pro kurs Jaderné chemie

Úvod do fúze

Vojtěch Svoboda
on behalf of the GOLEM tokamak team

December 16, 2019

http://golem.fjfi.cvut.cz/JACH2

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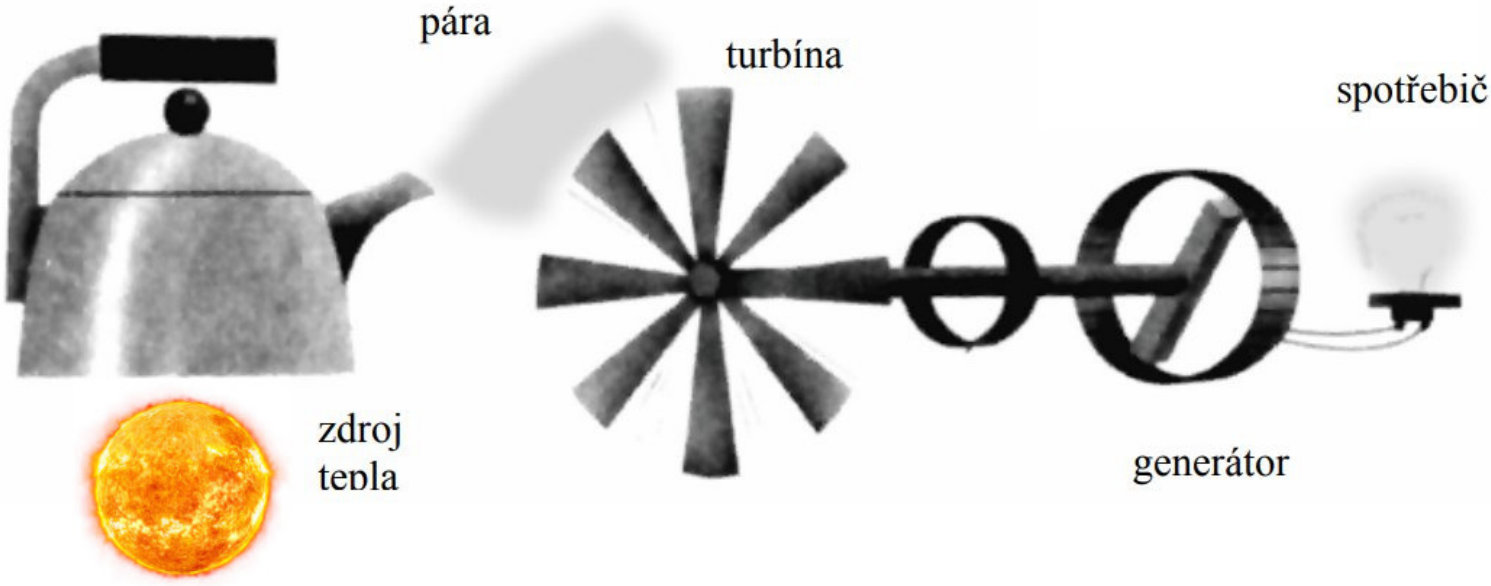
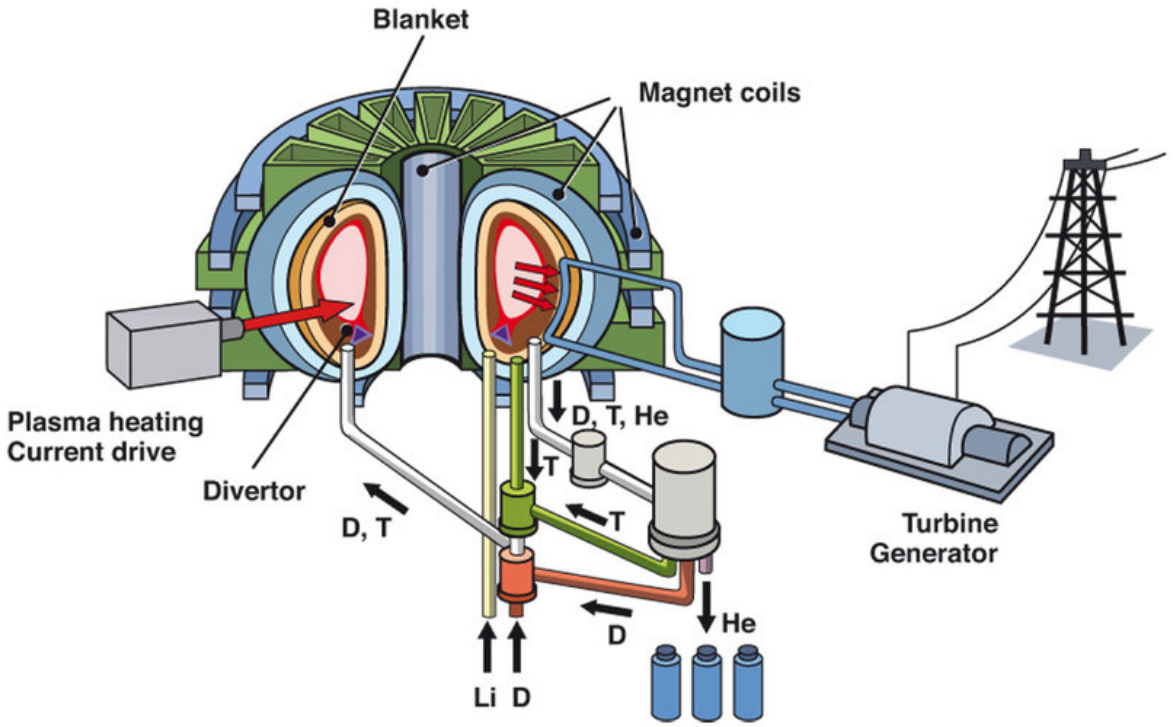
Topit malým Sluncem/hvězdou ??



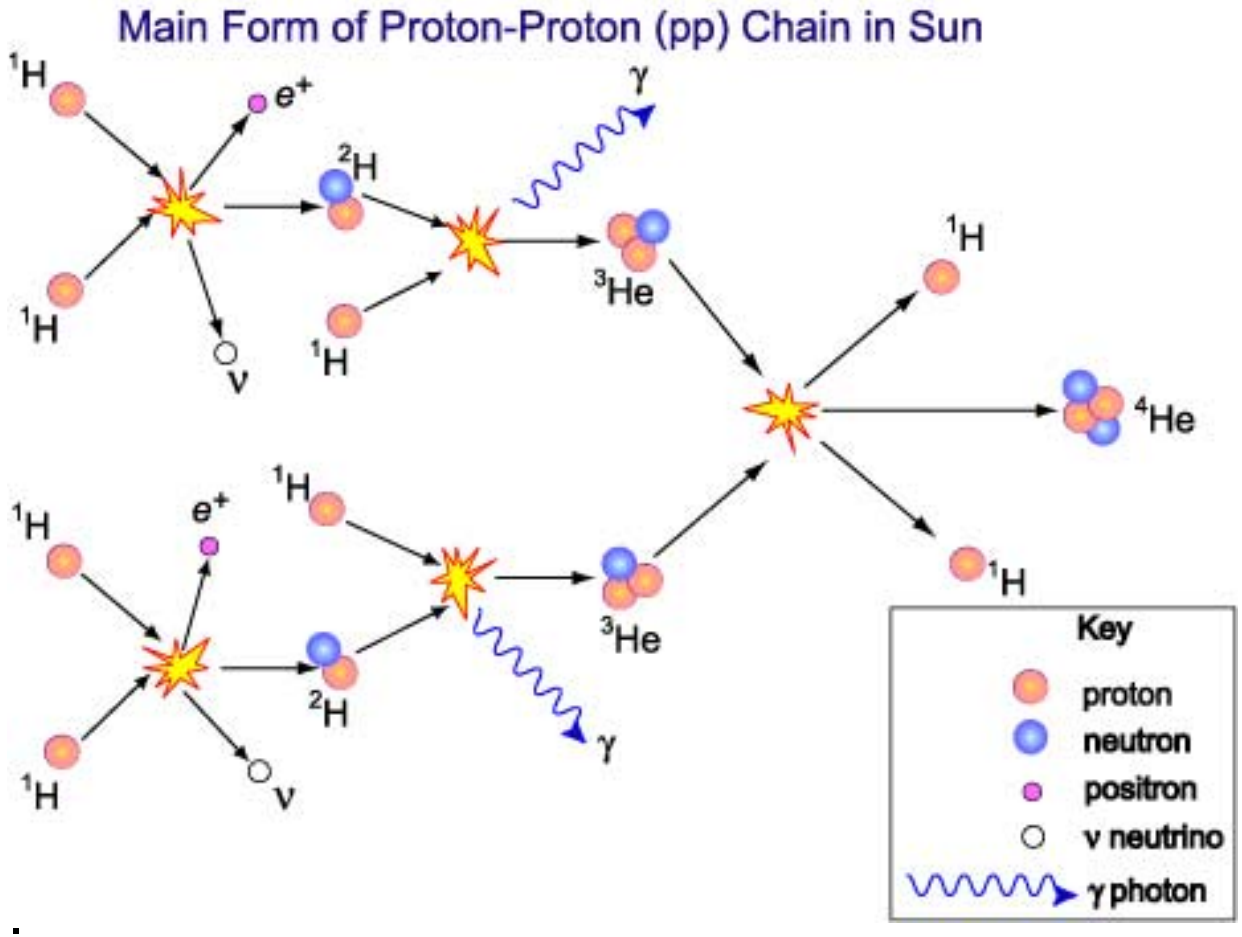
Vize: Jaderná elektrárna - slučovací/fúzní



Praha ($\sim$ 1 GW): ročně $\sim$ dodávka D-T směsi

Vypiplat technologii

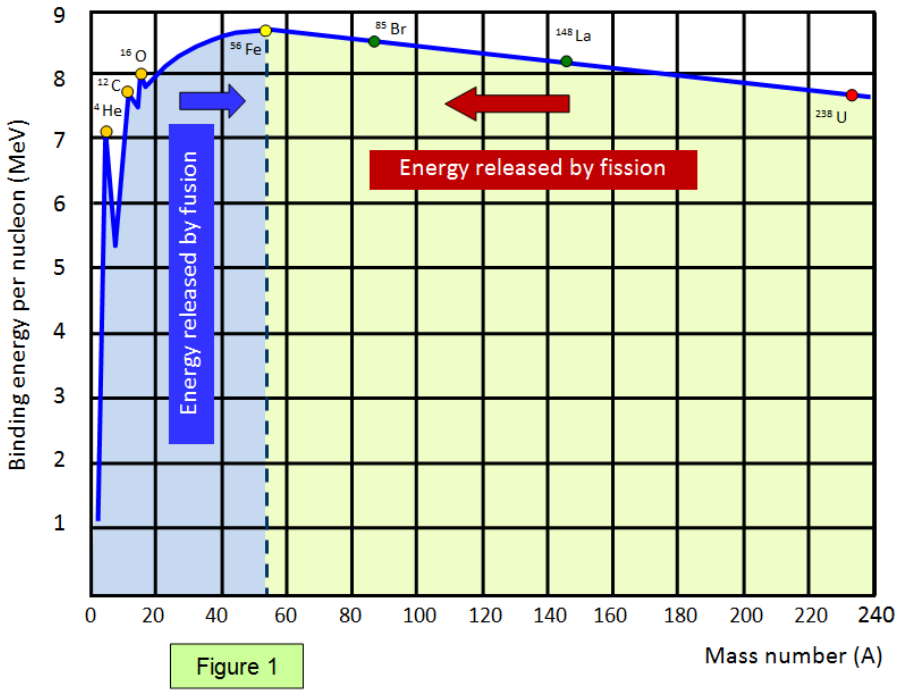
Inspirace: Slunce - protonový řetězec

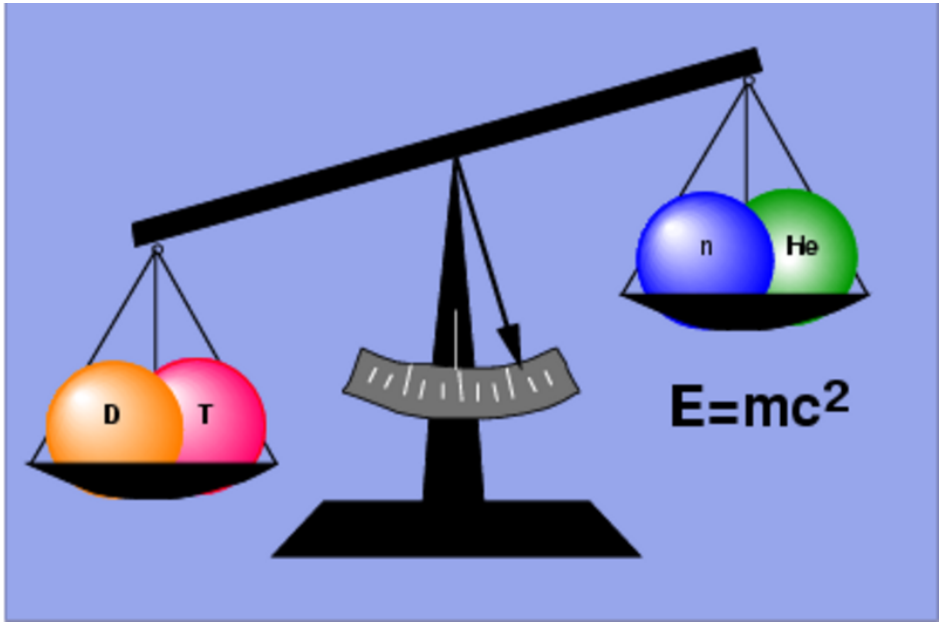


credit:CSIRO

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

Uvolnění vazebné energie atomových jader

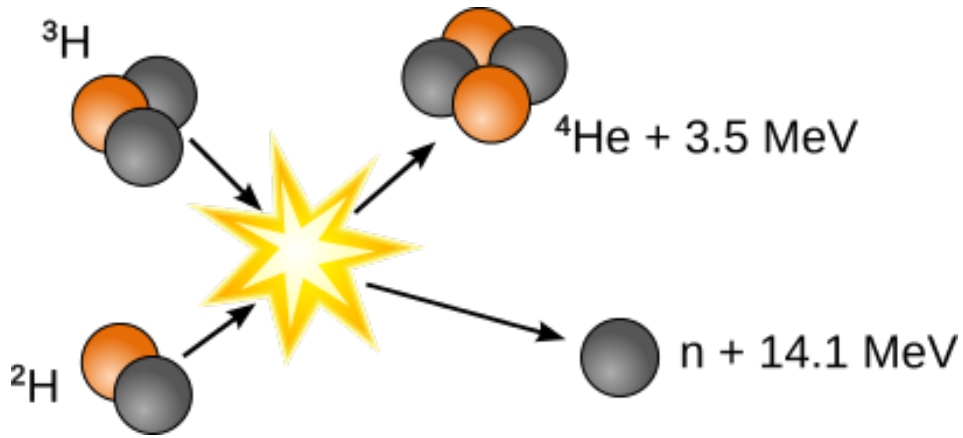




fúze lehkých jader X štěpení těžkých jader

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

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



credit:[?]

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

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

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

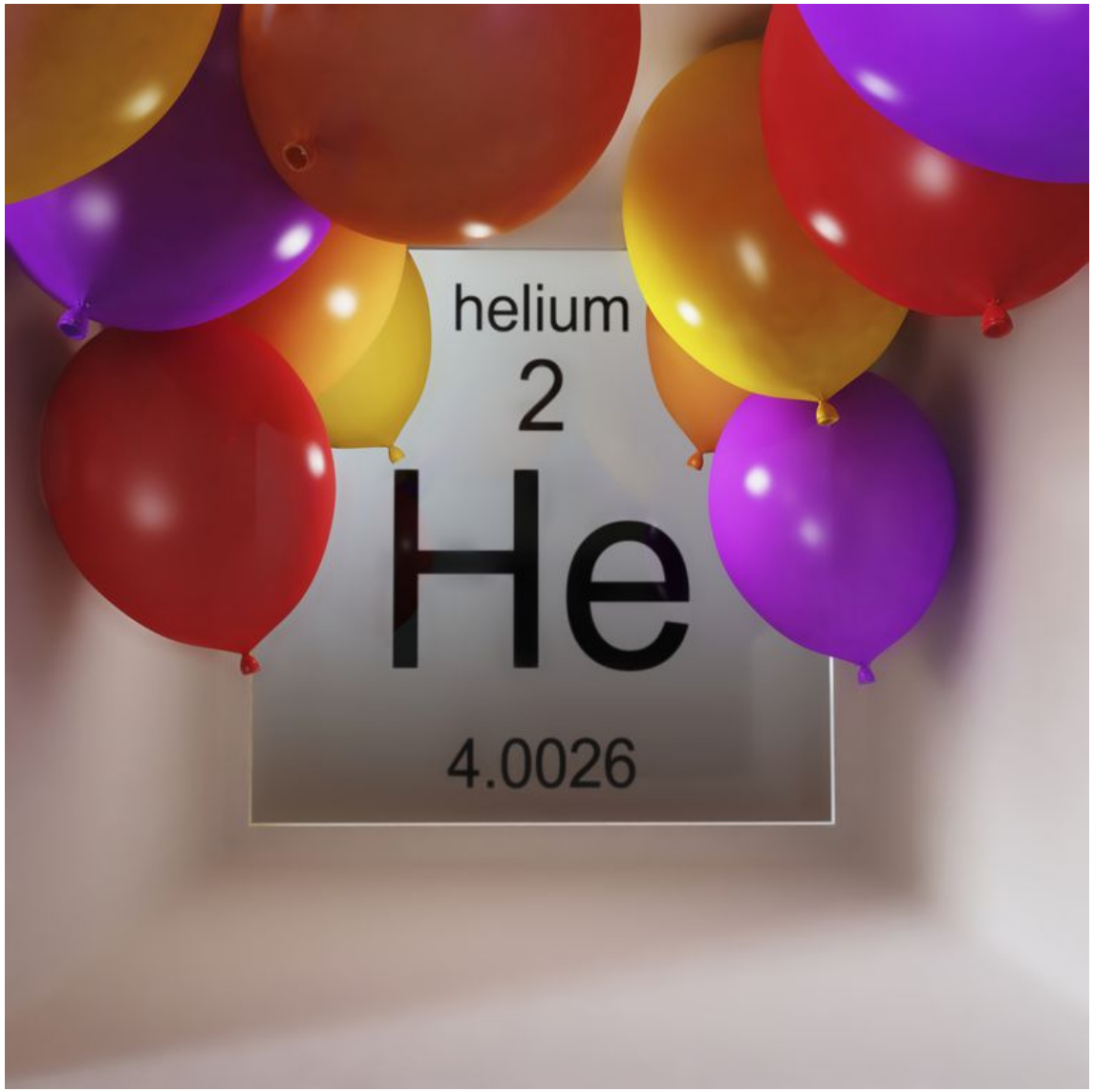
pak hmotnostní schodek $\Delta m = 0.01888 m_u$.

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

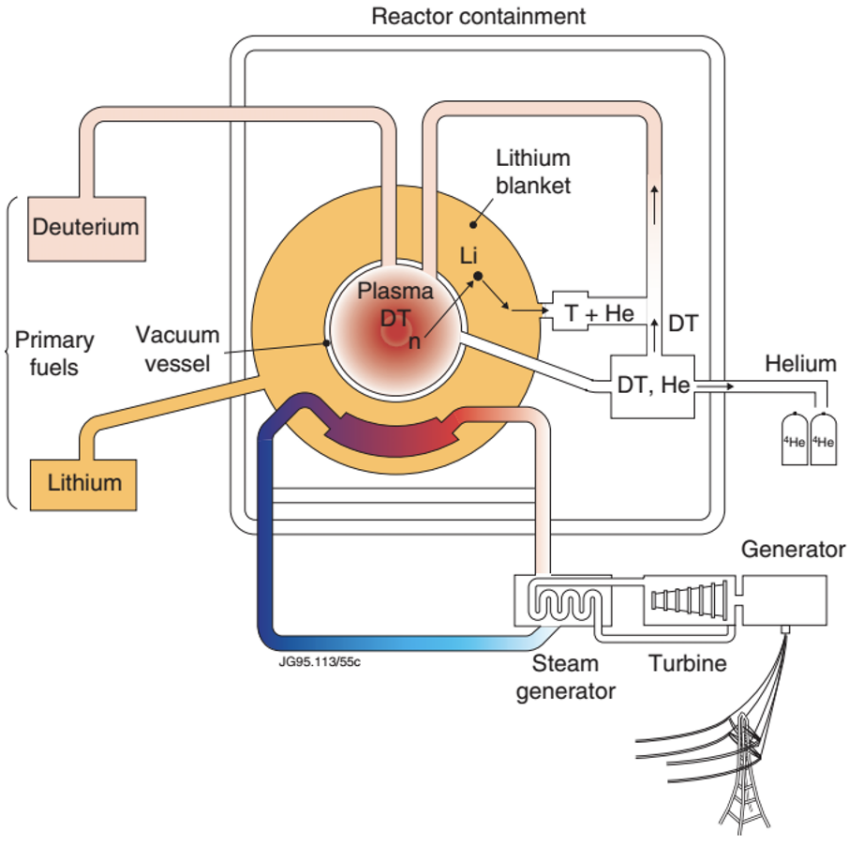
$$1\mathrm{eV} \sim 11600^\circ\mathrm{C} \approx \quad \mathbf{^2_1H_{100\ M\circ C} + {}^3_1H_{100\ M\circ C} \Rightarrow {}^4_2He_{35\ G\circ C} + {}^1_0n_{141\ G\circ C}}$$

Palivo: IAEA "Natural water"

Odpad



Bezpečnost



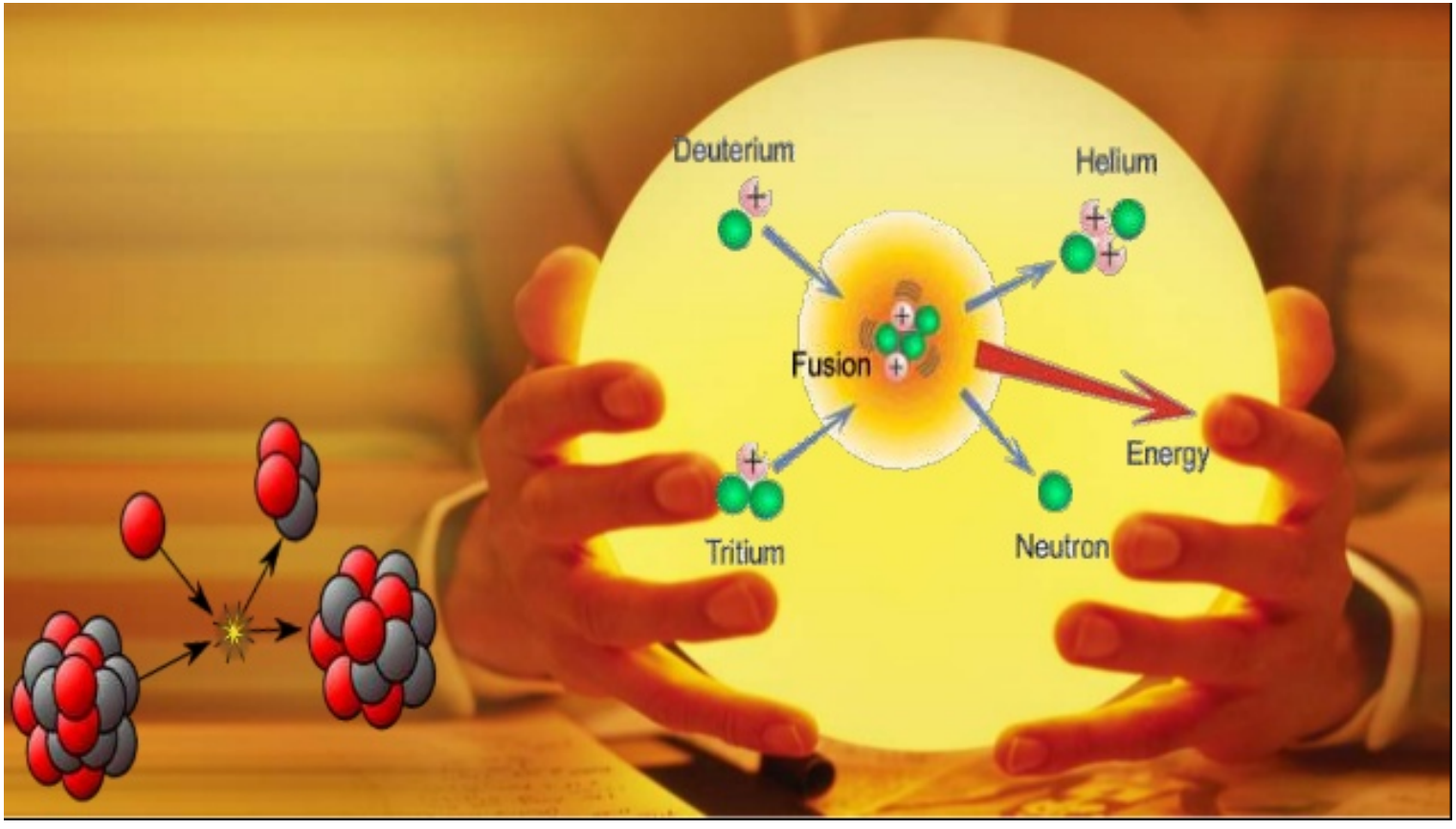
* Nejde o řetězovou reakci.
* Tritium: slabý β zářič $T_{1/2} = 12.5\ \mathrm{roku}$. Minimální nebezpečí.
* Minimalizovaný potenciál aktuálně přítomného D-T paliva.

1952 "Operation Ivy - Mike" První test vodíkové bomby

credit:YouTube:Ivy Mike Countdown and detonation

Toto není vhodná technologie

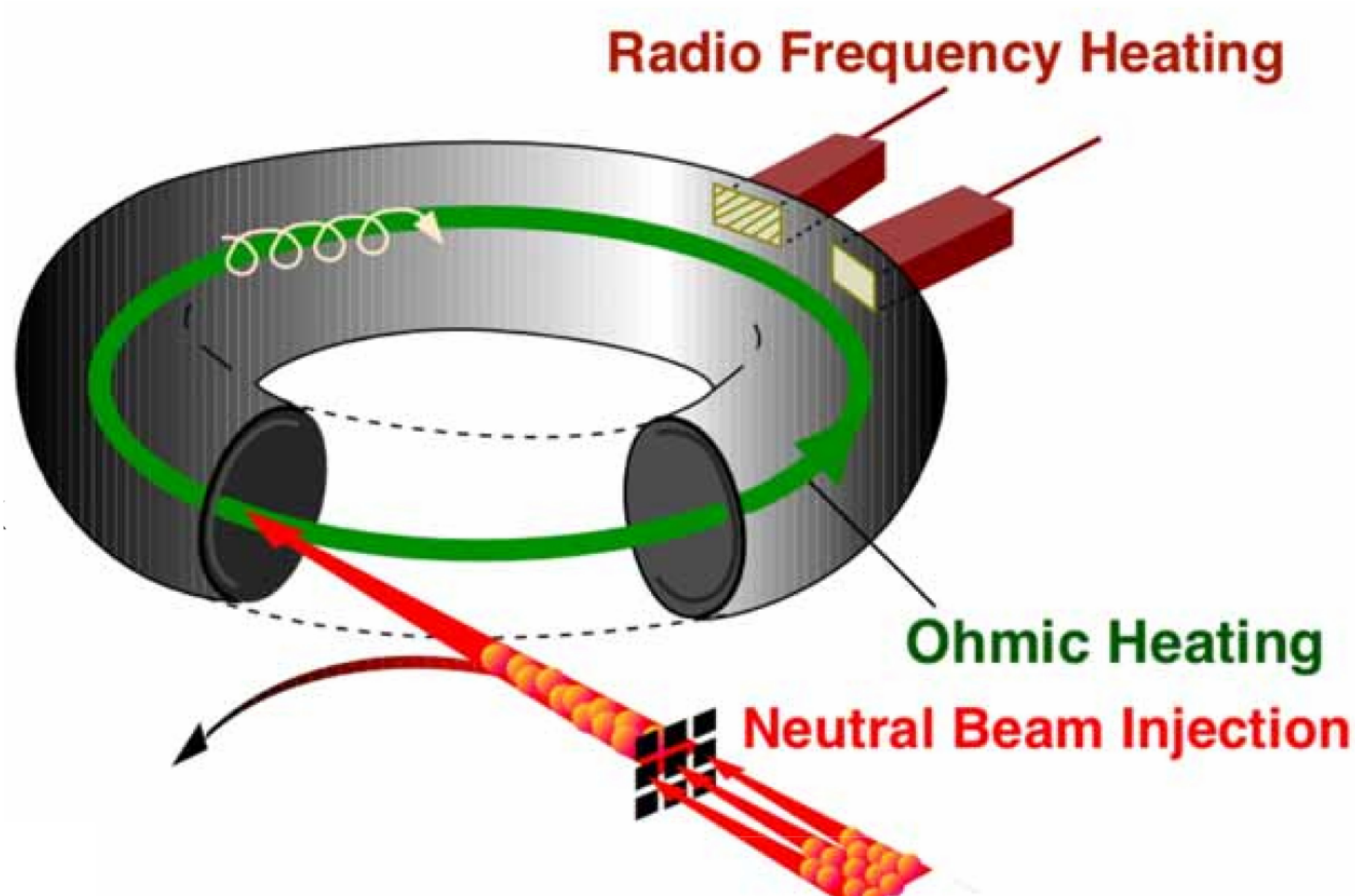
Hledá se vhodná fúzní technologie



Podmínky:

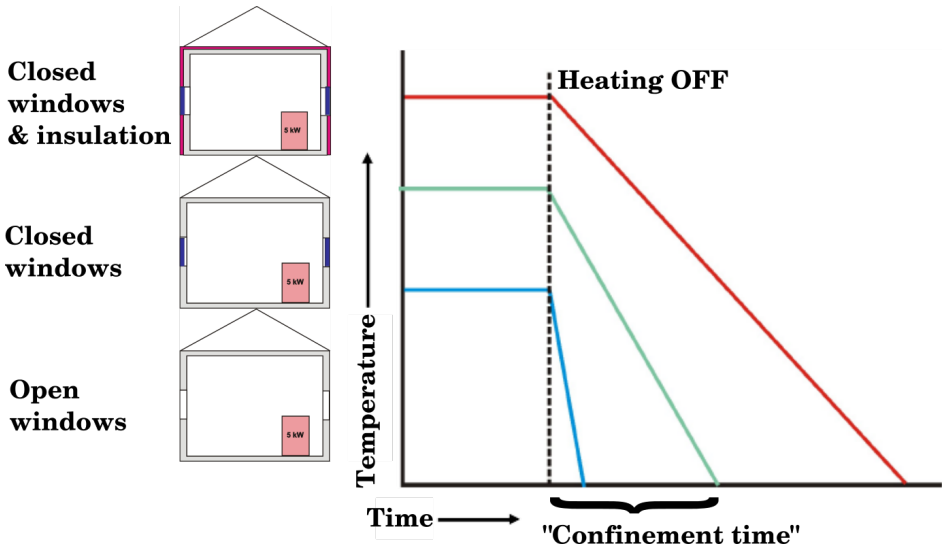
Zahřát na $\sim$ 100 000 000 °C & **udržet** po dobu $\sim$ 30 let

Ohřev plazmatu

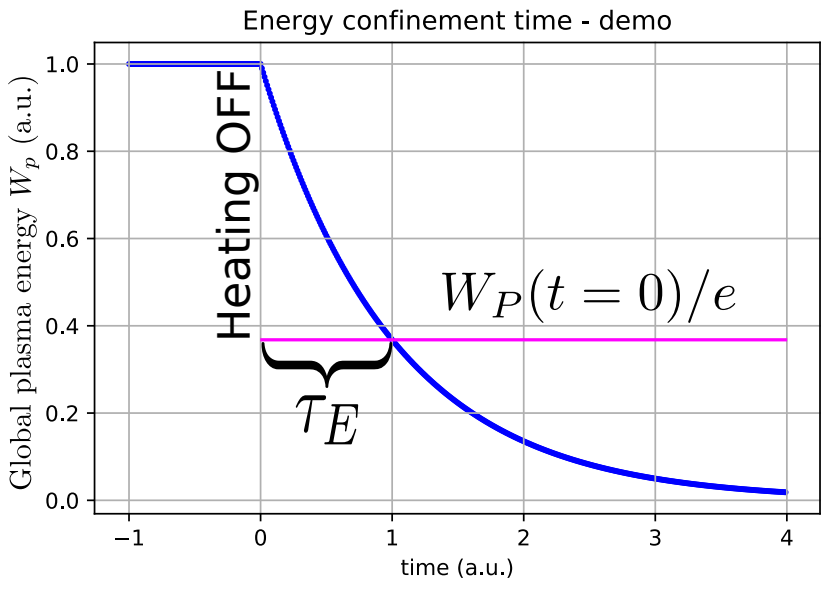


Towards ... Energy confinement time

House



Tokamak



Lawson criterion

credit:Lawson criterion @ Wiki

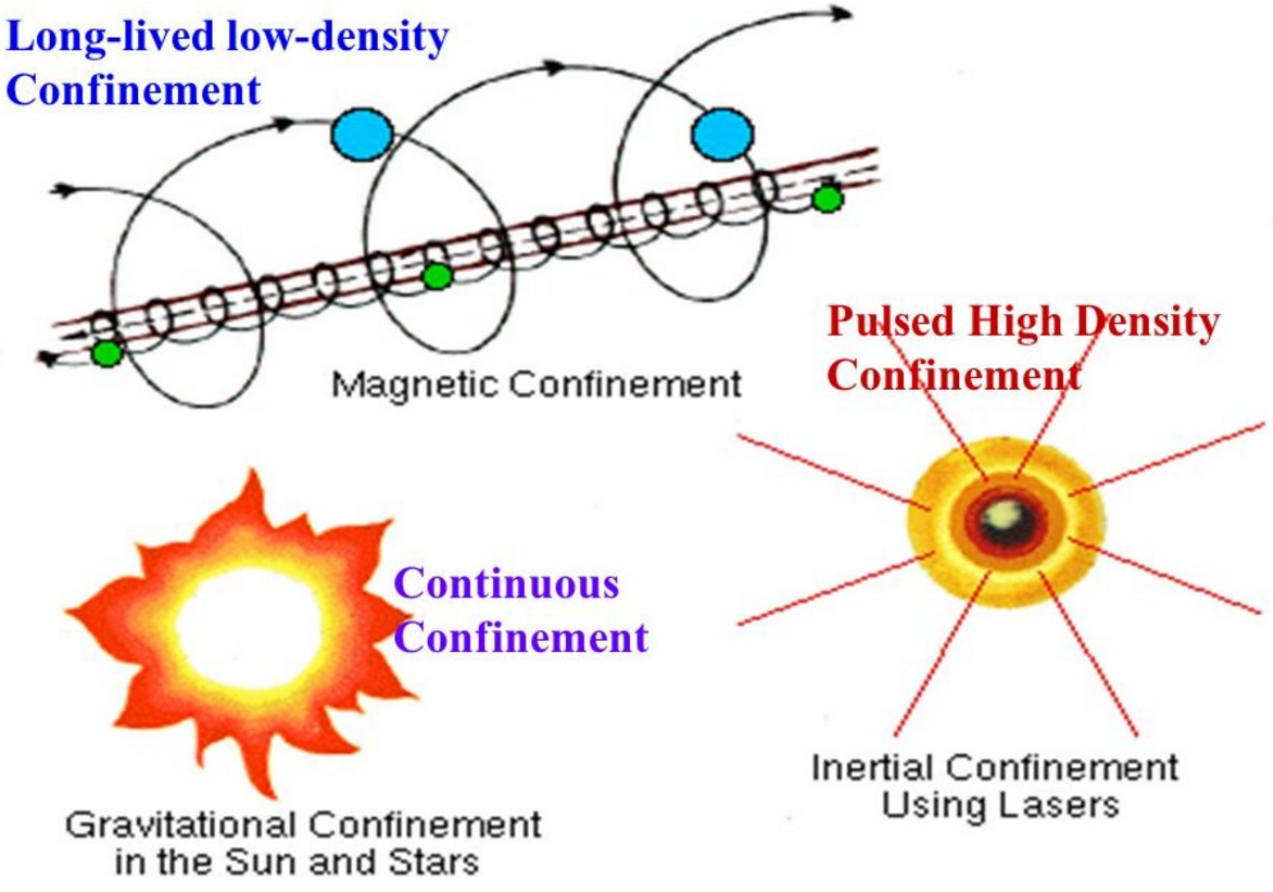
- The confinement time: $\tau_E = \frac{W}{P_{\mathrm{loss}}}$
- Energy density: $W = 3nk_{\mathrm{B}}T$
- Reactions per volume per time of fusion reactions is: $f = n_{\mathrm{d}} n_{\mathrm{t}} \langle \sigma v \rangle = \frac{1}{4} n^2 \langle \sigma v \rangle$
- Fusion heating fE_{ch}, where $E_{\mathrm{ch}} = 3.5\,\mathrm{MeV}$ should exceeds the losses: $fE_{\mathrm{ch}} \geq P_{\mathrm{loss}}$

$$n\tau_{\mathrm{E}} \geq L \equiv \frac{12}{E_{\mathrm{ch}}} \frac{k_{\mathrm{B}}T}{\langle \sigma v \rangle} \geq 1.5 \cdot 10^{20} \frac{\mathrm{s}}{\mathrm{m}^3}$$

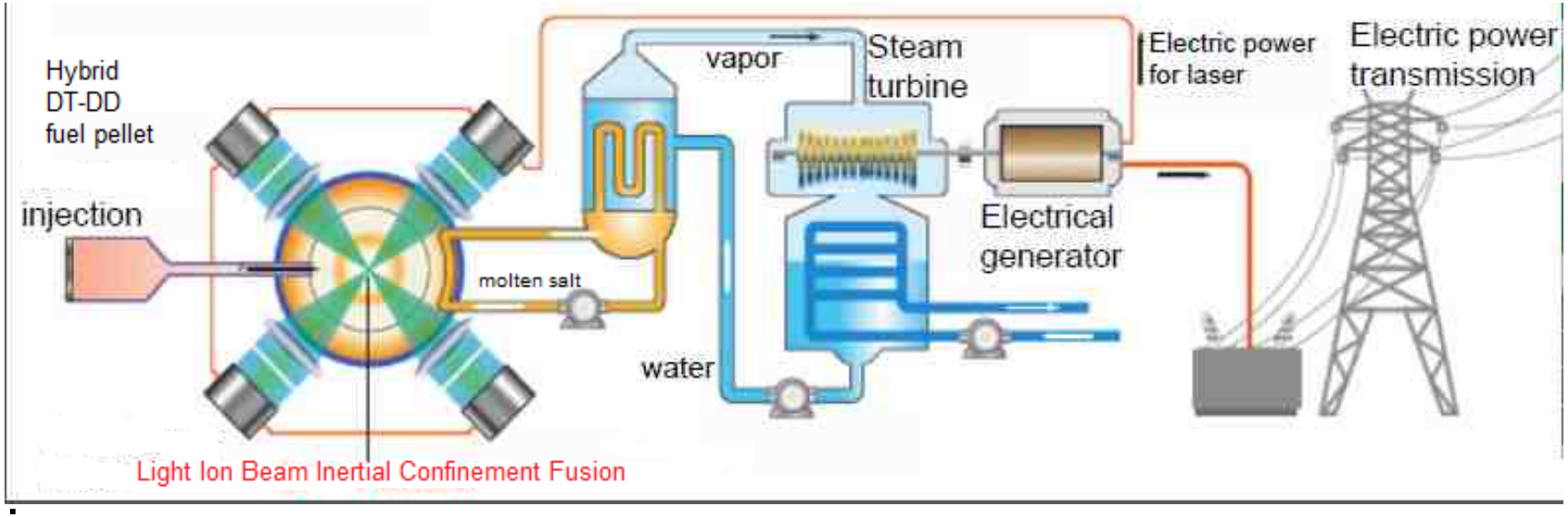
(DT reaction@minimum $\approx$ 26 keV)

Tři možné cesty jak udržet plazma pro fúzi

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



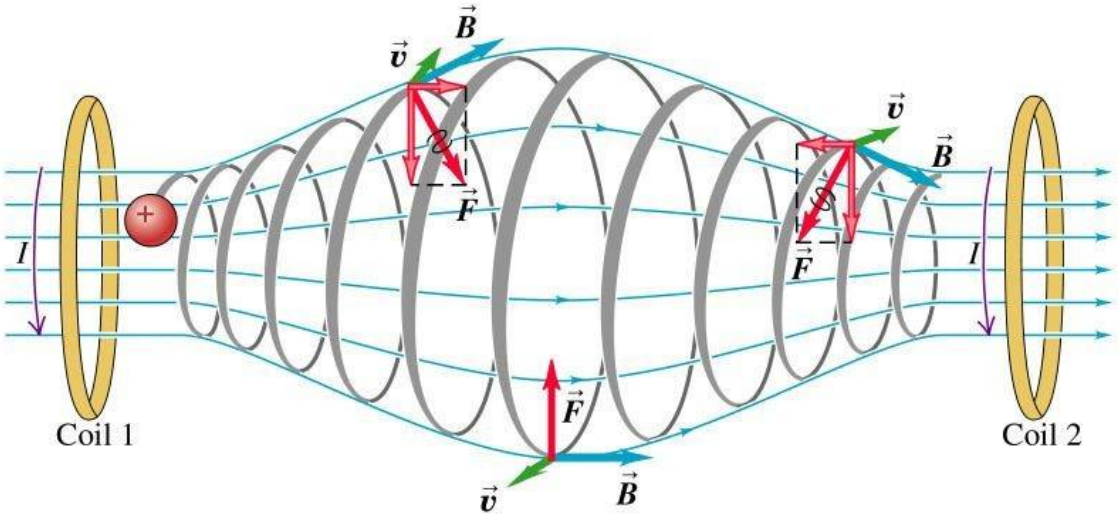
Inerciální fúze



credit:mext.jp

Velká výzva

Magnetické udržení: magnetická nádoba



Musíme ji ale svinout do kruhu (zbavit se podstav)

záchranný kruh/duše pneumatiky/kobliha - donut

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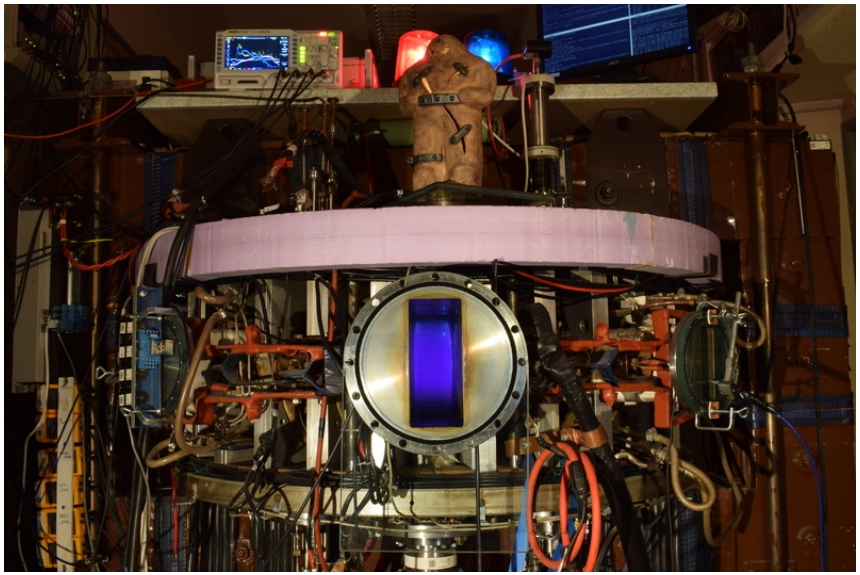
The GOLEM tokamak basic characteristics

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]

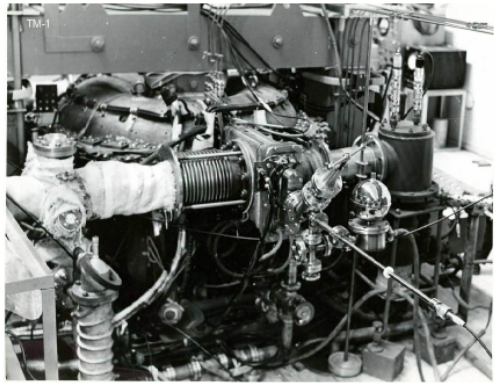
(in chronological order of start of operations)


Alcator C-Mod

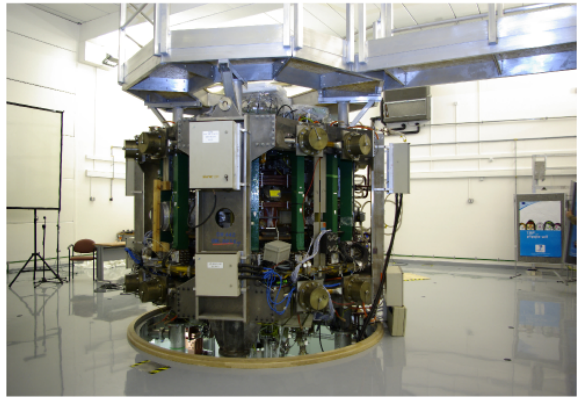
- 1960s: TM1-MH (since 1977 Castor; since 2007 Golem[12]) in Prague, Czech Republic. In operation in Kurchatov Institute since early 1960s but renamed to Castor in 1977 and moved to IPP CAS,[13] Prague; in 2007 moved to FNSPE, Czech Technical University in Prague and renamed to Golem.[14]
- 1975: T-10,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

The GOLEM tokamak 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

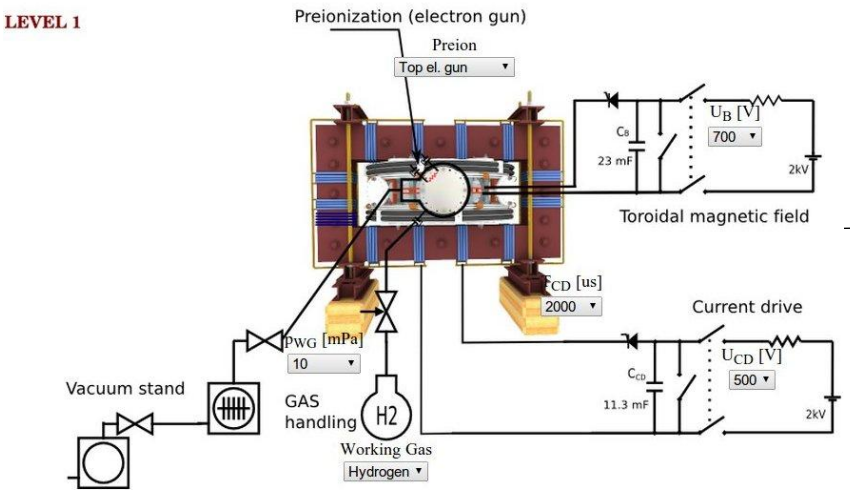
... somewhere, in the ancient cellars of Prague,

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

Tokamak technology setup



internet

USER authorization

WWW server

OpenSSH serve

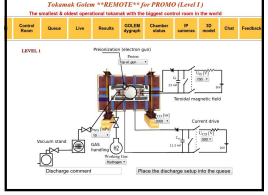
Control PC

OpenSSH server

Virtual control room (remote participation)

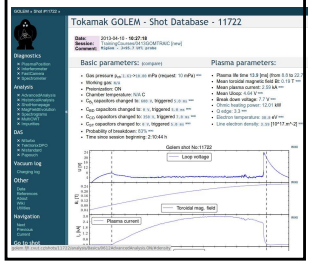
WWW control interface

HTML & PHP scripts



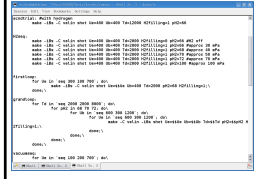
Data presentation

HTML (www pages)



SSH control interface

WINDOWS via putty

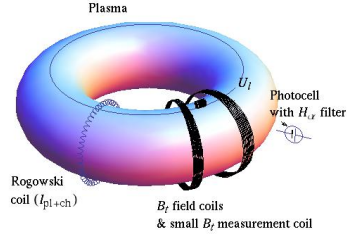


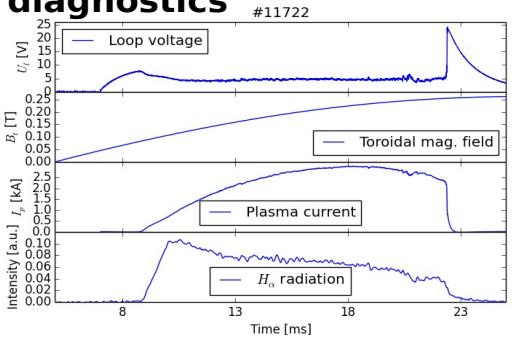
LINUX via ssh
or ssh+X tunnel
(advanced mode)

Data handling

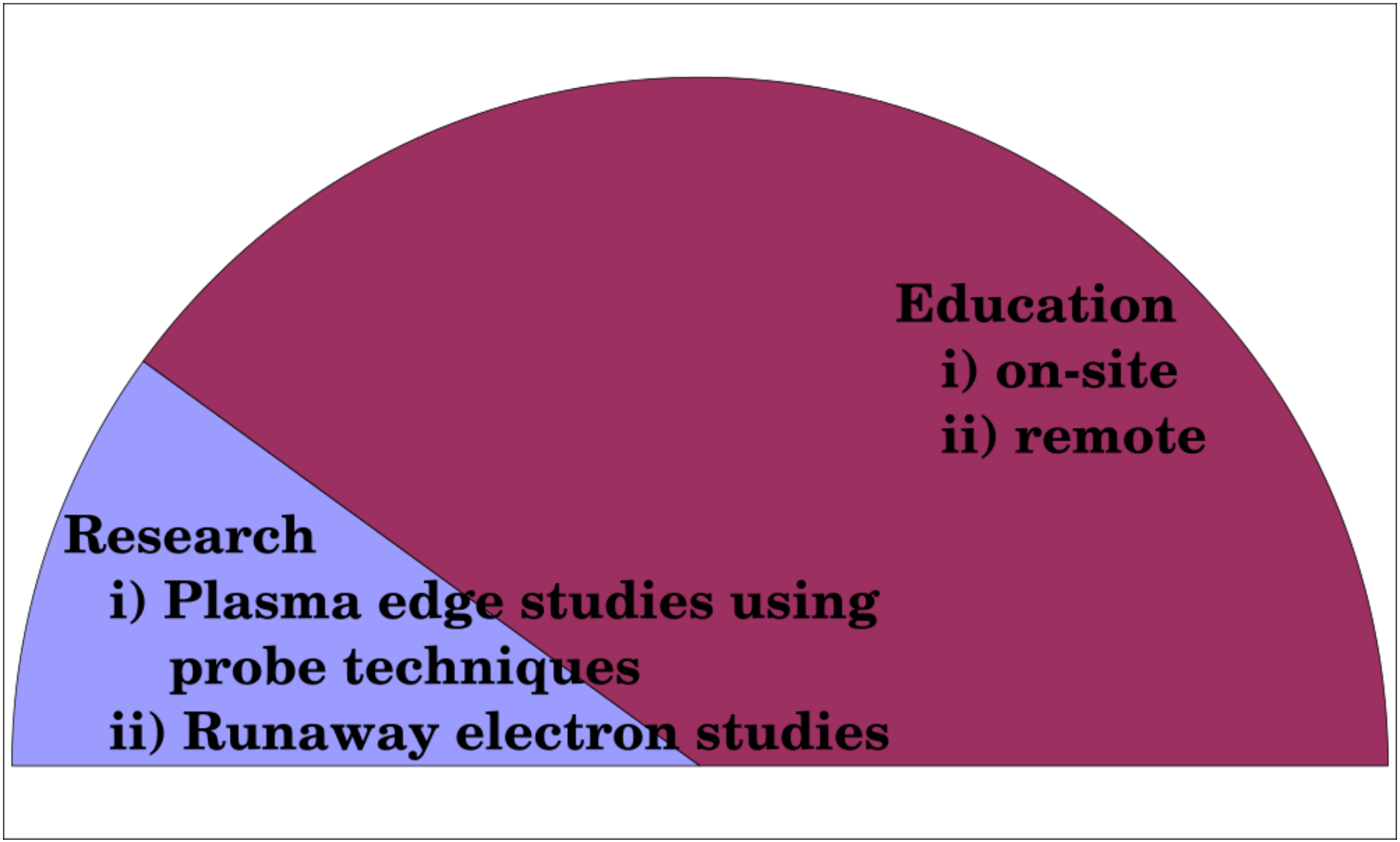
*wget
*gnuplot
*idl
*mathematica
*matlab
*etc...

Basic plasma diagnostics

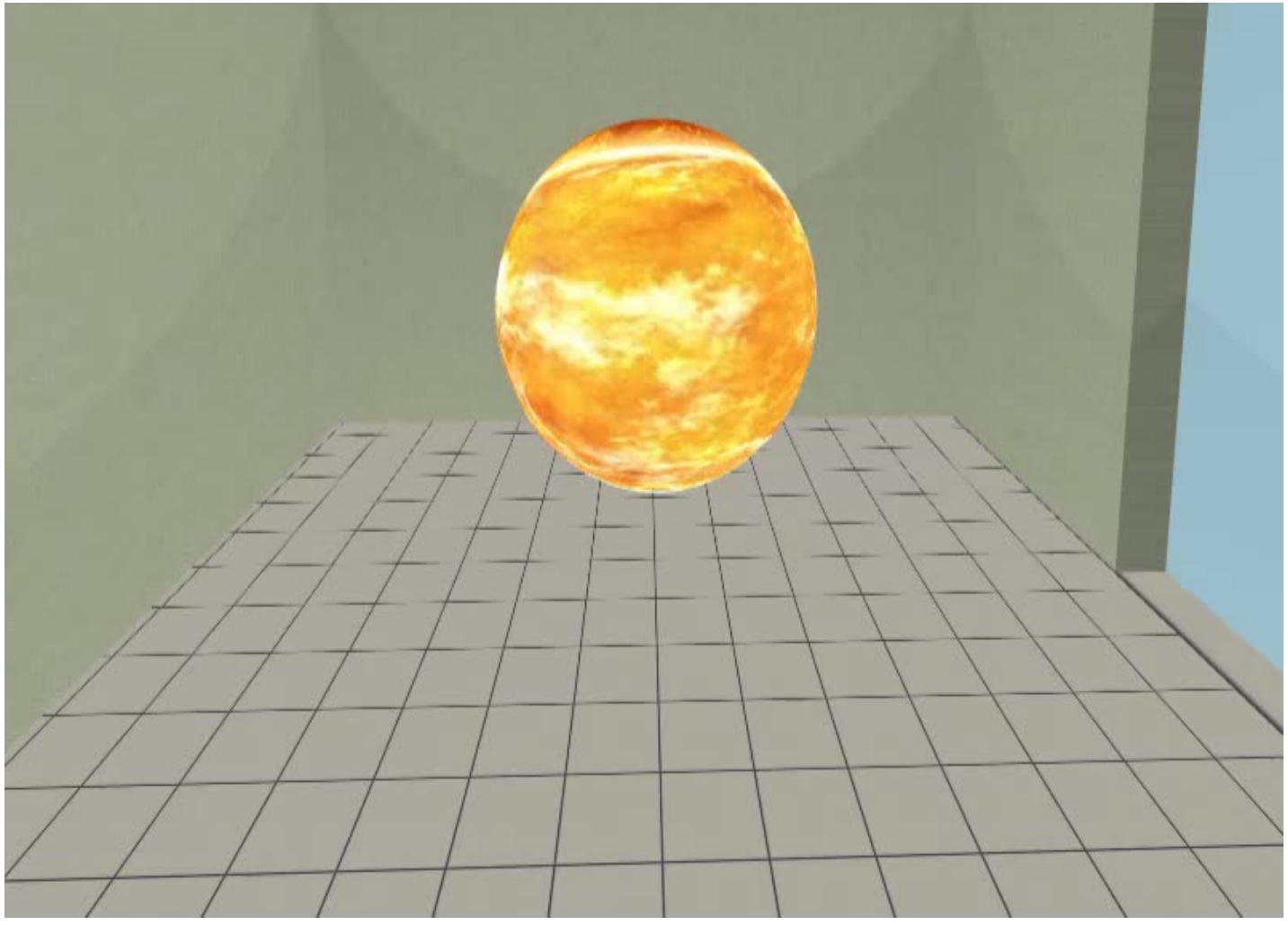




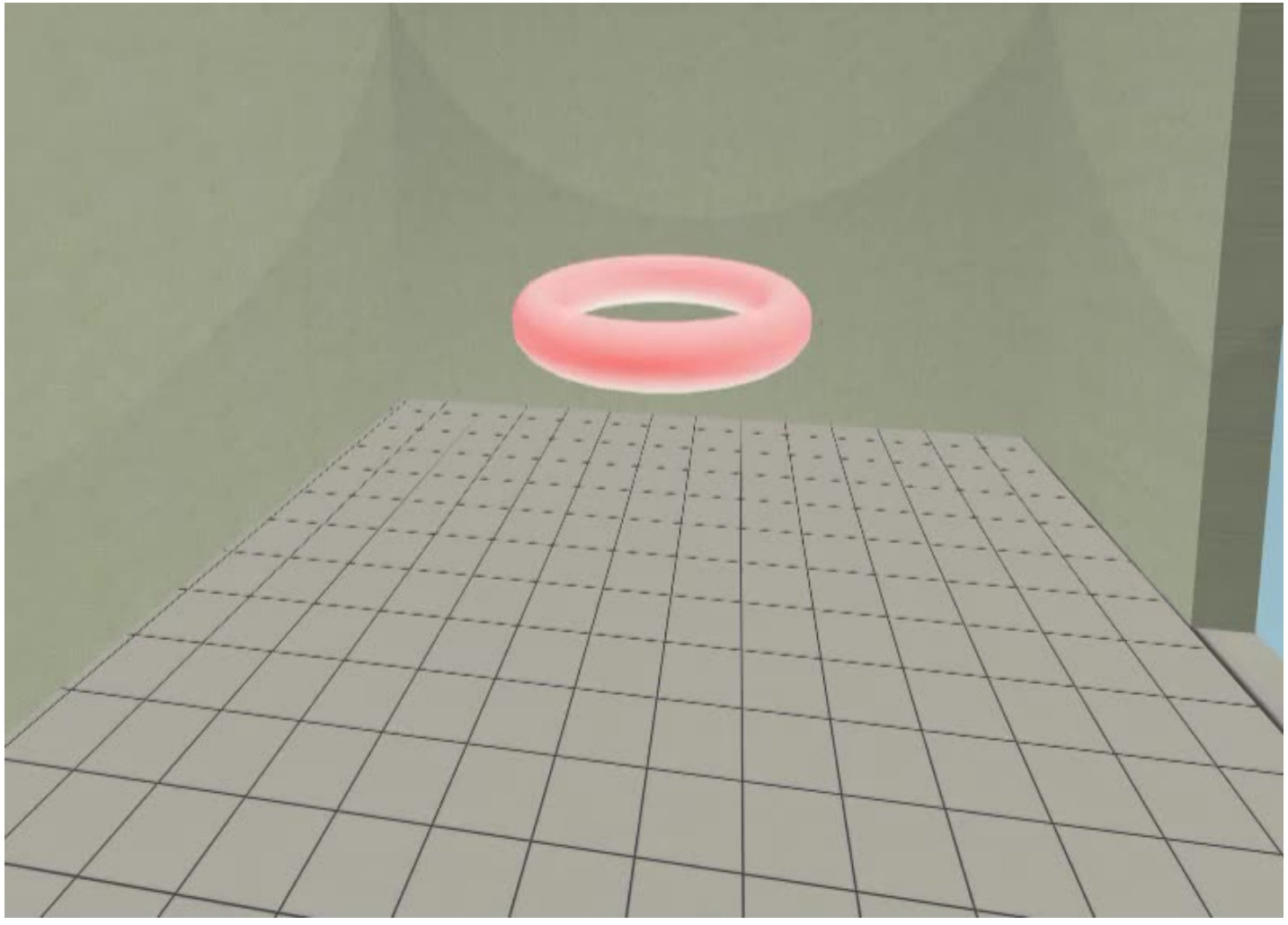
The GOLEM tokamak mission



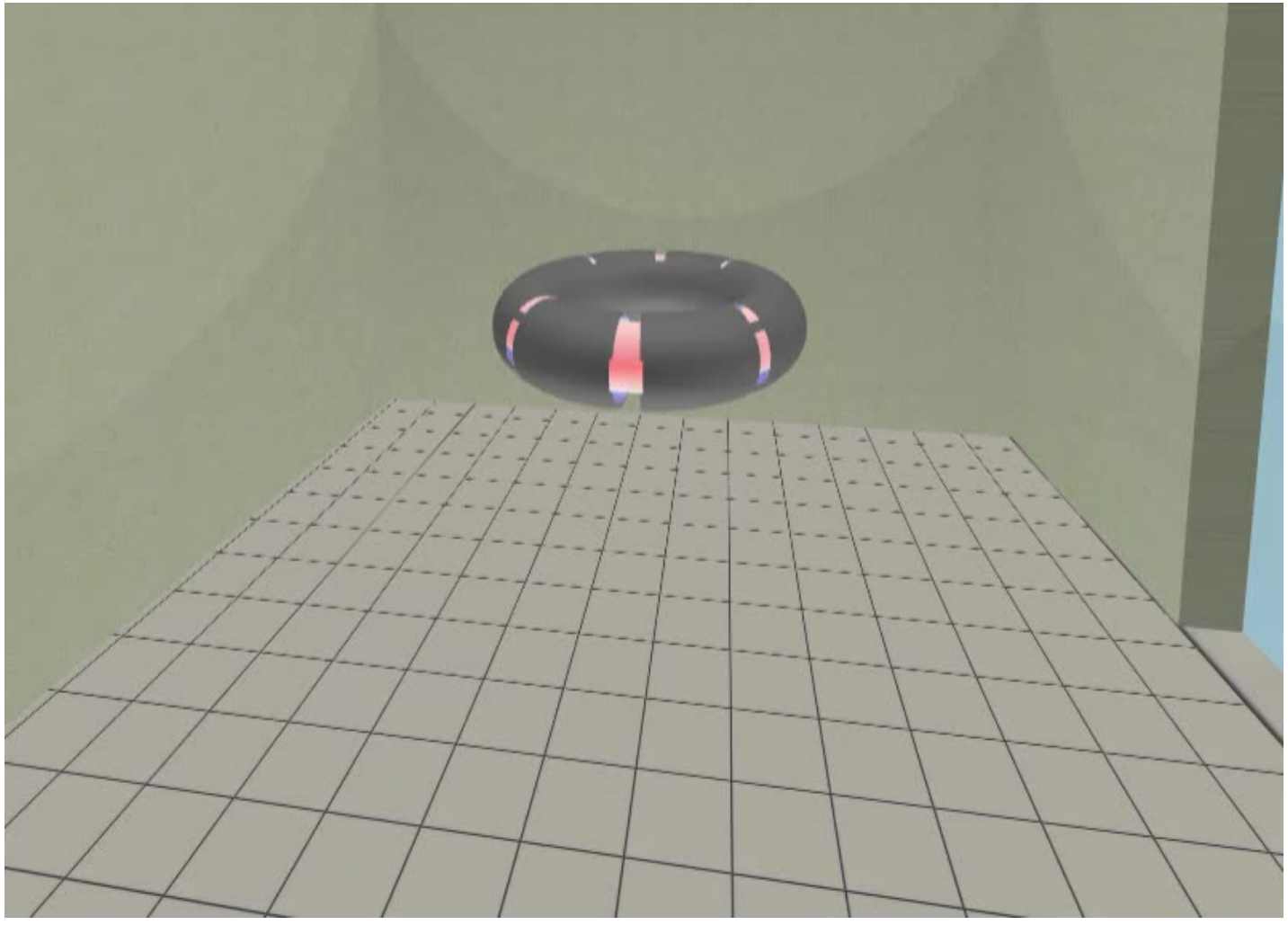
Our goal: the technology to create a μSun on the Earth



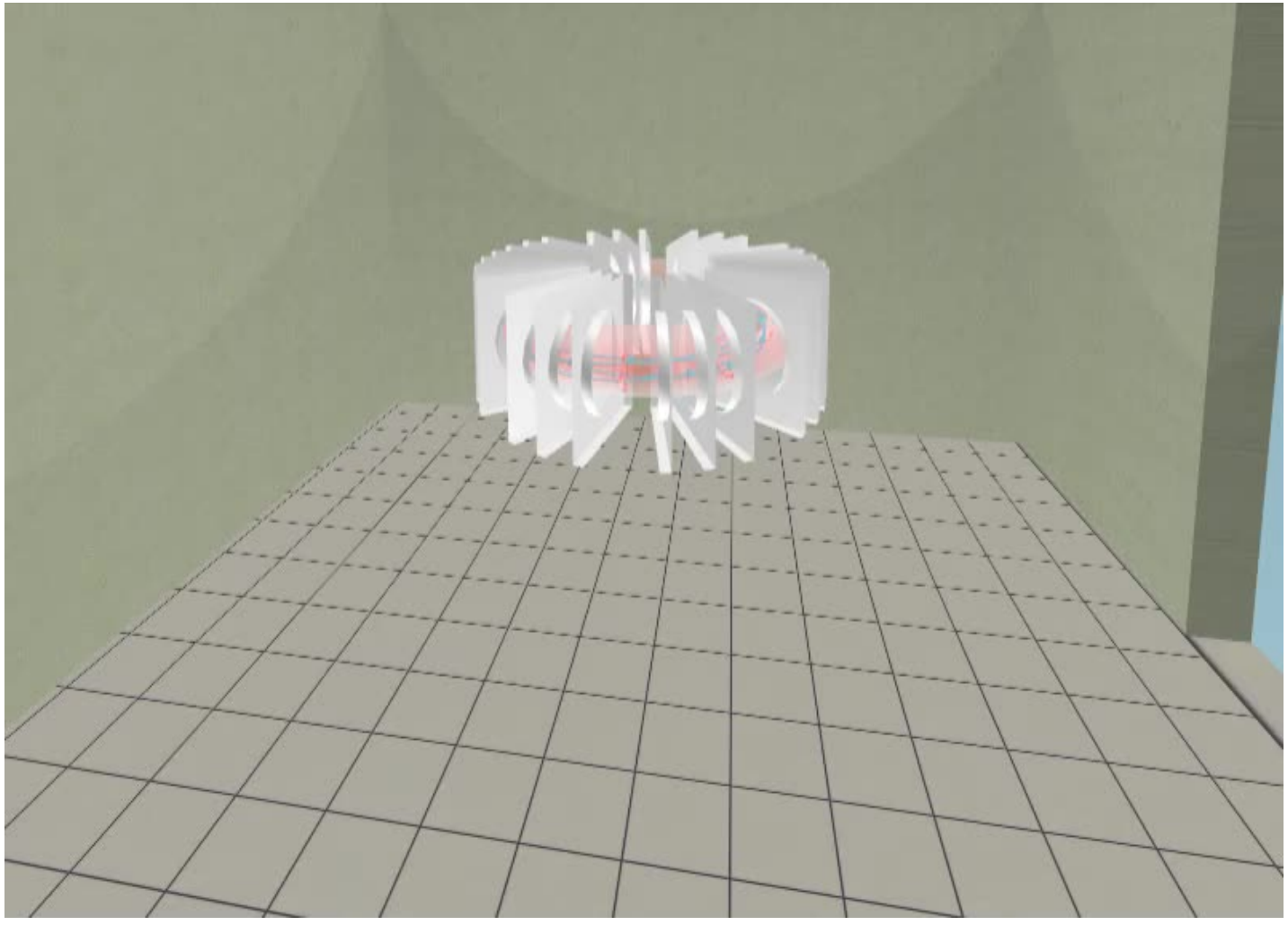
Magnetic confinement requires toroidal geometry



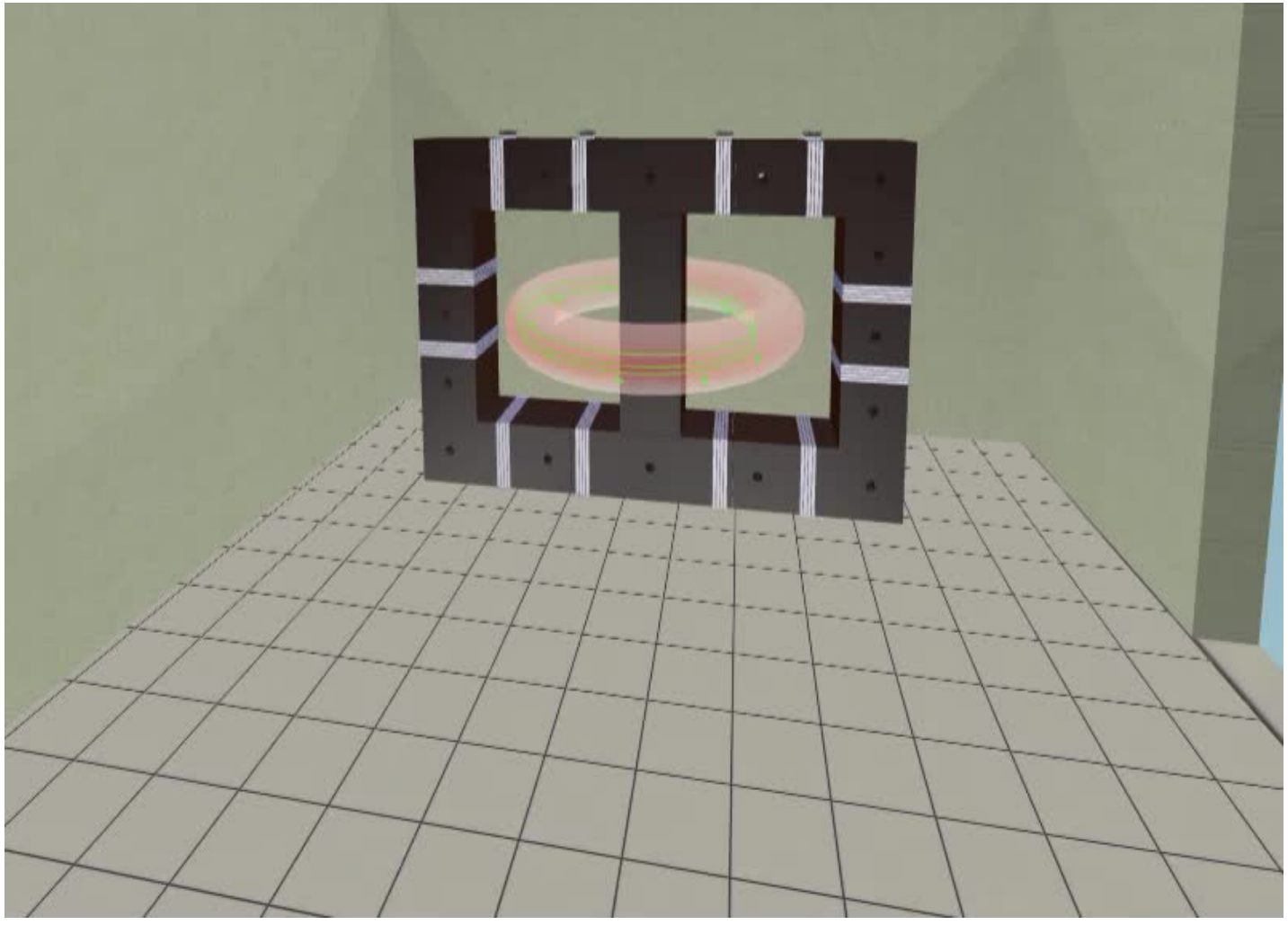
A chamber contains the thermonuclear reaction



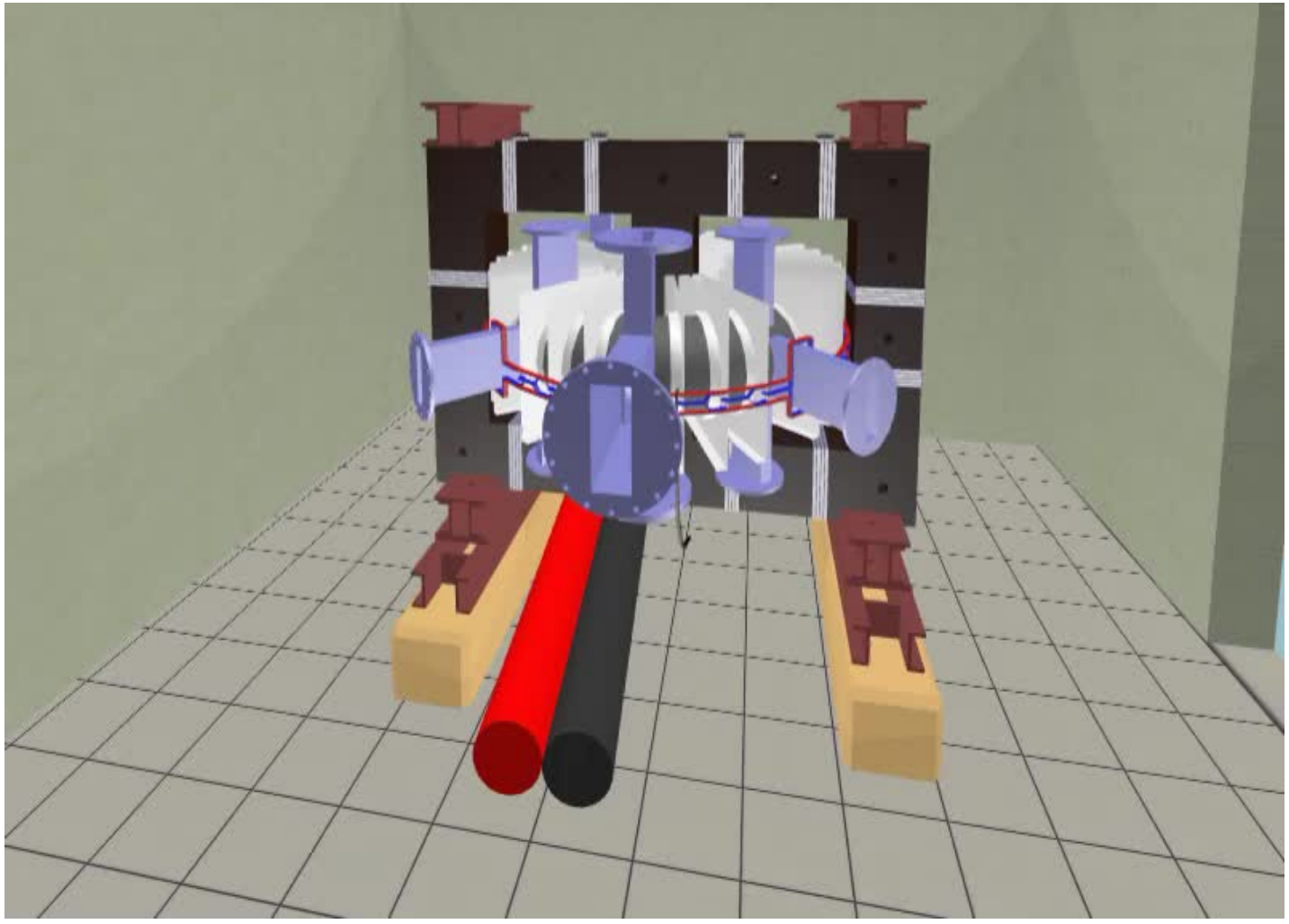
Toroidal magnetic field coils confine the plasma



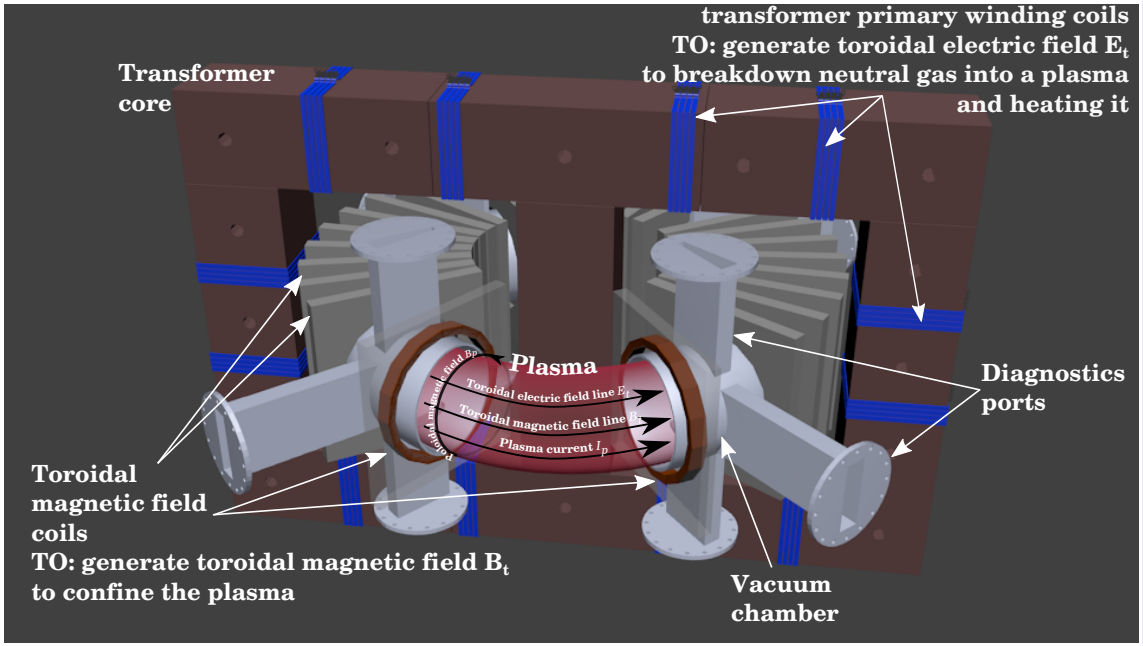
A transformer action creates and heats the plasma



The final technology altogether



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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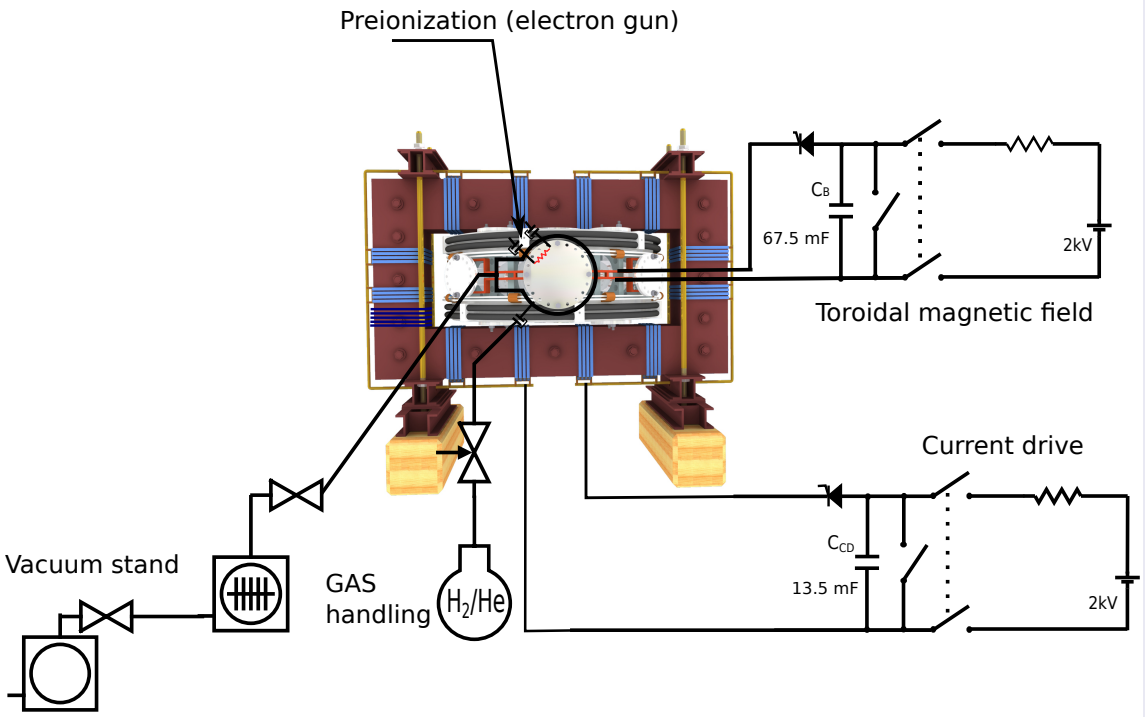

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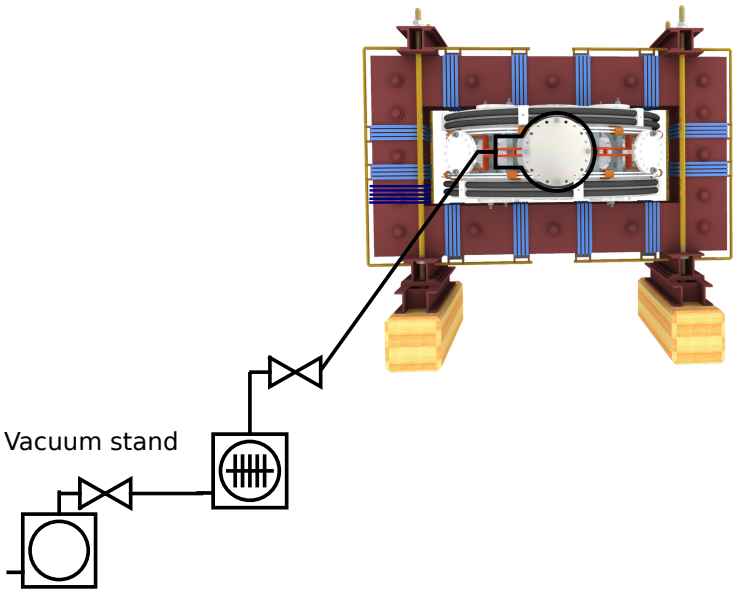

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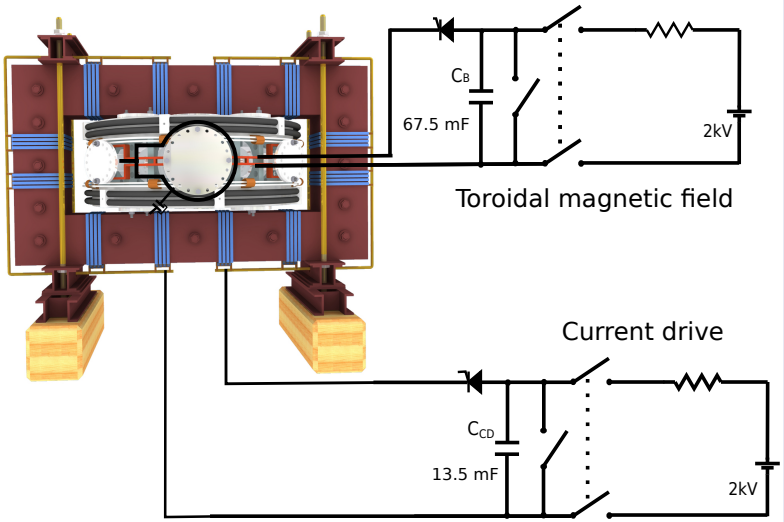

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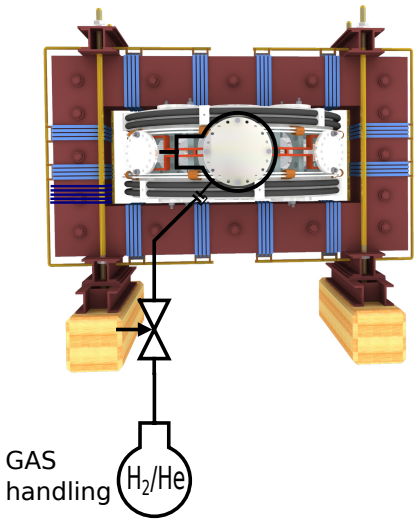

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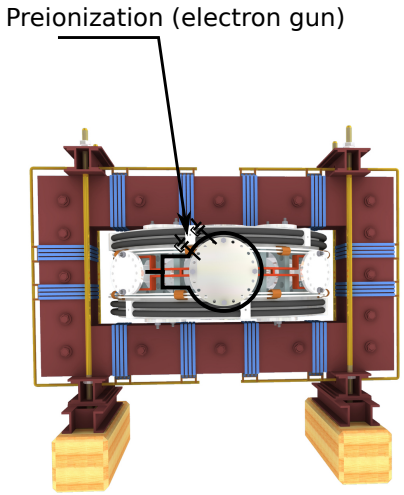
- post-discharge phase

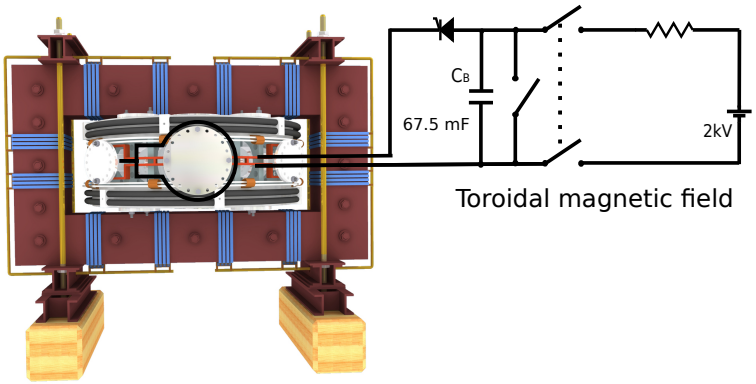
Plasma in Tokamak (GOLEM) - the least to do



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



To do:

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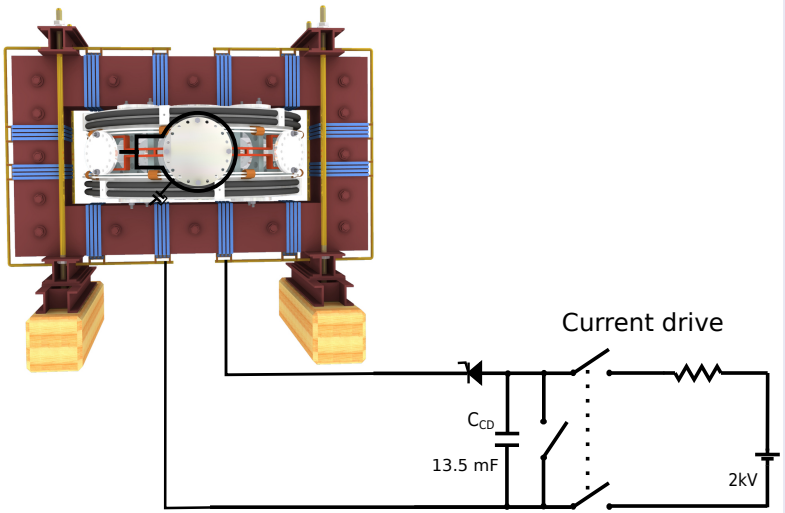
Plasma in Tokamak (GOLEM) - the least to do



To do:

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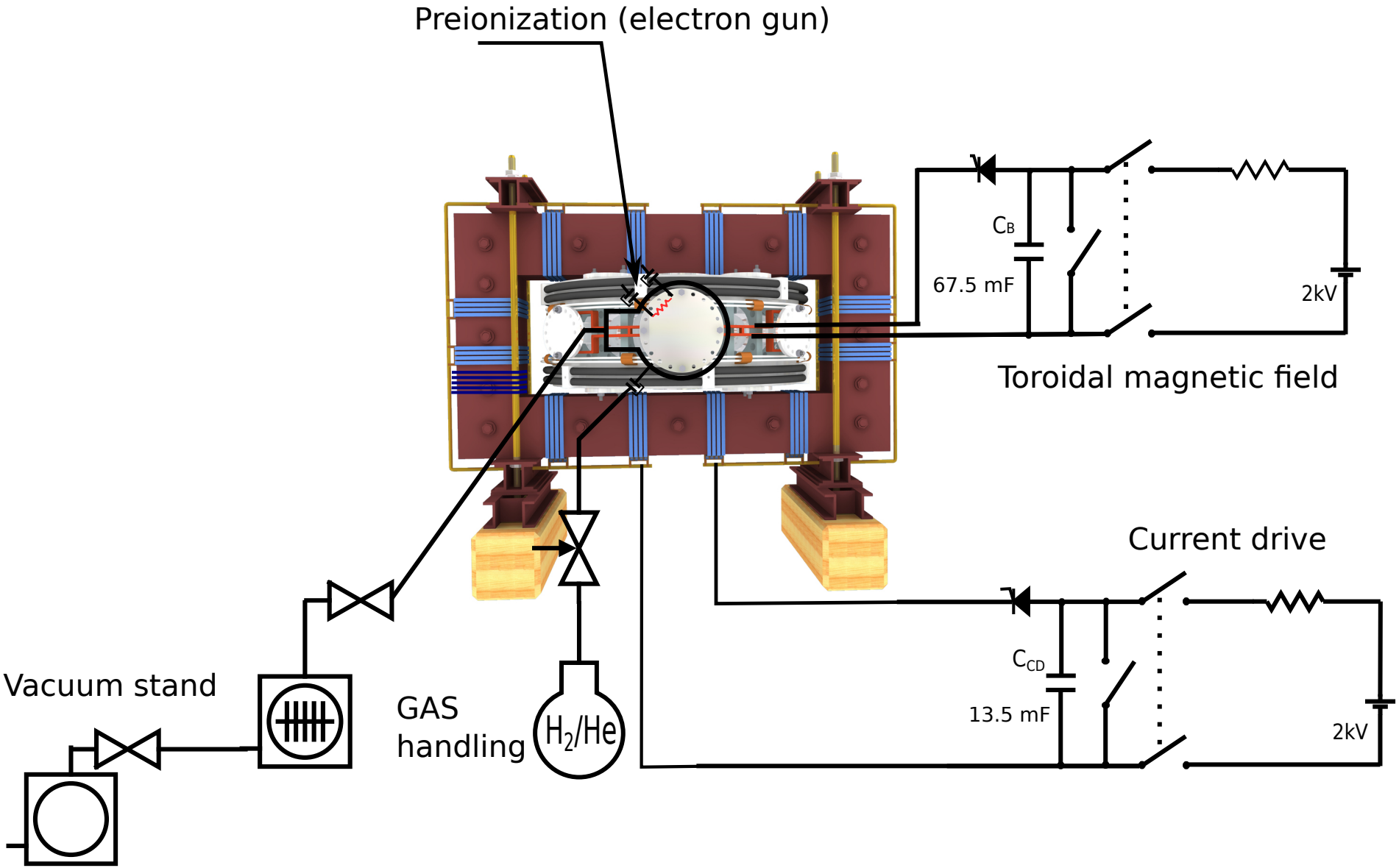
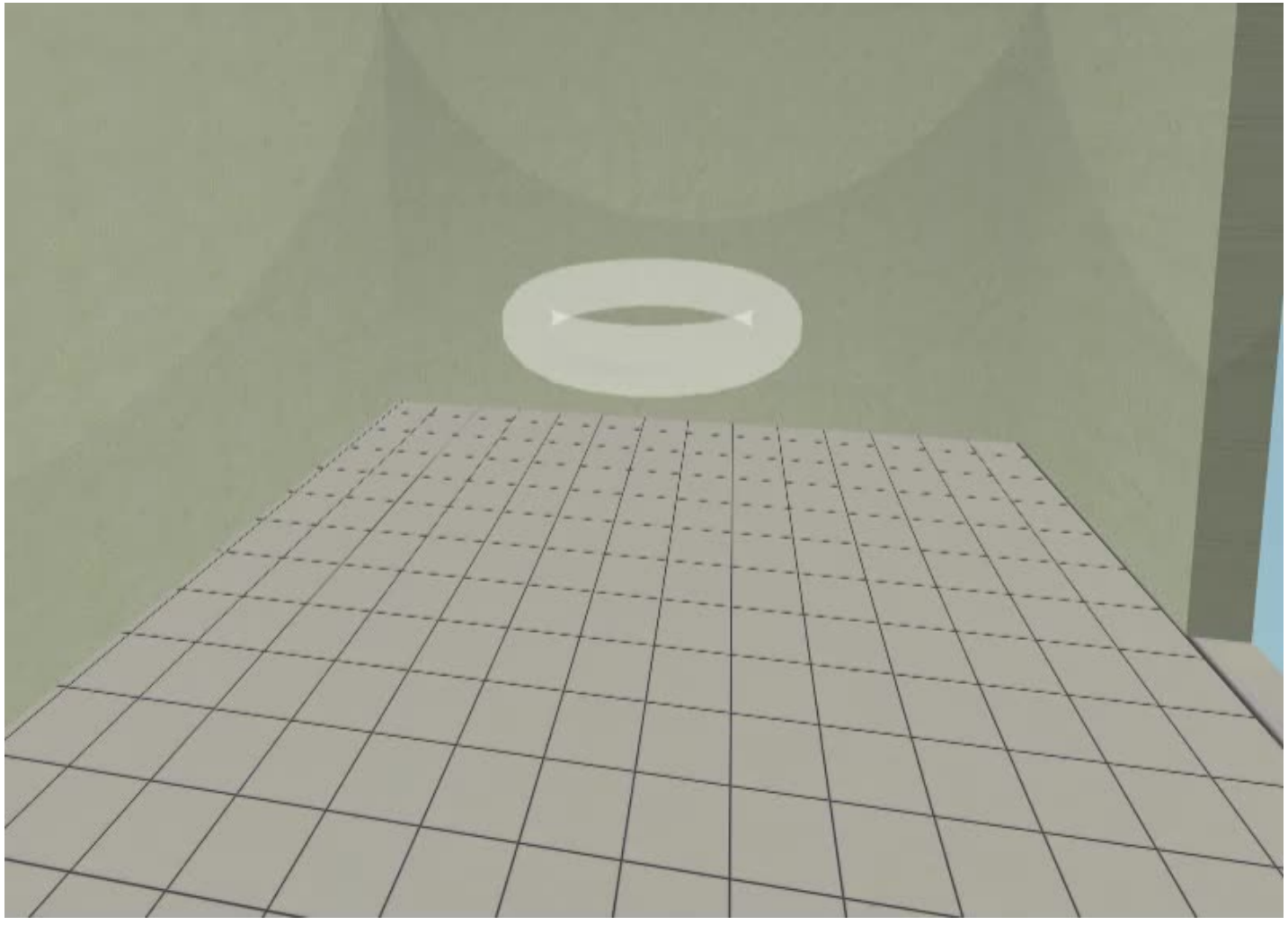
- discharge phase
  - Toroidal magnetic field to confine plasma
  - **Toroidal electric field to breakdown neutral gas into plasma**
  - **Toroidal electric field to heat the plasma**
  - Plasma positioning
  - Diagnostics
- post-discharge phase

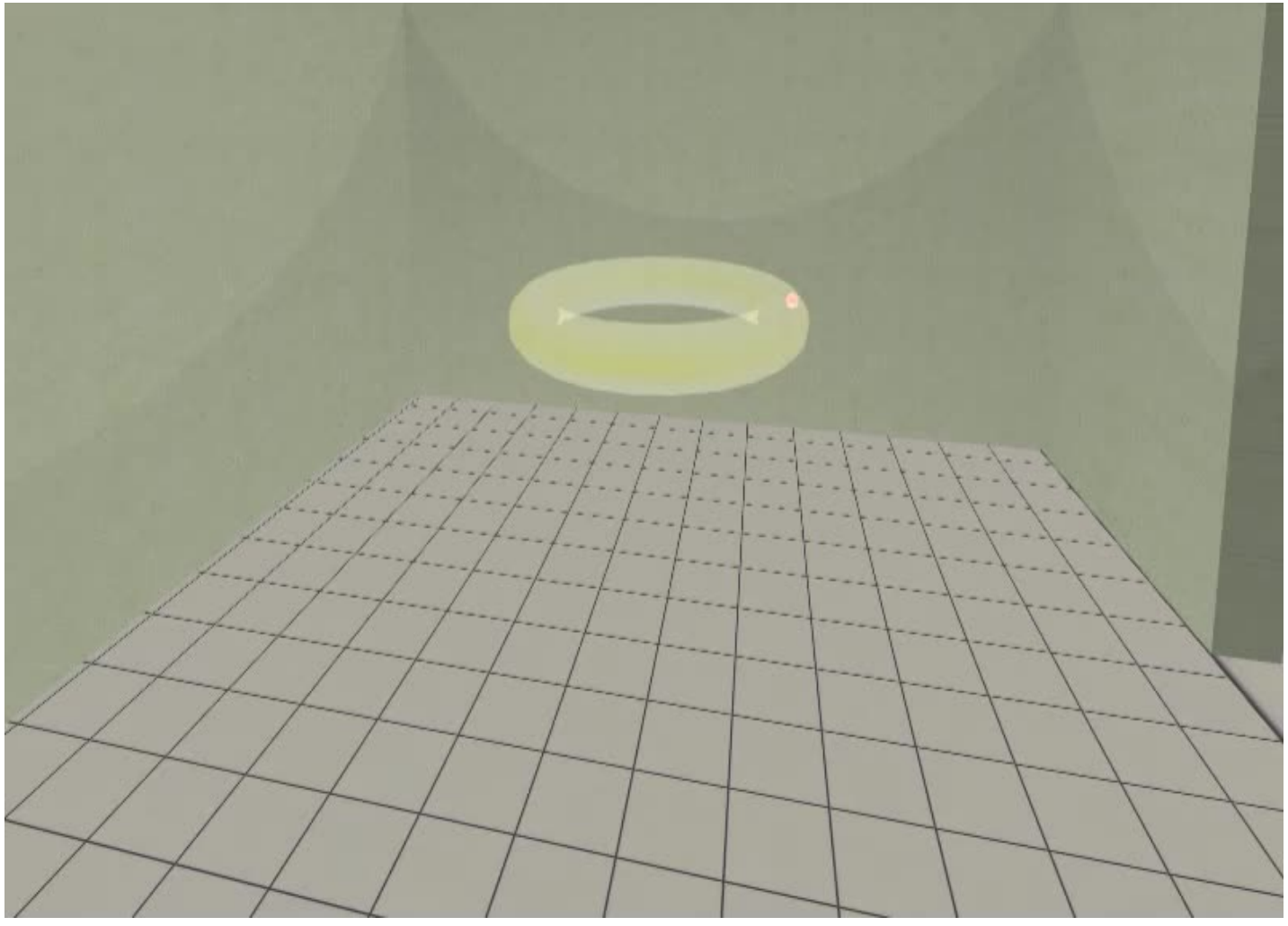
Tokamak GOLEM - schematic experimental setup



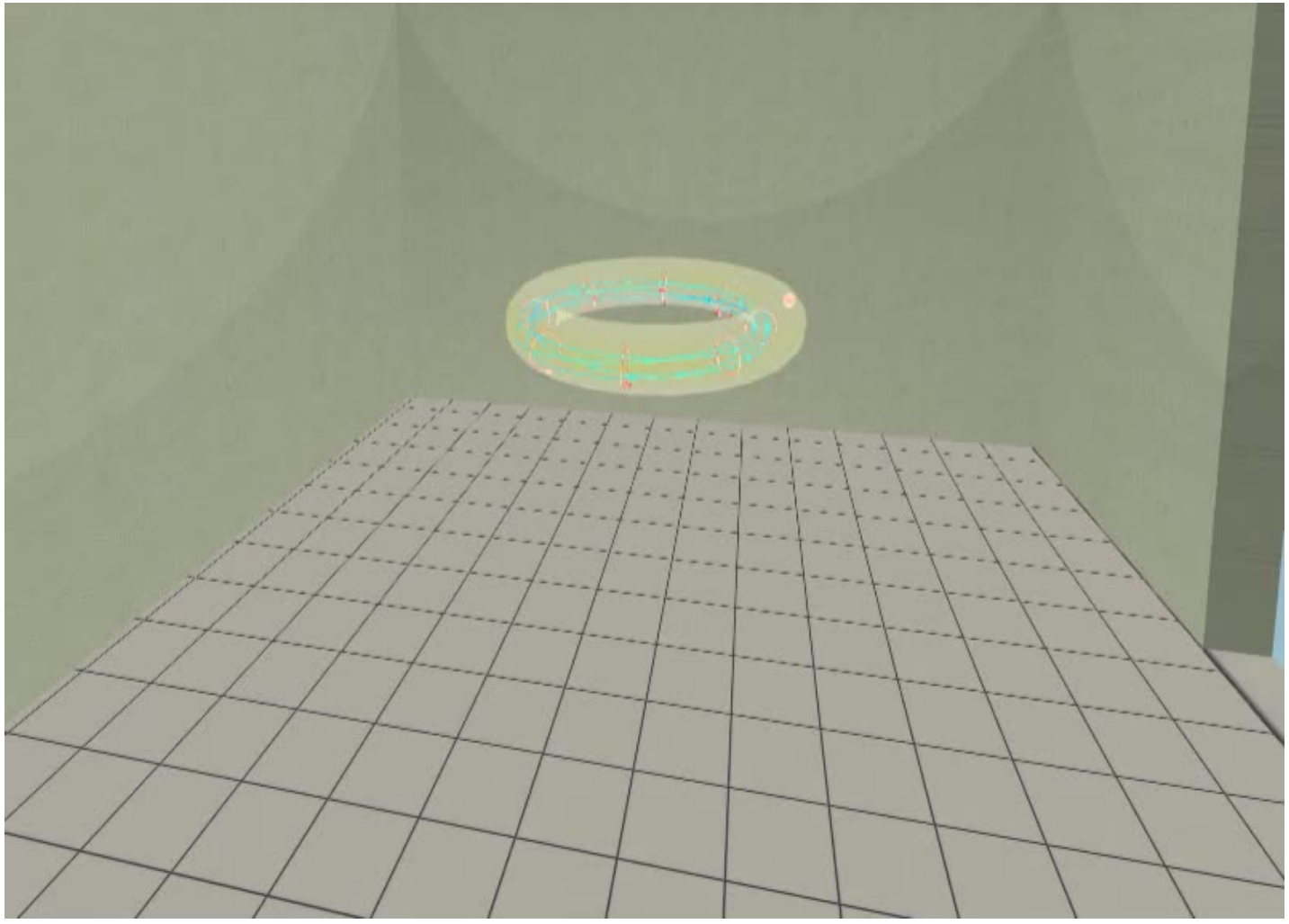
Introduce the working gas (Hydrogen x Helium)



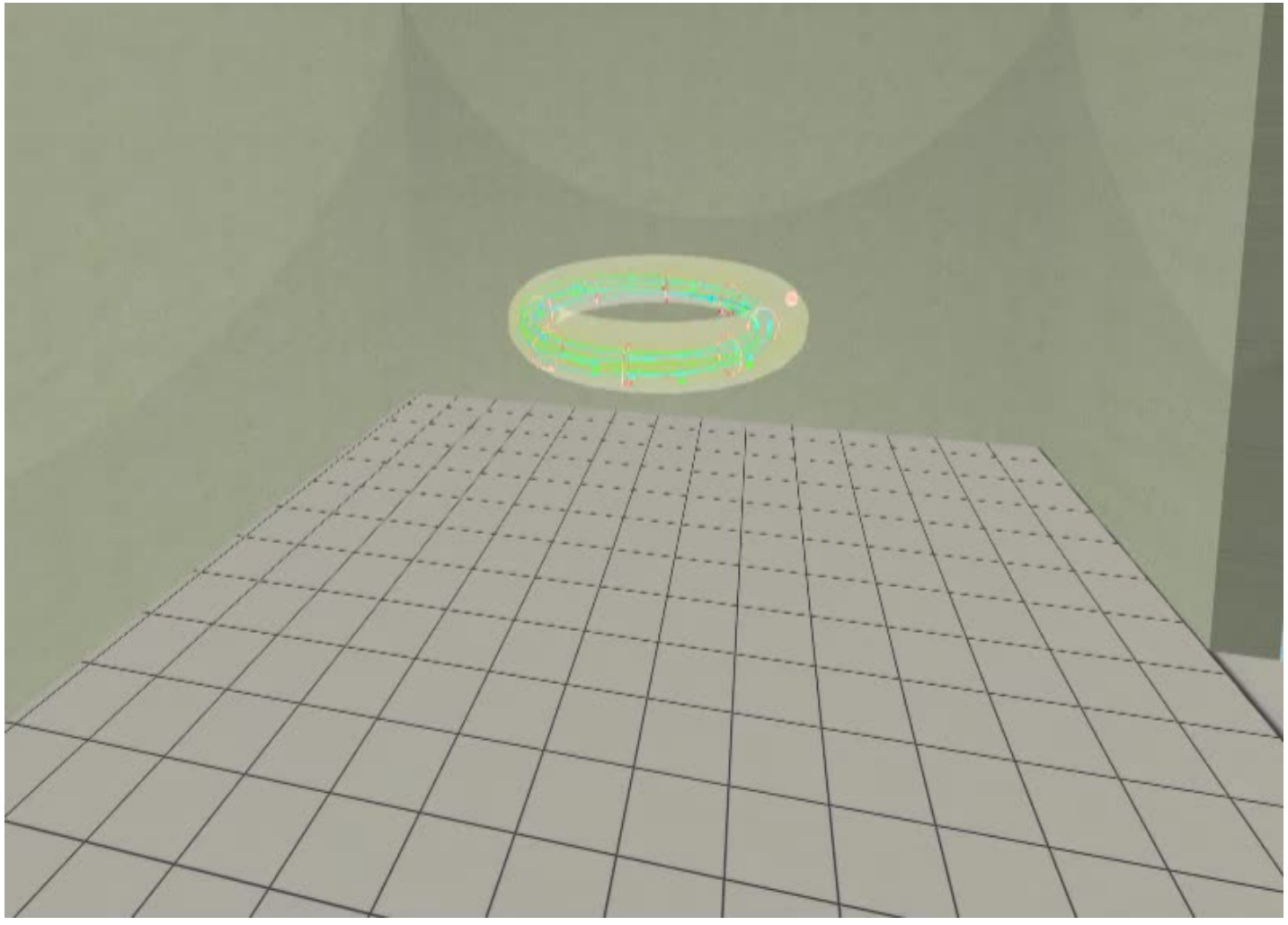
Switch on the preionization



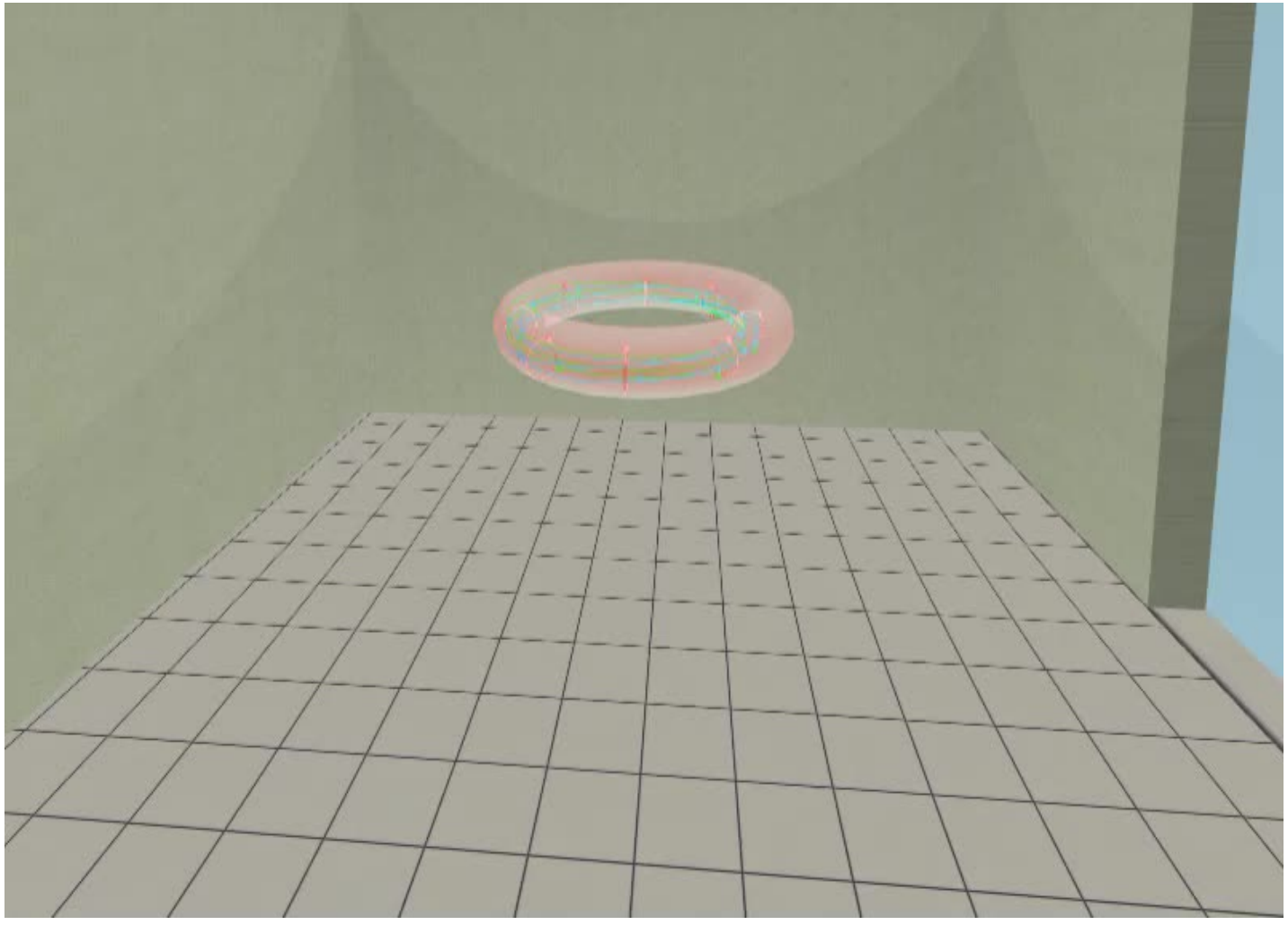
Introduce the magnetic field



Introduce the electric field



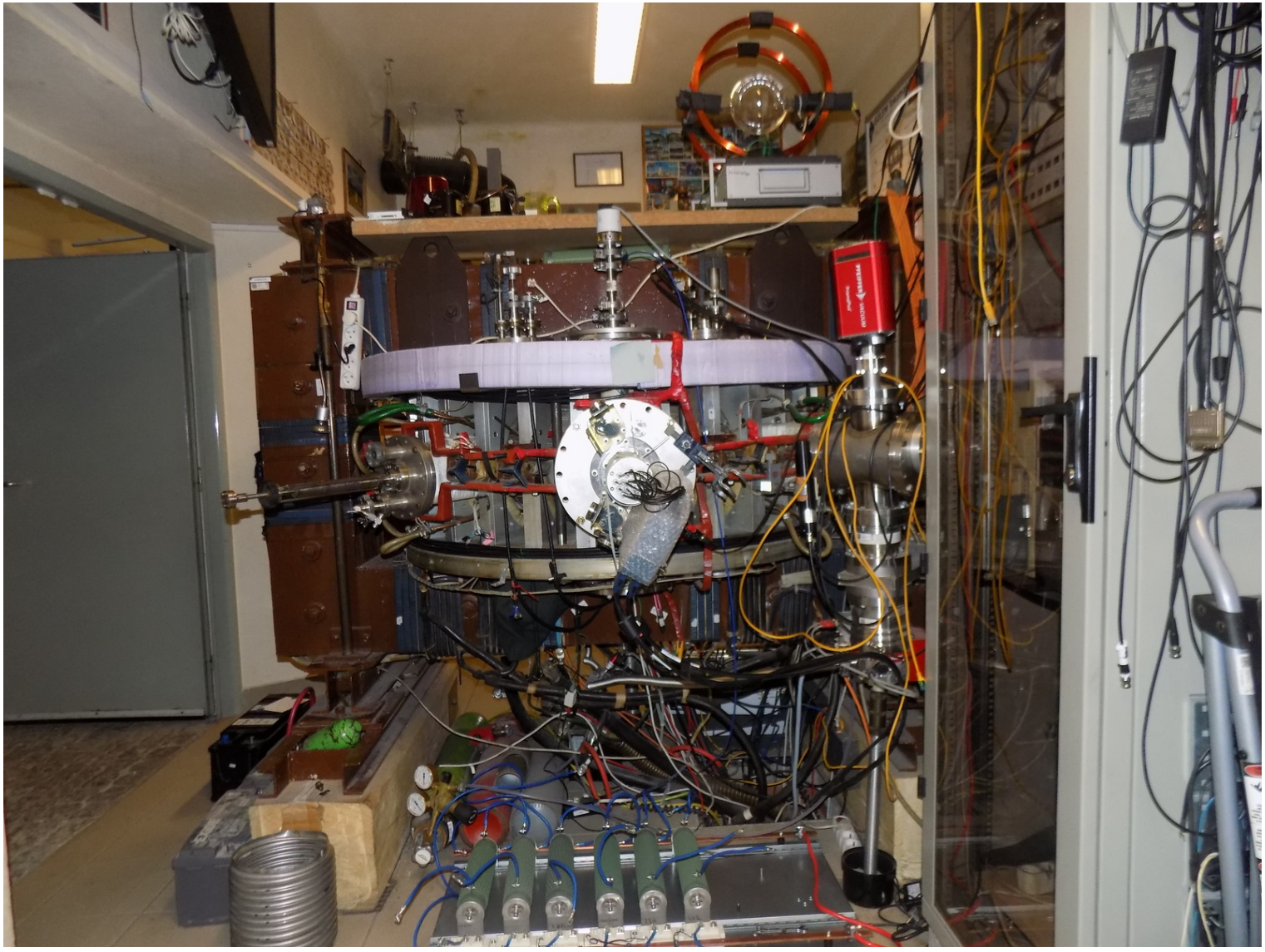
Plasma ..



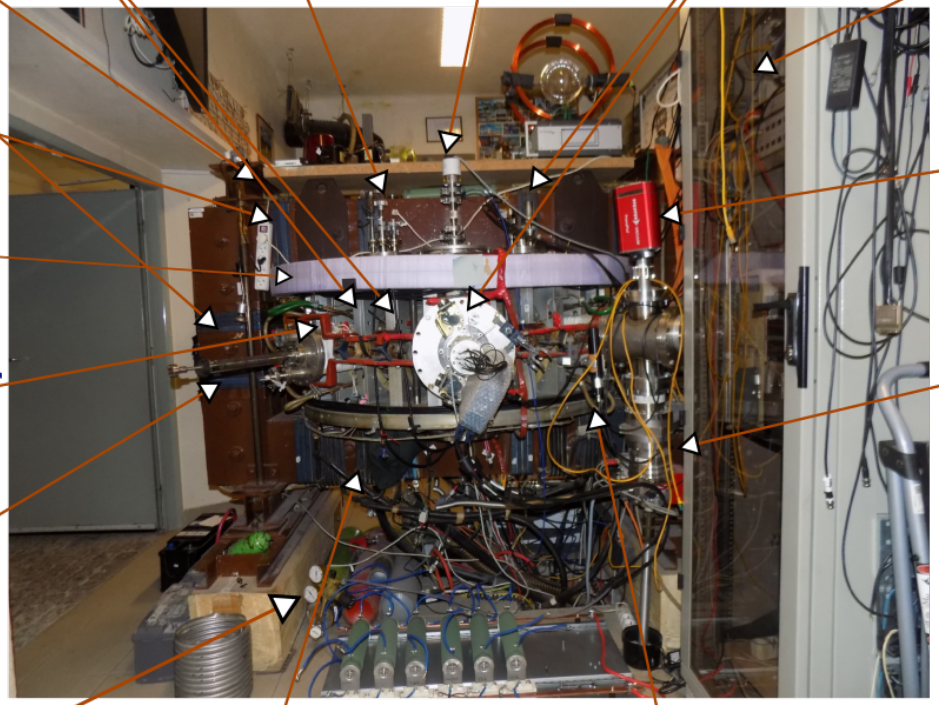
Infrastructure room (below tokamak) 10/16

Infrastructure room (below tokamak) 10/16

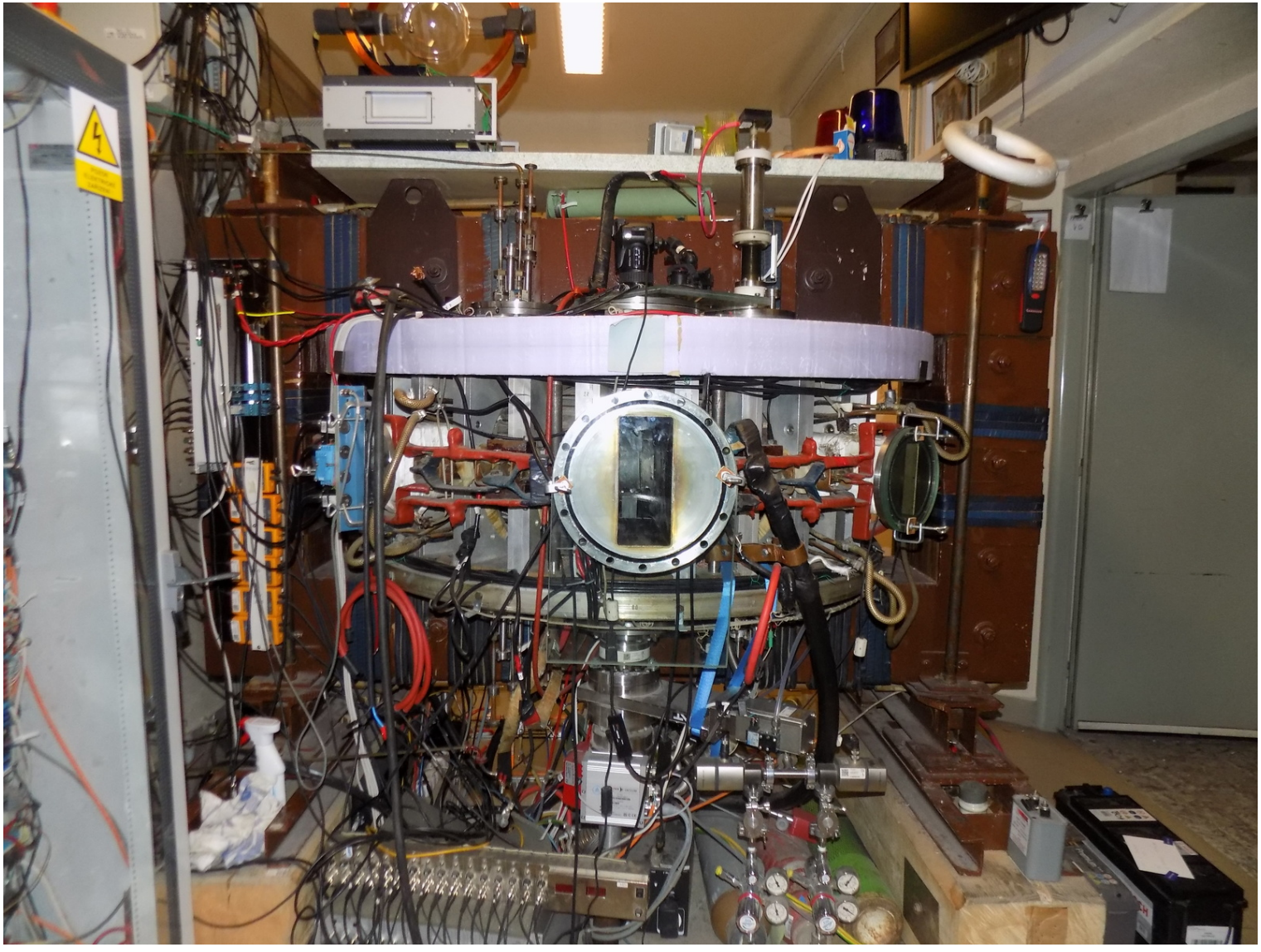
Tokamak room (North) 10/16



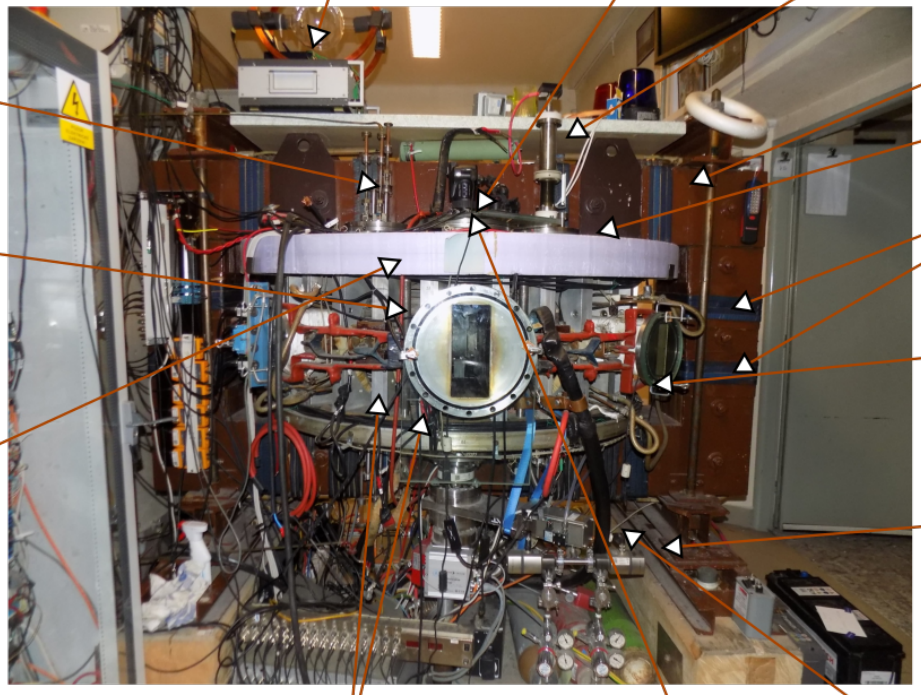
Tokamak room (North) 10/16



Tokamak room (South) 10/16

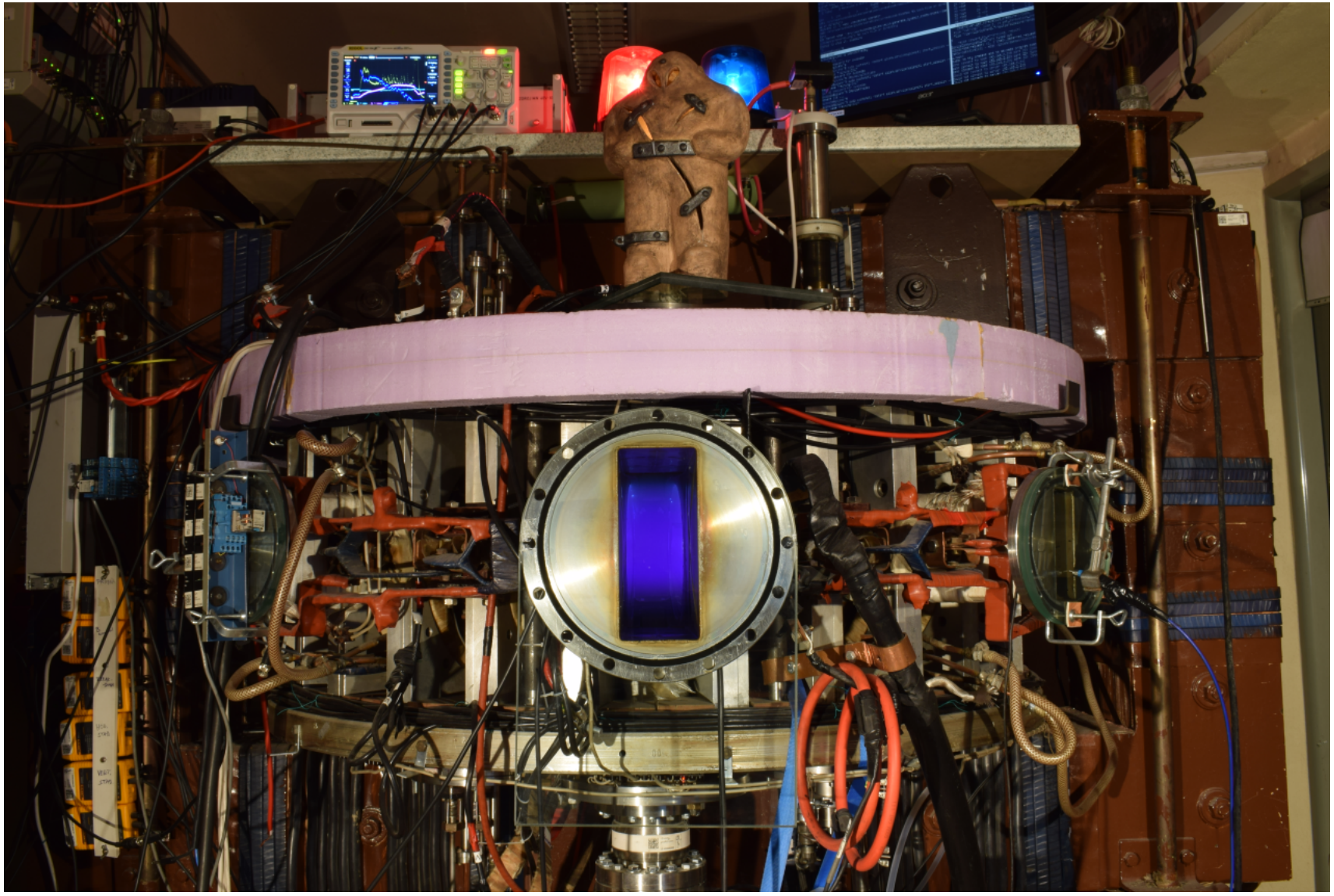


Tokamak room (South) 10/16

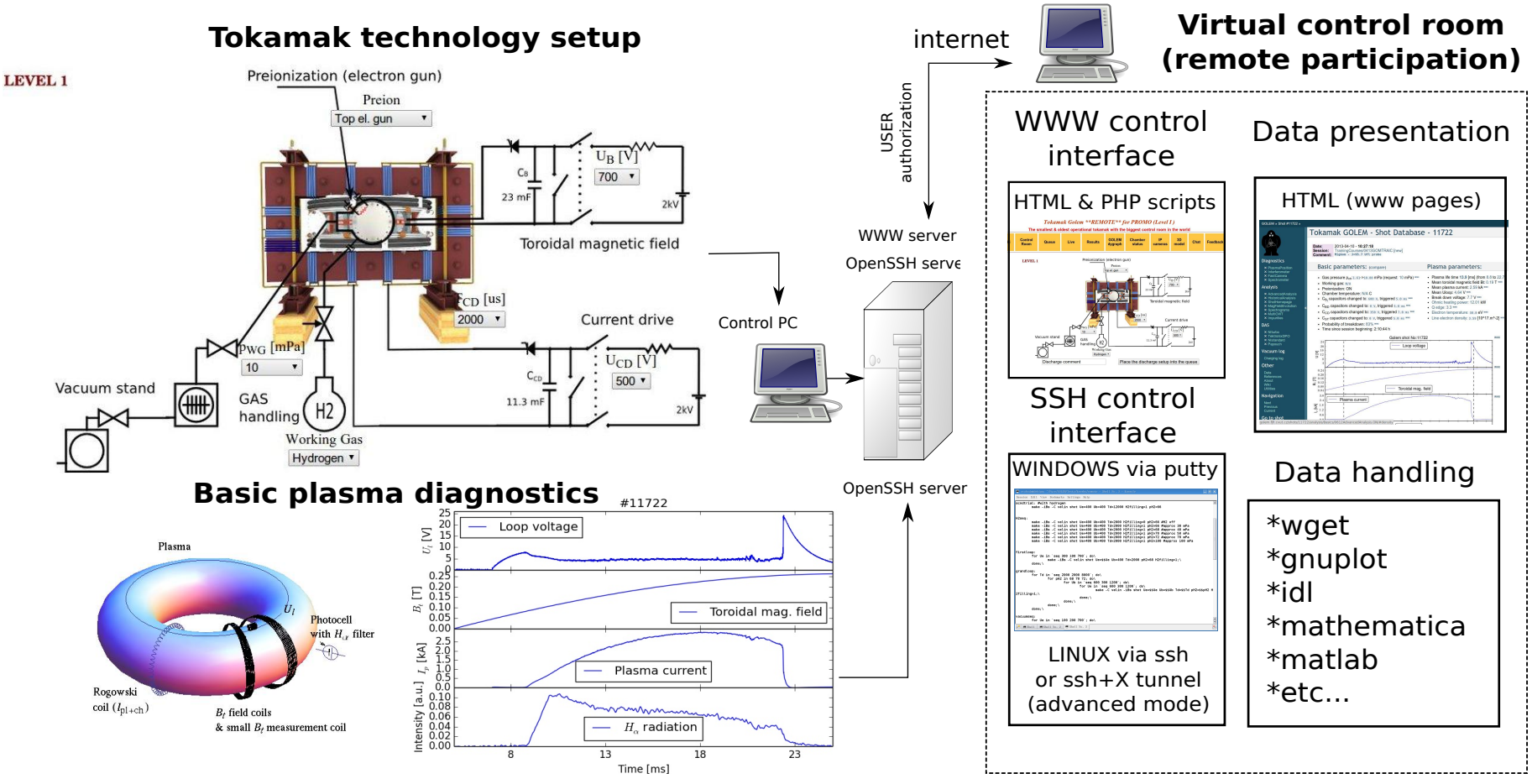


Velké ambice ....

Tokamak GOLEM



Tokamak GOLEM - experimentální schéma



GOLEM

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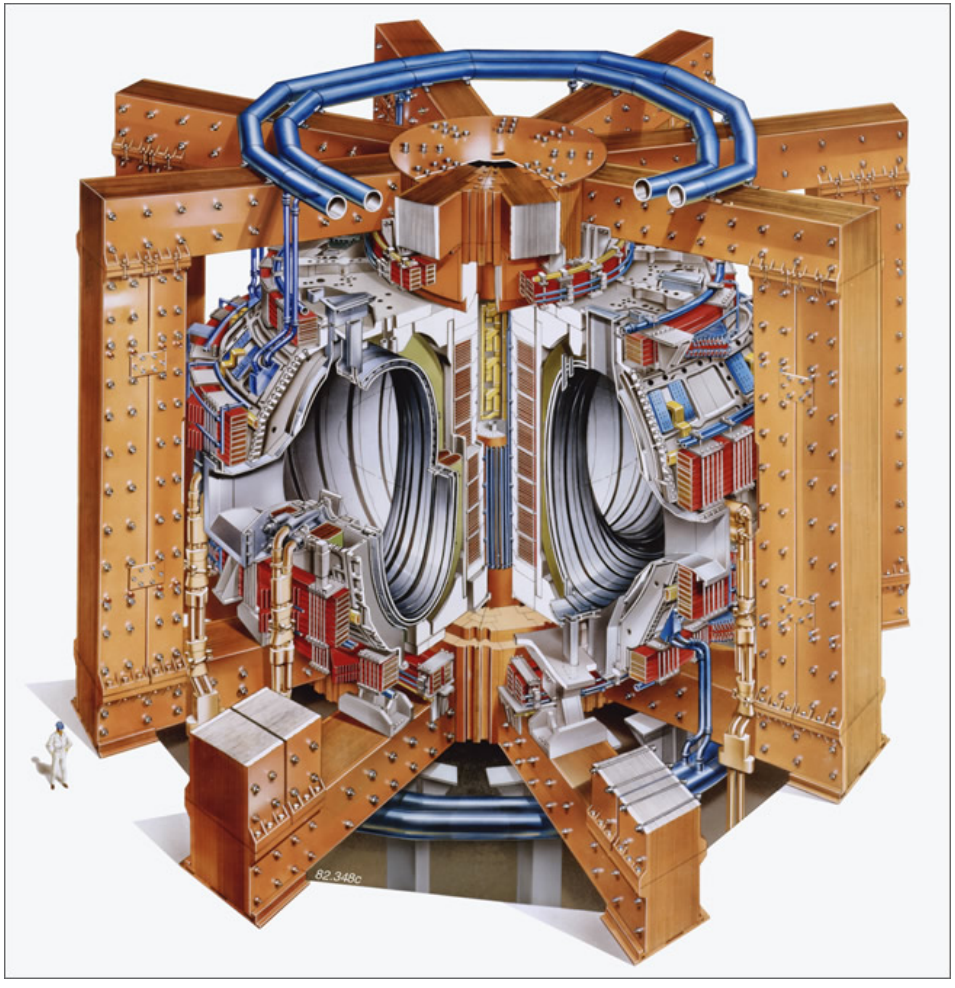
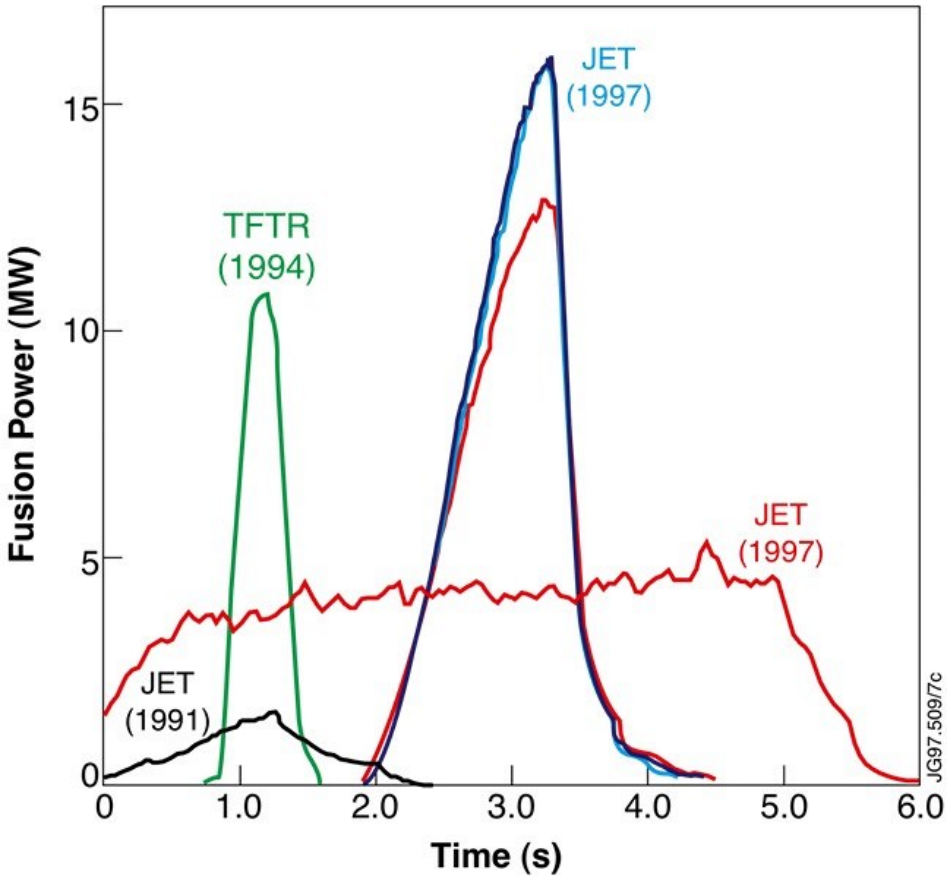
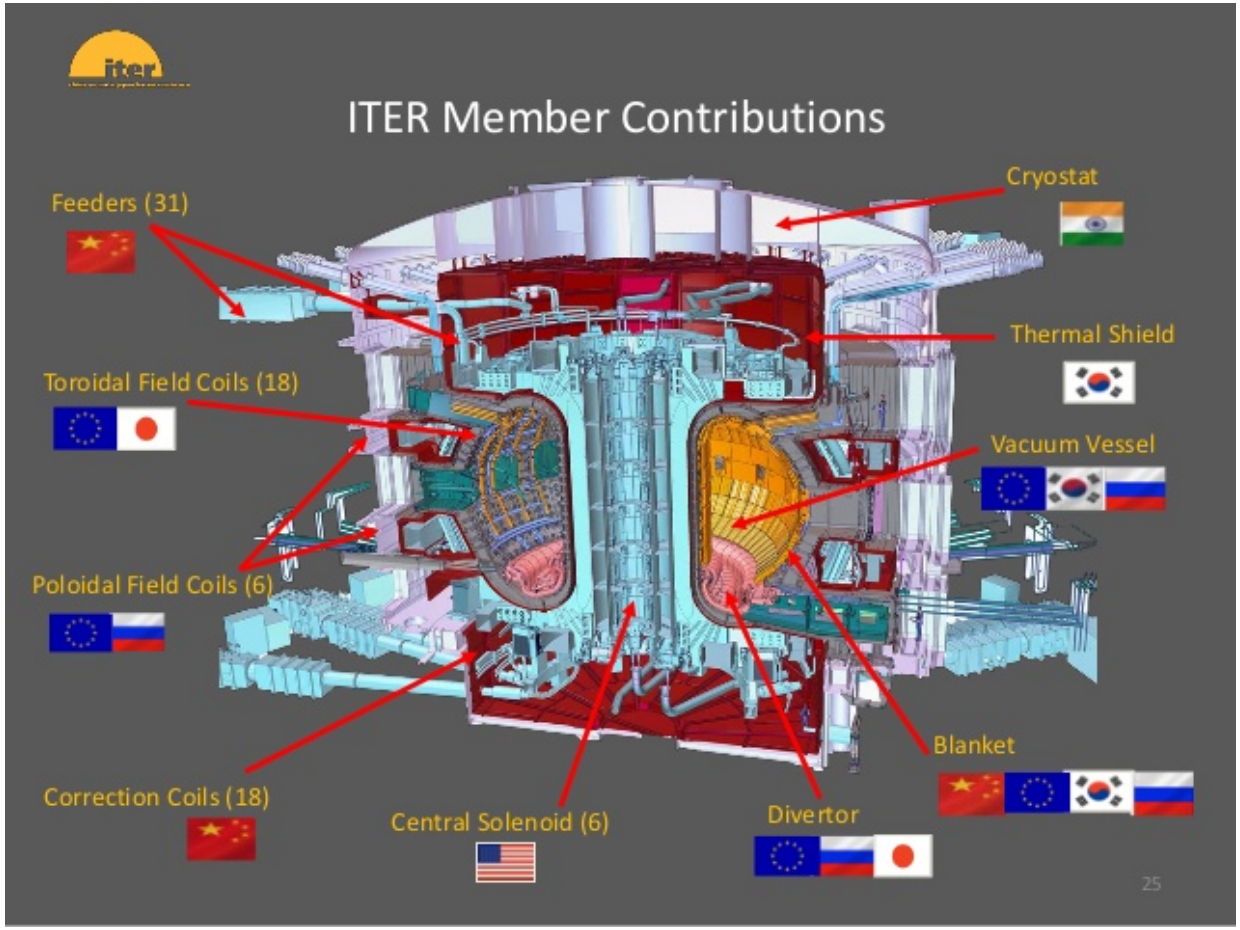
1997: Světový fúzní rekord @ JET (EU)





$P \approx 15$ MW, $Q \approx 0.65$, $\Delta T \approx 3$ s

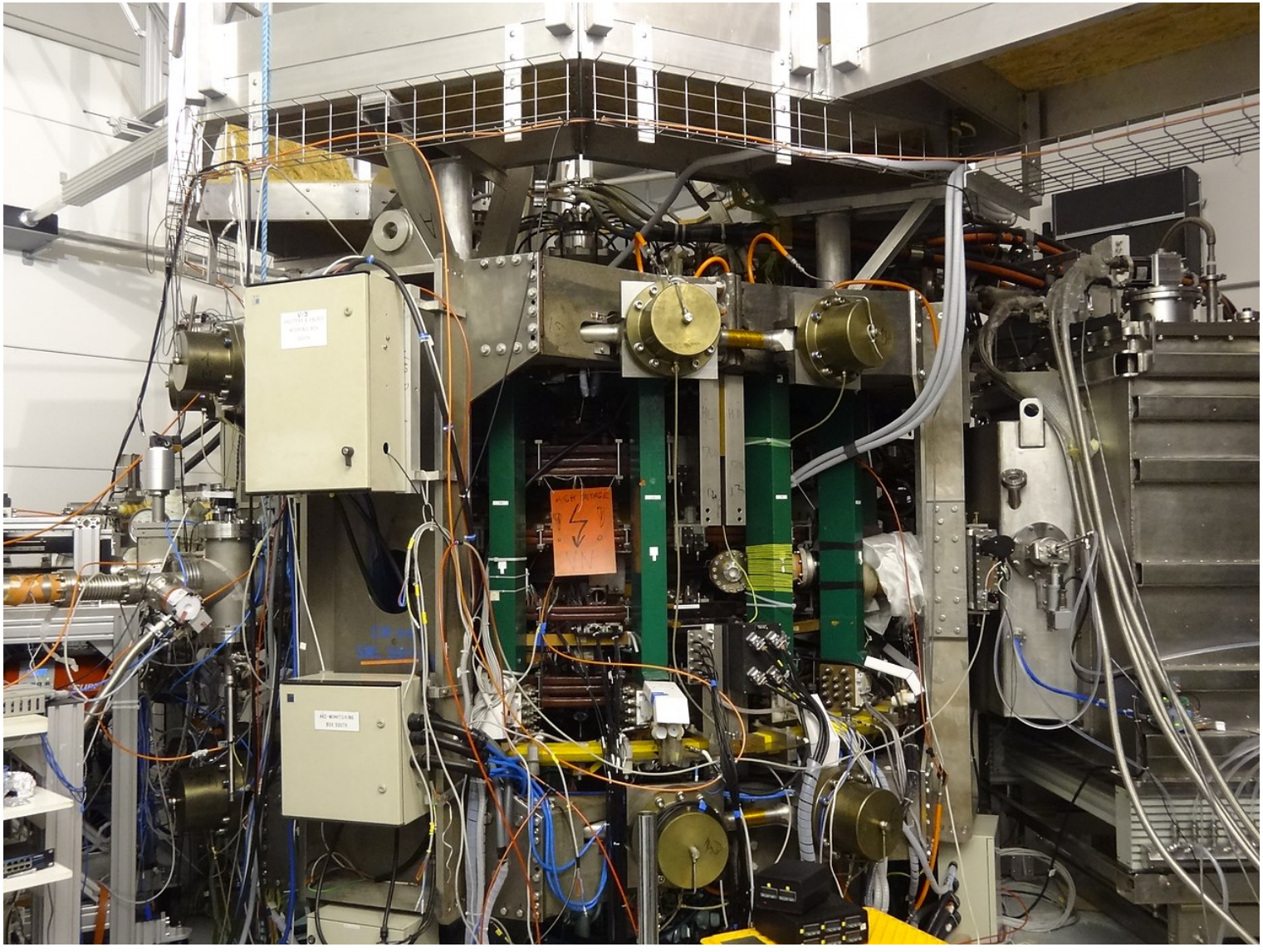
ITER (jižní Francie) $\approx$ 18 miliard EUR



Mise:

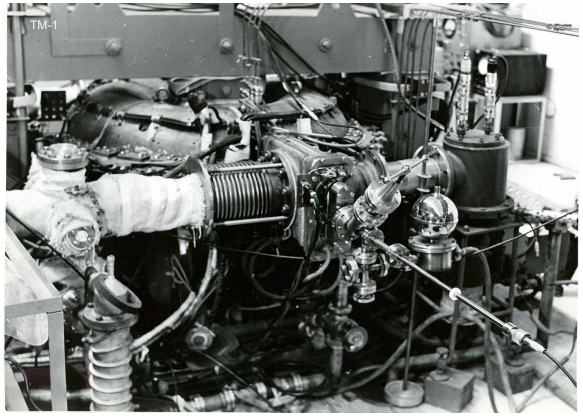
$P \approx 500$ MW, $Q \approx 10$, $\Delta T \approx 10$ minut, konkurenceschopná cena elektřiny

Příspěvek České republiky: tokamak COMPASS@IPP.CAS.CZ



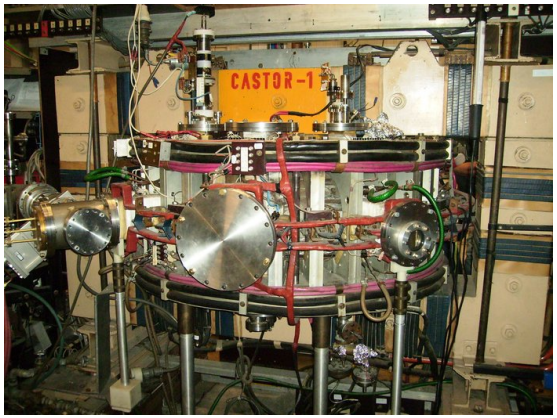
Děkuji za pozornost

Tokamak TM1
@Kurchatov Institute near Moscow
~1960-1977



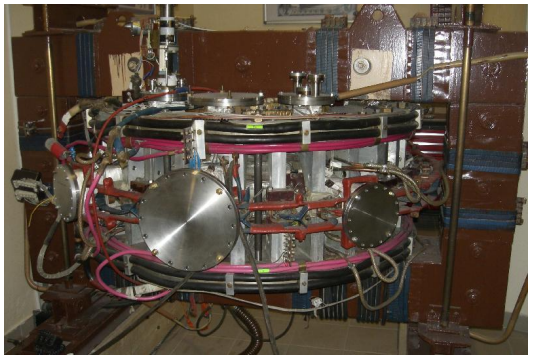
SCIENCE

Tokamak CASTOR
@Institue of Plasma Physics, Prague
1977-2007



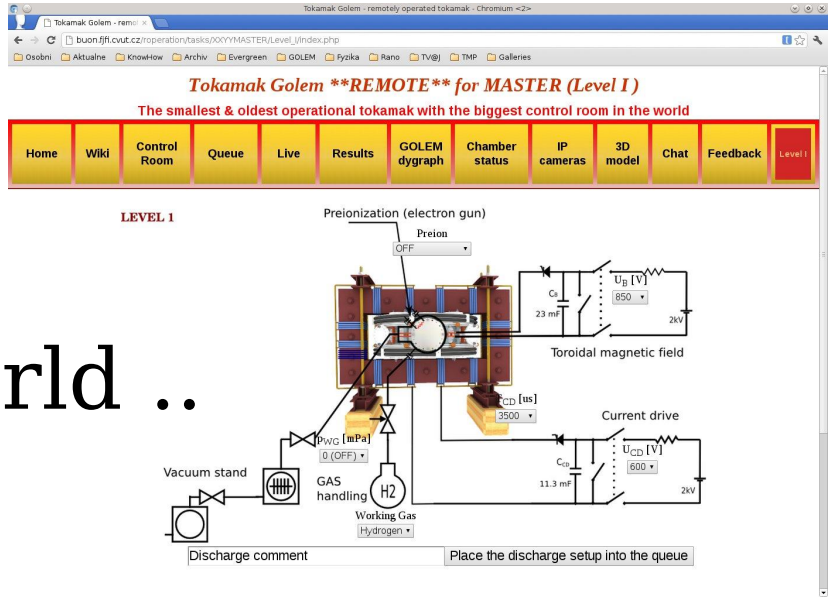
SCIENCE
& education

Tokamak GOLEM
@Czech Technical University, Prague
2007-



EDUCATION
& science

... with the biggest
control room
in the world ..



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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)


Alcator C-Mod

- 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

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.