Title

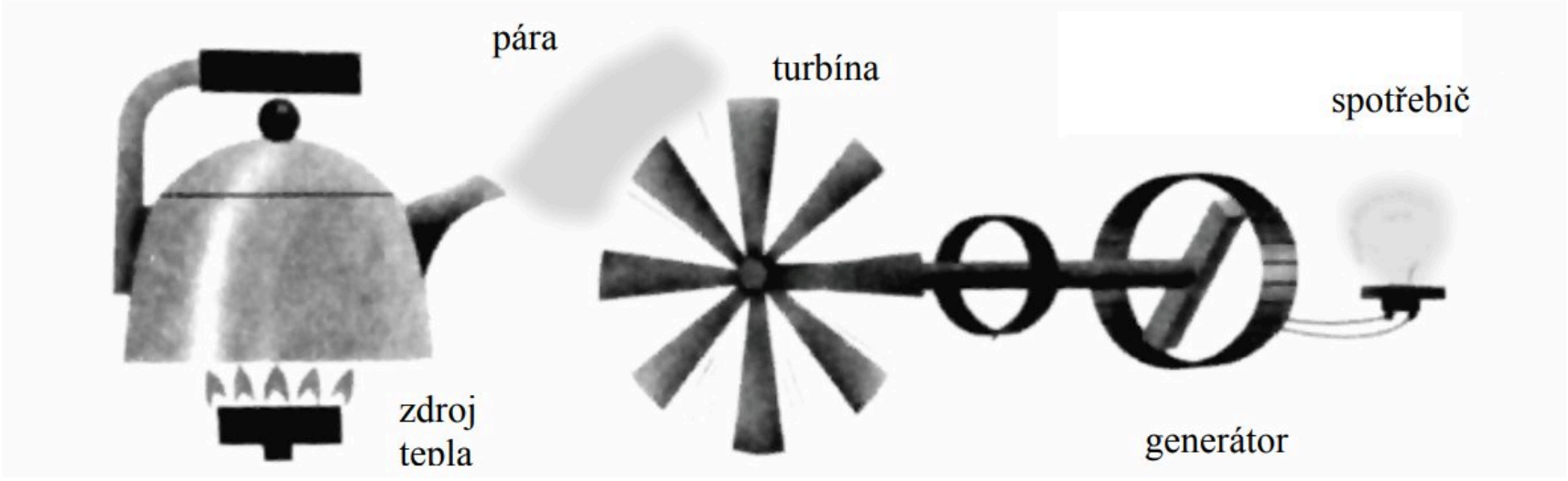
Tokamak GOLEM

Vojtěch Svoboda
on behalf of the tokamak GOLEM team
for **Basic excursions**

March 10, 2023

Table of Contents

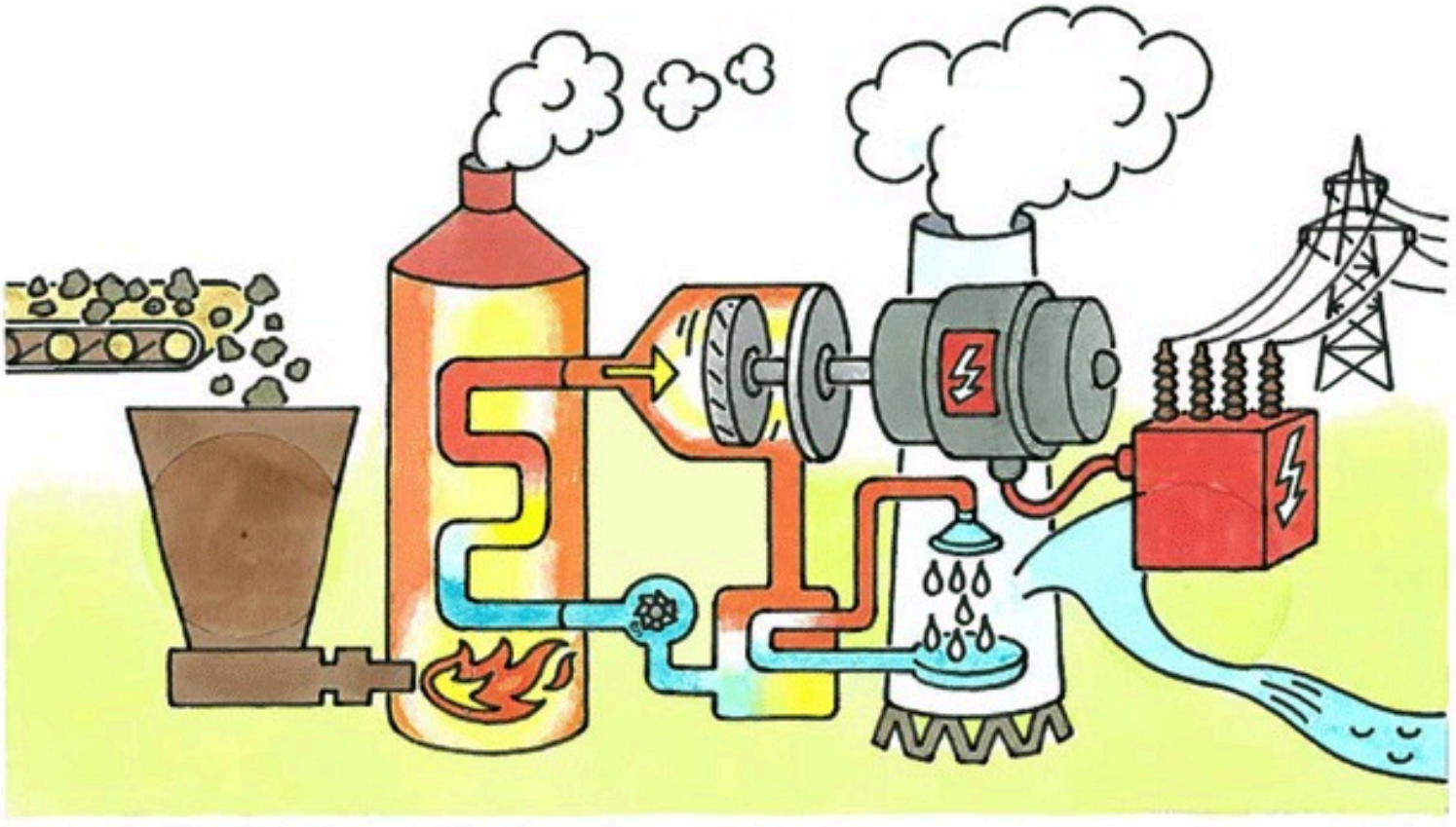
Thermal power plant - basic principle



The question:

?? WHAT TO BURN ??

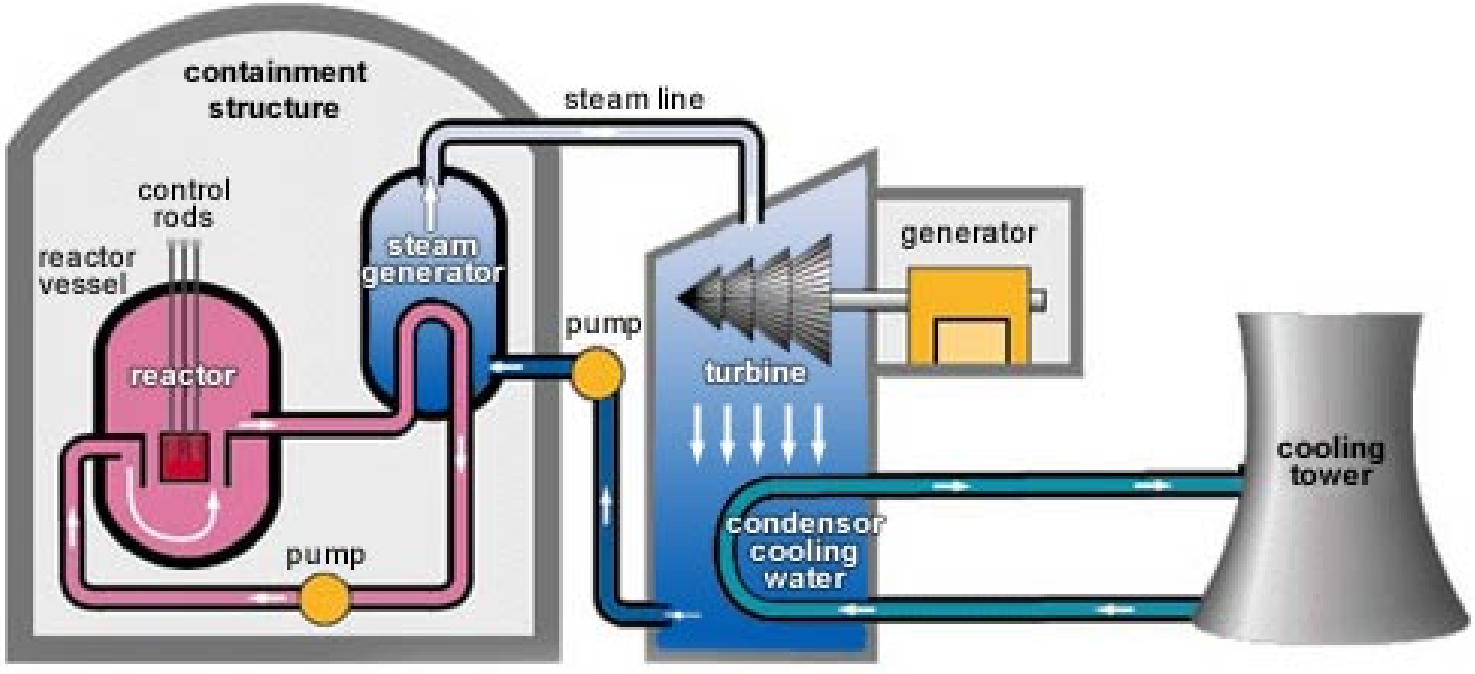
Coal power plant



Prague ($\sim$ 1 GW): daily $\sim$ train of coal

Emissions ...

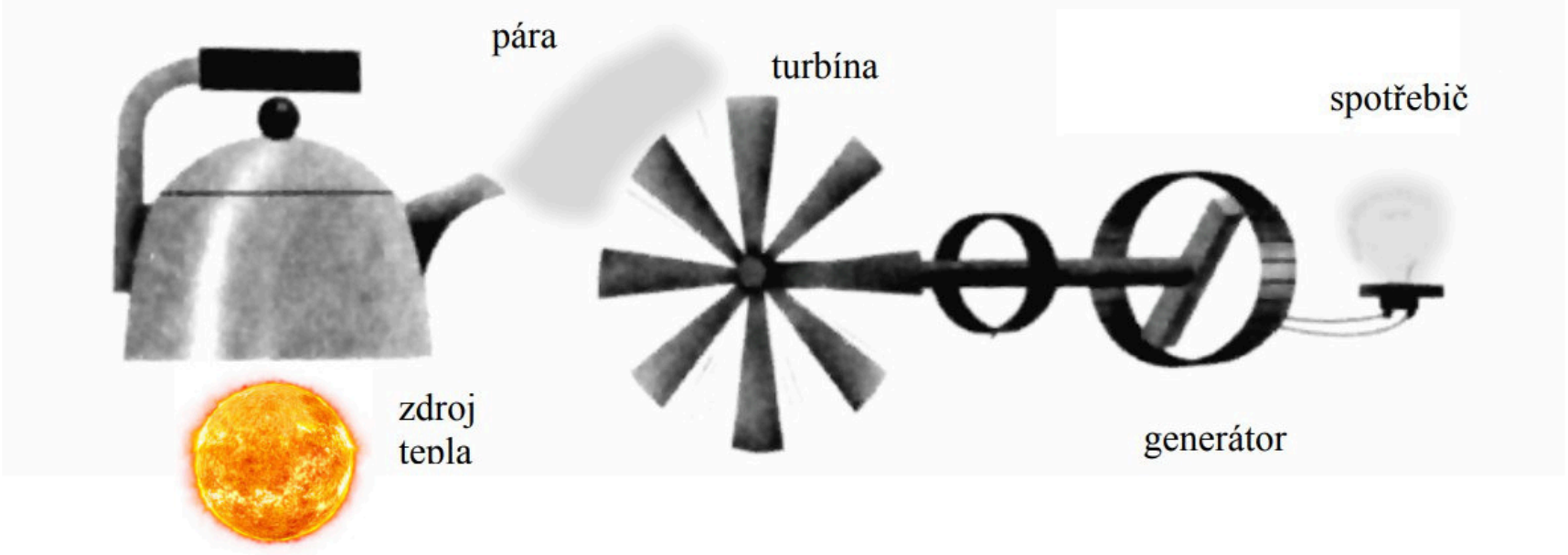
Nuclear power plant (fission)



Prague ($\sim$ 1 GW): $\sim$ carload of nuclear fuel per year

Tune the technology: Fuel, Waste, Safety.

Topit malým Sluncem/hvězdou ??



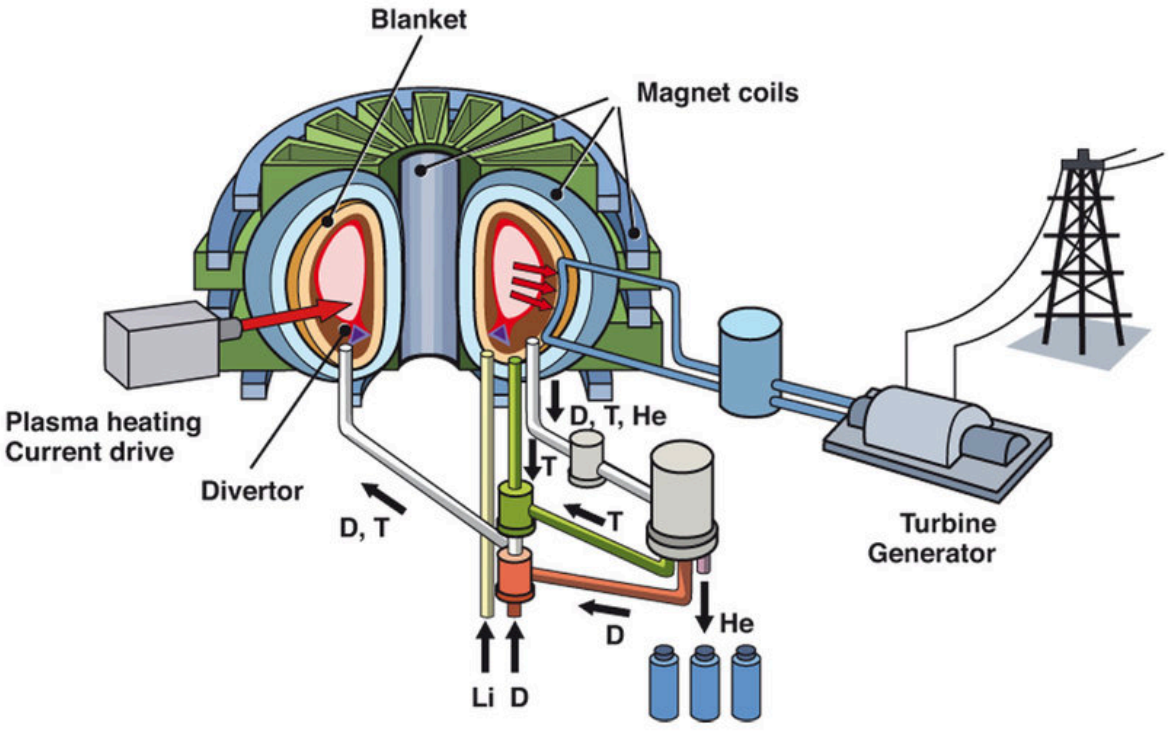
Výzva

1952 "Operation Ivy - Mike" První test vodíkové bomby

credit:YouTube:Ivy Mike Countdown and detonation

Toto není vhodná technologie

Vize: Jaderná elektrárna - slučovací/fúzní

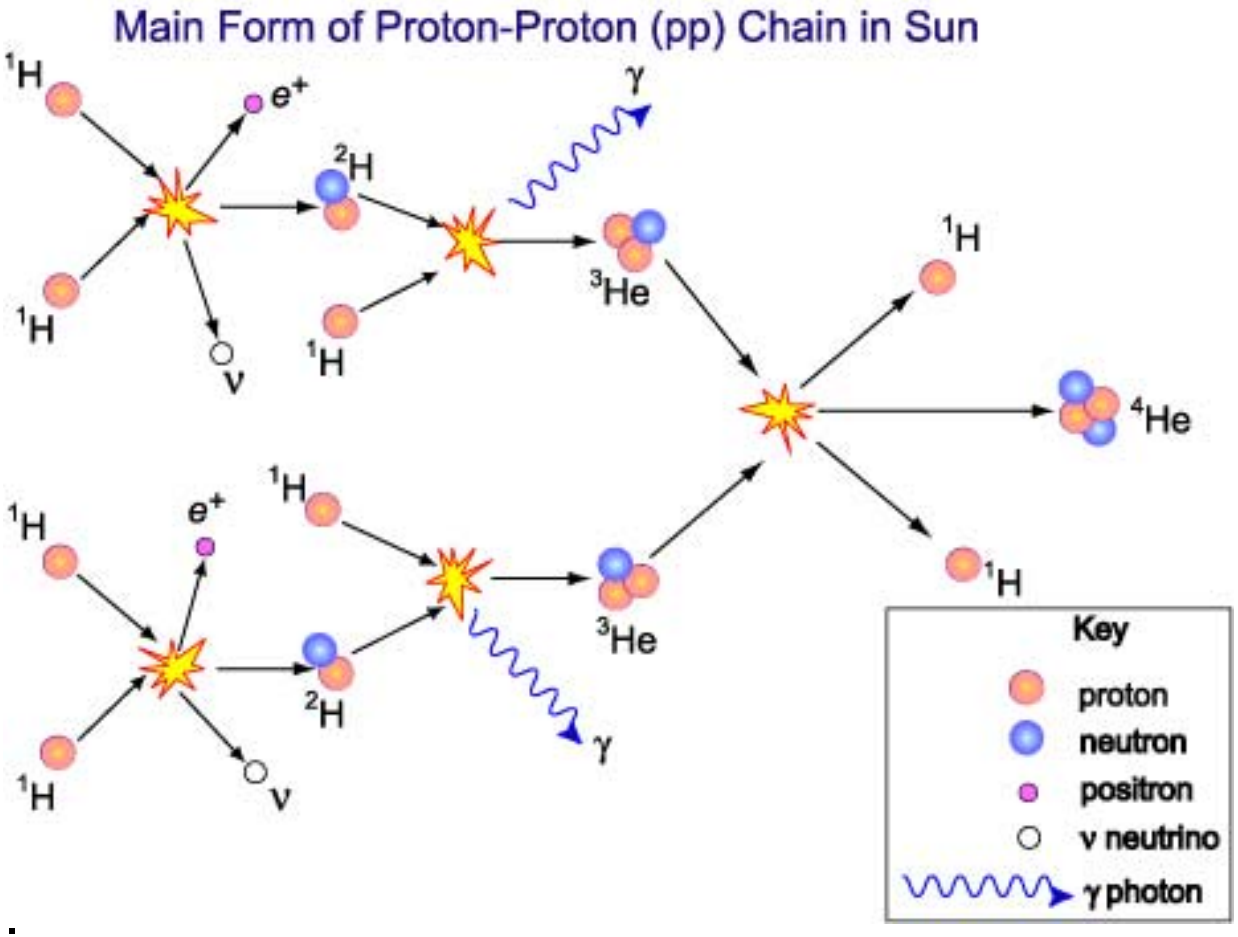


credit:[1]

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

Vypiplat technologii

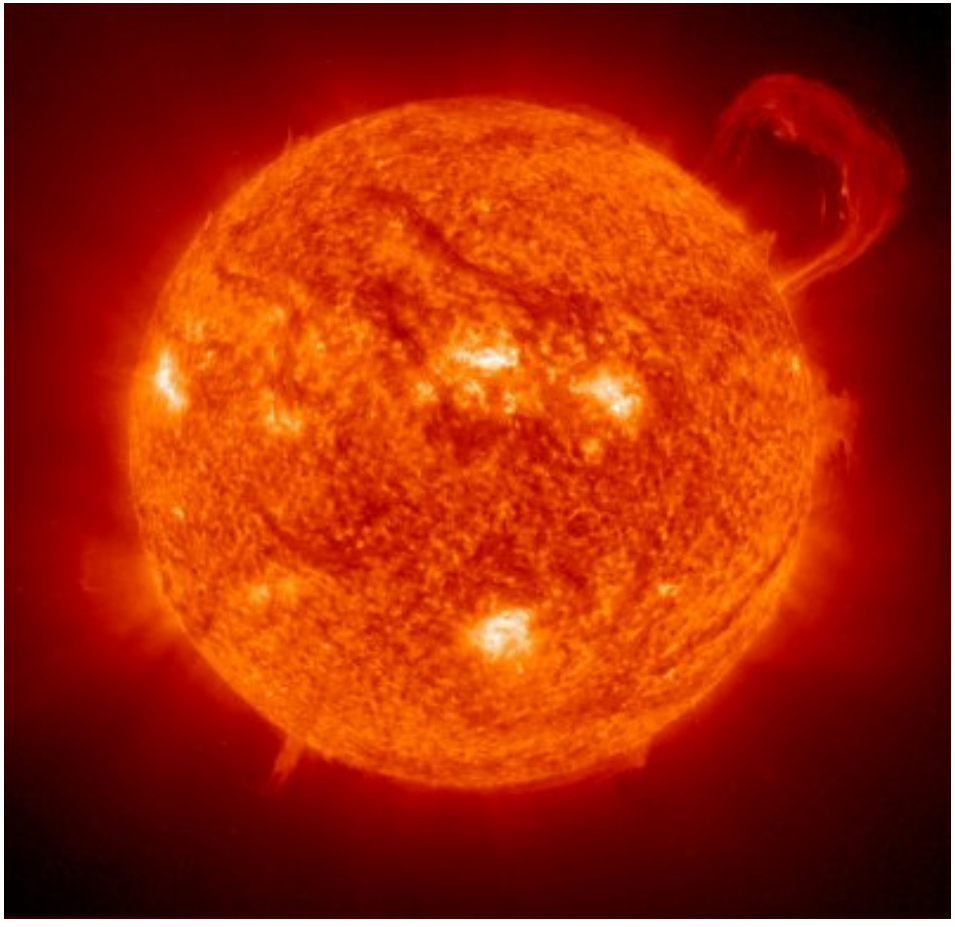
The Sun - Proton proton chain



credit:CSIRO

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

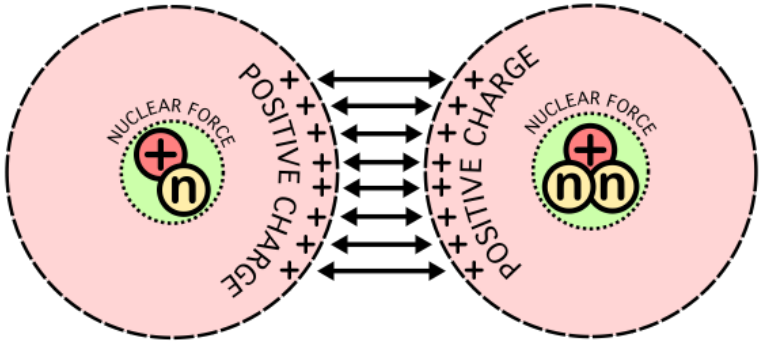
Star burning stages



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

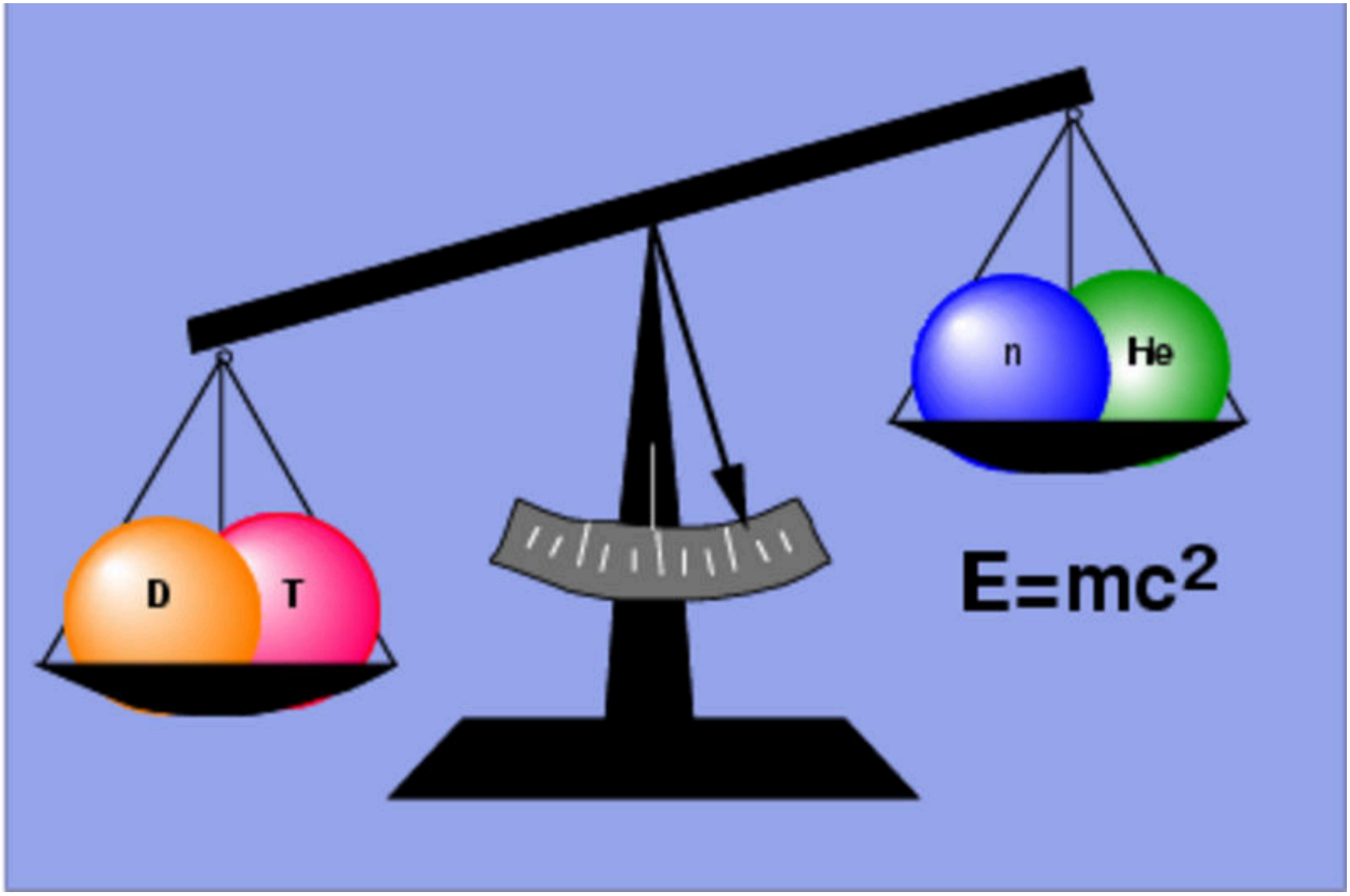
Electrostatic force - like charges repeal



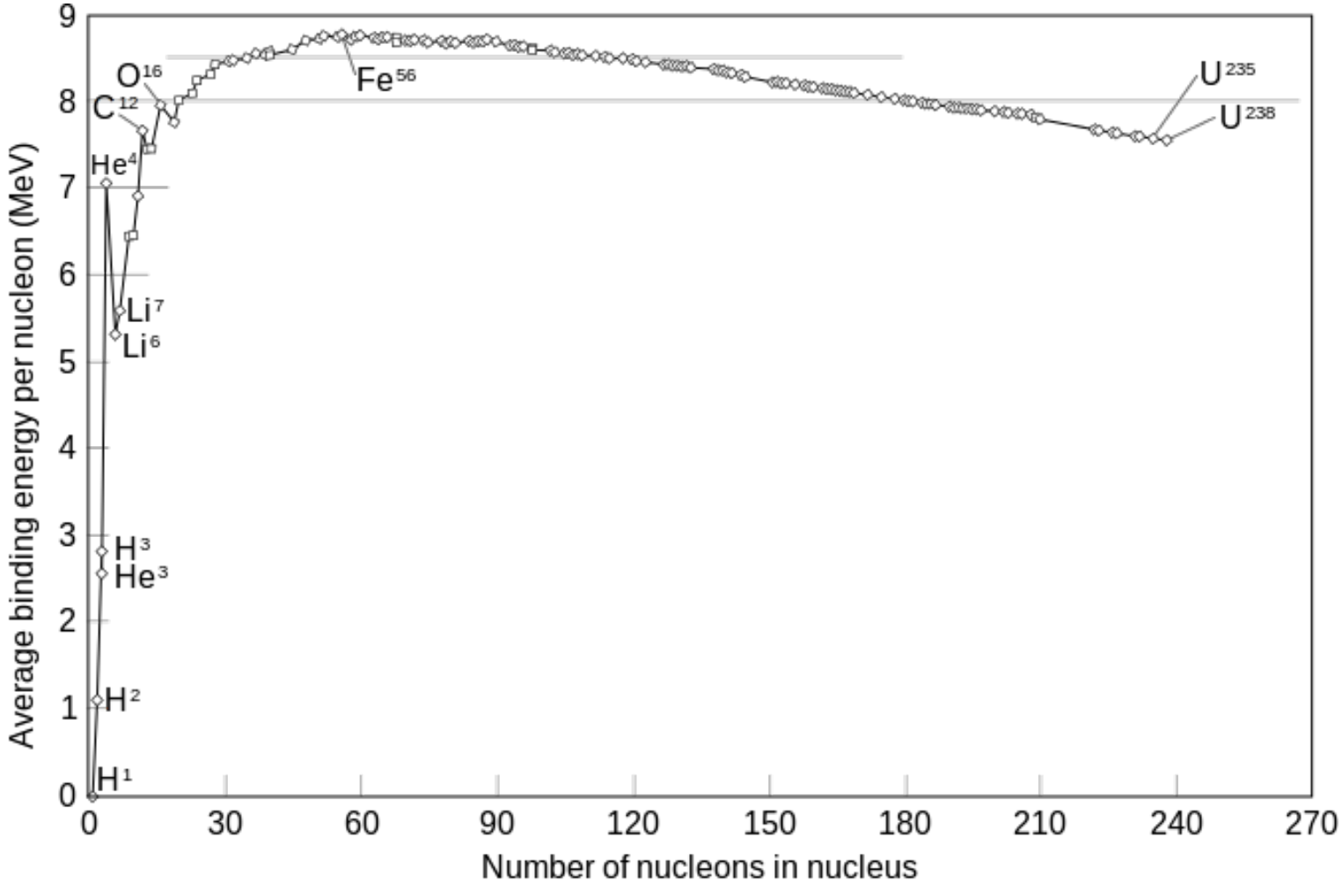
- Coulomb law:
  $F_E = \frac{1}{4\pi\epsilon_0}\frac{Q_1\ Q_2}{r^2}$

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

Binding energy releasing I

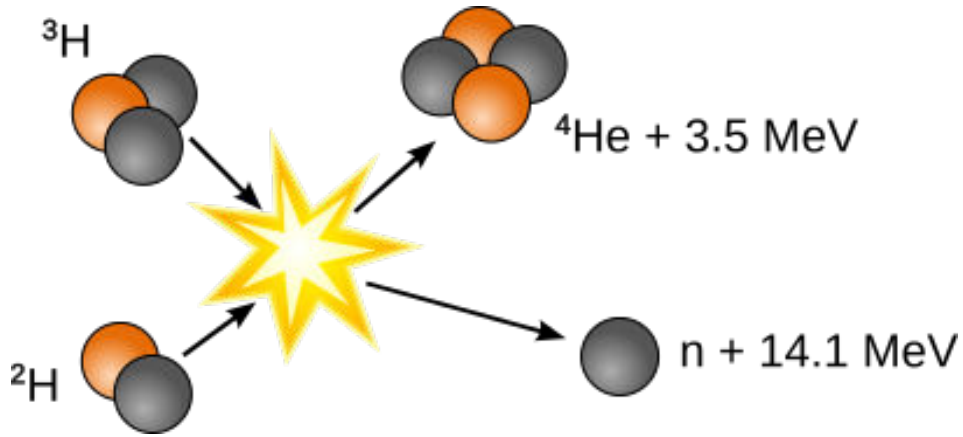


Binding energy per nucleon



credit:[2]

Fúzní $^{2}_{1}\mathrm{H}$ - $^{3}_{1}\mathrm{H}$ (deuterium - tritium) reakce (nejvhodnější kandidát do pozemských podmínek)



credit:[2]

$$\mathbf{^{2}_{1}H_{10\ keV} + {}^{3}_{1}H_{10\ keV} \Rightarrow {}^{4}_{2}He_{3.5\ MeV} + {}^{1}_{0}n_{14.1\ MeV}}$$

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

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

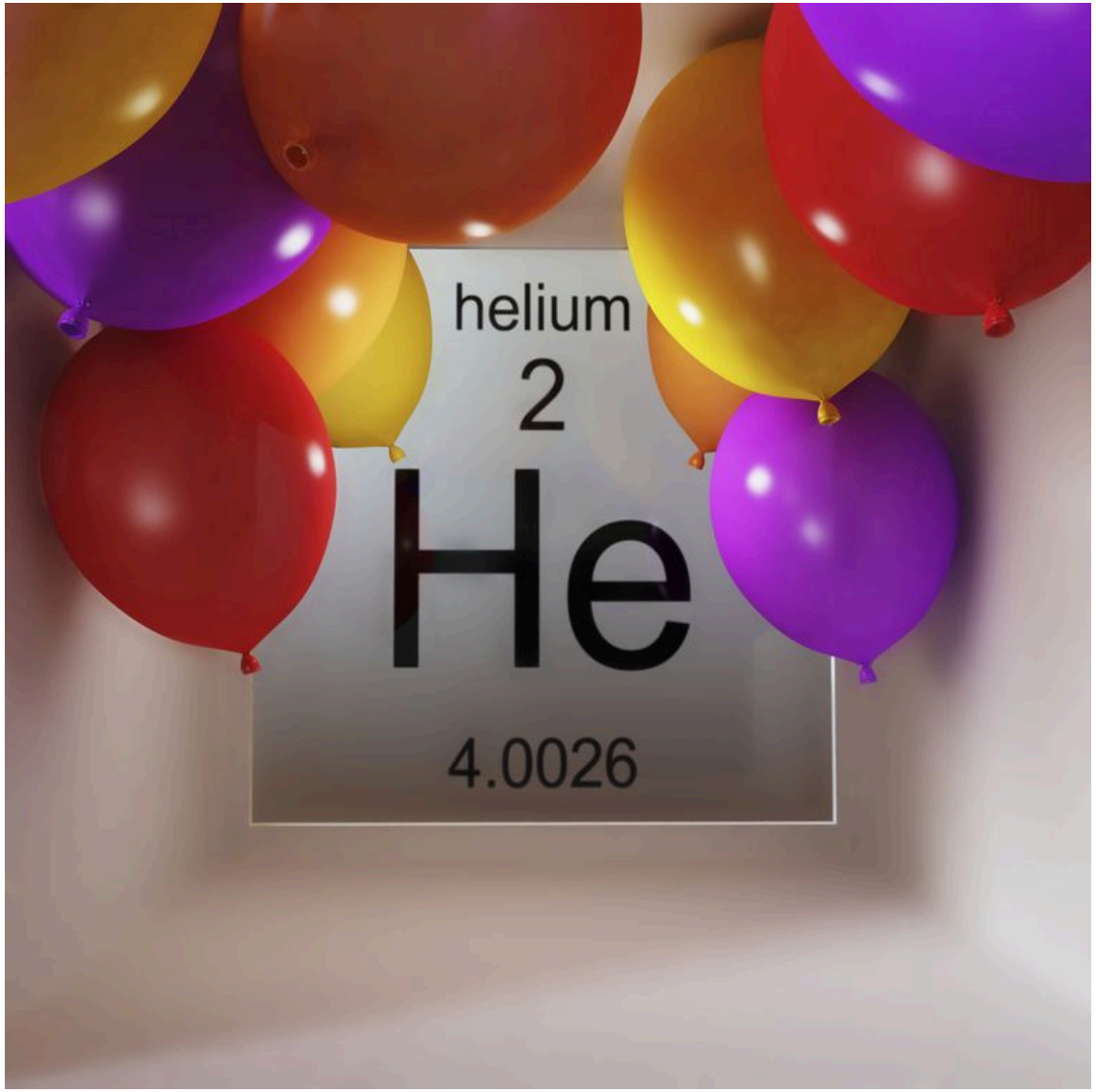
pak hmotnostní schodek $\Delta m = 0.01888 m_u$.

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

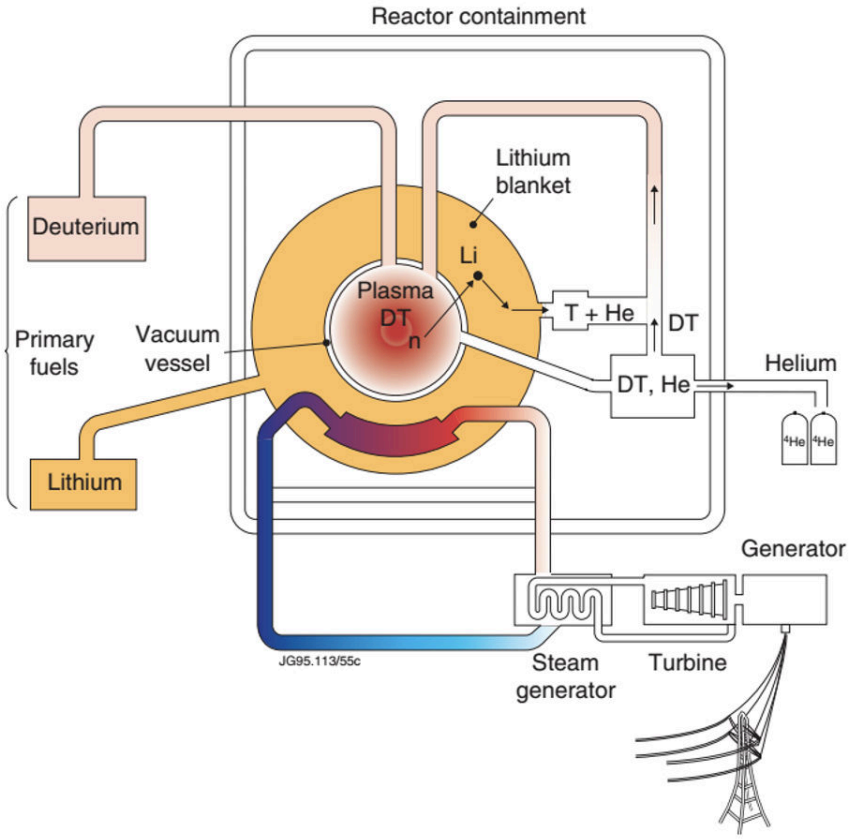
$$1\mathrm{eV} \sim 11600^{\circ}\mathrm{C} \approx \quad \mathbf{^{2}_{1}H_{100\ M^{\circ}C} + {}^{3}_{1}H_{100\ M^{\circ}C} \Rightarrow {}^{4}_{2}He_{35\ G^{\circ}C} + {}^{1}_{0}n_{141\ G^{\circ}C}}$$

Palivo: IAEA "Natural water"

Odpad

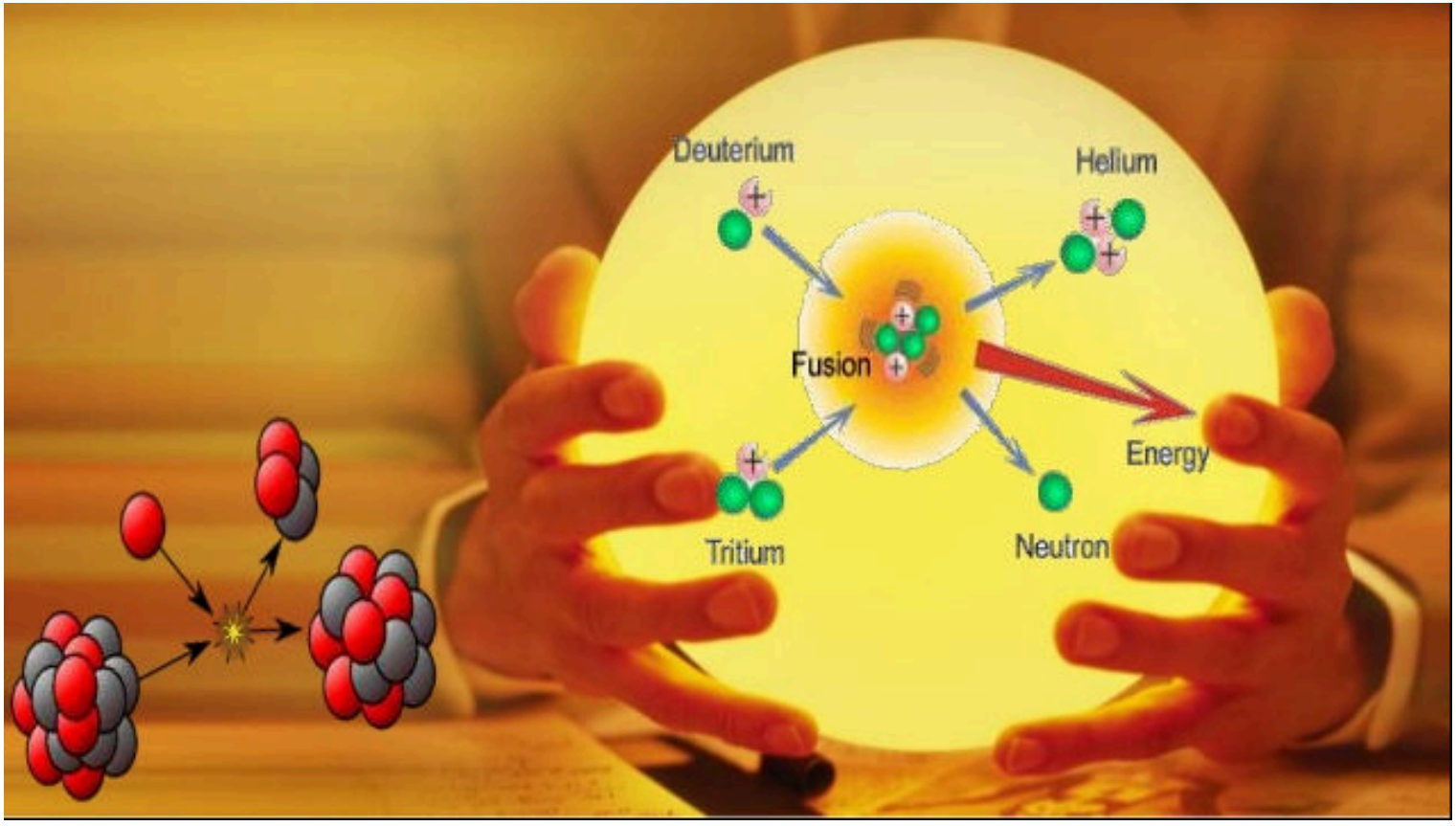


Bezpečnost



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

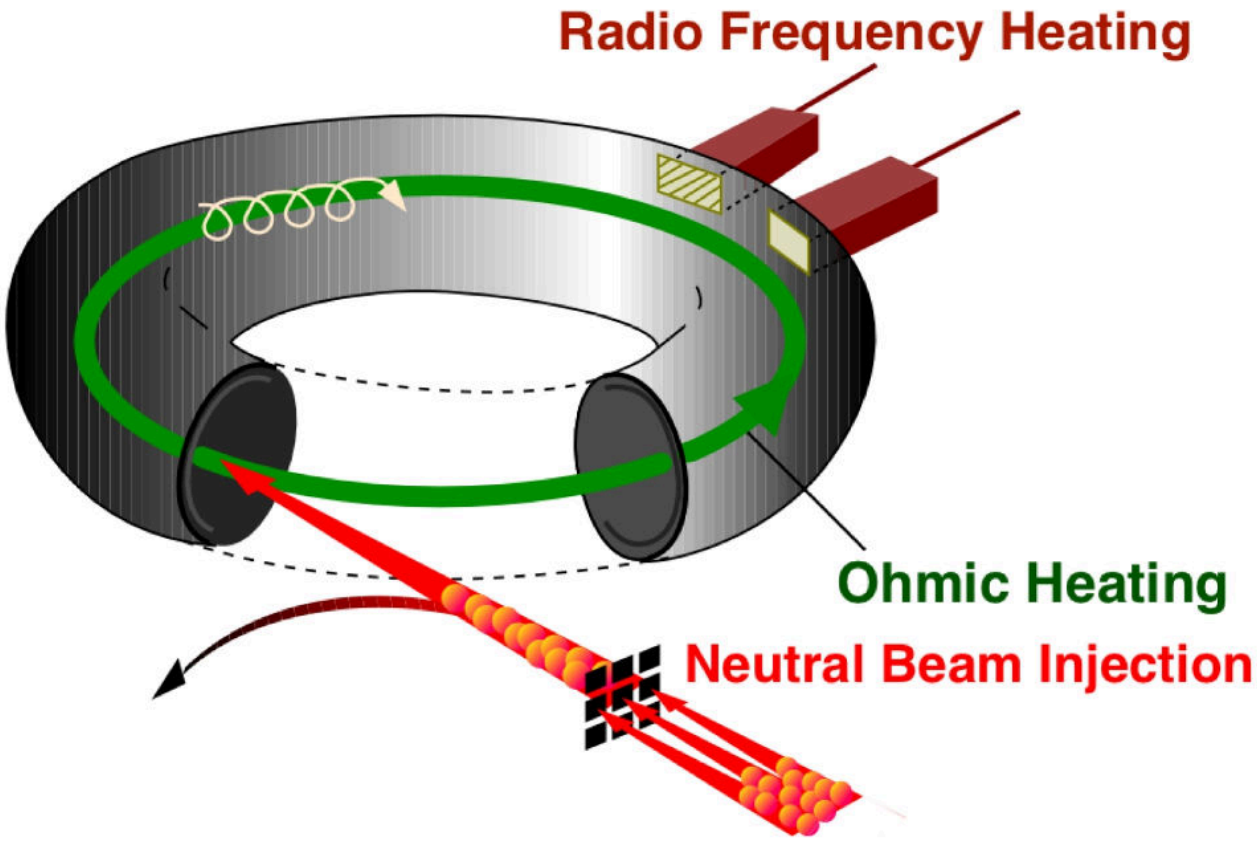
Hledá se vhodná fúzní technologie



Podmínky:

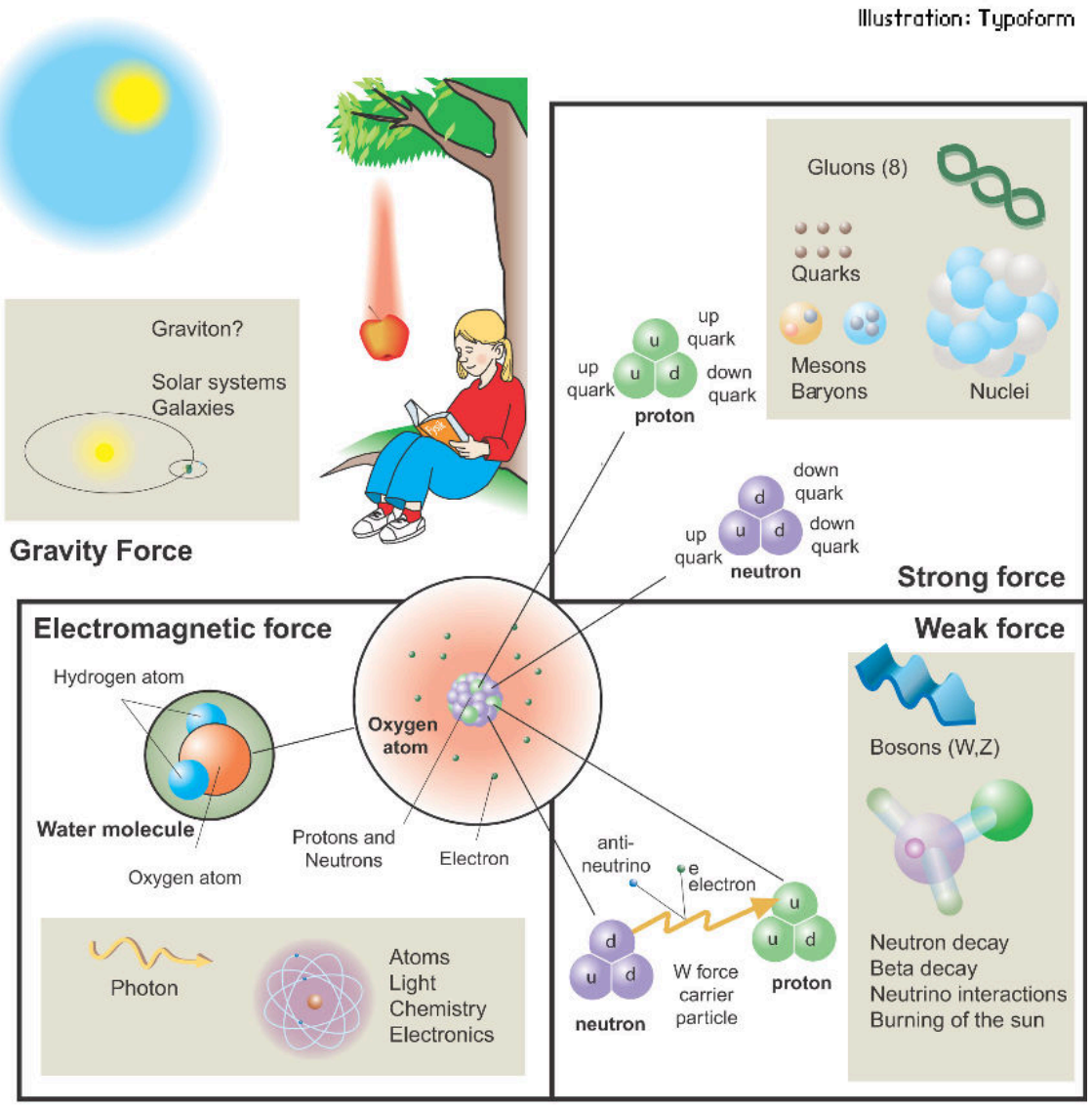
Zahřát na $\sim$ 100 000 000 °C & **udržet** po dobu $\sim$ 30 let + konkurenceschopnost

Ohřev plazmatu



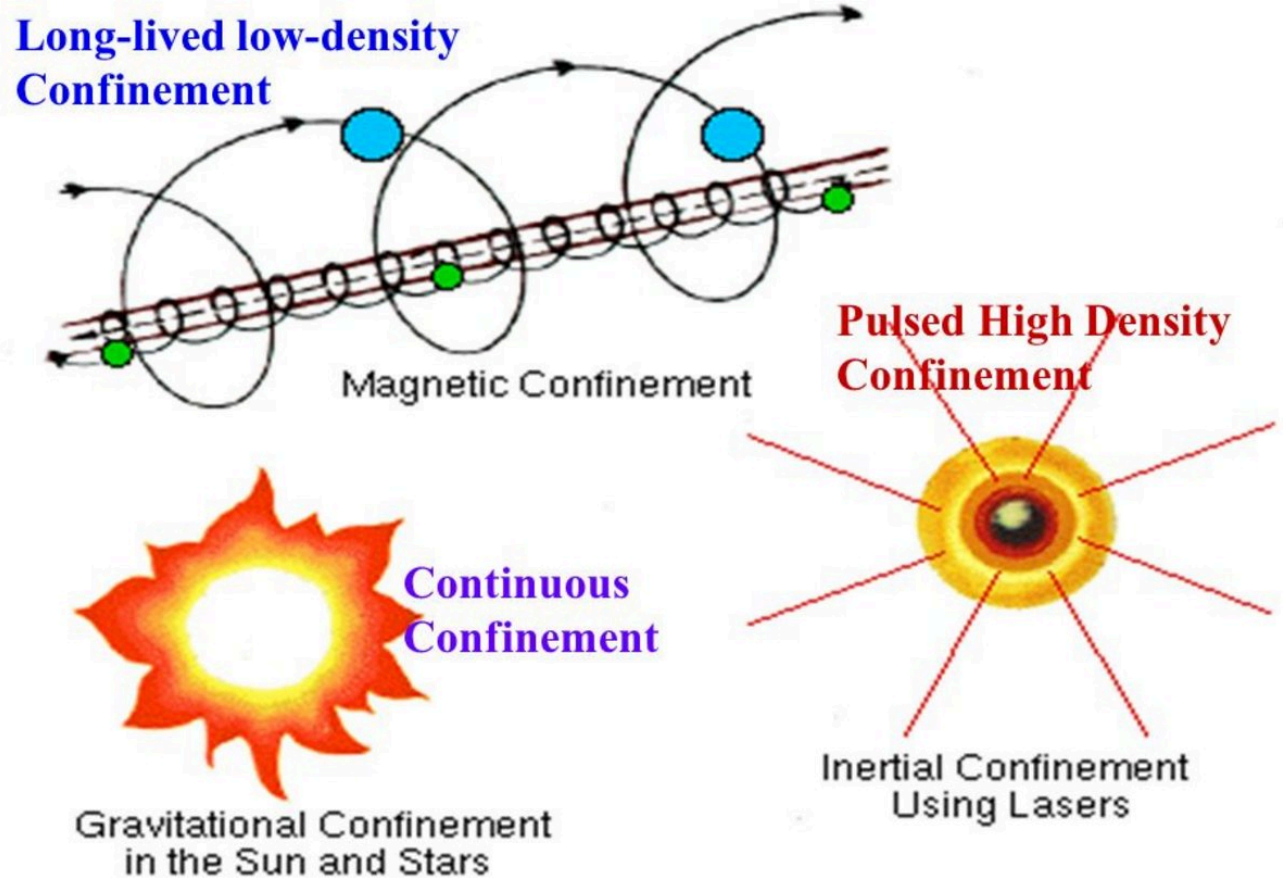
credit:[3]

Fundamental forces (to confine?)

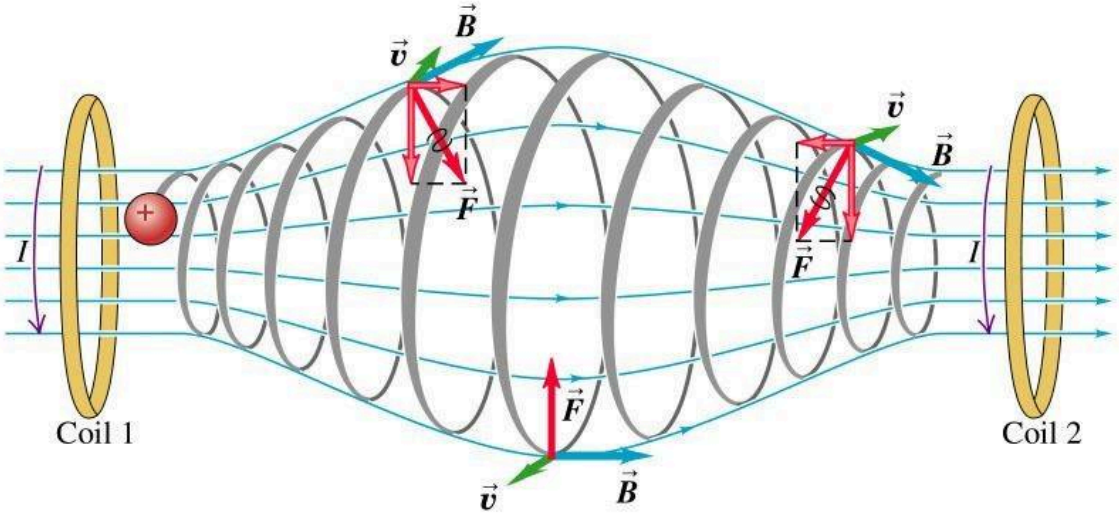


Tři možné cesty jak udržet plazma pro fúzi

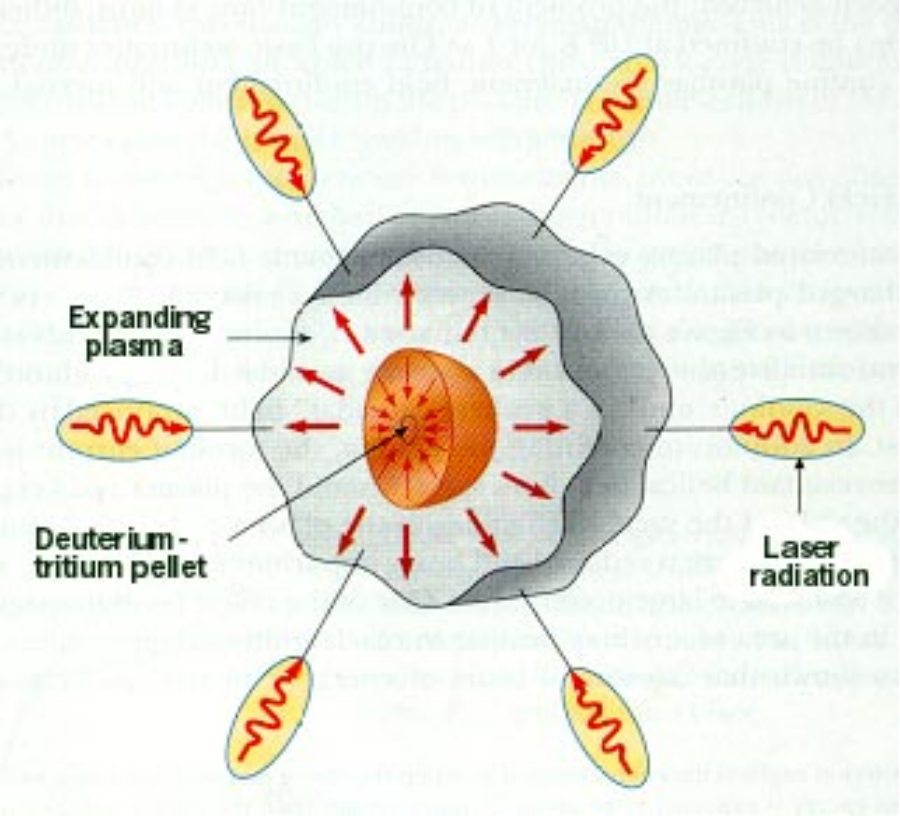
Lawsonovo kritérium: $n\tau_E \geq 1.5 \cdot 10^{20} \frac{\mathrm{s}}{\mathrm{m}^3}$ $(2 \times 6 > 11 \parallel 6 \times 2 > 11)$

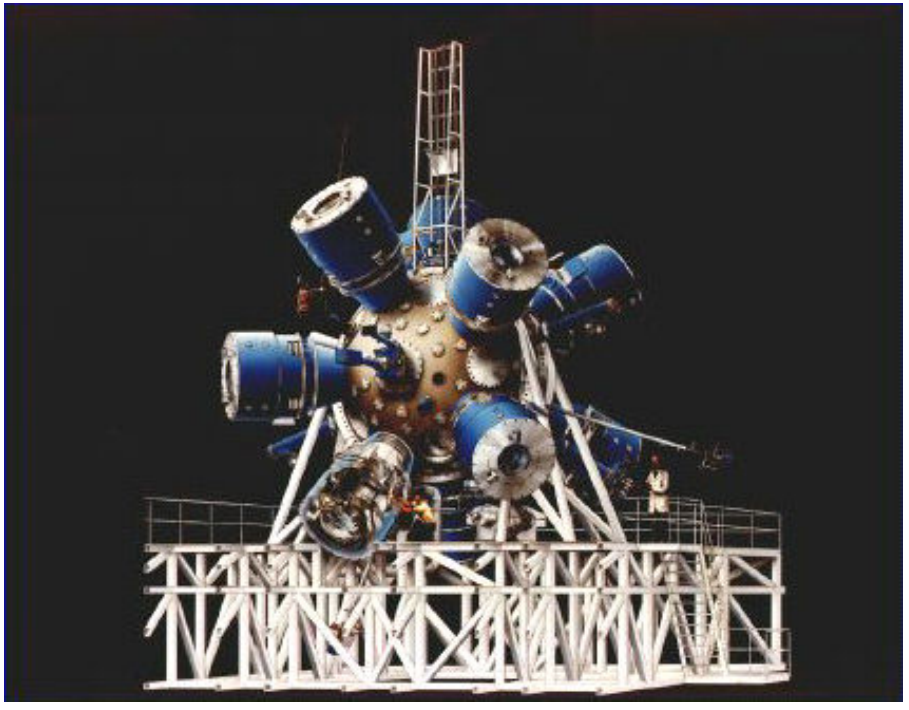


Magnetic confinement: magnetic bottle

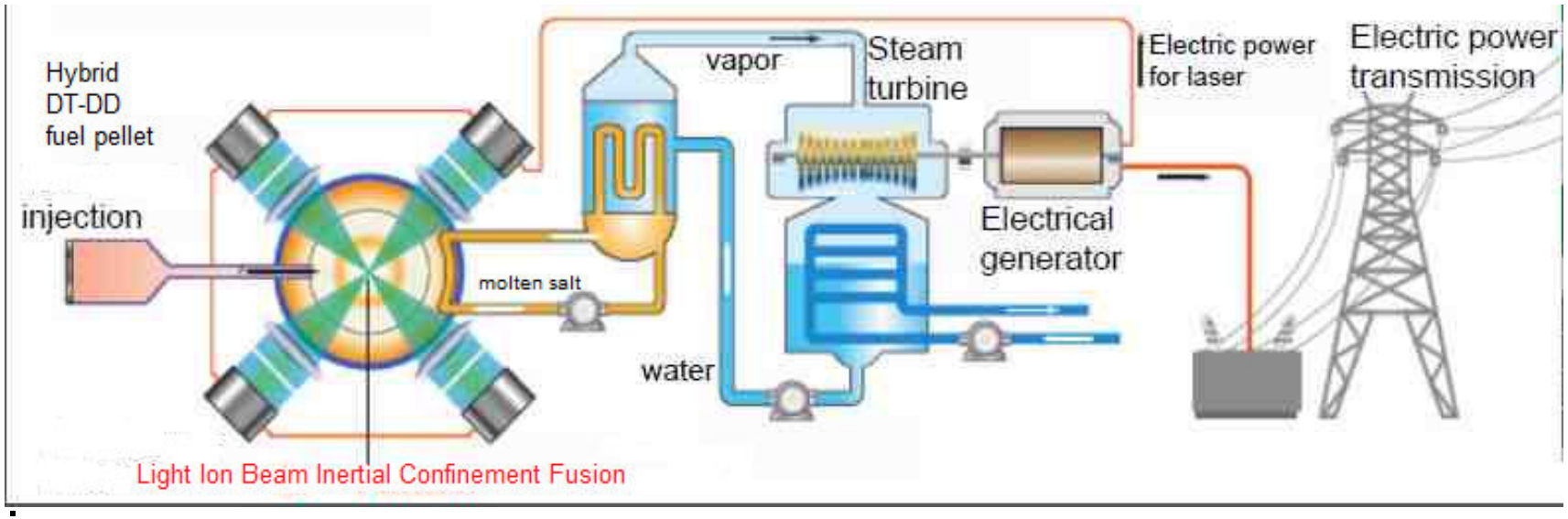


Inertial fusion





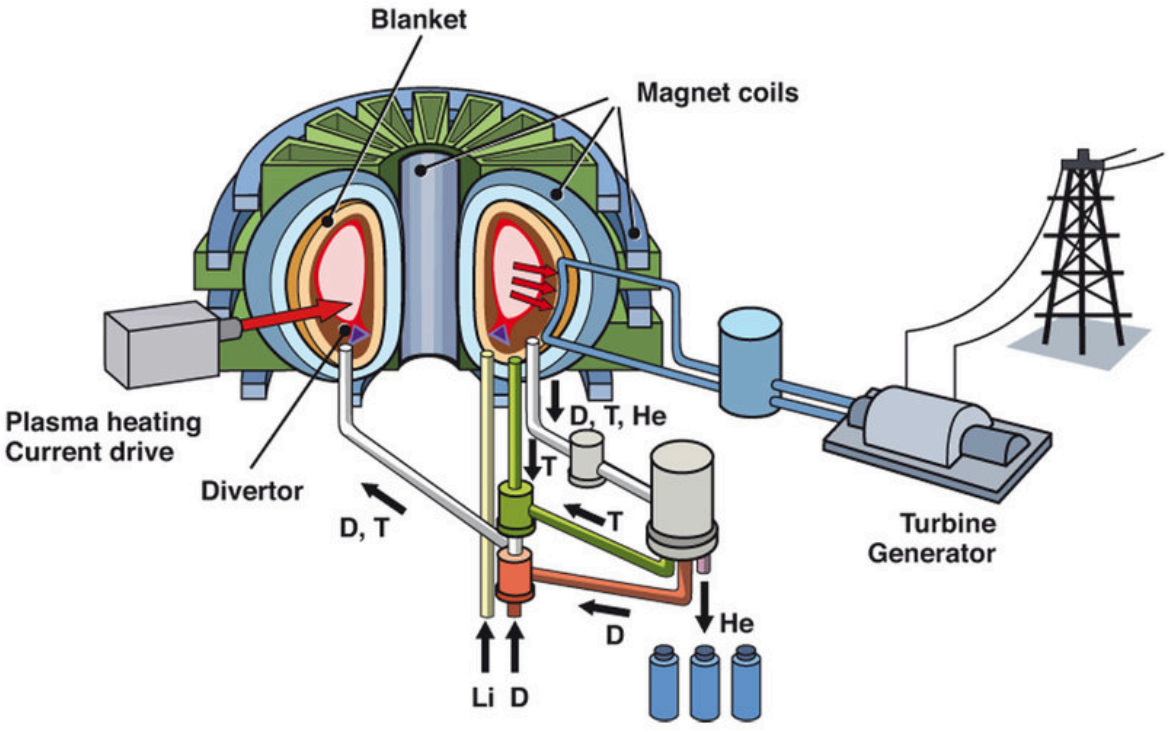
Inertial fusion



credit:mext.jp

Challenge

Vize: Jaderná elektrárna - slučovací/fúzní

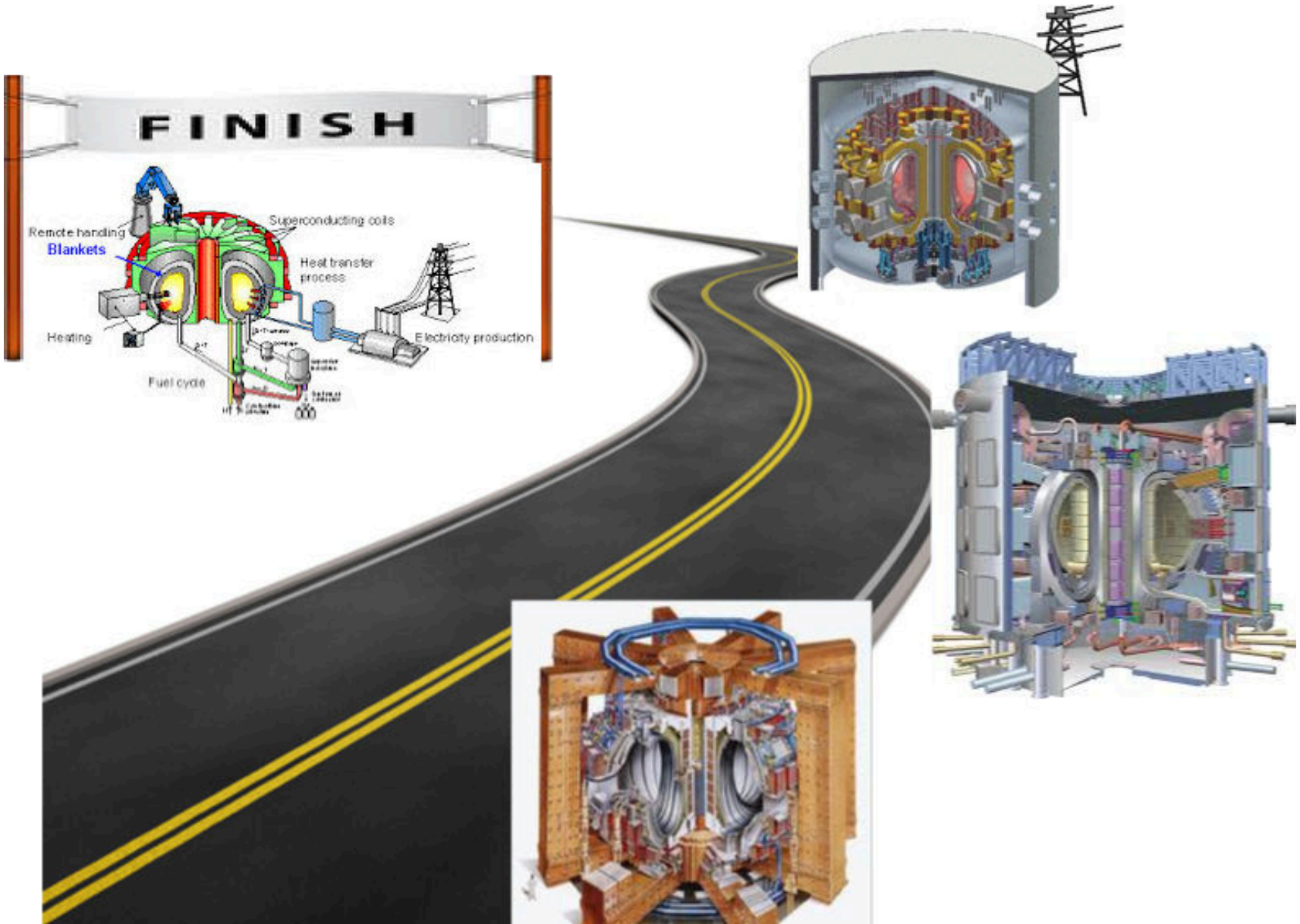


credit:[1]

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

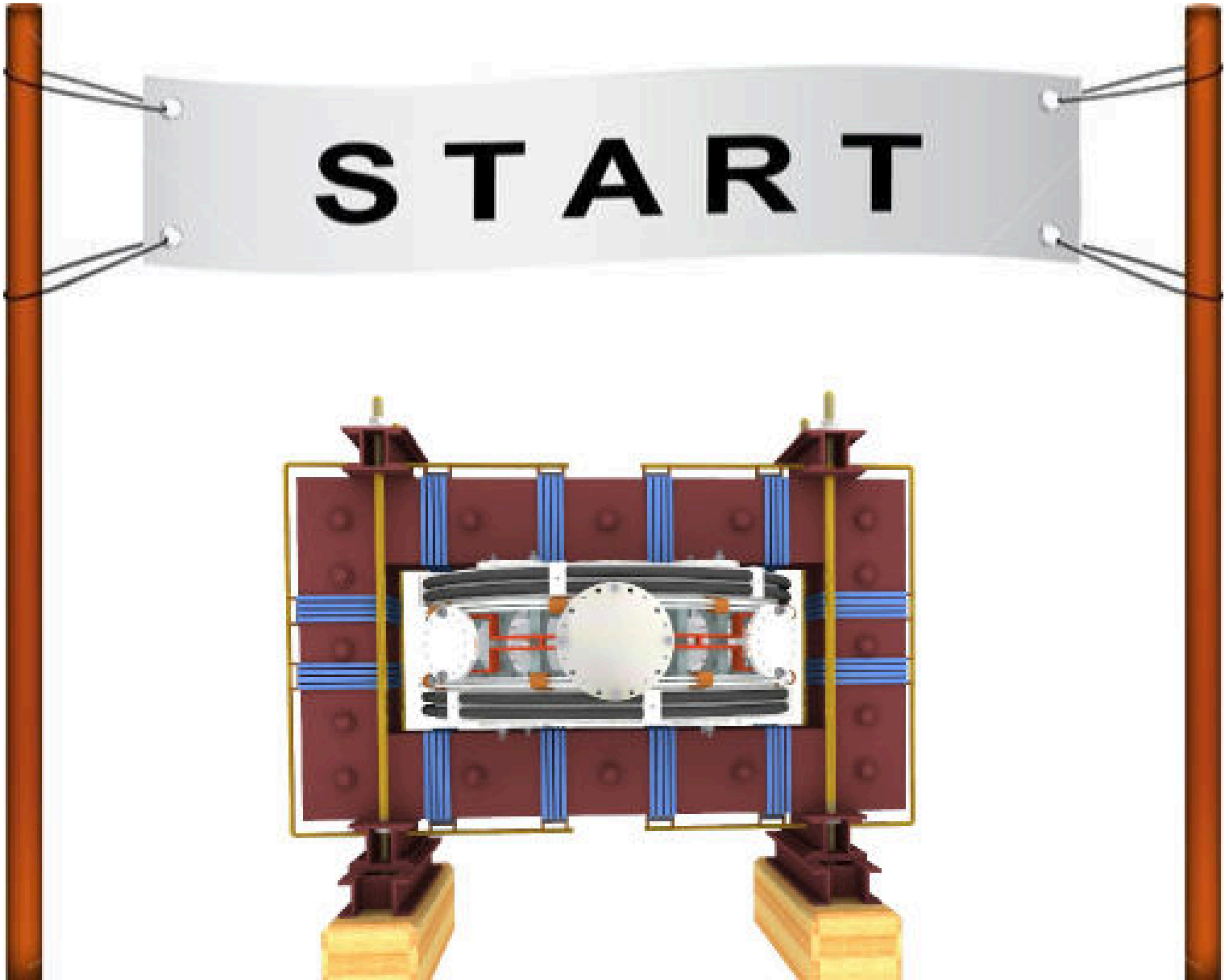
Vypiplat technologii

Milestones to Fusion Power Plant



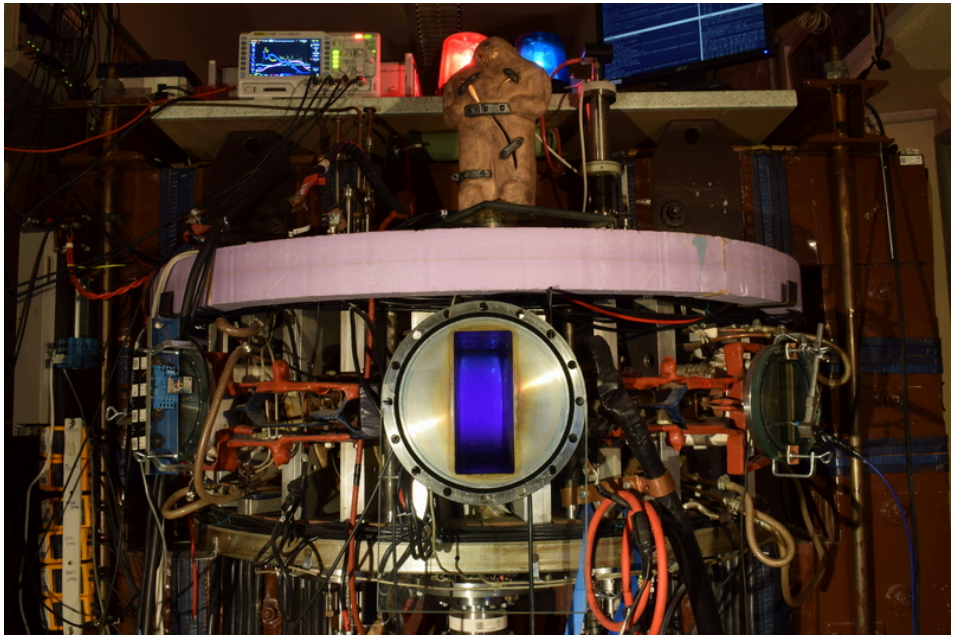
Education importance

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



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
- Maximum plasma current: $I_{\mathrm{p}}^{\mathrm{max}} < 8$ kA
- Maximum toroidal magnetic field: $B_{\mathrm{t}}^{\mathrm{max}} < 0.5$ T
- Typical electron density: $< n_e > \in (0.2, 3) \cdot 10^{19}$ m^{-3}
- Maximum electron temperature: $T_{\mathrm{e}}^{\mathrm{max}} < 80$ eV
- Maximum discharge duration: $\tau_{\mathrm{p}}^{\mathrm{max}} < 25$ ms

Tokamak GOLEM @ Wikipedia ..

File Edit View Go Bookmarks Tools Settings Window Help

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

home Kalendář Produkce Forecast Slovnik Rano

Not logged in Talk Contributions Create account Log in

Article Talk Read Edit View history Search

WIKIPEDIA
The Free Encyclopedia

Main page
Contents
Featured content
Current events

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]

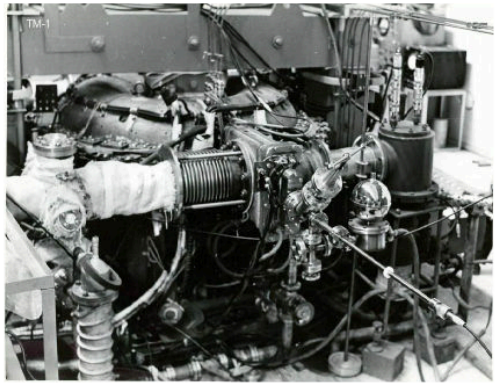
(in chronological order of start of operations)


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

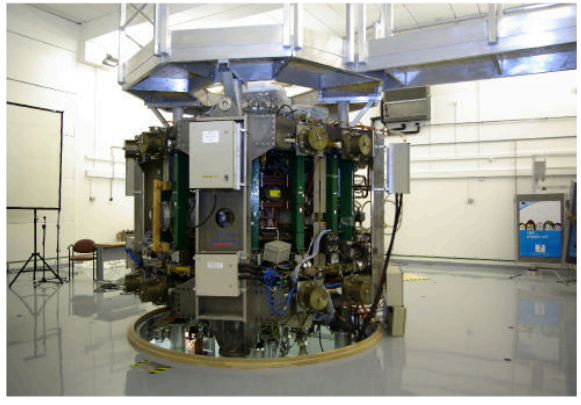
The GOLEM tokamak for education - historical background

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



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

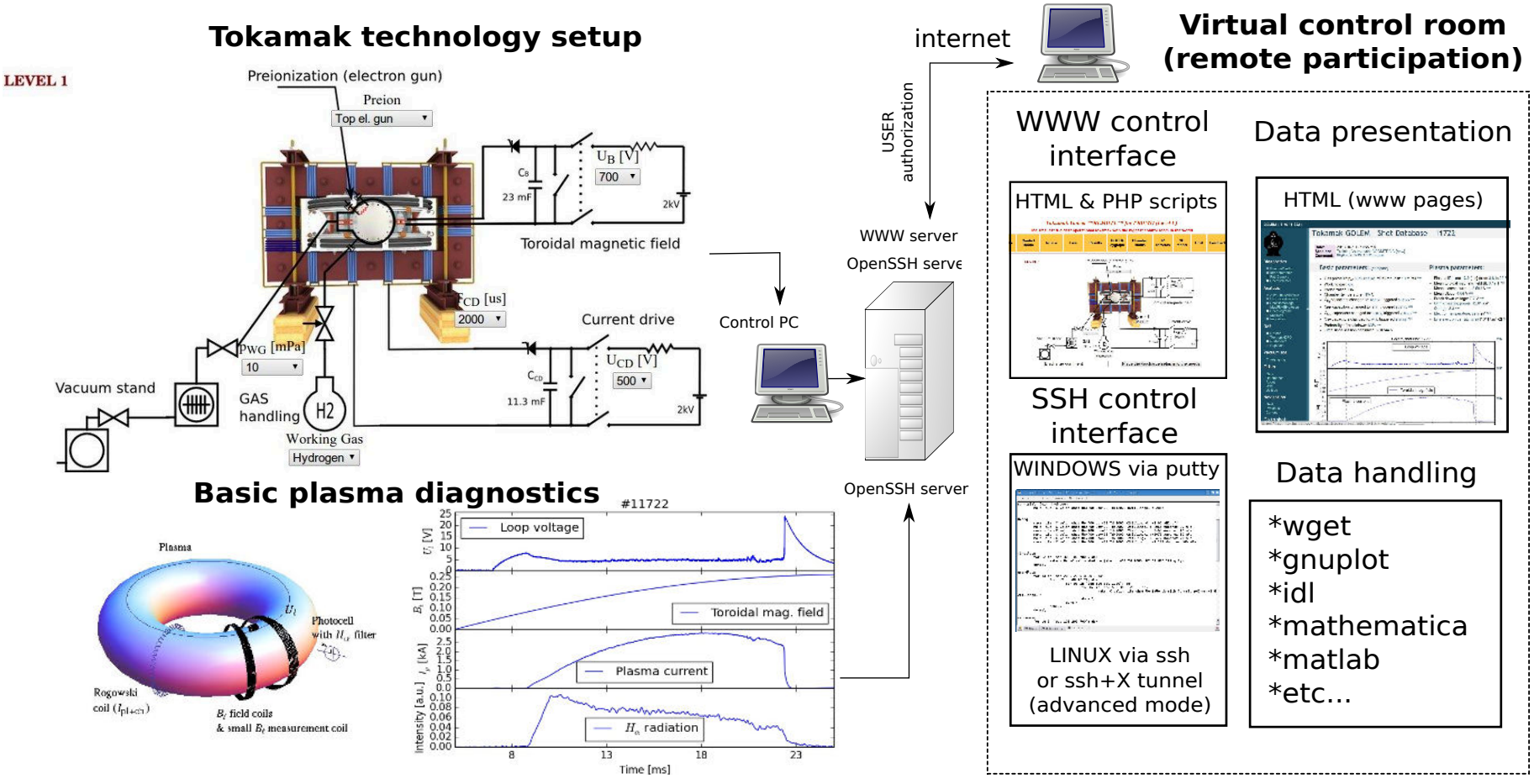
GOLEM

... 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. [4].

The global schematic overview of the GOLEM experiment



The GOLEM tokamak mission

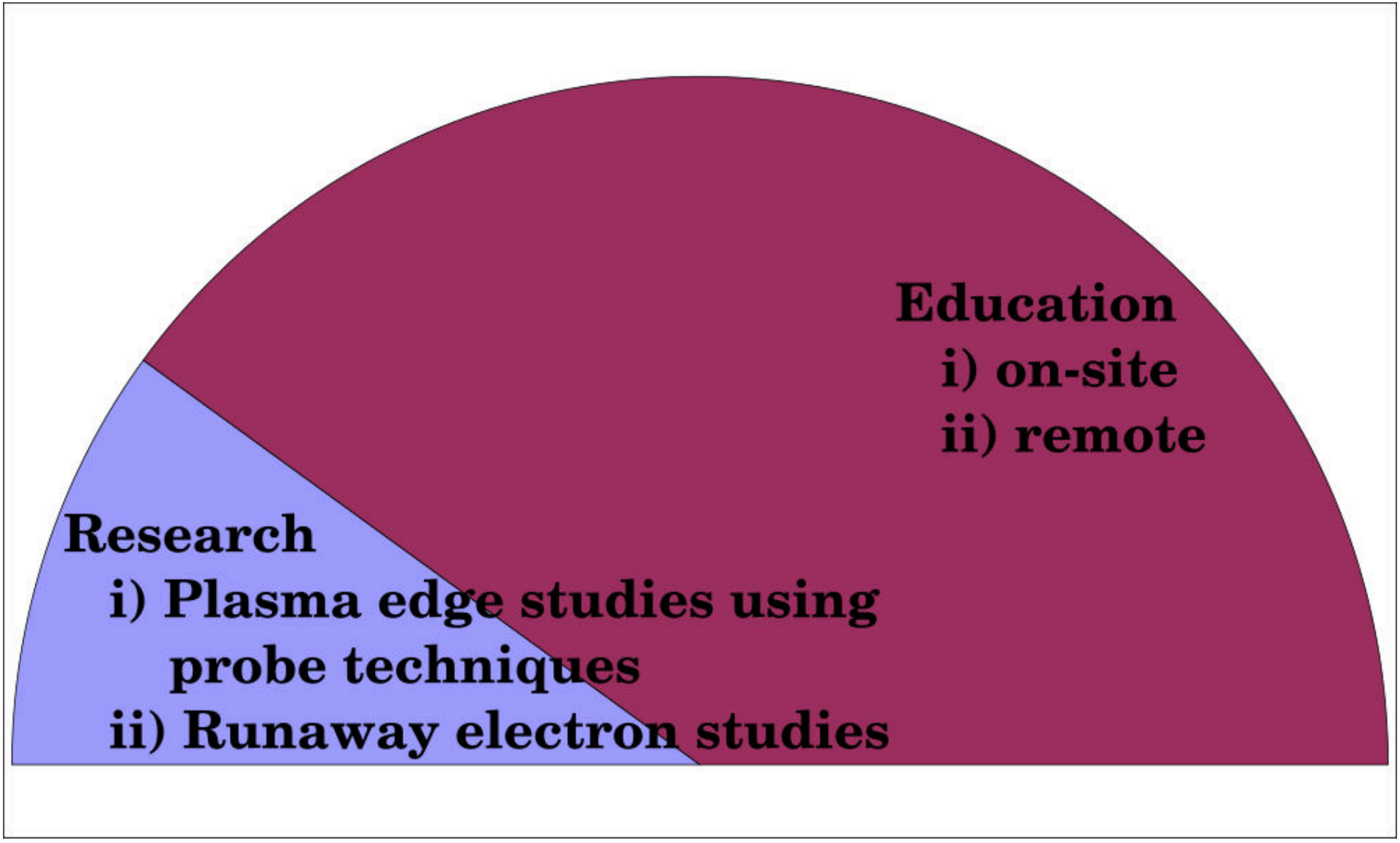
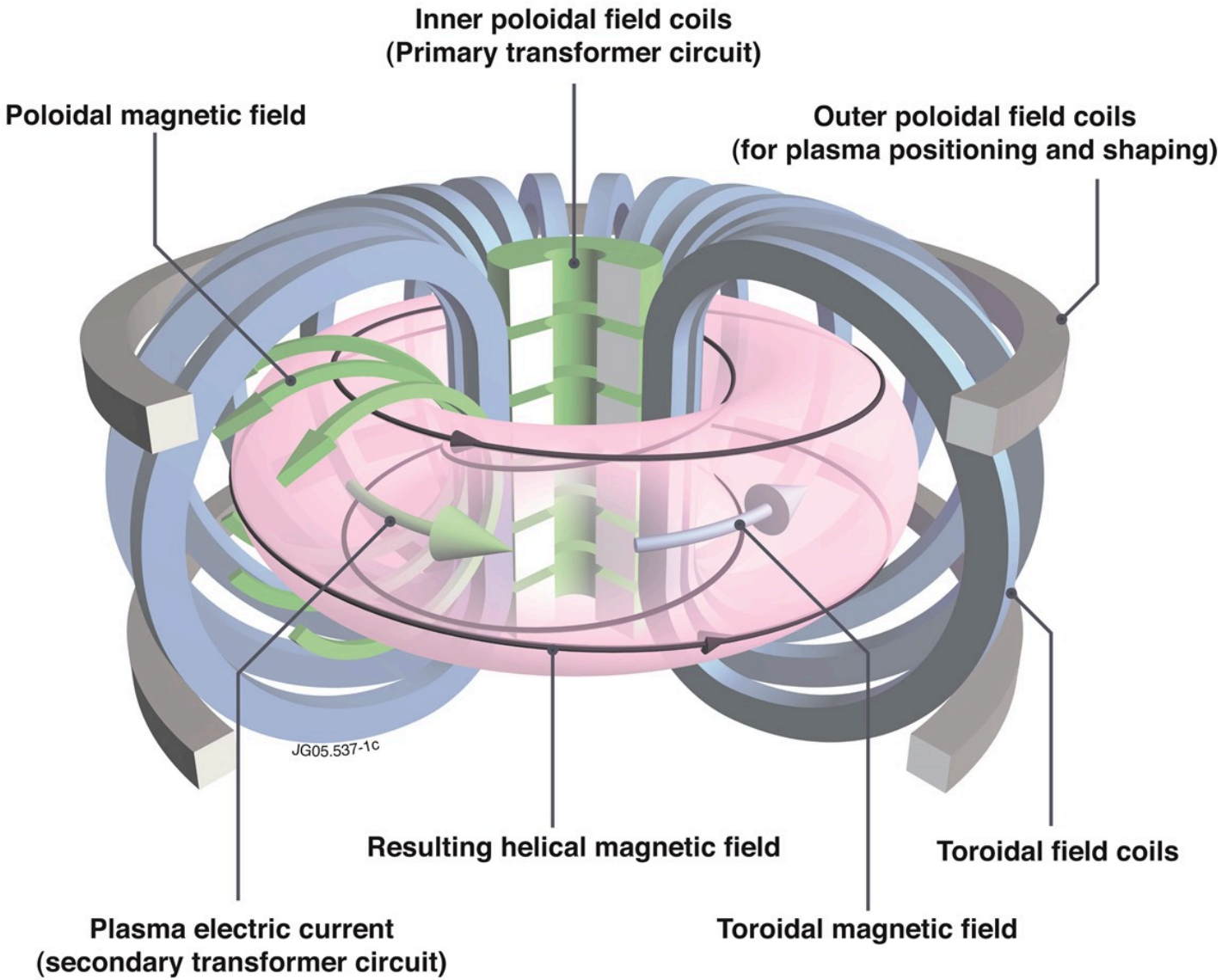


Table of Contents

Tokamak magnetic confinement concept



credit:Tokamak concept@Wiki

Tokamak (GOLEM) basic concept to confine and heat the plasma

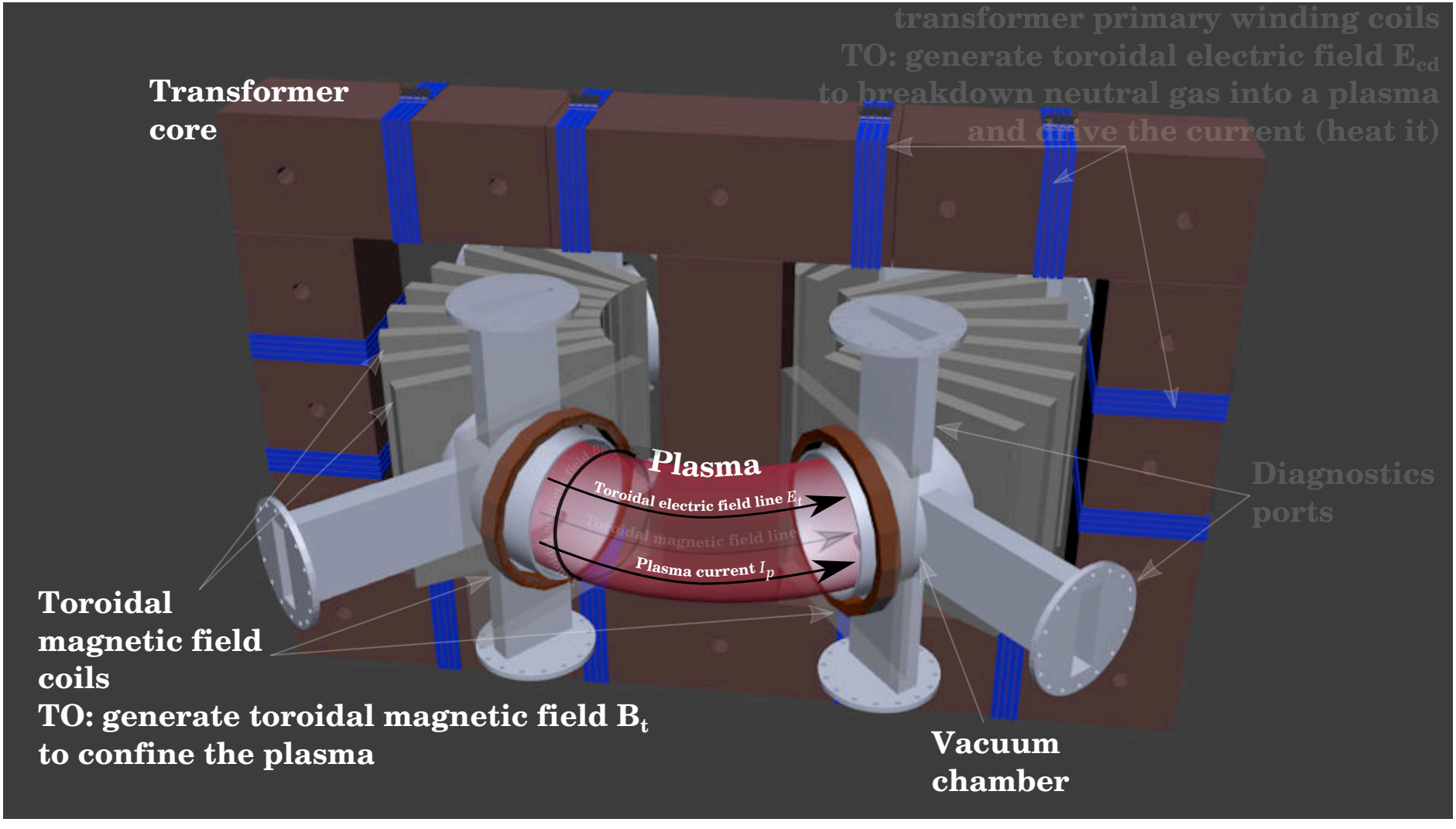
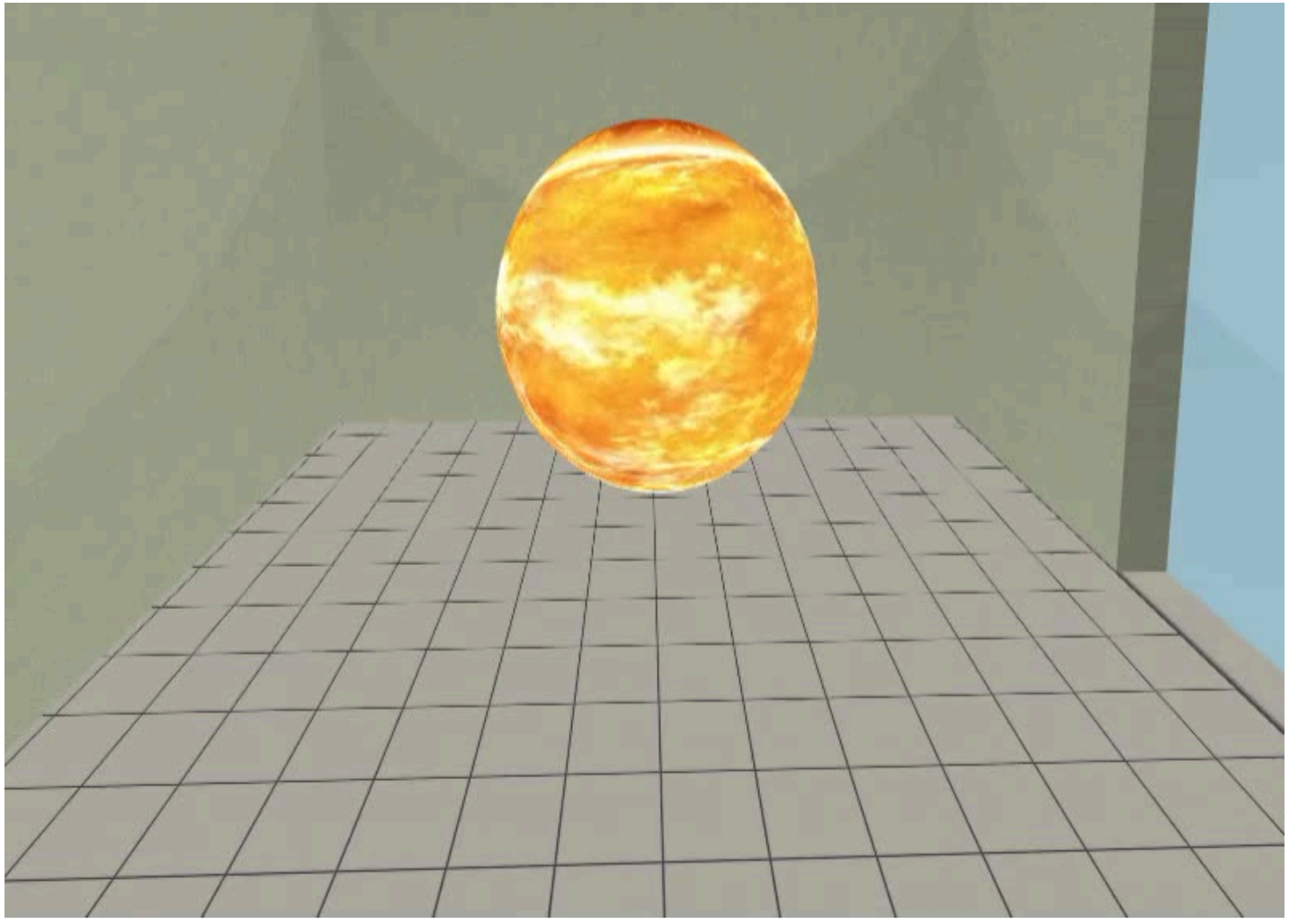
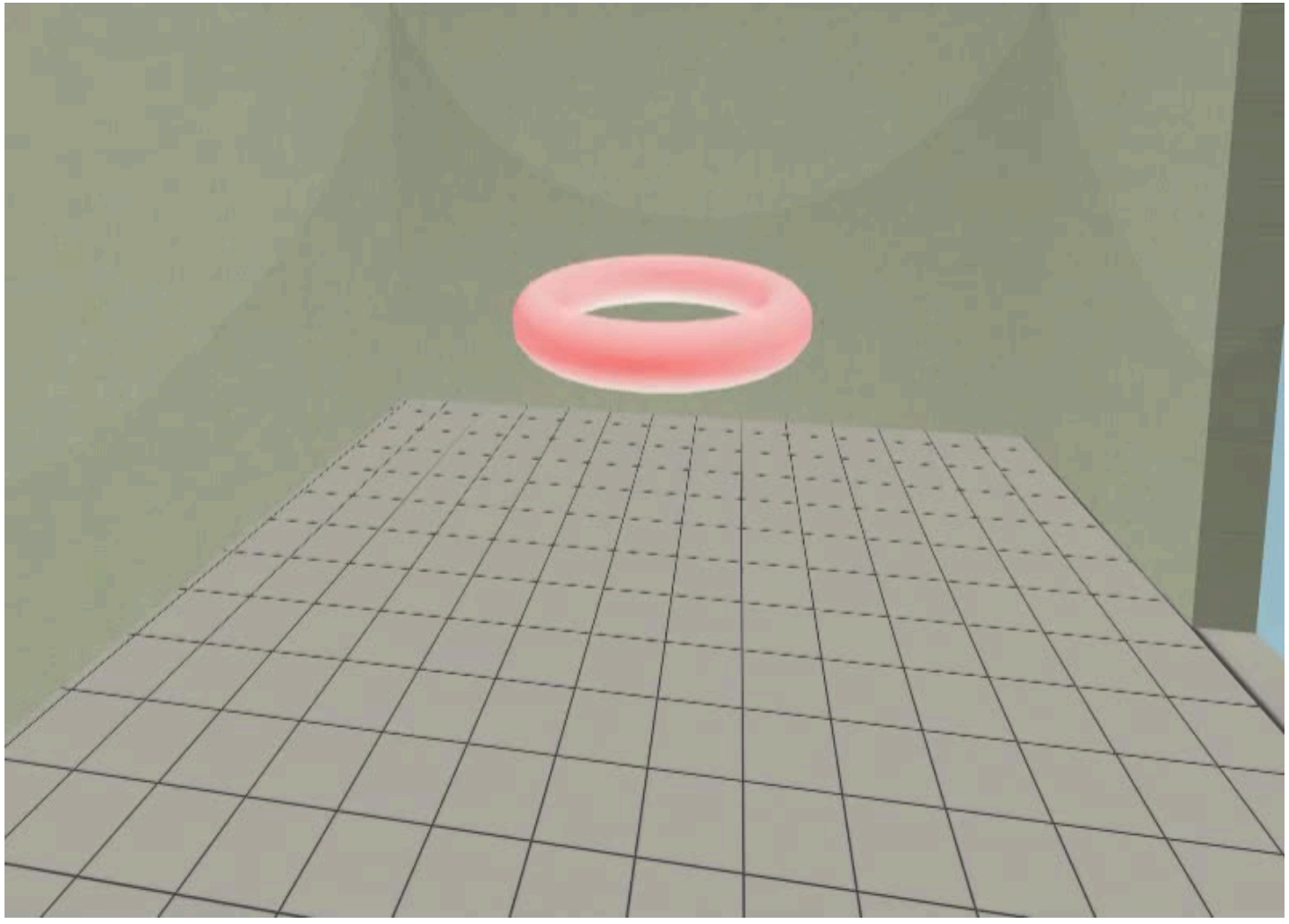


Table of Contents

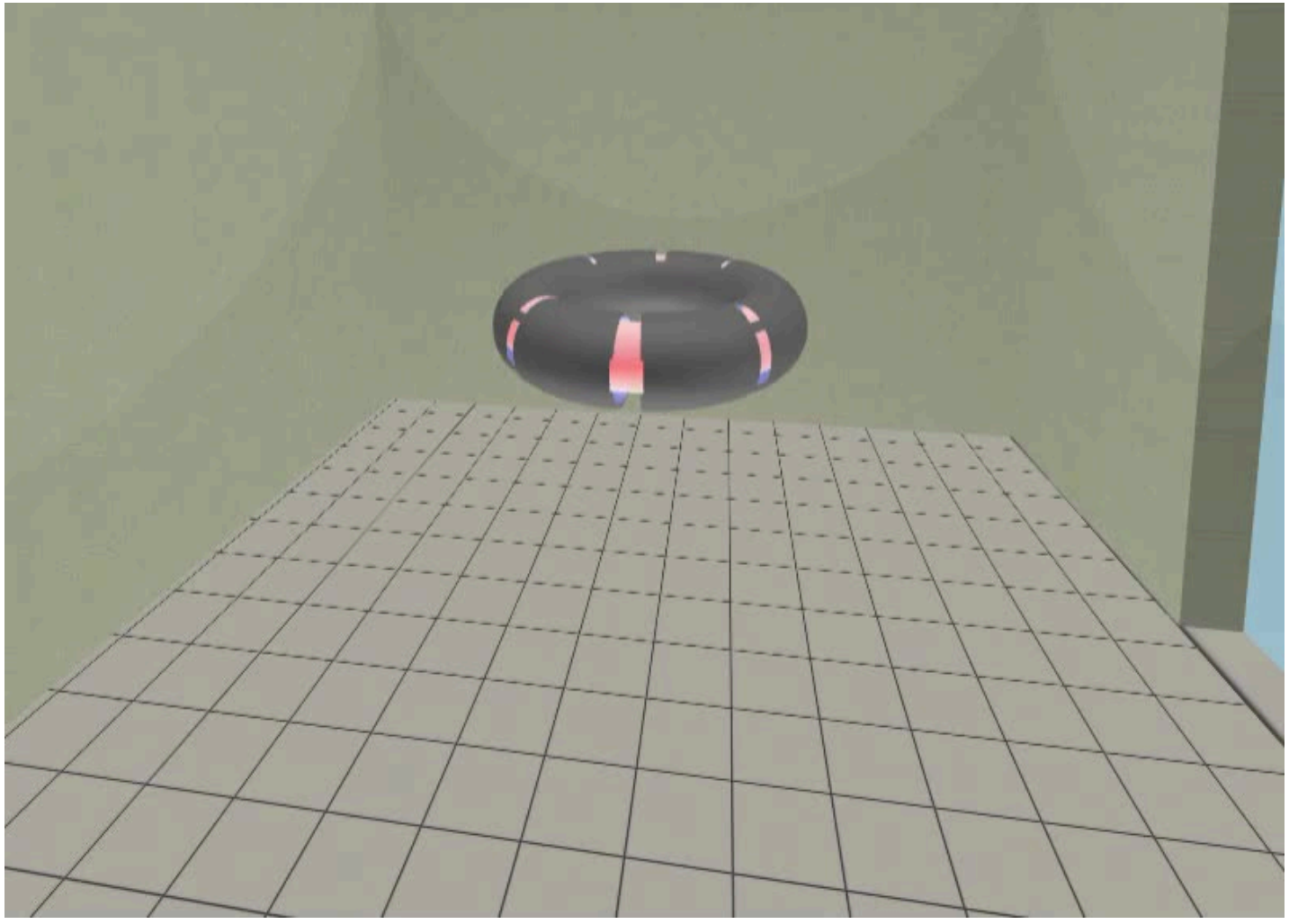
Our goal: the technology to create a μSun on the Earth



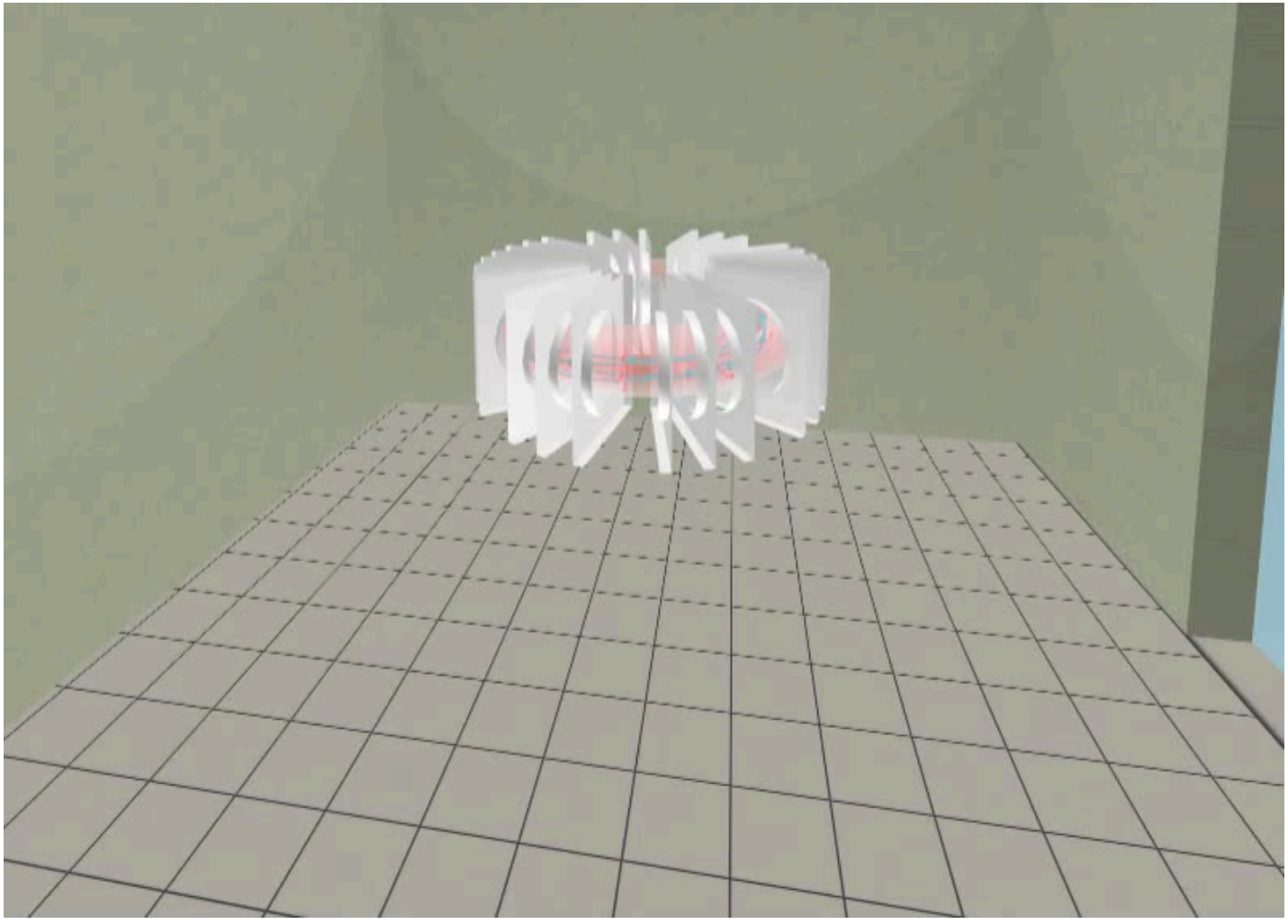
Magnetic confinement requires toroidal geometry



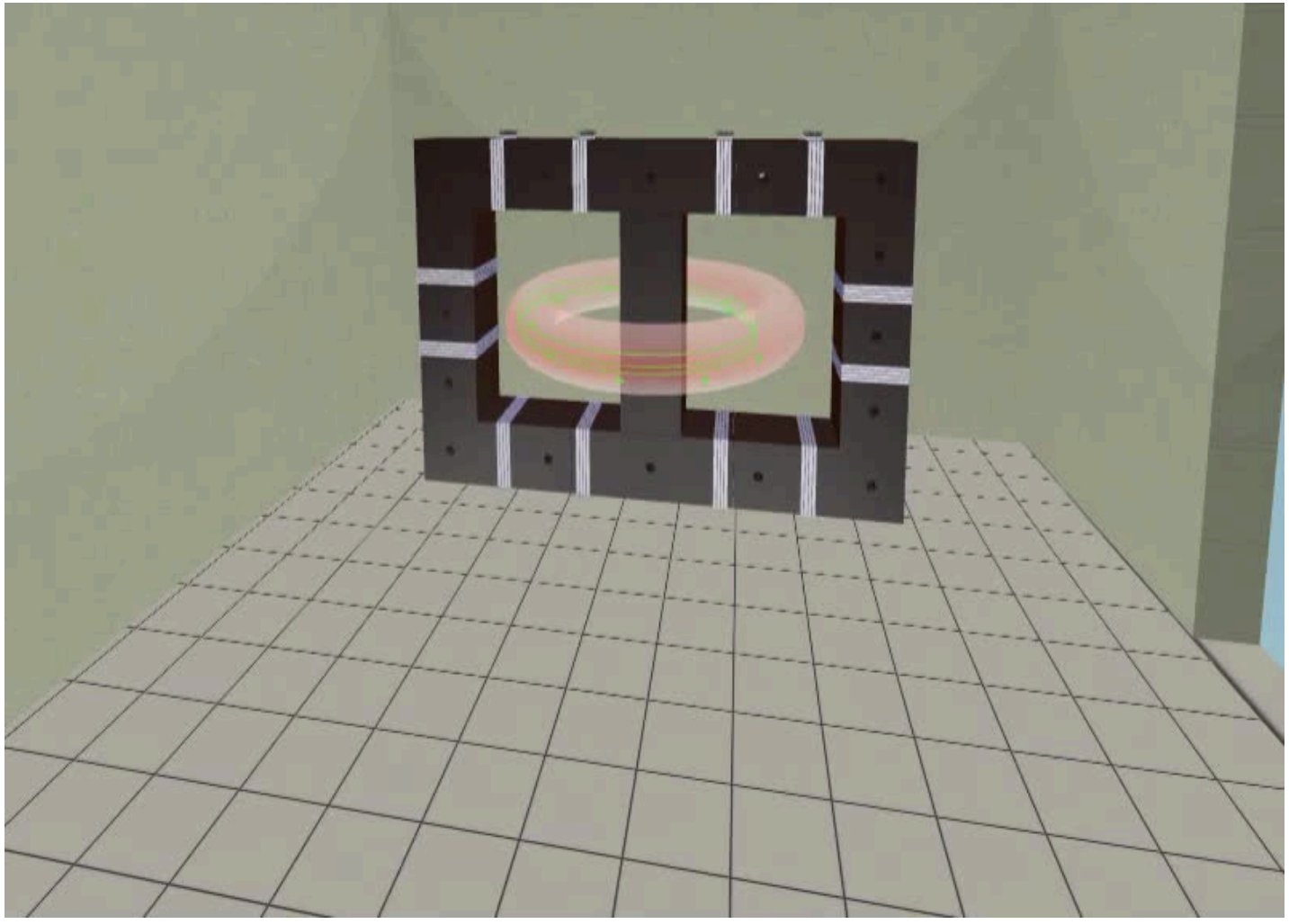
A chamber contains the thermonuclear reaction



Toroidal magnetic field coils confine the plasma



A transformer action creates and heats the plasma



The final technology altogether

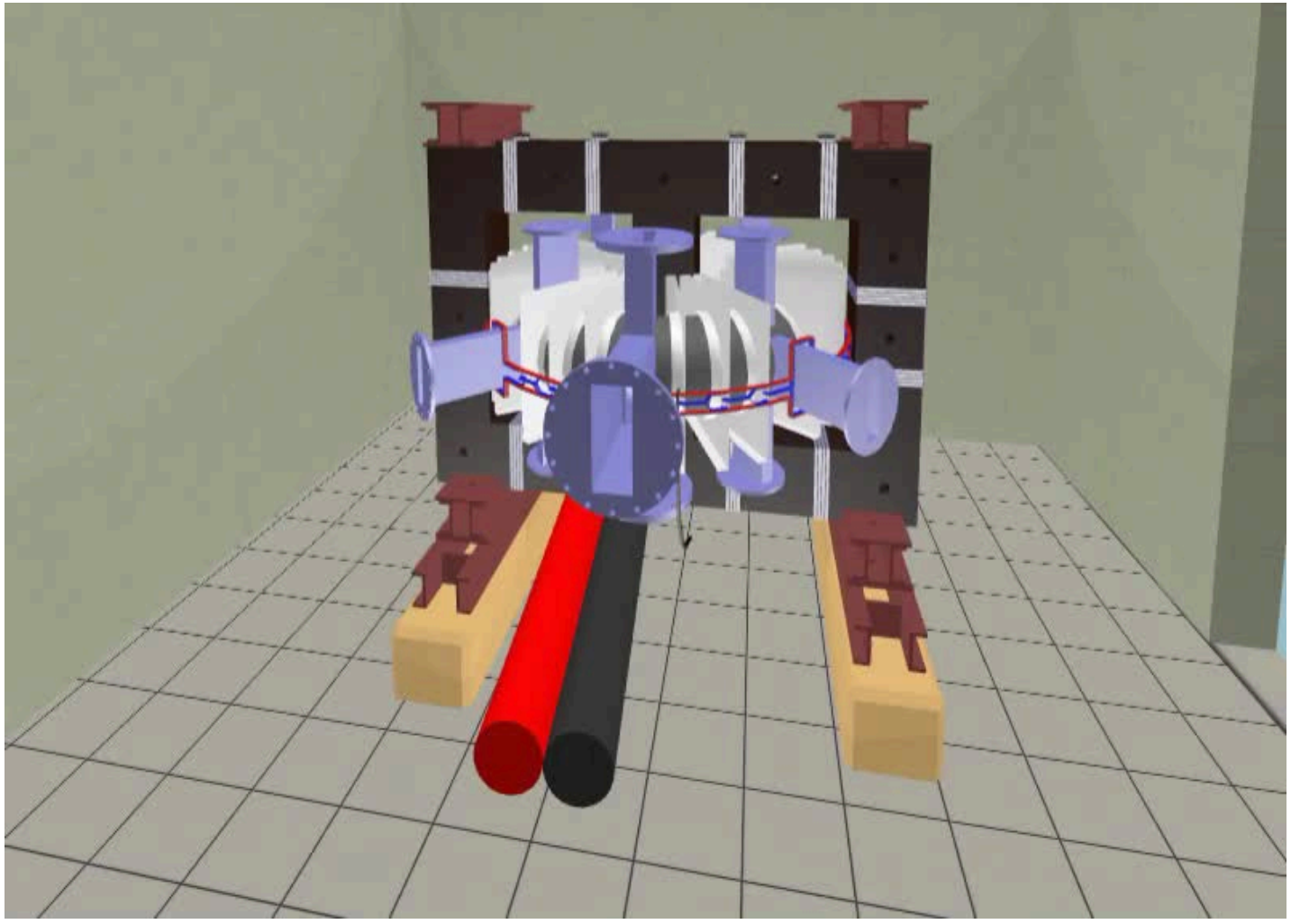
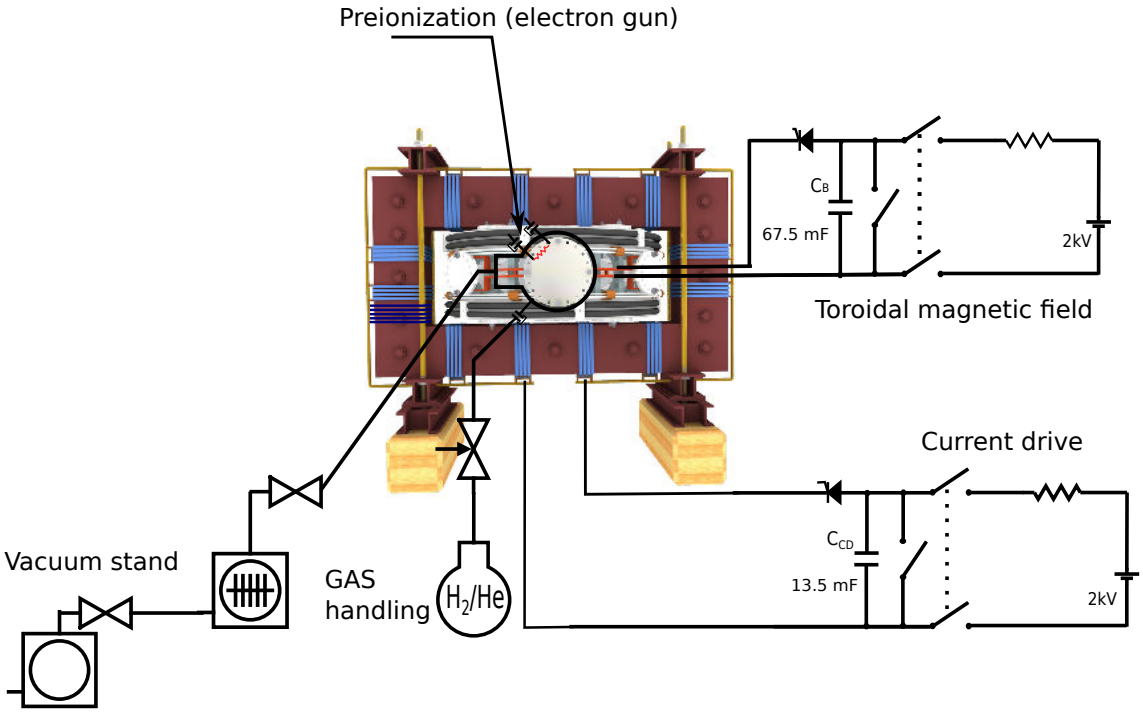


Table of Contents

Plasma in Tokamak (GOLEM) - the least to do

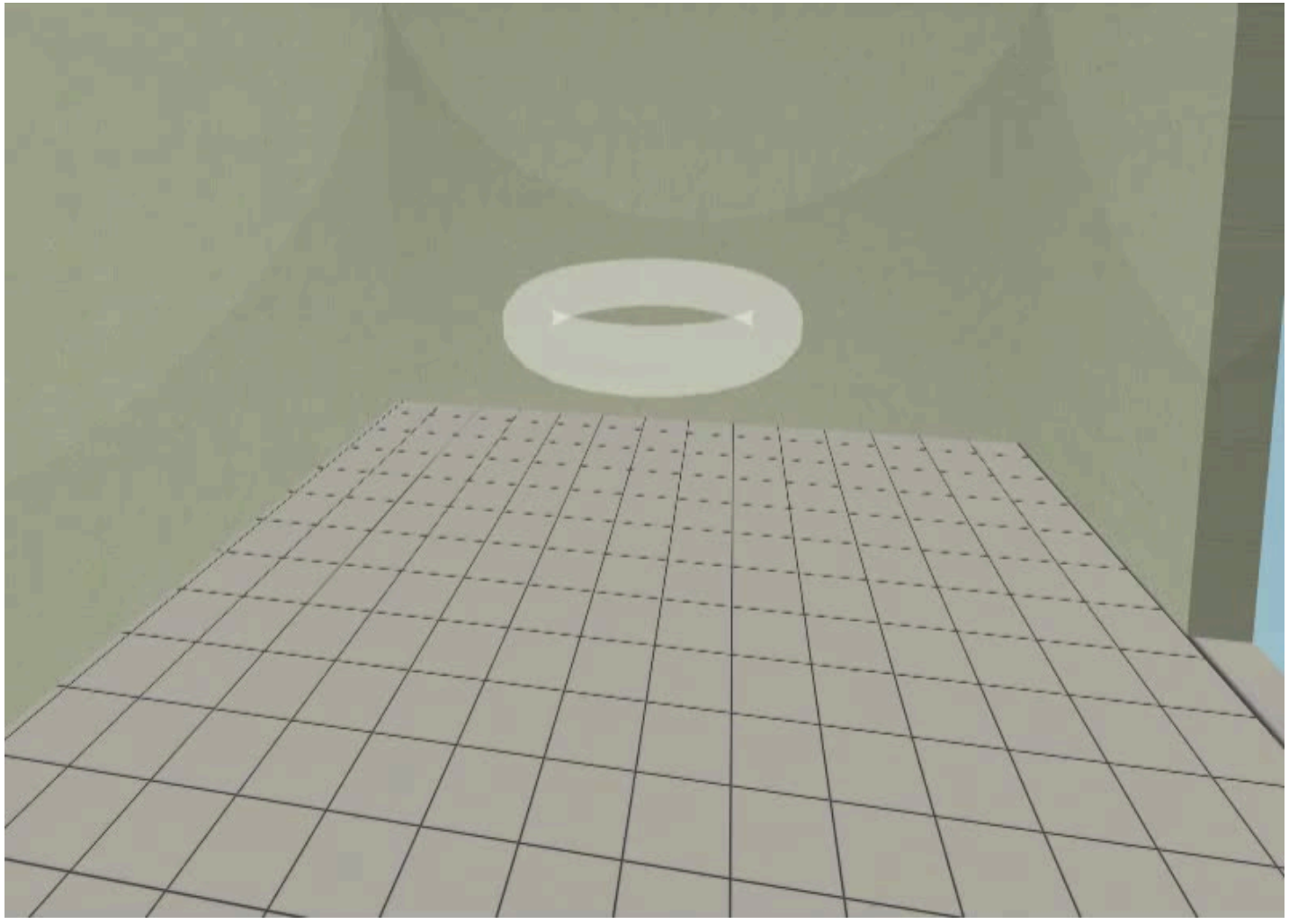


To do:

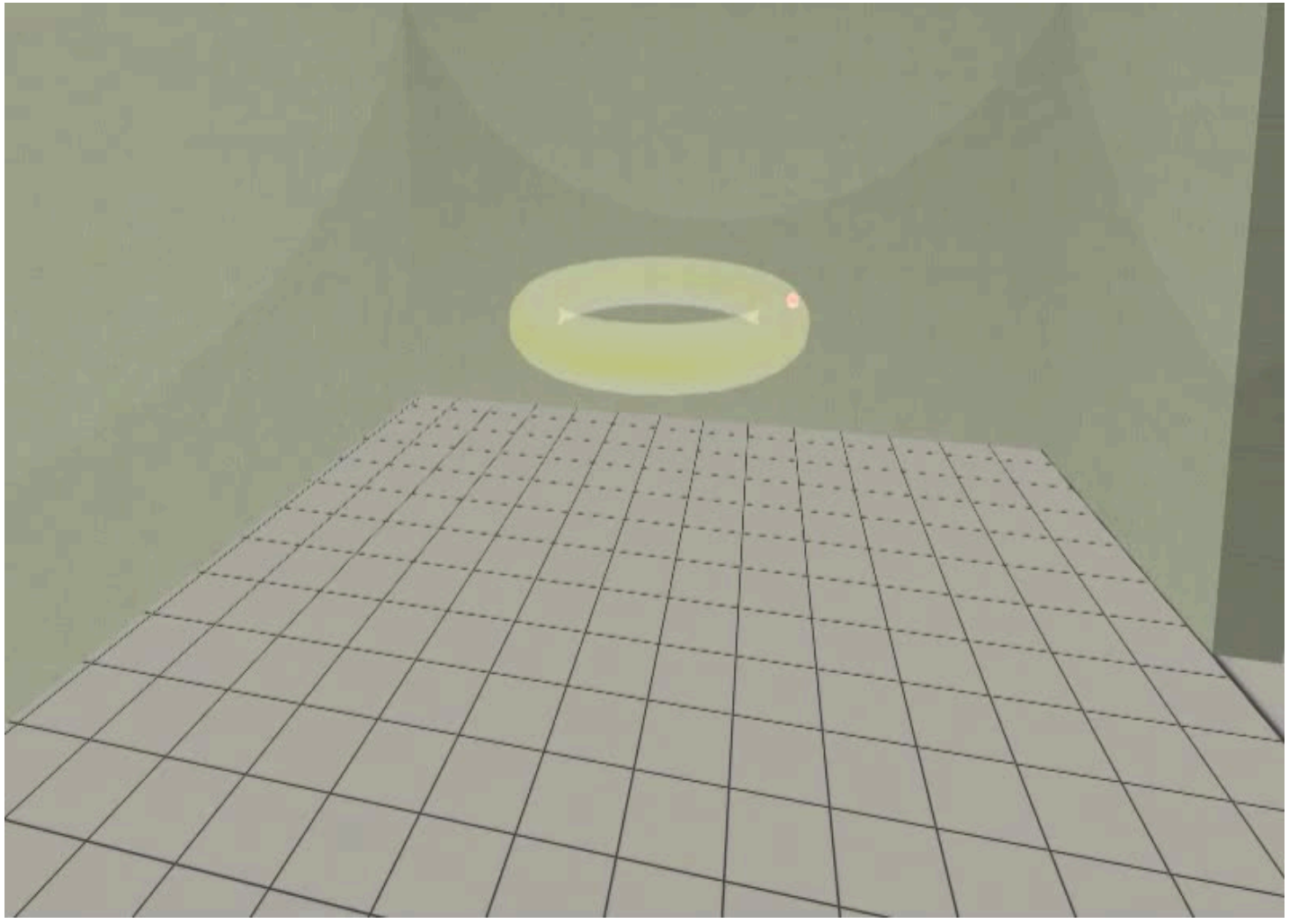
- session start phase:
  - Evacuate the chamber
- pre-discharge phase
  - Charge the capacitors
  - Fill in the working gas
  - Preionization
- discharge phase
  - Toroidal magnetic field to confine plasma
  - Toroidal electric field to breakdown neutral gas into plasma
  - Toroidal electric field to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

Table of Contents

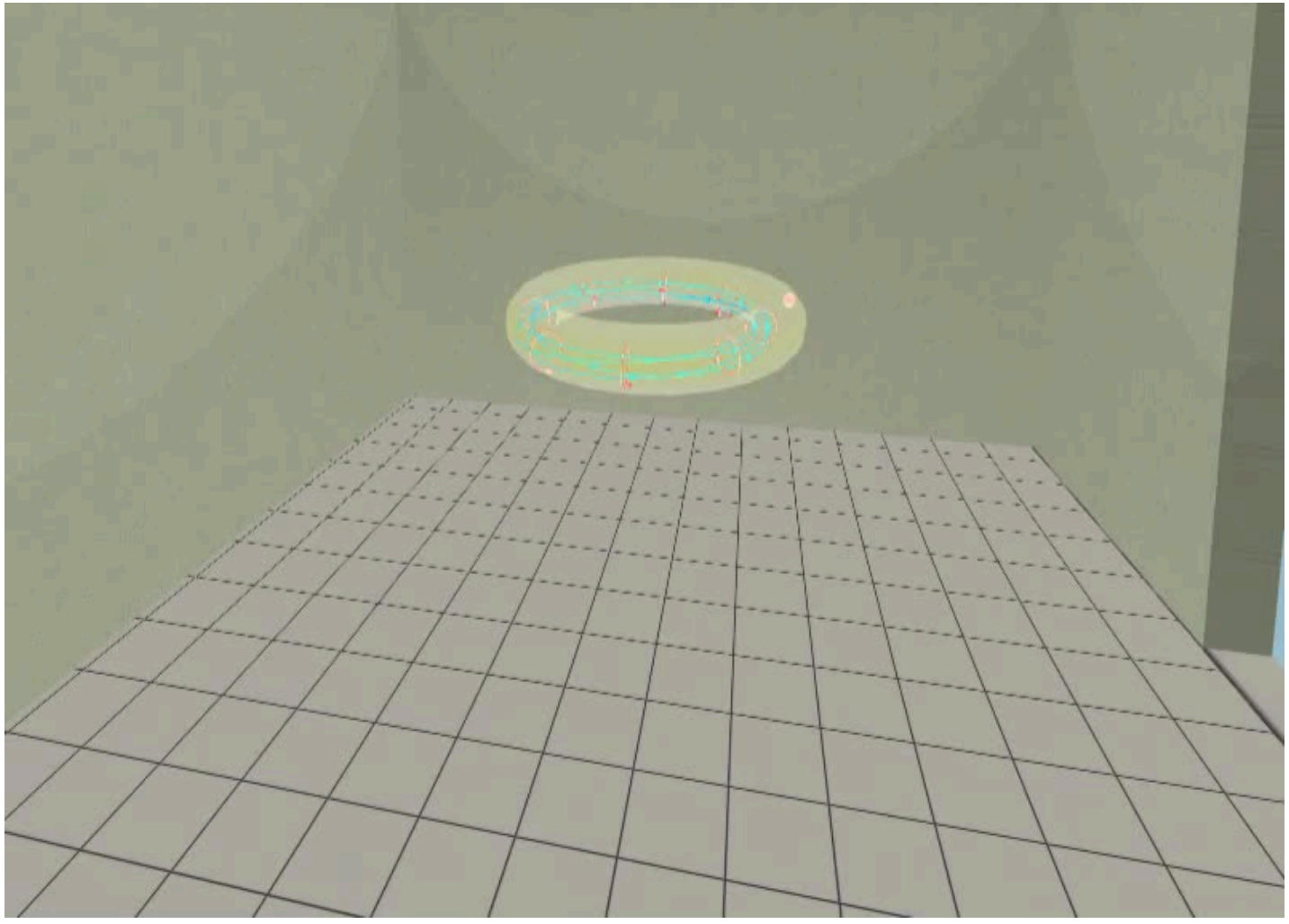
Introduce the working gas (Hydrogen x Helium)



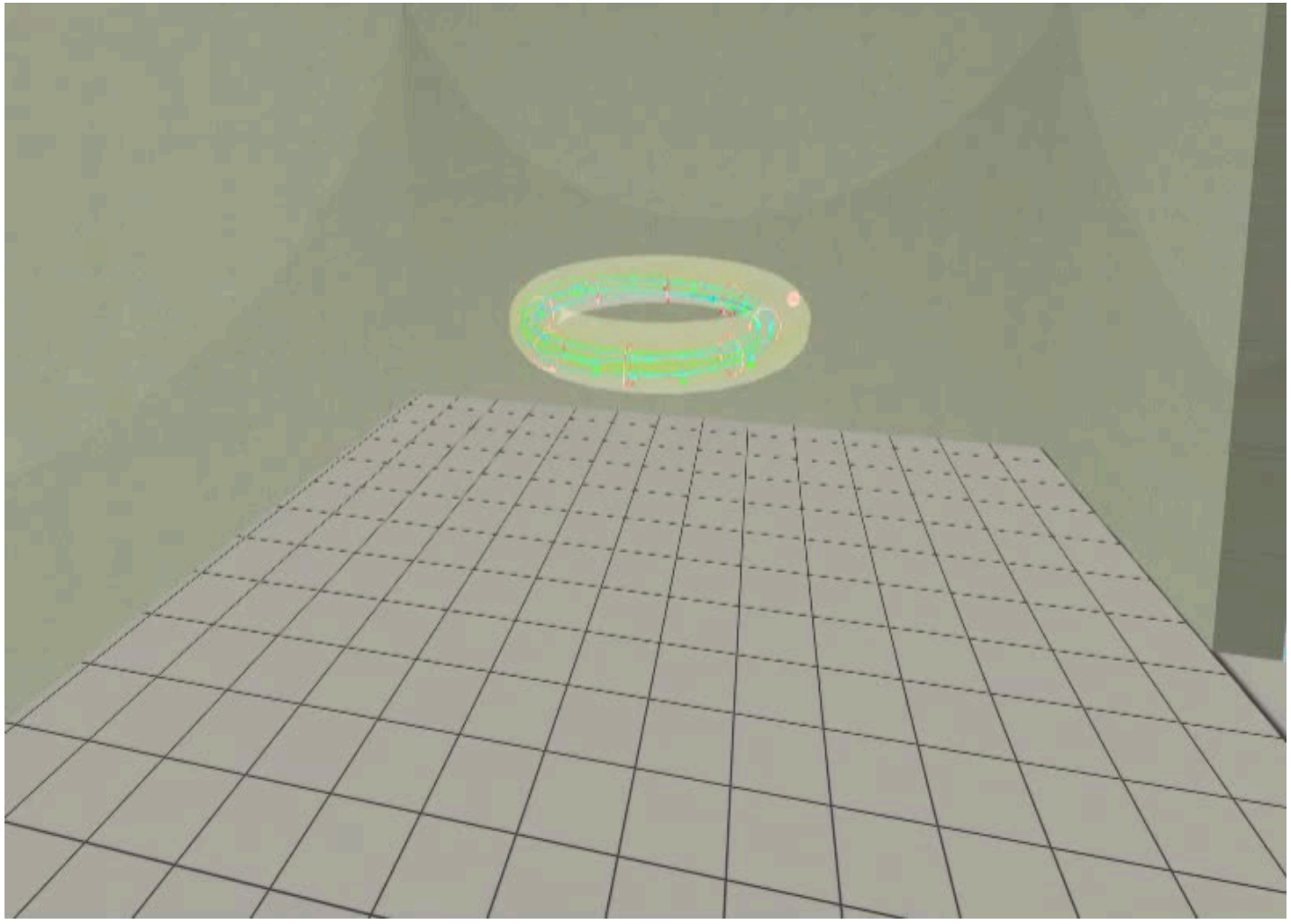
Switch on the preionization



Introduce the magnetic field



Introduce the electric field



Plasma ..

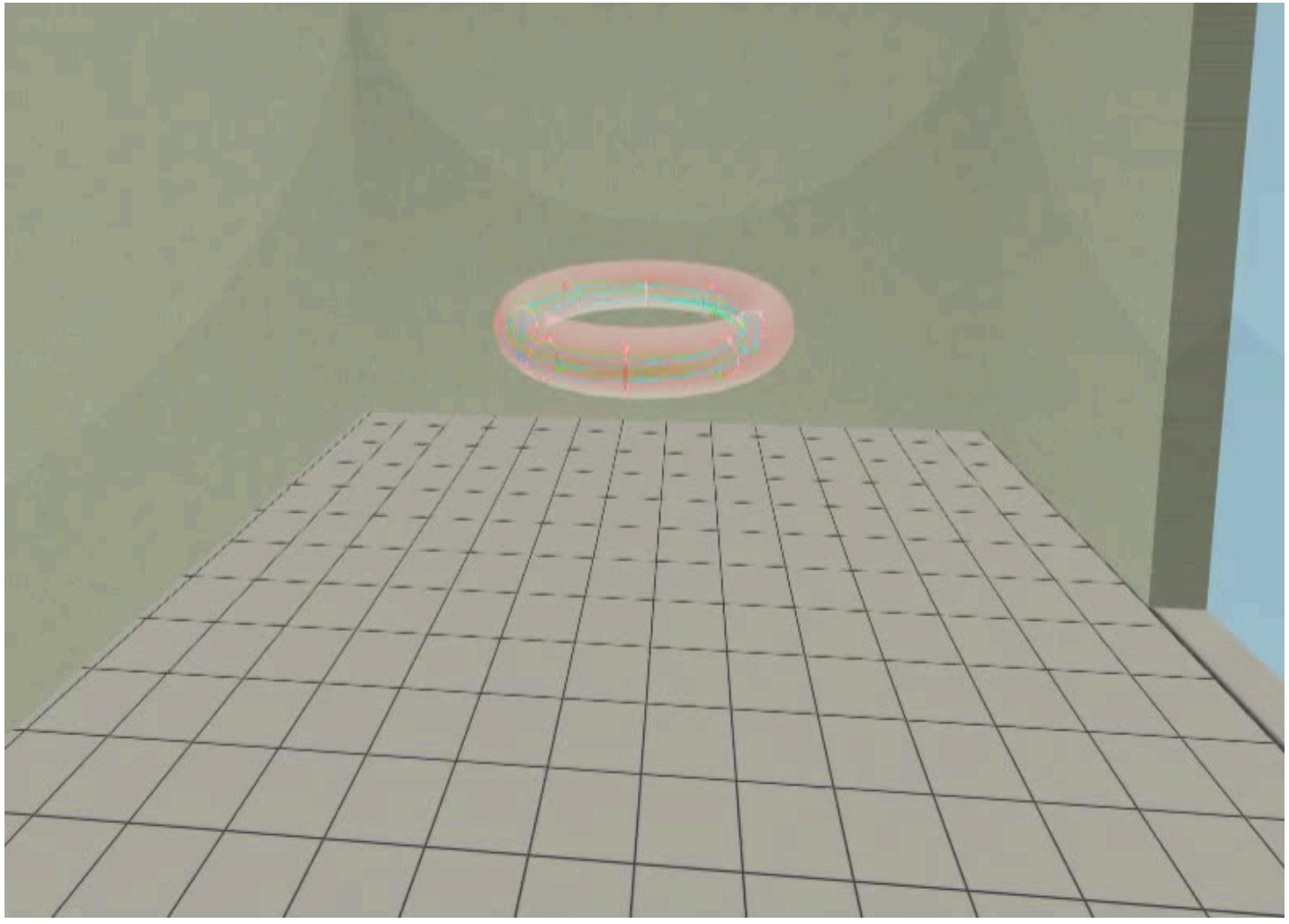
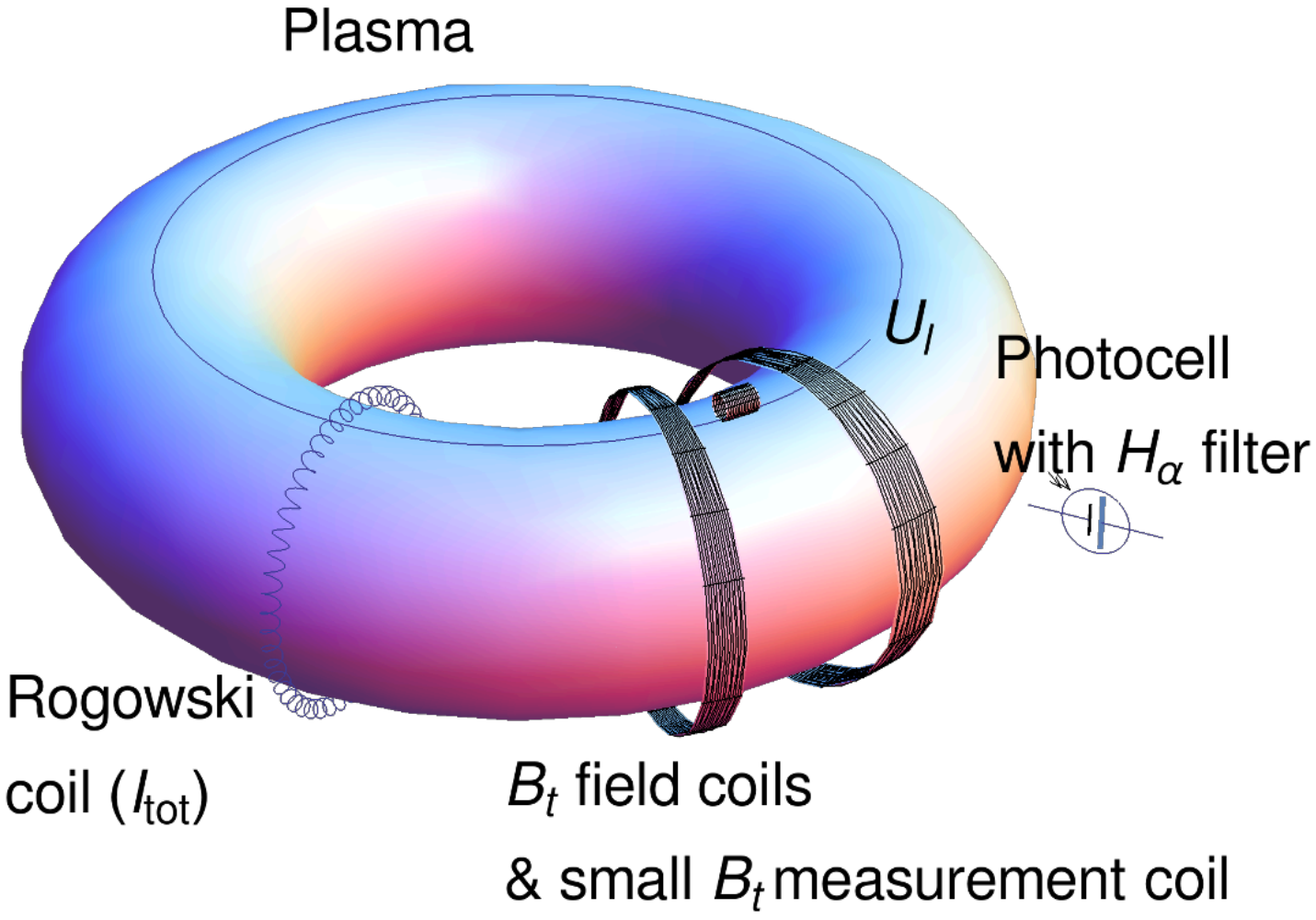


Table of Contents

The GOLEM tokamak - basic diagnostics



"Typical", well executed discharge @ GOLEM

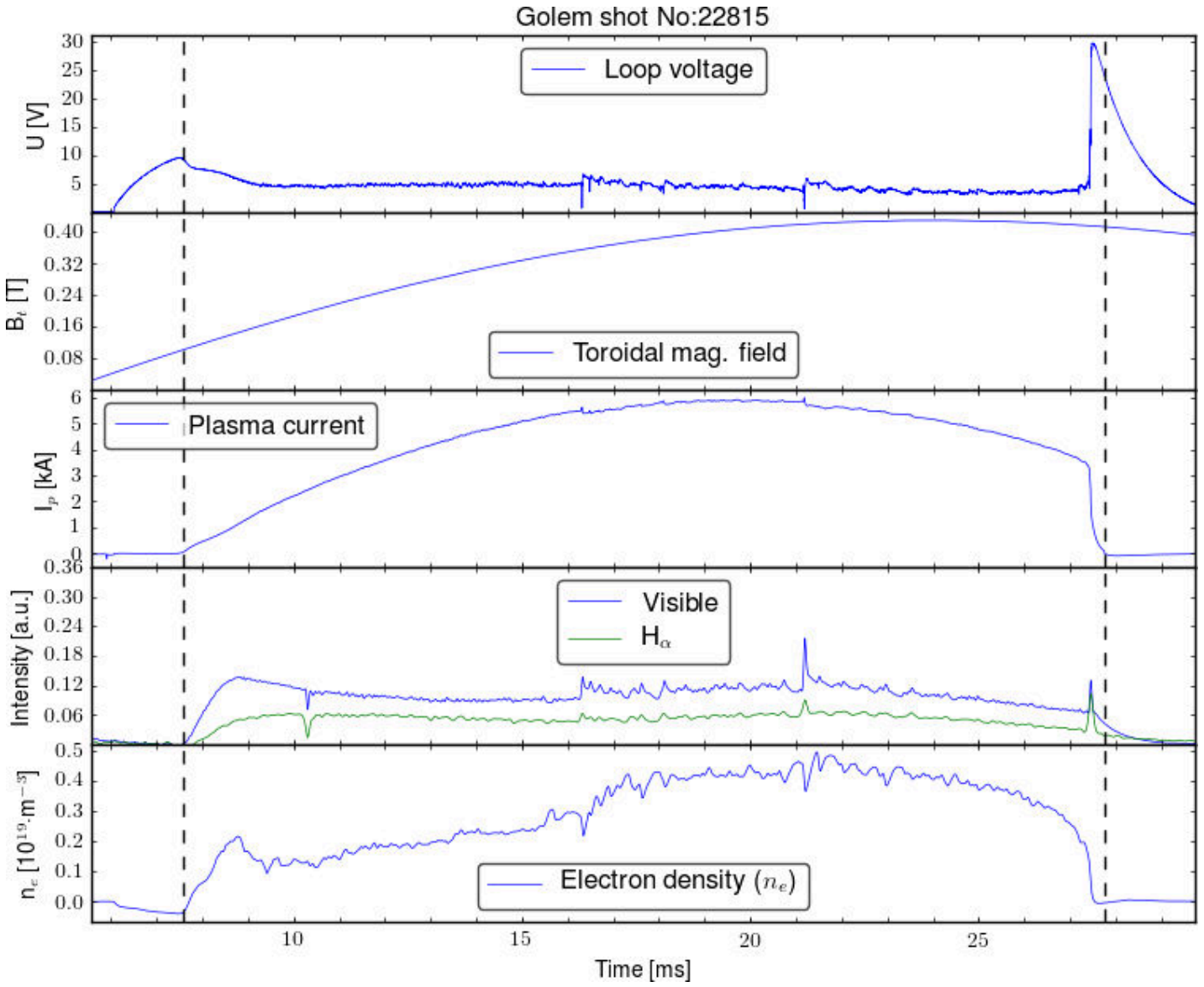
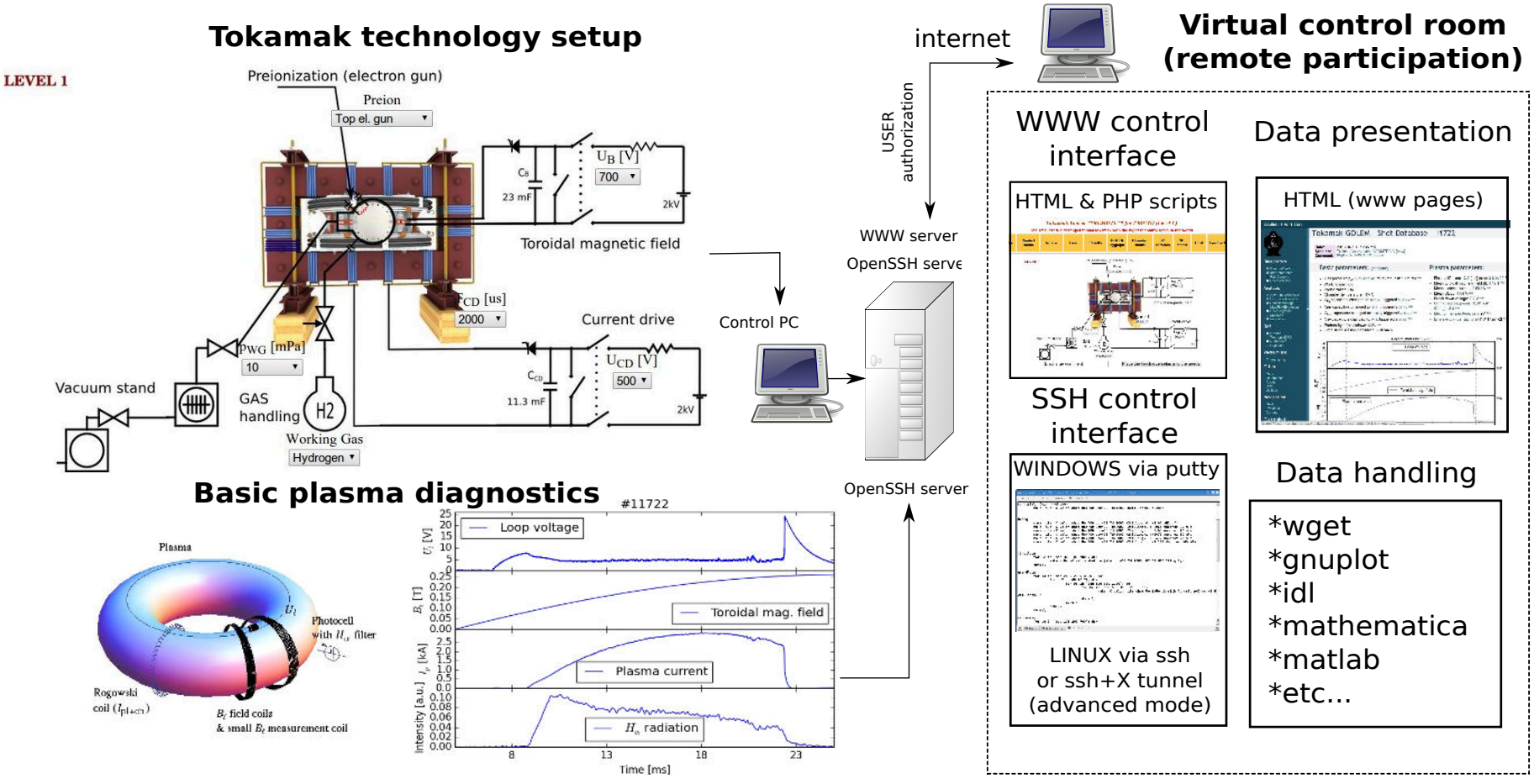
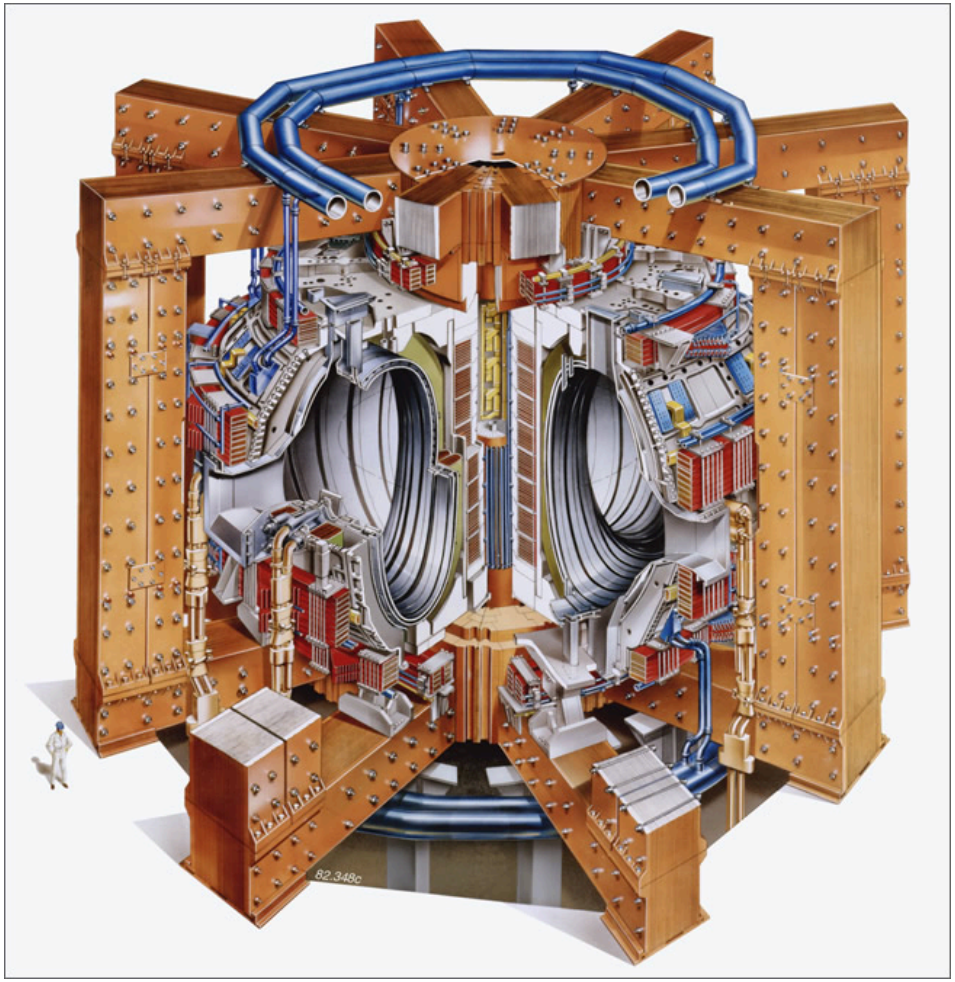


Table of Contents

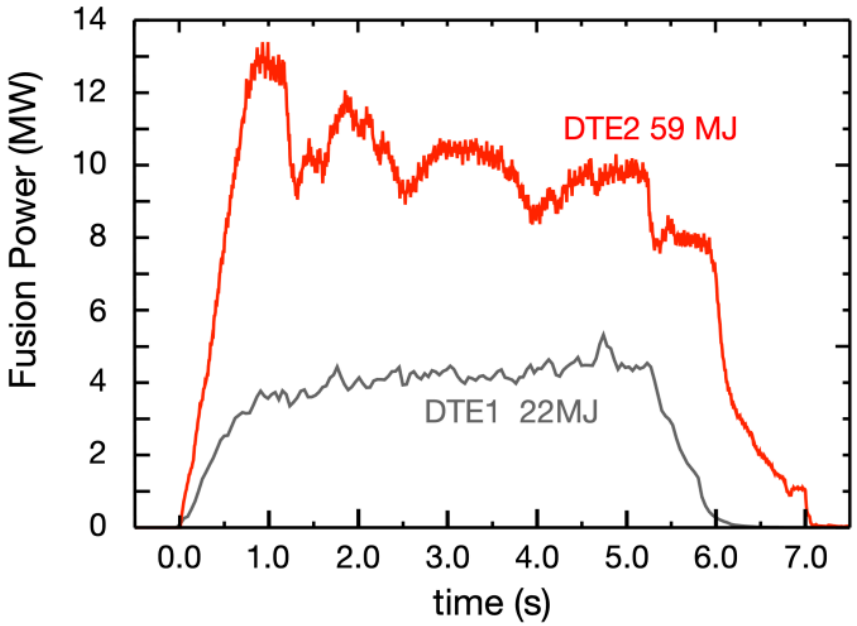
The global schematic overview of the GOLEM experiment



1997: Světový fúzní rekord @ JET (EU)

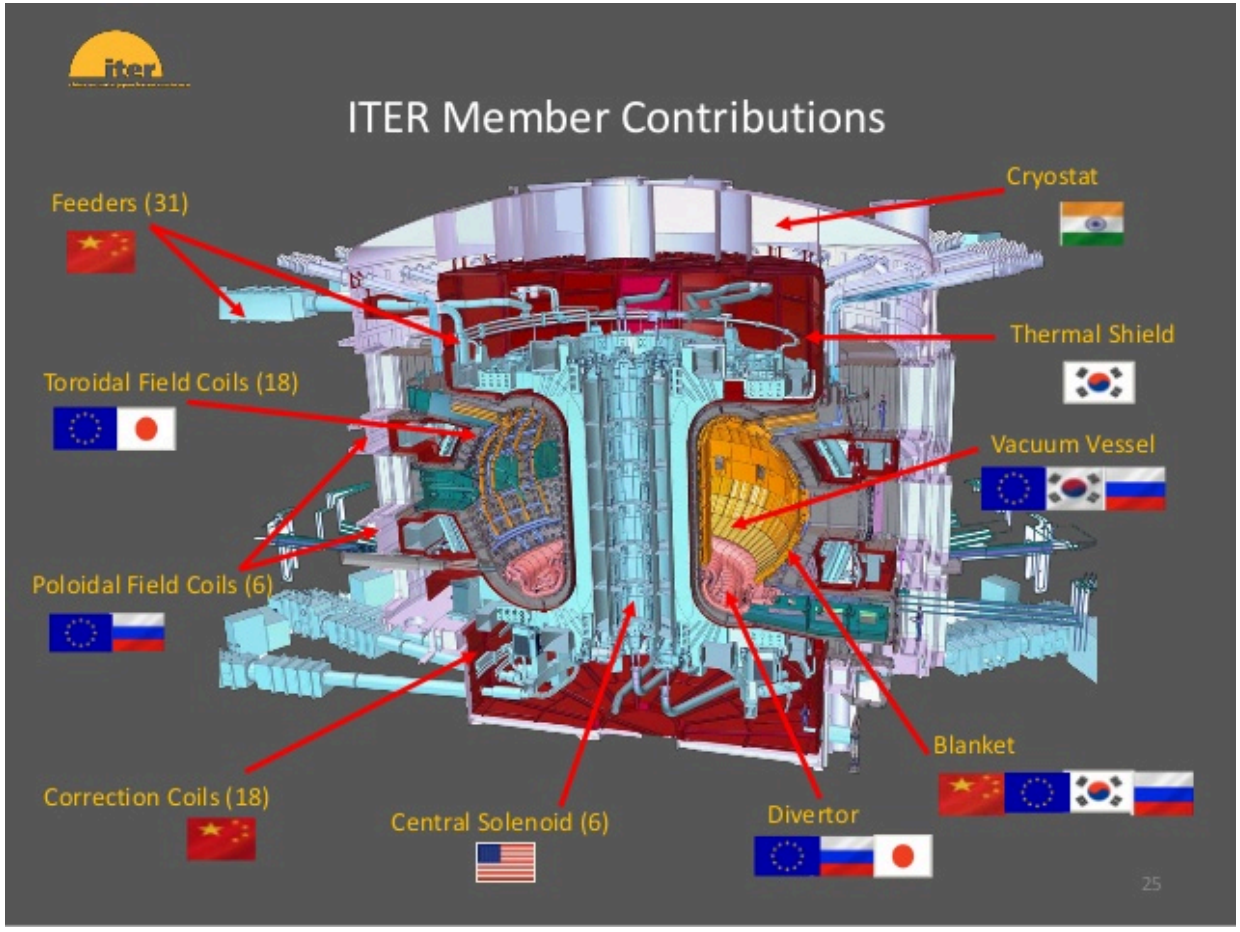


output comparison 1997 and 2021.png



1997: $P \approx 22$ MW, $Q \approx 0.65$, $\Delta T \approx 5$ s,
2022: $P \approx 59$ MW, $Q \approx ?$, $\Delta T \approx 6$ s

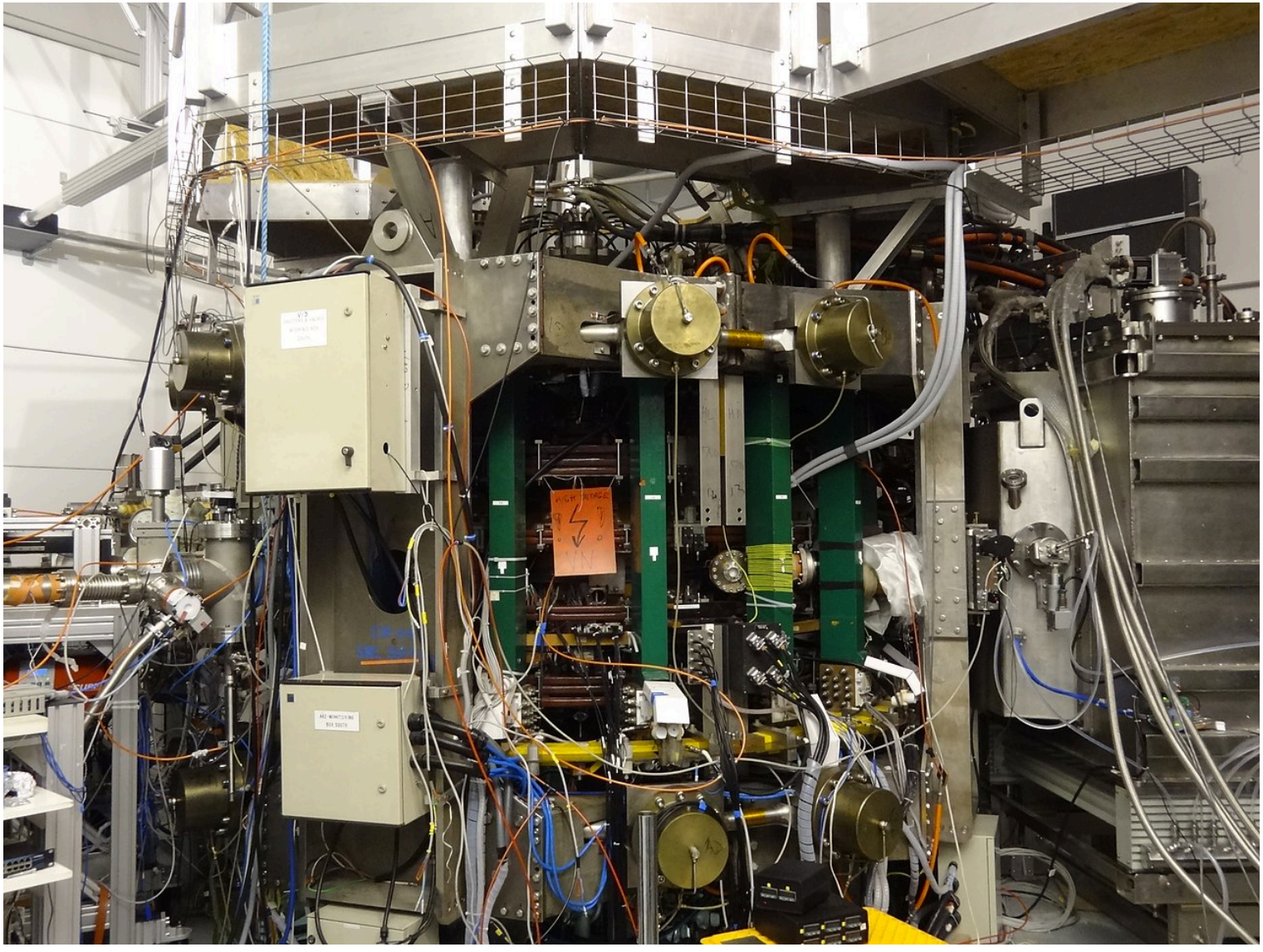
ITER (jižní Francie) $\approx$ 18 miliard EUR



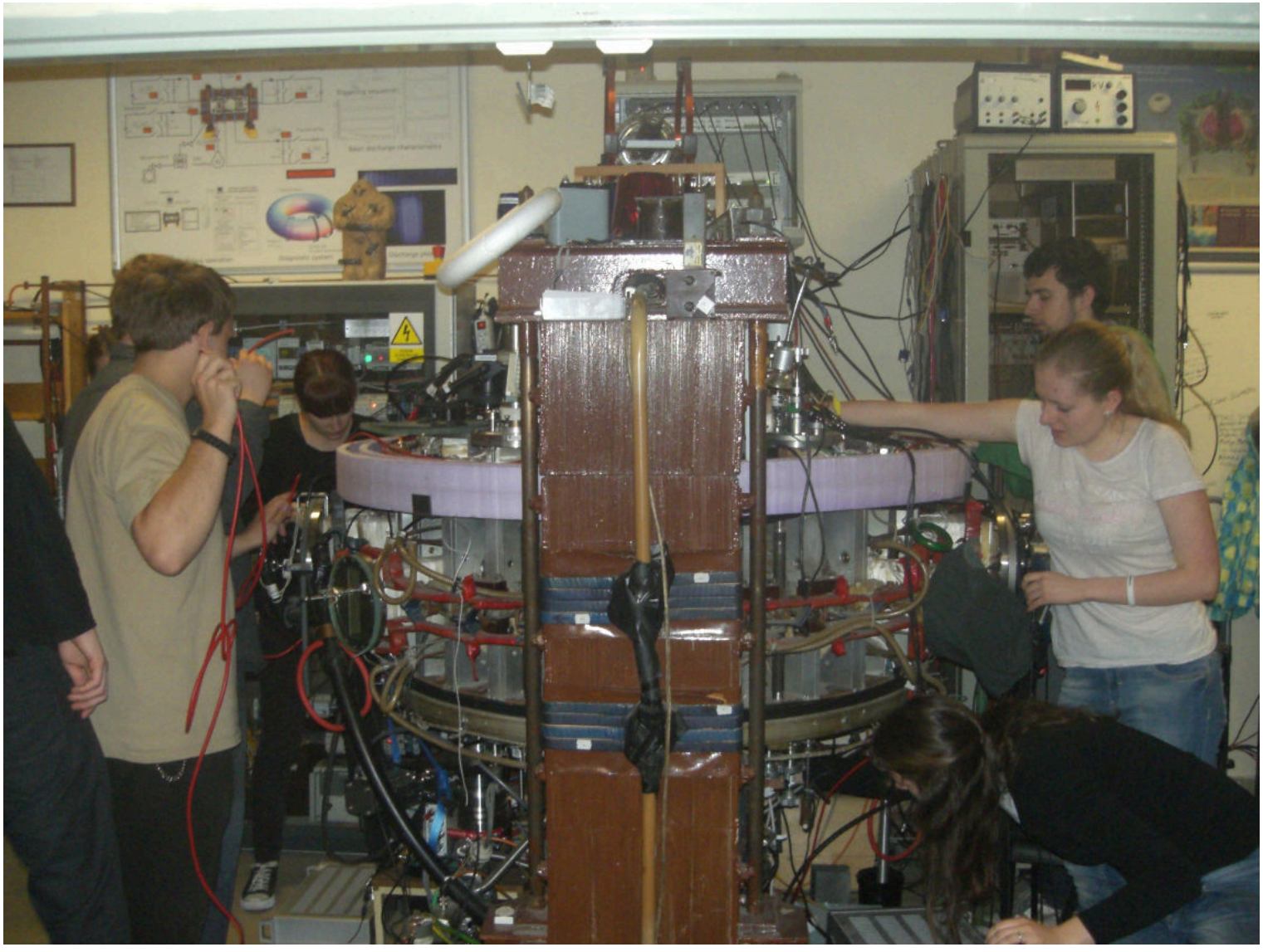
Mise:

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

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



Hands on tokamak



Tokamak GOLEM - vzdálené řízení: 2009-2019 inventura

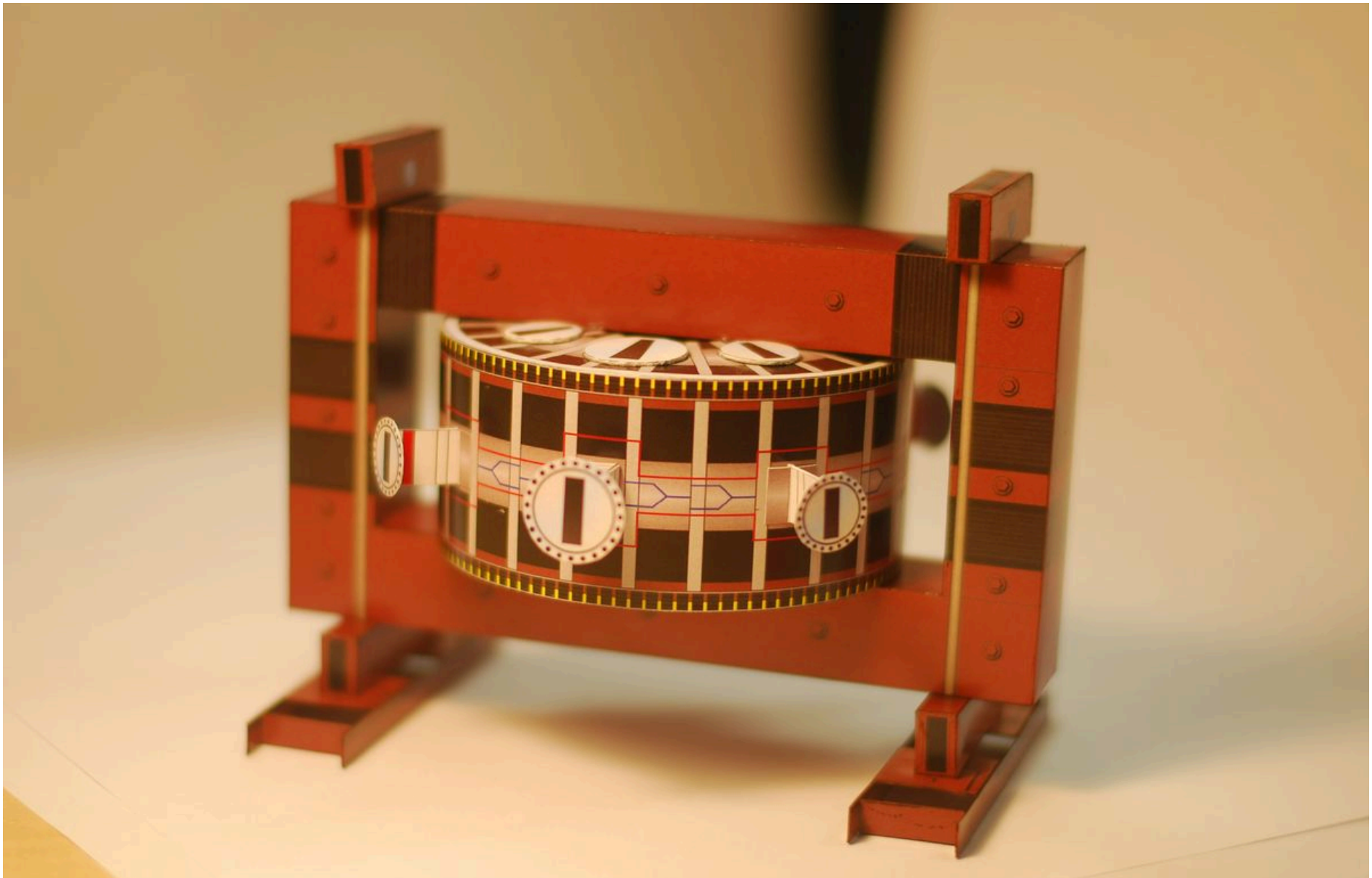
Studenti z TU Eindhoven, operující tokamak, 650 km vzdušnou čarou

- Demonstrace: Ghent University 09; Bochum University 13; Garching 13; Lemvig High School 14; Instituto Tecnologico Costa Rica 10; Armidale University 17.
- Zimní a letní školy: 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
- Pracovní semináře Kiten: 14,16-18; Observatorium Valasske Mezirici 14; Islamabad

Poplatek: pohlednice z místa vzdáleného řízení

GOLEM

Paper model ABC



Acknowledgement

Financial support highly appreciated:

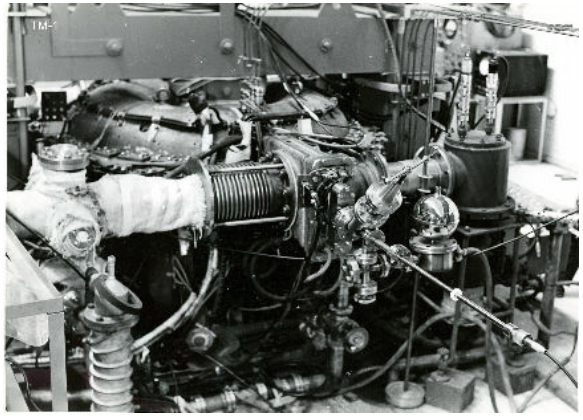
CTU RVO68407700, SGS 17/138/OHK4/2T/14, GAČR GA18-02482S, EU funds CZ.02.1.01/0.0/0.0/16_019/0000778 and CZ.02.2.69/0.0/0.0/16_027/0008465, IAEA F13019, FUSENET and EUROFUSION.

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

Tokamak TM1
@Kurchatov Institute near Moscow
~1960-1977

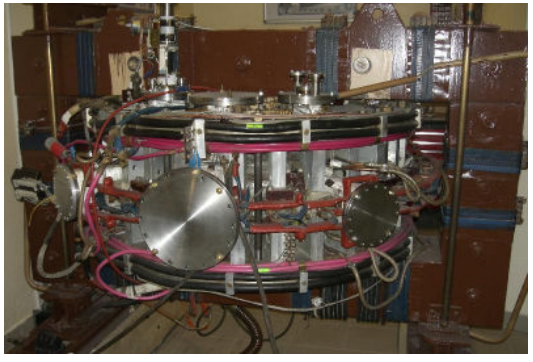


SCIENCE

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 ..

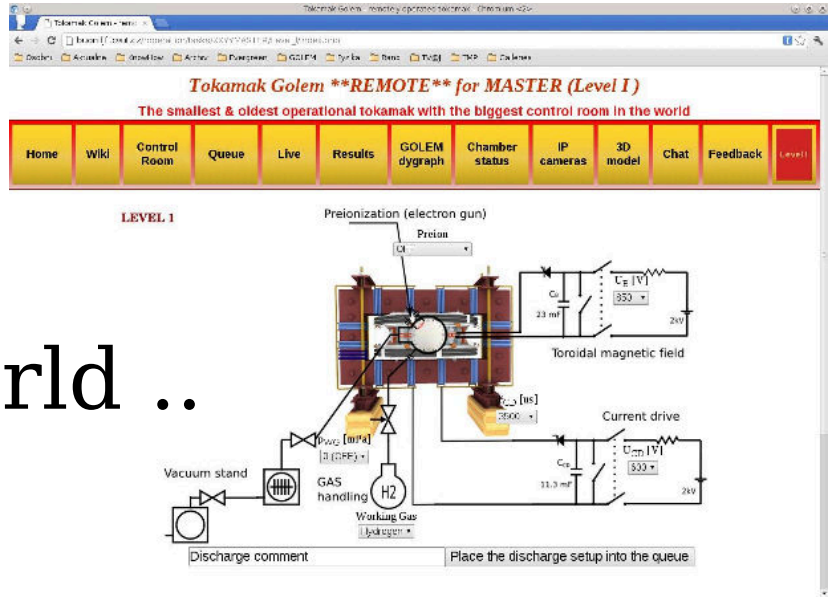


Table of Contents

References I

- Max-Planck-Institute. Fusion power:layout and function. https://www.ipp.mpg.de/14755/aufbau, 2020. [Online; accessed March 10, 2023].
- Wikipedia contributors. Nuclear fusion — Wikipedia, the free encyclopedia. https://en.wikipedia.org/w/index.php?title=Nuclear_fusion, 2018. [Online; accessed 21-December-2018].
- Eurofusion. Fusion spin-off: Ohmic heating networks. https://www.euro-fusion.org/news/detail/detail/News/fusion-spin-off-ohmic-heating-networks/, 2015. [Online; accessed March 10, 2023].

References II


Wikipedia contributors. Golem — Wikipedia, the free encyclopedia. https://en.wikipedia.org/w/index.php?title=Golem, 2020. [Online; accessed 29-March-2020].


V. Svoboda, B. Huang, J. Mlynar, G.I. Pokol, J. Stockel, and G. Vondrasek. Multi-mode Remote Participation on the Golem Tokamak. *Fusion Engineering and Design*, 86(6-8):1310–1314, 2011.


Brotankova, J. *Study of high temperature plasma in tokamak-like experimental devices*. PhD thesis, 2009.


Tokamak GOLEM contributors. Tokamak GOLEM at the Czech Technical University in Prague. http://golem.fjfi.cvut.cz, 2007. [Online; accessed March 10, 2023].

References III

J. Wesson. *Tokamaks*, volume 118 of *International Series of Monographs on Physics*. Oxford University Press Inc., New York, Third Edition, 2004.