

Vojtěch Svoboda  
on behalf of the tokamak GOLEM team  
with conceptual assistance from advanced AI tools  
  
for American University of Beirut

November 28, 2025

# 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

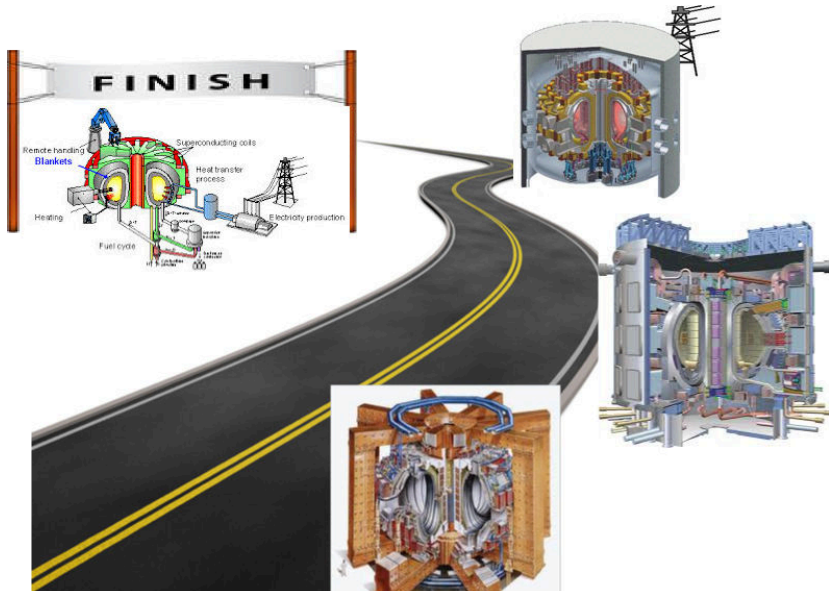
## 5 Conclusion

## 6 Appendix

# Table of Contents

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

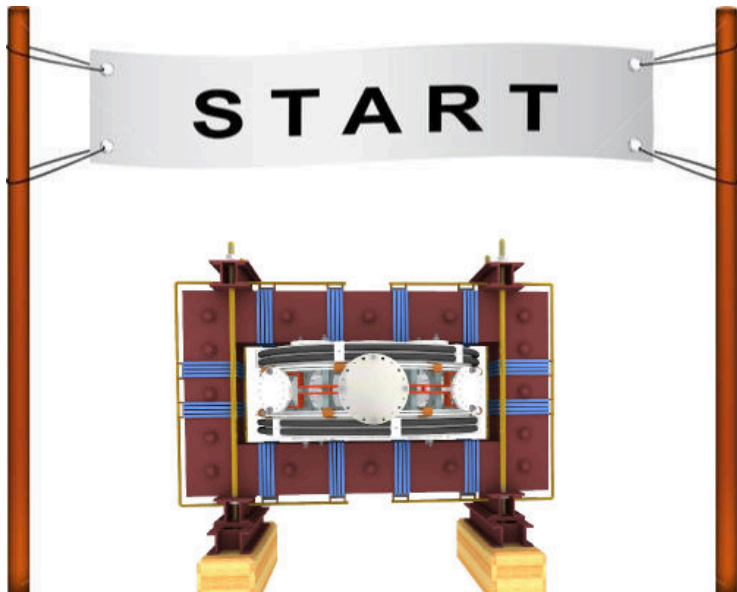
# Milestones to Fusion Power Plant



# 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

Not logged in [Talk](#) [Contributions](#) [Create account](#) [Log in](#)

Article **Talk** [Read](#) [Edit](#) [View history](#)

 **WIKIPEDIA**  
The Free Encyclopedia

[Main page](#)  
[Contents](#)  
[Featured content](#)  
[Current events](#)

## 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<sup>[122]</sup>) in Prague, Czech Republic. In operation in Kurchatov Institute since early 1960s but renamed to Castor in 1977 and moved to IPP CAS,<sup>[131]</sup> Prague; in 2007 moved to FNSPE, Czech Technical University in Prague and renamed to Golem.<sup>[14]</sup>
- 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,<sup>[15]</sup> at the CEA, Cadarache, France
- 1989: Aditya, at Institute for Plasma Research (IPR) in Gujarat, India
- 1980s: DIII-D,<sup>[16]</sup> in San Diego, USA; operated by General Atomics since the late 1980s
- 1989: COMPASS,<sup>[13]</sup> in Prague, Czech Republic; in operation since 2008, previously operated from 1989 to 1999 in Culham, United Kingdom
- 1990: FTU, in Frascati, Italy
- 1991: Tokamak ISTOK,<sup>[17]</sup> at the Instituto de Plasmas e Fusão Nuclear, Lisbon, Portugal;
- 1991: ASDEX Upgrade, in Garching, Germany



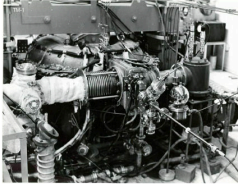
Alcator C-Mod



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

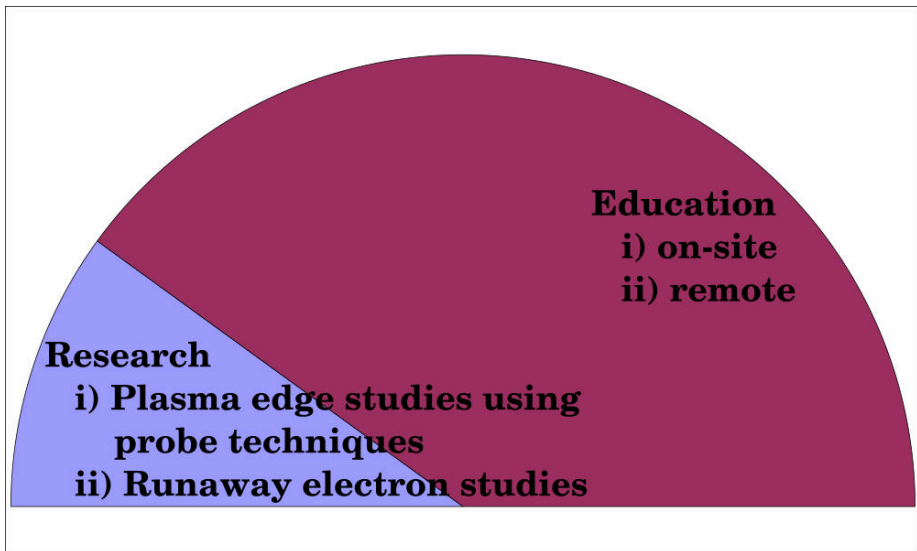
... somewhere, in the ancient cellars of Prague,

*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. . .*



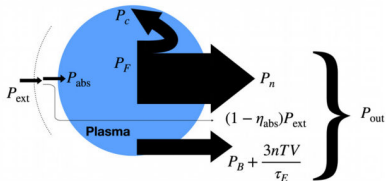
At the end of the 16th century, in the times when the Czech lands were ruled by Emperor Rudolf II, in Prague, there were Rabbi Judah Loew, well known alchemist, thinker, scholar, writer and inventor of the legendary GOLEM - a clay creature inspired with the Universe power that pursued his master's command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



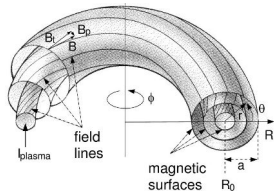
credit:[2]

- 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  $I_p$ .

# Production

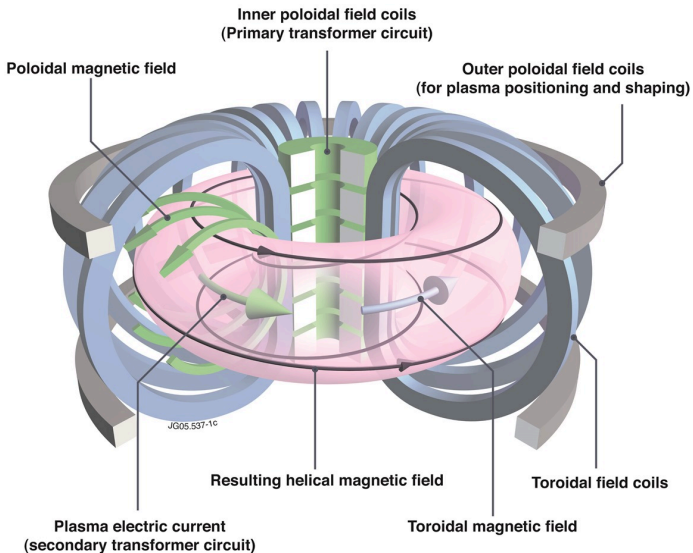
- Everything via <http://golem.fjfi.cvut.cz/Beirut>
  - This presentation
  - Control rooms
  - Contact: Vojtech Svoboda,  
+420 737673903,  
[vojtech.svoboda@fjfi.cvut.cz](mailto:vojtech.svoboda@fjfi.cvut.cz)
  - Videoconference:  
<https://meet.google.com/hnv-qjhu-xvi>



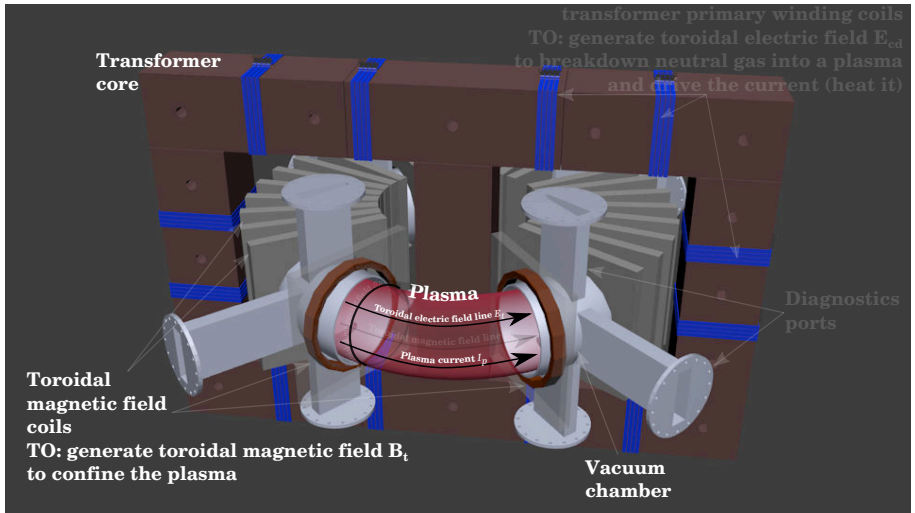
# Table of Contents

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

# Tokamak magnetic confinement concept

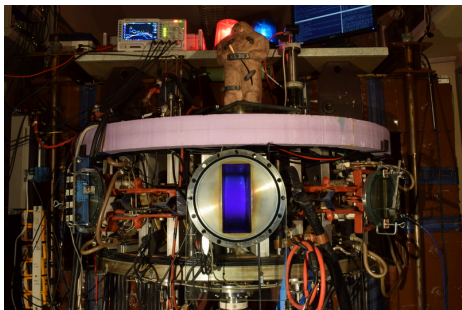


# Tokamak (GOLEM) basic concept to confine and heat the plasma



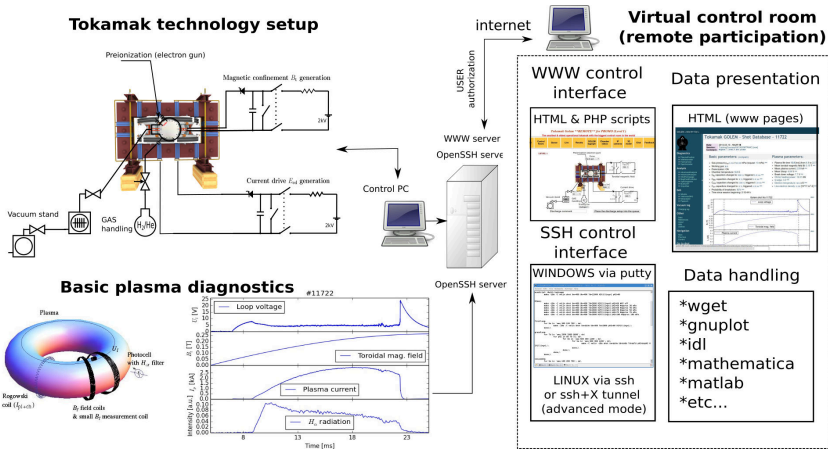
# The tokamak GOLEM basic characteristics

*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



# Table of Contents

## 1 Introduction

## 2 The Tokamak (GOLEM)

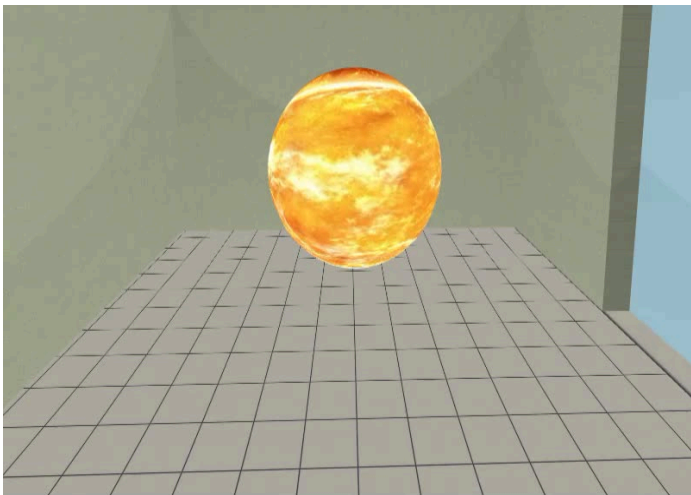
- The GOLEM tokamak concept
- The scenario to make the (GOLEM) tokamak discharge
- The scenario to discharge virtually
- The GOLEM tokamak - guide tour
- The GOLEM tokamak basic diagnostics

## 3 The Tokamak GOLEM (remote) operation

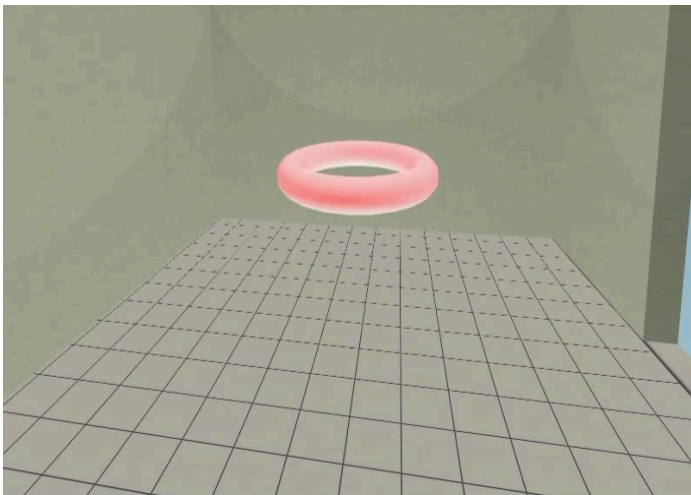
## 4 $\tau_{E,e}$ & $q$

## 5 Conclusion

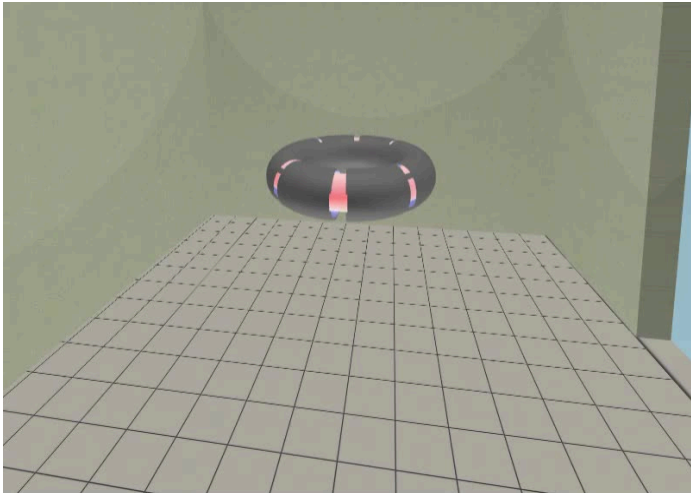
Our goal: the technology to create a  $\mu$ Sun on the Earth



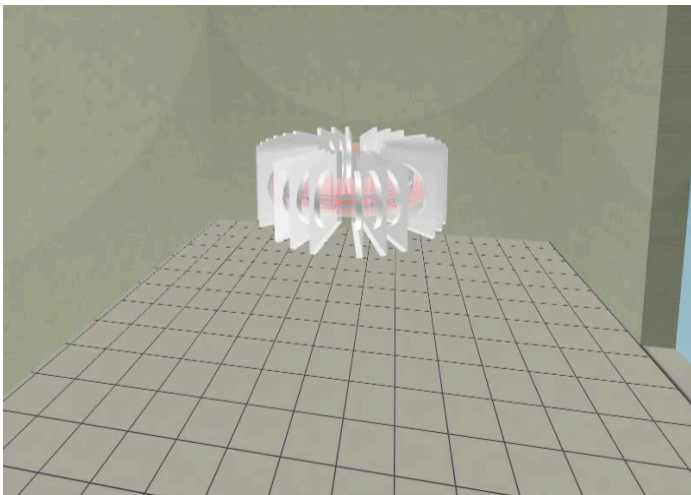
# Magnetic confinement requires toroidal geometry



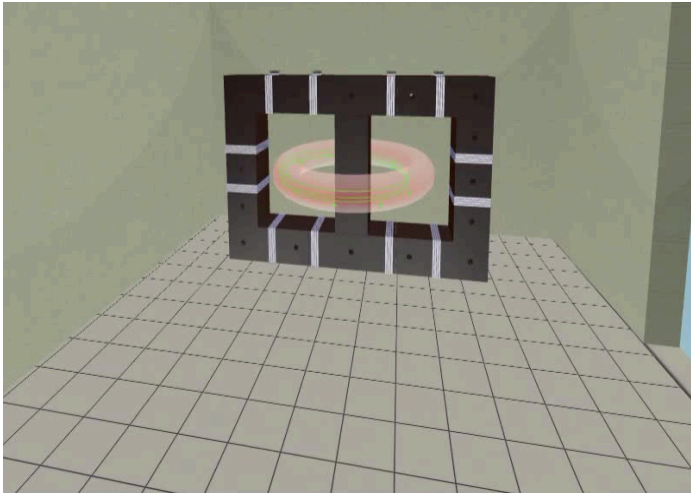
A chamber contains the thermonuclear reaction



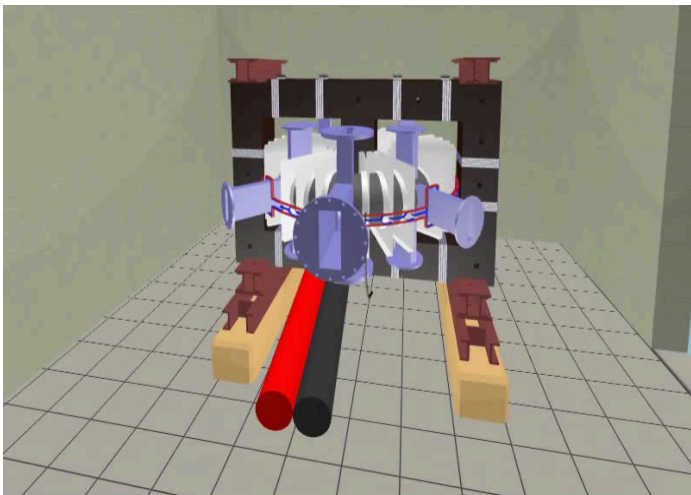
Toroidal magnetic field coils confine the plasma



A transformer action creates and heats the plasma



# The final technology altogether



# Table of Contents

## 1 Introduction

## 2 The Tokamak (GOLEM)

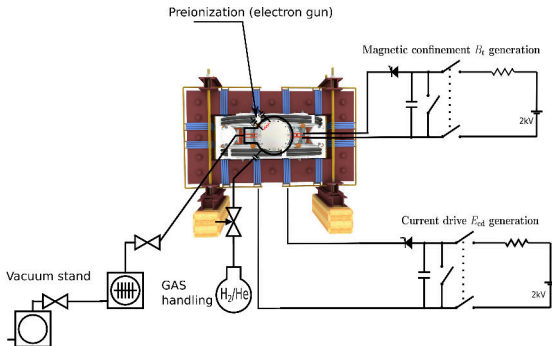
- The GOLEM tokamak concept
- The scenario to make the (GOLEM) tokamak discharge
- The scenario to discharge virtually
- The GOLEM tokamak - guide tour
- The GOLEM tokamak basic diagnostics

## 3 The Tokamak GOLEM (remote) operation

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

## 5 Conclusion

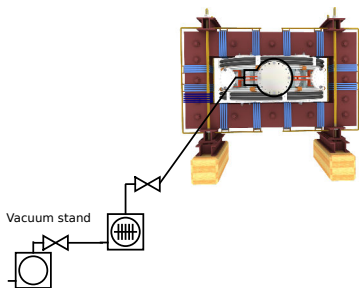
# Plasma in Tokamak (GOLEM) - the least to do



## 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

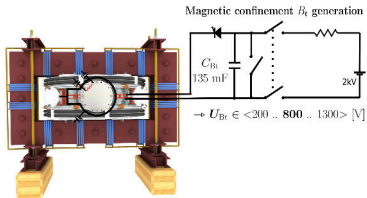
# Plasma in Tokamak (GOLEM) - the least to do



## 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

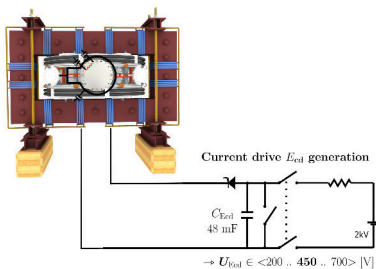
# Plasma in Tokamak (GOLEM) - the least to do



## 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

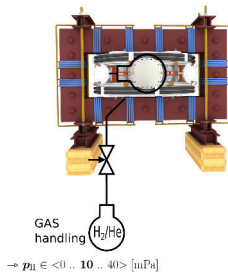
# Plasma in Tokamak (GOLEM) - the least to do



## 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

# Plasma in Tokamak (GOLEM) - the least to do



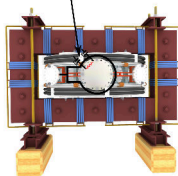
## To do:

- 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

# Plasma in Tokamak (GOLEM) - the least to do

Preionization (electron gun)

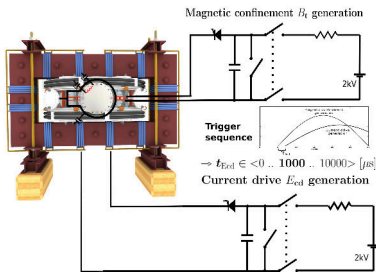
→  $S/W_{\text{preion}} \in \langle \text{on} \dots \text{off} \rangle [-]$



## 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
  - Data collection & analysis
  - Shot homepage creation

# Plasma in Tokamak (GOLEM) - the least to do



## To do:

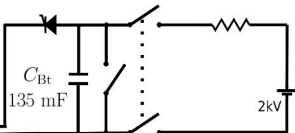
- session start phase:
  - Evacuate the chamber
- pre-discharge phase
  - Charge the capacitors
  - Fill in the working gas
  - Preionization
- discharge phase
  - **Trigger Magnetic confinement & Current drive**
  - Plasma positioning
  - Diagnostics
- post-discharge phase
  - Data collection & analysis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

# Tokamak GOLEM - schematic experimental setup

Preionization (electron gun)

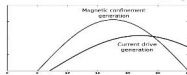
→  $S/W_{\text{preion}} \in \langle \text{on} \dots \text{on} \dots \text{off} \rangle [-]$

Magnetic confinement  $B_t$  generation

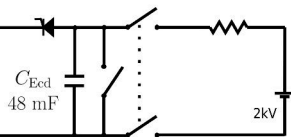


→  $U_{B_t} \in \langle 200 \dots 800 \dots 1300 \rangle [V]$

**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

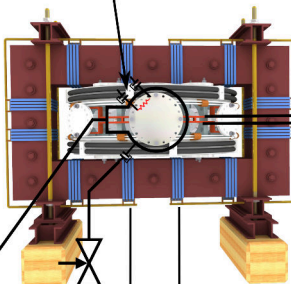


GAS handling



$H_2/He$

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

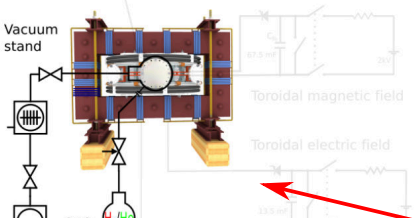


# Remote control interface of the GOLEM tokamak

Introduction Working gas Preionization Magnetic field Electric field Submit

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

Preionization (electron gun)



Vacuum stand

Toroidal magnetic field

Toroidal electric field

GAS handling

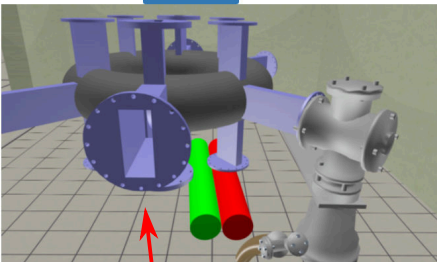
Gas type and pressure  $p_{WG} = 16 \text{ mPa}$

Hydrogen Helium

Next Set recommended value

rendering settings

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



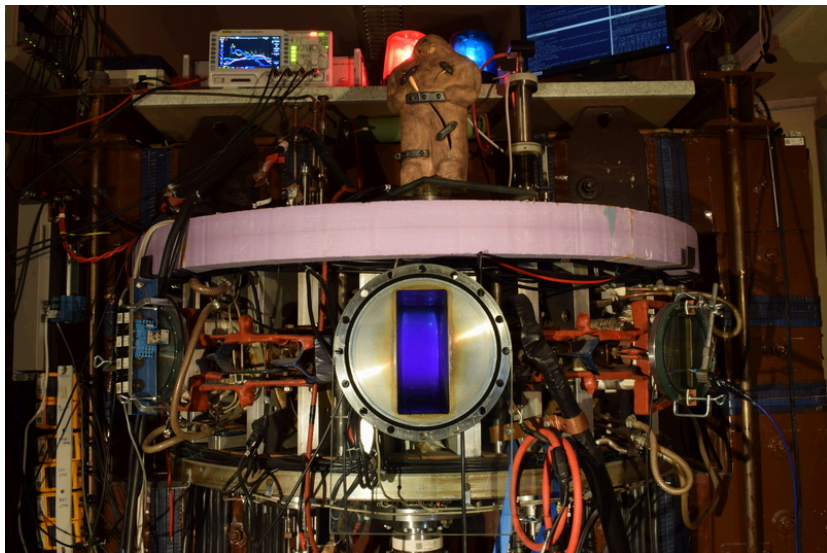
3D model rendering

engineering scheme

sliders and checkboxes

workflow buttons

Let's make a discharge



# Table of Contents

## 1 Introduction

## 2 The Tokamak (GOLEM)

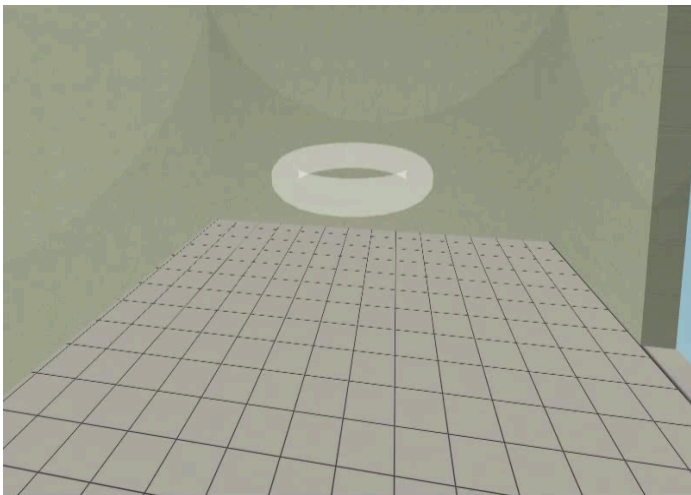
- The GOLEM tokamak concept
- The scenario to make the (GOLEM) tokamak discharge
- The scenario to discharge virtually
- The GOLEM tokamak - guide tour
- The GOLEM tokamak basic diagnostics

## 3 The Tokamak GOLEM (remote) operation

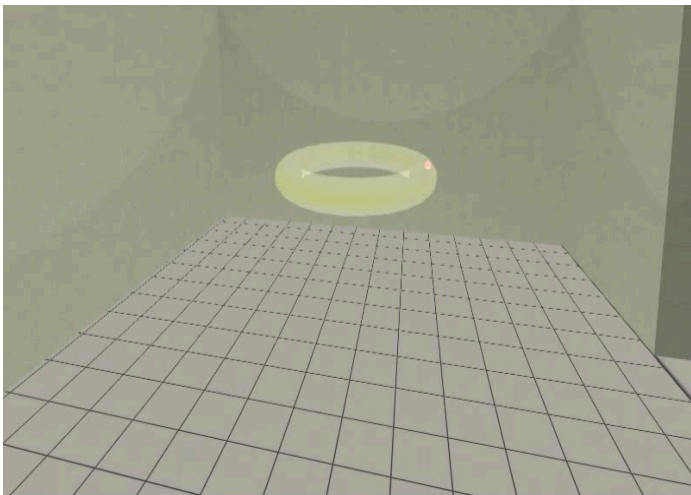
## 4 $\tau_{E,e}$ & $q$

## 5 Conclusion

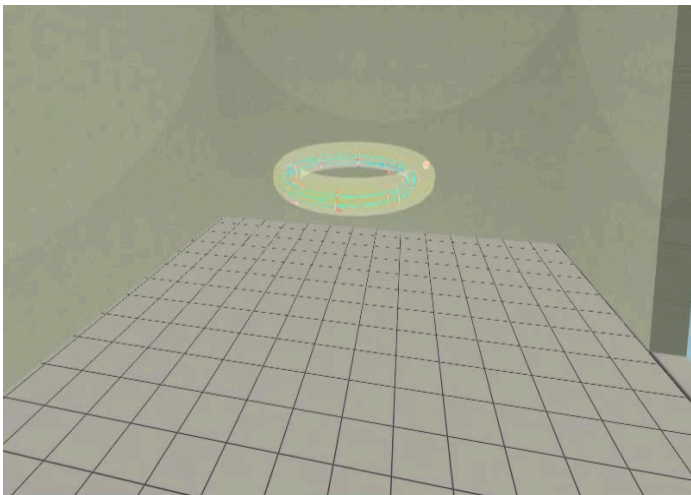
Introduce the working gas (Hydrogen x Helium)



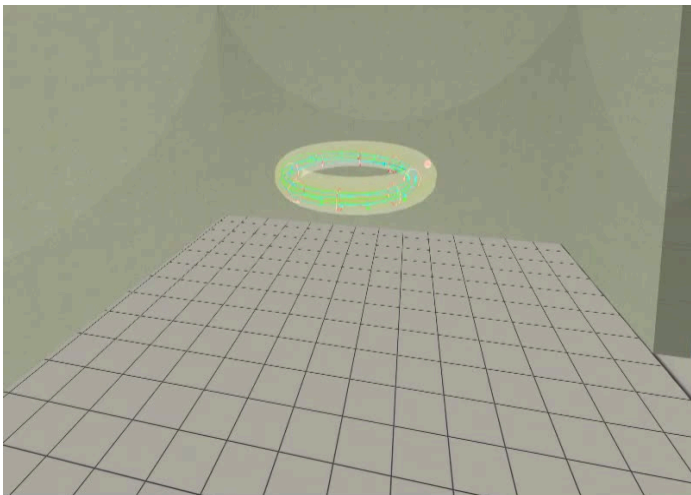
Switch on the preionization



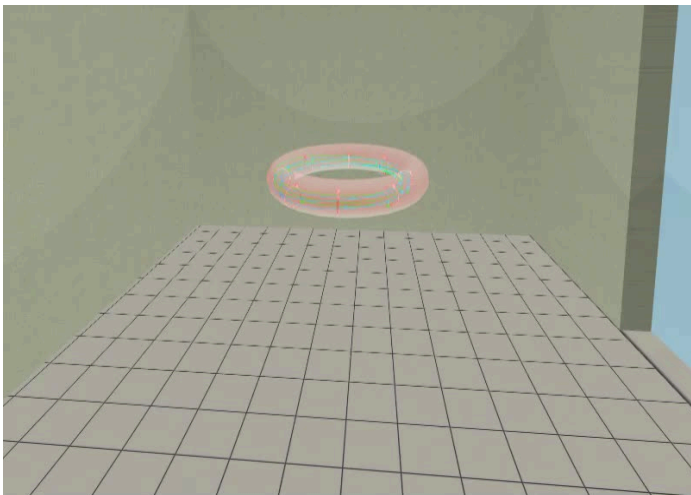
# Introduce the magnetic field



# Introduce the electric field



# Plasma ..



# Table of Contents

## 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

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

## 5 Conclusion

# 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

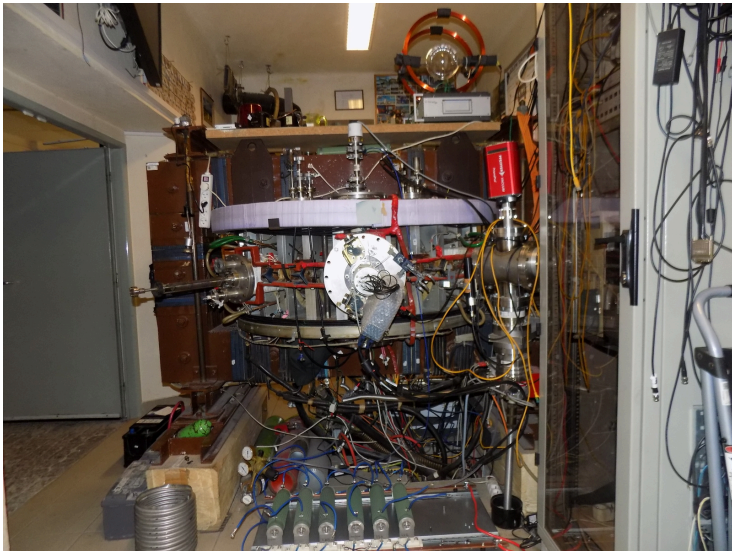
power  
supply  
2kV

Toroidal  
magnetic field B  
capacitors

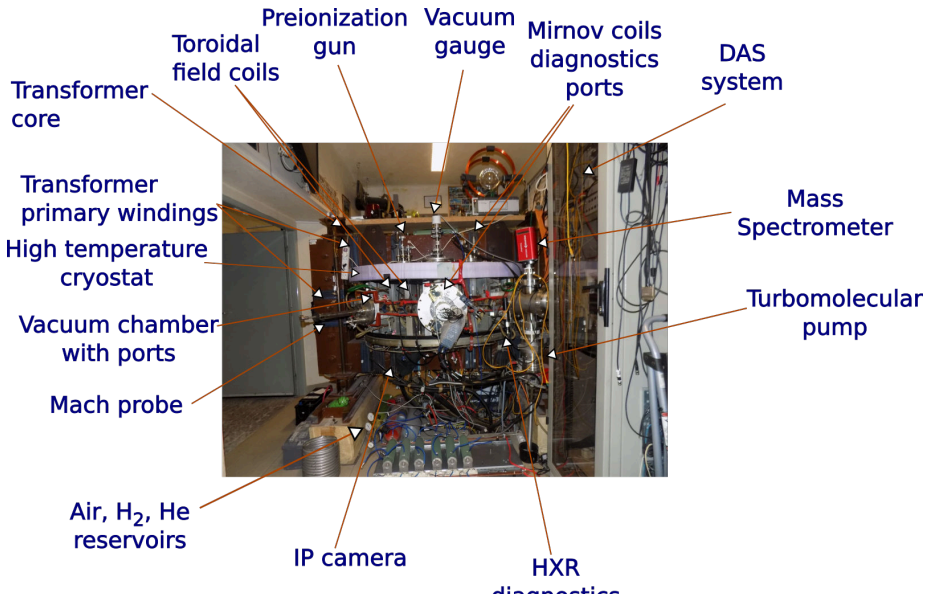
fire  
protection  
system



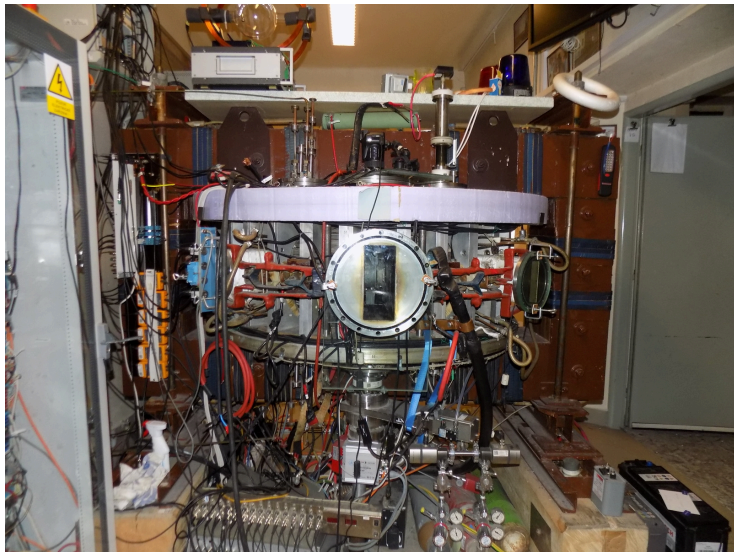
# Tokamak room (North) 10/16



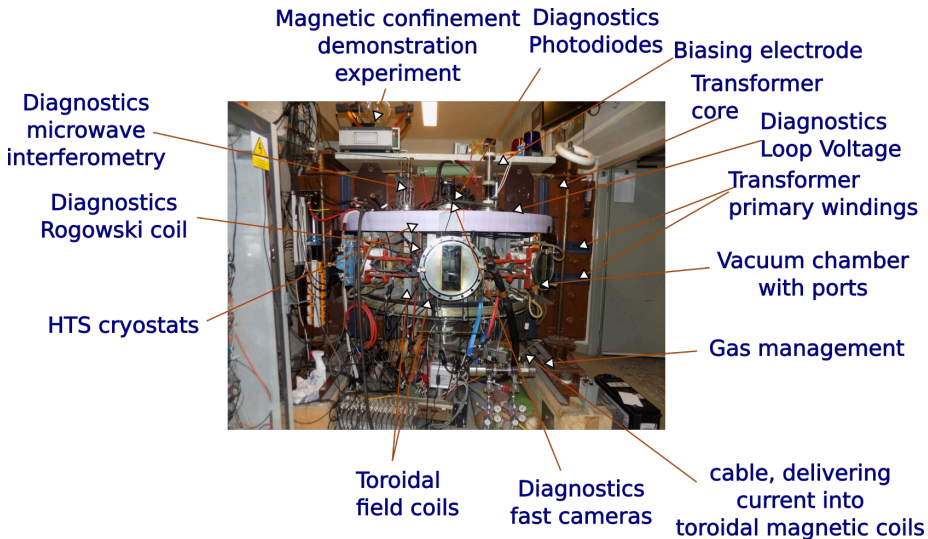
# Tokamak room (North) 10/16



# Tokamak room (South) 10/16



# Tokamak room (South) 10/16



# Table of Contents

## 1 Introduction

## 2 The Tokamak (GOLEM)

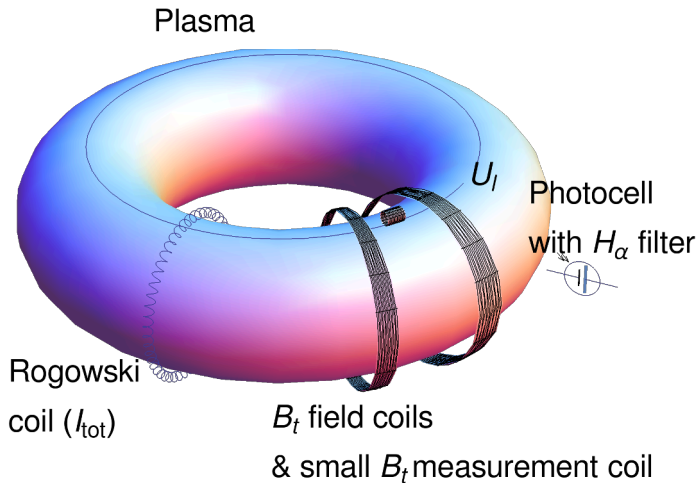
- The GOLEM tokamak concept
- The scenario to make the (GOLEM) tokamak discharge
- The scenario to discharge virtually
- The GOLEM tokamak - guide tour
- The GOLEM tokamak basic diagnostics

## 3 The Tokamak GOLEM (remote) operation

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

## 5 Conclusion

# 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

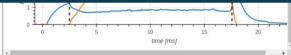
- Working Gas:  $p_{\text{discharge, before}} = 1,66 \text{ mPa}$ ;  $p_{\text{discharge, post}} = 10,40 \text{ mPa}$  ( $p_{\text{HWC}}^{\text{request}} = 10 \text{ mPa}$  @  $N_{\text{HWC}}^{\text{request}} = 4$ )
- Toroidal magnetic field:  $U_{\text{BI}}^{\text{request}} = 1200 \text{ V}$  @  $I_{\text{BI}}^{\text{request}} = 0,0 \text{ us}$
- 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:  $t_{\text{end}} = 17,57 \text{ ms}$ )



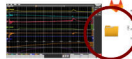
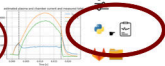
### Plasma parameters

- Loop voltage:  $U_{\text{loop}} = 8,02 \text{ V}$ ;  $\max_{r_{\text{c}}(\text{discharge})} U_{\text{loop}} = 9,89 \text{ V}$ ;  $U_{\text{loop,down}} = 10,83 \text{ V}$
- Toroidal magnetic field:  $B_t = 0,40 \text{ T}$ ;  $\max_{r_{\text{c}}(\text{discharge})} B_t = 0,57 \text{ T}$
- Plasma current:  $I_p = 9,67 \text{ kA}$ ;  $I_{\text{p,peak}} = 9,67 \text{ kA}$ ;  $I_{\text{p,avg}} = 11,66 \text{ kA}$



### 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 categories like 'Diagnostics', 'Other', and 'Navigation'. The main content area is titled 'On stage diagnostics' and features a flow diagram with stages: 'Data flow', 'measurement', 'digitization', and 'analysis'. A red circle highlights a specific data point in the 'analysis' stage. Below the browser window is a file index for the directory '/shots/39187/Devices/Oscilloscopes/TektrMSO56-a'. The index table lists files such as 'BasicDiagnostics.sh', 'ScreenShotAll.png', 'TektrMSO56\_ALL.csv', 'Universals.sh', 'das.jpg', 'ls-all', and 'rawdata.jpg'. A red arrow points from the highlighted data point in the browser to the 'BasicDiagnostics.sh' file in the index. Another red arrow points from the left side of the image to the 'BasicDiagnostics.sh' file.

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

Name	Last modified	Size	Description
<a href="#">Parent Directory</a>	-	-	-
<a href="#">BasicDiagnostics.sh</a>	2022-05-18 17:58	3.2K	
<a href="#">ScreenShotAll.png</a>	2022-05-18 17:58	184K	
<a href="#">TektrMSO56_ALL.csv</a>	2022-05-18 17:58	3.9M	
<a href="#">Universals.sh</a>	2022-05-18 17:58	1.2K	
<a href="#">das.jpg</a>	2022-05-18 17:58	13K	
<a href="#">ls-all</a>	2022-05-18 17:58	2.4K	
<a href="#">rawdata.jpg</a>	2022-05-18 17:58	13K	

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

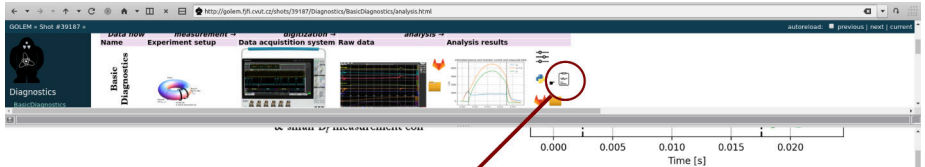
# Basic diagnostics - numerical processing, Jupyter-notebook@GitLab Download & play

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

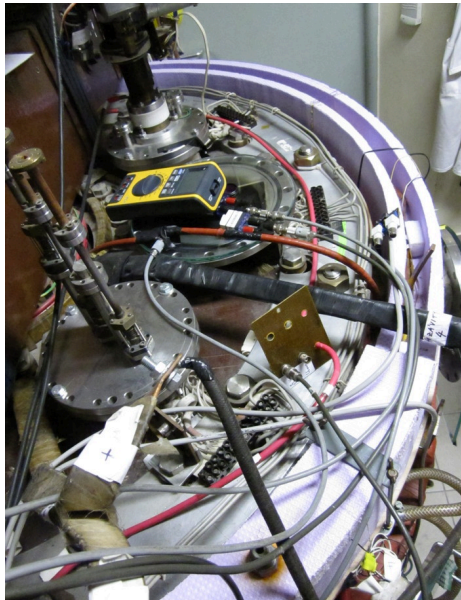
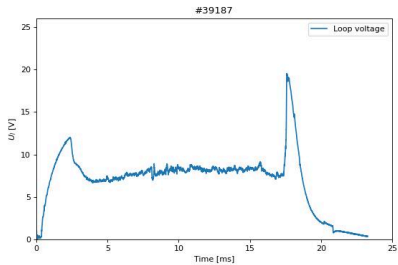
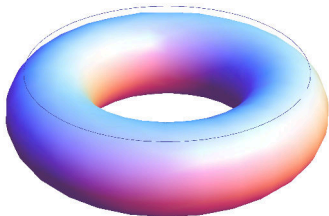
```
In [2]: import holoviews as hv
hv.extension('bokeh')
import hvplot.pandas
```



For conditional rich-text boxes

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

# Loop voltage $U_l$ @ the GOLEM tokamak



# Basic diagnostics - numerical processing, $U_{loop}$

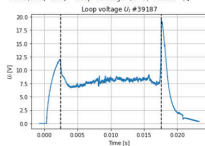
```
t_scale = 1e-3 if in_seconds else 1
if is_plasma:
    for t in (t_plasma_start, t_plasma_end):
        plt.axvline(t = t_scale, color='k', linestyle='--')
```

## $U_l$ 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[is_CD] = 0
ax = loop_voltage.plot(grid=True)
show_plasma_limits()
ax.set(xlabel='Time [s]', ylabel='SU_LS [V]', title='Loop voltage SU_LS #{}'.format(shot_no));
```

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



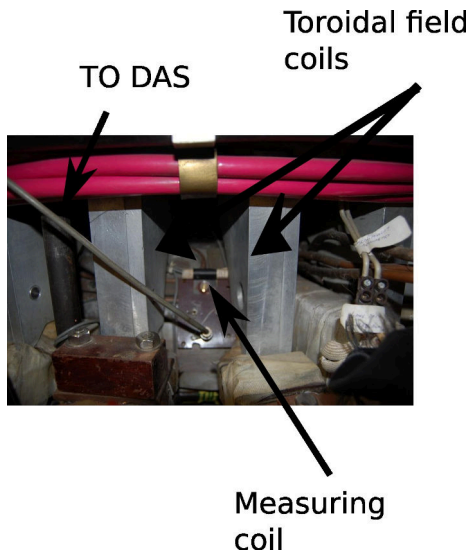
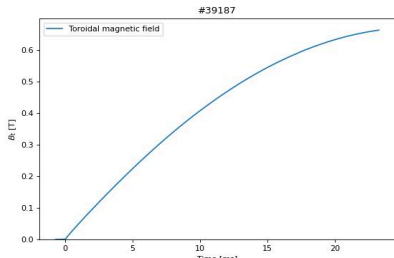
## $B_l$ calculation

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': # 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, $B_t$

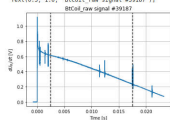
## $B_t$ calculation

### 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_start:]
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')]
```

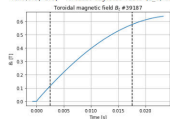


### Integration (It is a magnetic diagnostic) & calibration

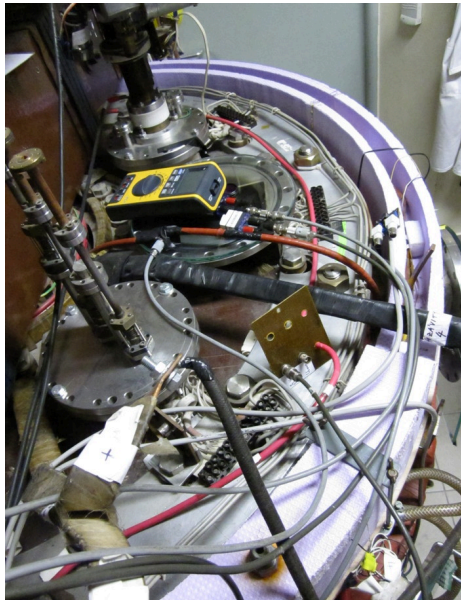
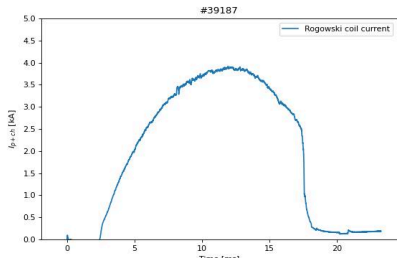
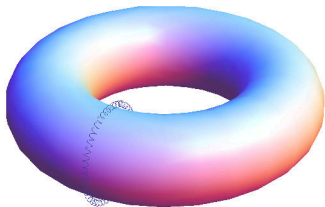
```
In [13]: K_BtCoil = float(read_parameter(shot_no, 'SystemParameters/K_BtCoil')) # Get BtCoil calibration factor
print('BtCoil calibration factor K_BtCoil={}'.format(K_BtCoil))
BtCoil calibration factor K_BtCoil=70.42 T/Vs)
```

```
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, $U_{ch+p}$

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

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

Check the data availability

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

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

Integration (it is a magnetic diagnostic) & calibration

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

Chamber current  $I_{ch}$  calculation

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

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

Plasma current  $I_p$  calculation

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

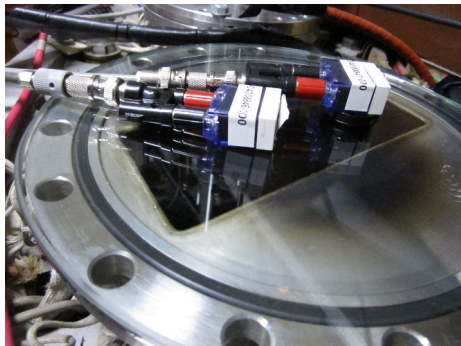
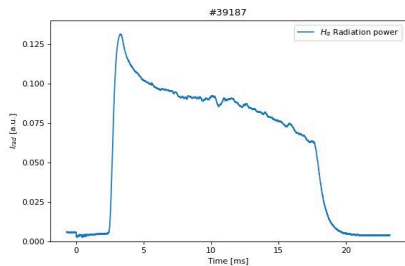
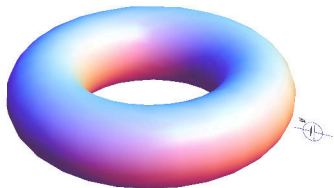
```
In [122]: if is_plasma:
    Ip_name = Ipcch - loop_voltage/R_chamber # creates a new Series
    Ip = Ipcch - I_ch
    Ip.name = 'Ip'
    Ip.name.plot(grid=True, label='naive I [ch]+I [R_ch]')
    ax = Ip.plot(grid=True, label='using SQ_L = R_ch) I (ch) - L_ch) / (R_ch) dt [s]')
    ax.legend()
 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

Out[122]: Plasma detected

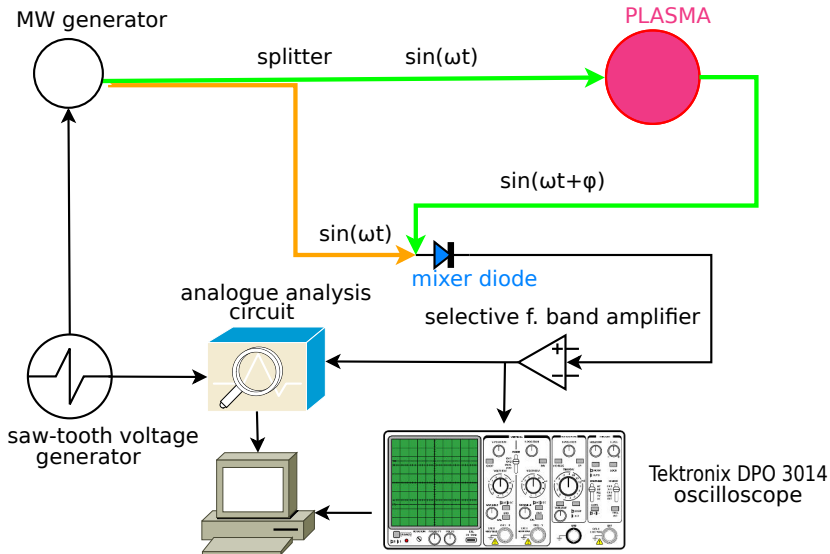
plasma lifetime of 15.1 ms, from 2.5 ms to 17.6 ms

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

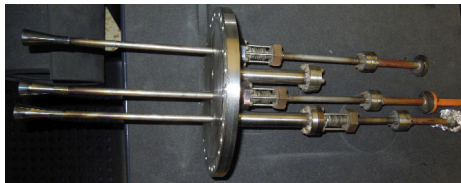
# Visible radiation



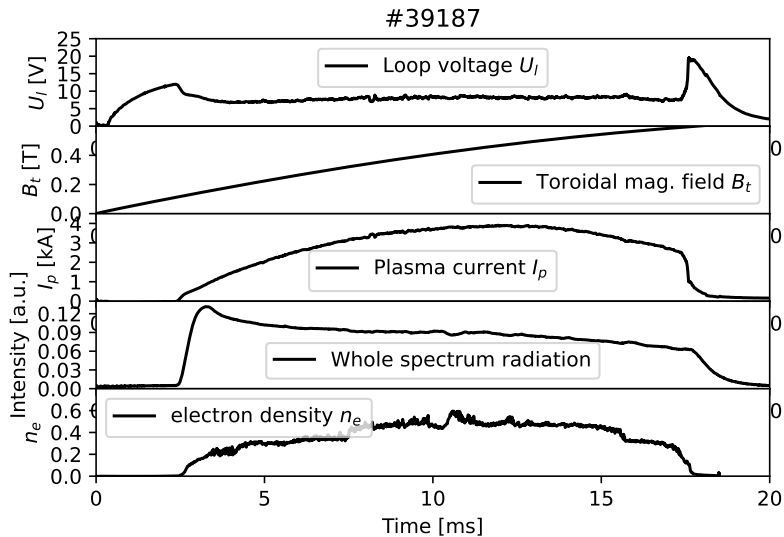
# Electron density $n_e$ interferometry measurement scheme



# The GOLEM tokamak interferometry HW




# Finally "Typical", well executed discharge @ GOLEM



# Shot homepage ( $\approx 2$ minutes after discharge execution)

GOLEM # Shot #40631
autoreload



**Diagnostics**

BasicDiagnostics  
DoubleRakeProbe  
Interferometry  
LimiterFlareCoils  
ScribbleProbes

**Other**

View  
Showroom

**Navigation**

Next  
Previous  
Current

**Go to shot**  
40631

**GOLEM utils**

Home  
Plot data  
Shot interval plot  
Manipulators control

**Database operations**

Shots listing  
Shots filtering

## Tokamak GOLEM - Shot Database - #40631

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

**The session mission** 1Final -> Dringent service

**The session ID** 40605

**The discharge comment** Rake probe 50mm

**Discharge command**

[Shot Logbook]

```

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

### 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

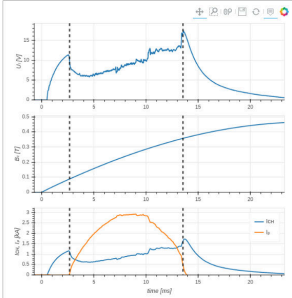
### Plasma:

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











### Plasma parameters:

- Loop voltage:  $\bar{U}_{loop} = 6.82$  V;  $max_{T_{ECC}}(I_{discharge}) U_{loop} = 16.17$  V;  $U_{breakdown} = 0.00$  V
- Toroidal magnetic field:  $B_t = 0.24$  T;  $max_{T_{ECC}}(I_{discharge}) B_t = 0.36$  T
- Plasma current:  $I_p = 2.28$  kA;  $max_{T_{ECC}}(I_{discharge}) I_p = 2.92$  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	
<b>Basic Diagnostics</b> 					
<b>Double rake probe</b> 					

**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

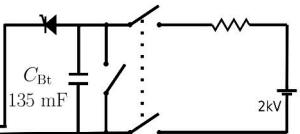
- 1 Introduction
- 2 The Tokamak (GOLEM)
- 3 The Tokamak GOLEM (remote) operation
  - Control room
  - Data handling @ the Tokamak GOLEM
- 4  $\tau_{E,e}$  &  $q$
- 5 Conclusion
- 6 Appendix

# Tokamak GOLEM - schematic experimental setup

Preionization (electron gun)

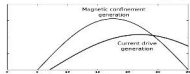
→  $S/W_{\text{preion}} \in \langle \text{on} \dots \text{on} \dots \text{off} \rangle [-]$

Magnetic confinement  $B_t$  generation

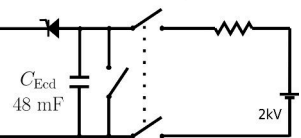


→  $U_{B_t} \in \langle 200 \dots 800 \dots 1300 \rangle [V]$

**Trigger sequence**



Current drive  $E_{cd}$  generation



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

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

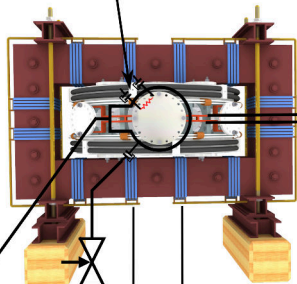
Vacuum stand



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 shows a web-based remote control interface for the GOLEM tokamak. At the top, there is a navigation bar with tabs for 'Introduction', 'Control room', 'Live', and 'Results'. The 'Control room' tab is active. Below the navigation bar, there are two main panels. The left panel is a control interface for the 'Working gas' section. It contains a schematic diagram of the tokamak's gas handling system, including a vacuum stand, a gas handling unit with  $H_2/He$  input, and a preionization section. The diagram is annotated with labels for 'Preionization (electron gun)', 'Vacuum stand', 'Toroidal magnetic field', and 'Toroidal electric field'. Below the diagram, 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 of the control panel are 'Next' and 'Set recommended value' buttons. The right panel shows a 3D model rendering of the tokamak's internal structure, with a red arrow pointing to a specific component. Above the 3D model, there are two buttons for '3D model rendering method': 'Static image (fast)' and 'Interactive X3DOM (slower)'. The text 'rendering settings' is written in red above these buttons. Red arrows from the text labels at the bottom point to the corresponding UI elements: '3D model rendering' points to the 3D model, 'engineering scheme' points to the schematic diagram, 'sliders and checkboxes' points to the pressure slider and radio buttons, and 'workflow buttons' points 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  $C_o$

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

$H_2/H_8$

Gas type and pressure  $p_{gas}$ : 38 mPa

Hydrogen Helium

Next Set recommended value

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

# Control room: Preionization

GOLEM remote Introduction Control room Live Results

Introduction Working gas Preionization Magnetic field Electric field Submit

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

### Preionization (electron gun)

Vacuum stand

GAS handling

Toroidal magnetic field

Toroidal electric field

67.5 mT

13.5 mV

200V

200V

ionization method

Electron gun  No ionization

Next

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

# Control room: Magnetic field $B_t$

GOLEM version: Introduction Control room Live Results

the Torus 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 Static image (best) Interactive X3DOM (viewer)

Set the voltage on the capacitors to be discharged into the toroidal field coils. The higher the voltage, the larger the magnetic field confining the plasma.

Preionization (electron gun)

Vacuum stand

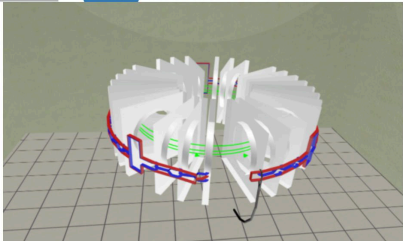
Toroidal magnetic field

Toroidal electric field

GAS handling

Capacitor voltage  $U_{C_1} = 600$  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  $t_{\text{cd}}$ : 0 micro seconds

Capacitor voltage  $U_{\text{cd}}$ : 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.

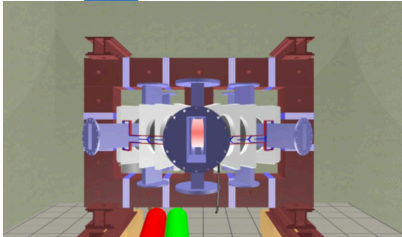
Comment

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 ( $\approx 2$ minutes after discharge execution)

GOLEM # Shot #40631
autoreload



**Diagnostics**

BasicDiagnostics  
DoubleRakeProbe  
Interferometry  
LimiterFlareCoils  
ScribbleProbes

**Other**

View  
Showroom

**Navigation**

Next  
Previous  
Current

**Go to shot**  
40631

**Golem utils**

Home  
Plot data  
Shot interval plot  
Manipulators control

**Database operations**

Shots listing  
Shots filtering

## Tokamak GOLEM - Shot Database - #40631

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

**The session mission** 1Final -> Dringent service

**The session ID** 40605

**The discharge comment** Rake probe 50mm

**Discharge command**

[Shot Logbook]

```

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

---

### Technological parameters

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

---

### Plasma:











- Plasma: yes or no:
- Time parameters:  $\Delta T_p = 10.88$  ms ( $t_{rom,tstart} = 2.67$  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;  $U_{inductance} = 0.00$  V
- Toroidal magnetic field:  $B_t = 0.24$  T;  $max_{T_{loop}}(I_{discharge}) B_t = 0.36$  T
- Plasma current:  $I_p = 2.28$  kA;  $max_{T_{loop}}(I_{discharge}) I_p = 2.92$  kA;  $t_p^{max} = 0.00$  ms

### On stage diagnostics

	Data flow	measurement	digitization	analysis	Analysis results
Name	Experiment setup		Data acquisition system	Raw data	
<b>Basic Diagnostics</b>  					
<b>Double rake probe</b> <small>@ BasicDiagnostics part</small> 					

**Without Analysis**





## Basic Diagnostics





# 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

# 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'
```

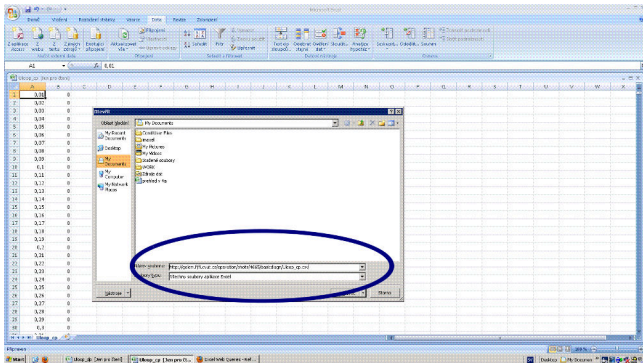
```
shot_no=39187;\
signal_id="Diagnostics/BasicDiagnostics/Results/U_loop.csv";\
gnuplot -p -e "set title \"Golem\";set datafile separator \" , \";\
set xlabel \"t [s]\";set ylabel \"U\";\
plot \"< \
wget -q -O - http://golem.fjfi.cvut.cz/shots/$shot_no/$signal_id\" \
w l t \"U\""
```

# 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.

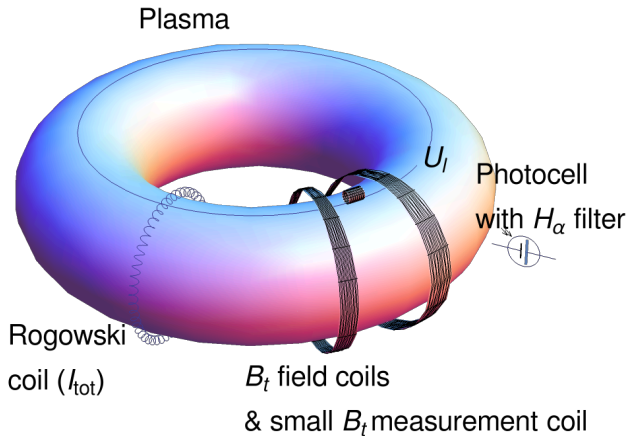
# Table of Contents

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

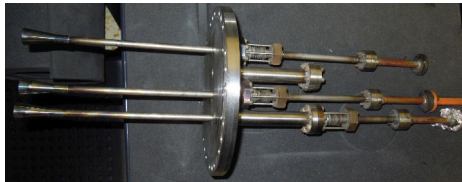
# Hands on the GOLEM tokamak - equipment



# The GOLEM tokamak - standard diagnostics



# The GOLEM tokamak interferometry HW

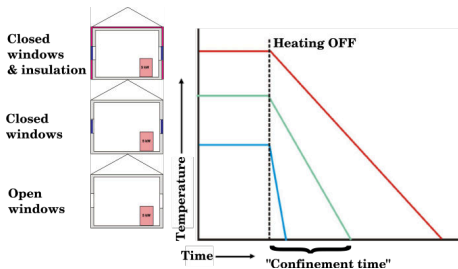


# Table of Contents

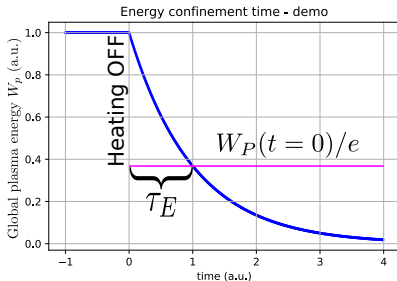
- 1 Introduction
- 2 The Tokamak (GOLEM)
- 3 The Tokamak GOLEM (remote) operation
- 4  $\tau_{E,e}$  &  $q$ 
  - The Electron energy confinement time calculation
  - The safety factor
- 5 Conclusion
- 6 Appendix

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

## House (cooling after heating stops)



## Tokamak (cooling after heating stops)

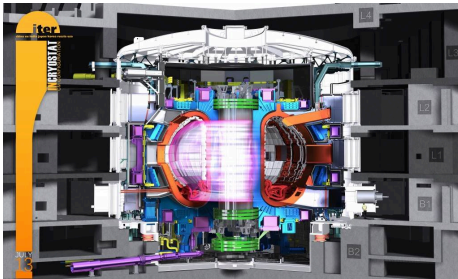


When heating is switched off, both systems lose their internal energy exponentially.  
This motivates the definition of the electron energy confinement time  $\tau_{E,e}$ .

# ITER vs GOLEM

**ITER:**

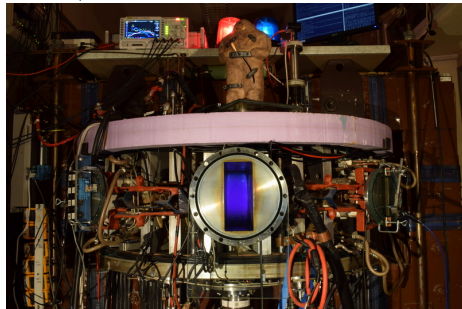
$$\tau_E \approx 3.6 \text{ s}$$



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:

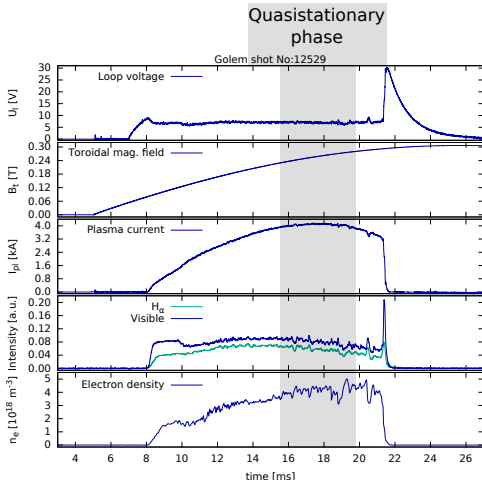
$$P_{OH} \approx P_{loss}.$$

- 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:

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

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

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

- All quantities are measurable @tG.

## Ohmic heating power $P_{\text{OH}}$ @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  $V_{\text{loop}}$  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:

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

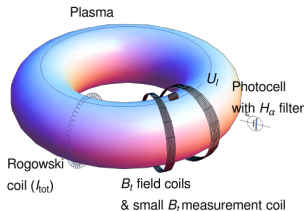
All entering quantities are experimentally accessible @tG:

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

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

# Table of Contents

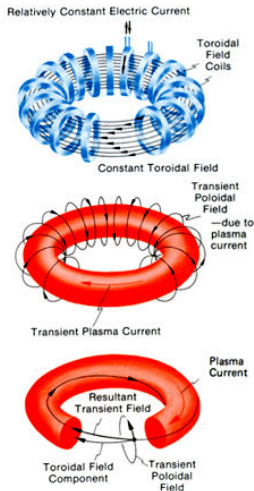
- 1 Introduction
- 2 The Tokamak (GOLEM)
- 3 The Tokamak GOLEM (remote) operation
- 4  $\tau_{E,e}$  &  $q$ 
  - The Electron energy confinement time calculation
  - The safety factor
- 5 Conclusion
- 6 Appendix

# Towards the Safety Factor $q$

## Magnetic field lines in a tokamak

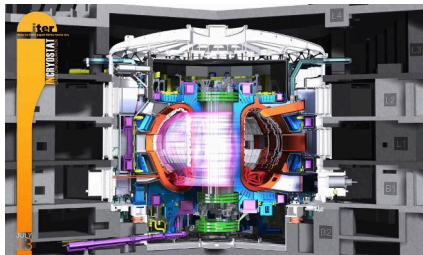
### Why it matters:

- $q$  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

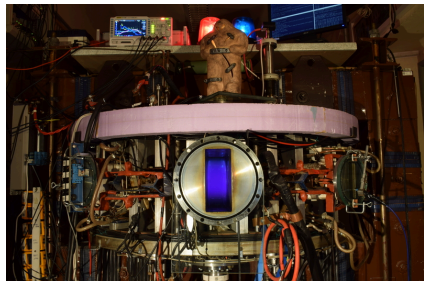


Typical edge safety factor:

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

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:**

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

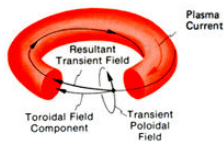
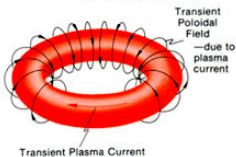
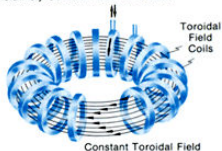
where  $B_t$  is the toroidal field,  $B_p(r)$  the poloidal field,  $R_0$  the major radius. Using Ampère's law:

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

This gives the practical form:

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

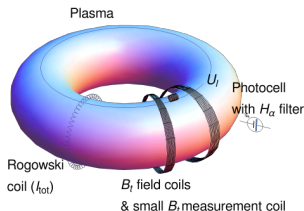
Relatively Constant Electric Current



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

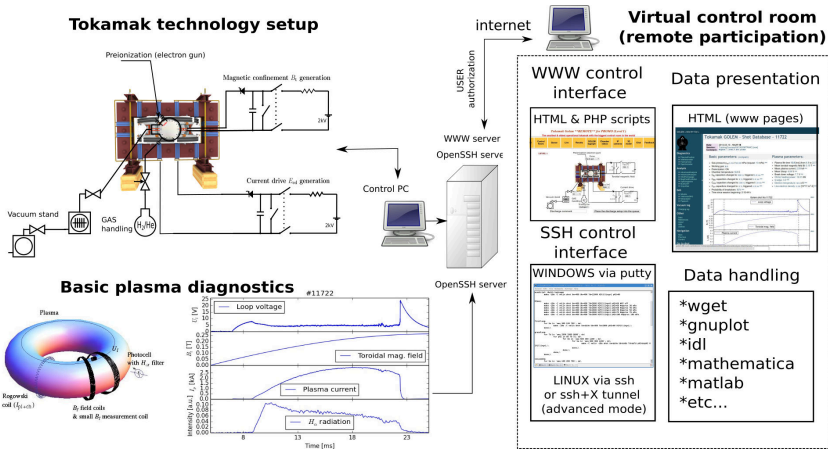
Safety factor at the edge:

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

# Table of Contents

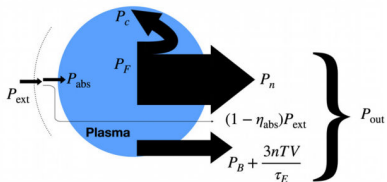
- 1 Introduction
- 2 The Tokamak (GOLEM)
- 3 The Tokamak GOLEM (remote) operation
- 4  $\tau_{E,e}$  &  $q$
- 5 Conclusion**
- 6 Appendix

# The global schematic overview of the tG experiment



# Two key fusion technology parameters you can touch experimentally

## Energy Confinement Time $\tau_E$



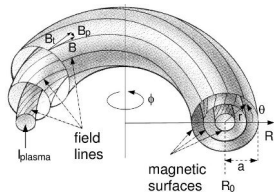
credit:[2]

- 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  $I_p$ .

# Production

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





# Acknowledgement

## Financial support highly appreciated:

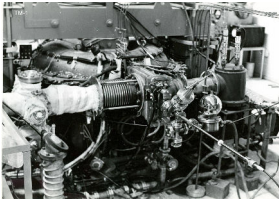
CTU RVO68407700, SGS 17/138/OHK4/2T/14, GAČR GA18-02482S, EU funds CZ.02.1.01/0.0/0.0/16\_019/0000778 and CZ.02.2.69/0.0/0.0/16\_027/0008465, IAEA F13019, FUSENET and EUROFUSION.

## Students, teachers, technicians (random order):

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

# Thank you for your attention

**Tokamak TM1**  
@Kurchatov Institute near Moscow  
~1960-1977



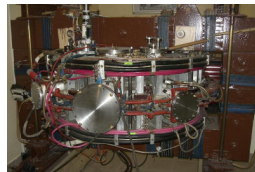
**SCIENCE**

**Tokamak CASTOR**  
@Institute of Plasma Physics, Prague  
1977-2007



**SCIENCE**  
& education

**Tokamak GOLEM**  
@Czech Technical University, Prague  
2007-



**EDUCATION**  
& science

... with the biggest  
control room  
in the world ..

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

Home	Wiki	Control Room	Queue	Live	Results	GOLEM Diagram	Chamber status	IP cameras	3D model	Chat	Feedback	Logout
------	------	--------------	-------	------	---------	---------------	----------------	------------	----------	------	----------	--------

**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





# Table of Contents

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

# References I

-  Wikipedia contributors. Golem — Wikipedia, the free encyclopedia. <https://en.wikipedia.org/w/index.php?title=Golem>, 2020. [Online; accessed 29-March-2020].
-  Samuel E. Wurzel and Scott C. Hsu. Progress toward fusion energy breakeven and gain as measured against the lawson criterion. *Physics of Plasmas*, 29(6):062103, 06 2022.
-  J. Wesson. *Tokamaks*, volume 118 of *International Series of Monographs on Physics*. Oxford University Press Inc., New York, Third Edition, 2004.
-  ITER contributors . ITER. <https://www.iter.org>, 2007. [Online; accessed 21-December-2018].

## References II

-  Tokamak GOLEM contributors. Tokamak GOLEM at the Czech Technical University in Prague. <http://golem.fjfi.cvut.cz>, 2007. [Online; accessed November 28, 2025].
-  Wikipedia contributors. Lawson criterion — Wikipedia, the free encyclopedia. [https://en.wikipedia.org/w/index.php?title=Lawson\\_criterion&oldid=888000448](https://en.wikipedia.org/w/index.php?title=Lawson_criterion&oldid=888000448), 2019. [Online; accessed 6-December-2019].
-  Wikipedia contributors. Safety factor (plasma physics) — Wikipedia, the free encyclopedia, 2025. [Online; accessed 24-November-2025].
-  Brotankova, J. *Study of high temperature plasma in tokamak-like experimental devices*. PhD thesis, 2009.