

Introduction to the tokamak operation (GOLEM specific) - Level 1

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

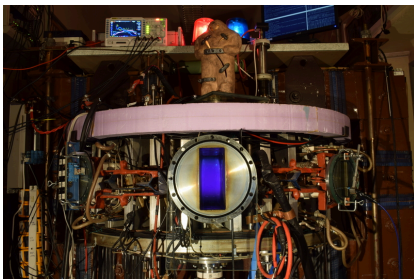
January 9, 2020

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 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
- Plasma minor radius: $a \approx 0.06$ m
- Maximum toroidal magnetic field $B_t^{max} < 0.5$ T
- Maximum plasma current $I_p^{max} < 8$ kA
- Typical electron density:
 $\langle n_e \rangle \approx 0.2 - 3 \times 10^{19} \text{ m}^{-3}$
- Effective ion charge: $Z_{eff} \approx 2.5$
- Maximum electron temperature $T_e^{max} < 100$ eV
- Maximum ion temperature $T_i^{max} < 50$ eV

Tokamak GOLEM @ Wikipedia ..

File Edit View Go Bookmarks Tools Settings Window Help
home Kalendaršŕ Produkcija Forecast Slovnik Rano
Not logged in Talk Contributions Create account Log in
Article Talk Read Edit View history Search



WIKIPEDIA
The Free Encyclopedia

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

Tokamak

From Wikipedia, the free encyclopedia

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

A **tokamak** (Russian: **токамак**) is a device that uses a powerful magnetic field to confine plasma in the shape of a torus. Achieving a stable plasma equilibrium requires magnetic field lines that move around the torus in a helical cusp. 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]

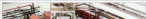
Currently in operation [edit]

(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 ISTOK,^[17] at the Instituto de Plasmas e Fusão Nuclear, Lisbon, Portugal;
- 1991: ASDEX Upgrade, in Garching, Germany

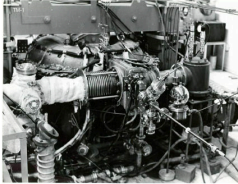


Alicator C-Mod



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**



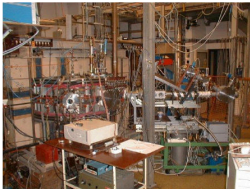
2006



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. . .

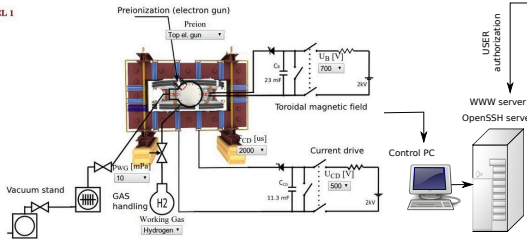


At the end of the 16th century, in the times when the Czech lands were ruled by Emperor Rudolf II, in Prague, there were Rabbi Judah Loew, well known alchemist, thinker, scholar, writer and inventor of the legendary GOLEM - a clay creature inspired with the Universe power that pursued his master's command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

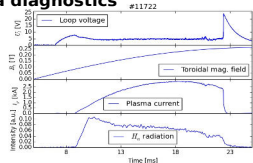
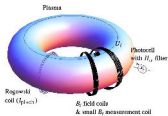
The global schematic overview of the GOLEM experiment

LEVEL 1

Tokamak technology setup



Basic plasma diagnostics



internet

Virtual control room (remote participation)

WWW control interface

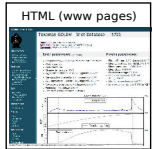


SSH control interface



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

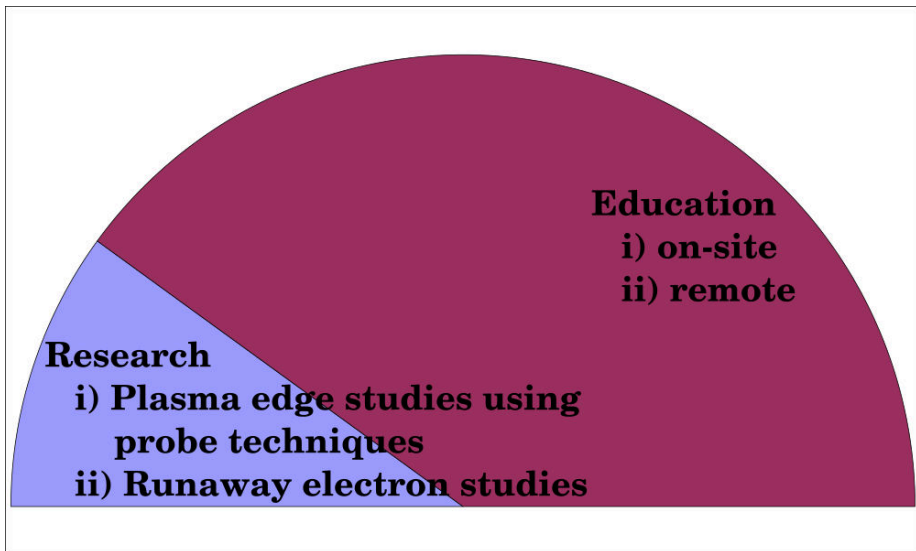
Data presentation



Data handling

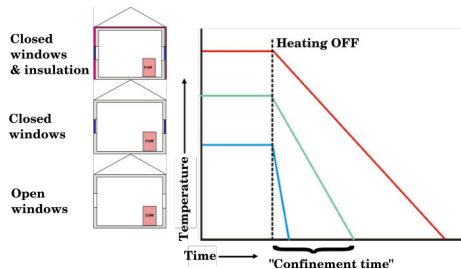
- *wget
- *gnuplot
- *idl
- *mathematica
- *matlab
- *etc...

The GOLEM tokamak mission

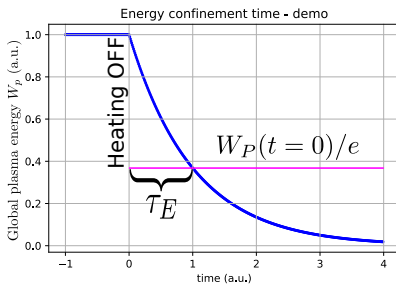


Towards ... Energy confinement time

House



Tokamak



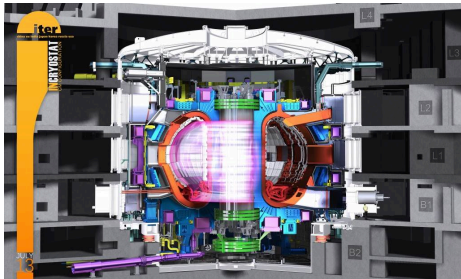
- The confinement time: $\tau_E = \frac{W}{P_{\text{loss}}}$
- Energy density: $W = 3nk_B T$
- Reactions per volume per time of fusion reactions is:
 $f = n_d n_t \langle \sigma v \rangle = \frac{1}{4} n^2 \langle \sigma v \rangle$
- Fusion heating fE_{ch} , where $E_{\text{ch}} = 3.5 \text{ MeV}$ should 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 $\approx 26 \text{ keV}$)

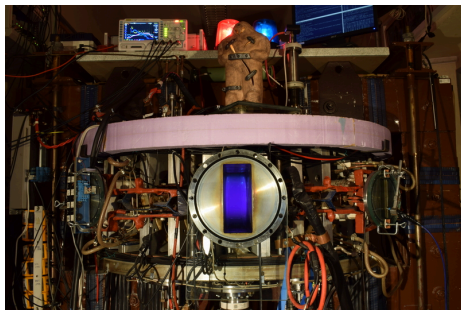
The competition

The ITER: 3.6 s



credit:[1]

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



credit:[2]

- Everything via <http://golem.fjfi.cvut.cz/Torino>
 - This presentation
 - Control rooms
 - Contact: Vojtech Svoboda,
+420 737673903,
svoboda@fjfi.cvut.cz
 - Chat:
tokamak.golem@gmail.com or
skype: tokamak.golem

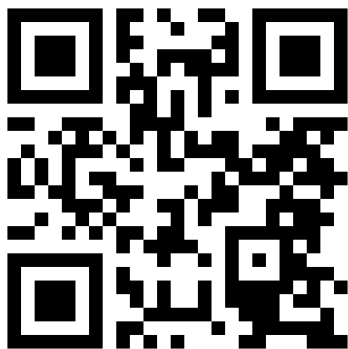
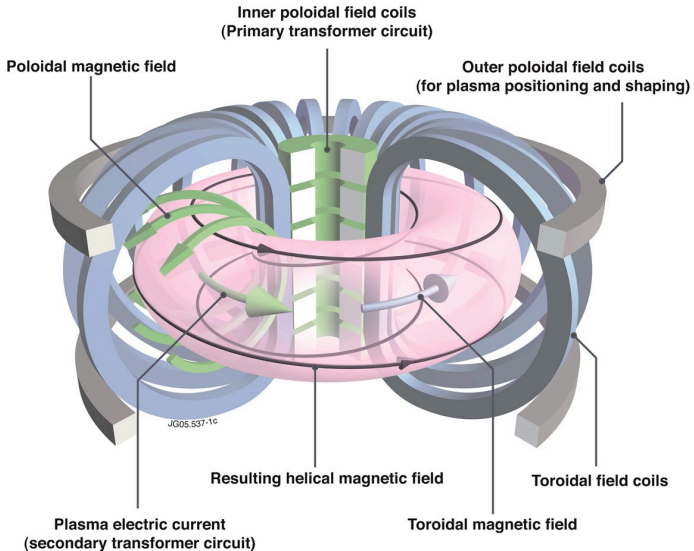


Table of Contents

- 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

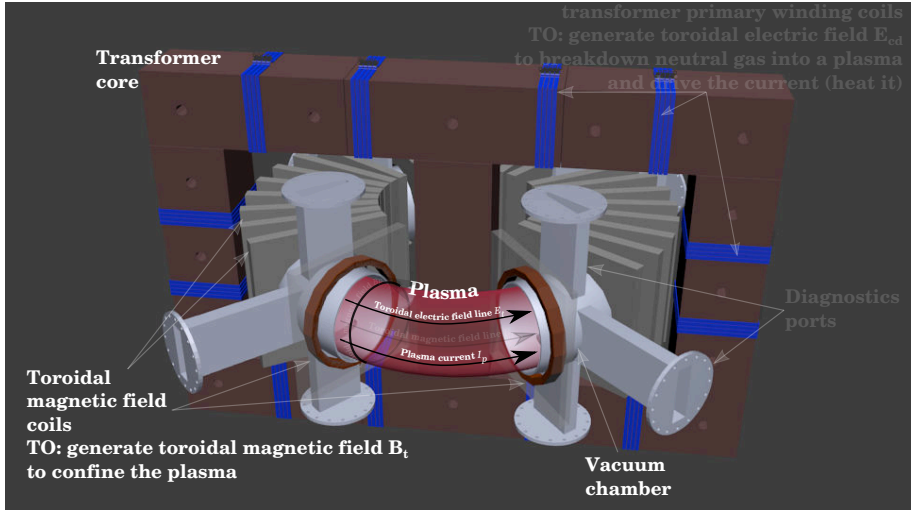


Table of Contents

1 Introduction

2 The Tokamak (GOLEM)

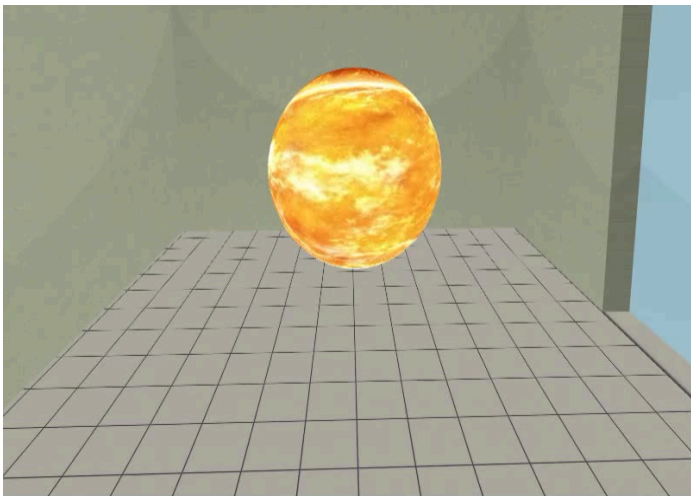
- The GOLEM tokamak concept
- The scenario to make the (GOLEM) tokamak discharge
- The scenario to discharge virtually
- The GOLEM tokamak basic diagnostics
- The GOLEM tokamak - guide tour

3 The Tokamak GOLEM (remote) operation

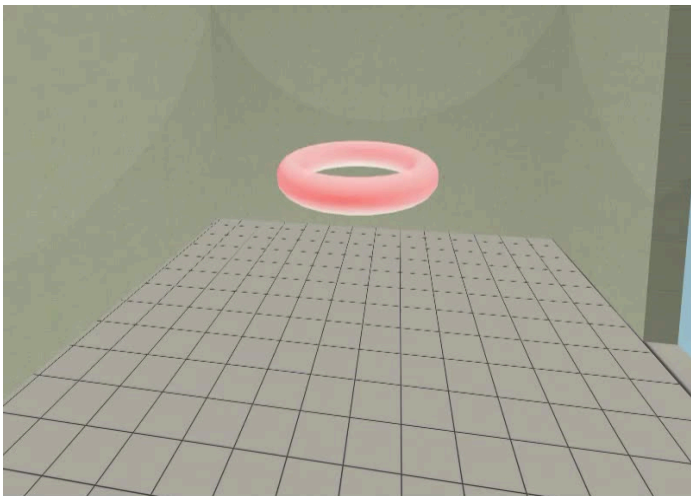
4 The Electron energy confinement time calculation (rough estimation)

5 Conclusion

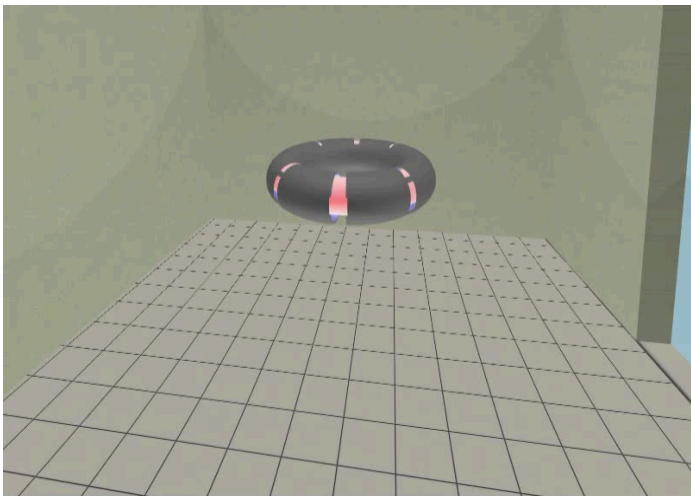
Our goal: the technology to create a μ Sun on the Earth



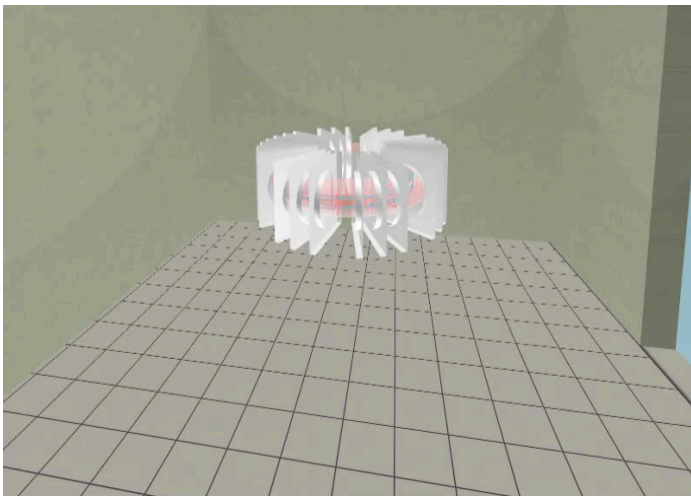
Magnetic confinement requires toroidal geometry



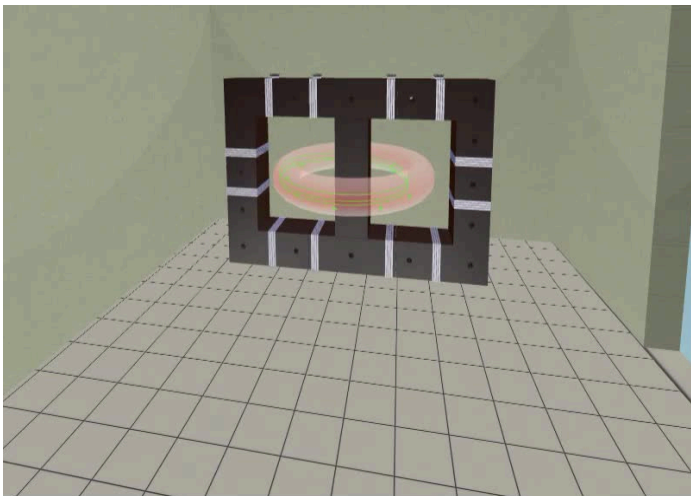
A chamber contains the thermonuclear reaction



Toroidal magnetic field coils confine the plasma



A transformer action creates and heats the plasma



The final technology altogether

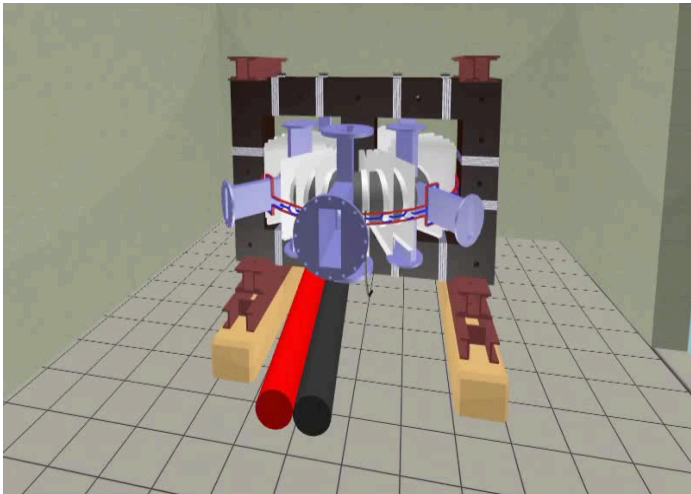


Table of Contents

1 Introduction

2 The Tokamak (GOLEM)

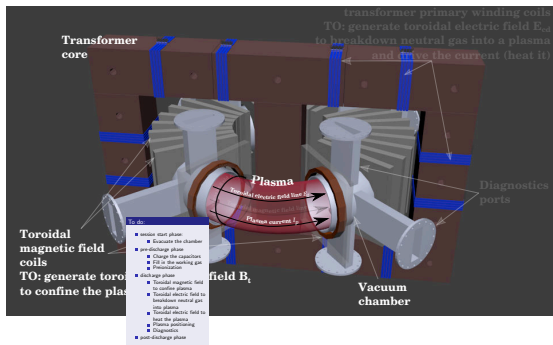
- The GOLEM tokamak concept
- The scenario to make the (GOLEM) tokamak discharge
- The scenario to discharge virtually
- The GOLEM tokamak basic diagnostics
- The GOLEM tokamak - guide tour

3 The Tokamak GOLEM (remote) operation

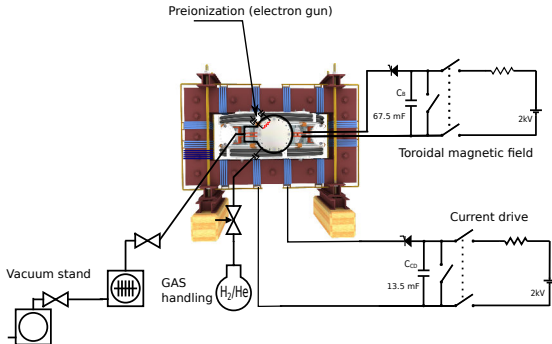
4 The Electron energy confinement time calculation (rough estimation)

5 Conclusion

Plasma in Tokamak (GOLEM) - the least to do



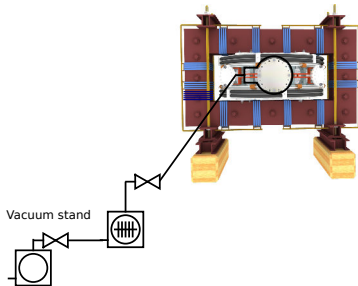
Plasma in Tokamak (GOLEM) - the least to do



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

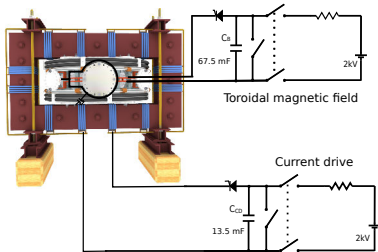
Plasma in Tokamak (GOLEM) - the least to do



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

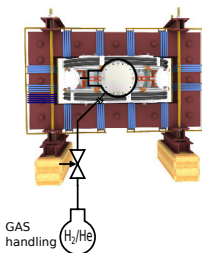
Plasma in Tokamak (GOLEM) - the least to do



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

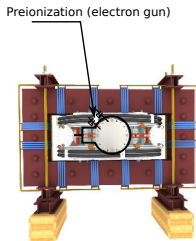
Plasma in Tokamak (GOLEM) - the least to do



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

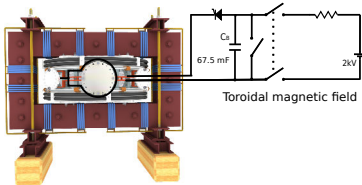
Plasma in Tokamak (GOLEM) - the least to do



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

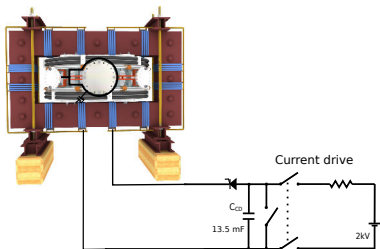
Plasma in Tokamak (GOLEM) - the least to do



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

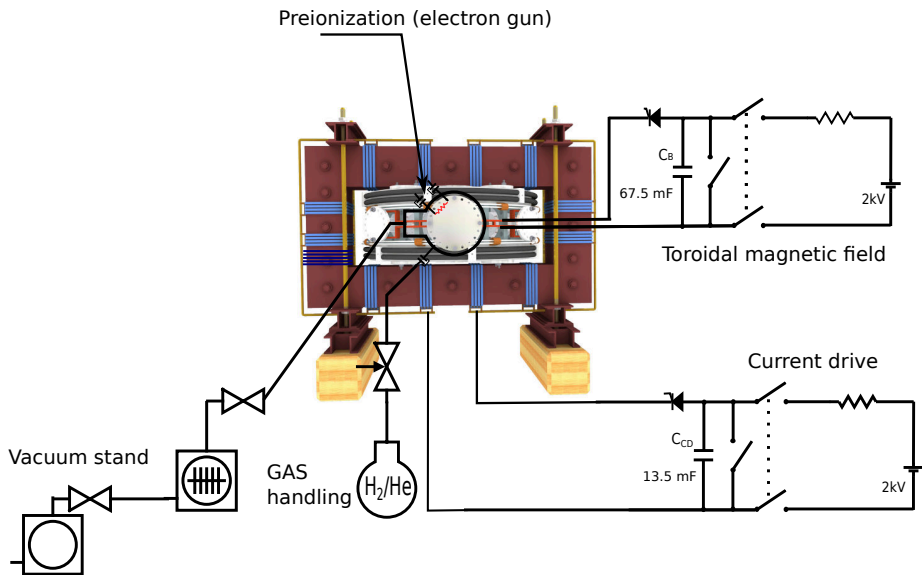


Table of Contents

1 Introduction

2 The Tokamak (GOLEM)

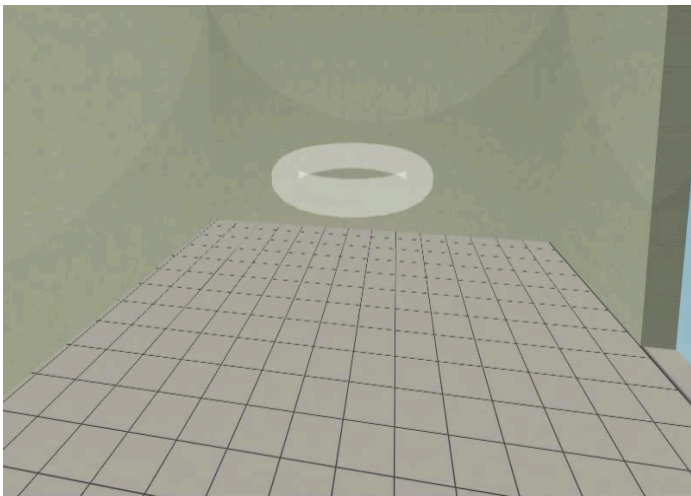
- The GOLEM tokamak concept
- The scenario to make the (GOLEM) tokamak discharge
- The scenario to discharge virtually
- The GOLEM tokamak basic diagnostics
- The GOLEM tokamak - guide tour

3 The Tokamak GOLEM (remote) operation

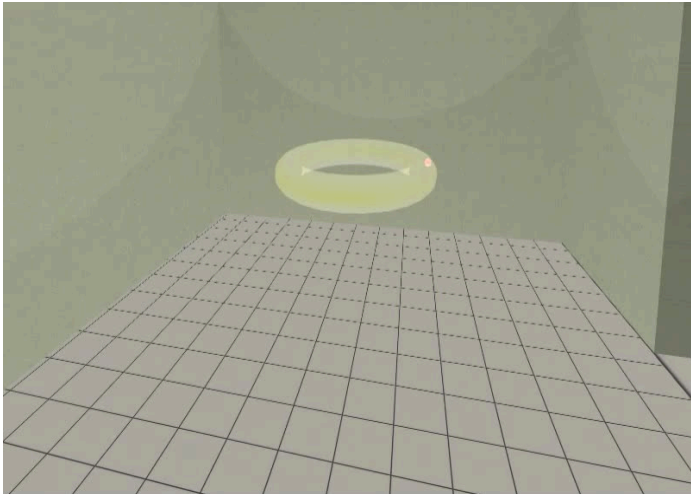
4 The Electron energy confinement time calculation (rough estimation)

5 Conclusion

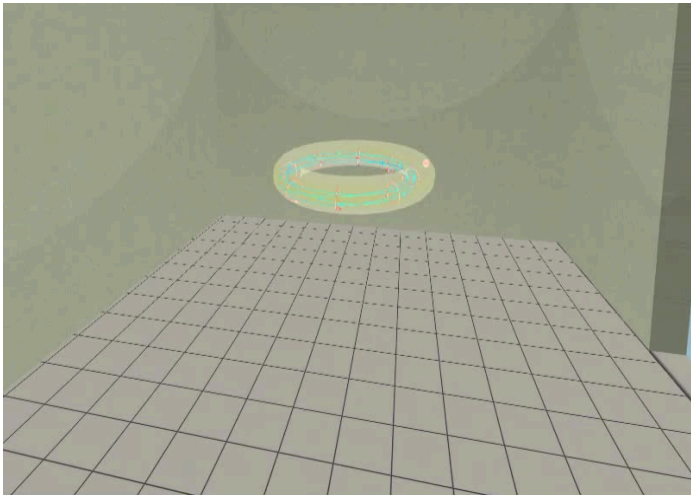
Introduce the working gas (Hydrogen x Helium)



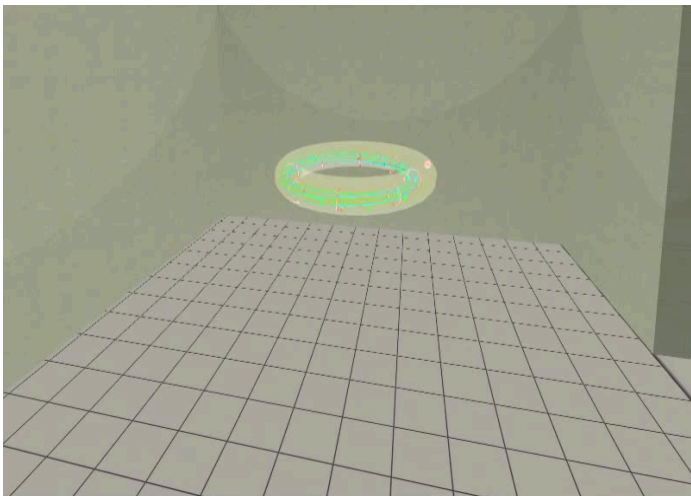
Switch on the preionization



Introduce the magnetic field



Introduce the electric field



Plasma ..

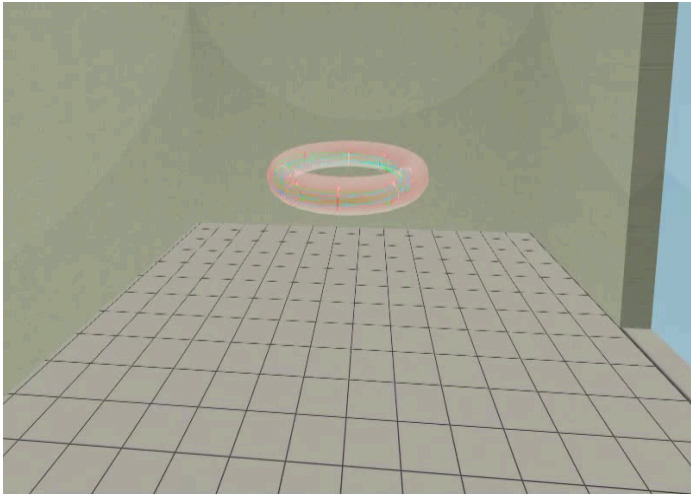


Table of Contents

1 Introduction

2 The Tokamak (GOLEM)

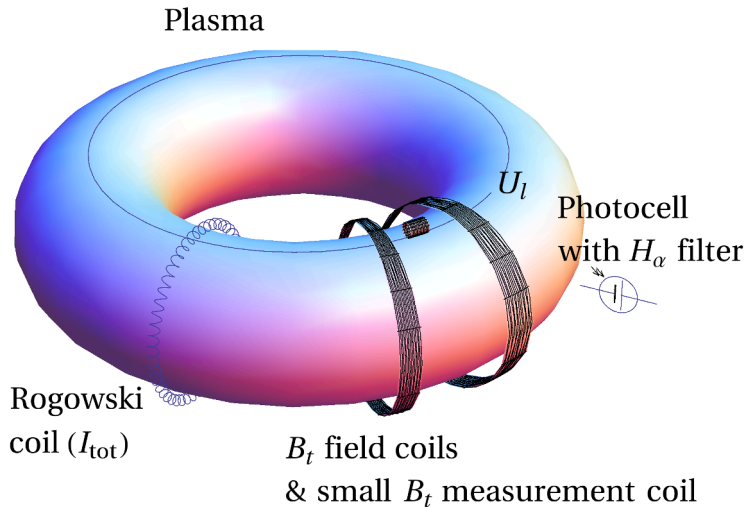
- The GOLEM tokamak concept
- The scenario to make the (GOLEM) tokamak discharge
- The scenario to discharge virtually
- The GOLEM tokamak basic diagnostics
- The GOLEM tokamak - guide tour

3 The Tokamak GOLEM (remote) operation

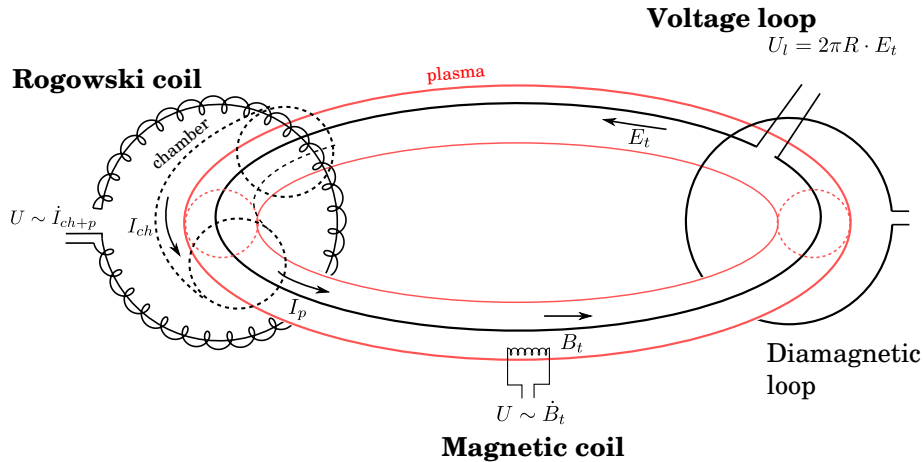
4 The Electron energy confinement time calculation (rough estimation)

5 Conclusion

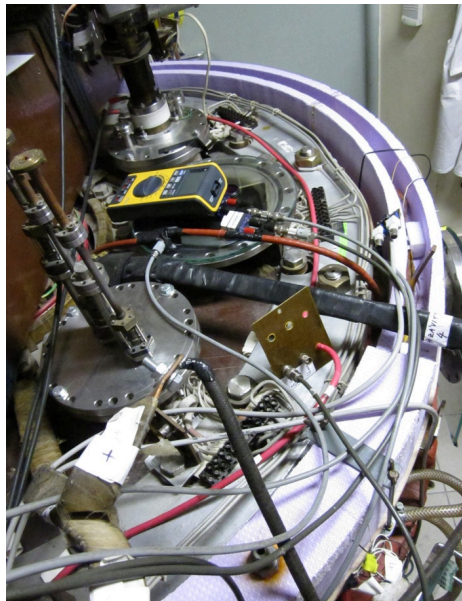
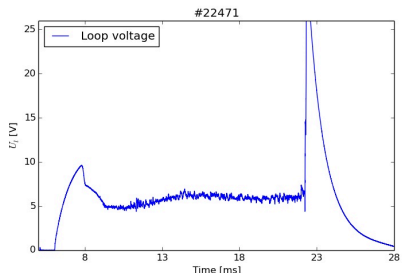
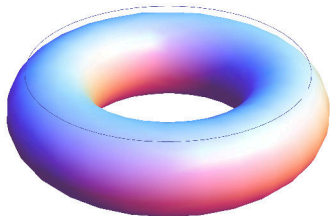
The GOLEM tokamak - basic diagnostics



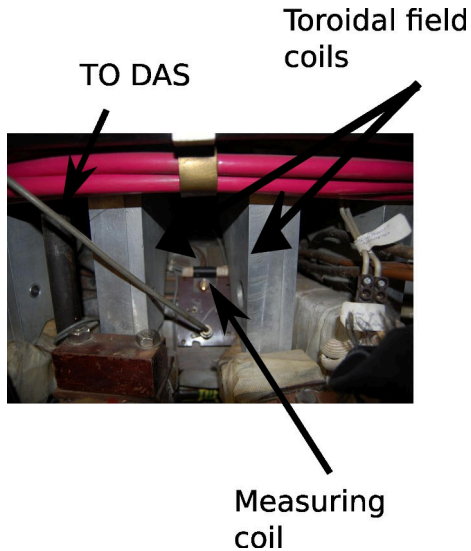
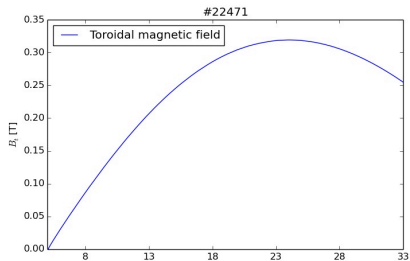
Schematic of electromagnetic diagnostics



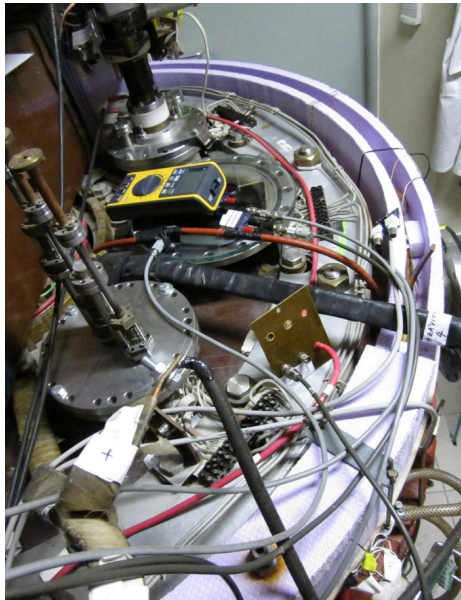
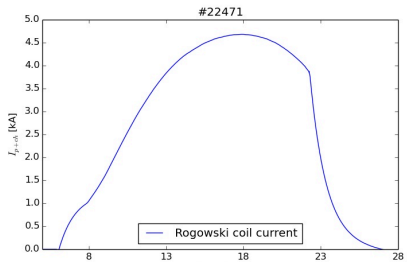
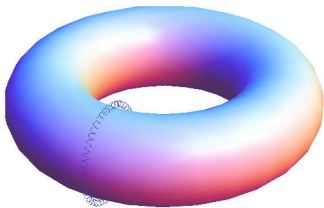
Loop voltage U_l @ the GOLEM tokamak



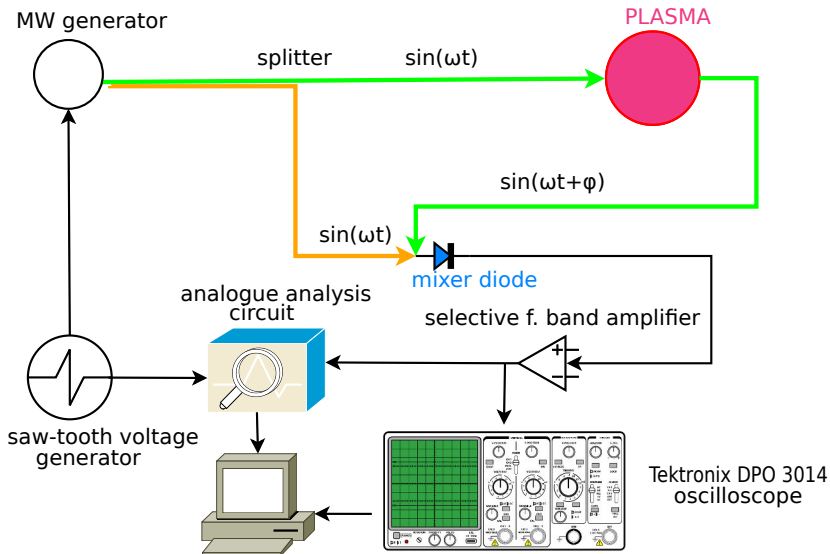
Toroidal magnetic field B_t @ the tokamak GOLEM



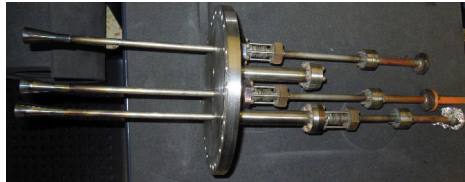
Total current I_{ch+p}



Electron density n_e interferometry measurement scheme



The GOLEM tokamak interferometry HW



"Typical", well executed discharge @ GOLEM

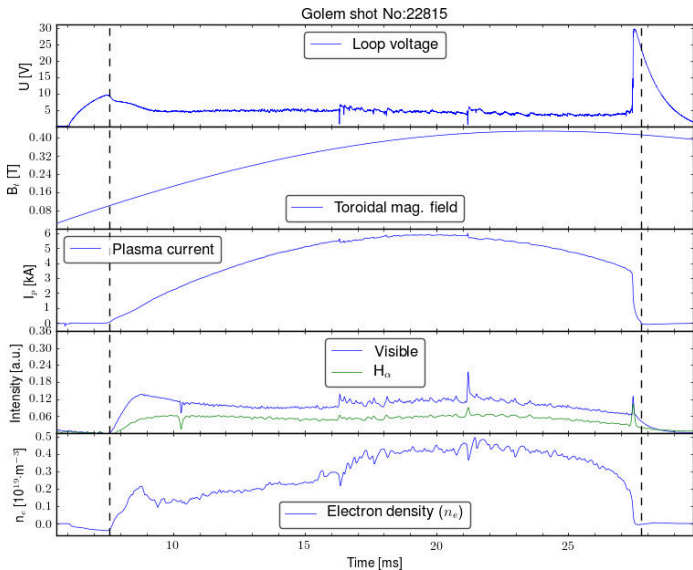


Table of Contents

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

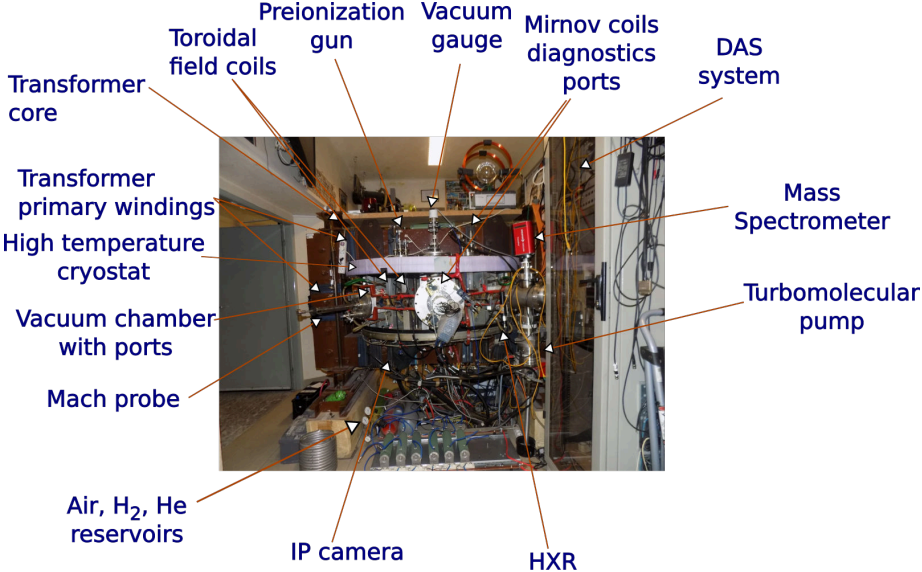
fire
protection
system



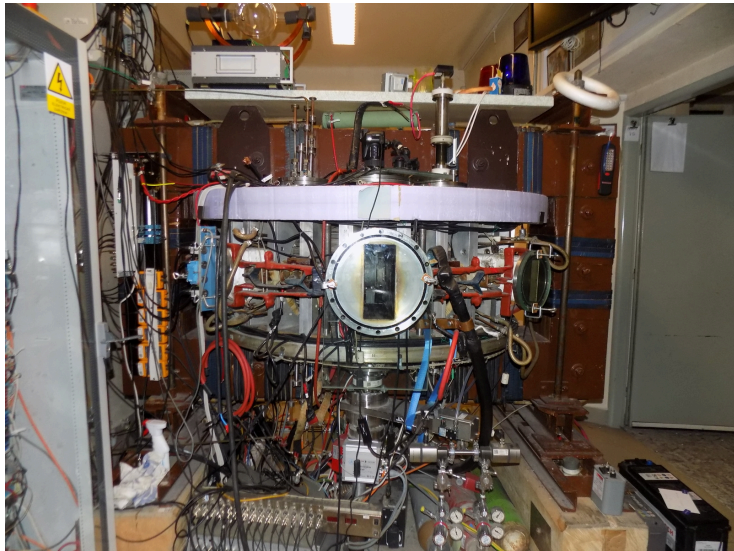
Tokamak room (North) 10/16



Tokamak room (North) 10/16



Tokamak room (South) 10/16



Tokamak room (South) 10/16

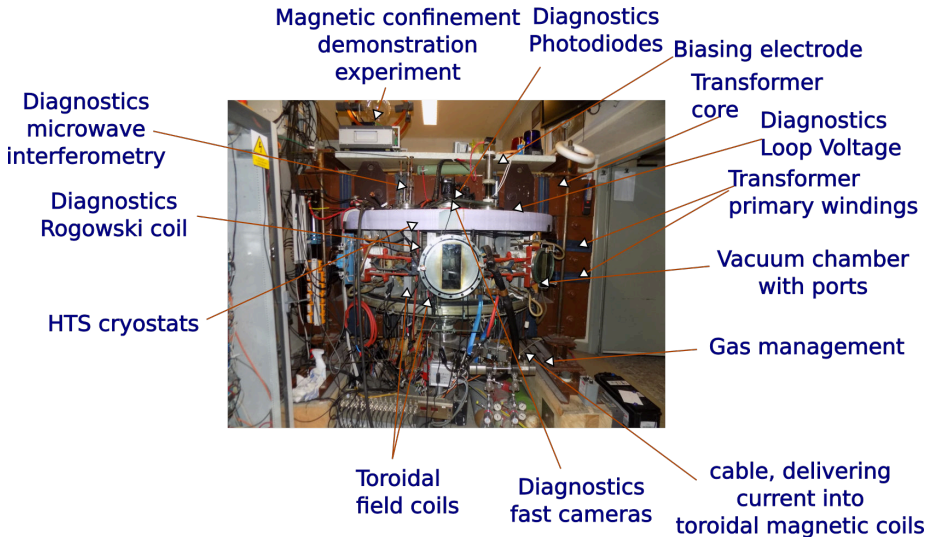


Table of Contents

- 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

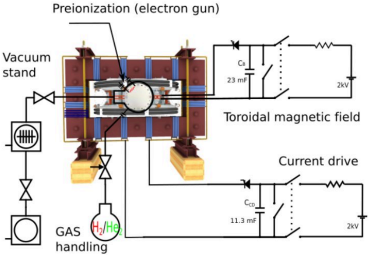
GOLEM remote Introduction **Control room** Live Results

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/H_3

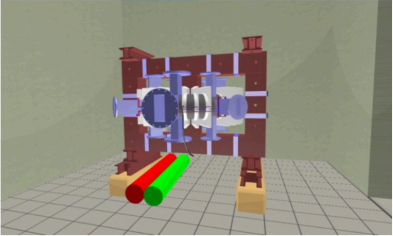
C_p 23 mF

C_{cp} 11.3 mF

2kV

2kV

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



[Next](#)

Control room: Working gas

GOLEM Interface PREIONIZATION **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_8

Toroidal magnetic field 67.5 mT

Toroidal electric field 13.5 mT

Gas type and pressure p_{gas} : 38 mPa

Hydrogen Helium

Next Set recommended value

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

Control room: Preionization

GOLEM homepage PREIONIZATION Control room Live Results

↑ Register Access Level 1 Help

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

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

Preionization (electron gun)

Vacuum stand

GAS handling

Toroidal magnetic field

Toroidal electric field

67.5 mF

13.5 mF

230V

230V

ionization method

Stuck-in gas No ionization

3D model rendering method

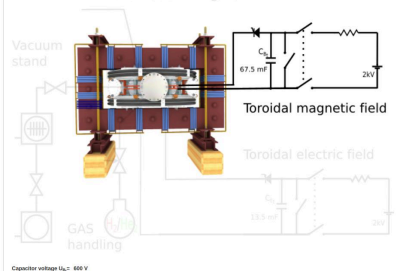
Control room: Magnetic field B_t

GOLEM interface: Introduction, Preionization, **Magnetic field**, Electric field, Submit

Press F11 to exit full screen
3D model rendering method: **Static image (fast)** Interactive X3DOM (slower)

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

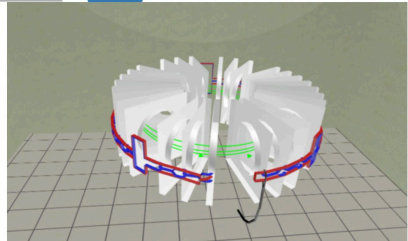
GAS handling

Toroidal magnetic field

Toroidal electric field

Capacitor voltage $U_{C0} = 600$ V

Next Set recommended value



Control room: Current drive E_{cd}

GOLEM Interface Introduction 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

40.5 mF

200V

Toroidal magnetic field

Toroidal electric field

13.5 mF

2kV

GAS handling

Time delay of electric field start after the magnetic field starts t_d : 0 micro seconds

Capacitor voltage U_c : 400 V

Next Set recommended value

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

Control room: ... and Submit

The screenshot displays the GOLEM control room interface. At the top, a navigation bar includes 'GOLEM', 'Introduction', 'Control room', 'Live', and 'Results'. On the right, it shows the user 'The Torneo Politecnico, Italy Group 1', 'Access Level 2', and a 'Help' icon.

The main interface is divided into two sections. The left section contains a navigation menu with tabs for 'Introduction', 'Working gas', 'Preionization', 'Magnetic field', 'Electric field', and 'Submit'. Below the menu, there is a text input field for a comment, a 'Submit' button, and instructions: 'Click the Submit button to send your configuration into the queue.' Below this, it says '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.' At the bottom of this section are two buttons: 'Watch the discharge Live!' and 'Go back to Introduction'.

The right section is titled '3D model rendering method' and has two options: 'Static image (fast)' and 'Interactive X3DOM (slow)'. Below this is a 3D rendering of the tokamak device, showing its complex structure with various components and a central chamber.

Shot homepage

GOLEM » Shot #22471 »



Diagnostics

- ✓ Interferometer
- ✓ Spectrometer
- ✗ FastCamera
- ✓ HXR

Analysis

- ✓ ShotHomepage

DAS

- ✓ TektronixDPO
- ✓ NIstandard
- ✓ Papouch_St
- ✓ Papouch_Ko
- ✓ Nloctopus

Vacuum log

Other

- Data
- References
- About
- Wiki
- Utilities

Navigation

- Next
- Previous

Tokamak GOLEM - Shot Database - 22471

Date: 2016-09-29 - 14:33:57
Session: TrainingCourses/Universities/Uni_Belgrade.rs/2016/
Comment: Standard discharge

Basic parameters: (compare)

- Gas pressure p_{ch} : 0.42 → 20.39 mPa (request: 20 mPa) ^{WIKI}
- Working gas: H
- Preionization: Upper el. gun
- Chamber temperature: 27.20 C
- C_B capacitors charged to: 800 V, triggered 5.0 ms ^{WIKI}
- C_{BD} capacitors charged to: 0 V, triggered 5.0 ms ^{WIKI}
- C_{CD} capacitors charged to: 400 V, triggered 6.0 ms ^{WIKI}
- C_{ST} capacitors charged to: 0 V, triggered 5.0 ms ^{WIKI}
- Probability of breakdown: 85% ^{WIKI}
- Time since session beginning: 0:07:50 h

Plasma parameters:

- Plasma life time 14.8 [ms] (from 7.8 to 22.6)
- Mean toroidal magnetic field B_t : 0.23 T ^{WIKI}
- Mean plasma current: 3.60 kA ^{WIKI}
- Mean Uloop: 5.92 V ^{WIKI}
- Break down voltage: 9.6 V ^{WIKI}
- Ohmic heating power: 21.33 kW
- Q edge: 2.9 ^{WIKI}
- Electron temperature: 41.1 eV ^{WIKI}
- Line electron density: 5.52 [$10^{17} m^{-2}$] ^{WIKI}

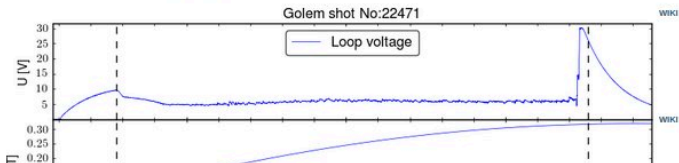


Table of Contents

- 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 or specific diagnostics have the format:

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

An overview of available data with identifiers, units, description, etc. for each discharge is at

```
http://golem.fjfi.cvut.cz/shots/<#ShotNo>/Data.php
```

Matlab

```
ShotNo=22471;
baseURL='http://golem.fjfi.cvut.cz/utis/data/';
identifier='loop_voltage';
%Create a path to data
dataURL=strcat(baseURL,int2str(ShotNo),'/',identifier);
% Write data from GOLEM server to a local file
urlwrite(dataURL,identifier);
% Load data
data = load(identifier, '\t');
% Plot and save the graph
plot(data(:,1)*1000, data(:,2), '.');
xlabel('Time [ms]');
ylabel('Ul [V]');
saveas(gcf, 'plot', 'jpeg');
exit;
```

Jupyter (python)

```
import numpy as np
import matplotlib.pyplot as plt

shot_no = 22471
identifier = "loop_voltage"
# 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/utis/data/"
data_file = ds.open(base_url+str(shot_no)+'/'+identifier)
#Load data from the file and plot to screen and to disk
data = np.loadtxt(data_file)
plt.plot(data[:,0], data[:,1]) #1. column vs 2. column
plt.savefig('graph.jpg')
plt.show()
```

Gnuplot

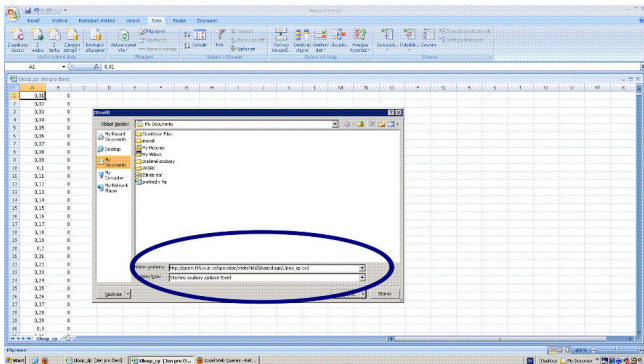
```
set macros;  
ShotNo = "22471";  
baseURL = "http://golem.fjfi.cvut.cz/utils/data/";  
identifier = "loop_voltage";  
#Create a path to data  
DataURL= "@baseURL@ShotNo/@identifier";  
#Write data from GOLEM server to a local file  
!wget -q @DataURL;  
#Plot the graph from a local file  
set datafile separator "\t";  
plotstyle = "with_lines_linestyle_-1"  
plot 'loop_voltage' using 1:2 @plotstyle;  
exit;  
  
# command line execution:  
# gnuplot Uloop.gp -persist
```

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

Excel



File→Open→

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

Spreadsheets (Excel and others)

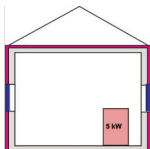
are not recommended, only tolerated.

Table of Contents

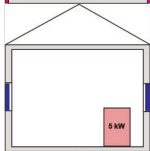
- 1 Introduction
- 2 The Tokamak (GOLEM)
- 3 The Tokamak GOLEM (remote) operation
- 4 The Electron energy confinement time calculation (rough estimation)**
- 5 Conclusion
- 6 Appendix

Energy balance of the house

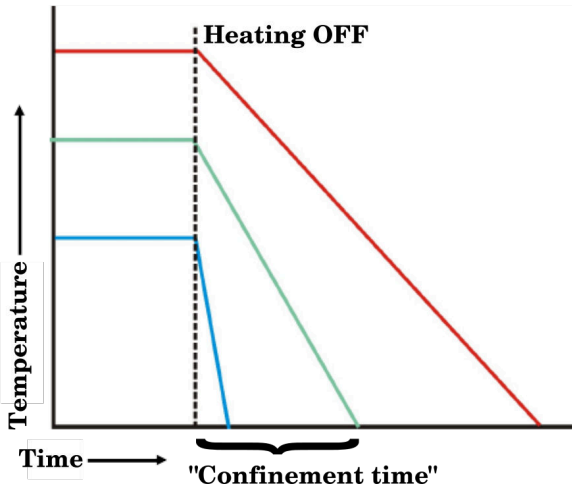
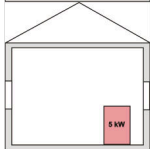
Closed windows & insulation



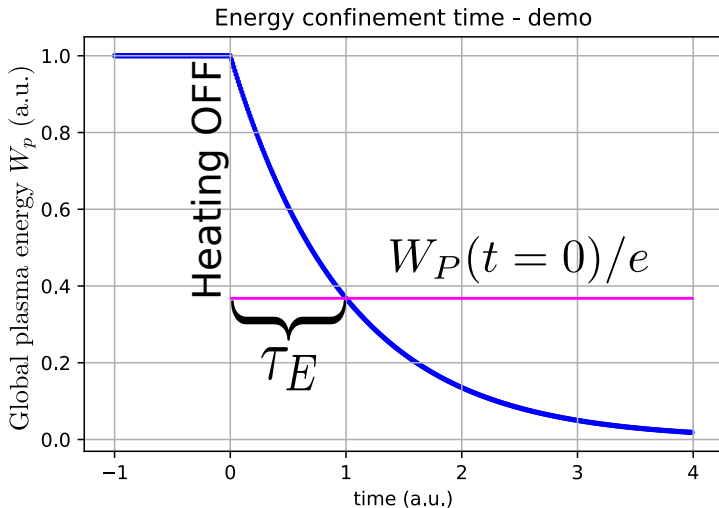
Closed windows



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

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

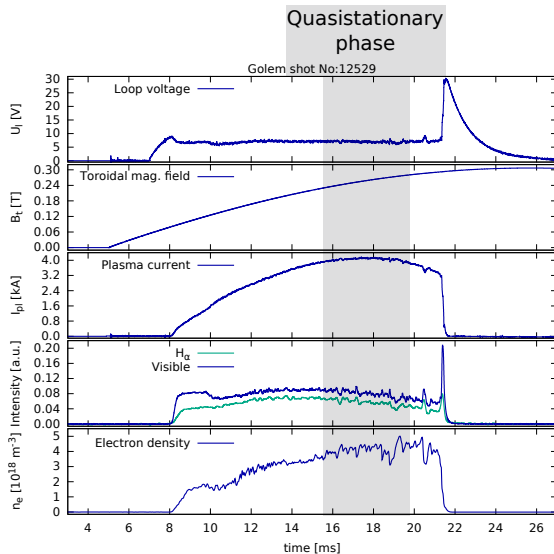
The energy confinement time is defined as the characteristic time scale of the exponential decay of the plasma energy W_p due to the loss power P_L :

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

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)

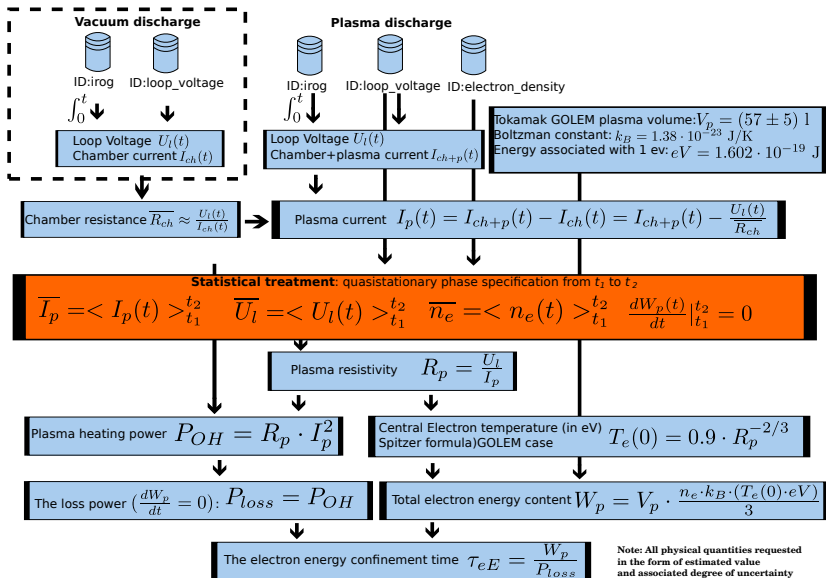
The time evolution of the central electron temperature $T_e(0, t)$ is calculated from equation based on Spitzer's resistivity formula (see eg. [4],[3]):

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

For particular case of the GOLEM tokamak it says:

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

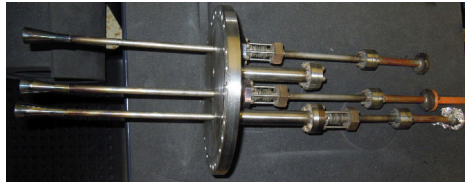
Towards Electron energy confinement time τ_{eE}



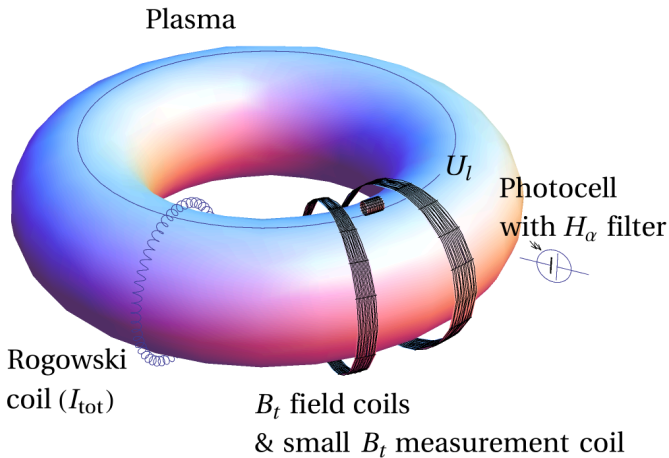
Hands on the GOLEM tokamak - equipment



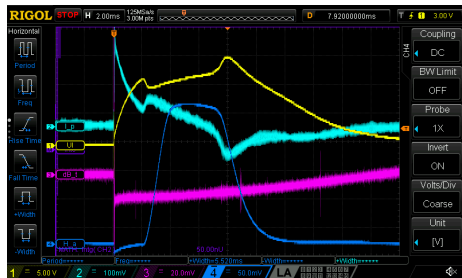
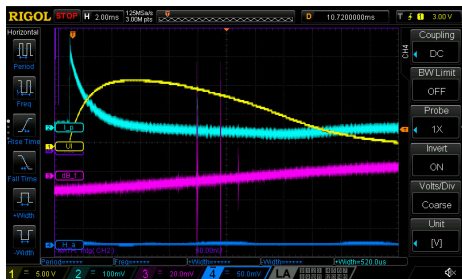
The GOLEM tokamak interferometry HW



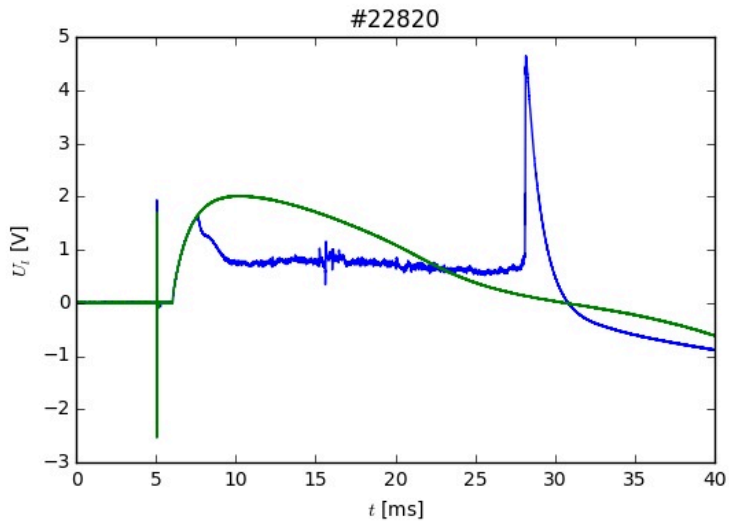
The GOLEM tokamak - standard diagnostics



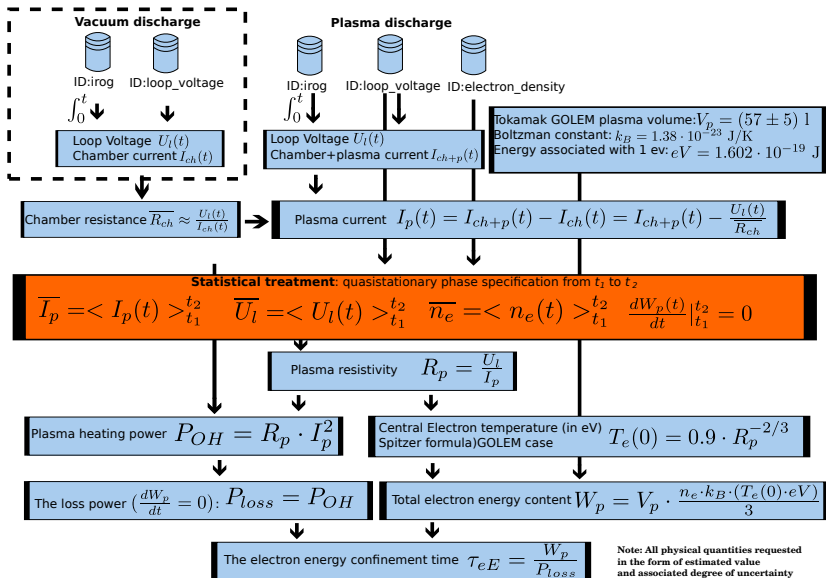
Vacuum x Plasma discharge @ Oscilloscope



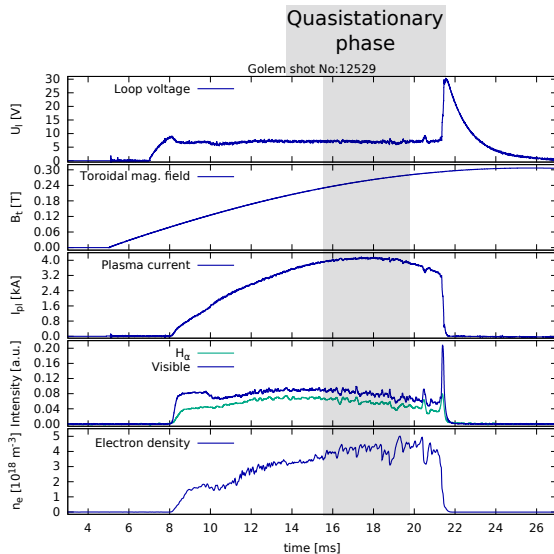
Vacuum x Plasma shot



Towards Electron energy confinement time τ_{eE}

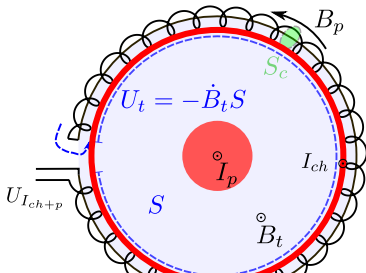
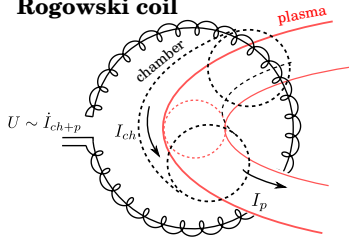


The discharge - quasistationary phase



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-wounded 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:

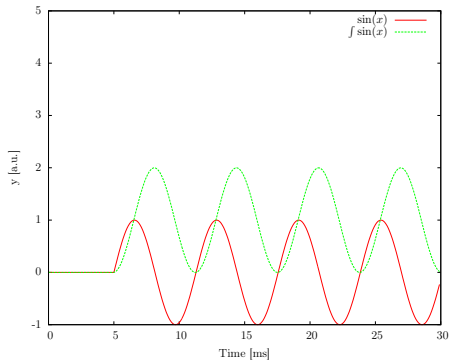
$$D_i = \frac{1}{C_d} \sum_{j=0}^{t/\Delta t} (U_i(t_j) - U_{offset}) \Delta t$$

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

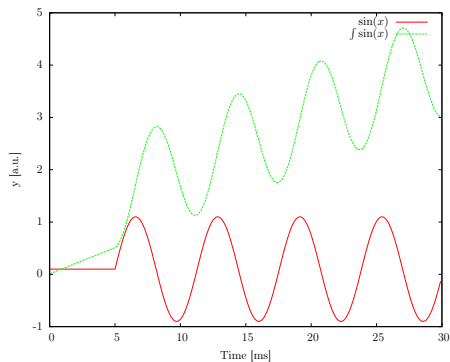
- The offset U_{offset} can be specified from the beginning of the data series before switching on the real experiment.

Magnetic measurement demo - game with U_{offset}

Without U_{offset}



With U_{offset}



Towards Electron energy confinement time τ_{eE}

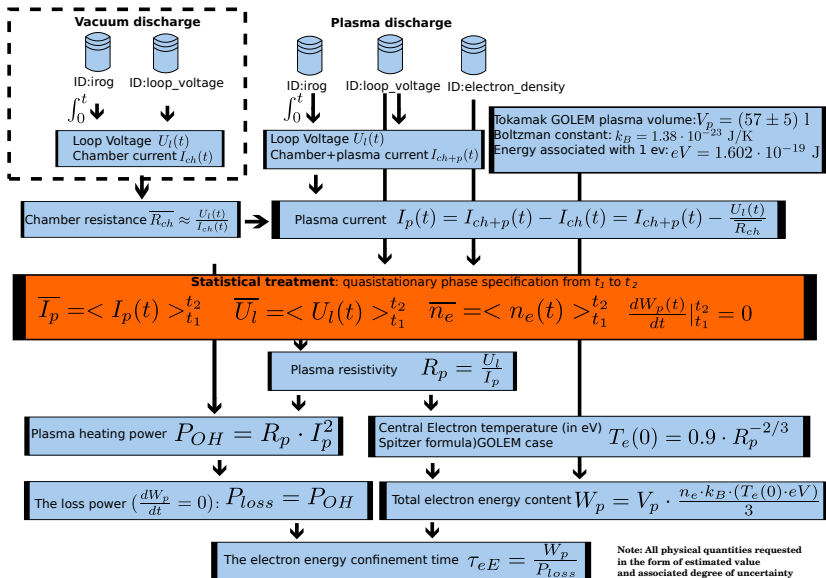


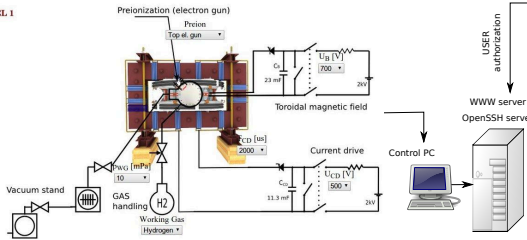
Table of Contents

- 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

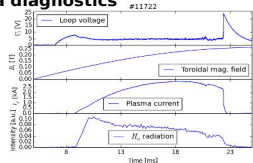
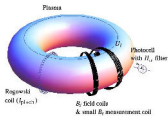
The global schematic overview of the GOLEM experiment

LEVEL 1

Tokamak technology setup



Basic plasma diagnostics

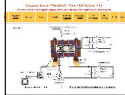


internet

Virtual control room (remote participation)

WWW control interface

HTML & PHP scripts



SSH control interface

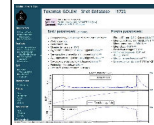
WINDOWS via putty



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

Data presentation

HTML (www pages)



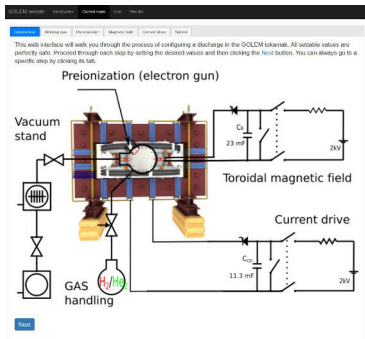
Data handling

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

- Everything via <http://golem.fjfi.cvut.cz/Torino>
 - This presentation
 - Control rooms
 - Contact: Vojtech Svoboda,
+420 737673903,
svoboda@fjfi.cvut.cz
 - Chat:
tokamak.golem@gmail.com or
skype: tokamak.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:

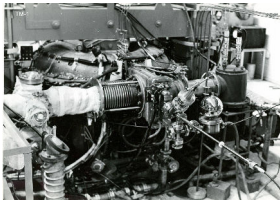
CTU RVO68407700, SGS 17/138/OHK4/2T/14, GAČR GA18-02482S, EU funds CZ.02.1.01/0.0/0.0/16_019/0000778 and CZ.02.2.69/0.0/0.0/16_027/0008465, IAEA F13019, FUSENET and EUROFUSION.

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 Čěrovský, 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



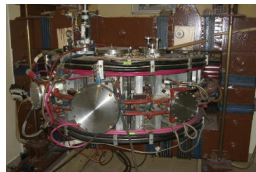
SCIENCE

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 room in the world

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

LEVEL 1

Preionization (electron gun)
Posias

Toroidal magnetic field

Current drive

Vacuum stand
GAS handling
Washing 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

-  Tokamak . 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 January 9, 2020].
-  J. Wesson. *Tokamaks*, volume 118 of *International Series of Monographs on Physics*. Oxford University Press Inc., New York, Third Edition, 2004.
-  Brotankova, J. Study of high temperature plasma in tokamak-like experimental devices. PhD. thesis 2009.
-  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.