

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 tokamak GOLEM Zonal flows experimentation

April 21, 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

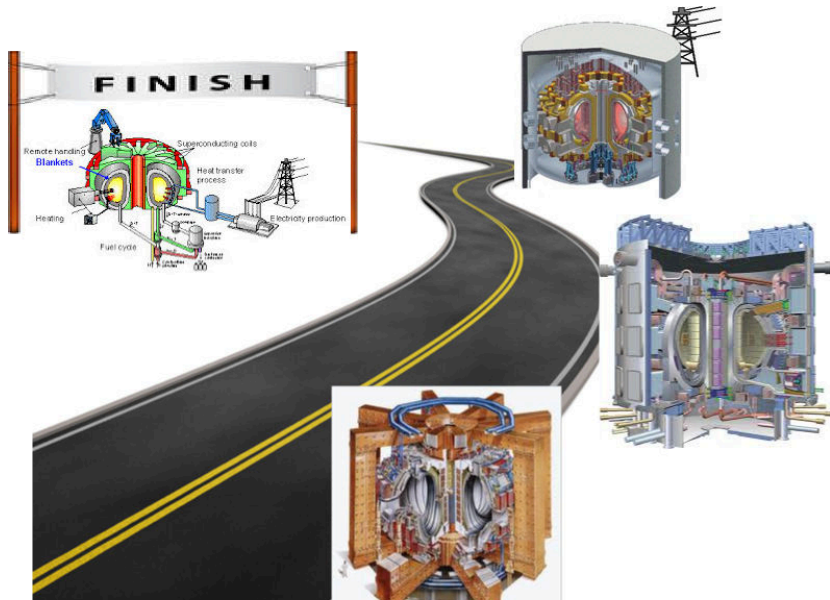
5 Conclusion

6 Appendix

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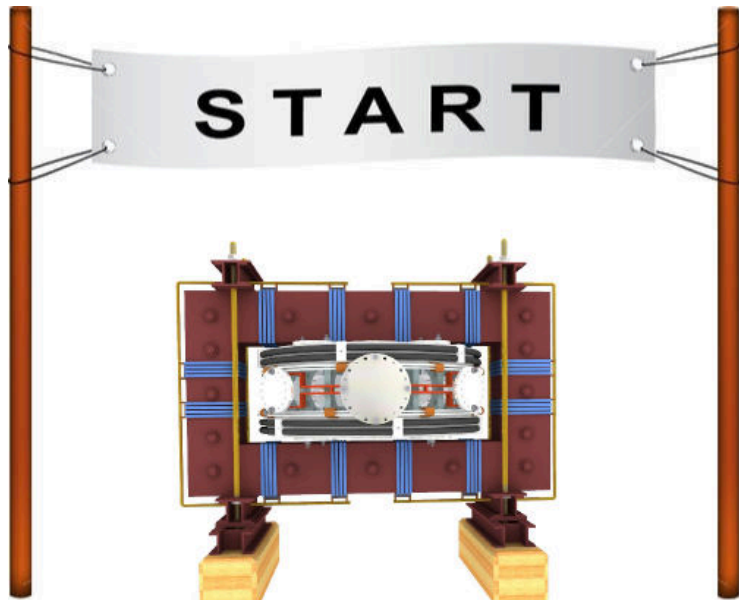
Milestones to Fusion Power Plant



Education importance



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



Tokamak GOLEM @ Wikipedia ..


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

home Kalendarj Produkce Forecast Slovnik Rano

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Tokamak

From Wikipedia, the free encyclopedia

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

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


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

Experimental tokamaks [[edit](#)]

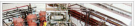
Currently in operation [[edit](#)]

(in chronological order of start of operations)

- 1960s: TM1-MH (since 1977 Castor; since 2007 Golem^[12]) in Prague, Czech Republic. In operation in Kurchatov Institute since early 1960s but renamed to Castor in 1977 and moved to IPP CAS,^[13] Prague; in 2007 moved to FNSPE, Czech Technical University in Prague and renamed to Golem.^[14]
- 1975: T-10, in Kurchatov Institute, Moscow, Russia (formerly Soviet Union); 2 MW
- 1983: Joint European Torus (JET), in Culham, United Kingdom
- 1985: JT-60, in Naka, Ibaraki Prefecture, Japan; (Currently undergoing upgrade to Super, Advanced model)
- 1987: STOR-M, University of Saskatchewan; Canada; first demonstration of alternating current in a tokamak.
- 1988: Tore Supra,^[15] at the CEA, Cadarache, France
- 1989: Aditya, at Institute for Plasma Research (IPR) in Gujarat, India
- 1980s: DIII-D,^[16] in San Diego, USA; operated by General Atomics since the late 1980s
- 1989: COMPASS,^[13] in Prague, Czech Republic; in operation since 2008, previously operated from 1989 to 1999 in Culham, United Kingdom
- 1990: FTU, in Frascati, Italy
- 1991: Tokamak ISTTOK,^[17] at the Instituto de Plasmas e Fusão Nuclear, Lisbon, Portugal;
- 1991: ASDEX Upgrade, in Garching, Germany



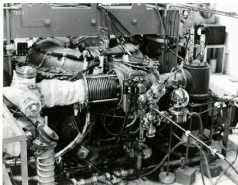
Alcator C-Mod



ida, the free encyclo... W Tokamak - Wikipedia, the free encyclo... (svoboda) buan@fi.cvut.cz - Konsole Knusader Inbox - svoboda@fi.cvut.cz - Mozilla

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

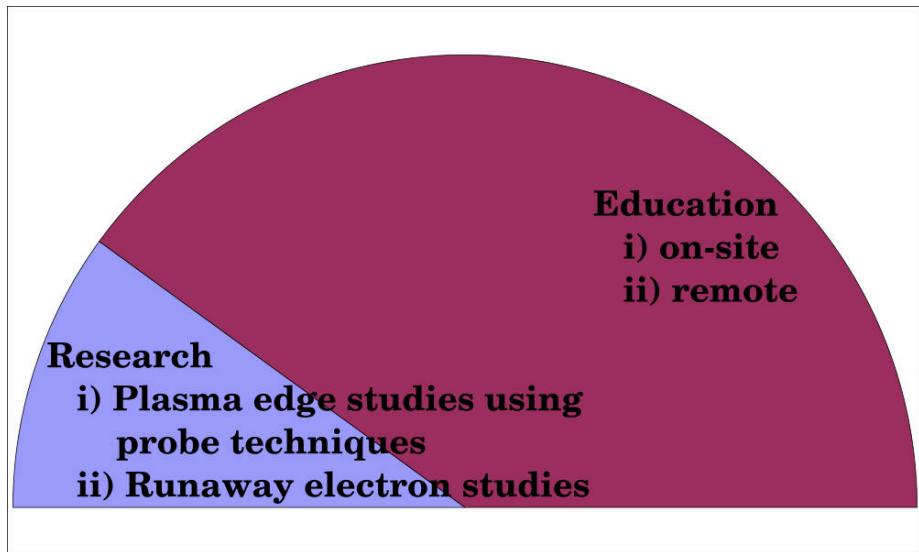
... somewhere, in the ancient cellars of Prague,

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. . .



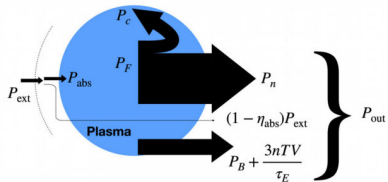
At the end of the 16th century, in the times when the Czech lands were ruled by Emperor Rudolf II, in Prague, there were Rabbi Judah Loew, well known alchemist, thinker, scholar, writer and inventor of the legendary GOLEM - a clay creature inspired with the Universe power that pursued his master's command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



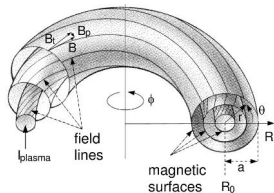
credit:[2]

- 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 .

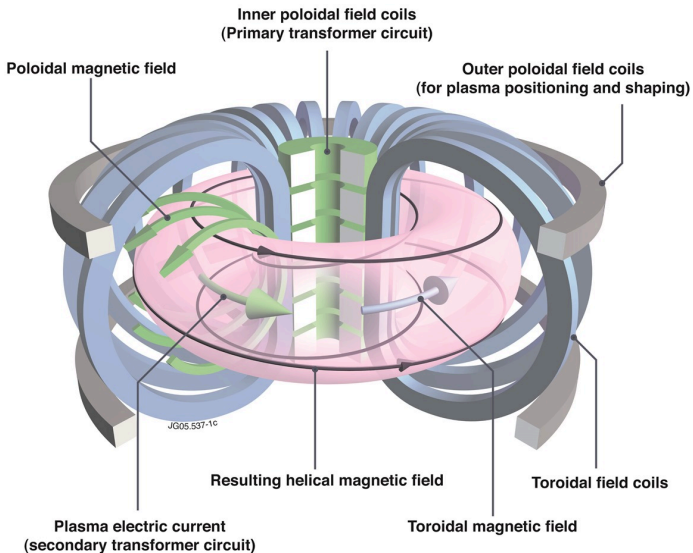
- Everything via <http://golem.fjfi.cvut.cz/ZonalFlows>
 - This presentation
 - Control rooms
 - Contact: Vojtech Svoboda,
+420 737673903,
vojtech.svoboda@fjfi.cvut.cz
 - Videoconference:
<https://meet.google.com/hnv-qjhu-xvi>



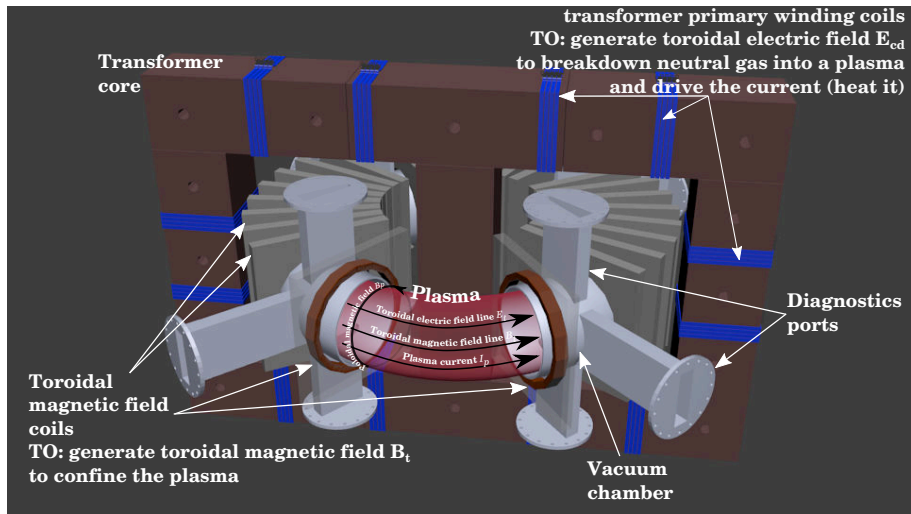
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Tokamak magnetic confinement concept

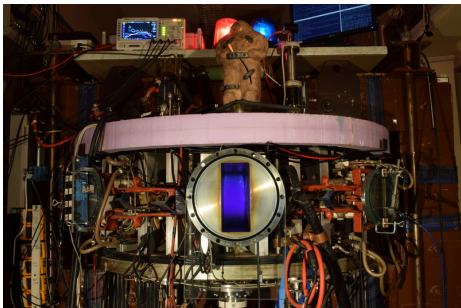


Tokamak (GOLEM) basic concept to confine and heat the plasma



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

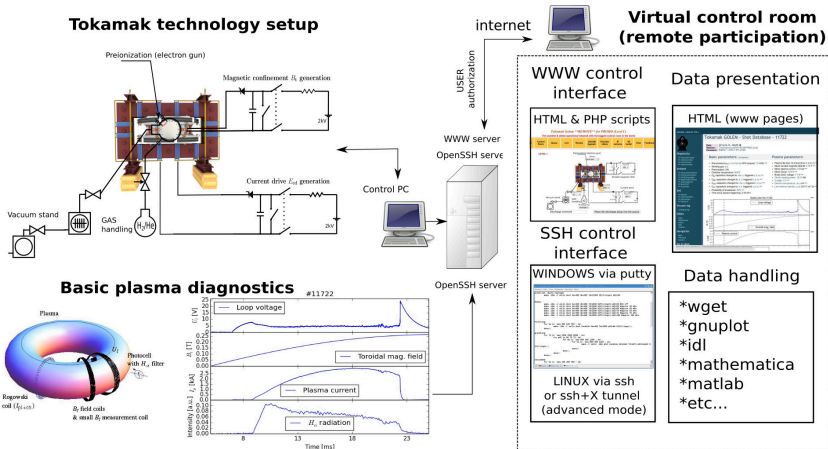


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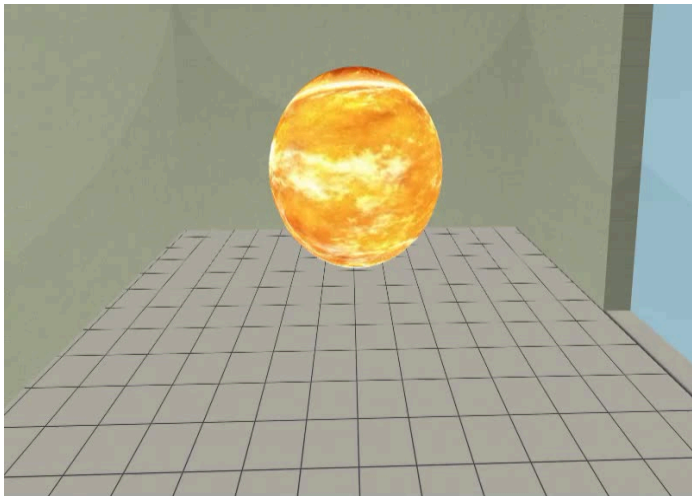
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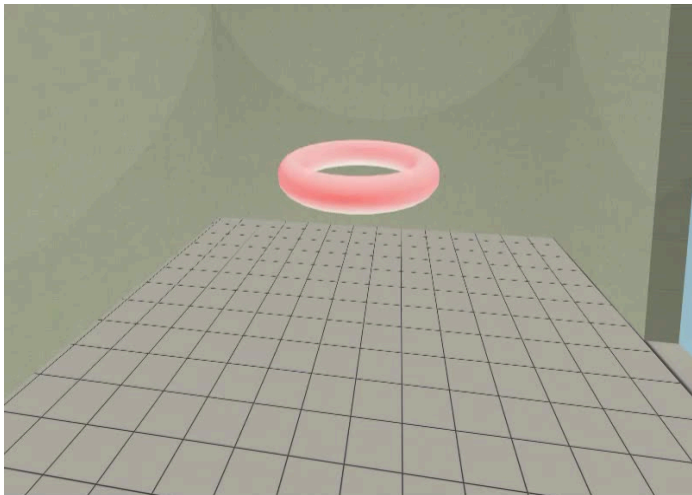
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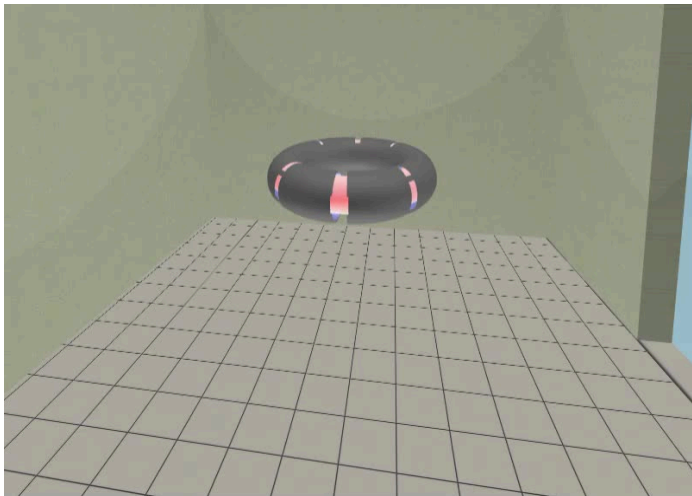
Our goal: the technology to create a μ Sun on the Earth



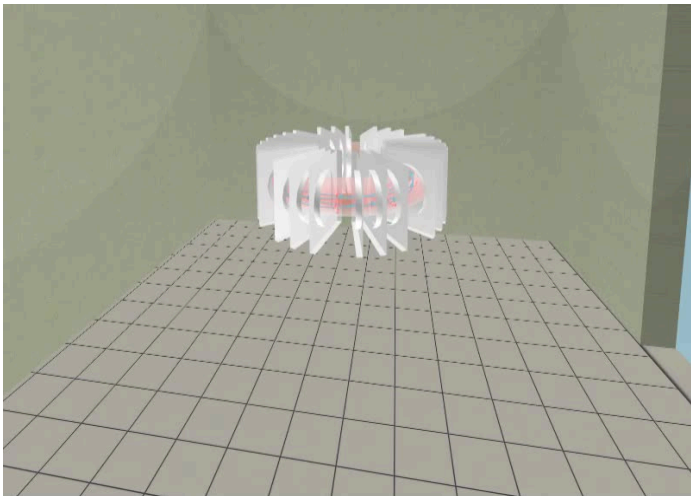
Magnetic confinement requires toroidal geometry



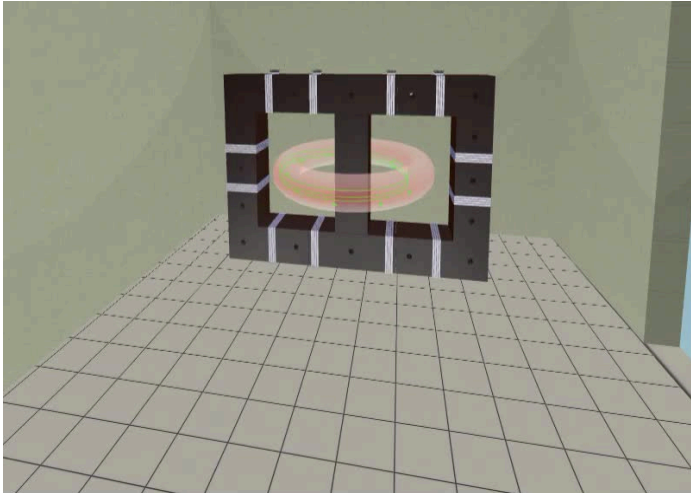
A chamber contains the thermonuclear reaction



Toroidal magnetic field coils confine the plasma



A transformer action creates and heats the plasma



The final technology altogether

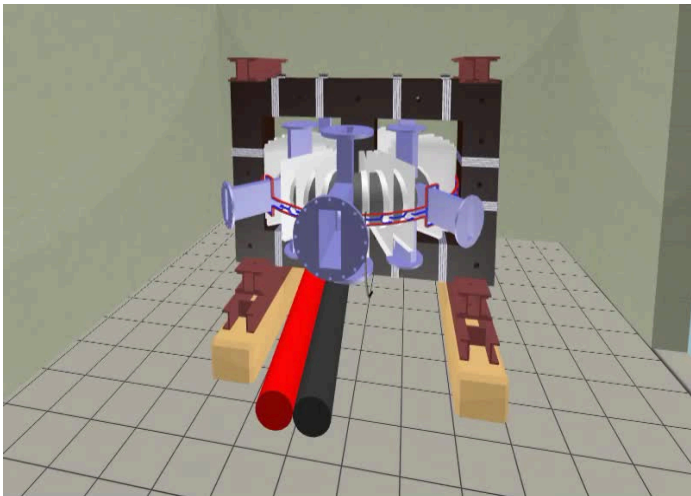


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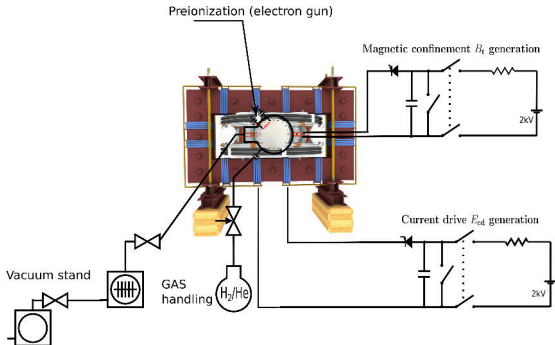
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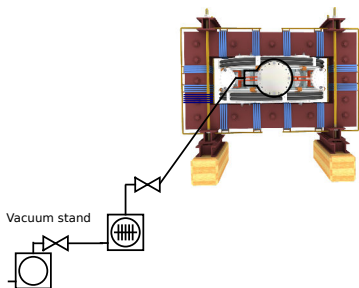
Plasma in Tokamak (GOLEM) - the least to do



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

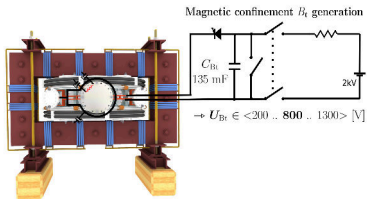
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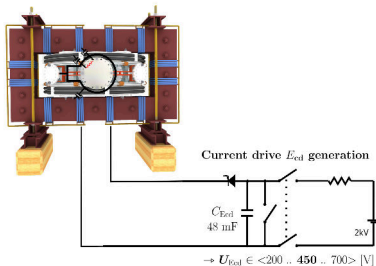
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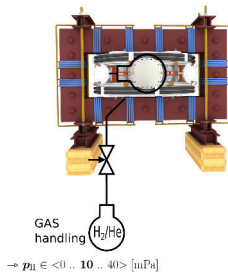
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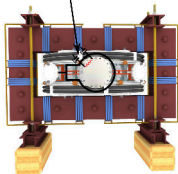


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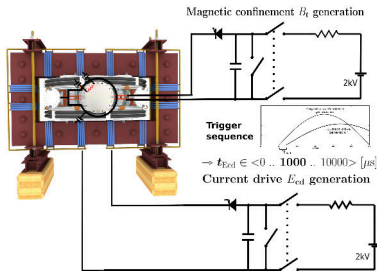
Preionization (electron gun)
→ $S/W_{\text{preion}} \in \langle \text{on} \dots \text{on} \dots \text{off} \rangle [-]$



To do:

- session start phase:
 - Evacuate the chamber
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 - Fill in the working gas
 - **Preionization**
- discharge phase
 - Trigger Magnetic confinement & Current drive
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- post-discharge phase
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Plasma in Tokamak (GOLEM) - the least to do



To do:

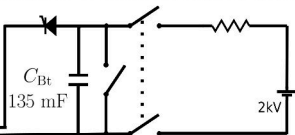
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 - Charge the capacitors
 - Fill in the working gas
 - Preionization
- discharge phase
 - **Trigger Magnetic confinement & Current drive**
 - Plasma positioning
 - Diagnostics
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Tokamak GOLEM - schematic experimental setup

Preionization (electron gun)

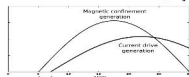
→ $S/W_{\text{preion}} \in \langle \text{on} \dots \text{on} \dots \text{off} \rangle [-]$

Magnetic confinement B_t generation

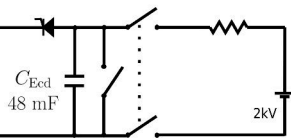


→ $U_{Bt} \in \langle 200 \dots 800 \dots 1300 \rangle [V]$

Trigger sequence



Current drive E_{cd} generation



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

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

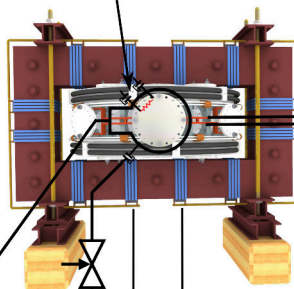
Vacuum stand



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

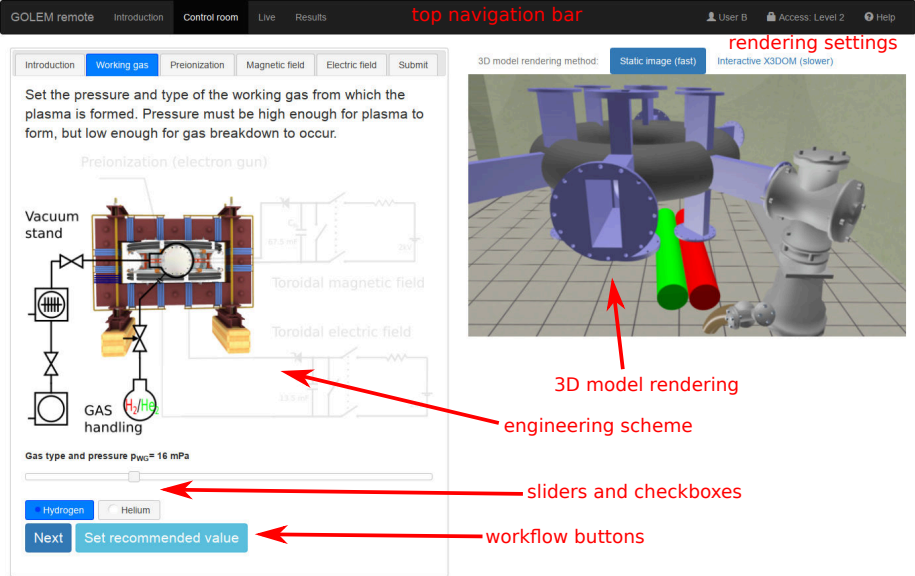
GAS handling H_2/He

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 screenshot displays the GOLEM remote control interface. At the top, a dark navigation bar contains the text 'GOLEM remote', 'Introduction', 'Control room', 'Live', and 'Results', along with user information 'User B', 'Access: Level 2', and a 'Help' icon. Below this is a secondary navigation bar with tabs for 'Introduction', 'Working gas', 'Preionization', 'Magnetic field', 'Electric field', and 'Submit'. The 'Working gas' tab is active. The main content area features a text instruction: '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 the text 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'. To the right, a 3D model rendering of the tokamak components is shown, with a red arrow pointing to it from the label '3D model rendering'. Below the diagram and 3D model, there is a slider for 'Gas type and pressure $p_{WG} = 16 \text{ mPa}$ ' and two radio buttons for 'Hydrogen' (selected) and 'Helium'. At the bottom, there are two buttons: 'Next' and 'Set recommended value'. Red arrows point from the labels 'sliders and checkboxes' and 'workflow buttons' to these elements. In the top right corner, there is a 'rendering settings' section with two options: 'Static image (fast)' (selected) and 'Interactive X3DOM (slower)'. A red arrow points from the label '3D model rendering engineering scheme' to the 3D model.

Let's make a discharge

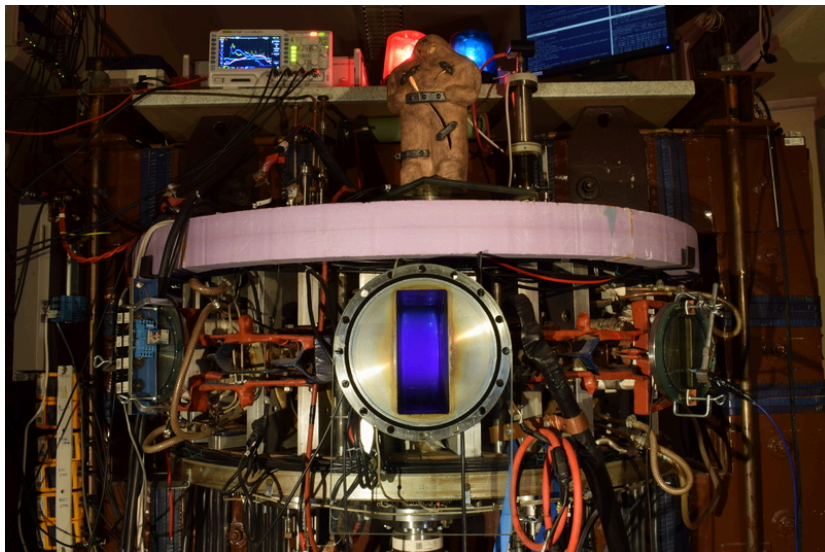


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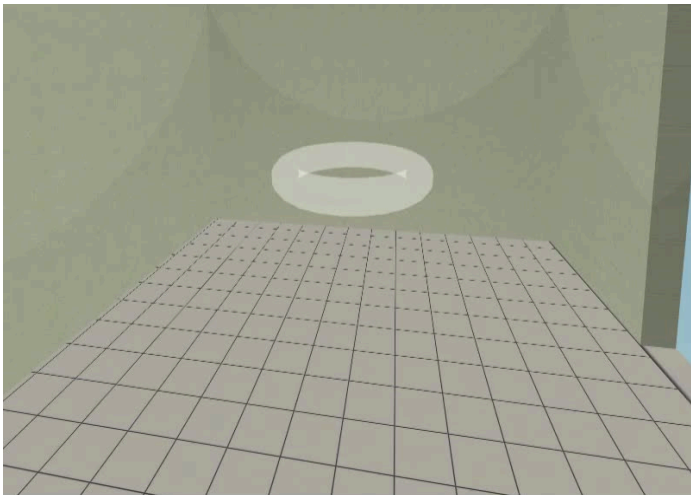
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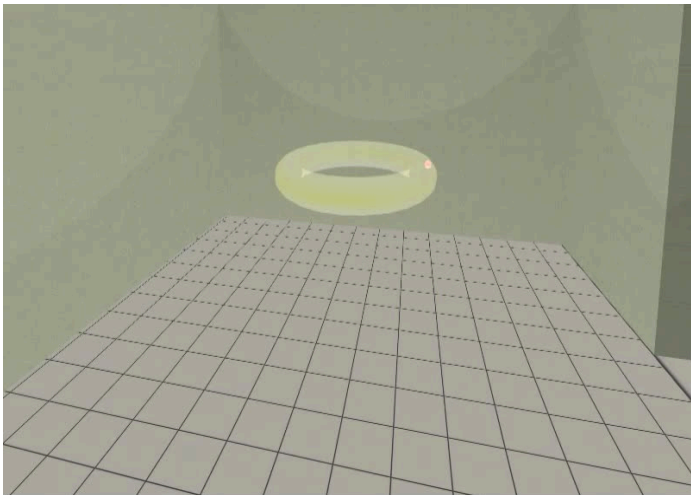
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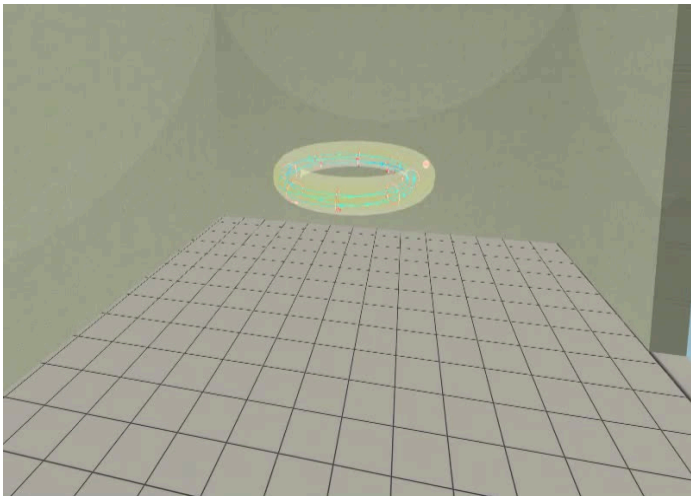
Introduce the working gas (Hydrogen x Helium)



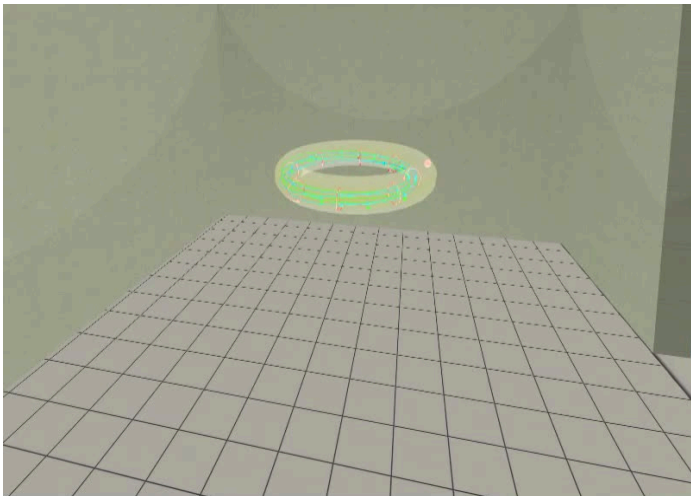
Switch on the preionization



Introduce the magnetic field



Introduce the electric field



Plasma ..

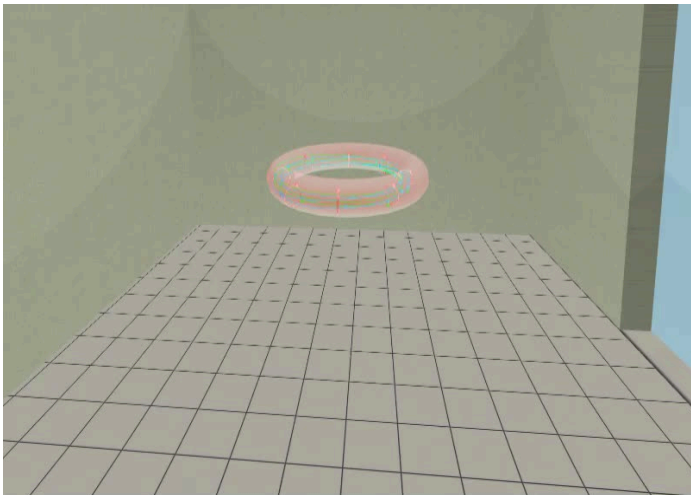


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Infrastructure room (below tokamak) 10/16



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

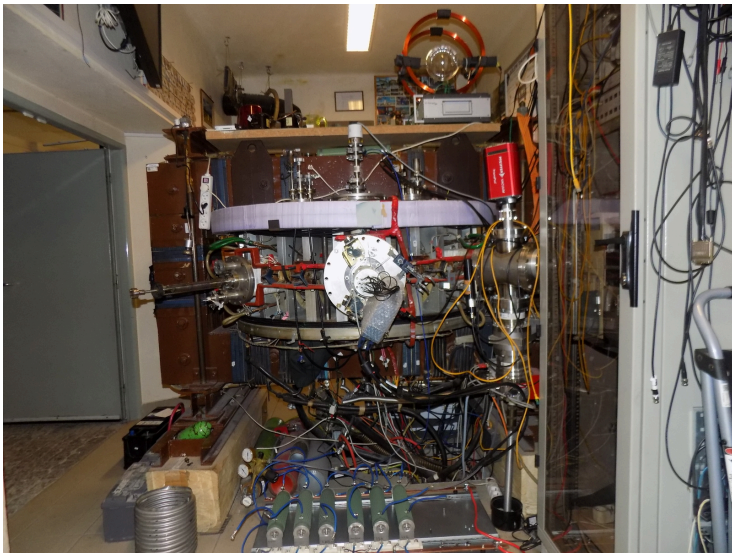
power
supply
2kV

Toroidal
magnetic field B
capacitors

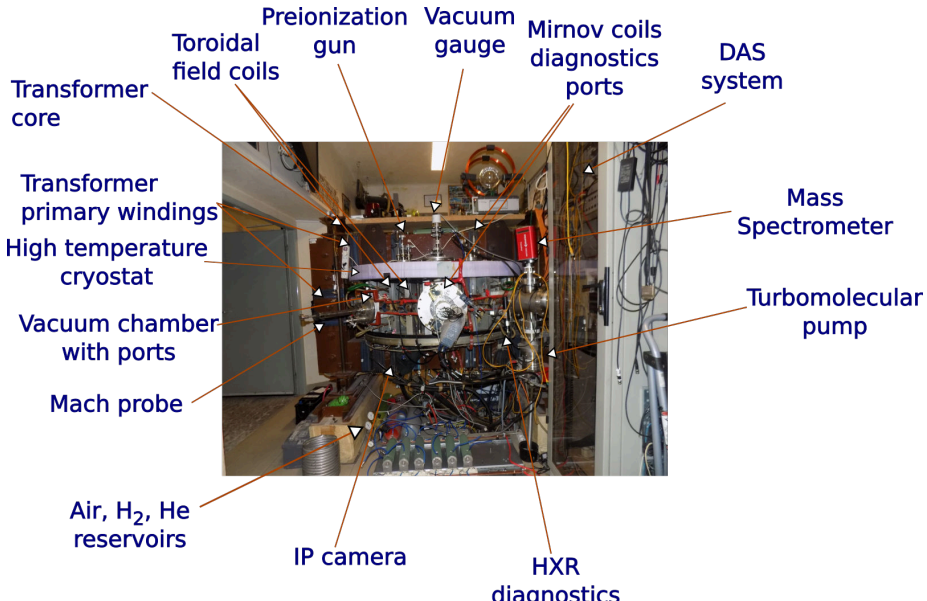
fire
protection
system



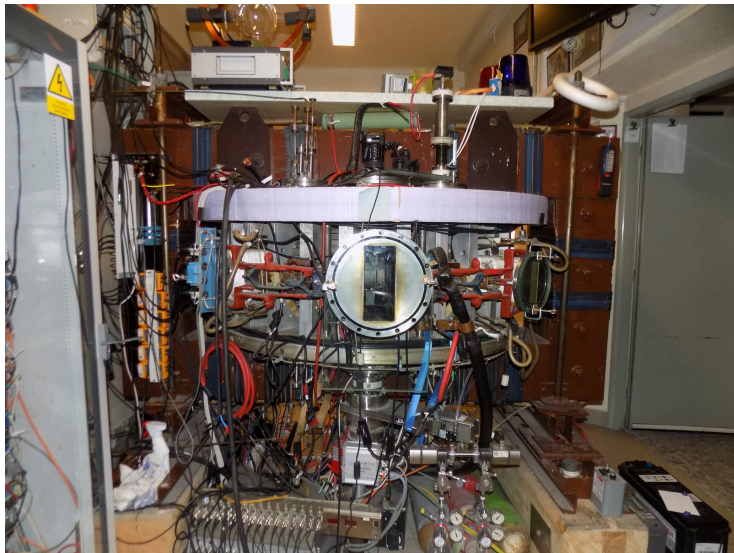
Tokamak room (North) 10/16



Tokamak room (North) 10/16



Tokamak room (South) 10/16



Tokamak room (South) 10/16

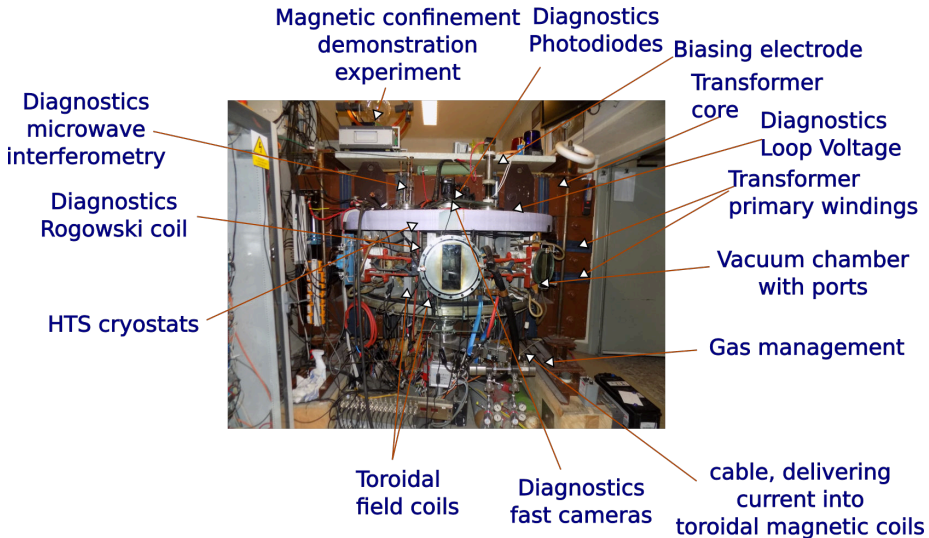


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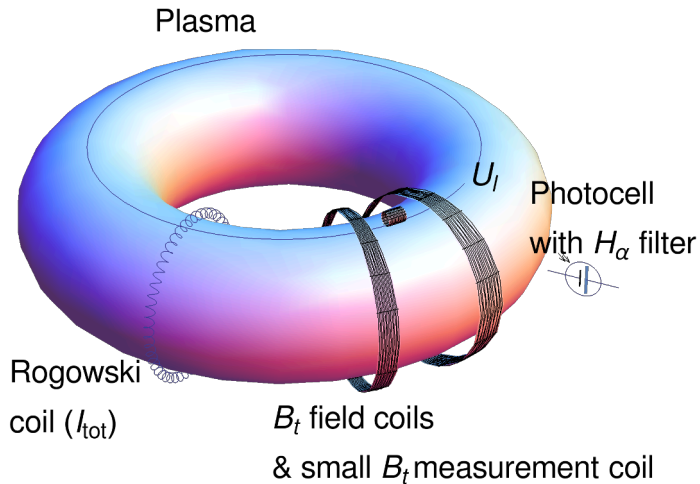
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The GOLEM tokamak - basic diagnostics



Hands on the GOLEM tokamak - equipment



Basic diagnostics - numerical processing, shot homepage

GOLEM #39187

Tokamak GOLEM - Shot Database - #39187

22-05-18 17:55:04

The date of discharge execution
The session mission
The session ID
The discharge comment
Discharge command

GOLEM II -> EDU (MHD + biasing)
39183
Vert & Rad Stab
copy | Dirigent.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_accel=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: $p_{\text{discharge, before}} = 1,66 \text{ mPa}$; $p_{\text{discharge, pos}} = 10,40 \text{ mPa}$ ($p_{\text{WG}}^{\text{request}} = 10 \text{ mPa}$ @ $\lambda_{\text{WG}}^{\text{request}} = H$)
- Toroidal magnetic field: $U_{\text{bus}}^{\text{request}} = 1200 \text{ V}$ @ $I_{\text{bus}}^{\text{request}} = 0,0 \text{ us}$
- Current drive field: $U_{\text{bus}}^{\text{request}} = 450 \text{ V}$ @ $I_{\text{bus}}^{\text{request}} = 350,0 \text{ us}$

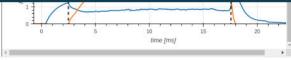
Plasma:

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

Plasma parameters:




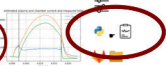
- Loop voltage: $U_{\text{loop}} = 8,02 \text{ V}$; $\max_{t \in [\text{discharge}]} U_{\text{loop}} = 9,89 \text{ V}$; $U_{\text{loop, down}} = 10,83 \text{ V}$
- Toroidal magnetic field: $\bar{B}_t = 0,40 \text{ T}$; $\max_{t \in [\text{discharge}]} \bar{B}_t = 0,57 \text{ T}$
- Plasma parameters: $T_e = 2,07 \text{ eV}$; $T_i = 2,67 \text{ eV}$; $\rho_{\text{max}} = 11,08 \text{ mg/m}^3$

GOLEM # Shot #39187



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 screenshot displays a web browser window with two main sections. The top section is a diagnostics interface for a Tektronix MSO56-a oscilloscope. It features a sidebar on the left with navigation options like 'Diagnostics', 'BasicDiagnostics', and 'ScreenShotAll.png'. The main content area is titled 'On stage diagnostics' and includes a 'Data flow' section with a graph and a 'measurement' section with various data acquisition system images. A red circle highlights a specific data point in the 'Raw data' section, and a red arrow points from this circle to the 'rawdata.jpg' file in the index below.

The bottom section is an 'Index of /shots/39187/Devices/Oscilloscopes/TektrMSO56-a' directory listing. It contains a table with columns for Name, Last modified, Size, and Description. The files listed are:

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	

At the bottom of the index, it states: Apache/2.4.38 (Debian) Server at golem.fffi.cvut.cz Port 80

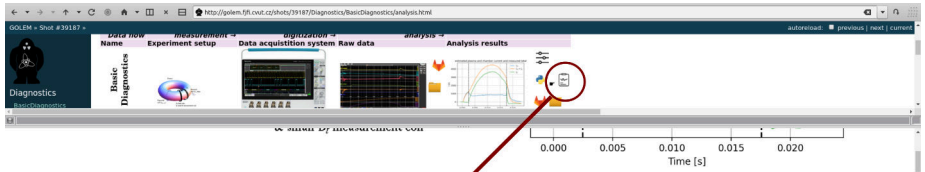
Basic diagnostics - numerical processing, Jupyter-notebook@GitLab Download & play

The screenshot displays a web browser window showing a GitLab repository page. The browser's address bar shows the URL: `https://gitlab.com/golem-tokamak/dirigent/-/blob/master/Diagnostics/BasicDiagnostics/StandardDAS.ipynb`. The repository page has a dark blue header with the GitLab logo, navigation links (About GitLab, Pricing, Talk to an expert), a search bar, and a 'Sign up now' button. A sidebar on the left lists repository features like Project information, Repository, Files, Commits, Branches, Tags, Contributors, Graph, Compare, Locked Files, Issues, Merge requests, CI/CD, and Deployments. The main content area shows the file 'StandardDAS.ipynb' (19.83 KIB) with an 'Open in Web IDE' button. The notebook's title is 'Tokamak GOLEM Basic diagnostics'. Below the title, there is a 'Procedure' section with a link 'This notebook to download' and a 'Prerequisites: function definitions' section. The 'Load libraries' section contains the following code:

```
%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 the 'Open in Web IDE' button to the 'Tokamak GOLEM Basic diagnostics' title. Another red arrow points from a circular icon in the notebook's top navigation bar to the 'Procedure' link.

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

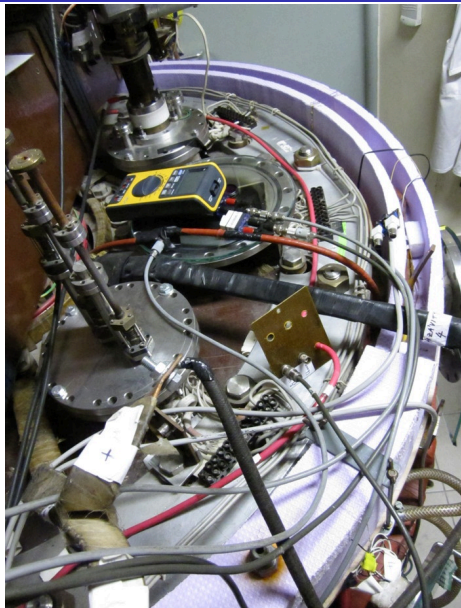
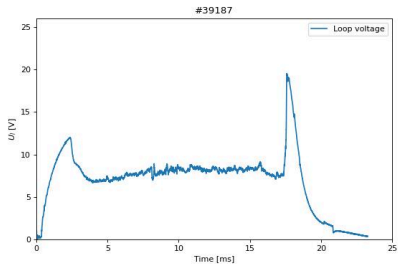
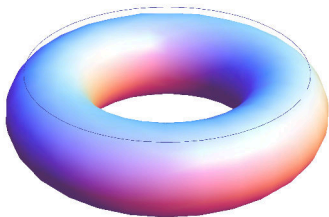
```
In [2]: import holoviews as hv
hv.extension('bokeh')
import hvplot.pandas
```



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}

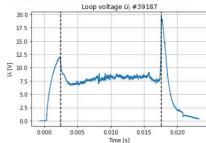
```
t_scale = 1e-3 if in_seconds else 1
if is_plasma:
    for t in (t_plasma_start, t_plasma_end):
        plt.axvline(x = T_scale, color='k', linestyle='--')
```

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': # 7000 hardcoded for now
    loop_voltage *= -1 # make positive
loop_voltage = correct_inf(loop_voltage)
loop_voltage.loc[:t_CD] = 0
ax = loop_voltage.plot(grid=True)
show_plasma_limits()
ax.set(xlabel='Time [s]', ylabel='SU IS [V]', title='Loop voltage SU IS #{}'.format(shot_no));
```

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



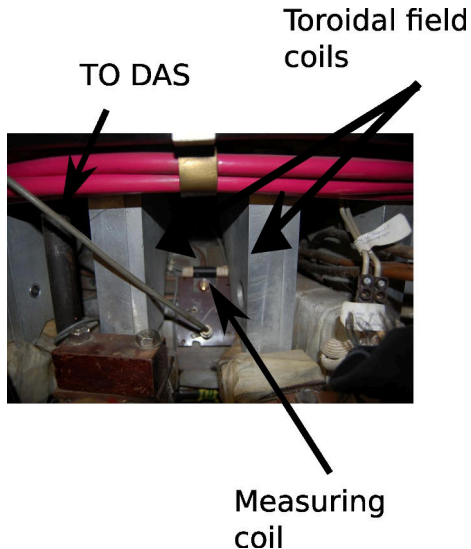
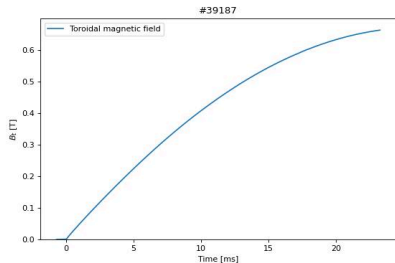
B_l calculation

Check the data availability

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

```
In [12]: dBt = read_signal(shot_no, 'U_BtCoil')
polarity_Bt = read_parameter(shot_no, 'Bt_orientation')
if polarity_Bt != 'CW': # 7000 hardcoded for now
    dBt *= -1 # make positive
dBt = correct_inf(dBt)
dBt = dBt.loc[offset_start_t].mean()
ax = dBt.plot(grid=True)
show_plasma_limits()
ax.set(xlabel='Time [s]', ylabel='sdu [0_t]/dTs [V]', title='BtCoil_raw signal #{}'.format(shot_no));
```

Toroidal magnetic field B_t @ the tokamak GOLEM



Basic diagnostics - numerical processing, B_t

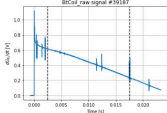
B_t calculation

Check the data availability

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

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

```
Out[12]: [Text(0.5, 0, 'Time [s]'),
Text(0, 0.5, 'dBt [V]'),
Text(0.5, 1.0, 'BtCoil raw signal #39187')]
BtCoil raw signal #39187
```

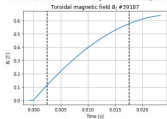


Integration (it is a magnetic diagnostic) & calibration

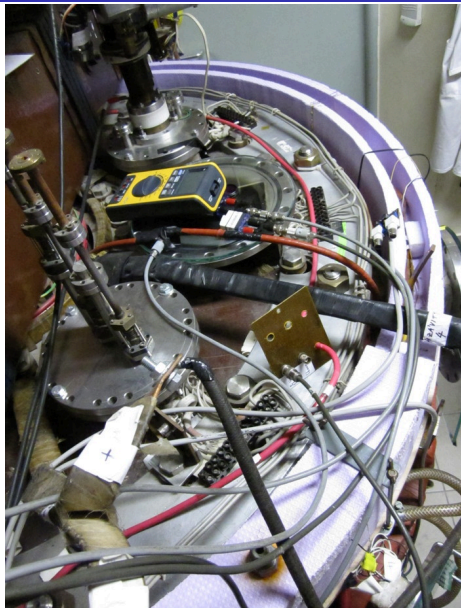
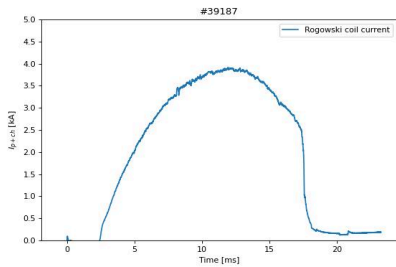
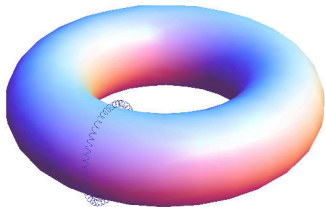
```
In [13]: K_BtCoil = float(read_parameter(shot_no, 'SystemParameters/K_BtCoil')) # Get BtCoil calibration factor
print('BtCoil calibration factor K_BtCoil={} T/(Vs)'.format(K_BtCoil))
BtCoil calibration factor K_BtCoil=70.42 T/(Vs)
```

```
In [14]: Bt = pd.Series(integrate.cumtrapz(dbt, x=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 [T] #{}'.format(shot_no));
```

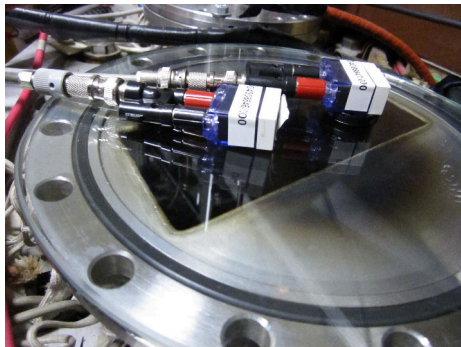
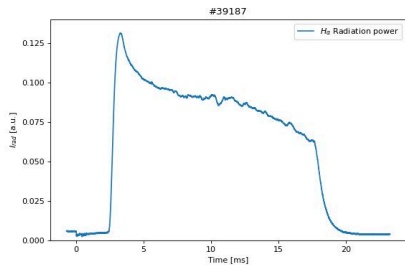
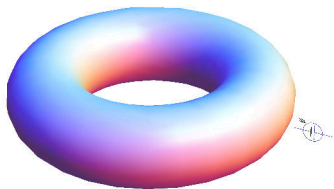
```
Out[14]: [Text(0.5, 0, 'Time [s]'),
Text(0, 0.5, 'Bt [T]'),
Text(0.5, 1.0, 'Toroidal magnetic field Bt [T] #39187')]
Toroidal magnetic field Bt #39187
```



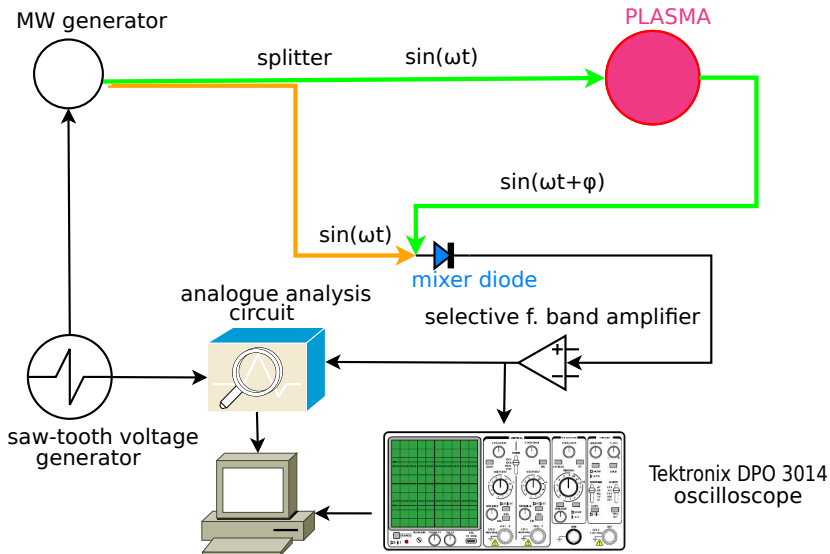
Total current I_{ch+p}



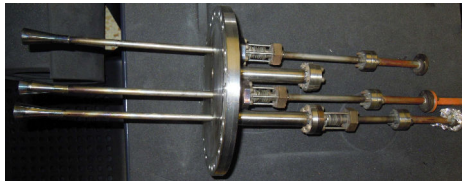
Visible radiation



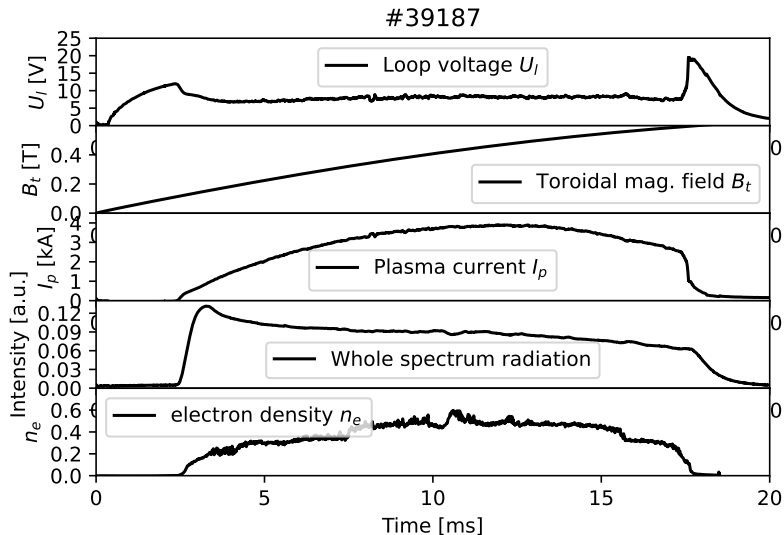
Electron density n_e interferometry measurement scheme



The GOLEM tokamak interferometry HW



Finally "Typical", well executed discharge @ GOLEM



Shot homepage (≈ 2 minutes after discharge execution)

GOLEM - Shot #40631
autoreload

Tokamak GOLEM - Shot Database - #40631

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

The session mission 1Final -> Dirigent service

The session ID 40605

The discharge comment Discharge command

Technological parameters

- Working Gas: $p_{\text{discharge, before}}^{\text{He}}=2.46$ mPa; $p_{\text{discharge, after}}^{\text{He}}=5.04$ mPa ($p_{\text{request}}^{\text{He}}=15$ mPa @ $v_{\text{WG}}^{\text{request}}=H$)
- Toroidal magnetic field: $I_{\text{t}}^{\text{request}}=800$ V @ $I_{\text{t}}^{\text{request}}=0.0$ kA
- Current drive field: $U_{\text{coil}}^{\text{request}}=450$ V @ $I_{\text{coil}}^{\text{request}}=500.0$ kA

Plasma:

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

Plasma parameters:

- Loop voltage: $U_{\text{loop}}=8.82$ V; $\max_{t \in [0; T_p]}(U_{\text{loop}})=16.17$ V; $U_{\text{residual}}=0.00$ V
- Toroidal magnetic field: $B_t=0.24$ T; $\max_{t \in [0; T_p]}(B_t)=0.36$ T
- Plasma current: $I_p=2.28$ kA; $\max_{t \in [0; T_p]}(I_p)=2.92$ kA; $t_p^{\text{start}}=0.00$ ms

Basic Diagnostics

On stage diagnostics

Name	measurement Experiment setup	digitization Data acquisition system	Raw data	analysis	Analysis results
Basic Diagnostics 					
Double rake probe <small>@ Shot#40631/shot part</small> 					Without Analysis

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

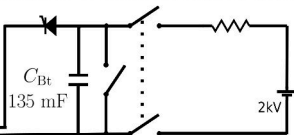
- 1 Introduction
- 2 The Tokamak (GOLEM)
- 3 The Tokamak GOLEM (remote) operation
 - Control room
 - Data handling @ the Tokamak GOLEM
- 4 $\tau_{E,e}$ & q
- 5 Conclusion
- 6 Appendix

Tokamak GOLEM - schematic experimental setup

Preionization (electron gun)

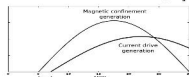
→ $S/W_{\text{preion}} \in \langle \text{on} \dots \text{on} \dots \text{off} \rangle [-]$

Magnetic confinement B_t generation

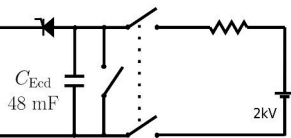


→ $U_{Bt} \in \langle 200 \dots 800 \dots 1300 \rangle [V]$

Trigger sequence



Current drive E_{cd} generation



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

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

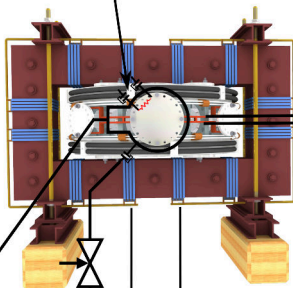
Vacuum stand



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

Control room: Introduction

GOLEM remote

Introduction

Control room

Live

Results

Prague

Access: Level 1

Help

Introduction

Working gas

Preionization

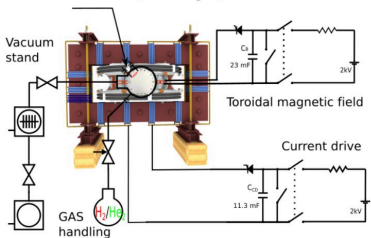
Magnetic field

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)

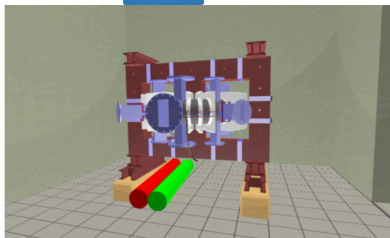


Next

3D model rendering method:

Static image (fast)

Interactive X3DOM (slower)



Control room: Working gas

GOLEM remote Introduction Control room Live Results Master Access Level Help

Introduction Working gas Preionization Magnetic field Electric field Submit

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

Preionization (electron gun)

Vacuum stand

GAS H_2/He handling

Toroidal magnetic field

Toroidal electric field

Gas type and pressure p_{gas} : 18 mPa

Hydrogen Helium

Next Set recommended value

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

Control room: Preionization

GOLEM remote Introduction Control room Live Results Master Access Level 1 Help

Introduction Working gas Preionization Magnetic field Electric field Submit

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

Preionization (electron gun)

Vacuum stand

Toroidal magnetic field

Toroidal electric field

GAS handling

67.5 mT

133.5 mV

20V

20V

Ionization method

Electron gun No ionization

Next

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

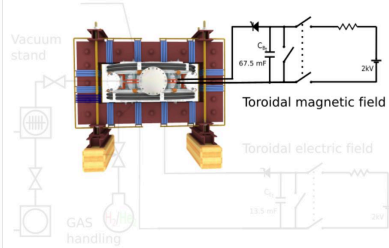
Control room: Magnetic field B_t

GOLEM remote Introduction Control room Live Results The Torino Politecnico Italy Group 1 Access: Level 2 Help

Introduction Working gas Preionization **Magnetic field** Electric field Submit Press F11 to exit full screen. [3D model rendering method](#) [State: mag field](#) [Interactive X3DOM \(slow\)](#)

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

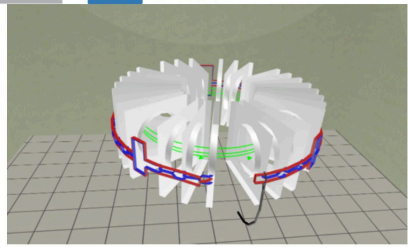
Toroidal magnetic field

Toroidal electric field

GAS handling

Capacitor voltage U_{C_2} : 600 V

Next



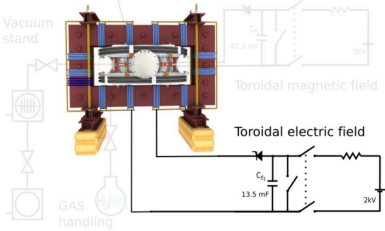
Control room: Current drive E_{cd}

GOLEM remote Introduction Control room Live Results The Toronno 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

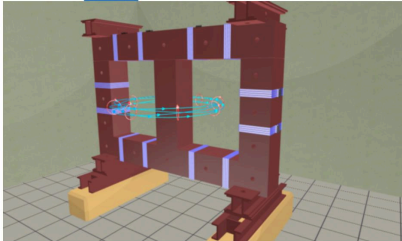
GAS handling

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 (slower)



Control room: ... and Submit

GOLEM remote Introduction Control room Live Results

the Torino Politecnico Italy Group 1 Access: Level 2 Help

Introduction Working gas Pressurization 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.

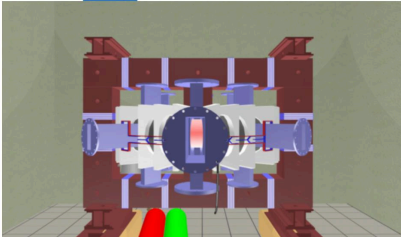
Comment

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 lab and start again. Or you can go to specific control tabs and reconfigure the discharge and then submit another discharge request.

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

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



The image shows a 3D model of a discharge chamber. It features a central cylindrical electrode with a red glow, surrounded by a complex arrangement of blue and white components, likely representing magnetic coils or gas inlets. The entire assembly is mounted on a dark red base. The background is a simple grey floor and wall.

Shot homepage (≈ 2 minutes after discharge execution)

GOLEM - Shot #40631
autoreload

Tokamak GOLEM - Shot Database - #40631

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

The session mission 1Final -> Dirigent service

The session ID 40605

The discharge comment Discharge command

Technological parameters

- Working Gas: $p_{discharge}^{before} = 2.46$ mPa; $p_{discharge}^{after} = 5.04$ mPa ($p_{request}^{before} = 15$ mPa @ $v_{request}^{before} = H$)
- Toroidal magnetic field: $I_{t0}^{request} = 800$ V @ $I_{t0}^{request} = 0.0$ us
- Current drive field: $U_{coil}^{request} = 450$ V @ $I_{coil}^{request} = 500.0$ us

Plasma:

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

Plasma parameters:

- Loop voltage: $U_{loop} = 8.82$ V; $max_{r=1}(dI_{charge})/dt_{loop} = 16.17$ V; $U_{residual} = 0.00$ V
- Toroidal magnetic field: $B_t = 0.24$ T; $max_{r=1}(dI_{charge})/dt = 0.36$ T
- Plasma current: $I_p = 2.28$ kA; $max_{r=1}(dI_{charge})/dt = 2.92$ kA; $t_{p}^{start} = 0.00$ ms

Basic Diagnostics

On stage diagnostics

Name	measurement Experiment setup	digitization Data acquisition system	Raw data	analysis	Analysis results
Basic Diagnostics					
	Double rake probe (from the tokamak part)				Without Analysis

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 - 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'
```

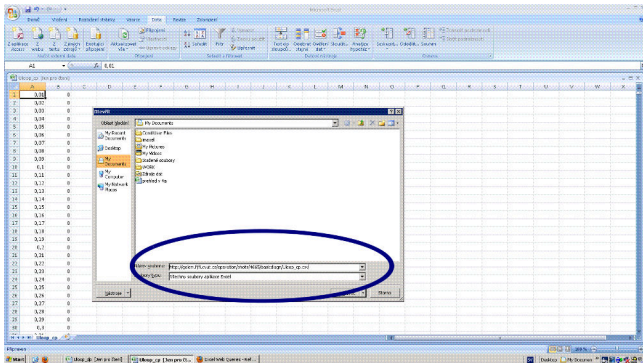
```
shot_no=39187;\  
signal_id="Diagnostics/BasicDiagnostics/Results/U_loop.csv";\  
gnuplot -p -e "set title \"Golem\";set datafile separator \",\";\  
set xlabel \"t [s]\";set ylabel \"U\";\  
plot \"< \  
wget -q -O - http://golem.fjfi.cvut.cz/shots/$shot_no/$signal_id\" \  
w l t \"U\""
```

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_i : `wget http://golem.fjfi.cvut.cz/utis/data/<#ShotNo>/loop_voltage`
 - To get whole shot: `wget -r -nH -cut-dirs=3 -no-parent -l2 -Pshot http://golem.fjfi.cvut.cz/shots/<#ShotNo>`

Excel



File→Open→

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

Spreadsheets (Excel and others)

are not recommended, only tolerated.

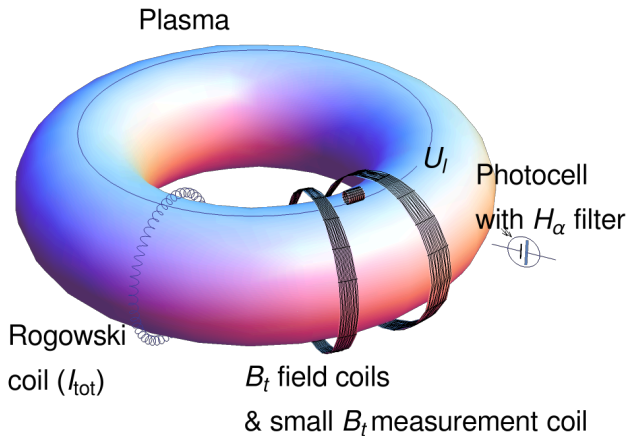
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Hands on the GOLEM tokamak - equipment



The GOLEM tokamak - standard diagnostics



The GOLEM tokamak interferometry HW

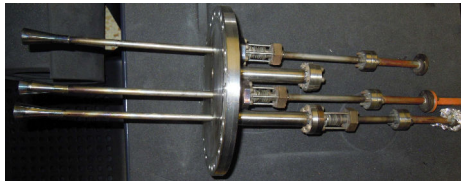
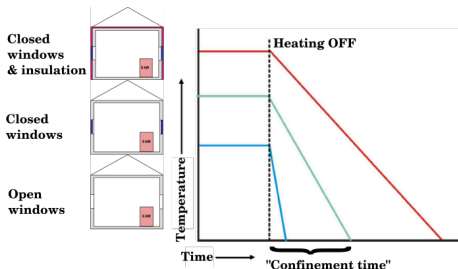


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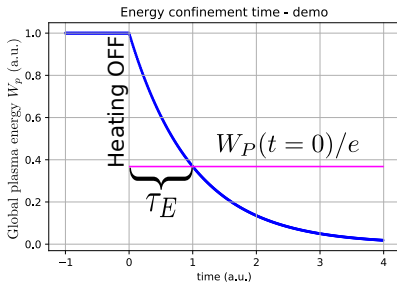
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Towards the Electron Energy Confinement Time $\tau_{E,e}$ @tG

House (cooling after heating stops)



Tokamak (cooling after heating stops)

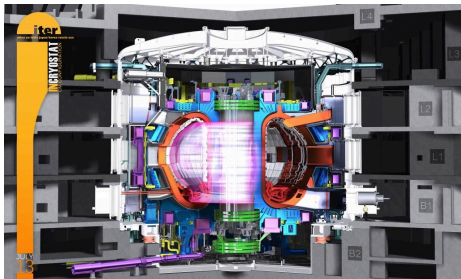


When heating is switched off, both systems lose their internal energy exponentially.
This motivates the definition of the electron energy confinement time $\tau_{E,e}$.

ITER vs GOLEM

ITER:

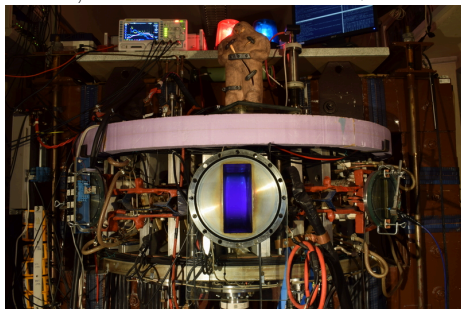
$$\tau_E \approx 3.6 \text{ s}$$



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:

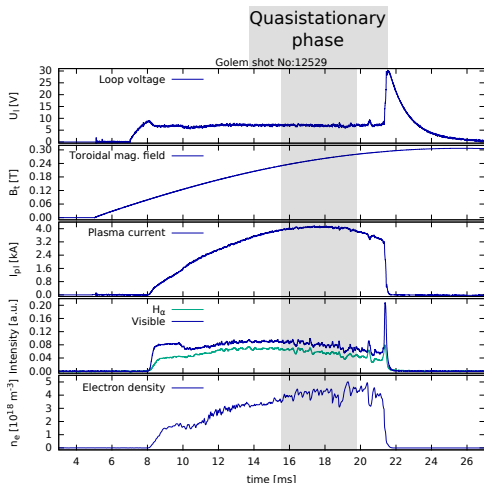
$$P_{OH} \approx P_{\text{loss}}.$$

- 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:

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

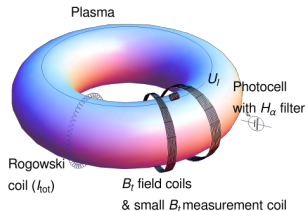
All entering quantities are experimentally accessible @tG:

- $P_{\text{OH}}(t) = V_{\text{loop}}(t) I_p(t)$,
- $T_e(t)$ 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 $[t_1, t_2]$:

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

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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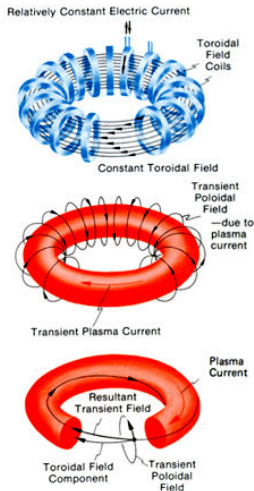
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Towards the Safety Factor q

Magnetic field lines in a tokamak

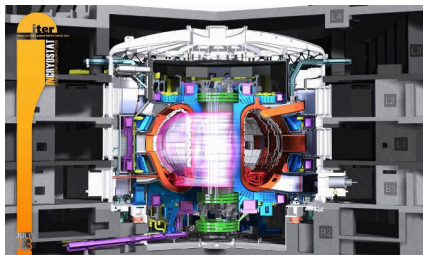
Why it matters:

- 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

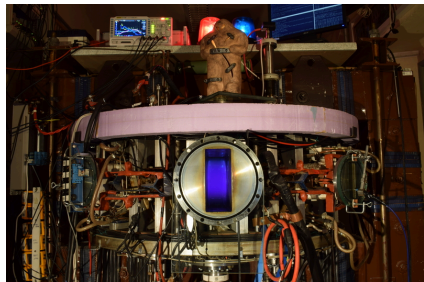


Typical edge safety factor:

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

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:

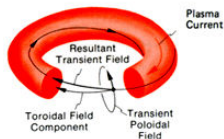
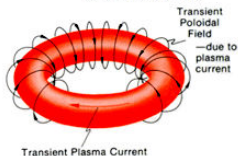
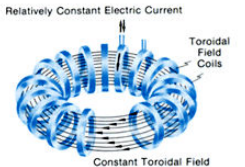
$$q(r) = \frac{rB_t}{R_0 B_p(r)}$$

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:

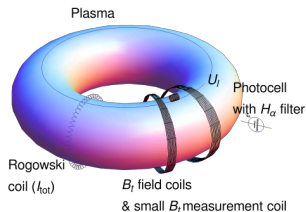
$$q(r) = \frac{2\pi r^2 B_t}{\mu_0 R_0 I_p(r)}$$



Magnetic field line winding

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

Directly measured 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:

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

Diagnostics relevant to $q(a)$ on GOLEM

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
 $\bar{I}_p = \langle I_p \rangle$

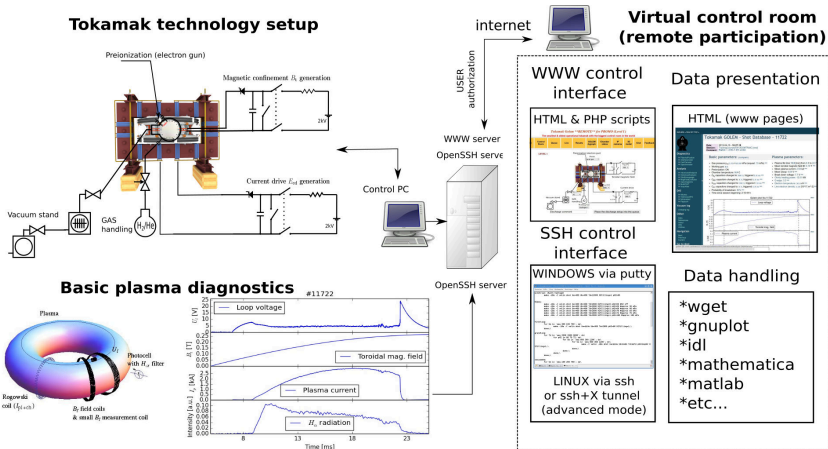
Safety factor at the edge:

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

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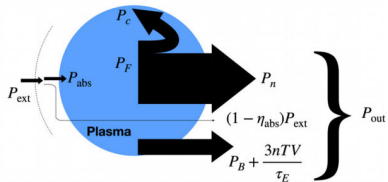
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The global schematic overview of the tG experiment



Two key fusion technology parameters you can touch experimentally

Energy Confinement Time τ_E



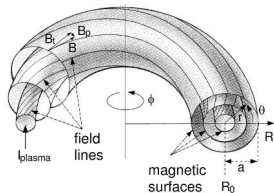
credit:[2]

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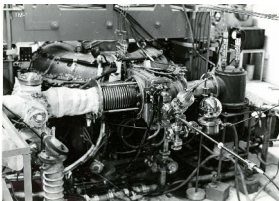
CTU RVO68407700, SGS 17/138/OHK4/2T/14, GAČR GA18-02482S, EU funds CZ.02.1.01/0.0/0.0/16_019/0000778 and CZ.02.2.69/0.0/0.0/16_027/0008465, IAEA F13019, FUSENET and EUROFUSION.

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Thank you for your attention

Tokamak TM1
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-1960-1977



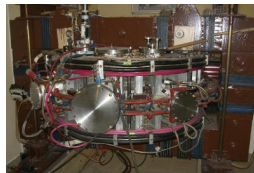
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**SCIENCE
& education**

Tokamak GOLEM
@Czech Technical University, Prague
2007-



**EDUCATION
& science**

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

Preionization (electron gun)
Posias
 C_1 [V] 300
200
Toroidal magnetic field
 C_2 [m] 200
Current drive
 C_{1m} [V] 300
300
Vacuum stand
GAS handling
Welding Gas
Discharge comment
Place the discharge setup into the queue





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