

Introduction to the tokamak GOLEM operation Practical guide

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on behalf of the tokamak GOLEM team
with conceptual assistance from advanced AI tools

for Warsaw University of Technology

January 8, 2026

Outline

1 Introduction

2 The Tokamak (GOLEM)

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

3 The Tokamak GOLEM (remote) operation

- Control room
- Data handling @ the Tokamak GOLEM

4 $\tau_{E,e}$ & q

- The Electron energy confinement time calculation
- The safety factor

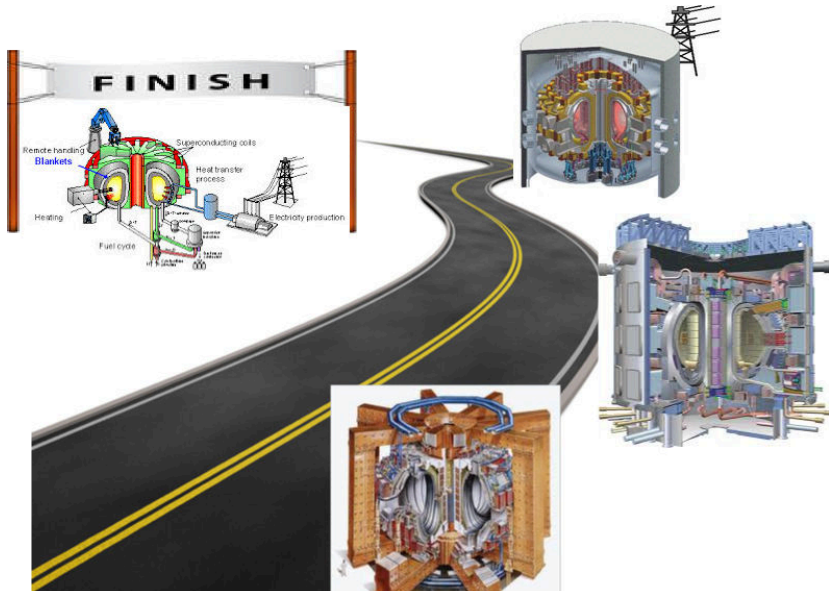
5 Conclusion

6 Appendix

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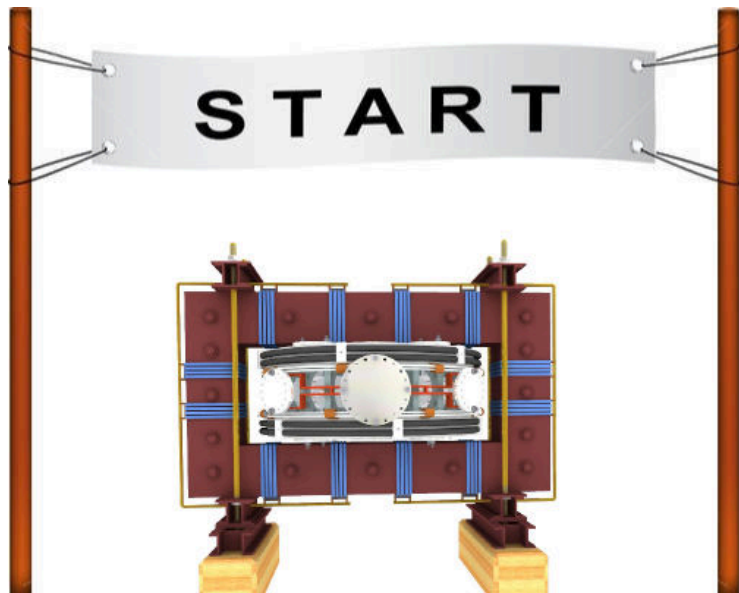
Milestones to Fusion Power Plant



Education importance



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



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



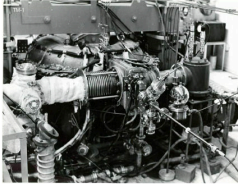
Alcator C-Mod



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

The tokamak GOLEM 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

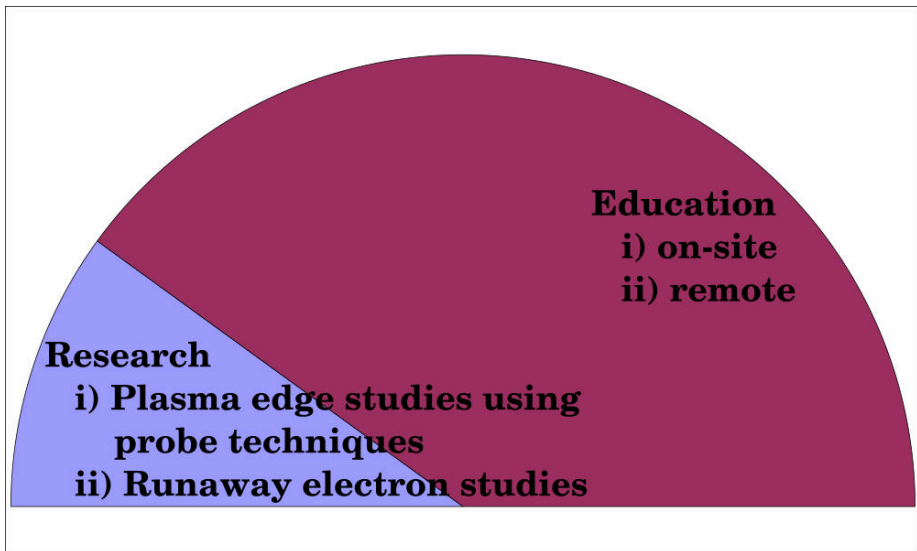
... somewhere, in the ancient cellars of Prague,

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. . .



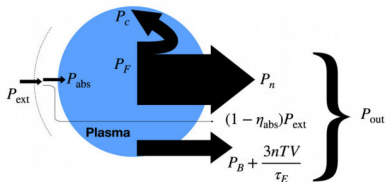
At the end of the 16th century, in the times when the Czech lands were ruled by Emperor Rudolf II, in Prague, there were Rabbi Judah Loew, well known alchemist, thinker, scholar, writer and inventor of the legendary GOLEM - a clay creature inspired with the Universe power that pursued his master's command 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. [1].

The tokamak GOLEM mission



Two key fusion technology parameters you can touch experimentally

Energy Confinement Time τ_E



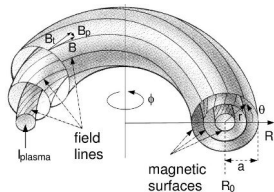
credit:[2]

- Indicates how long the plasma keeps its energy — a key fusion metric.

$$\tau_E = \frac{W_{\text{plasma}}}{P_{\text{loss}}}$$

- On tG, from energy balance, we estimate the electron component $\tau_{E,e}$ (we can measure only n_e and T_e).

Safety Factor q



credit:[3]

- Describes how magnetic field lines wind around the torus. Key stability parameter (MHD behaviour).

$$q(a) = \frac{2\pi a^2 B_t}{\mu_0 R I_p}$$

- On tG, derived from B_t and plasma current I_p .

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

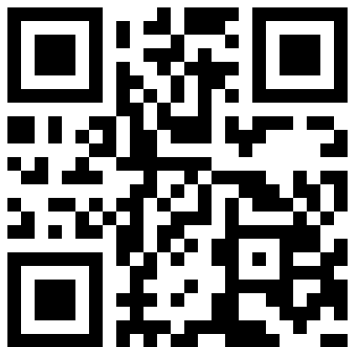
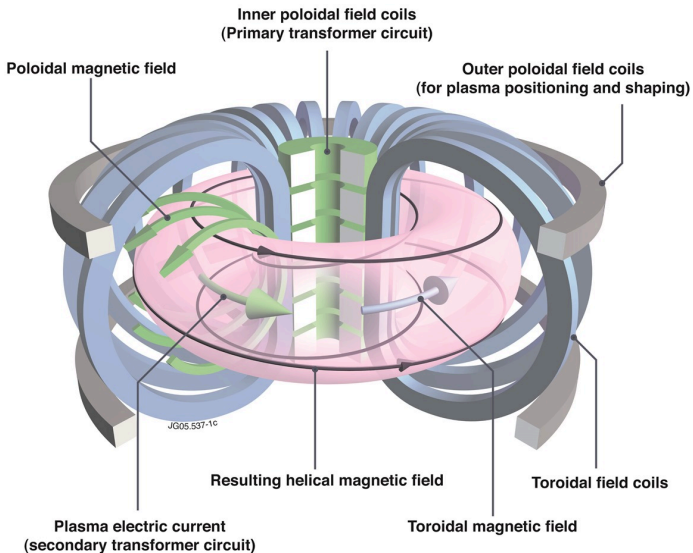


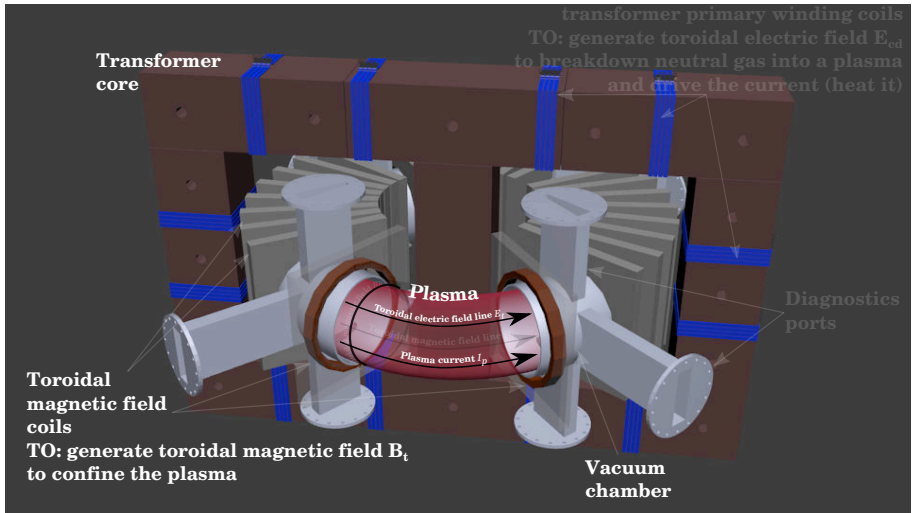
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Tokamak magnetic confinement concept

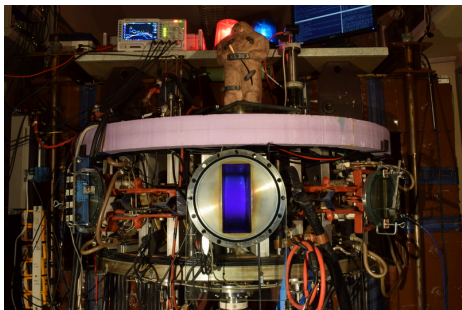


Tokamak (GOLEM) basic concept to confine and heat the plasma



The tokamak GOLEM 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:
 $I_p^{\max} < 12$ kA
- Maximum toroidal magnetic field: $B_t^{\max} < 0.7$ 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:
 $\tau_p^{\max} < 50$ ms

The global schematic overview of the tG experiment

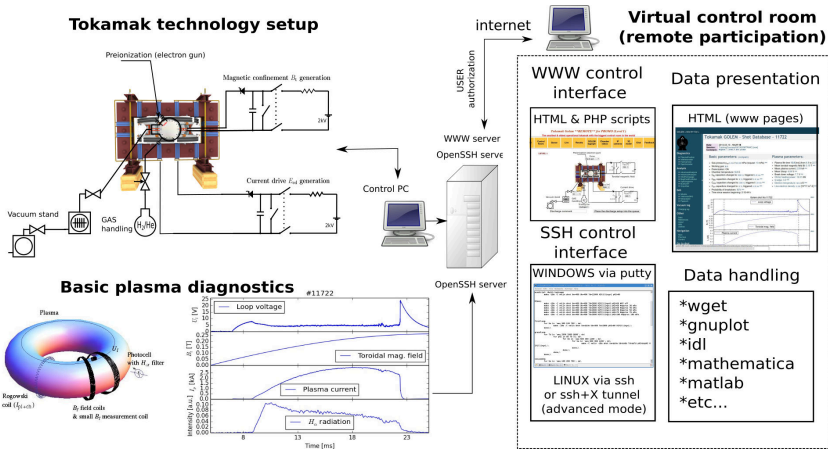


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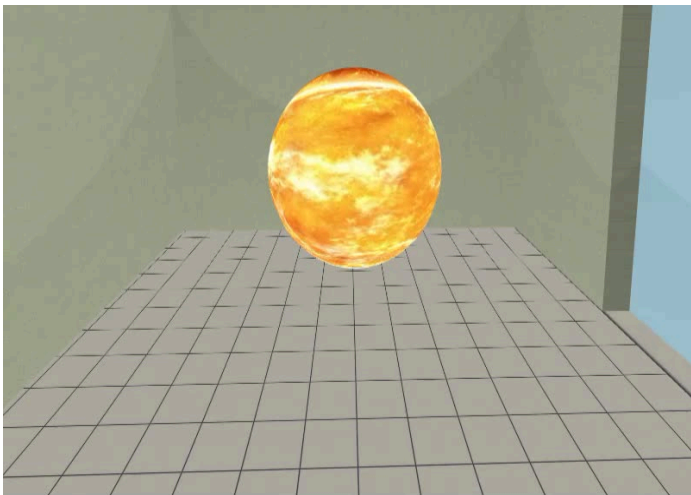
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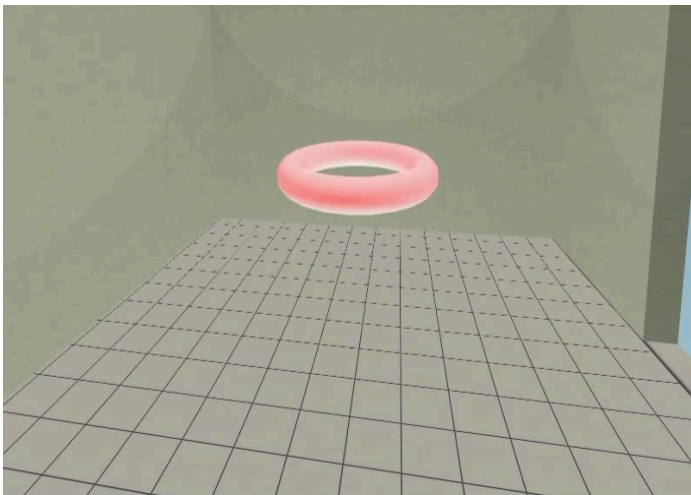
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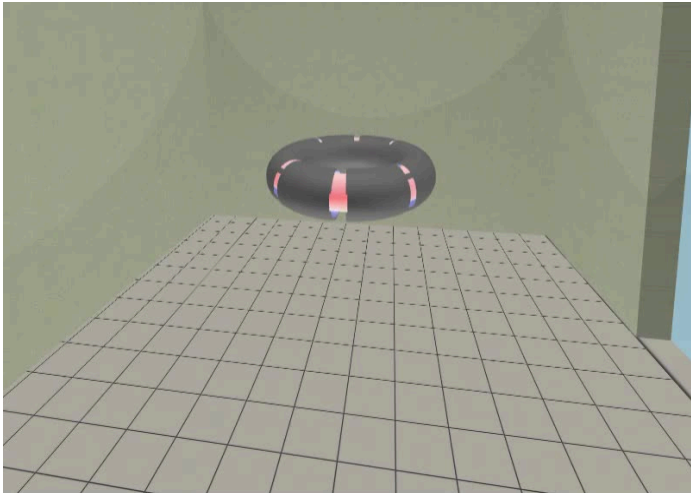
Our goal: the technology to create a μ Sun on the Earth



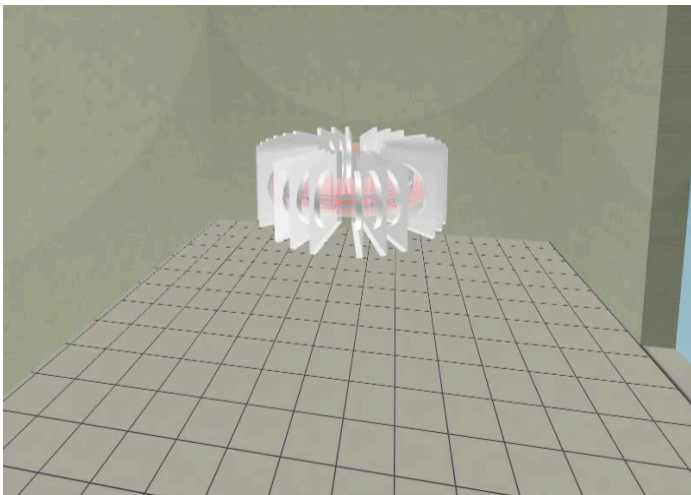
Magnetic confinement requires toroidal geometry



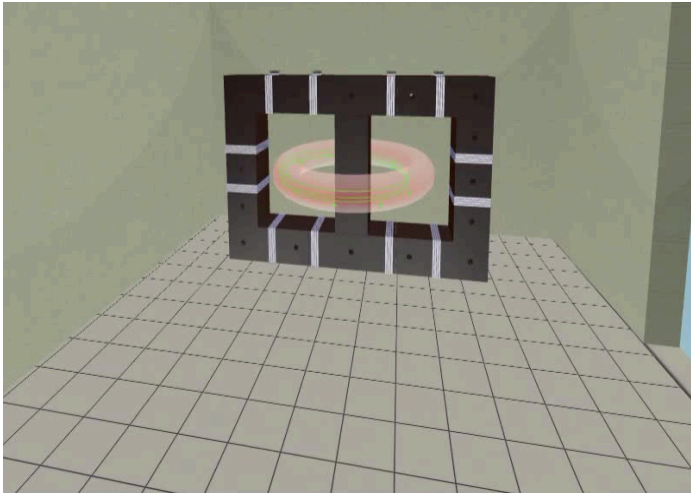
A chamber contains the thermonuclear reaction



Toroidal magnetic field coils confine the plasma



A transformer action creates and heats the plasma



The final technology altogether

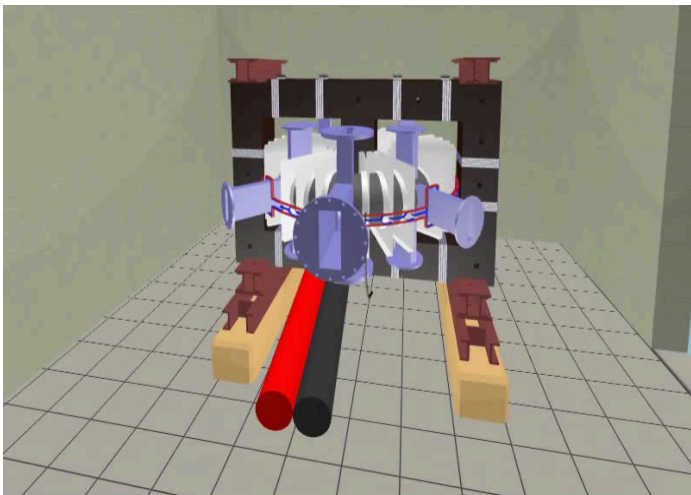


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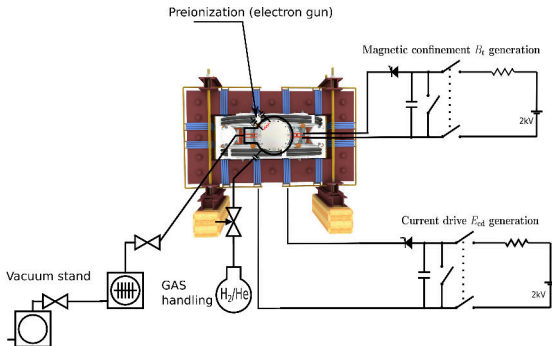
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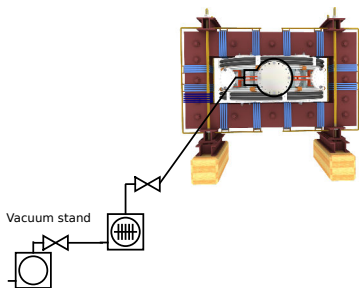
Plasma in Tokamak (GOLEM) - the least to do



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

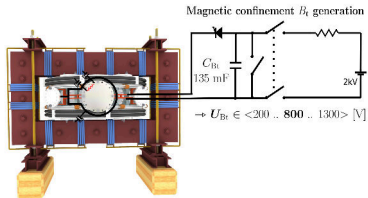
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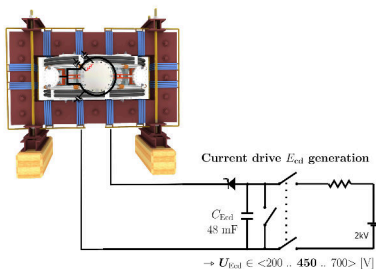
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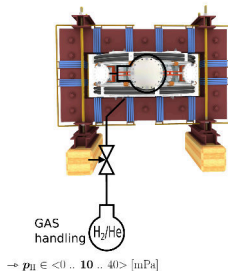
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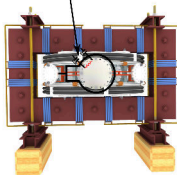
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Plasma in Tokamak (GOLEM) - the least to do

Preionization (electron gun)

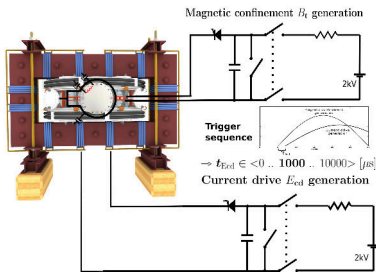
→ $S/W_{\text{preion}} \in \langle \text{on} \dots \text{off} \rangle [-]$



To do:

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

Plasma in Tokamak (GOLEM) - the least to do



To do:

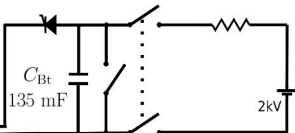
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 - Charge the capacitors
 - Fill in the working gas
 - Preionization
- discharge phase
 - **Trigger Magnetic confinement & Current drive**
 - Plasma positioning
 - Diagnostics
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 - Shot homepage creation

Tokamak GOLEM - schematic experimental setup

Preionization (electron gun)

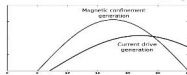
→ $S/W_{\text{preion}} \in \langle \text{on} \dots \text{on} \dots \text{off} \rangle [-]$

Magnetic confinement B_t generation

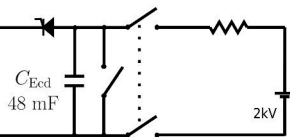


→ $U_{B_t} \in \langle 200 \dots 800 \dots 1300 \rangle [V]$

Trigger sequence



Current drive E_{cd} generation



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

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

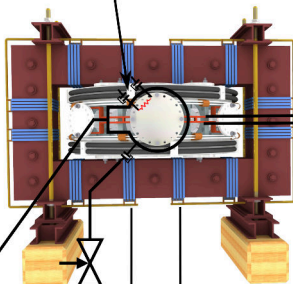
Vacuum stand



GAS handling



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



Remote control interface of the GOLEM tokamak

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

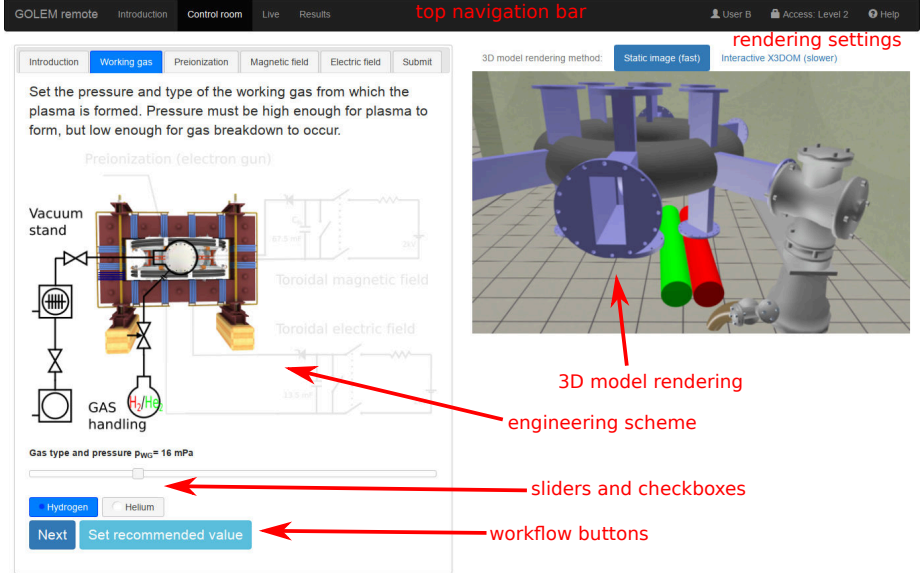
Next Set recommended value

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 'Working gas' configuration panel. This panel includes a schematic diagram of the tokamak's gas handling system, with labels for 'Preionization (electron gun)', 'Vacuum stand', 'Toroidal magnetic field', 'Toroidal electric field', and 'GAS handling'. Below the diagram, there are controls for 'Gas type and pressure $p_{WG} = 16 \text{ mPa}$ ', a slider, radio buttons for 'Hydrogen' and 'Helium', and 'Next' and 'Set recommended value' buttons. To the right, a 'rendering settings' panel shows a 3D model rendering of the tokamak's internal structure, with a red arrow pointing to it. The rendering is labeled '3D model rendering' and 'engineering scheme'. The interface also features a 'top navigation bar' with 'User B', 'Access: Level 2', and 'Help' options.

Let's make a discharge

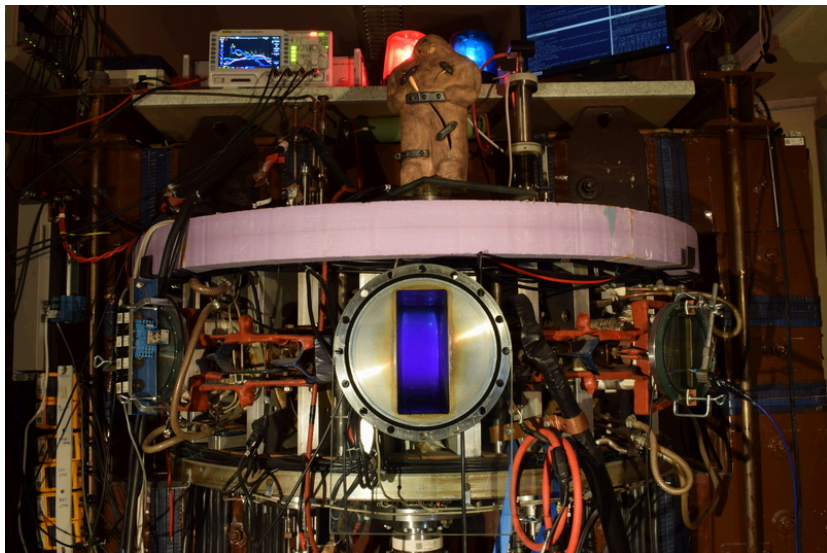


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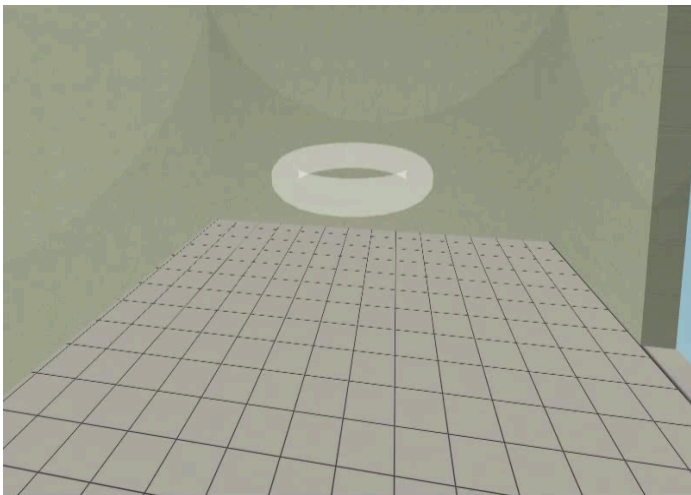
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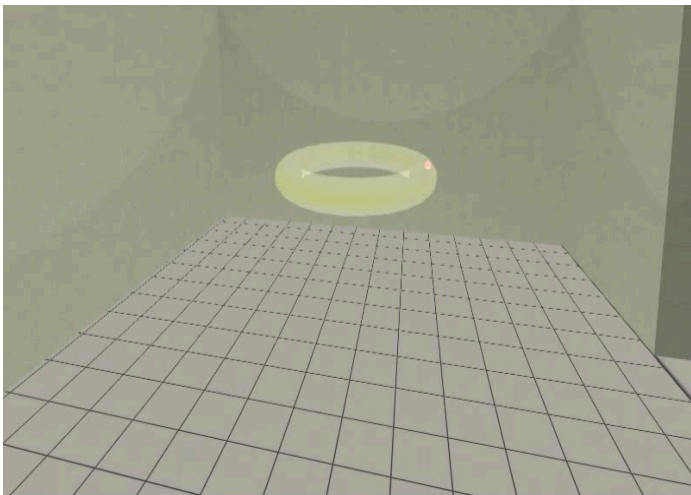
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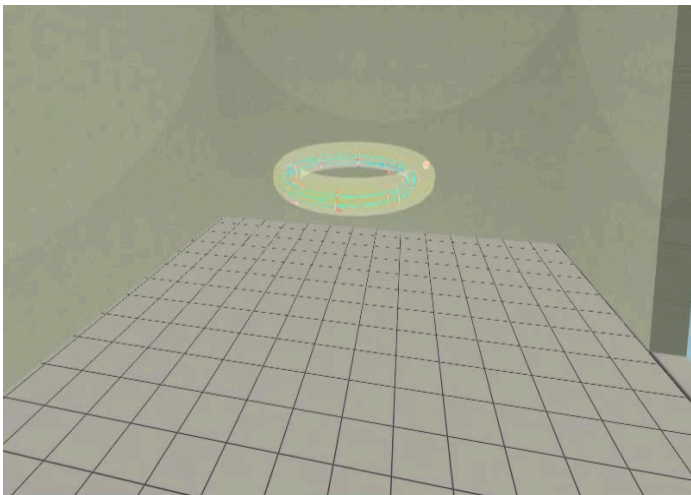
Introduce the working gas (Hydrogen x Helium)



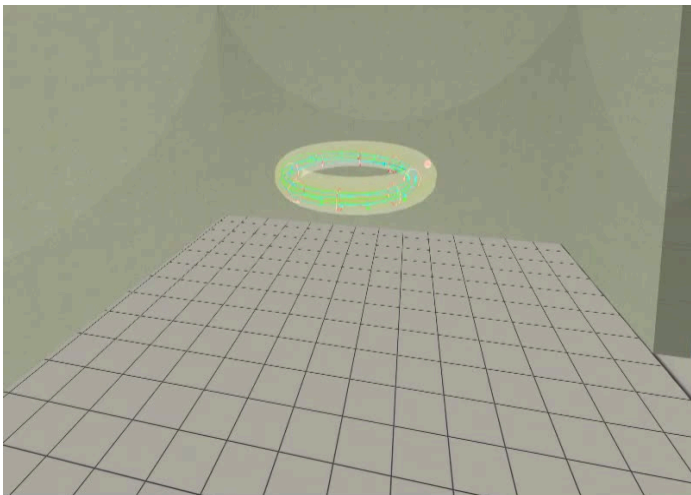
Switch on the preionization



Introduce the magnetic field



Introduce the electric field



Plasma ..

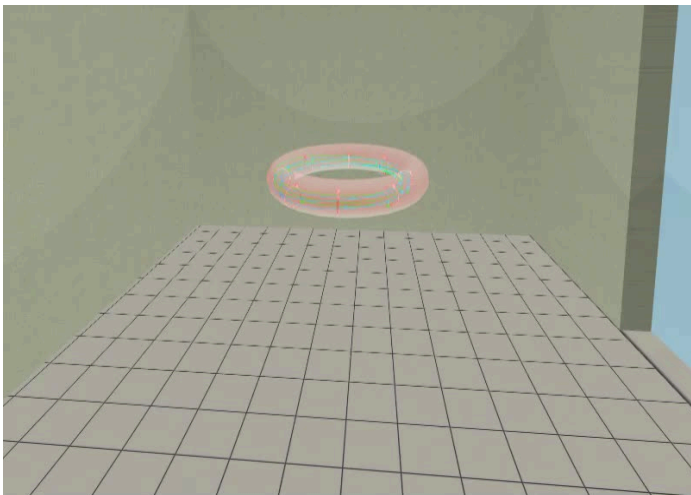


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Infrastructure room (below tokamak) 10/16



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

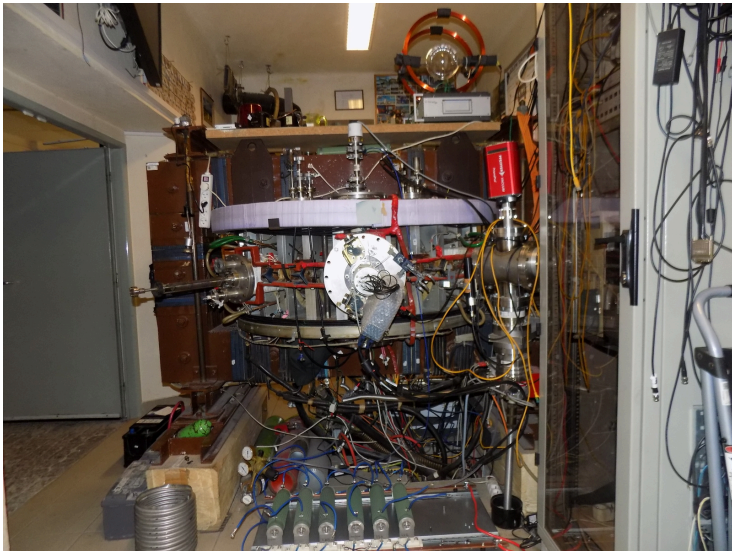
power
supply
2kV

Toroidal
magnetic field B
capacitors

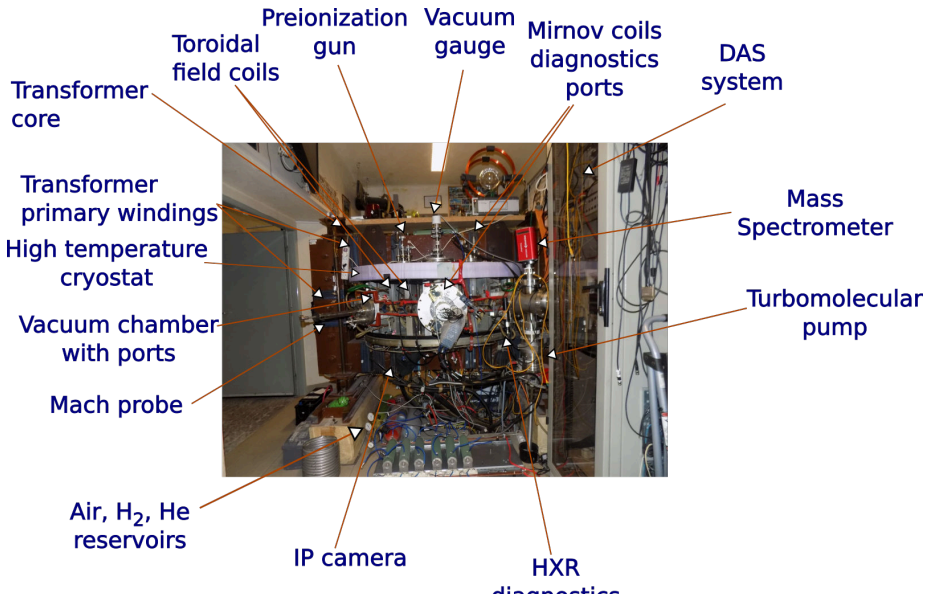
fire
protection
system



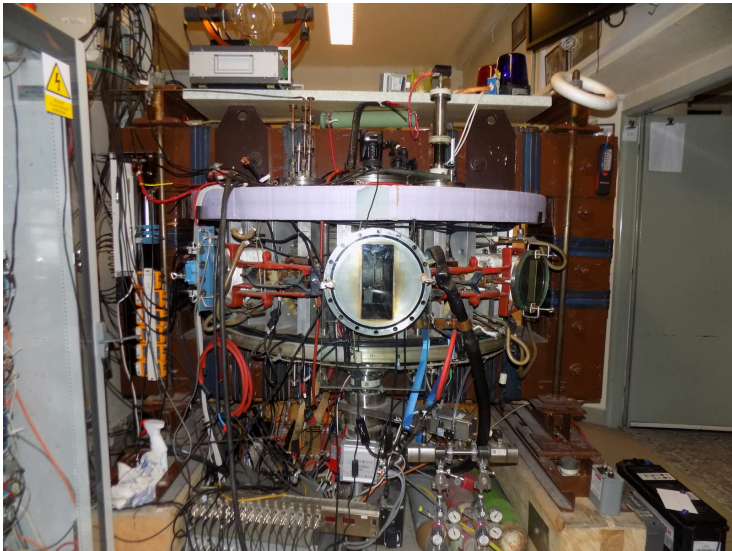
Tokamak room (North) 10/16



Tokamak room (North) 10/16



Tokamak room (South) 10/16



Tokamak room (South) 10/16

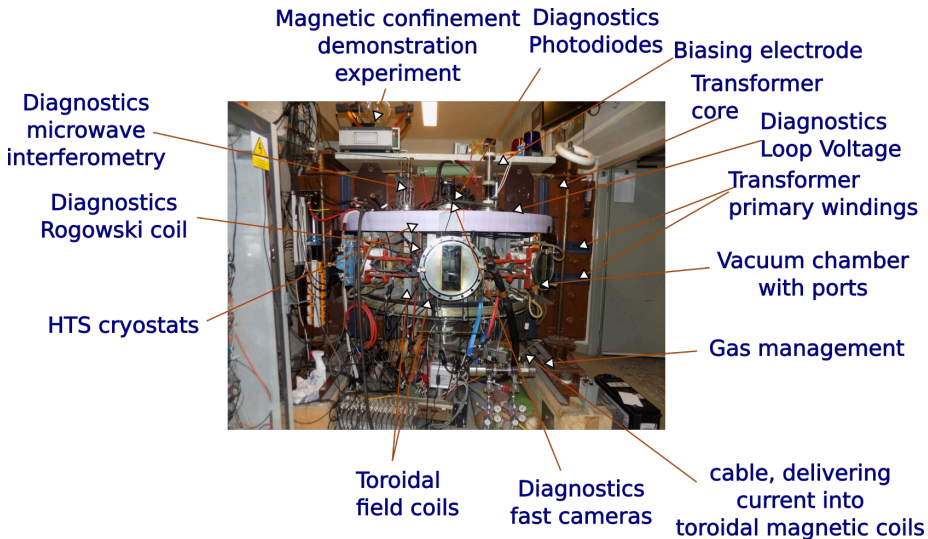


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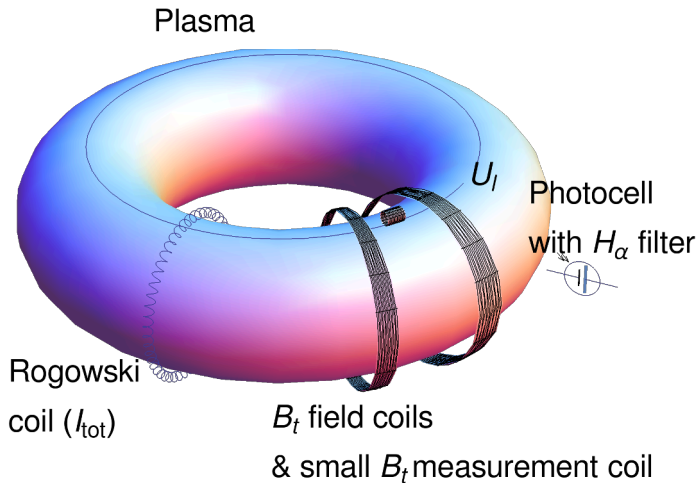
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The GOLEM tokamak - basic diagnostics



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 j, /Drigent.sh --discharge --UBT 1200 --TBT 0 --Ucd 450 --Tcd 350 --preionization 1 --gas H --pressure 10 --diagnostics.limitermirrorcoils "vacuum_shot=39109" --discharge.preionization "main_switch='on',powsup_heater=80,powsup_accel=100" --discharge.position_stabilization "main_switch='on',radial_switch='on',vertical_wavemode='3000,0,9000,-20;18000,0,20000,0,30000,0' --discharge.vertical_switch='on',radial_wavemode='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: $\bar{U}_{\text{loop}} = 8,02 \text{ V}$; $\max_{t \in [t_{\text{discharge}}]} \bar{U}_{\text{loop}} = 9,89 \text{ V}$; $U_{\text{loopdown}} = 10,83 \text{ V}$
- Toroidal magnetic field: $\bar{B}_t = 0,40 \text{ T}$; $\max_{t \in [t_{\text{discharge}}]} \bar{B}_t = 0,57 \text{ T}$
- Plasma current: $I_p = 9,67 \text{ kA}$; $\max_{t \in [t_{\text{discharge}}]} I_p = 9,67 \text{ kA}$; $I_{\text{pmax}} = 11,66 \text{ kA}$

On stage diagnostics

Data flow: measurement → digitization → analysis

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

Basic diagnostics - numerical processing, raw data

The image shows a web browser displaying a diagnostics interface for a Golem system. The top part of the browser shows a graph with a blue line and a red vertical line. Below the graph is a navigation menu with sections: Diagnostics (Basic Diagnostics, Fast Camera, etc.), Other, and Navigation. The main content area is titled "On stage diagnostics" and features a flow diagram: "Data flow" (Name) -> "measurement" (Experiment setup) -> "digitization" (Data acquisition system) -> "analysis" (Raw data) -> "Analysis results". A red circle highlights a folder icon in the "Raw data" section. Below the browser window 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 "Raw data" folder icon in the browser to the "TektrMSO56_ALL.csv" file in the index. Another red arrow points from the left edge of the image to the "BasicDiagnostics.sh" file in the index.

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

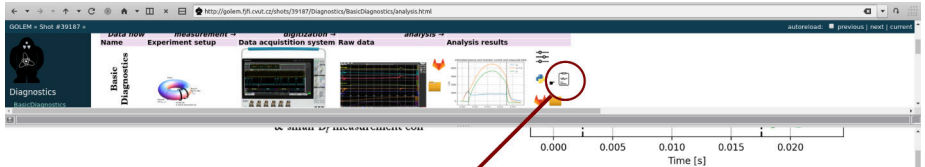
Basic diagnostics - numerical processing, Jupyter-notebook@GitLab Download & play

The screenshot displays a GitLab repository page for the project "Tokamak GOLEM Basic diagnostics". The main content area shows the Jupyter notebook "StandardDAS.ipynb" (19.83 KIB) with a download icon and a button labeled "Open in Web IDE". Below the notebook title, there is a "Procedure" section with a link "(This notebook to download)" and a "Prerequisites: function definitions" section. The code block shows the following Python imports:

```
%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
```

A red arrow points from a circled icon in a preview window above to the download button. The preview window shows a navigation bar with tabs for "Data flow", "Measurement", "Data acquisition system", "Raw data", and "Analysis results". The "Analysis results" tab is active, showing a plot of a signal over time.

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

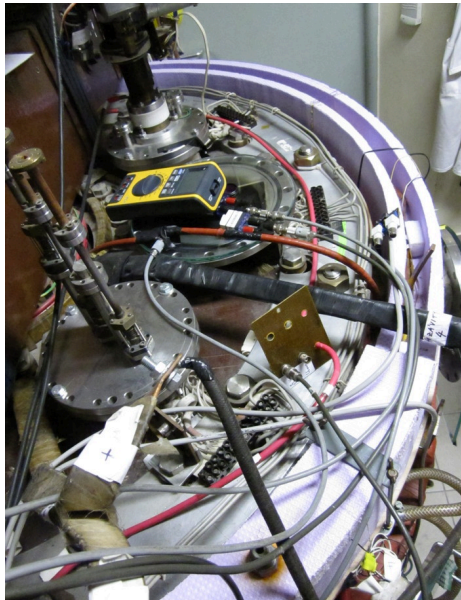
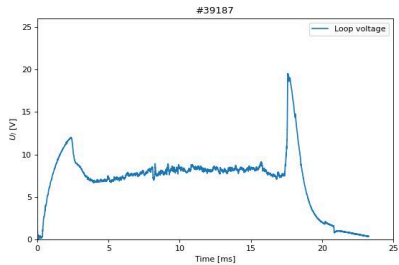
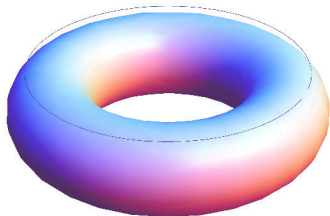
```
In [2]: import holoviews as hv
hv.extension('bokeh')
import hvplot.pandas
```



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}

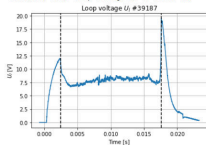
```
t_scale = 1e-3 if in_seconds else 1
if is_plasma:
    for t in (t_plasma_start, t_plasma_end):
        plt.axvline(t = t_scale, color='k', linestyle='--')
```

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[it_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')]
```



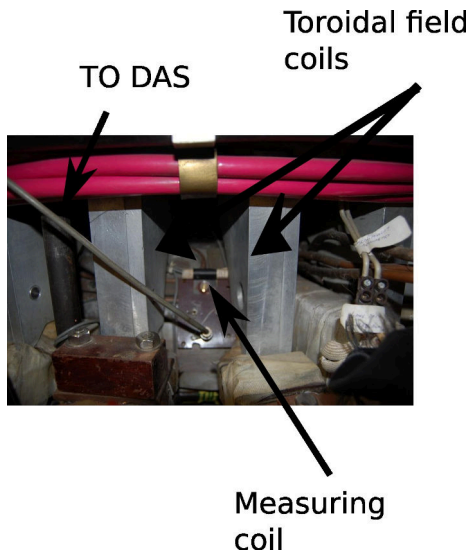
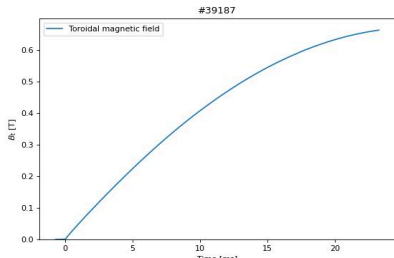
B_t calculation

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

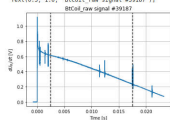
B_t calculation

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_infidBt
dBt = dBt.loc[offset_sl].mean()
ax = dBt.plot(grid=True)
show_plasma_limits()
ax.set(xlabel='Time [s]', ylabel='dBt [B.t)/dtS [V]', title='BtCoil_raw signal #{}'.format(shot_no));
```

```
Out[12]: [Text(0.5, 0, 'Time [s]'),
Text(0, 0.5, 'dBt [B.t)/dtS [V]'],
Text(0.5, 1.0, 'BtCoil_raw signal #39187')]
```

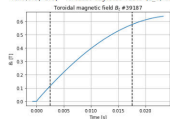


Integration (it is a magnetic diagnostic) & calibration

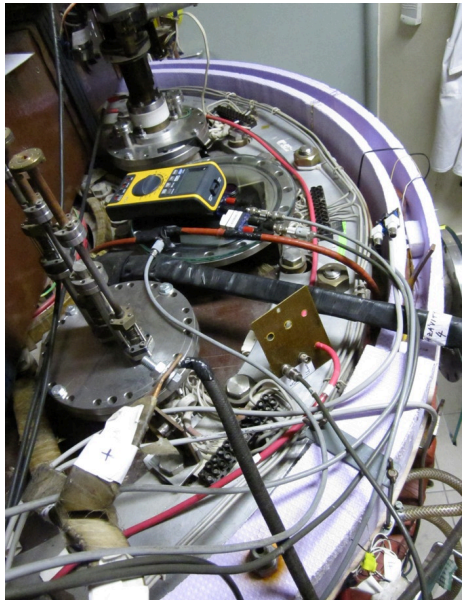
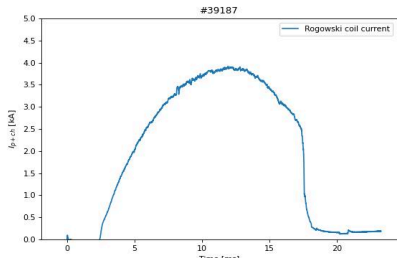
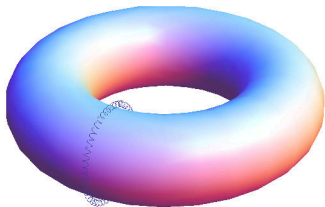
```
In [13]: K_BtCoil = float(read_parameter(shot_no, 'SystemParameters/K_BtCoil')) # Get BtCoil calibration factor
print('BtCoil calibration factor K_BtCoil={}'.format(K_BtCoil))
BtCoil calibration factor K_BtCoil=70.42 T/Vs)
```

```
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}

http://system.fyi.cvt.cz/shot/39187/Diagnostics/BasicDiagnostics/analysis.html

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

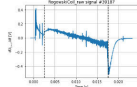
The Rogowski coil around the chamber measures the total current contained within its boundaries. Therefore, if there is plasma, it measures the sum of the plasma and chamber currents. In a vacuum discharge it measures only the chamber current.

Check the data availability

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

```
In [131]: dIpch = read_signal(shot_no, 'RogCoil') # 3300 horizontal bar now
if dIpch[0] == 0:
    dIpch = 1 # non active
dIpch = correct_bias(dIpch)
dIpch = dIpch * (1/2*pi*1e-7) # subtract offset
dIpch[0] = 0
ax = dIpch.plot(grid=True)
show plasma limits()
ax.set(xlabel='Time [s]', ylabel='dI_{p+ch} [A]', title='Rogowski coil raw signal #39187')
```

```
In [132]: Tstart0, S, R, Time [s]
Tstart0, S, R, 140, 1, 1, 0.018 [100]
Tstart0, S, R, RogowskiCoil_raw_signal_#39187 [100]
RogowskiCoil_raw_signal_#39187
```

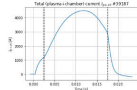


Integration (it is a magnetic diagnostic) & calibration

```
In [133]: K_RogowskiCoil = float(read_parameter(shot_no, 'SystemParameters/K_RogowskiCoil')) # get Rogowski coil calibration factor
print('Rogowski coil calibration factor: K_RogowskiCoil={0:.3f} A/V'.format(K_RogowskiCoil))
```

```
In [134]: Ipch = pd.Series(integrate.cumtrapz(dIpch, x=dIpch.index, initial=0) * K_RogowskiCoil,
                        x=dIpch.index, name='Ipch')
ax = Ipch.plot(grid=True)
show plasma limits()
ax.set(xlabel='Time [s]', ylabel='I_{p+ch} [A]', title='Total (plasma+chamber) current I_{p+ch} #39187')
```

```
In [135]: Tstart0, S, R, Time [s]
Tstart0, S, R, 140, 1, 1, 0.018 [100]
Tstart0, S, R, Total (plasma+chamber) current I_{p+ch} #39187 [100]
```



Chamber current I_{ch} calculation

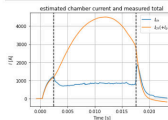
```
In [136]: R_chamber = float(read_parameter(shot_no, 'SystemParameters/R_chamber')) # get Chamber resistivity
print('Chamber resistivity R_chamber={0:.4f} Ohm'.format(R_chamber))
```

Chamber resistivity R_chamber=0.007 Ohm

```
In [137]: L_chamber = float(read_parameter(shot_no, 'SystemParameters/L_chamber')) # get Chamber inductance
print('Chamber inductance L_chamber={0:.4f} format(shot_no))
```

Chamber inductance L_chamber=40.4e-6 H

```
In [138]: for i in range(1, len(Ich) + 1):
ax = I.plot()
ax.legend()
show plasma limits()
ax.set(xlabel='Time [s]', ylabel='I_{ch} [A]', title='estimated chamber current and measured total')
plt.grid()
```



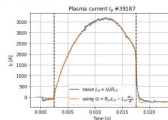
Plasma current I_p calculation

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 = Ipch - loop_voltage/R_chamber # creates a new Series
    Ip = Ipch - Ich
    Ip.name = 'Ip'
    Ip.name.plot(grid=True, label='naive I_{ch} [A] (ch)')
    ax = Ip.plot(grid=True, label='using SQ_{ch} = R_{ch} I_{ch} - L_{ch} / (rcd I_{ch}) [A]')
    ax.legend()
    show plasma limits()
    ax.set(xlabel='Time [s]', ylabel='I_{p} [A]', title='Plasma current I_{p} #39187')
else:
    Ip = Ipch * 0 # no current
    heating
```

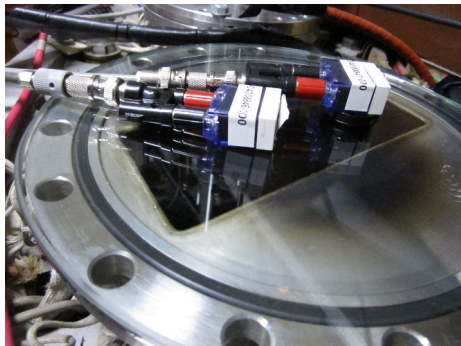
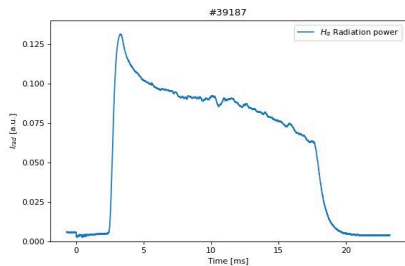
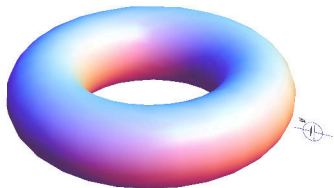
Out[122] Plasma detected

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

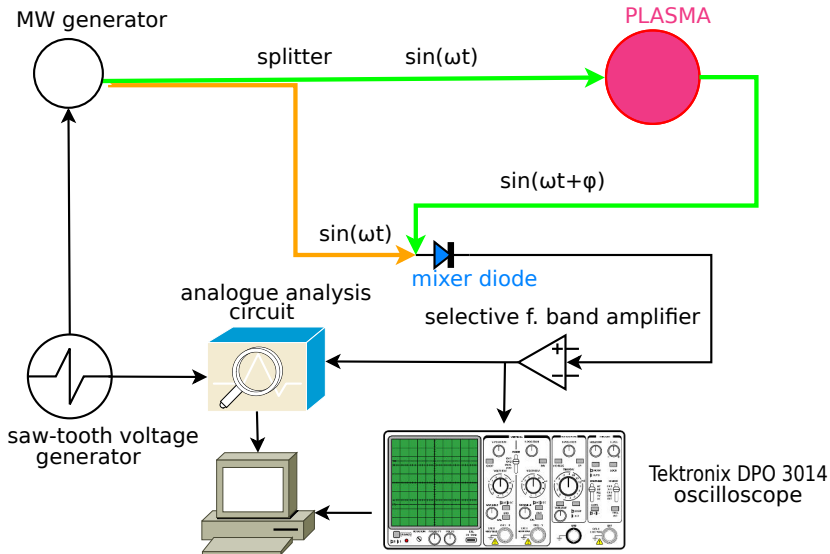


```
In [131]: fig = plt.figure(dpi=200)
for i in range(1, len(Ich) + 1):
    ax = I.plot()
```

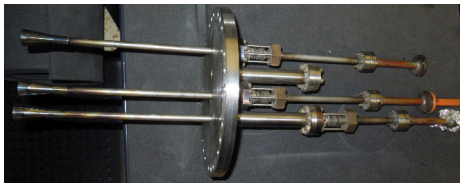
Visible radiation



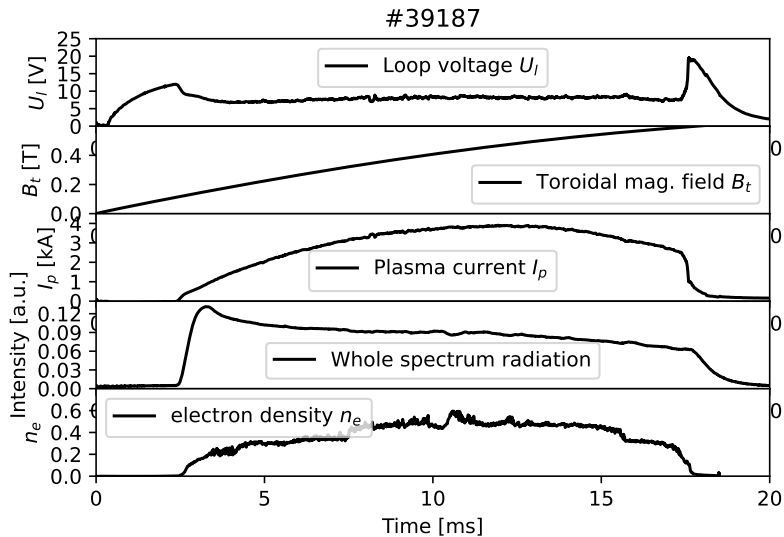
Electron density n_e interferometry measurement scheme



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
LimiterInterlocks
ScriptsAndProbes

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

[Shot Logbook]

```

jDringent.sh --discharge --UBt 800 --Tbt 0 --Utd 450 --Tod 500 --preionization 1 --gas H --pre
issue 13 --diagnostics.limiterinterlocks.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"
                    
```

Technological parameters

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

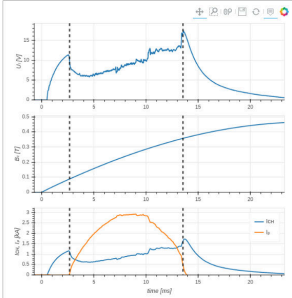
Plasma:

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

Basic Diagnostics



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> 

Table of Contents

- 1 Introduction
- 2 The Tokamak (GOLEM)
- 3 The Tokamak GOLEM (remote) operation**
- 4 $\tau_{E,e}$ & q
- 5 Conclusion
- 6 Appendix

Table of Contents

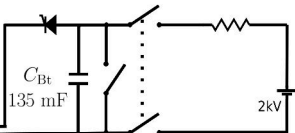
- 1 Introduction
- 2 The Tokamak (GOLEM)
- 3 The Tokamak GOLEM (remote) operation
 - Control room
 - Data handling @ the Tokamak GOLEM
- 4 $\tau_{E,e}$ & q
- 5 Conclusion
- 6 Appendix

Tokamak GOLEM - schematic experimental setup

Preionization (electron gun)

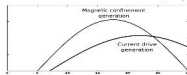
→ $S/W_{\text{preion}} \in \langle \text{on} \dots \text{on} \dots \text{off} \rangle [-]$

Magnetic confinement B_t generation

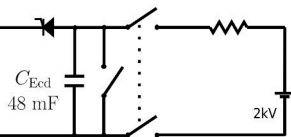


→ $U_{B_t} \in \langle 200 \dots 800 \dots 1300 \rangle [V]$

Trigger sequence



Current drive E_{cd} generation



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

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

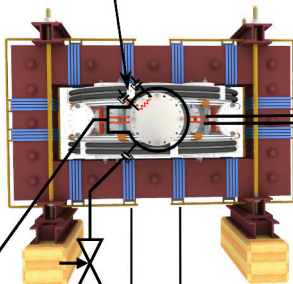
Vacuum stand



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

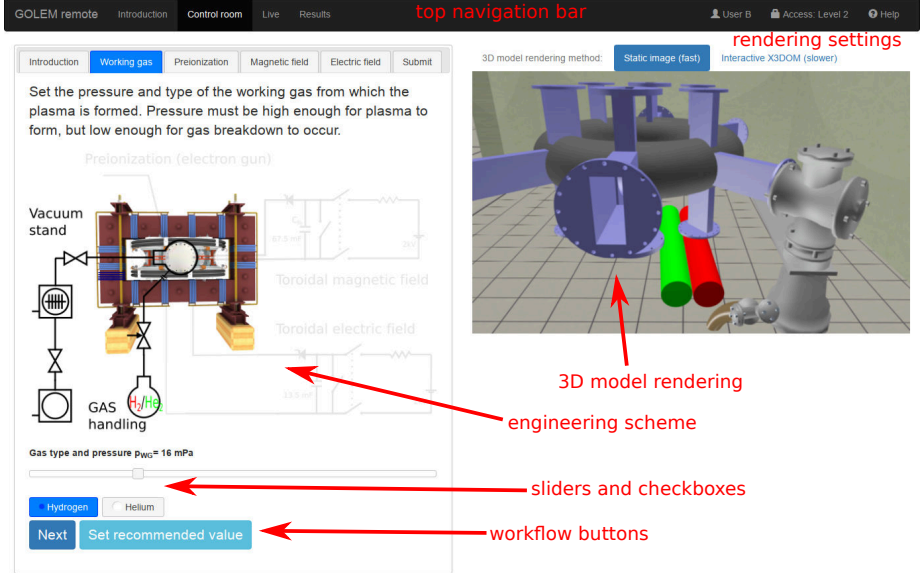
Next Set recommended value

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 tabs for 'Introduction', 'Working gas', 'Preionization', 'Magnetic field', 'Electric field', and 'Submit'. The 'Working gas' tab is selected, displaying instructions on setting gas pressure and type. A schematic diagram of the tokamak is shown, with labels for 'Preionization (electron gun)', 'Vacuum stand', 'Toroidal magnetic field', 'Toroidal electric field', and 'GAS handling'. Below the diagram, there are controls for 'Gas type and pressure $p_{WG} = 16 \text{ mPa}$ ', including a slider and radio buttons for 'Hydrogen' and 'Helium'. At the bottom, there are 'Next' and 'Set recommended value' buttons. To the right, a 3D model rendering of the tokamak components is shown, with a red arrow pointing to it from the text '3D model rendering'. The rendering settings are set to 'Static image (fast)'. A red arrow points from the text 'engineering scheme' to the schematic diagram. Another red arrow points from the text 'sliders and checkboxes' to the gas type and pressure controls. A final red arrow points from the text 'workflow buttons' to the 'Next' and 'Set recommended value' buttons.

Control room: Introduction

GOLEM remote Introduction **Control room** Live Results

Prague Access: Level 1 Help

Introduction Working gas Preionization Magnetic field Current drive Submit

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

Preionization (electron gun)

Vacuum stand

Preionization (electron gun)

Toroidal magnetic field

Current drive

GAS handling H_2/He

23 mF C_p

11.3 mF C_p

2kV

2kV

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

[Next](#)

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_9

67.5 mF 20V

13.5 mF 20V

Gas type and pressure p_{gas} : 38 mPa

Hydrogen Helium

Next Set recommended value

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

Control room: Preionization

GOLEM remote Introduction Control room Live Results

Introduction Working gas Preionization Magnetic field Electric field Submit

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

Preionization (electron gun)

Vacuum stand

GAS handling

Toroidal magnetic field

Toroidal electric field

67.5 mF

13.5 mF

20V

20V

ionization method

Electron gun No ionization

Next

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

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.

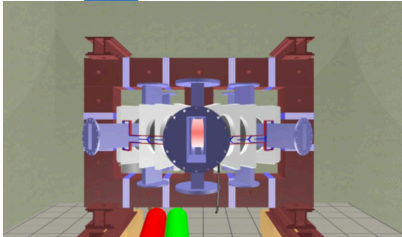
COMMENT

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
LimiterInterlocks
ScriptsAndProbes

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

[Shot Logbook]

```

jDringent.sh --discharge --Ubt 800 --Tbt 0 --Utd 450 --Tod 500 --preionization 1 --gas H --pre
issue 15 --diagnostics.limiterinterlocks.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"
                    
```

Technological parameters

- Working Gas: $P_{discharge, before} = 2.46$ mPa; $P_{discharge, after} = 5.04$ mPa ($P_{WG}^{response} = 15$ mPa @ $\Delta P_{WG}^{response} = 4$)
- Toroidal magnetic field: $U_{B_t}^{response} = 800$ V @ $I_{B_t}^{response} = 0.0$ us
- Current drive field: $U_{E_{ed}}^{response} = 450$ V @ $I_{E_{ed}}^{response} = 500.0$ 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; $max_{T_{inj}}(I_{discharge}) U_{loop} = 16.17$ V; $U_{breakdown} = 0.00$ V
- Toroidal magnetic field: $B_t = 0.24$ T; $max_{T_{inj}}(I_{discharge}) B_t = 0.36$ T
- Plasma current: $I_p = 2.28$ kA; $max_{T_{inj}}(I_{discharge}) I_p = 2.92$ kA; $t_p^{max} = 0.00$ ms

Basic Diagnostics



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 				 <p style="text-align: center;">Without Analysis</p>

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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'
```

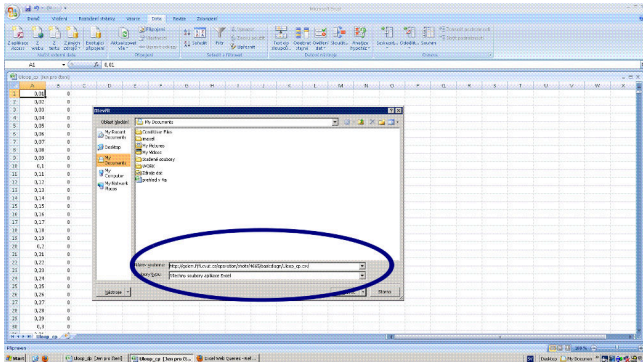
```
shot_no=39187;\
signal_id="Diagnostics/BasicDiagnostics/Results/U_loop.csv";\
gnuplot -p -e "set title \"Golem\";set datafile separator \"\",\"";\
set xlabel \"t [s]\";set ylabel \"U\";\
plot \"< \
wget -q -O - http://golem.fjfi.cvut.cz/shots/$shot_no/$signal_id\" \
w l t \"U\""
```

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.

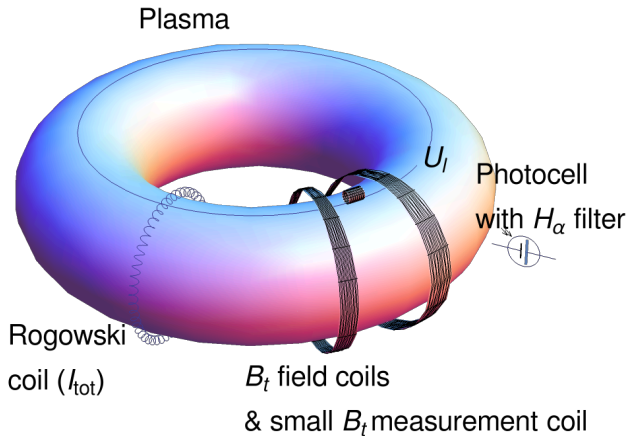
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Hands on the GOLEM tokamak - equipment



The GOLEM tokamak - standard diagnostics



The GOLEM tokamak interferometry HW

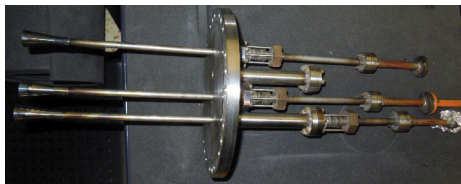
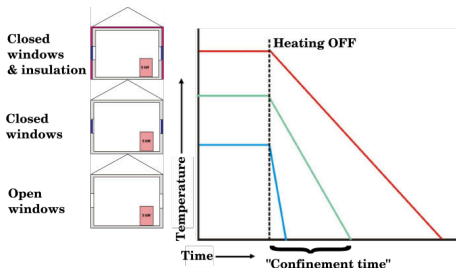


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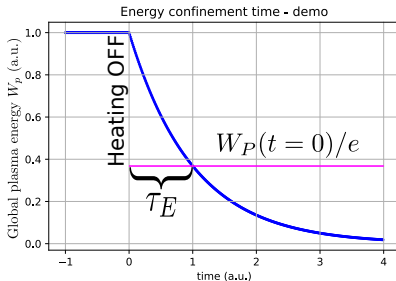
- 1 Introduction
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- 4 $\tau_{E,e}$ & q
 - The Electron energy confinement time calculation
 - The safety factor
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Towards the Electron Energy Confinement Time $\tau_{E,e}$ @tG

House (cooling after heating stops)



Tokamak (cooling after heating stops)

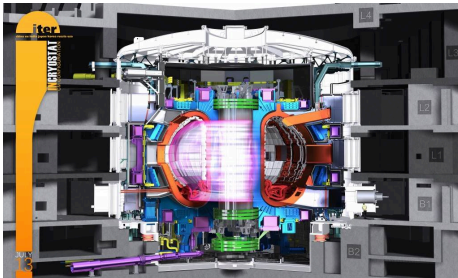


When heating is switched off, both systems lose their internal energy exponentially.
This motivates the definition of the electron energy confinement time $\tau_{E,e}$.

ITER vs GOLEM

ITER:

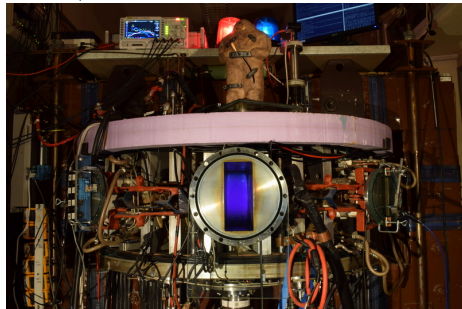
$$\tau_E \approx 3.6 \text{ s}$$



credit:[4]

GOLEM:

$$\tau_{E,e} \approx \text{on the order of } 10 \mu\text{s}$$



credit:[5]

Different scale, same physics — and you will measure it today @tG.

What follows — roadmap

- **Lawson criterion** — the fusion requirement
- **Quasi-stationary method @tG** — how we measure confinement
- **Ohmic heating power** P_{OH}
- **Electron temperature** from Spitzer conductivity T_e
- **Electron energy content** W_e
- **Putting it all together:** the confinement time $\tau_{E,e}$

- To achieve net fusion power, fusion heating must exceed losses:

$$P_{\text{fusion}} \geq P_{\text{loss}}.$$

- Plasma energy content:

$$W = 3nk_{\text{B}}T.$$

- Confinement time links energy to losses:

$$\tau_E = \frac{W}{P_{\text{loss}}}.$$

- Fusion reaction rate (DT):

$$f = \frac{1}{4}n^2\langle\sigma v\rangle, \quad P_{\text{fusion}} = f E_{\alpha}, \quad E_{\alpha} = 3.5 \text{ MeV}.$$

- Condition for ignition becomes the Lawson criterion:

$$n\tau_E \geq \frac{12}{E_{\alpha}} \frac{k_{\text{B}}T}{\langle\sigma v\rangle} \approx 1.5 \times 10^{20} \text{ s/m}^3 \quad (\text{DT at } T \approx 26 \text{ keV}).$$

Measuring $\tau_{E,e}$ @tG: the quasi-stationary method

- On GOLEM we cannot switch off the ohmic heating abruptly (capacitor discharge drives the current throughout the pulse).
- Therefore we use the **quasi-stationary phase** of the discharge:

$$\frac{dl_p}{dt} \approx 0, \quad \frac{dT_e}{dt} \approx 0, \quad \frac{dW_e}{dt} \approx 0.$$

- In this regime, the ohmic heating balances the losses:

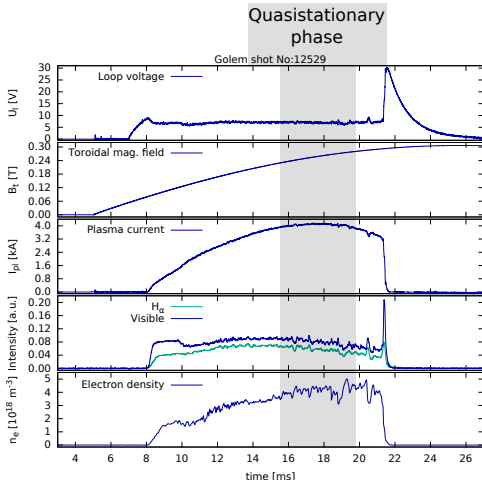
$$P_{OH} \approx P_{loss}.$$

- The electron energy confinement time becomes:

$$\tau_{E,e} \approx \frac{W_e}{P_{OH}}.$$

- This provides a consistent and reproducible estimate of $\tau_{E,e}$ suitable for a small tokamak like GOLEM.

The discharge — quasi-stationary phase



Quasi-stationary phase:

- Plasma current I_p , electron temperature T_e and density n_e vary only slowly.
- Therefore $dW_e/dt \approx 0$.
- Ohmic heating balances losses:

$$P_{OH} \approx P_{loss}.$$

- This is the interval used to estimate the electron energy confinement time:

$$\tau_{E,e} \approx \frac{W_e}{P_{OH}}.$$

- All quantities are measurable @tG.

Ohmic heating power P_{OH} @tG

On the GOLEM tokamak the plasma is heated solely by **ohmic heating**, driven by the toroidal electric field that sustains the plasma current I_p . The instantaneous ohmic heating power is directly obtained from two measurable quantities:

$$P_{\text{OH}}(t) = V_{\text{loop}}(t) I_p(t),$$

where V_{loop} is the toroidal loop voltage measured by the flux loop, and $I_p(t)$ is the plasma current from the Rogowski coil. In the quasi-stationary phase, where $dW_e/dt \approx 0$, this power balances the energy losses:

$$P_{\text{OH}} \approx P_{\text{loss}},$$

providing the key ingredient for estimating the electron energy confinement time $\tau_{E,e}$ @tG.

Central electron temperature T_e (Spitzer conductivity)

The time evolution of the central electron temperature $T_e(0, t)$ is obtained from Spitzer's resistivity formula for a collisional, fully ionized plasma.

- Spitzer resistivity (symbolically):

$$\eta(T_e) \propto Z_{\text{eff}} \ln \Lambda T_e^{-3/2}.$$

- Using $\eta = R_p A/L$ with plasma resistance $R_p(t)$ one may write for the on-axis temperature:

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

- For the particular case of the GOLEM tokamak (fixed geometry, $Z_{\text{eff}} \approx 1$, $\ln \Lambda \approx \text{const}$) all geometric and numerical factors can be grouped into a single coefficient, giving the practical formula:

$$T_e(0, t) \approx 0.9 \left(\frac{I_p(t)}{V_{\text{loop}}(t)} \right)^{2/3} \quad [\text{eV}; \text{A}, \text{V}].$$

- Thus @tG the central electron temperature can be estimated directly from the measured $I_p(t)$ and $V_{\text{loop}}(t)$.

Electron energy content W_e @tG

The electron energy content follows from the ideal-gas expression for a single thermal species:

$$W_e(t) = \frac{3}{2} n_e(t) k_B T_e(t) V_p,$$

where $n_e(t)$ is the line-averaged (or central) electron density, $T_e(t)$ the central electron temperature, and V_p the plasma volume. For a circular, low-aspect-ratio tokamak the plasma volume is well approximated by:

$$V_p \approx 2\pi^2 R_0 a^2,$$

with R_0 the major radius and a the minor radius. At GOLEM all quantities entering W_e are experimentally accessible:

- $n_e(t)$ from microwave interferometry,
- $T_e(t)$ from Spitzer conductivity,
- V_p from known machine geometry.

Thus $W_e(t)$ can be evaluated directly during the quasi-stationary phase of the discharge.

Electron energy confinement time $\tau_{E,e}$ @tG

In the quasi-stationary phase of the discharge, where $dW_e/dt \approx 0$, the ohmic heating balances the energy losses:

$$P_{\text{OH}} \approx P_{\text{loss}}.$$

The electron energy confinement time is therefore obtained as:

$$\tau_{E,e}(t) = \frac{W_e(t)}{P_{\text{OH}}(t)} = \frac{\frac{3}{2} n_e(t) k_B T_e(t) V_p}{V_{\text{loop}}(t) I_p(t)}.$$

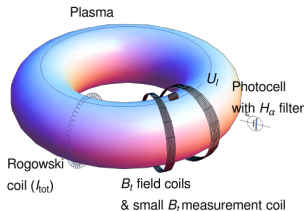
All entering quantities are experimentally accessible @tG:

- $P_{\text{OH}}(t) = V_{\text{loop}}(t) I_p(t)$,
- $T_e(t)$ from Spitzer conductivity,
- $n_e(t)$ from interferometry,
- V_p from machine geometry.

This yields a self-consistent, fully diagnostic-based estimate of the **electron energy confinement time** on the GOLEM tokamak.

Measured quantities @tG for computing $\tau_{E,e}$

Directly measured on GOLEM:



Diagnostics relevant to $\tau_{E,e}$ on GOLEM

- **Plasma current** $I_p(t)$ from the Rogowski coil (shown as the helical pickup).
- **Loop voltage** U_l (not needed for q , but measured).
- **Machine geometry:** major radius R_0 and minor radius a .
- **Electron density** from interferometry.

These are all required inputs to compute:

$$\tau_{E,e}(t) = \frac{W_e(t)}{P_{OH}(t)} = \frac{\frac{3}{2} n_e(t) k_B T_e(t) V_p}{V_{loop}(t) I_p(t)}.$$

From measured signals to $\tau_{E,e}$ @tG

Vacuum discharge

$$I_{\text{ch}}^{\text{vac}}(t), V_{\text{loop}}^{\text{vac}}(t)$$

Plasma discharge

$$I_{\text{ch+p}}(t), \\ V_{\text{loop}}(t), n_e(t)$$

Chamber resistance

$$R_{\text{ch}} \approx \frac{V_{\text{loop}}^{\text{vac}}}{I_{\text{ch}}^{\text{vac}}}$$

Plasma current

$$I_p = I_{\text{ch+p}} - \frac{V_{\text{loop}}}{R_{\text{ch}}}$$

Quasi-stationary interval $[t_1, t_2]$:

$$\bar{I}_p = \langle I_p \rangle, \quad \bar{V}_{\text{loop}} = \langle V_{\text{loop}} \rangle, \quad \bar{n}_e = \langle n_e \rangle$$

Plasma resistivity

$$R_p = \frac{\bar{V}_{\text{loop}}}{\bar{I}_p}$$

Central T_e (Spitzer)

$$T_e(0) \approx 0.9 R_p^{-2/3}$$

Ohmic heating

$$\bar{P}_{\text{OH}} = \bar{V}_{\text{loop}} \bar{I}_p$$

Electron energy

$$\bar{W}_e = \frac{3}{2} \bar{n}_e k_B T_e V_p$$

Electron energy confinement time

$$\tau_{E,e} = \frac{\bar{W}_e}{\bar{P}_{\text{OH}}}$$

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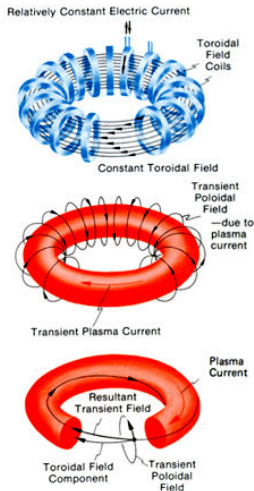
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 - The Electron energy confinement time calculation
 - The safety factor
- 5 Conclusion
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Towards the Safety Factor q

Magnetic field lines in a tokamak

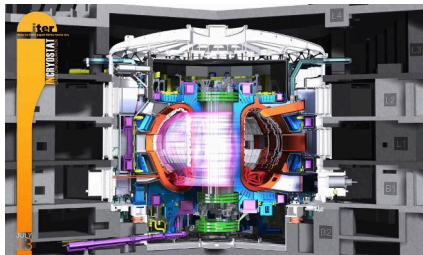
Why it matters:

- q measures how much field lines *twist* around the torus.
- A key parameter controlling MHD stability.
- Rational q surfaces ($q = m/n$) \rightarrow possible island formation.
- Operating limits: too low $q \rightarrow$ kink instabilities.
- ITER, JET, ASDEX-U all use $q(a)$ as a primary equilibrium metric.
- **Fundamental limits:** $q(0) > 1$ (avoid internal kink), $q(a) \gtrsim 2$ (avoid external kink).



ITER vs GOLEM: typical values of $q(a)$

ITER

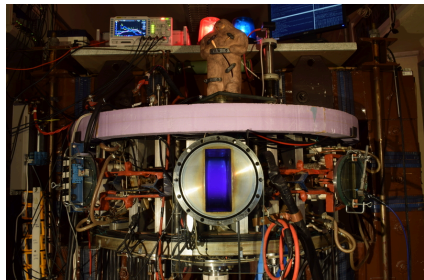


Typical edge safety factor:

$$q(a) \sim 3 - 4$$

Large device, strong shaping, high stability margin.

GOLEM



Typical edge safety factor:

$$q(a) \sim 2 - 6$$

Small device: circular plasma, flexible operating space.

What follows — roadmap to the safety factor q

- **Definition of the safety factor** — toroidal/poloidal twist of magnetic field lines.
- **Circular tokamak geometry** — relation between B_t , B_p and plasma current.
- **Quantities measured @tG** — $I_p(t)$ from Rogowski, B_t from toroidal field coils, geometry (R_0, a).
- **Computing the edge safety factor** — $q(a) = \frac{2\pi a^2 B_t}{\mu_0 R_0 I_p}$.
- **Typical operating window** — GOLEM: $2 < q(a) < 6$, stability limits $q(0) > 1$, $q(a) \gtrsim 2$.

Definition of the Safety Factor q

Geometric definition:

$$q(r) = \frac{\text{toroidal turns}}{\text{poloidal turns}}$$

In a circular tokamak:

$$q(r) = \frac{rB_t}{R_0 B_p(r)}$$

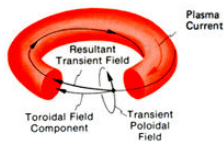
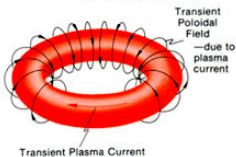
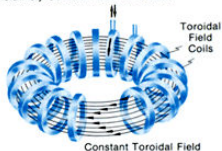
where B_t is the toroidal field, $B_p(r)$ the poloidal field, R_0 the major radius. Using Ampère's law:

$$B_p(r) = \frac{\mu_0 I_p(r)}{2\pi r}$$

This gives the practical form:

$$q(r) = \frac{2\pi r^2 B_t}{\mu_0 R_0 I_p(r)}$$

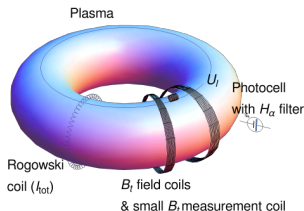
Relatively Constant Electric Current



Magnetic field line winding

Measured quantities @tG for computing $q(a)$

Directly measured on GOLEM:



Diagnostics relevant to $q(a)$ on GOLEM

- **Plasma current** $I_p(t)$ from the Rogowski coil (shown as the helical pickup).
- **Toroidal field** B_t from the TF coil current (and verified by the small B_t measurement coil).
- **Machine geometry:** major radius R_0 and minor radius a .

These are all required inputs to compute:

$$q(a) = \frac{2\pi a^2 B_t}{\mu_0 R_0 I_p}.$$

Computing the edge safety factor $q(a)$

Definition:

$$q(r) = \frac{rB_t}{R_0 B_p(r)}.$$

Using Ampère's law at the plasma edge:

$$B_p(a) = \frac{\mu_0 I_p}{2\pi a}.$$

Insert into the definition:

$$q(a) = \frac{2\pi a^2 B_t}{\mu_0 R_0 I_p}.$$

For GOLEM (fixed geometry):

$$K_{\text{geom}} = \frac{2\pi a^2}{\mu_0 R_0}$$

$$q(a) = K_{\text{geom}} \frac{B_t}{I_p}.$$

Thus: measuring $I_p(t)$ and knowing B_t is fully sufficient to compute $q(a)$ for any discharge on GOLEM.

From measured signals to the safety factor $q(a)$ @tG

Plasma current
 $I_p(t)$ from Rogowski

Toroidal field
 B_t from TF coils

GOLEM geometry (constant)
 R_0, a

Quasi-stationary interval
and mean current
 $\bar{I}_p = \langle I_p \rangle$

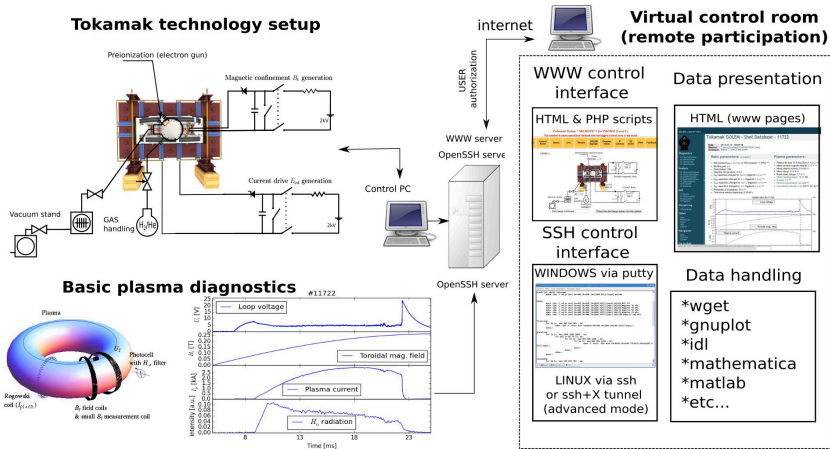
Safety factor at the edge:

$$q(a) = \frac{2\pi a^2 B_t}{\mu_0 R_0 \bar{I}_p}$$

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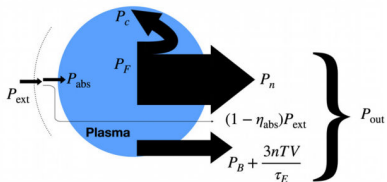
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The global schematic overview of the tG experiment



Two key fusion technology parameters you can touch experimentally

Energy Confinement Time τ_E



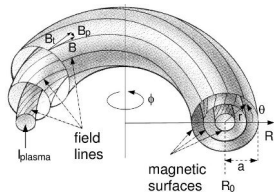
credit:[2]

- Indicates how long the plasma keeps its energy — a key fusion metric.

$$\tau_E = \frac{W_{\text{plasma}}}{P_{\text{loss}}}$$

- On tG, from energy balance, we estimate the electron component $\tau_{E,e}$ (we can measure only n_e and T_e).

Safety Factor q



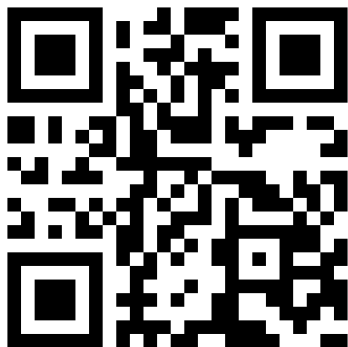
credit:[3]

- Describes how magnetic field lines wind around the torus. Key stability parameter (MHD behaviour).

$$q(a) = \frac{2\pi a^2 B_t}{\mu_0 R I_p}$$

- On tG, derived from B_t and plasma current I_p .

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



Fee: postcard from the venue of remote measurements



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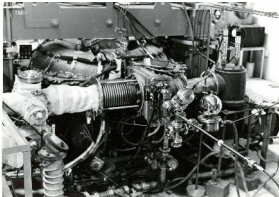
CTU RVO68407700, SGS 17/138/OHK4/2T/14, GAČR GA18-02482S, EU funds CZ.02.1.01/0.0/0.0/16_019/0000778 and CZ.02.2.69/0.0/0.0/16_027/0008465, IAEA F13019, FUSENET and EUROFUSION.

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Thank you for your attention

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@Kurchatov Institute near Moscow
~1960-1977



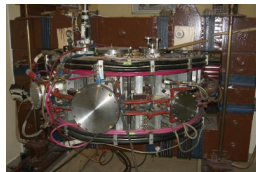
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SCIENCE
& education

Tokamak GOLEM
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2007-



EDUCATION
& science

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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
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LEVEL 1

Preionization (electron gun)
Proton
Toroidal magnetic field
Current drive
Vacuum stand
GAS handling
Working Gas

Discharge comment | Place the discharge setup into the queue.





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