

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

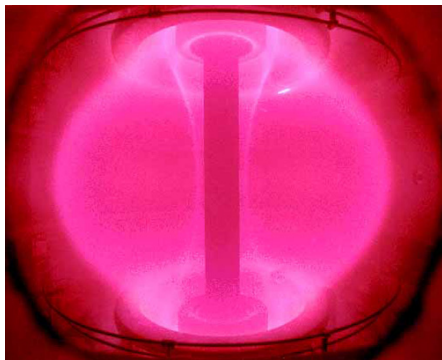
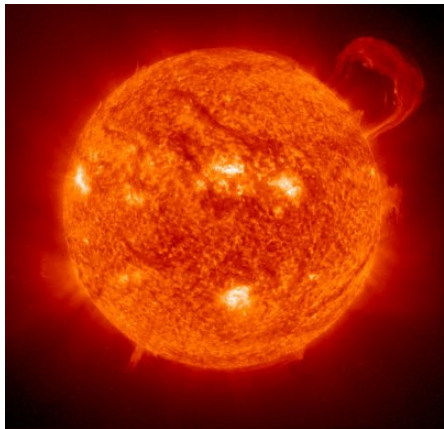
Vojtěch Svoboda
on behalf of the tokamak GOLEM team
for the TCN event, 1th edition

August 11, 2017

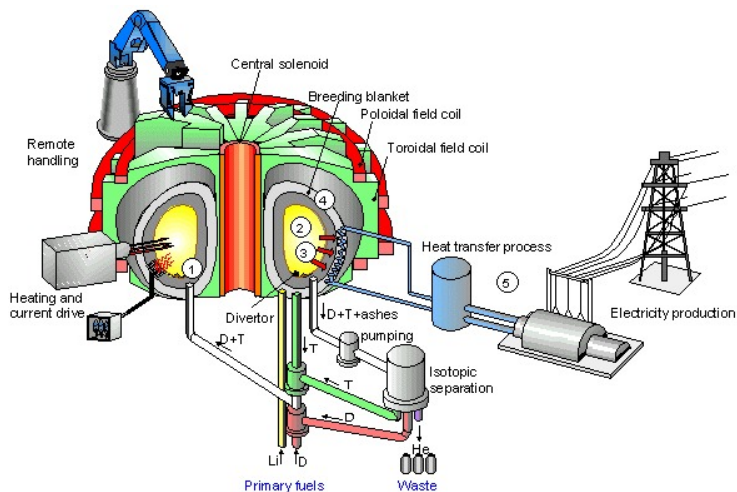
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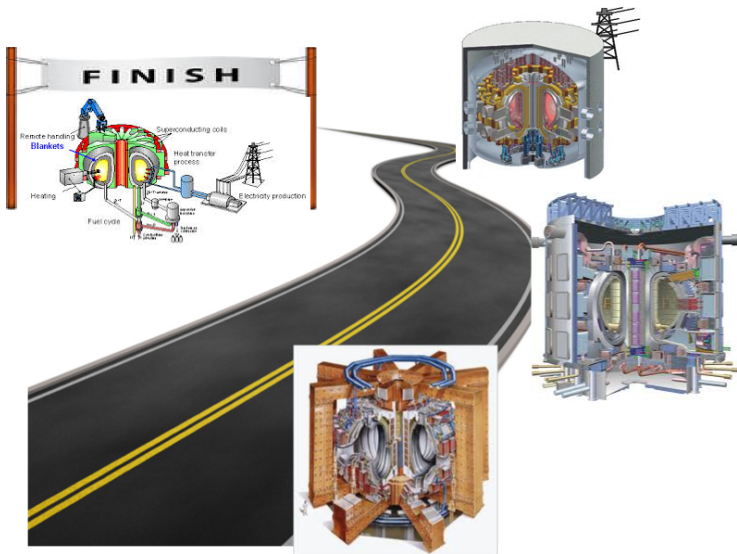
Foreword



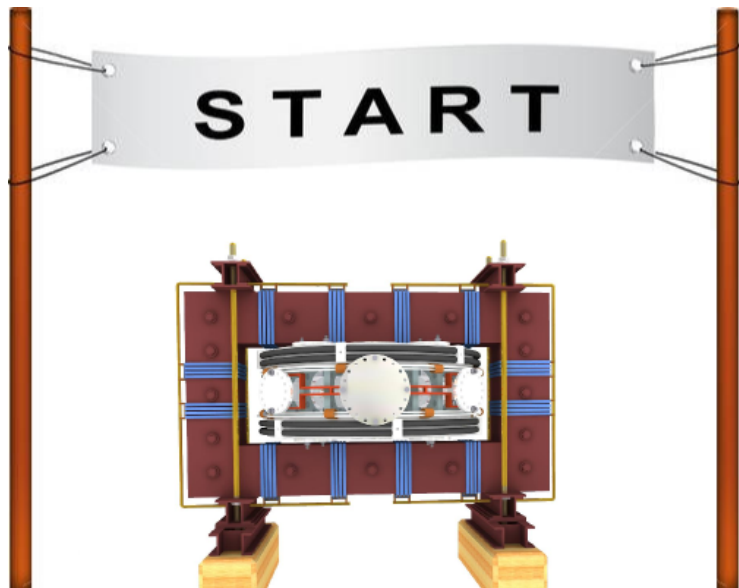
Our mission



Milestones to the Fusion Power Plant



Let's start with the tokamak GOLEM



Notice/Warning/Alert

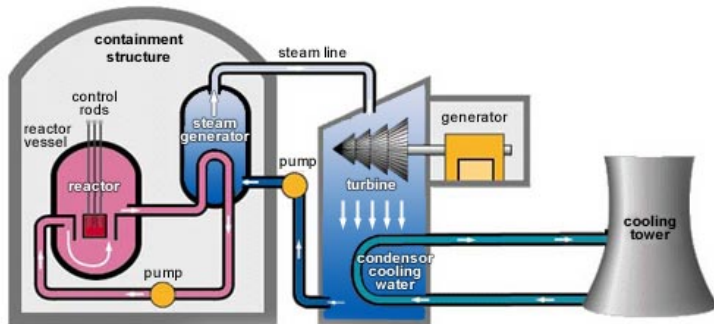
Everything simplified

... for educational purposes ..

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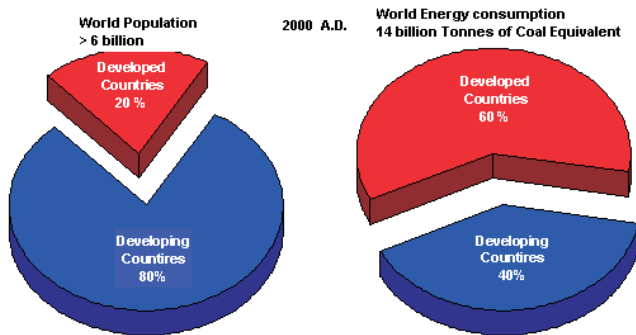
Thermal power plant - basic principle



The question:

?? WHAT TO BURN ??

World energy consumption



[credit:Energy Crisis and Environmental issues @ The World Reporter]

The 1GW (approx. Prague) annual power requirement

Coal

250 trains



Oil

11 super tankers



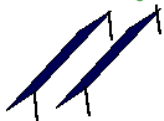
Fission

1.5 rail car load
Uranium Oxide



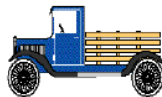
Solar

5000 acres of collectors
plus energy storage for
night and cloudy days

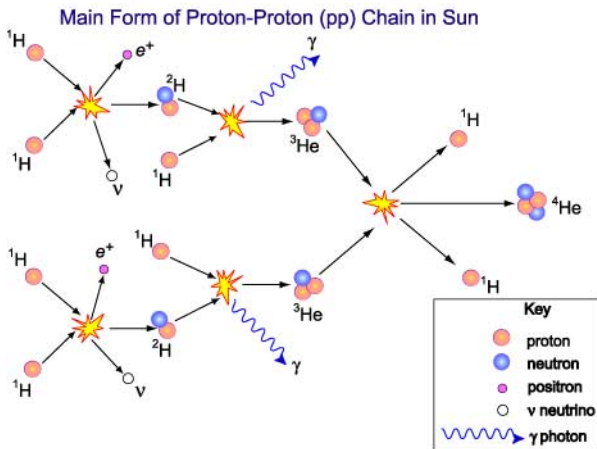


Fusion

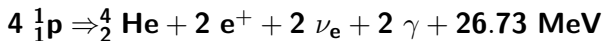
1/2 ton pickup truck
Deuterium & Tritium



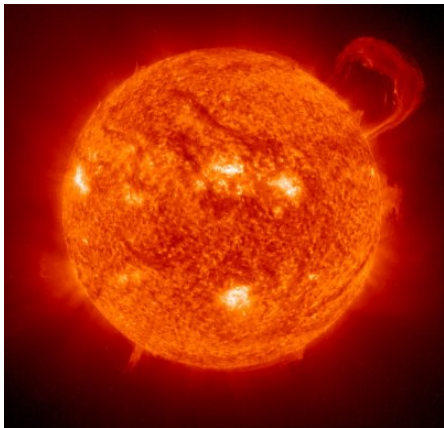
The Sun - Proton proton chain



[credit:CSIRO]



Harnessing the Sun's (star's) energy

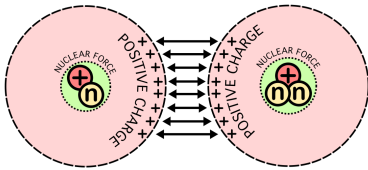


Core Burning Stages in a 25 Solar Mass Star:

<u>Fuel:</u>	<u>Products:</u>	<u>Temperature</u> <u>(K):</u>	<u>Minimum</u> <u>Mass:</u>	<u>Burning</u> <u>Period:</u>
H	He	4×10^6	0.1	7×10^6 years
He	C, O	1.2×10^8	0.4	5×10^5 years
C	Ne, Na, Mg, O	6×10^8	4	600 years
Ne	O, Mg	1.2×10^9	~8	1 year
O	Si, S, P	1.5×10^9	~8	~0.5 years
Si	Ni - Fe	2.7×10^9	~8	~1 day

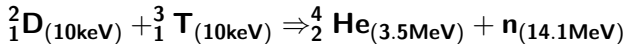
(Human body: 65% O, 18% C, 10% H, 3% N + Ca,P,K,S,Na,Cl,Mg ..)

Electrostatic force - like charges repel

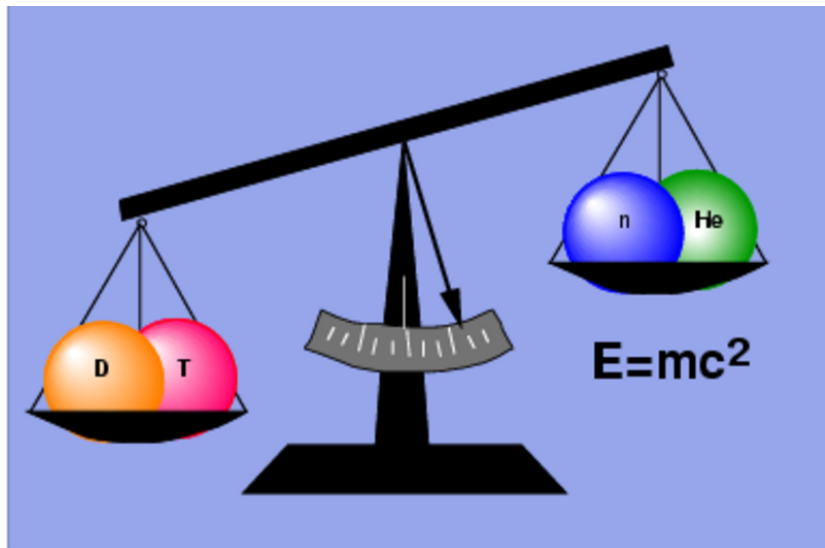


- Coulomb law:

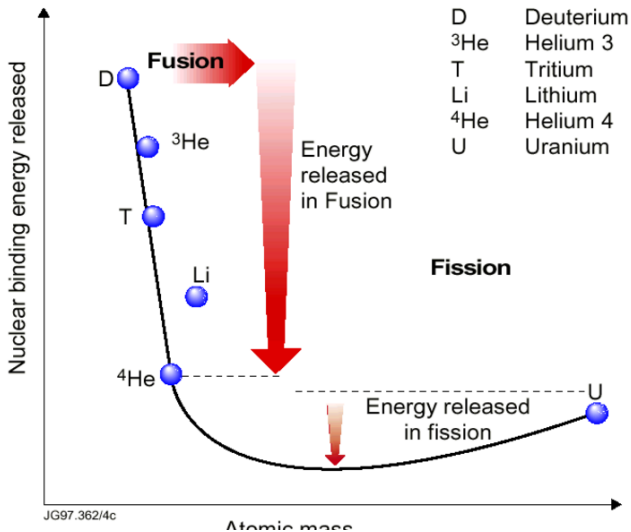
$$F_E = \frac{1}{4\pi\epsilon_0} \frac{Q_1 Q_2}{r^2}$$



Binding energy releasing I

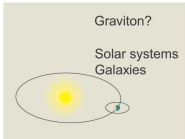


Binding energy releasing



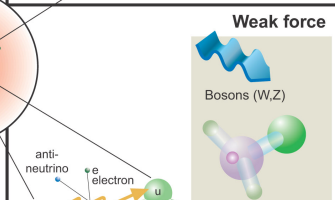
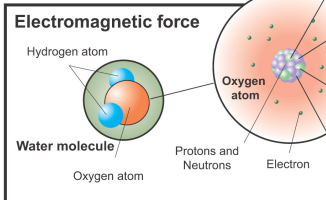
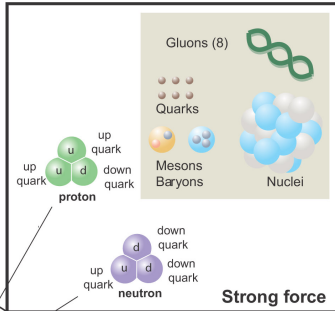
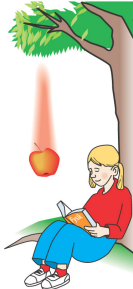
Fundamental forces (to confine?)

Illustration: Typoform

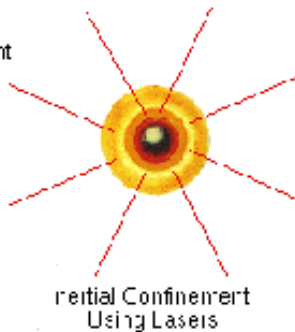
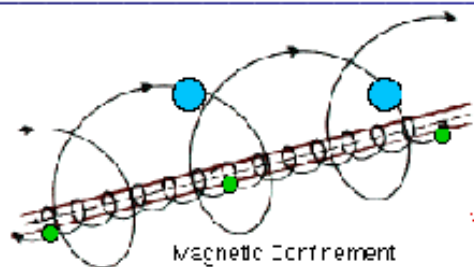


Gravity Force

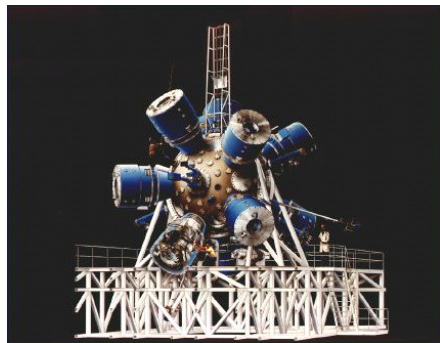
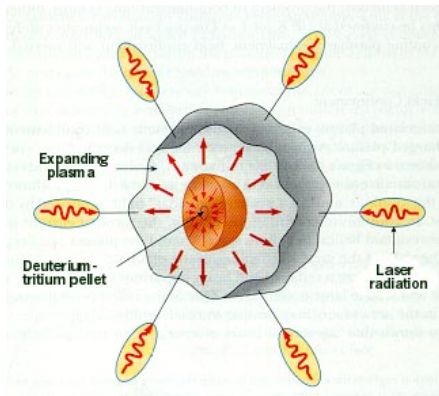
Graviton?
Solar systems
Galaxies



Three ways to confine plasma



Inertial fusion



Tokamak magnetic confinement concept

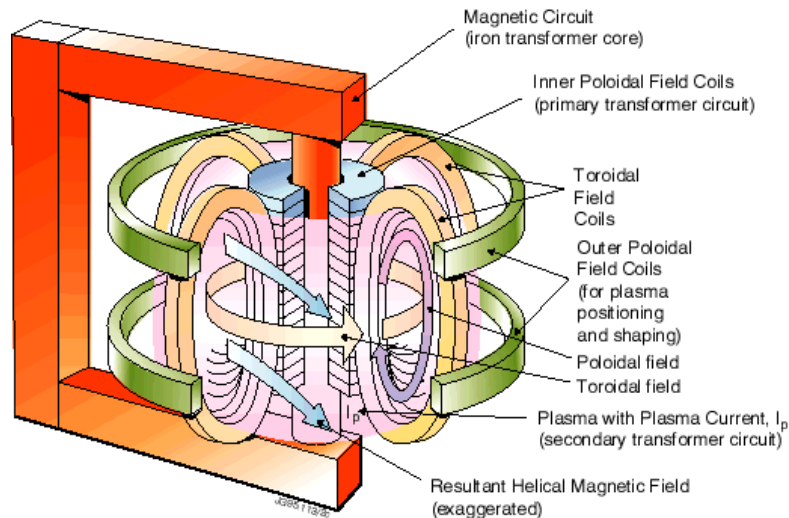
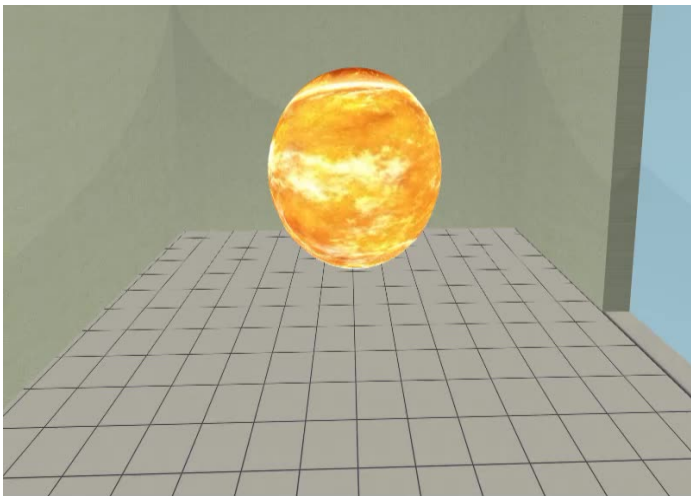


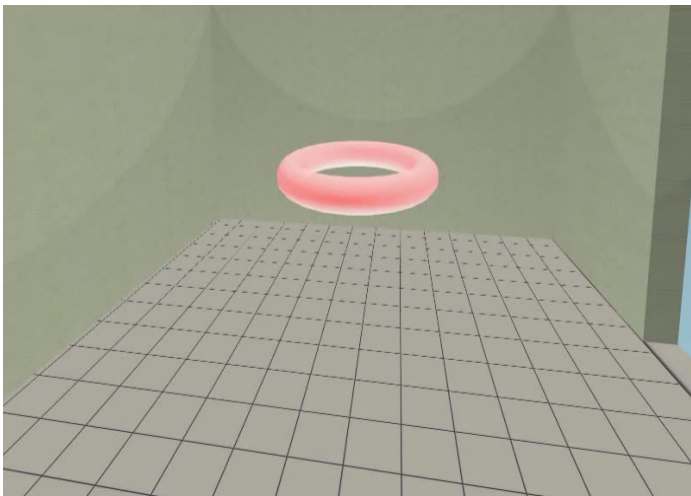
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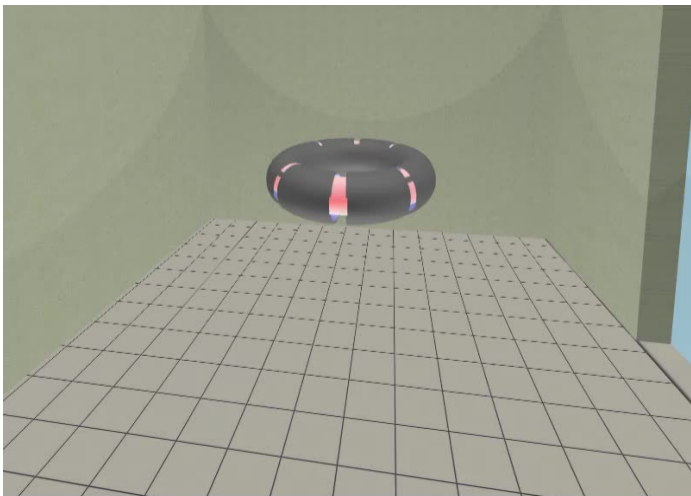
The technology to conquer: make a μ Sun on the Earth



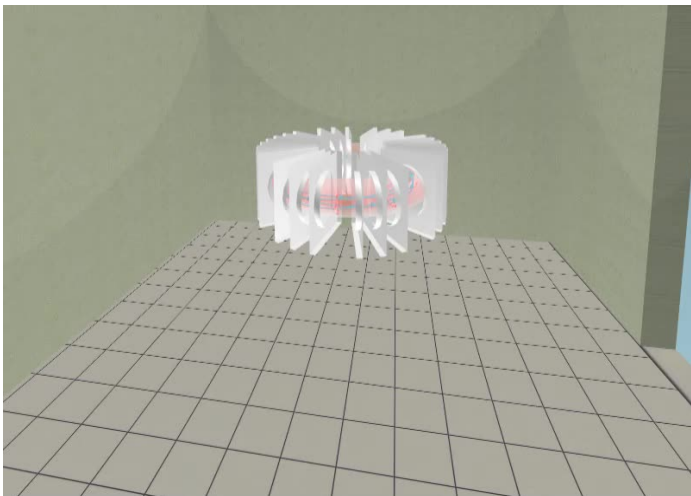
Magnetic confinement requires the toroidal geometry



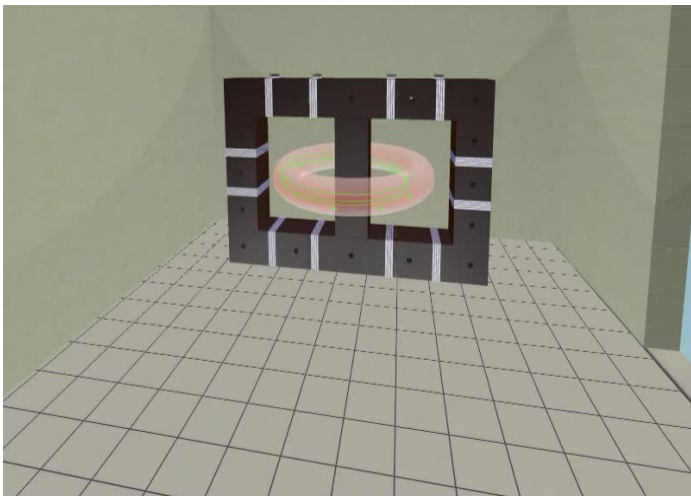
The thermonuclear reaction takes place in the chamber



Toroidal magnetic field coils secure the plasma confinement



Transformer secures the plasma creation and heating



The final technology altogether

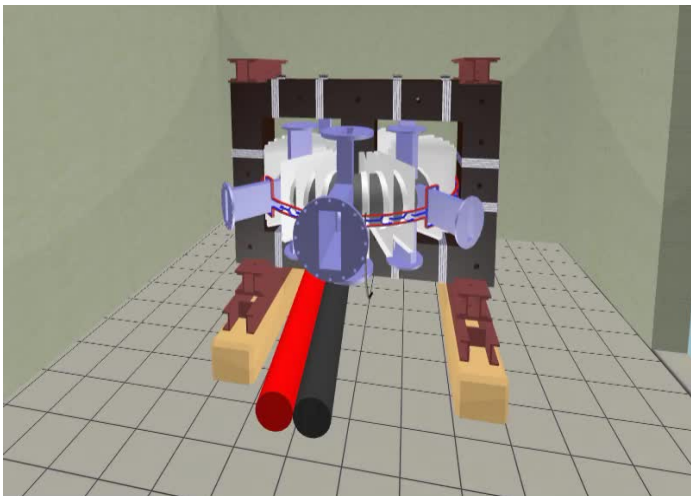
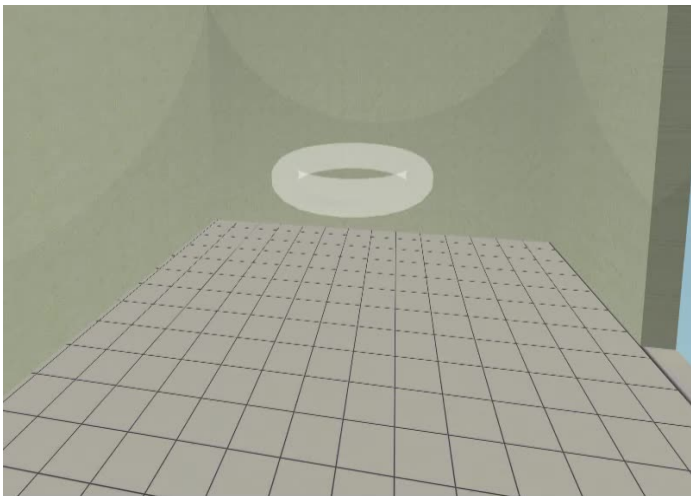


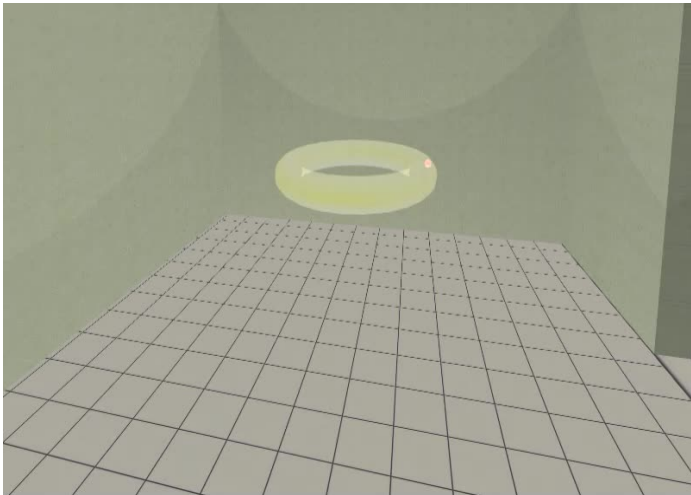
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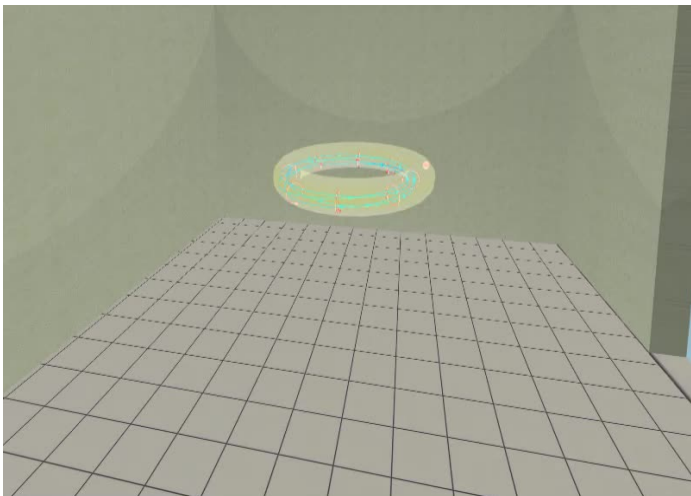
Introduce the working gas (Hydrogen x Helium)



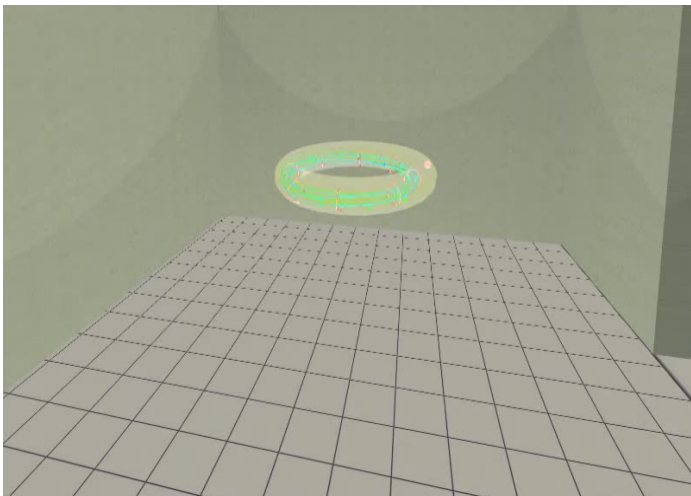
Switch on the preionization



Introduce the magnetic field



Introduce the electric field



Plasma ..

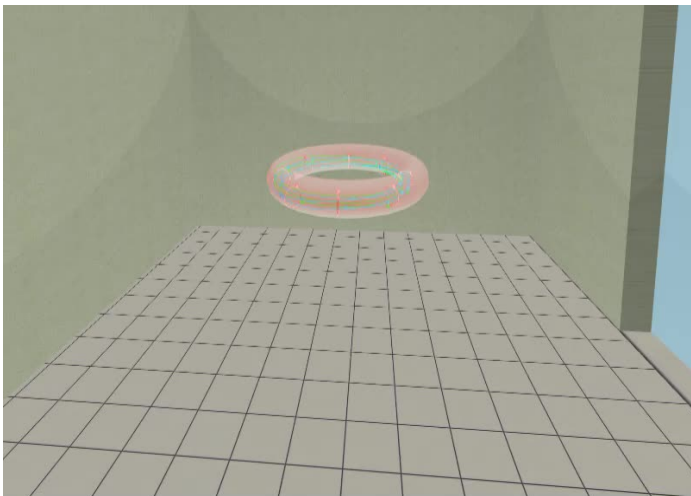
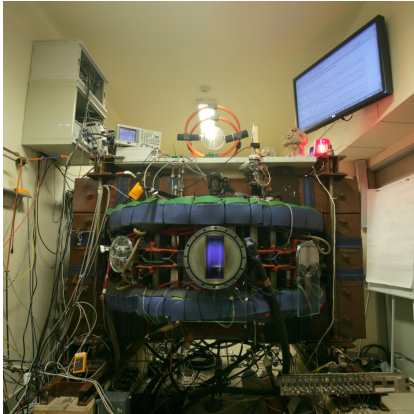


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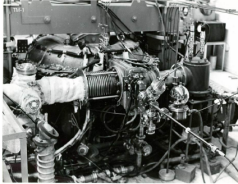
Tokamak GOLEM basic characteristics



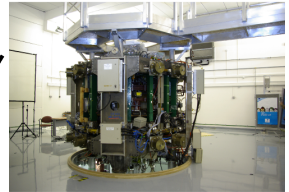
- Vessel major radius: $R_0 = 0.4$ m
- Vessel minor radius: $r_0 = 0.1$ m
- Plasma minor radius: $a = 0.06$ m
- Toroidal magnetic field: $B_t < 0.5$ T
- Plasma Current: $I_p = 8$ kA
- Electron density:
 $n_e \approx 0.2 - 3 \times 10^{19} \text{ m}^{-3}$
- Electron temperature: $T_e = 100$ eV
- Ion temperature: $T_i = 50$ eV
- Discharge length: $\tau_p = 25$ ms

Tokamak GOLEM 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

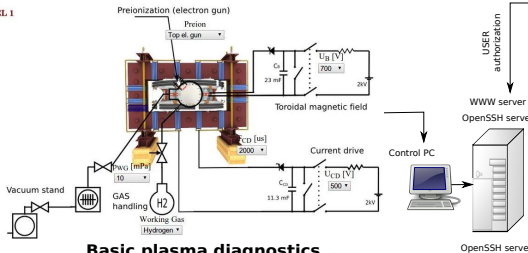


The new location of the tokamak is just next to the old Prague Jewish cemetery where Rabi Loew (Golem builder) is buried, and that is why it was renamed GOLEM (and also for the symbol of potential power you get if you know the magic). Interestingly, here in Prague, where the Golem legend originated, 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](https://en.wikipedia.org/wiki/Golem).

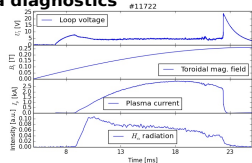
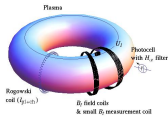
The global schematic overview of the GOLEM experiment

LEVEL 1

Tokamak technology setup



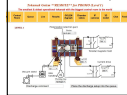
Basic plasma diagnostics



Virtual control room (remote participation)

WWW control interface

HTML & PHP scripts



SSH control interface

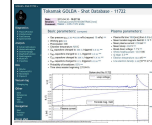
WINDOWS via putty



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

Data presentation

HTML (www pages)



Data handling

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

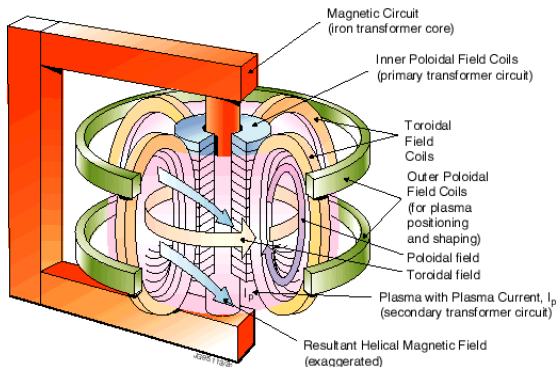
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Plasma in Tokamak (GOLEM) - the least to do

To do:

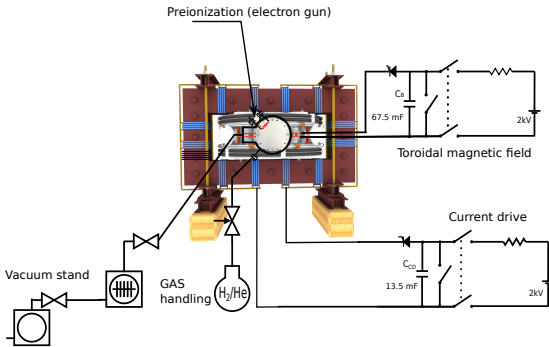
- session start phase:
 - Evacuate the chamber
- pre-discharge phase
 - Charge the capacitors
 - Fill in the working gas
 - Preionization
- discharge phase
 - Toroidal magnetic field to confine plasma
 - Toroidal electric field to breakdown neutral gas into plasma
 - Toroidal electric field to heat the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



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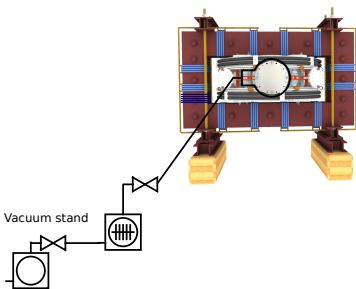
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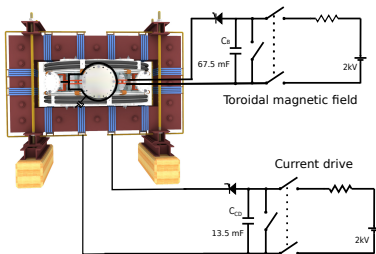
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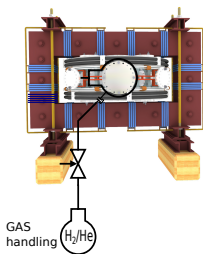
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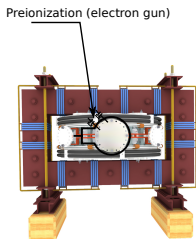
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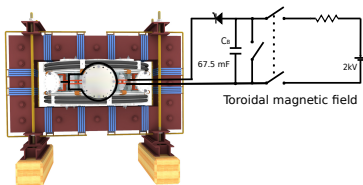
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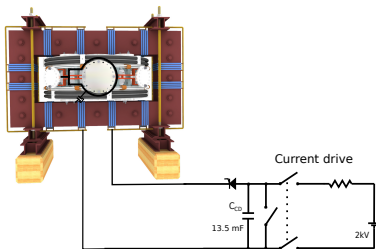
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Tokamak GOLEM - schematic experimental setup

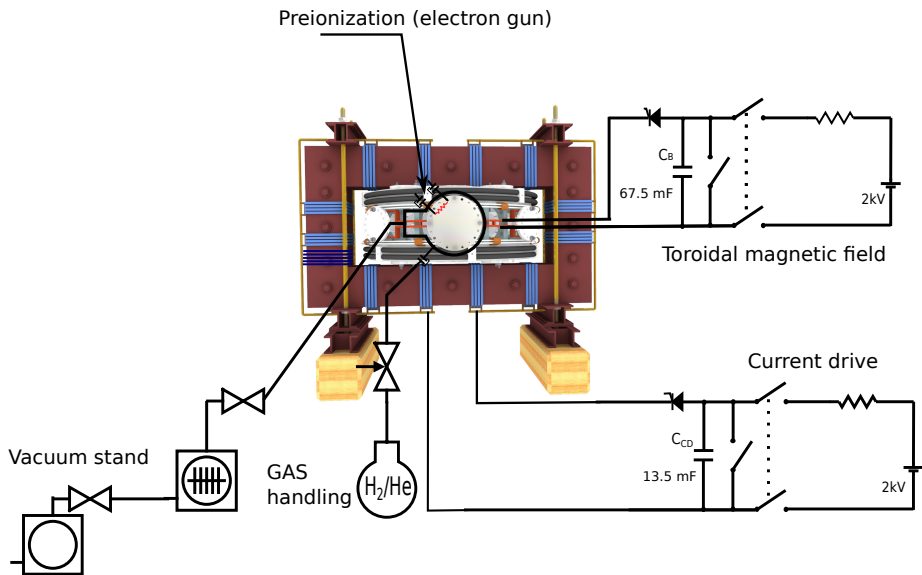
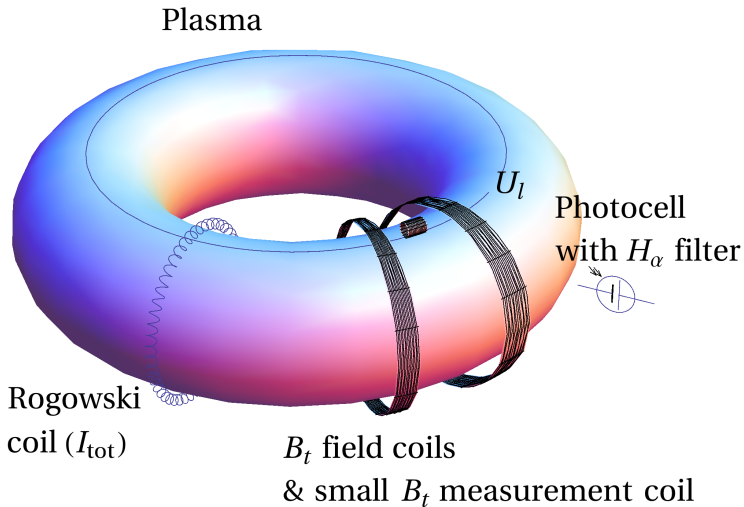


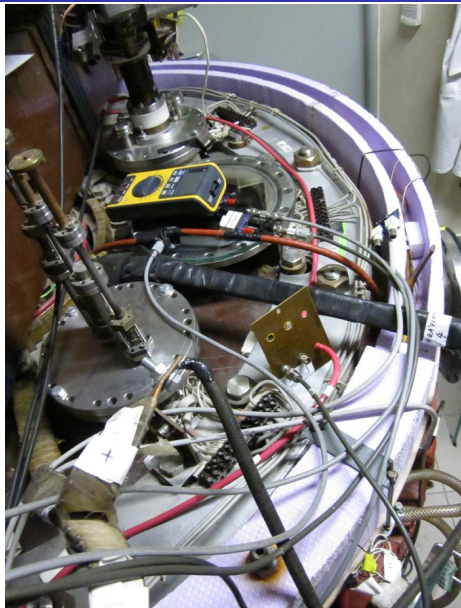
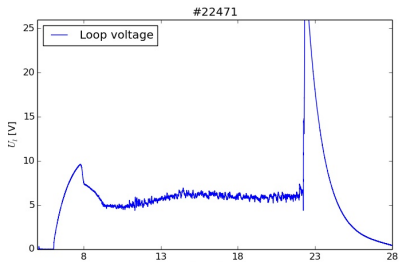
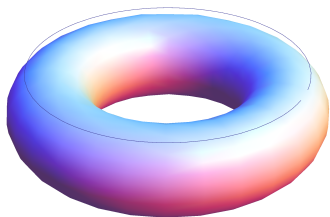
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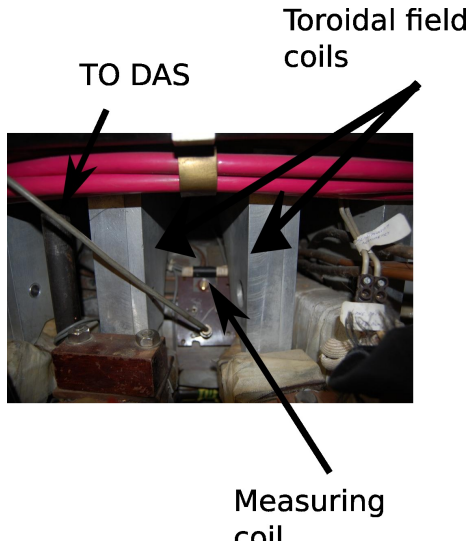
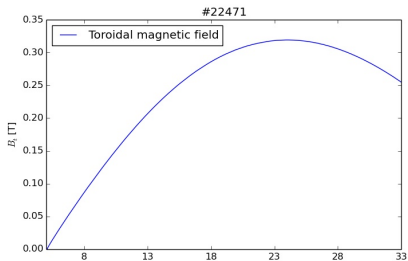
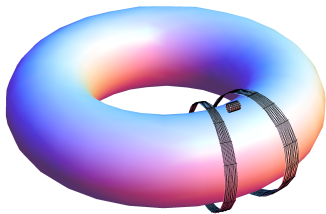
Tokamak GOLEM - basic diagnostics



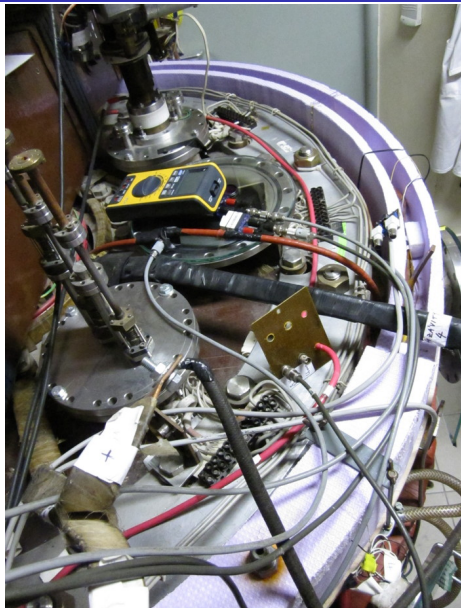
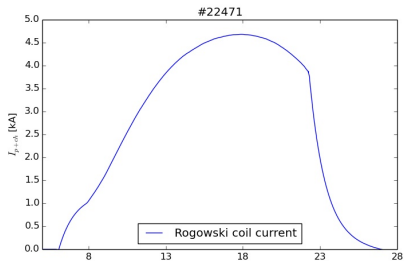
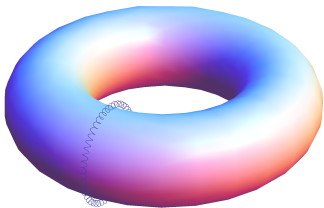
Loop voltage U_l



Toroidal magnetic field B_t



Total current I_{ch+p}



Basic diagnostics @ tokamak GOLEM

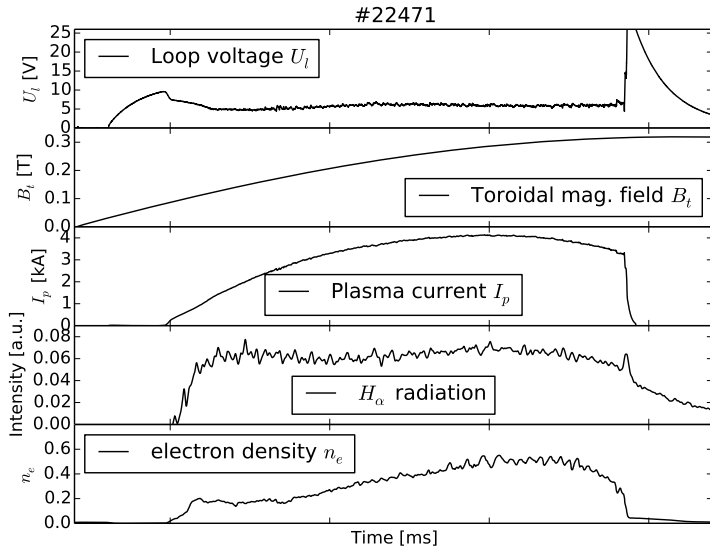


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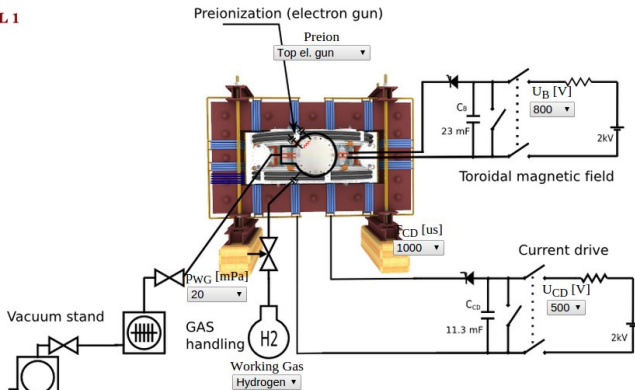
Remote operation

Tokamak Golem ****REMOTE**** for PROMO (Level I)

The smallest & oldest operational tokamak with the biggest control room in the world



LEVEL 1



Default discharge setup

Place the discharge setup into the queue

Note: We use cookies to record last set parameters in your browser to simplify parameter scans.



Diagnostics

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

Analysis

- ✓ ShotHomepage

DAS

- ✓ TektronixDPO
- ✓ Nlstandard
- ✓ Papouch_St
- ✓ Papouch_Ko
- ✓ Nlcoctopus

Vacuum log

Other

- Data
- References
- About
- Wiki
- Utilities

Navigation

- Next
- Previous
- Current

Tokamak GOLEM - Shot Database - 22471

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

Basic parameters: (compare)

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

Plasma parameters:

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

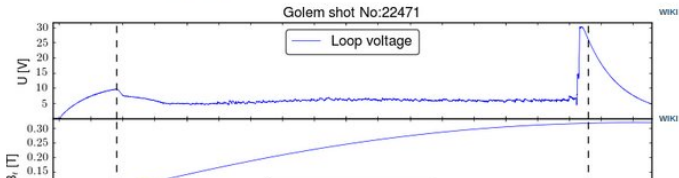


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GOLEM basic Data Acquisition System (DAS)

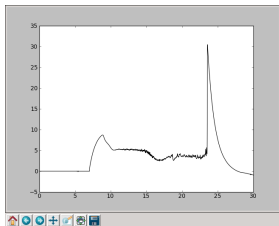
- $U_I, U_{B_t}, U_{I_{p+ch}}, I_{rad}$
- $\Delta t = 1\mu s / f = 1MHz$.
- Integration time = 40 ms, thus DAS produces 6 columns x 40000 rows data file.
- Discharge is triggered at 5th millisecond after DAS to have a zero status identification.



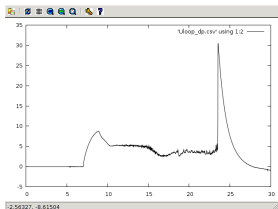
Data file example, DAS $\Delta t = 1\mu s / f = 1MHz$ (neutral gas into plasma breakdown focused)

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

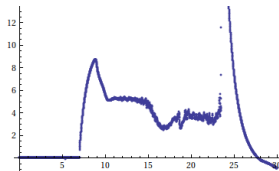
Plot 4665 U_l graph



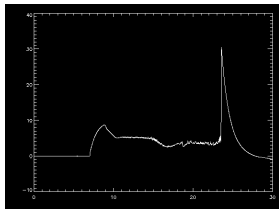
python



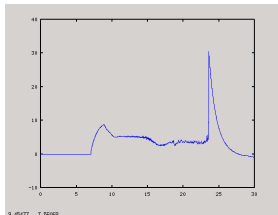
gnuplot



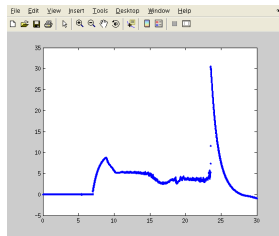
mathematica



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

Matlab

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

Jupyter (python)

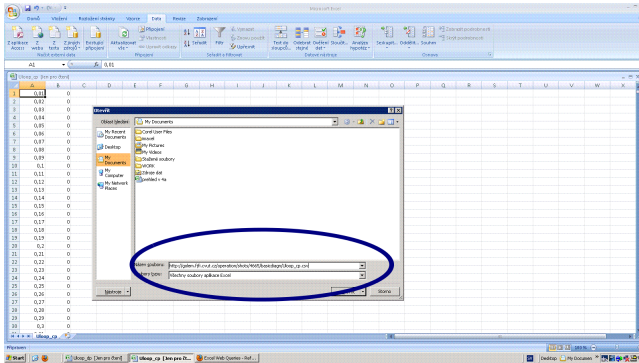
```
import matplotlib.pyplot as plt
from numpy import loadtxt
from urllib.request import urlopen

baseURL = "http://golem.fjfi.cvut.cz/Utils/data/"
ShotNo = 22639
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/utis/data/<#ShotNo>/<identifier>`

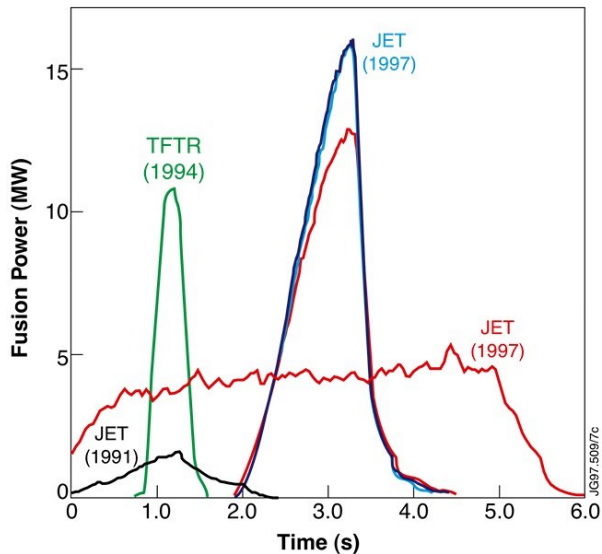
Spreadsheets (Excel and others)

are not recommended, only tolerated.

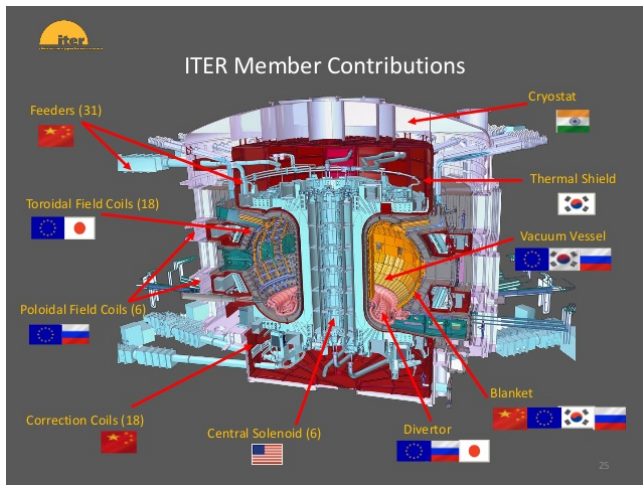
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Fusion record @ JET (EU)



ITER \approx 18 billion euros

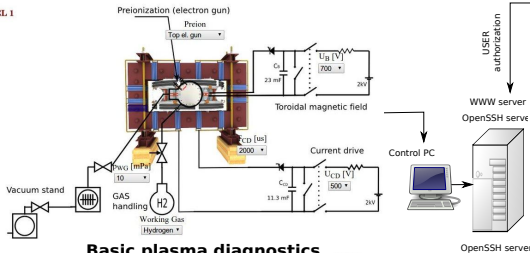


- Fusion power 0.5 GW for 10 min.
- $Q = 10$.
- Feasibility.

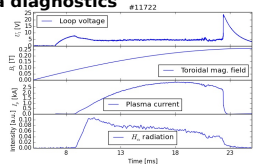
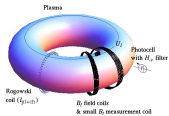
The global schematic overview of the GOLEM experiment

LEVEL 1

Tokamak technology setup



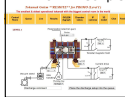
Basic plasma diagnostics



Virtual control room (remote participation)

WWW control interface

HTML & PHP scripts



SSH control interface

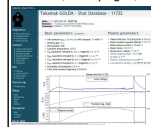
WINDOWS via putty



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

Data presentation

HTML (www pages)



Data handling

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

Production

- Everything via <http://golem.fjfi.cvut.cz/TCN>.
- GOLEM wiki: <http://golem.fjfi.cvut.cz/wiki>.
 - This presentation.
 - Control rooms.
 - Usefull tools.
- Mail: vojtech.svoboda@fjfi.cvut.cz
- Program 4 TCN
 - Dopo: přednáška
 - Odpo: vzdálené řízení tokamaku GOLEM - X skupin. !Pohlednice!
 - Podvečer: μ prezentace "Co jsme zkusili a co jsme zjistili." + diskuse
- + Výzva: letní tokamak.
- Čtvrtky ..

Acknowledgement

Acknowledgement

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

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2010 Tokamak GOLEM



The tokamak COMPASS with NBI



The tokamak COMPASS with NBI without plasma



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






2017 First Spitzer Stellarator



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