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

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

August 11, 2017

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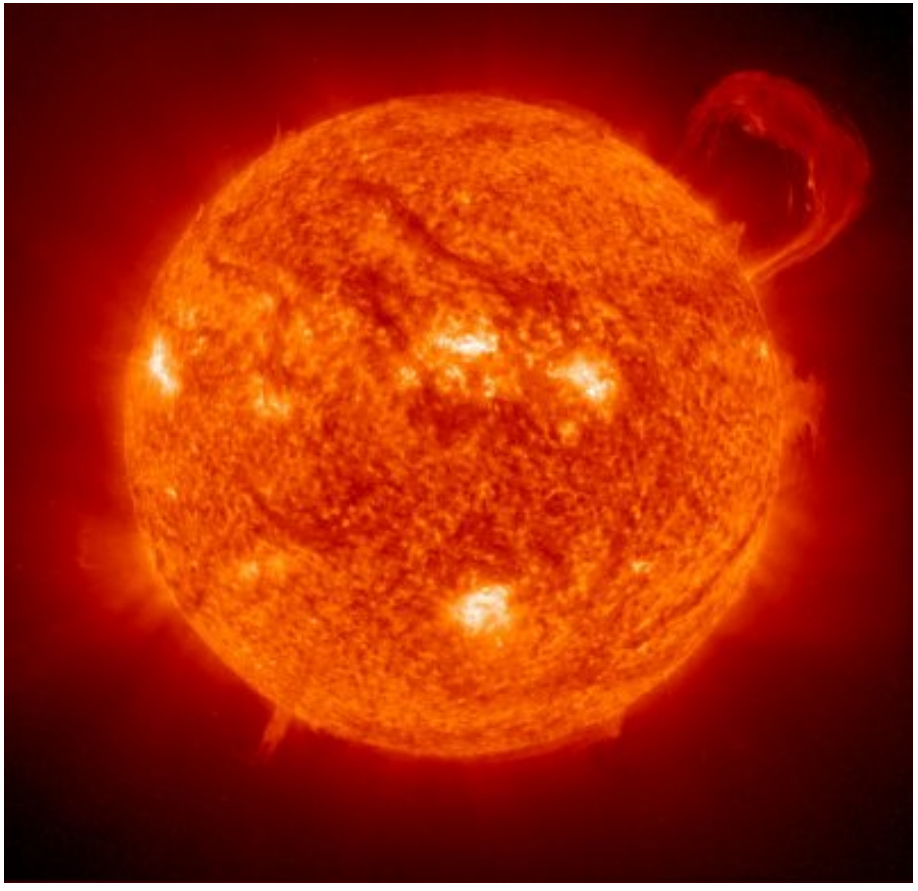
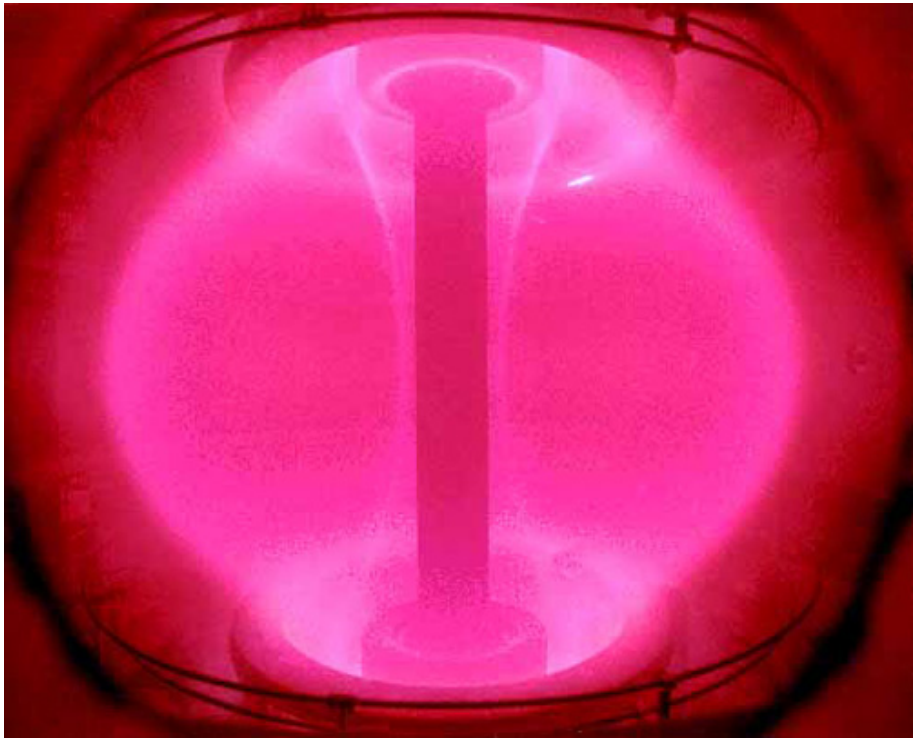
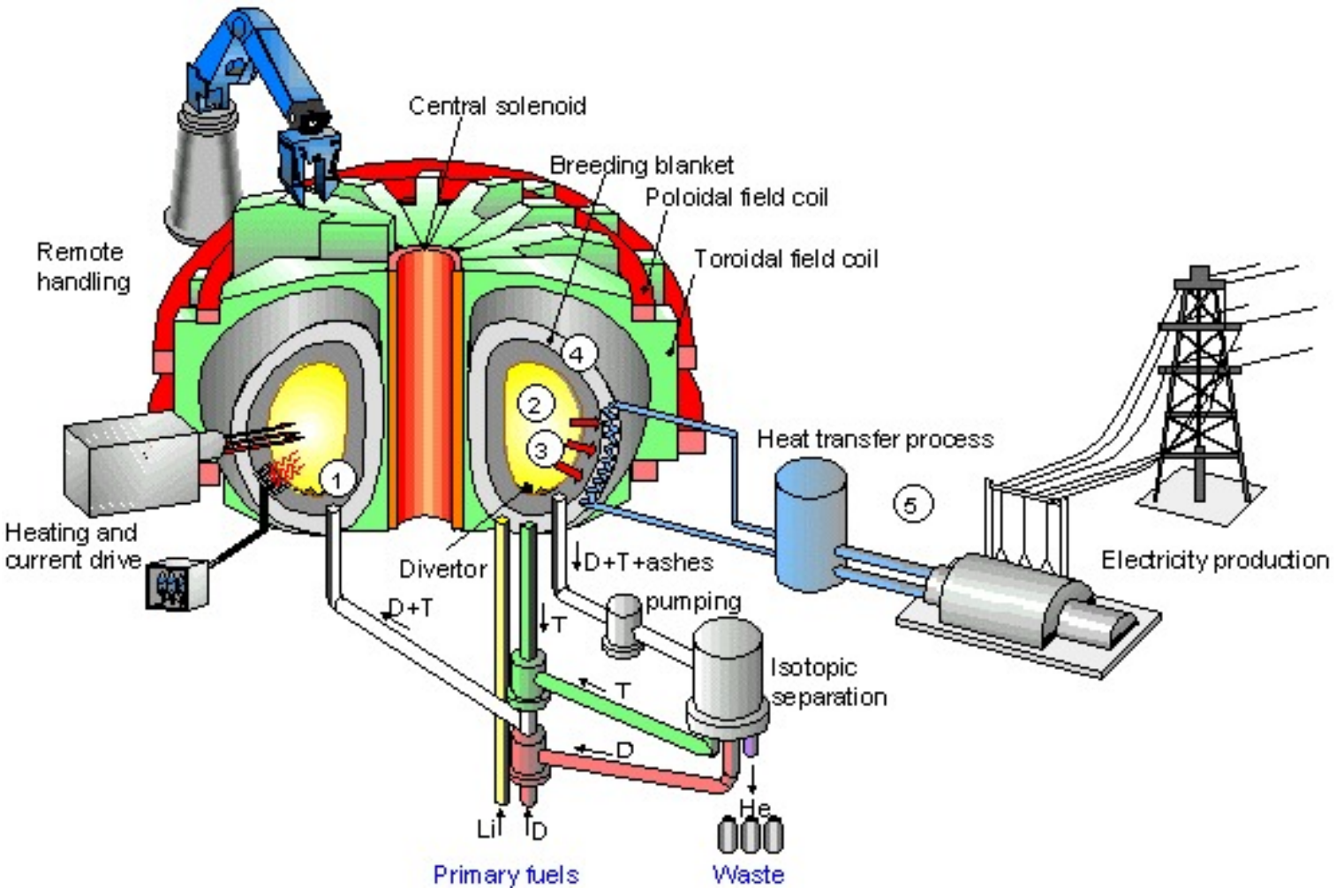
Foreword

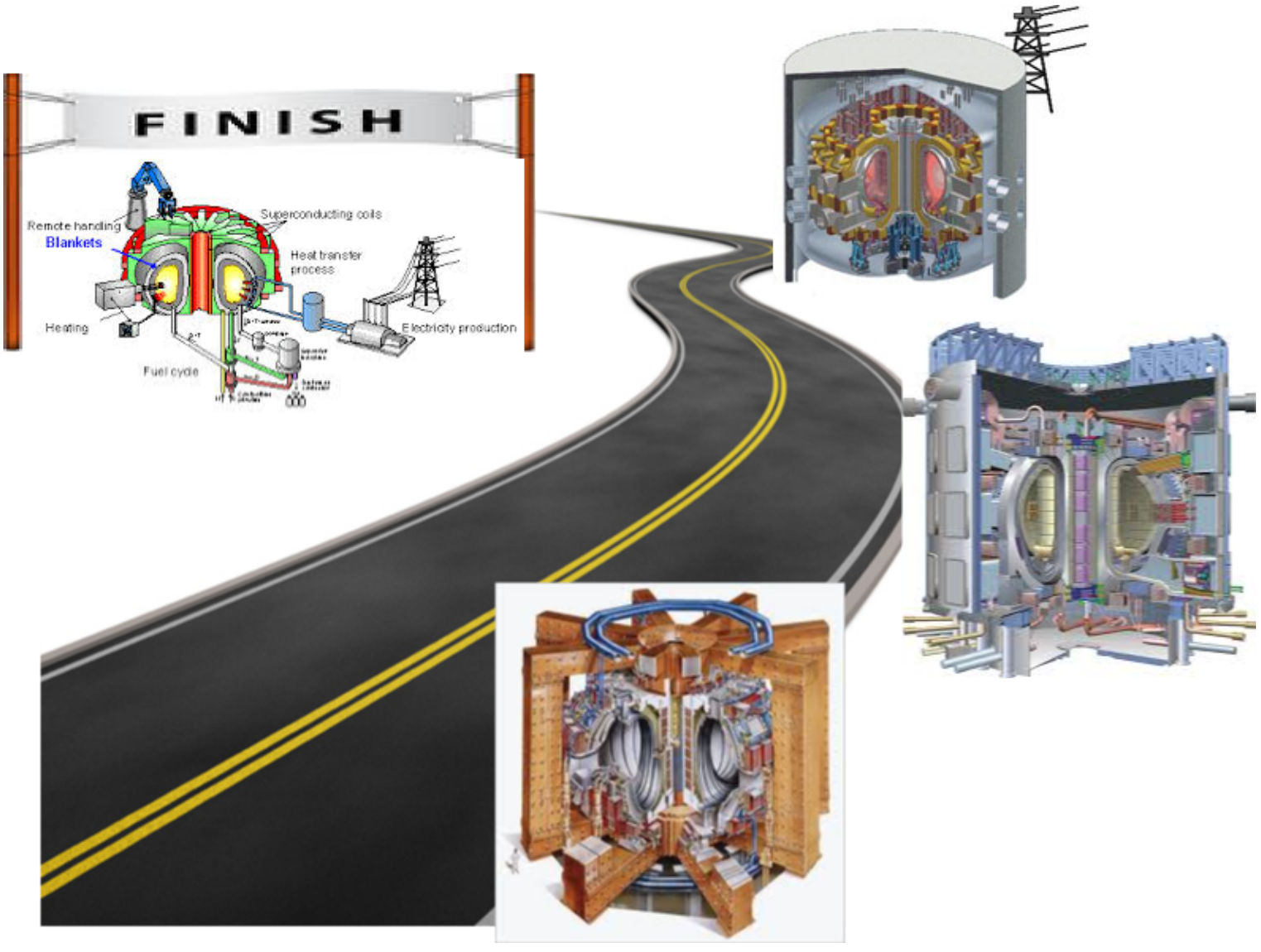




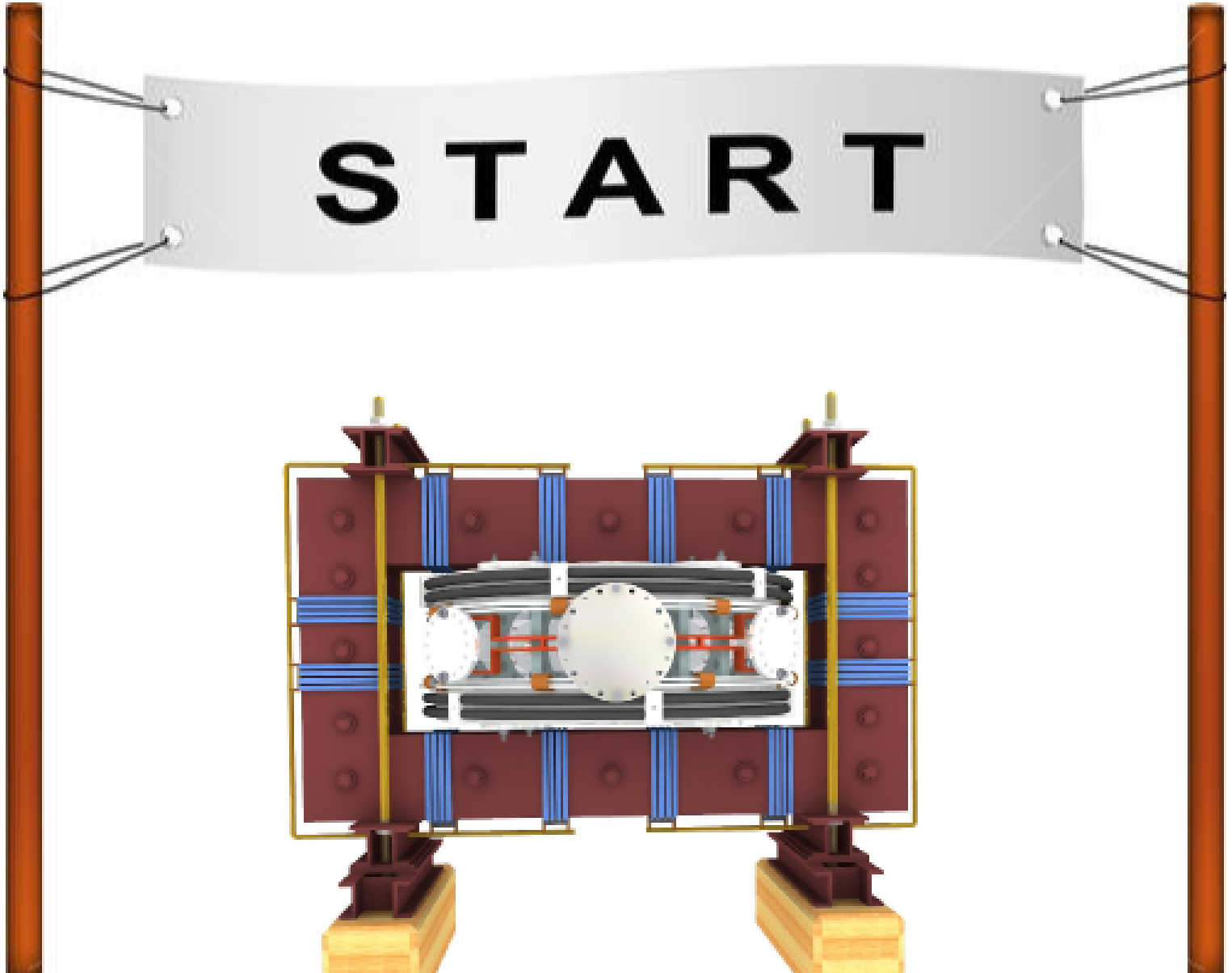
Our mission


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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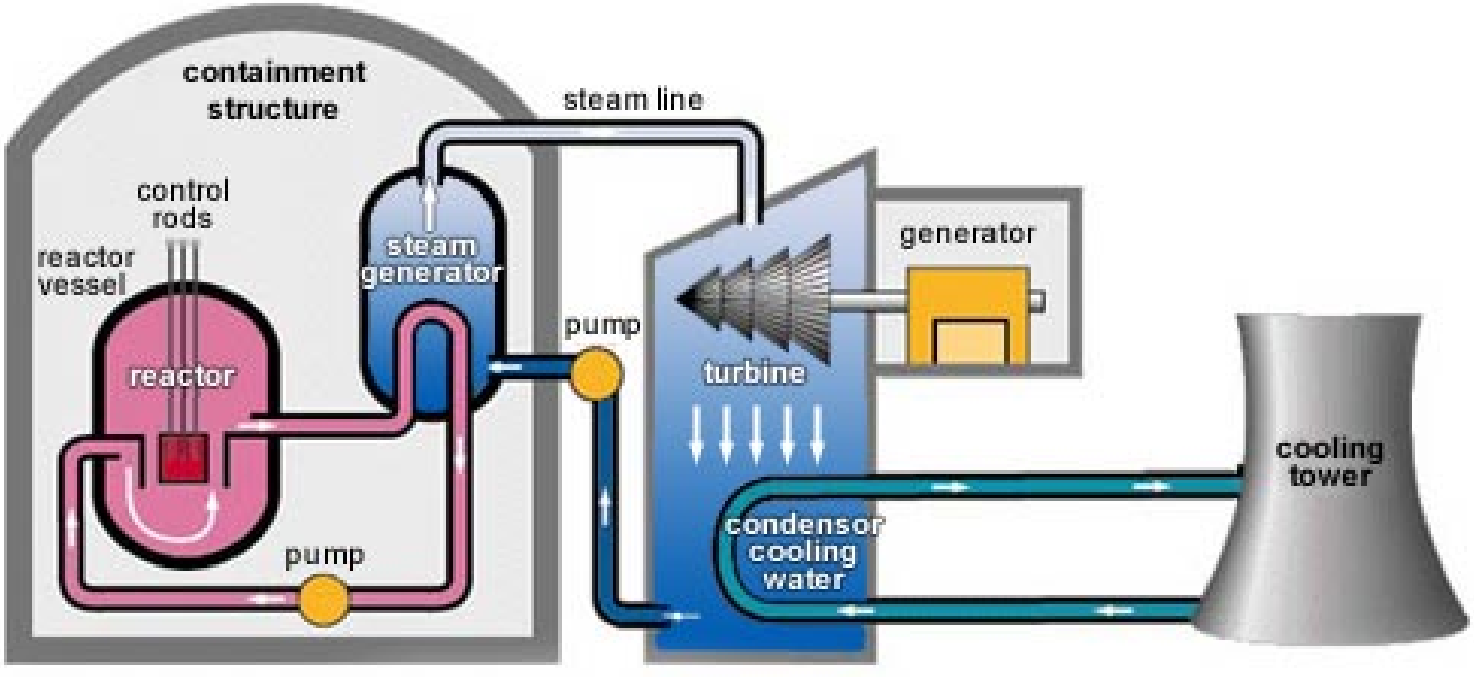
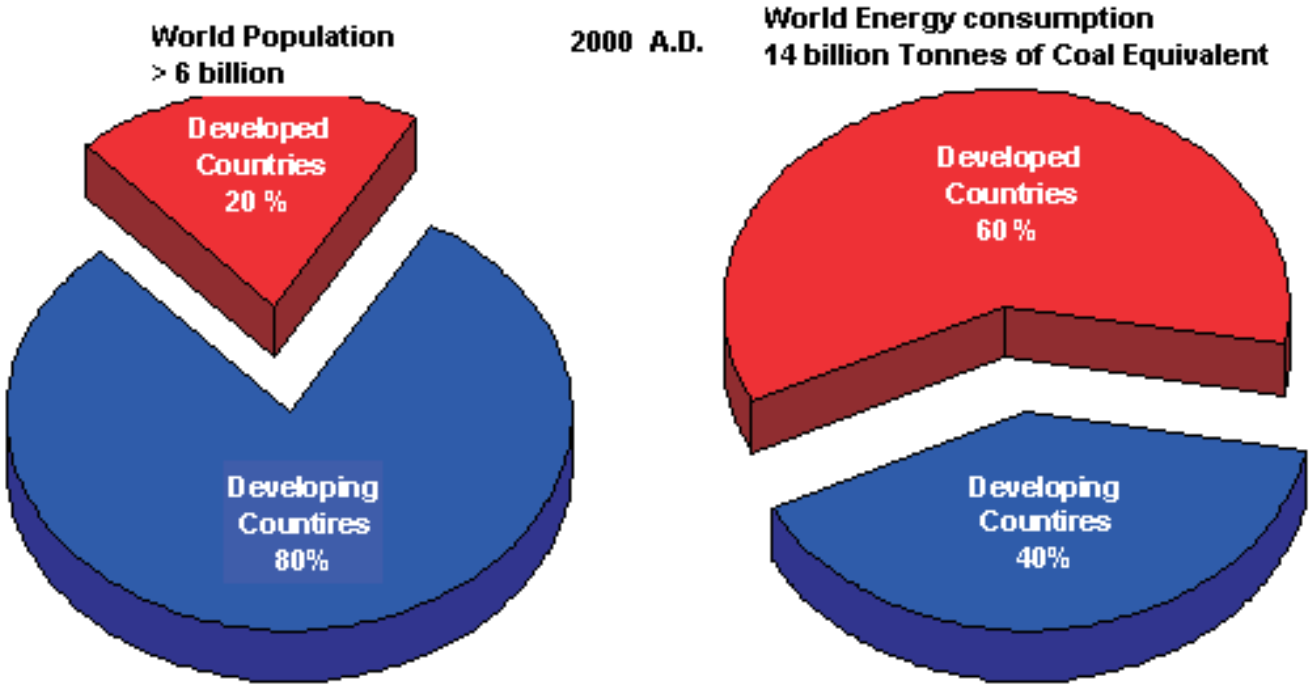
Thermal power plant - basic principle



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

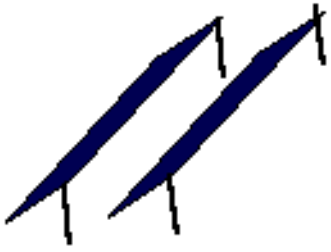
11 super tankers

Fission

1.5 rail car load
Uranium Oxide

Solar

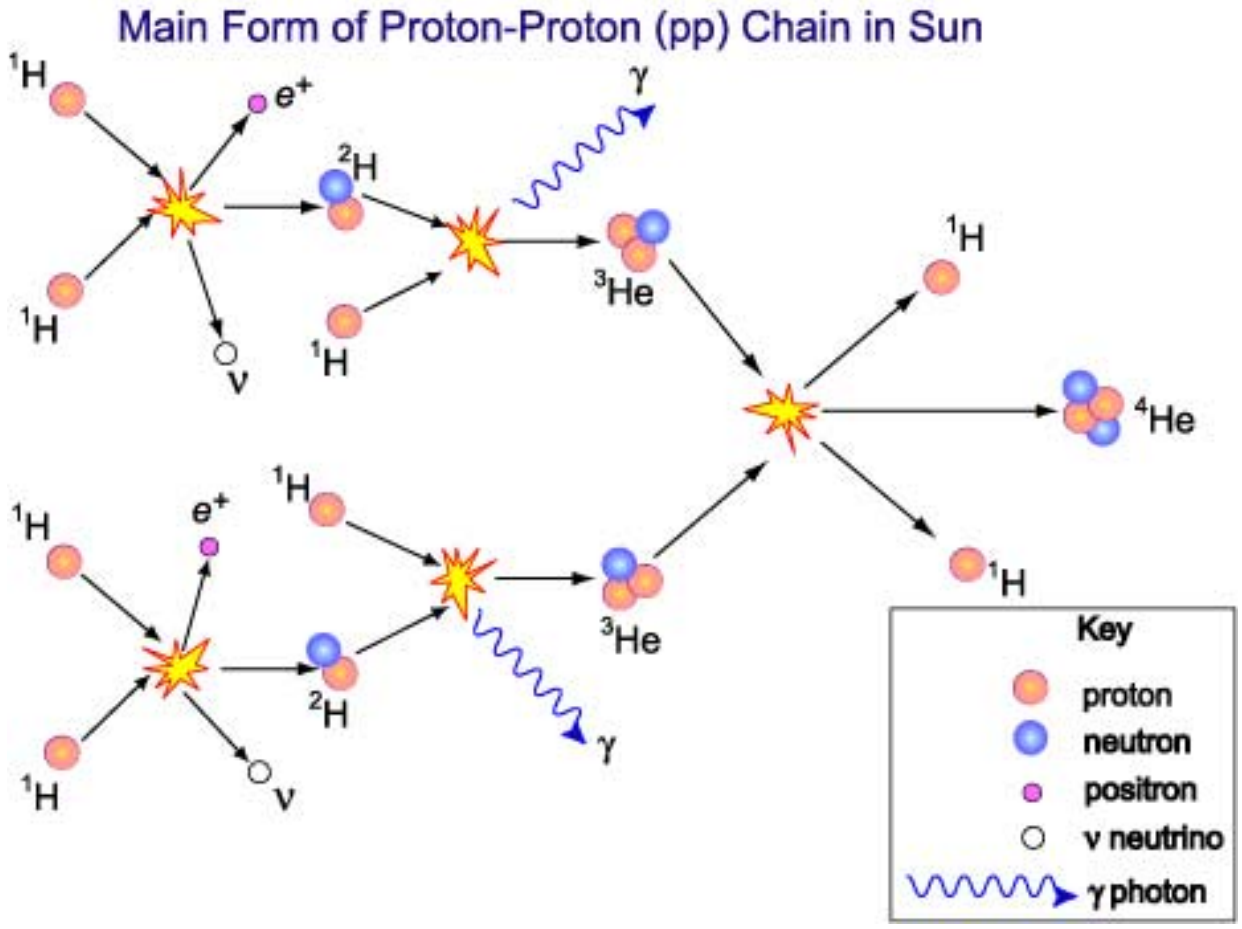
5000 acres of collectors
plus energy storage for
night and cloudy days



Fusion

1/2 ton pickup truck
Deuterium & Tritium

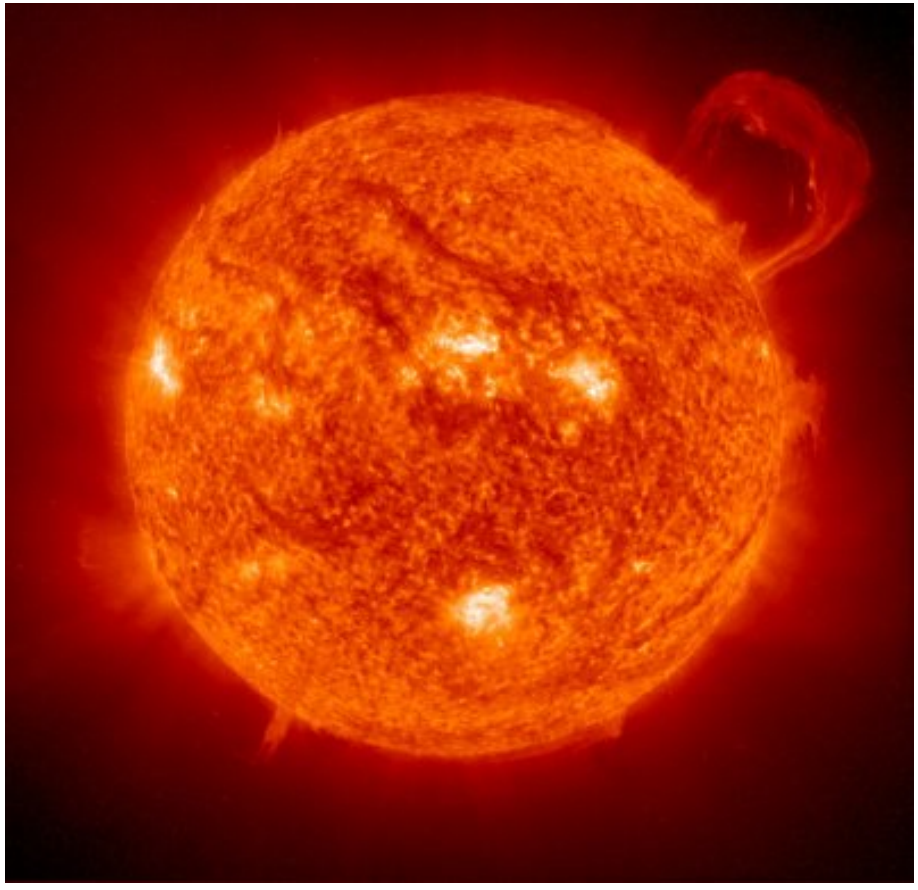
The Sun - Proton proton chain



. [credit:CSIRO]

$$4\ {}^1_1\mathbf{p} \Rightarrow {}^4_2\mathbf{He} + 2\ \mathbf{e}^+ + 2\ \nu_\mathbf{e} + 2\ \gamma + \mathbf{26.73\ MeV}$$

Harnessing the Sun's (star's) energy

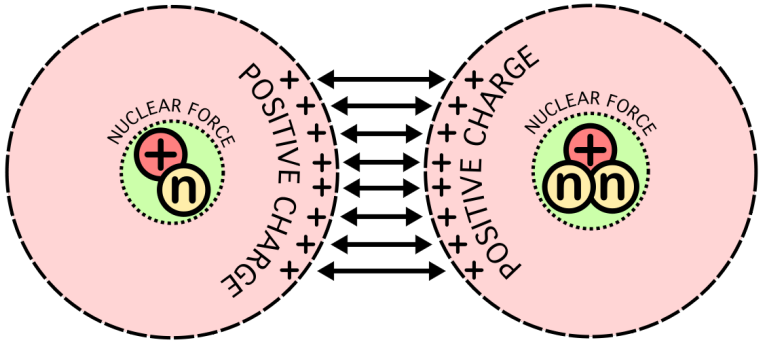


Core Burning Stages in a 25 Solar Mass Star:

Fuel:	Products:	Temperature (K):	Minimum Mass:	Burning Period:
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 ..)

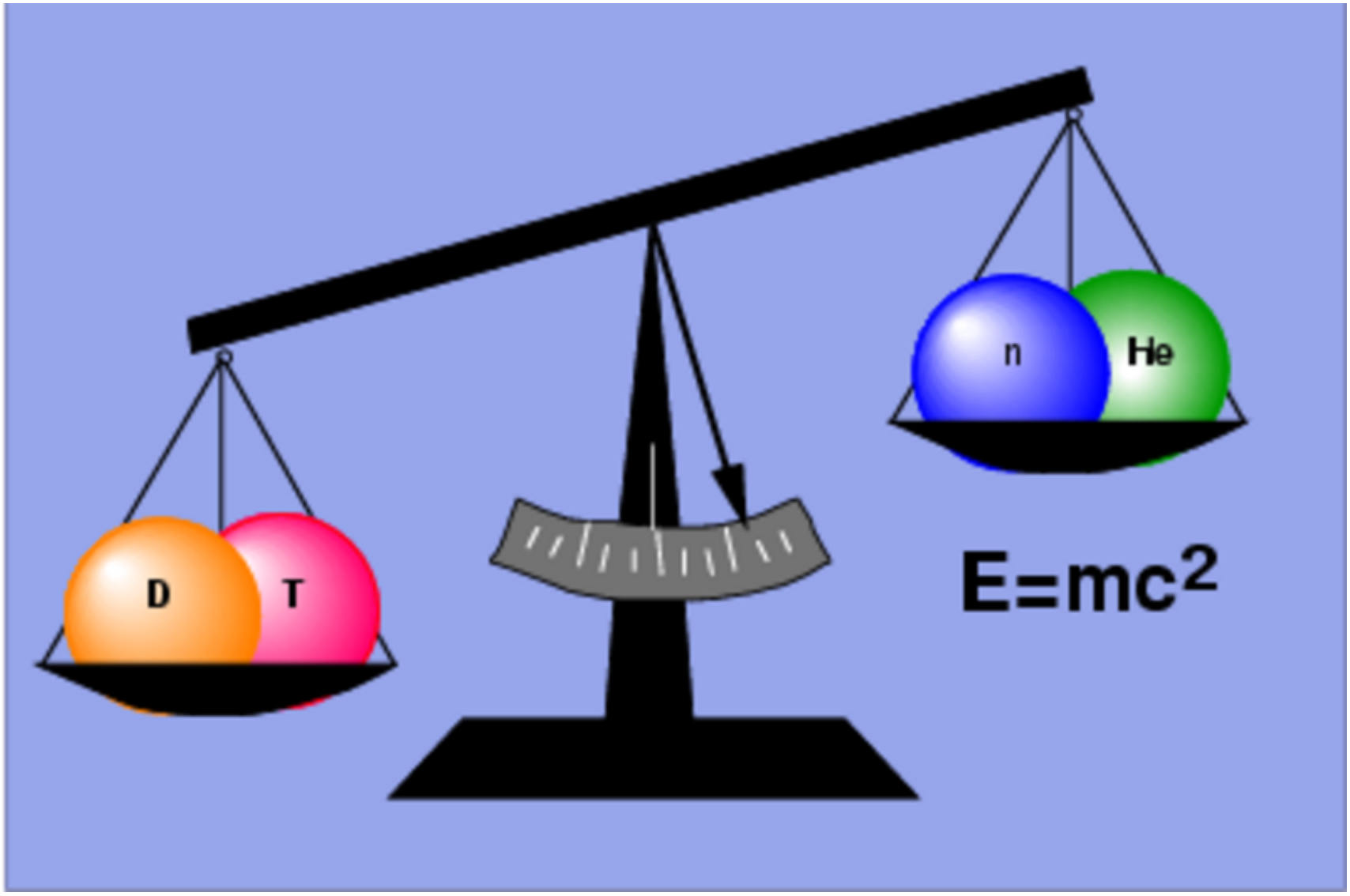
Electrostatic force - like charges repeal



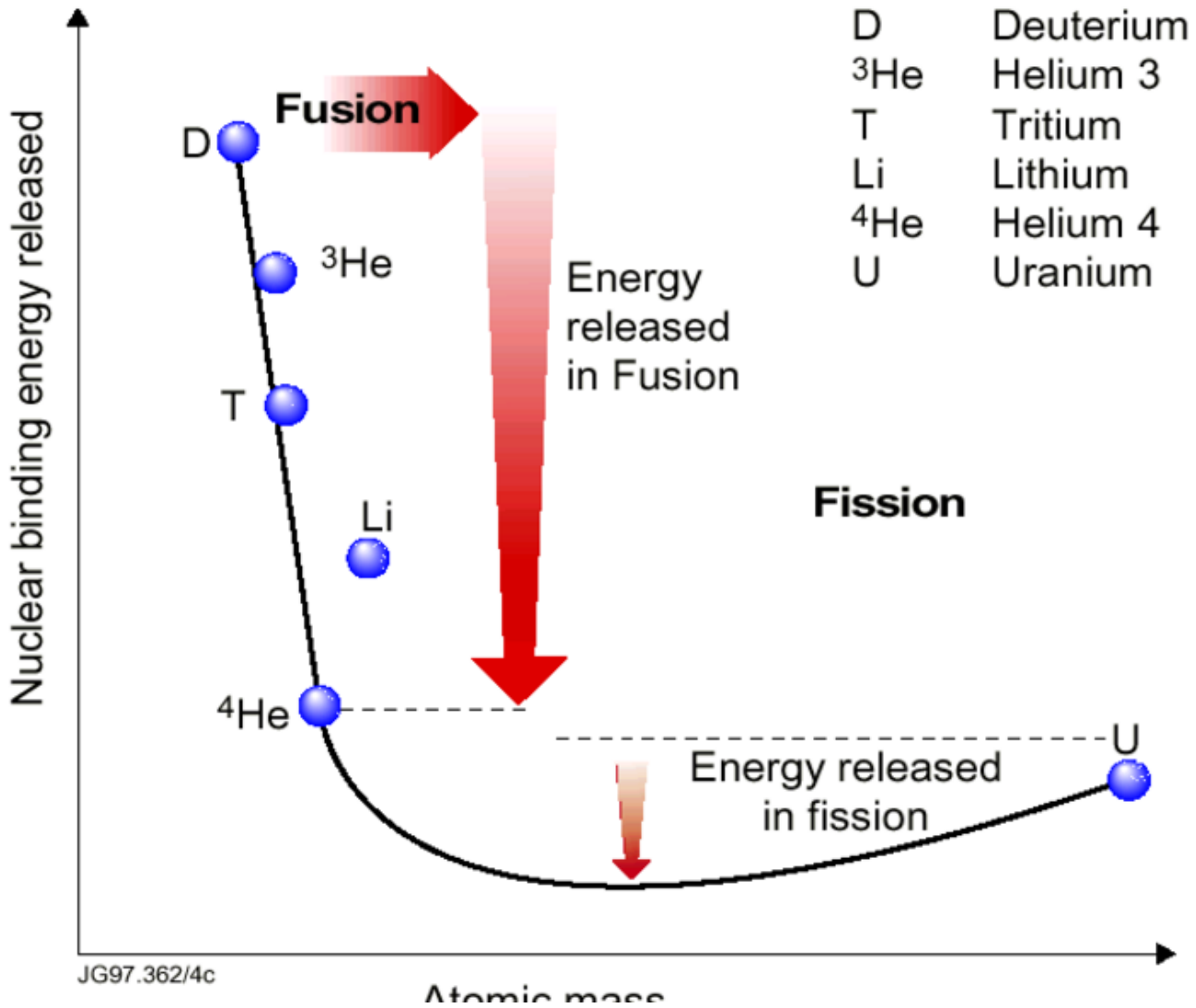
- Coulomb law:
  $F_E = \frac{1}{4\pi\epsilon_0}\frac{Q_1\ Q_2}{r^2}$

$$ {}^{2}_{1}\mathbf{D}_{(10\mathbf{keV})} + {}^{3}_{1}\mathbf{T}_{(10\mathbf{keV})} \Rightarrow {}^{4}_{2}\mathbf{He}_{(3.5\mathbf{MeV})} + \mathbf{n}_{(14.1\mathbf{MeV})} $$

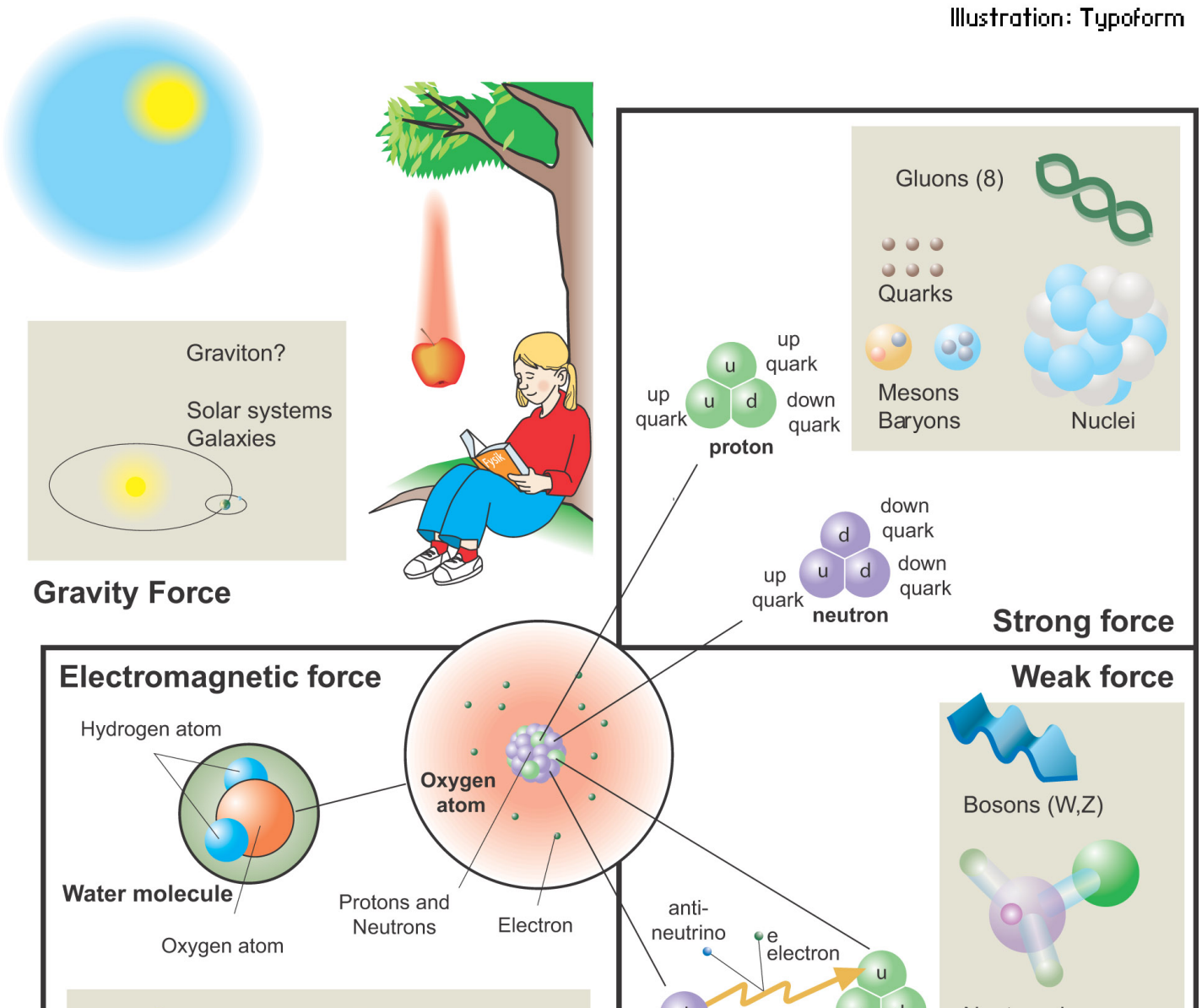
Binding energy releasing I



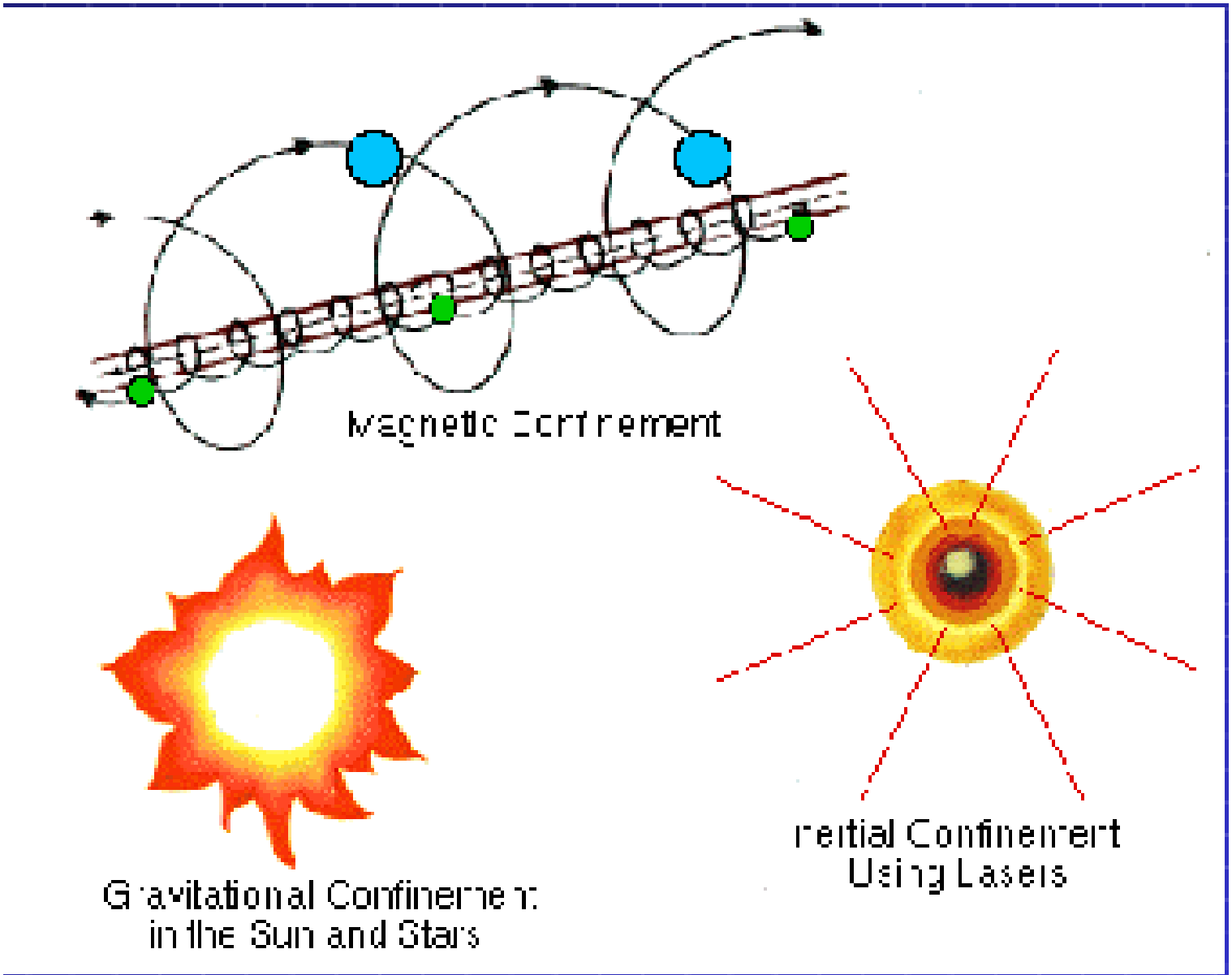
Binding energy releasing



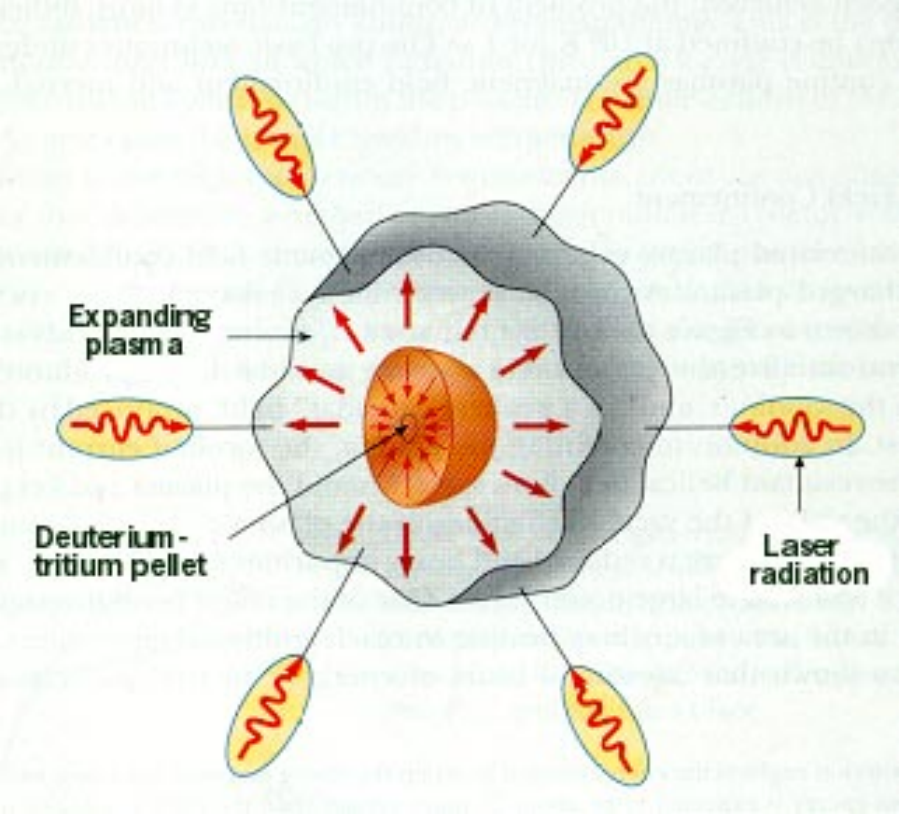
Fundamental forces (to confine?)

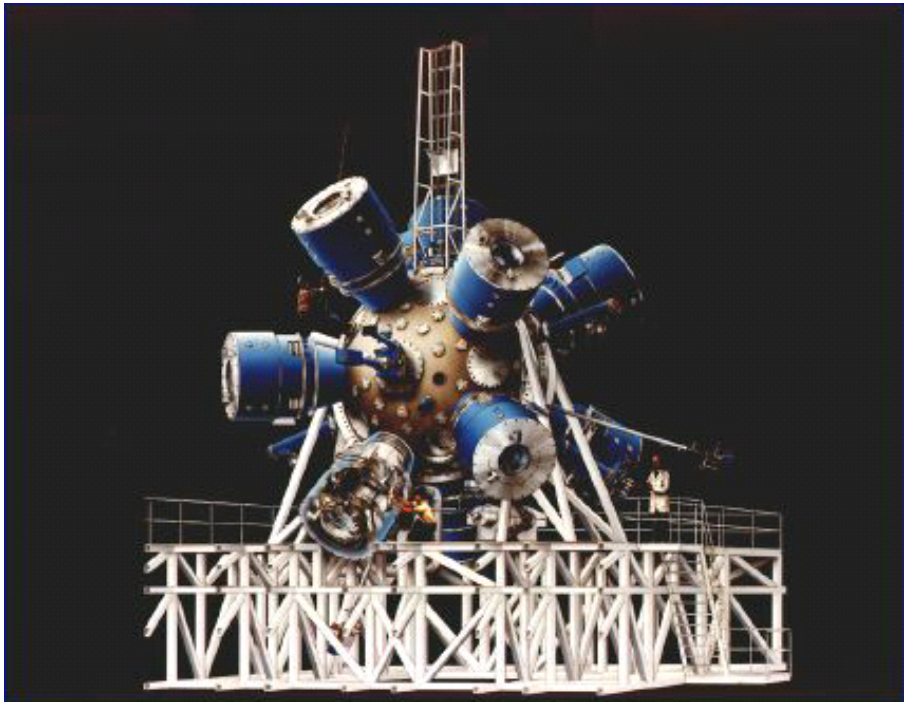


Three ways to confine plasma

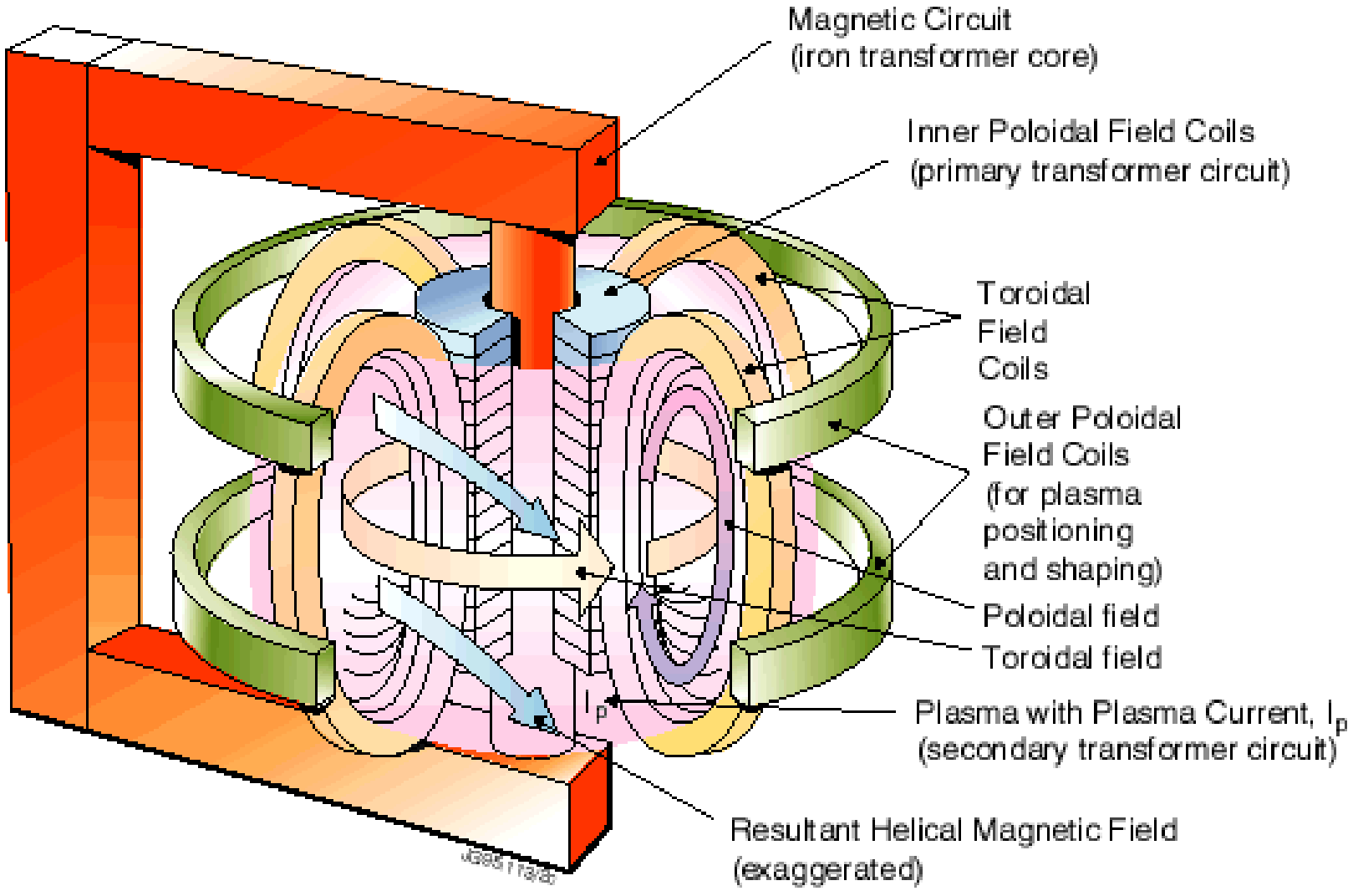


Inertial fusion





Tokamak magnetic confinement concept



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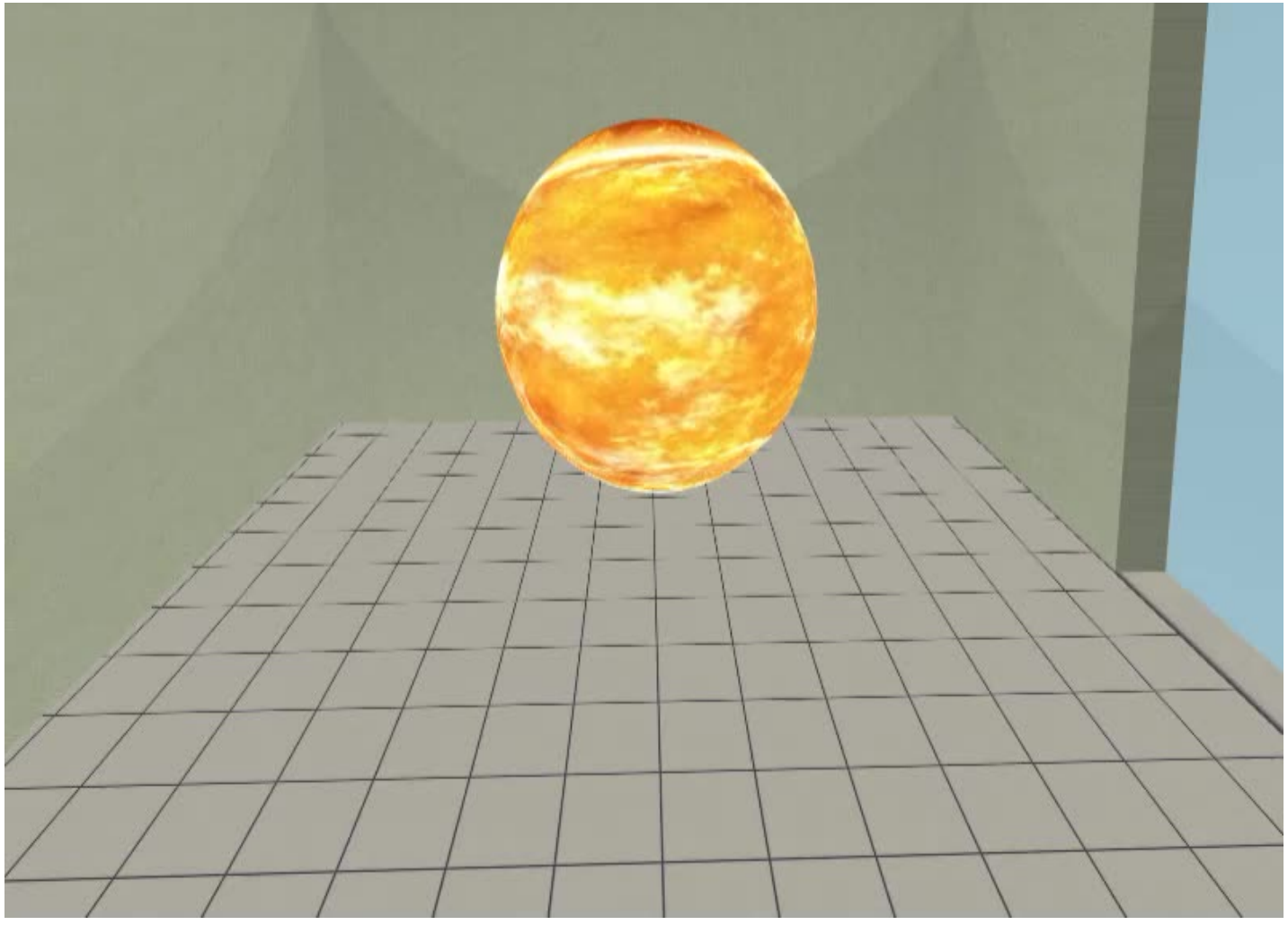
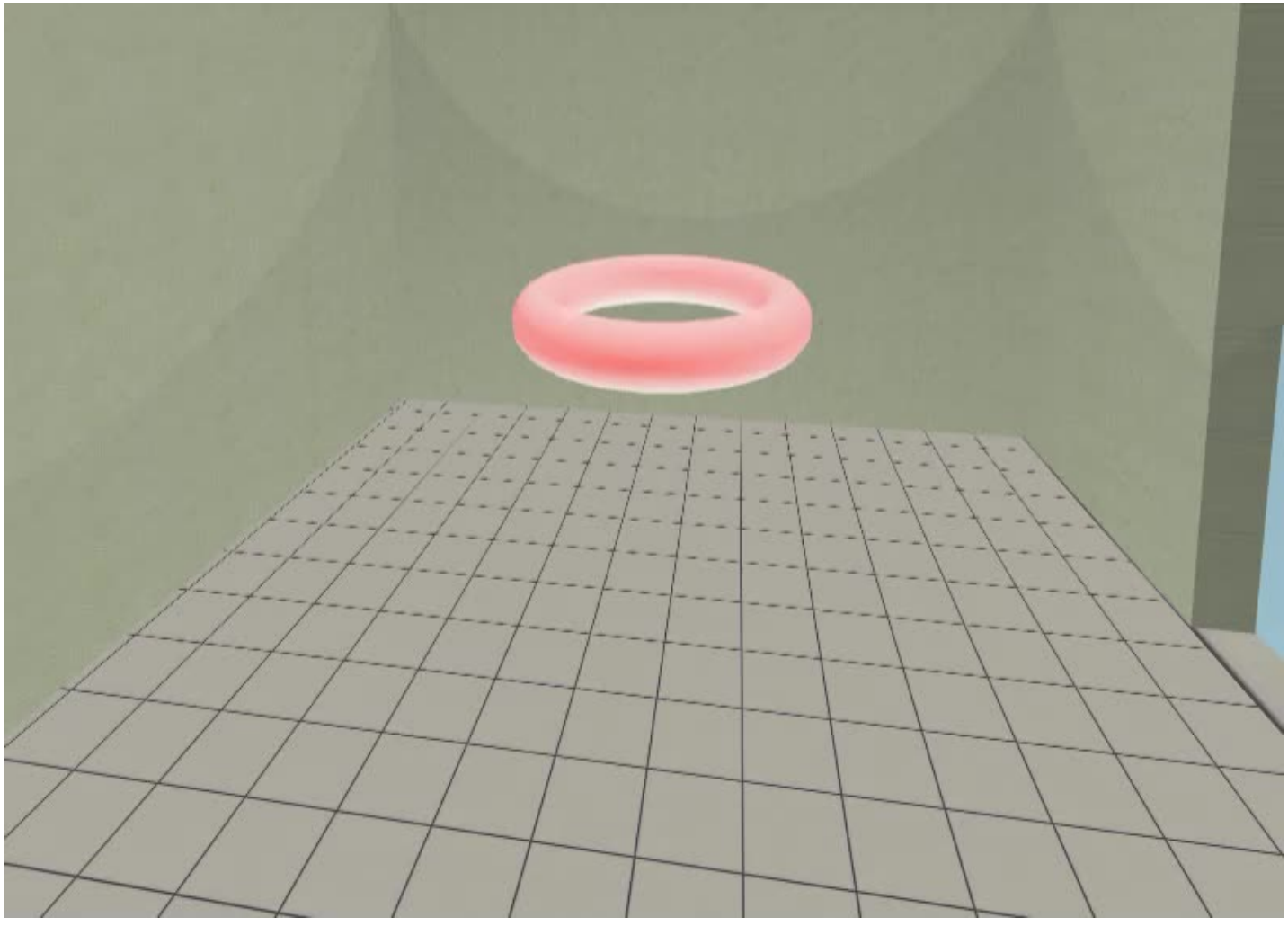
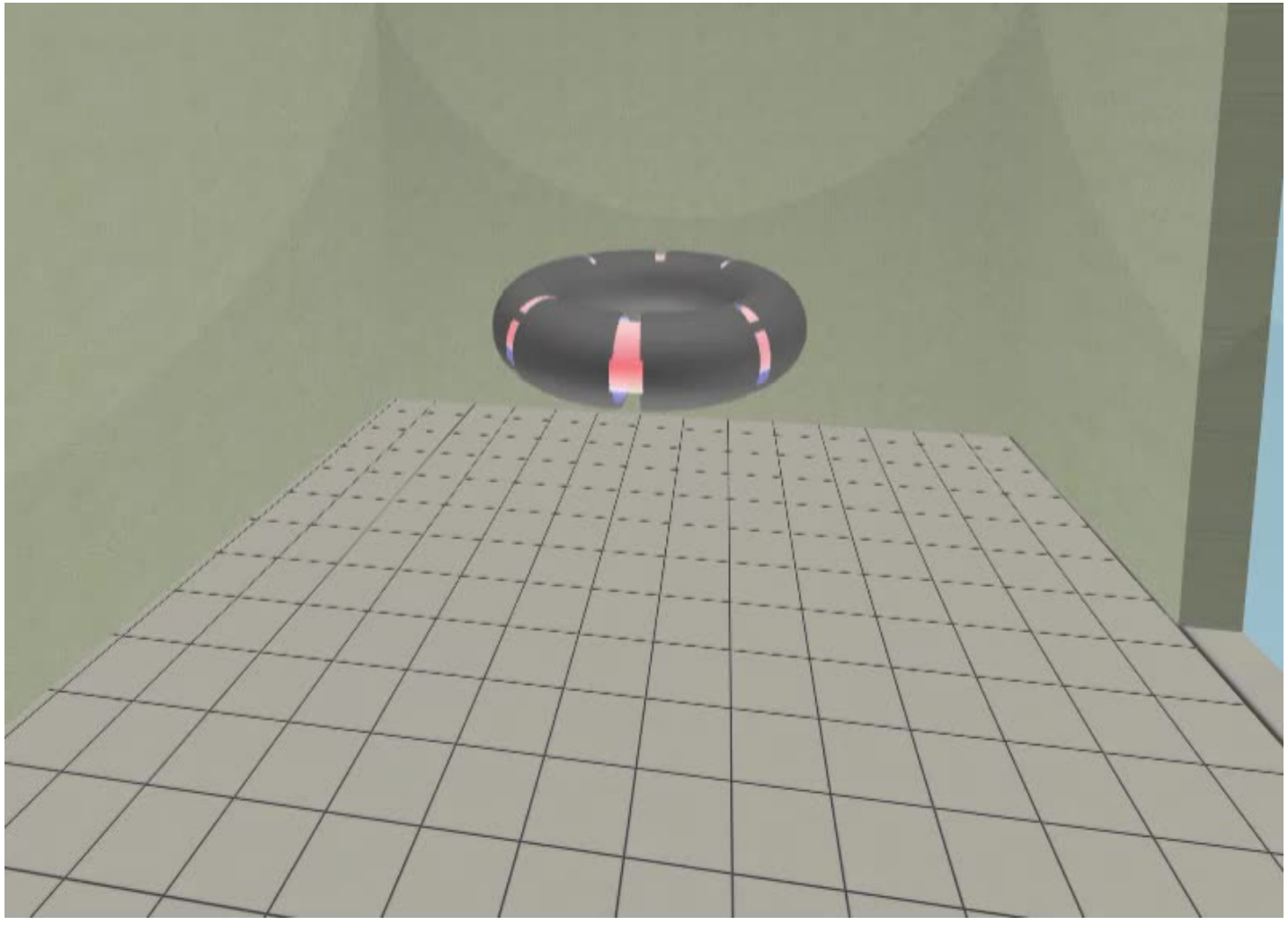
The technology to conquer: make a μSun on the Earth



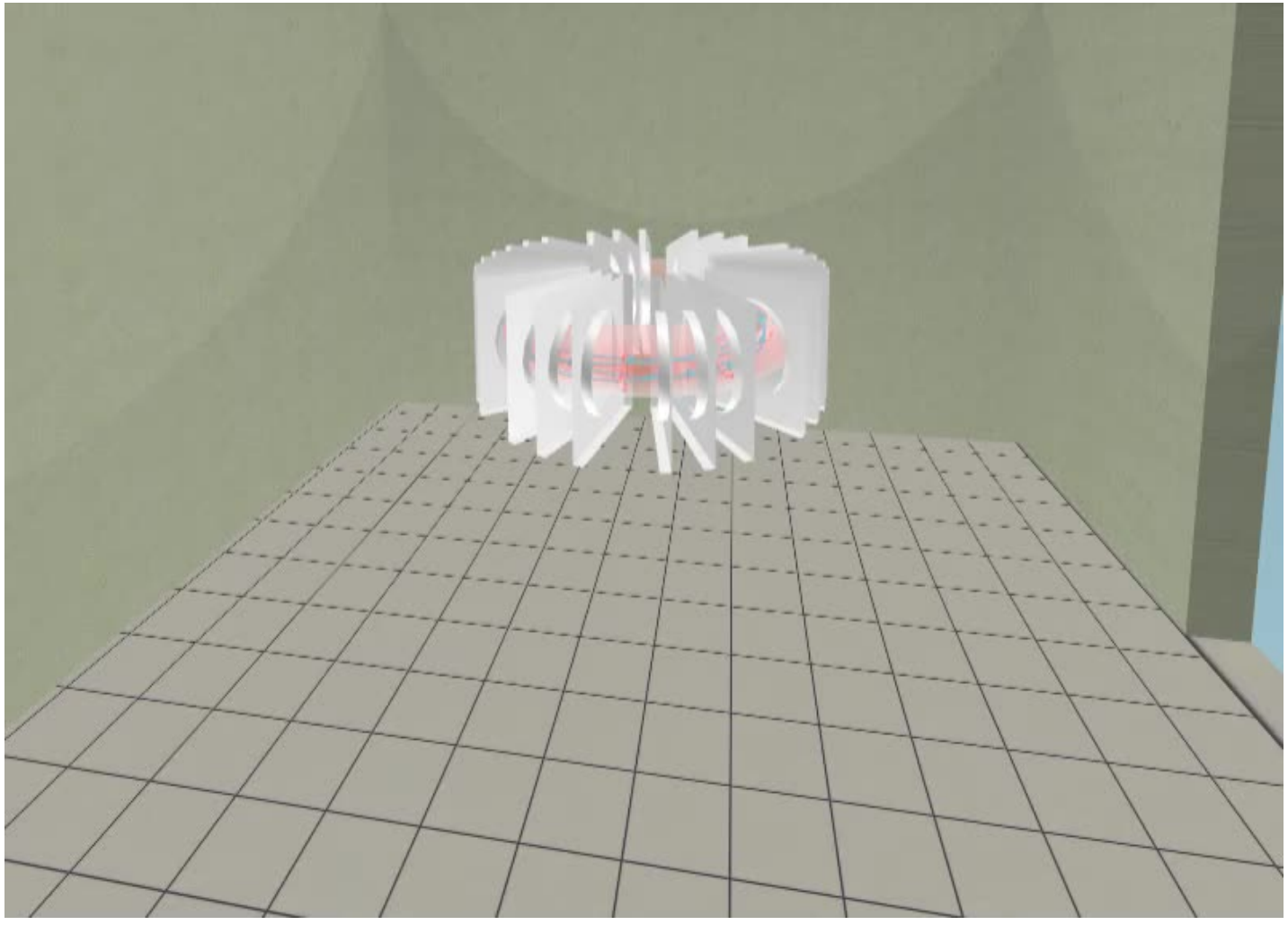
Magnetic confinement requires the toroidal geometry



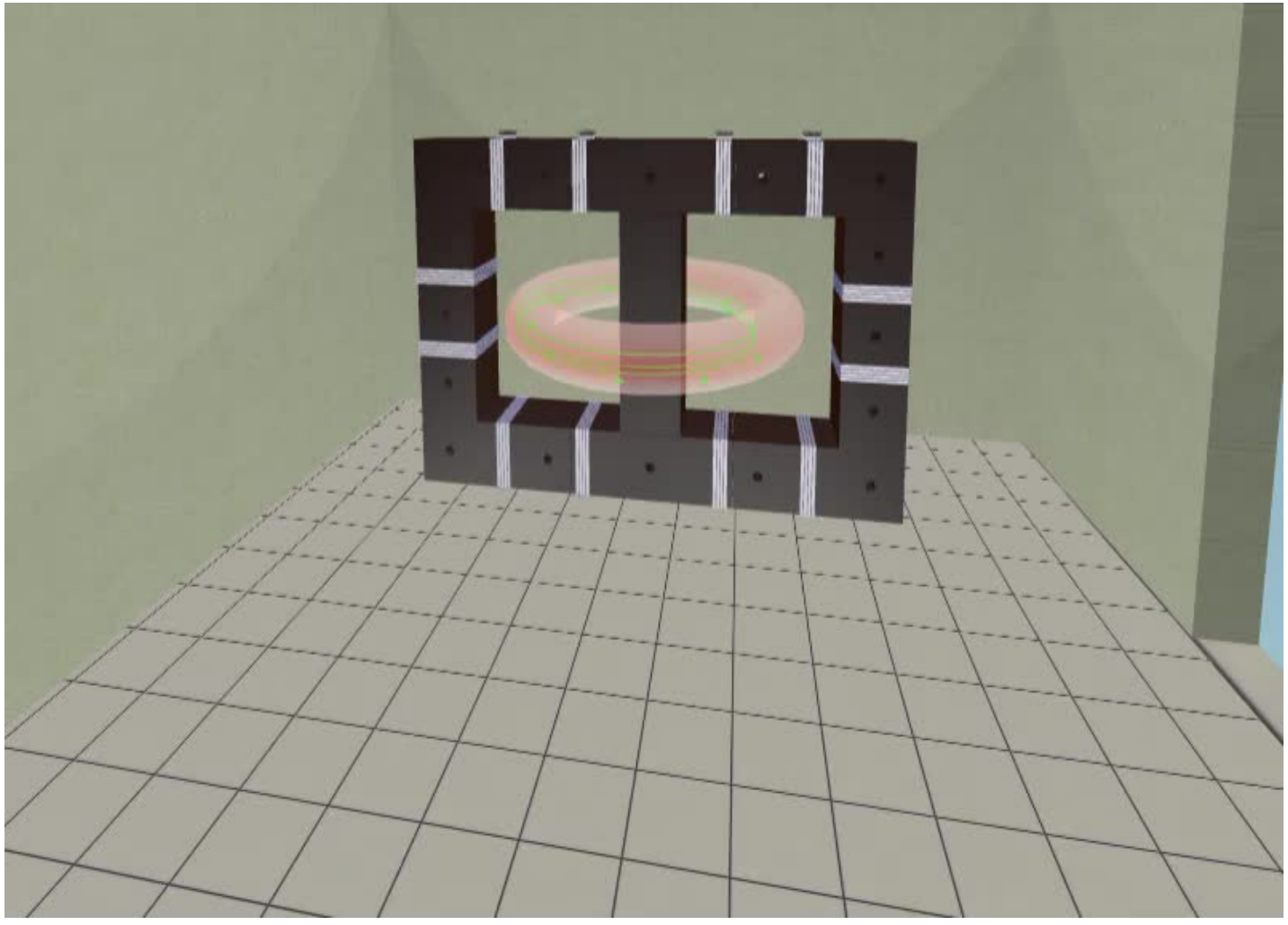
The thermonuclear reaction takes place in the chamber



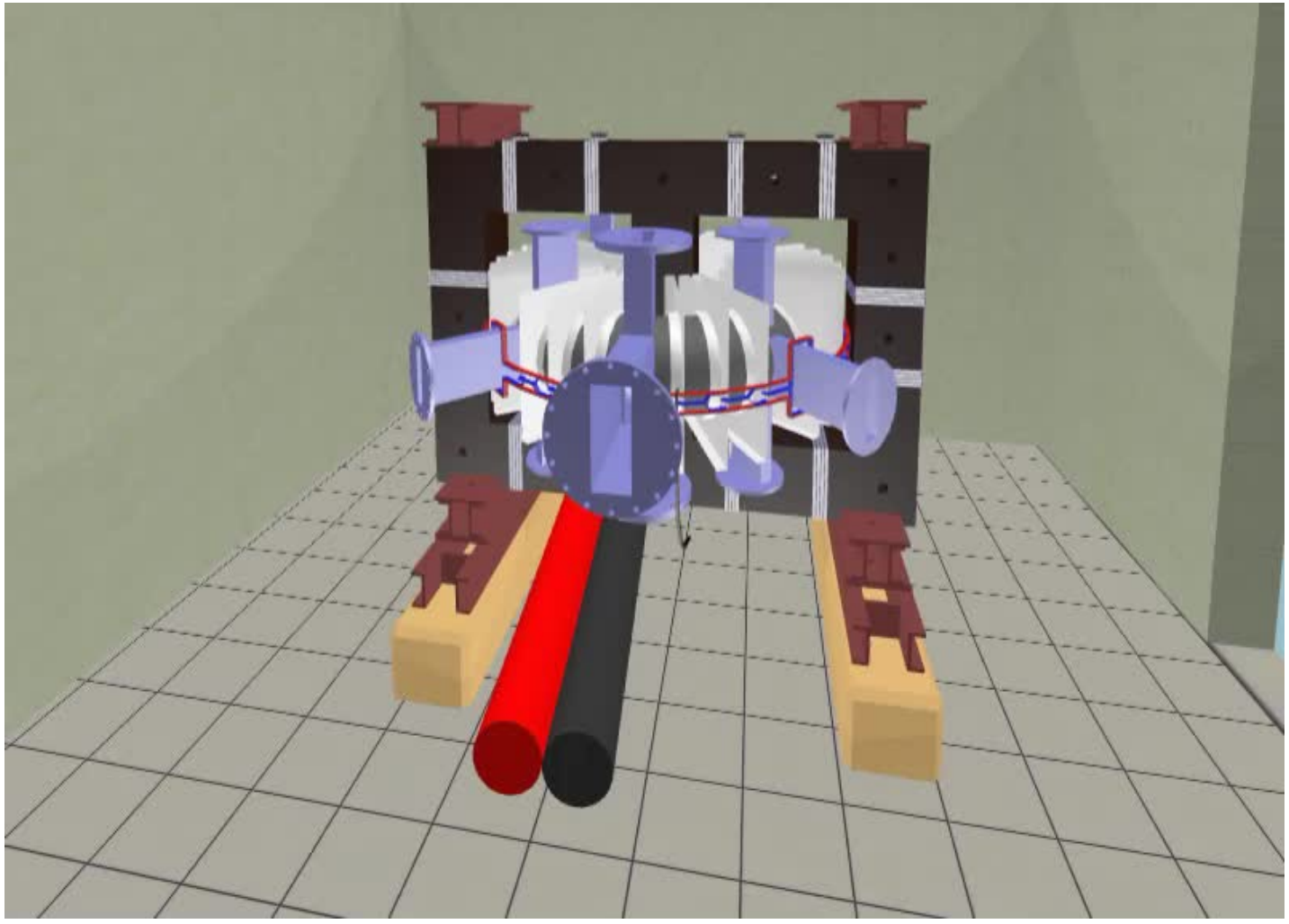
Toroidal magnetic field coils secure the plasma confinement



Transformer secures the plasma creation and heating



The final technology alltogether



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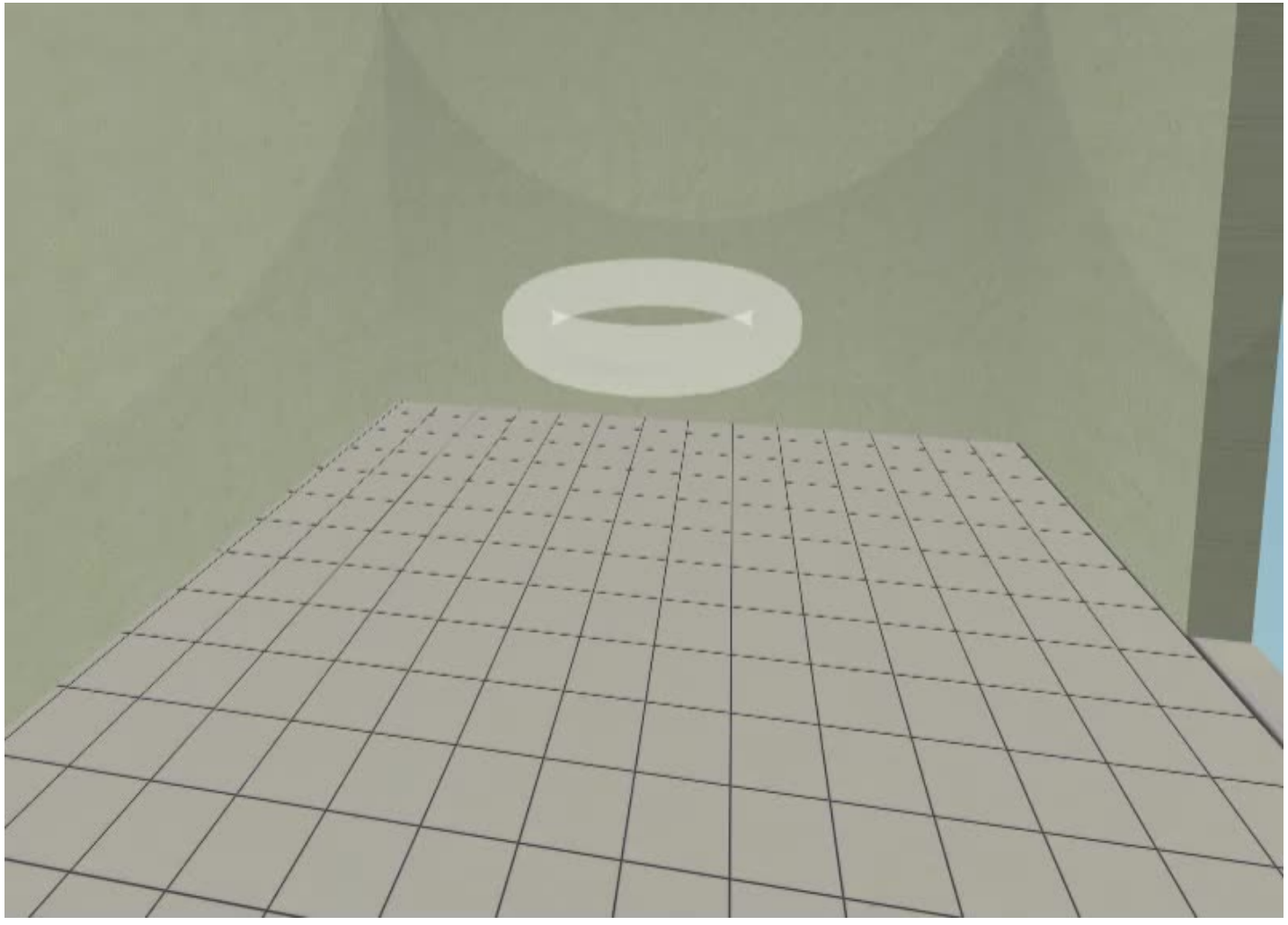
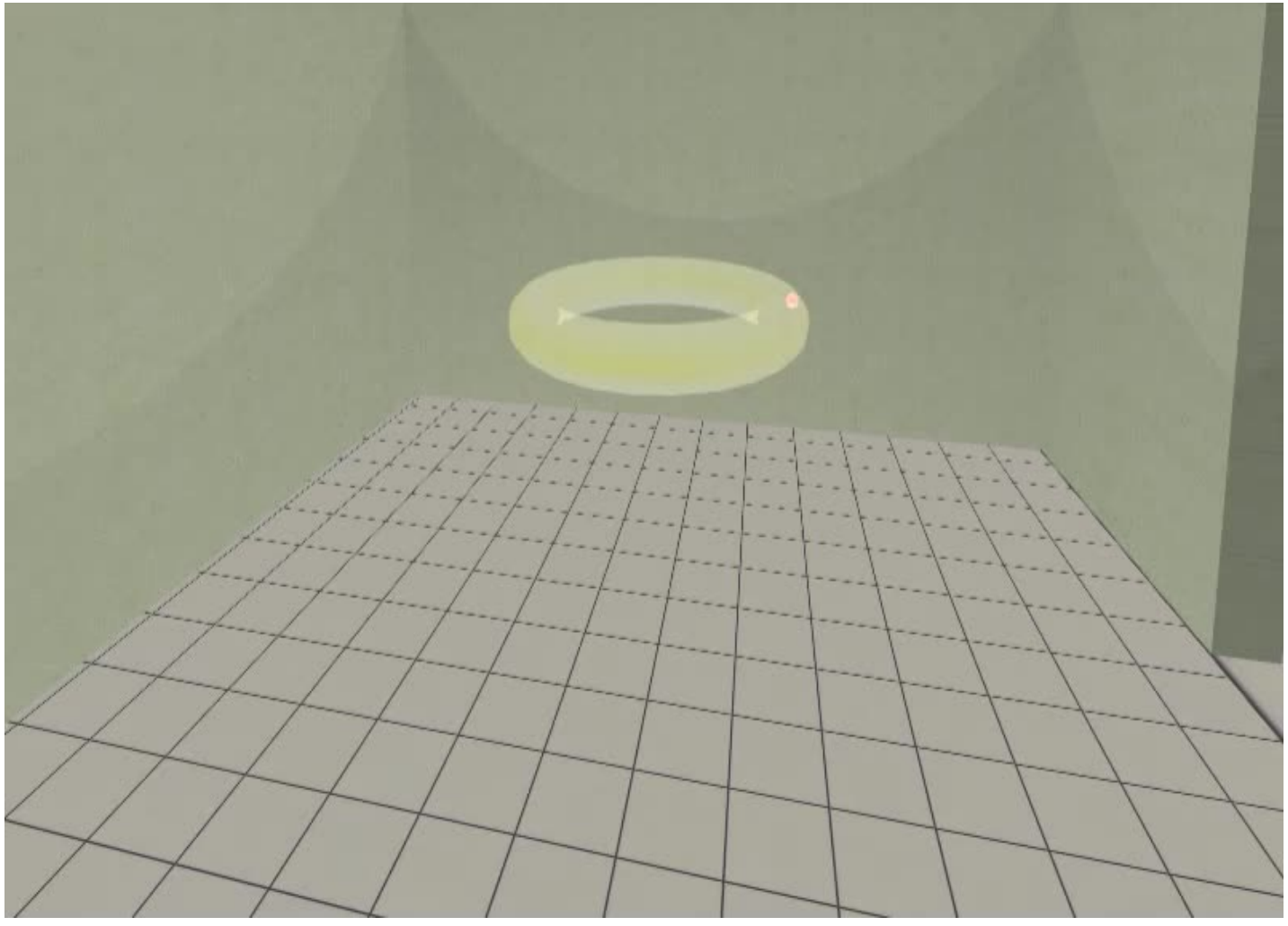
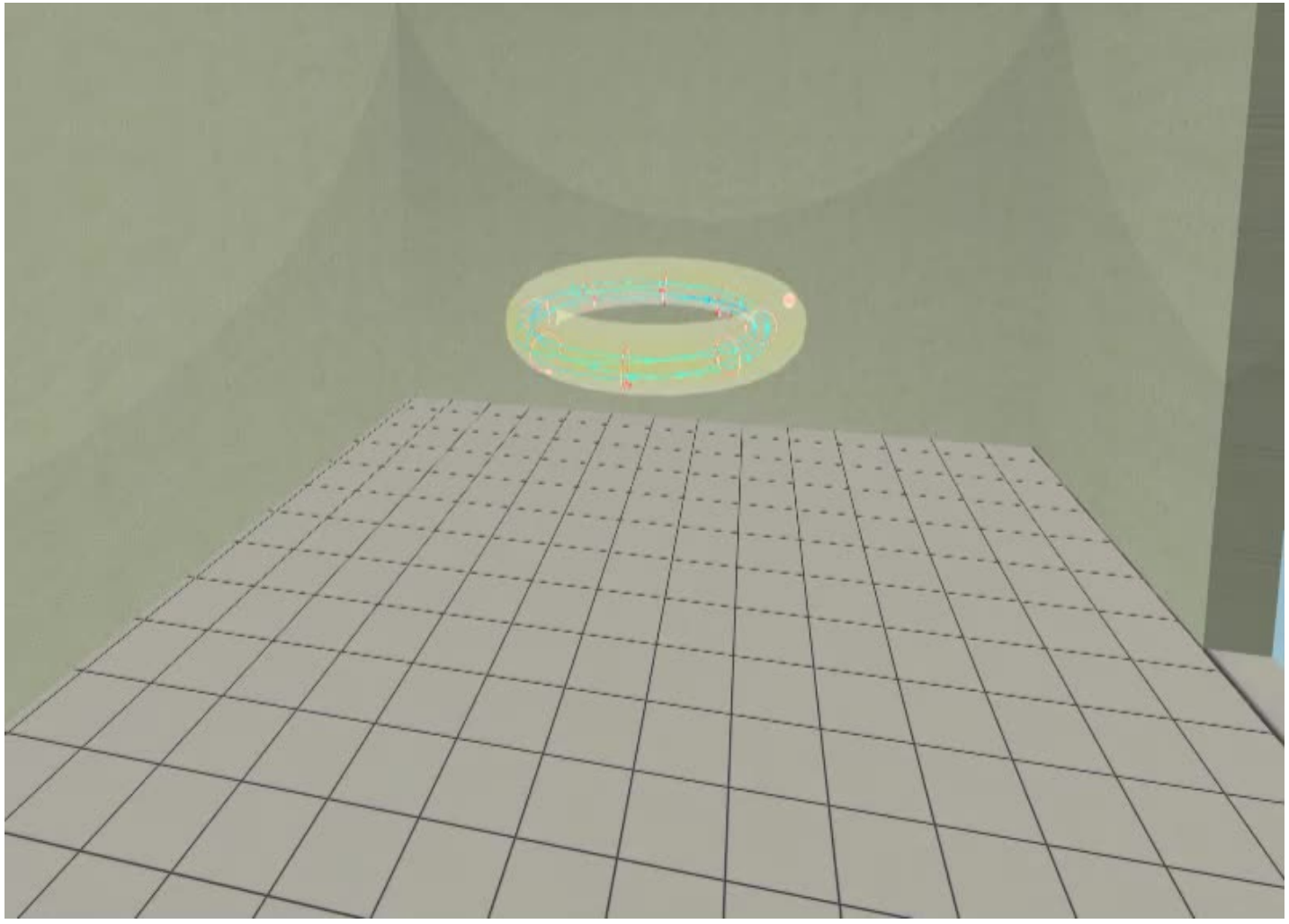
Introduce the working gas (Hydrogen x Helium)



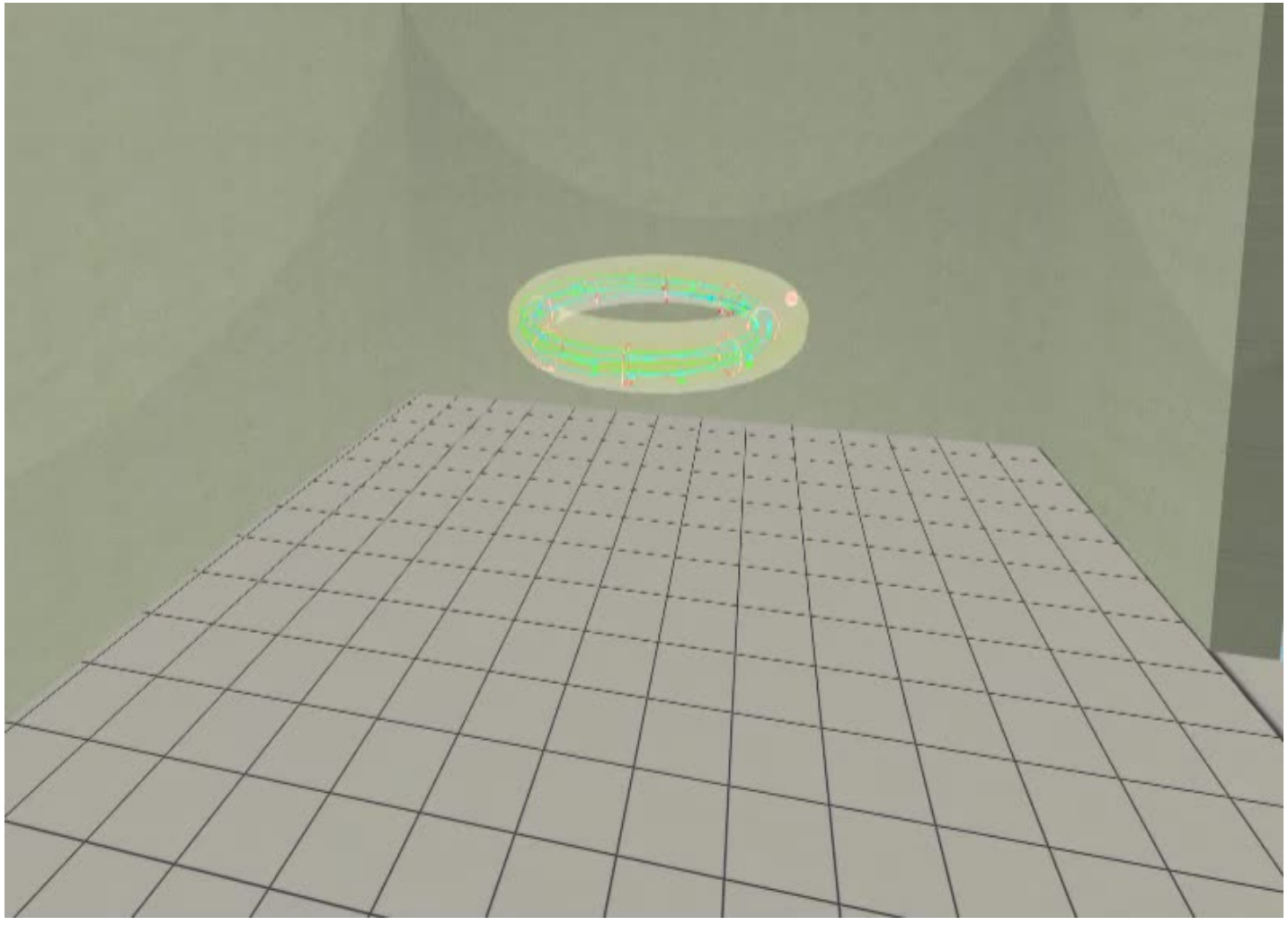
Switch on the preionization



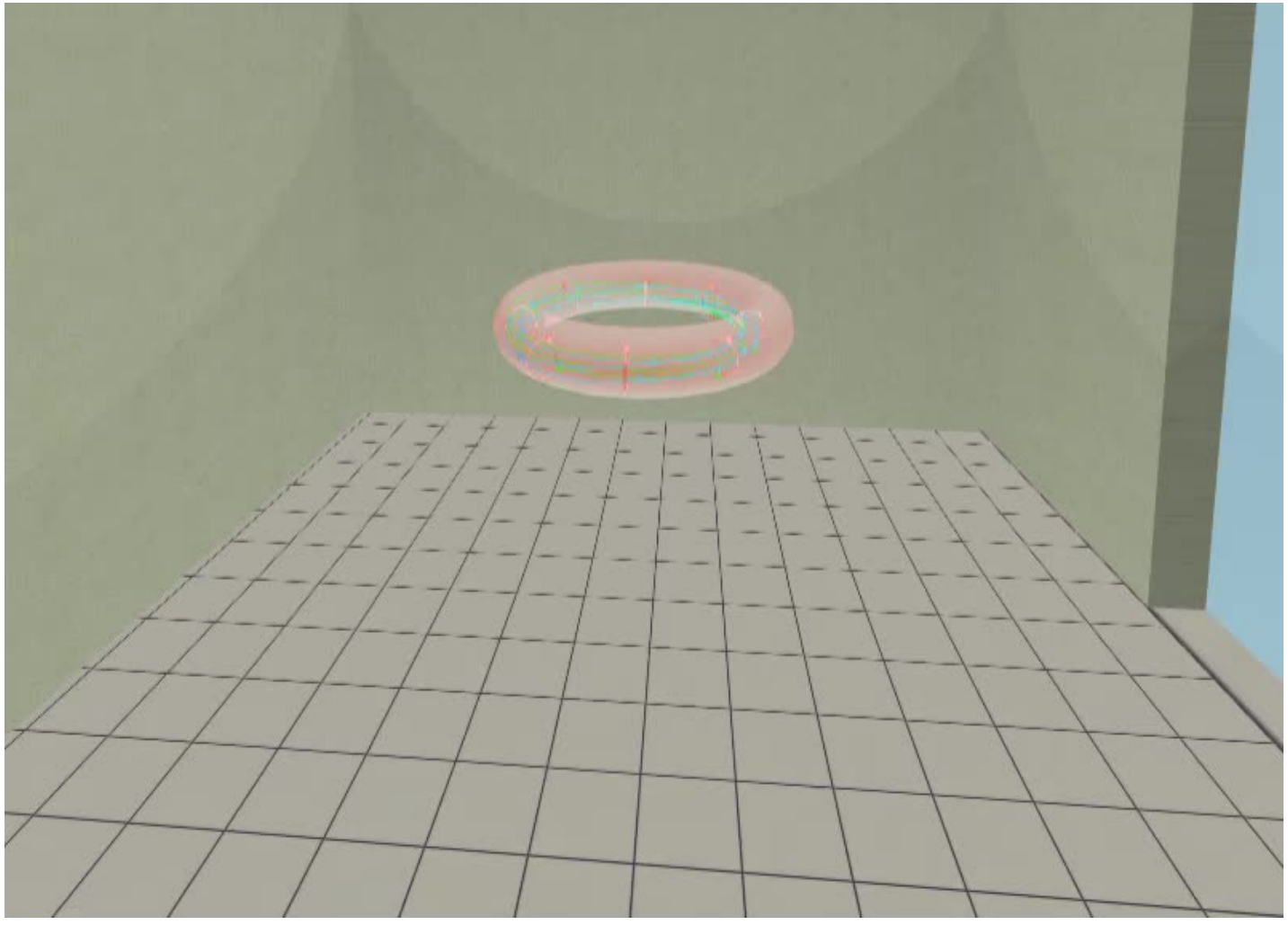
Introduce the magnetic field



Introduce the electric field



Plasma ..



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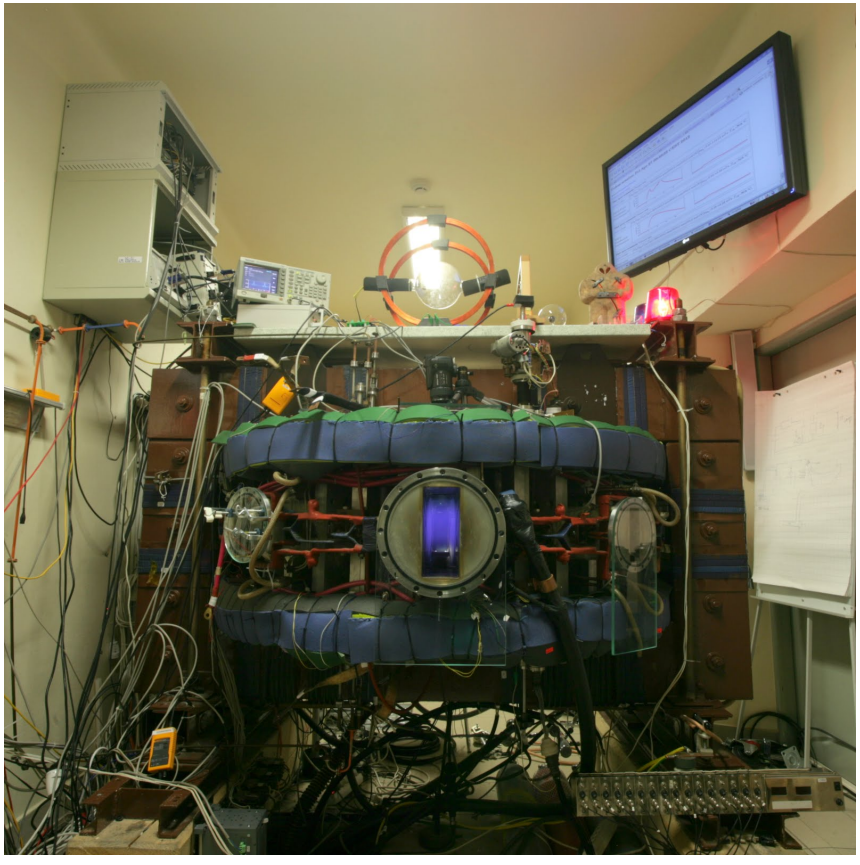
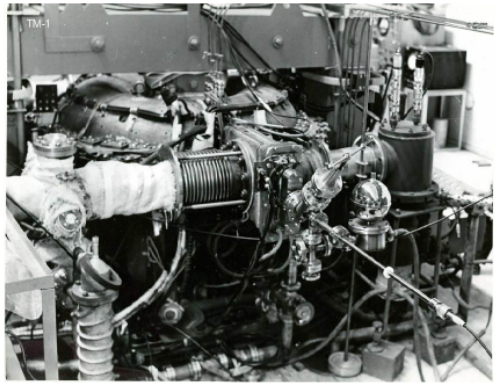
Tokamak GOLEM basic characteristics



- 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:
  $n_e \approx 0.2 - 3 \times 10^{19}\ m^{-3}$
- Electron temperature: $T_e = 100$ eV
- Ion temperature: $T_i = 50$ eV
- Discharge length: $\tau_p = 25$ ms

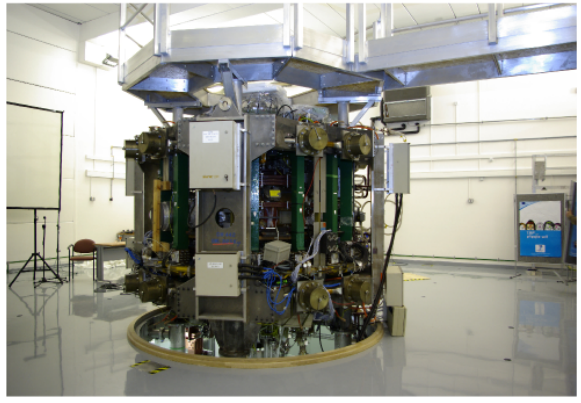
Tokamak GOLEM for education - historical background

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



1974

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



2006

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

2008

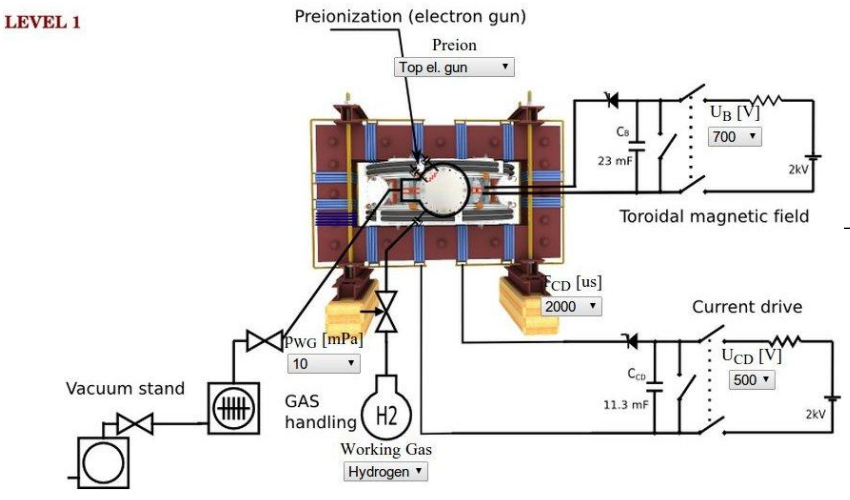
Czech Technical University Prague
Czech republic
GOLEM

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

Tokamak technology setup



internet

USER authorization

WWW server

OpenSSH serve

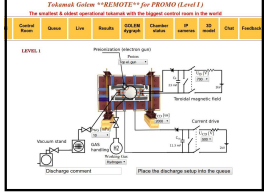
Control PC

OpenSSH server

Virtual control room (remote participation)

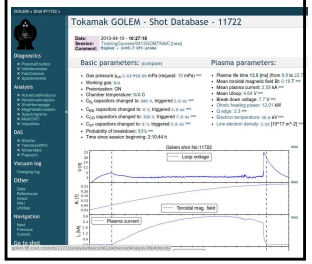
WWW control interface

HTML & PHP scripts



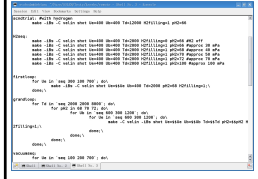
Data presentation

HTML (www pages)



SSH control interface

WINDOWS via putty

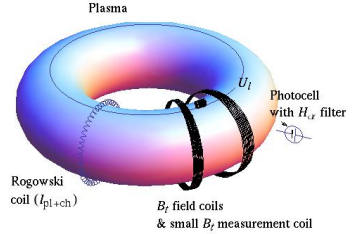


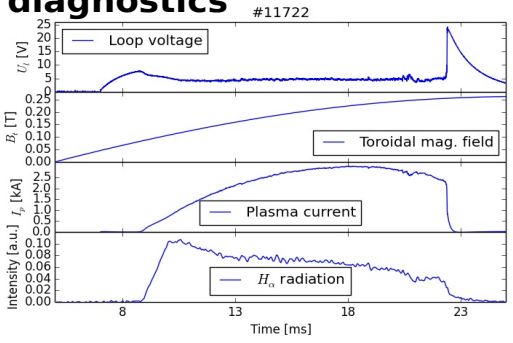
LINUX via ssh
or ssh+X tunnel
(advanced mode)

Data handling

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

Basic plasma diagnostics





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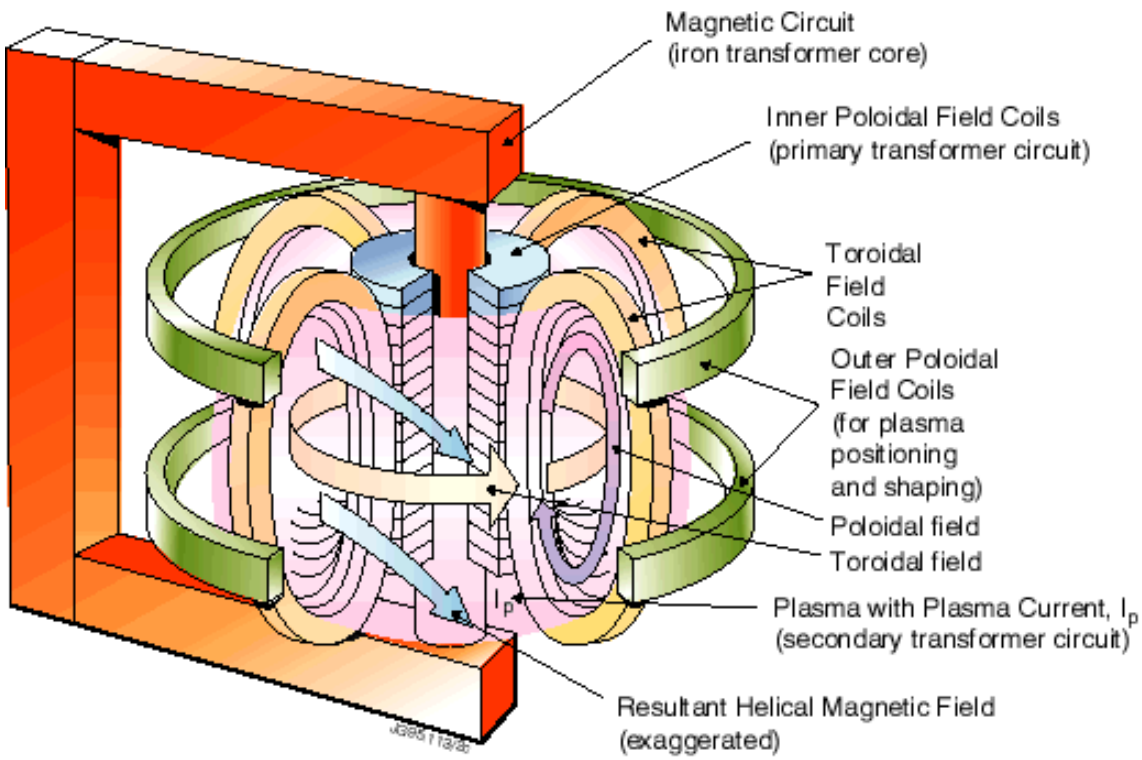
Plasma in Tokamak (GOLEM) - the least to do



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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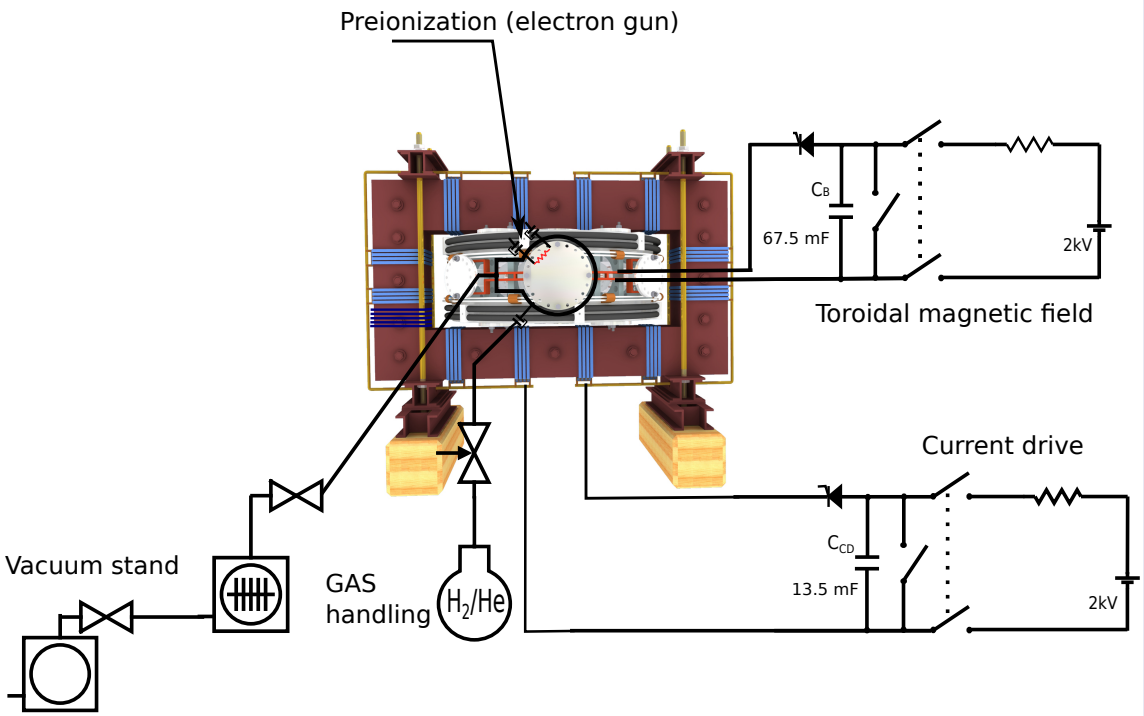

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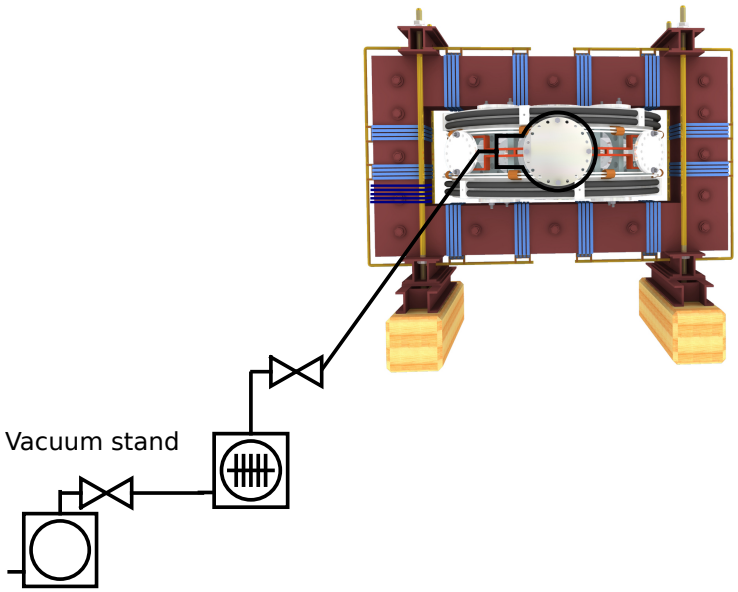

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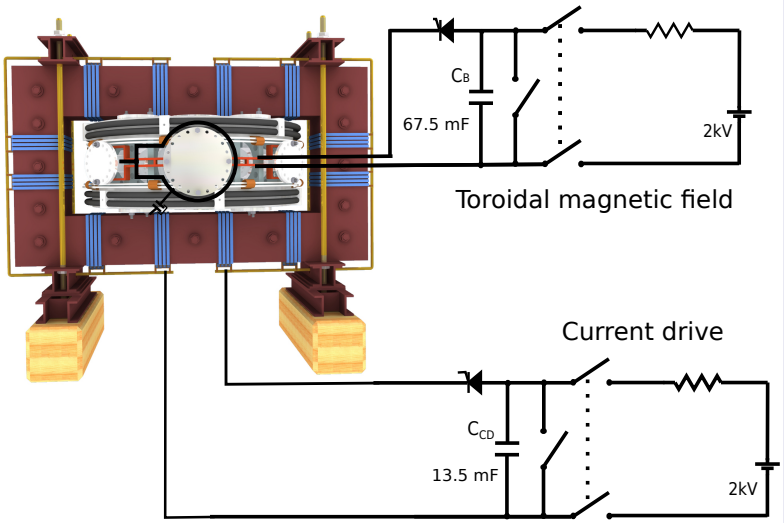

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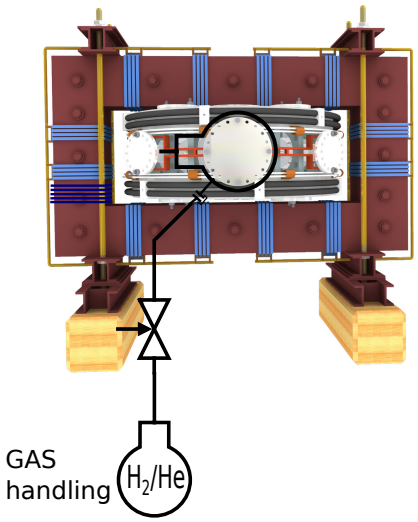
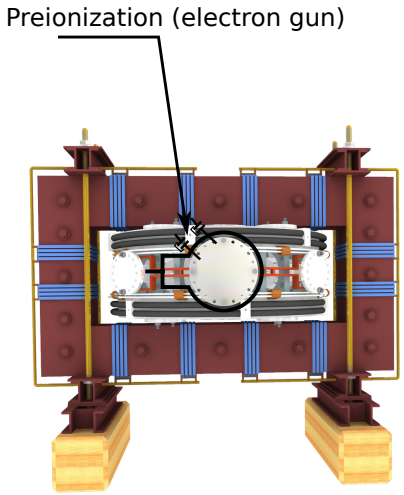
Plasma in Tokamak (GOLEM) - the least to do



To do:

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

Plasma in Tokamak (GOLEM) - the least to do



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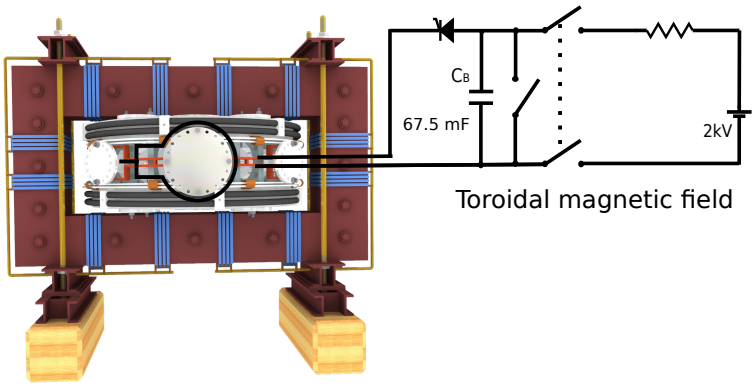

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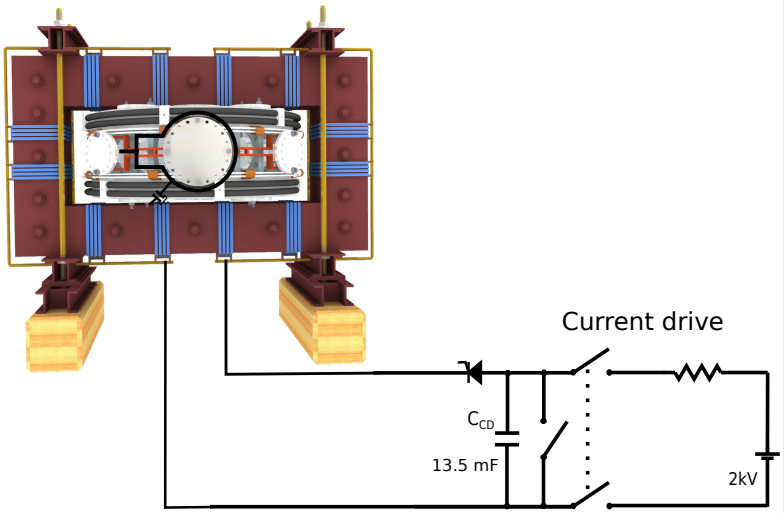
  - Diagnostics
- post-discharge phase

Plasma in Tokamak (GOLEM) - the least to do



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  - Evacuate the chamber
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  - Charge the capacitors
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  - Preionization
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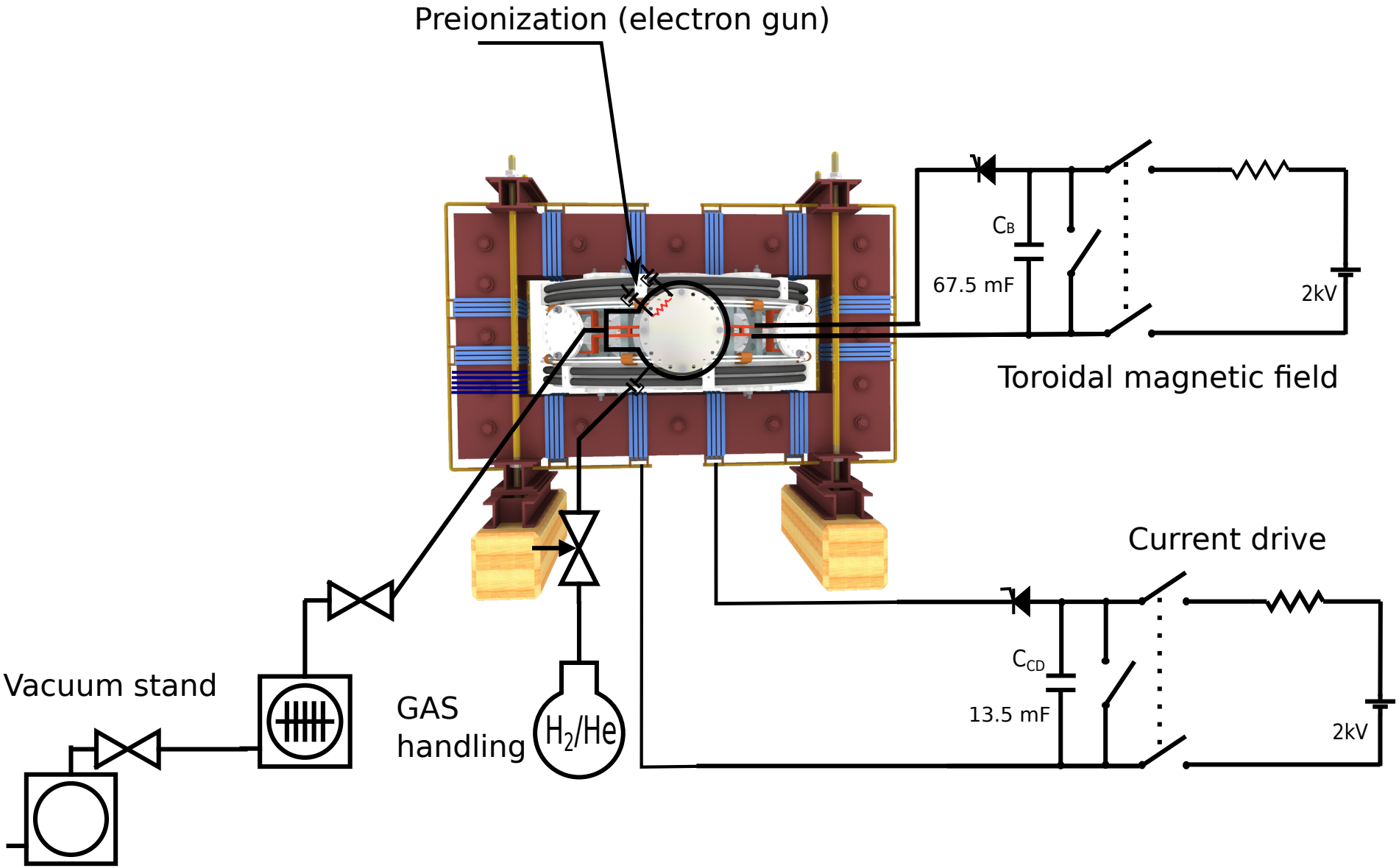
  - Toroidal magnetic field to confine plasma
  - **Toroidal electric field to breakdown neutral gas into plasma**
  - **Toroidal electric field to heat the plasma**
  - Plasma positioning
  - Diagnostics
- post-discharge phase

Tokamak GOLEM - schematic experimental setup



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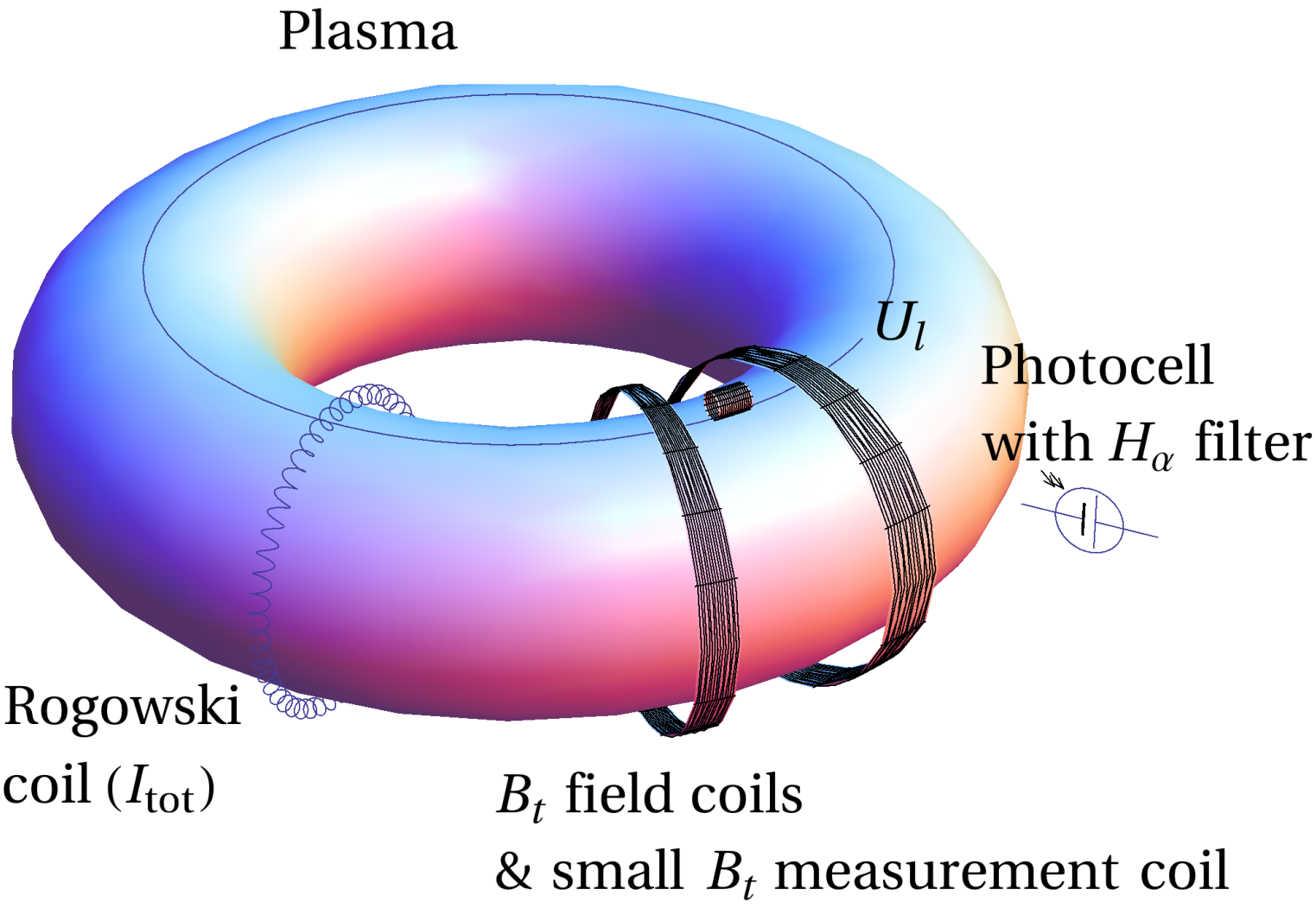
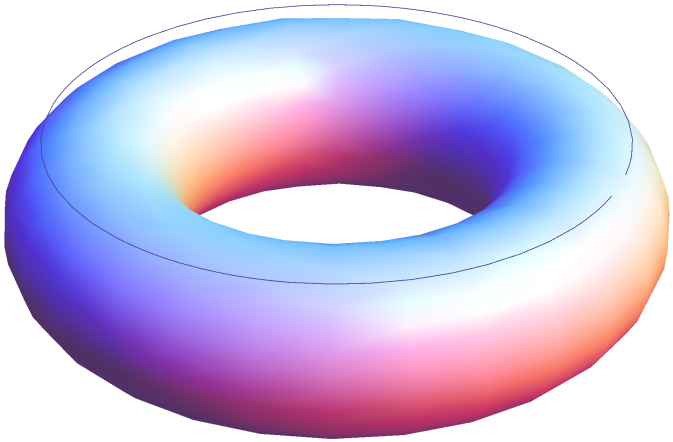
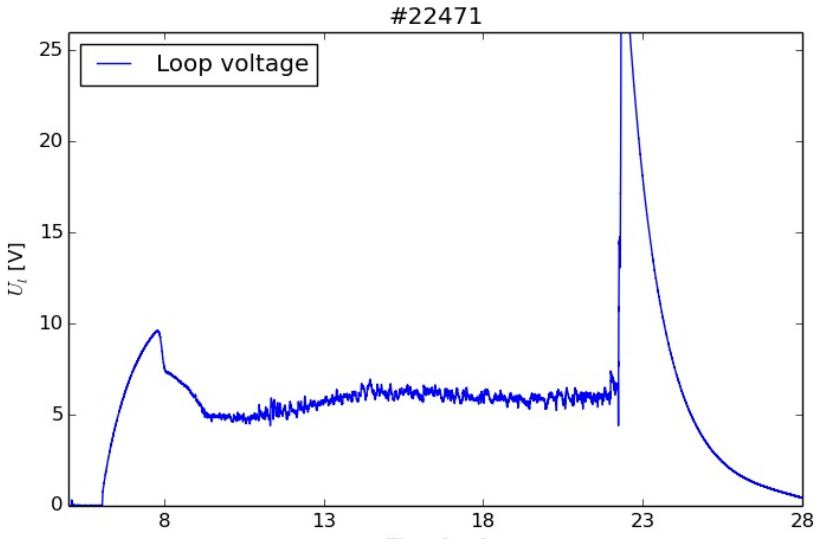
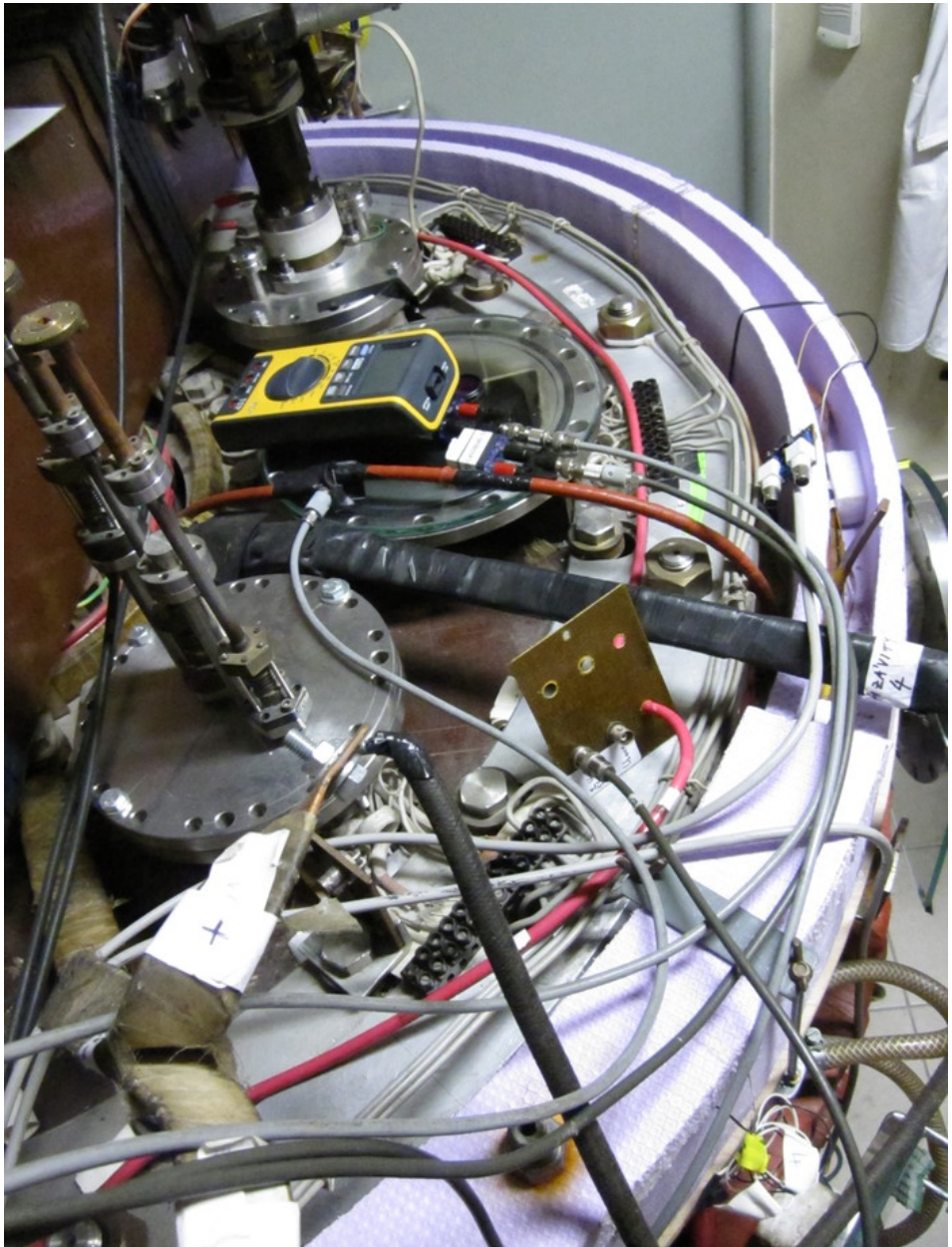
Tokamak GOLEM - basic diagnostics



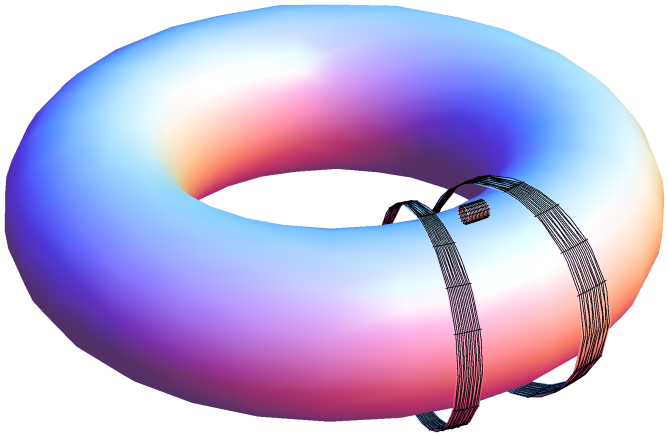
Loop voltage U_l

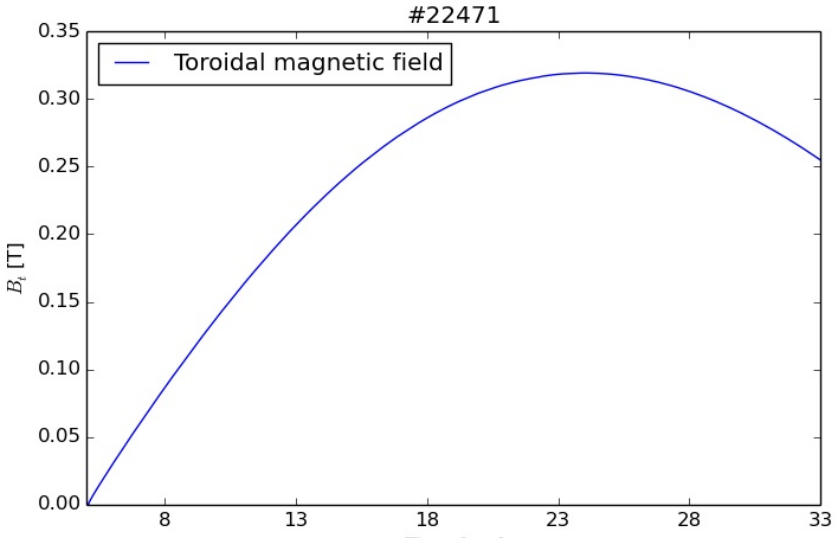


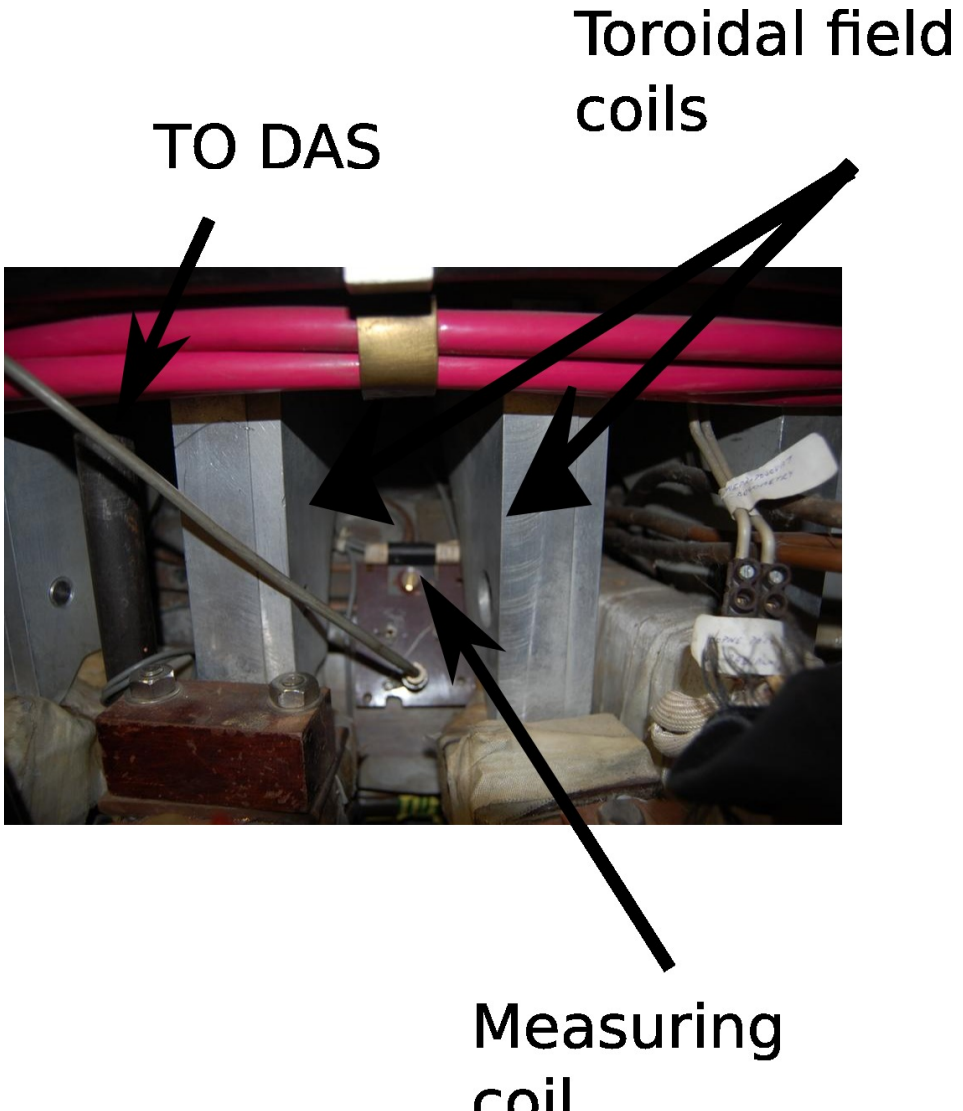




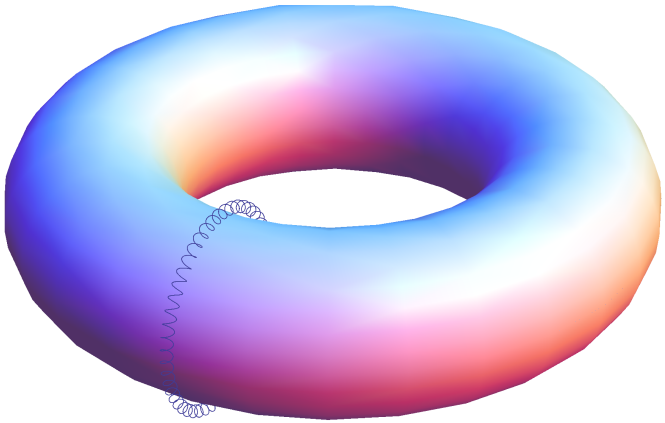
Toroidal magnetic field B_t

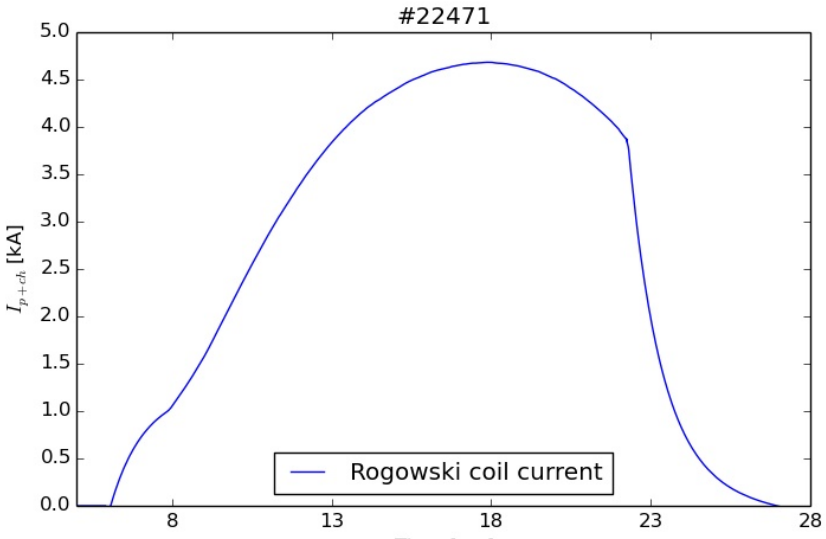


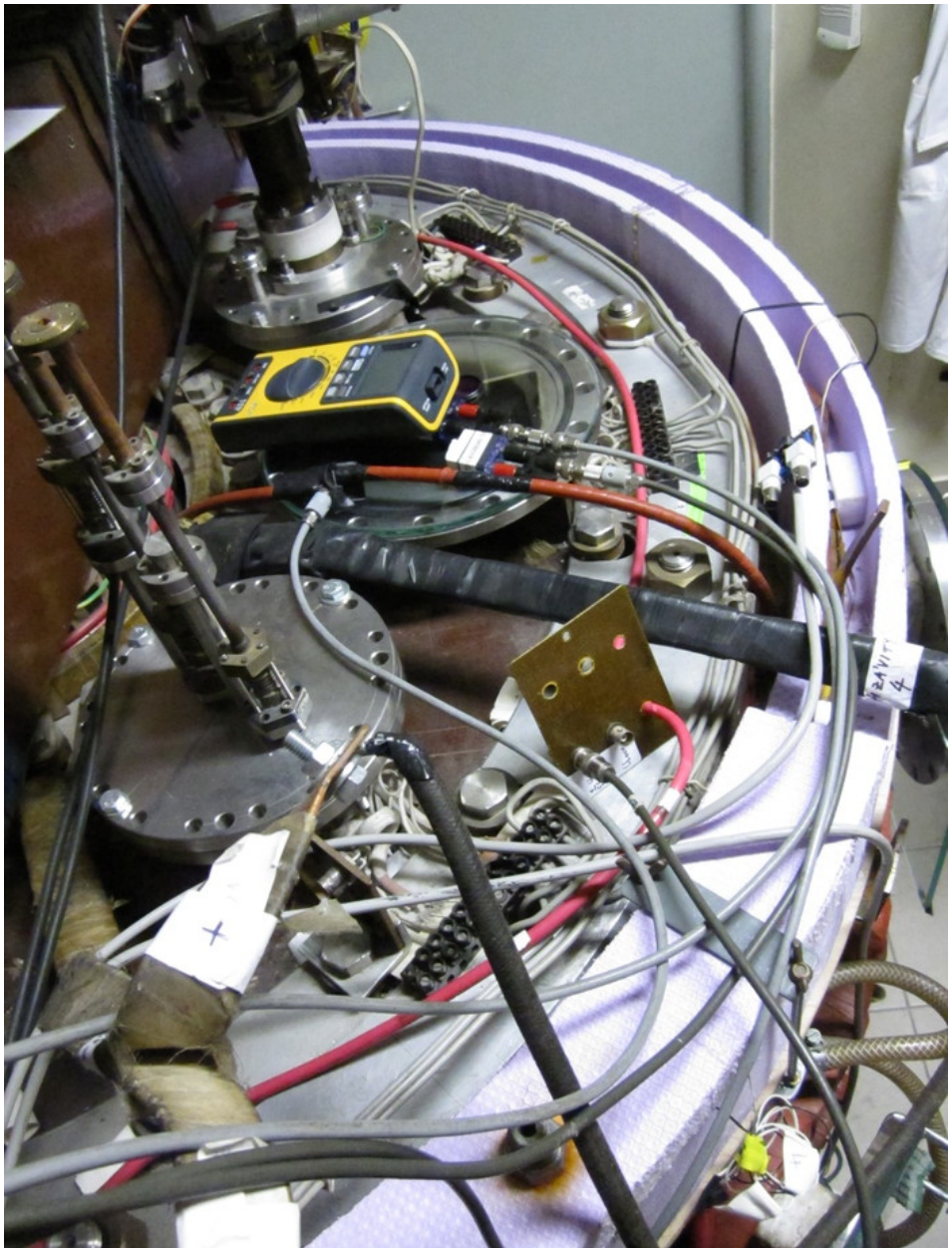




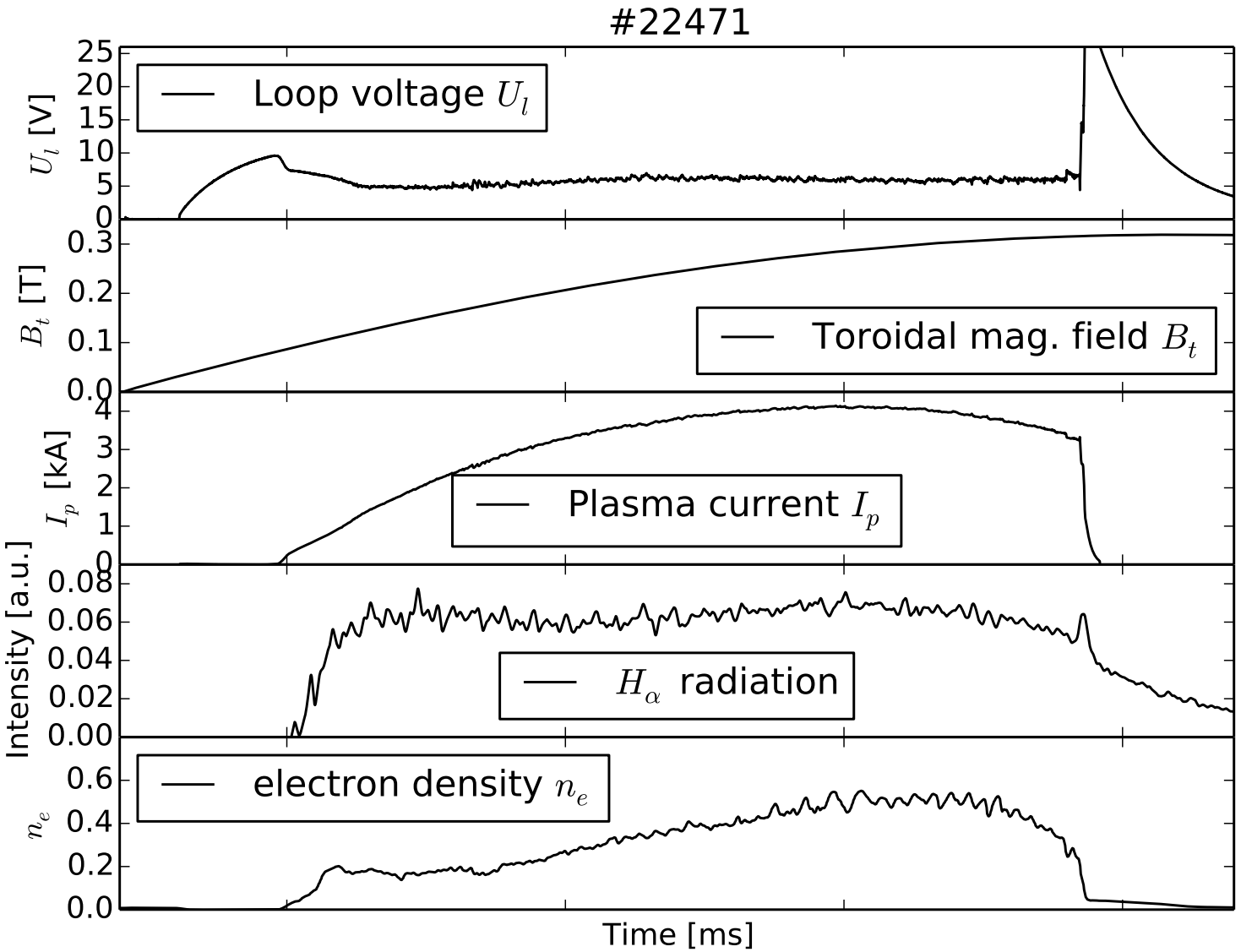
Total current I_{ch+p}







Basic diagnostics @ tokamak GOLEM



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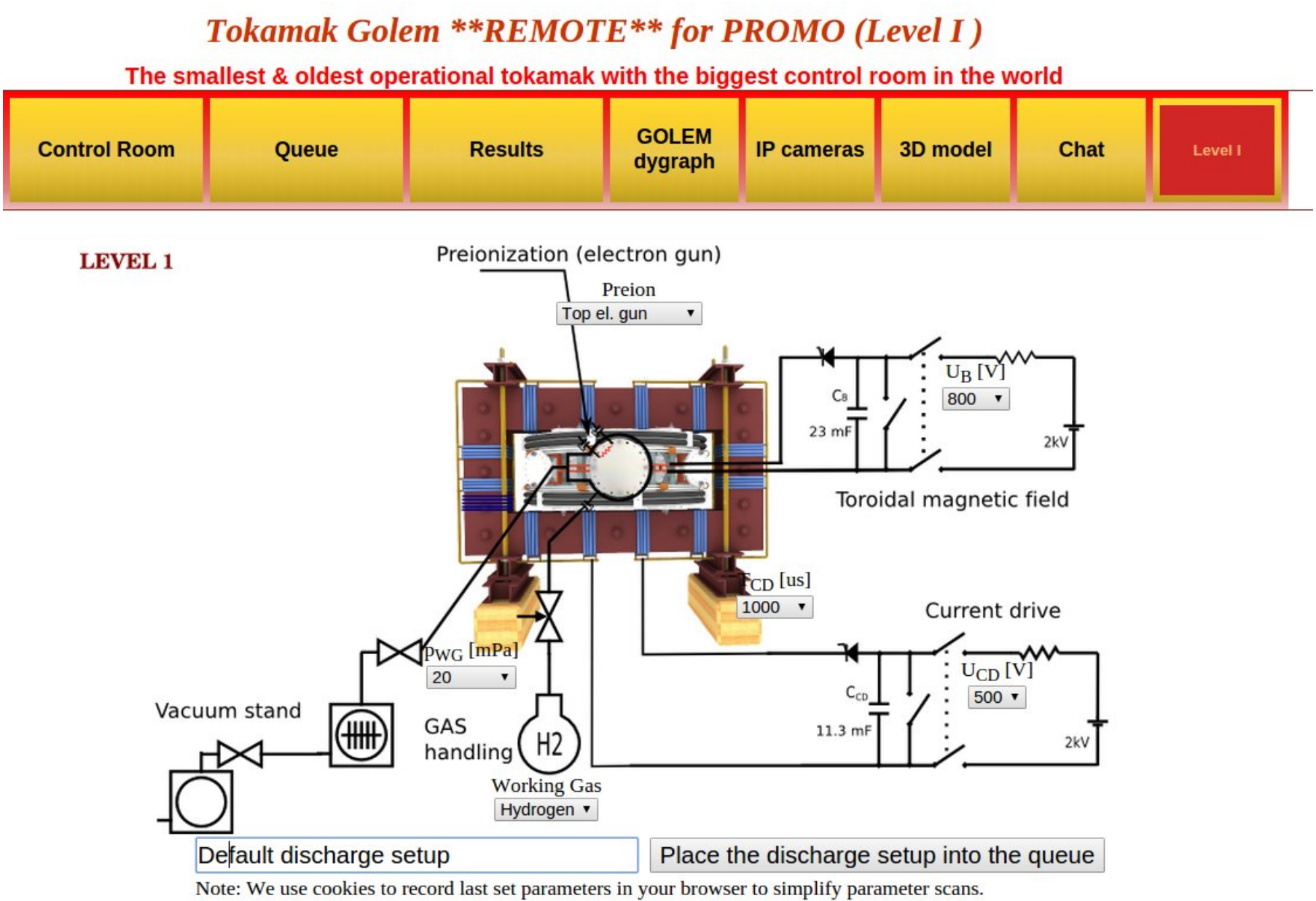
Remote operation



Shot homepage

Diagnostics

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

Analysis

- ✓ ShotHomepage

DAS

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

Vacuum log

Other

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Tokamak GOLEM - Shot Database - 22471

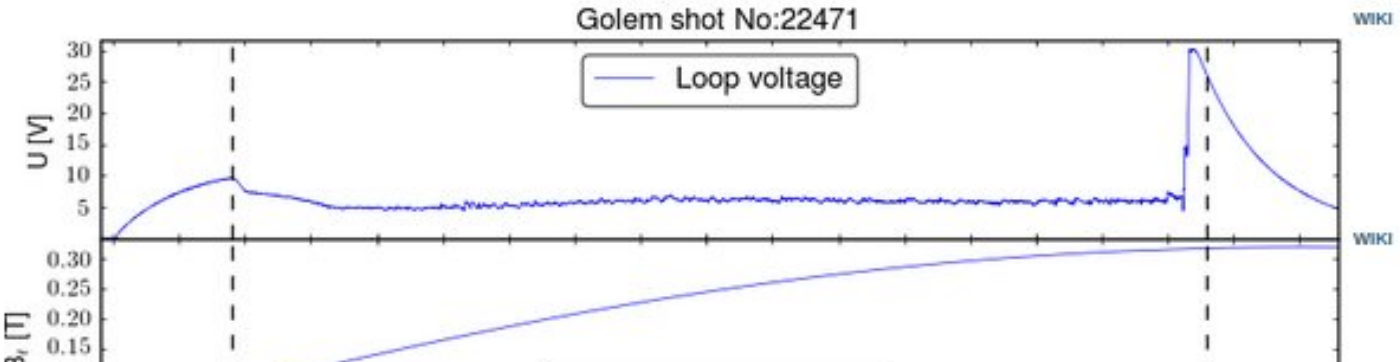
Date: 2016-09-29 - **14:33:57**
Session: TrainingCourses/Universities/Uni_Belgrade.rs/2016/
Comment: `Standard discharge`

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



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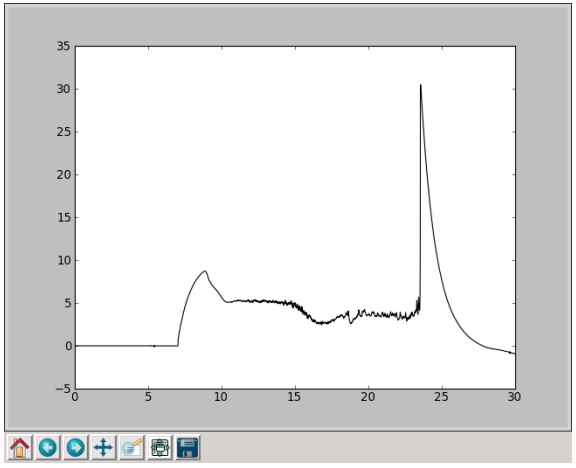
GOLEM **basic** Data Acquisition System (DAS)

- $U_I, U_{B_t}, U_{I_{p+ch}}, I_{rad}$
- $\Delta t = 1\mu s / \ f = 1MHz$.
- 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.

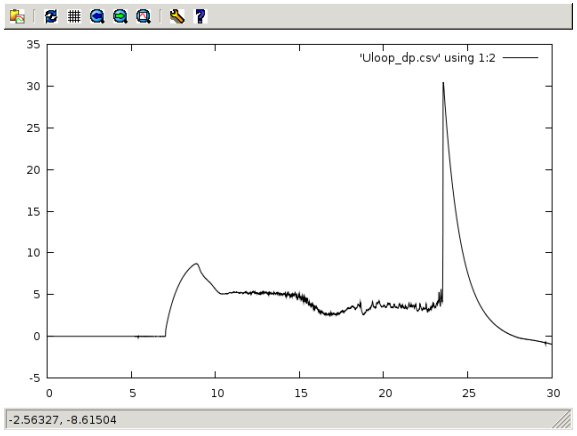
Data file example, DAS $\Delta t = 1\mu s/f = 1MHz$ (neutral gas into plasma breakdown focused)

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 ..	
:	:	:	:	:
:	:	:	:	:

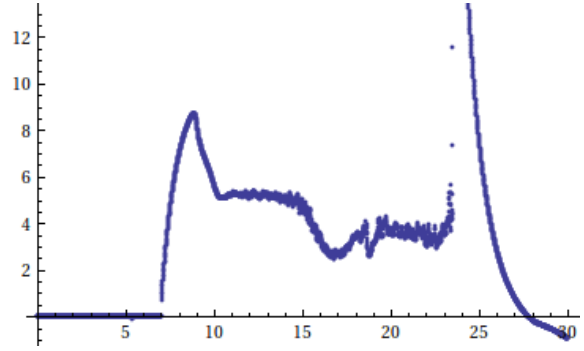
Plot 4665 U_l graph



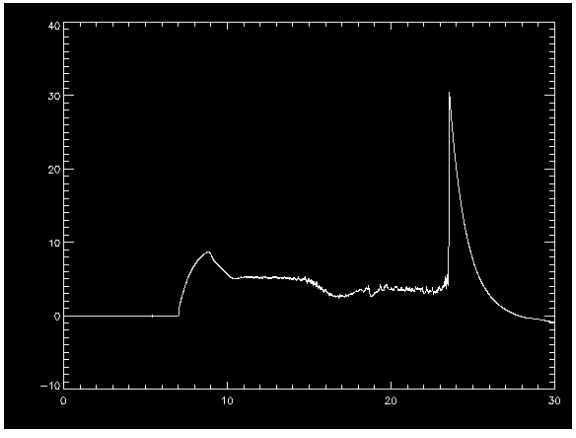
python



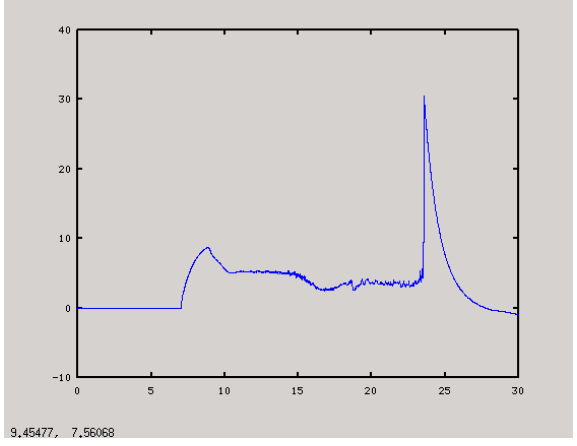
gnuplot



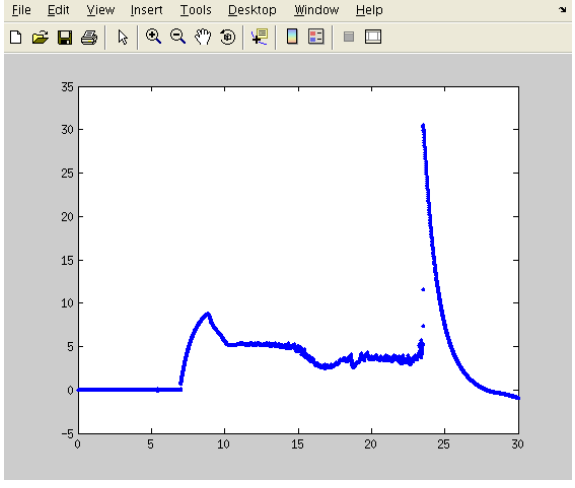
mathematica



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;
```

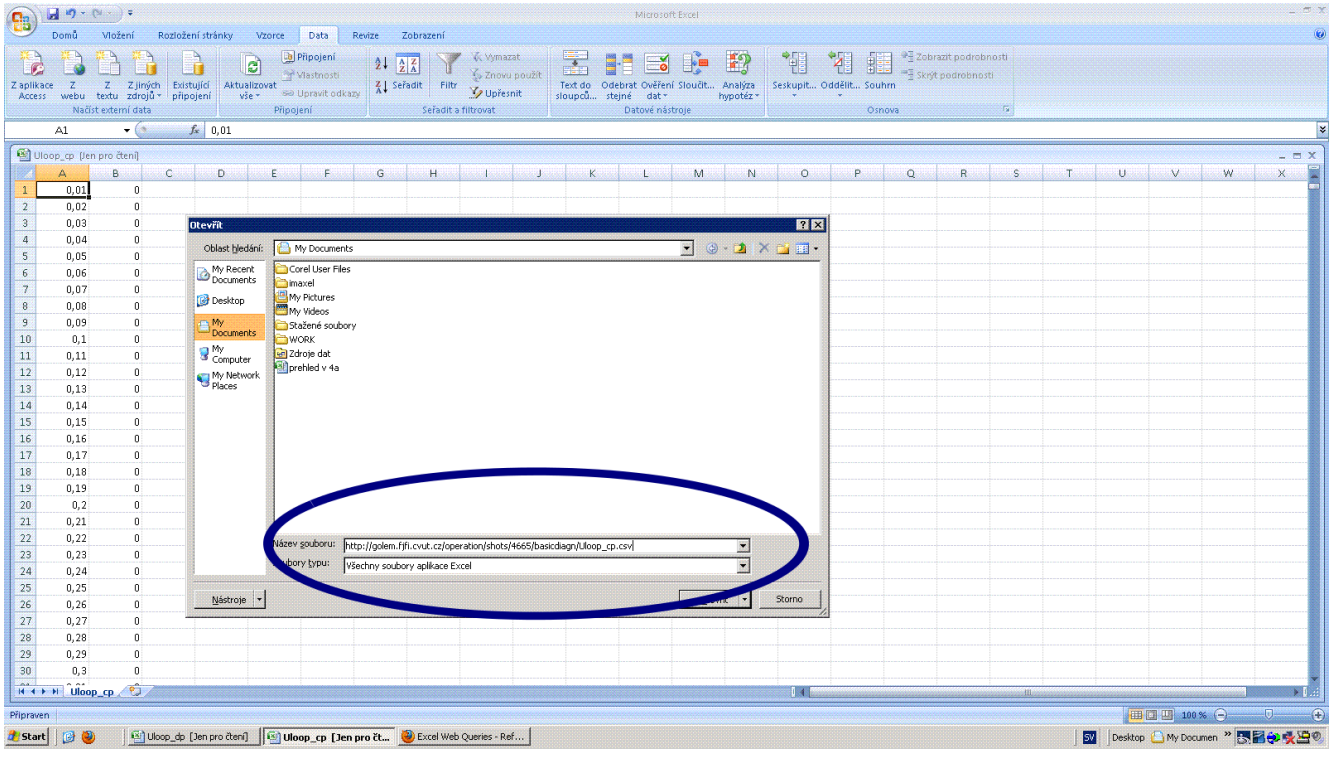
Jupyter (python)

```
import matplotlib.pyplot as plt
from numpy import loadtxt
from urllib.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/utils/data/<#ShotNo>/<identifier>`

Spredsheets (Excel and others)

are not recommended, only tolerated.

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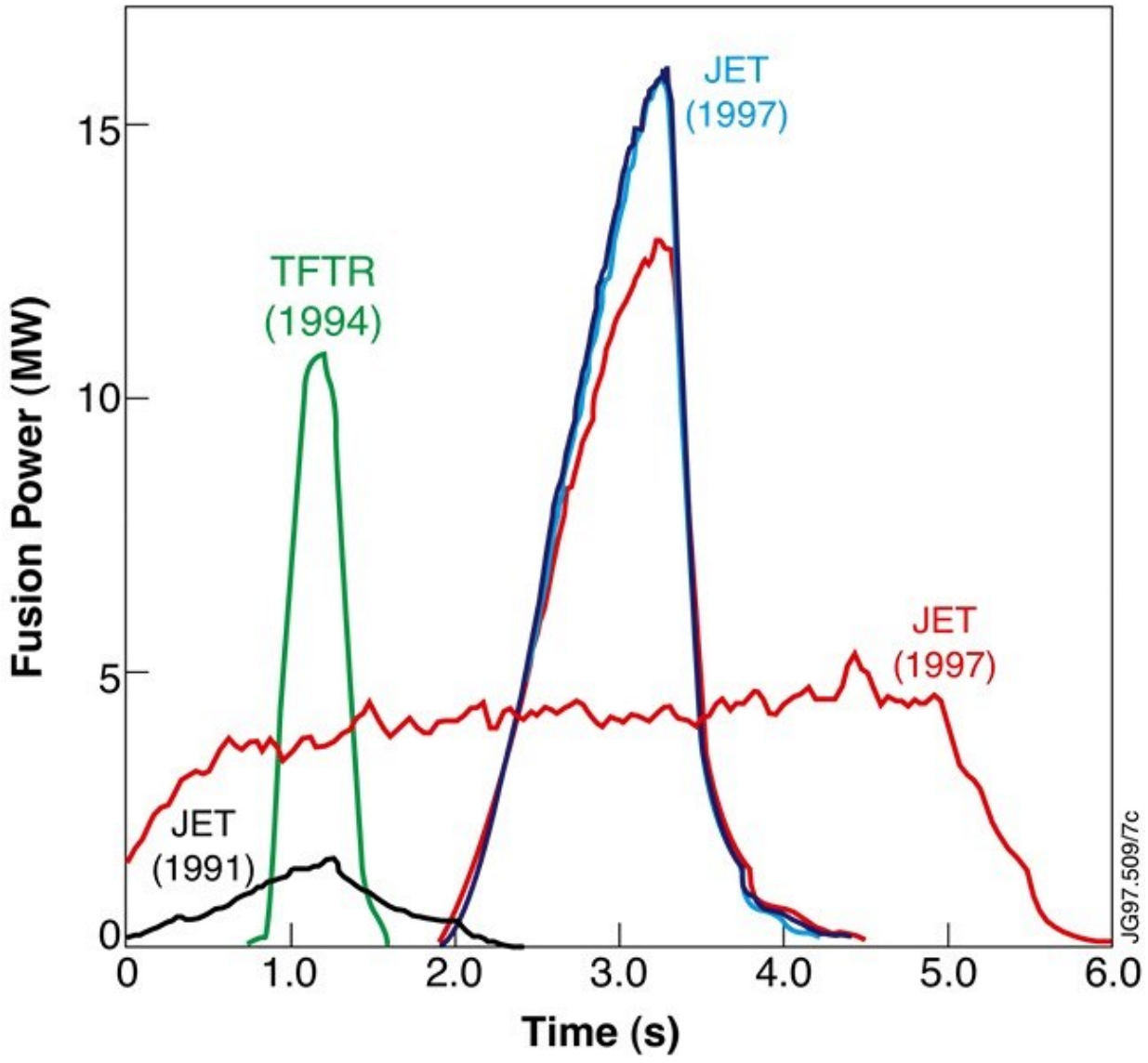
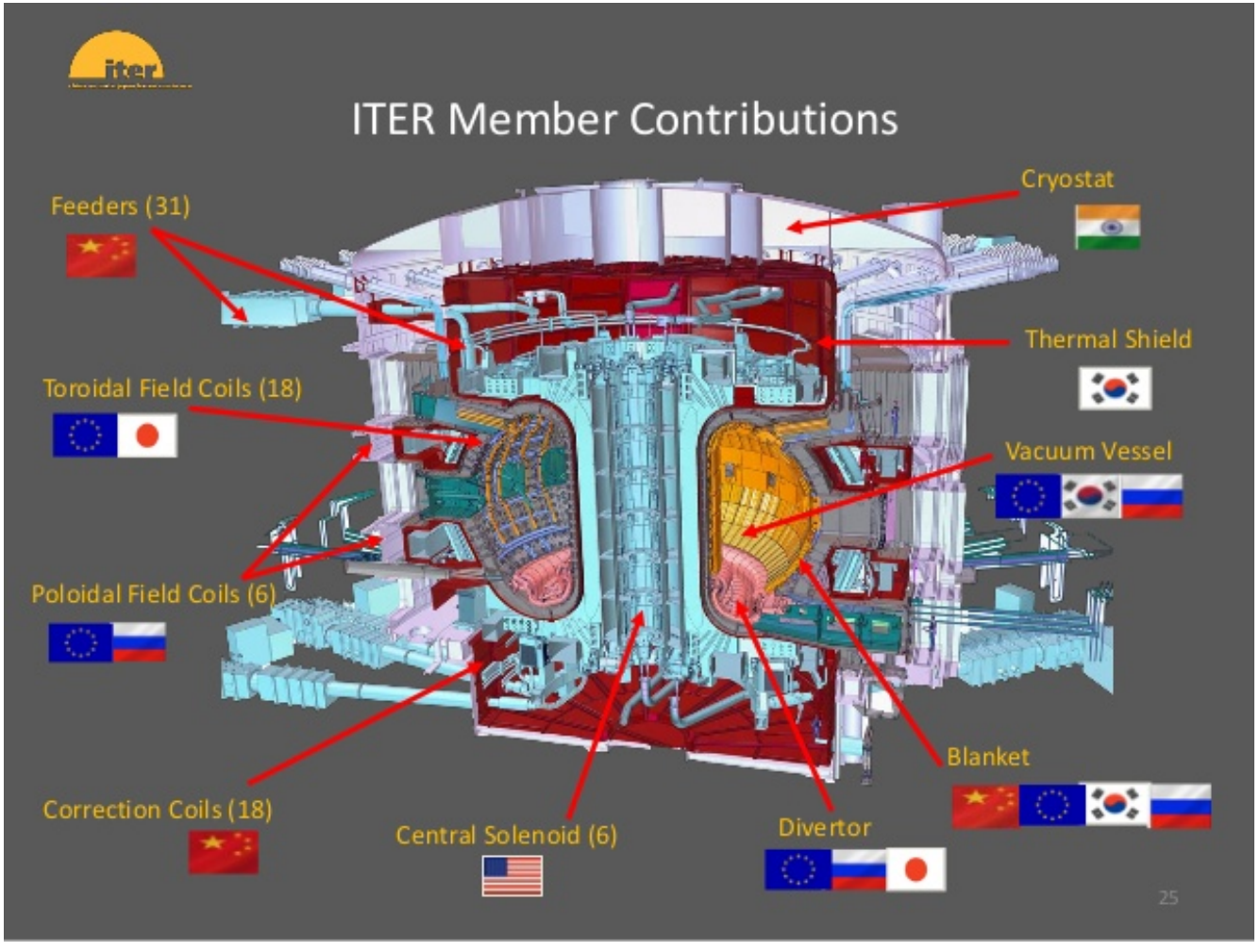
Fusion record @ JET (EU)

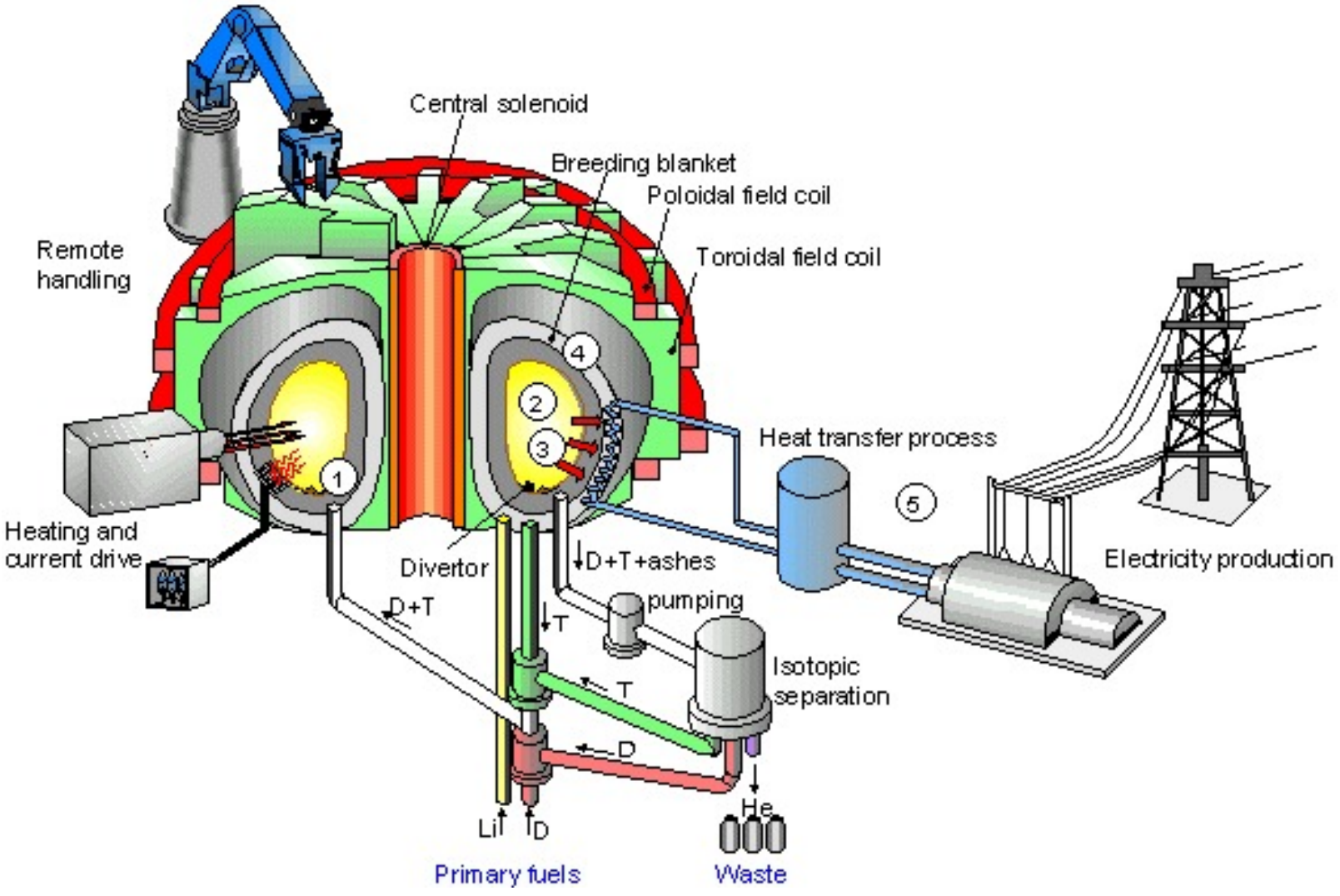


ITER $\approx$ 18 billion euros



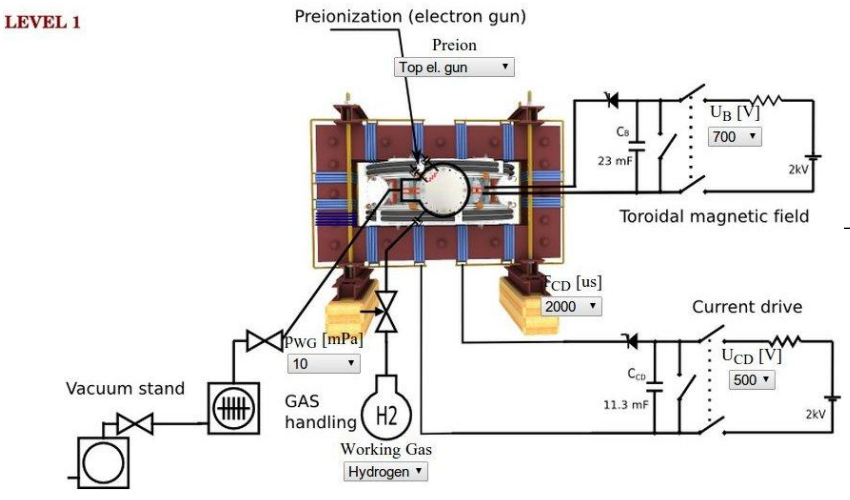
- Fusion power 0.5 GW for 10 min.
- $Q = 10$.
- Feasibility.

DEMO (before 2050)



The global schematic overview of the GOLEM experiment

Tokamak technology setup



internet

USER authorization

WWW server

OpenSSH serve

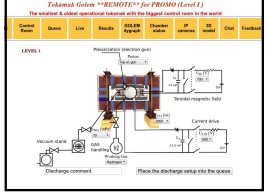
Control PC

OpenSSH server

Virtual control room (remote participation)

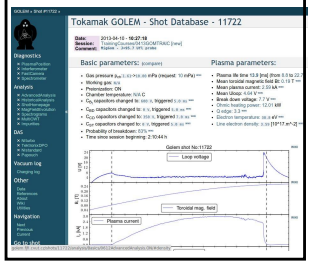
WWW control interface

HTML & PHP scripts



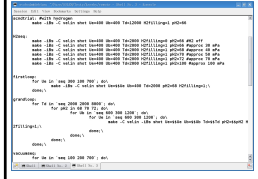
Data presentation

HTML (www pages)



SSH control interface

WINDOWS via putty

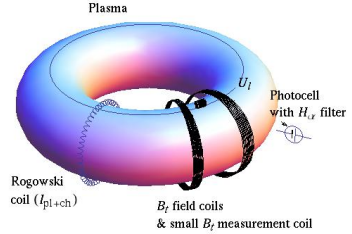


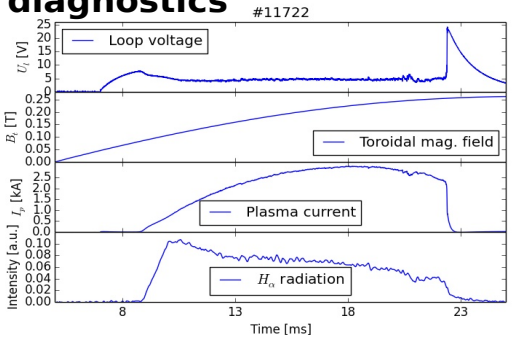
LINUX via ssh
or ssh+X tunnel
(advanced mode)

Data handling

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

Basic plasma diagnostics





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: μprezentace "Co jsme zkusili a co jsme zjistili." + diskuse
- + Výzva: letní tokamak.
- Čtvrtky ..

Acknowledgement

Acknowledgement

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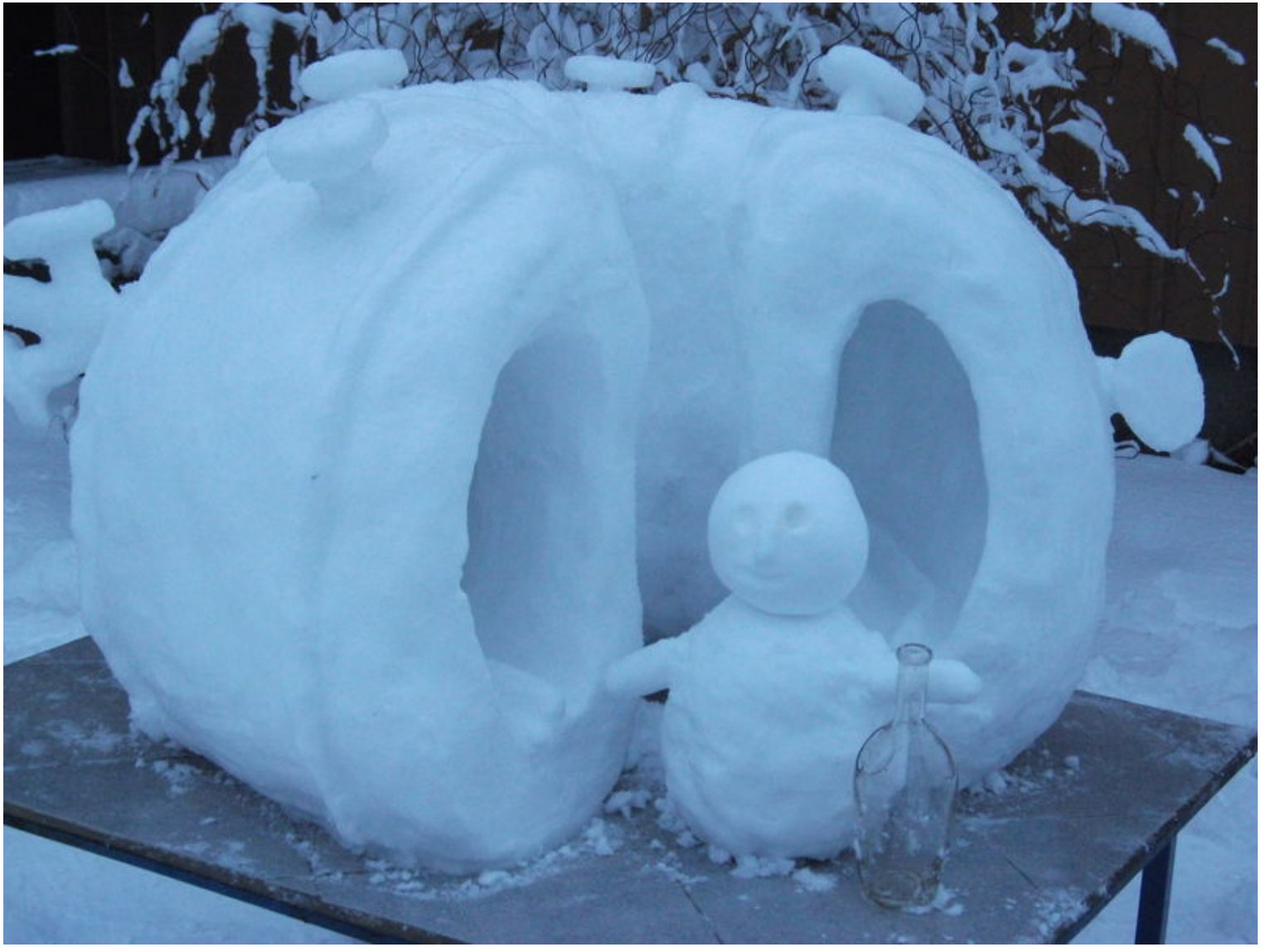
2010 Tokamak GOLEM



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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