

Introduction to the tokamak GOLEM operation Practical guide

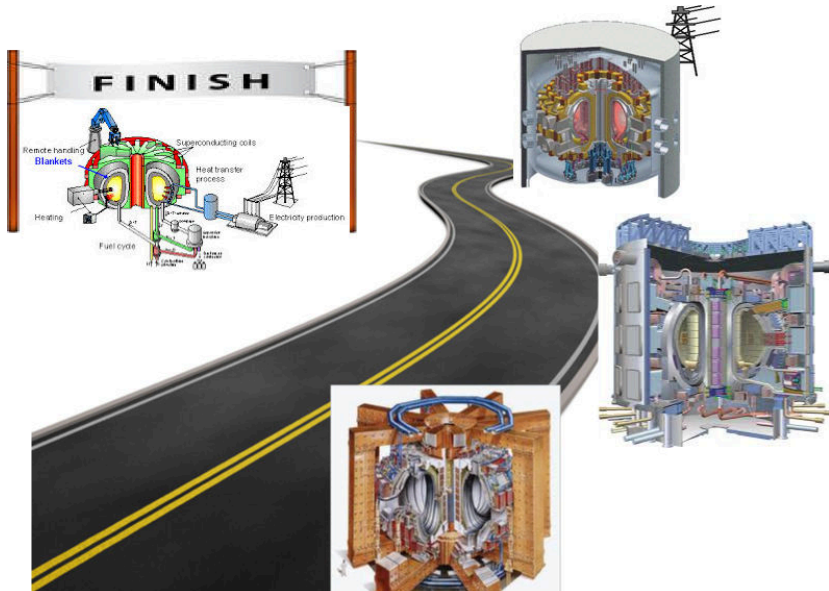
Vojtěch Svoboda
on behalf of the tokamak GOLEM team
for the Torino Politecnico, Italy

December 5, 2022

Table of Contents

- 1 Introduction
- 2 The Tokamak (GOLEM)
- 3 The Tokamak GOLEM (remote) operation
- 4 The Electron energy confinement time calculation (rough estimation)
- 5 Conclusion
- 6 Appendix

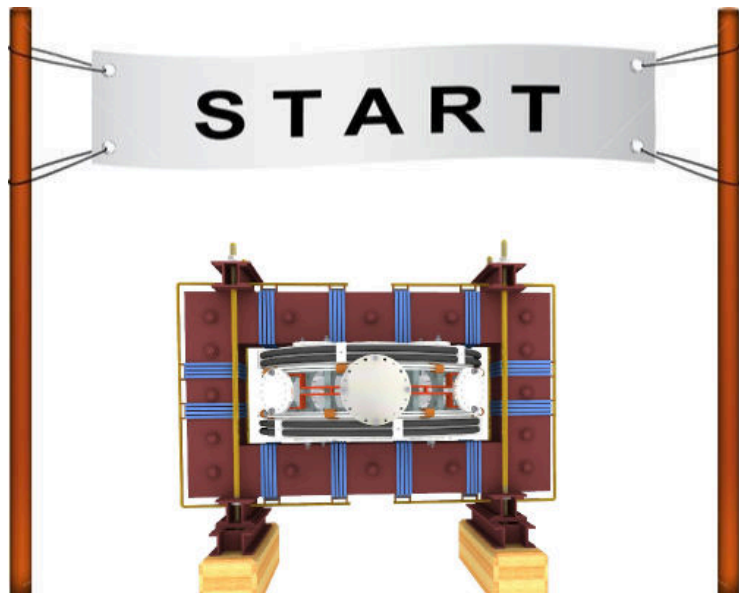
Milestones to Fusion Power Plant



Education importance

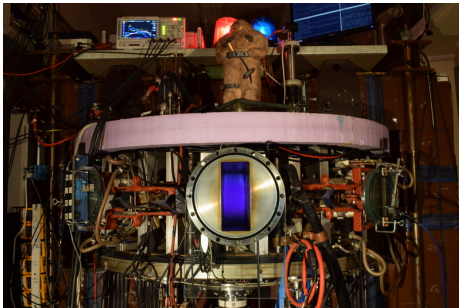


Let's start with the tokamak GOLEM - *the smallest tokamak in the World with the biggest control room*



The GOLEM tokamak basic characteristics

The grandfather of all tokamaks (ITER newslines 06/18)



- Vessel major radius: $R_0 = 0.4$ m
- Vessel minor radius: $r_0 = 0.1$ m
- Maximum plasma current:
 $I_p^{\max} < 8$ kA
- Maximum toroidal magnetic field: $B_t^{\max} < 0.5$ T
- Typical electron density:
 $\langle n_e \rangle \in (0.2, 3) \cdot 10^{19} \text{ m}^{-3}$
- Maximum electron temperature:
 $T_e^{\max} < 80$ eV
- Maximum discharge duration:
 $\tau_p^{\max} < 25$ ms

Tokamak GOLEM @ Wikipedia ..

File Edit View Go Bookmarks Tools Settings Window Help

home Kalendarj Produkce Forecast Slovnik Rano

Wikipedia logo

WIKIPEDIA
The Free Encyclopedia

Main page
Contents
Featured content
Current events

Not logged in Talk Contributions Create account Log in

Article Talk

Read Edit View history Search

Tokamak

From Wikipedia, the free encyclopedia

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

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


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

Experimental tokamaks [edit]

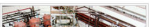
Currently in operation [edit]

(in chronological order of start of operations)

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

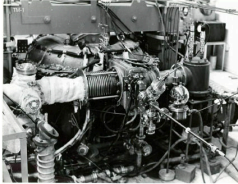


Alcator C-Mod



The GOLEM tokamak for education - historical background

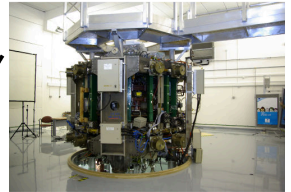
Kurchatov Institute near Moscow,
Soviet Union
1960: **TM1-MH**



1974



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



2006



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



2008



Czech Technical University Prague
Czech republic
GOLEM



GOLEM

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

there is hidden indeed "infernal" power. Yet it is the very power of celestial stars themselves. Calmly dormant, awaiting mankind to discover the magic key, to use this power for their benefit. . .

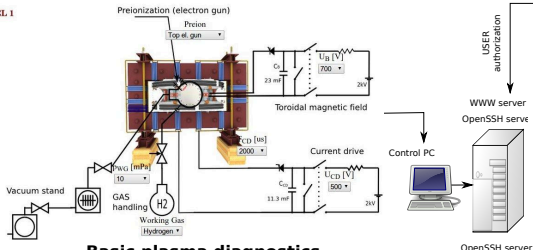


At the end of the 16th century, in the times when the Czech lands were ruled by Emperor Rudolf II, in Prague, there were Rabbi Judah Loew, well known alchemist, thinker, scholar, writer and inventor of the legendary GOLEM - a clay creature inspired with the Universe power that pursued his master's command after being brought to life with a shem, . Golem is not perceived as a symbol of evil, but rather as a symbol of power which might be useful but is very challenging to handle. To learn more of the Golem legend, see e.g. [1].

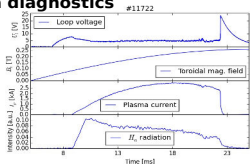
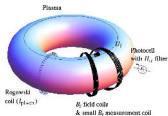
The global schematic overview of the GOLEM experiment

LEVEL 1

Tokamak technology setup



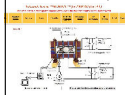
Basic plasma diagnostics



Virtual control room (remote participation)

WWW control interface

HTML & PHP scripts



SSH control interface

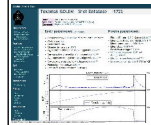
WINDOWS via putty



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

Data presentation

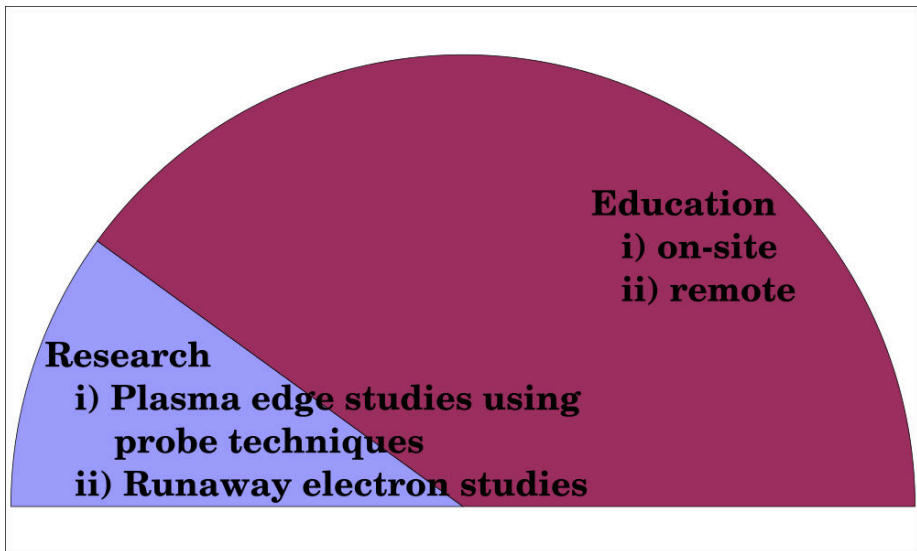
HTML (www pages)



Data handling

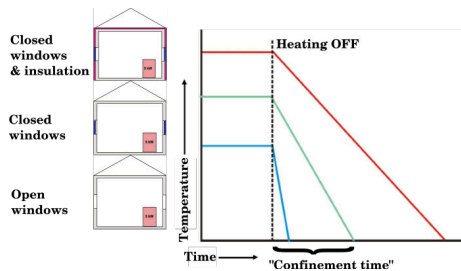
- *wget
- *gnuplot
- *idl
- *mathematica
- *matlab
- *etc...

The GOLEM tokamak mission

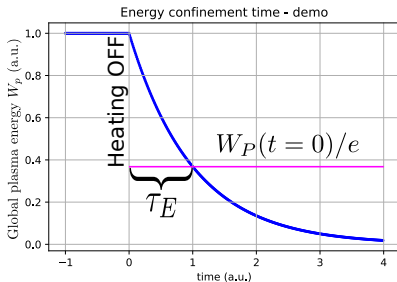


Towards ... Energy confinement time

House



Tokamak



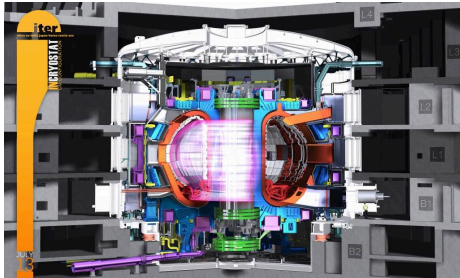
- The confinement time: $\tau_E = \frac{W}{P_{\text{loss}}}$
- Energy density: $W = 3nk_B T$
- Reactions per volume per time of fusion reactions is:
 $f = n_d n_t \langle \sigma v \rangle = \frac{1}{4} n^2 \langle \sigma v \rangle$
- Fusion heating fE_{ch} , where $E_{\text{ch}} = 3.5 \text{ MeV}$ should exceeds the losses:
 $fE_{\text{ch}} \geq P_{\text{loss}}$

$$n\tau_E \geq L \equiv \frac{12}{E_{\text{ch}}} \frac{k_B T}{\langle \sigma v \rangle} \geq 1.5 \cdot 10^{20} \frac{\text{s}}{\text{m}^3}$$

(DT reaction@minimum $\approx 26 \text{ keV}$)

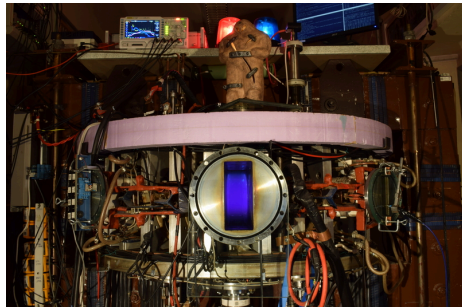
The competition

The ITER: 3.6 s



credit:[3]

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



credit:[4]

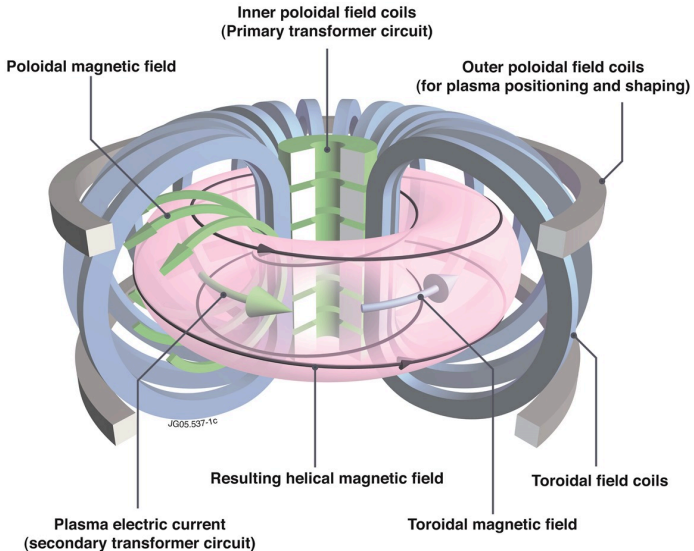
- Everything via <http://golem.fjfi.cvut.cz/Torino>
 - This presentation
 - Control rooms
 - Contact: Vojtech Svoboda,
+420 737673903,
svoboda@fjfi.cvut.cz
 - Videoconference
<https://meet.jit.si/golem>



Table of Contents

- 1 Introduction
- 2 The Tokamak (GOLEM)**
- 3 The Tokamak GOLEM (remote) operation
- 4 The Electron energy confinement time calculation (rough estimation)
- 5 Conclusion
- 6 Appendix

Tokamak magnetic confinement concept



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

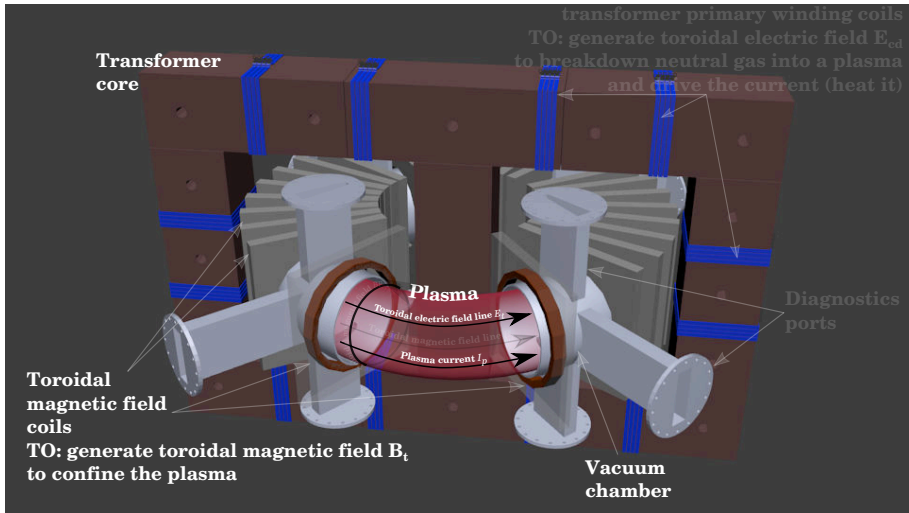


Table of Contents

1 Introduction

2 The Tokamak (GOLEM)

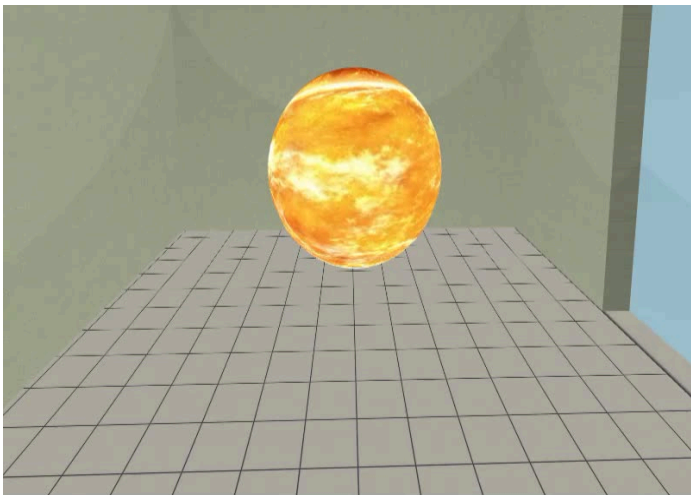
- The GOLEM tokamak concept
- The scenario to make the (GOLEM) tokamak discharge
- The scenario to discharge virtually
- The GOLEM tokamak basic diagnostics
- The GOLEM tokamak - guide tour

3 The Tokamak GOLEM (remote) operation

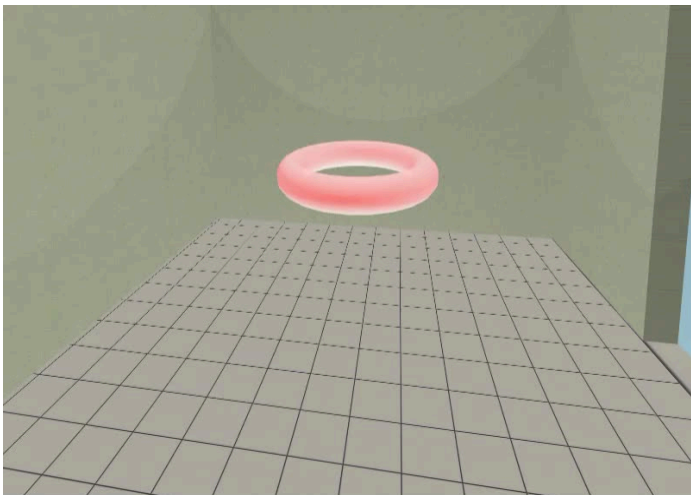
4 The Electron energy confinement time calculation (rough estimation)

5 Conclusion

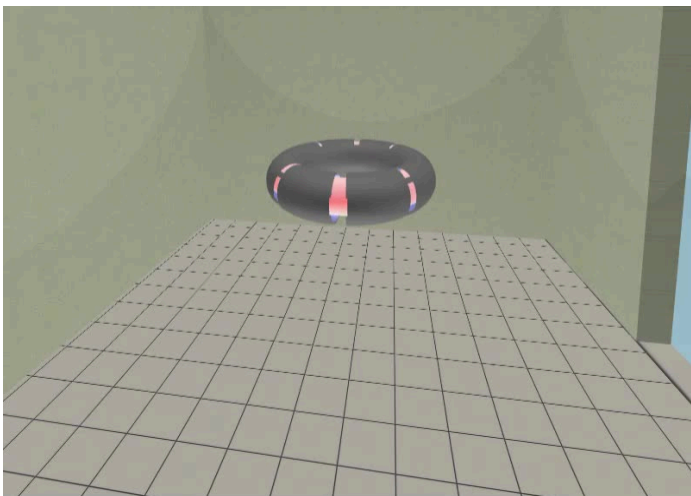
Our goal: the technology to create a μ Sun on the Earth



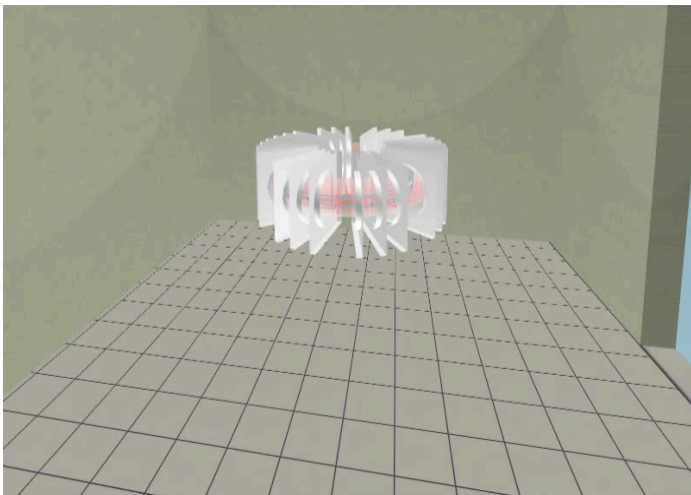
Magnetic confinement requires toroidal geometry



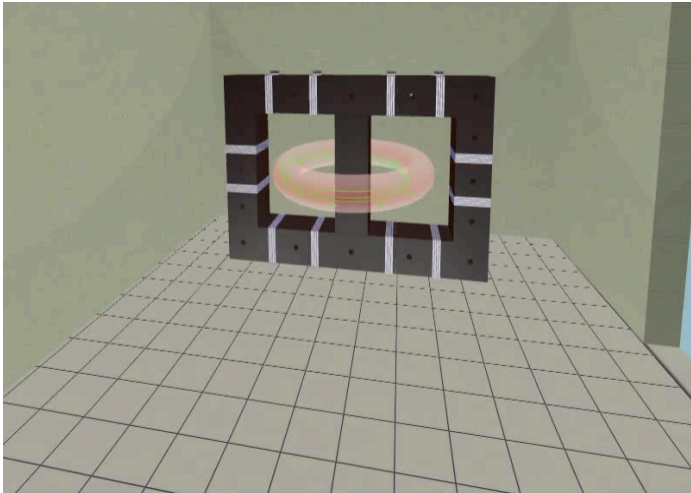
A chamber contains the thermonuclear reaction



Toroidal magnetic field coils confine the plasma



A transformer action creates and heats the plasma



The final technology altogether

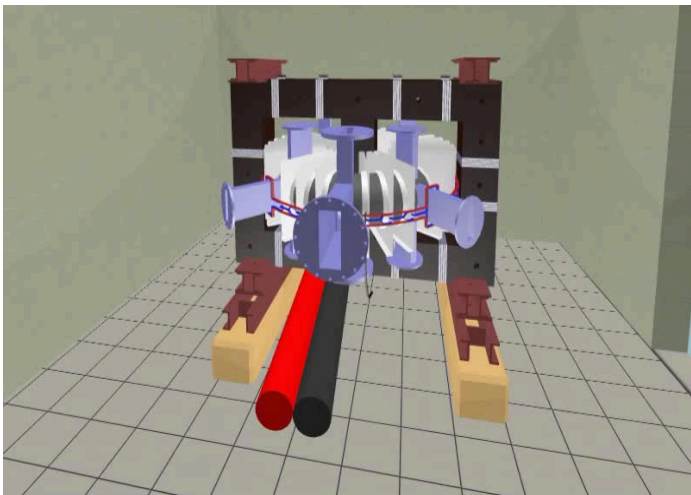


Table of Contents

1 Introduction

2 The Tokamak (GOLEM)

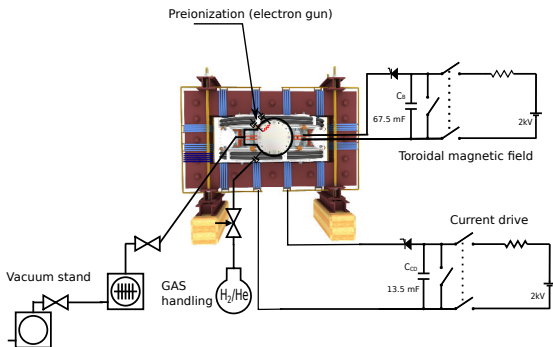
- The GOLEM tokamak concept
- The scenario to make the (GOLEM) tokamak discharge
- The scenario to discharge virtually
- The GOLEM tokamak basic diagnostics
- The GOLEM tokamak - guide tour

3 The Tokamak GOLEM (remote) operation

4 The Electron energy confinement time calculation (rough estimation)

5 Conclusion

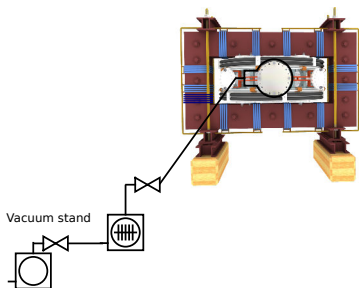
Plasma in Tokamak (GOLEM) - the least to do



To do:

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

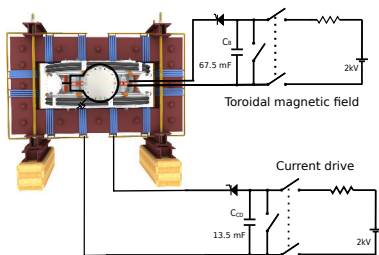
Plasma in Tokamak (GOLEM) - the least to do



To do:

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

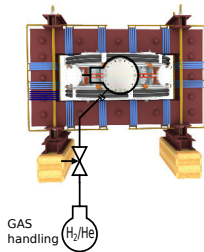
Plasma in Tokamak (GOLEM) - the least to do



To do:

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

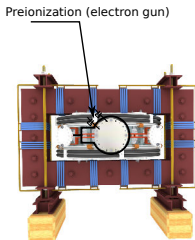
Plasma in Tokamak (GOLEM) - the least to do



To do:

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

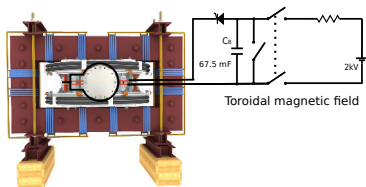
Plasma in Tokamak (GOLEM) - the least to do



To do:

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

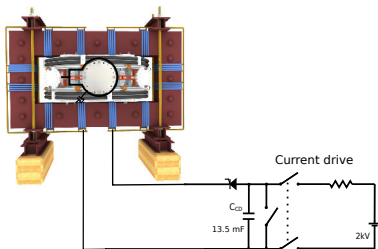
Plasma in Tokamak (GOLEM) - the least to do



To do:

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

Plasma in Tokamak (GOLEM) - the least to do



To do:

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

Tokamak GOLEM - schematic experimental setup

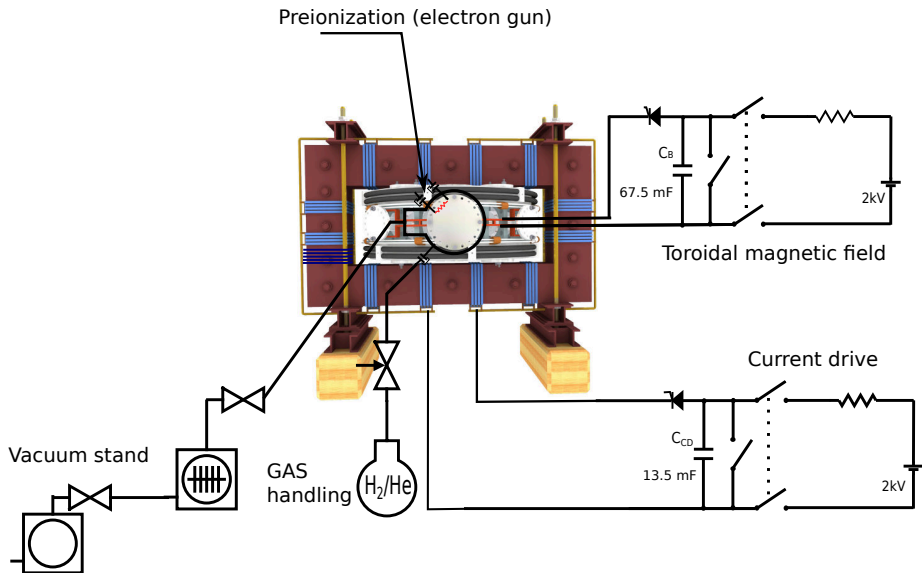


Table of Contents

1 Introduction

2 The Tokamak (GOLEM)

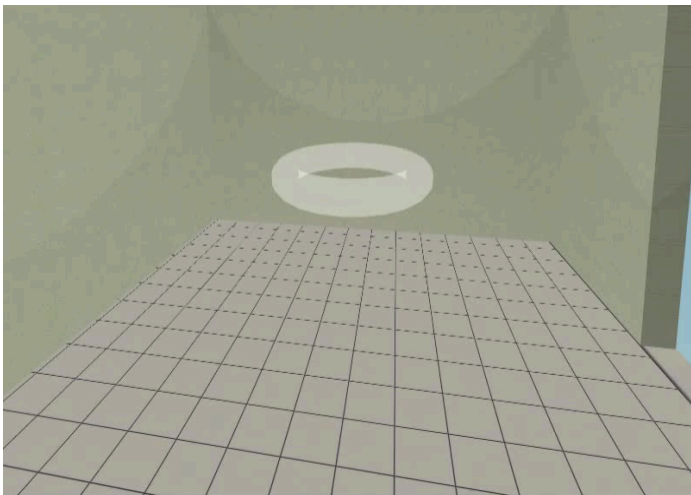
- The GOLEM tokamak concept
- The scenario to make the (GOLEM) tokamak discharge
- The scenario to discharge virtually
- The GOLEM tokamak basic diagnostics
- The GOLEM tokamak - guide tour

3 The Tokamak GOLEM (remote) operation

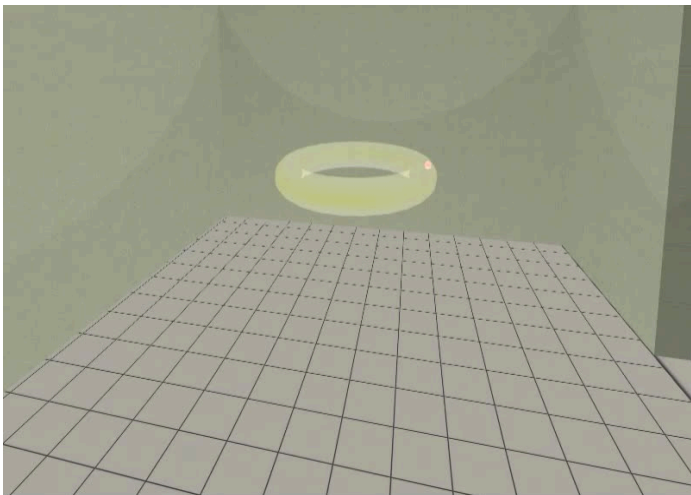
4 The Electron energy confinement time calculation (rough estimation)

5 Conclusion

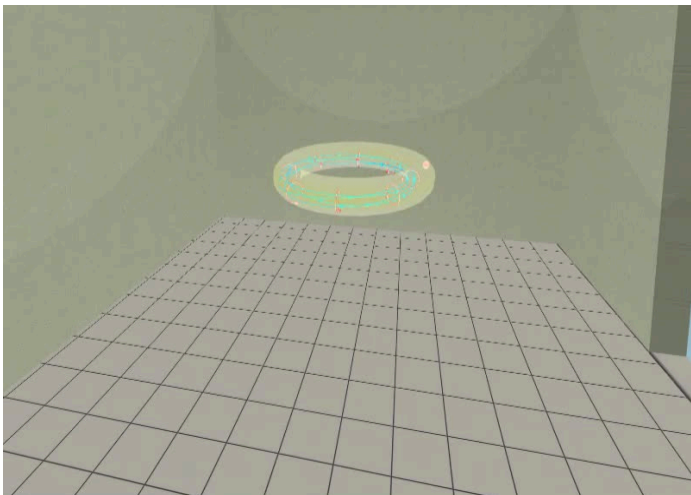
Introduce the working gas (Hydrogen x Helium)



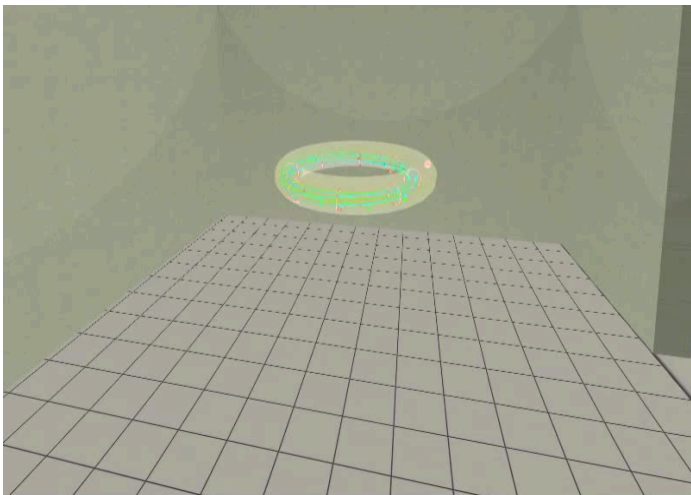
Switch on the preionization



Introduce the magnetic field



Introduce the electric field



Plasma ..

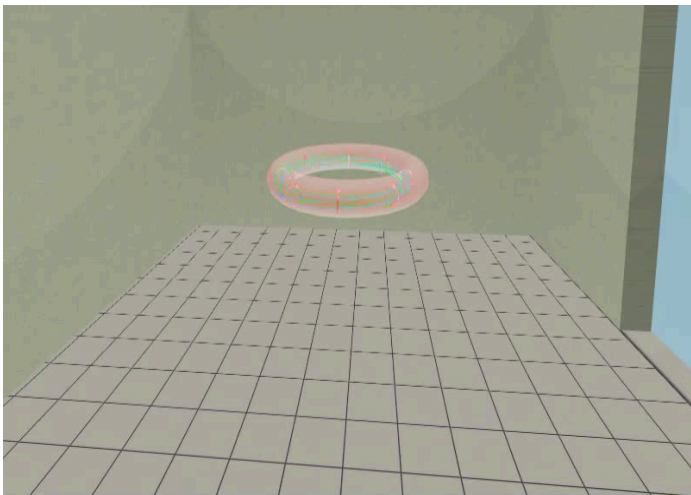


Table of Contents

1 Introduction

2 The Tokamak (GOLEM)

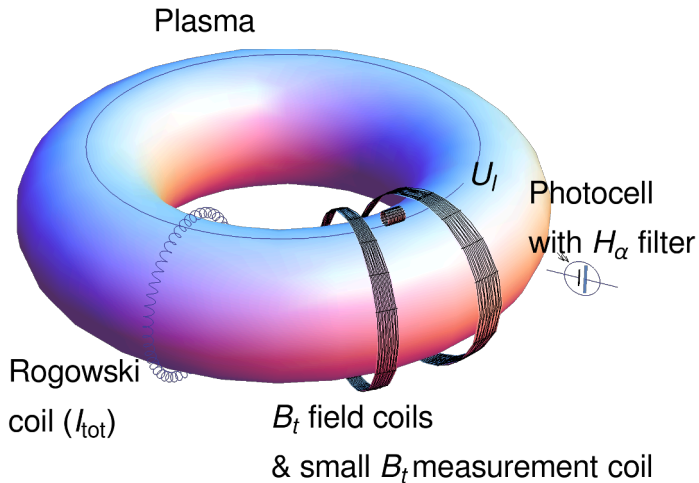
- The GOLEM tokamak concept
- The scenario to make the (GOLEM) tokamak discharge
- The scenario to discharge virtually
- The GOLEM tokamak basic diagnostics
- The GOLEM tokamak - guide tour

3 The Tokamak GOLEM (remote) operation

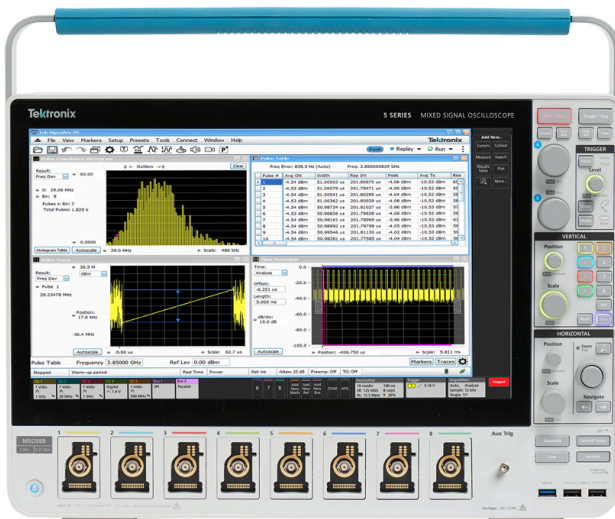
4 The Electron energy confinement time calculation (rough estimation)

5 Conclusion

The GOLEM tokamak - basic diagnostics



Data Acquisition System (Oscilloscope)



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',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: $\bar{U}_{\text{loop}} = 8,02 \text{ V}$; $\max_{t \in [t_{\text{discharge}}]} \bar{U}_{\text{loop}} = 9,89 \text{ V}$; $U_{\text{loop, down}} = 10,83 \text{ V}$
- Toroidal magnetic field: $\bar{B}_t = 0,40 \text{ T}$; $\max_{t \in [t_{\text{discharge}}]} \bar{B}_t = 0,57 \text{ T}$
- Plasma current: $I_p = 3,67 \text{ kA}$; $\max_{t \in [t_{\text{discharge}}]} I_p = 3,67 \text{ kA}$; $I_{\text{CD}} = 11,66 \text{ kA}$

GOLEM - Shot #39187

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 lists several files with their names, last modified dates, and sizes. A red arrow points from the highlighted data point in the browser to the 'TektrMSO56_ALL.csv' file in the index. Another red arrow points to the 'BasicDiagnostics.sh' file.

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

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

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

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

The screenshot displays a GitLab repository page for the project 'Tokamak GOLEM Basic diagnostics'. The top navigation bar includes 'About GitLab', 'Pricing', 'Talk to an expert', and a search bar. The left sidebar shows the repository structure, including 'Files', 'Commits', 'Branches', 'Tags', 'Contributors', 'Graph', 'Compare', 'Locked Files', 'Issues', 'Merge requests', 'CI/CD', 'Deployments', and 'Collapse sidebar'. The main content area shows the Jupyter notebook 'StandardDAS.ipynb' (19.83 KIB) with a blue 'Open in Web IDE' button. Below the notebook title, there is a 'Procedure' section with a link '(This notebook to download)'. A red arrow points from a circled icon in the notebook preview to the download button. The notebook content includes 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
```

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

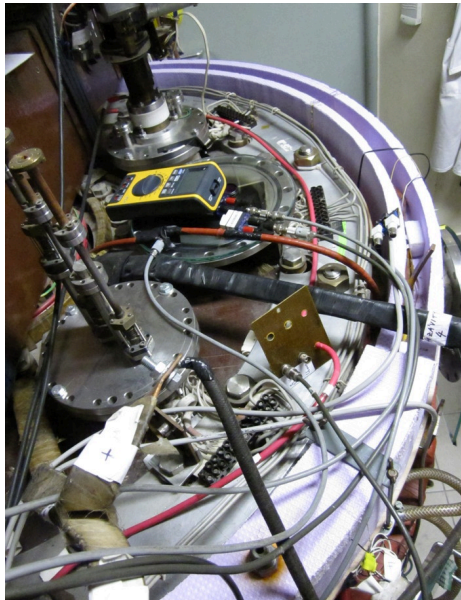
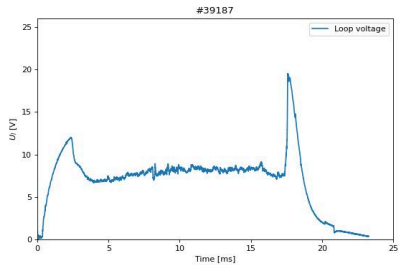
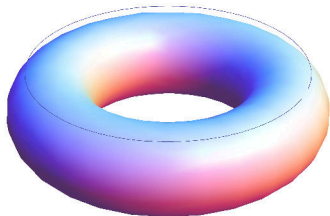
```
In [2]: import holoviews as hv
hv.extension('bokeh')
import hvplot.pandas
```



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}

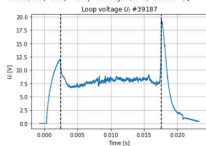
```
t_scale = 1e-3 if in_seconds else 1
if is_plasma:
    for t in (t_plasma_start, t_plasma_end):
        plt.axvline(t = t_scale, color='k', linestyle='--')
```

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')]
```



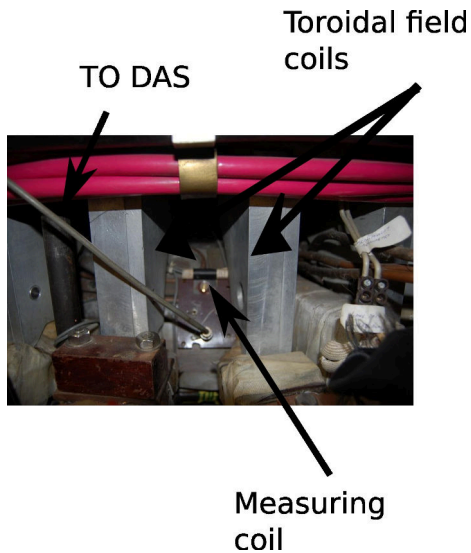
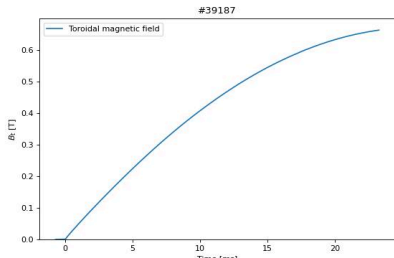
B_l calculation

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

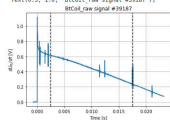
B_t calculation

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_s1].mean()
ax = dBt.plot(grid=True)
show_plasma_limits()
ax.set(xlabel='Time [s]', ylabel='dBt [B.t)/dtS [V]', title='BtCoil_raw signal #{}'.format(shot_no));
```

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

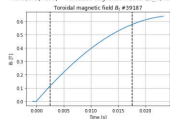


Integration (It is a magnetic diagnostic) & calibration

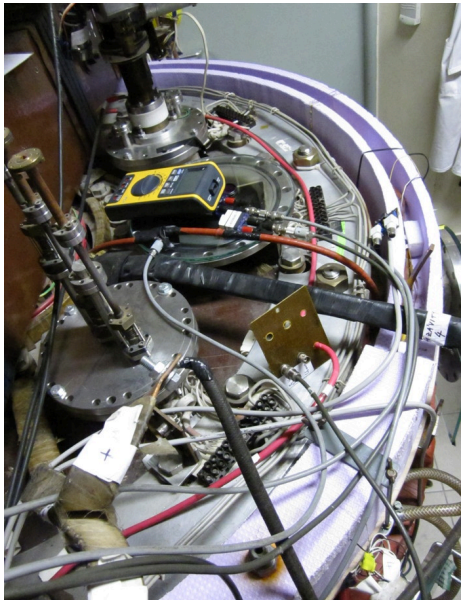
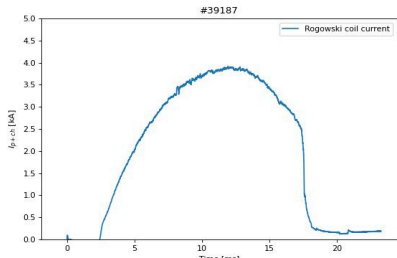
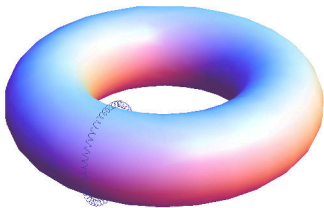
```
In [13]: K_BtCoil = float(read_parameter(shot_no, 'SystemParameters/K_BtCoil')) # Get BtCoil calibration factor
print('BtCoil calibration factor K_BtCoil={}'.format(K_BtCoil))
BtCoil calibration factor K_BtCoil=70.42 T/Vs)
```

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

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



Total current I_{ch+p}



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

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

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

Check the data availability

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

```
In [131]: dIpch = read_signal(shot_no, 'RogCoil') # 5000 horizontal for now
if dIpch[0] == 0:
    dIpch = 1 # non active
dIpch = correct_bias(dIpch)
dIpch = dIpch * (1/500) # subtract offset
dIpch[0] = 0
ax = dIpch.plot(grid=True)
show plasma limits()
ax.set(xlabel='Time [s]', ylabel='dI_{p+ch} [A]', title='Rogowski coil raw signal #131'.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={0:10.6} A/V'.format(K_RogowskiCoil))
In [132]: Ipch = pd.Series(integrate.cumtrapz(dIpch, x=dIpch.index, initial=0) * K_RogowskiCoil,
                        x=dIpch.index, name='Ipch')
ax = Ipch.plot(grid=True)
show plasma limits()
ax.set(xlabel='Time [s]', ylabel='I_{p+ch} [A]', title='Total (plasma+chamber) current #131'.format(shot_no))
```

Chamber current I_{ch} calculation

```
In [130]: R_chamber = float(read_parameter(shot_no, 'SystemParameters/R_chamber')) # Get Chamber resistivity
print('Chamber resistivity R_chamber={0}'.format(R_chamber))
Chamber resistivity R_chamber=0.007 Ohm
In [131]: I_chamber = float(read_parameter(shot_no, 'SystemParameters/I_chamber')) # Get Chamber inductance
print('Chamber inductance L_chamber={0}'.format(L_chamber))
Chamber inductance L_chamber=4e-06 H
```

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

Plasma current I_p calculation

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

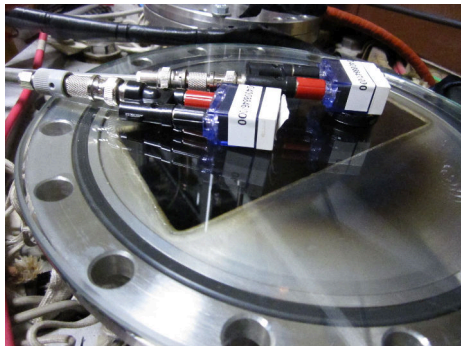
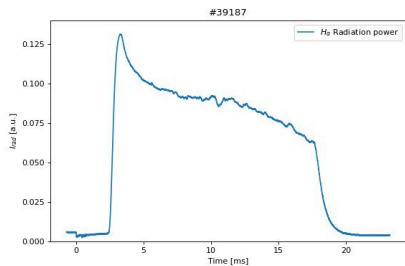
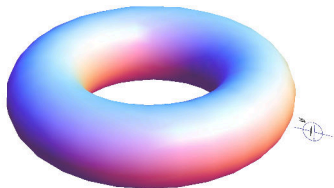
```
In [122]: if is_plasma:
    Ip_name = Ipch - loop_voltage/R_chamber # creates a new Series
    Ip = Ipch - I_ch
    Ip.name = 'Ip'
    Ip.name.plot(grid=True, label='naive I_{p} (A) (ch)')
    ax = Ip.plot(grid=True, label='using SQ_{p} = R_{ch} I_{ch} - L_{ch} \frac{dI_{ch}}{dt} (A)')
    ax.legend()
    show plasma limits()
    ax.set(xlabel='Time [s]', ylabel='I_{p} [A]', title='Plasma current I_{p} (pp) #131'.format(shot_no))
else:
    Ip = Ipch * 0 # no current
    heating
```

Out[122]: Plasma detected

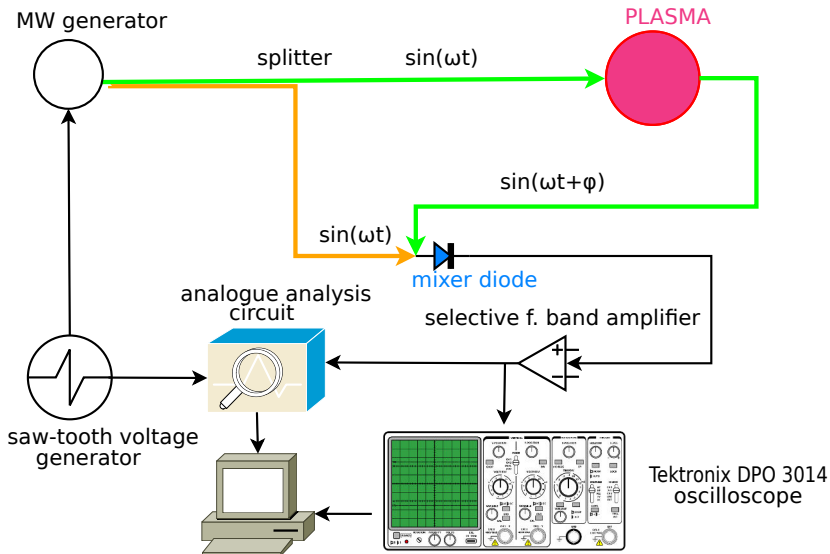
plasma lifetime of 15.1 ms, from 2.5 ms to 17.6 ms

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

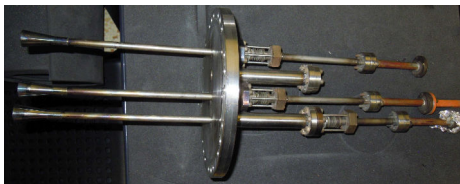
Visible radiation



Electron density n_e interferometry measurement scheme



The GOLEM tokamak interferometry HW



Finally "Typical", well executed discharge @ GOLEM

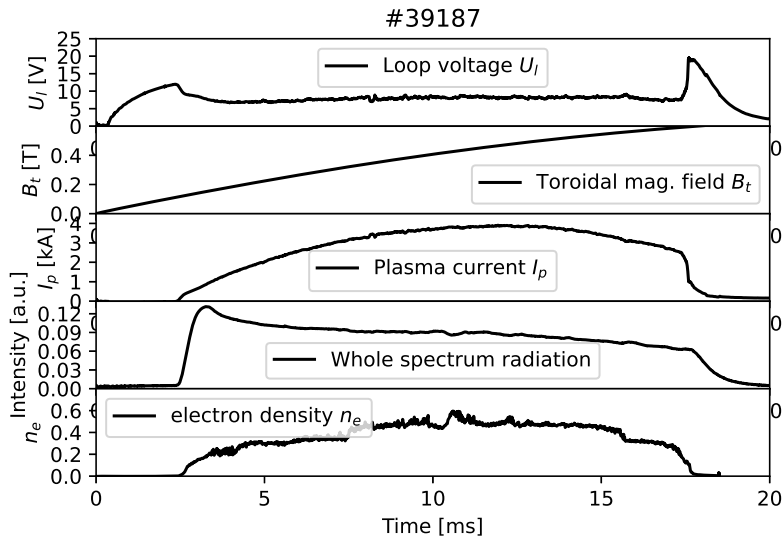


Table of Contents

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 basic diagnostics
- The GOLEM tokamak - guide tour

3 The Tokamak GOLEM (remote) operation

4 The Electron energy confinement time calculation (rough estimation)

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

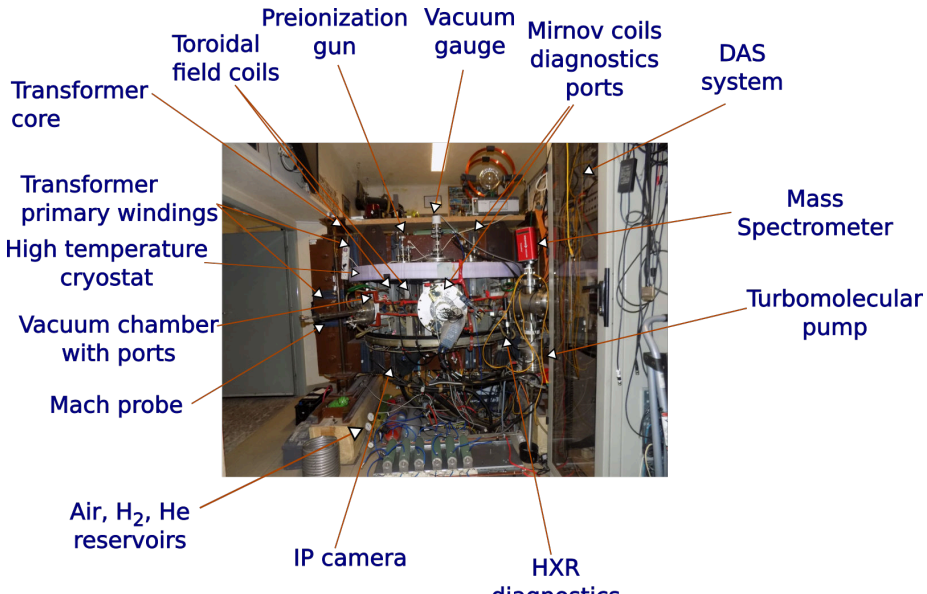
fire
protection
system



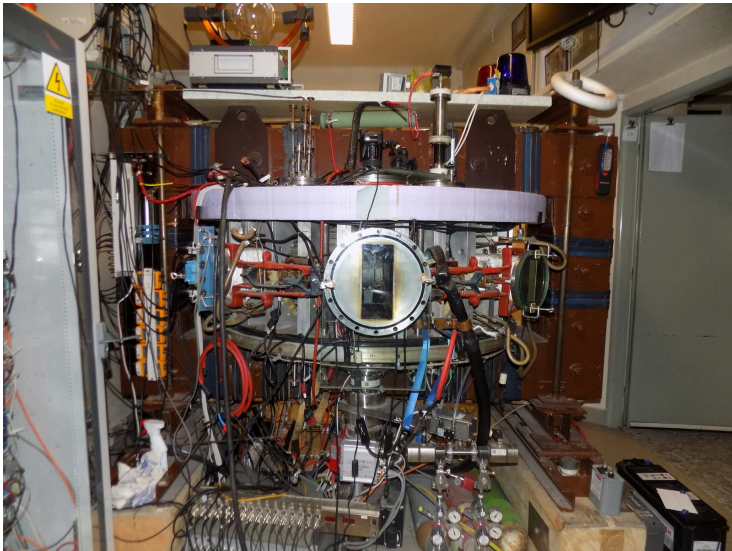
Tokamak room (North) 10/16



Tokamak room (North) 10/16



Tokamak room (South) 10/16



Tokamak room (South) 10/16

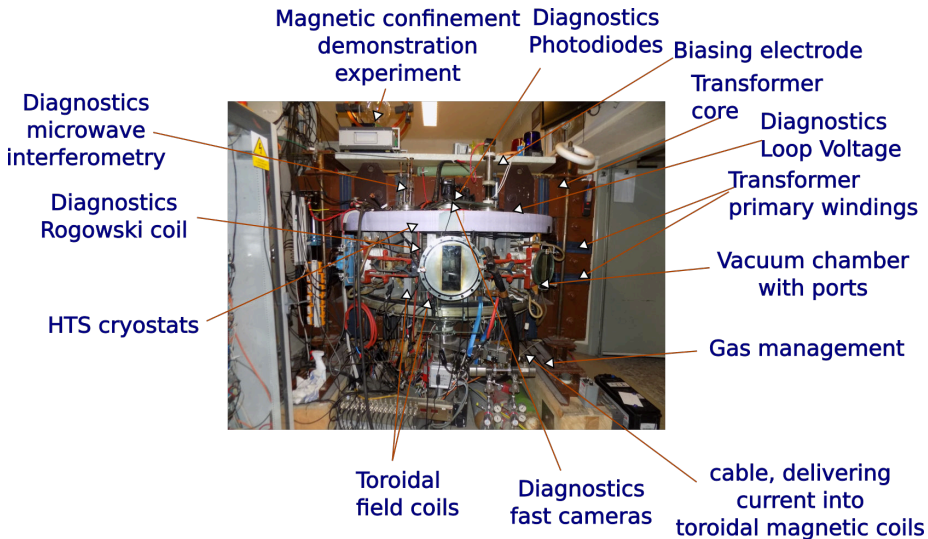


Table of Contents

- 1 Introduction
- 2 The Tokamak (GOLEM)
- 3 The Tokamak GOLEM (remote) operation**
- 4 The Electron energy confinement time calculation (rough estimation)
- 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 The Electron energy confinement time calculation (rough estimation)
- 5 Conclusion
- 6 Appendix

Control room: Introduction

GOLEM remote Introduction **Control room** Live Results

Prague Access: Level 1 Help

Introduction Working gas Preionization Magnetic field Current drive Submit

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

Preionization (electron gun)

Vacuum stand

Preionization (electron gun)

Toroidal magnetic field

Current drive

GAS handling H_2/He

23 mF C_p

11.3 mF C_p

2kV

2kV

Next

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

Control room: Working gas

GOLEM remote Introduction Control room Live Results

Introduction Working gas Preionization Magnetic field Electric field Submit

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

Preionization (electron gun)

Vacuum stand

GAS handling H_2/H_3

Toroidal magnetic field

Toroidal electric field

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

Preionization (electron gun)

Vacuum stand

GAS handling

Toroidal magnetic field

Toroidal electric field

67.5 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

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

Introduction Working gas Preionization **Magnetic field** Electric field Submit

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

Preionization (electron gun)

Vacuum stand

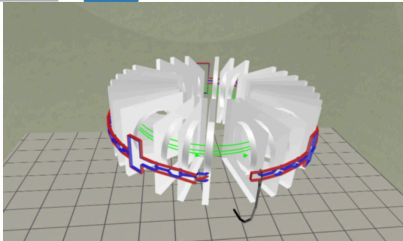
Toroidal magnetic field

Toroidal electric field

GAS handling

Capacitor voltage $U_{C_1} = 600$ V

Next Set recommended value



Control room: Current drive E_{cd}

GOLEM remote Introduction Control room Live Results

the Torneo Politecnico, Italy Group 1 Access: Level 2 Help

Introduction Working gas Preionization Magnetic field **Electric field** Submit

Set the voltage on the capacitors to be discharged into the [primary transformer winding](#). The higher the voltage, the larger the electric field creating and heating the plasma. The electric field capacitors are discharged after a configurable delay with respect to the magnetic field capacitors.

Preionization (electron gun)

Vacuum stand

Toroidal magnetic field

Toroidal electric field

GAS handling

Time delay of electric field start after the magnetic field starts t_{cd} : 0 micro seconds

Capacitor voltage U_{cd} : 400 V

Next Set recommended value

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

Control room: ... and Submit

GOLEM remote Introduction Control room Live Results

the Torneo Politecnico, Italy Group 1 Access: Level 2 Help

Introduction Working gas Preionization Magnetic field Electric field **Submit**

Write a comment describing your discharge configuration, i.e. the scientific aim of your experiment. Or just leave a friendly message.

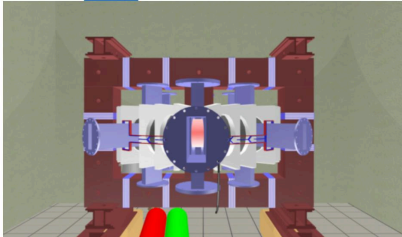
Comment

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

After submission you can watch the discharge Live or go back to the Introduction tab and start again. Or you can go to specific control tabs and reconfigure the discharge and then submit another discharge request.

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

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



Shot homepage

GOLEM » Shot #40032 »



Diagnostics

BasicDiagnostics
FastCameras
LimiterMinivCoils

Other

Wiki
Showroom

Navigation

Next
Previous
Current

Go to shot

#0032 | G00

Golem utils

Home
Plot data
Shot interval plot
Manipulators control

Database operations

Shots listing
Shots filtering

golem.ff.cvu.cz/shots/40032/

Tokamak GOLEM - Shot Database - #40032

Permalink to this headline

The date of discharge execution 22-11-10 20:06:01
The session mission BasicFastCamGM -> commissioning
The session ID 40013
The discharge comment posledni vyboj se stabilizaci -25
Discharge command .Dirigent.sh -discharge -Lbt 800 -Tbt 0 -Ucd 500 -Tcd 500 -preionization 1 -gas H -pressure 15 -diagnostics.limiterminivcoils -vacuum_shot-4001 6' -discharge.preionization "main_switch=on;powsup_heater=80;powsup_a coil=100 -discharge.position_stabilization "main_switch=on;radial_switch =on;vertical_waveworm=3000.0;1100.0;-25;2200.0;30000.0;vertical_switch =on;radial_waveworm=2000.0;3000.0;9000.0;12000.-25;24000.0;25000.0" -- ScanDefinition "40031" --comment "posledni vyboj se stabilizaci -25"

Technological parameters

- Working Gas: $p_{\text{discharge,before}}=0,90 \text{ mPa}$; $p_{\text{discharge,post}}=15,30 \text{ mPa}$ ($p_{\text{WG}}^{\text{request}}=15 \text{ mPa}$; $X_{\text{WG}}^{\text{request}}=H$)
- Toroidal magnetic field: $U_{\text{Bt}}^{\text{request}}=800 \text{ V}$; $B_t^{\text{request}}=0,0 \text{ us}$
- Current drive field: $U_{\text{Ed}}^{\text{request}}=500 \text{ V}$; $I_{\text{Ed}}^{\text{request}}=500,0 \text{ us}$

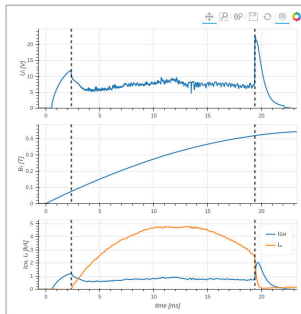
Plasma:

- Plasma: yes or no:
- Time parameters: $\Delta t_p=17,03 \text{ ms}$ (from $t_{\text{start}}=2,35 \text{ ms}$ to $t_{\text{end}}=19,38 \text{ ms}$)

Plasma parameters:

- Loop voltage: $\overline{U}_{\text{loop}}=7,39 \text{ V}$; $\max_{t \in [discharge]} U_{\text{loop}}=9,38 \text{ V}$; $U_{\text{breakdown}}=10,63 \text{ V}$
- Toroidal magnetic field: $\overline{B}_t=0,29 \text{ T}$; $\max_{t \in [discharge]} B_t=0,42 \text{ T}$
- Plasma current: $\overline{I}_p=4,09 \text{ kA}$; $\max_{t \in [discharge]} I_p=4,80 \text{ kA}$; $t_{\text{fp}}^{\text{max}}=13,17 \text{ ms}$

Basic Diagnostics



On stage diagnostics

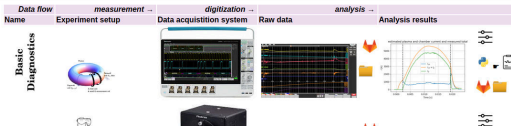


Table of Contents

- 1 Introduction
- 2 The Tokamak (GOLEM)
- 3 The Tokamak GOLEM (remote) operation**
 - Control room
 - Data handling @ the Tokamak GOLEM
- 4 The Electron energy confinement time calculation (rough estimation)
- 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)

```
1 import numpy as np
2 import matplotlib.pyplot as plt
3
4 shot_no = 39187
5 identifier = "U_Loop.csv"
6 DAS='Diagnostics/BasicDiagnostics/'
7 # create data cache in the 'golem_cache' folder
8 ds = np.DataSource('golem_cache')
9 #Create a path to data and download and open the file
10 base_url = "http://golem.fjfi.cvut.cz/shots/"
11 data_file = ds.open(base_url + str(shot_no)+ '/' +DAS +identifier)
12 #Load data from the file and plot to screen and to disk
13 data = np.loadtxt(data_file,delimiter=",")
14 plt.title('#'+str(shot_no))
15 plt.plot(data[:,0]*1000, data[:,1]) #1. column vs 2. column
16 plt.xlabel('Time [ms]');plt.ylabel('$U_1$ [V]');
17 plt.savefig('graph.jpg')
18 plt.show()
19
20 #Run it: save it as script.py and run "python script.py" or execute in a
```

Matlab

```
1 ShotNo=39187
2 baseURL='http://golem.fjfi.cvut.cz/shots/';
3 diagnPATH='/Diagnostics/BasicDiagnostics/U_Loop.csv';
4 %Create a path to data
5 dataURL=strcat(baseURL,int2str(ShotNo),diagnPATH);
6 % Write data from GOLEM server to a local file
7 urlwrite(dataURL,'LoopVoltage');
8 % Load data
9 data = load('LoopVoltage', '\t');
10 % Plot and save the graph
11 f = figure('visible', 'off');
12 hold on
13 plot(data(:,1)*1000, data(:,2), '.');
14 xlabel('Time [ms]')
15 ylabel('U_1 [V]')
16 hold off
17 print -djpeg plot.jpg
18 close(f)
19 exit;
```

Octave

```
1 ShotNo=39187
2 baseURL='http://golem.fjfi.cvut.cz/shots/';
3 diagnPATH='/Diagnostics/BasicDiagnostics/U_Loop.csv';
4 %Create a path to data
5 dataURL=strcat(baseURL,int2str(ShotNo),diagnPATH);
6 % Write data from GOLEM server to a local file
7 urlwrite(dataURL,'U_Loop.csv');
8 % Load data
9 data = load('U_Loop.csv', '\t');
10 % Plot and save the graph
11 plot(data(:,1)*1000, data(:,2), '.');
12 xlabel('time [ms]')
13 ylabel('U_{loop} [V]')
14 saveas(gcf, 'plot', 'jpg');
15 exit;
```

Gnuplot

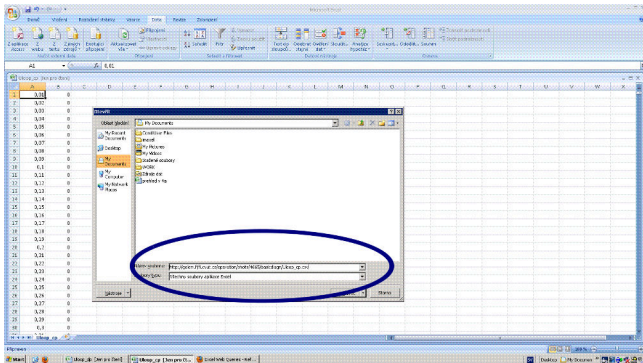
```
1 identifier = 'U_Loop.csv' ;
2 ShotNo = '39187'
3 # Create a path to the data
4 DAS='Diagnostics/BasicDiagnostics/'
5 baseURL='http://golem.fjfi.cvut.cz/shots/'
6 DataURL= baseURL.ShotNo.'/'.DAS.identifier
7 set datafile separator ',';
8 set title "Uloop for #".ShotNo;
9 # Write data from GOLEM erver to a local file
10 ! wget -q @DataURL ;
11 # Plot the graph from a local file
12 set xrange [0:0.02];set xlabel 'Time [s]';set ylabel 'U_1 [V]'
13 set terminal jpeg
14 plot identifier u 1:2 w l t 'Uloop'
15
16 # Command line: cat script.gp |gnuplot > graph.jpg
```


GNU Wget

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

- Runs on most UNIX-like operating systems as well as Microsoft Windows.
- Homepage: <http://www.gnu.org/software/wget/>
- Basic usage:
 - To get U_l : `wget http://golem.fjfi.cvut.cz/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)

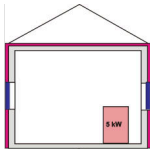
are not recommended, only tolerated.

Table of Contents

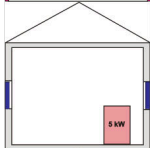
- 1 Introduction
- 2 The Tokamak (GOLEM)
- 3 The Tokamak GOLEM (remote) operation
- 4 The Electron energy confinement time calculation (rough estimation)**
- 5 Conclusion
- 6 Appendix

Energy balance of the house

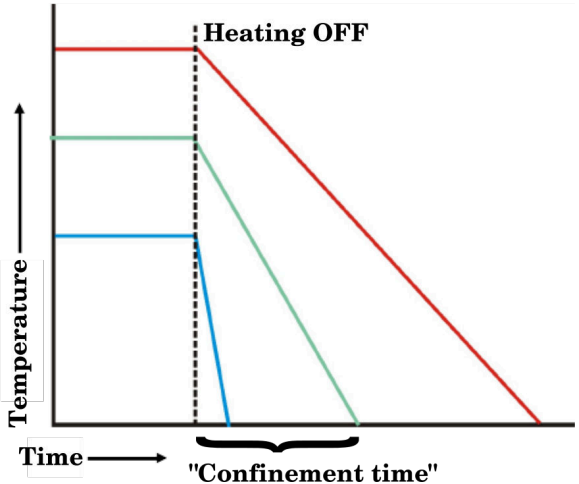
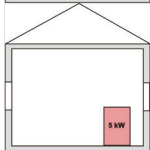
Closed windows & insulation



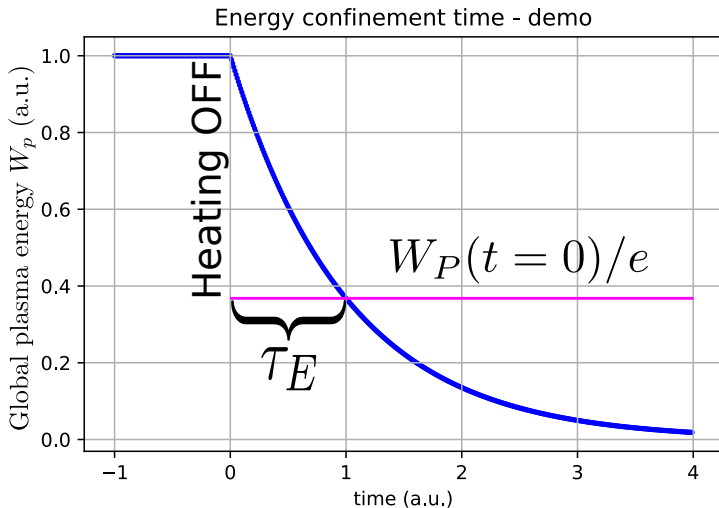
Closed windows



Open windows



Energy balance of the tokamak



Energy confinement time

Under the assumption of a simplified power balance, the heating power P_H is partially absorbed in the plasma and leads to an increase of the plasma energy W_p and the rest is lost as the loss power P_L

$$P_H = \frac{dW_p}{dt} + P_L$$

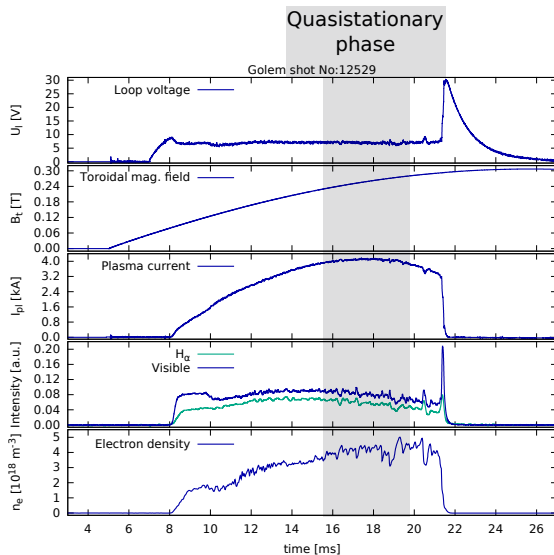
The energy confinement time is defined as the characteristic time scale of the exponential decay of the plasma energy W_p due to the loss power P_L :

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

Choosing the quasistationary phase of the plasma discharge, where $\frac{dW_p}{dt} = 0$ gives:

$$\tau_E(t) = \frac{W_p(t)}{P_H(t)}$$

The discharge - quasistationary phase



Plasma heating power

On the GOLEM tokamak the only heating mechanism of the plasma is ohmic heating P_{OH} resulting from the plasma current I_p flowing in a conductor with finite resistivity R_p . The time dependence of the ohmic heating power can be calculated as:

$$P_H(t) = P_{OH}(t) = R_p(t) \cdot I_p^2(t)$$

Plasma Energy

The global plasma energy content W_p can be simply calculated from the temperature estimation $T_e(0, t)$, average density n_e and plasma volume V_p , based on the ideal gas law, taking into account the assumed

$T_e(r, t) = T_e(0, t) \left(1 - \frac{r^2}{a^2}\right)^2$ temperature profile:

$$W_p(t) = V_p \frac{n_e k_B T_e(0, t)}{3}.$$

The information that the magnetic field reduces the degrees of freedom of the particles to two has been used to derive this formula.

- $V_p \approx 80 \text{ l}$

Central Electron Temperature estimation (Spitzer Formula)

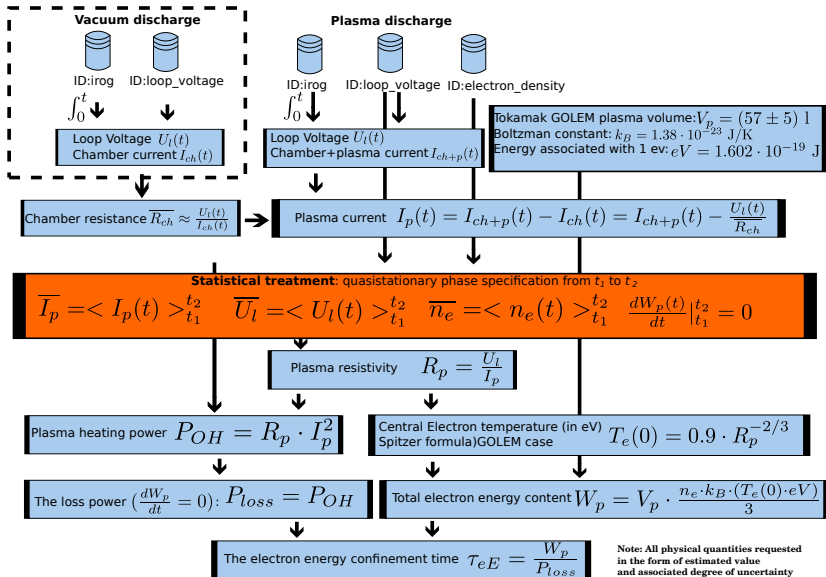
The time evolution of the central electron temperature $T_e(0, t)$ is calculated from equation based on Spitzer's resistivity formula (see eg. [5],[6]):

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

For particular case of the GOLEM tokamak it says:

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

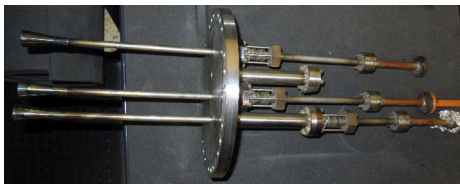
Towards Electron energy confinement time τ_{eE}



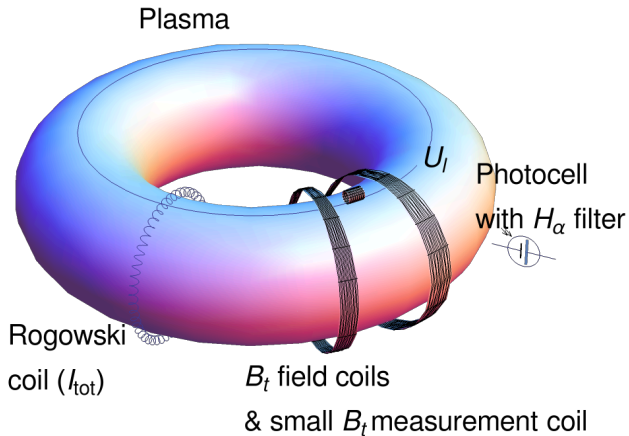
Hands on the GOLEM tokamak - equipment



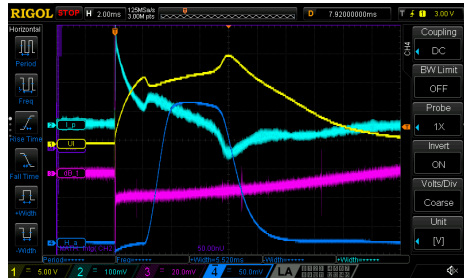
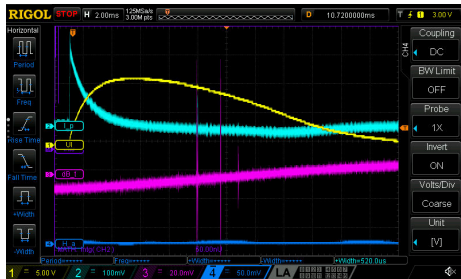
The GOLEM tokamak interferometry HW



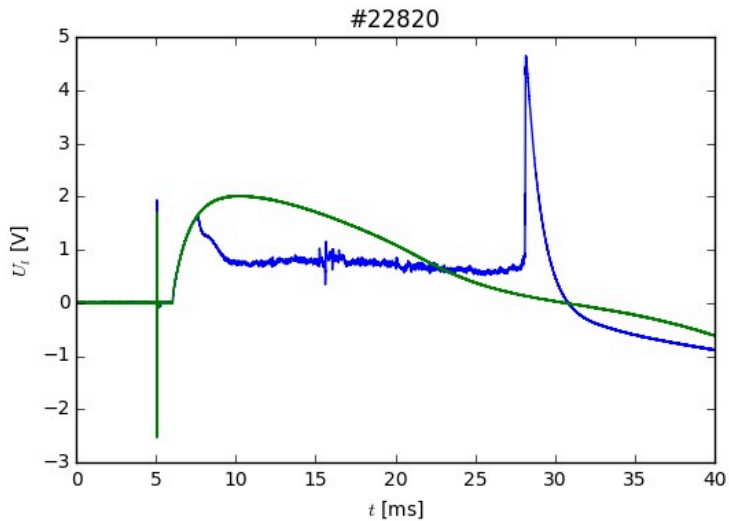
The GOLEM tokamak - standard diagnostics



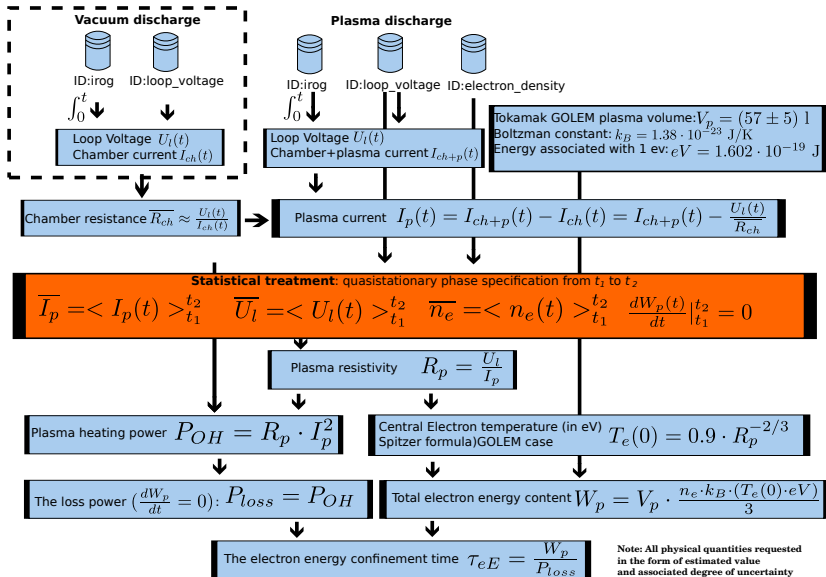
Vacuum x Plasma discharge @ Oscilloscope



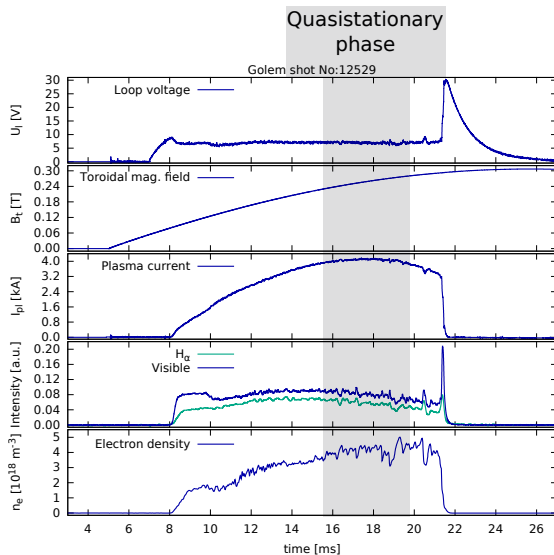
Vacuum x Plasma shot



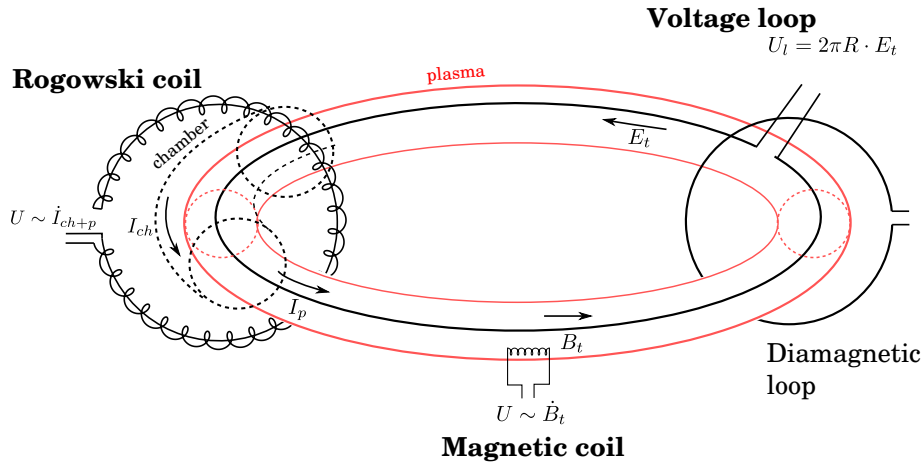
Towards Electron energy confinement time τ_{eE}



The discharge - quasistationary phase

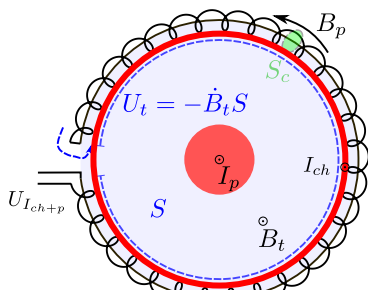
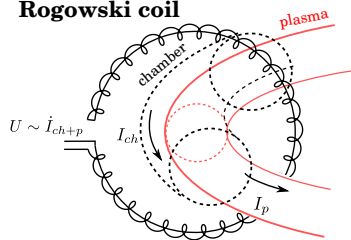


Schematic of electromagnetic diagnostics



Rogowski coil for the (chamber & plasma) current I_{ch+p} measurements

Rogowski coil



- Ampere's Law: $\nabla \times \mathbf{B} = \mu_0 \mathbf{j}$ (neglecting $\dot{\mathbf{D}}$)
- current through (const) surface S :

$$\int \mathbf{j} \cdot d\mathbf{S} = I_{ch+p}$$
- (const) poloidal field along surface border l : $\int \nabla \times \mathbf{B} \cdot d\mathbf{S} = \oint B_p dl = I B_p$
- voltage induced: $U_{I_{ch+p}} + U_t - U_t = -N \dot{B}_p S_c = -\mu_0 \frac{N S_c}{l} \dot{I}_{ch+p}$
- The wire of the coil is back-wound to omit a strong toroidal magnetic field B_t signal.

Magnetic measurements generally I

- Raw signals (analog $U_r(t)$ or, respectively, its discretized digital U_i counterpart form) must be specially maintained:
 - corrected for the DC bias U_{offset} of the measurement circuit,
 - integrated (pure diagnostics signal voltage $U_d(t)$ is induced by the time derivative of the appropriate magnetic flux),
 - multiplied by calibration factors C_d (C_{Bt} , C_{RC}).
- We can express the basic relationship $U_r(t) = U_d(t) + U_{offset}$
- The measured signal $U_d(t)$ is proportional to the time derivative of the original physical quantity $D(t)$ signal (it is a magnetic measurement):

$$U_d(t) \propto \frac{dD(t)}{dt}, \text{ or } U_d(t) = C_d \frac{dD(t)}{dt}$$

Where the linearity coefficient C_d is called a calibration factor.

Magnetic measurements generally II

- To determine the desired physical quantity $D(t)$, we just have to perform an integration over time:

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

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

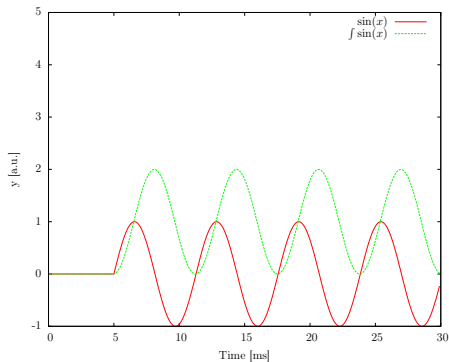
$$D_i = \frac{1}{C_d} \sum_{j=0}^{t/\Delta t} (U_i(t_j) - U_{offset}) \Delta t$$

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

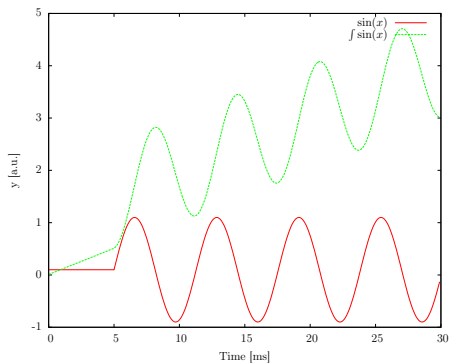
- The offset U_{offset} can be specified from the beginning of the data series before switching on the real experiment.

Magnetic measurement demo - game with U_{offset}

Without U_{offset}



With U_{offset}



Towards Electron energy confinement time τ_E

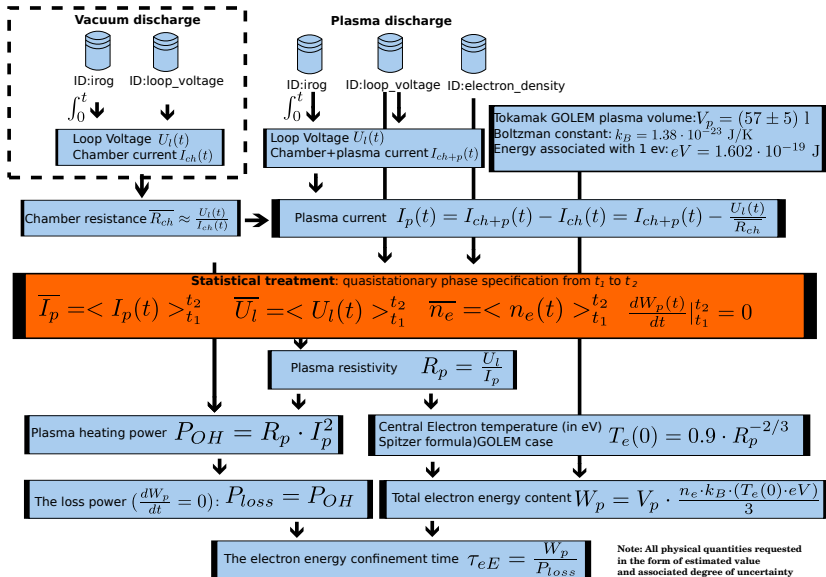


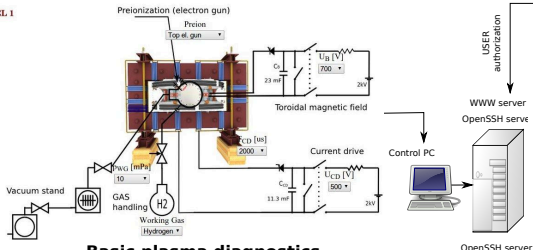
Table of Contents

- 1 Introduction
- 2 The Tokamak (GOLEM)
- 3 The Tokamak GOLEM (remote) operation
- 4 The Electron energy confinement time calculation (rough estimation)
- 5 Conclusion**
- 6 Appendix

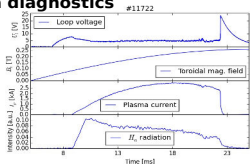
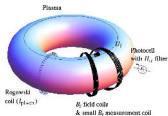
The global schematic overview of the GOLEM experiment

LEVEL 1

Tokamak technology setup



Basic plasma diagnostics



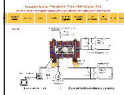
internet



**Virtual control room
(remote participation)**

WWW control interface

HTML & PHP scripts



SSH control interface

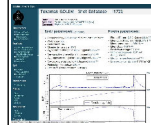
WINDOWS via putty



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

Data presentation

HTML (www pages)



Data handling

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

WWW server
OpenSSH server



OpenSSH server

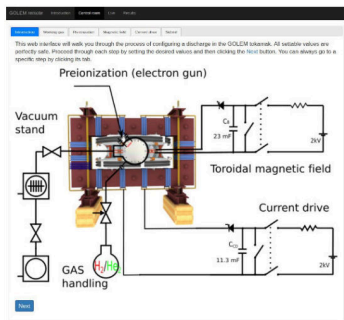


Control PC

- Everything via <http://golem.fjfi.cvut.cz/Torino>
 - This presentation
 - Control rooms
 - Contact: Vojtech Svoboda,
+420 737673903,
svoboda@fjfi.cvut.cz
 - Videoconference
<https://meet.jit.si/golem>



Recommended values for the GOLEM tokamak operation



- Preionization: Top electron gun
- Gas: Hydrogen. A Working gas pressure: p_{WG} [mPa] $< 0, 40 >$ mPa
- A voltage to charge the Current drive field E_t capacitor: U_{E_t} [V] $< 400, 700 >$ V
- A voltage to charge the Toroidal magnetic field B_t capacitor: U_{B_t} [V] $< 600, 1200 >$ V
- Time delay of the E_t trigger with respect to the B_t trigger: T_{CD} [μ s] $< 0, 10000 >$ μ s

Fee: postcard from the venue of remote measurements



Acknowledgement

Financial support highly appreciated:

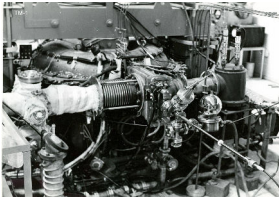
CTU RVO68407700, SGS 17/138/OHK4/2T/14, GAČR GA18-02482S, EU funds CZ.02.1.01/0.0/0.0/16_019/0000778 and CZ.02.2.69/0.0/0.0/16_027/0008465, IAEA F13019, FUSENET and EUROFUSION.

Students, teachers, technicians (random order):

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

Thank you for your attention

Tokamak TM1
@Kurchatov Institute near Moscow
~1960-1977



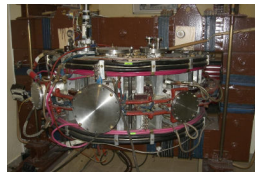
SCIENCE

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



SCIENCE
& education

Tokamak GOLEM
@Czech Technical University, Prague
2007-



EDUCATION
& science

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

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

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

LEVEL 1

Preionization (electron gun)
Proton
Toroidal magnetic field
Current drive
Vacuum island
GAS handling
Working Gas
Discharge comment
Place the discharge setup into the queue.




Table of Contents

- 1 Introduction
- 2 The Tokamak (GOLEM)
- 3 The Tokamak GOLEM (remote) operation
- 4 The Electron energy confinement time calculation (rough estimation)
- 5 Conclusion
- 6 Appendix**

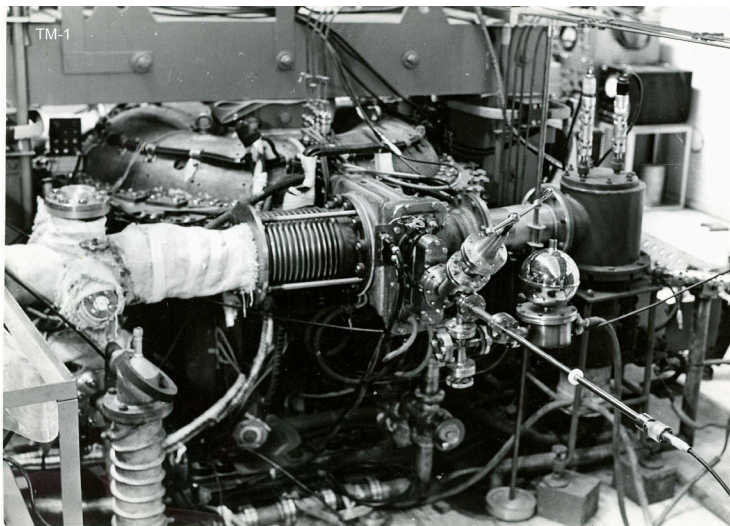
References I

-  **Wikipedia contributors.** Golem — Wikipedia, the free encyclopedia. <https://en.wikipedia.org/w/index.php?title=Golem>, 2020. [Online; accessed 29-March-2020].
-  **Wikipedia contributors.** Lawson criterion — Wikipedia, the free encyclopedia. https://en.wikipedia.org/w/index.php?title=Lawson_criterion&oldid=888000448, 2019. [Online; accessed 6-December-2019].
-  **ITER contributors .** ITER. <https://www.iter.org>, 2007. [Online; accessed 21-December-2018].
-  **Tokamak GOLEM contributors.** Tokamak GOLEM at the Czech Technical University in Prague. <http://golem.fjfi.cvut.cz>, 2007. [Online; accessed December 5, 2022].

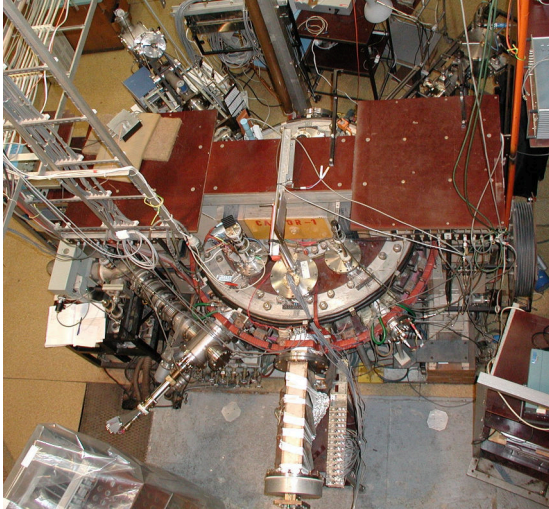
References II

-  Brotankova, J. *Study of high temperature plasma in tokamak-like experimental devices*. PhD thesis, 2009.
-  J. Wesson. *Tokamaks*, volume 118 of *International Series of Monographs on Physics*. Oxford University Press Inc., New York, Third Edition, 2004.
-  V. Svoboda, B. Huang, J. Mlynar, G.I. Pokol, J. Stockel, and G Vondrasek. Multi-mode Remote Participation on the GOLEM Tokamak. *Fusion Engineering and Design*, 86(6-8):1310–1314, 2011.

XX/YY: TM-1



XX/YY: CASTOR



12/07: Last minutes at the IPP Prague

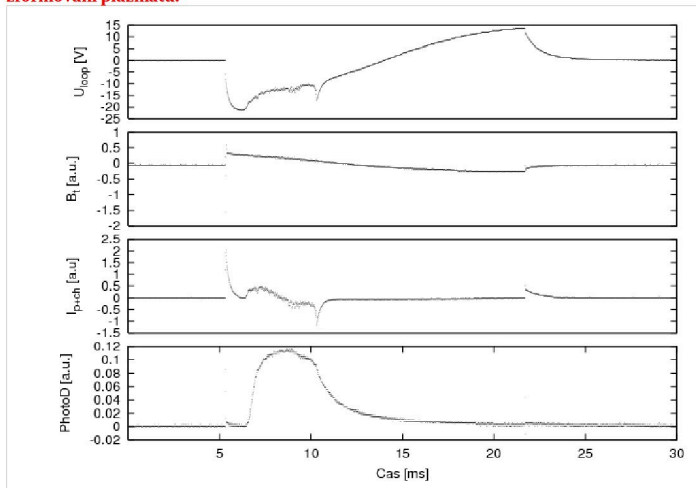


12/07: First minutes at the CTU Prague



07/09: First plasma in the tokamak GOLEM

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



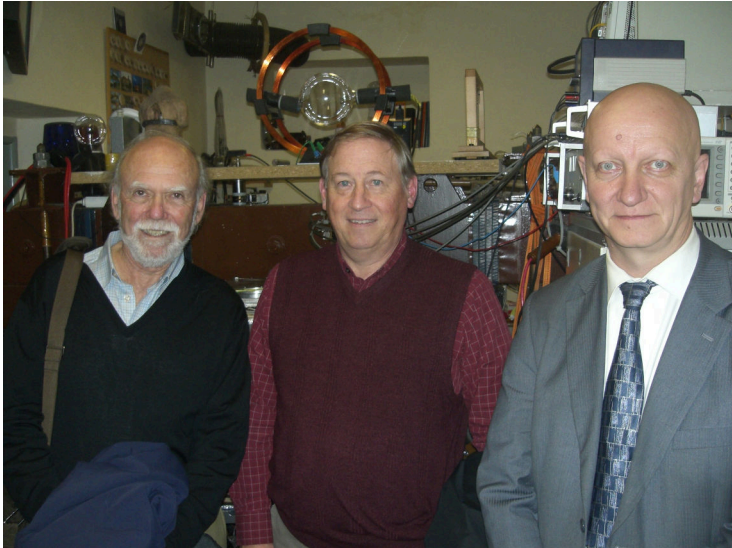
O tom svědčí:

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

09/09: Tokamak and tokamak



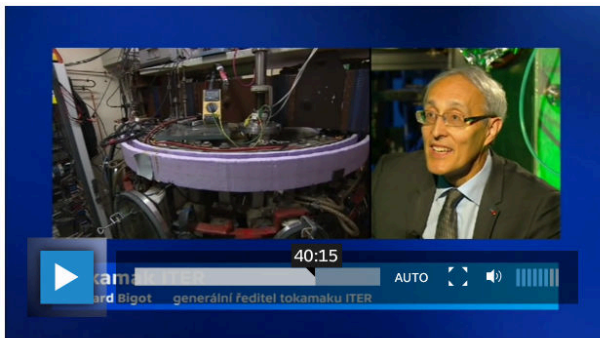
11/11: NP laureat at tokamak GOLEM



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



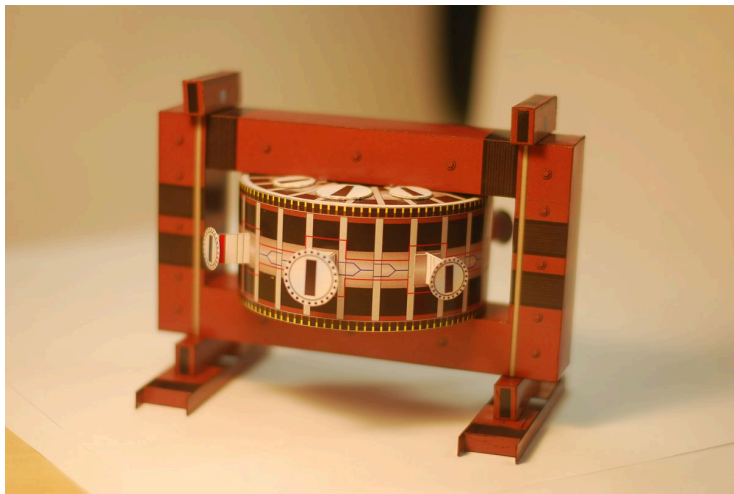
0916: ITER DG, Mr. Bernard Bigot (Shot #22185)



Quotation from Czech Television Hydepark

I am very pleased with the GOLEM ...

09/19 Paper model ABC



2010: Tokamak GOLEM



2011: The tokamak COMPASS with NBI



2016: ITER segment



2017: First Spitzer Stellarator



10/15: Trojan horse - #20000

GOLEM - Shot #20000 - previous | next | current

Tokamak GOLEM - Shot Database - 20000

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

Diagnostics

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

Analysis

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

DAS

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

Vacuum log

Charging log

Other


Data
References
About
Wiki
Utilities

Navigation

Next
Previous
Current

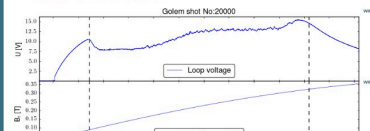
Go to shot
20000

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



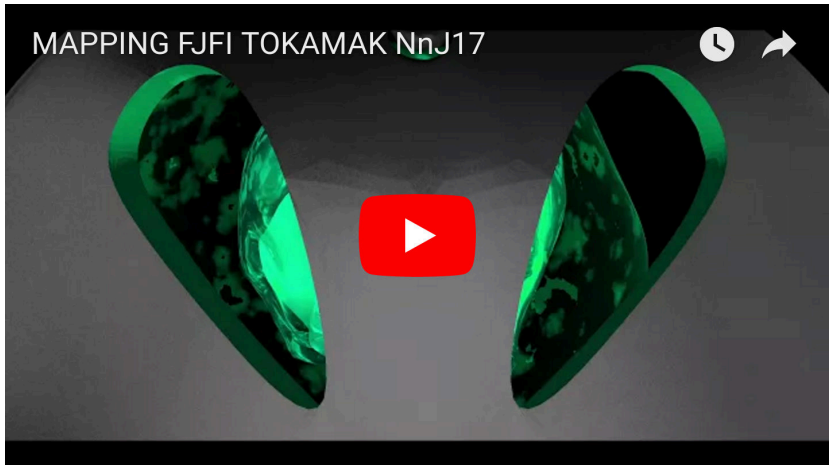
Basic parameters: (compare) **Plasma parameters:**

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



11/17: GOLEM tokamak "mapping"

Tokamak GOLEM



Základní (řádová) statistika k 30.11.2012

Počet dní od instalace: 1815.

Počet operačních dní: ≈ 438 .

Počet hodin: ≈ 1954

Počet shotů: 10417.

Počet shotů – $>$ plazma: ≈ 7600 .

Průměrná délka výboje: ≈ 7 ms.

Celková délka trvání plazmatu: < 60 s.