Title

Introduction to the tokamak GOLEM operation
Practical guide

Vojtěch Svoboda
on behalf of the tokamak GOLEM team
for French Master students event @ Cadarache, France

March 10, 2025

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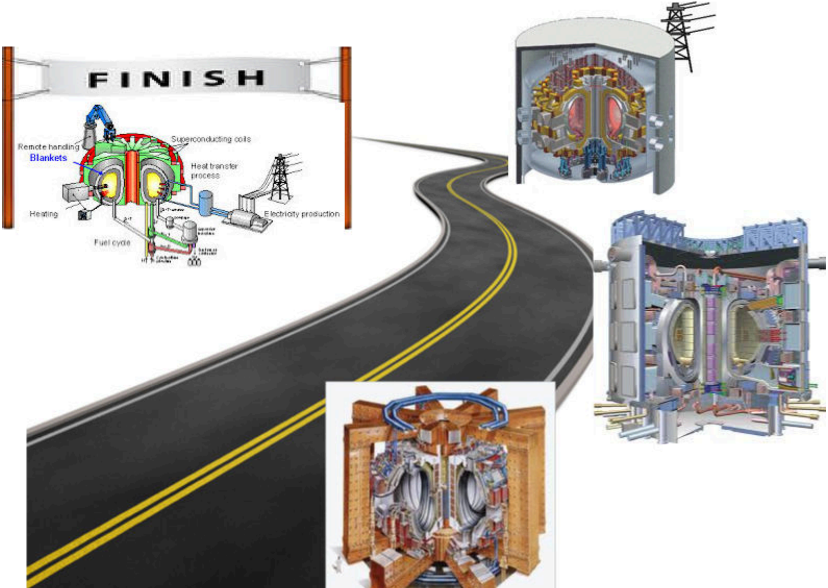
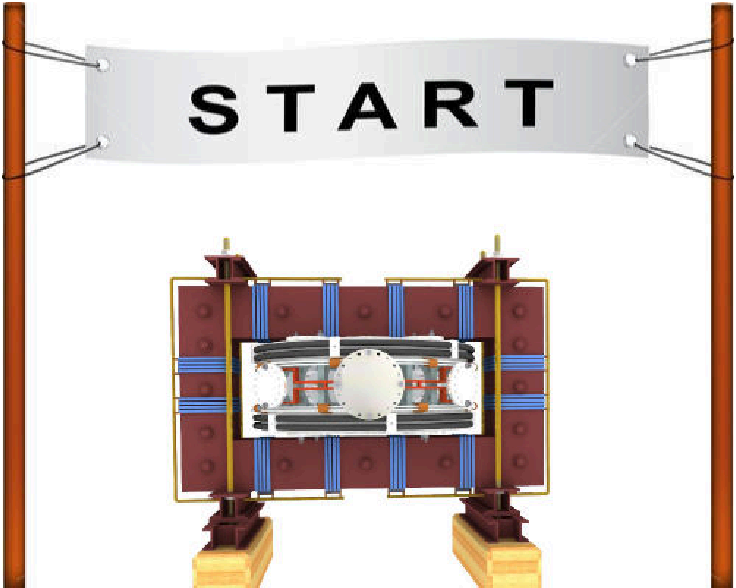
Milestones to Fusion Power Plant

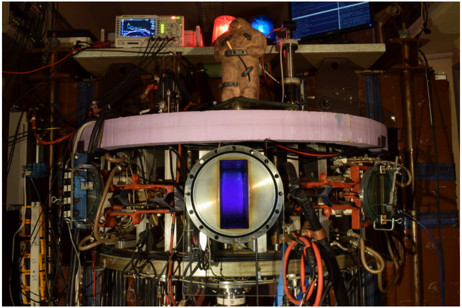


Education importance

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

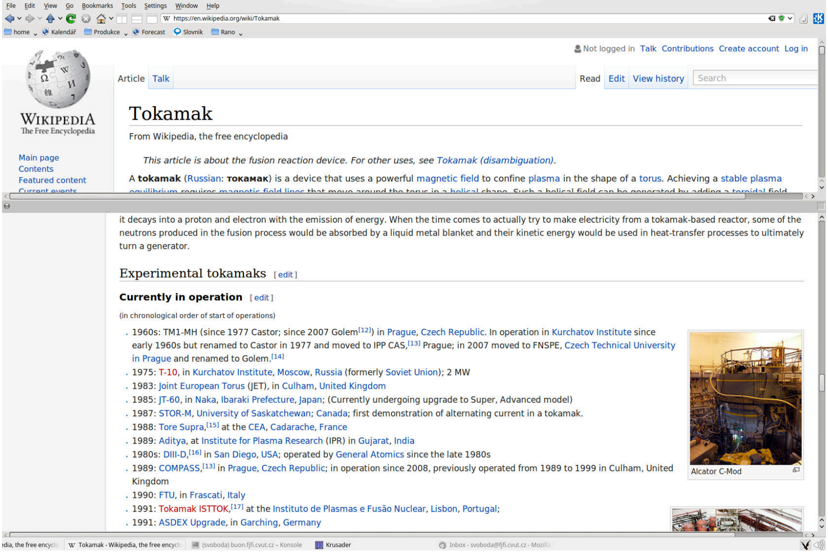


The GOLEM tokamak basic characteristics
The grandfather of all tokamaks (ITER newsline 06/18)



- Vessel major radius: $R_0 = 0.4$ m
- Vessel minor radius: $r_0 = 0.1$ m
- Maximum plasma current: $I_{\rm p}^{\rm max} < 8$ kA
- Maximum toroidal magnetic field: $B_{\rm t}^{\rm max} < 0.5$ T
- Typical electron density: $< n_e > \in (0.2, 3) \cdot 10^{19}$ m^{-3}
- Maximum electron temperature: $T_{\rm e}^{\rm max} < 80$ eV
- Maximum discharge duration: $\tau_{\rm p}^{\rm max} < 25$ ms

Tokamak GOLEM @ Wikipedia ..



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

...

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

Experimental tokamaks [edit]

Currently in operation [edit]

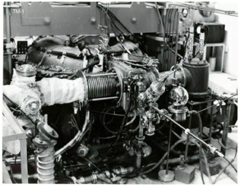
(in chronological order of start of operations)

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

Alcator C-Mod

The GOLEM tokamak for education - historical background

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



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

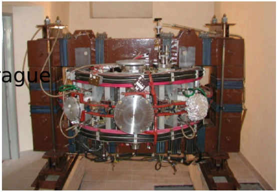
1974

2006

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

2008

Czech Technical University Prague
Czech republic
GOLEM



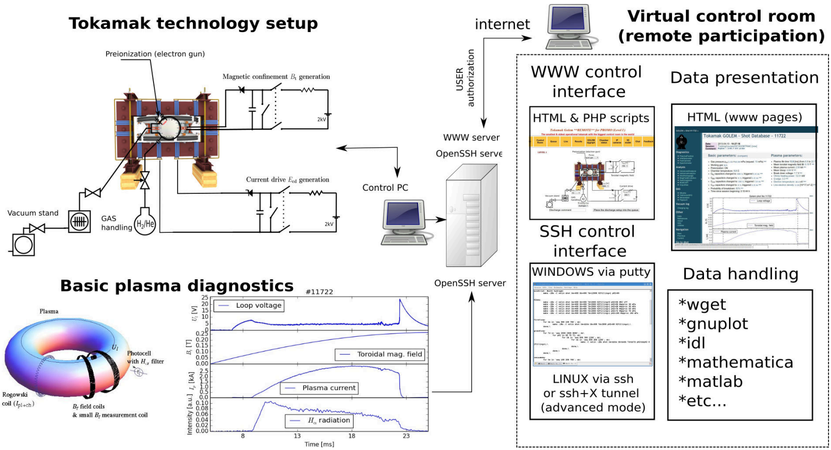
GOLEM

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

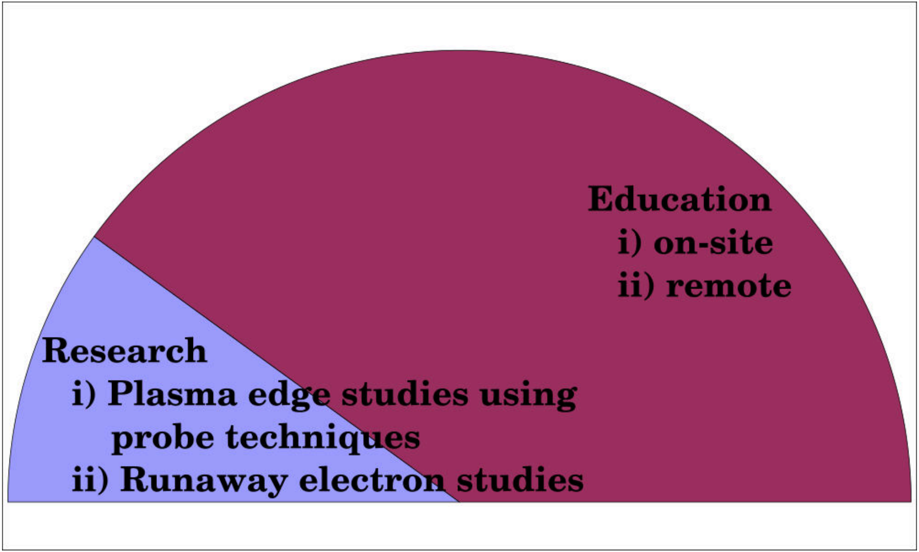
there is hidden indeed "infernal" power. Yet it is the very power of celestial stars themselves. Calmly dormant, awaiting mankind to discover the magic key, to use this power for their benefit...

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

The global schematic overview of the tokamak GOLEM experiment



The GOLEM tokamak mission



Production

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

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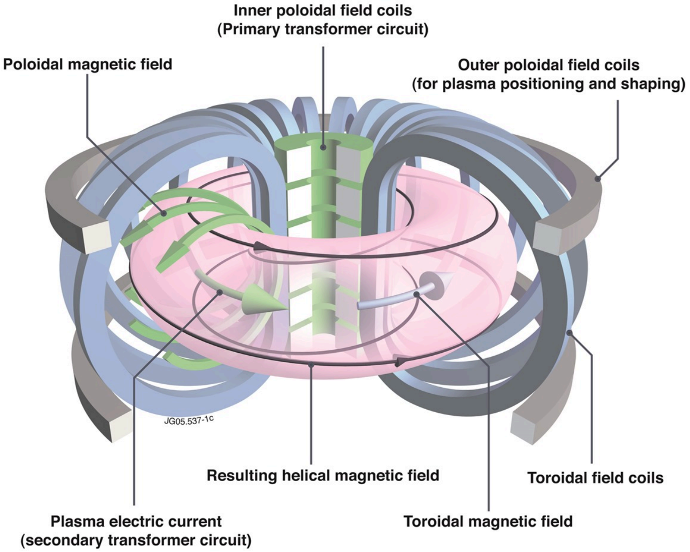
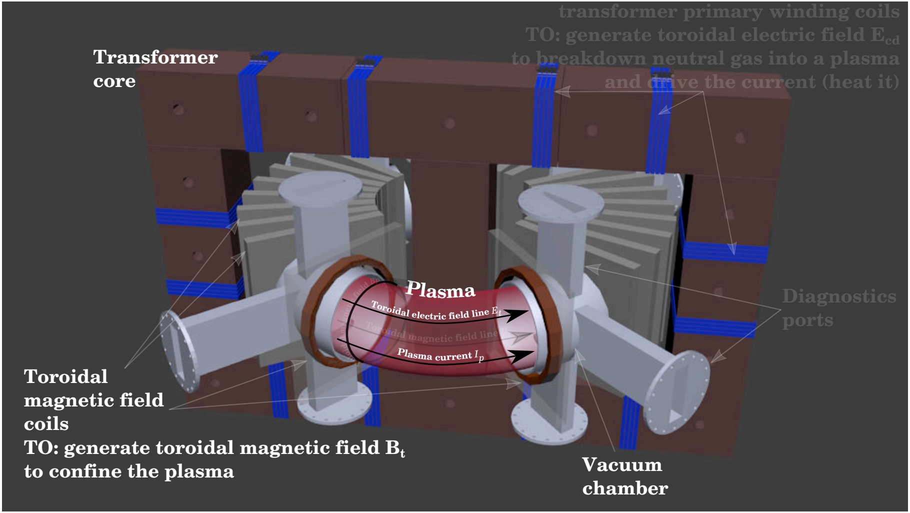
Tokamak magnetic confinement concept



credit:Tokamak concept@Wiki

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



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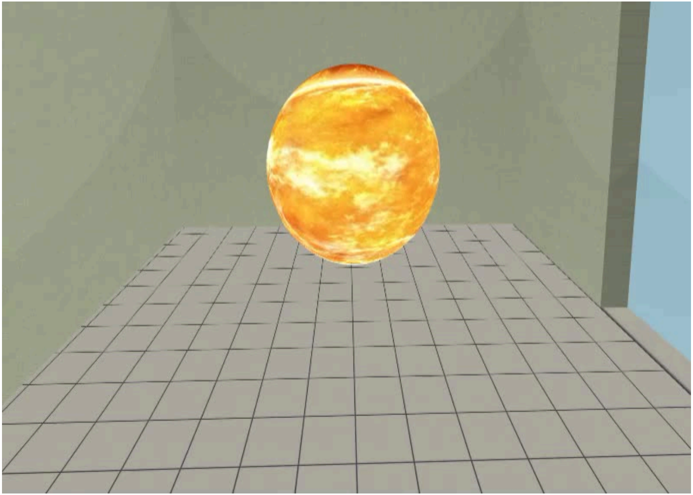
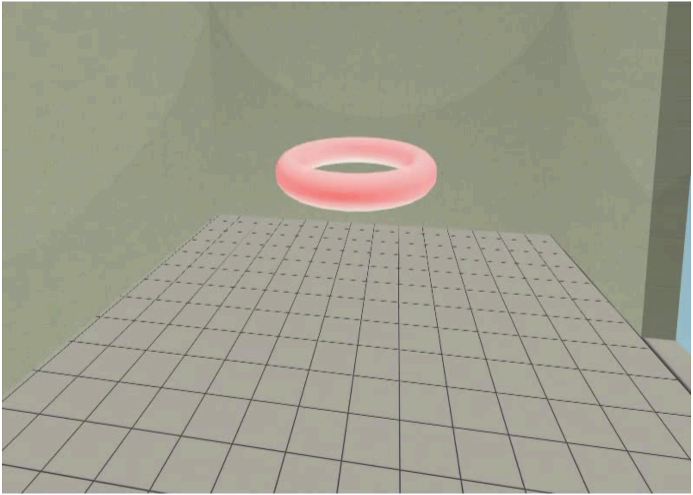
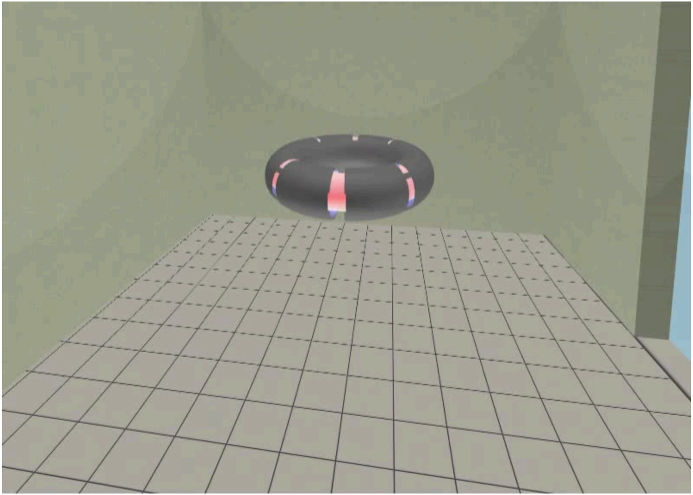
Our goal: the technology to create a μSun on the Earth



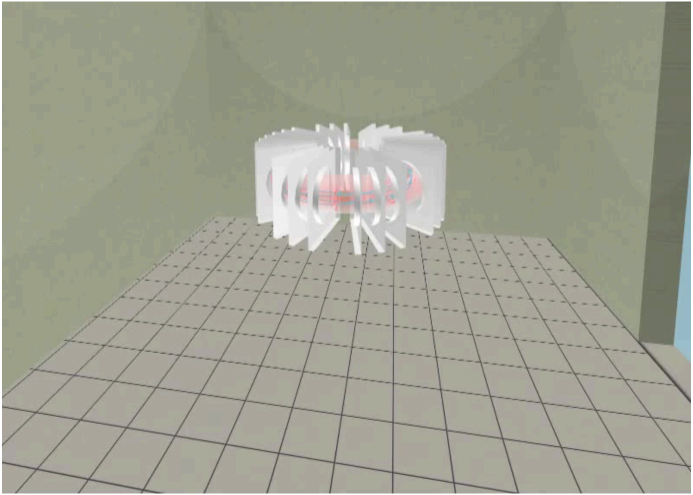
Magnetic confinement requires toroidal geometry



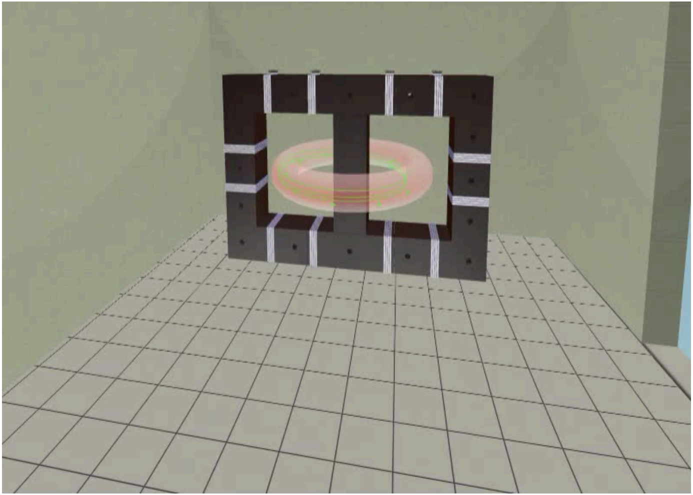
A chamber contains the thermonuclear reaction



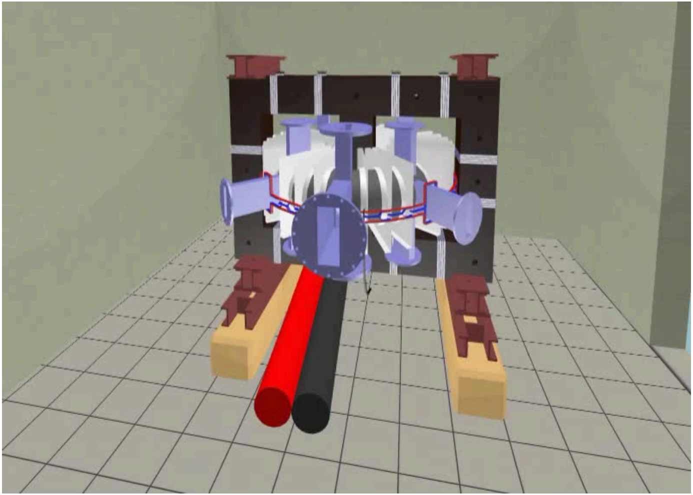
Toroidal magnetic field coils confine the plasma



A transformer action creates and heats the plasma



The final technology altogether



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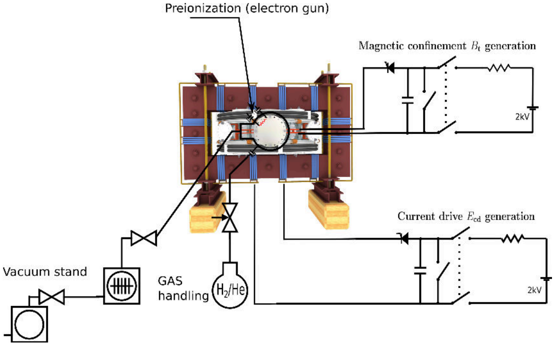
Plasma in Tokamak (GOLEM) - the least to do



To do:

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

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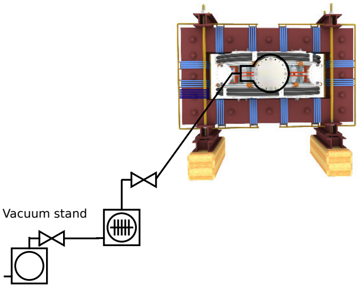

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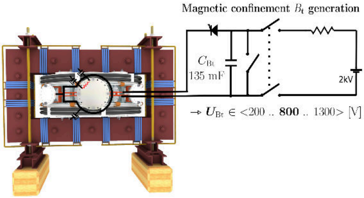

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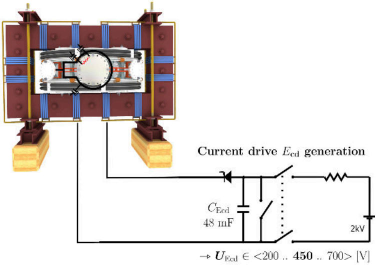

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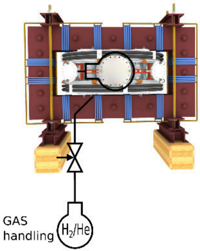

$\rightarrow p_{\mathrm{H}} \in <0 .. \mathbf{10} .. 40> [\mathrm{mPa}]$

To do:

- session start phase:
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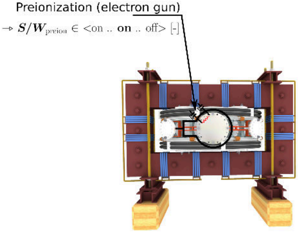

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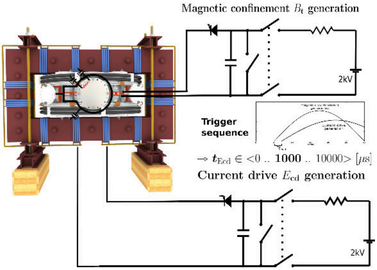

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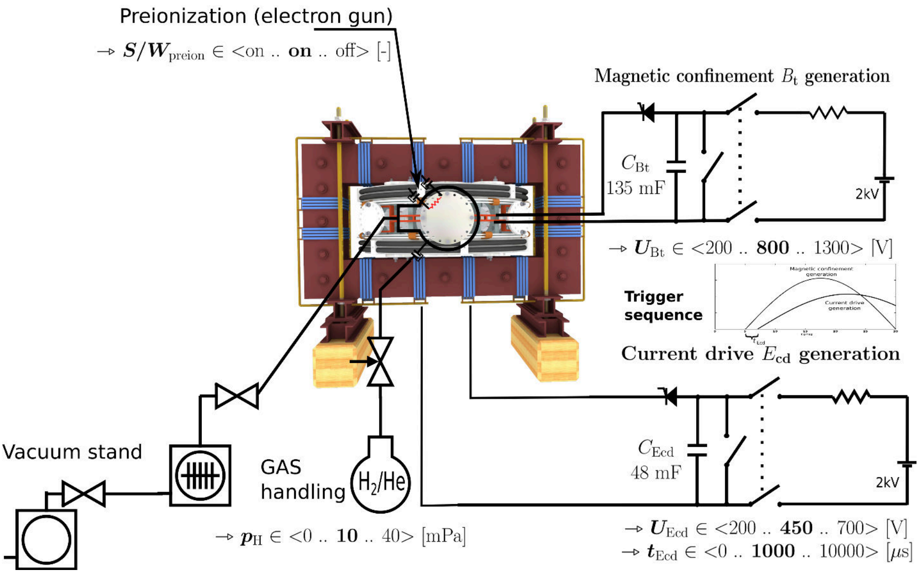
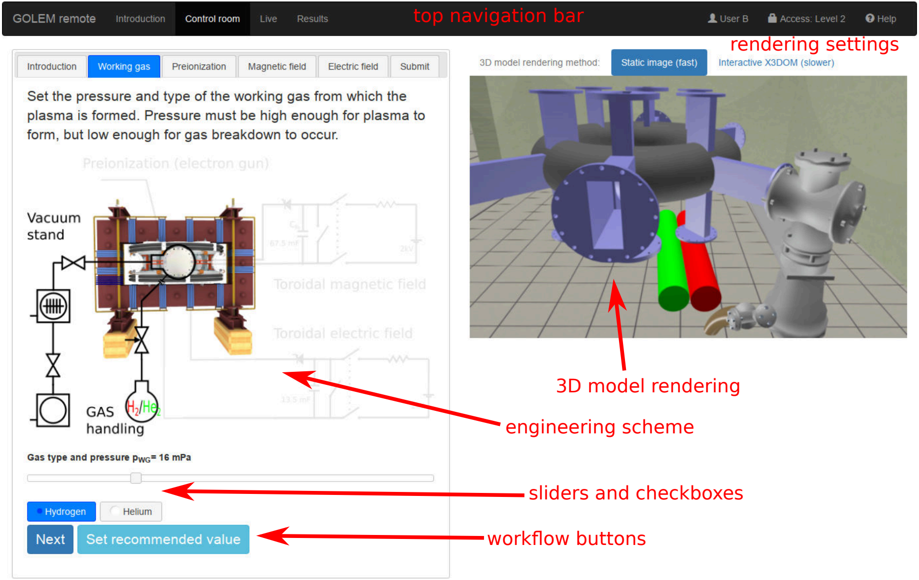
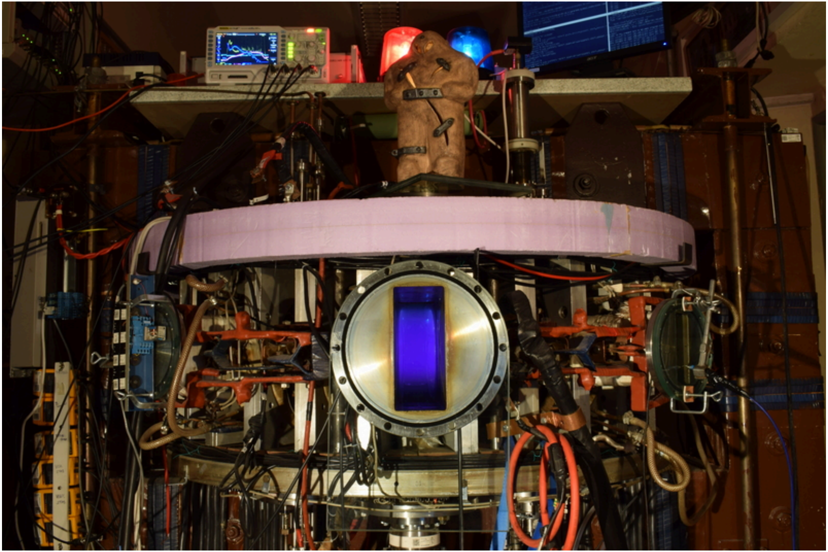
Tokamak GOLEM - schematic experimental setup



Remote control interface of the GOLEM tokamak



Let's make a discharge



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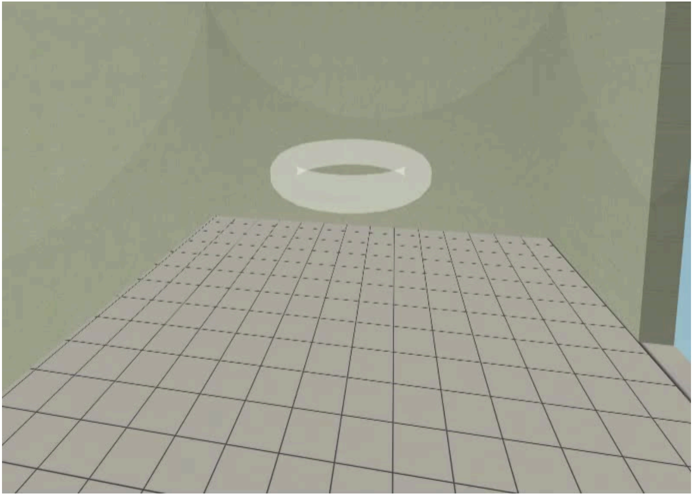
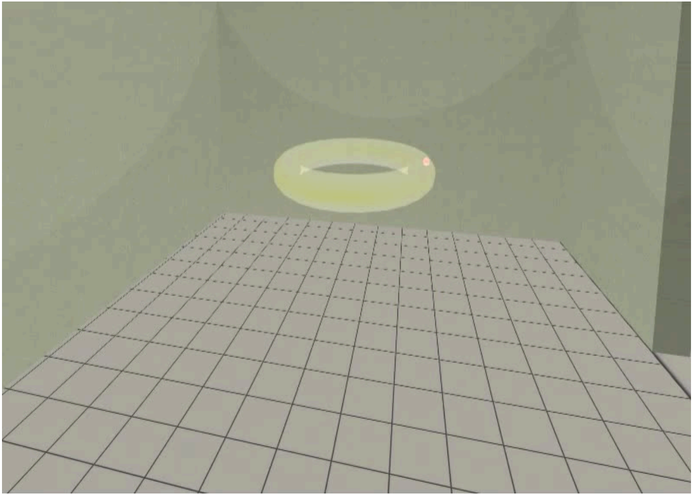
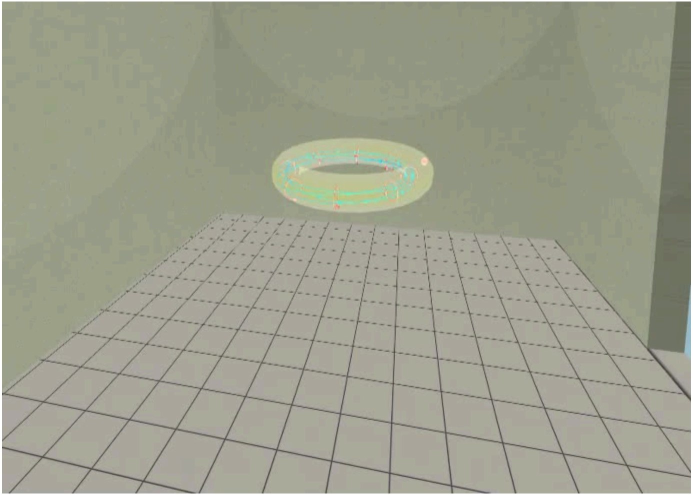
Introduce the working gas (Hydrogen x Helium)



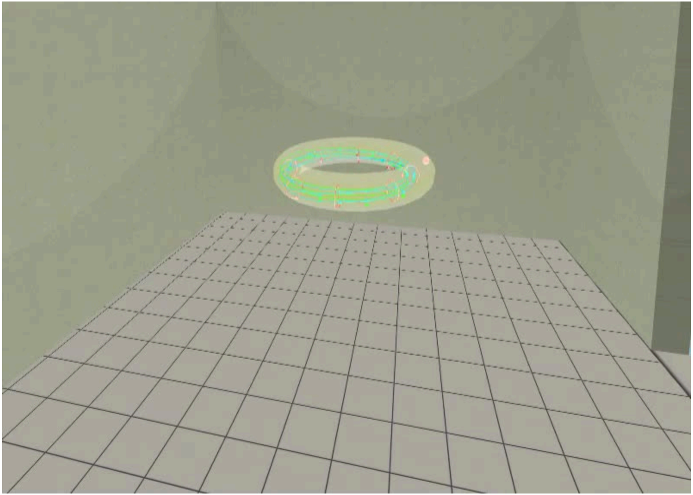
Switch on the preionization



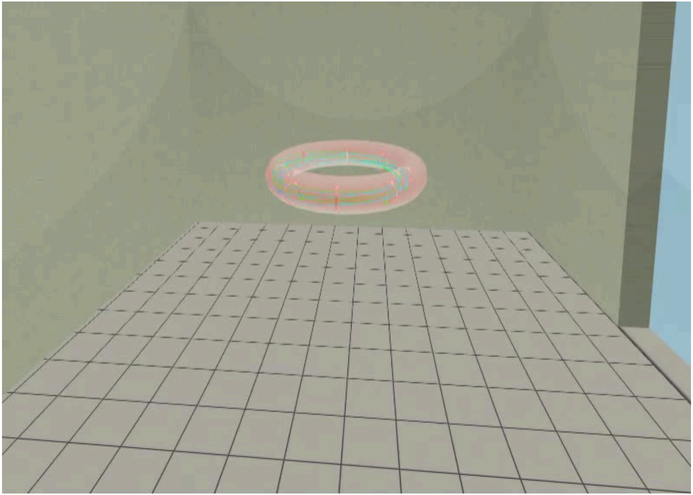
Introduce the magnetic field



Introduce the electric field



Plasma ..



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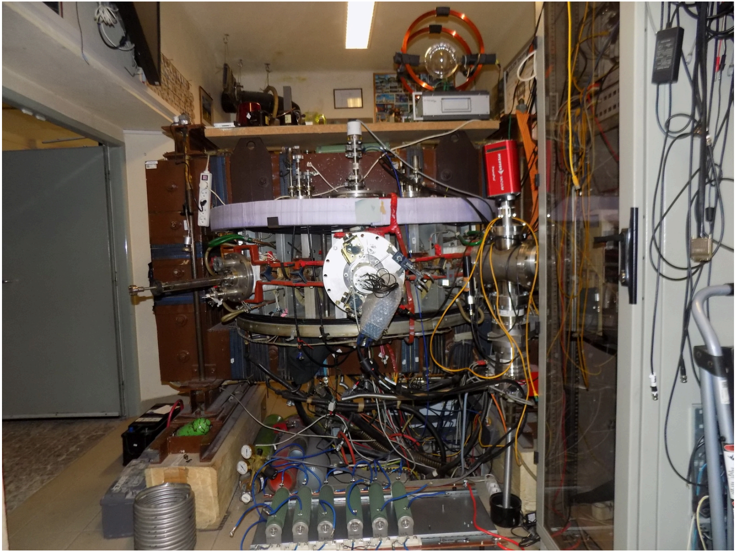
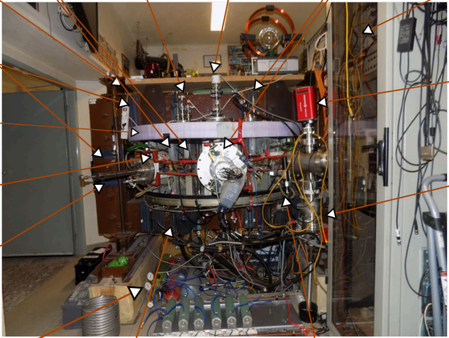
Infrastructure room (below tokamak) 10/16

Infrastructure room (below tokamak) 10/16

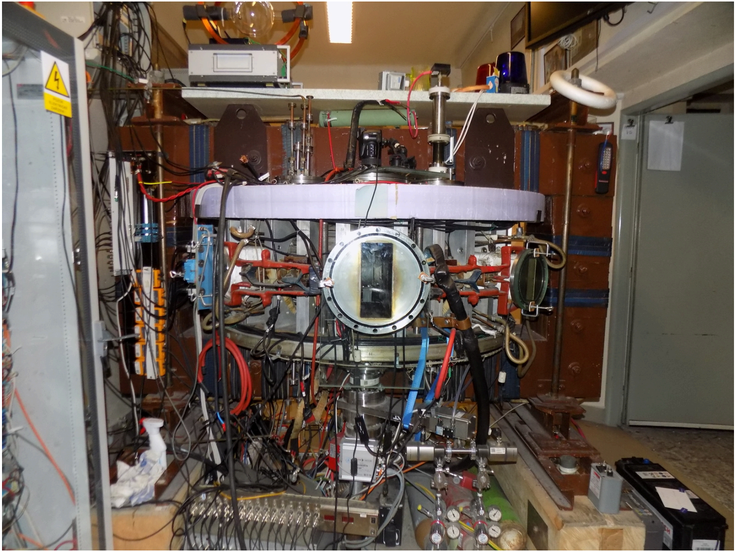
Tokamak room (North) 10/16



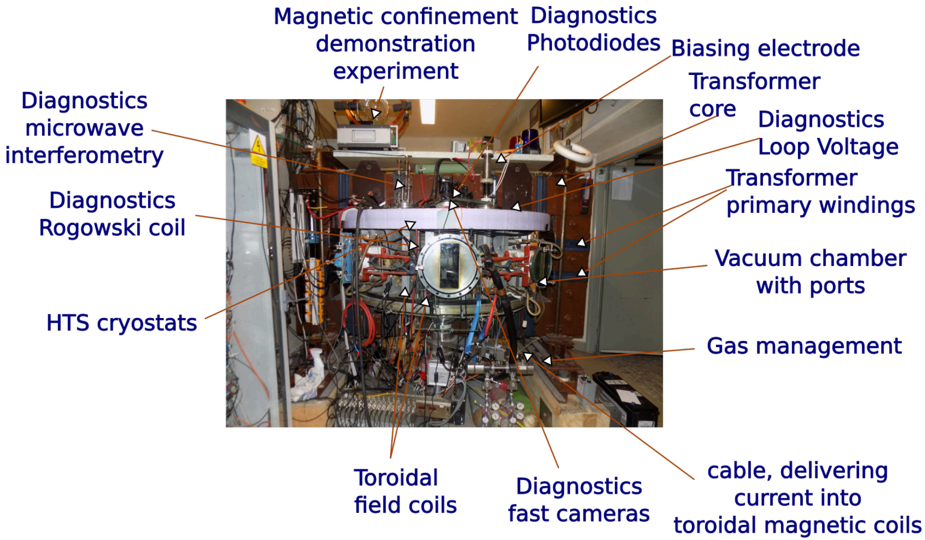
Tokamak room (North) 10/16



Tokamak room (South) 10/16



Tokamak room (South) 10/16



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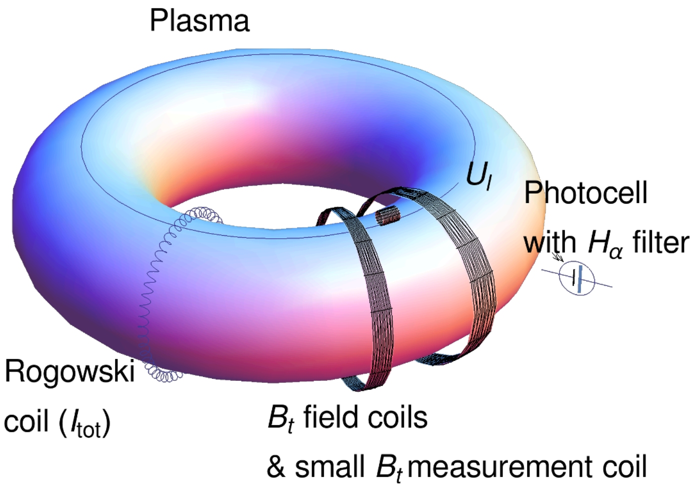
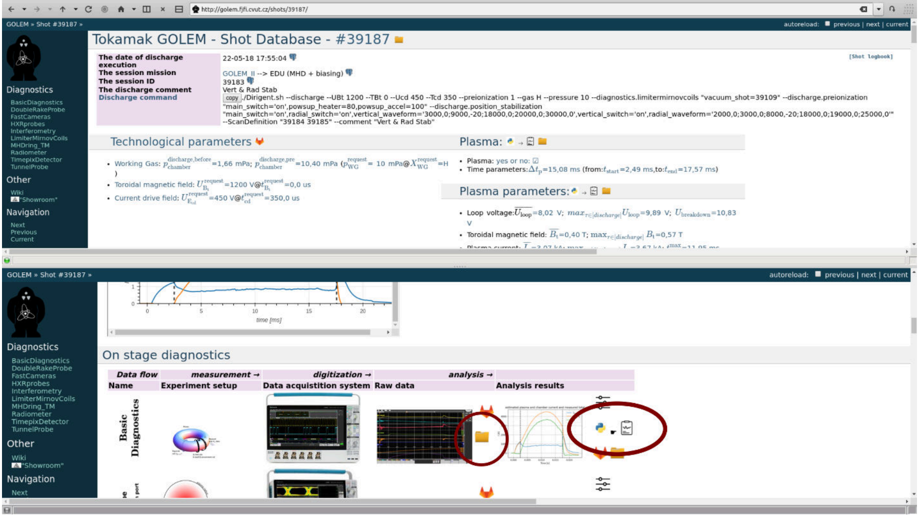
The GOLEM tokamak - basic diagnostics

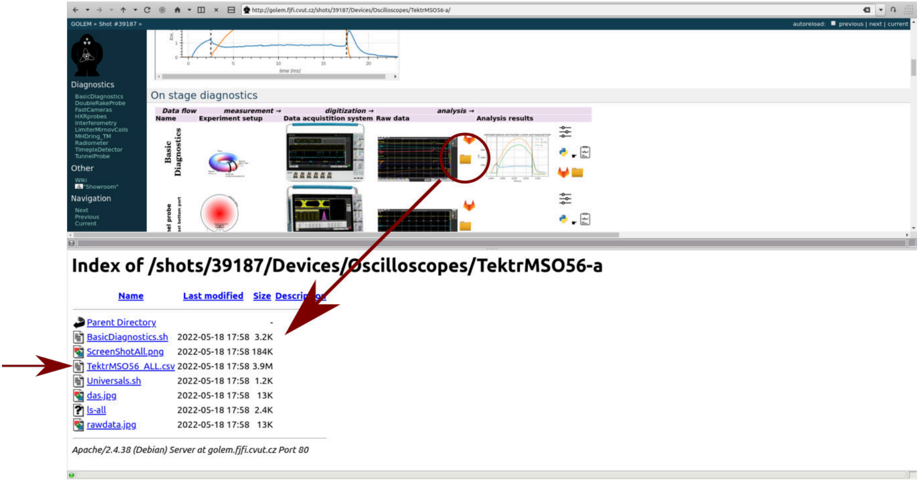


Hands on the GOLEM tokamak - equipment

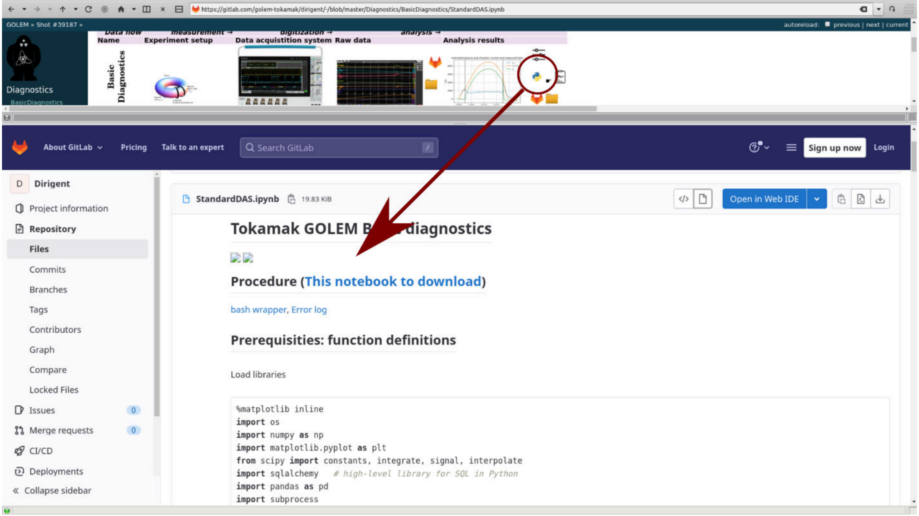
Basic diagnostics - numerical processing, shot homepage



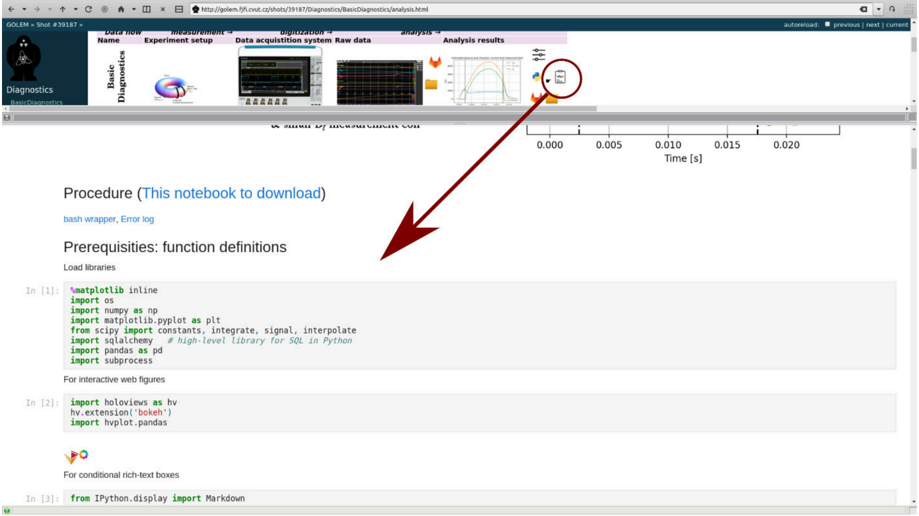
Basic diagnostics - numerical processing, raw data



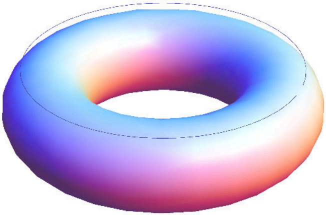
Basic diagnostics - numerical processing, Jupyter-notebook@GitLab **Download & play**

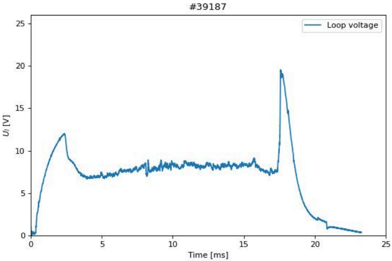


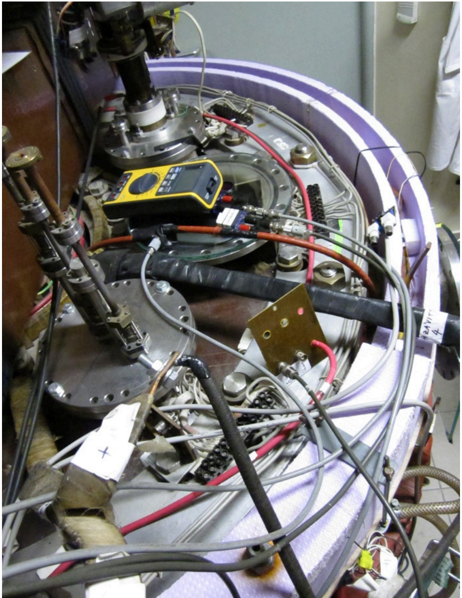
Basic diagnostics - numerical processing, Jupyter-notebook applied on the Discharge



Loop voltage U_l @ the GOLEM tokamak







Basic diagnostics - numerical processing, U_{loop}

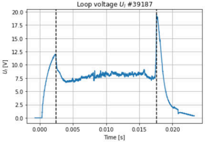
```
    t_scale = 1e-3 if in_seconds else 1
    if is_plasma:
        for t in (t_plasma_start, t_plasma_end):
            plt.axvline(t * t_scale, color='k', linestyle='--')
```

U_l management

Check the data availability

In [11]:
```
loop_voltage = read_signal(shot_no, 'U_Loop')
polarity_CD = read_parameter(shot_no, 'CD_orientation')
if polarity_CD != 'CW':                     # TODO 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="$U_l$ [V]", title="Loop voltage $U_l$ #{}".format(shot_no));
```

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



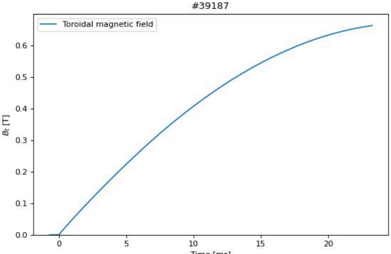
B_t calculation

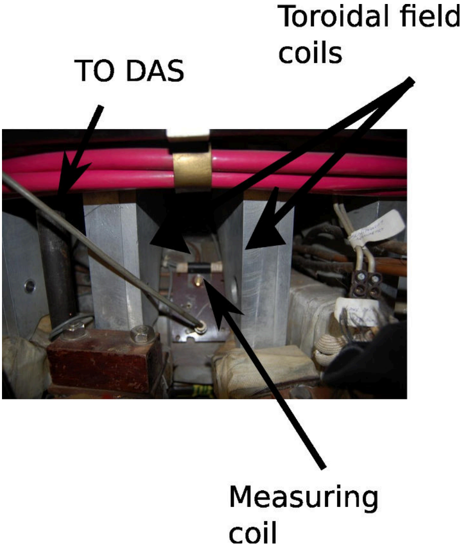
Check the data availability

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':                     # TODO 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="$dU_{B_t}/dt$ [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

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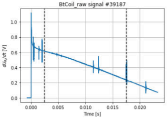
dBt -= dBt.loc[offset_sl].mean()
ax = dBt.plot(grid=True)
show_plasma_limits()
ax.set(xlabel="Time [s]", ylabel="$dU_{B_t}/dt$ [V]", title="BtCoil_raw signal #{}".format(shot_no));
```

Out[12]:
```
[Text(0.5, 0, 'Time [s]'),
 Text(0, 0.5, '$dU_{B_t}/dt$ [V]'),
 Text(0.5, 1.0, 'BtCoil_raw signal #39187')]
```



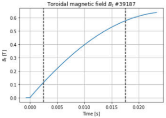
Integration (it is a magnetic diagnostic) & calibration

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

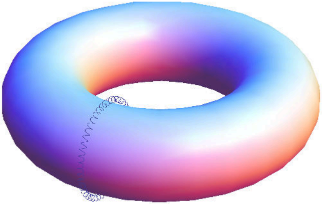
```
BtCoil calibration factor K_BtCoil=70.42 T/(Vs)
```

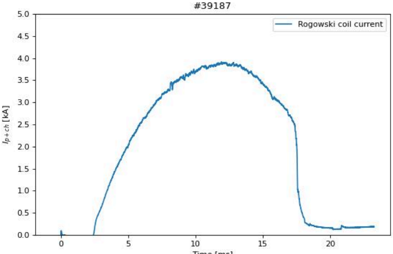
In [14]:
```
Bt = pd.Series(integrate.cumtrapz(dBt, x=dBt.index, initial=0) * K_BtCoil,
               index=dBt.index, name='Bt')
ax = Bt.plot(grid=True)
show_plasma_limits()
ax.set(xlabel="Time [s]", ylabel="$B_t$ [T]", title="Toroidal magnetic field $B_t$ #{}".format(shot_no));
```

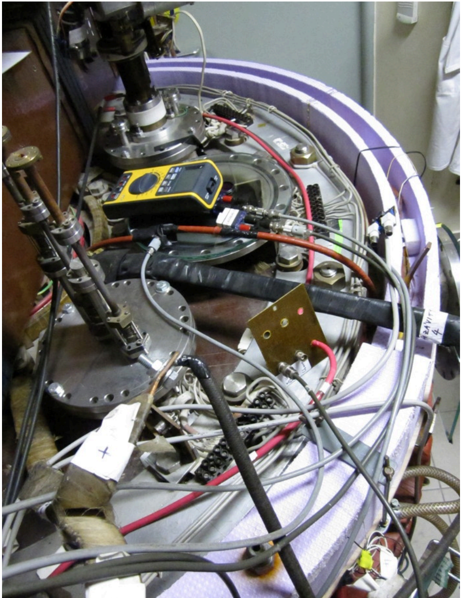
Out[14]:
```
[Text(0.5, 0, 'Time [s]'),
 Text(0, 0.5, '$B_t$ [T]'),
 Text(0.5, 1.0, 'Toroidal magnetic field $B_t$ #39187')]
```



Total current I_{ch+p}







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

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

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

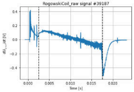
The Rogowski coil around the chamber measures the total current contained within its boundaries. Therefore, if there is plasma, it measures the sum of the plasma and chamber currents. In a vacuum discharge it measures only the chamber current.

Check the data availability

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

In [15]:
```
dIpch = read_signal(shot_no, 'U_RogCoil')
if polarity_CD == 'CW':                    # TODO hardcoded for now!
    dIpch *= -1  # make positive
dIpch = correct_inf(dIpch)
dIpch -= dIpch.loc[offset_sl].mean() # subtract offset
dIpch.loc[:t_CD] = 0
ax = dIpch.plot(grid=True)
show_plasma_limits()
ax.set(xlabel="Time [s]", ylabel="$dU_{I_{p+ch}}/dt$ [V]", title="RogowskiCoil_raw signal #{}".format(shot_no));
```

Out[15]:
```
[Text(0.5, 0, 'Time [s]'),
 Text(0, 0.5, '$dU_{I_{p+ch}}/dt$ [V]'),
 Text(0.5, 1.0, 'RogowskiCoil_raw signal #39187')]
```



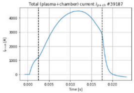
Integration (it is a magnetic diagnostic) & calibration

In [16]:
```
K_RogowskiCoil = float(read_parameter(shot_no, 'SystemParameters/K_RogowskiCoil')) # Get RogowskiCoil calibration factor
print('RogowskiCoil calibration factor K_RogowskiCoil={} A/(Vs)'.format(K_RogowskiCoil))
```

```
RogowskiCoil calibration factor K_RogowskiCoil=5300000.0 A/(Vs)
```

In [17]:
```
Ipch = pd.Series(integrate.cumtrapz(dIpch, x=dIpch.index, initial=0) * K_RogowskiCoil,
                 index=dIpch.index, name='Ipch')
ax = Ipch.plot(grid=True)
show_plasma_limits()
ax.set(xlabel="Time [s]", ylabel="$I_{p+ch}$ [A]", title="Total (plasma+chamber) current $I_{{p+ch}}$ #{}".format(shot_no));
```

Out[17]:
```
[Text(0.5, 0, 'Time [s]'),
 Text(0, 0.5, '$I_{p+ch}$ [A]'),
 Text(0.5, 1.0, 'Total (plasma+chamber) current $I_{p+ch}$ #39187')]
```



Chamber current I_{ch} calculation

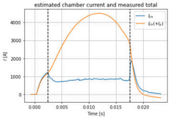
In [18]:
```
R_chamber = float(read_parameter(shot_no, 'SystemParameters/R_chamber')) # Get Chamber resistivity
print('Chamber resistivity R_chamber={} Ohm'.format(R_chamber))
```

```
Chamber resistivity R_chamber=0.0097 Ohm
```

In [19]:
```
L_chamber = float(read_parameter(shot_no, 'SystemParameters/L_chamber')) # Get Chamber inductance
print('Chamber inductance L_chamber={} H'.format(L_chamber))
```

```
Chamber inductance L_chamber=1e-06 H
```

In [21]:
```
for I in [Ich.rename('$I_{ch}$'), Ipch.rename('$I_{ch}(+I_p)$')]:
    ax = I.plot()
ax.legend()
show_plasma_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

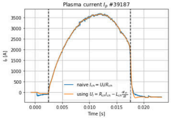
$I_p = I_{p+ch} - I_{ch}$

In [22]:
```
if is_plasma:
    Ip_naive = Ipch - loop_voltage/R_chamber  # creates a new Series
    Ip = Ipch - Ich
    Ip.name = 'Ip'
    Ip_naive.plot(grid=True, label='naive $I_{ch}=U_l/R_{ch}$')
    ax = Ip.plot(grid=True, label=r'using $U_l = R_{ch} I_{ch} - L_{ch} \frac{d I_{ch}}{dt}$')
    ax.legend()
    show_plasma_limits()
    ax.set(xlabel="Time [s]", ylabel="$I_{p}$ [A]", title="Plasma current $I_{{p}}$ #{}".format(shot_no));
else:
    Ip = Ipch * 0  # no current
heading
```

Out[22]:

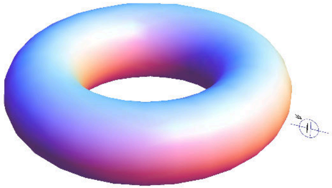
Plasma detected

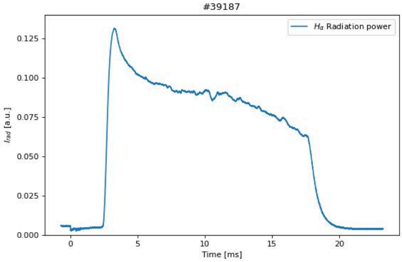
plasma lifetime of 15.1 ms, from 2.5 ms to 17.6 ms

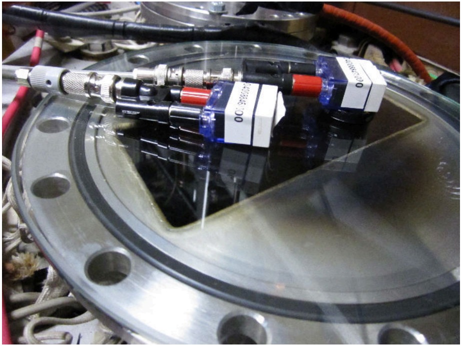


In [23]:
```
fig = plt.figure(dpi=200)
for I in [Ich.rename('$I_{ch}$'), Ipch.rename('$I_{ch}+I_p$'), Ip.rename('$I_p$')]:
    ax = I.plot()
```

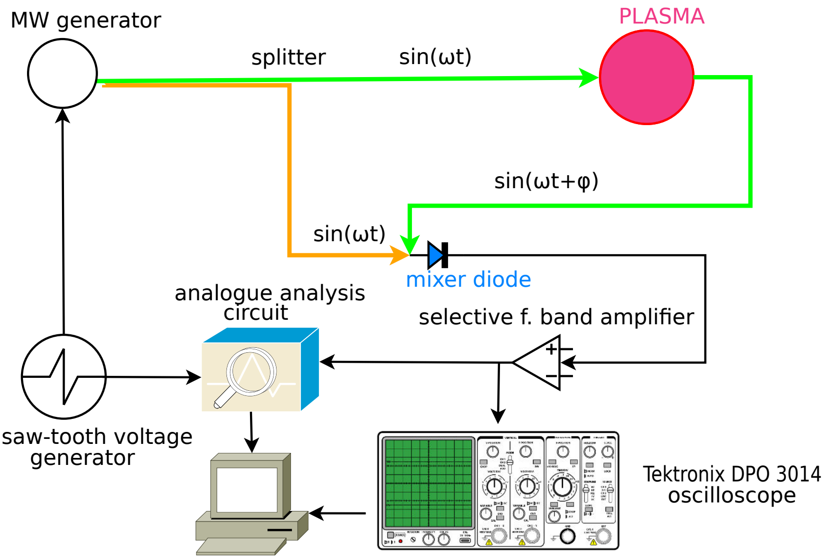
Visible radiation



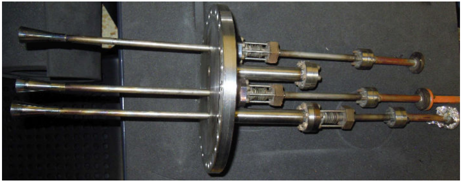




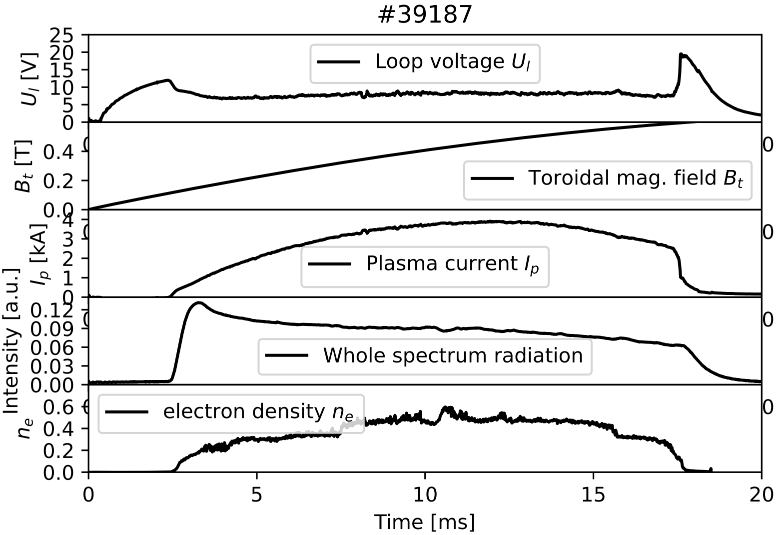
Electron density n_e interferometry measurement scheme



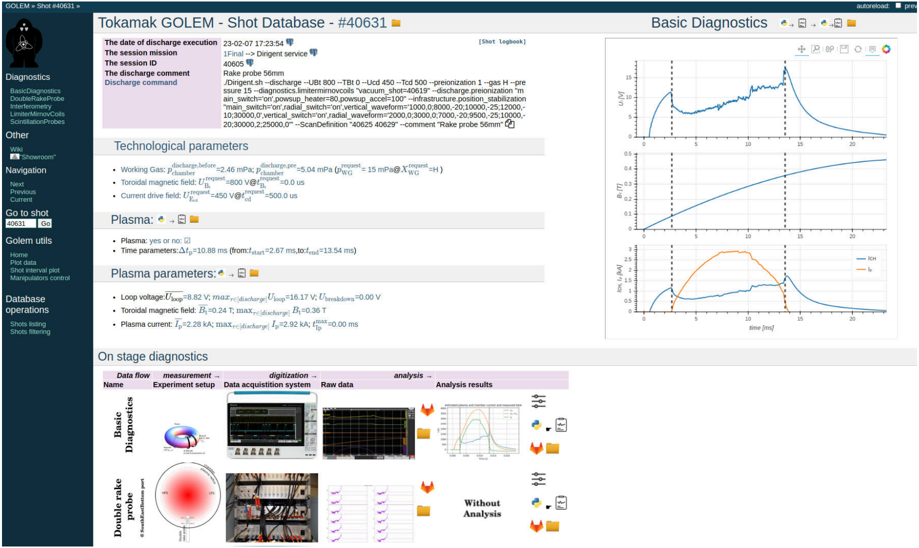
The GOLEM tokamak interferometry HW



Finally "Typical", well executed discharge @ GOLEM



Shot homepage (≈ 2 minutes after discharge execution)



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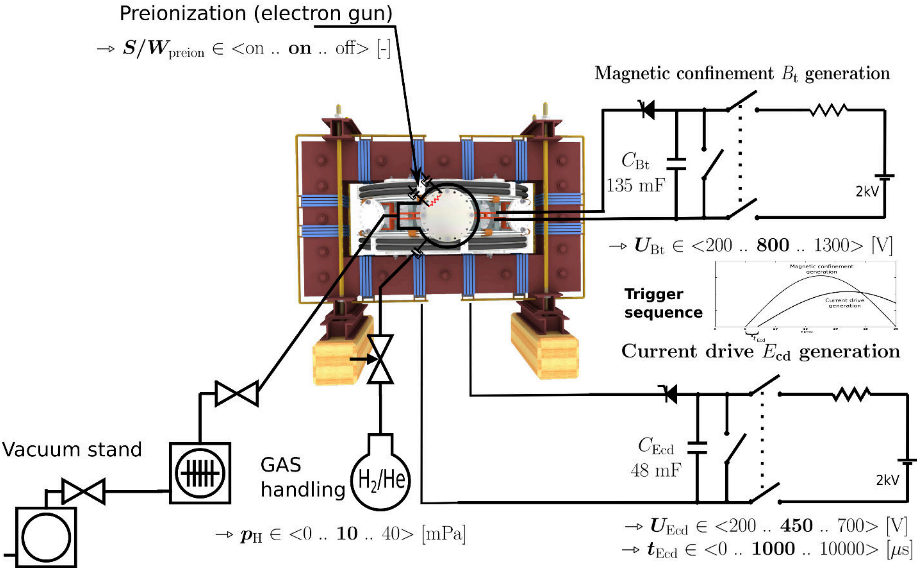
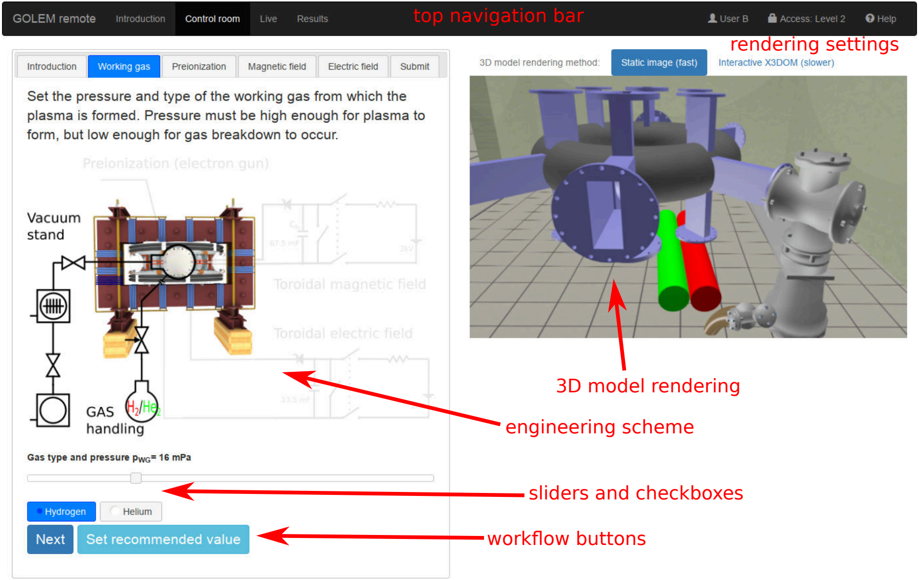
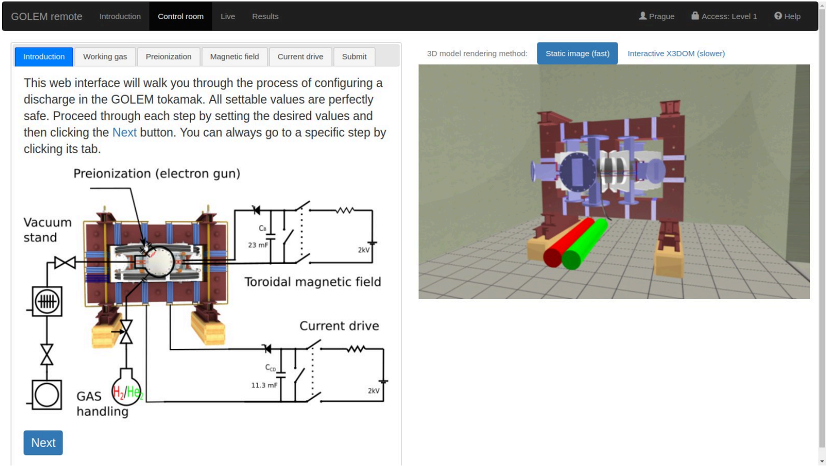
Tokamak GOLEM - schematic experimental setup



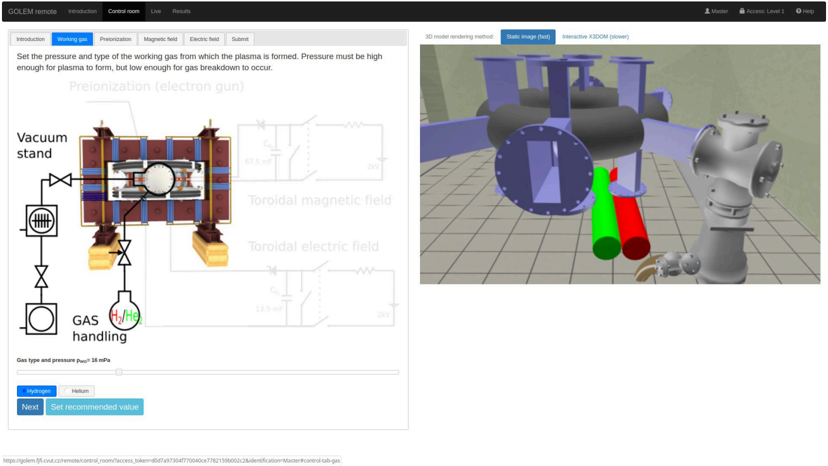
Remote control interface of the GOLEM tokamak



Control room: Introduction



Control room: Working gas

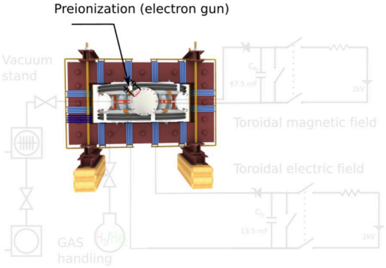


Control room: Preionization

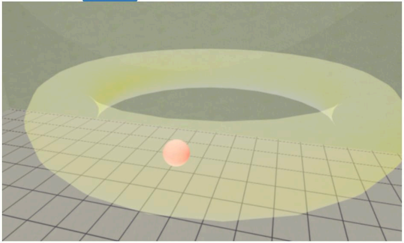
GOLEM remote | Introduction | Control room | Live | Results | Master | Access: Level 1 | Help

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

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



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



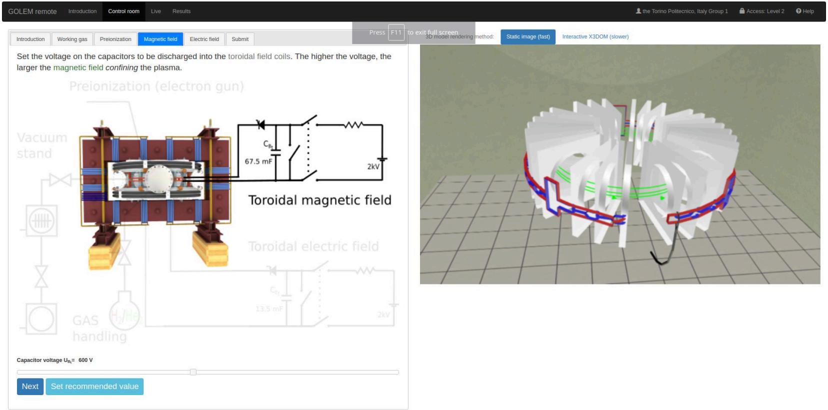
Ionization method

Electron gun | No ionization

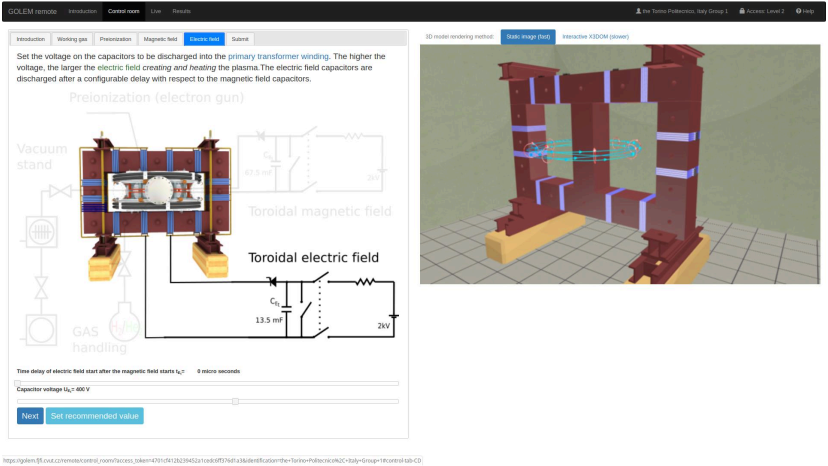
Next

https://golem.fjfi.cvut.cz/remote/control_room/?access_token=d0d7a97304f770040ce7782159b002c2&identification=Master#control-tab-preion

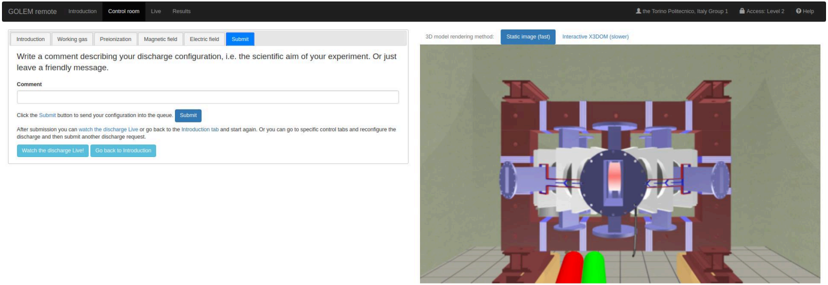
Control room: Magnetic field B_t



Control room: Current drive E_{cd}

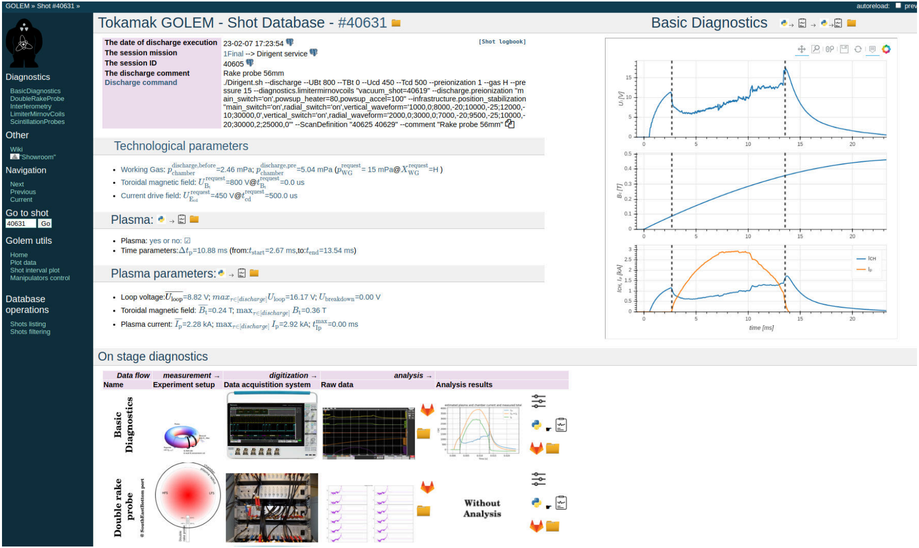


Control room: ... and Submit



https://golem.fjfi.cvut.cz/remote/control_room/?access_token=4701cf412b239452a1cedc6ff376d1a3&identification=the+Torino+Politecnico%2C+Italy+Group+1#control-tab-submit

Shot homepage (≈ 2 minutes after discharge execution)



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GOLEM **basic** Data Acquisition System (DAS)

- $U_l, U_{B_t}, U_{I_{p+ch}}, I_{rad}$
- $\Delta t = 1\mu s / \ f = 1MHz$.
- Integration time = 40 ms, thus DAS produces 6 colums 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	$\approx U_l$	$\approx U_{\frac{dB_T}{dt}}$	$\approx U_{\frac{d(I_{p+ch})}{dt}}$	$\approx I_{rad}$
⋮	⋮	⋮	⋮	⋮
first	≈	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	≈	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('$U_l$ [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_l [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_l [V]'
set terminal jpeg; plot identifier u 1:2 w l t 'Uloop'
```

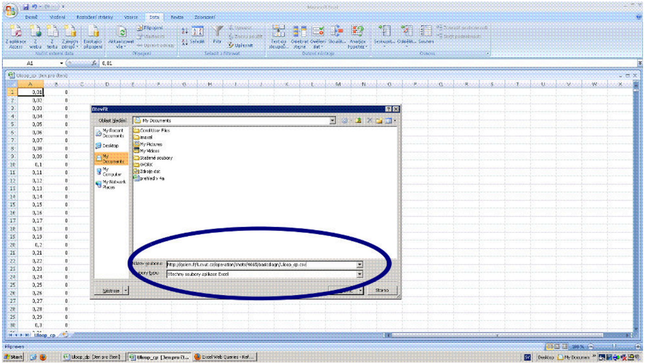
```
shot_no=39187;\
signal_id="Diagnostics/BasicDiagnostics/Results/U_loop.csv";\
gnuplot -p -e "set title \"Golem\";set datafile separator \",\";\
set xlabel \"t [s]\";set ylabel \"U\";\
plot \"< \
wget -q -O - http://golem.fjfi.cvut.cz/shots/$shot_no/$signal_id\" \
w l t \"U\""
```

GNU Wget

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

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

Spredsheets (Excel and others)

are not recommended, only tolerated.

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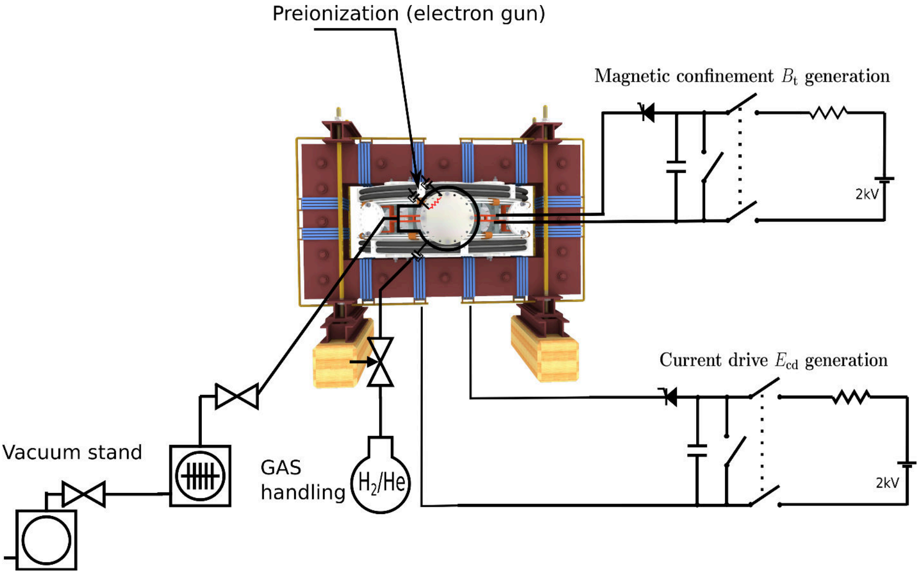
The global schematic overview of the tokamak GOLEM experiment



Production

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

Fee: postcard from the venue of remote measurements

Acknowledgement

Financial support highly appreciated:

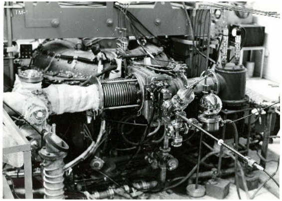
CTU RVO68407700, SGS 17/138/OHK4/2T/14, GAČR GA18-02482S, EU funds CZ.02.1.01/0.0/0.0/16_019/0000778 and CZ.02.2.69/0.0/0.0/16_027/0008465, IAEA F13019, FUSENET and EUROFUSION.

Students, teachers, technicians (random order):

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

Thank you for your attention

Tokamak TM1
@Kurchatov Institute near Moscow
~1960-1977



SCIENCE

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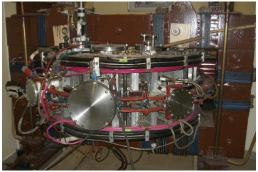
@Institue of Plasma Physics, Prague
1977-2007

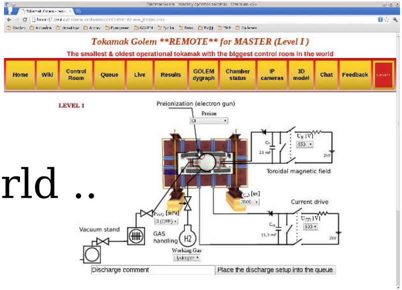
SCIENCE
& education

Tokamak GOLEM
@Czech Technical University, Prague
2007-



EDUCATION
& science

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



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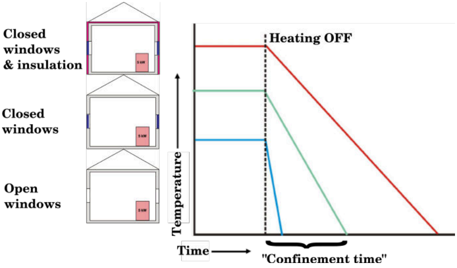
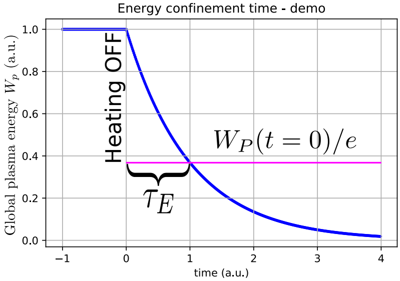
Towards ... Energy confinement time

House



Tokamak



Lawson criterion

credit:Lawson criterion @ Wiki [5]

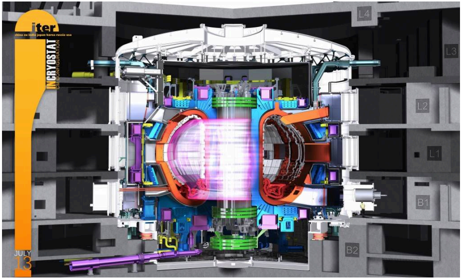
- Net power = Efficiency $\times$ (Fusion - Radiation loss - Conduction loss)
- The confinement time: $\tau_E = \frac{W}{P_{\mathrm{loss}}}$
- Energy density $W = 3nk_{\mathrm{B}}T$ & rate of radiation and conduction energy loss per unit volume P_{loss}
- Reactions per volume per time of fusion reactions is: $f = n_{\mathrm{d}}n_{\mathrm{t}}\langle\sigma v\rangle = \frac{1}{4}n^2\langle\sigma v\rangle$
- Fusion heating fE_{ch}, where $E_{\mathrm{ch}} = 3.5\,\mathrm{MeV}$ should exceeds the losses: $fE_{\mathrm{ch}} \geq P_{\mathrm{loss}}$

$$n\tau_{\mathrm{E}} \geq L \equiv \frac{12}{E_{\mathrm{ch}}}\frac{k_{\mathrm{B}}T}{\langle\sigma v\rangle} \geq 1.5 \cdot 10^{20}\frac{\mathrm{s}}{\mathrm{m}^3}$$

(DT reaction@minimum $\approx$ 26 keV)

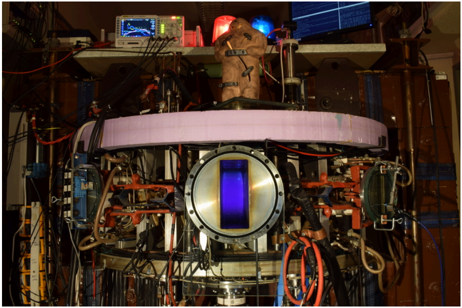
The competition

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}

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

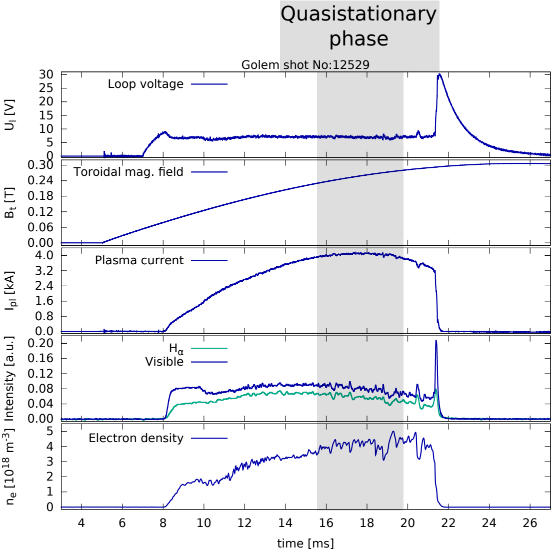
The energy confinement time is defined as the characteristic time scale of the exponential decay of the plasma energy W_p due to the loss power P_{Loss}:

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

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.

- $V_p \approx 80$ l

Central Electron Temperature estimation (Spitzer Formula)

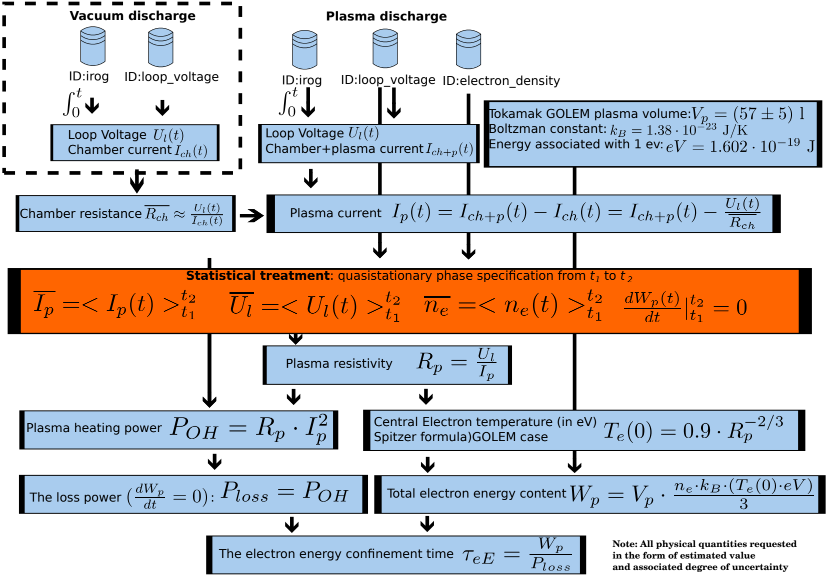
The time evolution of the central electron temperature $T_e(0,t)$ is calculated from equation based on Spitzer's resistivity formula (see eg. [2],[4]):

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

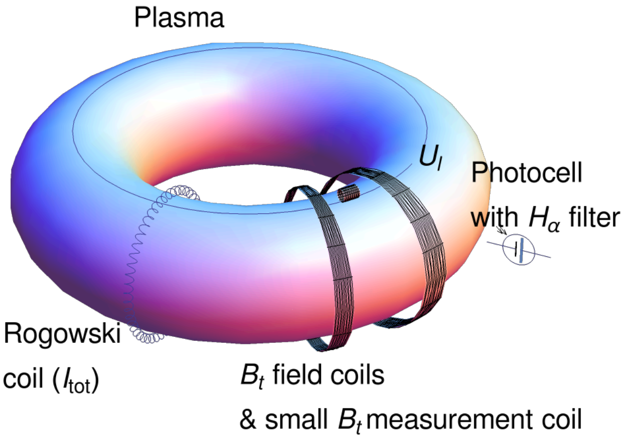
For particular case of the GOLEM tokamak it says:

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

Towards Electron energy confinement time τ_E

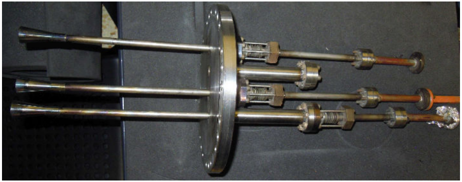


The GOLEM tokamak - standard diagnostics

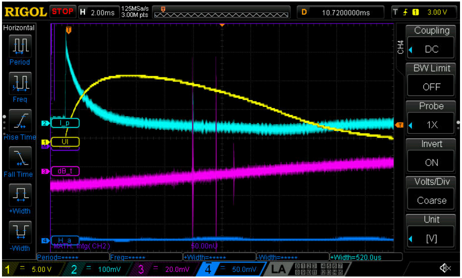


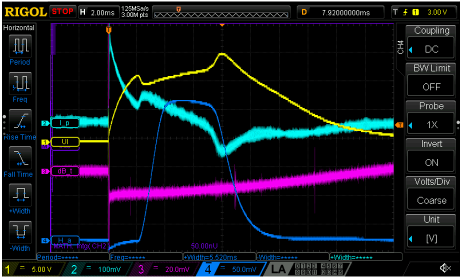
Hands on the GOLEM tokamak - equipment

The GOLEM tokamak interferometry HW

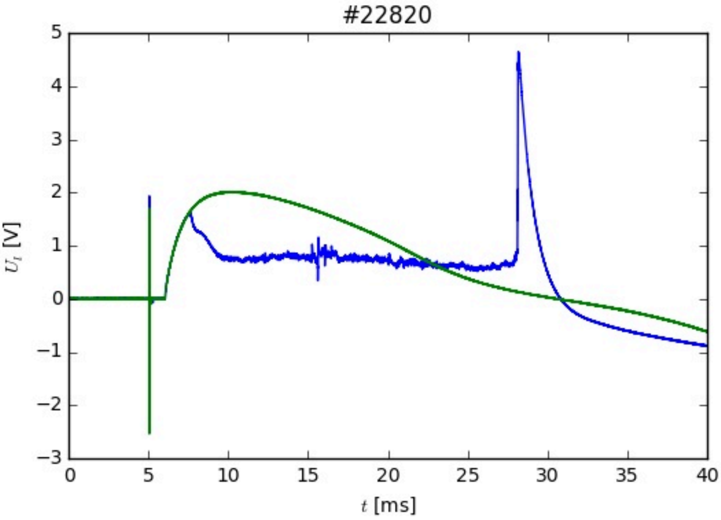


Vacuum x Plasma discharge @ Oscilloscope





Vacuum x Plasma shot



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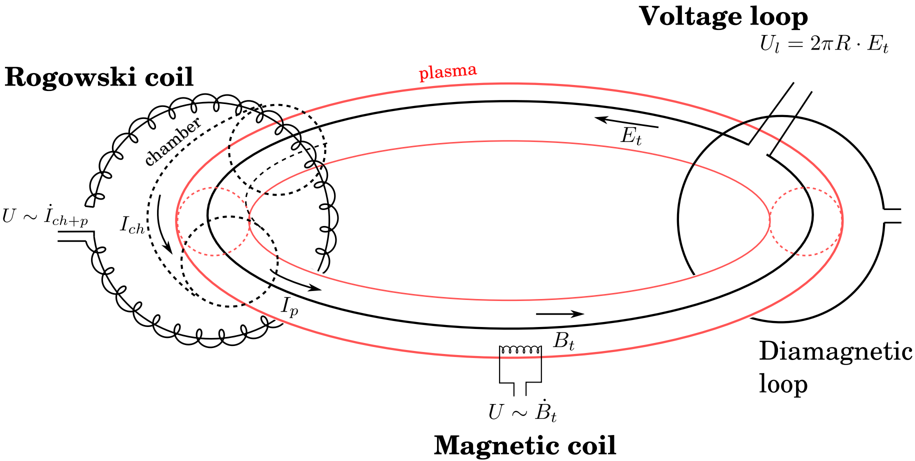
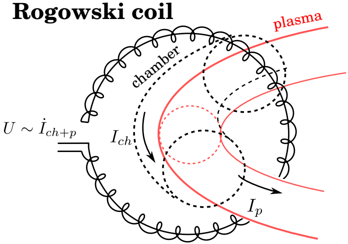
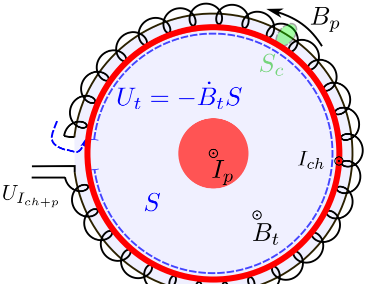
Schematic of electromagnetic diagnostics



credit:[4]

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





- 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: $\int \nabla \times \mathbf{B} \cdot d\mathbf{S} = \oint B_p dl = l B_p$
- 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 ommit 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 specialy 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 ($C_B t$, 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:

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

- 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:

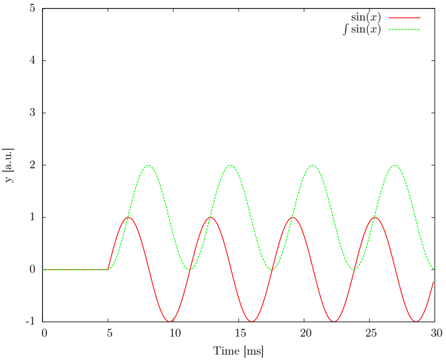
$$D_i = \frac{1}{C_d}\sum_{j=0}^{t/\Delta t} (U_i(t_j) - U_{offset})\Delta t$$

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

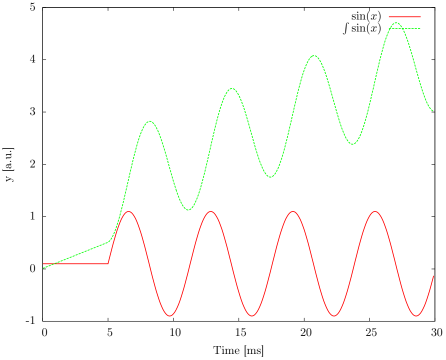
- The offset U_{offset} can be specified from the beggining of the data series before switching on the real experiment.

Magnetic measurement demo - game with U_{offset}

Without U_{offset}



With U_{offset}



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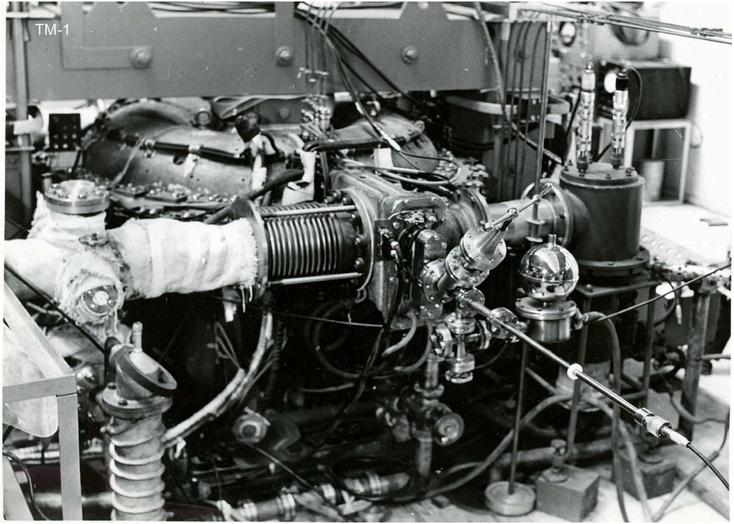
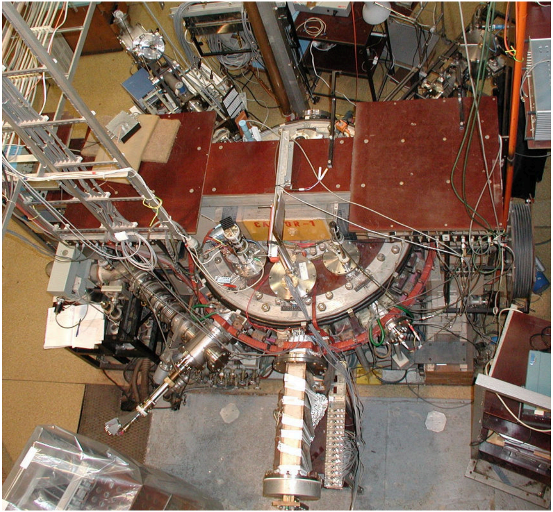
XX/YY: TM-1



XX/YY: CASTOR

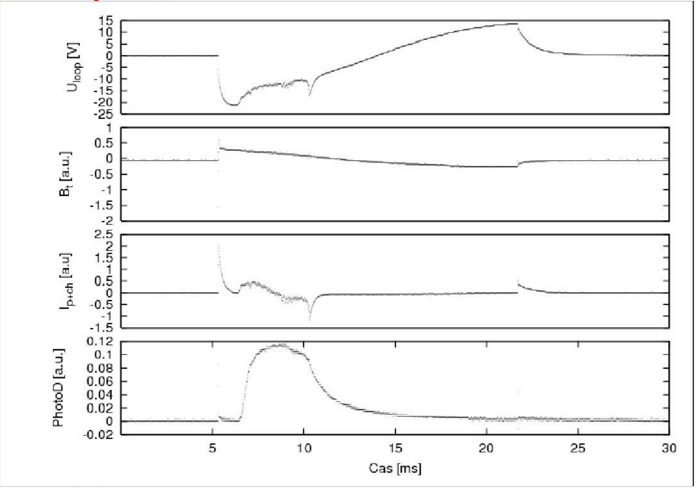


12/07: Last minutes at the IPP Prague

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.

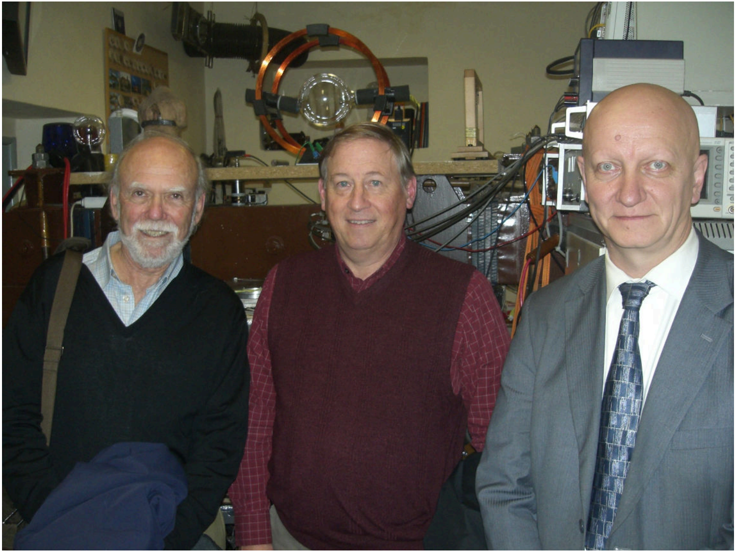


O tom svědčí:

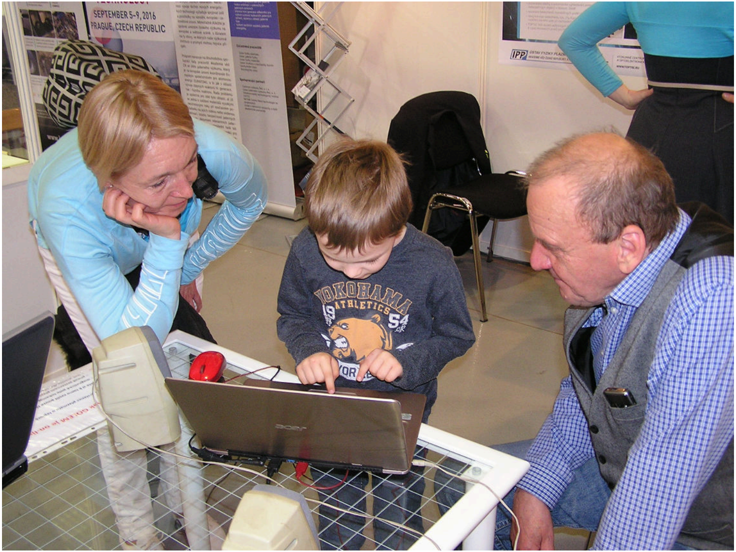
1. Rychlý pokles napětí na závit v čase t = 6-7 ms a jeho malé fluktuace.které lze vidět až

09/09: Tokamak and tokamak

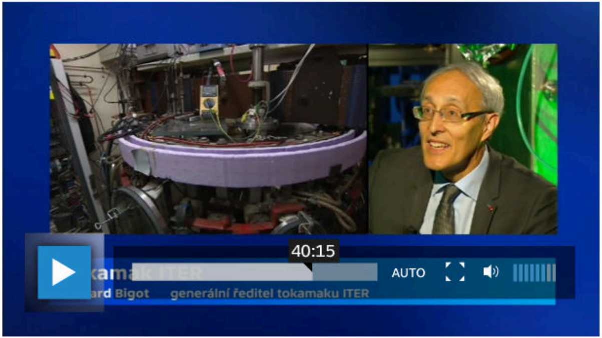
11/11: NP laureat at tokamak GOLEM



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



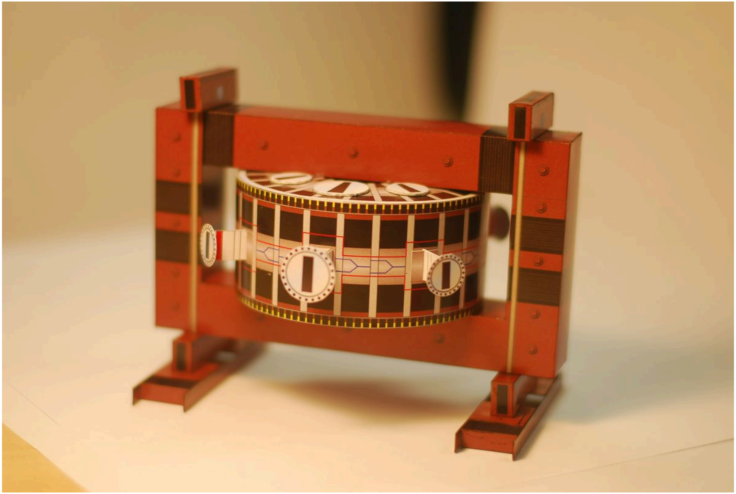
0916: ITER DG, Mr. Bernard Bigot (Shot #22185)



Quotation from Czech Television Hydepark

I am very pleased with the GOLEM ...

09/19 Paper model ABC



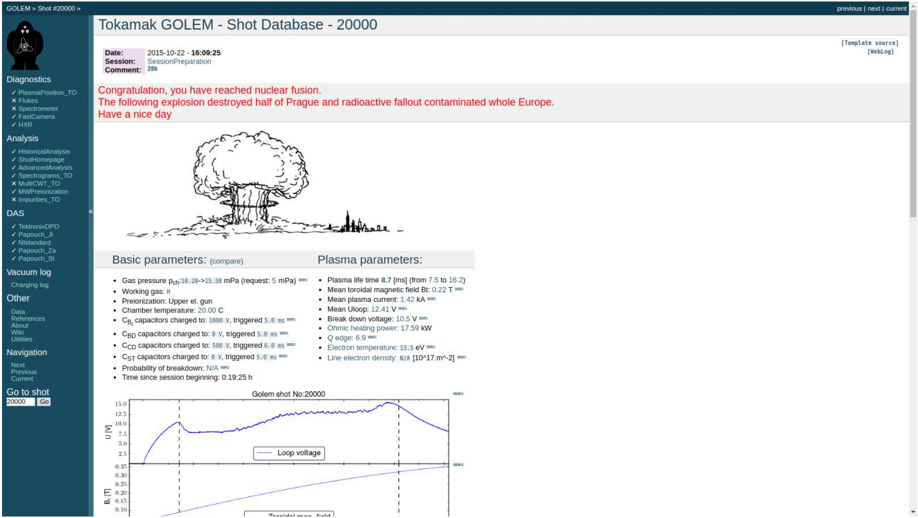
2010: Tokamak GOLEM

2011: The tokamak COMPASS with NBI

2016: ITER segment

2017: First Spitzer Stellarator

10/15: Trojan horse - #20000



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 delka trvání plazmatu: $<$ 60 s.