:	:	:	:
:	:	:	:	:

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

```
1 ShotNo=35464
2 baseURL='http://golem.fjfi.cvut.cz/shots/';
3 diagnPATH='Diagnostics/BasicDiagnostics/U_Loop.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;
```

Jupyter (python)

```
1 import numpy as np
2 import pandas as pd
3 import matplotlib.pyplot as plt
4 shot_no = 35464
5 data_URL = "http://golem.fjfi.cvut.cz/shots/{shot_no}/Diagnostics/
   BasicDiagnostics/{identifier}.csv"
6 ds = np.DataSource(destpath="/tmp")
7 def open_remote(shot_no, identifier, url_template):
8     return ds.open(url_template.format(shot_no=shot_no, identifier=
   identifier))
9 def read_signal(shot_no, identifier):
10     file = open_remote(shot_no, identifier, data_URL)
11     return pd.read_csv(file, names=["Time", identifier],
12                        index_col="Time", squeeze=True)
13 loop_voltage = read_signal(shot_no, "U_Loop")
14 ax = loop_voltage.plot(grid=True)
15 ax.set(xlabel="Time [s]", ylabel="$U_{l}$ [V]", title="Loop voltage $U_{l}$
   {}".format(shot_no));
16
17 plt.savefig("graph.jpg")
```

Gnuplot

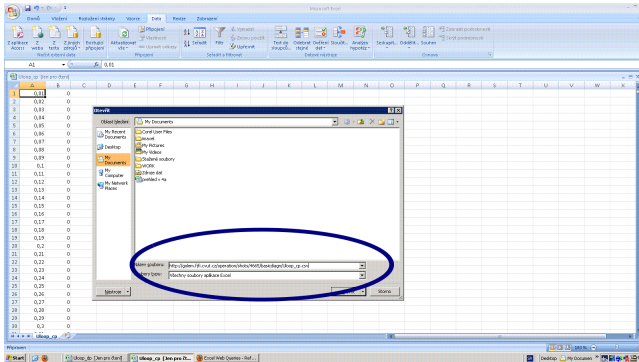
```
1 ShotNo=33993
2 gnuplot -e "set terminal jpeg;set datafile separator ',';set title '
  Uloop';plot '< wget -q -O - http://golem.fjfi.cvut.cz/shots/"$ShotNo
  "/DASs/StandardDAS/LoopVoltageCoil_raw.csv' u 1:2 w l t 'Uloop'" >
  plot.jpg
```

GNU Wget

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

- Runs on most UNIX-like operating systems as well as Microsoft Windows.
- Homepage: <http://www.gnu.org/software/wget/>
- Basic usage:
 - To get U_l : `wget http://golem.fjfi.cvut.cz/utills/data/<#ShotNo>/loop_voltage`
 - To get whole shot: `wget -r -nH -cut-dirs=3 -no-parent -l2 -Pshot http://golem.fjfi.cvut.cz/shots/<#ShotNo>`

Excel



File→Open→

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

Spreadsheets (Excel and others)

are not recommended, only tolerated.

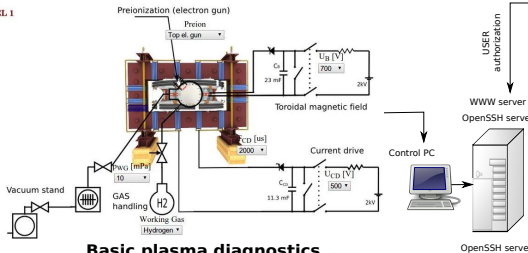
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The global schematic overview of the GOLEM experiment

LEVEL 1

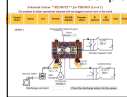
Tokamak technology setup



Virtual control room (remote participation)

WWW control interface

HTML & PHP scripts



SSH control interface

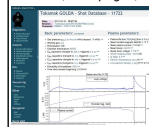
WINDOWS via putty



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

Data presentation

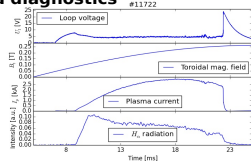
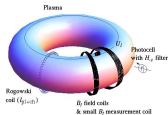
HTML (www pages)



Data handling

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

Basic plasma diagnostics



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



Acknowledgement

Financial support highly appreciated:

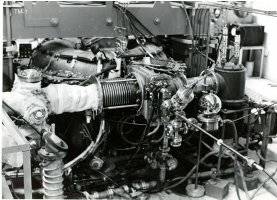
CTU RVO68407700, SGS 17/138/OHK4/2T/14, GAČR GA18-02482S, EU funds CZ.02.1.01/0.0/0.0/16_019/0000778 and CZ.02.2.69/0.0/0.0/16_027/0008465, IAEA F13019, FUSENET and EUROFUSION.

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 Čeřovský, Bořek Leitl, Martin Himmel. Petr Švihra, Petr Mácha, Vojtěch Fišer, Filip Papoušek, Sergei Kulkov, Martin Imříšek.

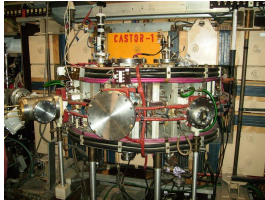
Thank you for your attention

Tokamak TM1
@Kurchatov Institute near Moscow
~1960-1977



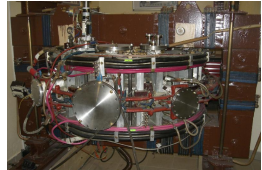
SCIENCE

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 ..

Tokamak Golem **REMOTE for MASTER (Level 1)**
The earliest & oldest operational tokamak with the biggest control room in the world

Home	WSU	Control Room	Queue	Live	Results	GOLEM diagram	Chamber status	IP camera	3D model	Chat	Feedback	Logout
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LEVEL 1

Preionization (electron gun)
Preion:

Toroidal magnetic field

Current drive

Discharge comment:

Place the discharge setup into the queue

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