

Introduction to the tokamak GOLEM operation Practical guide

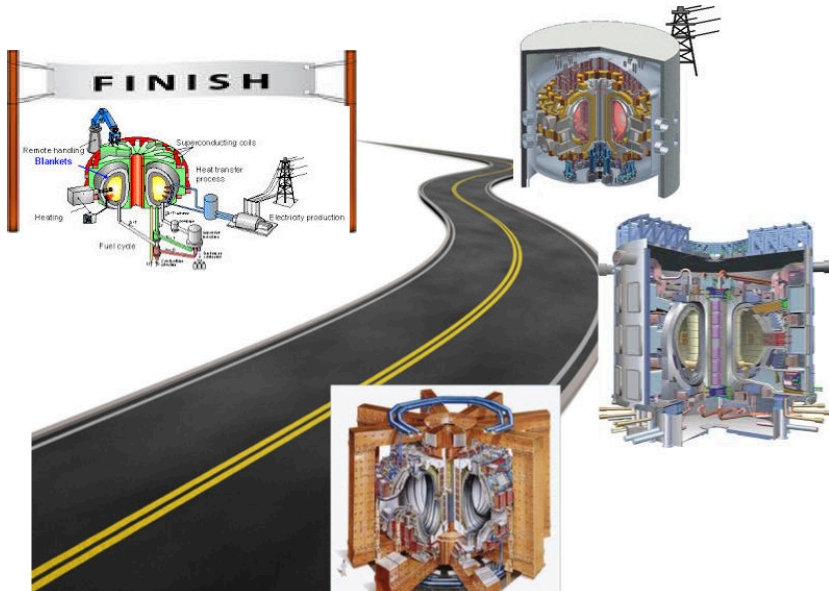
Vojtěch Svoboda
on behalf of the tokamak GOLEM team
for for the TU Eindhoven, Netherlands

March 25, 2025

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- 2 The Tokamak (GOLEM)
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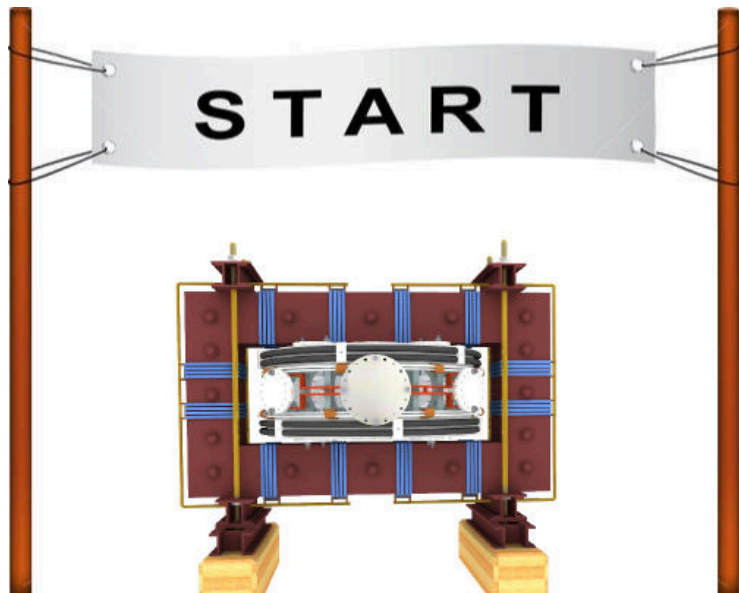
Milestones to Fusion Power Plant



Education importance

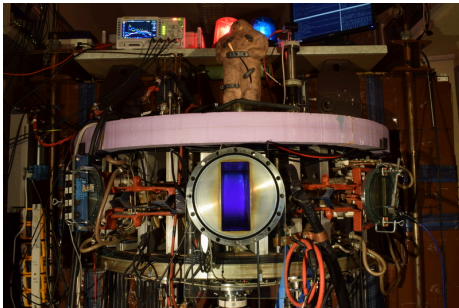


Let's start with the tokamak GOLEM - *the smallest tokamak in the World with the biggest control room*



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 ..


File Edit View Go Bookmarks Tools Settings Window Help

W https://en.wikipedia.org/wiki/Tokamak

home Kalendarj Produkce Forecast Slovník Ráno

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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 wrap 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^[122]) in Prague, Czech Republic. In operation in Kurchatov Institute since early 1960s but renamed to Castor in 1977 and moved to IPP CAS,^[131] 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



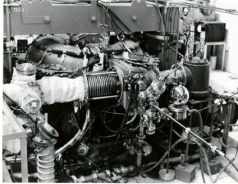
Alcator C-Mod



ida, the free encyclo... W Tokamak - Wikipedia, the free encyclo... [svoboda] buon@fi.cvut.cz - Kosside [Krusader] Inbox - svoboda@fi.cvut.cz - Mail

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

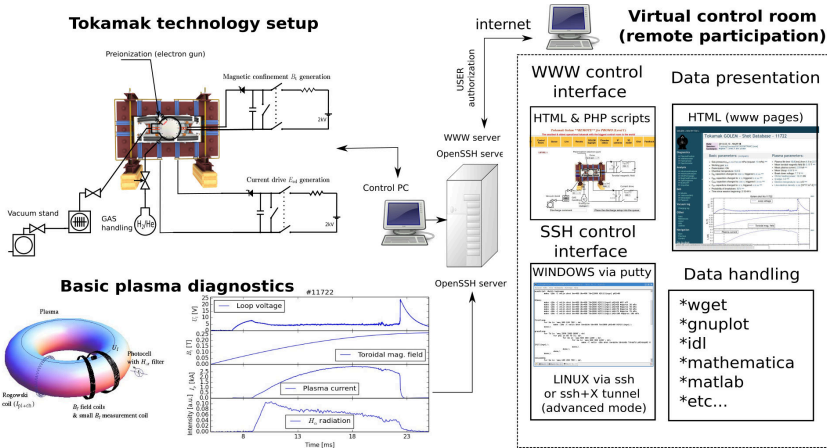
... somewhere, in the ancient cellars of Prague,

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. . .

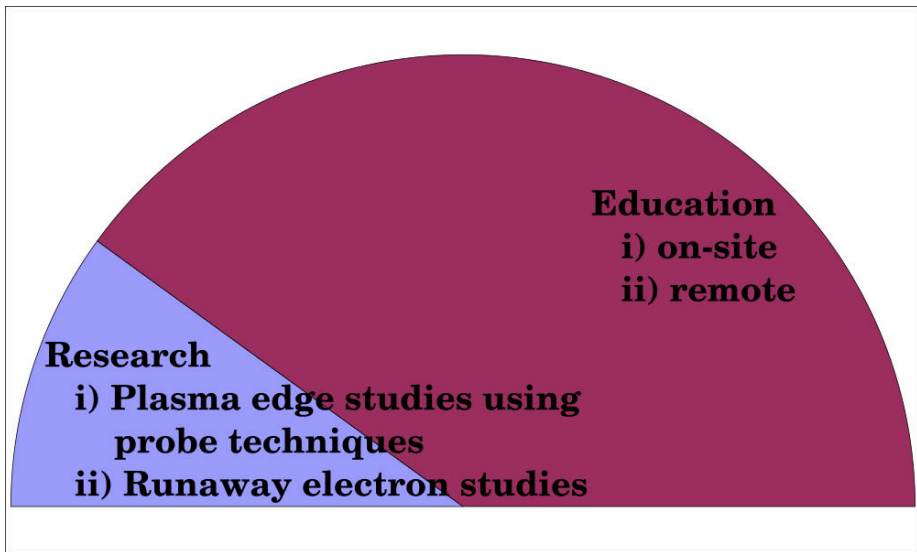


At the end of the 16th century, in the times when the Czech lands were ruled by Emperor Rudolf II, in Prague, there were Rabbi Judah Loew, well known alchemist, thinker, scholar, writer and inventor of the legendary GOLEM - a clay creature inspired with the Universe power that pursued his master's command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



The GOLEM tokamak mission



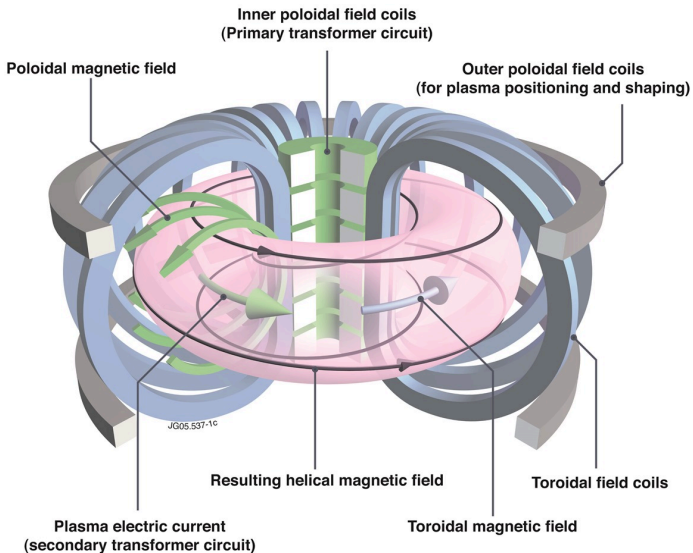
- Everything via <http://golem.fjfi.cvut.cz/Eindhoven>
 - This presentation
 - Control rooms
 - Contact: Vojtech Svoboda,
+420 737673903,
vojtech.svoboda@fjfi.cvut.cz
 - Videoconference:
<https://meet.google.com/hnv-qjhu-xvi>



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Tokamak magnetic confinement concept



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

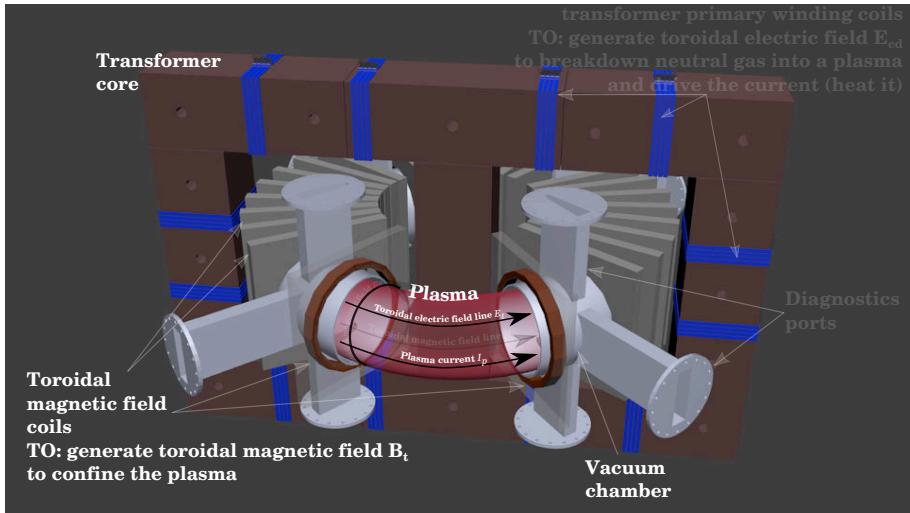


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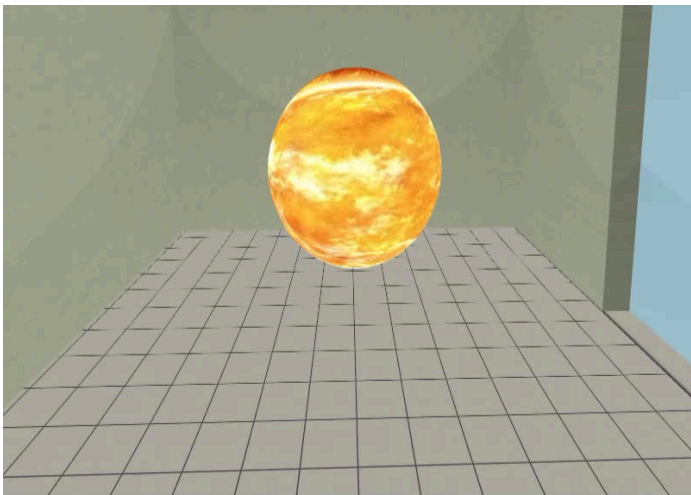
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- The GOLEM tokamak basic diagnostics

3 The Tokamak GOLEM (remote) operation

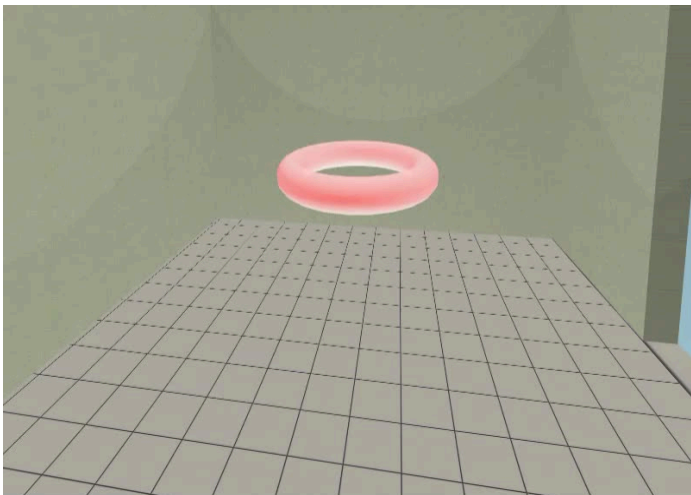
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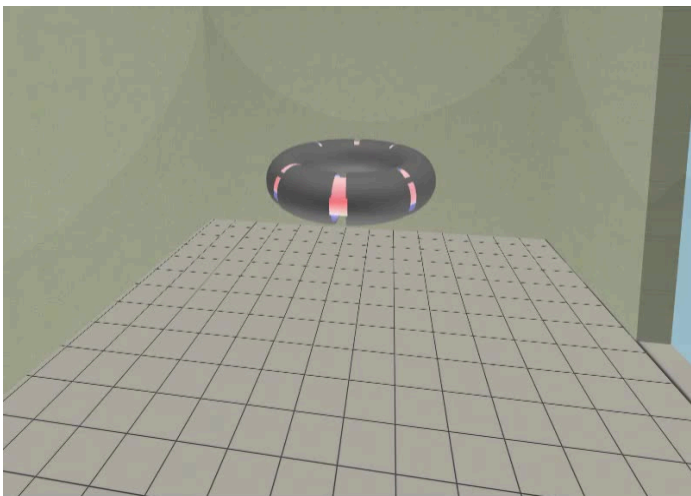
Our goal: the technology to create a μ Sun on the Earth



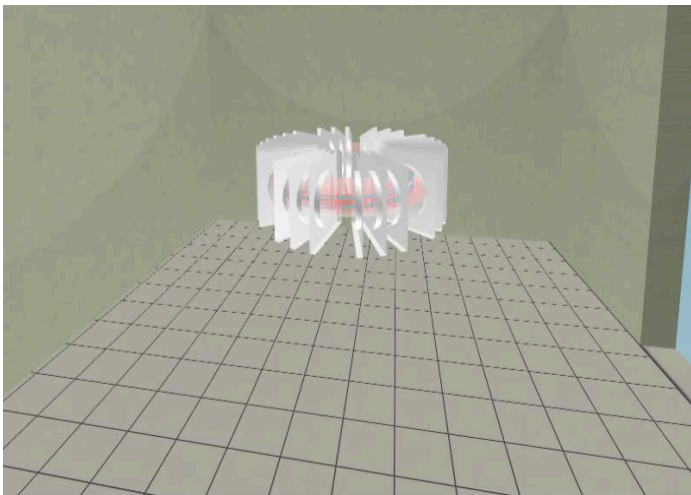
Magnetic confinement requires toroidal geometry



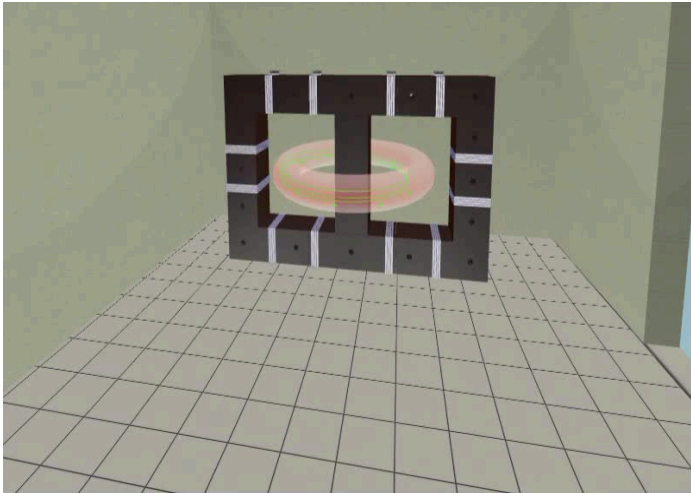
A chamber contains the thermonuclear reaction



Toroidal magnetic field coils confine the plasma



A transformer action creates and heats the plasma



The final technology altogether

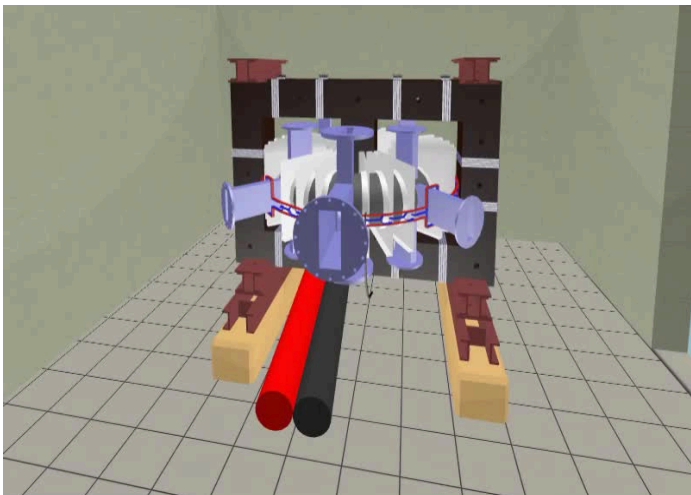


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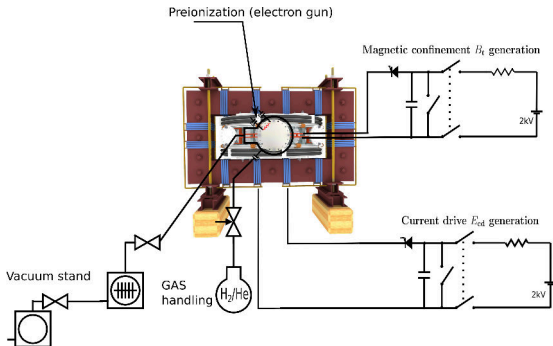
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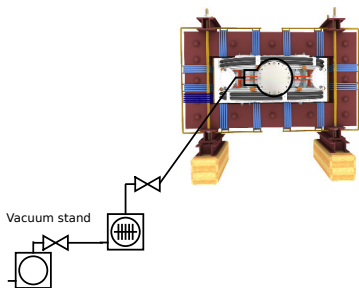
Plasma in Tokamak (GOLEM) - the least to do



To do:

- session start phase:
 - Evacuate the chamber
- pre-discharge phase
 - Charge the capacitors
 - Fill in the working gas
 - Preionization
- discharge phase
 - Trigger Magnetic confinement & Current drive
 - Plasma positioning
 - Diagnostics
- post-discharge phase
 - Data collection & analysis
 - Shot homepage creation

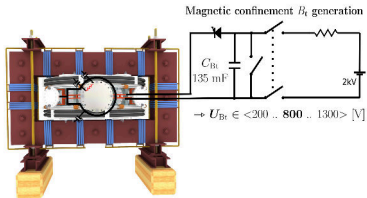
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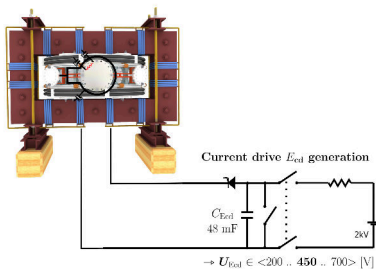
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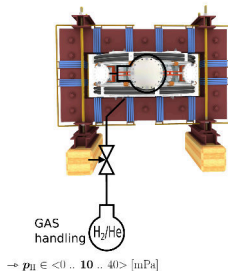
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Plasma in Tokamak (GOLEM) - the least to do



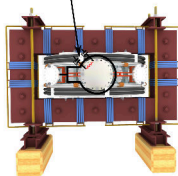
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Plasma in Tokamak (GOLEM) - the least to do

Preionization (electron gun)

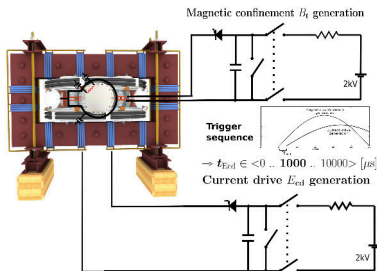
→ $S/W_{\text{preion}} \in \langle \text{on} \dots \text{off} \rangle [-]$



To do:

- session start phase:
 - Evacuate the chamber
- pre-discharge phase
 - Charge the capacitors
 - Fill in the working gas
 - **Preionization**
- discharge phase
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Plasma in Tokamak (GOLEM) - the least to do



To do:

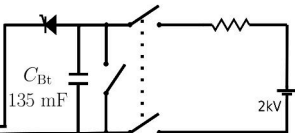
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 - Diagnostics
- post-discharge phase
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 - Shot homepage creation

Tokamak GOLEM - schematic experimental setup

Preionization (electron gun)

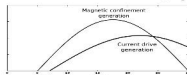
→ $S/W_{\text{preion}} \in \langle \text{on} \dots \text{on} \dots \text{off} \rangle [-]$

Magnetic confinement B_t generation

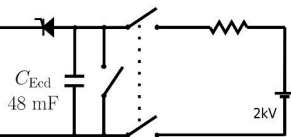


→ $U_{B_t} \in \langle 200 \dots 800 \dots 1300 \rangle [V]$

Trigger sequence



Current drive E_{cd} generation



→ $U_{E_{cd}} \in \langle 200 \dots 450 \dots 700 \rangle [V]$

→ $t_{E_{cd}} \in \langle 0 \dots 1000 \dots 10000 \rangle [\mu s]$

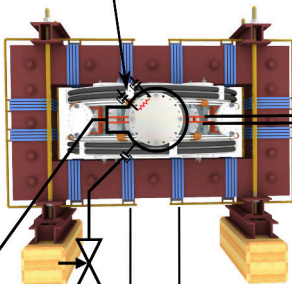
Vacuum stand



GAS handling



→ $p_H \in \langle 0 \dots 10 \dots 40 \rangle [\text{mPa}]$

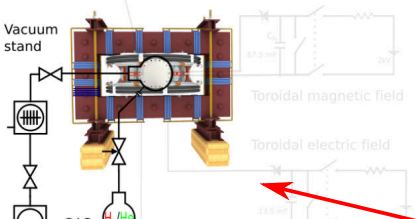


Remote control interface of the GOLEM tokamak

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

Toroidal magnetic field

Toroidal electric field

GAS handling

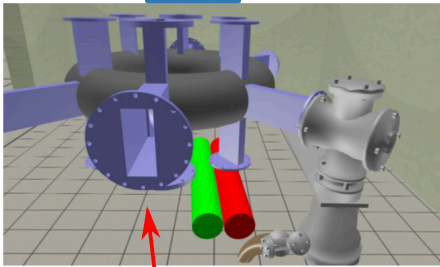
Gas type and pressure $p_{WG} = 16 \text{ mPa}$

Hydrogen Helium

Next Set recommended value

rendering settings

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



3D model rendering

engineering scheme

sliders and checkboxes

workflow buttons

Let's make a discharge

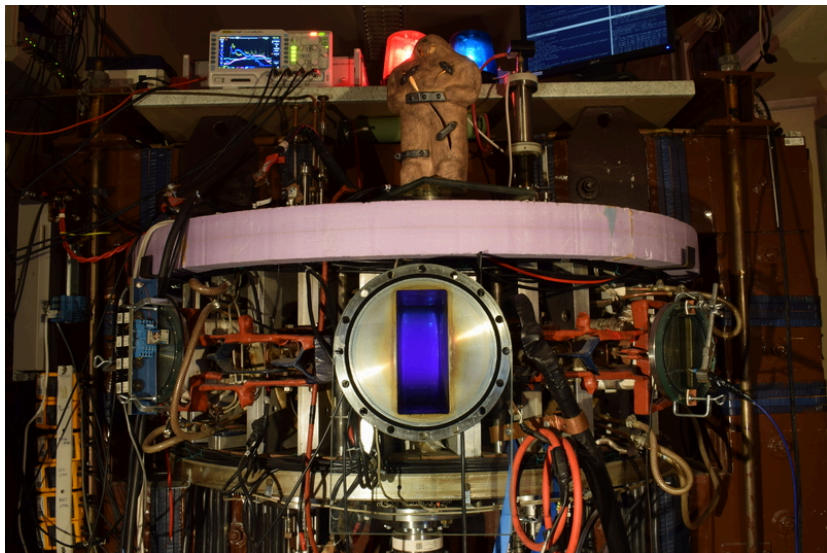


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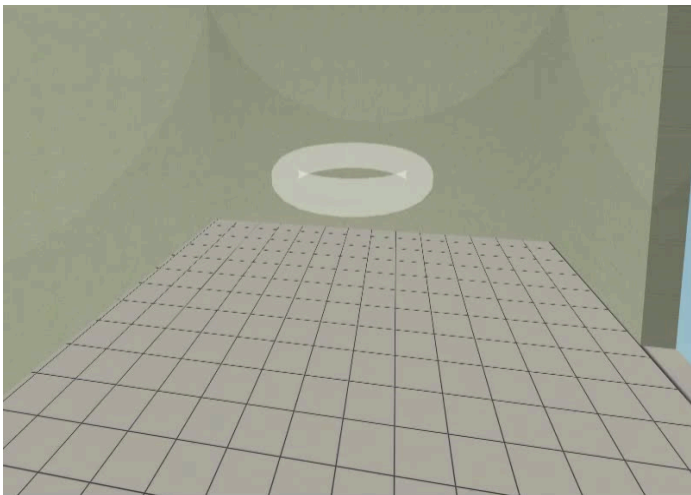
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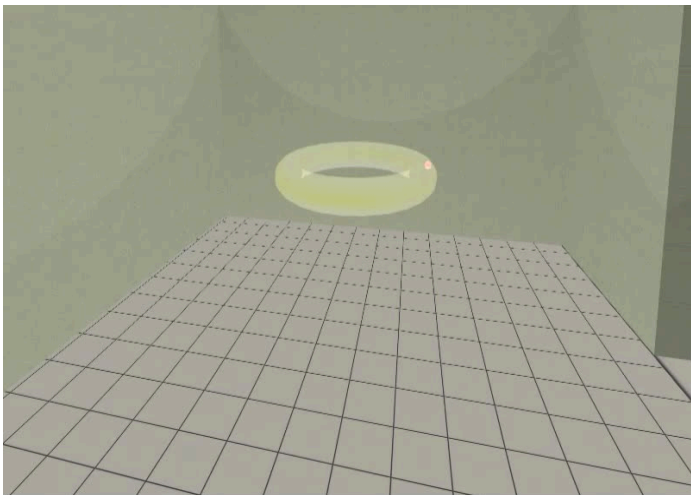
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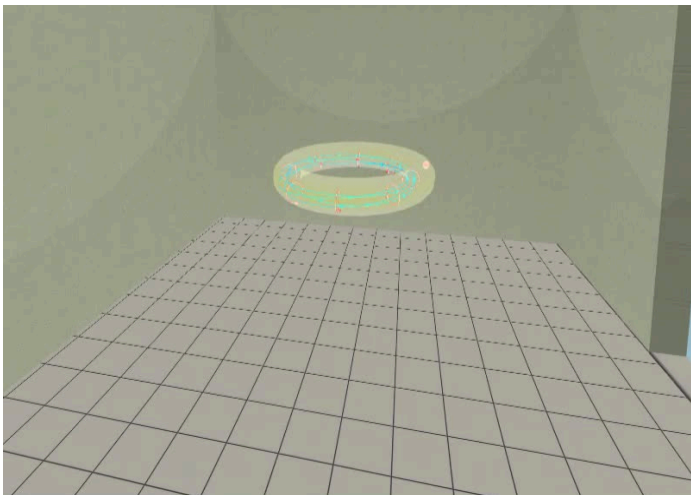
Introduce the working gas (Hydrogen x Helium)



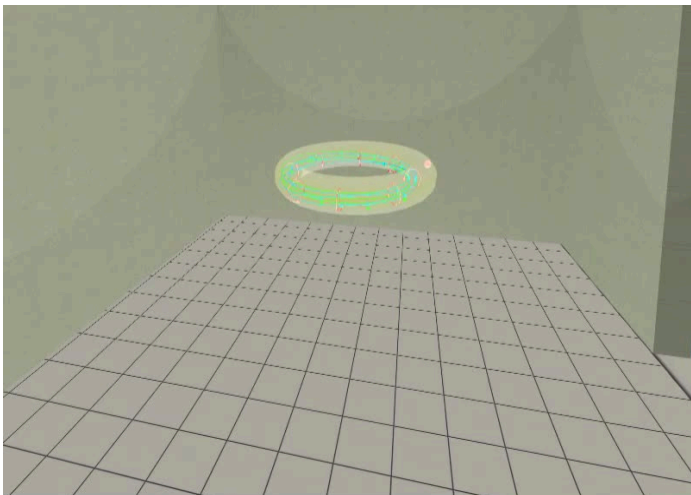
Switch on the preionization



Introduce the magnetic field



Introduce the electric field



Plasma ..

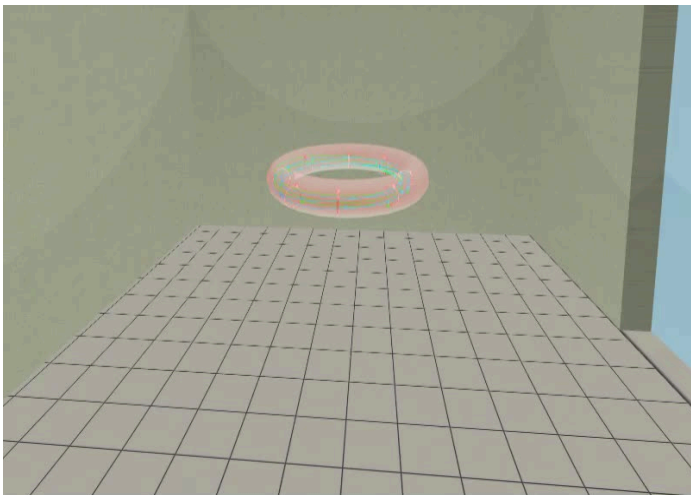


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Infrastructure room (below tokamak) 10/16



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

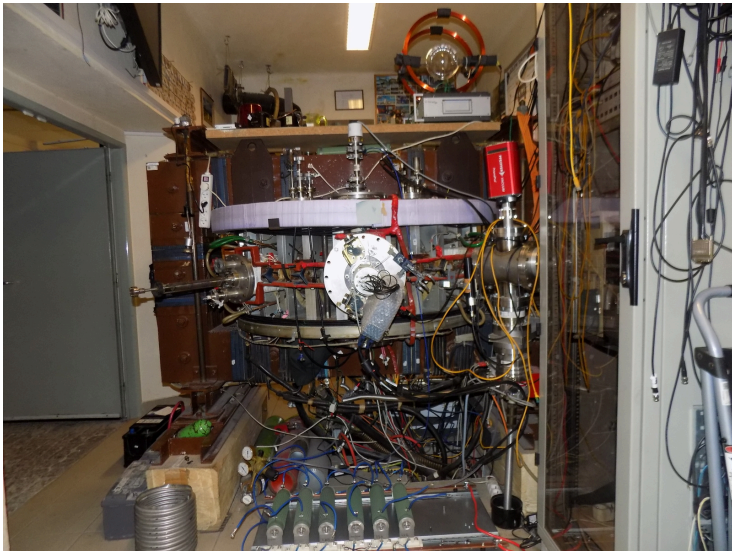
power
supply
2kV

Toroidal
magnetic field B
capacitors

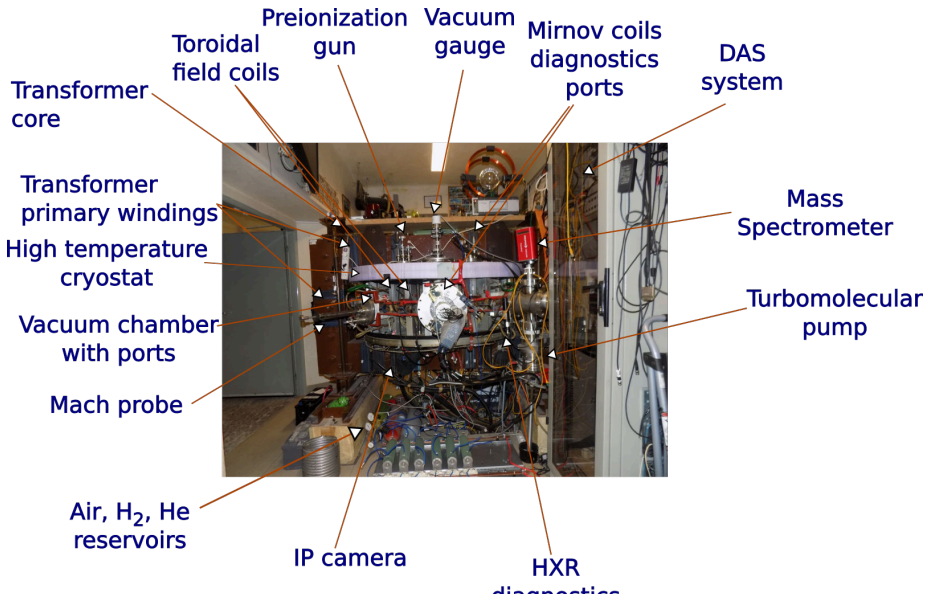
fire
protection
system



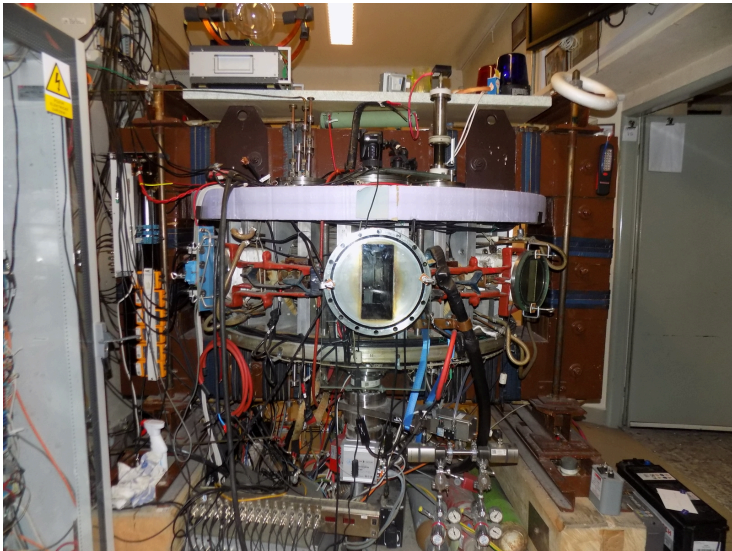
Tokamak room (North) 10/16



Tokamak room (North) 10/16



Tokamak room (South) 10/16



Tokamak room (South) 10/16

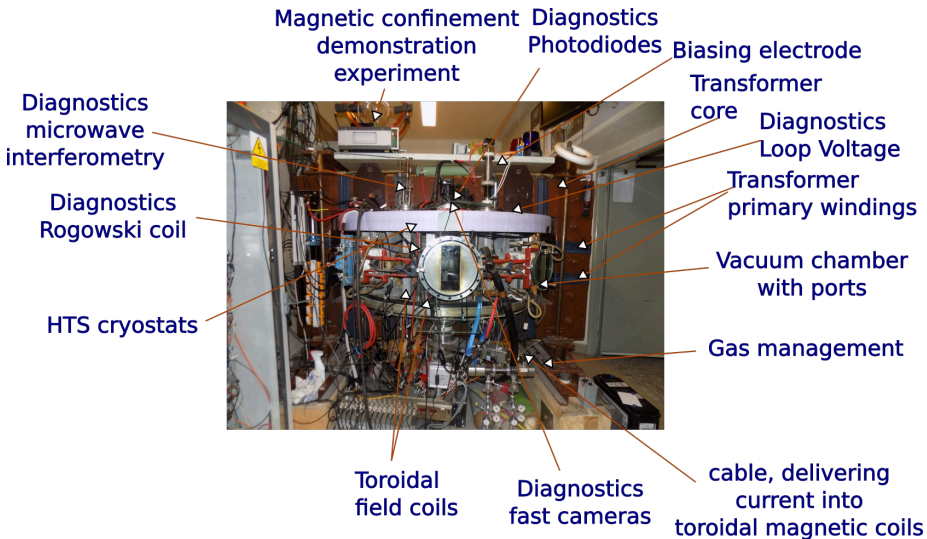


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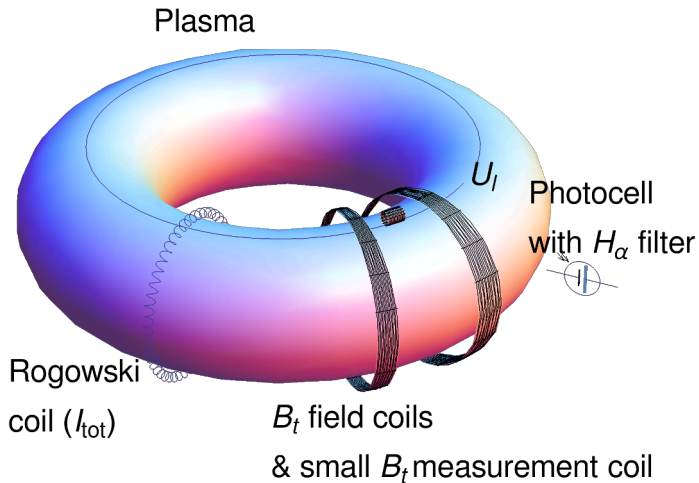
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The GOLEM tokamak - basic diagnostics



Hands on the GOLEM tokamak - equipment



Basic diagnostics - numerical processing, shot homepage

GOLEM - Shot #39187

Tokamak GOLEM - Shot Database - #39187

The date of discharge execution 22-05-18 17:55:04

The session mission GOLEM II -> EDU (MHD + biasing)

The session ID 39183

The discharge comment Vert & Rad Stab

Discharge command
`loop ./Drigent.sh --discharge --UBT 1200 --TBT 0 --Ucd 450 --Tcd 350 --preionization 1 --gas H --pressure 10 --diagnostics.limitermimovcoils "vacuum_shot=39109" --discharge.preionization "main_switch='on',powsup_heater=80,powsup_acce=100" --discharge.position_stabilization "main_switch='on',radial_switch='on',vertical_waveform='3000,0,9000,-20,18000,0,20000,0,30000,0',vertical_switch='on',radial_waveform='2000,0,3000,0,8000,-20,18000,0,19000,0,25000,0'" --ScanDefinition "39184 39185" --comment "Vert & Rad Stab"`

Technological parameters

- Working Gas: $p_{\text{discharge, before}} = 1,66 \text{ mPa}$; $p_{\text{discharge, post}} = 10,40 \text{ mPa}$ ($p_{\text{HWC}}^{\text{request}} = 10 \text{ mPa}$ @ $A_{\text{HWC}}^{\text{request}} = 4 \text{ H}$)
- Toroidal magnetic field: $U_{\text{BI}}^{\text{request}} = 1200 \text{ V}$ @ $I_{\text{BI}}^{\text{request}} = 0,0 \text{ us}$
- Current drive field: $U_{\text{CD}}^{\text{request}} = 450 \text{ V}$ @ $I_{\text{CD}}^{\text{request}} = 350,0 \text{ us}$

Plasma:

- Plasma: yes or no:
- Time parameters: $\Delta T_p = 15,08 \text{ ms}$ (from: $t_{\text{start}} = 2,49 \text{ ms}$, to: $t_{\text{end}} = 17,57 \text{ ms}$)

Plasma parameters:

- Loop voltage: $\overline{U}_{\text{loop}} = 8,02 \text{ V}$; $\max_{r_{\text{c}}(\text{discharge})} \overline{U}_{\text{loop}} = 9,89 \text{ V}$; $U_{\text{loopdown}} = 10,83 \text{ V}$
- Toroidal magnetic field: $\overline{B}_t = 0,40 \text{ T}$; $\max_{r_{\text{c}}(\text{discharge})} \overline{B}_t = 0,57 \text{ T}$
- Plasma current: $I_p = 3,67 \text{ kA}$; $\max_{r_{\text{c}}(\text{discharge})} I_p = 3,67 \text{ kA}$; $I_{\text{pmax}} = 3,66 \text{ kA}$

On stage diagnostics

Data flow measurement → digitization → analysis →

Name	Experiment setup	Data acquisition system	Raw data	Analysis results
Basic Diagnostics				

Navigation: Next, Previous, Current

Basic diagnostics - numerical processing, raw data

The image shows a web browser displaying a diagnostic interface for a Golem shot. The top part is a dashboard with a sidebar on the left and a main content area. The sidebar includes sections for 'Diagnostics', 'Other', and 'Navigation'. The main content area is titled 'On stage diagnostics' and features a data flow diagram with stages: 'Name', 'Experiment setup', 'Data acquisition system', 'Raw data', and 'Analysis results'. A red circle highlights a folder icon in the 'Raw data' stage. Below the dashboard is a file index for the path '/shots/39187/Devices/Oscilloscopes/TektrMSO56-a'. The index table lists files with their names, last modified dates, and sizes. A red arrow points from the highlighted folder icon in the dashboard to the 'BasicDiagnostics.sh' file in the index. Another red arrow points from the left edge of the image to the 'BasicDiagnostics.sh' file. At the bottom of the index, it says 'Apache/2.4.38 (Debian) Server at golem.fjfi.cvut.cz Port 80'.

Index of /shots/39187/Devices/Oscilloscopes/TektrMSO56-a

Name	Last modified	Size	Description
Parent Directory	-	-	-
BasicDiagnostics.sh	2022-05-18 17:58	3.2K	
ScreenshotAll.png	2022-05-18 17:58	184K	
TektrMSO56_ALL.csv	2022-05-18 17:58	3.9M	
Universals.sh	2022-05-18 17:58	1.2K	
das.jpg	2022-05-18 17:58	13K	
ls-all	2022-05-18 17:58	2.4K	
rawdata.jpg	2022-05-18 17:58	13K	

Apache/2.4.38 (Debian) Server at golem.fjfi.cvut.cz Port 80

Basic diagnostics - numerical processing, Jupyter-notebook@GitLab Download & play

The screenshot shows a web browser displaying a GitLab repository page for 'Tokamak GOLEM Basic diagnostics'. The browser's address bar shows the URL: `https://gitlab.com/golem-tokamak/dirigent/-/blob/master/Diagnostics/basicDiagnostics/StandardDAS.ipynb`. The page header includes navigation tabs for 'Data flow', 'Measurement', 'Data acquisition system', 'Raw data', and 'Analysis results'. Below the header is a navigation bar with 'About GitLab', 'Pricing', 'Talk to an expert', a search bar, and 'Sign up now' and 'Login' buttons. The left sidebar contains a navigation menu with 'Dirigent', 'Project information', 'Repository', 'Files', 'Commits', 'Branches', 'Tags', 'Contributors', 'Graph', 'Compare', 'Locked Files', 'Issues', 'Merge requests', 'CI/CD', 'Deployments', and 'Collapse sidebar'. The main content area shows the file 'StandardDAS.ipynb' (19.83 KIB) with a blue 'Open in Web IDE' button. The notebook content includes the title 'Tokamak GOLEM Basic diagnostics', a 'Procedure' section with a link to download the notebook, and a 'Prerequisites: function definitions' section with a code block for loading libraries.

StandardDAS.ipynb 19.83 KIB

Open in Web IDE

Tokamak GOLEM Basic diagnostics

[Procedure \(This notebook to download\)](#)

[bash wrapper](#), [Error log](#)

Prerequisites: function definitions

Load libraries

```
%matplotlib inline
import os
import numpy as np
import matplotlib.pyplot as plt
from scipy import constants, integrate, signal, interpolate
import sqlalchemy # high-level library for SQL in Python
import pandas as pd
import subprocess
```


Basic diagnostics - numerical processing, Jupyter-notebook applied on the Discharge



Procedure ([This notebook to download](#))

[bash wrapper](#), [Error log](#)

Prerequisites: function definitions

Load libraries

```
In [1]: %matplotlib inline
import os
import numpy as np
import matplotlib.pyplot as plt
from scipy import constants, integrate, signal, interpolate
import sqlalchemy # high-level library for SQL in Python
import pandas as pd
import subprocess
```

For interactive web figures

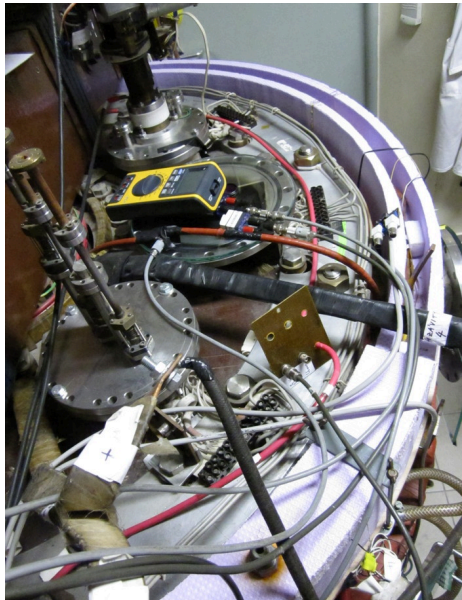
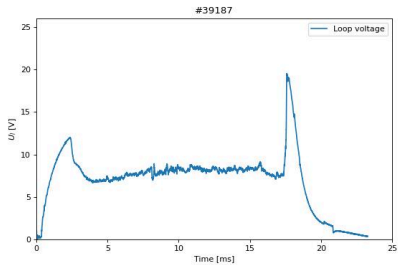
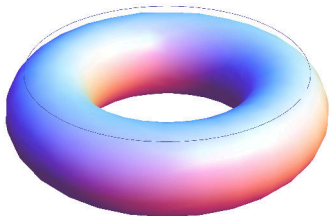
```
In [2]: import holoviews as hv
hv.extension('bokeh')
import hvplot.pandas
```



For conditional rich-text boxes

```
In [3]: from IPython.display import Markdown
```

Loop voltage U_l @ the GOLEM tokamak



Basic diagnostics - numerical processing, U_{loop}

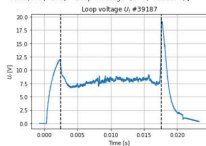
```
t_scale = 1e-3 if in_seconds else 1
if is_plasma:
    for t in (t_plasma_start, t_plasma_end):
        plt.axvline(t = t_scale, color='k', linestyle='--')
```

U_l management

Check the data availability

```
In [11]: loop_voltage = read_signal(shot_no, 'U_Loop')
polarity_CD = read_parameter(shot_no, 'CD_orientation')
if polarity_CD != 'CW': # T000 hardcoded for now!
    loop_voltage *= -1 # make positive
loop_voltage = correct_inf(loop_voltage)
loop_voltage.loc[is_CD] = 0
ax = loop_voltage.plot(grid=True)
show_plasma_limits()
ax.set(xlabel='Time [s]', ylabel='SU_LS [V]', title='Loop voltage SU_LS #{}'.format(shot_no));
```

```
Out[11]: [Text(0.5, 0, 'Time [s]'),
Text(0, 0.5, 'SU_LS [V]'),
Text(0.5, 1.0, 'Loop voltage SU_LS #39187')]
```



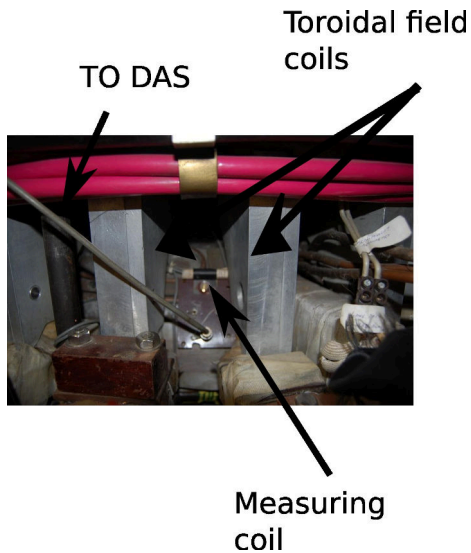
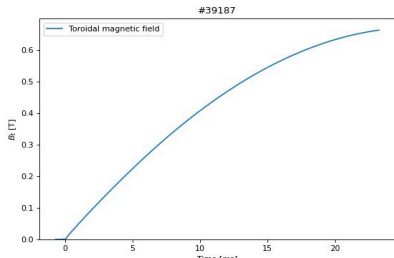
B_t calculation

Check the data availability

It is as magnetic measurement, so the raw data only give $\frac{dB_t}{dt}$

```
In [12]: dBt = read_signal(shot_no, 'U_BtCoil')
polarity_BT = read_parameter(shot_no, 'BT_orientation')
if polarity_BT != 'CW': # T000 hardcoded for now!
    dBt *= -1 # make positive
dBt = correct_inf(dBt)
dBt -= dBt.loc[offset_s1].mean()
ax = dBt.plot(grid=True)
show_plasma_limits()
ax.set(xlabel='Time [s]', ylabel='dBt [V]', title='BtCoil raw signal #{}'.format(shot_no));
```

Toroidal magnetic field B_t @ the tokamak GOLEM



Basic diagnostics - numerical processing, B_t

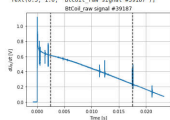
B_t calculation

Check the data availability

It is as magnetic measurement, so the raw data only give $\frac{dB_t}{dt}$

```
In [12]: dBt = read_signal(shot_no, '0_BtCoil')
polarity_Bt = read_parameter(shot_no, 'Bt_orientation')
if polarity_Bt != 'CW':
    dBt *= -1 # make positive # 1000 hardcoded for now!
dBt = correct_inf(dBt)
dBt = dBt.loc[offset_start:].mean()
ax = dBt.plot(grid=True)
show_plasma_limits()
ax.set(xlabel='Time [s]', ylabel='dBt [B/s]', title='BtCoil_raw signal #{}'.format(shot_no));
```

```
Out[12]: [Text(0.5, 0, 'Time [s]'),
Text(0, 0.5, 'dBt [B/s]', title='BtCoil_raw signal #39187')]
Text(0.5, 1.0, 'BtCoil_raw signal #39187')]
```

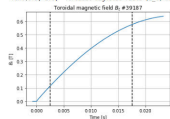


Integration (it is a magnetic diagnostic) & calibration

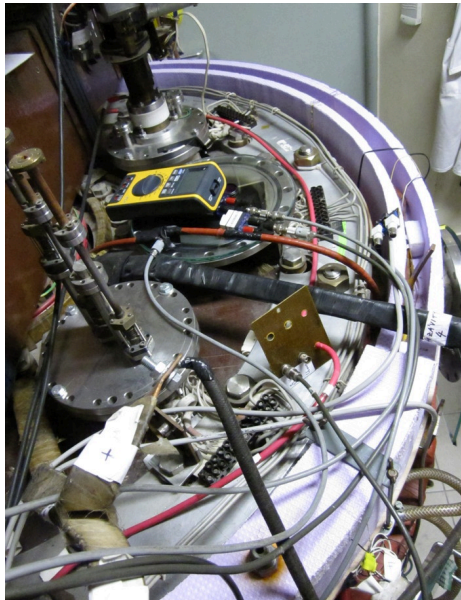
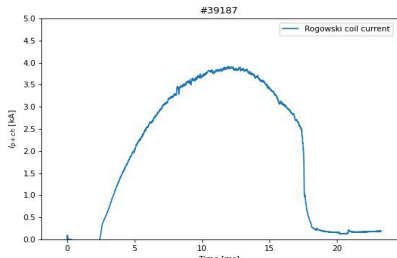
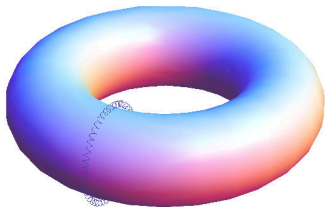
```
In [13]: K_BtCoil = float(read_parameter(shot_no, 'SystemParameters/K_BtCoil')) # Get BtCoil calibration factor
print('BtCoil calibration factor K_BtCoil: {} T/(Vs)'.format(K_BtCoil))
BtCoil calibration factor K_BtCoil=70.42 T/(Vs)
```

```
In [14]: BT = pd.Series(integrate.cumtrapz(dBt, axis=dBt.index, initial=0) * K_BtCoil,
index=dBt.index, name='Bt')
ax = BT.plot(grid=True)
show_plasma_limits()
ax.set(xlabel='Time [s]', ylabel='Bt [T]', title='Toroidal magnetic field Bt ts #{}'.format(shot_no));
```

```
Out[14]: [Text(0.5, 0, 'Time [s]'),
Text(0, 0.5, 'Bt [T]',
Text(0.5, 1.0, 'Toroidal magnetic field Bt ts #39187')]
```



Total current I_{ch+p}



Basic diagnostics - numerical processing, U_{ch+p}

Chamber (+ Plasma) current I_{p+ch} calculation

The Rogowski coil around the chamber measures the total current contained within its boundaries. Therefore, if there is plasma, it measures the sum of the plasma and chamber currents. In a vacuum discharge it measures only the chamber current.

Check the data availability

Because it is a magnetic measurement, the raw data only gives $\frac{dI_{p+ch}}{dt}$

```
In [131]: dIpcch = read_signal(shot_no, 'RogCoil') # 5000 horizontal for now
if dIpcch[0] == 0:
    dIpcch *= 1 # zero positive
dIpcch = correct_bias(dIpcch)
dIpcch = dIpcch[scf(First_s),:max()] # subtract offset
dIpcch[0] = 0
ax = dIpcch.plot(grid=True)
show plasma limits()
ax.set(xlabel='Time [s]', ylabel='dIpcch [A/s]', title='RogowskiCoil_raw signal_#%d'.format(shot_no))
```

Integration (it is a magnetic diagnostic) & calibration

```
In [130]: K_RogowskiCoil = float(read_parameter(shot_no, 'SystemParameters/K_RogowskiCoil')) # Get RogowskiCoil calibration factor
print('RogowskiCoil calibration factor: K_RogowskiCoil=%f A/V' % K_RogowskiCoil)
In [132]: Ipcch = pd.Series(integrate.cumtrapz(dIpcch, x=dIpcch.index, initial=0) * K_RogowskiCoil,
                          x=dIpcch.index, name='Ipcch')
ax = Ipcch.plot(grid=True)
show plasma limits()
ax.set(xlabel='Time [s]', ylabel='Ipcch [A]', title='Total (plasma+chamber) current_#%d'.format(shot_no))
```

Chamber current I_{ch} calculation

```
In [133]: R_chamber = float(read_parameter(shot_no, 'SystemParameters/R_chamber')) # Get Chamber resistivity
print('Chamber resistivity R_chamber=%f Ohm' % R_chamber)
Chamber resistivity R_chamber=0.007 Ohm
In [134]: I_chamber = float(read_parameter(shot_no, 'SystemParameters/I_chamber')) # Get Chamber inductance
print('Chamber inductance L_chamber=%f format(shot_no))
Chamber inductance L_chamber=4e-06 H
```

```
In [131]: for i in range(1, len(shots)):
ax = I.plot(i)
ax.legend()
show plasma limits(i)
ax.set(xlabel='Time [s]', ylabel='I [A]', title='estimated chamber current and measured total')
plt.grid(i)
```

Plasma current I_p calculation

If there is plasma, the plasma current can be estimated as the difference between the total measured current and the estimated chamber current $I_p = I_{p+ch} - I_{ch}$

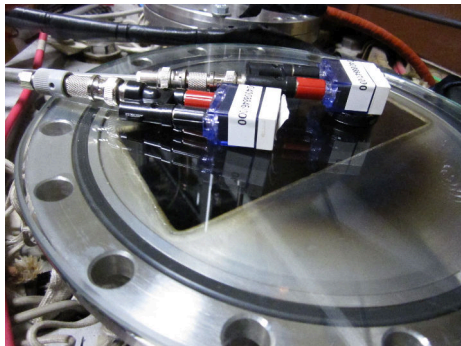
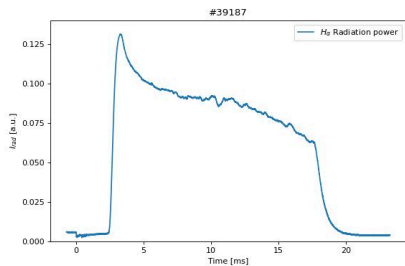
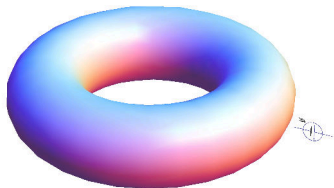
```
In [122]: if is_plasma:
    Ip_name = Ipcch - loop_voltage/R_chamber # creates a new Series
    Ip = Ipcch - I_ch
    Ip.name = 'Ip'
    Ip.name.plot(grid=True, label='naive Ii (ch)+Ii (ch)')
    ax = Ip.plot(grid=True, label='using SQ_L = R_chamber * I_ch + L_ch / (rcdch)dt')
    ax.legend()
    show plasma limits()
    ax.set(xlabel='Time [s]', ylabel='Ip [A]', title='Plasma current Ii (pp)=%d'.format(shot_no))
else:
    Ip = Ipcch * 0 # no current
    heating
```

Out[122]: Plasma detected

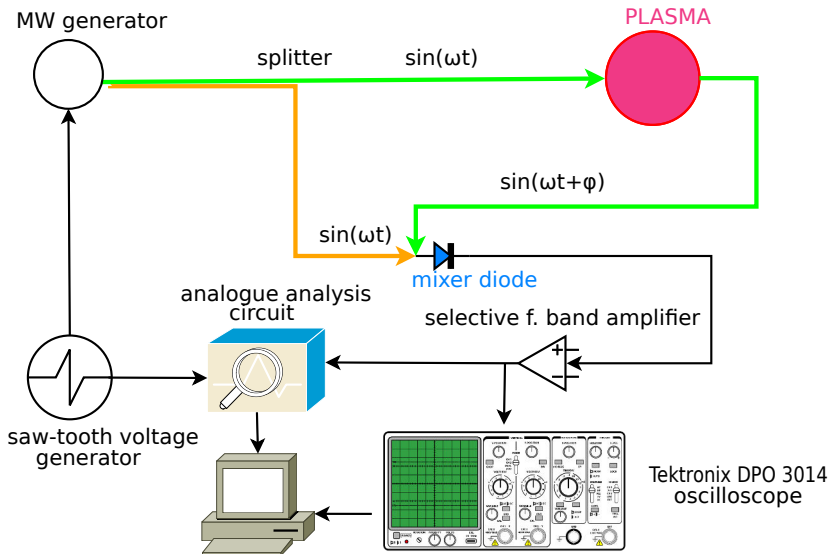
plasma lifetime of 15.1 ms, from 2.5 ms to 17.6 ms

```
In [131]: fig = plt.figure(dpi=200)
for i in range(1, len(shots)):
    ax = I.plot(i)
```

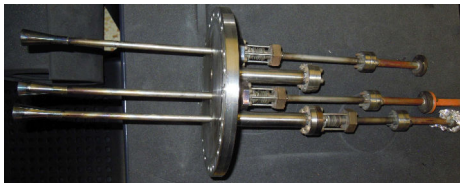
Visible radiation



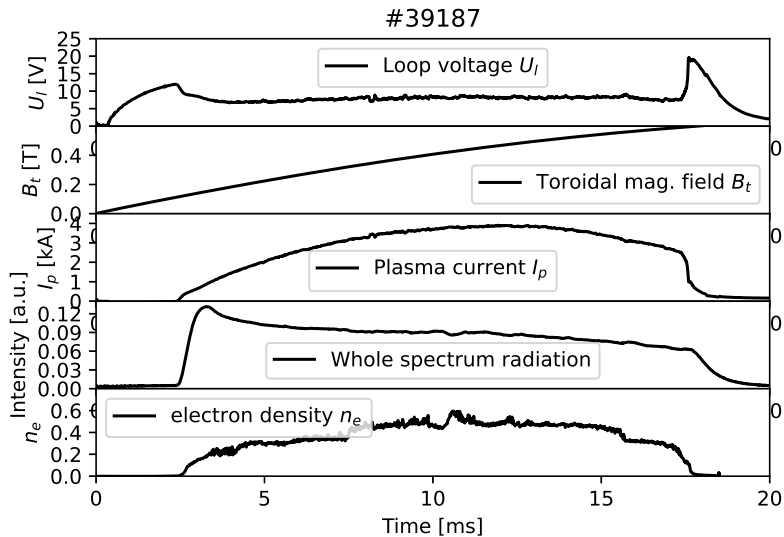
Electron density n_e interferometry measurement scheme



The GOLEM tokamak interferometry HW




Finally "Typical", well executed discharge @ GOLEM



Shot homepage (≈ 2 minutes after discharge execution)

GOLEM # Shot #40631
autoreload



Diagnostics

BasicDiagnostics
DoubleRakeProbe
Interferometry
LimiterFlareCoils
ScribbleProbes

Other

View Showroom

Navigation

Next
Previous
Current

Go to shot
40631

Golem utils

Home
Plot data
Shot interval plot
Manipulators control

Database operations

Shots listing
Shots filtering

Tokamak GOLEM - Shot Database - #40631

The date of discharge execution 23-02-07 17:23:54

The session mission 1Final -> Dringent service

The session ID 40605

The discharge comment Rake probe 50mm

Discharge command

```

jDringent.sh --discharge --UBt 800 --Tbt 0 --Utd 450 --Tod 500 --preionization 1 --gas H --pre
issue 15 --diagnostics.limiterflarescoils.vacuum_shot=40615F --discharge.preionization "m
in_switch=on;radial_heater=80;powsupp_accel=100" --infrastructure.position_stabilization
"main_switch=on;radial_switch=on;vertical_waveform=1000,0.8000,-20,10000,-25,12000,-
10,30000,0;vertical_switch=on;radial_waveform=2000,0.3000,0.7000,-20,9500,-25,10000,-
20,30000,2,25000,0" --ScanDefinition 40625 40629F --comment "Rake probe 50mm"
                    
```

[Shot Logbook]

Technological parameters

- Working Gas: $P_{discharge, before} = 2.46$ mPa; $P_{discharge, pre} = 5.04$ mPa ($P_{WG}^{response} = 15$ mPa @ $\Delta T_{WG}^{response} = 4$ H)
- Toroidal magnetic field: $U_{B_t}^{response} = 800$ V @ $I_{B_t}^{response} = 0.0$ us
- Current drive field: $U_{Ecu}^{response} = 450$ V @ $I_{Ecu}^{response} = 500.0$ us











Plasma:

- Plasma: yes or no:
- Time parameters: $\Delta t_p = 10.88$ ms ($t_{rom_start} = 2.67$ ms, $t_{rom_end} = 13.54$ ms)

Plasma parameters:

- Loop voltage: $U_{loop} = 6.82$ V; $max_{T_{loop}}(I_{discharge}) U_{loop} = 16.17$ V; $U_{inductance} = 0.00$ V
- Toroidal magnetic field: $B_t = 0.24$ T; $max_{T_{loop}}(I_{discharge}) B_t = 0.36$ T
- Plasma current: $I_p = 2.28$ kA; $max_{T_{loop}}(I_{discharge}) I_p = 2.92$ kA; $t_p^{max} = 0.00$ ms

On stage diagnostics

Data flow	measurement	digitization	analysis	Analysis results
Name	Experiment setup	Data acquisition system	Raw data	Analysis results
<p>Basic Diagnostics</p> 				
<p>Double rake probe</p> 				<p>Without Analysis</p> 

Basic Diagnostics



The figure displays three vertically stacked plots showing diagnostic data over a 25 ms interval. The top plot shows the voltage $U[V]$ (0 to 12) with a sharp peak at approximately 14 ms. The middle plot shows the current $I[kA]$ (0 to 0.8) increasing linearly from 0 to about 0.6 kA. The bottom plot shows the magnetic field $B_t [mT]$ (0 to 2.2) with a peak at approximately 14 ms. Vertical dashed lines indicate specific time points in the discharge.

Table of Contents

- 1 Introduction
- 2 The Tokamak (GOLEM)
- 3 The Tokamak GOLEM (remote) operation**
- 4 Conclusion
- 5 Appendix

Table of Contents

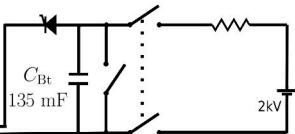
- 1 Introduction
- 2 The Tokamak (GOLEM)
- 3 The Tokamak GOLEM (remote) operation**
 - Control room
 - Data handling @ the Tokamak GOLEM
- 4 Conclusion
- 5 Appendix

Tokamak GOLEM - schematic experimental setup

Preionization (electron gun)

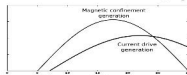
→ $S/W_{\text{preion}} \in \langle \text{on} \dots \text{on} \dots \text{off} \rangle [-]$

Magnetic confinement B_t generation

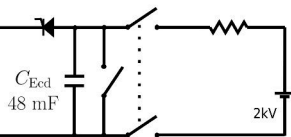


→ $U_{B_t} \in \langle 200 \dots 800 \dots 1300 \rangle [V]$

Trigger sequence



Current drive E_{cd} generation



→ $U_{E_{cd}} \in \langle 200 \dots 450 \dots 700 \rangle [V]$

→ $t_{E_{cd}} \in \langle 0 \dots 1000 \dots 10000 \rangle [\mu s]$

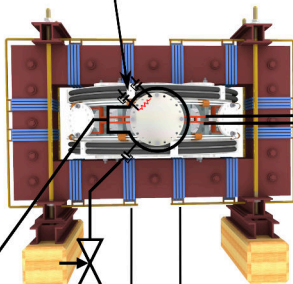
Vacuum stand



GAS handling



→ $p_H \in \langle 0 \dots 10 \dots 40 \rangle [\text{mPa}]$



Remote control interface of the GOLEM tokamak

GOLEM remote Introduction Control room Live Results top navigation bar User B Access: Level 2 Help

Introduction Working gas Preionization Magnetic field Electric field Submit rendering settings

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

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

Toroidal magnetic field

Toroidal electric field

GAS handling H_2/He

Gas type and pressure $p_{WG} = 16 \text{ mPa}$

Hydrogen Helium

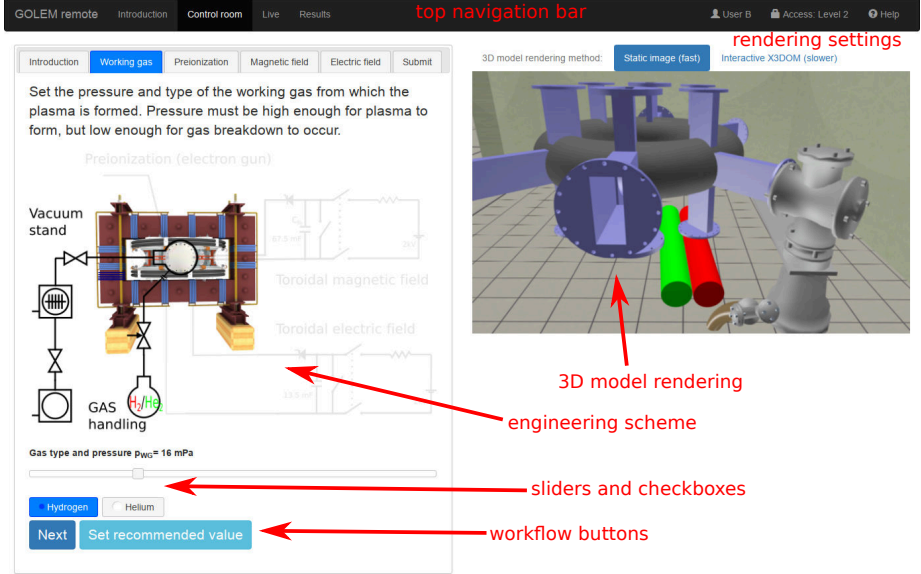
Next Set recommended value

3D model rendering

engineering scheme

sliders and checkboxes

workflow buttons



The image displays the remote control interface for the GOLEM tokamak. At the top, a navigation bar includes 'GOLEM remote', 'Introduction', 'Control room', 'Live', and 'Results'. The 'Control room' section is active, showing a 'top navigation bar' with 'Introduction', 'Working gas', 'Preionization', 'Magnetic field', 'Electric field', and 'Submit'. The 'Working gas' tab is selected, displaying instructions: '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.' Below this is a schematic diagram of the tokamak system, including a 'Vacuum stand', 'Preionization (electron gun)', 'GAS handling' (with H_2/He gas), 'Toroidal magnetic field', and 'Toroidal electric field'. A '3D model rendering' of the tokamak components is shown on the right, with a red arrow pointing to it. The rendering is labeled '3D model rendering' and 'engineering scheme'. The 'rendering settings' section shows '3D model rendering method' with options 'Static image (fast)' and 'Interactive X3DOM (slower)'. Below the diagram, there are 'sliders and checkboxes' for 'Gas type and pressure $p_{WG} = 16 \text{ mPa}$ ', with radio buttons for 'Hydrogen' (selected) and 'Helium'. At the bottom, there are 'workflow buttons' for 'Next' and 'Set recommended value'.

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_c 2kV

11.3 mF C_d 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

Toroidal magnetic field

Toroidal electric field

GAS handling

H_2/H_8

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 mT 20V

13.5 mV 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

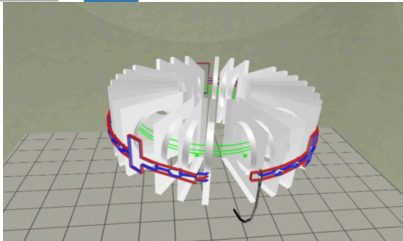
Toroidal magnetic field

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.

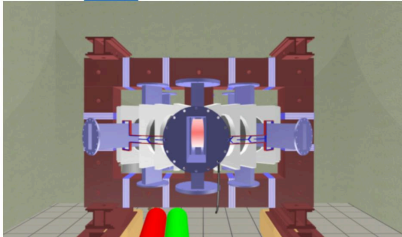
Comment

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 (≈ 2 minutes after discharge execution)

GOLEM # Shot #40631
autoreload



Diagnostics

- BasicDiagnostics
- DoubleRakeProbe
- Interferometry
- LimitersV coils
- ScintillationProbes

Other

- Web
- Showroom

Navigation

- Next
- Previous
- Current

Go to shot

40631

GOLEM utils

- Home
- Plot data
- Shot retrieval plot
- Manipulators control

Database operations

- Shots listing
- Shots filtering

Tokamak GOLEM - Shot Database - #40631

The date of discharge execution 23-02-07 17:23:54

The session mission 1Final -> Dringent service

The session ID 40605

The discharge comment Rake probe 50mm

Discharge command

[Shot Logbook]

```

jDringent.sh --discharge --UBt 800 --Tbt 0 --Utd 450 --Tod 500 --preionization 1 --gas H --pre
issue 13 --diagnostics.limitersmvcoils "vacuum_shot=40615" --discharge.preionization "m
in_switch=on;radial_heater=80;powsupp_accel=100" --infrastructure.position_stabilization
"main_switch=on;radial_switch=on;vertical_waveform=1000,0.8000,-20,10000,-25,12000,-
10,30000,0;vertical_switch=on;radial_waveform=2000,0.3000,0.7000,-20,9500,-25,10000,-
20,30000,2,25000,0" --ScanDefinition "40625 40629" --comment "Rake probe 50mm"
                    
```

Technological parameters

- Working Gas: $P_{discharge, before} = 2.46$ mPa; $P_{discharge, pre} = 5.04$ mPa ($P_{WG}^{response} = 15$ mPa @ $\Delta P_{WG}^{response} = H$)
- Toroidal magnetic field: $U_{B_t}^{response} = 800$ V @ $I_{B_t}^{response} = 0.0$ us
- Current drive field: $U_{Ecd}^{response} = 450$ V @ $I_{Ecd}^{response} = 500.0$ us











Plasma:

- Plasma: yes or no:
- Time parameters: $\Delta t_p = 10.88$ ms ($t_{rom_start} = 2.67$ ms, $t_{rom_end} = 13.54$ ms)

Plasma parameters:

- Loop voltage: $U_{loop} = 6.82$ V; $max_{T_{loop}}(I_{discharge}) U_{loop} = 16.17$ V; $U_{breakdown} = 0.00$ V
- Toroidal magnetic field: $B_t = 0.24$ T; $max_{T_{loop}}(I_{discharge}) B_t = 0.36$ T
- Plasma current: $I_p = 2.28$ kA; $max_{T_{loop}}(I_{discharge}) I_p = 2.92$ kA; $t_p^{max} = 0.00$ ms

On stage diagnostics

Data flow	measurement	digitization	analysis	Analysis results
Name	Experiment setup	Data acquisition system	Raw data	Analysis results
Basic Diagnostics 				
Double rake probe 				Without Analysis 

Basic Diagnostics


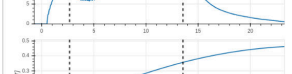
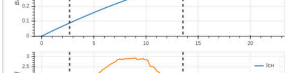




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 - Control room
 - Data handling @ the Tokamak GOLEM
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GOLEM basic Data Acquisition System (DAS)

- $U_I, U_{B_t}, U_{I_{p+ch}}, I_{rad}$
- $\Delta t = 1\mu s / f = 1MHz$.
- 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)

```
import numpy as np
import matplotlib.pyplot as plt

shot_no = 39187
identifier = "U_loop.csv"
DAS='Diagnostics/BasicDiagnostics/Results/'
# 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/shots/"
data_file = ds.open(base_url + str(shot_no)+ '/' +DAS +identifier)
#Load data from the file and plot to screen and to disk
data = np.loadtxt(data_file,delimiter=",")
plt.title('#'+str(shot_no))
plt.plot(data[:,0]*1000, data[:,1]) #1. column vs 2. column
plt.xlabel('Time [ms]');plt.ylabel('$U_1$ [V]');
plt.savefig('graph.jpg')
plt.show()

#Run it: save it as script.py and run "python script.py" or execute in a
```

Matlab

```
ShotNo=39187
baseURL='http://golem.fjfi.cvut.cz/shots/';
diagnPATH='/Diagnostics/BasicDiagnostics/Results/U_loop.csv';
%Create a path to data
dataURL=strcat(baseURL,int2str(ShotNo),diagnPATH);
% Write data from GOLEM server to a local file
urlwrite(dataURL,'LoopVoltage');
% Load data
data = load('LoopVoltage', '\t');
% Plot and save the graph
f = figure('visible', 'off');
hold on
plot(data(:,1)*1000, data(:,2), '.');
xlabel('Time [ms]')
ylabel('U_1 [V]')
hold off
print -djpeg plot.jpg
close(f)
exit;
```

Octave

```
ShotNo=39187
baseUrl='http://golem.fjfi.cvut.cz/shots/';
diagnPATH='/Diagnostics/BasicDiagnostics/Results/U_loop.csv';
%Create a path to data
dataURL=strcat(baseUrl,int2str(ShotNo),diagnPATH);
% Write data from GOLEM server to a local file
urlwrite(dataURL,'U_Loop.csv');
% Load data
data = load('U_Loop.csv', '\t');
% Plot and save the graph
plot(data(:,1)*1000, data(:,2), '.');
xlabel('time [ms]')
ylabel('U_{loop} [V]')
saveas(gcf, 'plot', 'jpg');
exit;
```

Gnuplot

```
identifier = 'U_loop.csv' ;
ShotNo = '39187'
# Create a path to the data
DAS='Diagnostics/BasicDiagnostics/Results/'
baseURL='http://golem.fjfi.cvut.cz/shots/'
DataURL= baseURL.ShotNo.'/'.DAS.identifier
set datafile separator ',';
set title "Uloop for #".ShotNo;
! wget -q @DataURL ;# Write data from GOLEM erver to a local file
# Plot the graph from a local file
set xrange [0:0.02];set xlabel 'Time [s]';set ylabel 'U_1 [V]'
set terminal jpeg; plot identifier u 1:2 w l t 'Uloop'
```

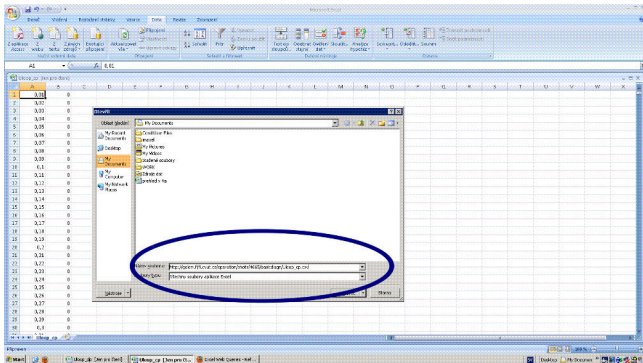
```
shot_no=39187;\
signal_id="Diagnostics/BasicDiagnostics/Results/U_loop.csv";\
gnuplot -p -e "set title \"Golem\";set datafile separator \",\";\
set xlabel \"t [s]\";set ylabel \"U\";\
plot \"< \
wget -q -O - http://golem.fjfi.cvut.cz/shots/$shot_no/$signal_id\" \
w l t \"U\""
```

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>`

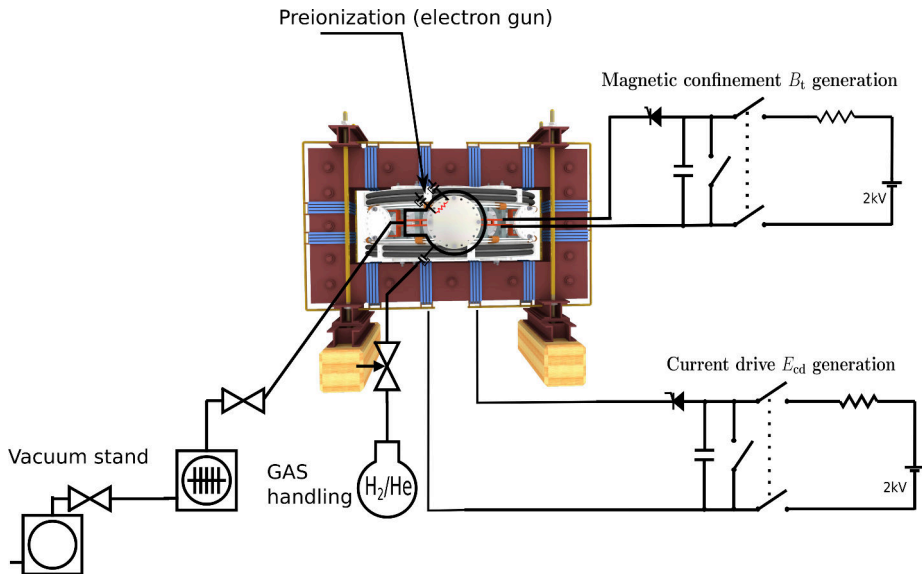
Spreadsheets (Excel and others)

are not recommended, only tolerated.

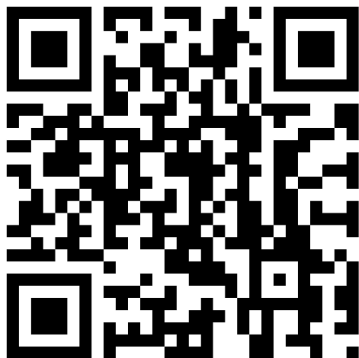
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The global schematic overview of the tokamak GOLEM experiment



- Everything via <http://golem.fjfi.cvut.cz/Eindhoven>
 - This presentation
 - Control rooms
 - Contact: Vojtech Svoboda,
+420 737673903,
vojtech.svoboda@fjfi.cvut.cz
 - Videoconference:
<https://meet.google.com/hnv-qjhu-xvi>



Acknowledgement

Financial support highly appreciated:

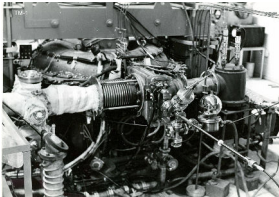
CTU RVO68407700, SGS 17/138/OHK4/2T/14, GAČR GA18-02482S, EU funds CZ.02.1.01/0.0/0.0/16_019/0000778 and CZ.02.2.69/0.0/0.0/16_027/0008465, IAEA F13019, FUSENET and EUROFUSION.

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 Čerovský, 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



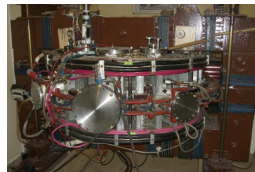
SCIENCE

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 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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References I

-  Wikipedia contributors. Golem — Wikipedia, the free encyclopedia. <https://en.wikipedia.org/w/index.php?title=Golem>, 2020. [Online; accessed 29-March-2020].
-  Brotankova, J. *Study of high temperature plasma in tokamak-like experimental devices*. PhD thesis, 2009.
-  Tokamak GOLEM contributors. Tokamak GOLEM at the Czech Technical University in Prague. <http://golem.fjfi.cvut.cz>, 2007. [Online; accessed March 25, 2025].
-  J. Wesson. *Tokamaks*, volume 118 of *International Series of Monographs on Physics*. Oxford University Press Inc., New York, Third Edition, 2004.

References II



-  **Wikipedia contributors.** Lawson criterion — Wikipedia, the free encyclopedia. https://en.wikipedia.org/w/index.php?title=Lawson_criterion&oldid=888000448, 2019. [Online; accessed 6-December-2019].
-  **ITER contributors .** ITER. <https://www.iter.org>, 2007. [Online; accessed 21-December-2018].

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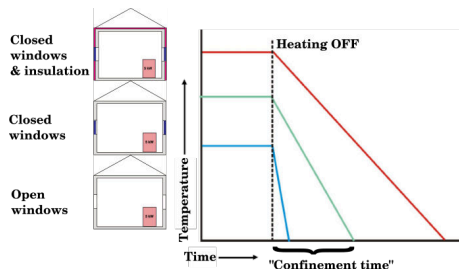
4 Conclusion

5 Appendix

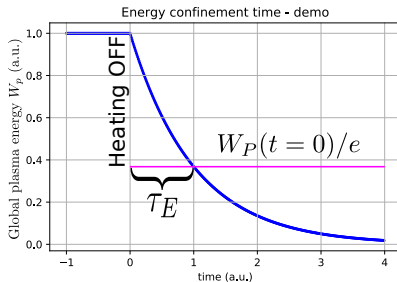
- The Electron energy confinement time calculation (rough estimation)
- A small note on magnetic measurements
- Few moments from the tokamak GOLEM history

Towards ... Energy confinement time

House



Tokamak



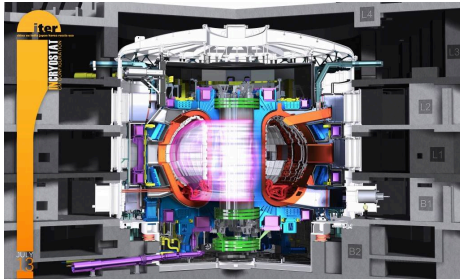
- Net power = Efficiency \times (Fusion - Radiation loss - Conduction loss)
- The confinement time: $\tau_E = \frac{W}{P_{\text{loss}}}$
- Energy density $W = 3nk_B T$ & rate of radiation and conduction energy loss per unit volume P_{loss}
- Reactions per volume per time of fusion reactions is:
 $f = n_d n_t \langle \sigma v \rangle = \frac{1}{4} n^2 \langle \sigma v \rangle$
- Fusion heating fE_{ch} , where $E_{\text{ch}} = 3.5 \text{ MeV}$ should exceed 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 $\approx 26 \text{ keV}$)

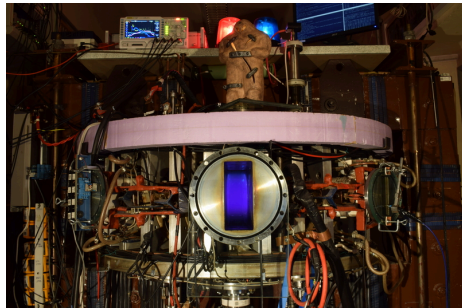
The competition

The ITER: 3.6 s



credit:[6]

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



credit:[3]

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_{Loss}

$$P_H = \frac{dW_p}{dt} + P_{Loss}$$

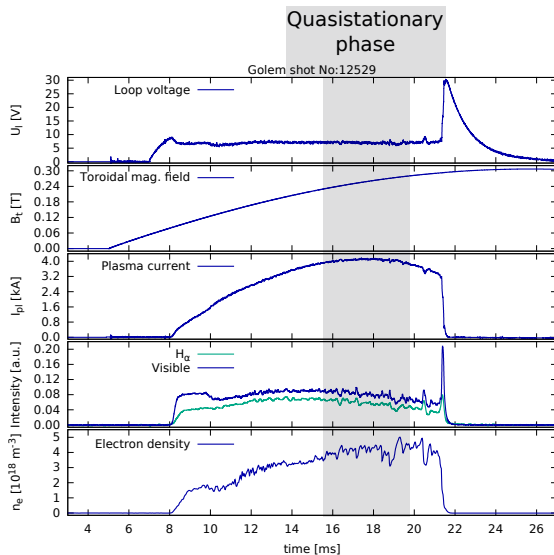
The energy confinement time is defined as the characteristic time scale of the exponential decay of the plasma energy W_p due to the loss power P_{Loss} :

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

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)

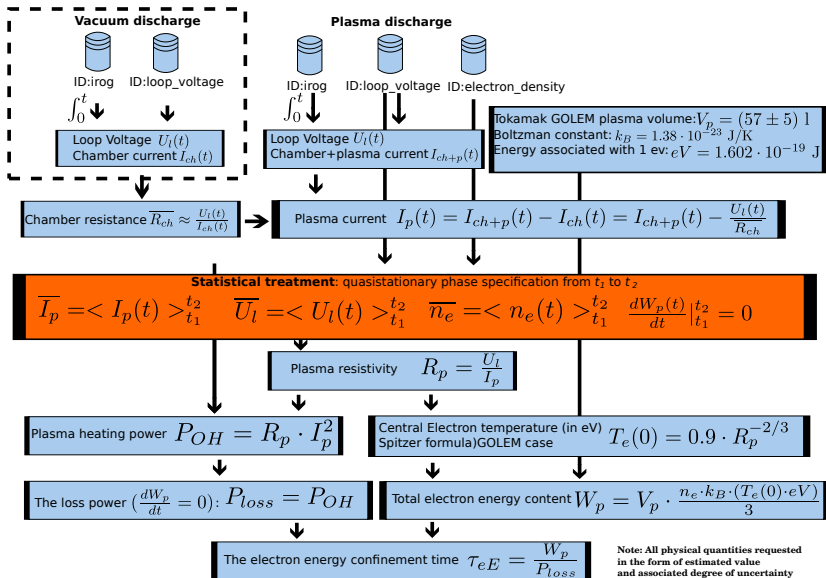
The time evolution of the central electron temperature $T_e(0, t)$ is calculated from equation based on Spitzer's resistivity formula (see eg. [2],[4]):

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

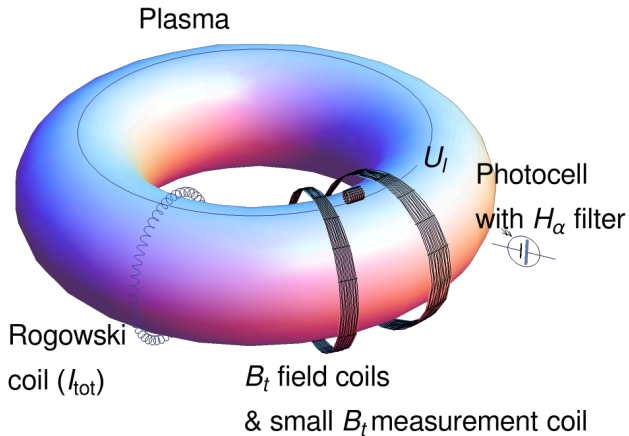
For particular case of the GOLEM tokamak it says:

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

Towards Electron energy confinement time τ_E



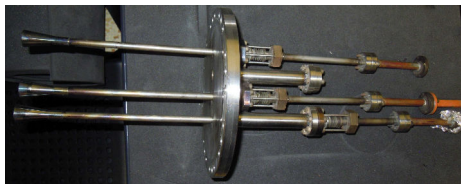
The GOLEM tokamak - standard diagnostics



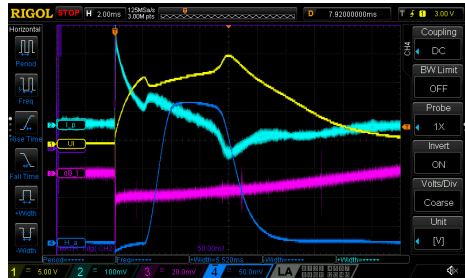
Hands on the GOLEM tokamak - equipment



The GOLEM tokamak interferometry HW



Vacuum x Plasma discharge @ Oscilloscope



Vacuum x Plasma shot

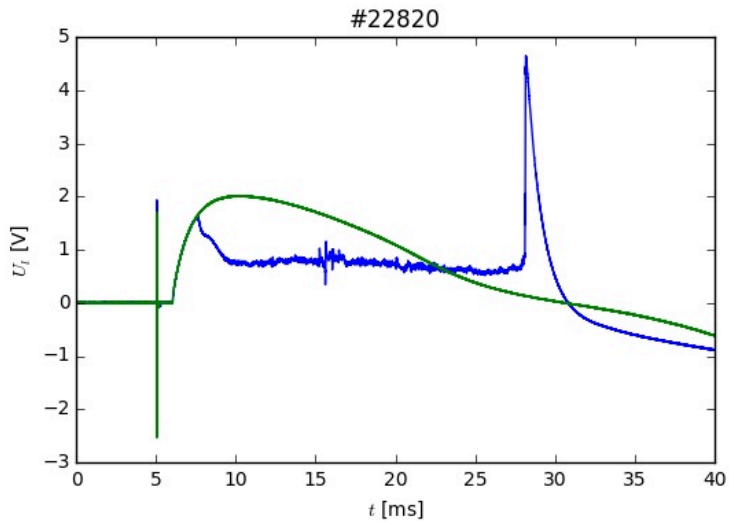


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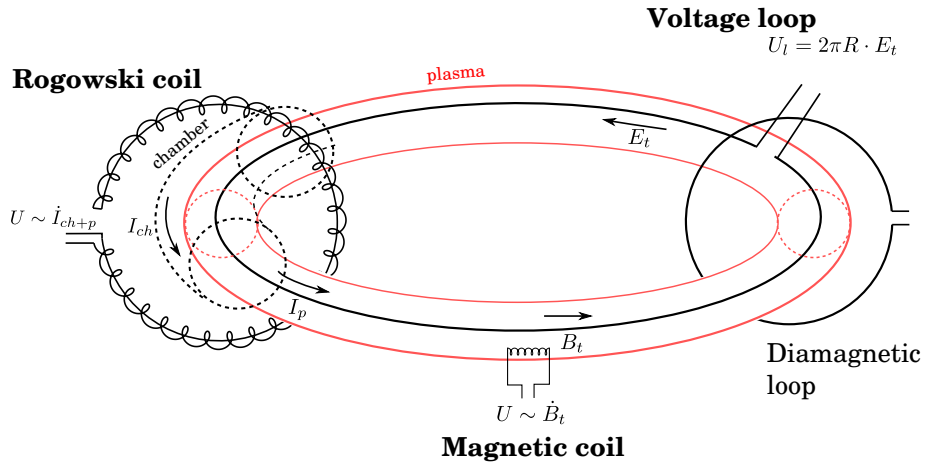
3 The Tokamak GOLEM (remote) operation

4 Conclusion

5 Appendix

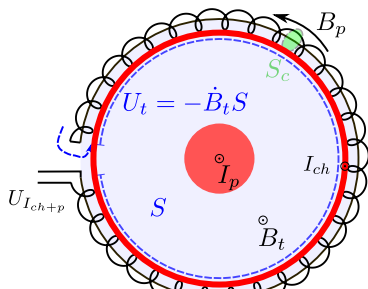
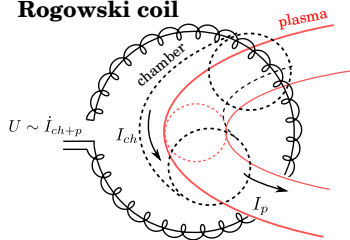
- The Electron energy confinement time calculation (rough estimation)
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Schematic of electromagnetic diagnostics



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-wounded 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:

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

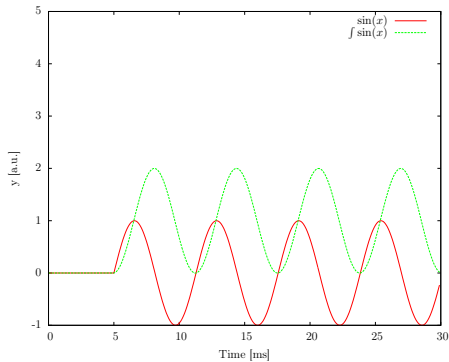
- In reality, the measurement is not continuous. The system performs a series of measurements U_i separated by with time step $\Delta t = 1 \text{ us}$.
- In practice, we replace the integral by a sum:

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

- 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}

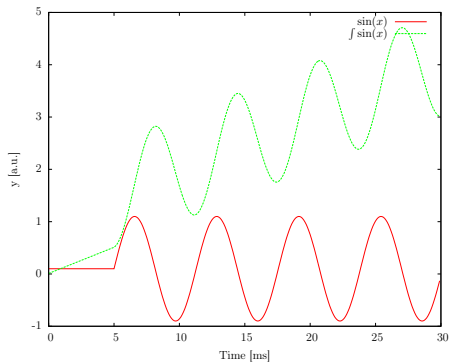


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1 Introduction

2 The Tokamak (GOLEM)

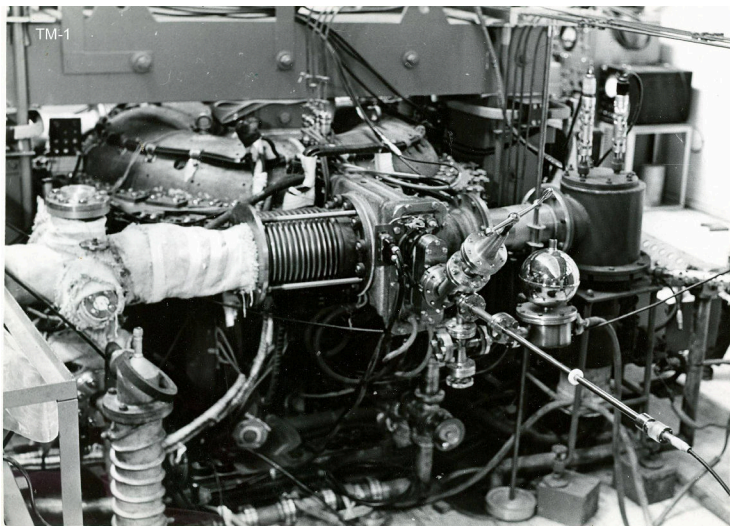
3 The Tokamak GOLEM (remote) operation

4 Conclusion

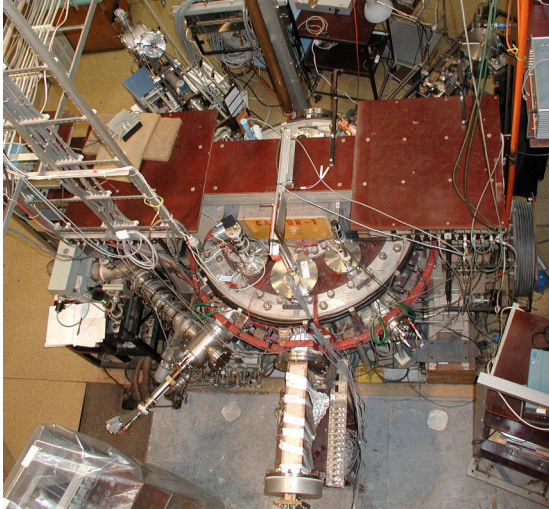
5 Appendix

- The Electron energy confinement time calculation (rough estimation)
- A small note on magnetic measurements
- Few moments from the tokamak GOLEM history

XX/YY: TM-1



XX/YY: CASTOR



12/07: Last minutes at the IPP Prague

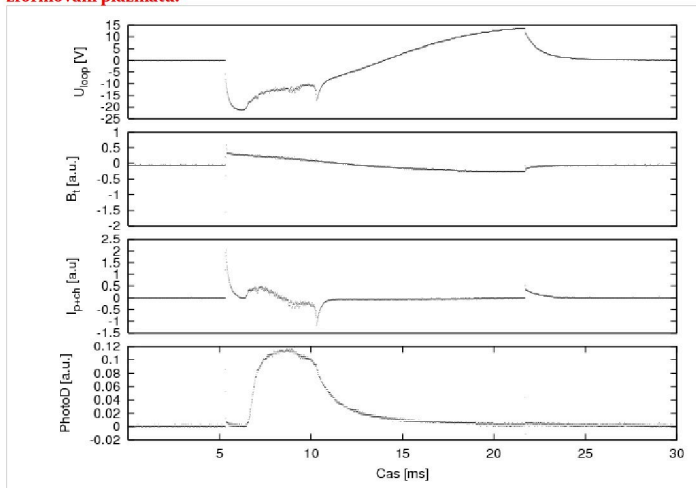


12/07: First minutes at the CTU Prague



07/09: First plasma in the tokamak GOLEM

Časové průběhy signálů zřetelně ukazují, že došlo k průrazu neutrálního plynu a k zformování plazmatu.



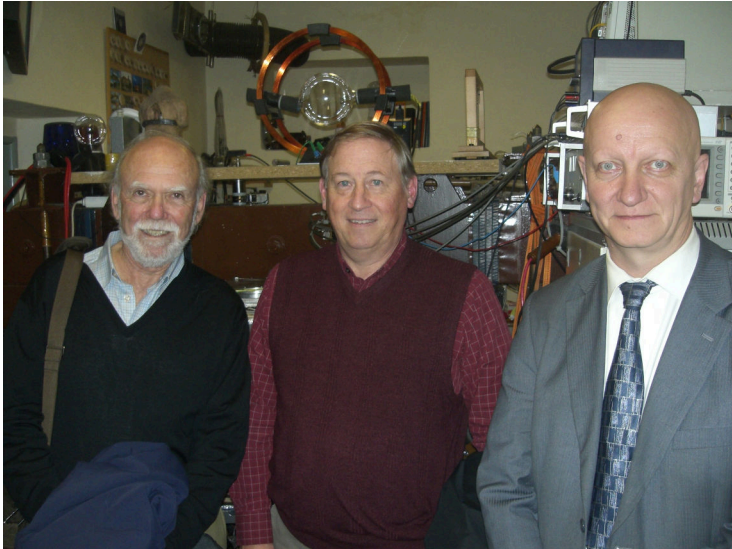
O tom svědčí:

1. Rychlý pokles napětí na závit v čase $t = 6-7$ ms a jeho malé fluktuační, které lze vidět až

09/09: Tokamak and tokamak



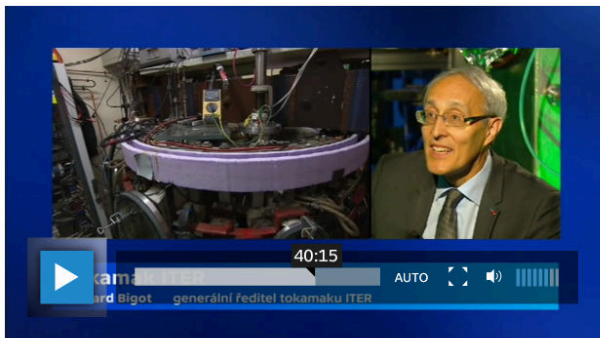
11/11: NP laureat at tokamak GOLEM



05/16: The youngest tokamak (GOLEM) operator, Adam (7 years).



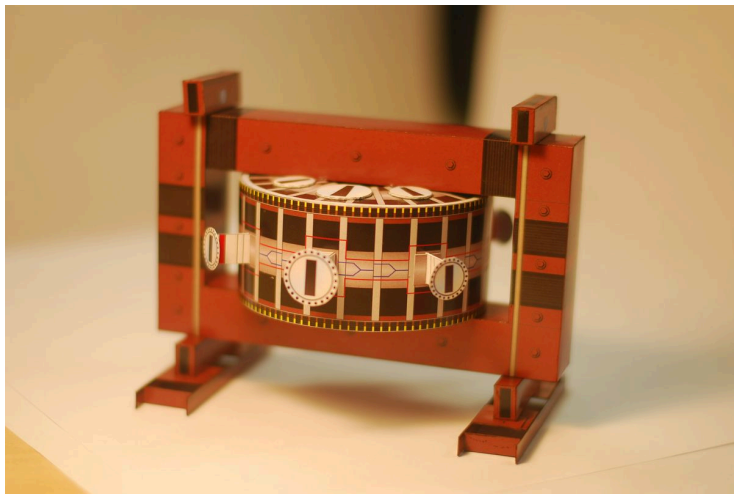
0916: ITER DG, Mr. Bernard Bigot (Shot #22185)



Quotation from Czech Television Hydepark

I am very pleased with the GOLEM ...

09/19 Paper model ABC



2010: Tokamak GOLEM



2011: The tokamak COMPASS with NBI



2016: ITER segment



2017: First Spitzer Stellarator



10/15: Trojan horse - #20000

GOLEM - Shot #20000 - previous | next | current

Tokamak GOLEM - Shot Database - 20000

Date: 2015-10-22 - 16:09:25
Session: SessionPreparation
Comment: 20k [Template source] [WebLog]

Diagnostics

- ✓ PlasmaPosition_TO
- ✗ Filers
- ✗ Spectrometer
- ✓ FastCamera
- ✓ HXR

Analysis

- ✓ HistoricalAnalysis
- ✓ ShotHomepage
- ✓ AdvancedAnalysis
- ✓ Spectrogramm_TO
- ✗ MultiCWT_TO
- ✓ MWPreparation
- ✗ Inquiries_TO

DAS

- ✓ TektronixCPO
- ✓ Pappouch_3
- ✓ Notstandard
- ✓ Pappouch_Za
- ✓ Pappouch_Sl

Vacuum log

Charging log

Other


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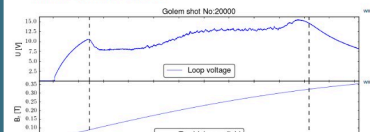
Go to shot
20000

Congratulation, you have reached nuclear fusion.
The following explosion destroyed half of Prague and radioactive fallout contaminated whole Europe.
Have a nice day



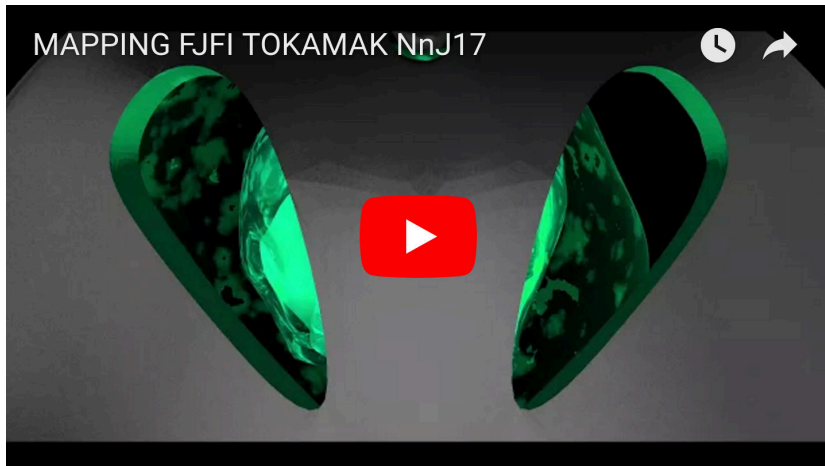
Basic parameters: (compare) **Plasma parameters:**

- Gas pressure $p_{D,20}$: 10.28 -> 15.38 mPa (request: 5 mPa) ^{Wiki}
- Working gas: H
- Preionization: Upper el. gun
- Chamber temperature: 20.00 C
- C_{B1} capacitors charged to: 1000 V, triggered 5:0.85 ^{Wiki}
- C_{B2} capacitors charged to: 0 V, triggered 5:0.85 ^{Wiki}
- C_{C2} capacitors charged to: 500 V, triggered 6:0.85 ^{Wiki}
- C_{S1} capacitors charged to: 0 V, triggered 5:0.85 ^{Wiki}
- Probability of breakdown: N/A ^{Wiki}
- Time since session beginning: 0:19:25 h
- Plasma life time t_{pl} [ms] (from 7.5 to 16.2)
- Mean toroidal magnetic field Bt: 0.22 T ^{Wiki}
- Mean plasma current: 1.42 kA ^{Wiki}
- Mean Uloop: 12.41 V ^{Wiki}
- Break down voltage: 10.5 V ^{Wiki}
- Ohmic heating power: 17.59 kW
- Q edge: 6.9 ^{Wiki}
- Electron temperature: 13.5 eV ^{Wiki}
- Line electron density: N/A [10^{17}m^{-2}] ^{Wiki}



11/17: GOLEM tokamak "mapping"

Tokamak GOLEM



Základní (řádová) statistika k 30.11.2012

Počet dní od instalace: 1815.

Počet operačních dní: ≈ 438 .

Počet hodin: ≈ 1954

Počet shotů: 10417.

Počet shotů – $>$ plazma: ≈ 7600 .

Průměrná délka výboje: ≈ 7 ms.

Celková délka trvání plazmatu: < 60 s.