Introduction to tokamak operation (GOLEM specific) - Level 1

Vojtěch Svoboda
on behalf of the tokamak GOLEM team
for the Cadarache event, 5^{th} edition

February 28, 2017

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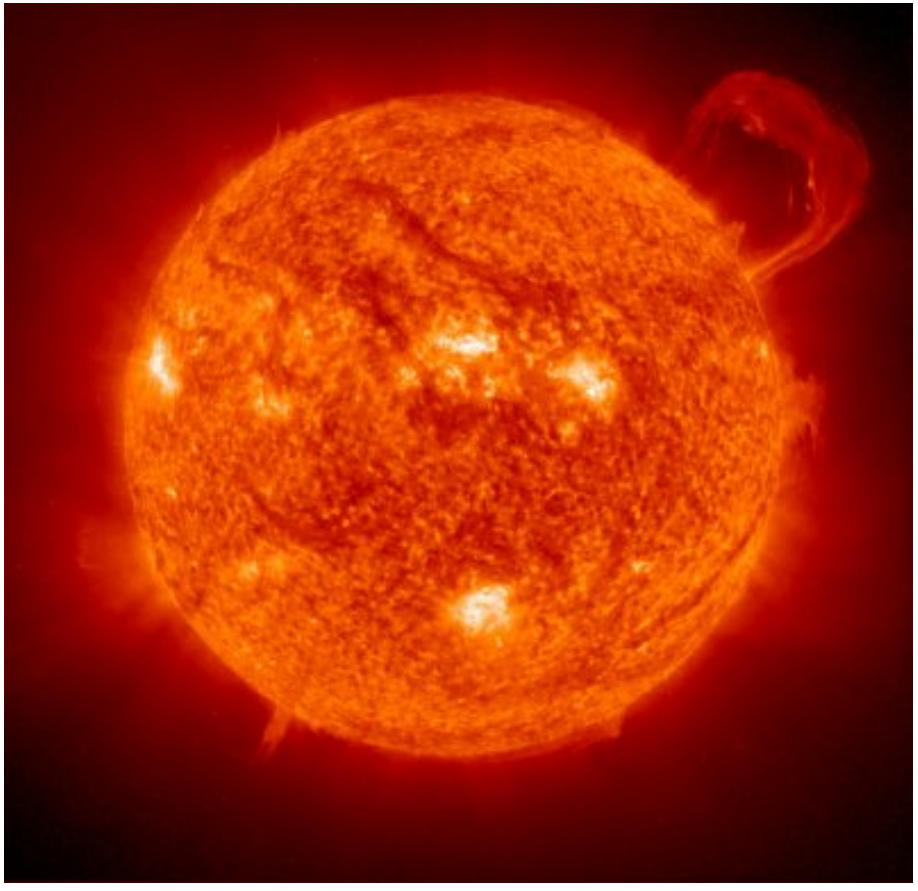
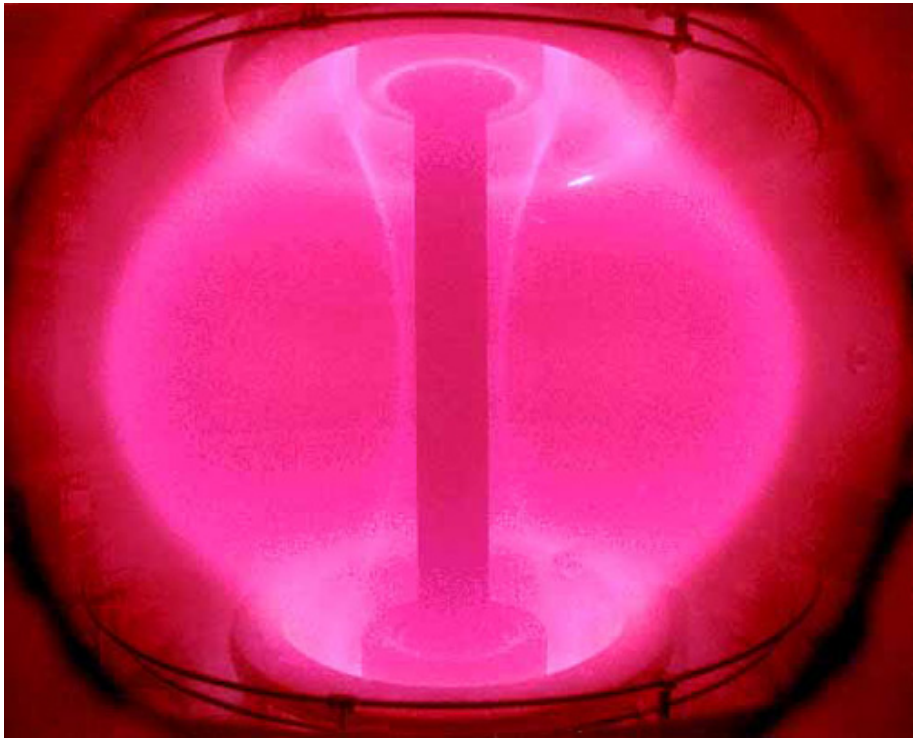
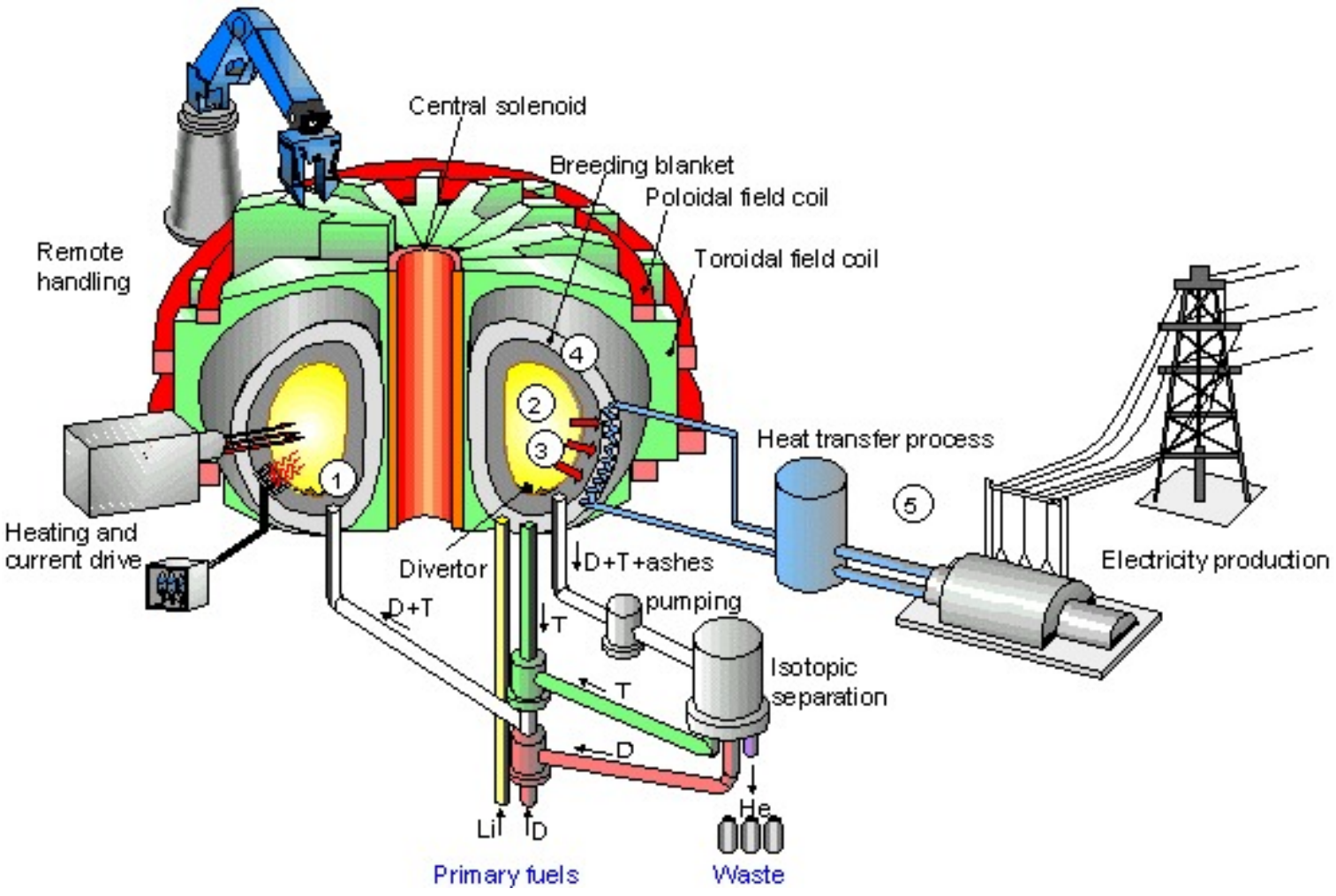
Foreword

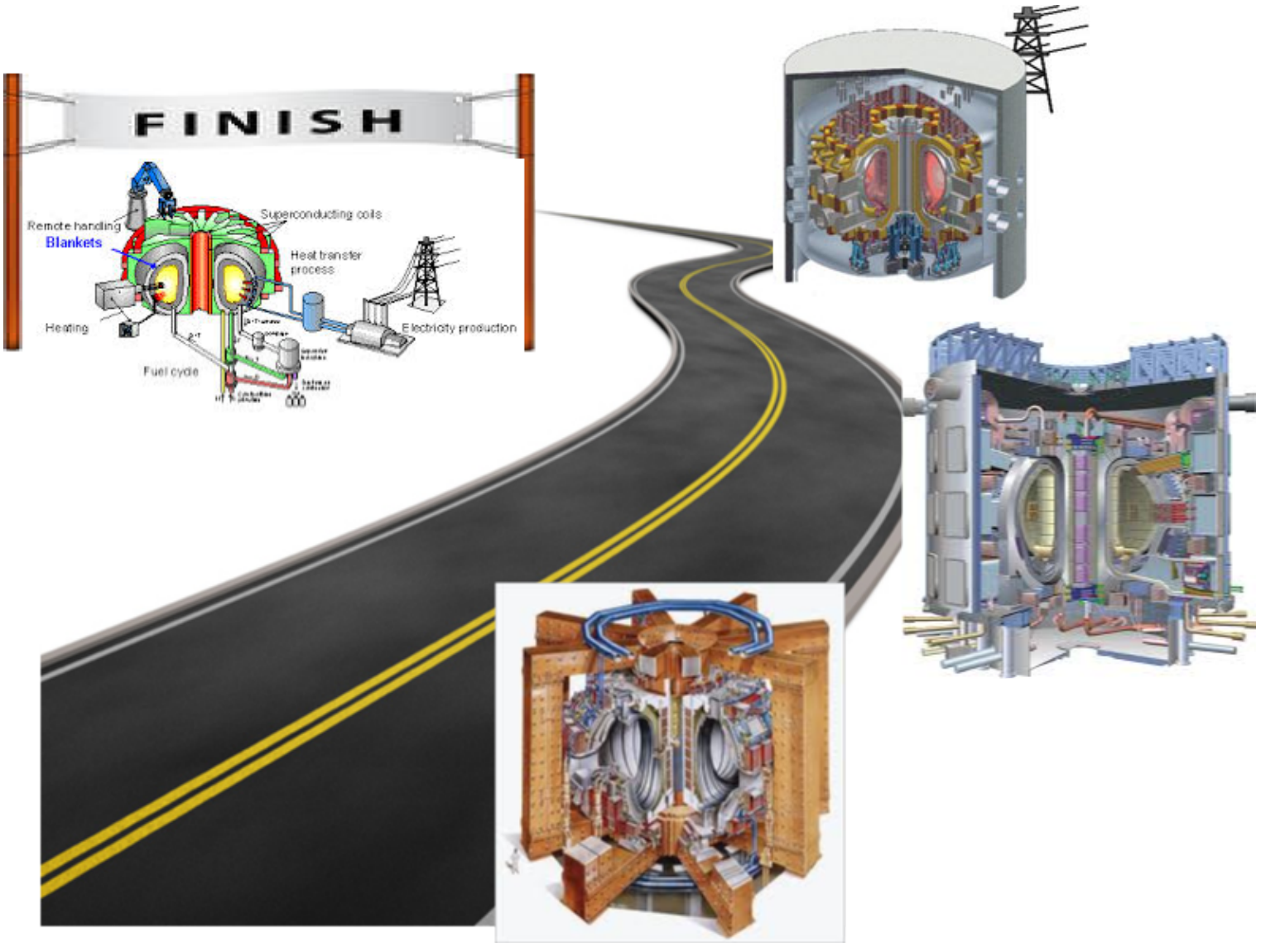




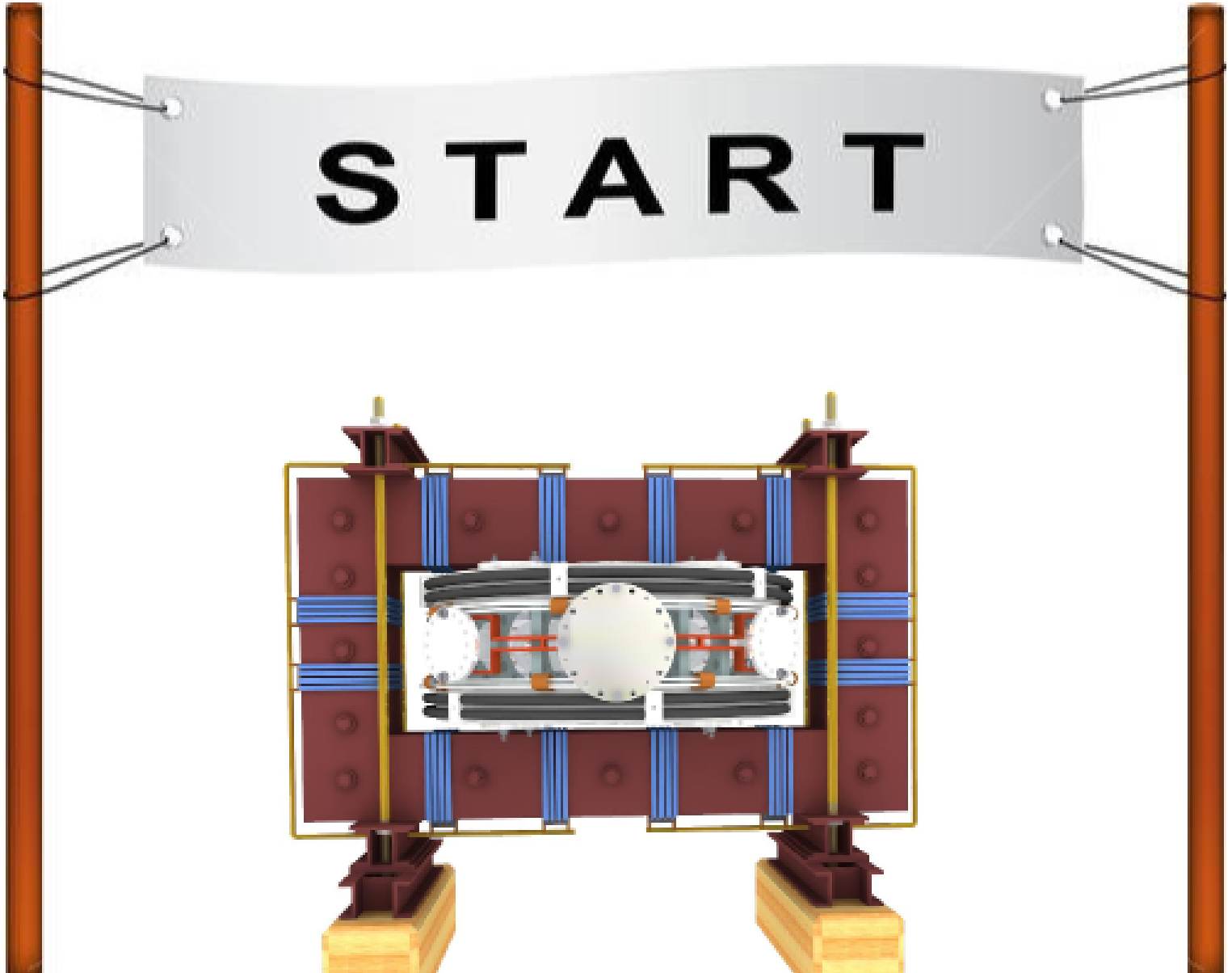
Our mission


Central solenoid
Breeding blanket
Poloidal field coil
Remote handling
Toroidal field coil
4
2
3
1
Heat transfer process
5
Heating and current drive
Divertor
D+T+ashes
Electricity production
D+T
pumping
T
Isotopic separation
T
D
He
Li
D
Primary fuels
Waste

Milestones to the Fusion Power Plant



Let's start with the tokamak GOLEM



Notice/Warning/Alert

Everything simplified

... for educational purposes ..

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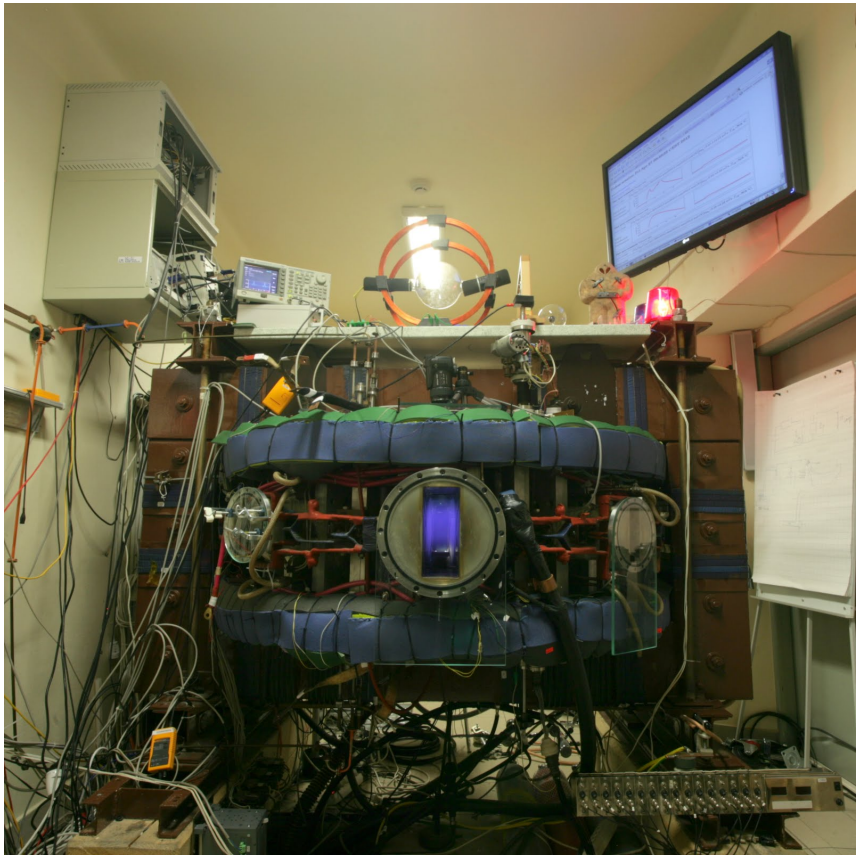
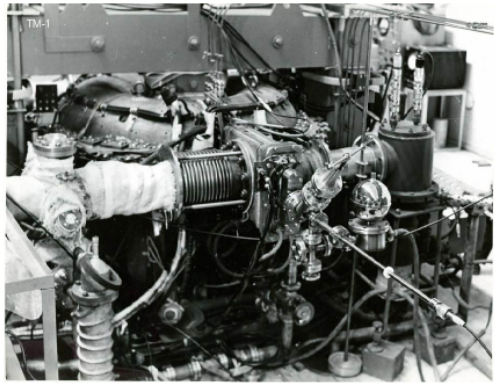
Basic characteristics



- Vessel major radius: $R_0 = 0.4$ m
- Vessel minor radius: $r_0 = 0.1$ m
- Minor radius $r_0 = 0.1$ m
- Plasma radius $a = 0.085$ m
- Toroidal magnetic field $B_t < 0.5$ T
- Plasma current $I_p < 8$ kA
- Plasma density
  $n \approx 0.2 - 3 \times 10^{19}/\mathrm{m}^{-3}$
- Electron temperature $T_e < 100$ eV
- Ion temperature $T_i < 50$ eV
- Length of the discharge $\tau < 20$ ms

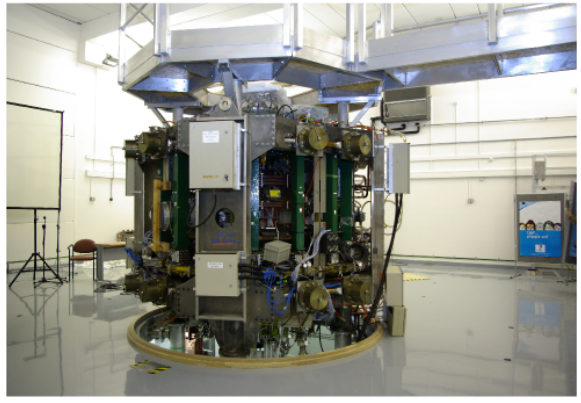
Tokamak GOLEM for education - historical background

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**

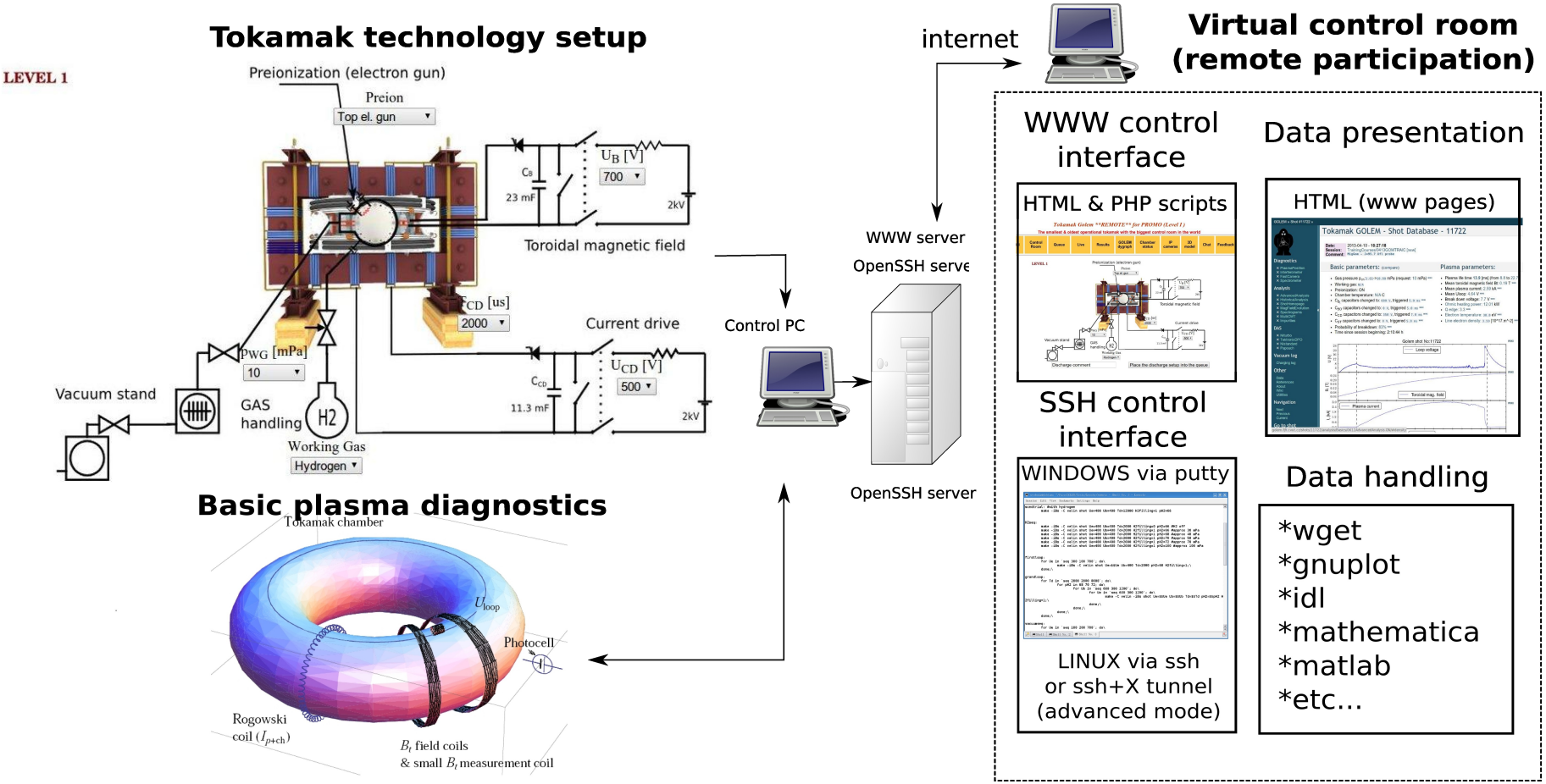
2008

Czech Technical University Prague
Czech republic
GOLEM

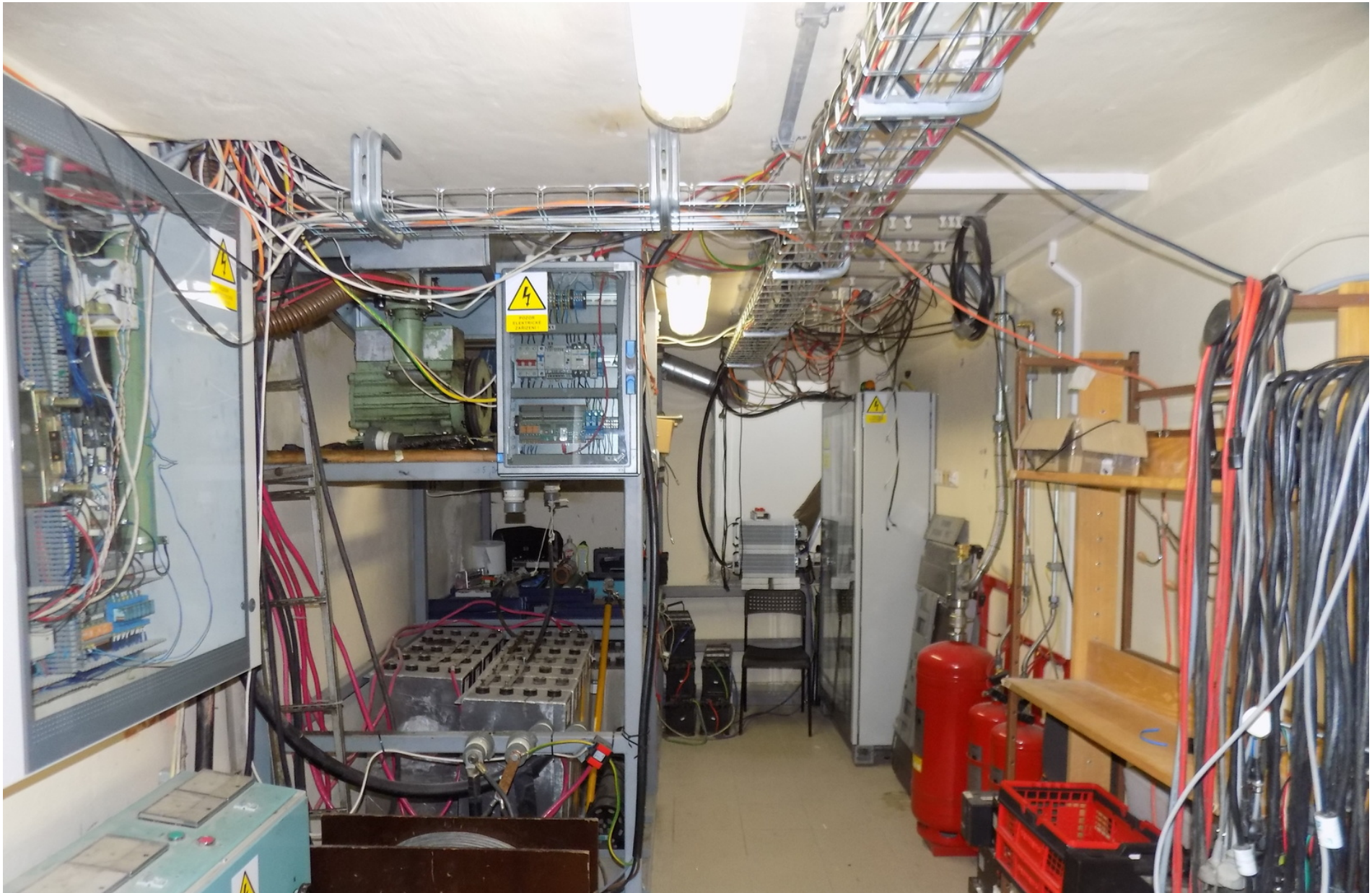
GOLEM

The new location of the tokamak is just next to the old Prague Jewish cemetery where Rabi Loew (Golem builder) is burried, and that is why it was renamed GOLEM (and also for the symbol of potential power you get if you know the magic). Interestingly, here in Prague, where the Golem legend originated, Golem is not perceived as a symbol of evil, but rather as a symbol of power which might be useful but is very challenging to handle. To learn more of the Golem legend, see e.g. wikipedia.

The global schematic overview of the GOLEM experiment

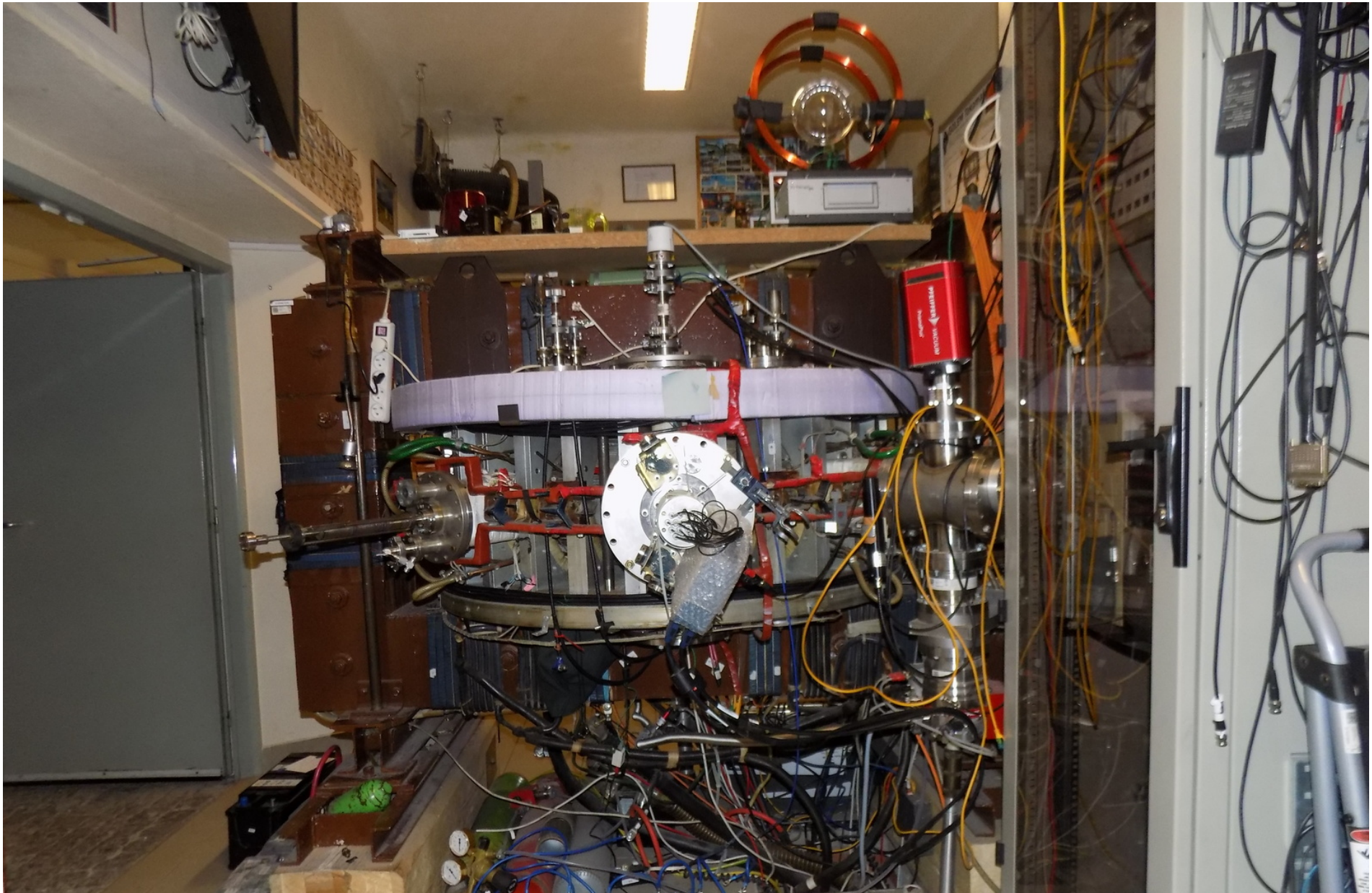


Infrastructure room (below tokamak) 10/16

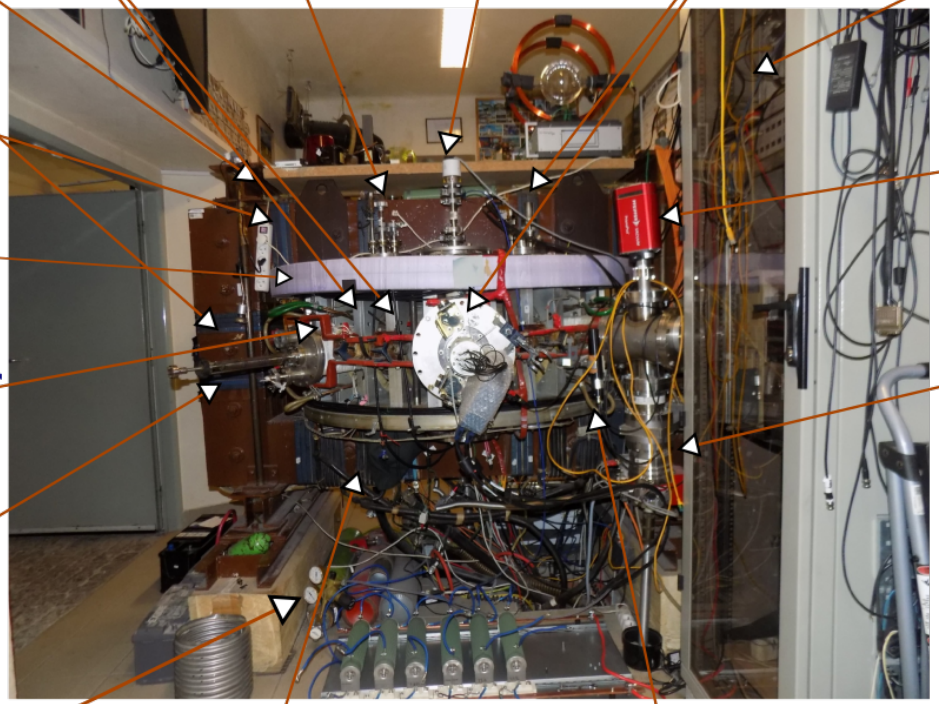


Infrastructure room (below tokamak) 10/16

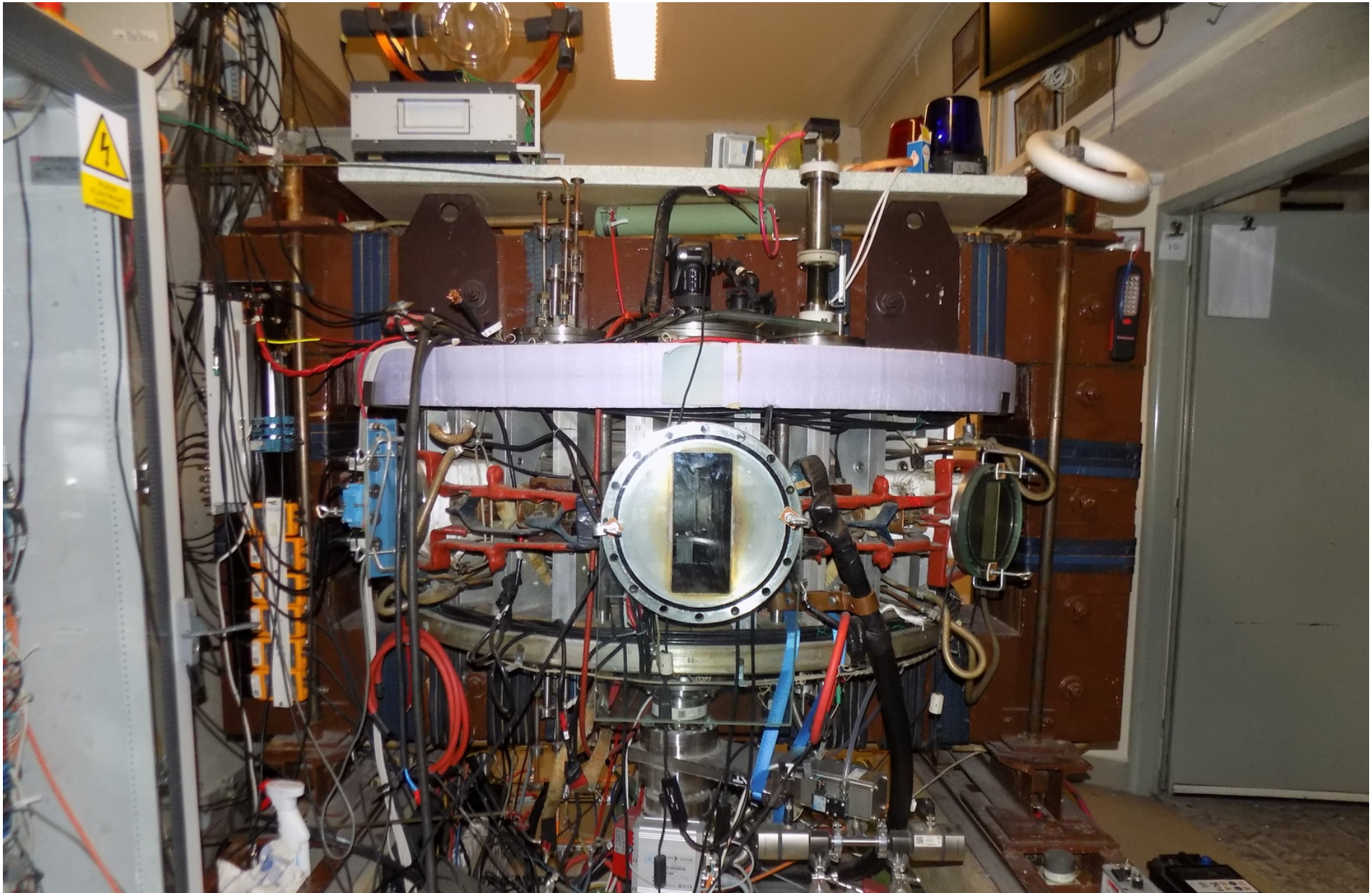
Tokamak room (North) 10/16



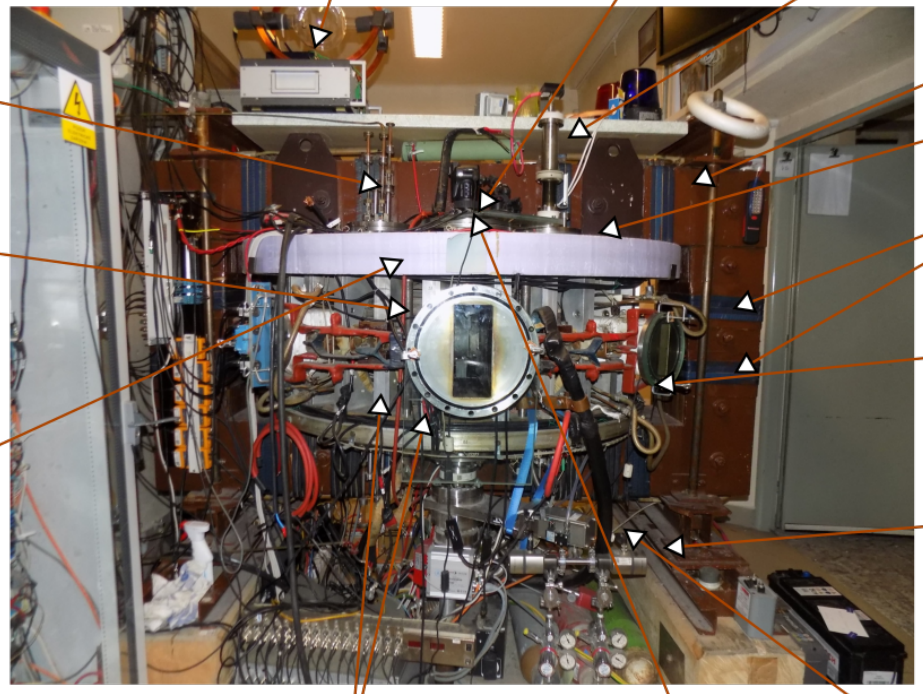
Tokamak room (North) 10/16



Tokamak room (South) 10/16



Tokamak room (South) 10/16



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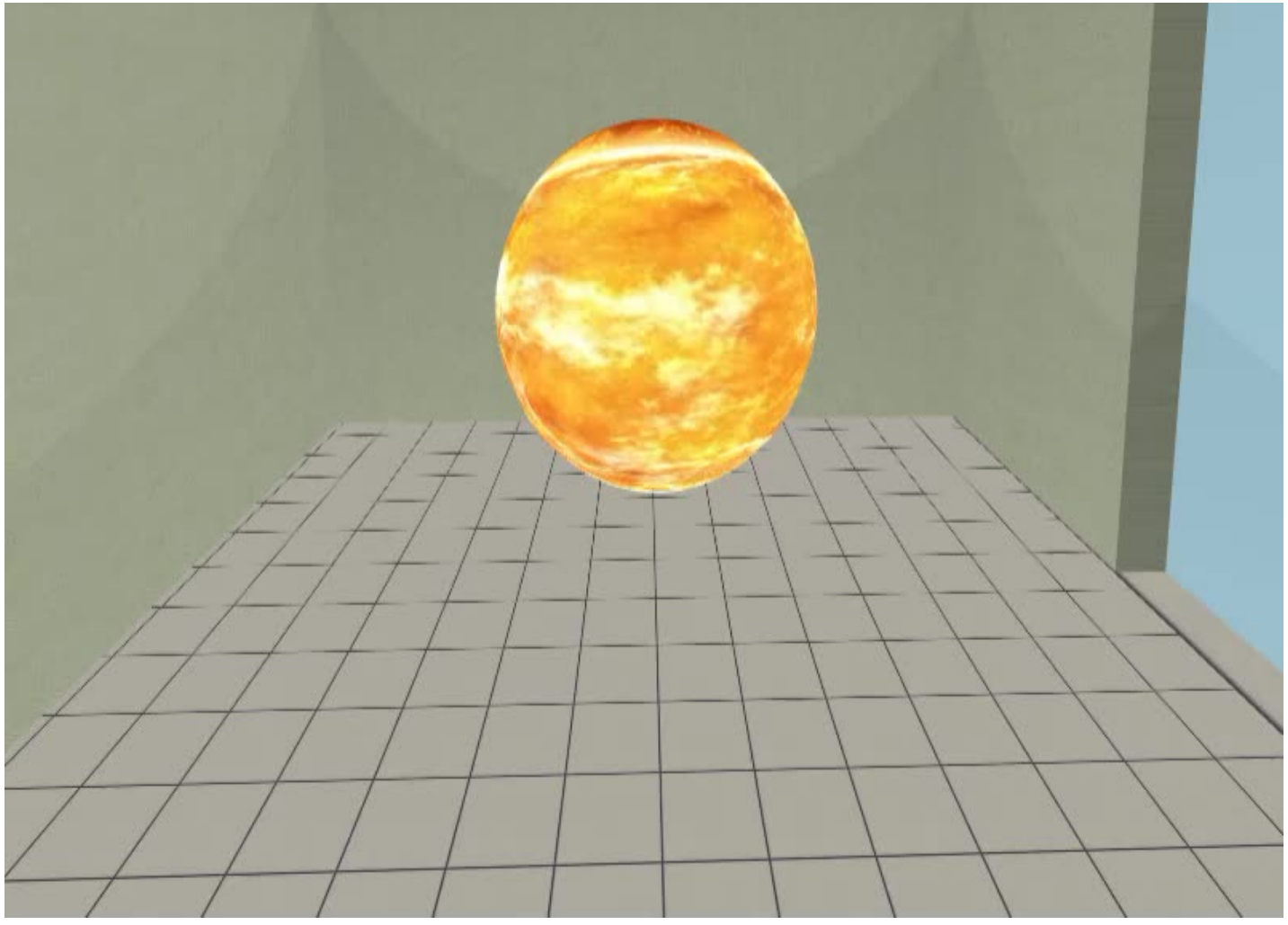
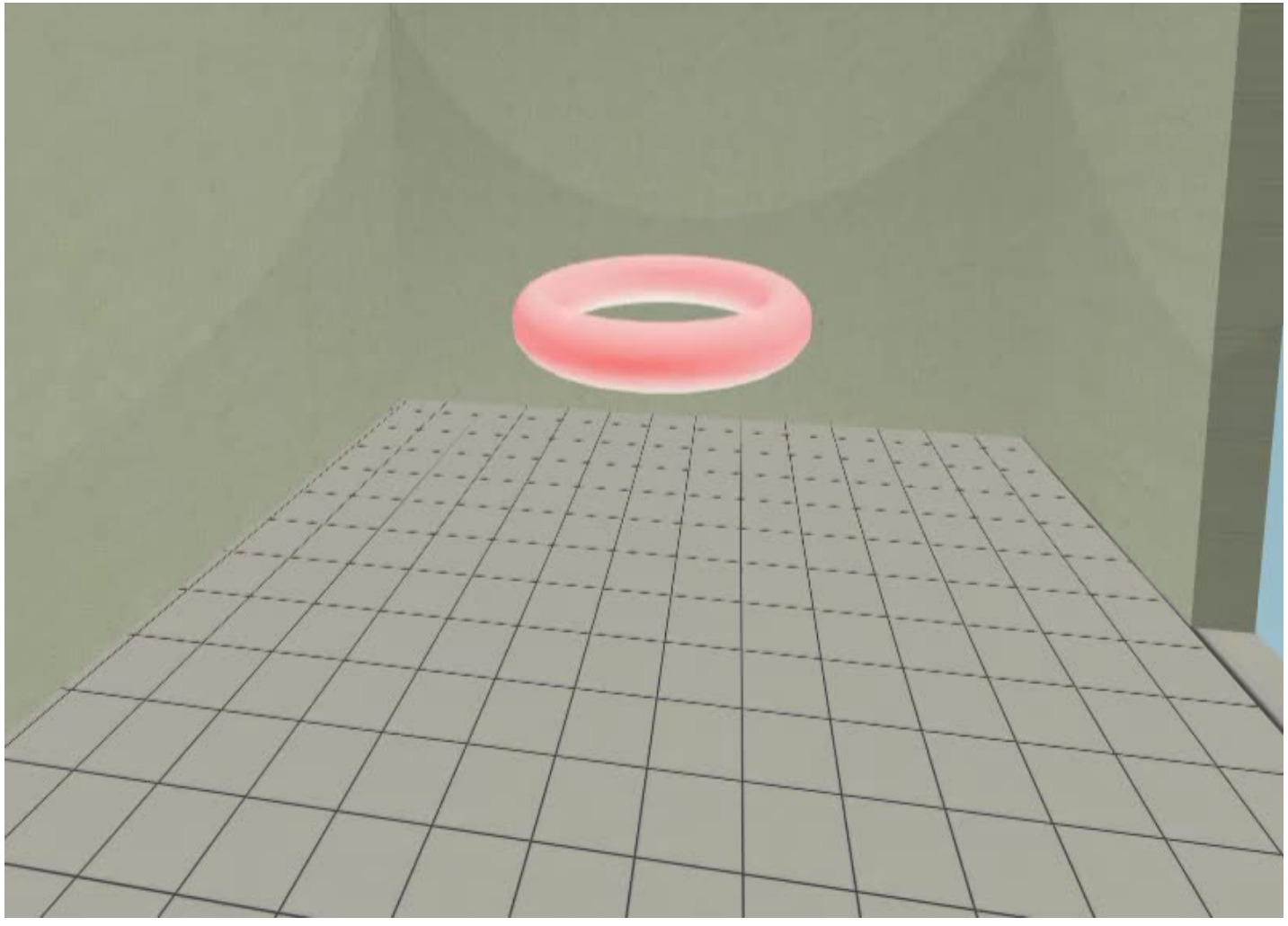
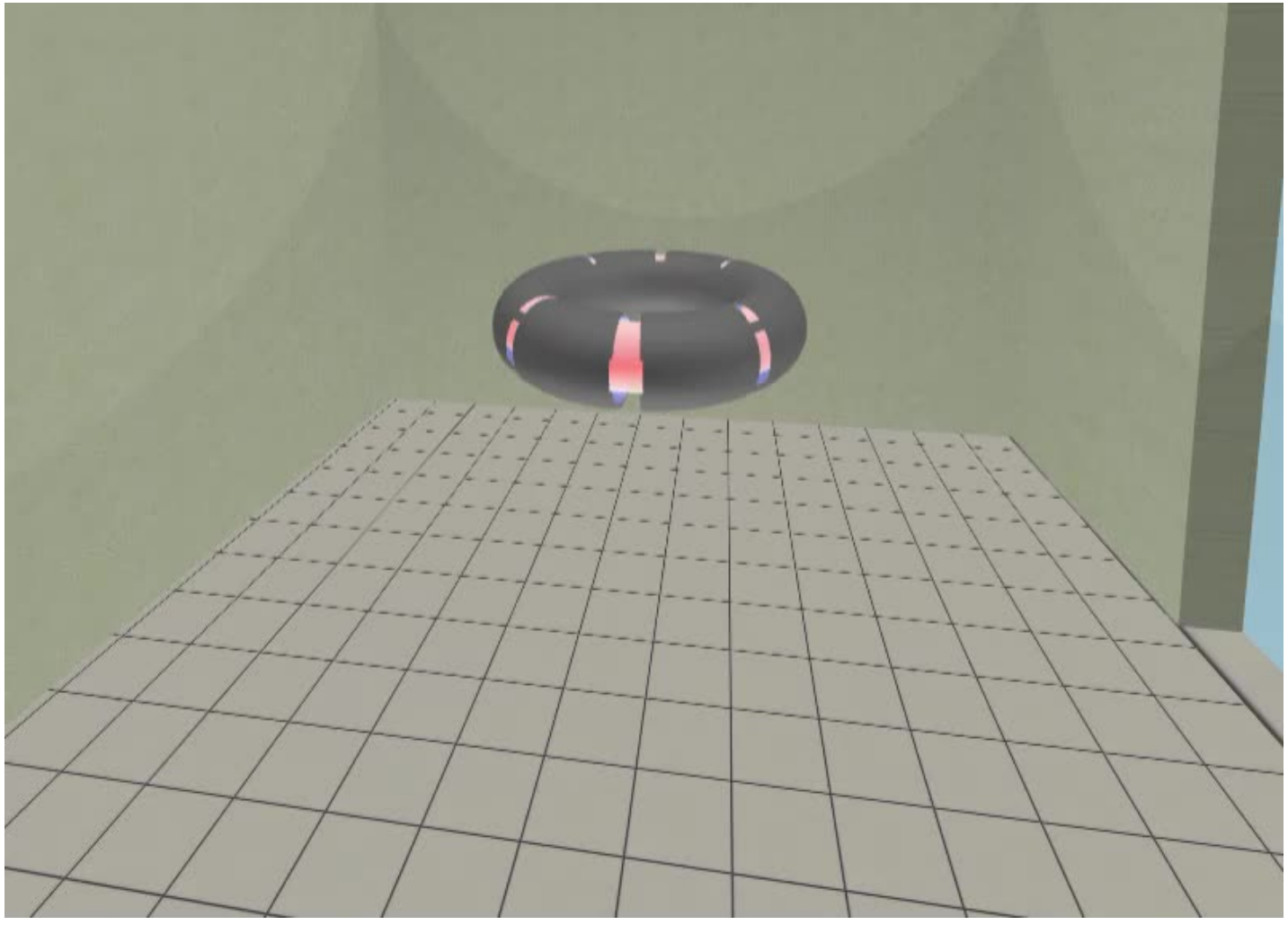
The technology to conquer: make a μSun on the Earth



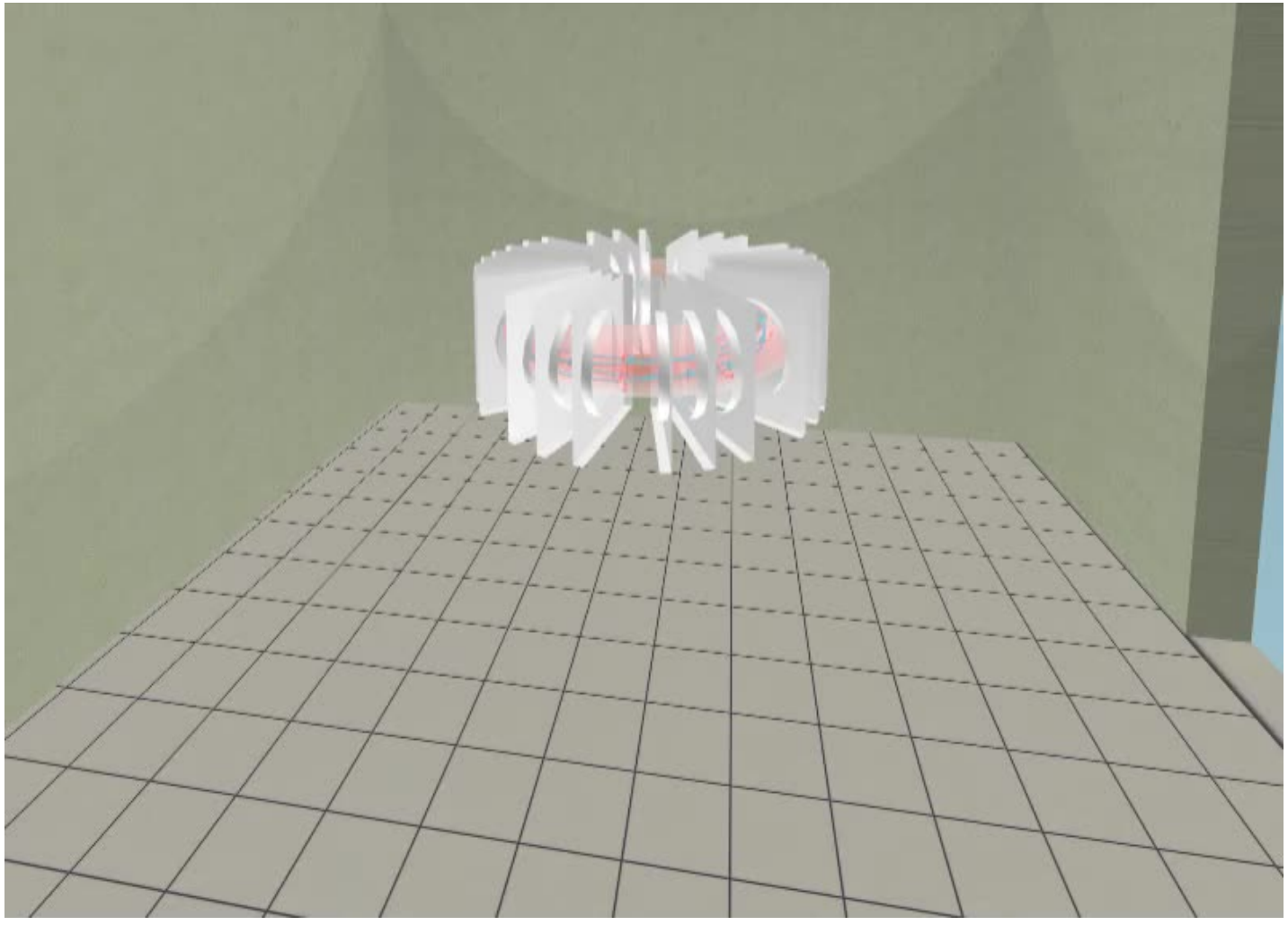
Magnetic confinement requires the toroidal geometry



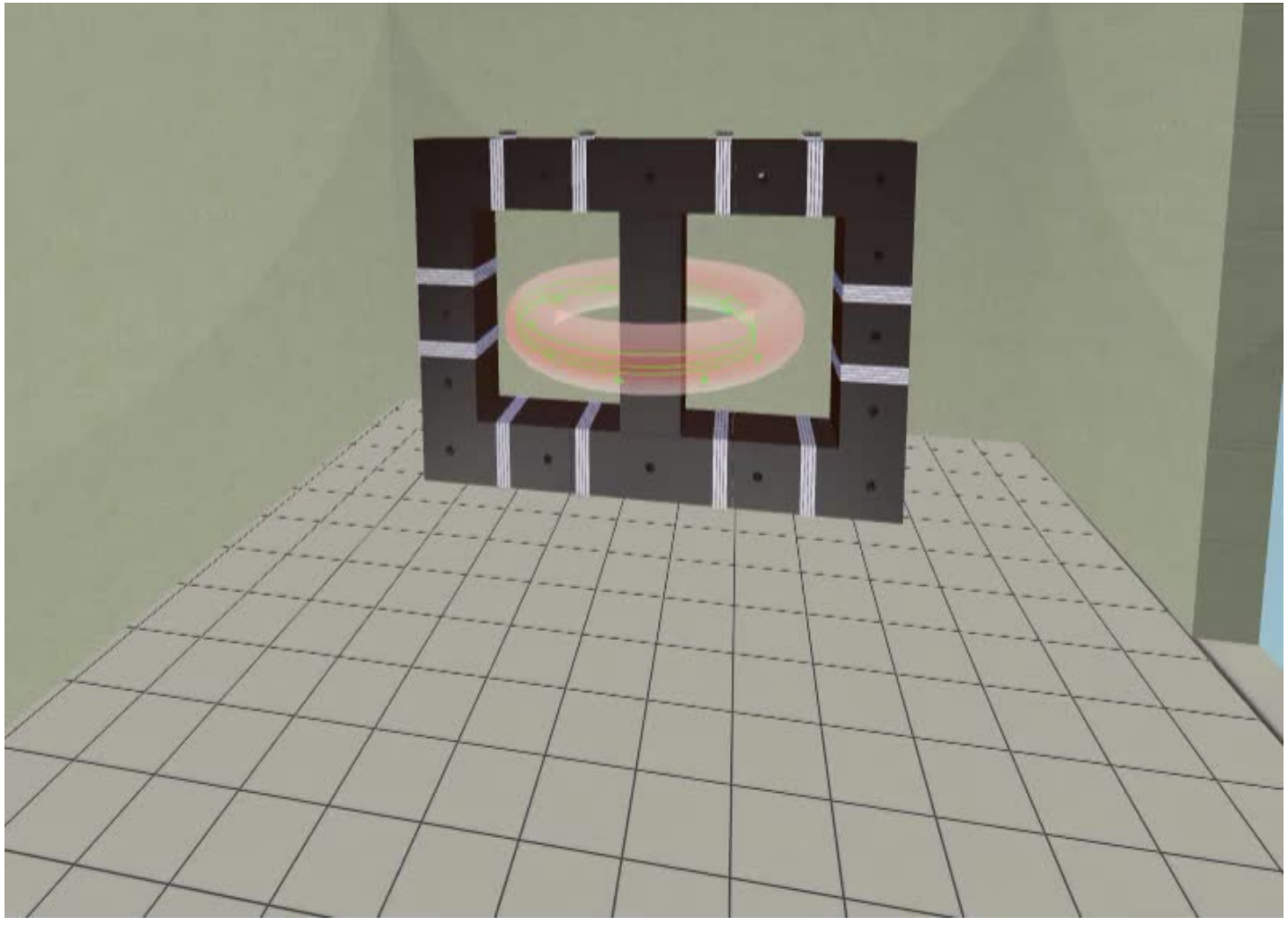
The thermonuclear reaction takes place in the chamber



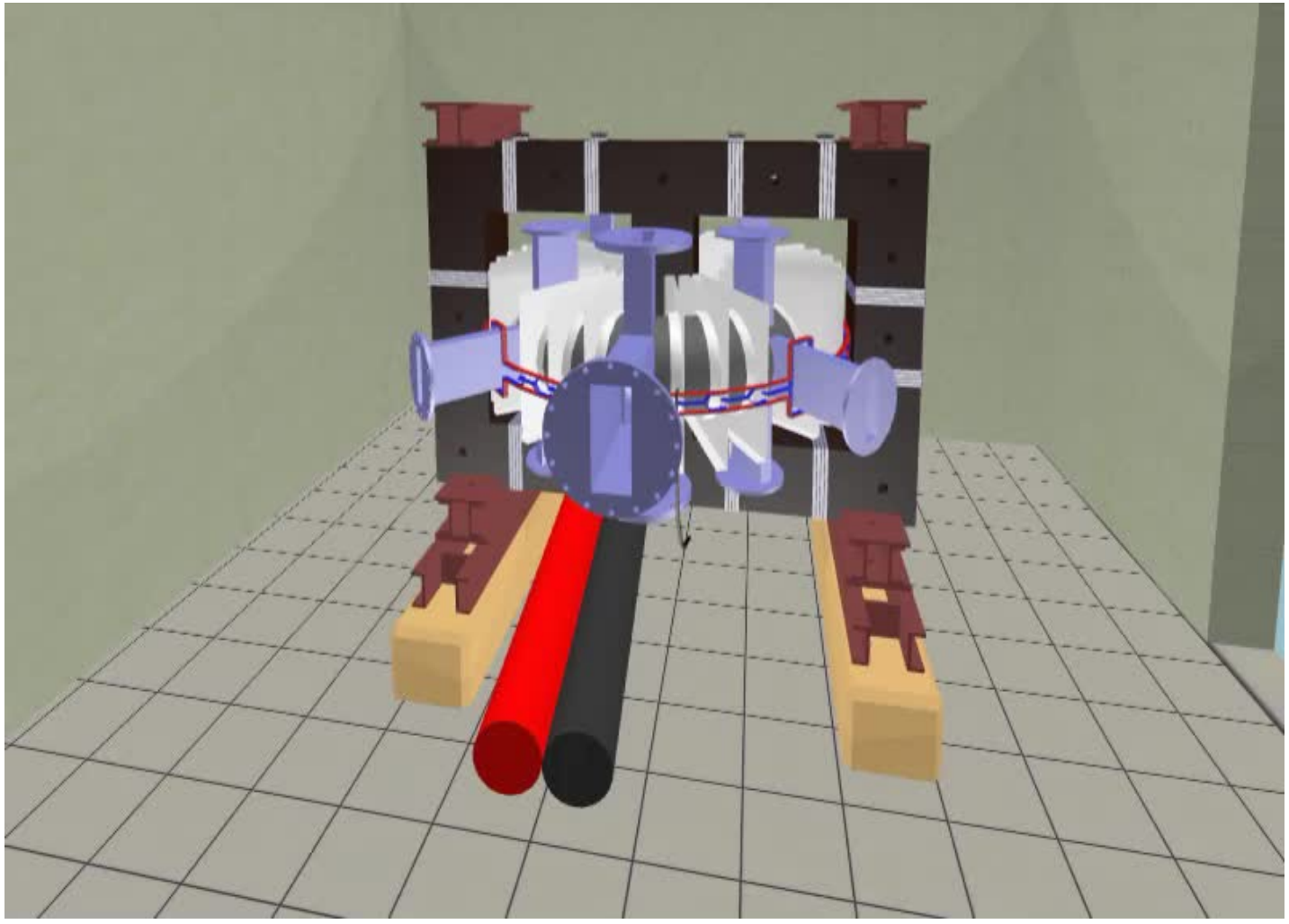
Toroidal magnetic field coils secure the plasma confinement



Transformer secures the plasma creation and heating



The final technology alltogether



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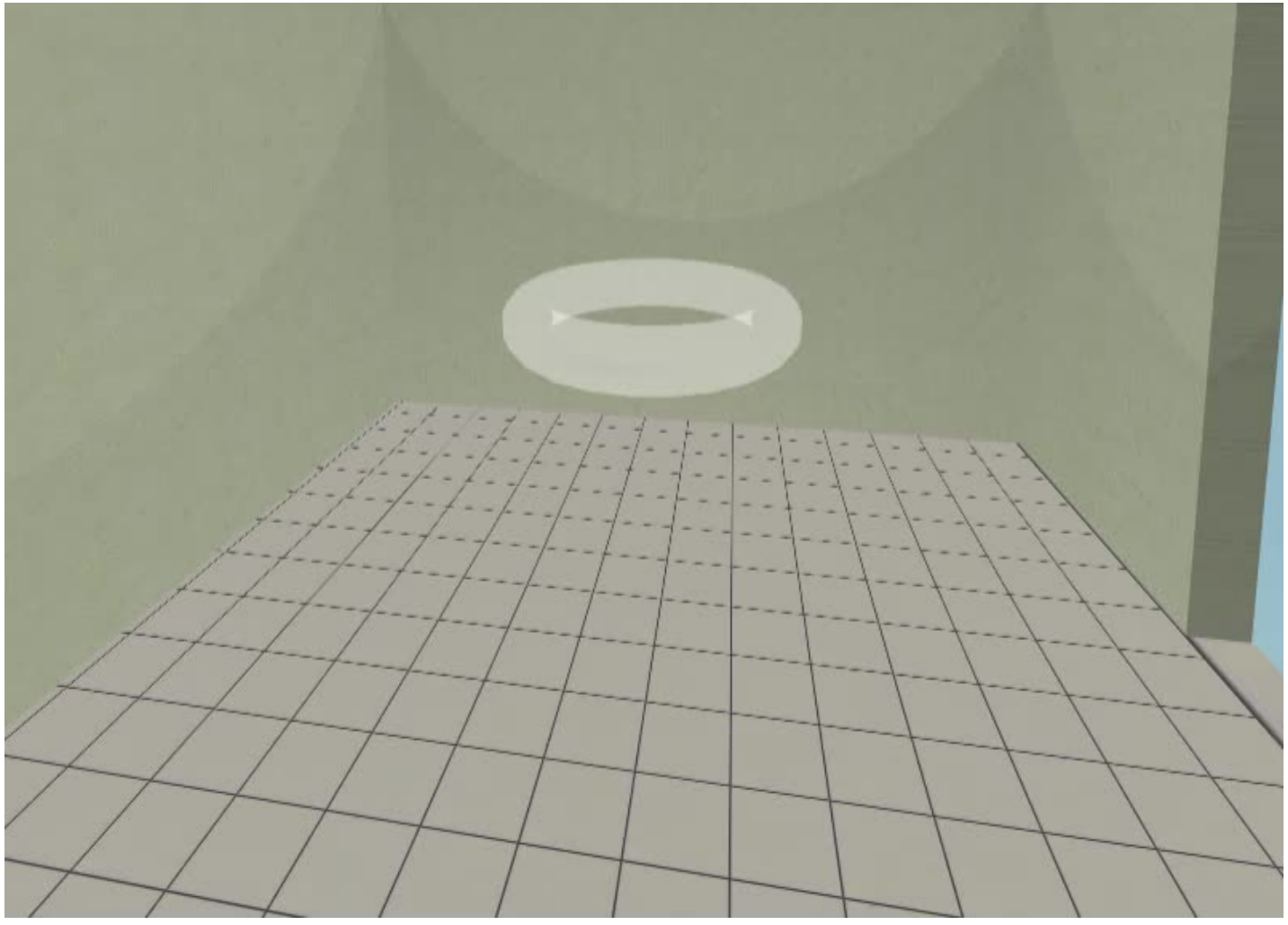
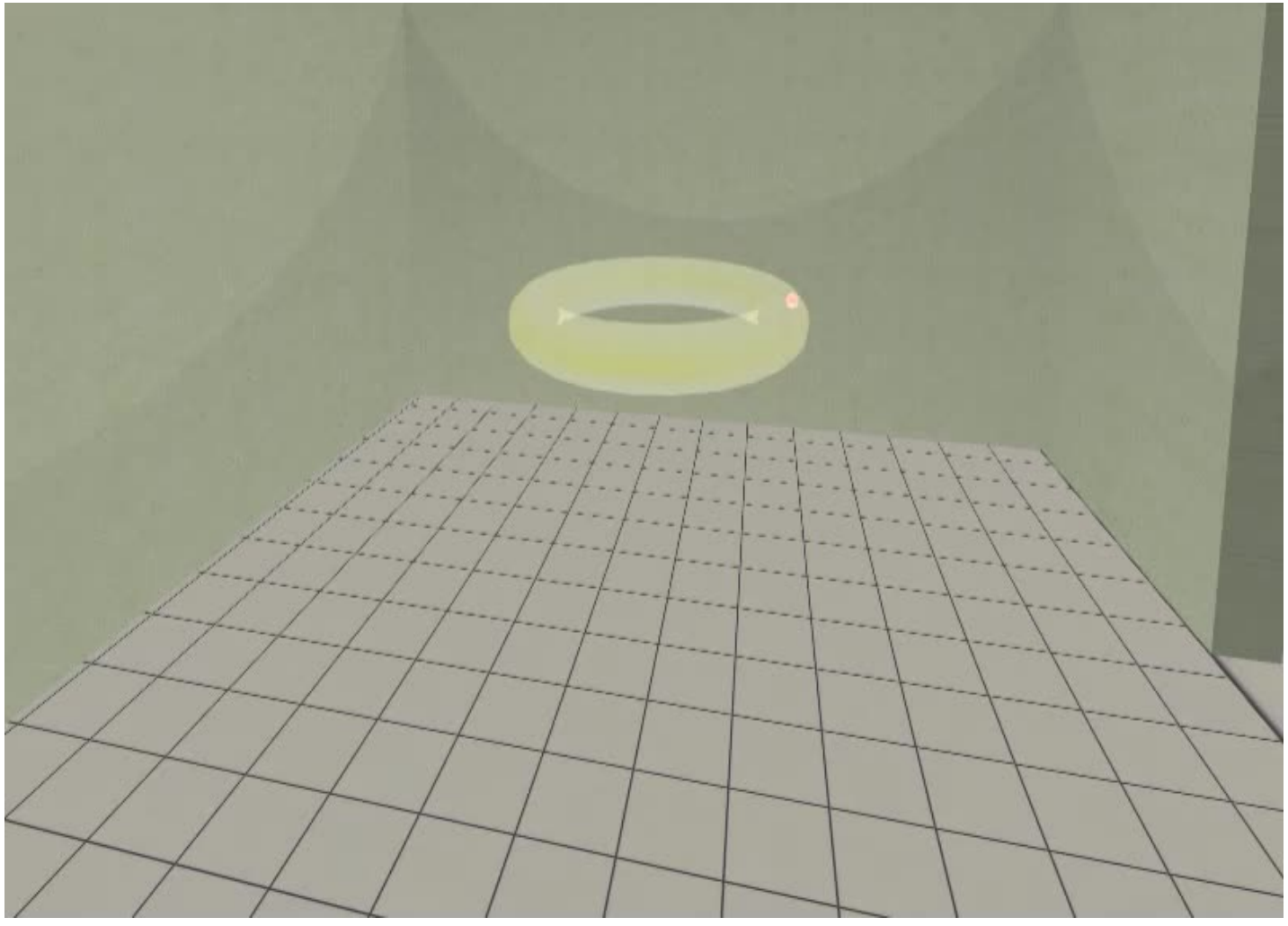
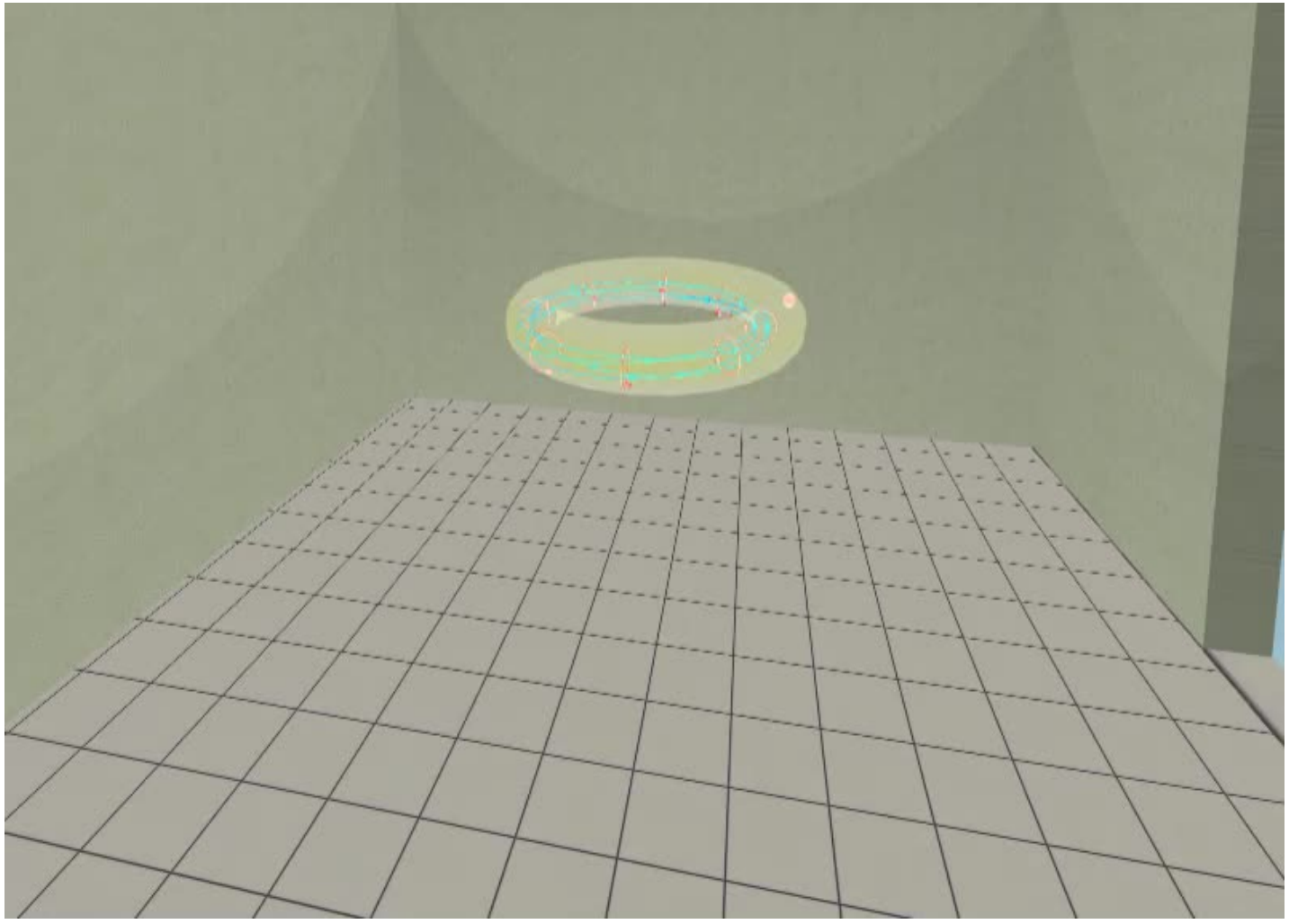
Introduce the working gas (Hydrogen x Helium)



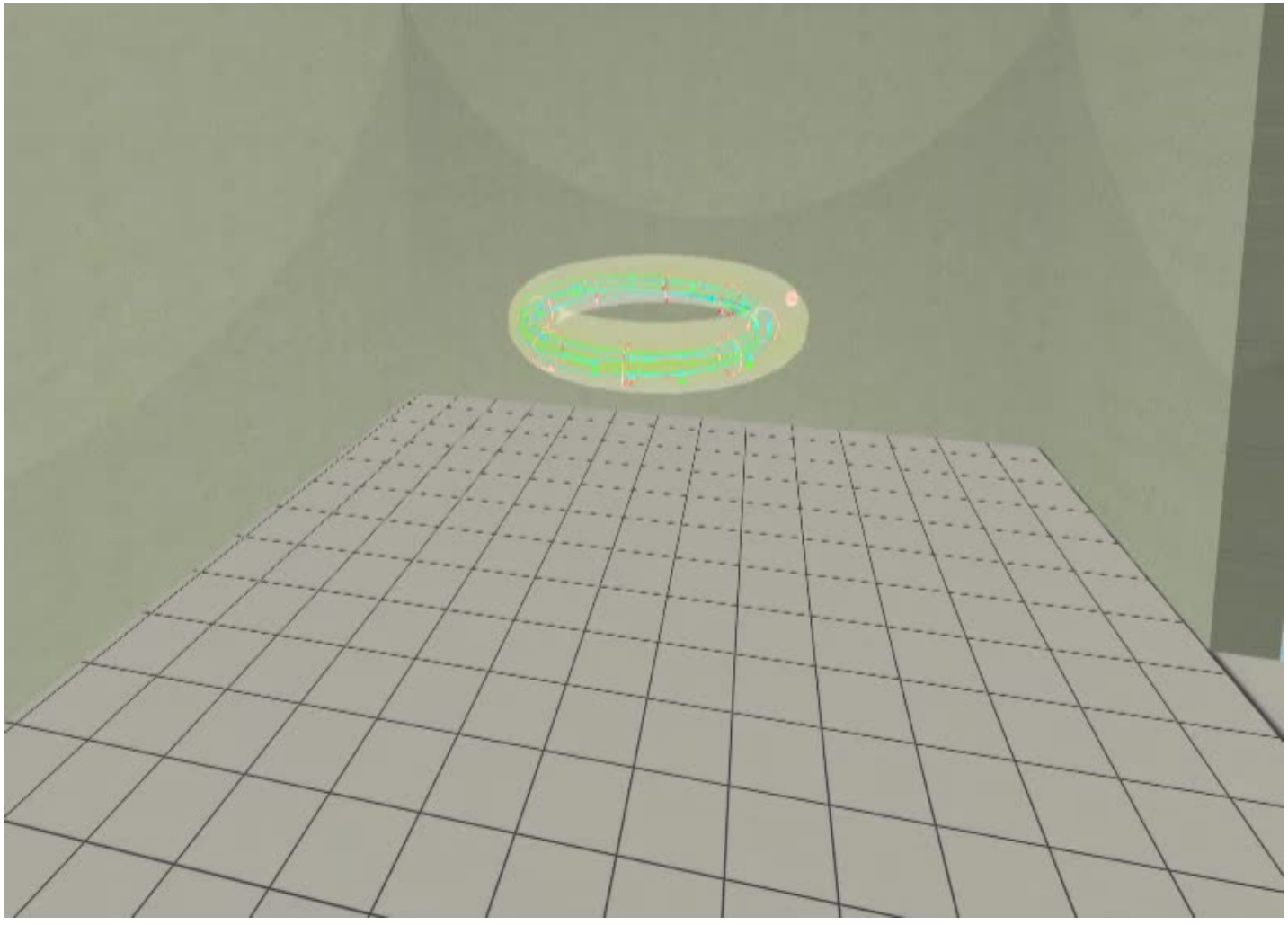
Switch on the preionization



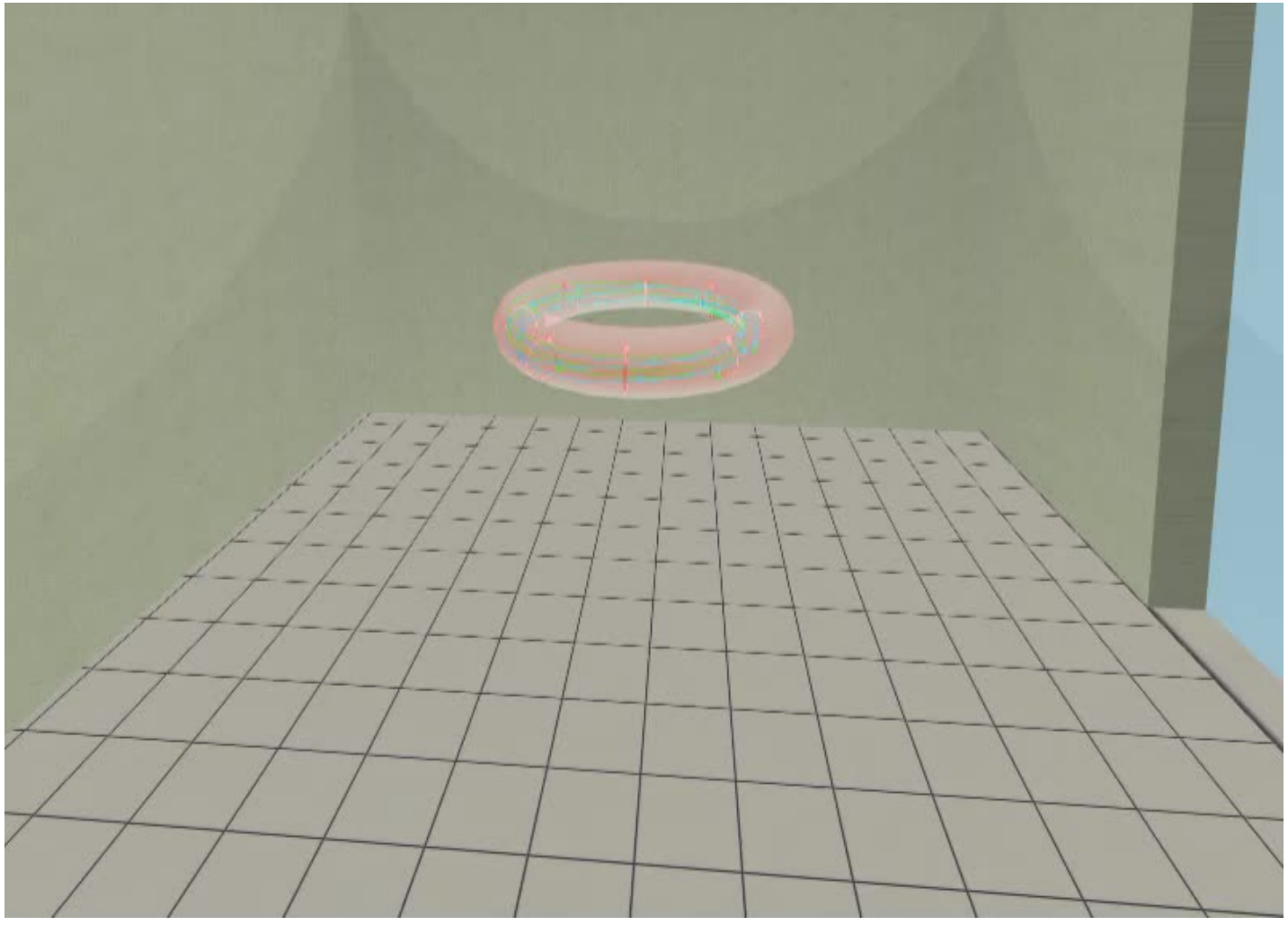
Introduce the magnetic field



Introduce the electric field



Plasma ..



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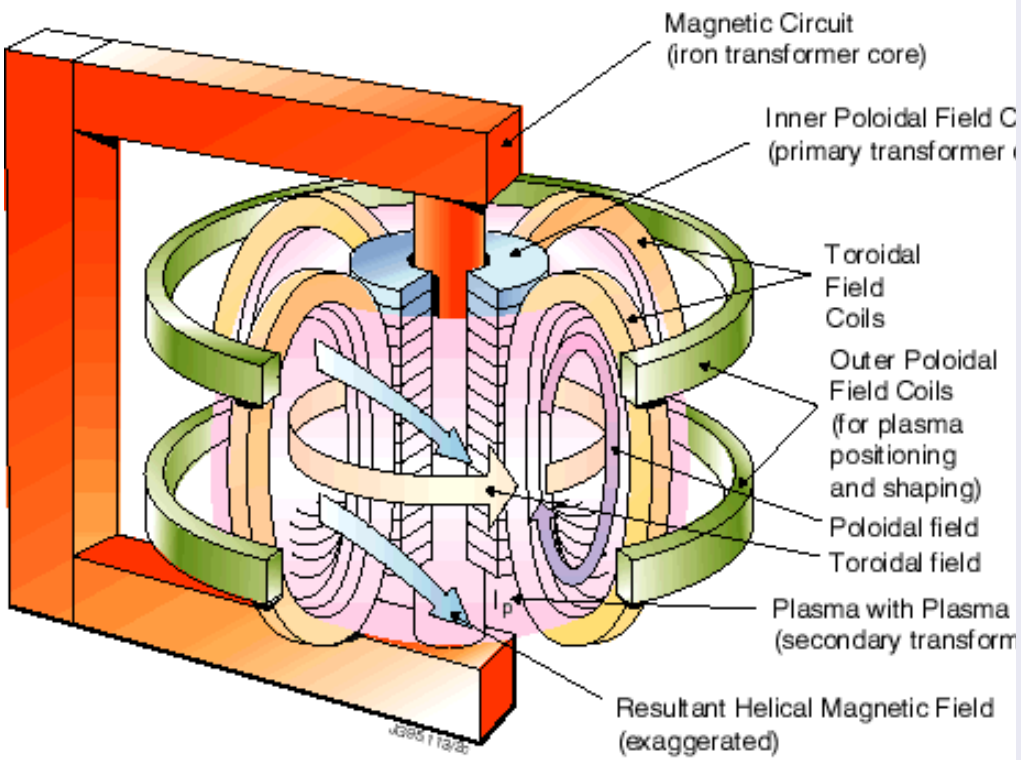
Plasma in Tokamak (GOLEM) - the least to do



To do:

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

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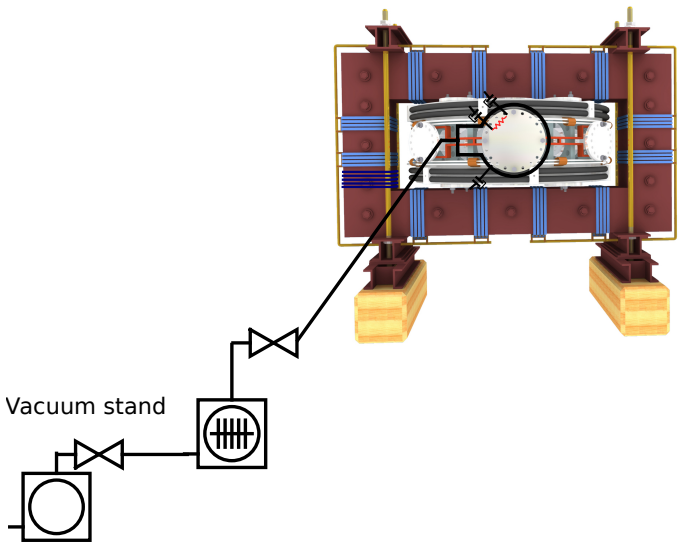

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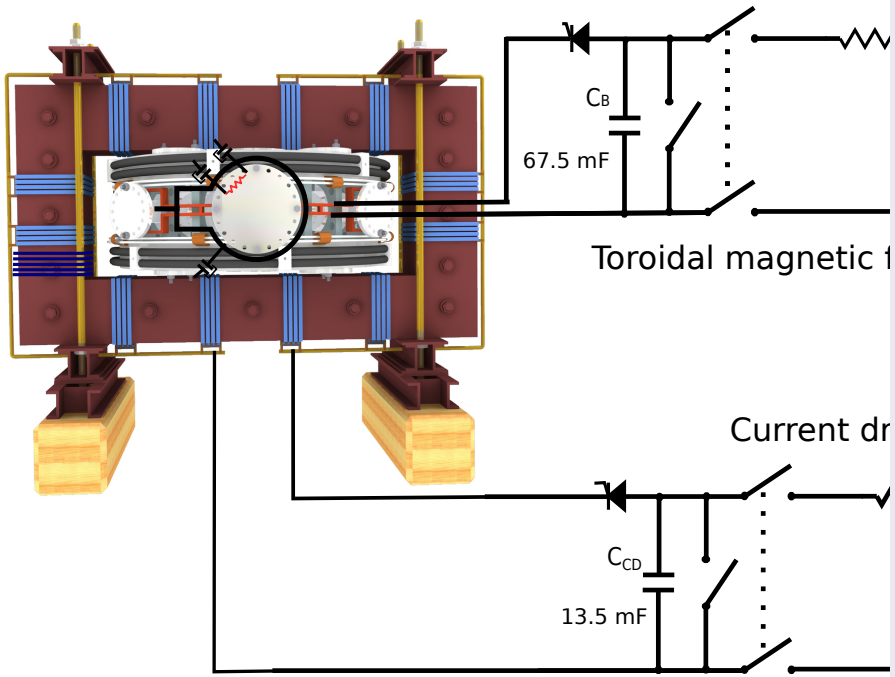

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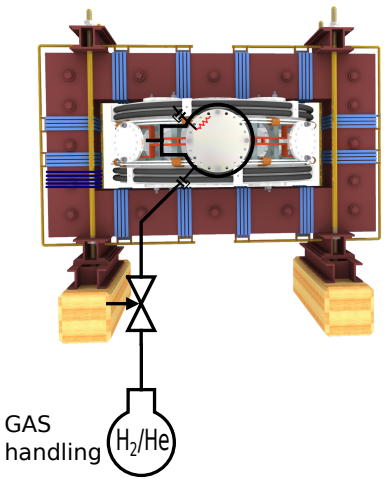

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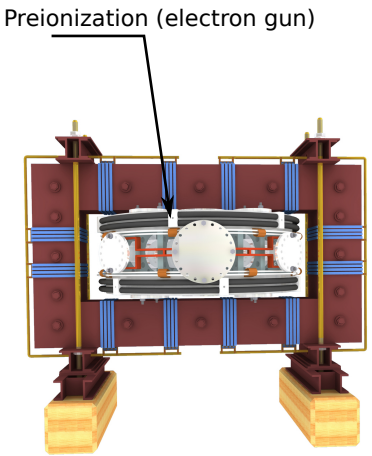

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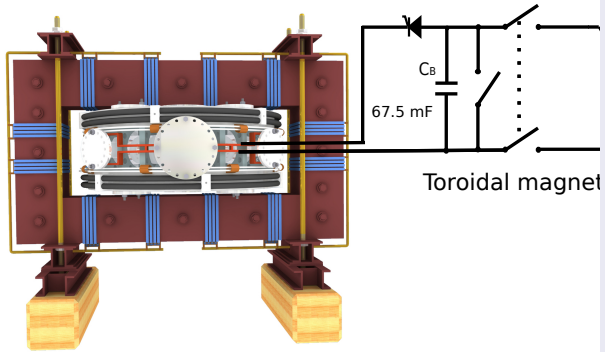

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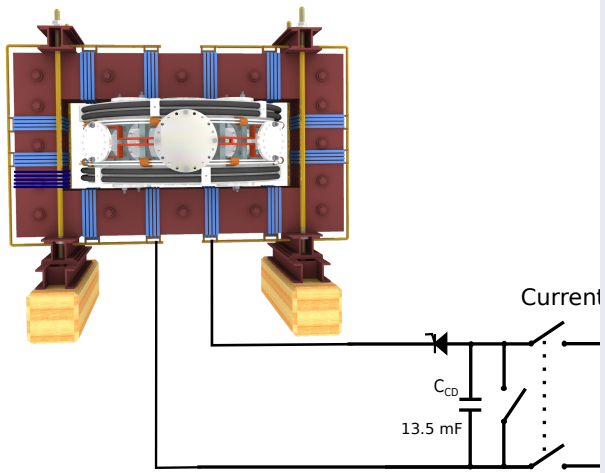

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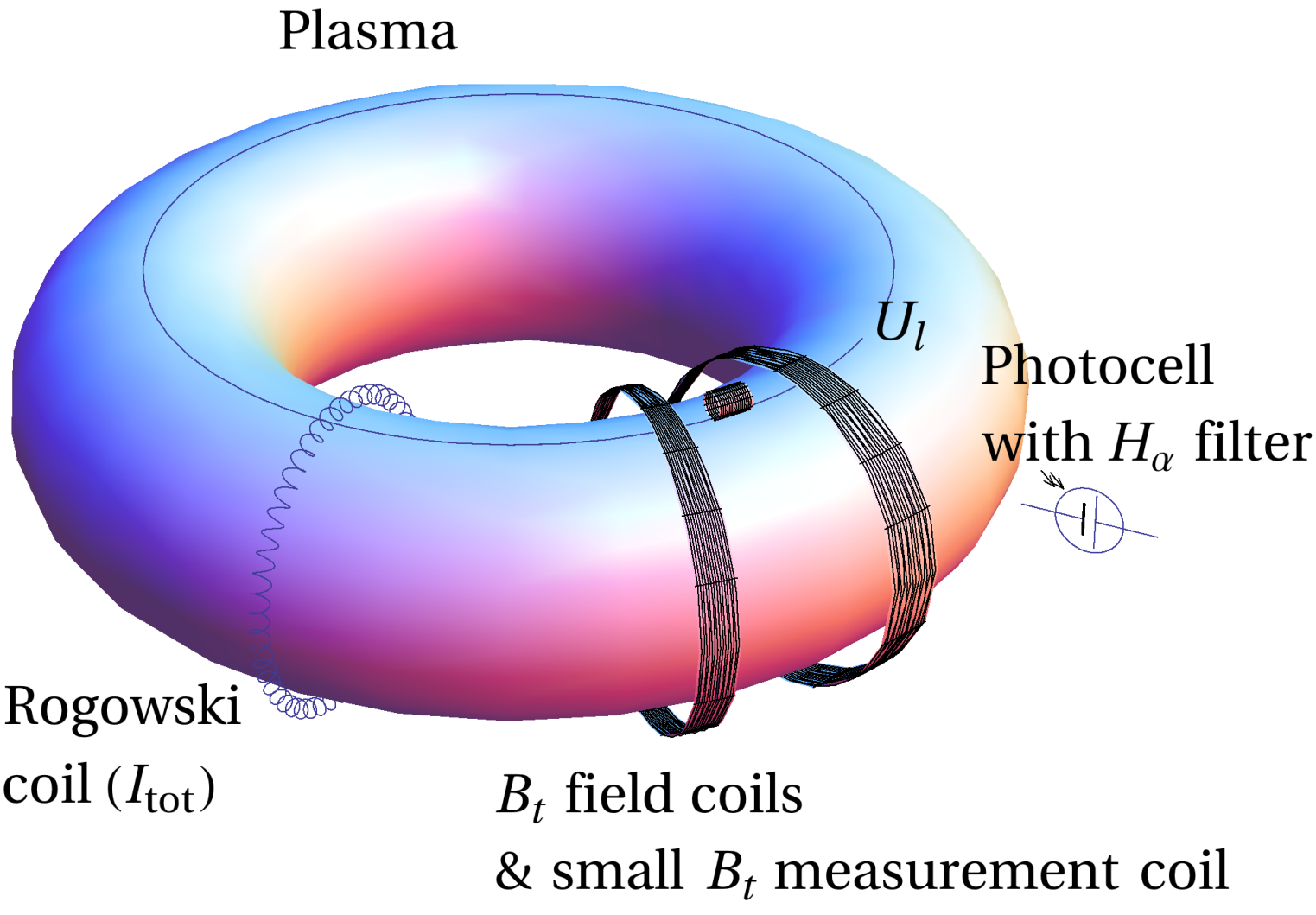
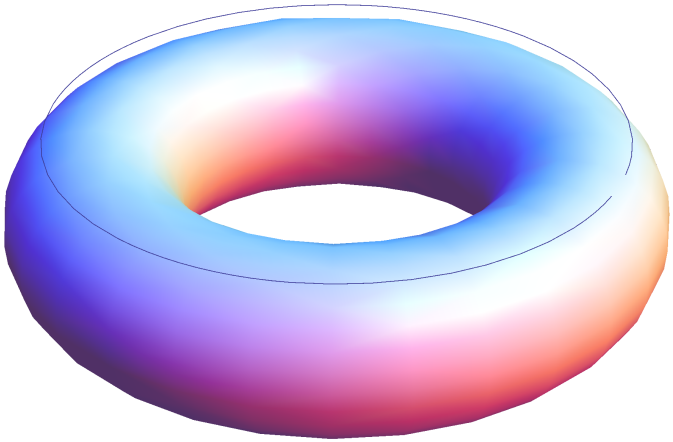
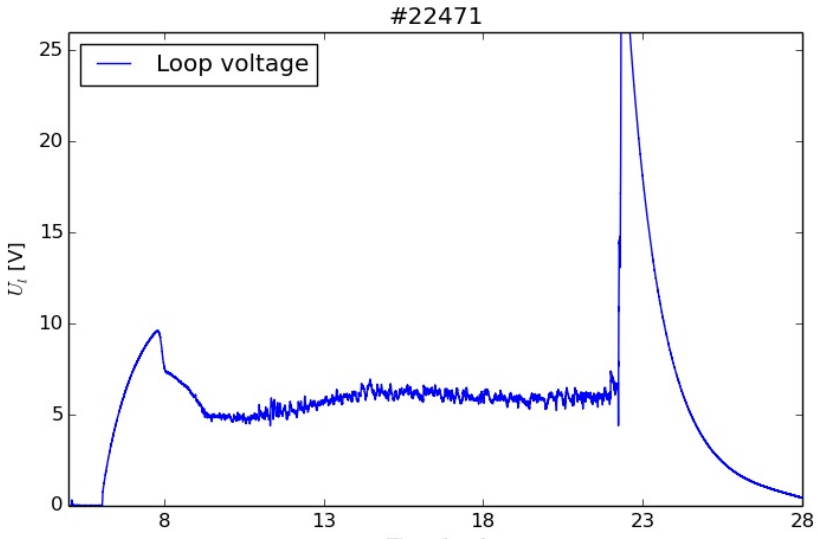
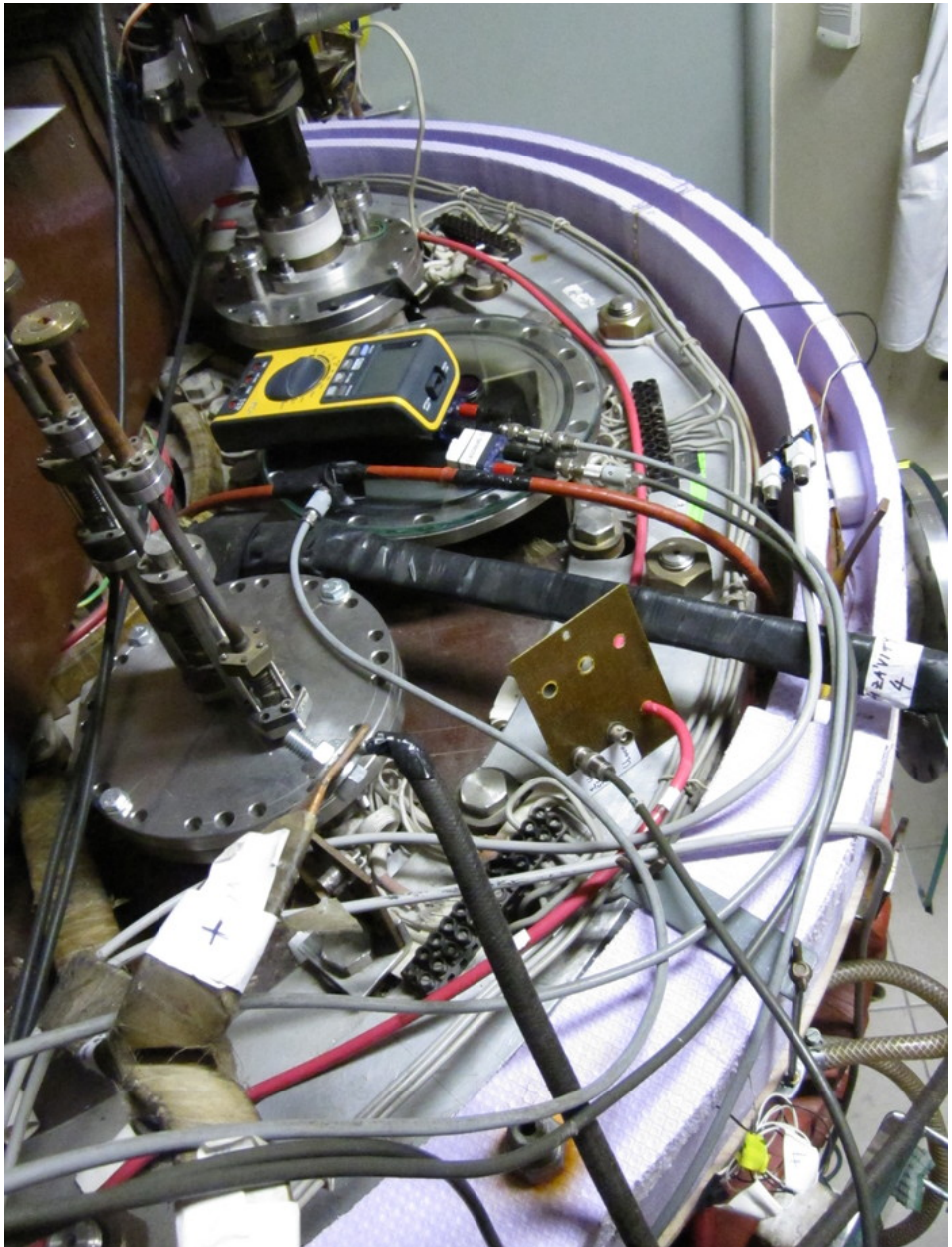
Tokamak GOLEM - basic diagnostics



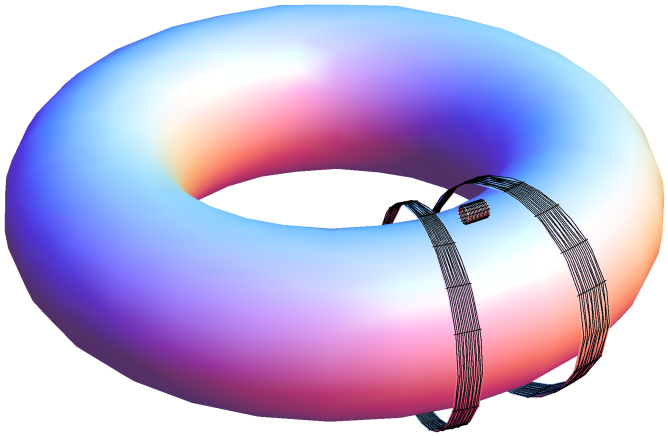
Loop voltage U_l

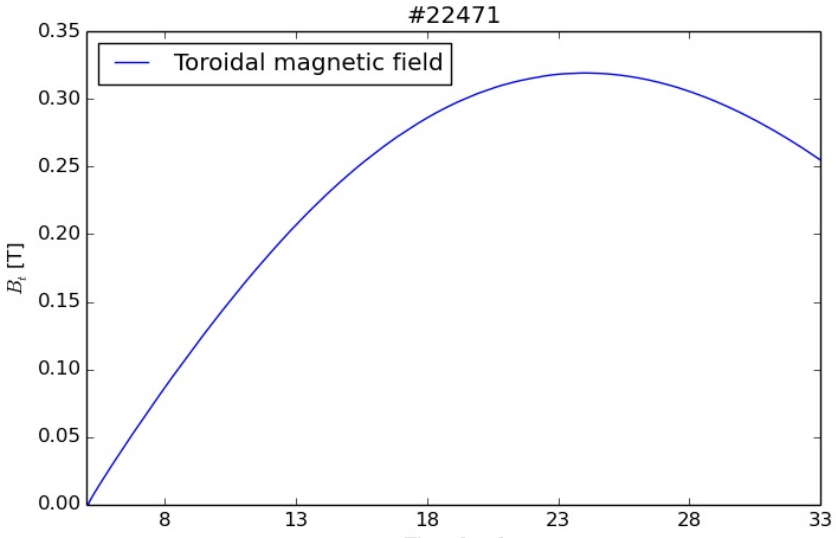


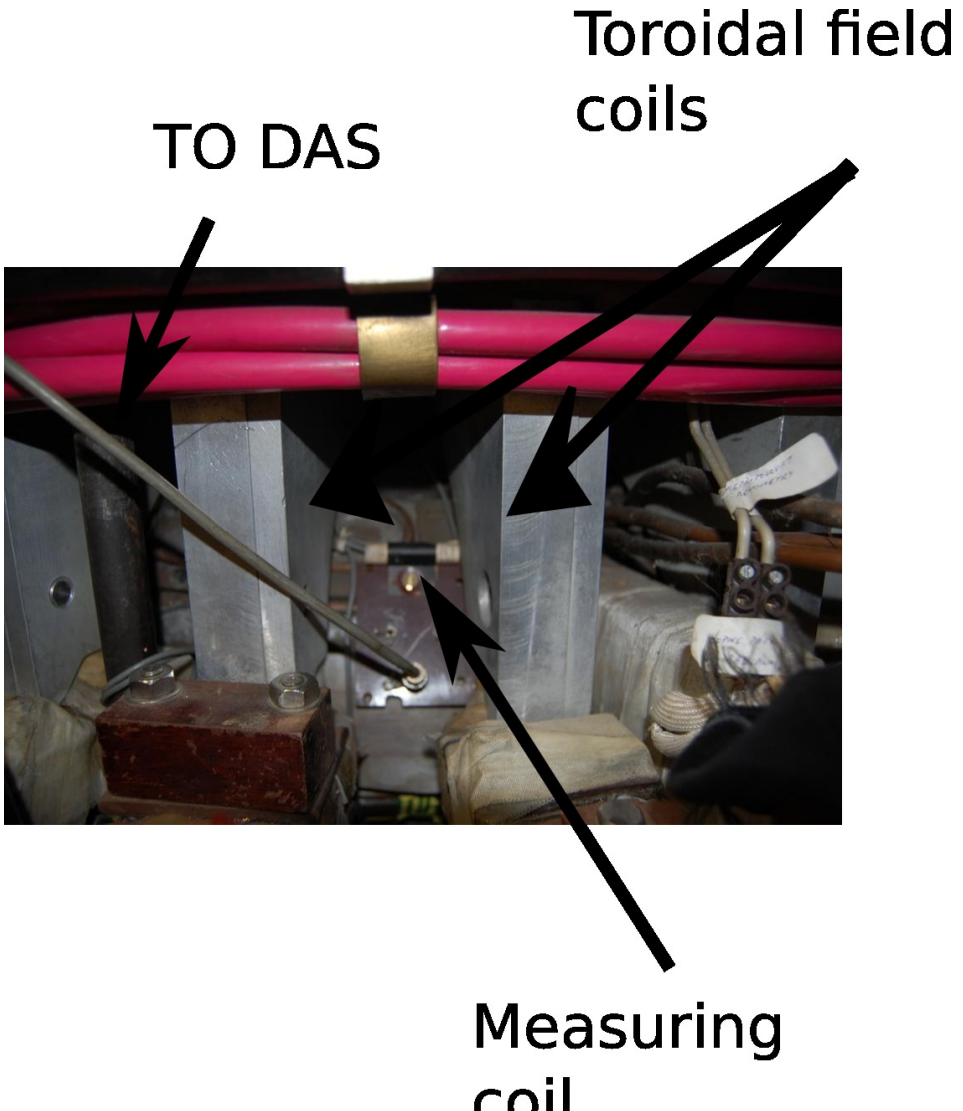




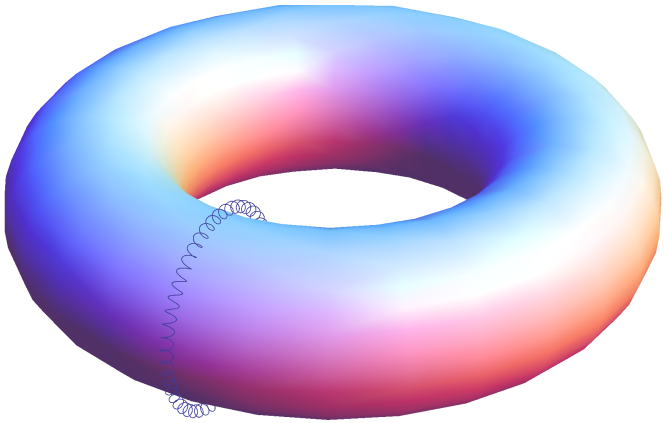
Toroidal magnetic field B_t

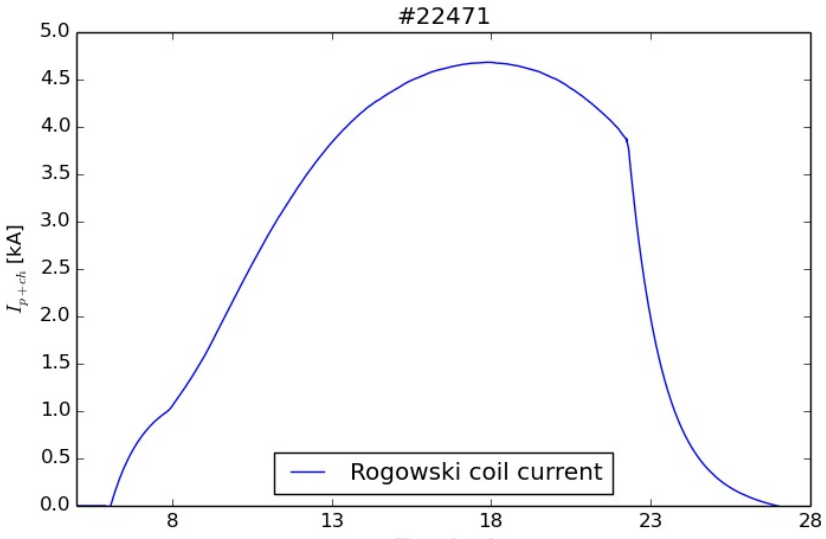


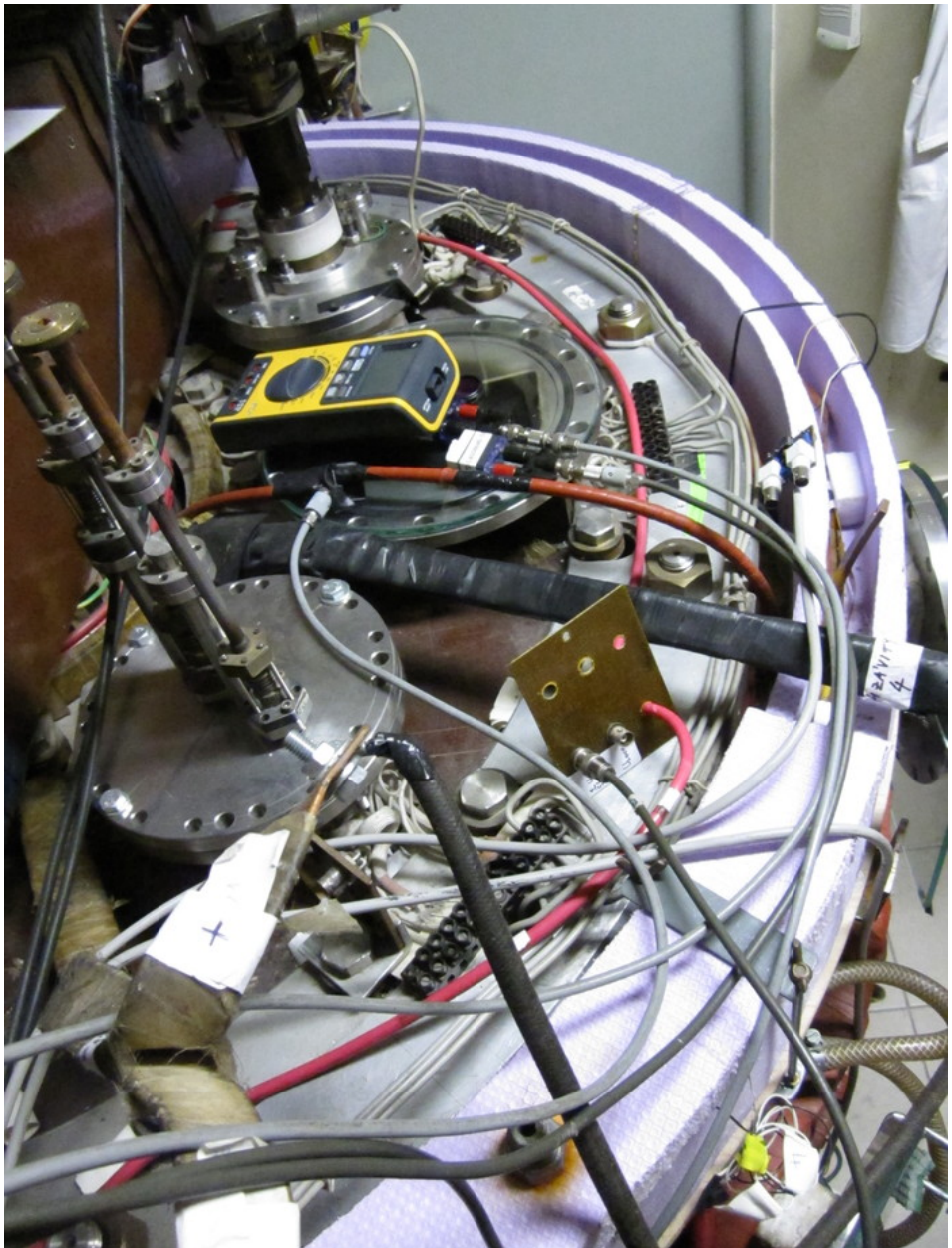




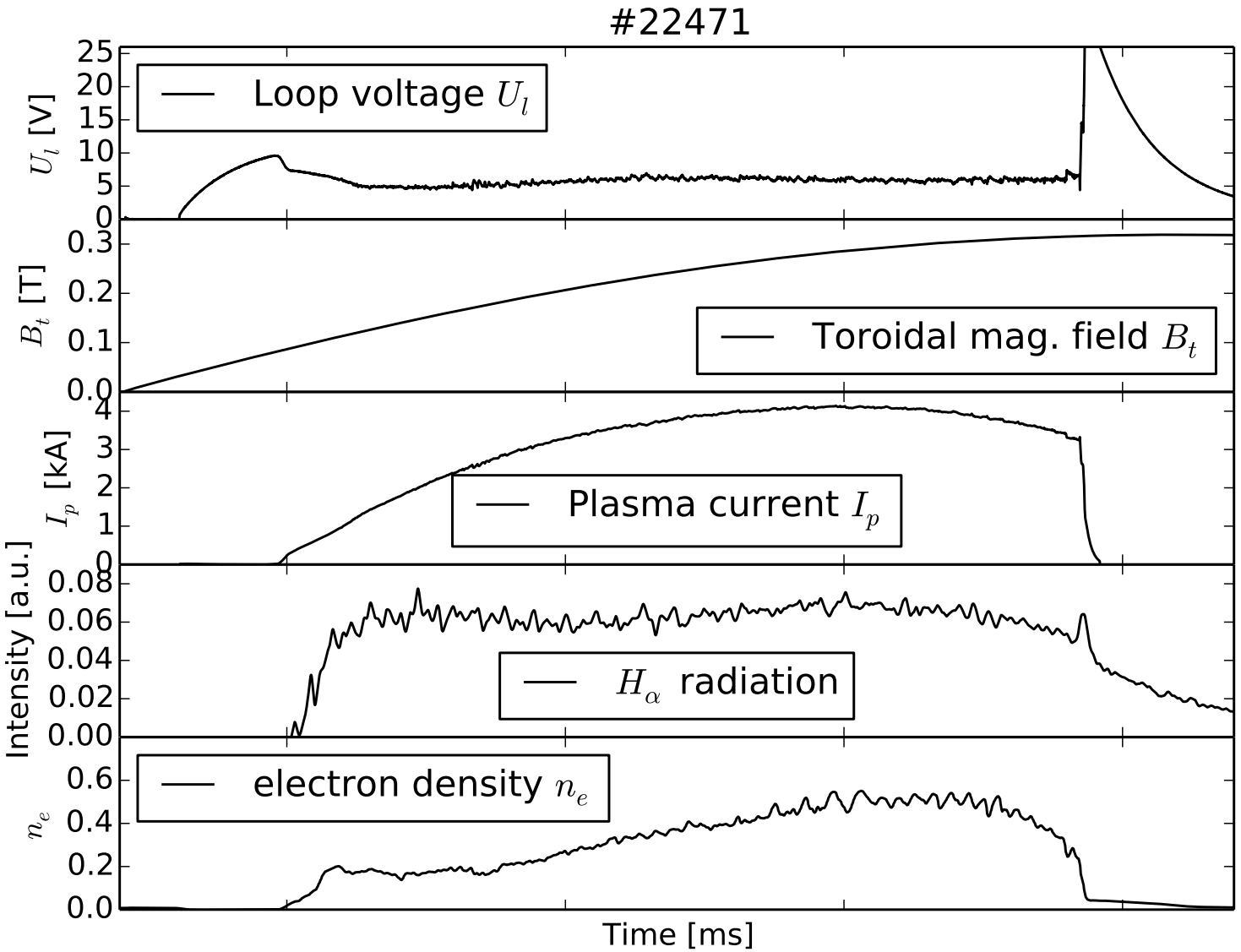
Total current I_{ch+p}



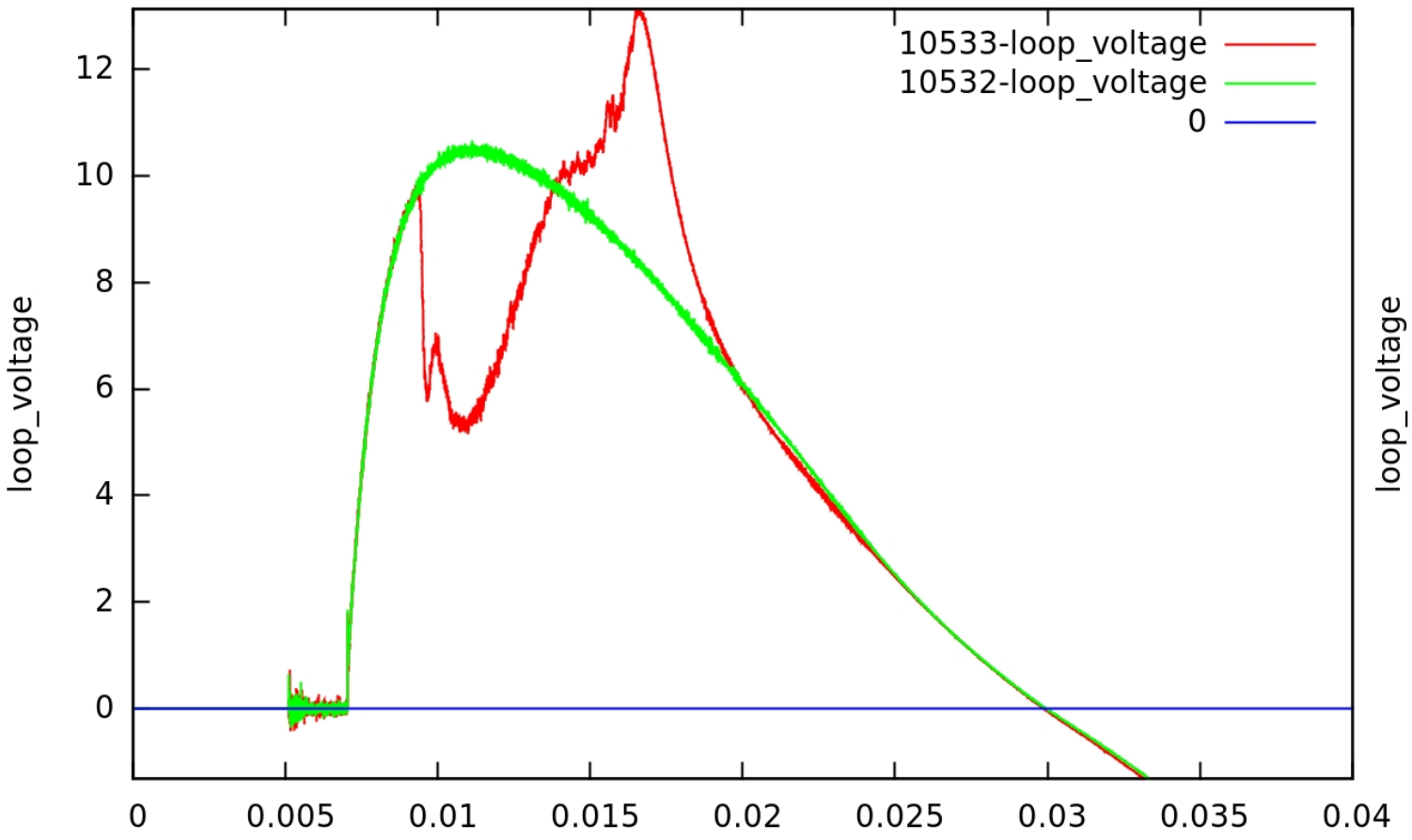




Basic diagnostics @ tokamak GOLEM



Plasma x vacuum discharge



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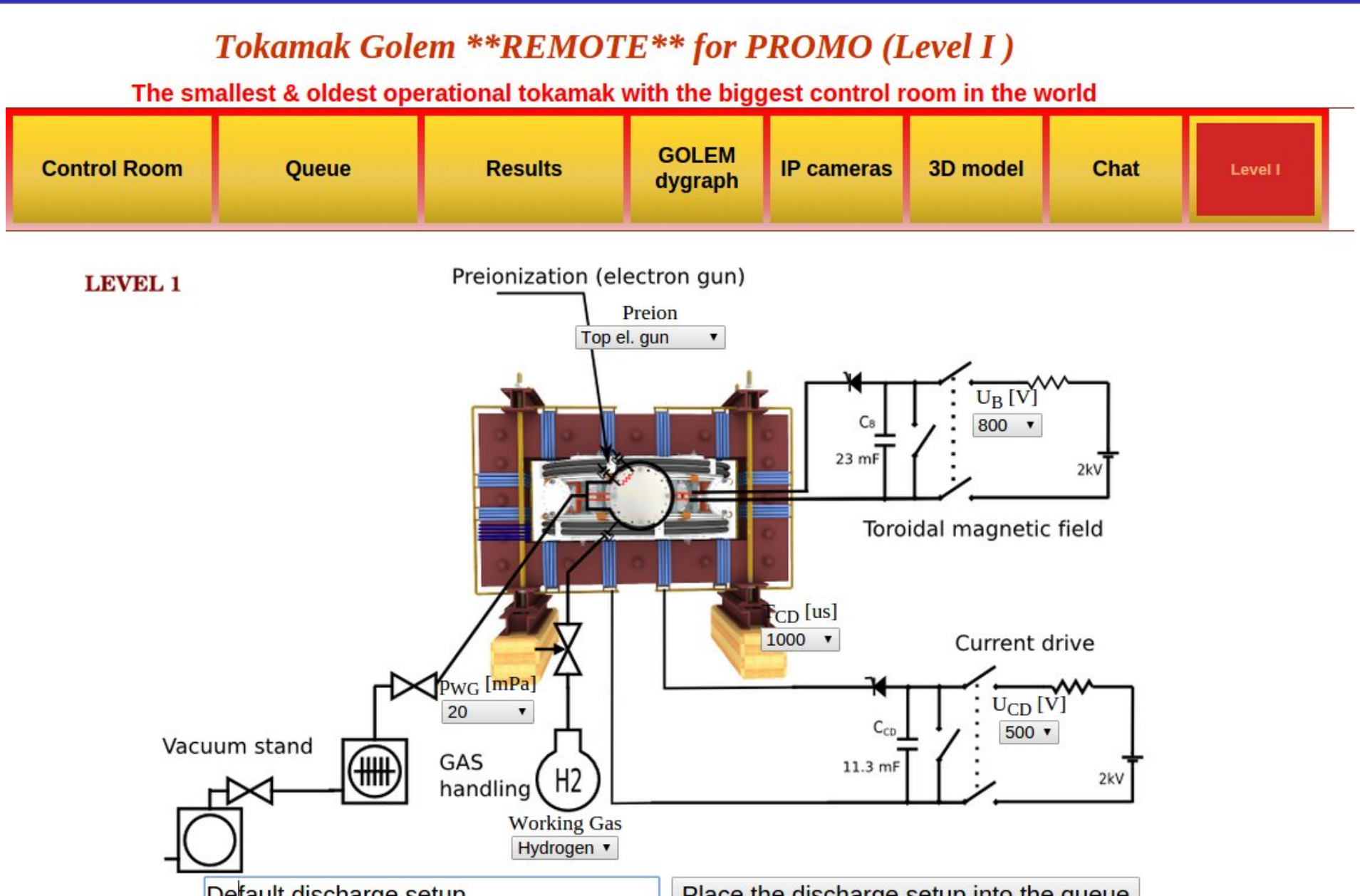
Remote operation



Shot homepage

GOLEM » Shot #22471 »

Tokamak GOLEM - Shot Database - 22471

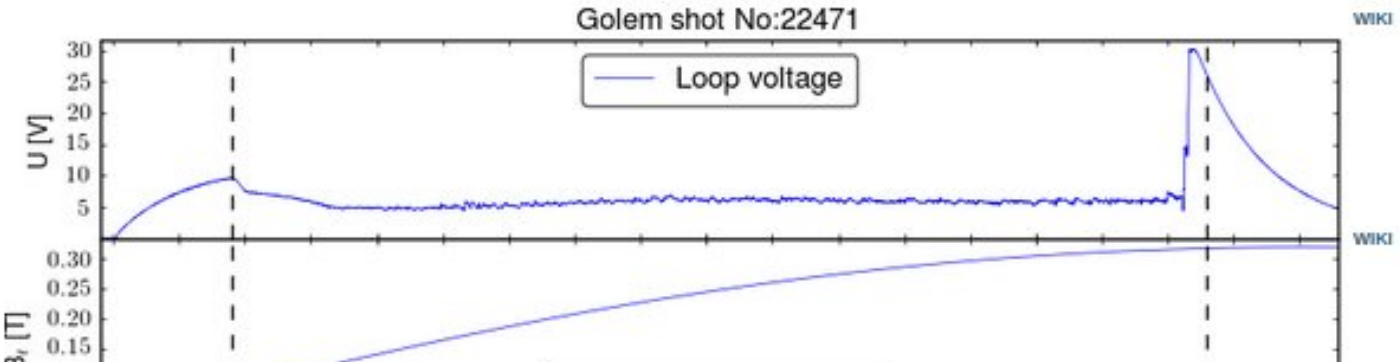
Date: 2016-09-29 - **14:33:57**
Session: TrainingCourses/Universities/Uni_Belgrade.rs/2016/
Comment: `Standard discharge`

Basic parameters: (compare)

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

Plasma parameters:

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



Diagnostics

- ✓ Interferometer
- ✓ Spectrometer
- ✕ FastCamera
- ✓ HXR

Analysis

- ✓ ShotHomepage

DAS

- ✓ TektronixDPO
- ✓ NIstandard
- ✓ Papouch_St
- ✓ Papouch_Ko
- ✓ NIoctopus

Vacuum log

Other

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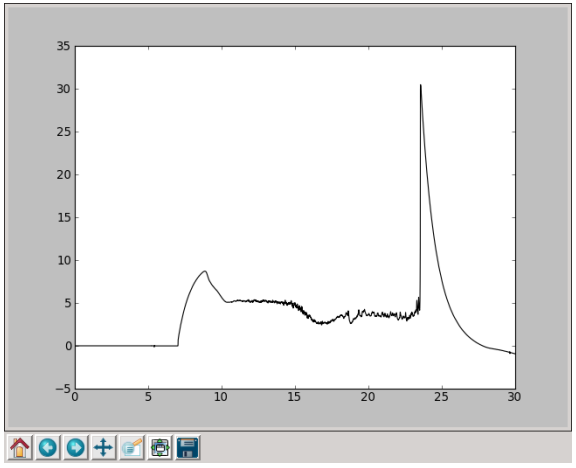
GOLEM **basic** Data Acquisition System (DAS)

- $U_I, U_{B_t}, U_{I_{p+ch}}, I_{rad}$
- $\Delta t = 1\mu s / \ f = 1MHz$.
- Integration time = 40 ms, thus DAS produces 6 colums x 40000 rows data file.
- Discharge is triggered at 5th milisecond after DAS to have a zero status identification.

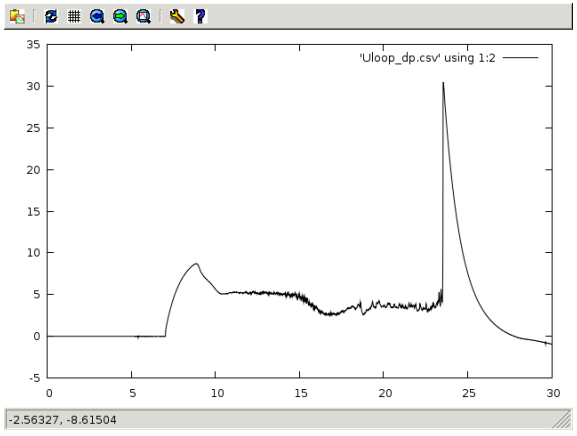
Data file example, DAS $\Delta t = 1\mu s/f = 1MHz$ (neutral gas into plasma breakdown focused)

t	$\approx U_I$	$\approx U_{\frac{dB_T}{dt}}$	$\approx U_{\frac{d(I_{p+ch})}{dt}}$	$\approx I_{rad}$
:	:	:	:	:
:	:	:	:	:
first	$\approx$	7405	lines ..	
:	:	:	:	:
:	:	:	:	:
0.007383	1.53931	0.390015	0.048828	0.001831
0.007384	1.53686	0.395508	0.067749	0.00061
0.007385	1.54053	0.391235	0.079956	0.00061
0.007386	1.53686	0.38147	0.072632	0
0.007387	1.54297	0.397949	0.059204	0.00061
0.007388	1.54053	0.384521	0.05249	0.00061
0.007389	1.54053	0.39856	0.068359	0.001221
0.00739	1.54053	0.393677	0.082397	0.001221
0.007391	1.53809	0.38208	0.072632	0.001221
0.007392	1.54297	0.400391	0.056763	0.00061
0.007393	1.54419	0.383911	0.053101	0.00061
0.007394	1.53931	0.397339	0.068359	0.001221
0.007395	1.54297	0.391846	0.084229	0.00061
0.007396	1.54541	0.394897	0.074463	0.00061
0.007397	1.54297	0.388184	0.056763	0.001221
0.007398	1.54297	0.391846	0.056763	0.00061
0.007399	1.54297	0.394287	0.06897	0.00061
:	:	:	:	:
:	:	:	:	:
next	$\approx$	32500	lines ..	
:	:	:	:	:
:	:	:	:	:

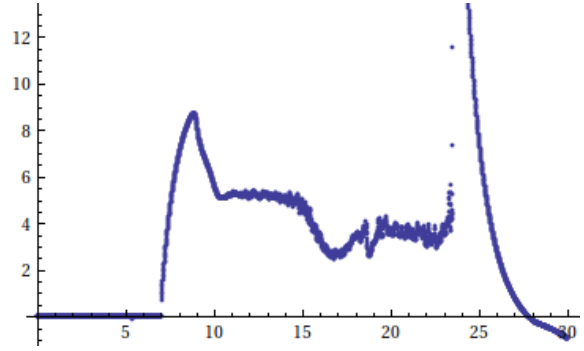
Plot 4665 U_l graph



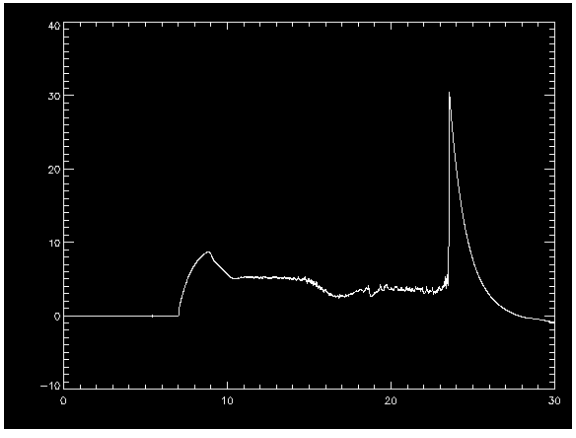
python



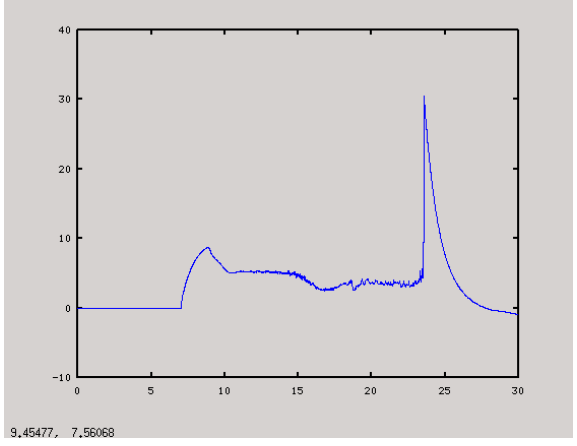
gnuplot



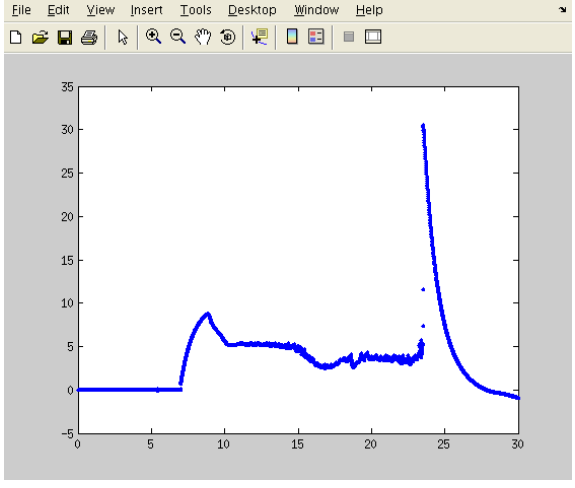
mathematica



idl



octave



matlab

Data access

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

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

Actually last discharge has the web page:

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

Particular data from DAS or specific diagnostics have the format:

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

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>`

Matlab

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

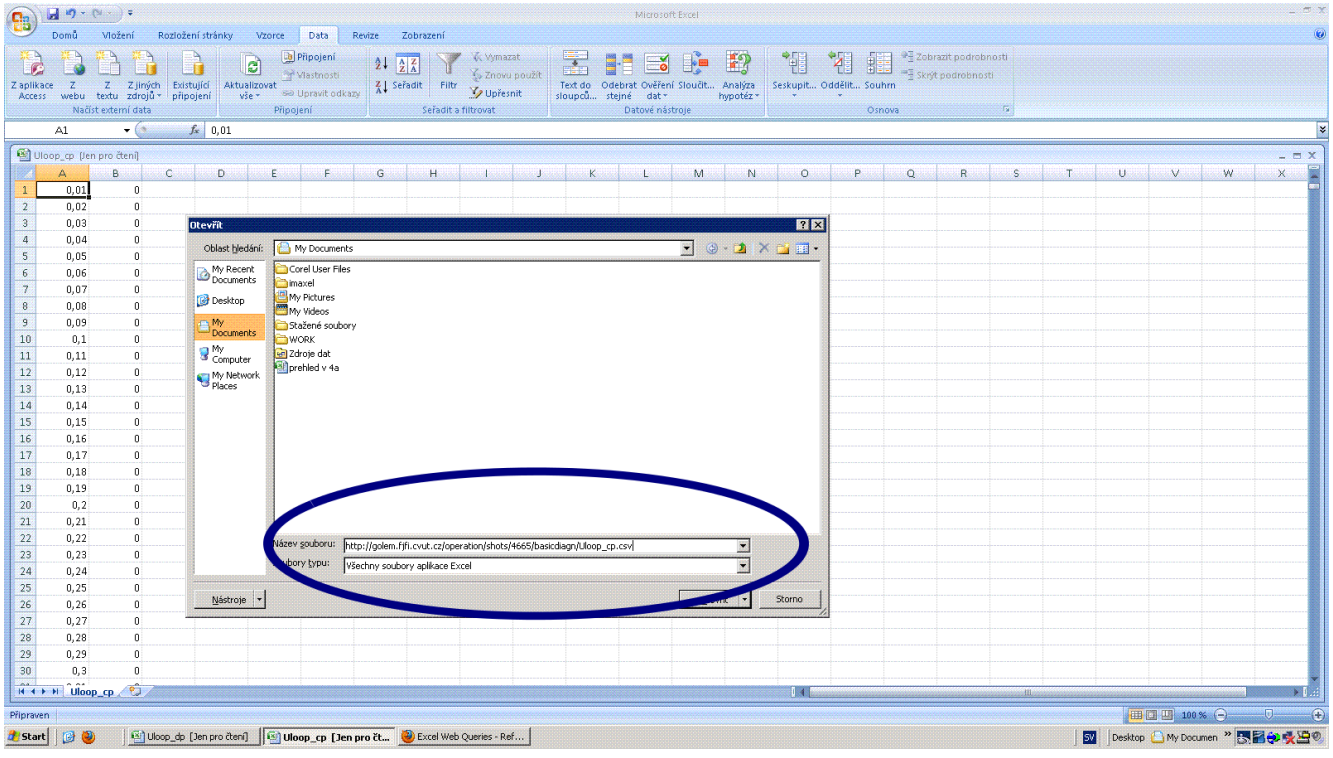
Jupyter (python)

```
import matplotlib.pyplot as plt
from numpy import loadtxt
from urllib import urlopen

baseURL = "http://golem.fjfi.cvut.cz/utils/data/"
ShotNo = 22471
identifier = "loop_voltage"
#Create a path to data
dataURL = urlopen(baseURL+ str(ShotNo) + '/' + identifier)
#Load data from GOLEM server
data=loadtxt(dataURL, delimiter='\t')
#Plot the graph
plt.plot(data[:,0], data[:,1], 'k-')
plt.savefig('graph.jpg')
plt.show()
```

Gnuplot

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

# command line execution:
# gnuplot Uloop.gp -persist
```

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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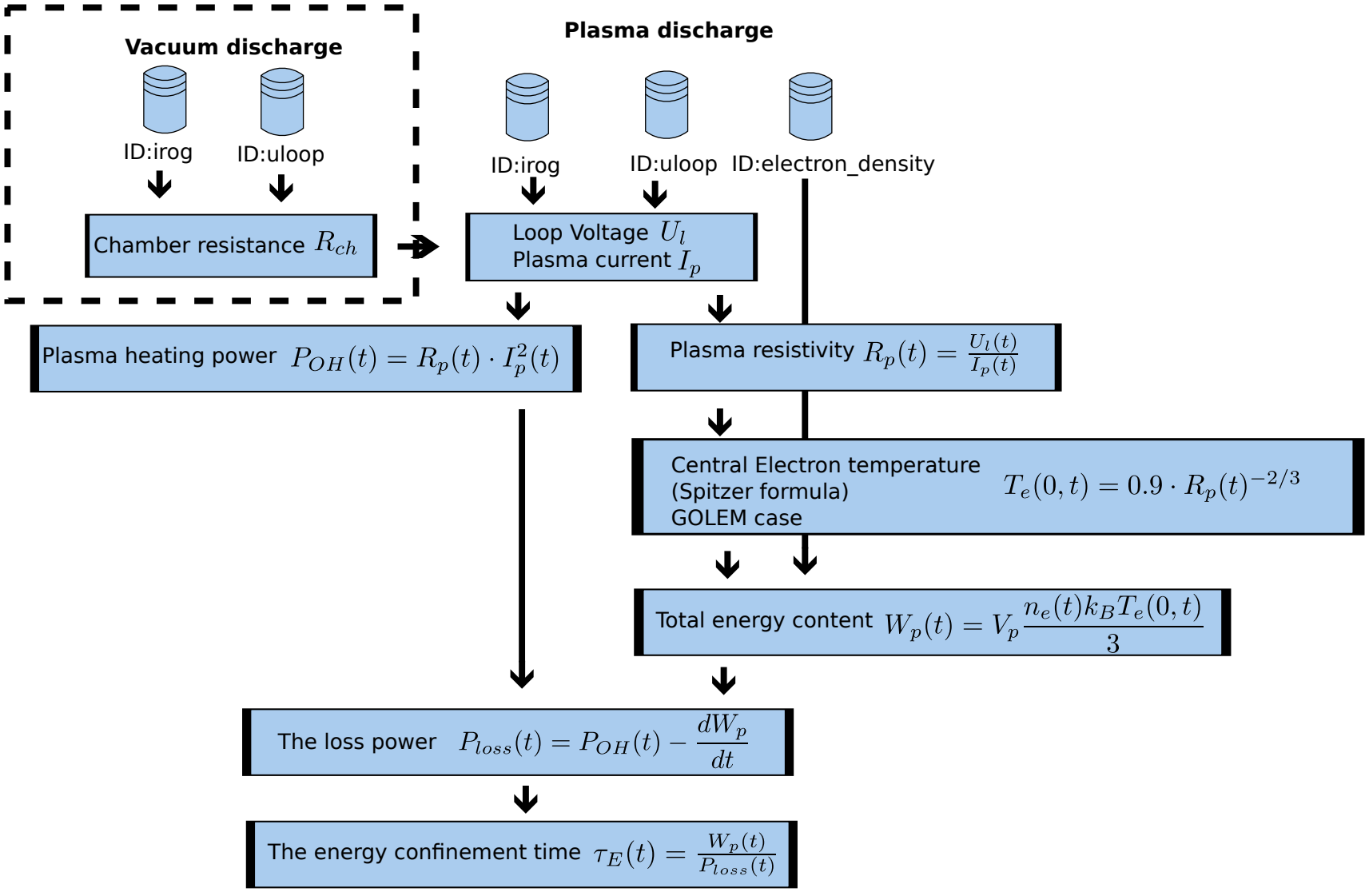
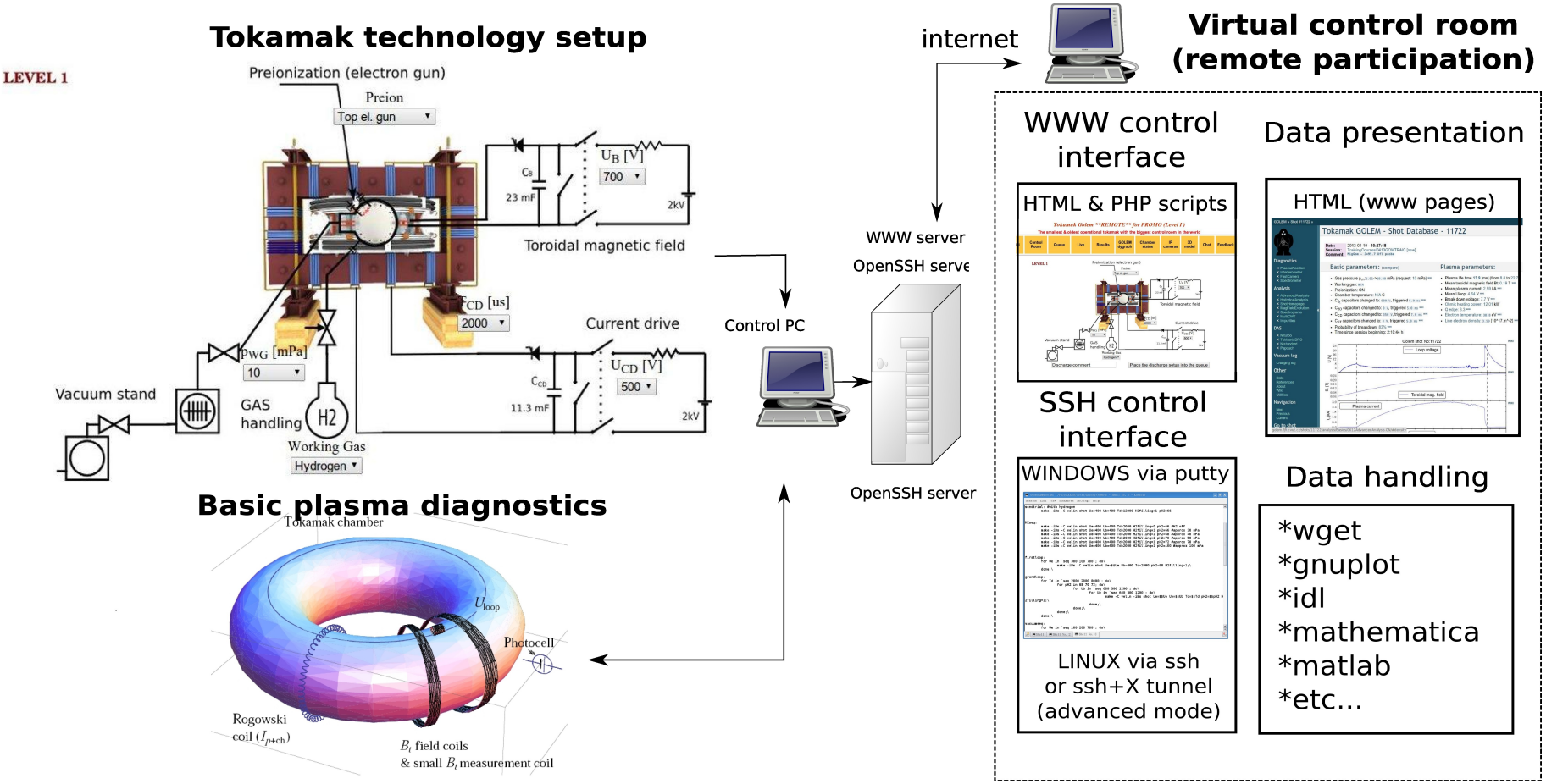
Towards Energy confinement time τ_E



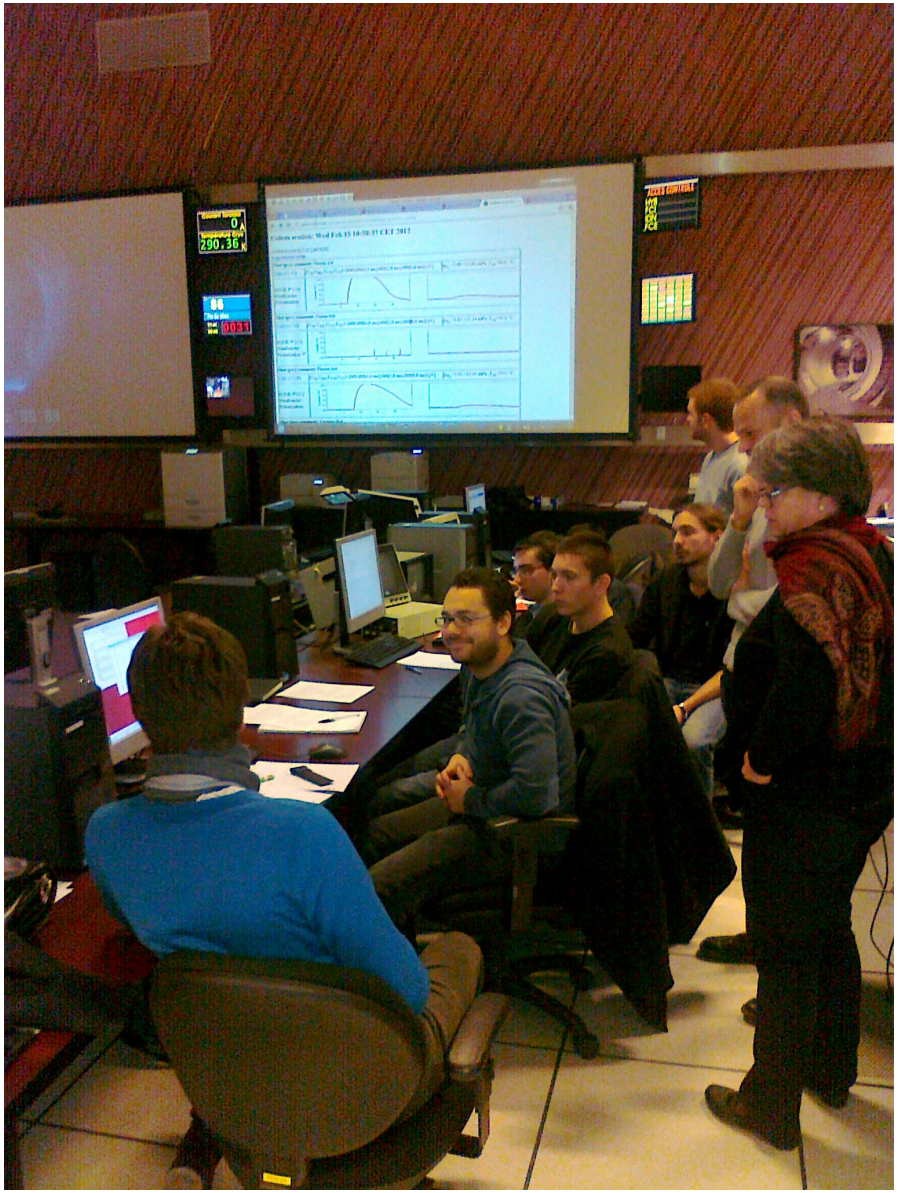
The global schematic overview of the GOLEM experiment



Production

- Everything via `http://golem.fjfi.cvut.cz/fumtraic`
  - This presentation
  - Control rooms
  - Contact: Vojtech Svoboda, +420 737673903,
  - Chat: vojtech.svob@gmail.com

Looking forward to see you on .. Wednesday



Any chat from mobile phone?

Acknowledgement

Acknowledgement

The financial support by FUSENET, MSM 6840770039, MSM 6840770014 and A1581 is acknowledged.

Special thanks to the GOLEM team (students, teachers, technicians)

Edita Bromova, Vladimir Fuchs, Ondrej Grover, Igor Jex, Jindrich Kocman, Jaroslav Krbec, Borek Leitl, Tomas Markovic, Lukas Matena, Michal Odstrcil, Tomas Odstrcil, Ondrej Pluhar, Gergo Pokol, Jan Stockel, Tereza Ruzickova, Gabriel Vondrasek, Ondrej Vrba, Frantisek Zacek and Jiri Zara.

Winter school of Plasma Physics - Marianska 2016 (Toroidal field coil 4 ITER, cooling test)

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Physical Quantities @ the tokamak GOLEM

Loop Voltage: U_l [V]
Total (plasma+chamber) current: I_{p+ch} [A]
Chamber current: I_{ch} [A]
Plasma current: I_p [A]
Plasma resistivity: R_p [Ω]
Plasma heating power: P_{OH} [W]
Total plasma energy content: W_p [J]
Chamber resistivity: R_{ch} [Ω]
Electron temperature: T_e [eV]
Energy confinement time: τ_E [s]
Plasma volume: $V_p = 0{,}057$ $[m^3]$
Rogowski coil calibration constant: $K_{Rogowski} = 5.3 \cdot 10^6$ [A/Vs]
Loop Voltage calibration constant: $K_{LoopVoltage} = 5.5$ [-]
Boltzmann constant : $k_B = 1.38064852 \cdot 10^{-23}$ [J/K]