

## Introduction to the tokamak GOLEM operation Practical guide

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

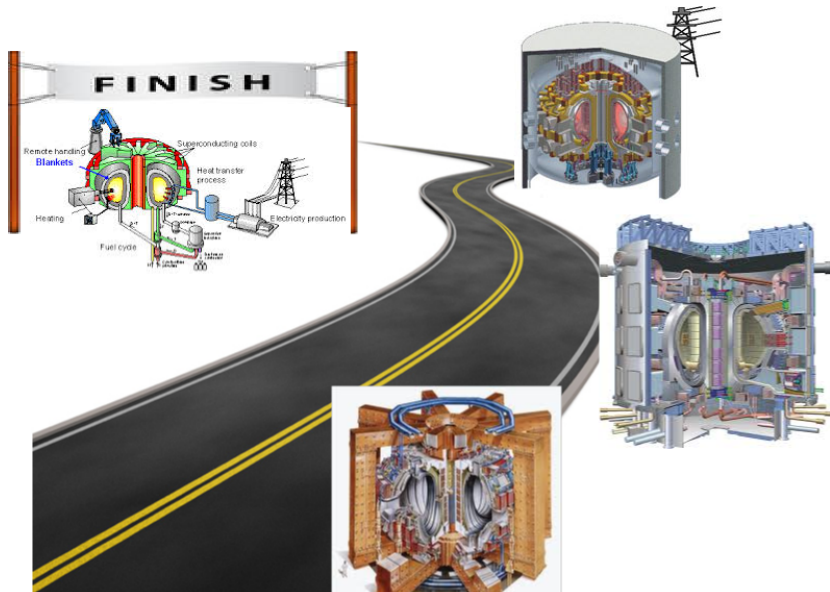
March 25, 2025

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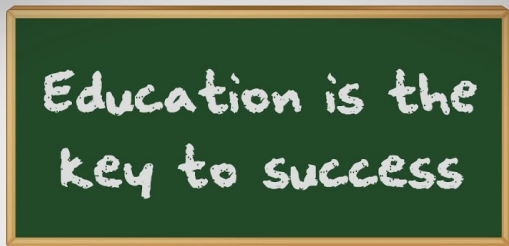
- 1 Introduction
- 2 The Tokamak (GOLEM)
- 3 The Tokamak GOLEM (remote) operation
- 4 Conclusion
- 5 Appendix



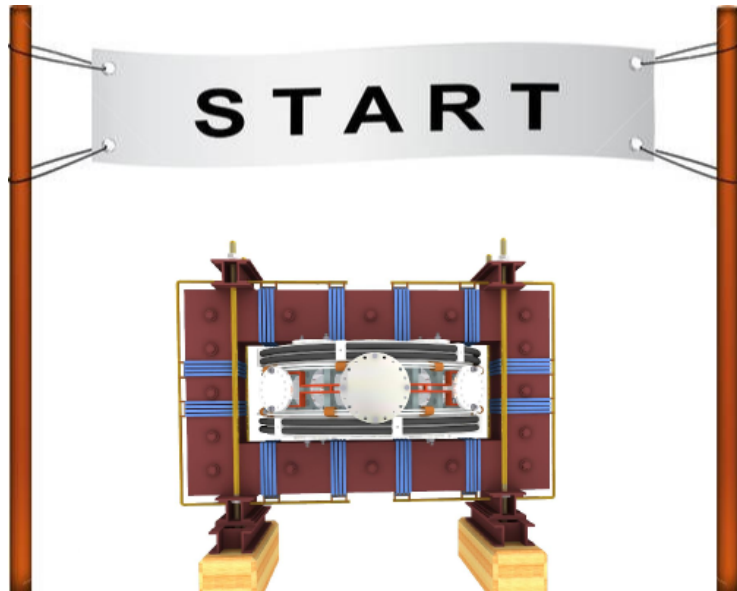
# Milestones to Fusion Power Plant



# Education importance

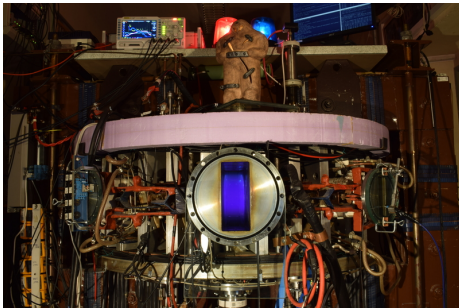


Let's start with the tokamak GOLEM - *the smallest tokamak in the World with the biggest controll room*




# 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 ..



WIKIPEDIA  
The Free Encyclopedia

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## Tokamak

From Wikipedia, the free encyclopedia

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

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


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

### Experimental tokamaks [ edit ]

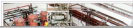
#### Currently in operation [ edit ]

(in chronological order of start of operations)

- 1960s: TM1-MH (since 1977 Castor; since 2007 Golem<sup>[12]</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>[13]</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



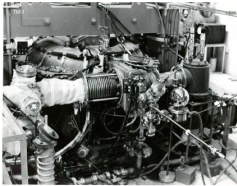
Alcator C-Mod



Wikipedia - Wikipedia, the free encyclopedia | [svoboda] brum [fj.cvut.cz - Kossile] | Krušader | Inbox - svoboda@fj.cvut.cz - Mozilla

# The GOLEM tokamak for education - historical background

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



1974

Institute of Plasma Physics  
Czech republic

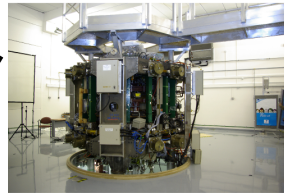
**CASTOR**

**COMPASS**

2008

Czech Technical University Prague  
Czech republic  
**GOLEM**

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



2006



# GOLEM

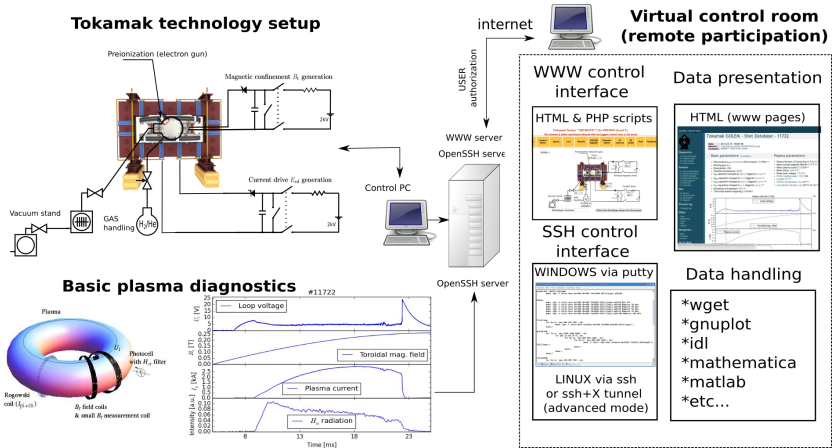
... somewhere, in the ancient cellars of Prague,

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



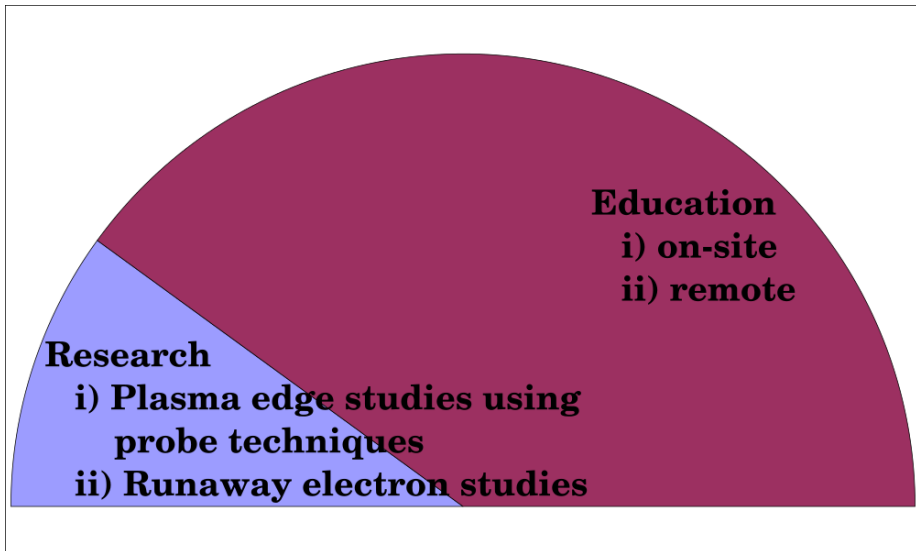
At the end of the 16th century, in the times when the Czech lands were ruled by Emperor Rudolf II, in Prague, there were Rabbi Judah Loew, well known alchemist, thinker, scholar, writer and inventor of the legendary GOLEM - a clay creature inspired with the Universe power that pursued his master's command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

# The global schematic overview of the tokamak GOLEM experiment





# The GOLEM tokamak mission



# Production

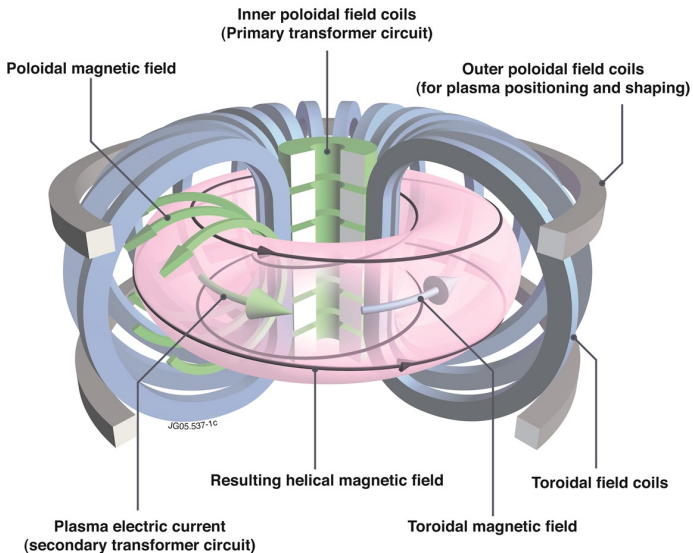
- Everything via <http://golem.fjfi.cvut.cz/Eindhoven>
  - This presentation
  - Control rooms
  - Contact: Vojtech Svoboda,  
+420 737673903,  
[vojtech.svoboda@fjfi.cvut.cz](mailto:vojtech.svoboda@fjfi.cvut.cz)
  - Videoconference:  
<https://meet.google.com/hnv-qjhu-xvi>



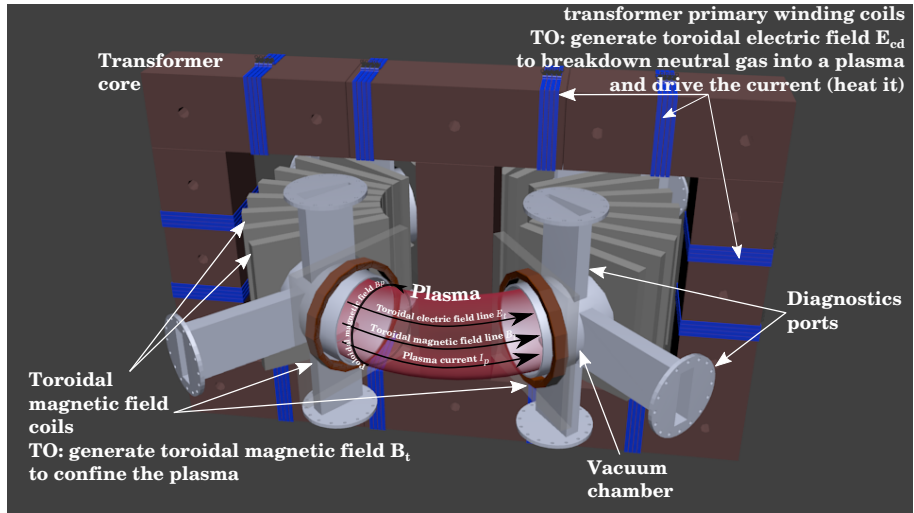
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# Tokamak magnetic confinement concept



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



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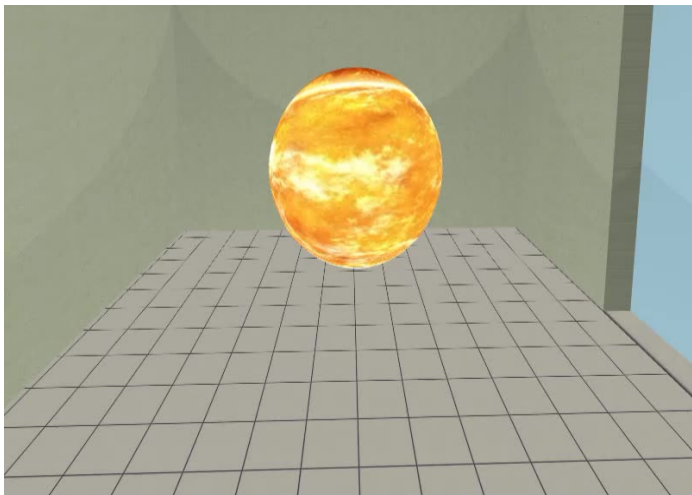
- The GOLEM tokamak concept
- The scenario to make the (GOLEM) tokamak discharge
- The scenario to discharge virtually
- The GOLEM tokamak - guide tour
- The GOLEM tokamak basic diagnostics

## 3 The Tokamak GOLEM (remote) operation

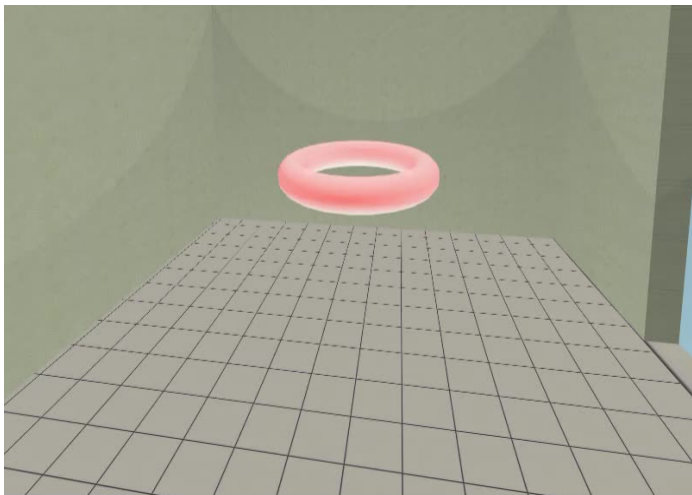
## 4 Conclusion

## 5 Appendix

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

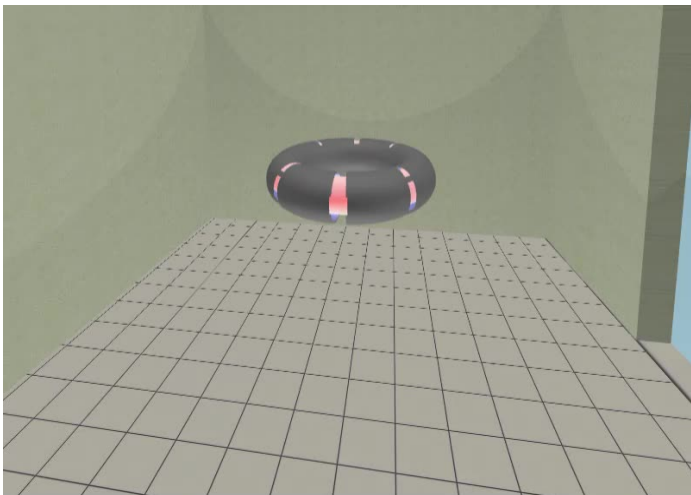


# Magnetic confinement requires toroidal geometry

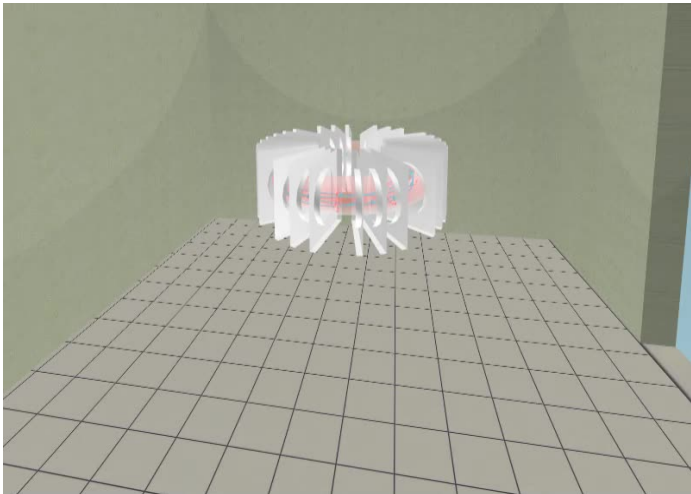




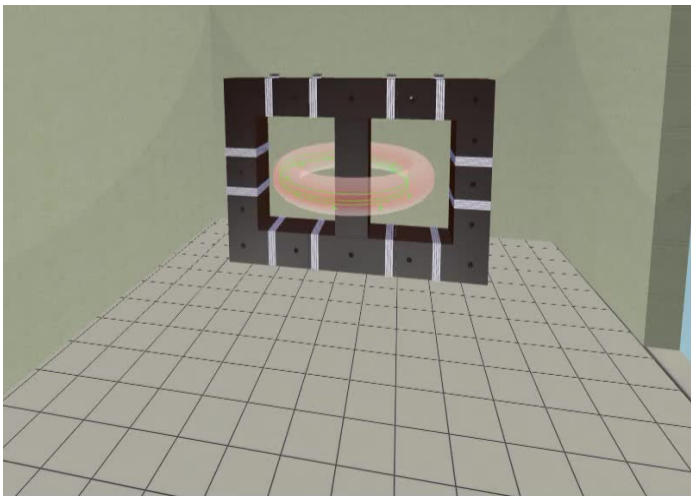
A chamber contains the thermonuclear reaction



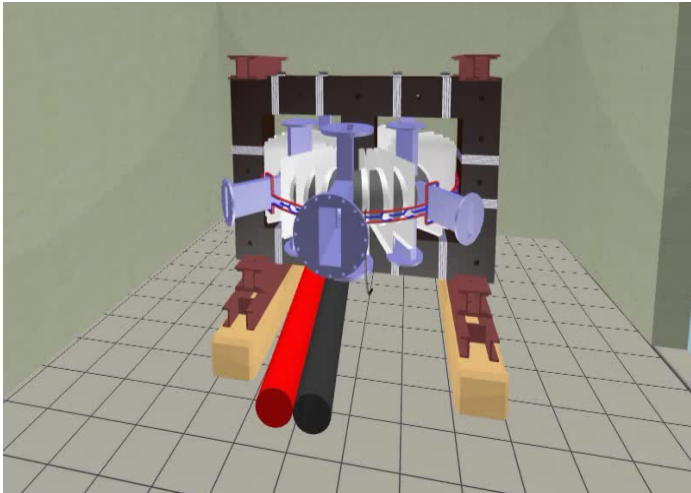
Toroidal magnetic field coils confine the plasma



A transformer action creates and heats the plasma



# The final technology altogether



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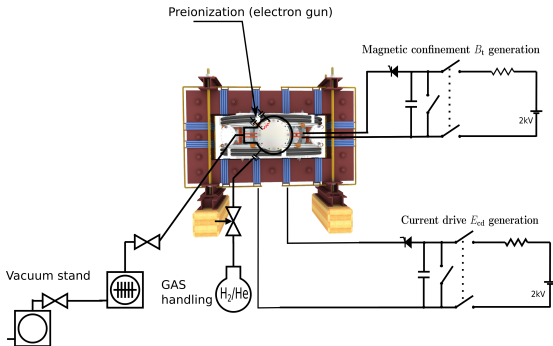
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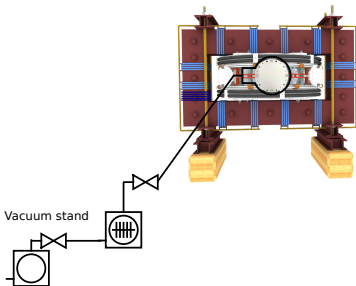
# Plasma in Tokamak (GOLEM) - the least to do



## To do:

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

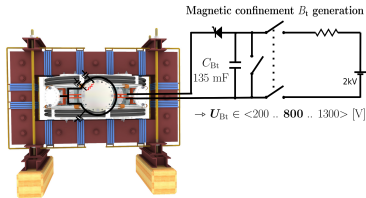
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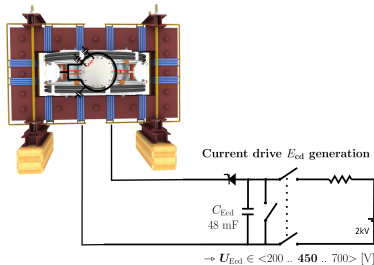


## To do:

- session start phase:
  - Evacuate the chamber
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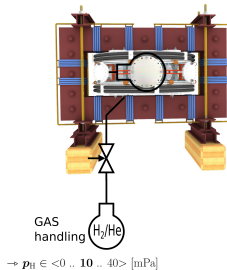
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# Plasma in Tokamak (GOLEM) - the least to do



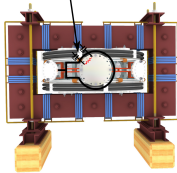
## To do:

- session start phase:
  - Evacuate the chamber
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  - **Fill in the working gas**
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  - Plasma positioning
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# Plasma in Tokamak (GOLEM) - the least to do

Preionization (electron gun)

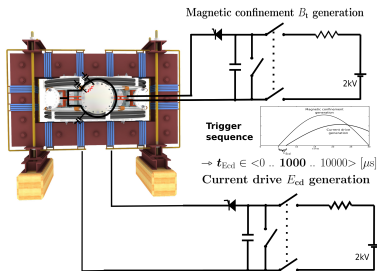
→  $S/W_{\text{preion}} \in \langle \text{on} \dots \text{off} \rangle [-]$



## To do:

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

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



## To do:

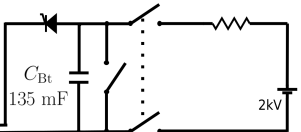
- session start phase:
  - Evacuate the chamber
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  - Charge the capacitors
  - Fill in the working gas
  - Preionization
- discharge phase
  - **Trigger Magnetic confinement & Current drive**
  - Plasma positioning
  - Diagnostics
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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

# Tokamak GOLEM - schematic experimental setup

Preionization (electron gun)

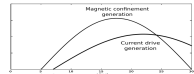
→  $S/W_{\text{preion}} \in \langle \text{on} \dots \text{on} \dots \text{off} \rangle [-]$

Magnetic confinement  $B_t$  generation

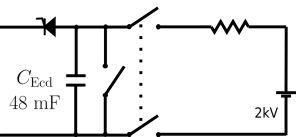


→  $U_{Bt} \in \langle 200 \dots 800 \dots 1300 \rangle [V]$

**Trigger sequence**



Current drive  $E_{cd}$  generation



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

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

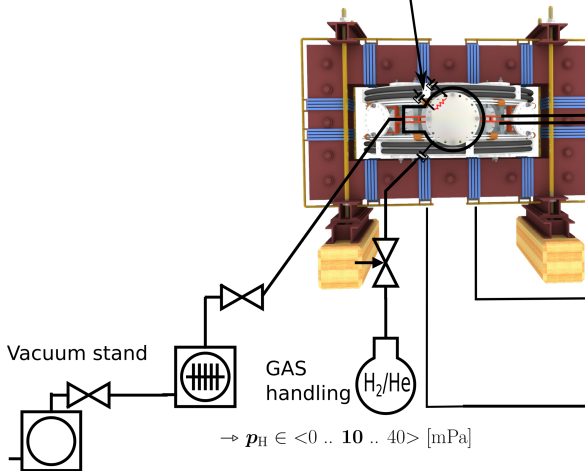
Vacuum stand

GAS

handling

$H_2/He$

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



# 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

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

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

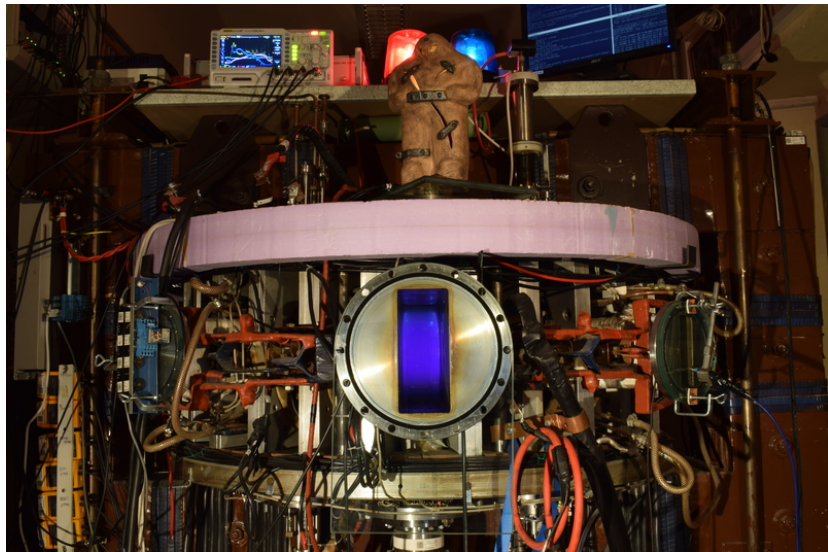
3D model rendering

engineering scheme

sliders and checkboxes

workflow buttons

Let's make a discharge



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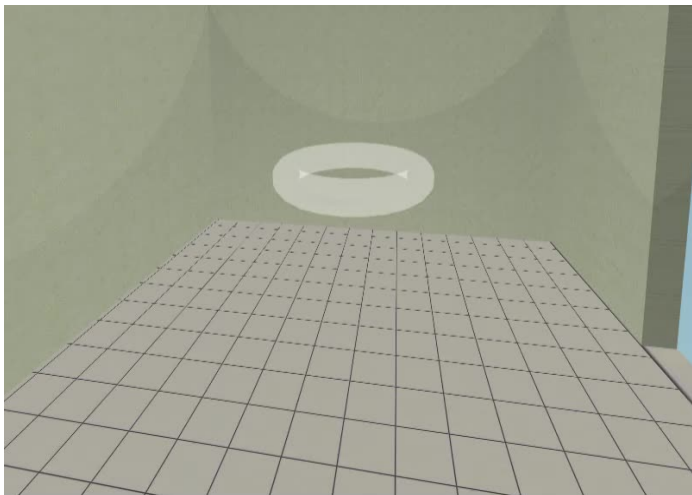
## 3 The Tokamak GOLEM (remote) operation

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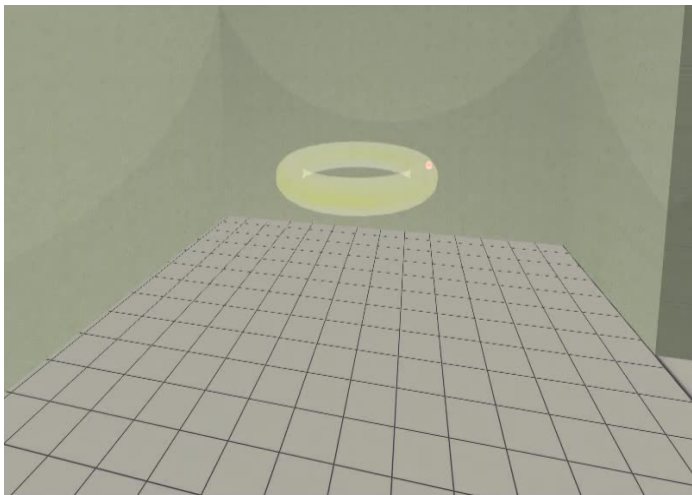
## 5 Appendix



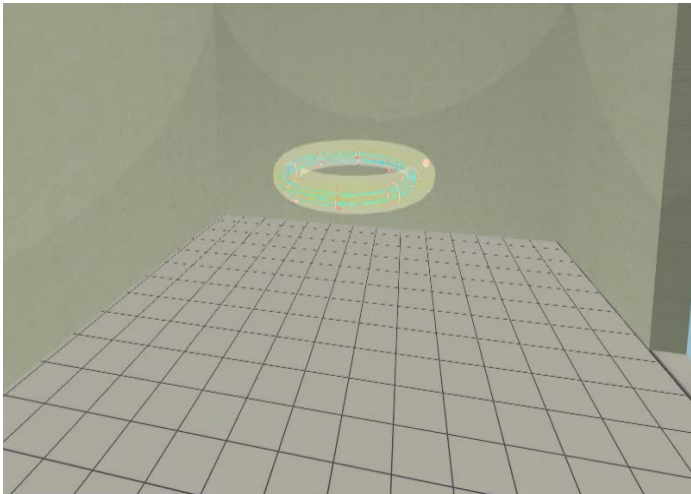
Introduce the working gas (Hydrogen x Helium)



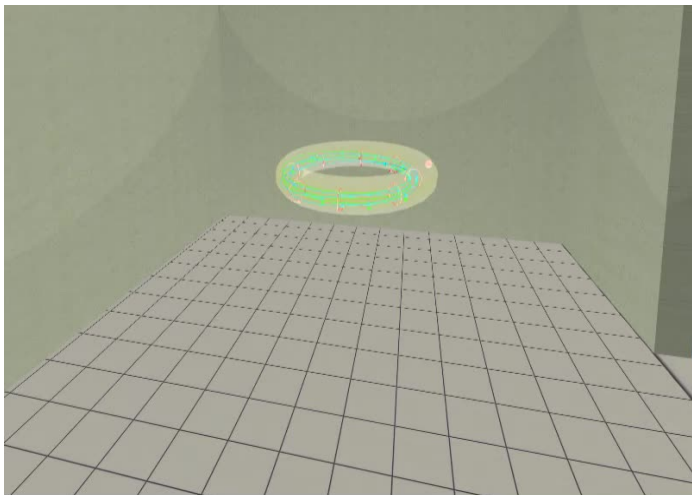
Switch on the preionization



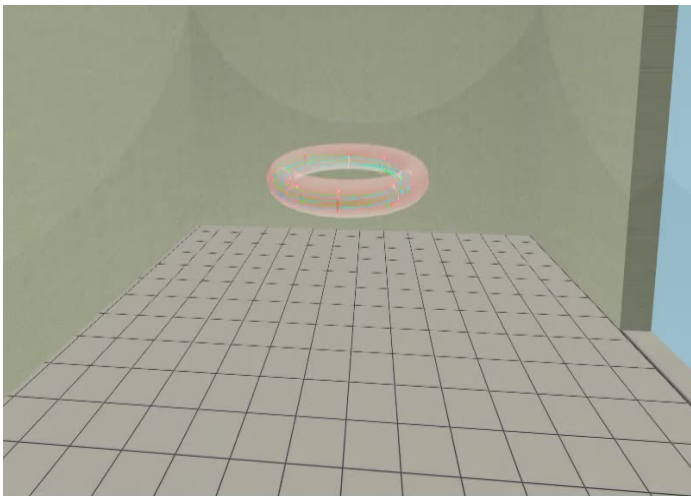
# Introduce the magnetic field



# Introduce the electric field



# Plasma ..



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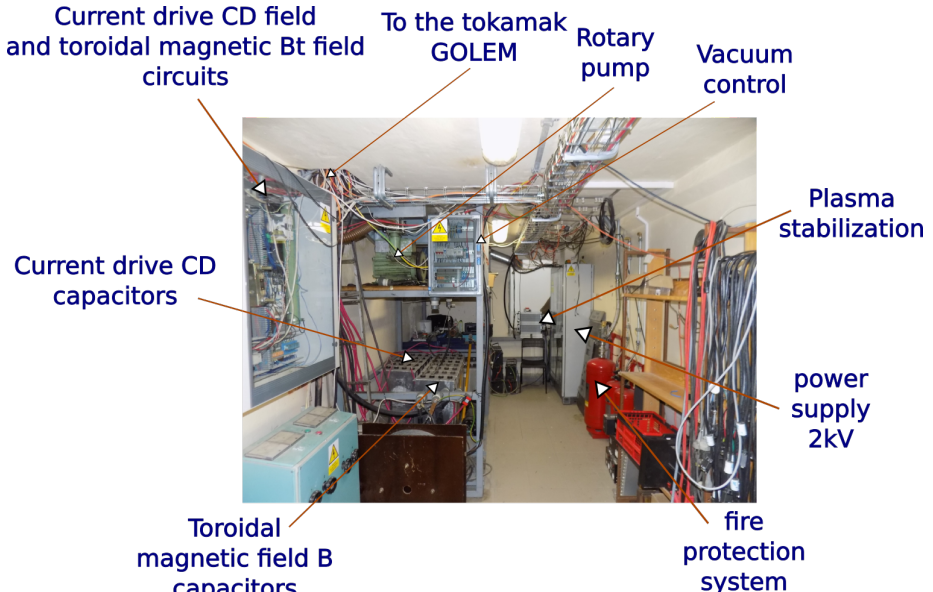
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# Infrastructure room (below tokamak) 10/16

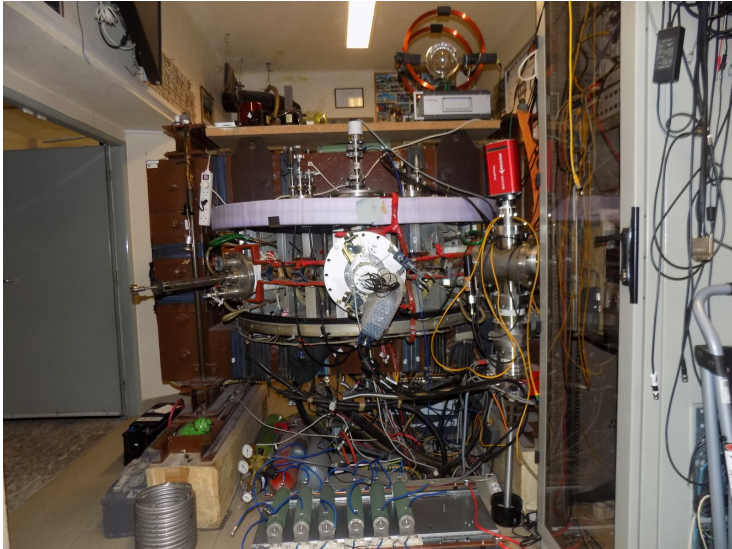


# Infrastructure room (below tokamak) 10/16

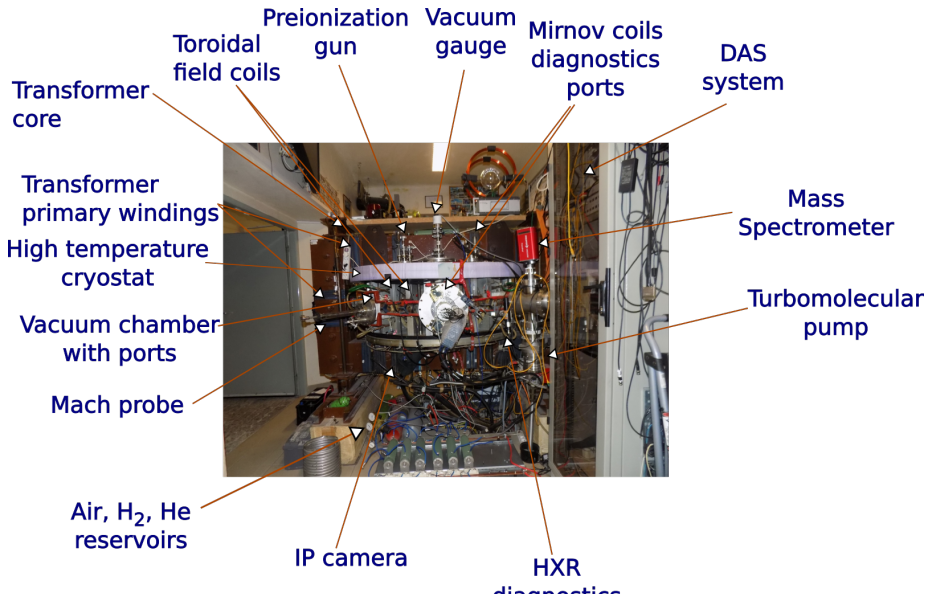




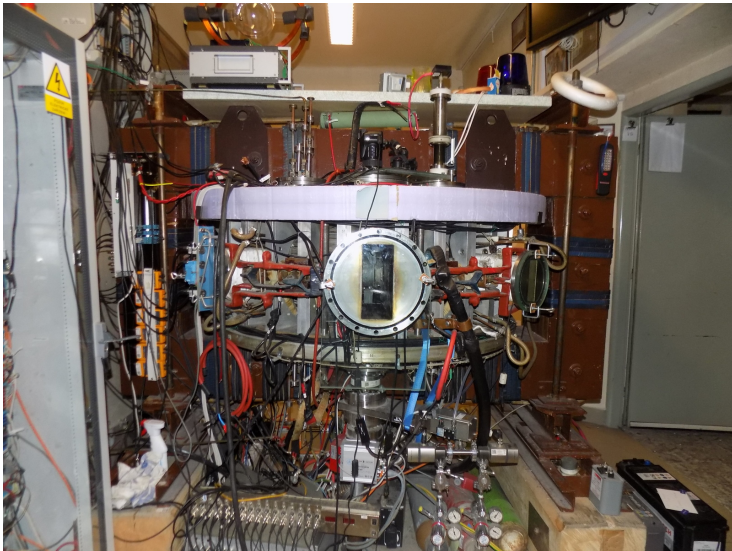
# Tokamak room (North) 10/16



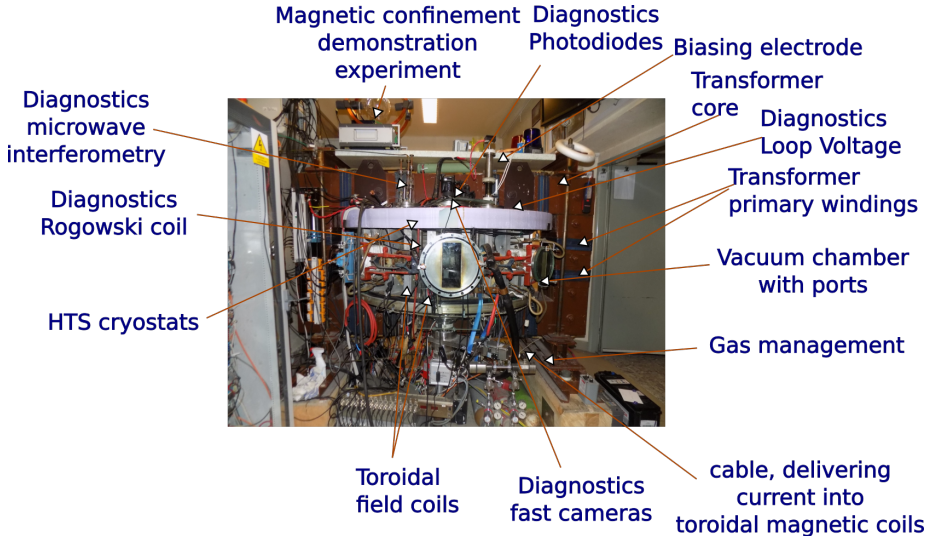
# Tokamak room (North) 10/16



# Tokamak room (South) 10/16



# Tokamak room (South) 10/16



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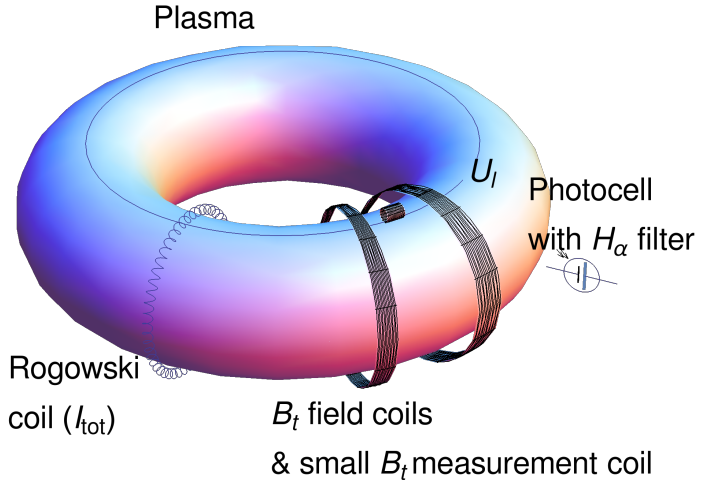
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# The GOLEM tokamak - basic diagnostics




# Hands on the GOLEM tokamak - equipment



# Basic diagnostics - numerical processing, shot homepage

GOLEM > Shot #39187 >



Diagnostics

- BasicDiagnostics
- DoubleRakeProbe
- FastCameras
- HXRprobes
- Interferometry
- LimiterMimovCoils
- MHDring\_TM
- Radiometer
- TimepixDetector
- TunnelProbe

Other

- Wiki
- Showroom"

Navigation

- Next
- Previous
- Current

Tokamak GOLEM - Shot Database - #39187

The date of discharge execution

22-05-18 17:55:04

The session mission

GOLEM --> EDU (MHD + biasing)

The session ID

39183

The discharge comment

Vert & Rad Stab  
loggy./Dirigent.sh --discharge --UBT 1200 --TBT 0 --Ucd 450 --Tcd 350 --preionization 1 --gas H --pressure 10 --diagnostics.limitermimovcoils ~vacuum\_shot=39109\* --discharge.preionization  
"main\_switch=on",powsup\_heater=80,powsup\_accel=100\* --discharge.position\_stabilization  
"main\_switch=on",radial\_switch=on",vertical\_waveform=3000,0;9000,-20;18000,0;20000,0;30000,0",vertical\_switch=on",radial\_waveform=2000,0;3000,0;8000,-20;18000,0;19000,0;25000,0"  
--ScanDefinition "39184 39185" --comment "Vert & Rad Stab"

Technological parameters

- Working Gas:  $p_{\text{discharge}} = 1,66 \text{ mPa}$ ;  $p_{\text{discharge}}^{\text{request}} = 10,40 \text{ mPa}$  ( $p_{\text{WGC}}^{\text{request}} = 10 \text{ mPa}$  @  $\lambda_{\text{WGC}}^{\text{request}} = H$ )
- Toroidal magnetic field:  $U_{\text{BL}}^{\text{request}} = 1200 \text{ V}$  @  $I_{\text{BL}}^{\text{request}} = 0,0 \text{ us}$
- Current drive field:  $U_{\text{Ecd}}^{\text{request}} = 450 \text{ V}$  @  $I_{\text{Ecd}}^{\text{request}} = 350,0 \text{ us}$


Plasma:

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

Plasma parameters:

- Loop voltage:  $U_{\text{loop}} = 8,02 \text{ V}$ ;  $\text{max}_{\text{rc}}[\text{discharge}] U_{\text{loop}} = 9,89 \text{ V}$ ;  $U_{\text{breakdown}} = 10,83 \text{ V}$
- Toroidal magnetic field:  $B_t = 0,40 \text{ T}$ ;  $\text{max}_{\text{rc}}[\text{discharge}] B_t = 0,57 \text{ T}$
- Plasma current:  $I_p = 0,27 \text{ kA}$ ;  $\text{max}_{\text{rc}}[\text{discharge}] I_p = 0,27 \text{ kA}$ ;  $\text{max}_{\text{rc}}[\text{discharge}] I_p = 0,27 \text{ kA}$

GOLEM > Shot #39187 >



Diagnostics

- BasicDiagnostics
- DoubleRakeProbe
- FastCameras
- HXRprobes
- Interferometry
- LimiterMimovCoils
- MHDring\_TM
- Radiometer
- TimepixDetector
- TunnelProbe

Other

- Wiki
- Showroom"

Navigation

- Next
- Previous
- Current

On stage diagnostics

Data flow

measurement →

digitization →

analysis →

Name


Experiment setup


Data acquisition system

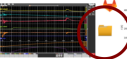
Raw data

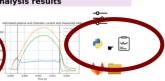
Analysis results

Basic Diagnostics



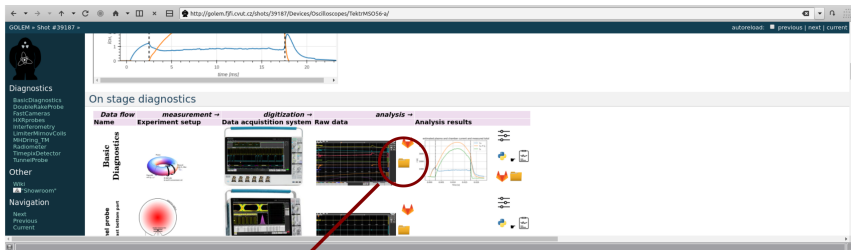








# Basic diagnostics - numerical processing, raw data



## 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 web interface for the repository `tokamak/golem-dirigent`. The repository is named `Tokamak GOLEM Basic diagnostics`. The file `StandardDAS.ipynb` (19.83 KiB) is selected. The notebook's header shows a Jupyter icon circled in red, with a red arrow pointing to the file name. The notebook content includes a procedure to download the notebook and prerequisites for function definitions.

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

**Prerequisites: function definitions**

Load libraries

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

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



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

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

Prerequisites: function definitions

Load libraries

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

For interactive web figures

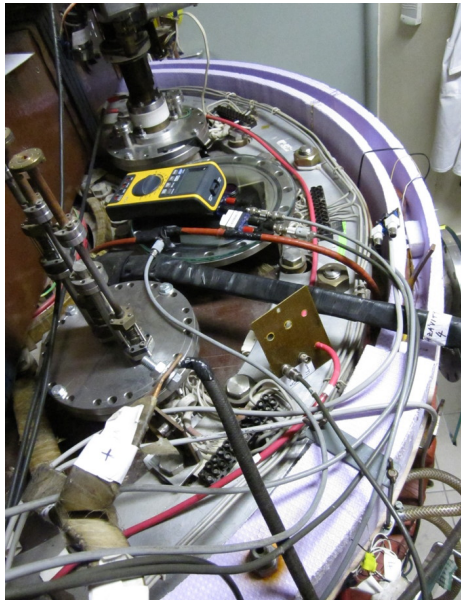
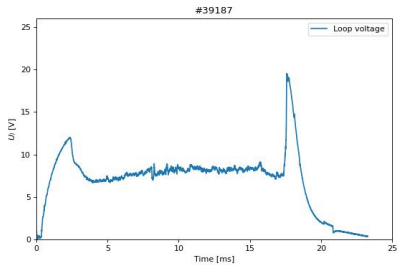
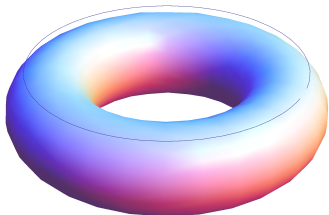
```
In [2]: import holoviews as hv
hv.extension('bokeh')
import hvplot.pandas
```



For conditional rich-text boxes

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

# Loop voltage $U_l$ @ the GOLEM tokamak



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

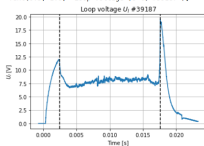
```
t_scale = 1e-3 if in_seconds else 1
if is_plasma:
    for t in (t_plasma_start, t_plasma_end):
        plt.axvlineat = t_scale, color='k', linestyle='--')
```

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

```
Out[11]: [Text(0.5, 0, 'Time [s]'),
Text(0, 0.5, 'SU_l$ [V]'),
Text(0.5, 1.0, 'Loop voltage SU_l$ #29187')]
```



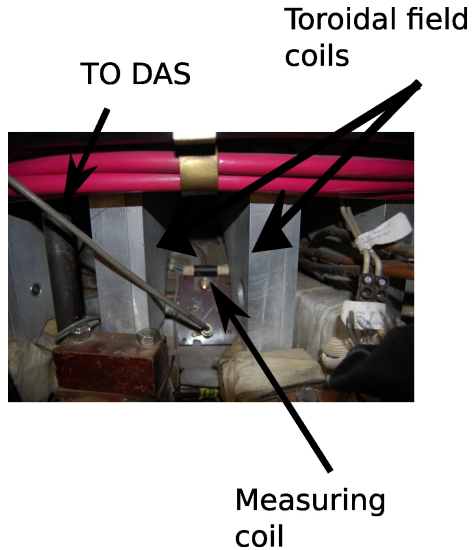
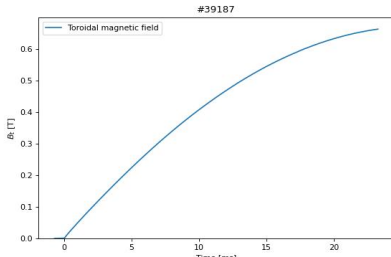
## $B_t$ calculation

Check the data availability

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

```
In [12]: dBt = read_signal(shot_no, 'U_BtCoil')
polarity_Bt = read_parameter(shot_no, 'Bt_orientation')
if polarity_Bt != 'CW': # T000 hardcoded for now!
    dBt *= -1 # make positive
dBt = correct_inf(dBt)
dBt -= dBt.loc[offset_sl].mean()
ax = dBt.plot(grid=True)
show_plasma_limits()
ax.set(xlabel='Time [s]', ylabel='dBt_0_t)/dt$ [V]', title='BtCoil_raw signal #{}'.format(shot_no));
```

# Toroidal magnetic field $B_t$ @ the tokamak GOLEM



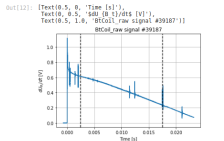
# Basic diagnostics - numerical processing, $B_t$

## $B_t$ 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
dBt = correct_inf(dBt)
dBt = dBt.loc[offset_sl].mean()
ax = dBt.plot(grid=True)
show_plasma_limits()
ax.set(xlabel='Time [s]', ylabel='dBt [V]', title='BtCoil raw signal #{}'.format(shot_no));
```

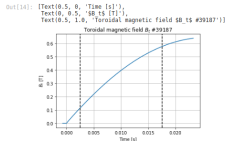


Integration (it is a magnetic diagnostic) & calibration

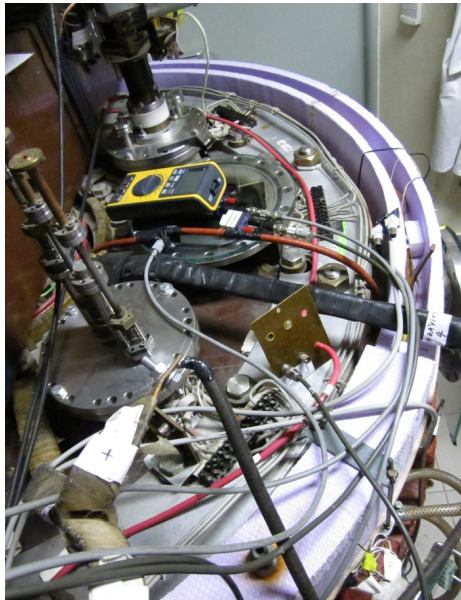
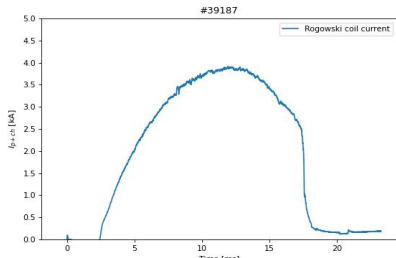
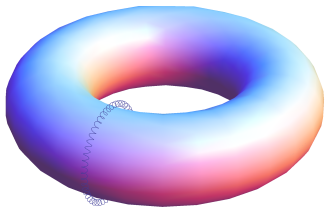
```
In [13]: K_BtCoil = float(read_parameter(shot_no, 'SystemParameters/K_BtCoil')) # Get BtCoil calibration factor
print('BtCoil calibration factor K_BtCoil= {} T/Vs'.format(K_BtCoil))

BtCoil calibration factor K_BtCoil=70.42 T/Vs
```

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



Total current  $I_{ch+p}$





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

http://ipdem.fjfi.cvut.cz/shots/39187/Diagnostics/BasicDiagnostics/analysis.html

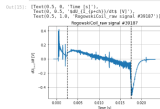
## Chamber (+ Plasma) current $I_{p+ch}$ calculation

The Rogowski coil around the chamber measures the total current contained within its boundaries. Therefore, if there is plasma, it measures the sum of the plasma and chamber currents, i.e. a narrow 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, 'U_RogCoil') # 3000 hardcoded for now
if polarity_03 == '0':
    dIpch *= -1 # new positive
dIpch = correct_int(dIpch)
dIpch = dIpch * (offset_s13/1000) # subtract offset
dIpch.set('t', 0) # s
ax = dIpch.plot(grid=True)
show_figure_limits()
ax.set_xlabel('Time [s]', ylabel='dIpch [A/s]', title='RogowskiCoil raw signal #39187')
plt.grid()
```

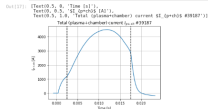


### Integration (it is a magnetic diagnostic) & calibration

```
In [130]: R_RogowskiCoil = float(read_parameter(shot_no, 'SystemParameters/R_RogowskiCoil')) # der RogowskiCoil calibration factor
print('RogowskiCoil calibration factor: R_RogowskiCoil: A/Vs', format(R_RogowskiCoil))

RogowskiCoil calibration factor: R_RogowskiCoil: 3380000.0 A/Vs

In [132]: Spch = pd.Series(integrate(currents_dIpch, width=0.001, initial=0) * R_RogowskiCoil,
                           index=currents_dIpch.index, name='Spch')
ax = Spch.plot(grid=True)
show_figure_limits()
ax.set_xlabel('Time [s]', ylabel='Spch [A]', title='Total (Plasma+chamber) current Spch [A] #39187')
plt.grid()
```



### Chamber current $I_{ch}$ calculation

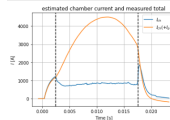
```
In [130]: R_chamber = float(read_parameter(shot_no, 'SystemParameters/R_chamber')) # der Chamber resistivity
print('Chamber resistivity R_chamber: Ohm', format(R_chamber))

Chamber resistivity R_chamber: 0.007 Ohm

In [131]: L_chamber = float(read_parameter(shot_no, 'SystemParameters/L_chamber')) # der Chamber inductance
print('Chamber inductance L_chamber: H', format(L_chamber))

Chamber inductance L_chamber: 46 H
```

```
In [121]: var = ax[1].twinx().twinx() ax[1].ch[0] = Ipch.rename('I_{ch+P}_{p}')
ax = I.plot()
ax.legend()
show_figure_limits()
ax.set_xlabel('Time [s]', ylabel='I [A]', title='estimated chamber current and measured total')
plt.grid()
```



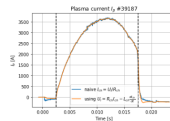
## Plasma current $I_p$ calculation

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 [121]: if is_plasma:
    Ip_naive = Ipch - loop_voltage/R_chamber # creates a new Series
    Ip = Ipch - I_ch
    Ip.name = 'Ip'
    Ip_naive.plot(grid=True, label='naive I_{ch+P}_{p}')
    ax = Ip.plot(grid=True, label='using Spch = R_{ch} I_{ch} - L_{ch} / \tau_{w(d I_{ch}) dt}')
    ax.legend()
    show_figure_limits()
    ax.set_xlabel('Time [s]', ylabel='I_{p} [A]', title='Plasma current I_{p} [A] #39187')
else:
    Ip = Ipch * 0 # no current
    heading
```

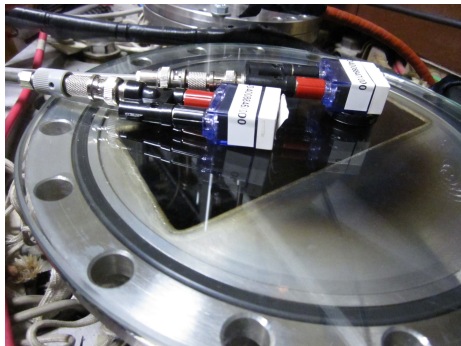
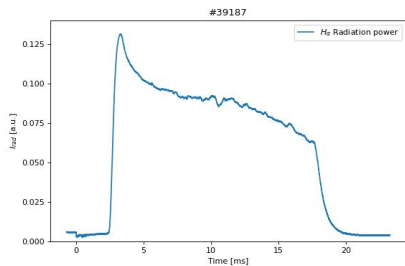
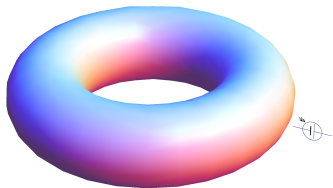
### Plasma detected

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

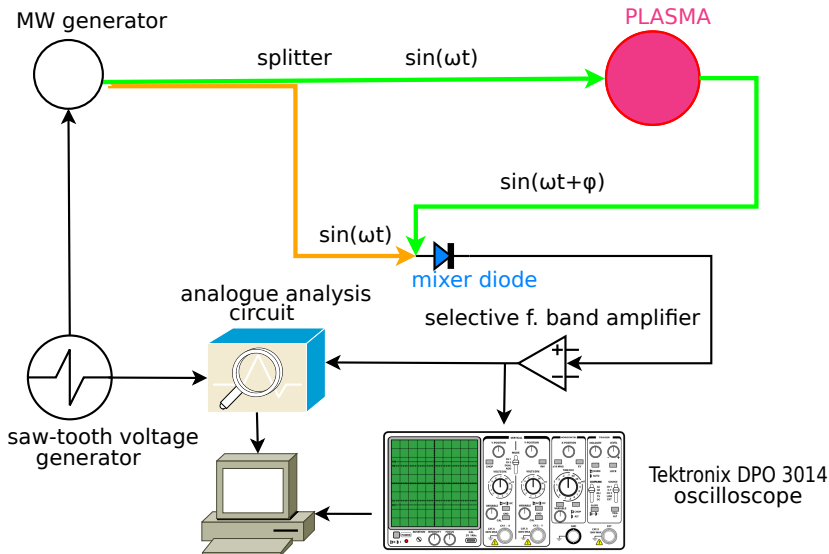


```
In [131]: fig = plt.figure(dpi=200)
for i in I.ch.rename('I_{ch+P}_{p}', Ipch.rename('I_{ch+P}_{p}'), Ip.rename('I_{p}')):
    ax = I.plot()
```

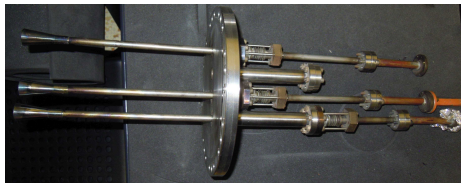
# Visible radiation



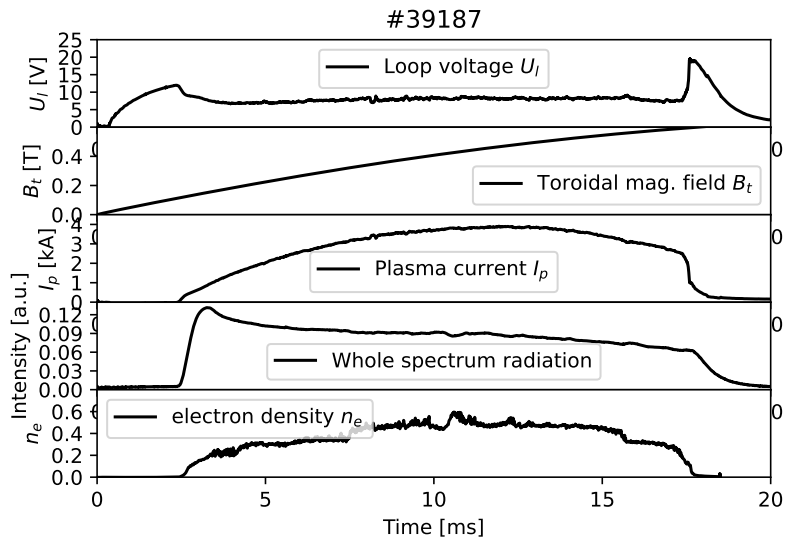
# Electron density $n_e$ interferometry measurement scheme



# The GOLEM tokamak interferometry HW




# Finally "Typical", well executed discharge @ GOLEM



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

GOLEM ~ Shot #40631 ~
autoreload ~ pre



## Tokamak GOLEM - Shot Database - #40631

**The date of discharge execution** 23-02-07 17:23:54  
**The session mission** 1Ftrial -> Diagnet service  
**The session ID** 40605  
**The discharge command** Rake probe 56mm  
 Discharge command  

```
/Dirigent.sh --discharge --UBt 800 --Tbt 0 --Uod 450 --Tod 500 --preionization 1 --gas H --pre
ssure 15 --diagnostics limtermimovcoils "vacuum_shot=40619" --discharge.preionization "m
in_switch=on,powup_heater=80,powup_accel=100"--infrastructure.position_stabilization
"main_switch=on,radiat_switch=on,vertical_waveform=1000,0.8000,-20,10000,-25,12000,-
10,30000,0,vertical_switch=on,radiat_waveform=2000,0.3000,0.7000,-20,9500,-25,10000,-
20,30000,2,25000,0"--ScanDefinition "40625 40629"--comment "Rake probe 56mm"
```

**Other**  
[Wiki](#)  
[Showrooms"](#)  
**Navigation**  
[Next](#)  
[Previous](#)  
[Current](#)  
**Go to shot**  
   
**Golem utils**  
[Home](#)  
[Plot data](#)  
[Shot interval plot](#)  
[Manipulators control](#)  
**Database operations**  
[Shots listing](#)  
[Shots filtering](#)

### Basic Diagnostics

[Shot logbook]

**Technological parameters**

- Working Gas:  $p_{\text{chamber}}^{\text{discharge\_before}}$ =2.46 mPa,  $p_{\text{chamber}}^{\text{discharge\_pre}}$ =5.04 mPa @  $\lambda_{\text{WG}}^{\text{request}} = 15 \text{ mPa}$ @ $\lambda_{\text{WG}}^{\text{request}} = \text{H}$ )
- Toroidal magnetic field:  $U_{\text{BI}}^{\text{request}}=800 \text{ V}@I_{\text{BI}}^{\text{request}}=0.0 \text{ us}$
- Current drive field:  $I_{\text{BI}}^{\text{request}}=450 \text{ V}@I_{\text{BI}}^{\text{request}}=500.0 \text{ us}$







**Plasma:** ☒ ☐ ☐

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

**Plasma parameters:** ☒ ☐ ☐

- Loop voltage:  $\overline{U}_{\text{loop}}=8.82 \text{ V}$ ;  $\max_{rc[\text{discharge}]} U_{\text{loop}}=16.17 \text{ V}$ ;  $U_{\text{breakdown}}=0.00 \text{ V}$
- Toroidal magnetic field:  $B_t=0.24 \text{ T}$ ;  $\max_{rc[\text{discharge}]} B_t=0.36 \text{ T}$
- Plasma current:  $I_p=2.28 \text{ kA}$ ;  $\max_{rc[\text{discharge}]} I_p=2.92 \text{ kA}$ ;  $t_{\text{ip}}^{\text{max}}=0.00 \text{ ms}$

### On stage diagnostics

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

# Table of Contents

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

# Table of Contents

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

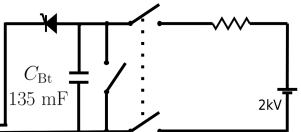


# Tokamak GOLEM - schematic experimental setup

Preionization (electron gun)

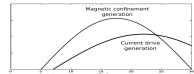
→  $S/W_{\text{preion}} \in \langle \text{on} \dots \text{on} \dots \text{off} \rangle [-]$

Magnetic confinement  $B_t$  generation

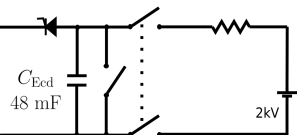


→  $U_{Bt} \in \langle 200 \dots 800 \dots 1300 \rangle [V]$

**Trigger sequence**



Current drive  $E_{cd}$  generation



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

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

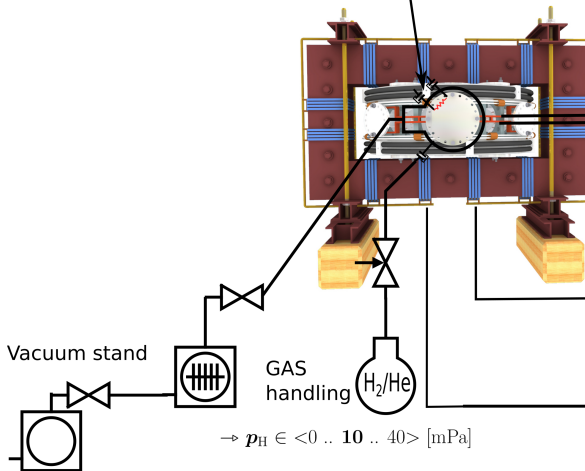
Vacuum stand

GAS

handling

$H_2/He$

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



# 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

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

Hydrogen Helium

Next Set recommended value

3D model rendering

engineering scheme

sliders and checkboxes

workflow buttons

The screenshot displays the GOLEM remote control interface. At the top is a navigation bar with links: GOLEM remote, Introduction, Control room, Live, Results, top navigation bar, User B, Access: Level 2, and Help. Below this is a sidebar with tabs: Introduction, Working gas (selected), Preionization, Magnetic field, Electric field, and Submit. The main content area is titled 'Working gas' and contains a text instruction: 'Set the pressure and type of the working gas from which the plasma is formed. Pressure must be high enough for plasma to form, but low enough for gas breakdown to occur.' Below the text is a schematic diagram of the tokamak system, showing the vacuum stand, preionization (electron gun), gas handling, and toroidal magnetic and electric fields. To the right of the schematic is a 3D model rendering of the tokamak, showing the vacuum chamber, gas handling system, and toroidal fields. Red arrows point to specific UI elements: '3D model rendering' points to the 3D model, 'engineering scheme' points to the schematic diagram, 'sliders and checkboxes' points to the gas type and pressure controls, 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

Toroidal magnetic field

Current drive

GAS handling

$H_2/He$

23 mF

2kV

11.3 mF

2kV

[Next](#)

3D model rendering method:

Static image (fast)

Interactive X3DOM (slower)

# Control room: Working gas

GOLEM remote   Introduction   **Control room**   Live   Results

Map   Access: Level 2   Help

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

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

Preionization (electron gun)

Vacuum stand

GAS handling

Toroidal magnetic field

Toroidal electric field

Gas type and pressure  $p_{\text{gas}} > 18 \text{ mPa}$

Hydrogen   Helium

Next   Set recommended value

2D model rendering method   **Static image (left)**   Interactive X3DOM (arrow)

# Control room: Preionization

GOLEM remote

Introduction

Control room

Live

Results

Master

Access: Level 2

Help

Introduction

Working gas

Preionization

Magnetic field

Electric field

Submit

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

### Preionization (electron gun)

Vacuum stand

Toroidal magnetic field

Toroidal electric field

GAS handling

67.5 mF

13.5 mF

2kV

2kV

Ionization method

☒ Electron gun

☐ No ionization

Next

3D model rendering method

Static image (best)

Interactive X3DOM (slower)

# Control room: Magnetic field $B_t$

GOLEM remote Introduction Control room Live Results

Press P11 to exit full screen 3D model rendering method Static image (best) Interactive X3DOM (slower)

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

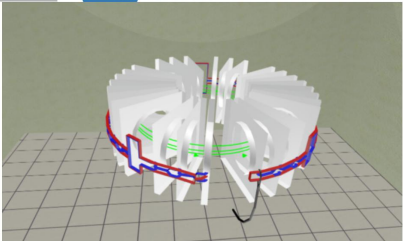
Toroidal magnetic field

Toroidal electric field

GAS handling

Capacitor voltage  $U_{C_1} = 600 \text{ V}$

Next Set recommended value



The diagram illustrates the experimental setup for the magnetic field control. It includes a vacuum stand housing a central chamber, a preionization electron gun, and gas handling components. Two capacitors,  $C_1$  (67.5 mF) and  $C_2$  (13.5 mF), are connected to the toroidal magnetic field coils. The setup is powered by a 2kV source. A 3D model on the right shows the toroidal magnetic field structure, with green lines representing the magnetic field lines and red/blue lines representing the electric field lines.

# Control room: Current drive $E_{cd}$

GOLEM remoteIntroductionControl roomLiveResults

3D model rendering methodStatic image (best)Interactive X3DOM (slower)

IntroductionWorking gasPreionizationMagnetic fieldElectric fieldSubmit

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

GAS handling

Toroidal magnetic field

Toroidal electric field

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

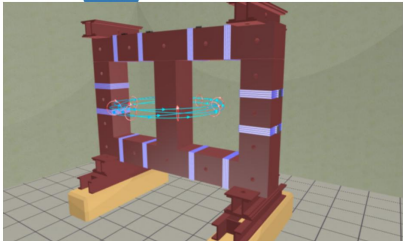
Capacitor voltage  $U_{cd}$ : 400 V

NextSet recommended value

3D model rendering method

Static image (best)

Interactive X3DOM (slower)



[https://golem.fkf.it/cvz/remote/control\\_room/?access\\_token=4701cf4126239452a1e0d0f276d7a3&description=the+Torion+Politecnico&CD=<Italy>Group+1+Control+sub-CD](https://golem.fkf.it/cvz/remote/control_room/?access_token=4701cf4126239452a1e0d0f276d7a3&description=the+Torion+Politecnico&CD=<Italy>Group+1+Control+sub-CD)

# Control room: ... and Submit

GOLEM remote

Introduction

Control room

Live

Results

100 Yttrium Polytoron, Ray Group 1

Access: Level 2

Help

Introduction

Working gas

Precorization

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)

A 3D rendering of a complex scientific apparatus, likely a discharge cell or a small-scale fusion reactor. It features a central cylindrical component with a glowing red interior, surrounded by a series of blue and white cylindrical structures. The entire assembly is mounted on a dark red base with various pipes and connections. The background is a simple, light-colored wall and floor.



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

GOLEM » Shot #40631 »

Diagnostics

[BasicDiagnostics](#)  
[DoubleRakeProbe](#)  
[Interferometry](#)  
[LimiterMirrorCats](#)  
[ScintillationProbes](#)

Other

[Web](#)  
[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 56mm

Discharge command

```

JDringent.sh --discharge --Ubt 800 --Tbt 0 --Uod 450 --Tod 500 --preionization 1 --gas H --pre
issue 15 --diagnostics.limitermirrorcats "vacuum_shot=40619" --discharge.preionization "m
ain_switch=on;radial_heater=80;powsup_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 56mm"

```

[Shot Logbook]

Technological parameters

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

Plasma: ☐ ☐ ☐

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

Plasma parameters: ☐ ☐ ☐

- Loop voltage:  $U_{loop}=8.82$  V;  $max_{rvc}(discharge) U_{loop}=16.17$  V;  $U_{breakdown}=0.00$  V
- Toroidal magnetic field:  $B_t=0.24$  T;  $max_{rvc}(discharge) B_t=0.36$  T
- Plasma current:  $I_p=2.28$  kA;  $max_{rvc}(discharge) I_p=2.92$  kA;  $I_p^{max}=0.00$  ms

Basic Diagnostics

On stage diagnostics

Data flow

measurement

digitization

analysis

Name

Experiment setup

Data acquisition system

Raw data

Analysis results

Basic Diagnostics

Double rake probe

Without Analysis

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- 2 The Tokamak (GOLEM)
- 3 The Tokamak GOLEM (remote) operation
  - Control room
  - Data handling @ the Tokamak GOLEM
- 4 Conclusion
- 5 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 milisecond 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;\nsignal_id="Diagnostics/BasicDiagnostics/Results/U_loop.csv";\
```

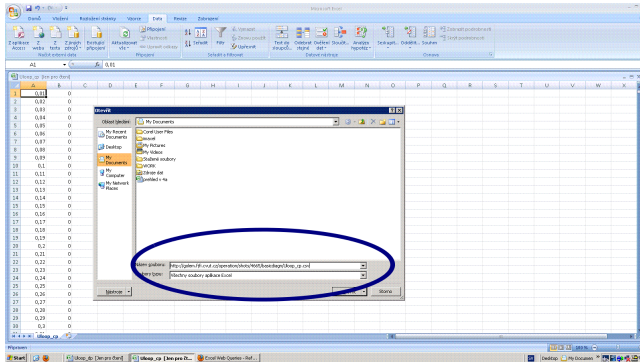


# GNU Wget

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

- Runs on most UNIX-like operating systems as well as Microsoft Windows.
- Homepage: <http://www.gnu.org/software/wget/>
- Basic usage:
  - To get  $U_l$ : `wget http://golem.fjfi.cvut.cz/utis/data/<#ShotNo>/loop_voltage`
  - To get whole shot: `wget -r -nH -cut-dirs=3 -no-parent -l2 -Pshot http://golem.fjfi.cvut.cz/shots/<#ShotNo>`

# Excel



File→Open→

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

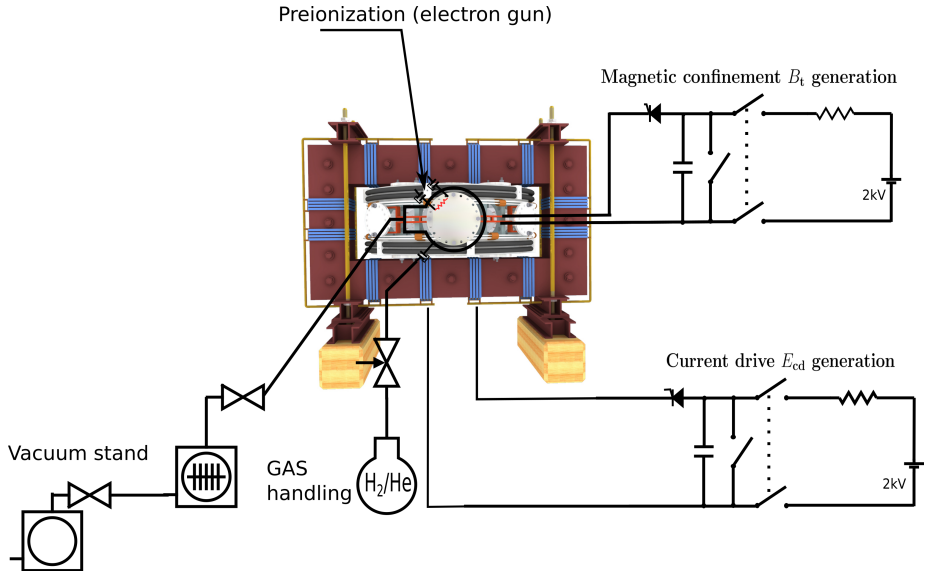
Spreadsheets (Excel and others)

are not recommended, only tolerated.

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# The global schematic overview of the tokamak GOLEM experiment



# Production

- Everything via <http://golem.fjfi.cvut.cz/Eindhoven>
  - 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>



Fee: postcard from the venue of remote measurements



# Acknowledgement

## Financial support highly appreciated:

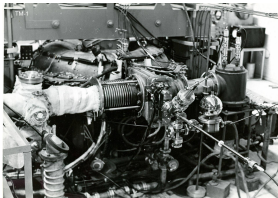
CTU RVO68407700, SGS 17/138/OHK4/2T/14, GAČR GA18-02482S, EU funds CZ.02.1.01/0.0/0.0/16\_019/0000778 and CZ.02.2.69/0.0/0.0/16\_027/0008465, IAEA F13019, FUSENET and EUROFUSION.

## 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 Leidl, 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**

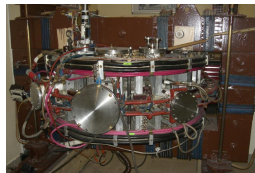


## SCIENCE

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

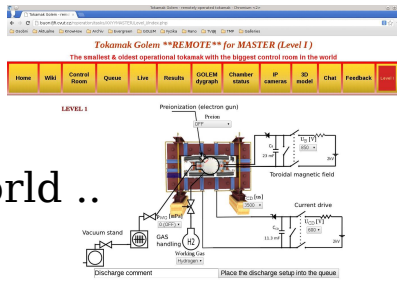
**SCIENCE**  
& education

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



## EDUCATION

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











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# References I

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

# References II

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

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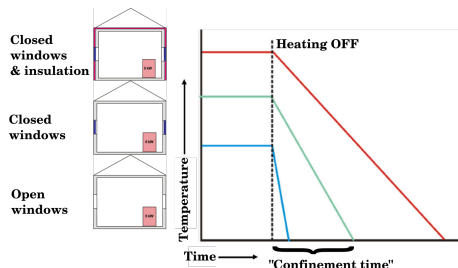
4 Conclusion

5 Appendix

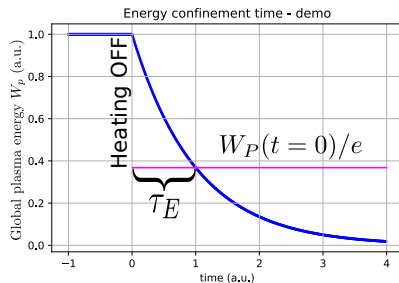
- The Electron energy confinement time calculation (rough estimation)
- A small note on magnetic measurements
- Few moments from the tokamak GOLEM history

# Towards ... Energy confinement time

## House



## Tokamak



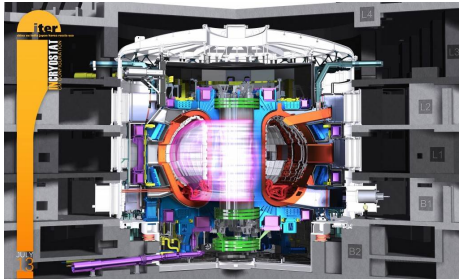
- Net power = Efficiency  $\times$  (Fusion - Radiation loss - Conduction loss)
- The confinement time:  $\tau_E = \frac{W}{P_{\text{loss}}}$
- Energy density  $W = 3nk_B T$  & rate of radiation and conduction energy loss per unit volume  $P_{\text{loss}}$
- Reactions per volume per time of fusion reactions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

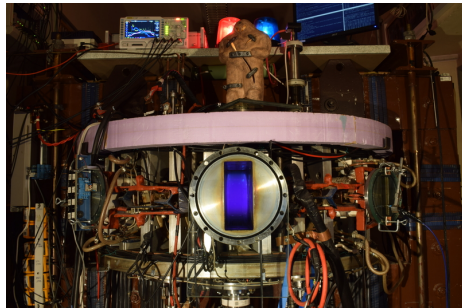
# The competition

The ITER: 3.6 s



credit:[6]

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



credit:[3]

# Energy confinement time

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

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

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

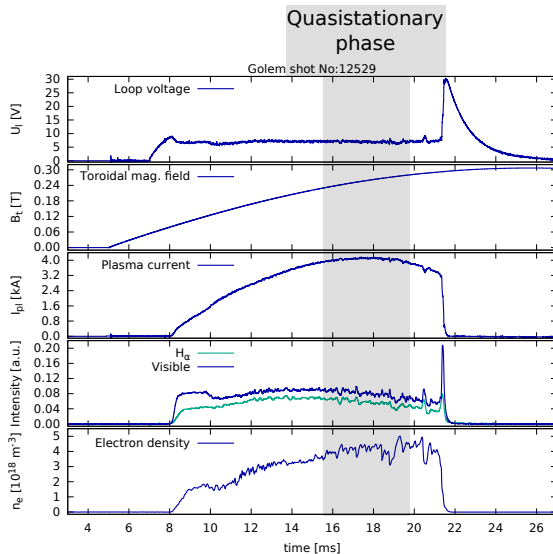
$$\tau_E = \frac{W_p}{P_{Loss}} = \frac{W_p}{P_H - dW_p/dt}$$

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

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



# The discharge - quasistationary phase



# Plasma heating power

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

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

# Plasma Energy

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

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

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

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

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

# Central Electron Temperature estimation (Spitzer Formula)

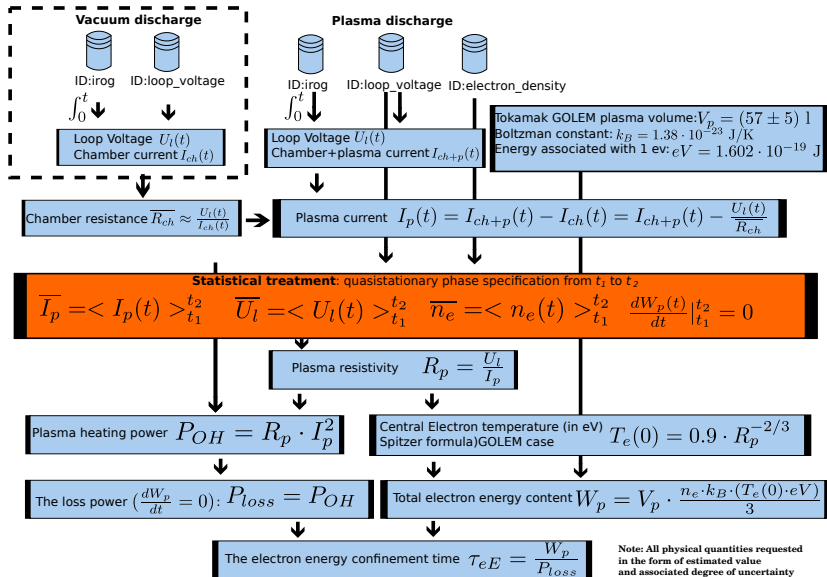
The time evolution of the central electron temperature  $T_e(0, t)$  is calculated from equation based on Spitzer's resistivity formula (see eg. [2],[4]):

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

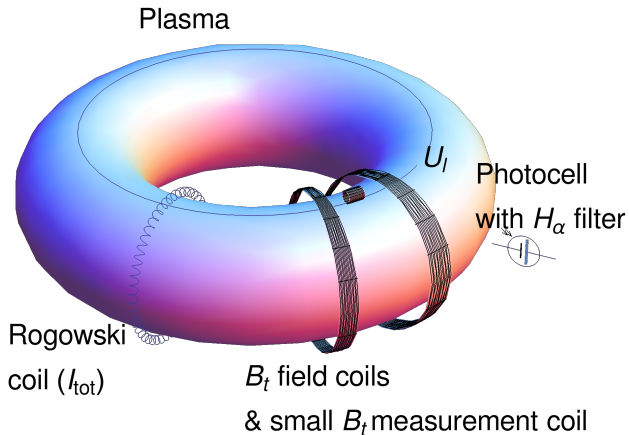
For particular case of the GOLEM tokamak it says:

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

# Towards Electron energy confinement time $\tau_E$



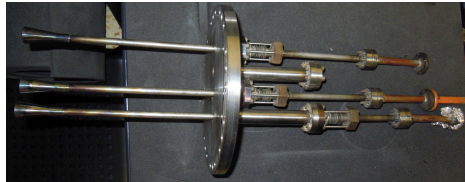
# The GOLEM tokamak - standard diagnostics



# Hands on the GOLEM tokamak - equipment

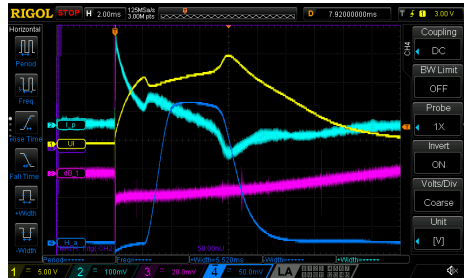
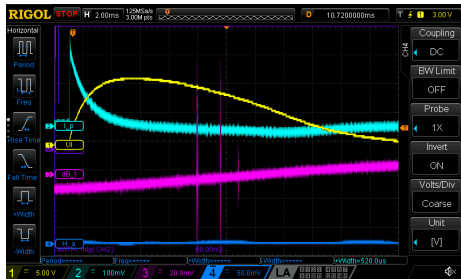


# The GOLEM tokamak interferometry HW

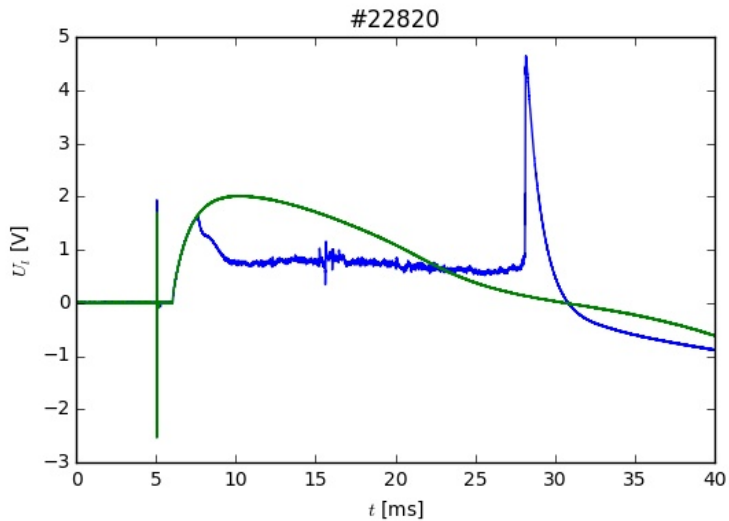




# Vacuum x Plasma discharge @ Oscilloscope



# Vacuum x Plasma shot



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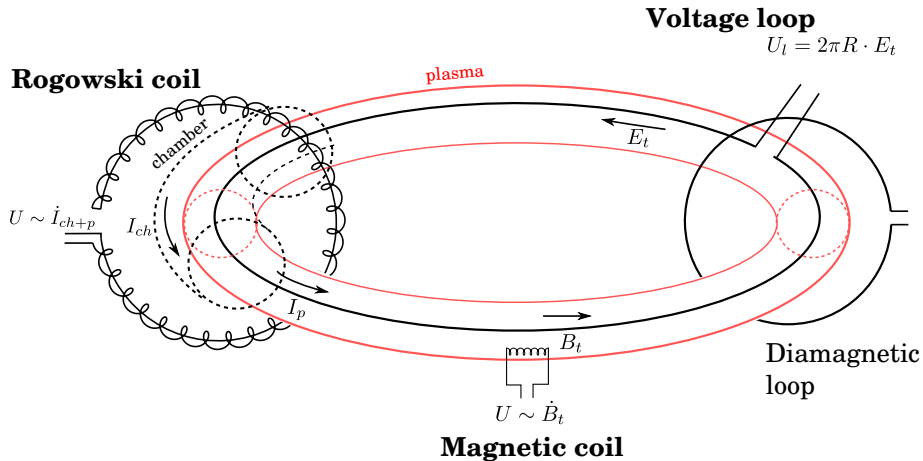
3 The Tokamak GOLEM (remote) operation

4 Conclusion

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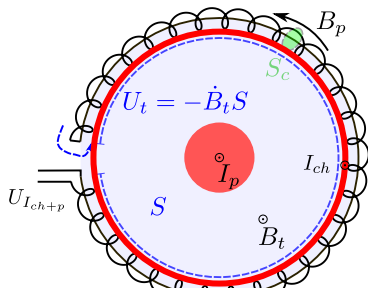
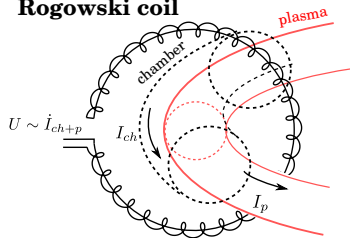
- The Electron energy confinement time calculation (rough estimation)
- A small note on magnetic measurements
- Few moments from the tokamak GOLEM history

# 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, it's 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:

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

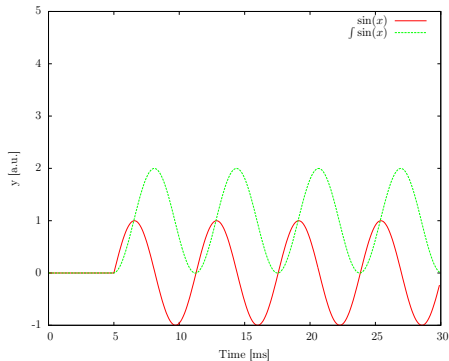
- In reality, the measurement is not continuous. The system performs a series of measurements  $U_i$  separated by with time step  $\Delta t = 1$  us.
- In practice, we replace the integral by a sum:

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

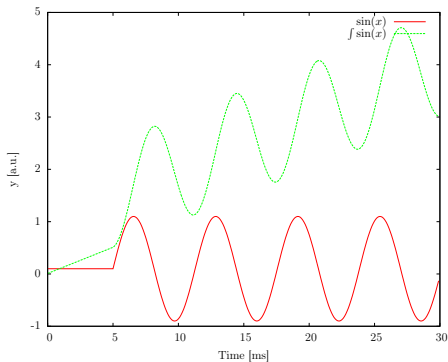
- The offset  $U_{offset}$  can be specified from the beginning of the data series before switching on the real experiment.

# Magnetic measurement demo - game with $U_{offset}$

Without  $U_{offset}$



With  $U_{offset}$





# Table of Contents

1 Introduction

2 The Tokamak (GOLEM)

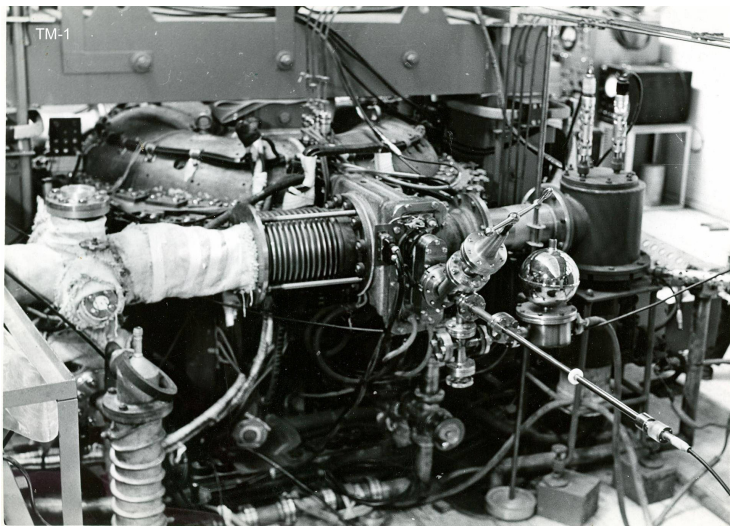
3 The Tokamak GOLEM (remote) operation

4 Conclusion

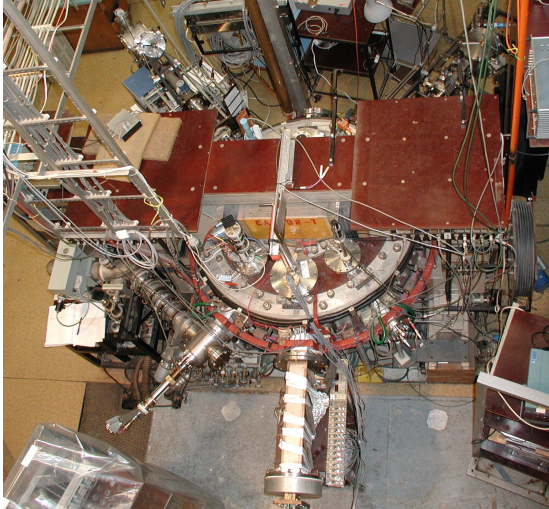
5 Appendix

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

XX/YY: TM-1



# XX/YY: CASTOR



## 12/07: Last minutes at the IPP Prague

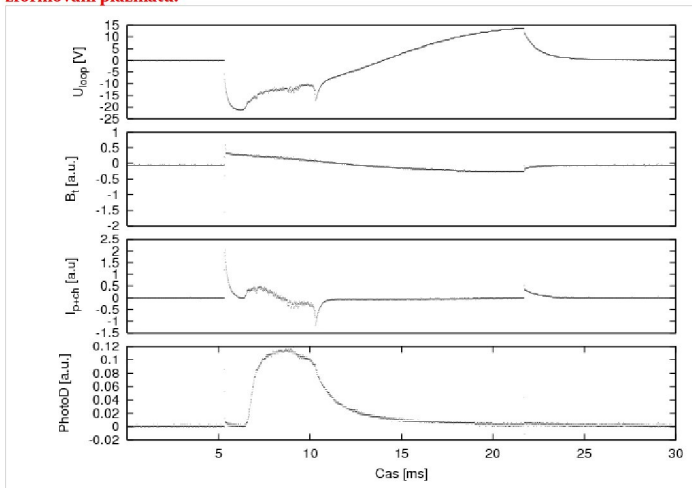


## 12/07: First minutes at the CTU Prague



# 07/09: First plasma in the tokamak GOLEM

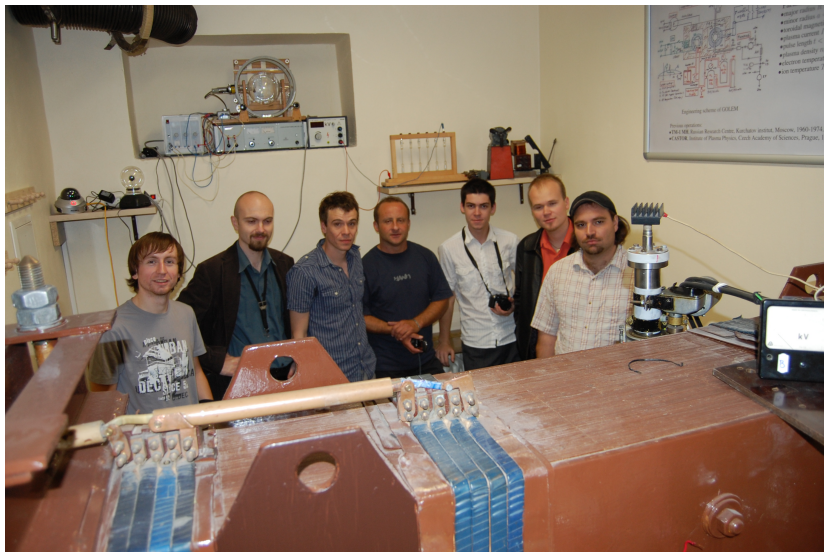
Časové průběhy signálů zřetelně ukazují, že došlo k průrazu neutrálního plynu a k zformování plazmatu.



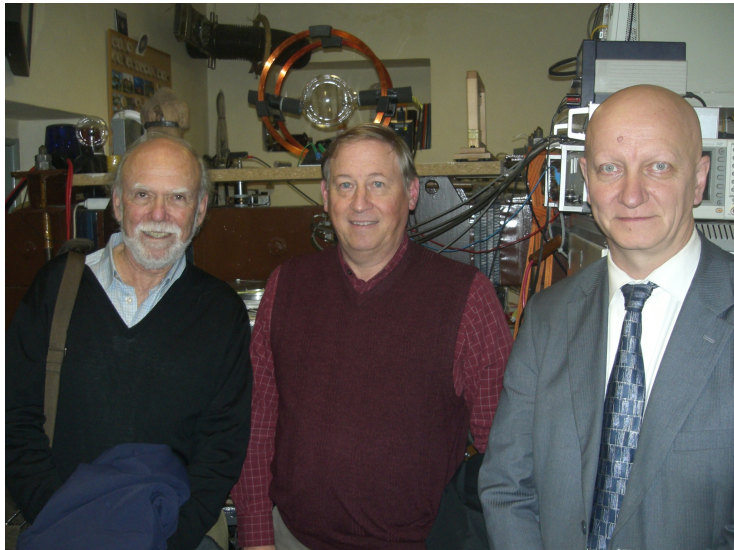
O tom svědčí:

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

# 09/09: Tokamak and tokamak



# 11/11: NP laureat at tokamak GOLEM

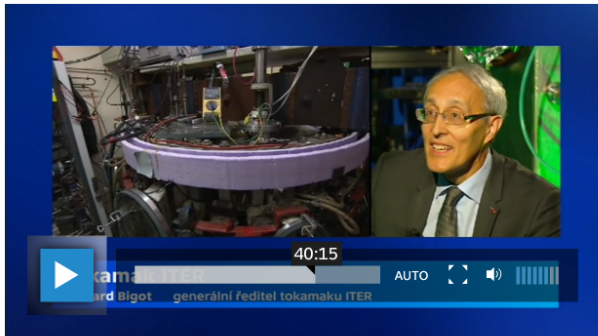




# 05/16: The youngest tokamak (GOLEM) operator, Adam (7 years).



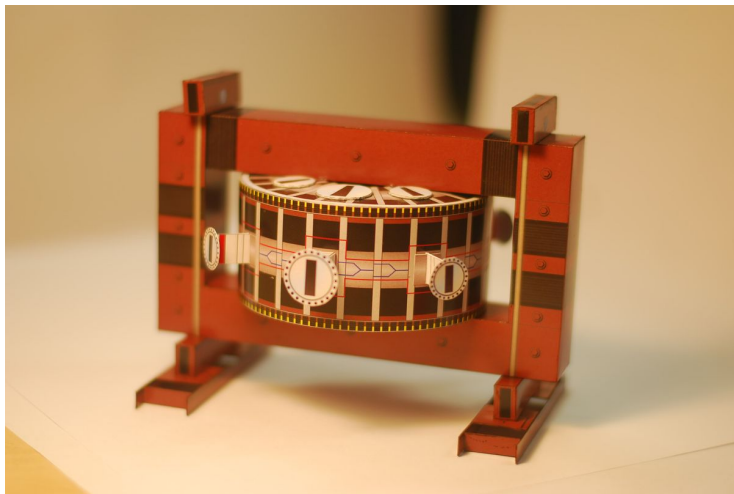
## 0916: ITER DG, Mr. Bernard Bigot (Shot #22185)



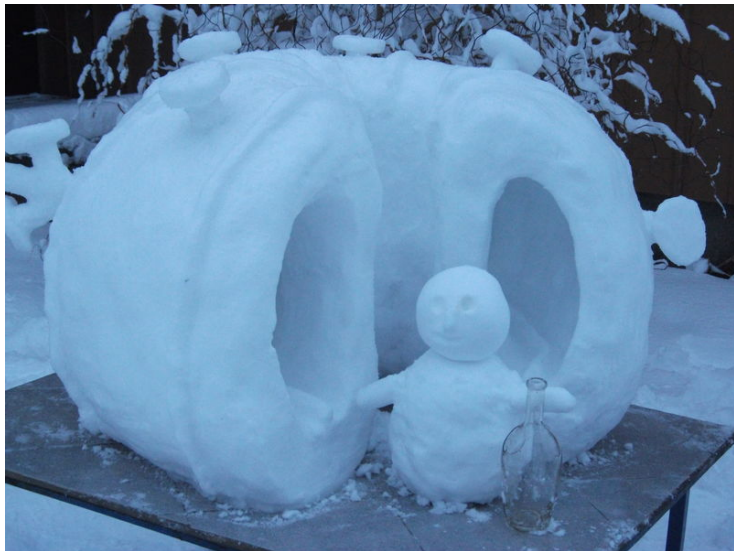
Quotation from Czech Television Hydepark

*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 -



## Diagnostics

- ✓ PlasmaPosition\_TO
- ✗ Rules
- ✓ Spectrometer
- ✓ FastCamera
- ✓ HXR

## Analysis

- ✓ HistoricalAnalysis
- ✓ ShotHomepage
- ✓ AdvancedAnalysis
- ✓ Spectrograms\_TO
- ✗ MultiCWT\_TO
- ✓ MWPrevisualization
- ✗ Impurities\_TO

## DAS

- ✓ TektronixDPO
- ✓ Papouch\_3
- ✓ Nistandard
- ✓ Papouch\_Za
- ✓ Papouch\_Si

## Vacuum log

Charging log

## Other

- Data
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## Navigation

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## Go to shot

20000

Go

previous | next | current

## Tokamak GOLEM - Shot Database - 20000

[Template source]  
[WebLog]

Date: 2015-10-22 - 16:09:25  
Session: SessionPreparation  
Comment: 20k

Congratulation, you have reached nuclear fusion.

The following explosion destroyed half of Prague and radioactive fallout contaminated whole Europe.  
Have a nice day

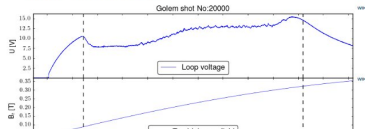


### Basic parameters: (compare)

- Gas pressure  $p_{D_2}$ : 18.38 > 15.38 mPa (request: 5 mPa) <sup>Wiki</sup>
- Working gas: H
- Preionization: Upper el. gun
- Chamber temperature: 20.00 C
- $C_B$  capacitors charged to: 1000 V, triggered 5.0 85 <sup>Wiki</sup>
- $C_{BD}$  capacitors charged to: 0 V, triggered 5.0 85 <sup>Wiki</sup>
- $C_{CD}$  capacitors charged to: 500 V, triggered 5.0 85 <sup>Wiki</sup>
- $C_{ST}$  capacitors charged to: 0 V, triggered 5.0 85 <sup>Wiki</sup>
- Probability of breakdown: N/A <sup>Wiki</sup>
- Time since session beginning: 0:19:25 h

### Plasma parameters:

- Plasma life time 8.7 [ms] (from 7.5 to 16.2) <sup>Wiki</sup>
- Mean toroidal magnetic field Bt: 0.22 T <sup>Wiki</sup>
- Mean plasma current: 1.42 kA <sup>Wiki</sup>
- Mean Uloop: 12.41 V <sup>Wiki</sup>
- Break down voltage: 10.5 V <sup>Wiki</sup>
- Ohmic heating power: 17.59 kW
- Q edge: 6.9 <sup>Wiki</sup>
- Electron temperature: 13.5 eV <sup>Wiki</sup>
- Line electron density: N/A [ $10 \cdot 17. m^{-2}$ ] <sup>Wiki</sup>





11/17: GOLEM tokamak "mapping"

# Tokamak GOLEM



# Základní (řádová) statistika k 30.11.2012

Počet dní od instalace: 1815.

Počet operačních dní:  $\approx 438$ .

Počet hodin:  $\approx 1954$

Počet shotů: 10417.

Počet shotů –  $>$  plazma:  $\approx 7600$ .

Průměrná délka výboje:  $\approx 7$  ms.

**Celková délka trvání plazmatu:  $< 60$  s.**