Title

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

for American University of Beirut

November 28, 2025

Outline

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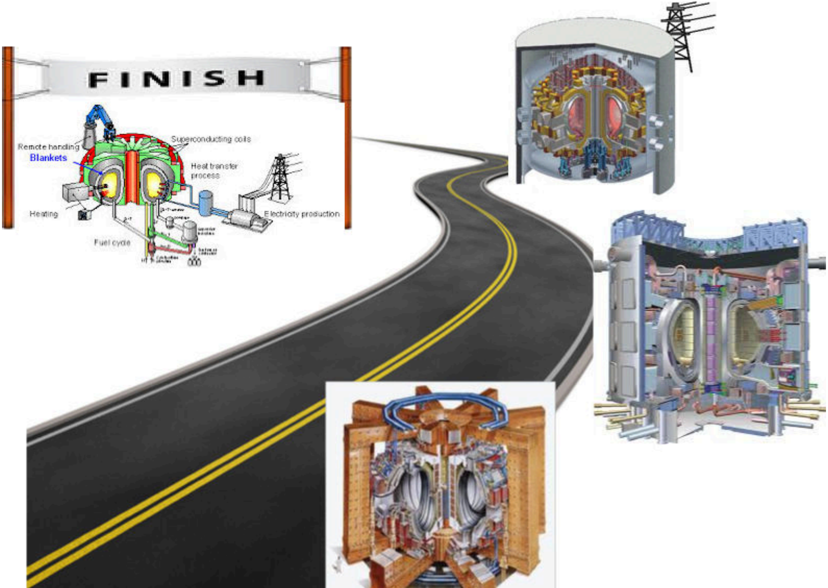
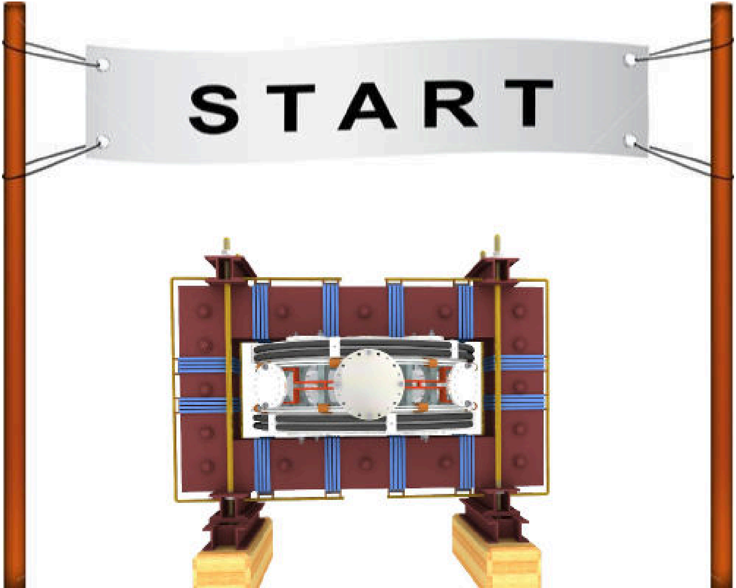
Milestones to Fusion Power Plant



Education importance

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



Tokamak GOLEM @ Wikipedia ..

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Tokamak

From Wikipedia, the free encyclopedia

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

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

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

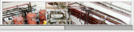
Experimental tokamaks [edit]

Currently in operation [edit]

(in chronological order of start of operations)

- 1960s: TM1-MH (since 1977 Castor; since 2007 Golem[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

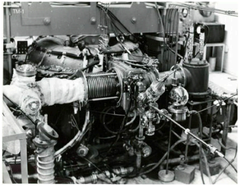
Alcator C-Mod



dia, the free encyclo | Tokamak - Wikipedia, the free encyclo | (svoboda) buon.fjfi.cvut.cz - Konsole | Krusader | Inbox - svoboda@fjfi.cvut.cz - Mozilla

The tokamak GOLEM for education - historical background

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



1974

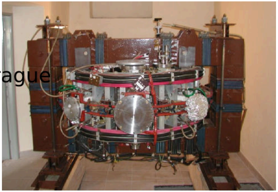
Culham Centre for Fusion Energy
Great Britain
1989: **COMPASS-D**

2006

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

2008

Czech Technical University Prague
Czech republic
GOLEM



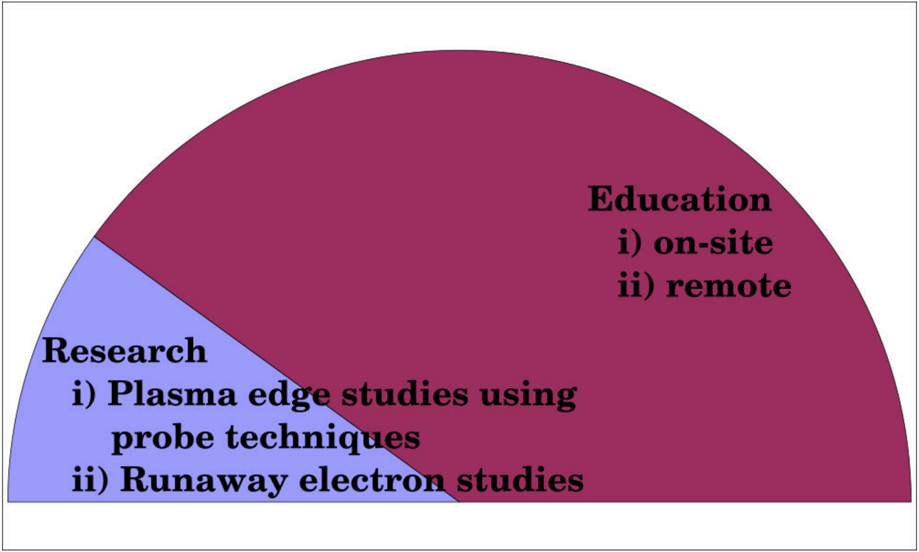
GOLEM

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

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

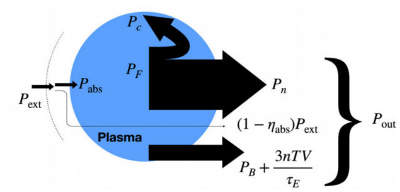
At the end of the 16th century, in the times when the Czech lands were ruled by Emperor Rudolf II, in Prague, there were Rabbi Judah Loew, well known alchemist, thinker, scholar, writer and inventor of the legendary GOLEM - a clay creature inspired with the Universe power that pursued his master's command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

The tokamak GOLEM mission



Two key fusion technology parameters you can touch experimentally

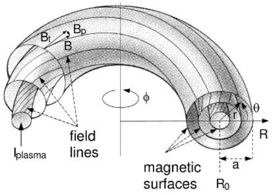
Energy Confinement Time τ_E



credit:[2]

- Indicates how long the plasma keeps its energy — a key fusion metric.
- $$\tau_E = \frac{W_{\text{plasma}}}{P_{\text{loss}}}$$
- On tG, from energy balance, we estimate the electron component $\tau_{E,e}$ (we can measure only n_e and T_e).

Safety Factor q



credit:[3]

- Describes how magnetic field lines wind around the torus. Key stability parameter (MHD behaviour).
- $$q(a) = \frac{2\pi a^2 B_{\text{t}}}{\mu_0 R I_p}$$
- On tG, derived from B_{t} and plasma current I_p.

Production

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

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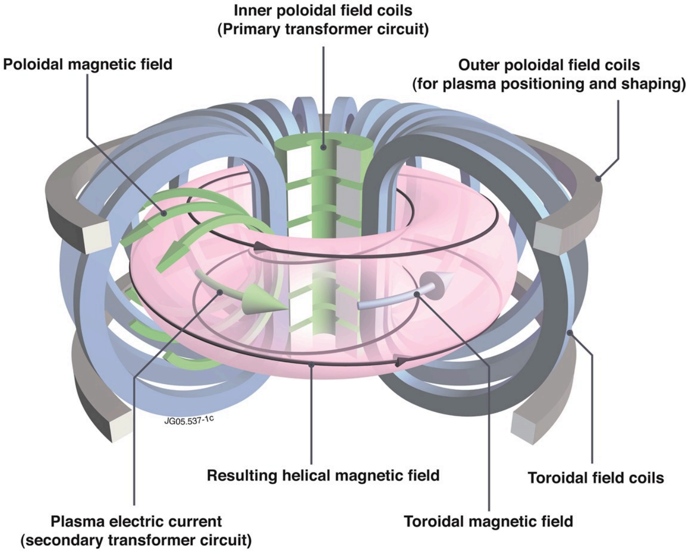
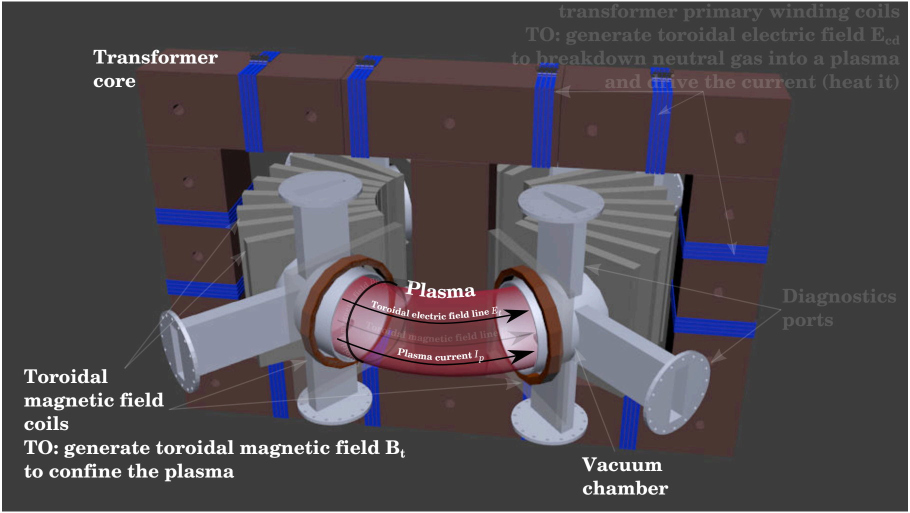
Tokamak magnetic confinement concept

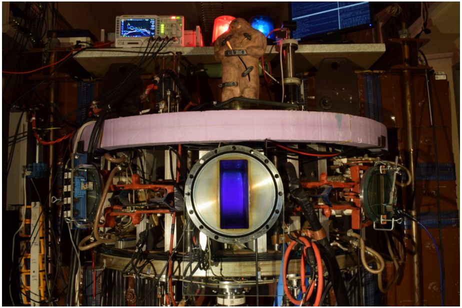


credit:Tokamak concept@Wiki

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

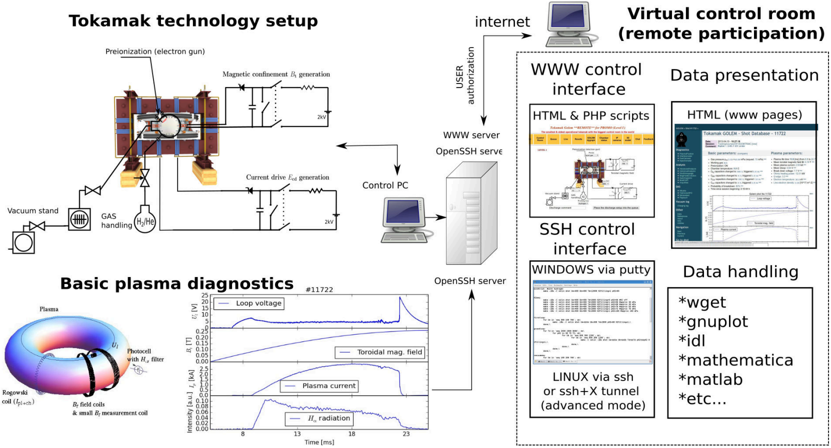


The tokamak GOLEM basic characteristics
The grandfather of all tokamaks (ITER newsline 06/18)



- Vessel major radius: $R_0 = 0.4$ m
- Vessel minor radius: $r_0 = 0.1$ m
- Maximum plasma current: $I_\mathrm{p}^\mathrm{max} < 12$ kA
- Maximum toroidal magnetic field: $B_\mathrm{t}^\mathrm{max} < 0.7$ T
- Typical electron density: $< n_e > \in (0.2, 3) \cdot 10^{19}$ m^{-3}
- Maximum electron temperature: $T_\mathrm{e}^\mathrm{max} < 80$ eV
- Maximum discharge duration: $\tau_\mathrm{p}^\mathrm{max} < 50$ ms

The global schematic overview of the tG experiment



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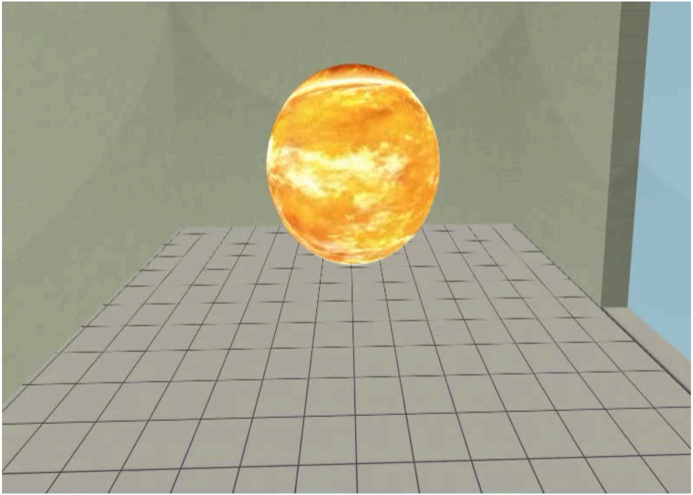
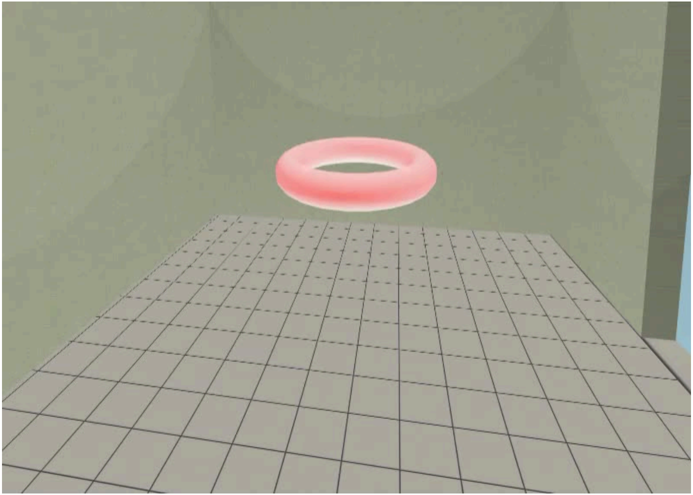
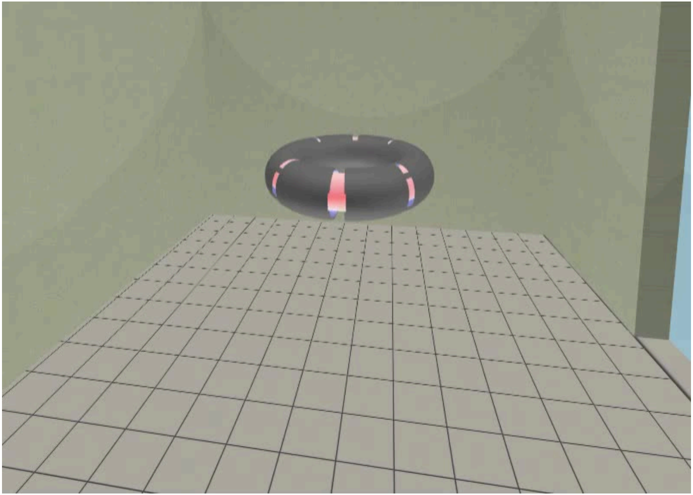
Our goal: the technology to create a μSun on the Earth



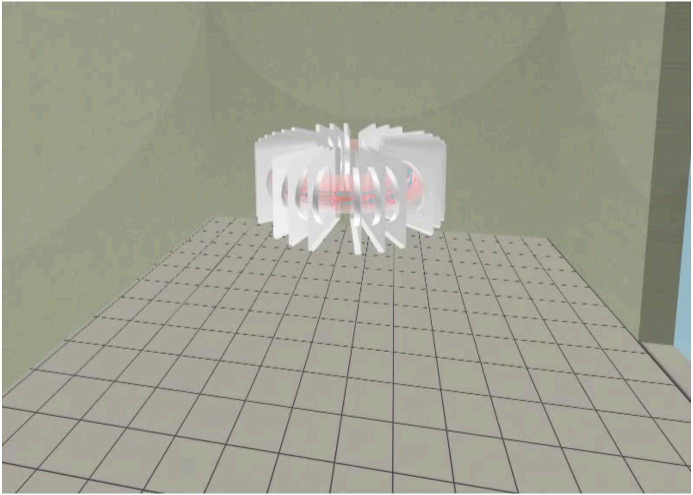
Magnetic confinement requires toroidal geometry



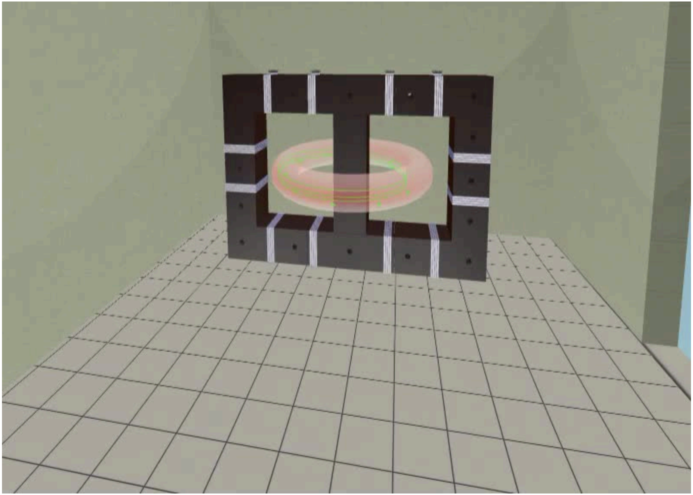
A chamber contains the thermonuclear reaction



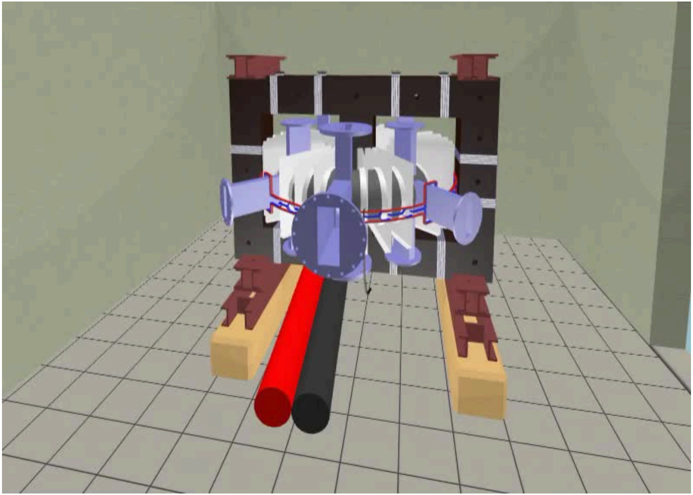
Toroidal magnetic field coils confine the plasma



A transformer action creates and heats the plasma



The final technology altogether



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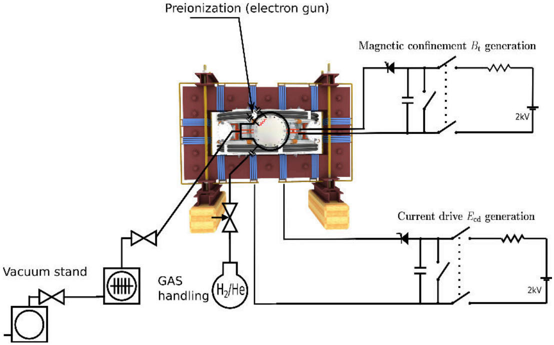
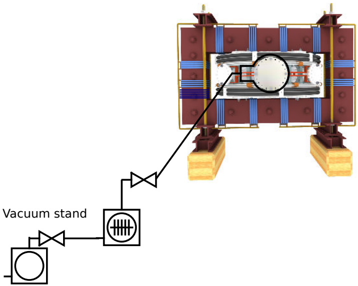
Plasma in Tokamak (GOLEM) - the least to do



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

Plasma in Tokamak (GOLEM) - the least to do



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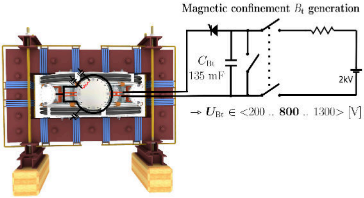

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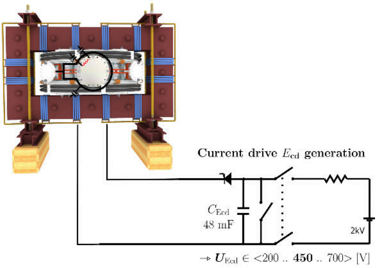

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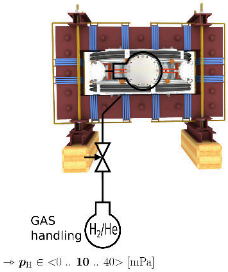

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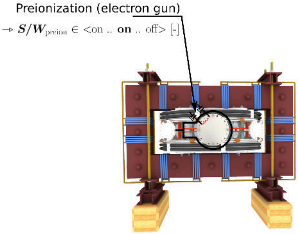

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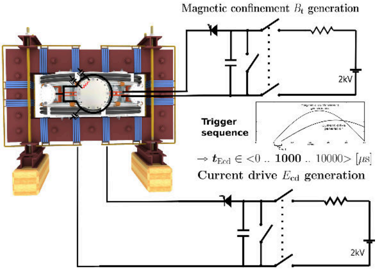
Plasma in Tokamak (GOLEM) - the least to do



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- post-discharge phase
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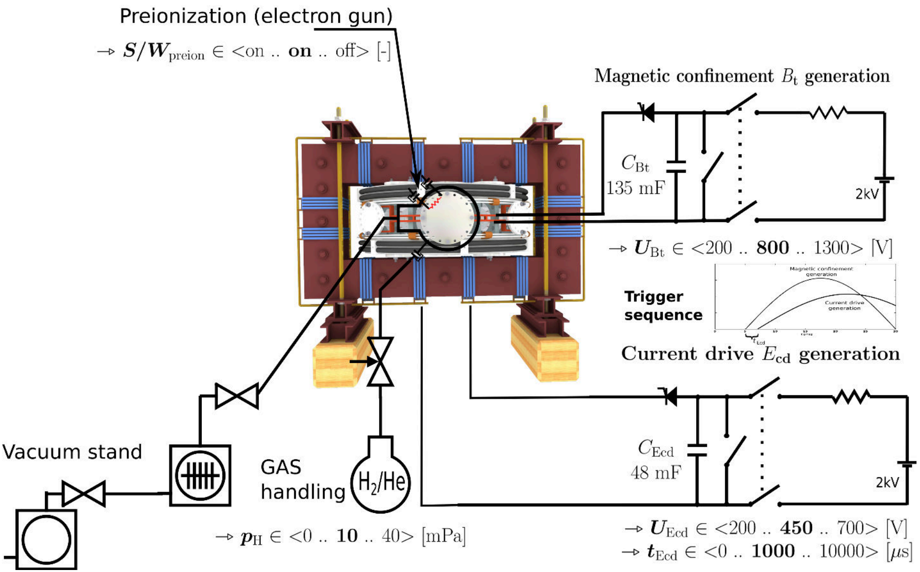
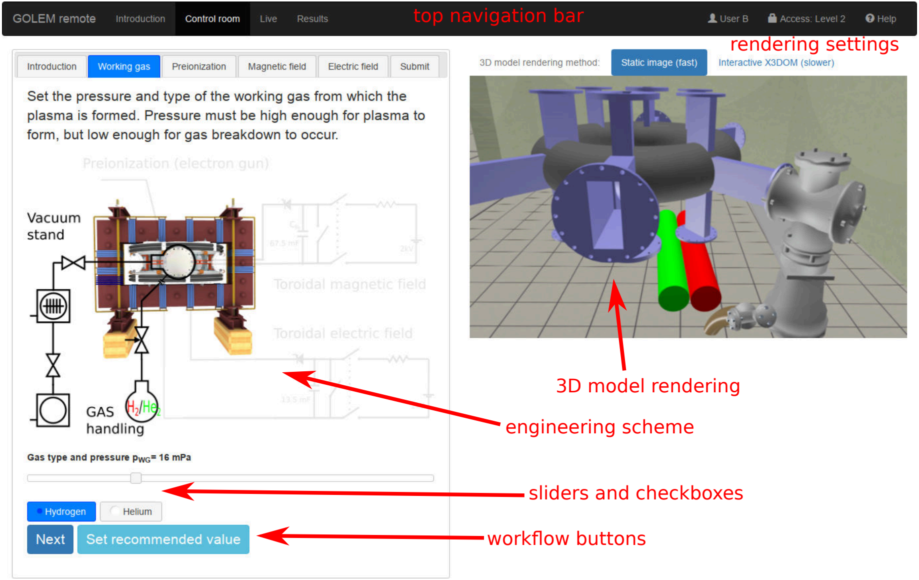
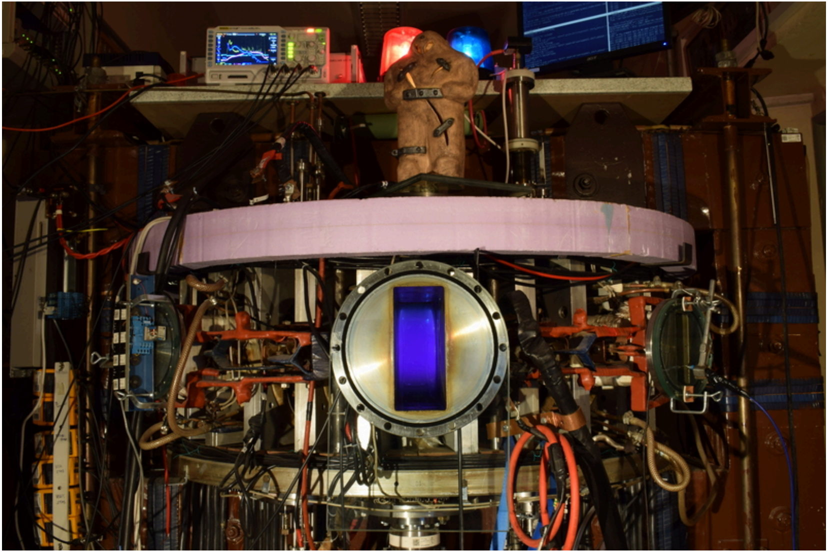
Tokamak GOLEM - schematic experimental setup



Remote control interface of the GOLEM tokamak



Let’s make a discharge



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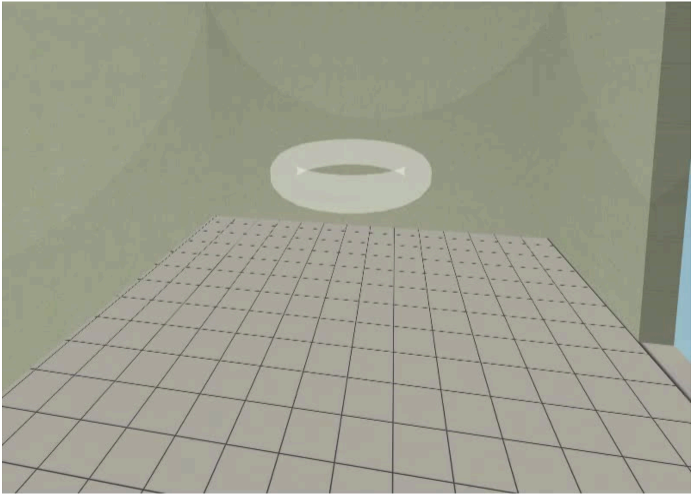
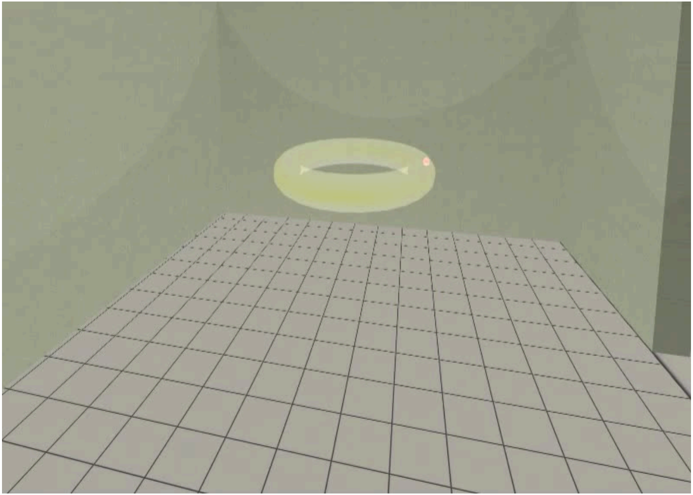
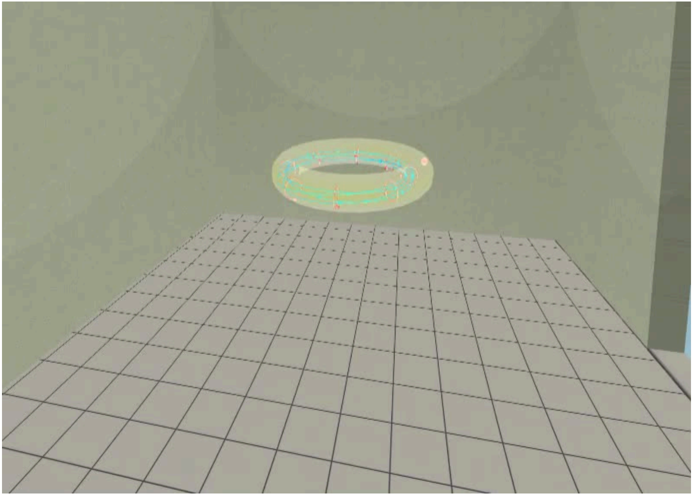
Introduce the working gas (Hydrogen x Helium)



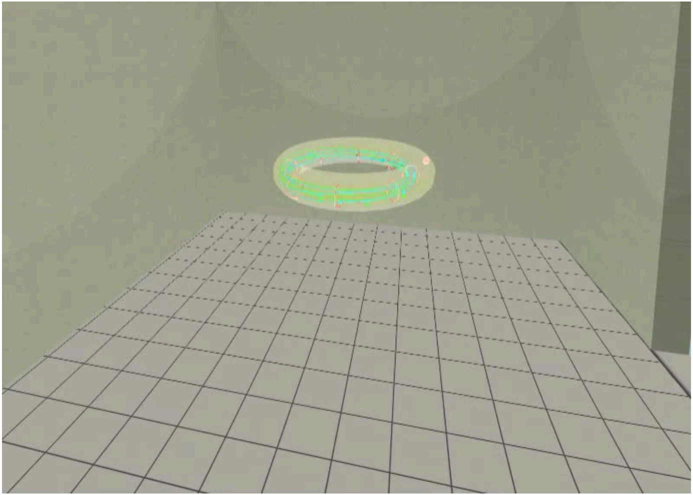
Switch on the preionization



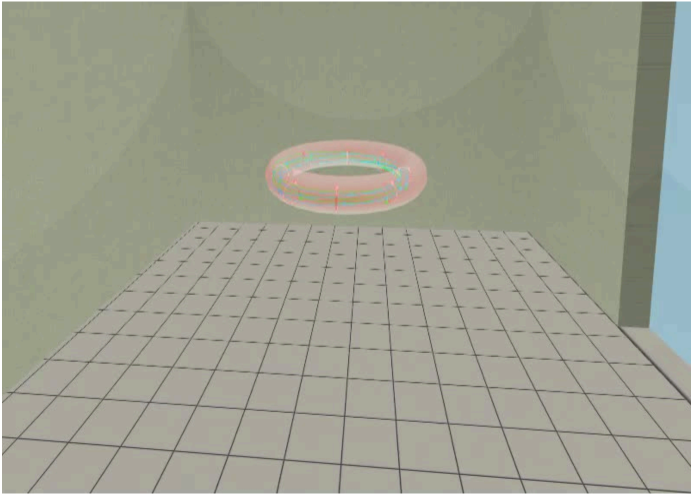
Introduce the magnetic field



Introduce the electric field



Plasma ..



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Infrastructure room (below tokamak) 10/16

Infrastructure room (below tokamak) 10/16

Current drive CD field and toroidal magnetic Bt field circuits

To the tokamak GOLEM

Rotary pump

Vacuum control

Plasma stabilization

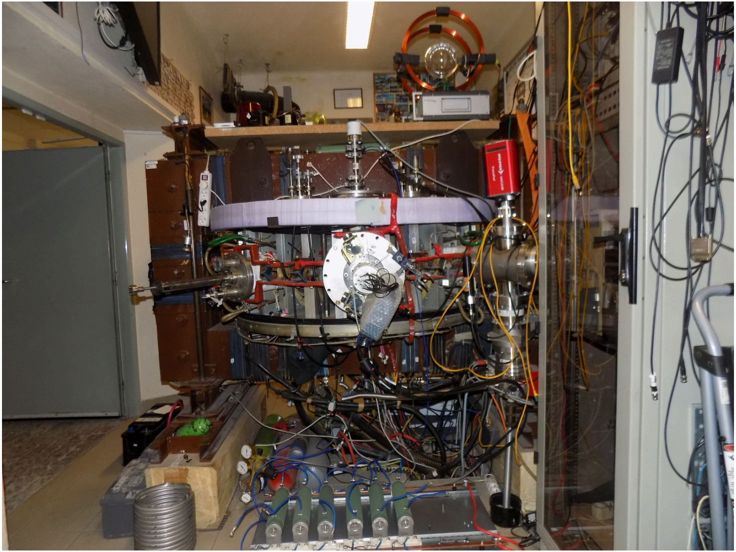
Current drive CD capacitors

power supply 2kV

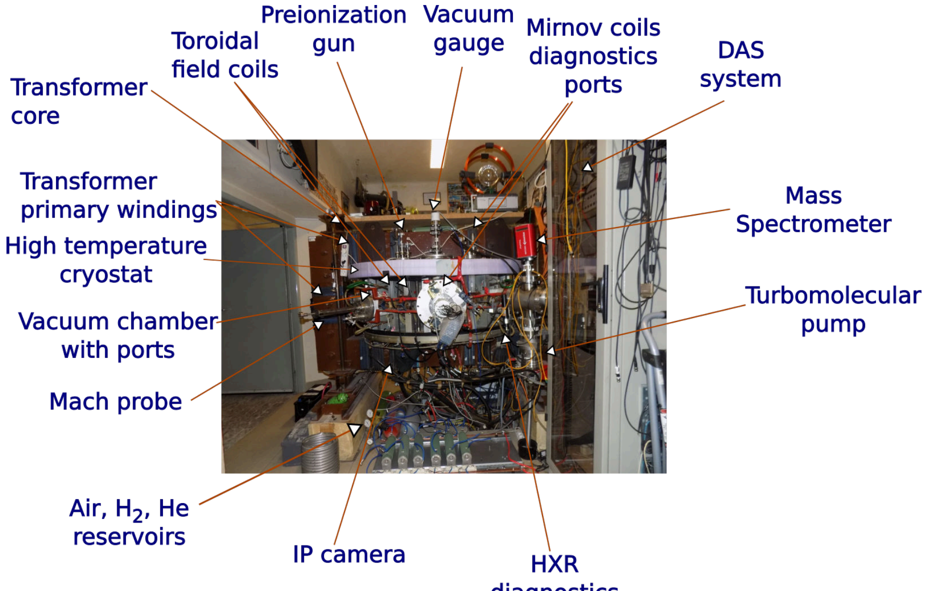
Toroidal magnetic field B capacitors

fire protection system

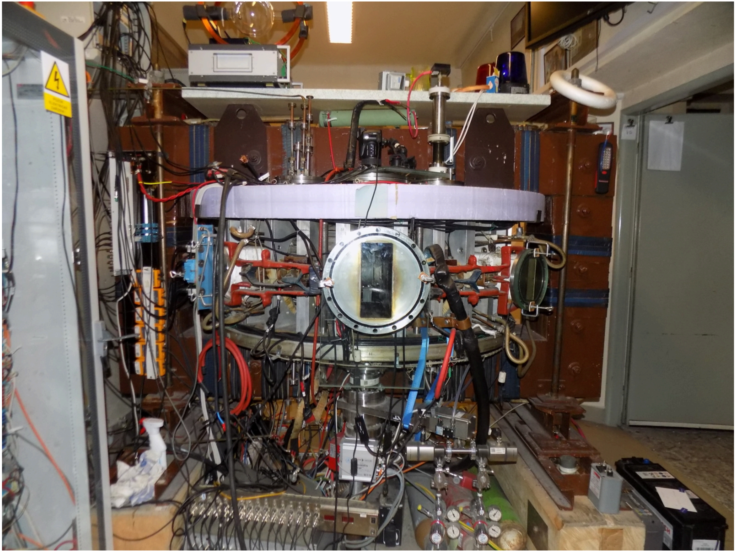
Tokamak room (North) 10/16



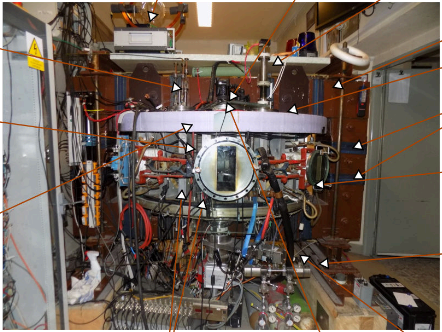
Tokamak room (North) 10/16



Tokamak room (South) 10/16



Tokamak room (South) 10/16



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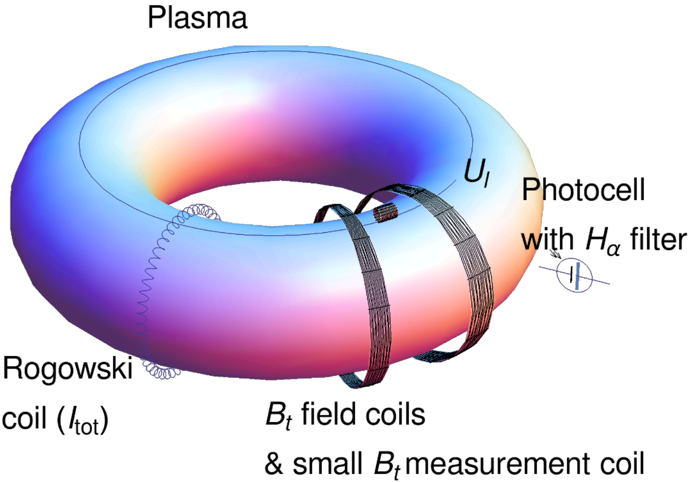
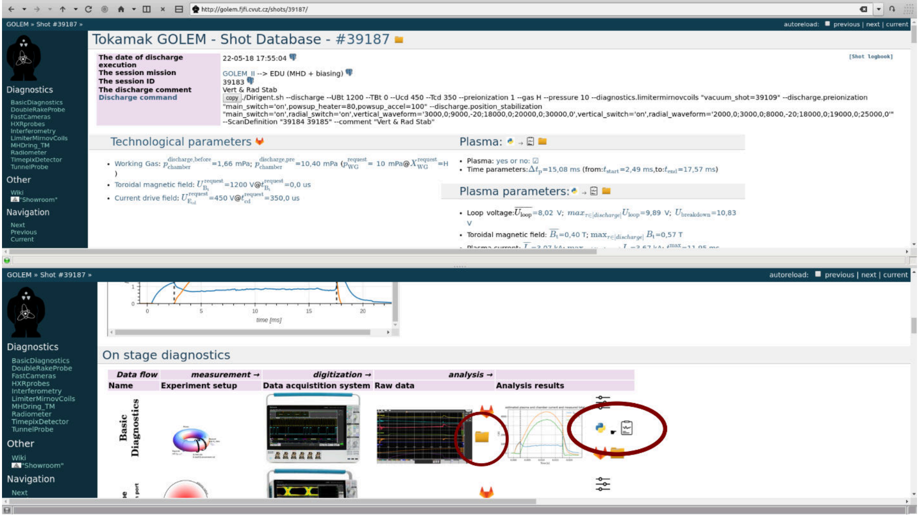
The GOLEM tokamak - basic diagnostics

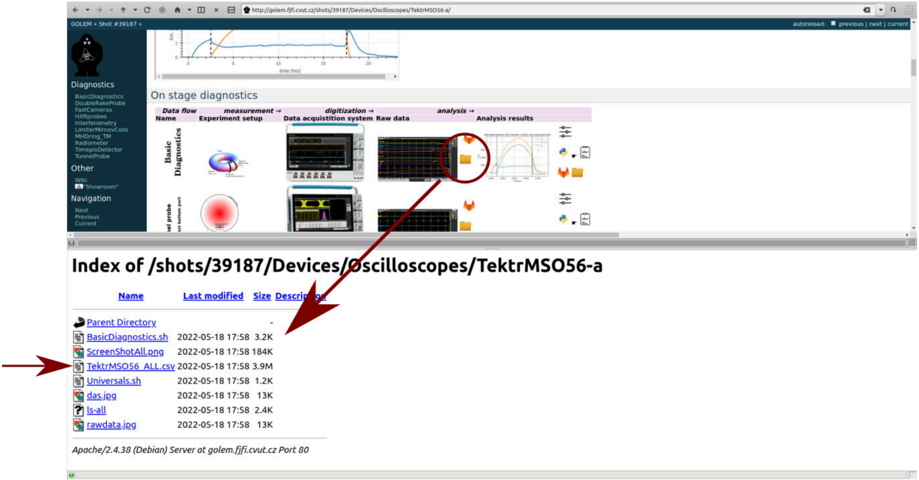


Hands on the GOLEM tokamak - equipment

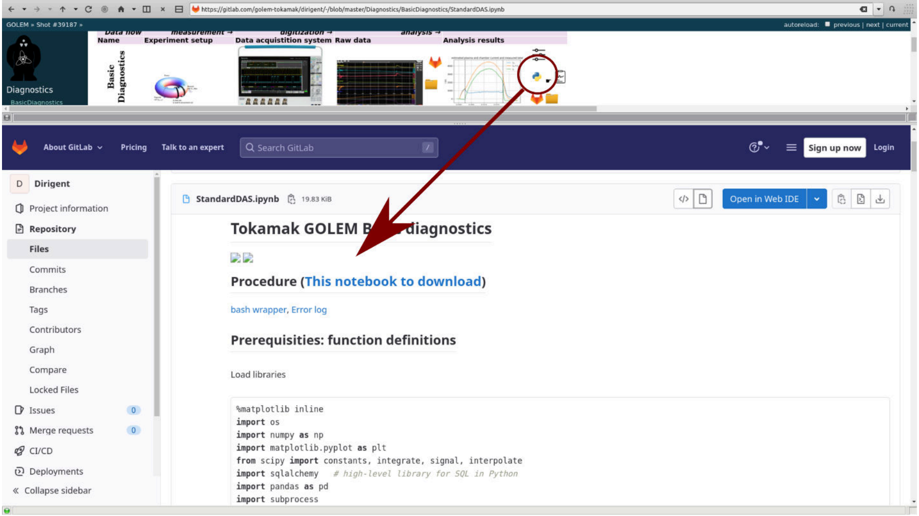
Basic diagnostics - numerical processing, shot homepage



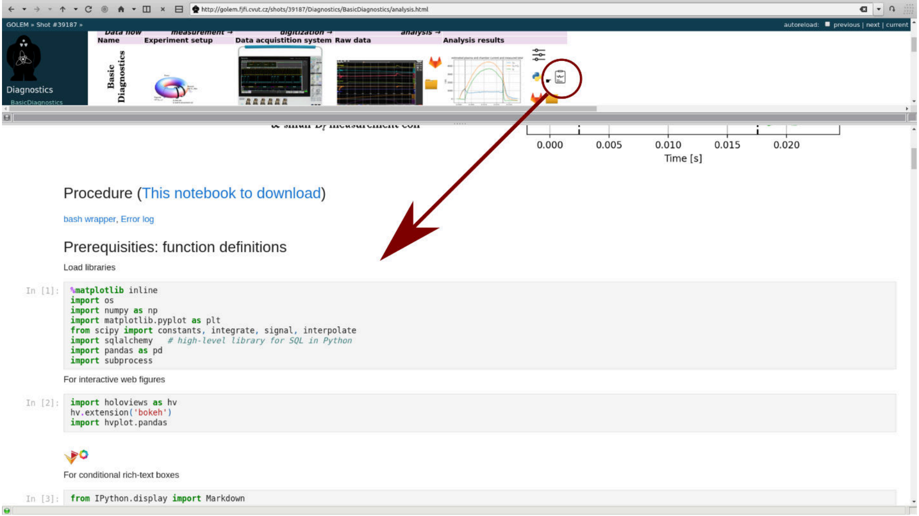
Basic diagnostics - numerical processing, raw data



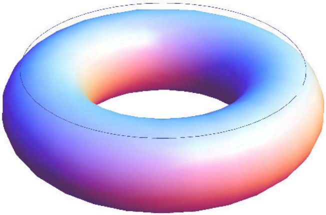
Basic diagnostics - numerical processing, Jupyter-notebook@GitLab **Download & play**

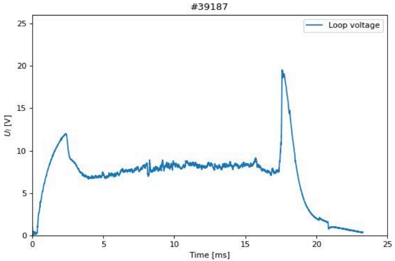


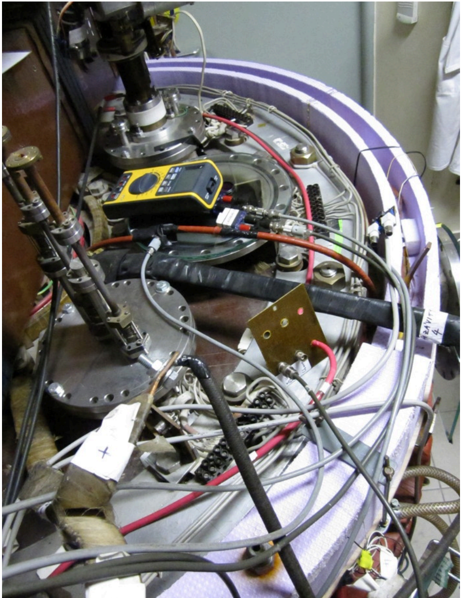
Basic diagnostics - numerical processing, Jupyter-notebook applied on the Discharge



Loop voltage U_l @ the GOLEM tokamak







Basic diagnostics - numerical processing, U_{loop}

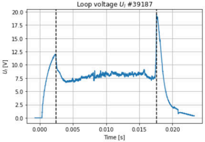
```
    t_scale = 1e-3 if in_seconds else 1
    if is_plasma:
        for t in (t_plasma_start, t_plasma_end):
            plt.axvline(t * t_scale, color='k', linestyle='--')
```

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')]
```



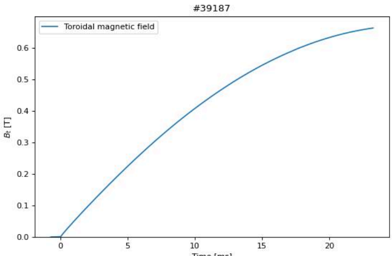
B_t calculation

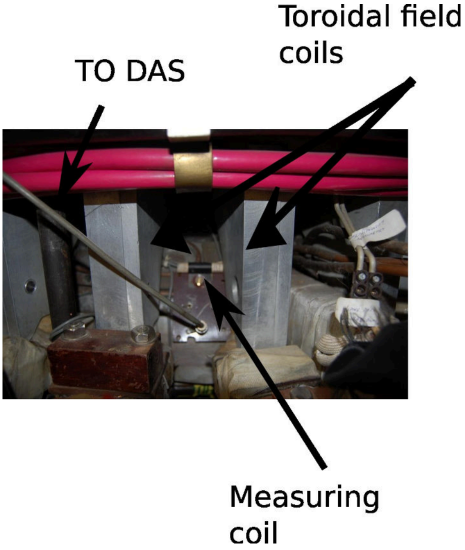
Check the data availability

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

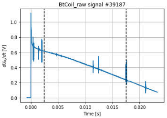
B_t calculation

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));
```

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')]
```



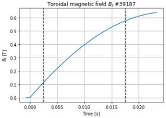
Integration (it is a magnetic diagnostic) & calibration

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))
```

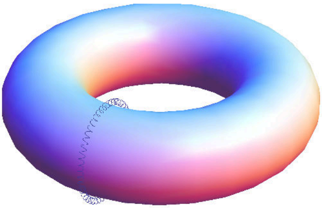
```
BtCoil calibration factor K_BtCoil=70.42 T/(Vs)
```

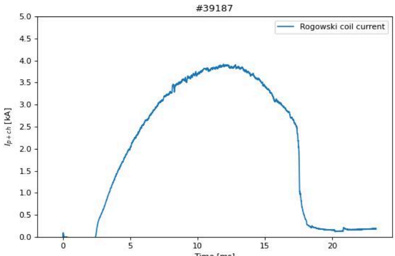
In [14]:
```
Bt = pd.Series(integrate.cumtrapz(dBt, x=dBt.index, initial=0) * K_BtCoil,
               index=dBt.index, name='Bt')
ax = Bt.plot(grid=True)
show_plasma_limits()
ax.set(xlabel="Time [s]", ylabel="$B_t$ [T]", title="Toroidal magnetic field $B_t$ #{}".format(shot_no));
```

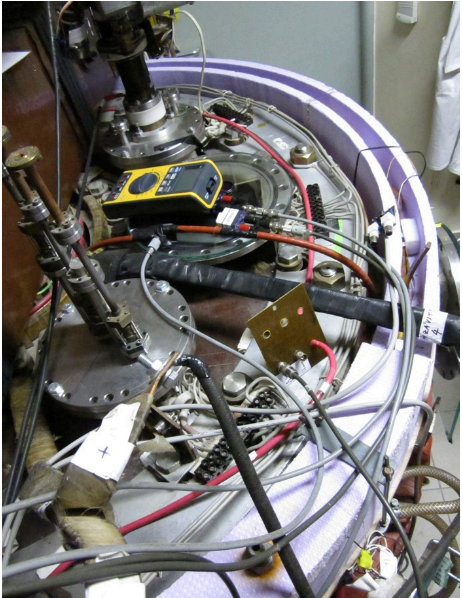
Out[14]:
```
[Text(0.5, 0, 'Time [s]'),
 Text(0, 0.5, '$B_t$ [T]'),
 Text(0.5, 1.0, 'Toroidal magnetic field $B_t$ #39187')]
```



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

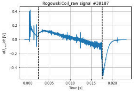
The Rogowski coil around the chamber measures the total current contained within its boundaries. Therefore, if there is plasma, it measures the sum of the plasma and chamber currents. In a vacuum discharge it measures only the chamber current.

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')]
```



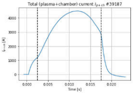
Integration (it is a magnetic diagnostic) & calibration

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

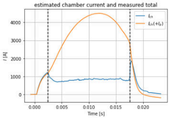
In [18]:
```
R_chamber = float(read_parameter(shot_no, 'SystemParameters/R_chamber')) # Get Chamber resistivity
print('Chamber resistivity R_chamber={} Ohm'.format(R_chamber))
```

```
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

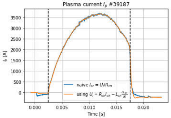
$I_p = I_{p+ch} - I_{ch}$

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]:

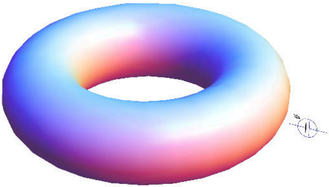
Plasma detected

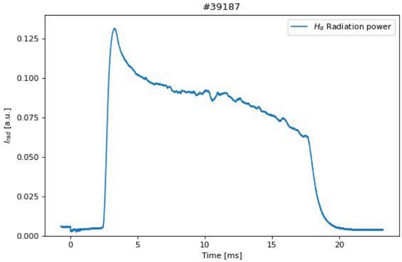
plasma lifetime of 15.1 ms, from 2.5 ms to 17.6 ms

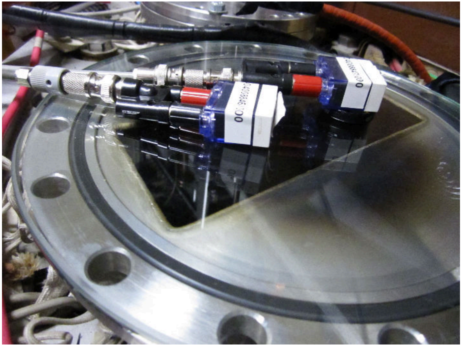


In [23]:
```
fig = plt.figure(dpi=200)
for I in [Ich.rename('$I_{ch}$'), Ipch.rename('$I_{ch}+I_p$'), Ip.rename('$I_p$')]:
    ax = I.plot()
```

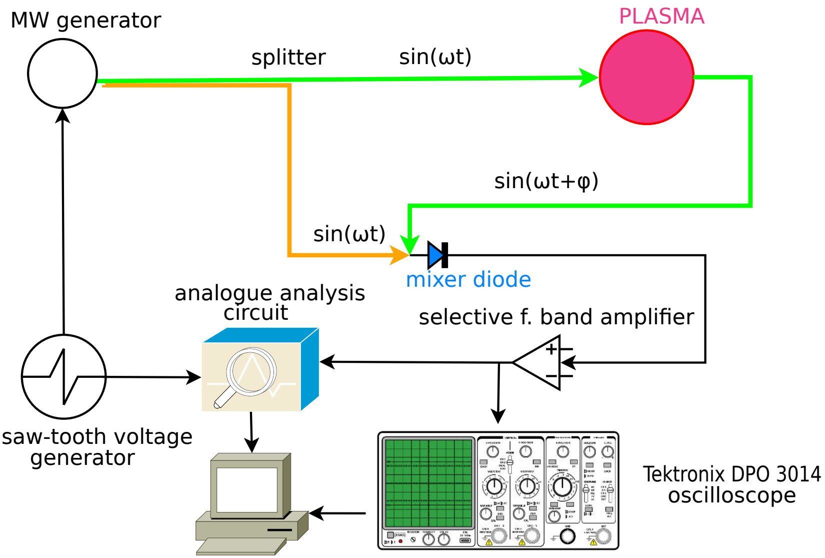
Visible radiation



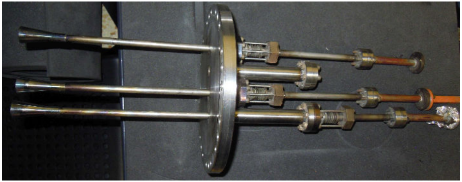




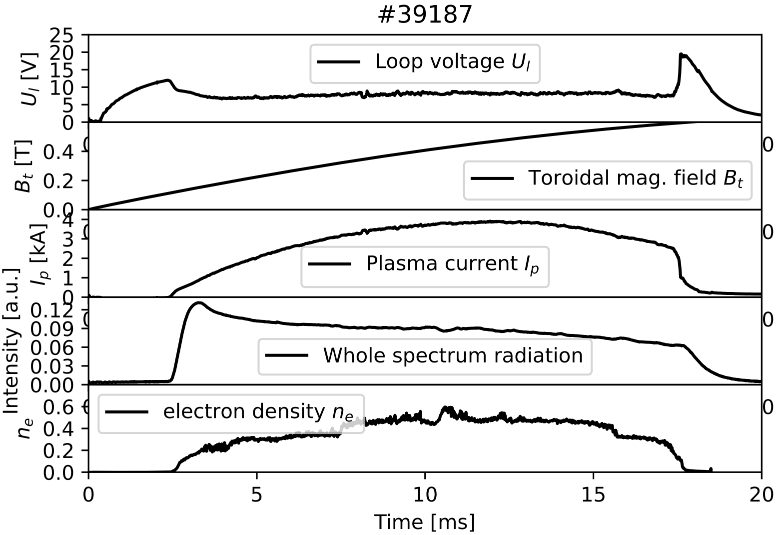
Electron density n_e interferometry measurement scheme



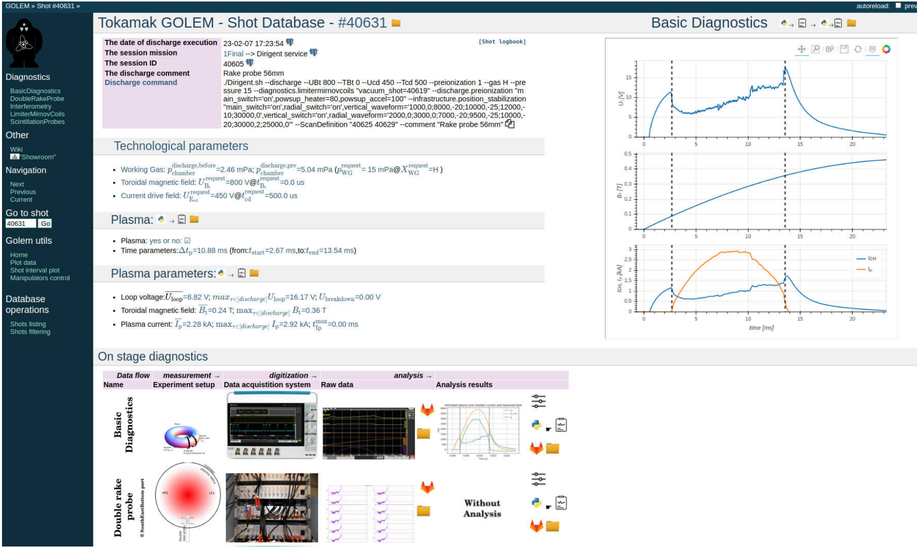
The GOLEM tokamak interferometry HW



Finally "Typical", well executed discharge @ GOLEM



Shot homepage (≈ 2 minutes after discharge execution)



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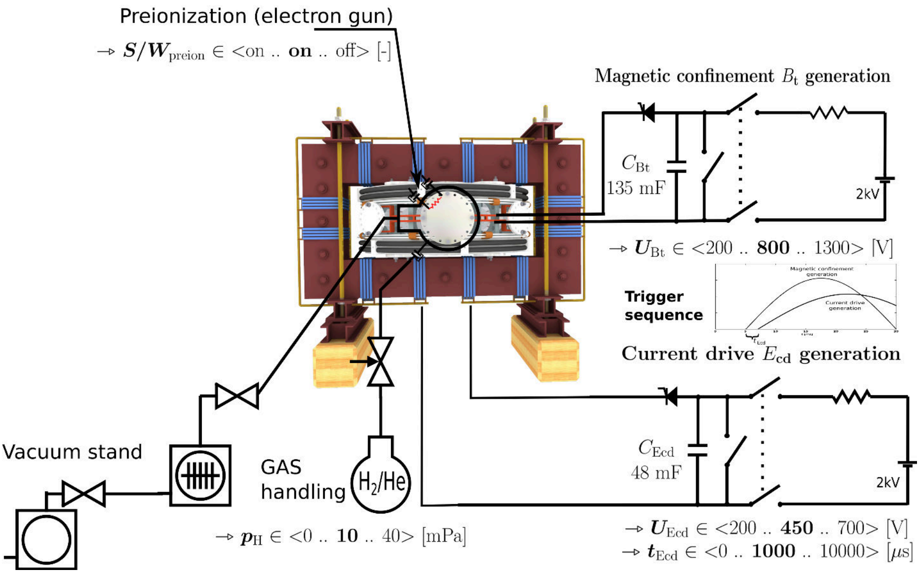
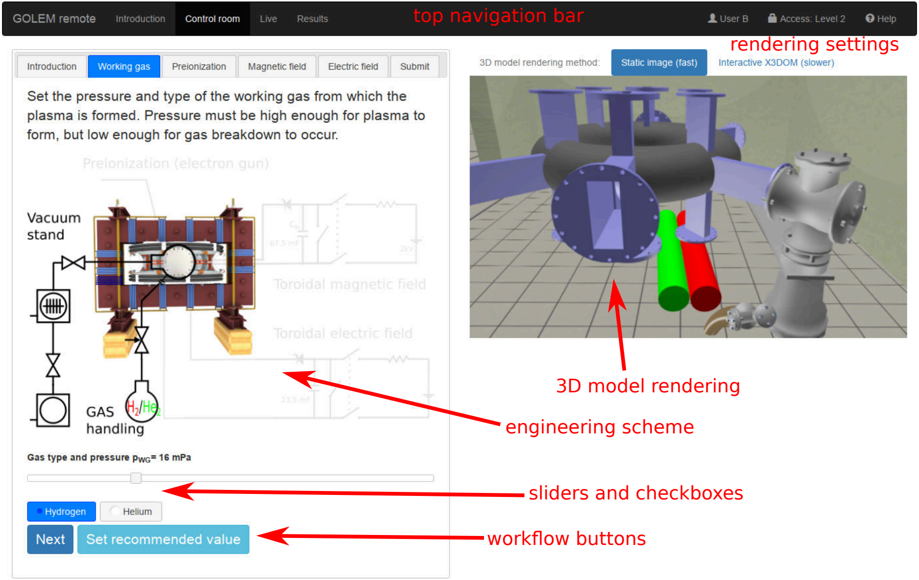
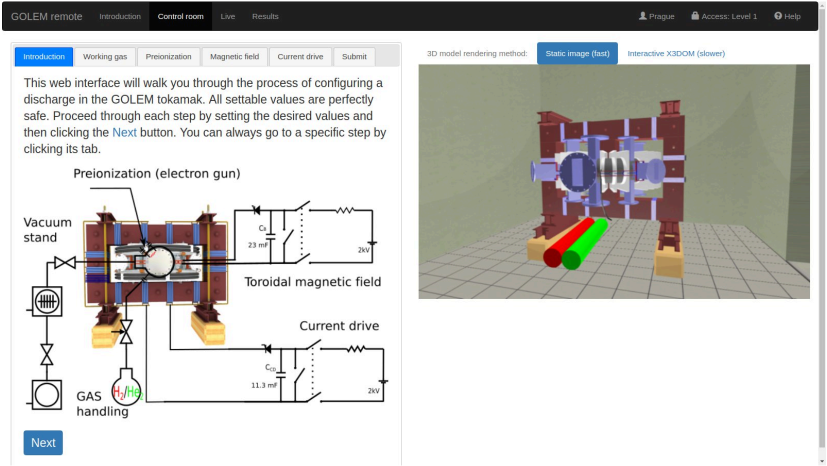
Tokamak GOLEM - schematic experimental setup



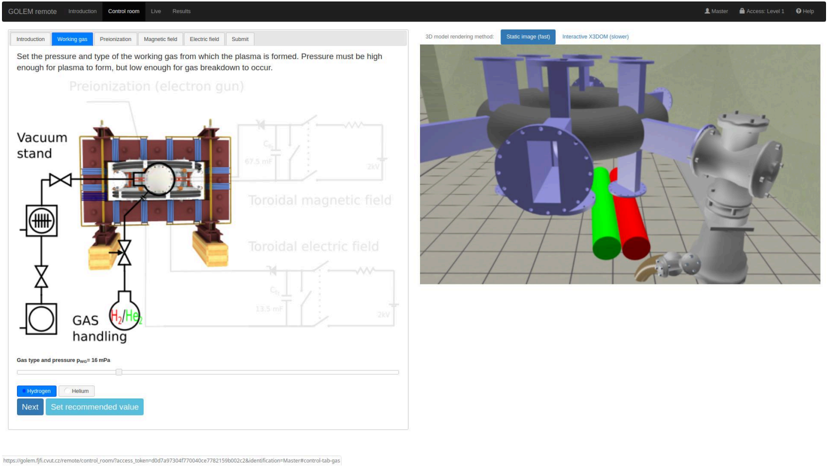
Remote control interface of the GOLEM tokamak



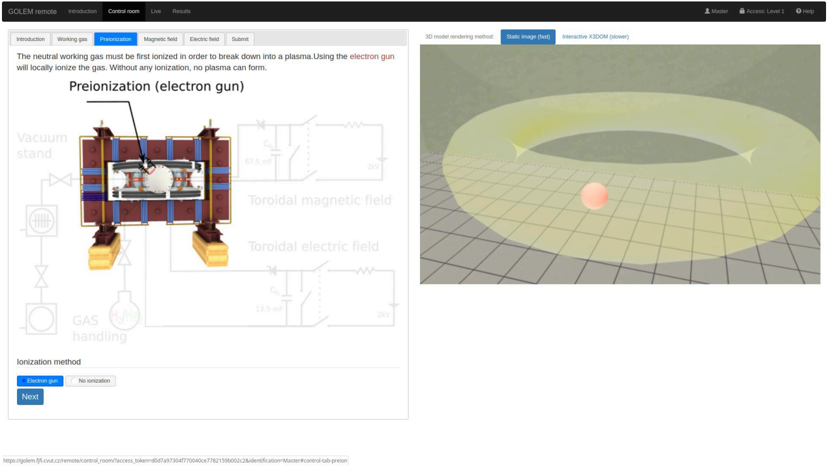
Control room: Introduction



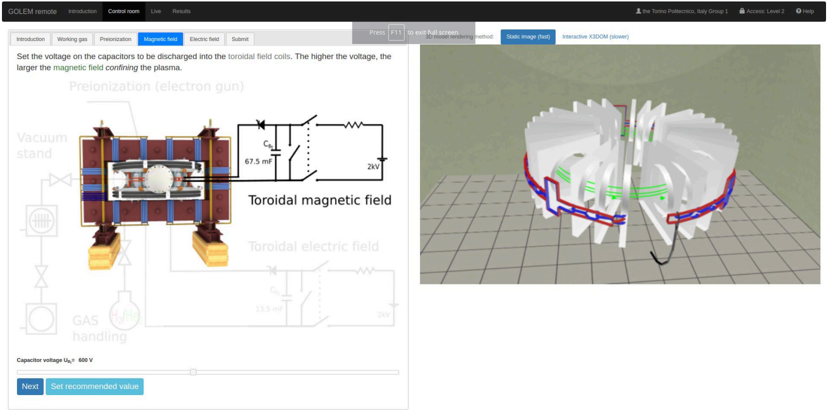
Control room: Working gas



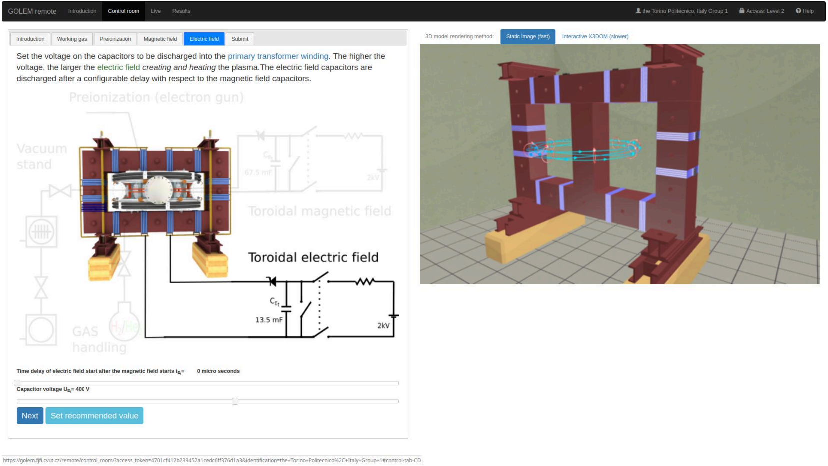
Control room: Preionization



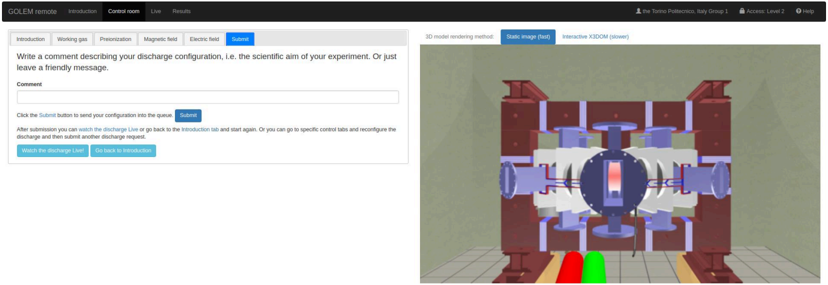
Control room: Magnetic field B_t



Control room: Current drive E_{cd}

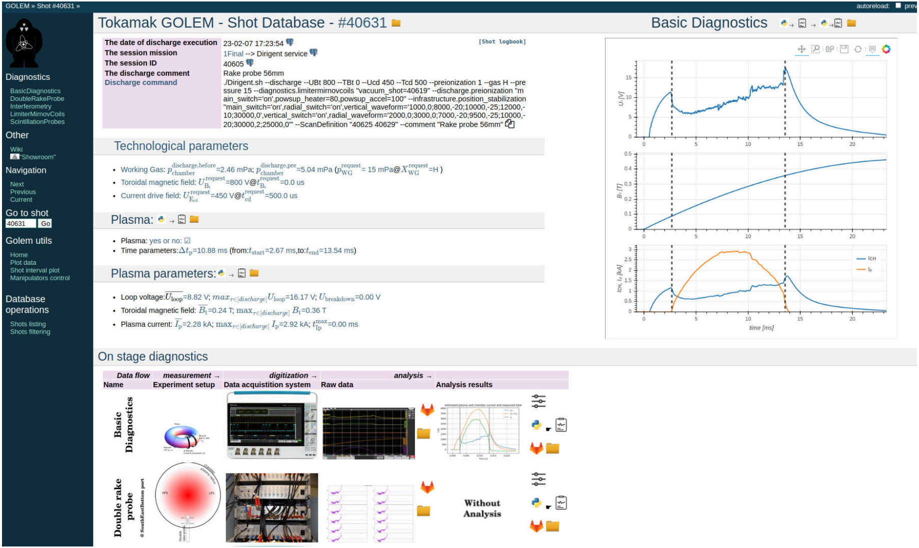


Control room: ... and Submit



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)

- $U_l, U_{B_t}, U_{I_{p+ch}}, I_{rad}$
- $\Delta t = 1\mu s / f = 1 MHz$.
- 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	$\approx$	7405	lines ..	
⋮	⋮	⋮	⋮	⋮
0.007383	1.53931	0.390015	0.048828	0.001831
0.007384	1.53686	0.395508	0.067749	0.00061
0.007385	1.54053	0.391235	0.079956	0.00061
0.007386	1.53686	0.38147	0.072632	0
0.007387	1.54297	0.397949	0.059204	0.00061
0.007388	1.54053	0.384521	0.05249	0.00061
0.007389	1.54053	0.39856	0.068359	0.001221
0.00739	1.54053	0.393677	0.082397	0.001221
0.007391	1.53809	0.38208	0.072632	0.001221
0.007392	1.54297	0.400391	0.056763	0.00061
0.007393	1.54419	0.383911	0.053101	0.00061
0.007394	1.53931	0.397339	0.068359	0.001221
0.007395	1.54297	0.391846	0.084229	0.00061
0.007396	1.54541	0.394897	0.074463	0.00061
0.007397	1.54297	0.388184	0.056763	0.001221
0.007398	1.54297	0.391846	0.056763	0.00061
0.007399	1.54297	0.394287	0.06897	0.00061
⋮	⋮	⋮	⋮	⋮
next	$\approx$	32500	lines ..	
⋮	⋮	⋮	⋮	⋮

Data access

All the recorded data and the settings for each discharge (shot) are available at the GOLEM website. The root directory for the files is:

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

The most recent discharge has the web page:

`http://golem.fjfi.cvut.cz/shots/0`

Particular data from DAS specified with `<DASname>` and `<DASchannelidentifier>` have the format:

`http://golem.fjfi.cvut.cz/<#ShotNo>/<DASname>/<DASchannelidentifier>`

Jupyter (python)

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

shot_no = 39187
identifier = "U_loop.csv"
DAS='Diagnostics/BasicDiagnostics/Results/'
# create data cache in the 'golem_cache' folder
ds = np.DataSource('golem_cache')
#Create a path to data and download and open the file
base_url = "http://golem.fjfi.cvut.cz/shots/"
data_file = ds.open(base_url + str(shot_no)+ '/' +DAS +identifier)
#Load data from the file and plot to screen and to disk
data = np.loadtxt(data_file,delimiter=",")
plt.title('#'+str(shot_no))
plt.plot(data[:,0]*1000, data[:,1]) #1. column vs 2. column
plt.xlabel('Time [ms]');plt.ylabel('$U_l$ [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'
```

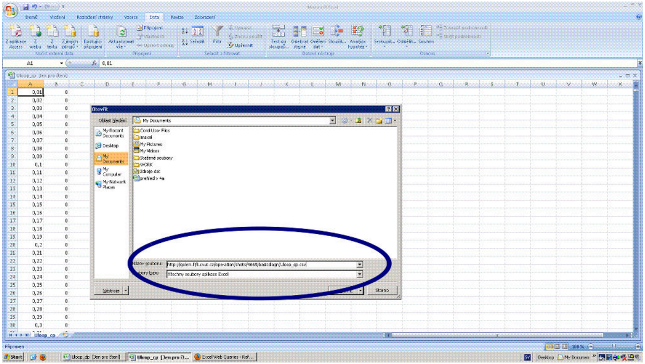
```
shot_no=39187;\
signal_id="Diagnostics/BasicDiagnostics/Results/U_loop.csv";\
gnuplot -p -e "set title \"Golem\";set datafile separator \",\";\
set xlabel \"t [s]\";set ylabel \"U\";\
plot \"< \
wget -q -O - http://golem.fjfi.cvut.cz/shots/$shot_no/$signal_id\" \
w l t \"U\""
```

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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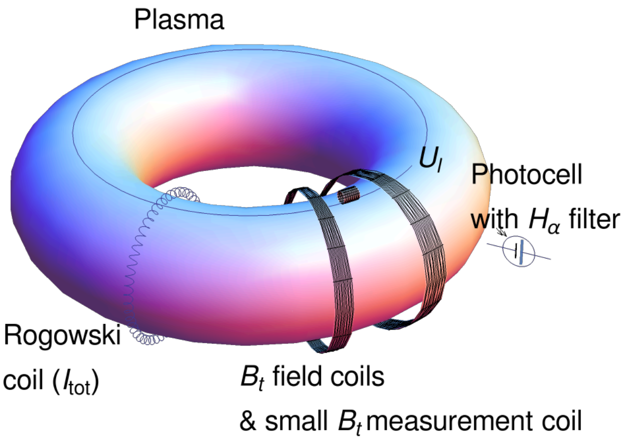
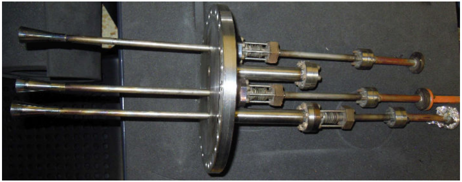
Hands on the GOLEM tokamak - equipment

The GOLEM tokamak - standard diagnostics



The GOLEM tokamak interferometry HW



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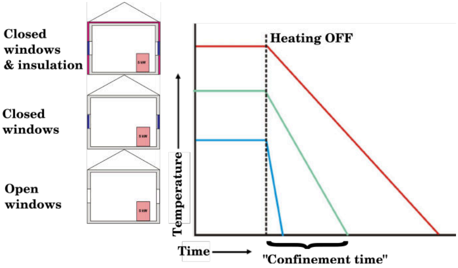
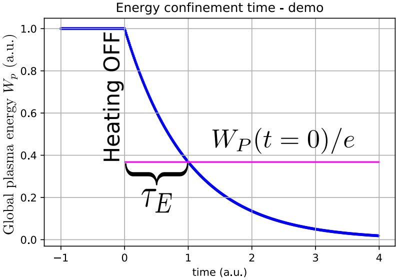
Towards the Electron Energy Confinement Time $\tau_{E,e}$ @tG

House (cooling after heating stops)



Tokamak (cooling after heating stops)

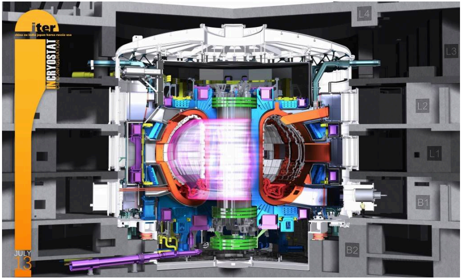


When heating is switched off, both systems lose their internal energy exponentially. This motivates the definition of the electron energy confinement time $\tau_{E,e}$.

ITER vs GOLEM

ITER:

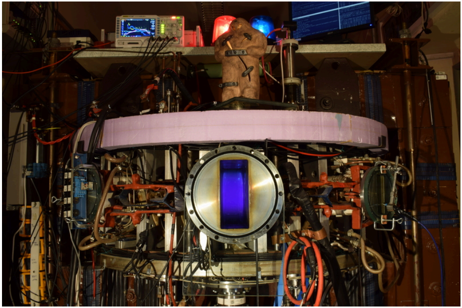
$\tau_E \approx 3.6\ \mathrm{s}$



credit:[4]

GOLEM:

$\tau_{E,e} \approx$ on the order of $10\ \mu\mathrm{s}$



credit:[5]

Different scale, same physics — and you will measure it today @tG.

What follows — roadmap

- **Lawson criterion** — the fusion requirement
- **Quasi–stationary method @tG** — how we measure confinement
- **Ohmic heating power** P_{OH}
- **Electron temperature** from Spitzer conductivity T_e
- **Electron energy content** W_e
- **Putting it all together:** the confinement time $\tau_{E,e}$

Lawson criterion

credit:Lawson criterion @ Wiki [6]

- To achieve net fusion power, fusion heating must exceed losses:

$$P_{\mathrm{fusion}} \geq P_{\mathrm{loss}}.$$

- Plasma energy content:

$$W = 3nk_{\mathrm{B}}T.$$

- Confinement time links energy to losses:

$$\tau_E = \frac{W}{P_{\mathrm{loss}}}.$$

- Fusion reaction rate (DT):

$$f = \frac{1}{4}n^2\langle\sigma v\rangle, \qquad P_{\mathrm{fusion}} = f\,E_\alpha, \qquad E_\alpha = 3.5\ \mathrm{MeV}.$$

- Condition for ignition becomes the Lawson criterion:

$$n\tau_E \geq \frac{12}{E_\alpha}\frac{k_{\mathrm{B}}T}{\langle\sigma v\rangle} \approx 1.5\times 10^{20}\,\mathrm{s/m^3} \quad (\text{DT at } T \approx 26\ \mathrm{keV}).$$

Measuring $\tau_{E,e}$ @tG: the quasi–stationary method

- On GOLEM we cannot switch off the ohmic heating abruptly (capacitor discharge drives the current throughout the pulse).
- Therefore we use the **quasi–stationary phase** of the discharge:

$$\frac{dI_p}{dt} \approx 0, \qquad \frac{dT_e}{dt} \approx 0, \qquad \frac{dW_e}{dt} \approx 0.$$

- In this regime, the ohmic heating balances the losses:

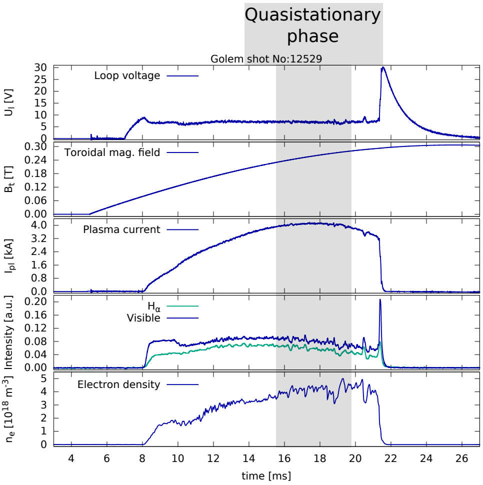
$$P_{\mathrm{OH}} \approx P_{\mathrm{loss}}.$$

- The electron energy confinement time becomes:

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

- This provides a consistent and reproducible estimate of $\tau_{E,e}$ suitable for a small tokamak like GOLEM.

The discharge — quasi–stationary phase



Quasi–stationary phase:

- Plasma current I_p, electron temperature T_e and density n_e vary only slowly.
- Therefore $dW_e/dt \approx 0$.
- Ohmic heating balances losses:

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

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

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

- All quantities are measurable @tG.

Ohmic heating power P_{OH} @tG

On the GOLEM tokamak the plasma is heated solely by **ohmic heating**, driven by the toroidal electric field that sustains the plasma current I_p. The instantaneous ohmic heating power is directly obtained from two measurable quantities:

$$P_{\mathrm{OH}}(t) = V_{\mathrm{loop}}(t)\, I_p(t),$$

where V_{loop} is the toroidal loop voltage measured by the flux loop, and $I_p(t)$ is the plasma current from the Rogowski coil. In the quasi–stationary phase, where $dW_e/dt \approx 0$, this power balances the energy losses:

$$P_{\mathrm{OH}} \approx P_{\mathrm{loss}},$$

providing the key ingredient for estimating the electron energy confinement time $\tau_{E,e}$ @tG.

Central electron temperature T_e (Spitzer conductivity)

The time evolution of the central electron temperature $T_e(0,t)$ is obtained from Spitzer's resistivity formula for a collisional, fully ionized plasma.

- Spitzer resistivity (symbolically):

$$\eta(T_e) \propto Z_{\mathrm{eff}} \ln\Lambda \, T_e^{-3/2}.$$

- Using $\eta = R_p A/L$ with plasma resistance $R_p(t)$ one may write for the on–axis temperature:

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

- For the particular case of the GOLEM tokamak (fixed geometry, $Z_{\mathrm{eff}} \approx 1$, $\ln\Lambda \approx \mathrm{const}$) all geometric and numerical factors can be grouped into a single coefficient, giving the practical formula:

$$T_e(0,t) \approx 0.9 \left(\frac{I_p(t)}{V_{\mathrm{loop}}(t)} \right)^{2/3} \qquad [\mathrm{eV};\ \mathrm{A}, \mathrm{V}].$$

- Thus @tG the central electron temperature can be estimated directly from the measured $I_p(t)$ and $V_{\mathrm{loop}}(t)$.

Electron energy content W_e @tG

The electron energy content follows from the ideal-gas expression for a single thermal species:

$$W_e(t) = \frac{3}{2}\, n_e(t)\, k_\mathrm{B}\, T_e(t)\, V_p,$$

where $n_e(t)$ is the line-averaged (or central) electron density, $T_e(t)$ the central electron temperature, and V_p the plasma volume. For a circular, low–aspect–ratio tokamak the plasma volume is well approximated by:

$$V_p \approx 2\pi^2 R_0 a^2,$$

with R_0 the major radius and a the minor radius. At GOLEM all quantities entering W_e are experimentally accessible:

- $n_e(t)$ from microwave interferometry,
- $T_e(t)$ from Spitzer conductivity,
- V_p from known machine geometry.

Thus $W_e(t)$ can be evaluated directly during the quasi–stationary phase of the discharge.

Electron energy confinement time $\tau_{E,e}$ @tG

In the quasi–stationary phase of the discharge, where $dW_e/dt \approx 0$, the ohmic heating balances the energy losses:

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

The electron energy confinement time is therefore obtained as:

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

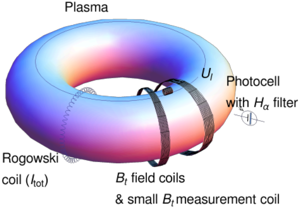
All entering quantities are experimentally accessible @tG:

- $P_{\mathrm{OH}}(t) = V_{\mathrm{loop}}(t)\, I_p(t)$,
- $T_e(t)$ from Spitzer conductivity,
- $n_e(t)$ from interferometry,
- V_p from machine geometry.

This yields a self–consistent, fully diagnostic–based estimate of the **electron energy confinement time** on the GOLEM tokamak.

Measured quantities @tG for computing $\tau_{E,e}$

Directly measured on GOLEM:



Diagnostics relevant to $\tau_{E,e}$ on GOLEM

- **Plasma current** $I_p(t)$ from the Rogowski coil (shown as the helical pickup).
- **Loop voltage** U_l (not needed for q, but measured).
- **Machine geometry:** major radius R_0 and minor radius a.
- **Electron density** from interferometry.

These are all required inputs to compute:

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

From measured signals to $\tau_{E,e}$ @tG

Vacuum discharge
$I_{\rm ch}^{\rm vac}(t),\ V_{\rm loop}^{\rm vac}(t)$

Plasma discharge
$I_{\rm ch+p}(t)$,
$V_{\rm loop}(t),\ n_e(t)$

Chamber resistance
$$R_{\rm ch} \approx \frac{V_{\rm loop}^{\rm vac}}{I_{\rm ch}^{\rm vac}}$$

Plasma current
$$I_p = I_{\rm ch+p} - \frac{V_{\rm loop}}{R_{\rm ch}}$$

Quasi–stationary interval $[t_1, t_2]$:
$$\bar{I}_p = \langle I_p \rangle, \quad \bar{V}_{\rm loop} = \langle V_{\rm loop} \rangle, \quad \bar{n}_e = \langle n_e \rangle$$

Plasma resistivity
$$R_p = \frac{\bar{V}_{\rm loop}}{\bar{I}_p}$$

Central T_e (Spitzer)
$$T_e(0) \approx 0.9\, R_p^{-2/3}$$

Ohmic heating
$$\bar{P}_{\rm OH} = \bar{V}_{\rm loop}\, \bar{I}_p$$

Electron energy
$$\bar{W}_e = \tfrac{3}{2}\, \bar{n}_e k_{\rm B} T_e V_p$$

Electron energy confinement time
$$\tau_{E,e} = \frac{\bar{W}_e}{\bar{P}_{\rm OH}}$$

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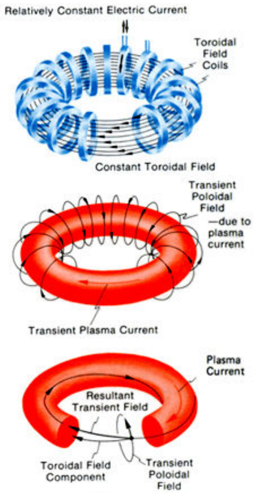
Towards the Safety Factor q



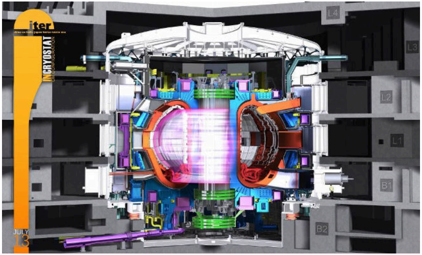
Magnetic field lines in a tokamak

Why it matters:

- q measures how much field lines *twist* around the torus.
- A key parameter controlling MHD stability.
- Rational q surfaces ($q = m/n$) $\rightarrow$ possible island formation.
- Operating limits: too low $q \rightarrow$ kink instabilities.
- ITER, JET, ASDEX-U all use $q(a)$ as a primary equilibrium metric.
- **Fundamental limits:** $q(0) > 1$ (avoid internal kink), $q(a) \gtrsim 2$ (avoid external kink).

ITER vs GOLEM: typical values of $q(a)$

ITER

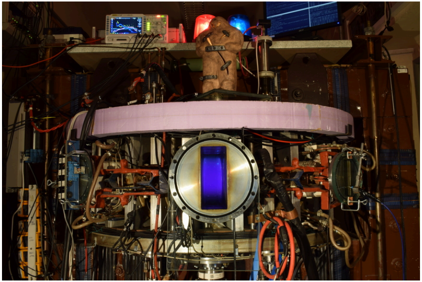


Typical edge safety factor:

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

Large device, strong shaping, high stability margin.

GOLEM



Typical edge safety factor:

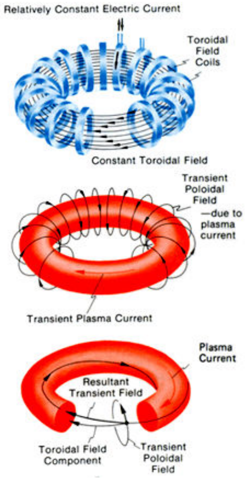
$$q(a) \sim 2 - 6$$

Small device: circular plasma, flexible operating space.

What follows — roadmap to the safety factor q

- **Definition of the safety factor** — toroidal/poloidal twist of magnetic field lines.
- **Circular tokamak geometry** — relation between B_t, B_p and plasma current.
- **Quantities measured @tG** — $I_p(t)$ from Rogowski, B_t from toroidal field coils, geometry (R_0, a).
- **Computing the edge safety factor** — $q(a) = \dfrac{2\pi a^2 B_t}{\mu_0 R_0 I_p}$.
- **Typical operating window** — GOLEM: $2 < q(a) < 6$, stability limits $q(0) > 1$, $q(a) \gtrsim 2$.

Definition of the Safety Factor q



Magnetic field line winding

Geometric definition:

$$q(r) = \frac{\text{toroidal turns}}{\text{poloidal turns}}$$

In a circular tokamak:

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

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

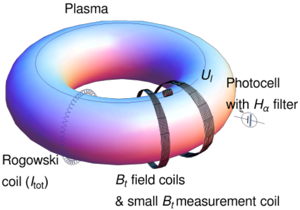
$$B_p(r) = \frac{\mu_0 I_p(r)}{2\pi r}$$

This gives the practical form:

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

Measured quantities @tG for computing $q(a)$

Directly measured on GOLEM:



Diagnostics relevant to $q(a)$ on GOLEM

- **Plasma current** $I_p(t)$ from the Rogowski coil (shown as the helical pickup).
- **Toroidal field** B_t from the TF coil current (and verified by the small Bt measurement coil).
- **Machine geometry:** major radius R_0 and minor radius a.

These are all required inputs to compute:

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

Computing the edge safety factor $q(a)$

Definition:

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

Using Ampère's law at the plasma edge:

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

Insert into the definition:

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

For GOLEM (fixed geometry):

$$K_{\mathrm{geom}} = \frac{2\pi a^2}{\mu_0 R_0}$$

$$q(a) = K_{\mathrm{geom}} \frac{B_t}{I_p}.$$

Thus:measuring $I_p(t)$ and knowing B_t is fully sufficient to compute $q(a)$ for any discharge on GOLEM.

From measured signals to the safety factor $q(a)$ @tG

Plasma current
$I_p(t)$ from Rogowski

Toroidal field
B_t from TF coils

GOLEM geometry (constant)
$R_0, \ a$

Quasi–stationary interval
and mean current
$\bar{I}_p = \langle I_p \rangle$

Safety factor at the edge:

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

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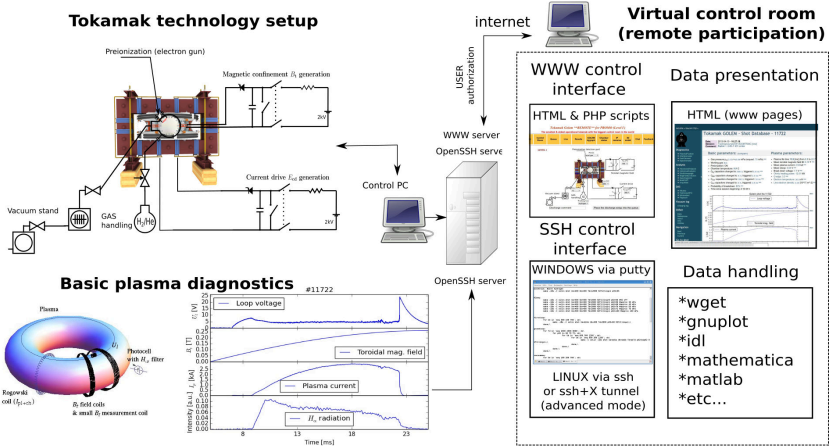
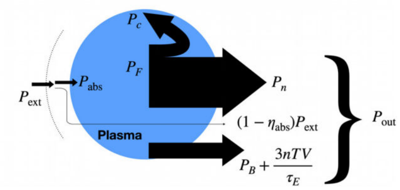
The global schematic overview of the tG experiment



Two key fusion technology parameters you can touch experimentally

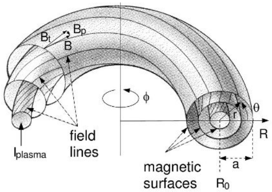
Energy Confinement Time τ_E



credit:[2]

- Indicates how long the plasma keeps its energy — a key fusion metric.
-
$$\tau_E = \frac{W_{\text{plasma}}}{P_{\text{loss}}}$$
- On tG, from energy balance, we estimate the electron component $\tau_{E,e}$ (we can measure only n_e and T_e).

Safety Factor q



credit:[3]

- Describes how magnetic field lines wind around the torus. Key stability parameter (MHD behaviour).
-
$$q(a) = \frac{2\pi a^2 B_t}{\mu_0 R I_p}$$
- On tG, derived from B_t and plasma current I_p.

Production

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

Fee: postcard from the venue of remote measurements

Acknowledgement

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Thank you for your attention

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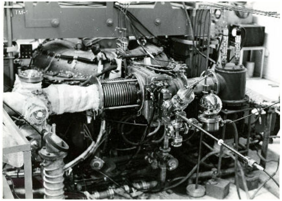
~1960-1977



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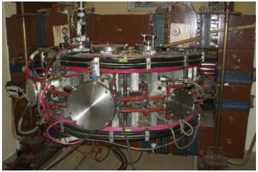

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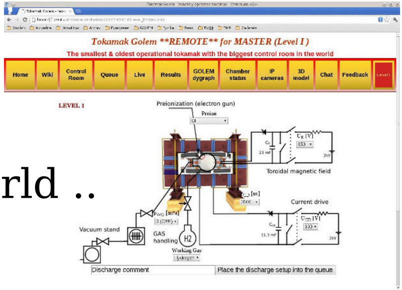

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