Oživování novodobého GOLEMa

Vojtěch Svoboda
pro **Fyzikální čtvrtek @ FEL ČVUT**

December 13, 2019

Objednávka

Ahoj Vojto, napadlo mě, zda bys nechtěl udělat u nás na FEL jeden Fyzikální čtvrtek o Golemovi. Kolega Fabián právě dává dohromady program. Myslím, že by naše studenty, ale i veřejnost, která tam chodí, zajímalo, že tu je malý tokamak s ovládáním po síti, ale i to, jak jsi ho vzkřísil z přístrojové márnice a vdechl mu nový život a jak slouží studentům i vědě. Pokud bys do toho šel, byl bych moc rád.

Díky za jakoukoli zprávu, Petr

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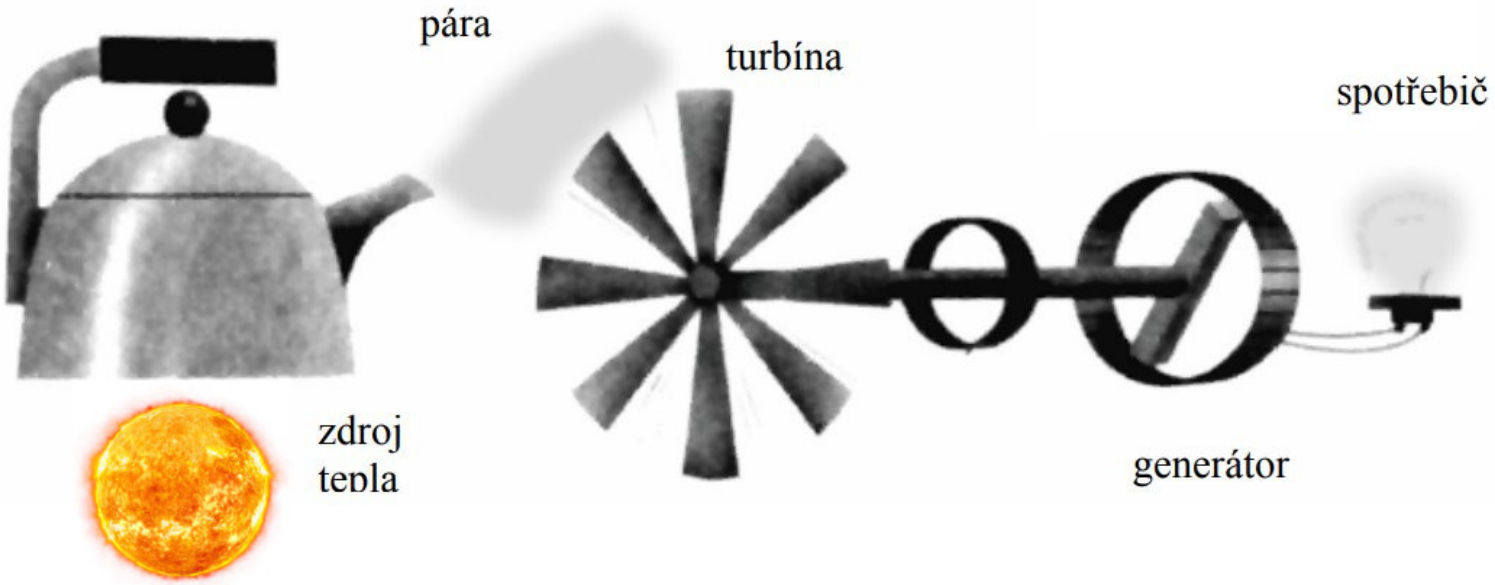
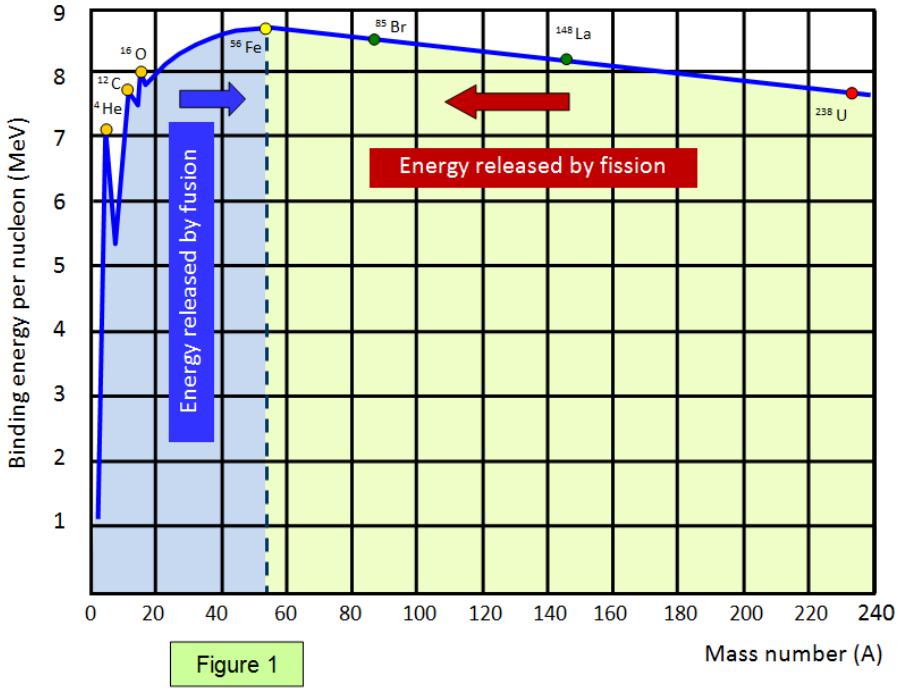
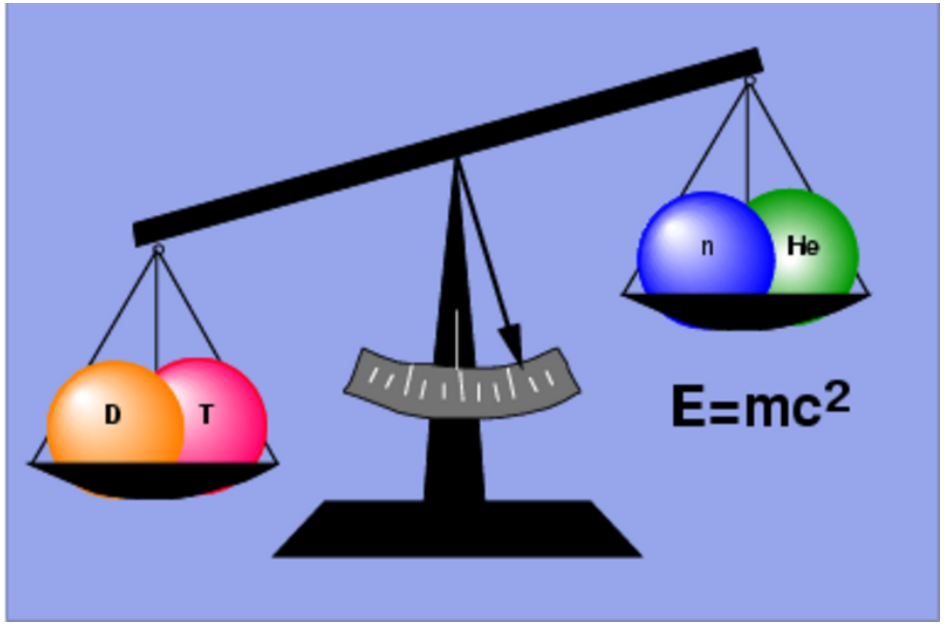
Topit malým Sluncem/hvězdou ??



Výzva

Uvolnění vazebné energie atomových jader

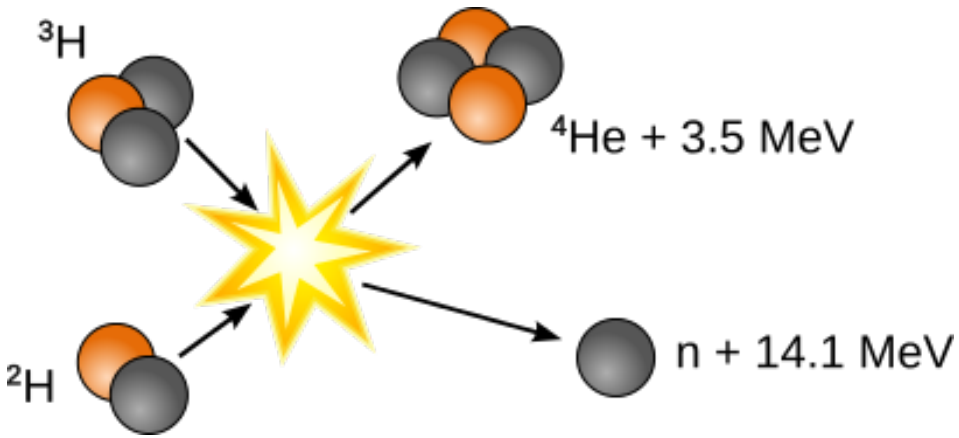




fúze lehkých jader X štěpení těžkých jader

$$^{2}\mathbf{D}+^{3}\mathbf{T} \Rightarrow ^{4}\mathbf{He}+^{1}\mathbf{n}+\mathbf{17.6MeV} \quad \mathbf{X} \quad ^{235}\mathbf{U}+\mathbf{n_{thermal}} \Rightarrow ^{89}\mathbf{Kr}+^{144}\mathbf{Ba}+\mathbf{3n}+\mathbf{176MeV}$$

Fúzní $^2_1\mathrm{H}$ - $^3_1\mathrm{H}$ (deuterium - tritium) reakce (nejvhodnější kandidát do pozemských podmínek)



credit:[?]

$$\mathbf{^2_1H_{10\ keV} + ^3_1H_{10\ keV} \Rightarrow ^4_2He_{3.5\ MeV} + ^1_0n_{14.1\ MeV}}$$

$$m_{^2\mathrm{H}} = 2.01355 m_u,\ m_{^3\mathrm{H}} = 3.01550 m_u,\ m_{\mathrm{He}} = 4.00150 m_u,\ m_{\mathrm{n}} = 1.007332 m_u$$

$$m_{(^2\mathrm{H}+^3\mathrm{H})} = 5.02905 m_u, m_{(\mathrm{He+n})} = 5.01017 m_u,$$

pak hmotnostní schodek $\Delta m = 0.01888 m_u$.

$E = \Delta m\ c^2$: $E = \Delta m$ krát $\frac{c^2 m_u}{e}$=17.6 MeV

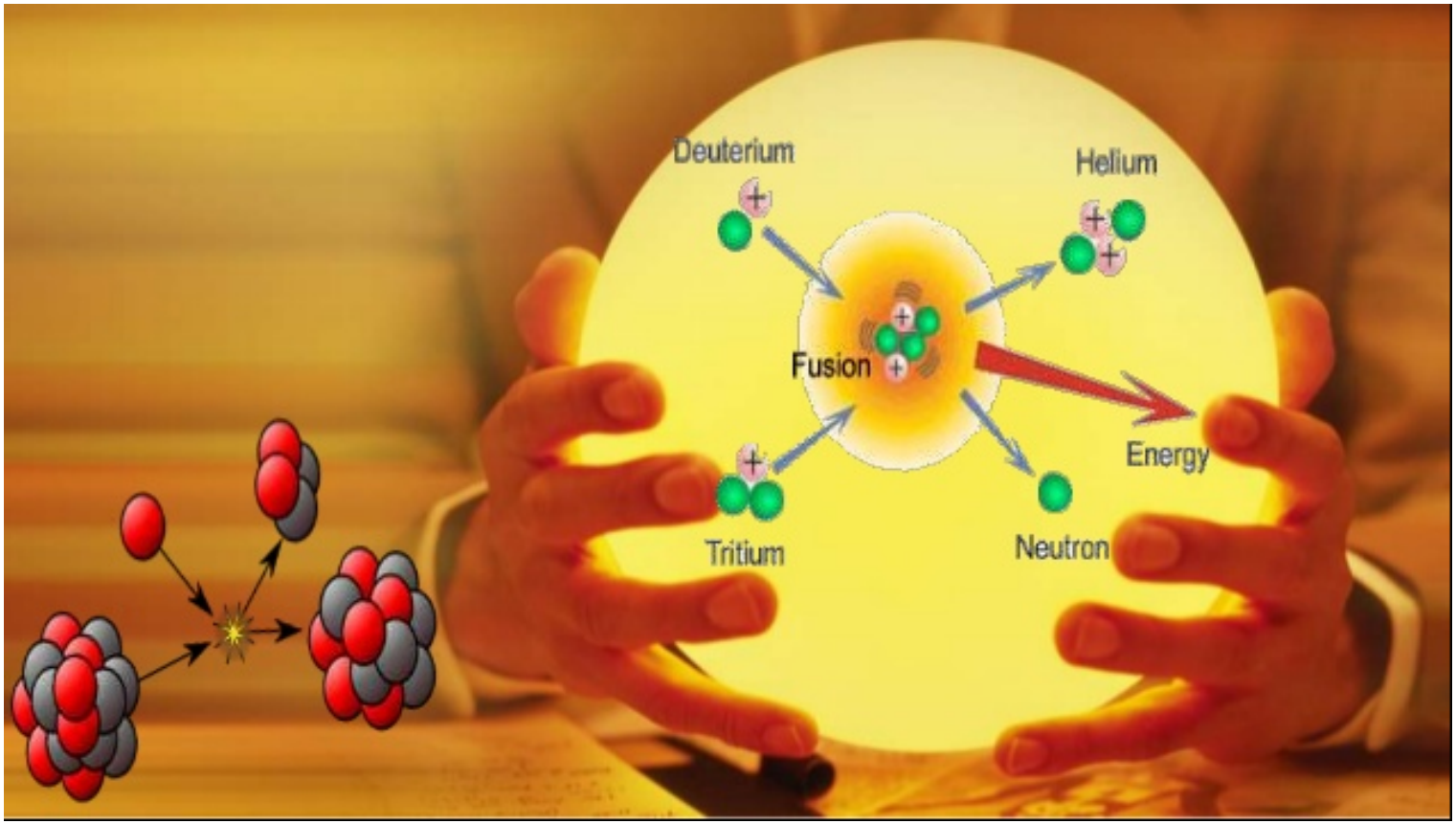
$$1\mathrm{eV} \sim 11600°\mathrm{C} \approx \mathbf{^2_1H_{100\ M°C} + ^3_1H_{100\ M°C} \Rightarrow ^4_2He_{35\ G°C} + ^1_0n_{141\ G°C}}$$

1952 "Operation Ivy - Mike" První test vodíkové bomby

credit:YouTube:Ivy Mike Countdown and detonation

Toto není vhodná technologie

Hledá se vhodná fúzní technologie

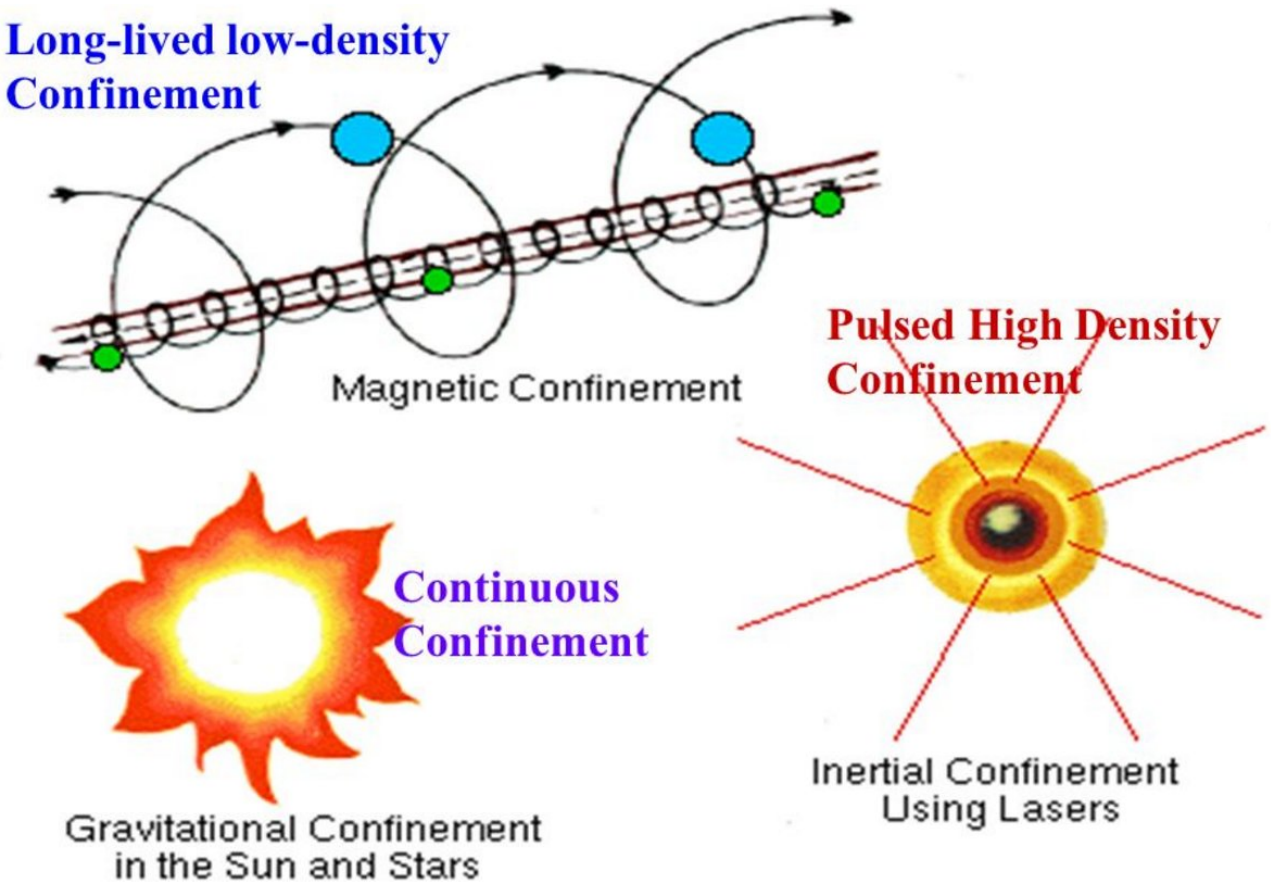


Podmínky:

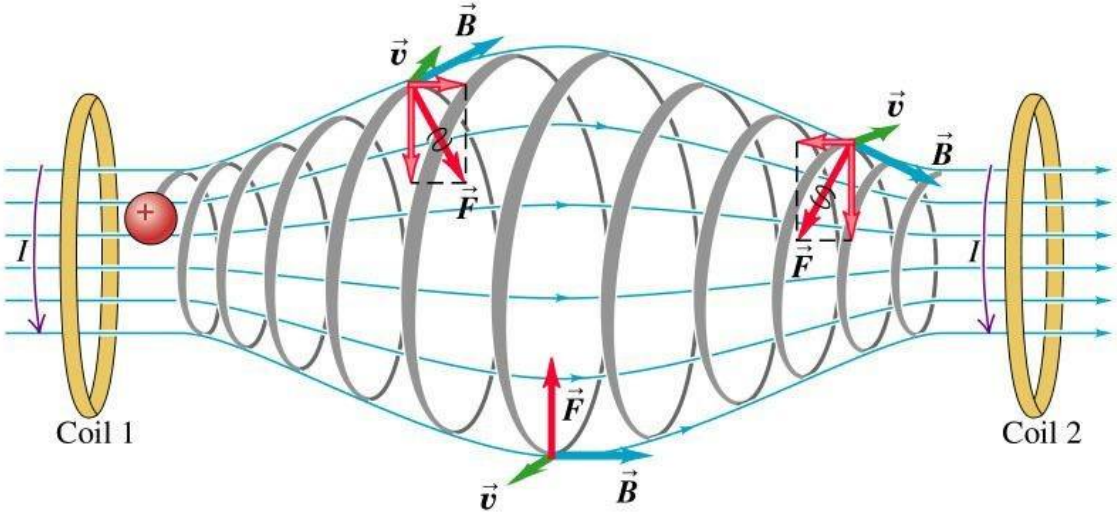
Zahřát na $\sim$ 100 000 000 °C & **udržet** po dobu $\sim$ 30 let

Tři možné cesty jak udržet plazma pro fúzi

Lawsonovo kritérium: $n\tau_E \geq 1.5 \cdot 10^{20} \frac{\mathrm{s}}{\mathrm{m}^3}$ $(2 \times 6 > 11 \;\|\; 6 \times 2 > 11)$



Magnetické udržení: magnetická nádoba



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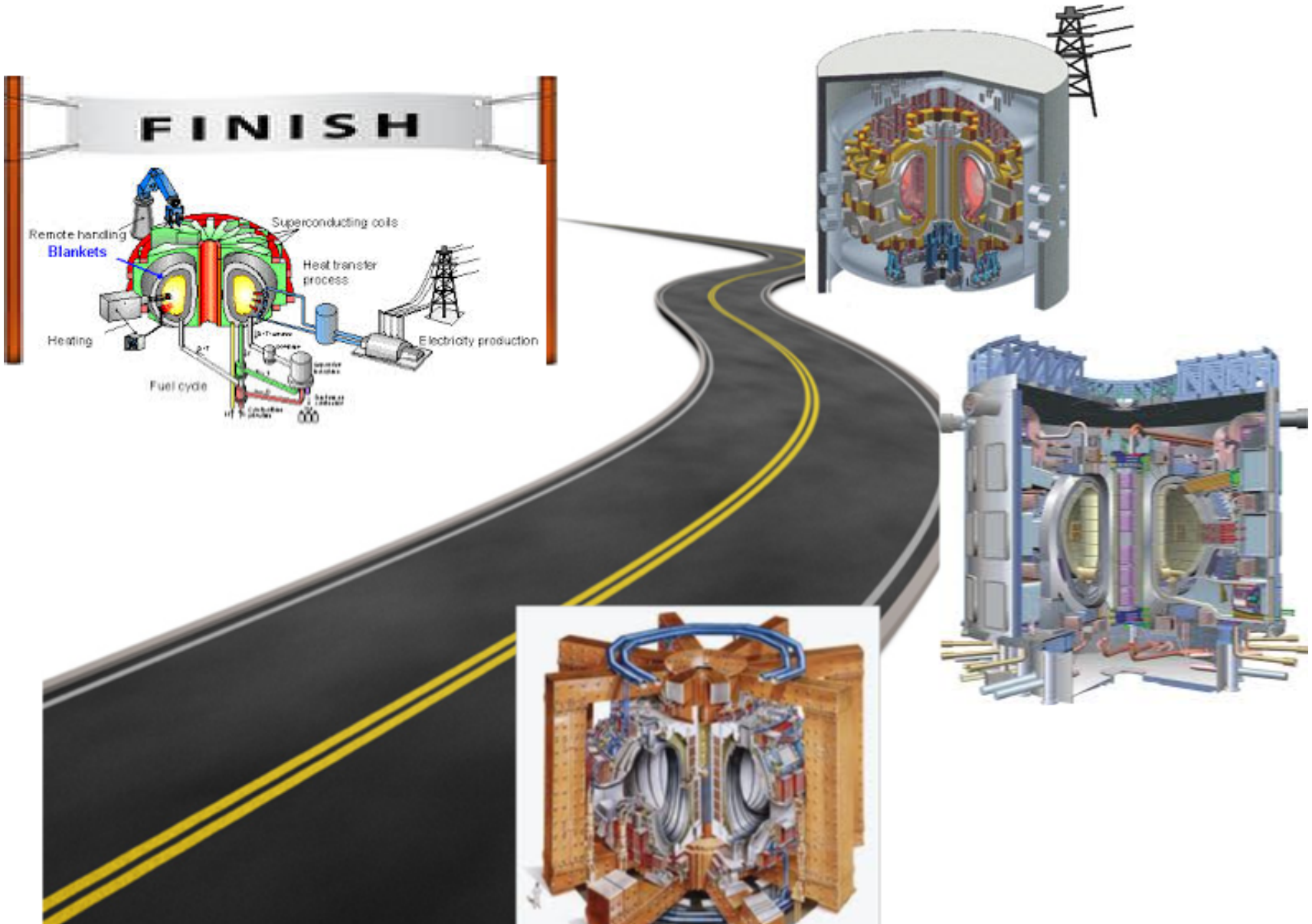
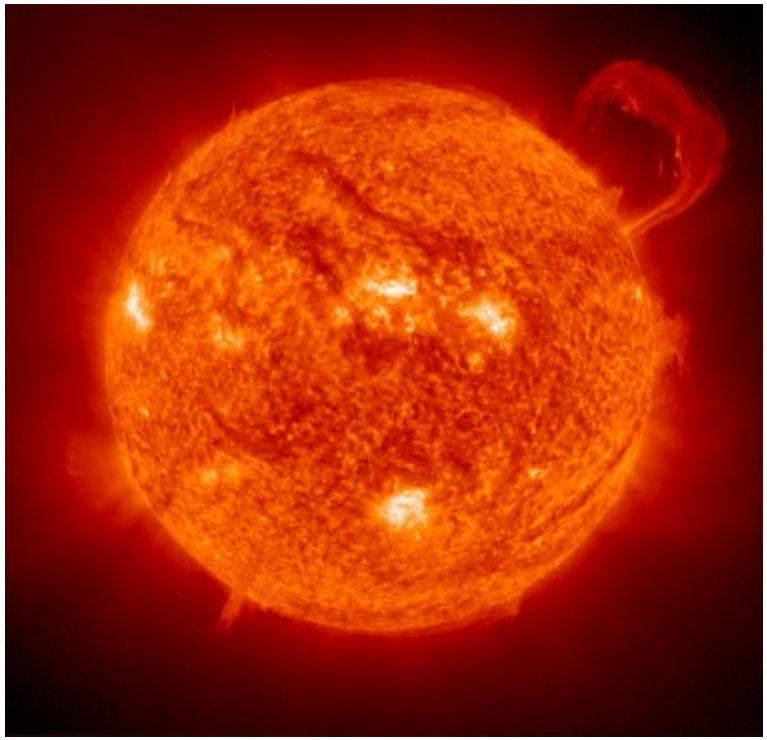
Musíme ji ale svinout do kruhu (zbavit se podstav)

záchranný kruh/duše pneumatiky/kobliha - donut

Milestones to Fusion Power Plant



The challenge



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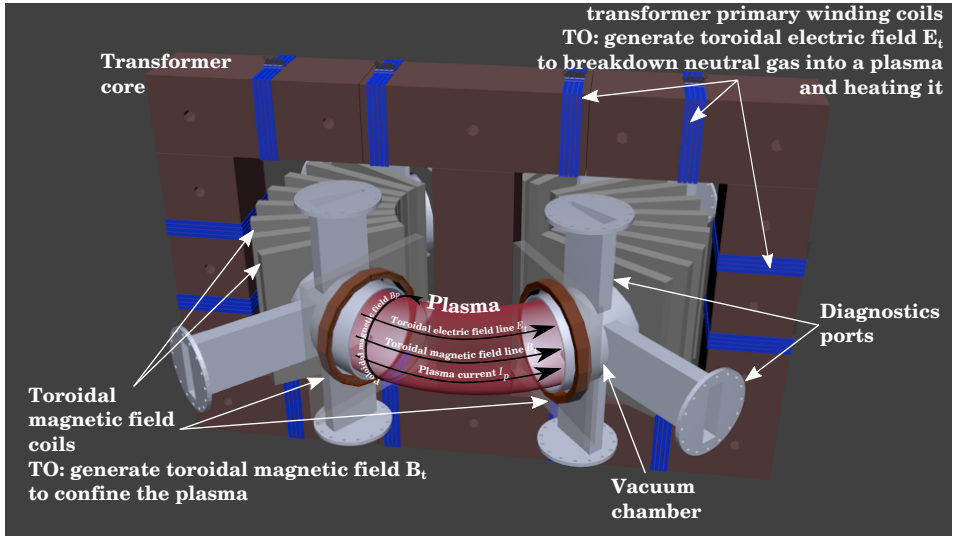

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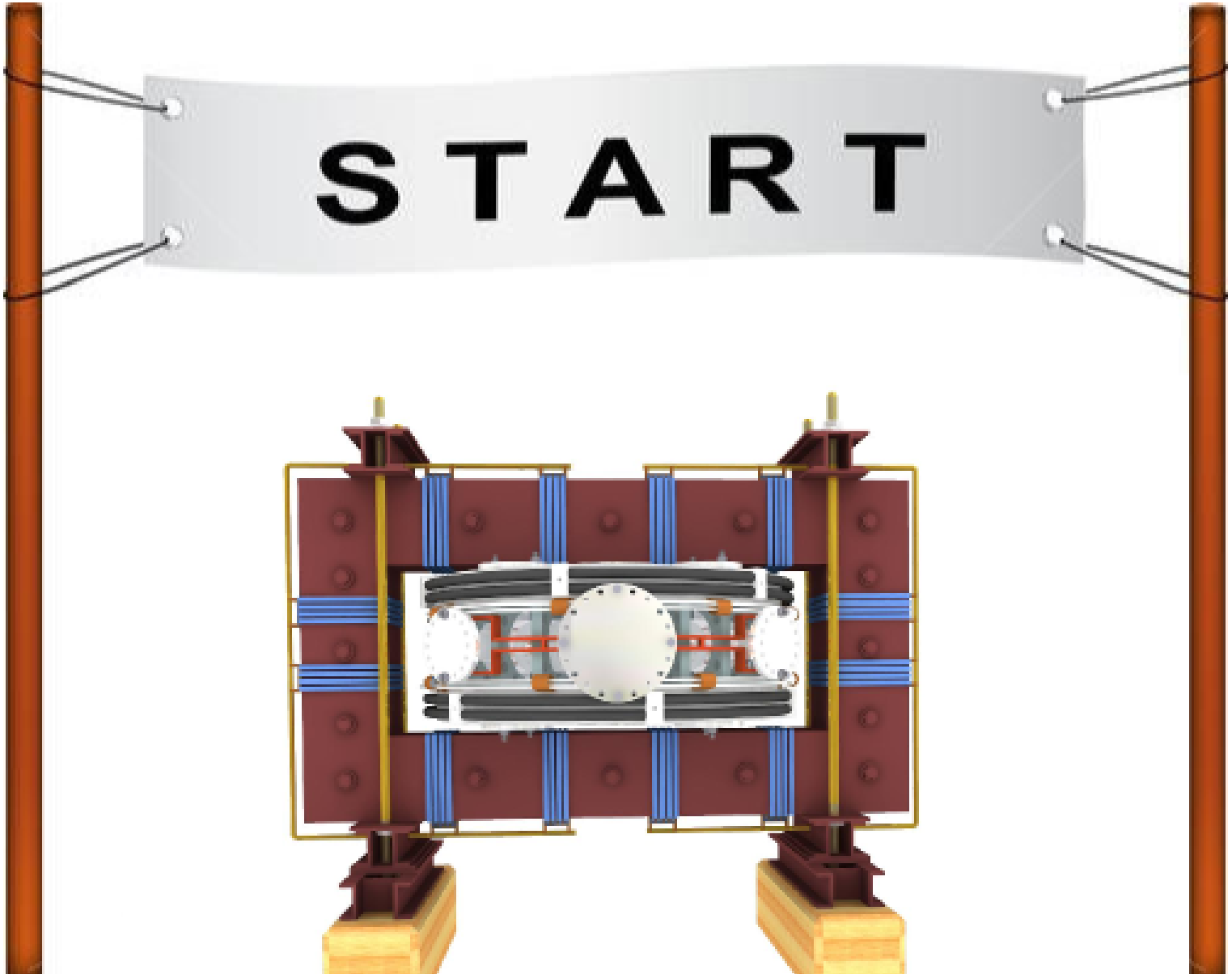
μSun on the Earth

... to heat & **confine** ...

Velké ambice ....

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



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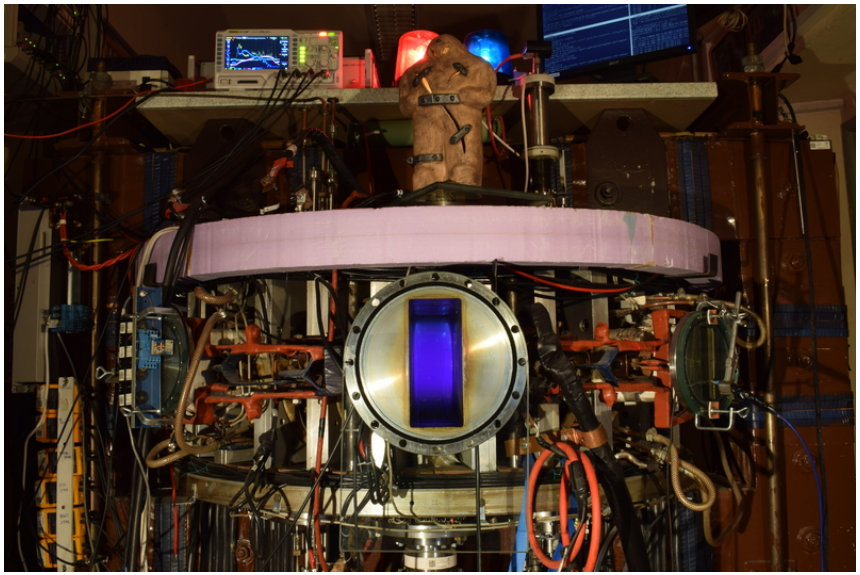
The GOLEM tokamak basic characteristics

The grandfather of all tokamaks (ITER newsline 06/18)



- Vessel major radius $R_0 = 0.4$ m
- Vessel minor radius $r_0 = 0.1$ m
- Plasma minor radius: $a \approx 0.06$ m
- Maximum toroidal magnetic field $B_t^{max} < 0.5$ T
- Maximum plasma current $I_p^{max} < 8$ kA
- Typical electron density: $< n_e > \approx 0.2 - 3 \ \times 10^{19}$ m^{-3}
- Effective ion charge: $Z_{eff} \approx 2.5$
- Maximum electron temperature $T_e^{max} < 100$ eV
- Maximum ion temperature $T_i^{max} < 50$ eV

Tokamak GOLEM @ Wikipedia ..

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https://en.wikipedia.org/wiki/Tokamak

home Kalendář Produkce Forecast Slovník Rano

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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.

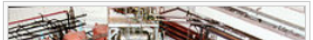
Experimental tokamaks [edit]

Currently in operation [edit]

(in chronological order of start of operations)

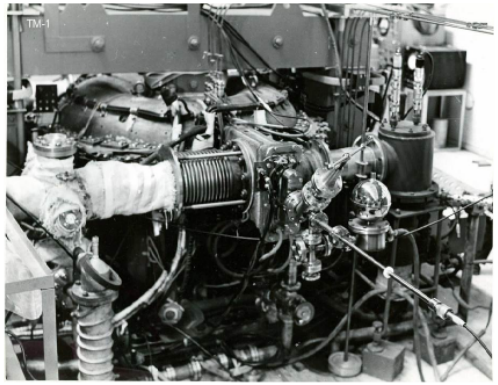
- 1960s: TM1-MH (since 1977 Castor; since 2007 Golem[12]) in Prague, Czech Republic. In operation in Kurchatov Institute since early 1960s but renamed to Castor in 1977 and moved to IPP CAS,[13] Prague; in 2007 moved to FNSPE, Czech Technical University in Prague and renamed to Golem.[14]
- 1975: T-10, 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



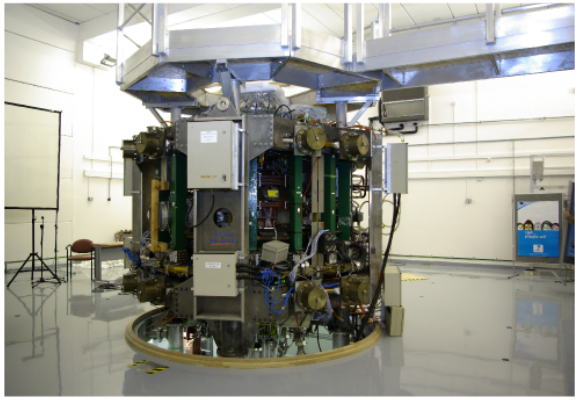
The GOLEM tokamak for education - historical background

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



1974

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

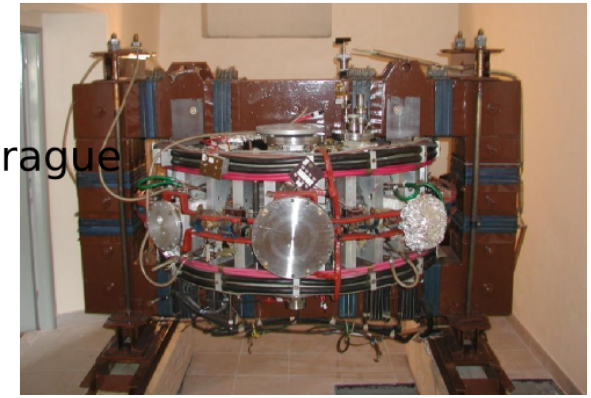


2006

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

2008

Czech Technical University Prague
Czech republic
GOLEM



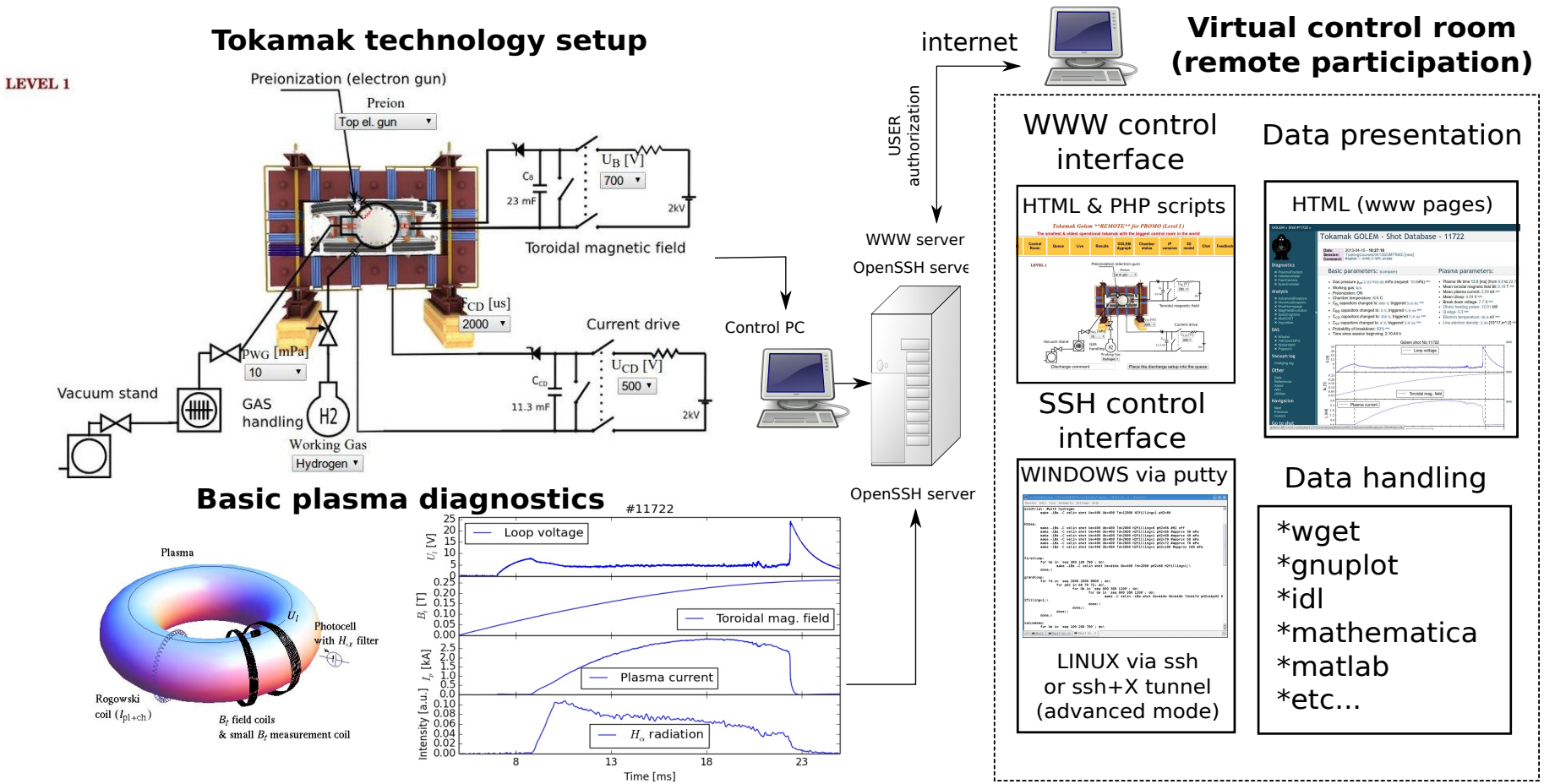
GOLEM

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

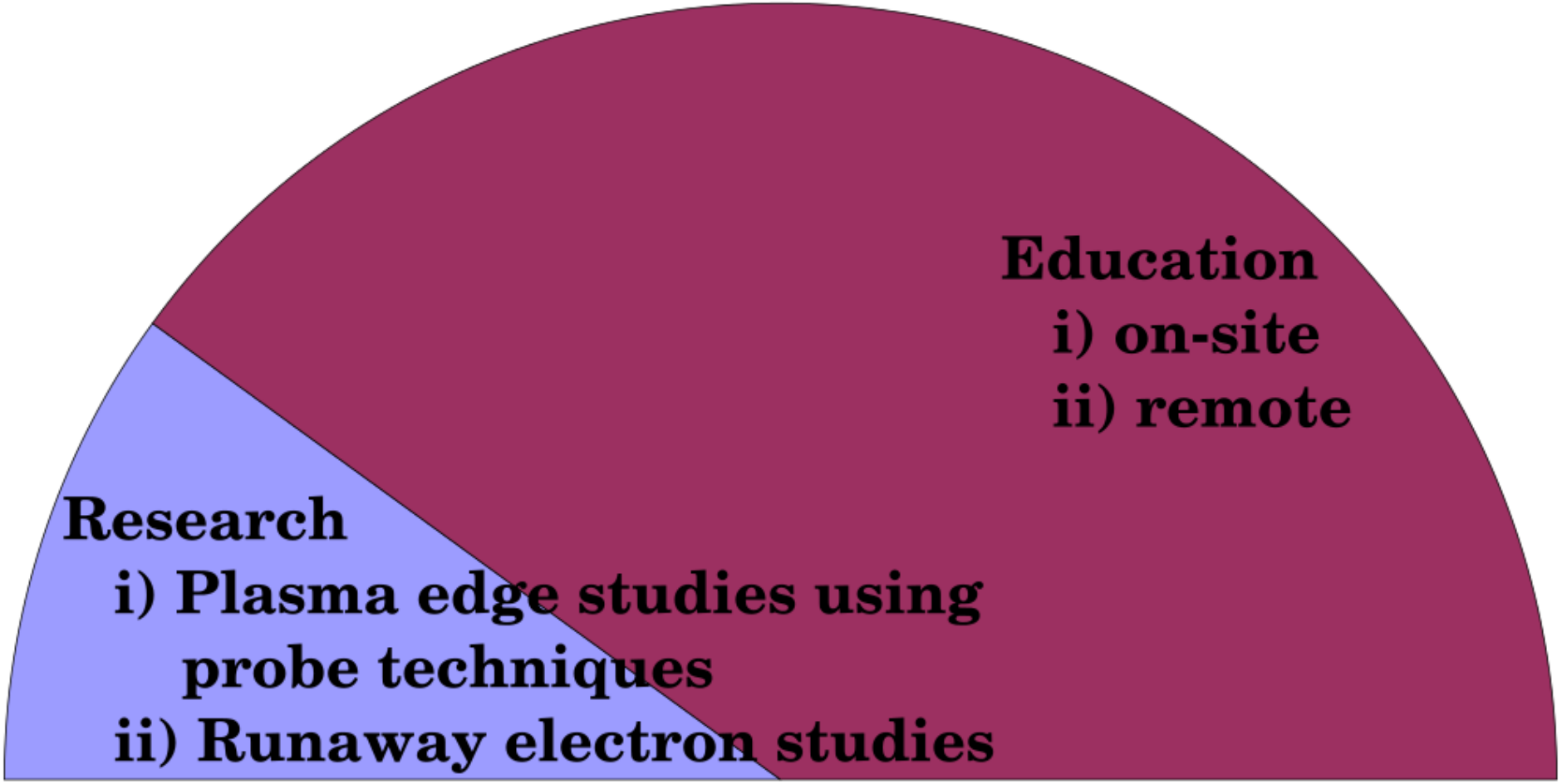
there is hidden indeed "infernal" power. Yet it is the very power of celestial stars themselves. Calmly dormant, awaiting mankind to discover the magic key, to use this power for their benefit. . .

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. Wikipedia/Golem.

The global schematic overview of the GOLEM experiment



The GOLEM tokamak mission



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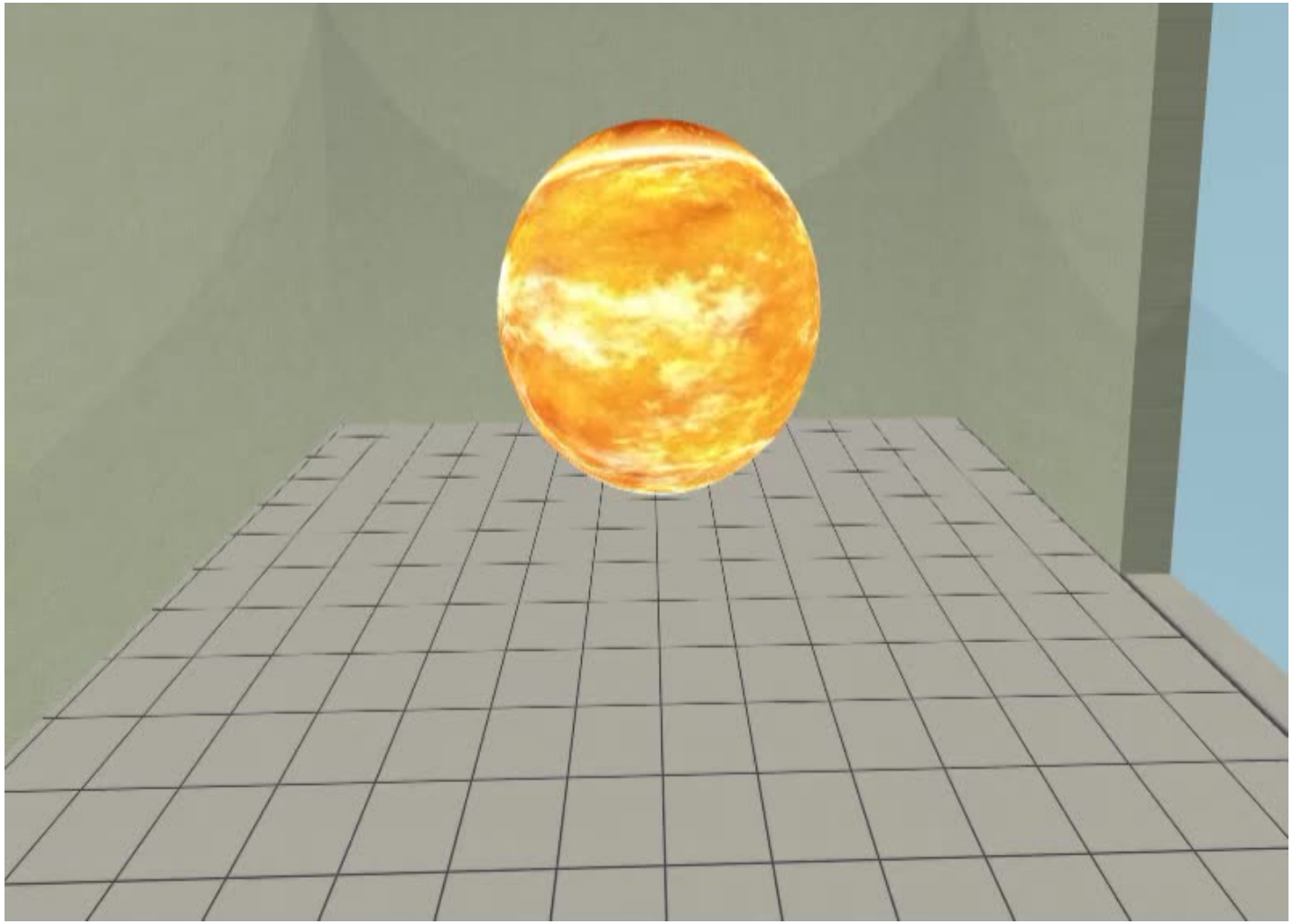
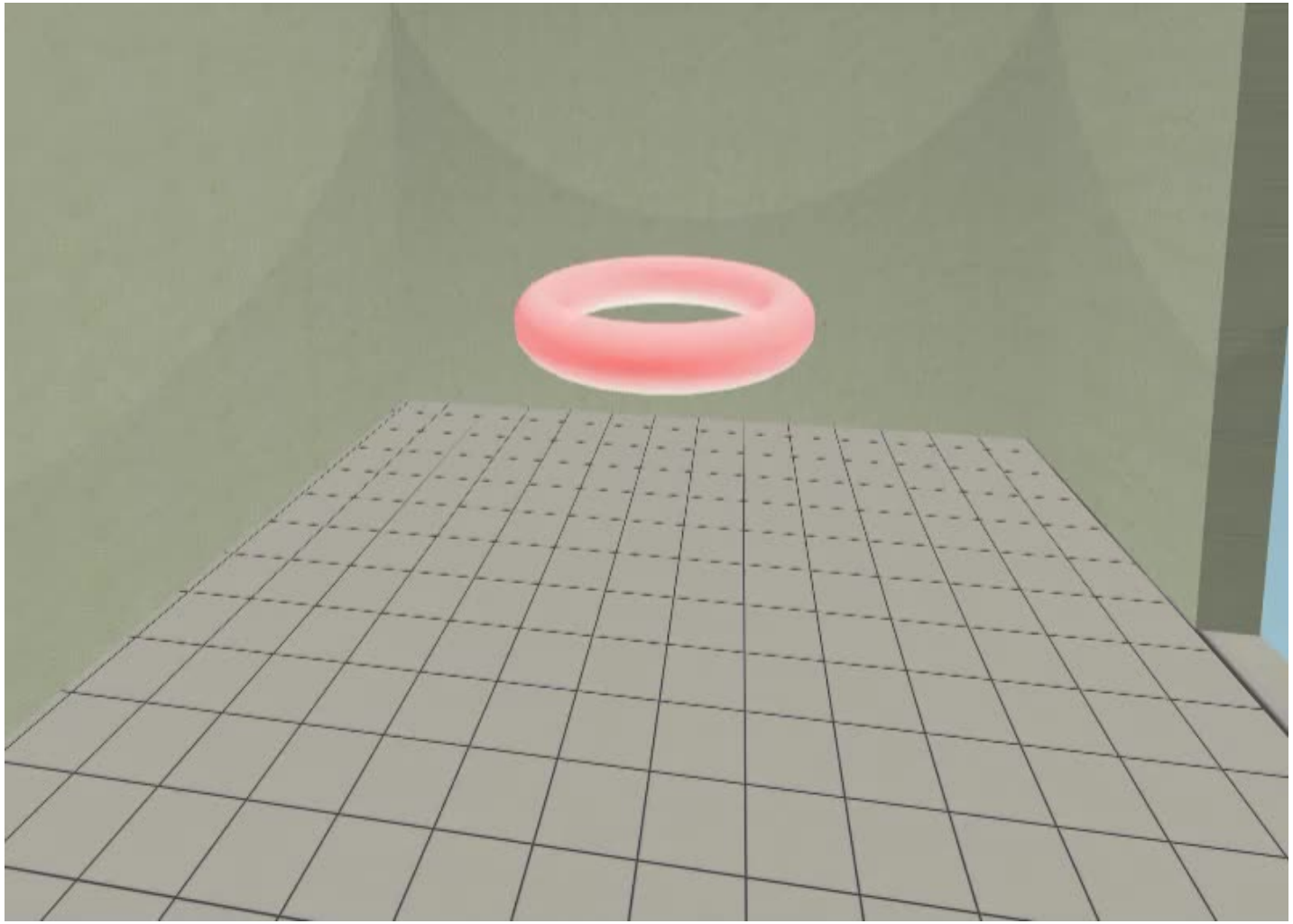
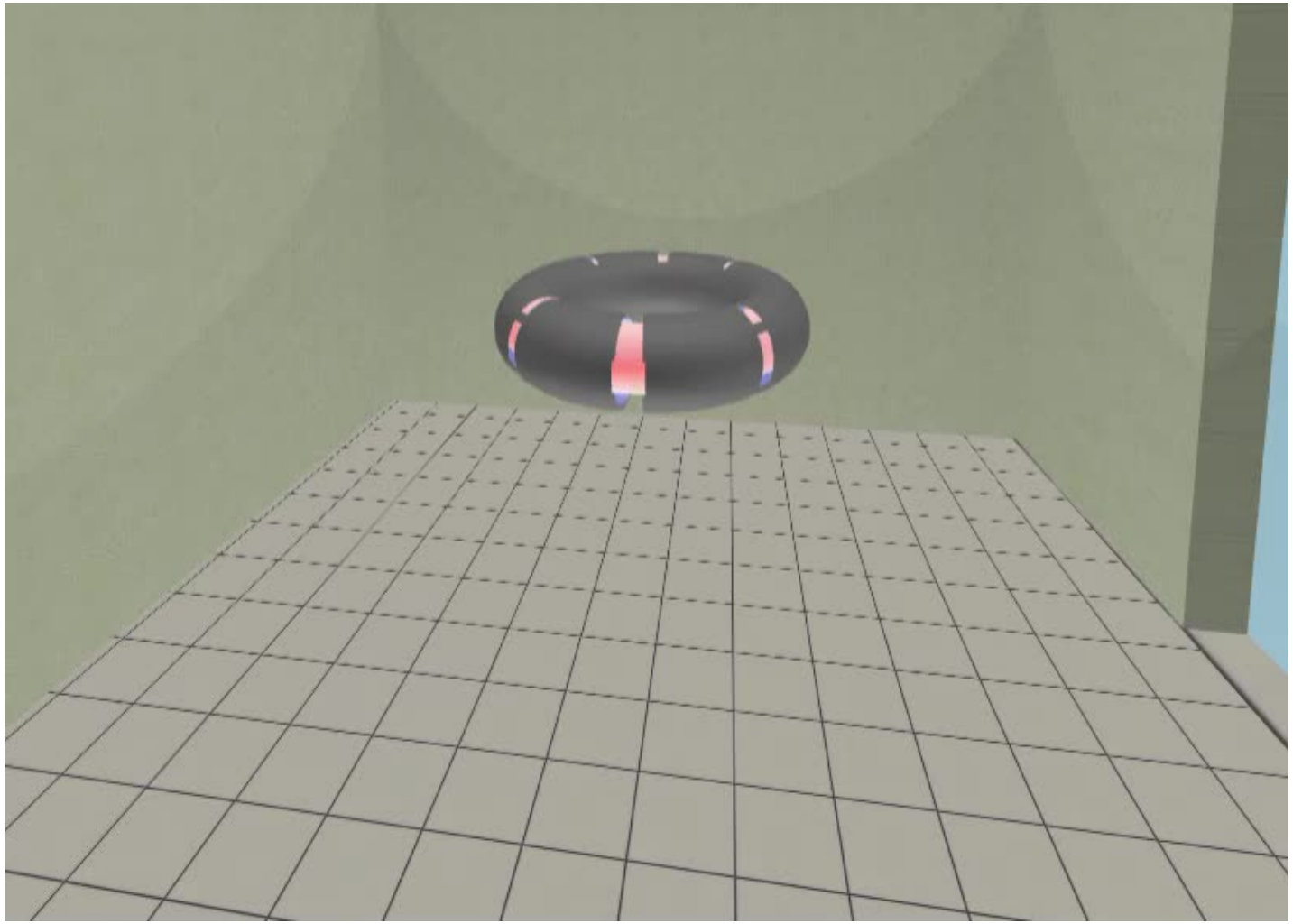
Our goal: the technology to create a μSun on the Earth



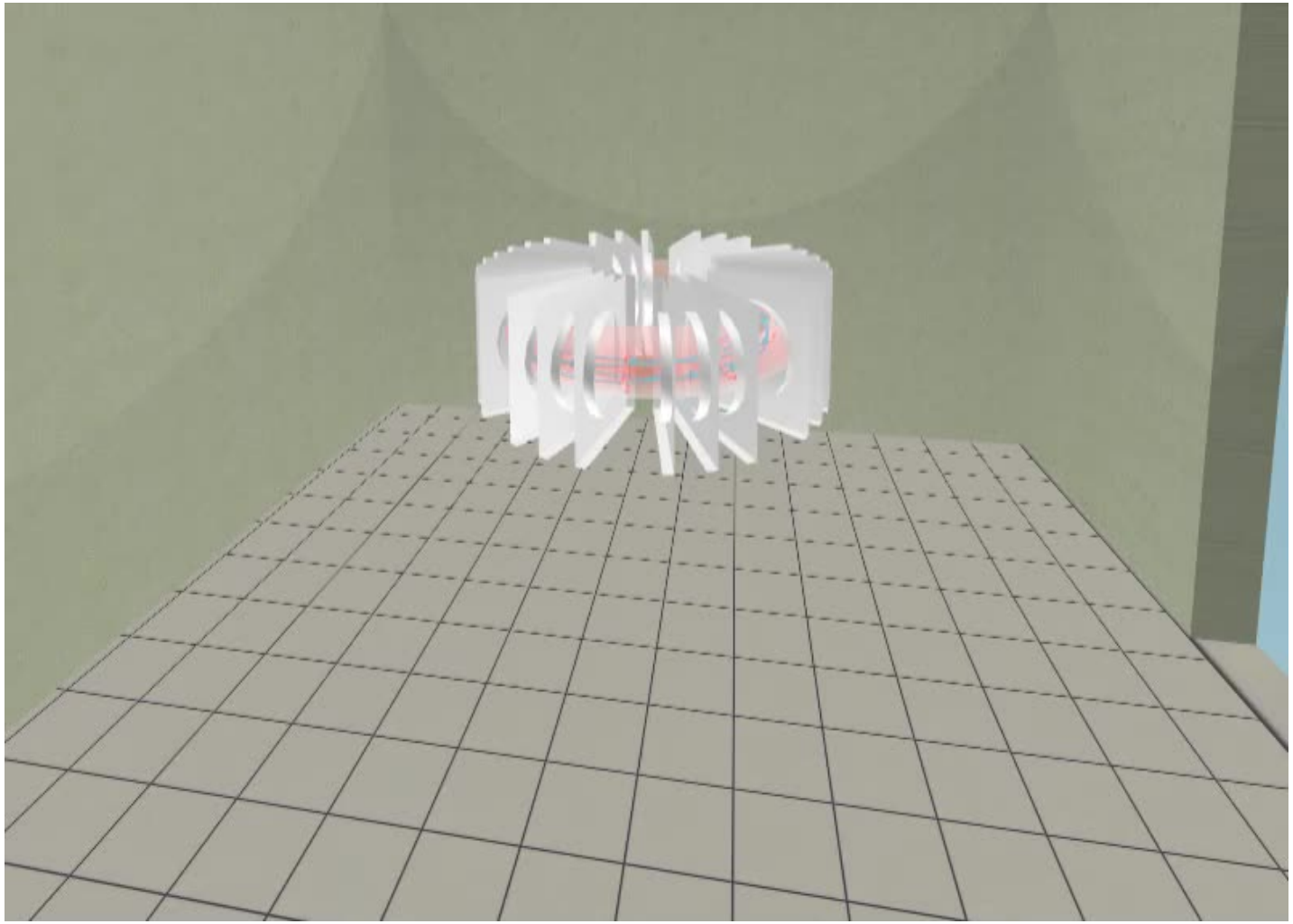
Magnetic confinement requires toroidal geometry



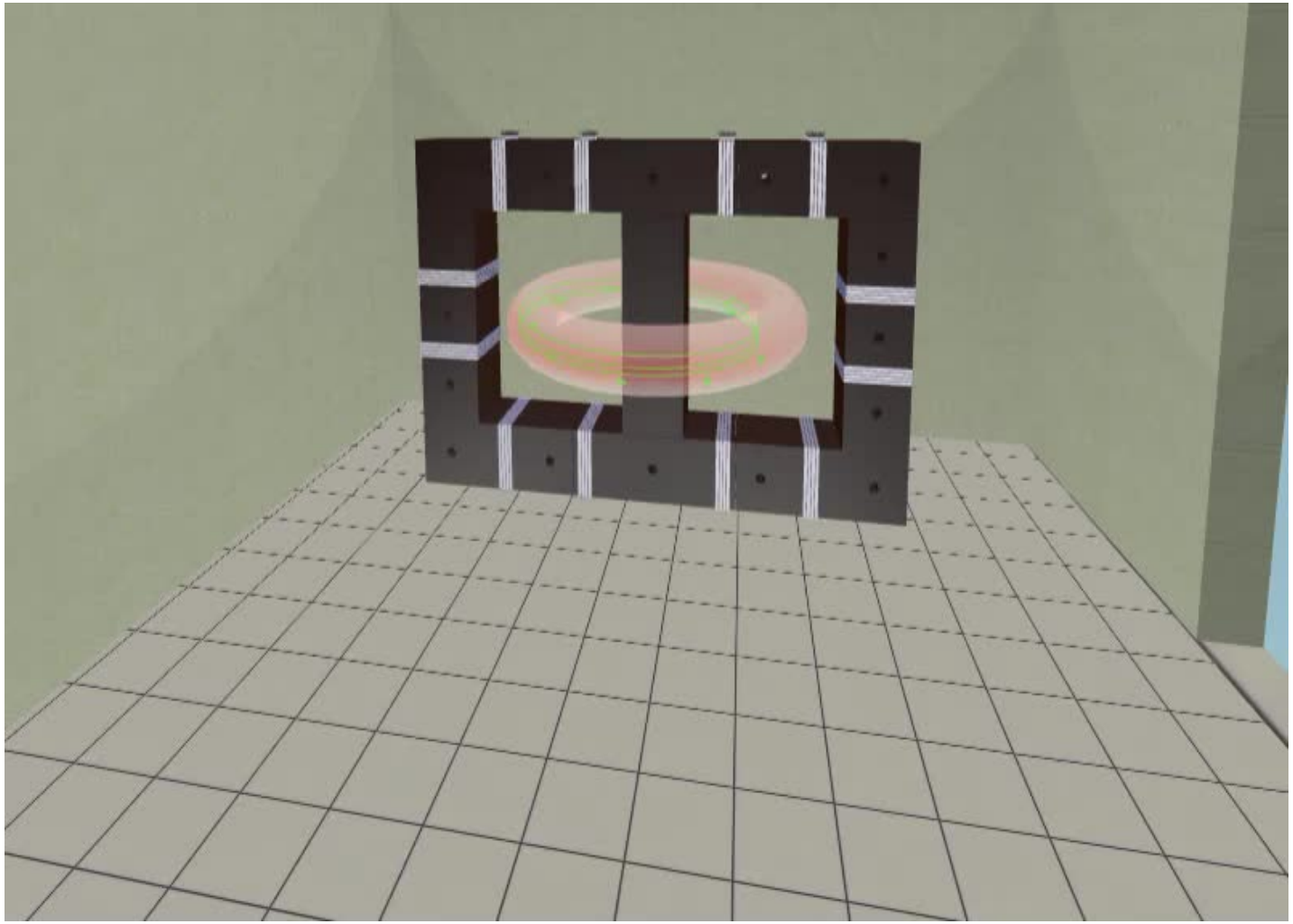
A chamber contains the thermonuclear reaction



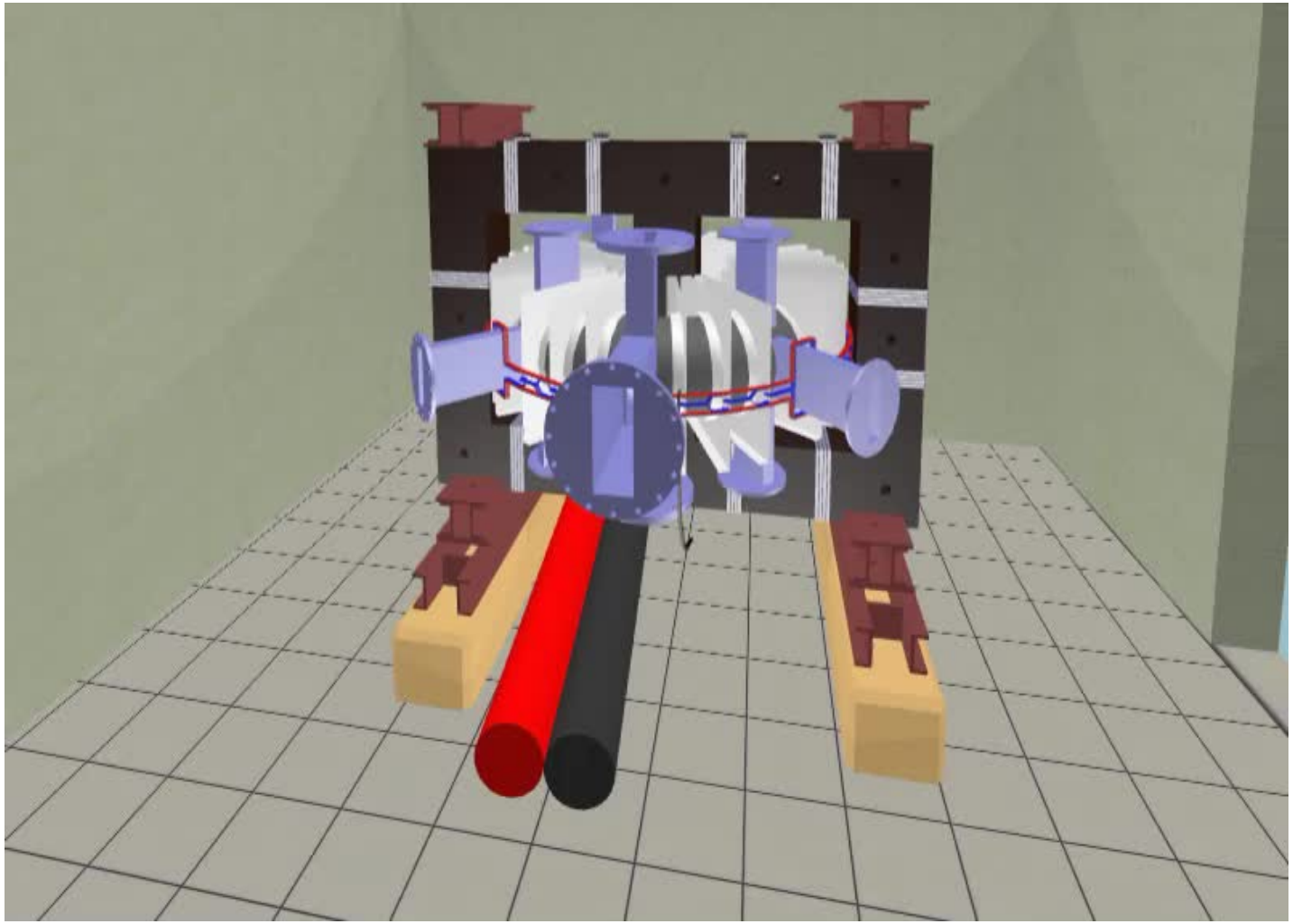
Toroidal magnetic field coils confine the plasma



A transformer action creates and heats the plasma



The final technology altogether



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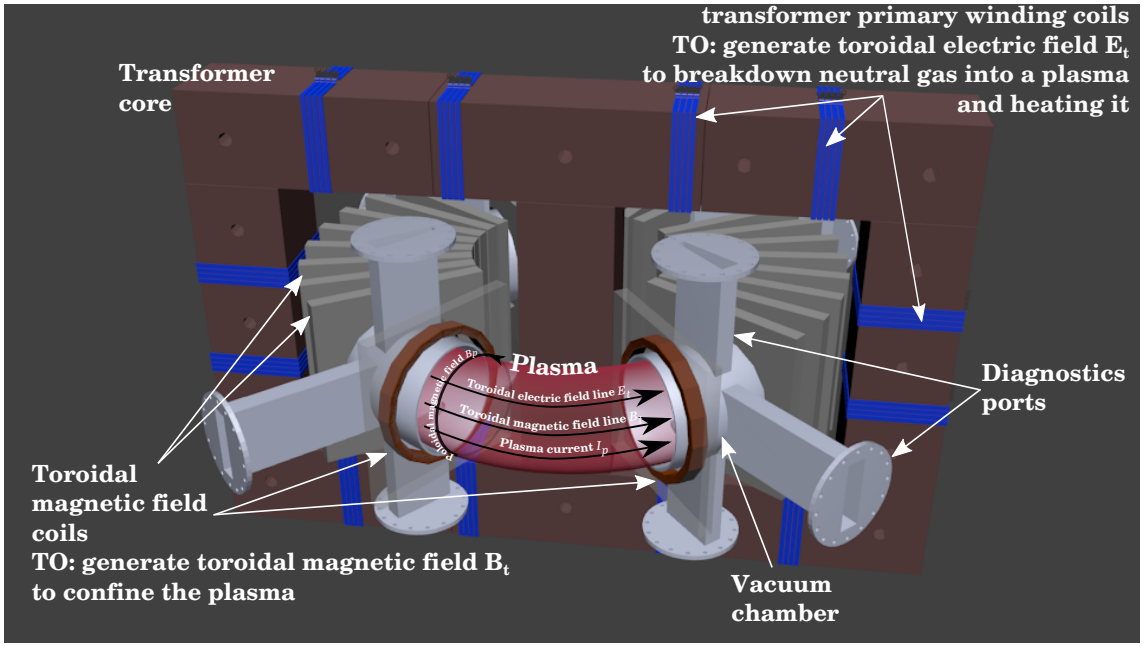
Plasma in Tokamak (GOLEM) - the least to do



To do:

- session start phase:
  - Evacuate the chamber
- pre-discharge phase
  - Charge the capacitors
  - Fill in the working gas
  - Preionization
- discharge phase
  - 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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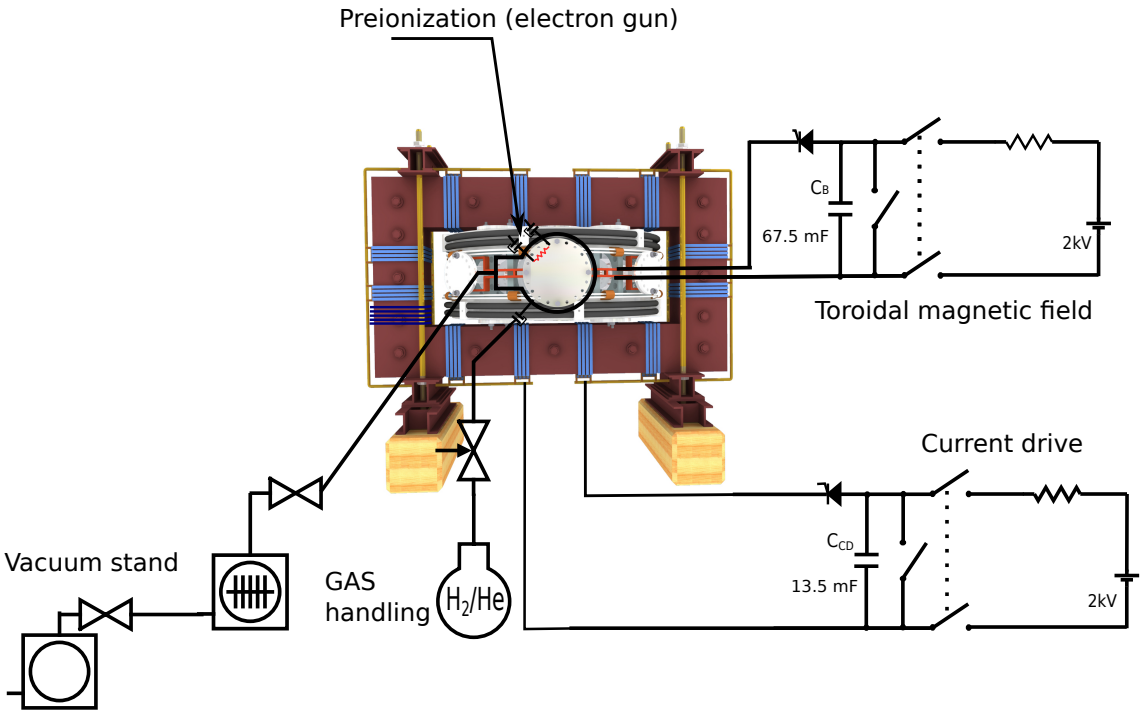

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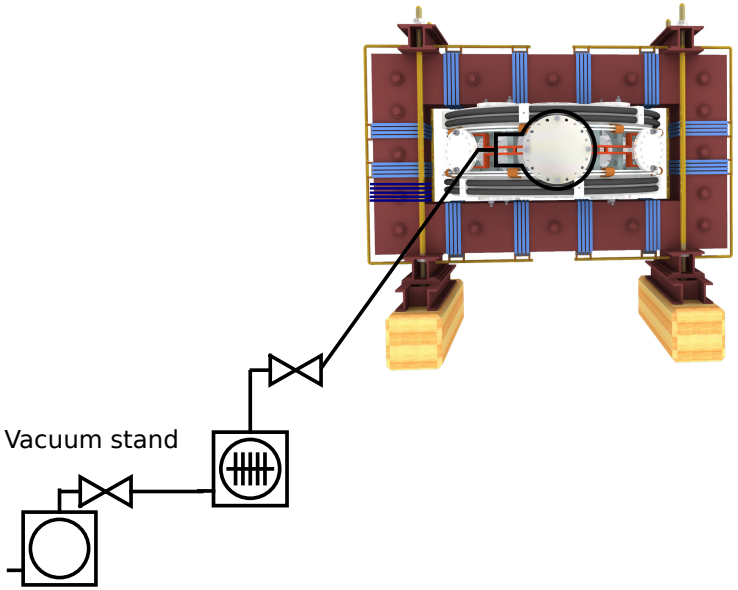

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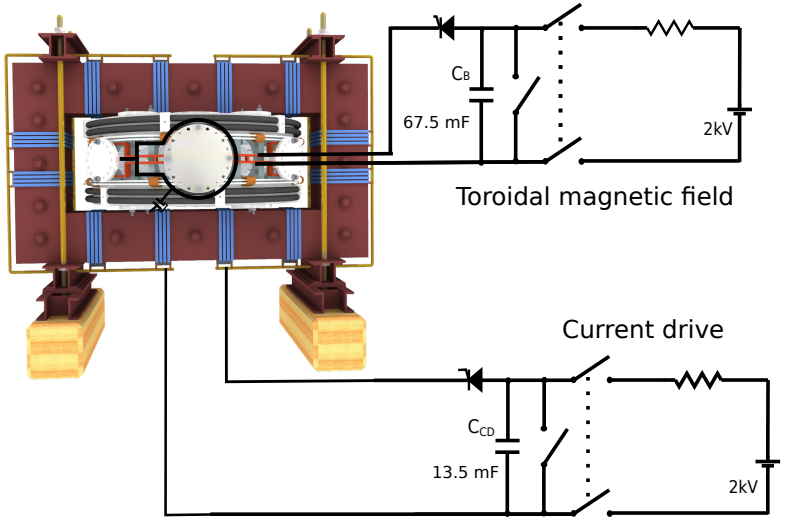

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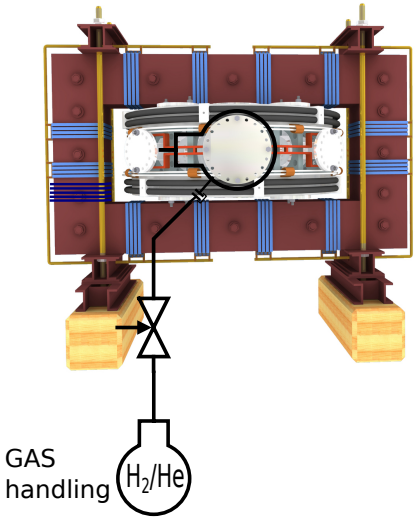

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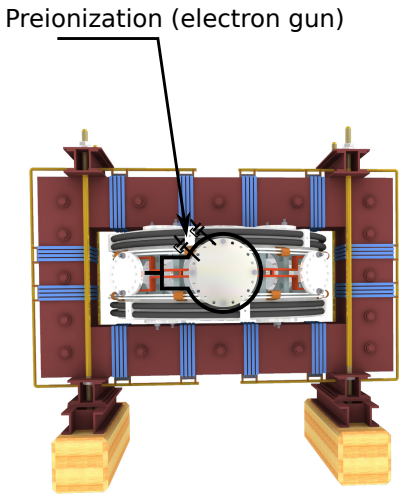

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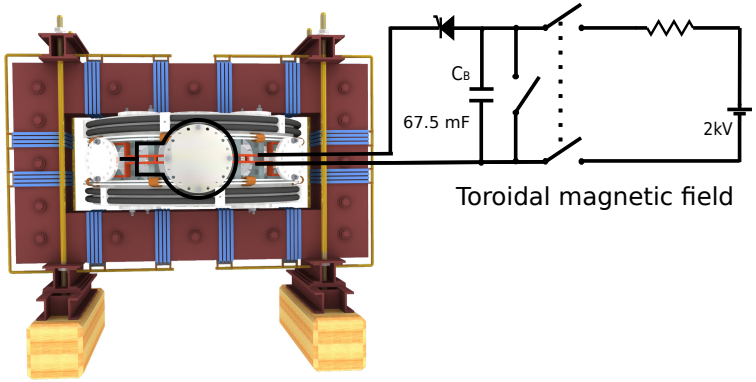

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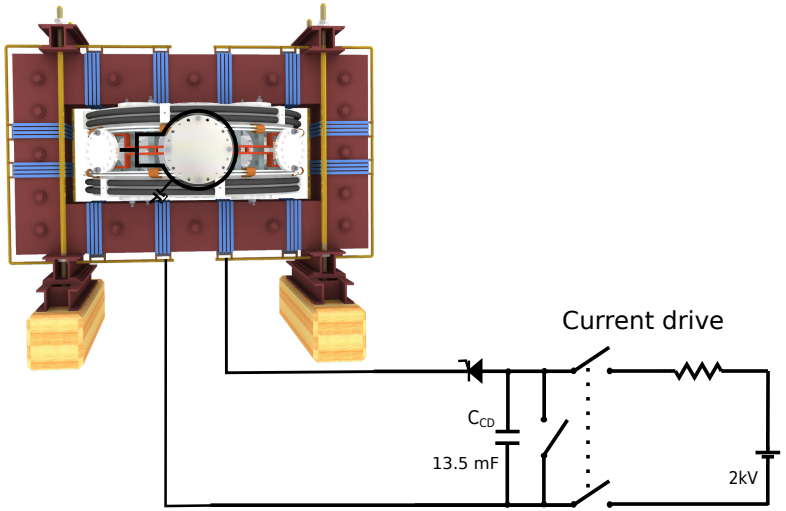

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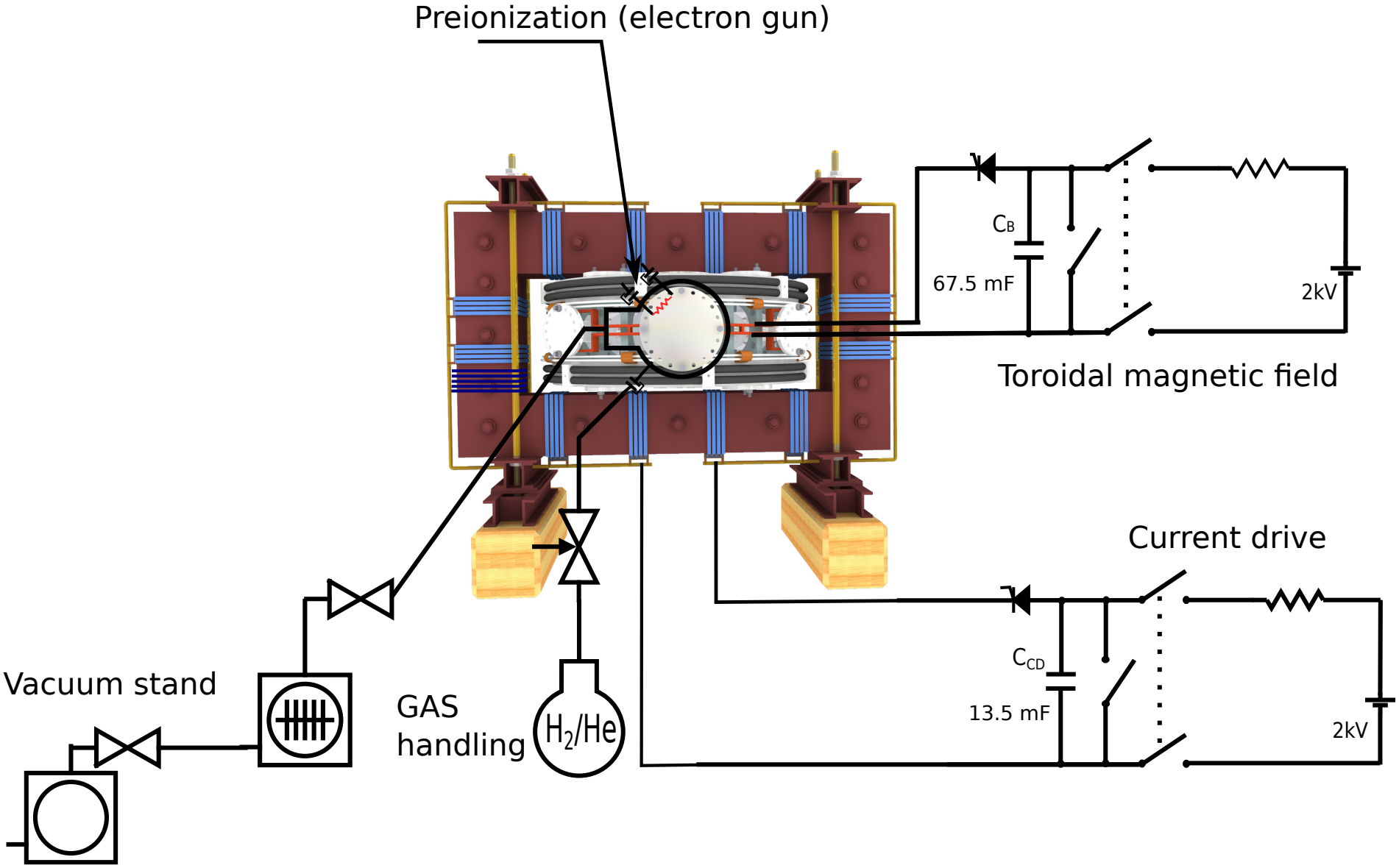
Tokamak GOLEM - schematic experimental setup



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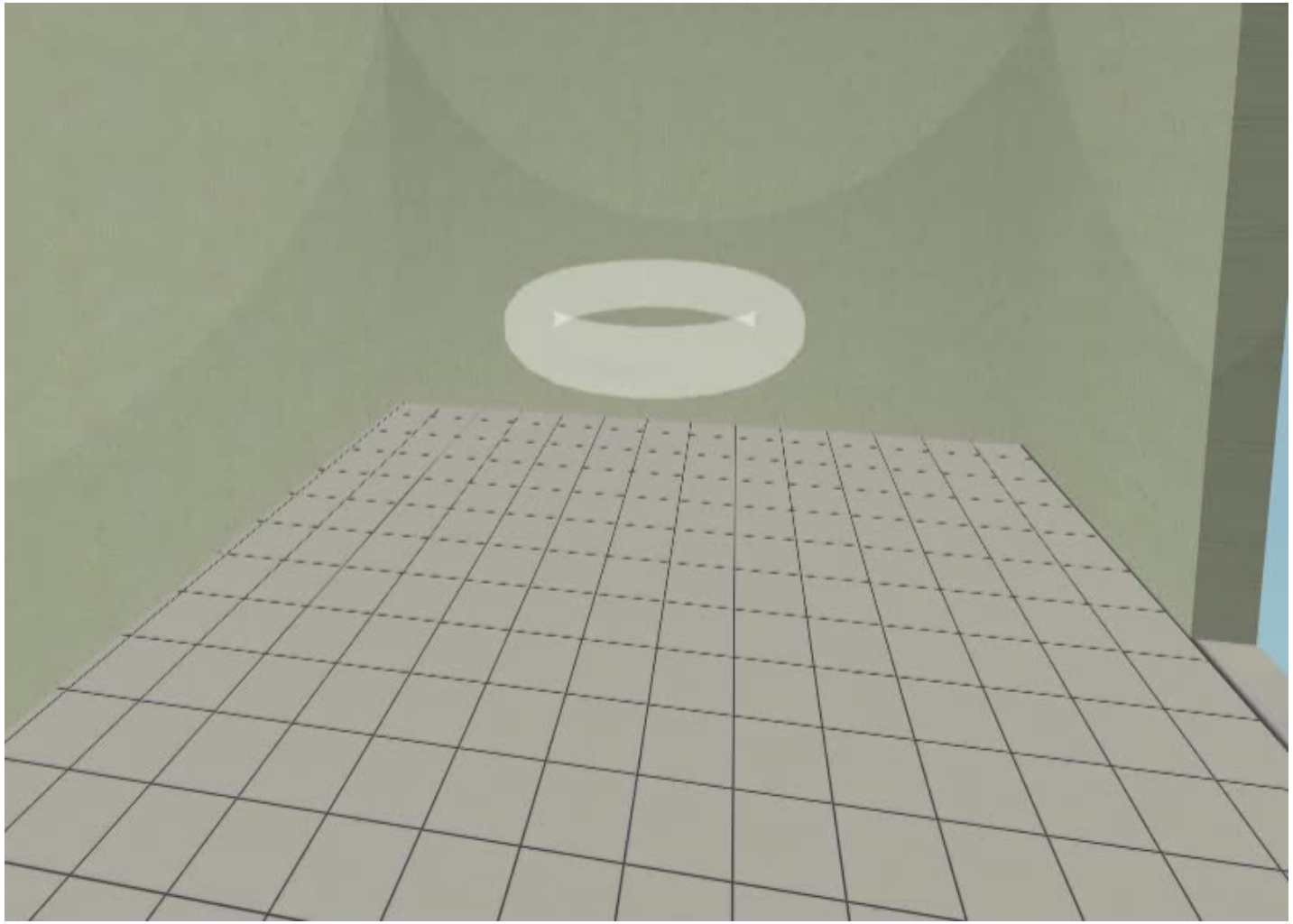
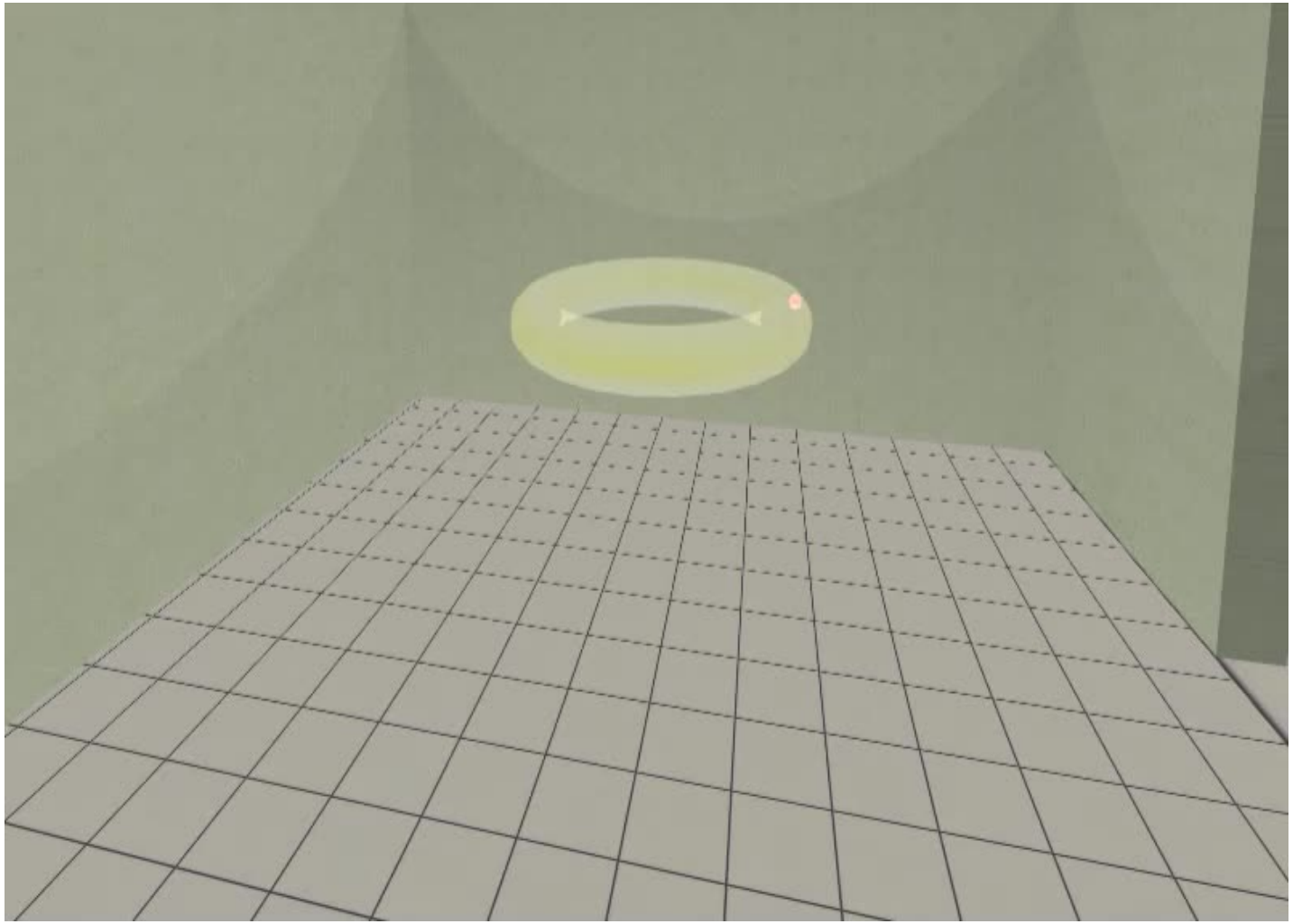
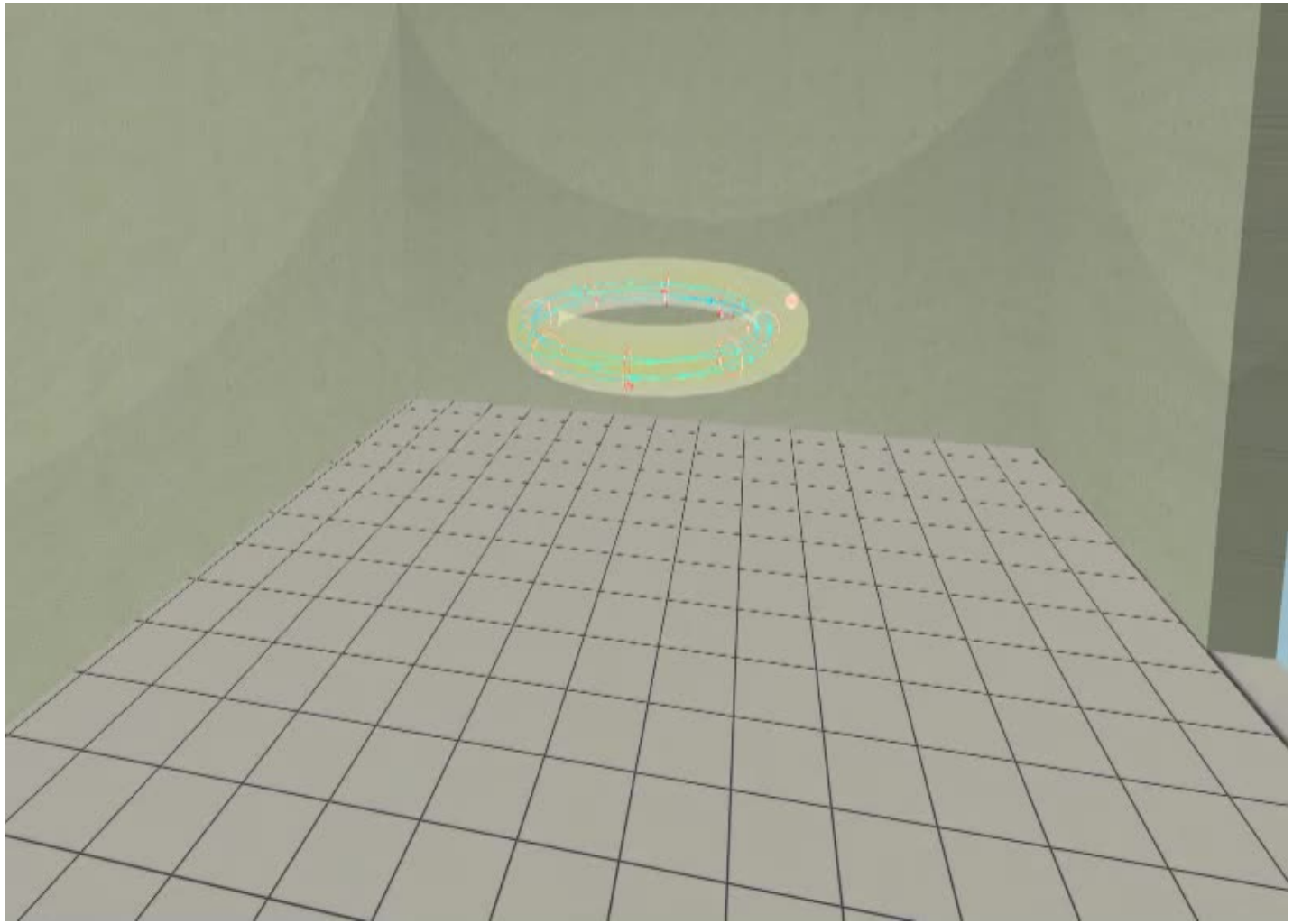
Introduce the working gas (Hydrogen x Helium)



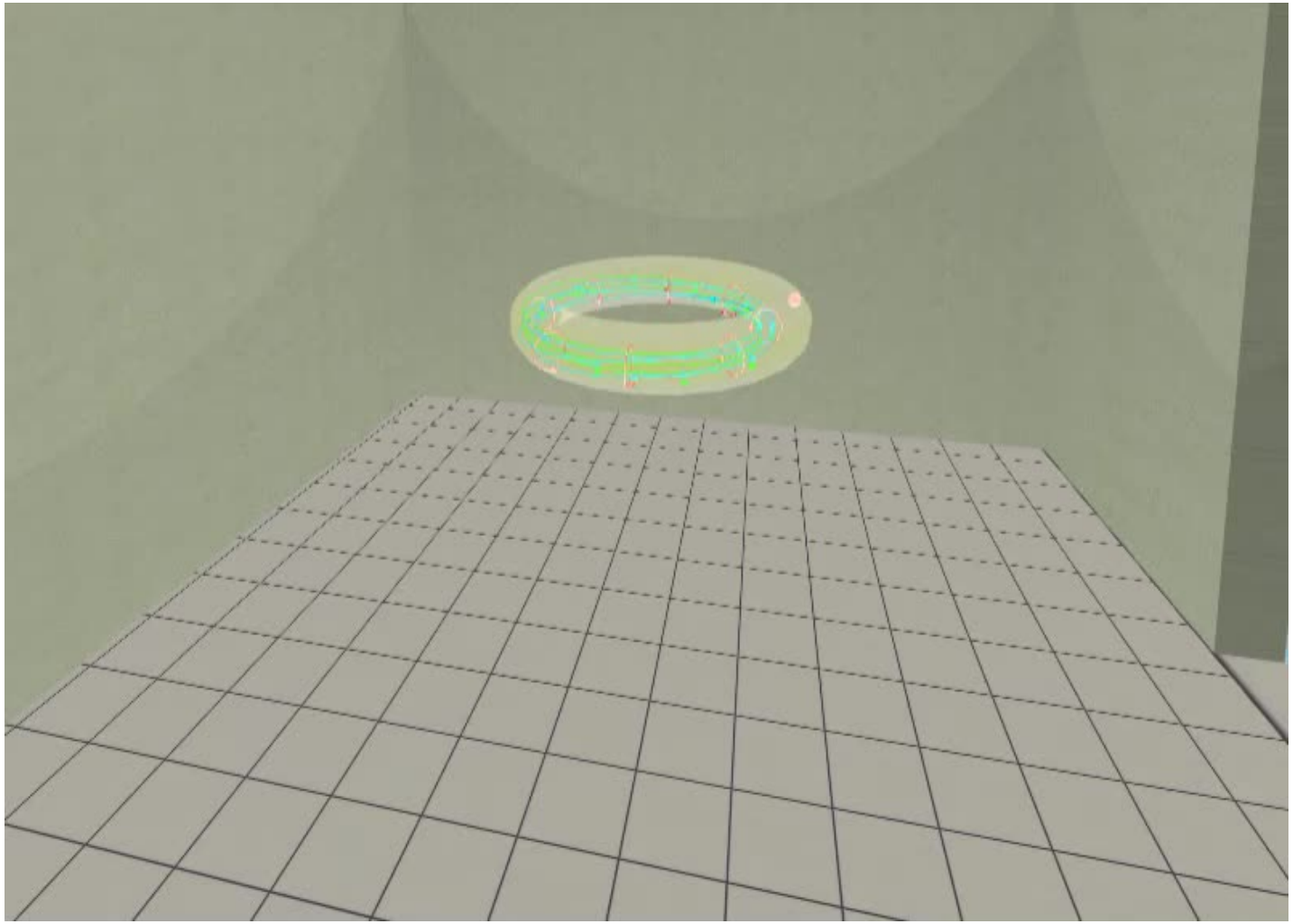
Switch on the preionization



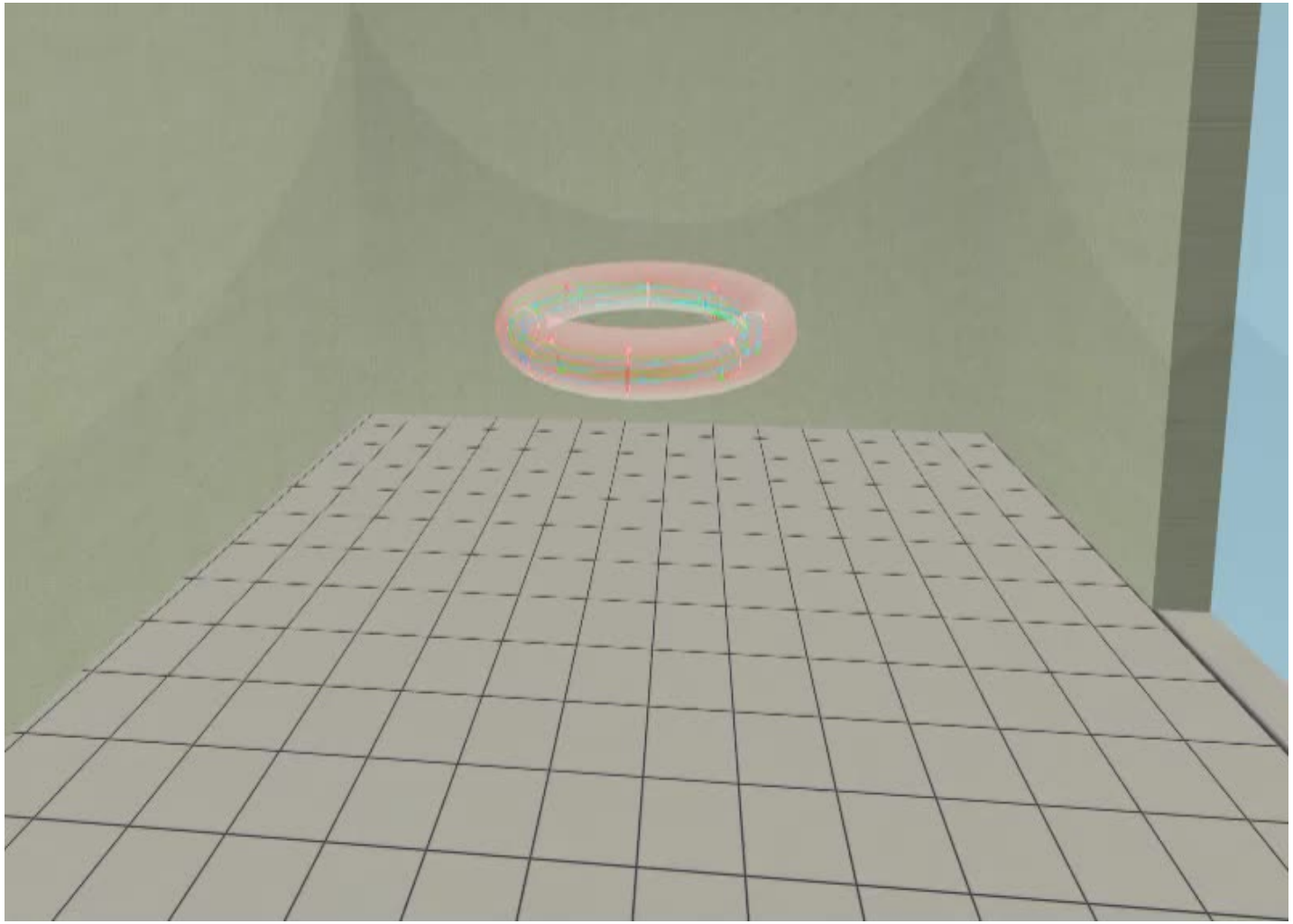
Introduce the magnetic field



Introduce the electric field



Plasma ..



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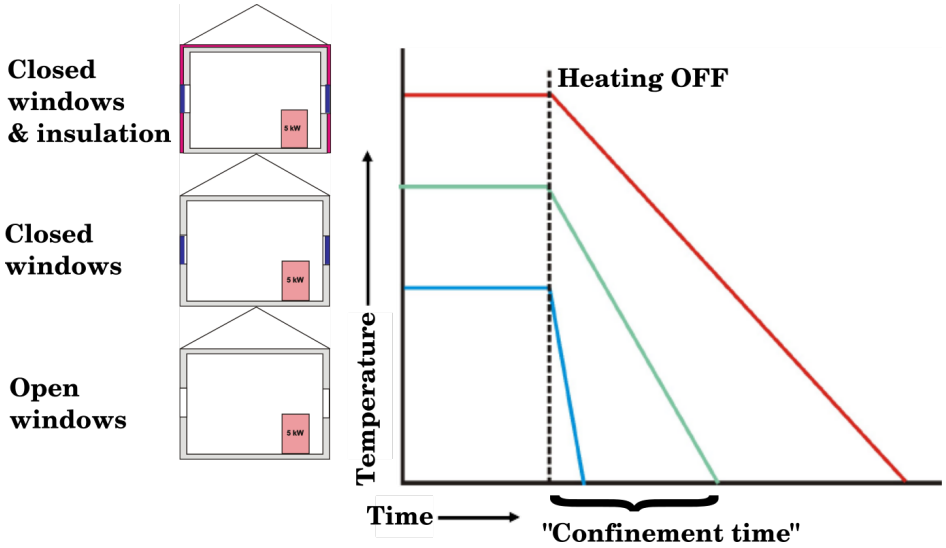
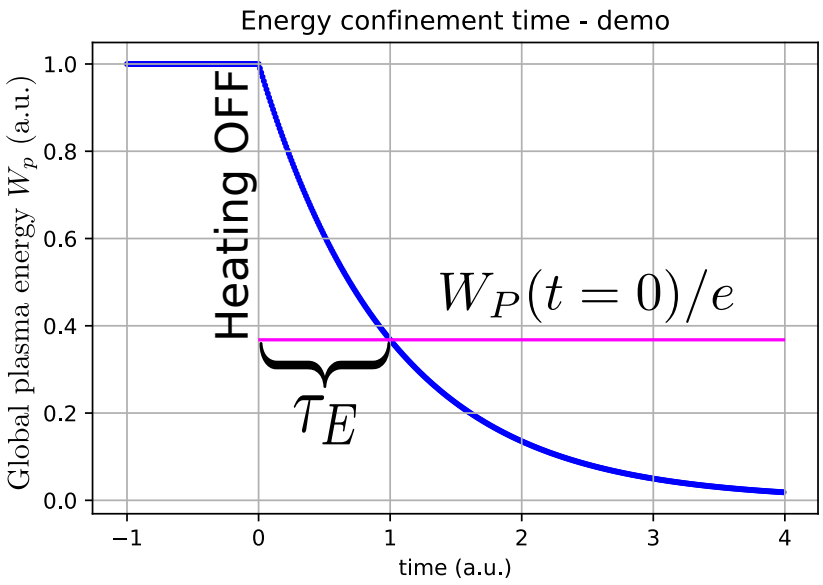
Towards ... Energy confinement time

House

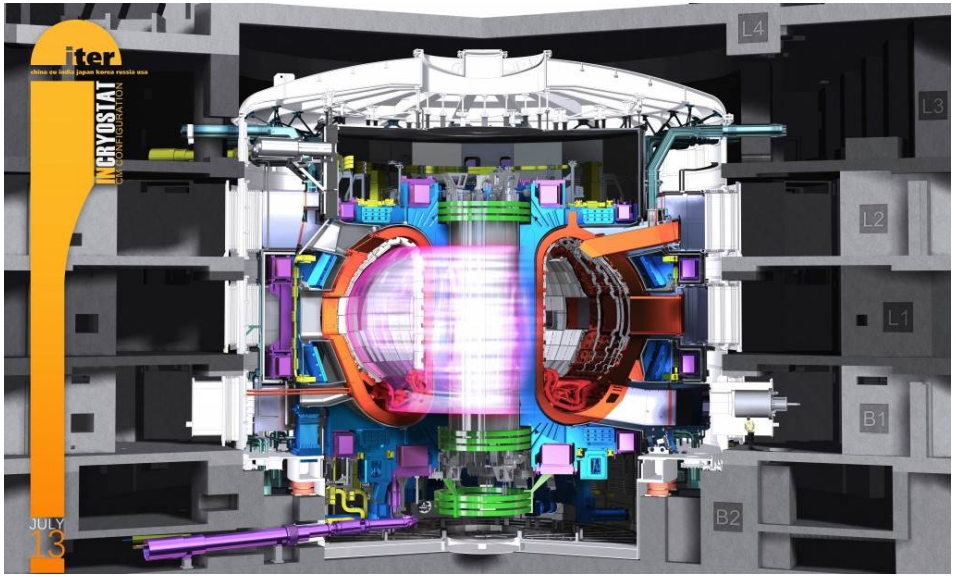


Tokamak



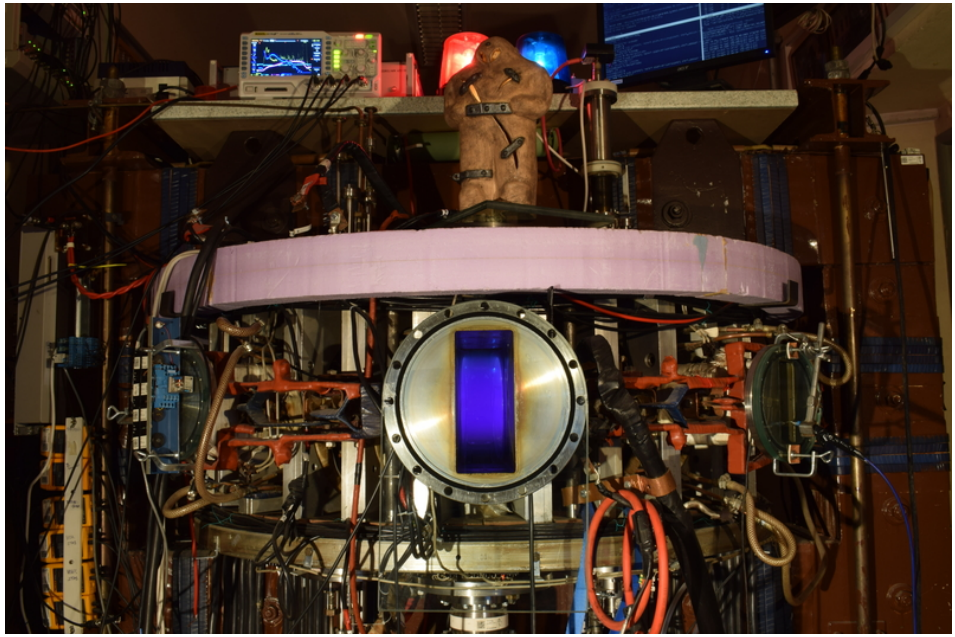
The competition

The ITER: 3.6 s



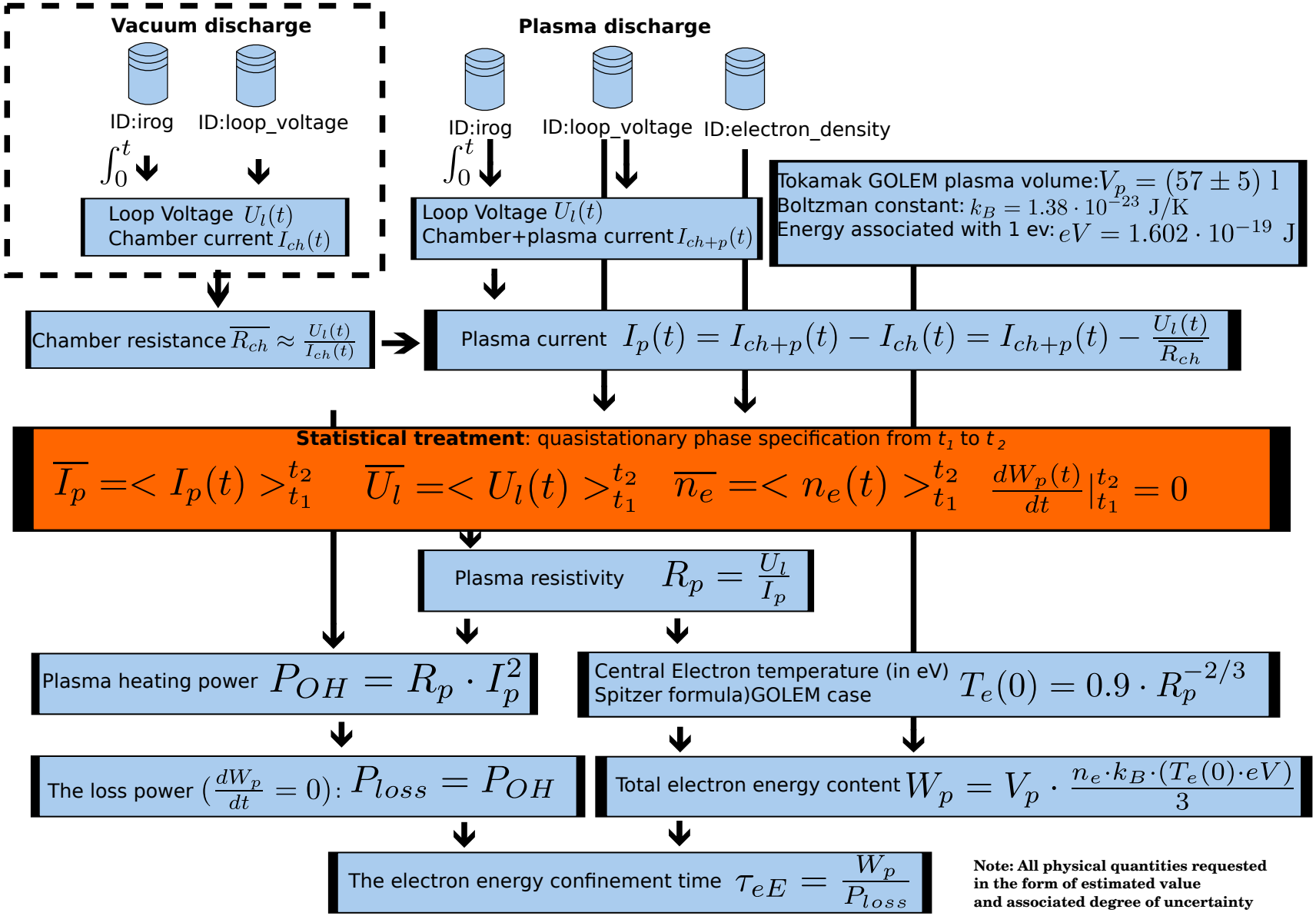
credit:[?]

The GOLEM: ??? s or ms or us ??

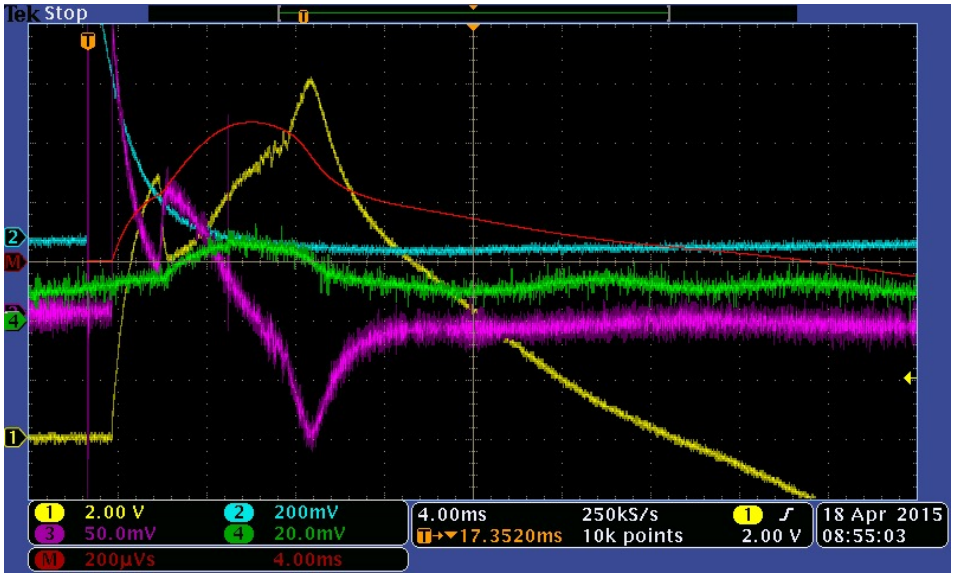


credit:[?]

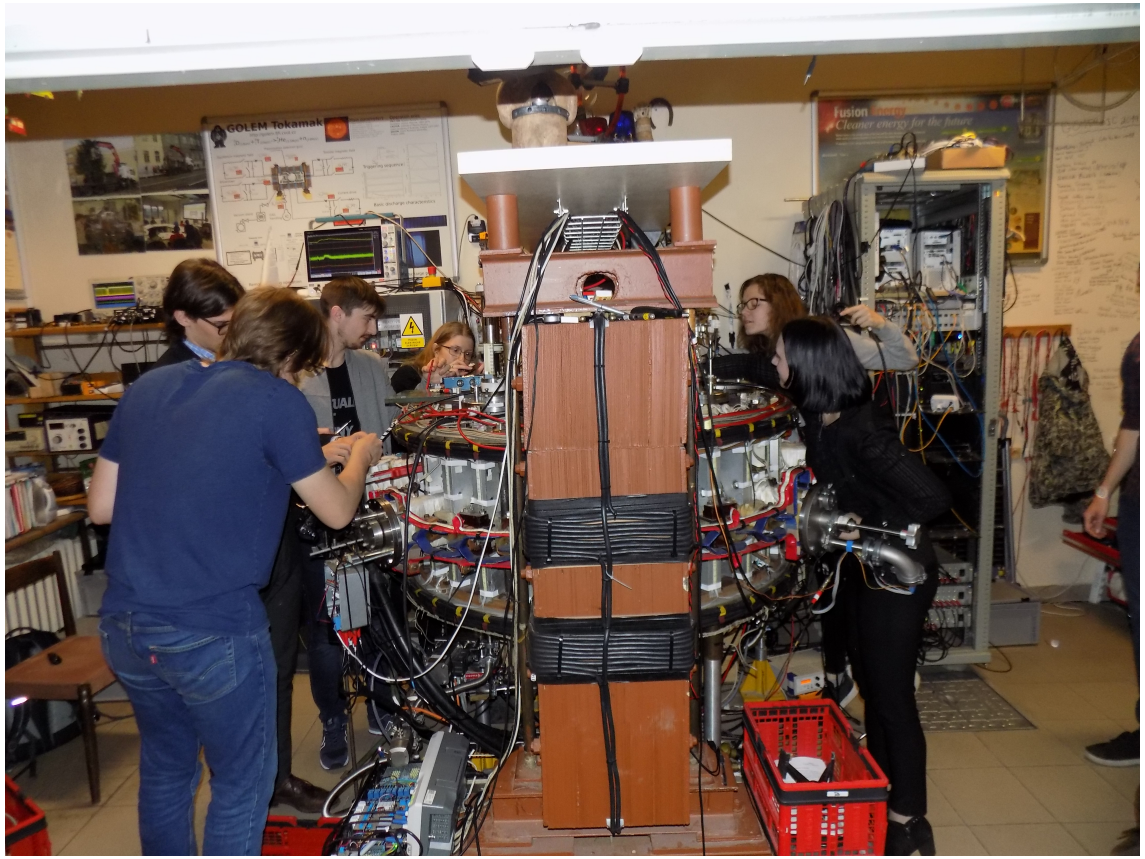
Towards Electron energy confinement time τ_E



Hands on the GOLEM tokamak

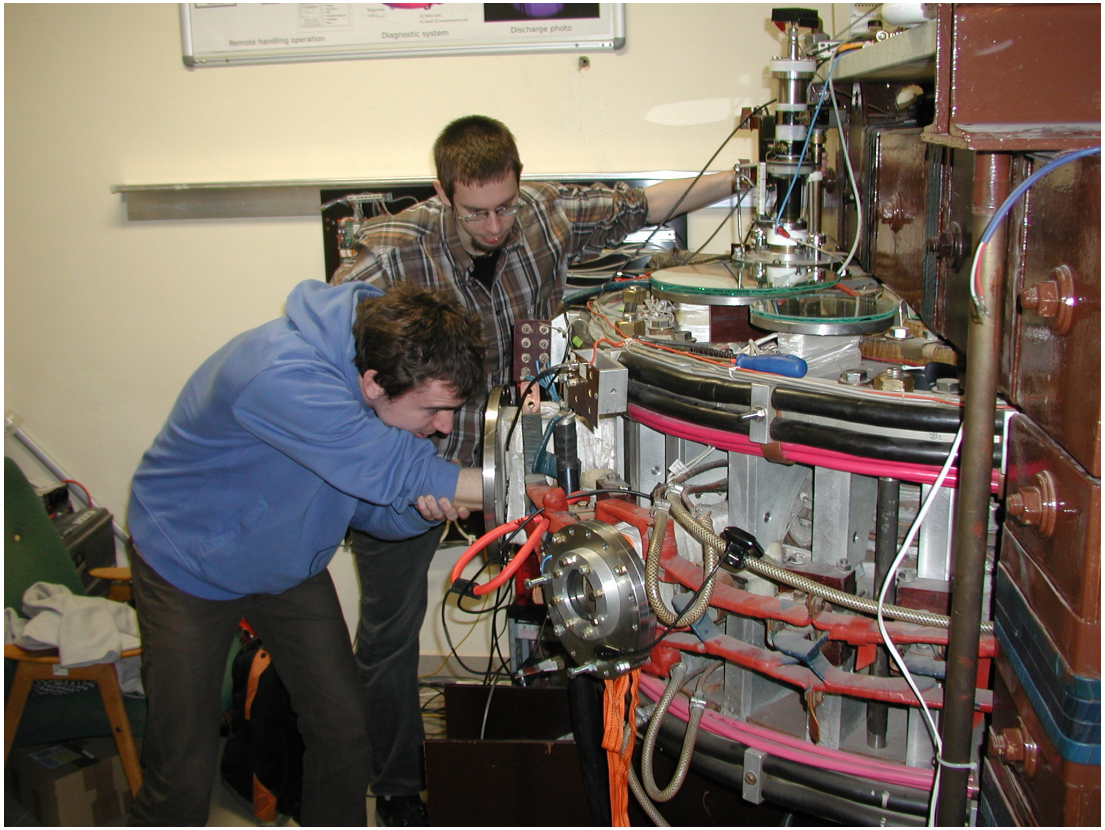


Hands on the GOLEM tokamak



- Laboratory Practice for Basic course of Physics 2015-19 (CT University Bachelor level).
- Advanced plasma training course 2014-19 (CT University Master level).
- Week of scientists 2013-19 (Czech republic High school level).
- International Golem Training Course 2013,2019 (Master and PhD level).

Bachelor & Master thesis made @ tokamak GOLEM



- **Bachelor thesis:** Magnetic field configurations and their measurement, Interactive model, Plasma flow velocity measurements using Mach probe arrays, Virtual model, Bolometric measurements, Breakdown studies, Vertical plasma stabilization.
- **Master thesis:** Microwave interferometry, Remote operation of the vertical plasma stabilization, Measurements of magnetic fields.

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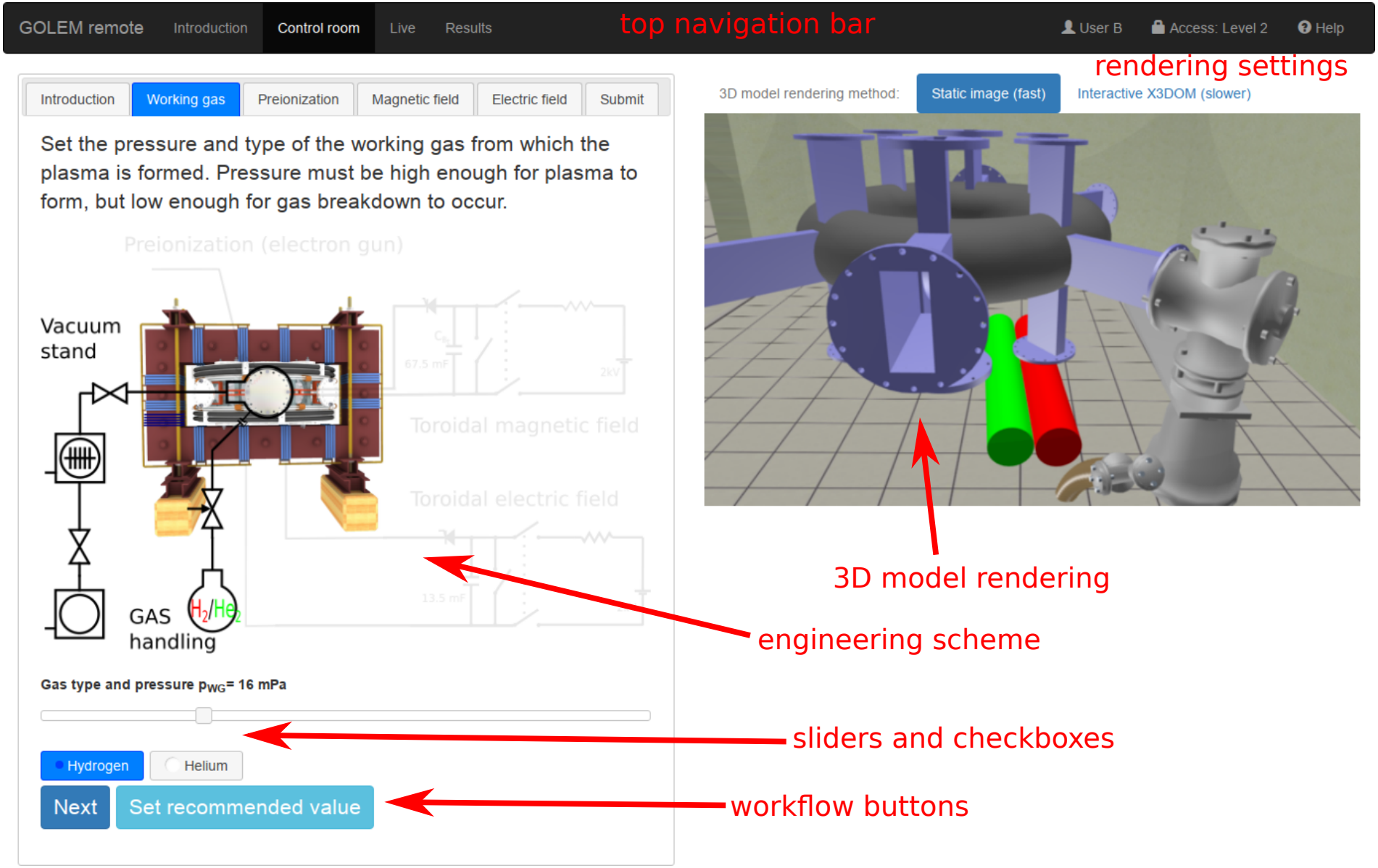
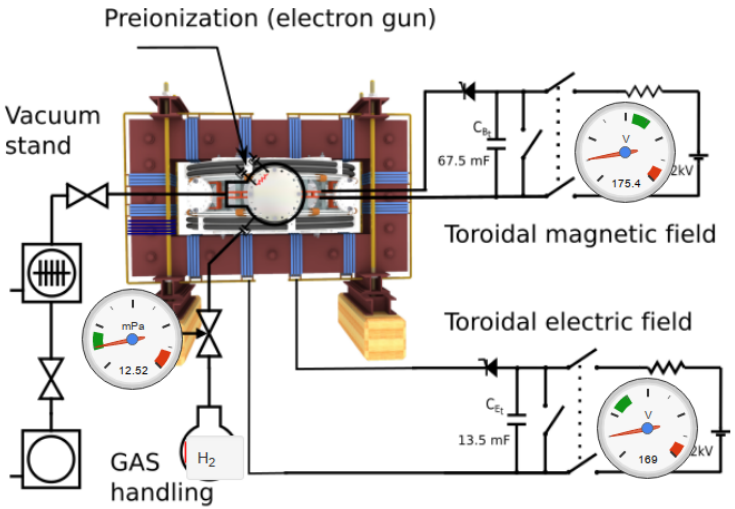
Remote control interface of the GOLEM tokamak



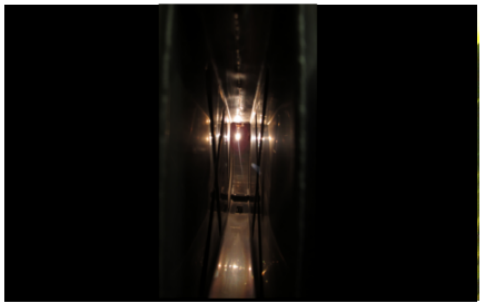
Live real-time view of the experiment

GOLEM remote | Introduction | Control room | Live | Results | User B | Access: Level 2 | Help



Charging capacitors, setting working gas pressure

Tokamak chamber camera



Room camera

Discharge request queue

Status	User	Comment	U_{B_t} [V]	U_{E_t} [V]	gas [mPa]
In progress	User A	plasma reference	800	450	16 (H)
Waiting	User A	higher pressure	800	450	20 (H)
Waiting	User B	strong E field	600	500	16 (H)

Shot homepage

GOLEM » Shot #22471 »

Diagnostics

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

Analysis

- ✓ ShotHomepage

DAS

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

Vacuum log

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Tokamak GOLEM - Shot Database - 22471

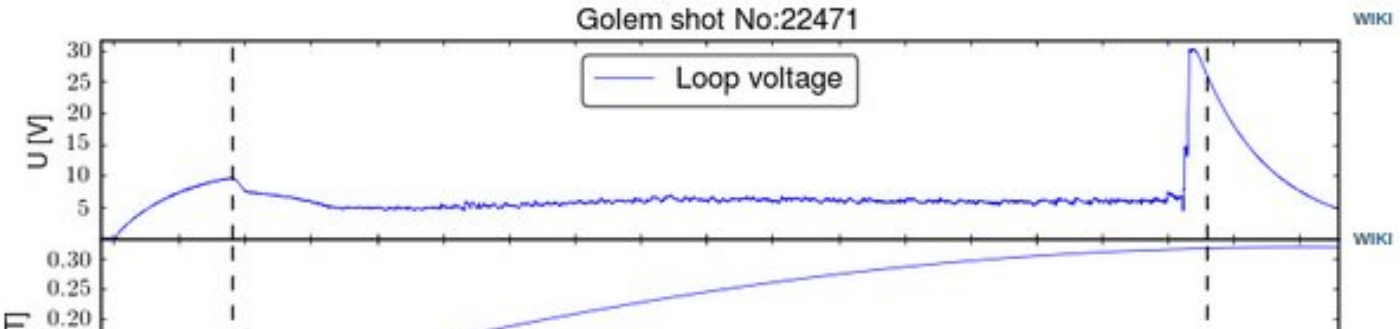
Date: 2016-09-29 - **14:33:57**
Session: TrainingCourses/Universities/Uni_Belgrade.rs/2016/
Comment: `Standard discharge`

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

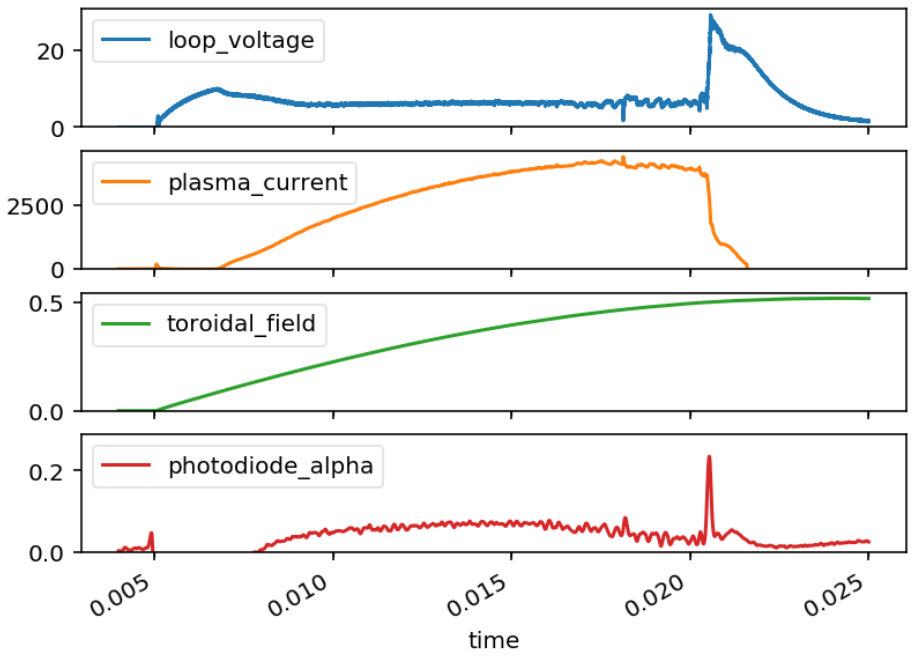
Plasma parameters:

- 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



Remote data access (using a few high level functions)

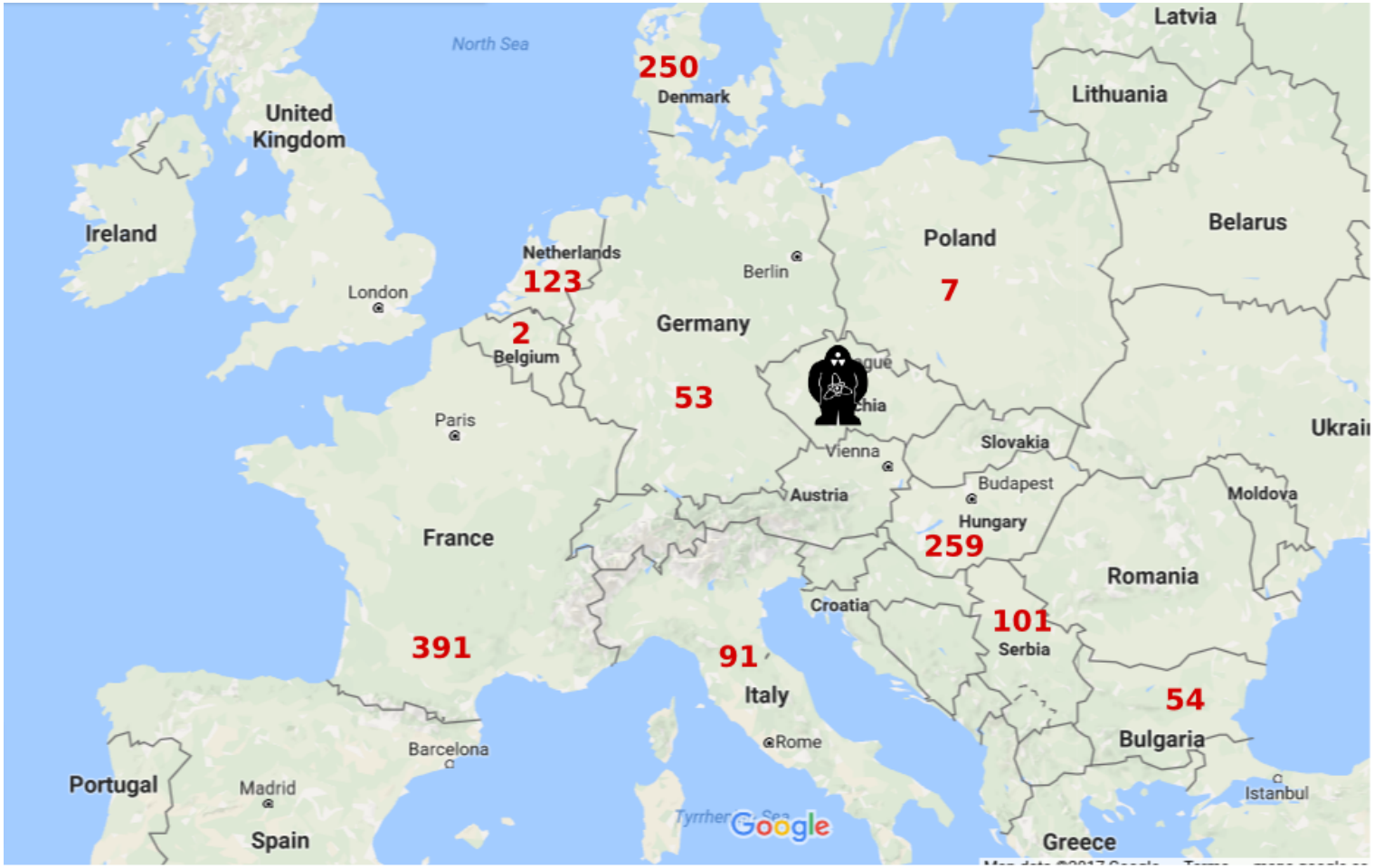
```
import pandas as pd
import matplotlib.pyplot as plt
URL = 'http://golem.fjfi.cvut.cz/utils/data/{}/
# function for reading 1D y(t) signals
def read_signal1d(shot_number, signal_id):
    url = URL.format(shot_number, signal_id)
    return pd.read_table(url,names=['time',sign
                         index_col='time')
# read the specified signals
shot_no = 29395
U_l = read_signal1d(shot_no, 'loop_voltage')
I_p = read_signal1d(shot_no, 'plasma_current')
P_OH = U_l*I_p
# vectorized, time-aligned operation
B_t = read_signal1d(shot_no, 'toroidal_field')
H_a = read_signal1d(shot_no, 'photodiode_alpha'
# combine into a data frame table
df = pd.concat([U_l, I_p, B_t, H_a], axis='colu
# plot the data table in subplots from 4 to 25
df.loc[4e-3:25e-3].plot(subplots=True, ylim=(0,
plt.show()
# display the figure in a window
```



Remote control 2009-2019 inventory

- Demonstrations: Ghent University 09; Bochum University 13; Garching 13; Lemvig High School 14; Instituto Tecnologico Costa Rica 10; Armidale University 17.
- Training courses: French Training Course & EM 12-14,16-19; Bangkok 16-19; TU Eindhoven 11,15-19;TU Kobehaven 14,15,18;Grenoble TU 15, University of Belgrade 15-18; BUTE Budapest 10,12-18; University of Padova 14,16,18; TU Torino 16-18, St. Peterburg University 18-19. Kharkov University 19
- Workshops Kiten: 14,16,18; Observatorium Valasske Mezirici 14; Islamabad 14.

Remote discharges over the Czech borders (up to 2017)



+ IN ~ 10, + PK ~ 70, + OTHERS ~ 100

Σ(09/12-02/17)~1500

Fee: postcard from the venue of remote measurements

Tokamak GOLEM - Toilet discharge

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

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Acknowledgement

Financial support highly appreciated:

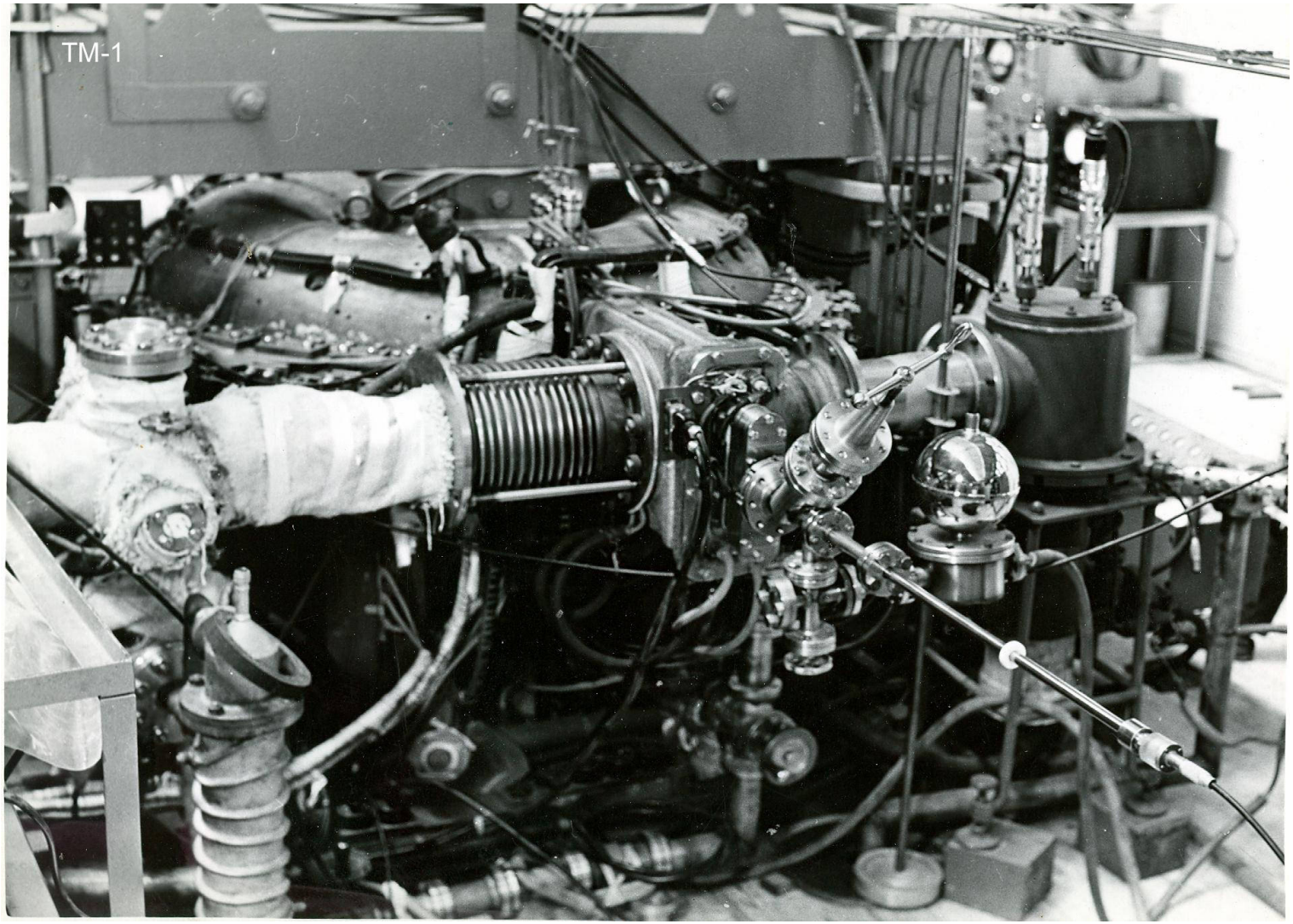
CTU RVO68407700, SGS 17/138/OHK4/2T/14, GAČR GA18-02482S, EU funds CZ.02.1.01/0.0/0.0/16_019/0000778 and CZ.02.2.69/0.0/0.0/16_027/0008465, IAEA F13019, FUSENET and EUROFUSION.

Students, teachers, technicians (random order):

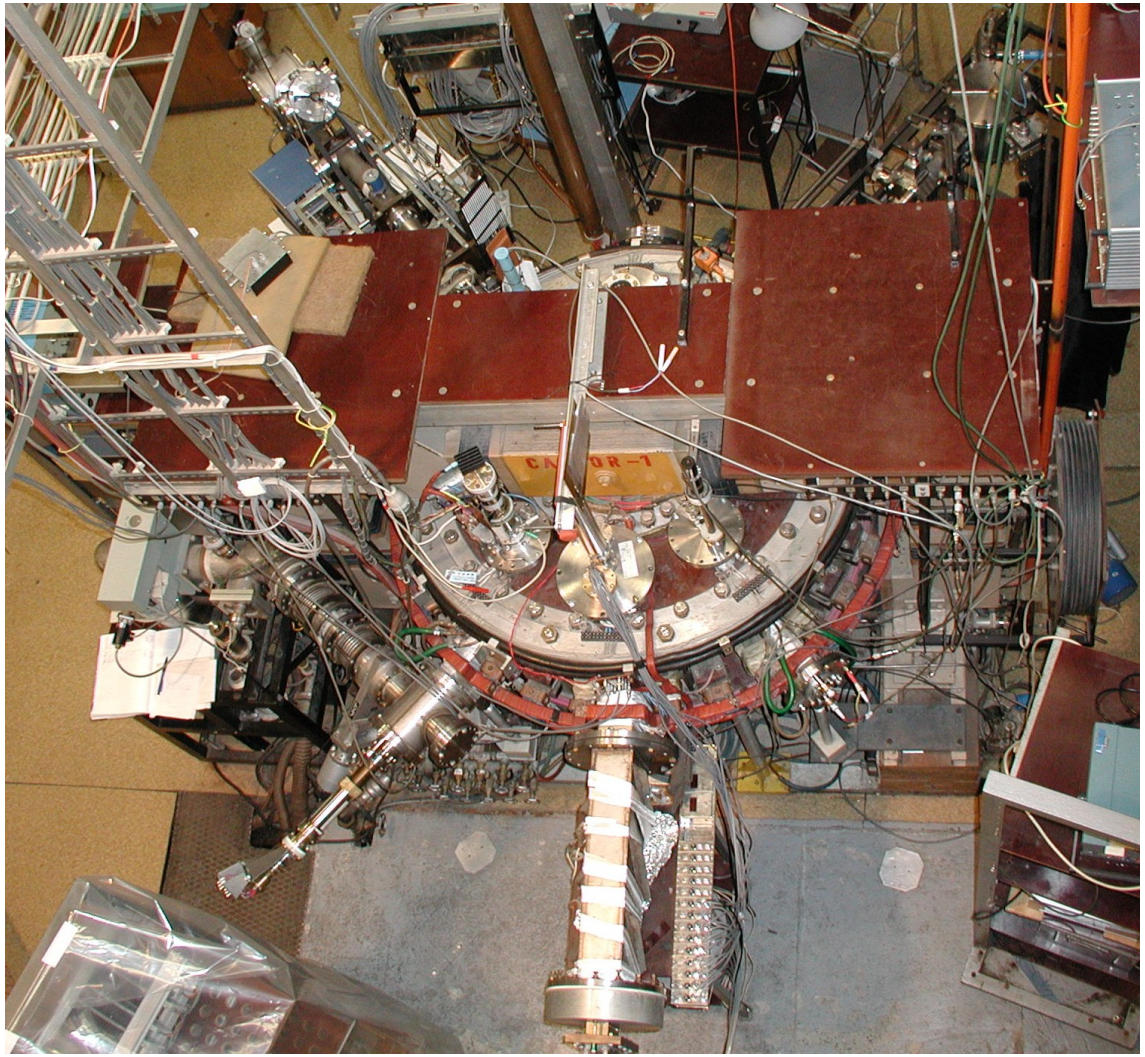
Vladimír Fuchs, Ondřej Grover, Jindřich Kocman, Tomáš Markovič, Michal Odstrčil, Tomáš Odstrčil, Gergo Pokol, Igor Jex, Gabriel Vondrášek, František Žácek, Lukáš Matěna, Jan Stockel, Jan Mlynář, Jaroslav Krbec, Radan Salomonovič, Vladimír Linhart, Kateřina Jiráková, Ondřej Ficker, Pravesh Dhyani, Juan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

Thank you for your attention

XX/YY: TM-1



XX/YY: CASTOR

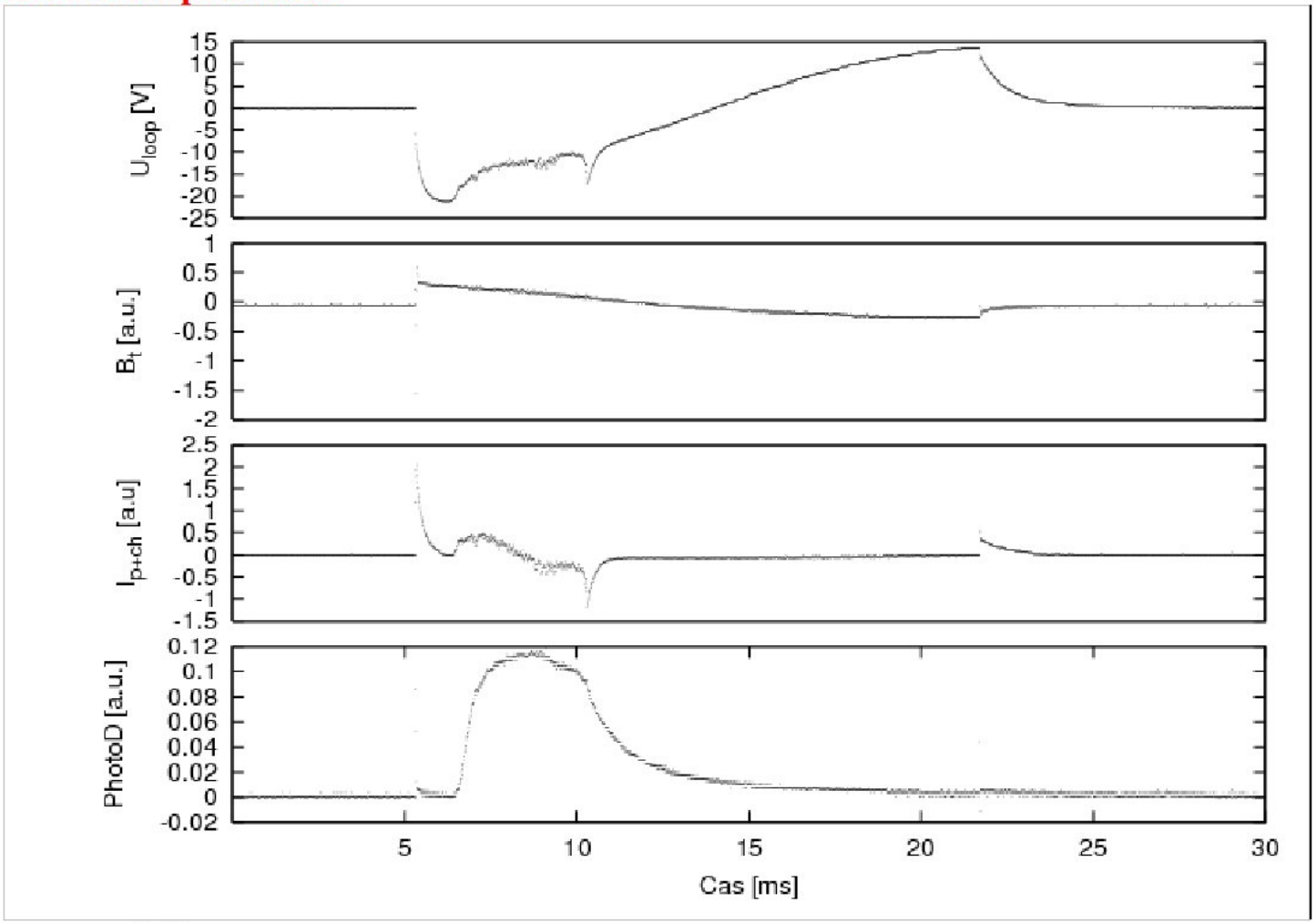


12/07: Last minutes at the IPP Prague

12/07: First minutes at the CTU Prague

07/09: First plasma in the tokamak GOLEM

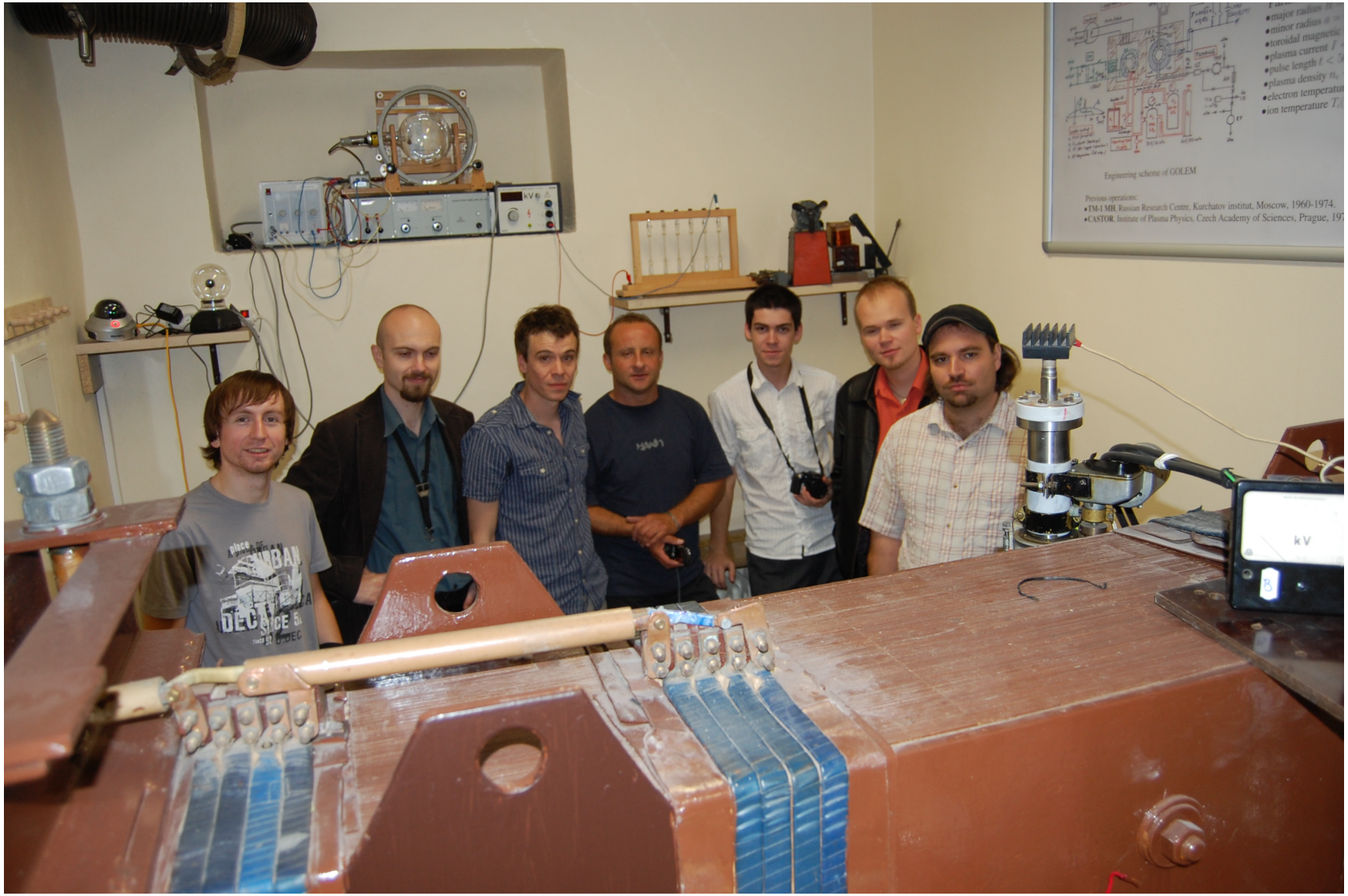
Časové průběhy signálů zřetelně ukazují, že došlo k průrazu neutrálního plynu a k zformování plazmatu.



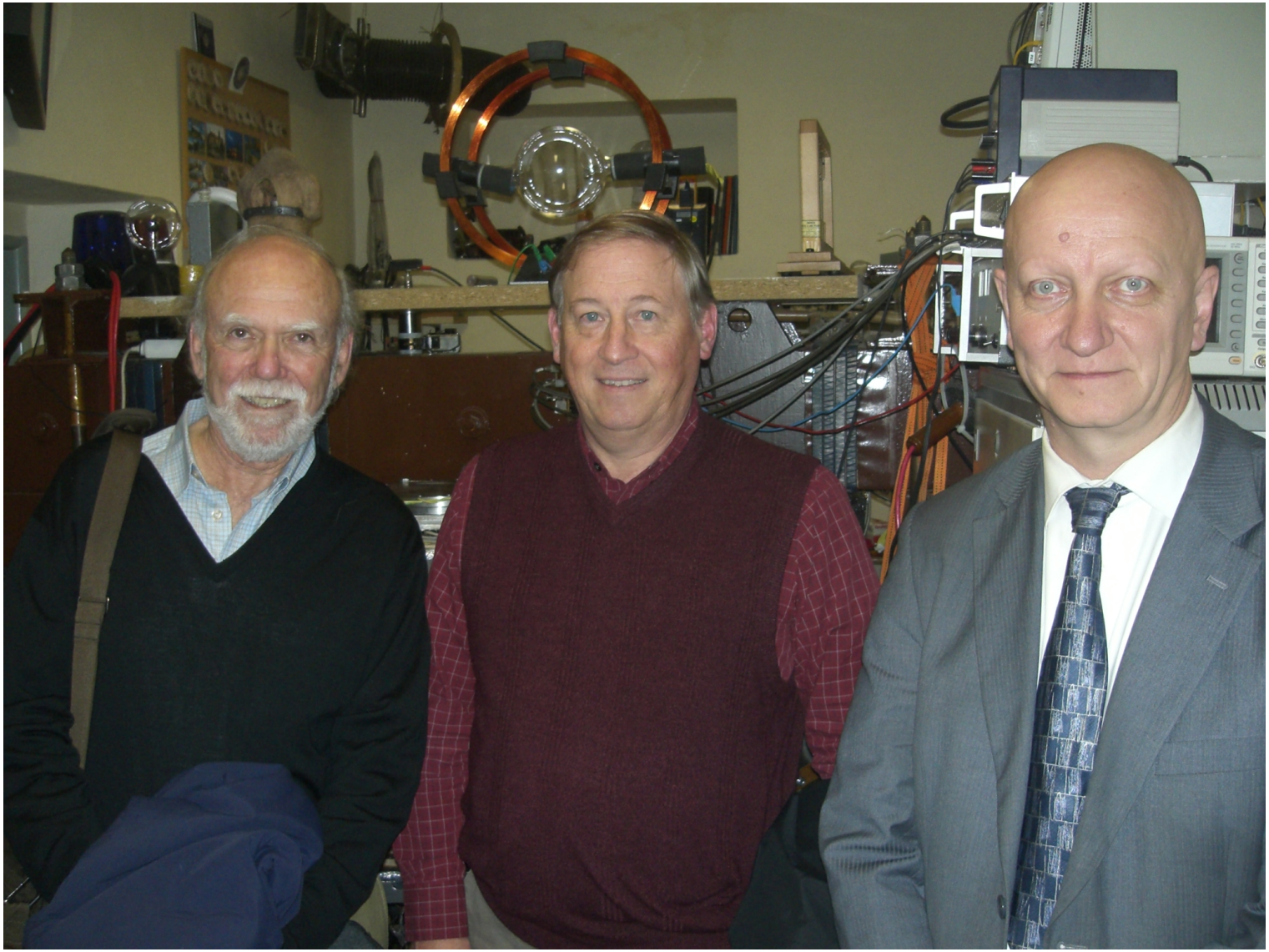
O tom svědčí:

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

09/09: Tokamak and tokamak

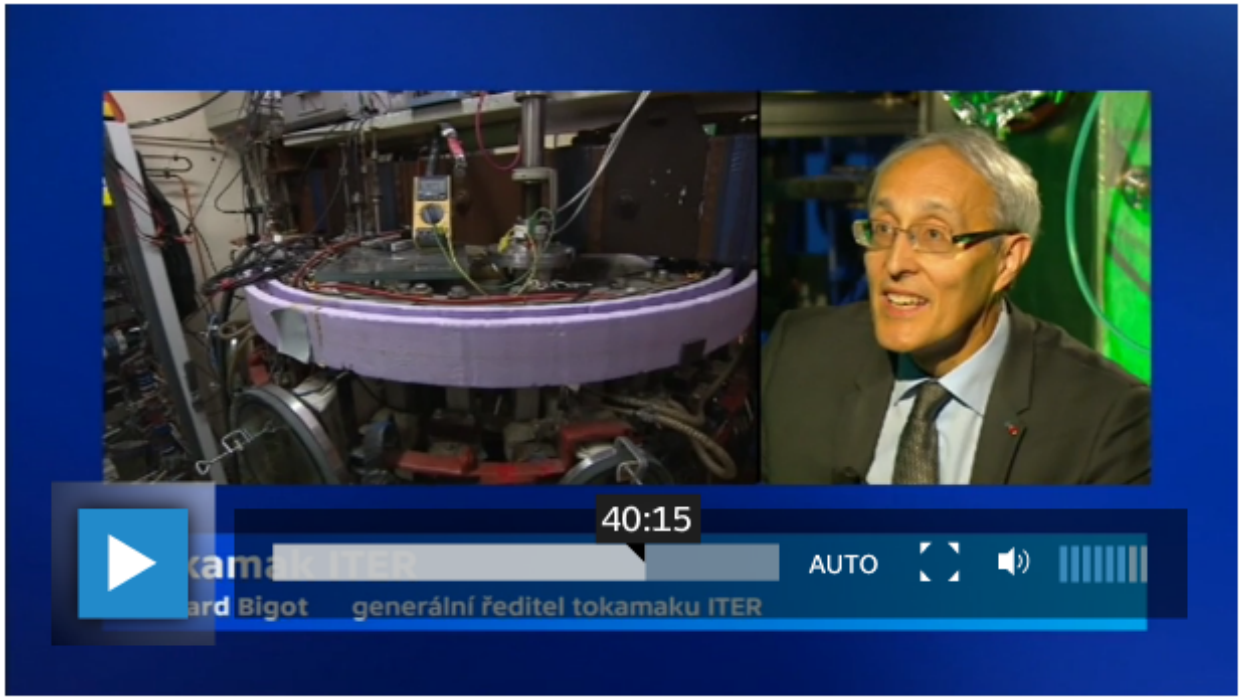


11/11: NP laureat at tokamak GOLEM



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

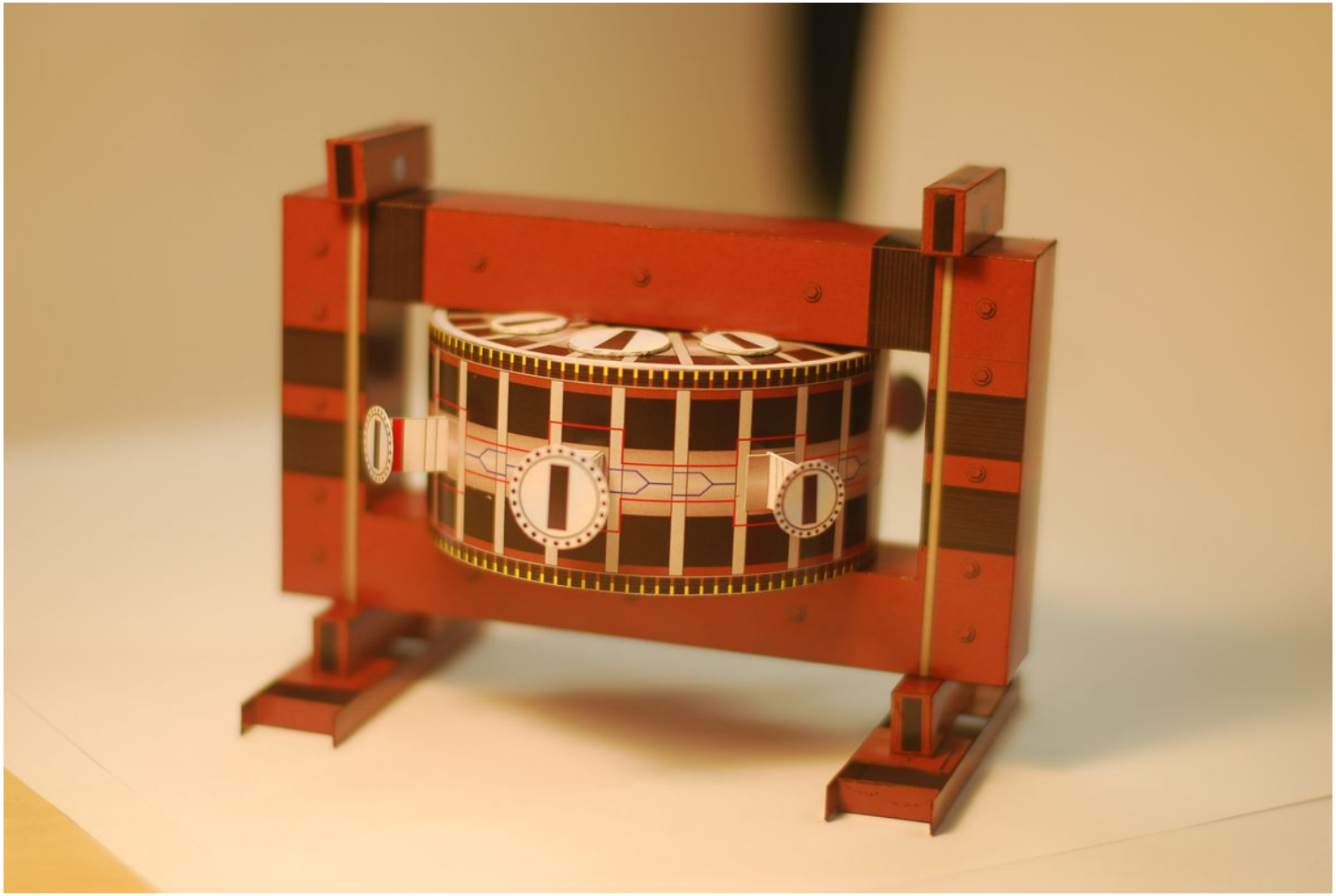
0916: ITER DG, Mr. Bernard Bigot (Shot #22185)



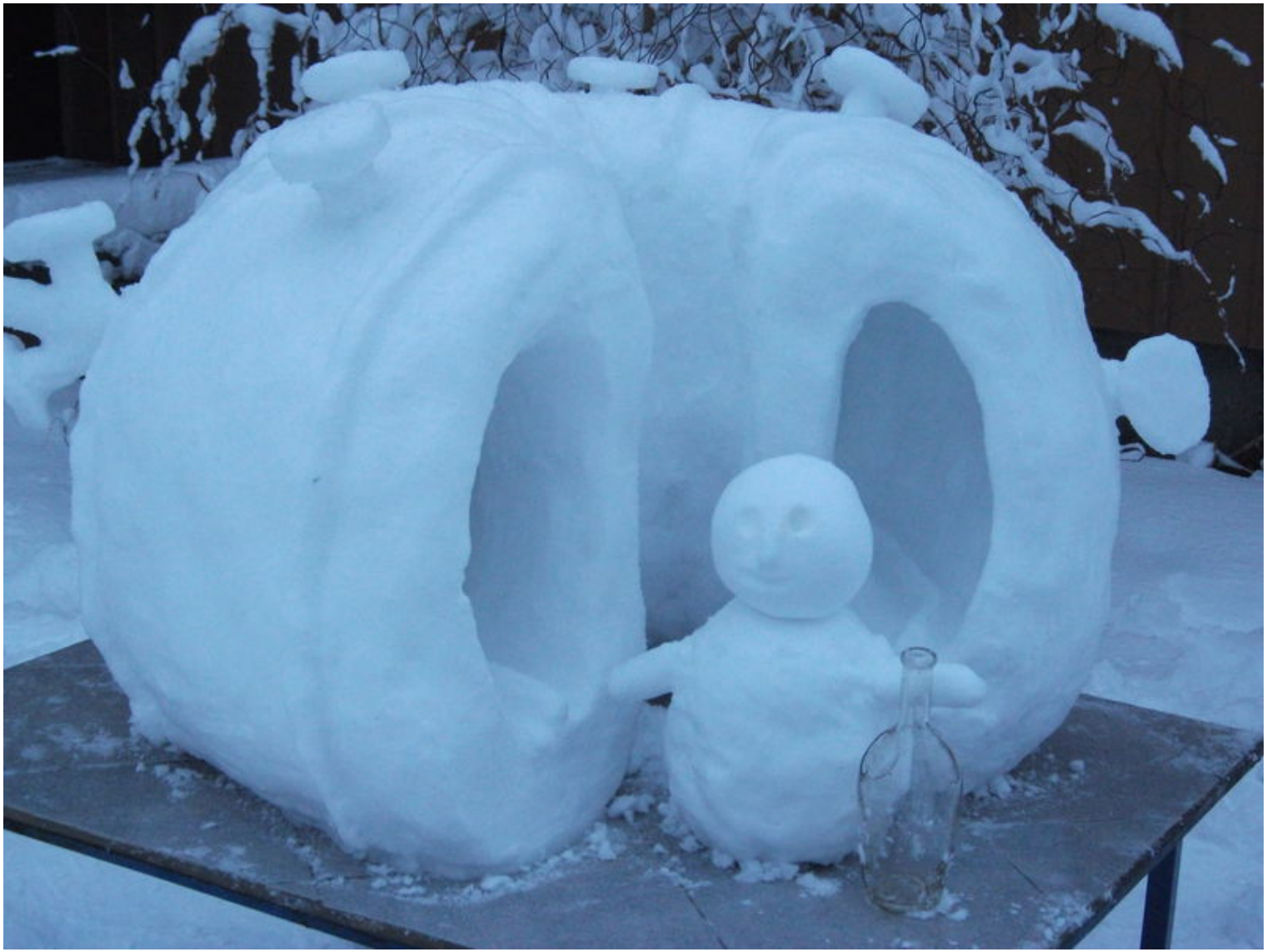
Quotation from Czech Television Hydepark

I am very pleased with the GOLEM ...

Paper model ABC



2010: Tokamak GOLEM



2011: The tokamak COMPASS with NBI

2016: ITER segment

2017: First Spitzer Stellarator

10/15: Trojan horse - #20000

GOLEM » Shot #20000 »

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Tokamak GOLEM - Shot Database - 20000

[Template source]
[WebLog]

Date: 2015-10-22 - **16:09:25**
Session: SessionPreparation
Comment: 20k

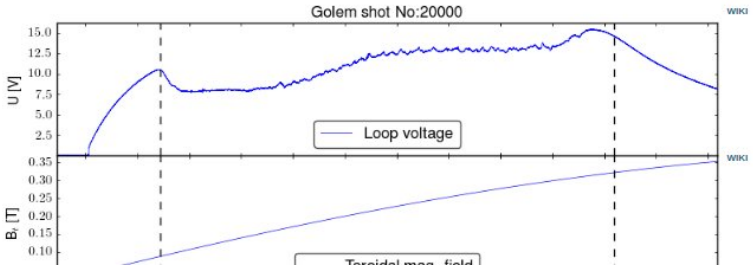
Congratulation, you have reached nuclear fusion.
The following explosion destroyed half of Prague and radioactive fallout contaminated whole Europe.
Have a nice day

Basic parameters: (compare)

- Gas pressure p_{ch}:10.28->15.38 mPa (request: 5 mPa) WIKI
- Working gas: H
- Preionization: Upper el. gun
- Chamber temperature: 20.00 C
- C_{B_t} capacitors charged to: 1000 V, triggered 5.0 ms WIKI
- C_{BD} capacitors charged to: 0 V, triggered 5.0 ms WIKI
- C_{CD} capacitors charged to: 500 V, triggered 6.0 ms WIKI
- C_{ST} capacitors charged to: 0 V, triggered 5.0 ms WIKI
- Probability of breakdown: N/A WIKI
- Time since session beginning: 0:19:25 h

Plasma parameters:

- Plasma life time **8.7** [ms] (from 7.5 to 16.2)
- Mean toroidal magnetic field Bt: 0.22 T WIKI
- Mean plasma current: 1.42 kA WIKI
- Mean Uloop: 12.41 V WIKI
- Break down voltage: 10.5 V WIKI
- Ohmic heating power: 17.59 kW
- Q edge: 6.9 WIKI
- Electron temperature: 13.5 eV WIKI
- Line electron density: N/A [10^17.m^-2] WIKI



Diagnostics
- ✓ PlasmaPosition_TO
- ✗ Flukes
- ✗ Spectrometer
- ✓ FastCamera
- ✓ HXR

Analysis
- ✓ HistoricalAnalysis
- ✓ ShotHomepage
- ✓ AdvancedAnalysis
- ✓ Spectrograms_TO
- ✗ MultiCWT_TO
- ✓ MWPreionization
- ✗ Impurities_TO

DAS
- ✓ TektronixDPO
- ✓ Papouch_Ji
- ✓ NIstandard
- ✓ Papouch_Za
- ✓ Papouch_St

Vacuum log
- Charging log

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20000 Go

Tokamak GOLEM

Základní (řádová) statistika k 30.11.2012

Počet dní od instalace: 1815.

Počet operačních dní: $\approx$ 438.

Počet hodin: $\approx$ 1954

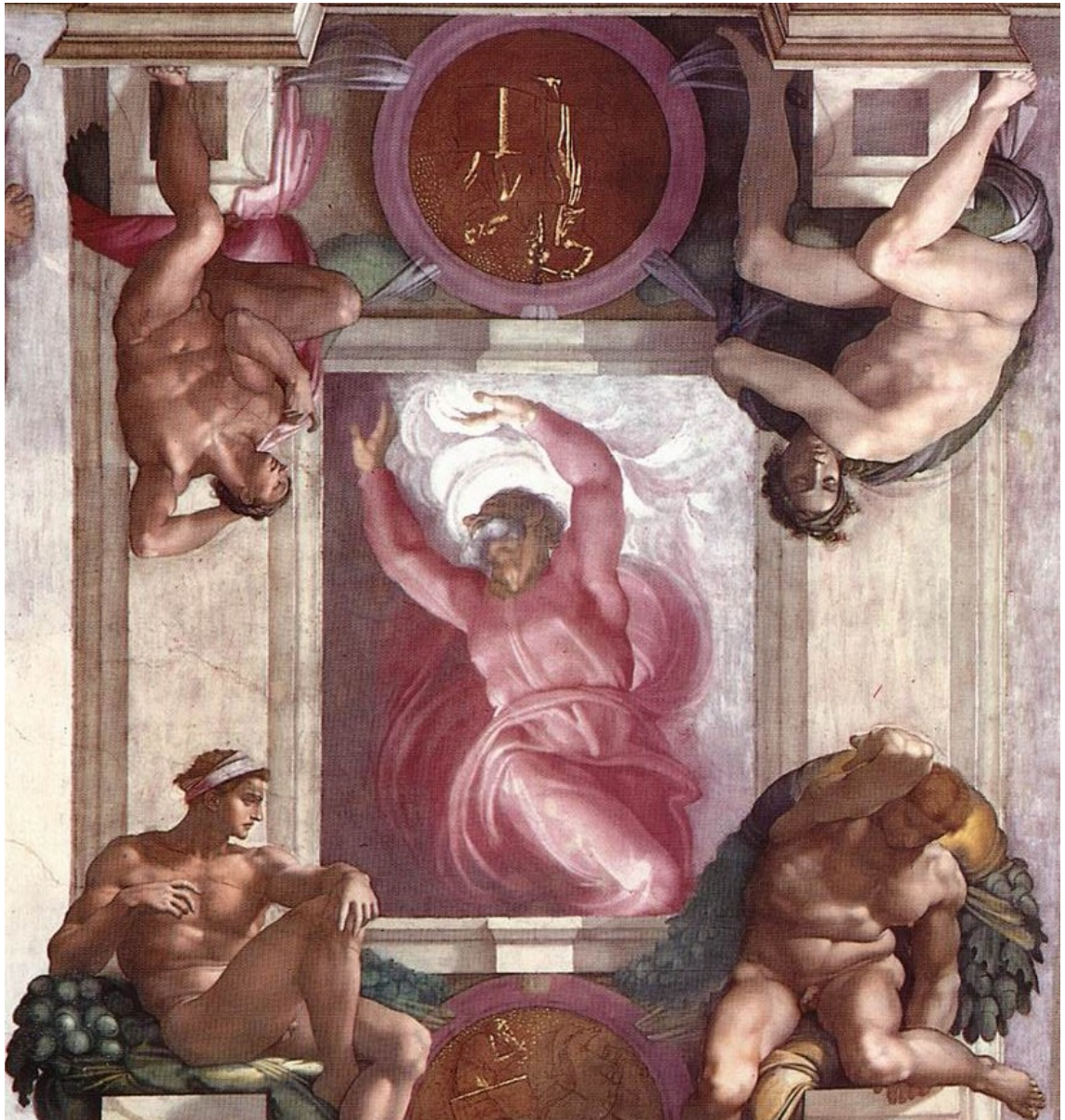
Počet shotů: 10417.

Počet shotů $->$ plazma: $\approx$ 7600.

Průměrná délka výboje: $\approx$ 7 ms.

Celková delka trvání plazmatu: $<$ 60 s.

0916: Noc vědců - řeholnice mezi návštěvníky



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