Spoutání energie hvězd v pozemských podmínkách

Vojtěch Svoboda

Základní popularizační přednáška

May 29, 2024

Fakulta jaderná a fyzikálně inženýrská (FJFI)
České vysoké učení technické v Praze

Hlavní budova FJFI v Praze - Břehová

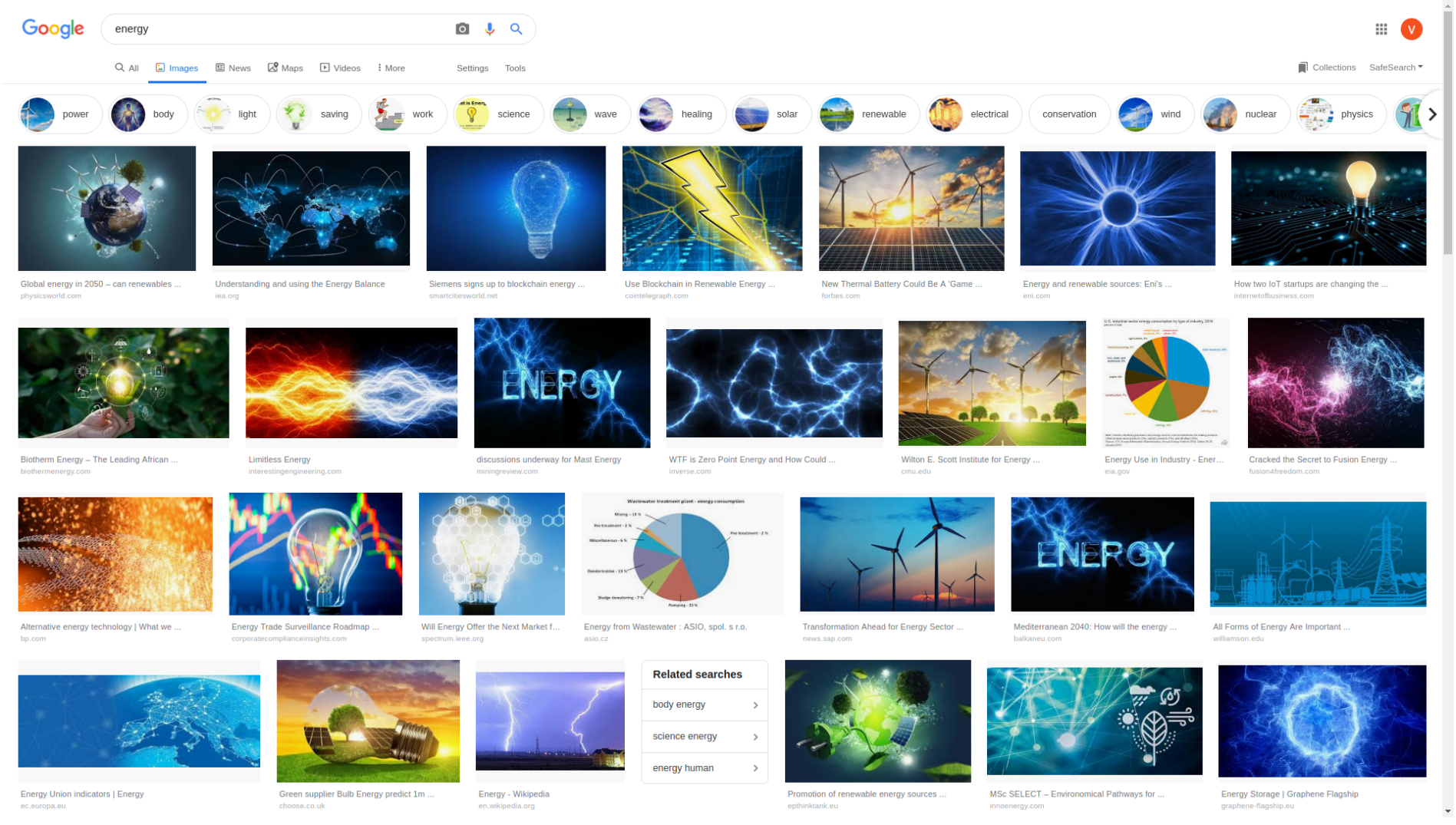
insignie FJFI

Betlémská kaple - slavnostní síň ČVUT

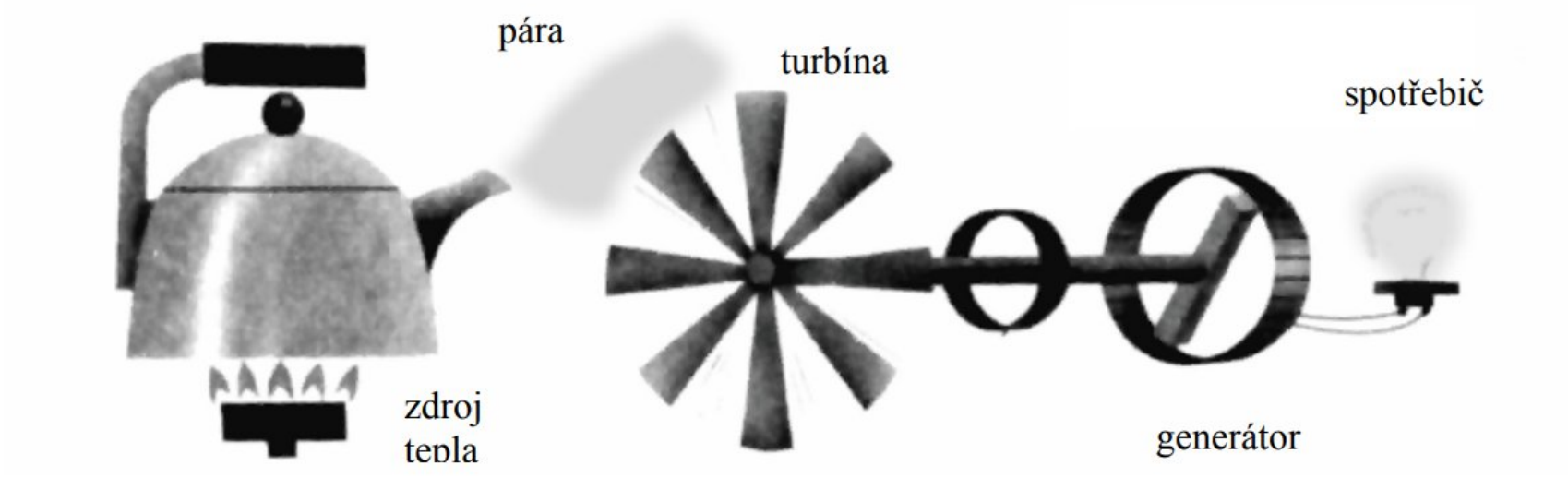
- ČVUT založena roku 1707 císařem Josefem I.
- ČVUT má přibližně 2700 zaměstnanců, 16500 vysokoškolských studentů, 1700 doktorandů. ($\approx$ 2500 zahraničních studentů).
- FJFI byla založena v roce 1955 s posláním vyškolit nové odborníky na vznikající československý jaderný program.
- FJFI je v současné době centrem vzdělávání a výzkumu, které se specializuje na hraniční oblasti mezi moderní vědou a jejich aplikacemi v technologiích, medicíně, ekonomii, biologii, ekologii a dalších oborech.

Google: Energy

About 2,950,000,000 results (0.60 seconds)



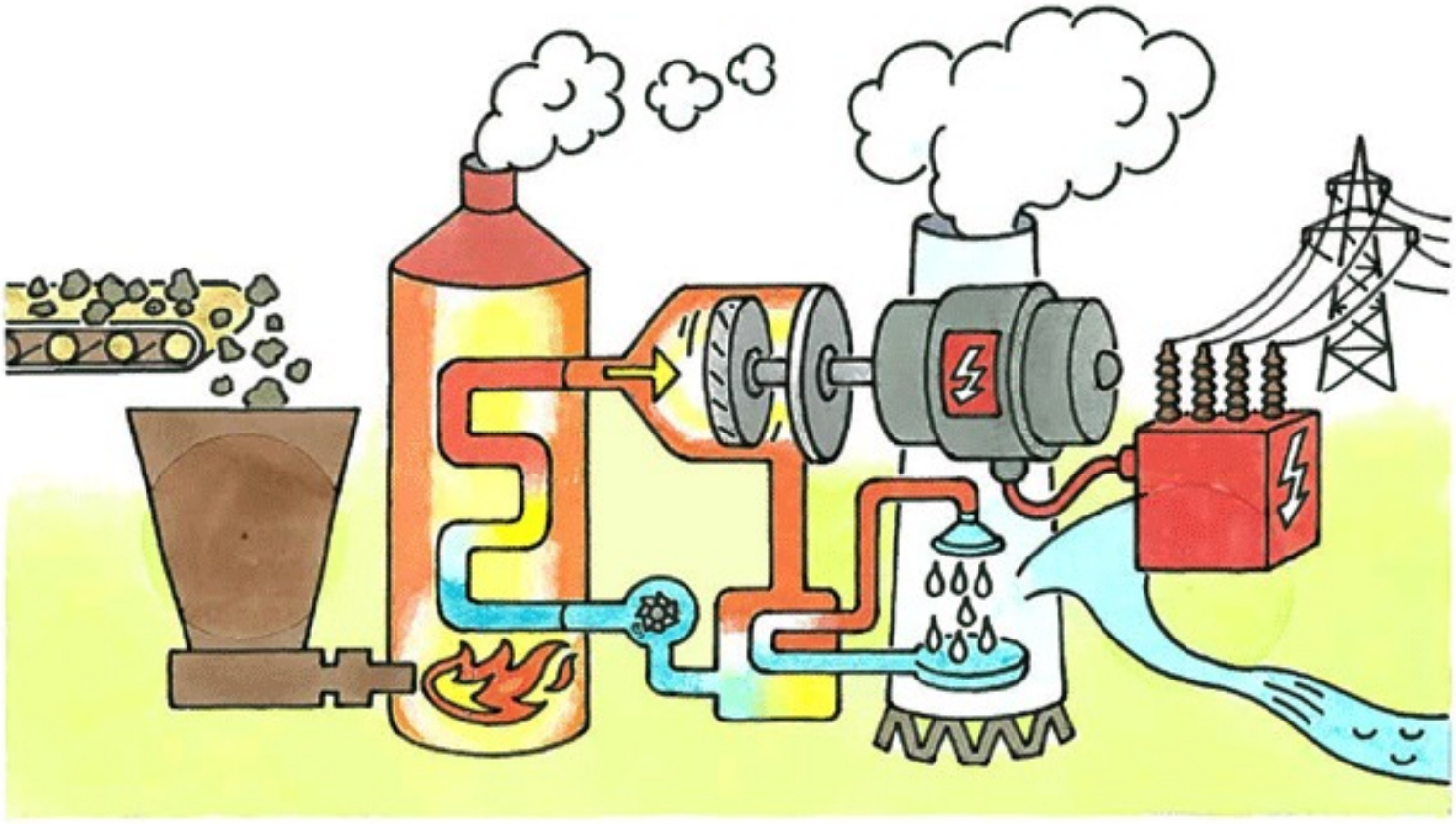
Základní princip tepelné elektrárny



Základní otázka zní:

?? Čím topit ??

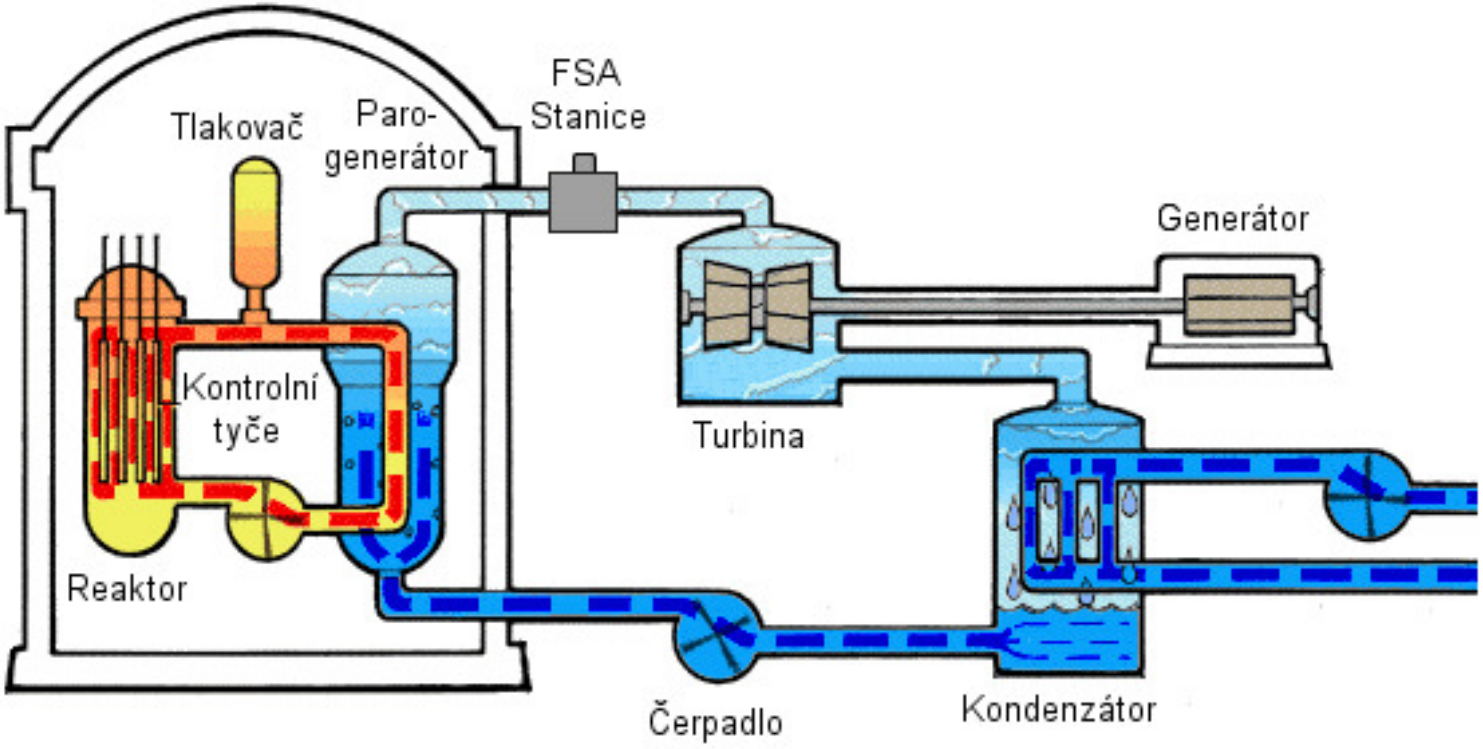
Uhelná elektrárna



Praha ($\sim$ 1 GW): denně $\sim$ vlak uhlí

Emise

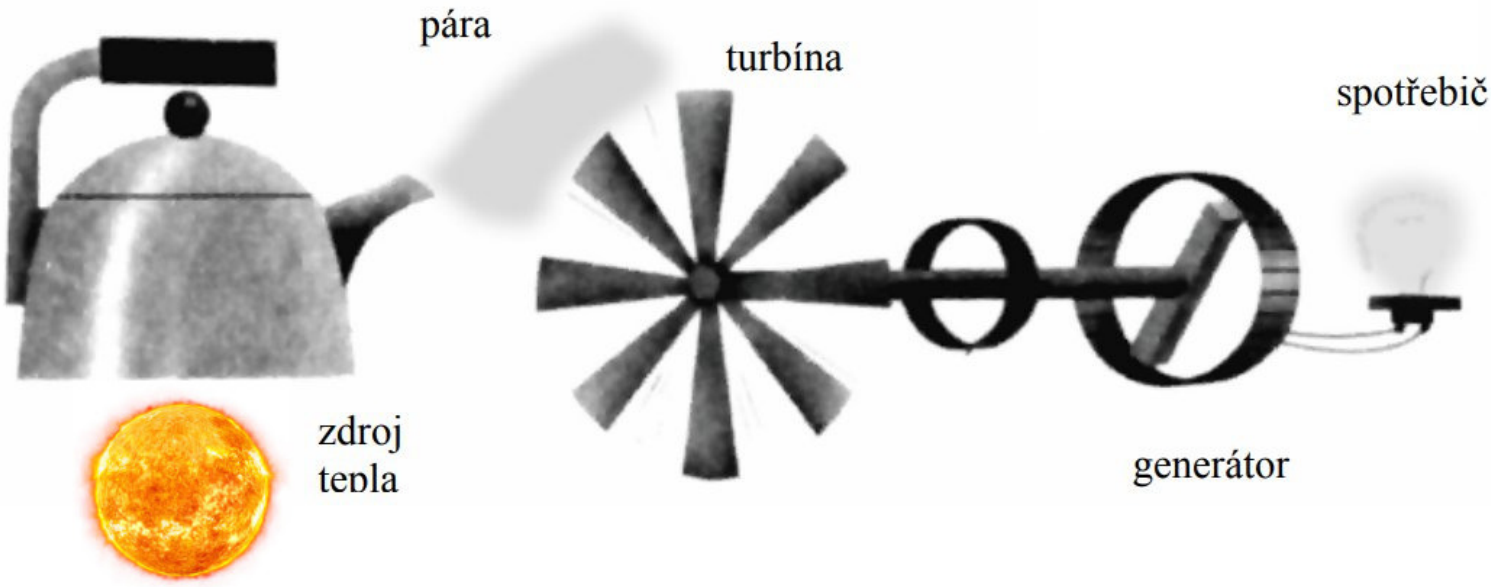
Jaderná elektrárna - štěpná



Praha ($\sim$ 1 GW): ročně $\sim$ vagón jaderného paliva

Dotáhnout technologii: Suroviny, Odpad, Bezpečnost

Topit malým Sluncem/hvězdou ??



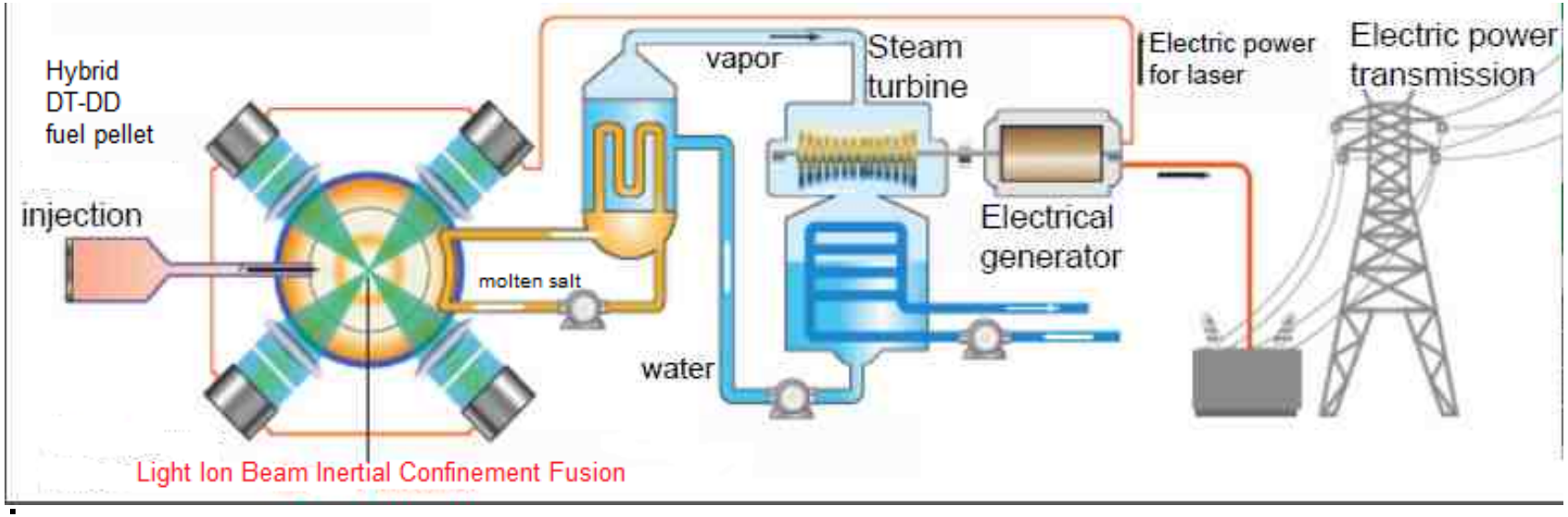
Výzva

1952 "Operation Ivy - Mike" První test vodíkové bomby

credit:YouTube:Ivy Mike Countdown and detonation

Toto není vhodná technologie

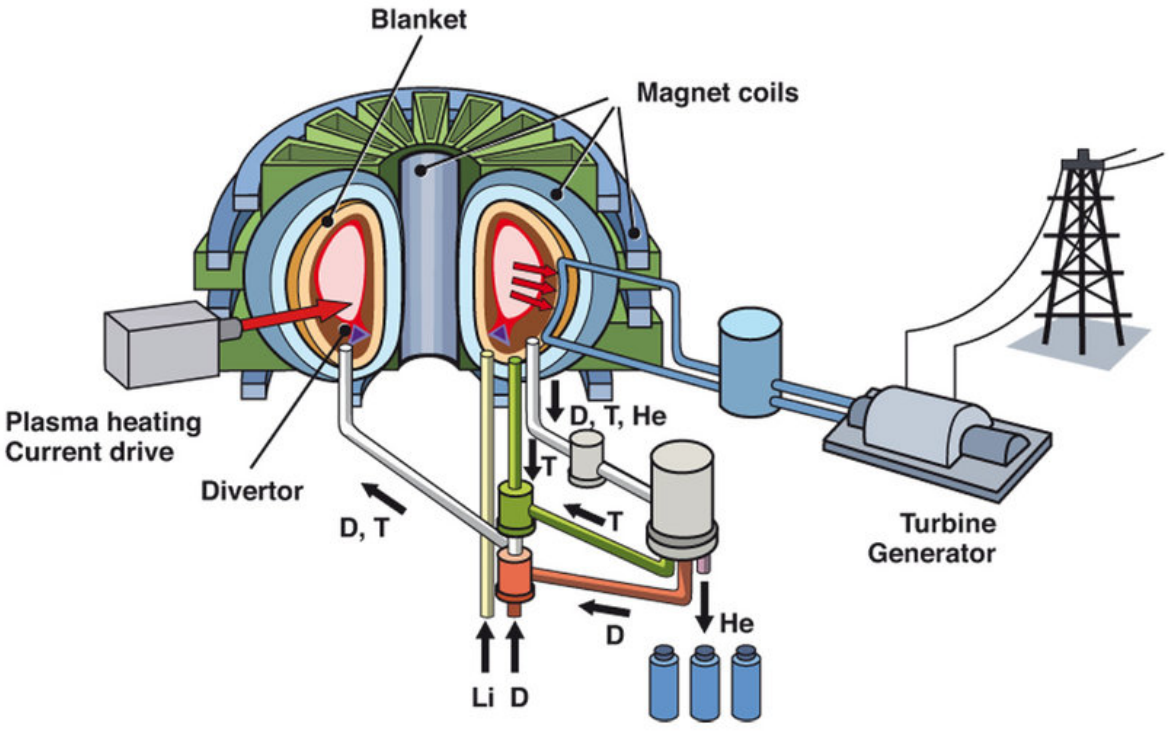
Inerciální fúze



credit:mext.jp

Velká výzva

Vize: Jaderná elektrárna - slučovací/fúzní

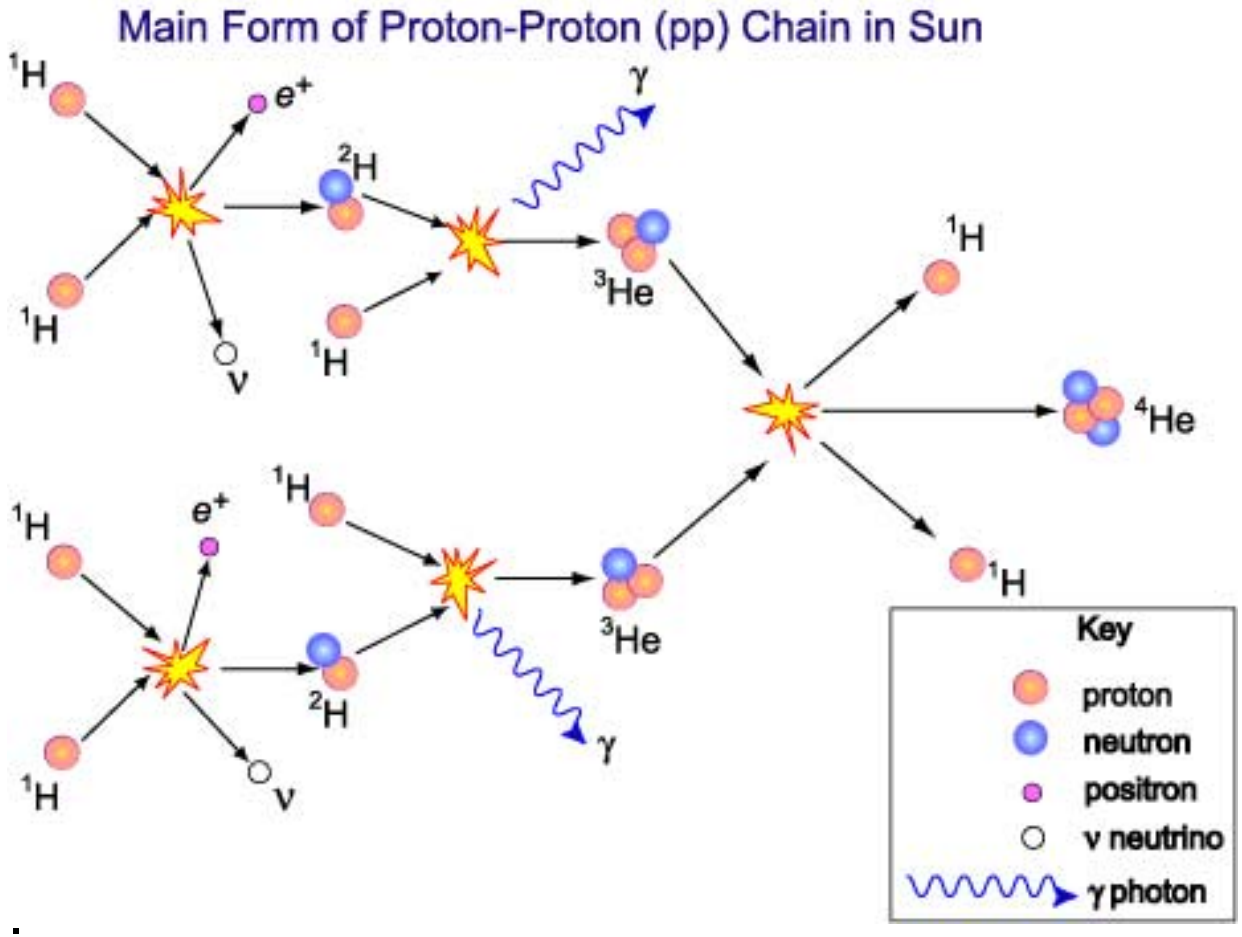


credit:[1]

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

Vypiplat technologii

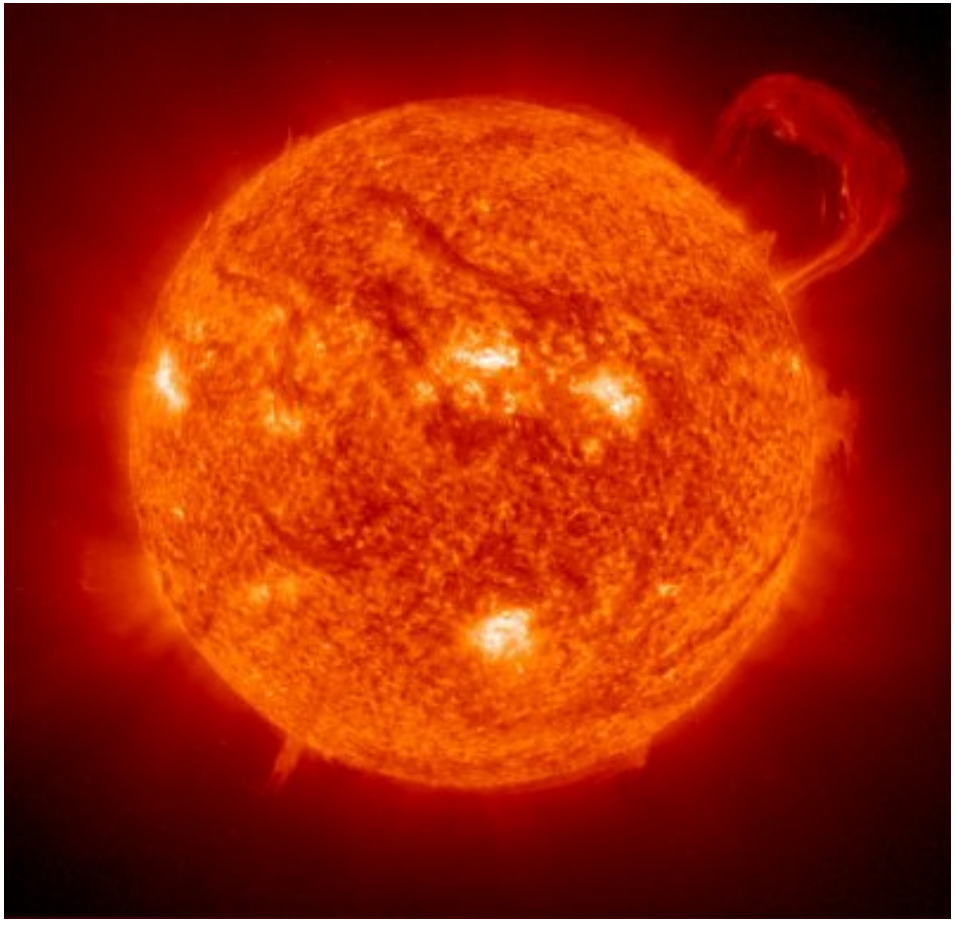
Inspirace: Slunce - protonový řetězec



credit:CSIRO

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

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

Uvolnění vazebné energie atomových jader

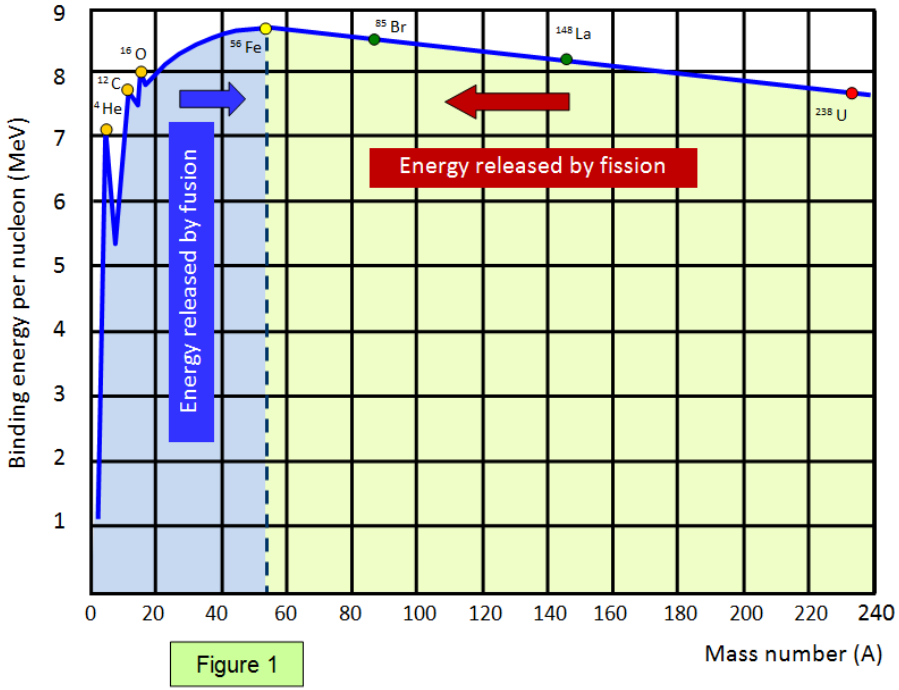
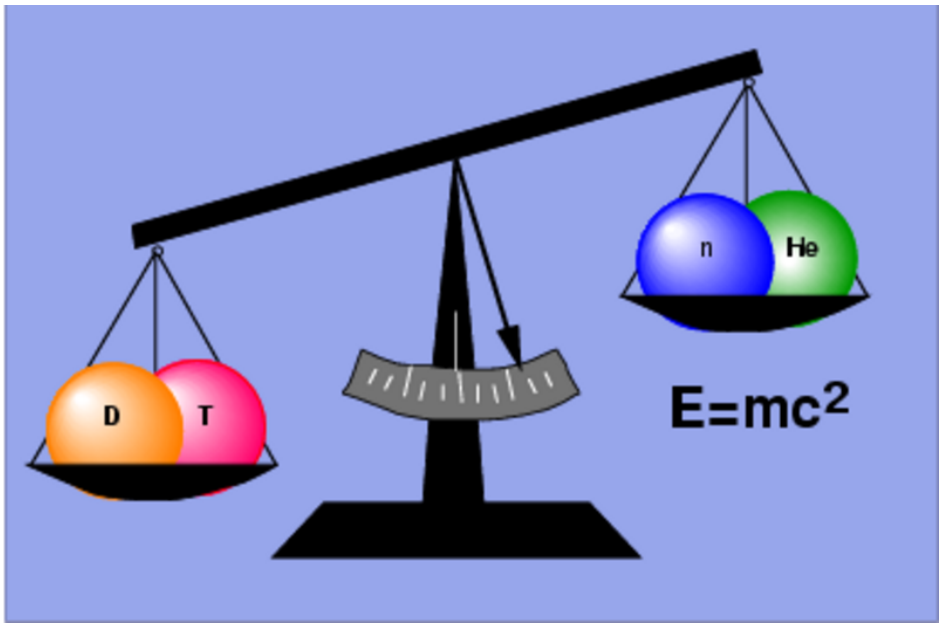


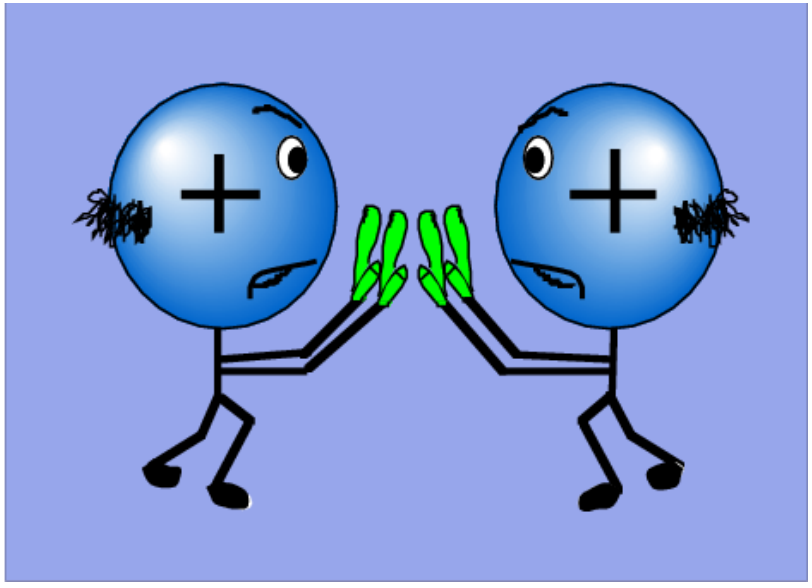
Figure 1



fúze lehkých jader X štěpení těžkých jader

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

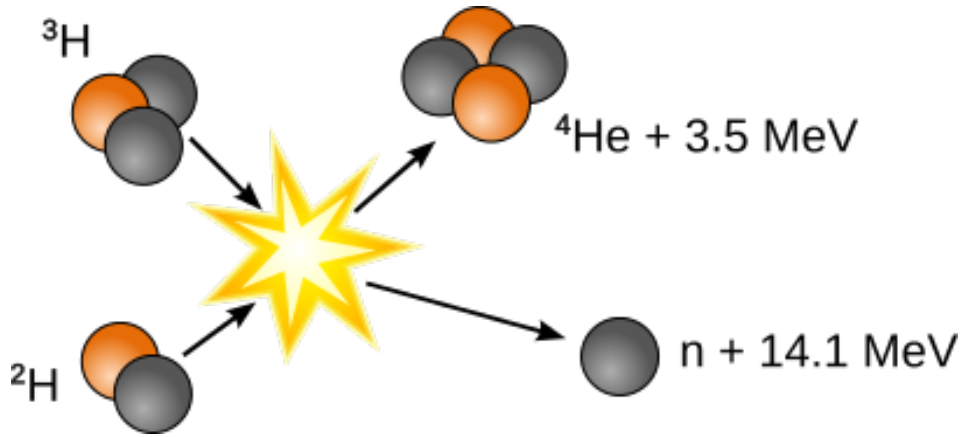
Proč tak obrovské teploty?



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

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

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



credit:[2]

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

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

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

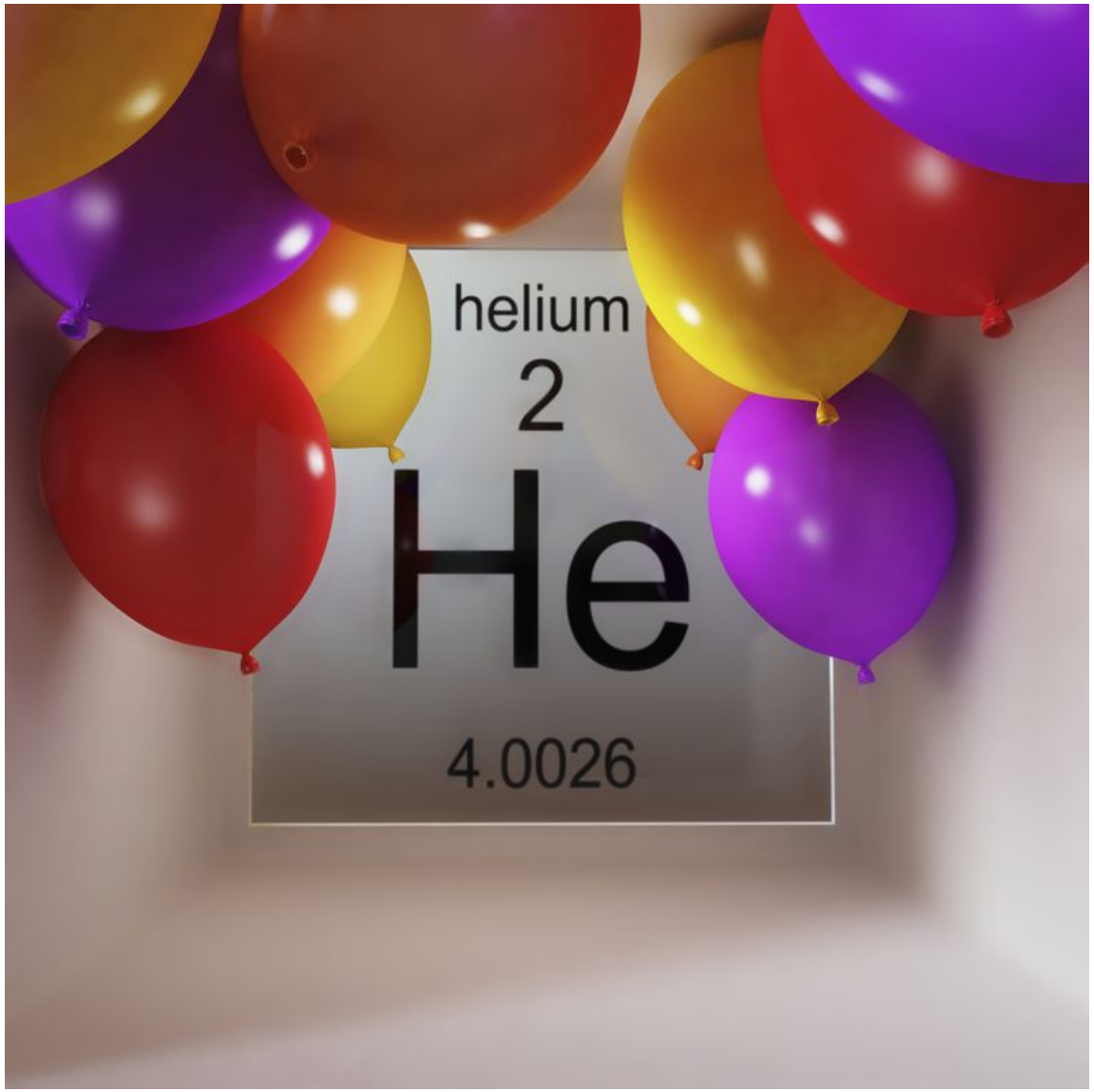
pak hmotnostní schodek $\Delta m = 0.01888 m_u$.

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

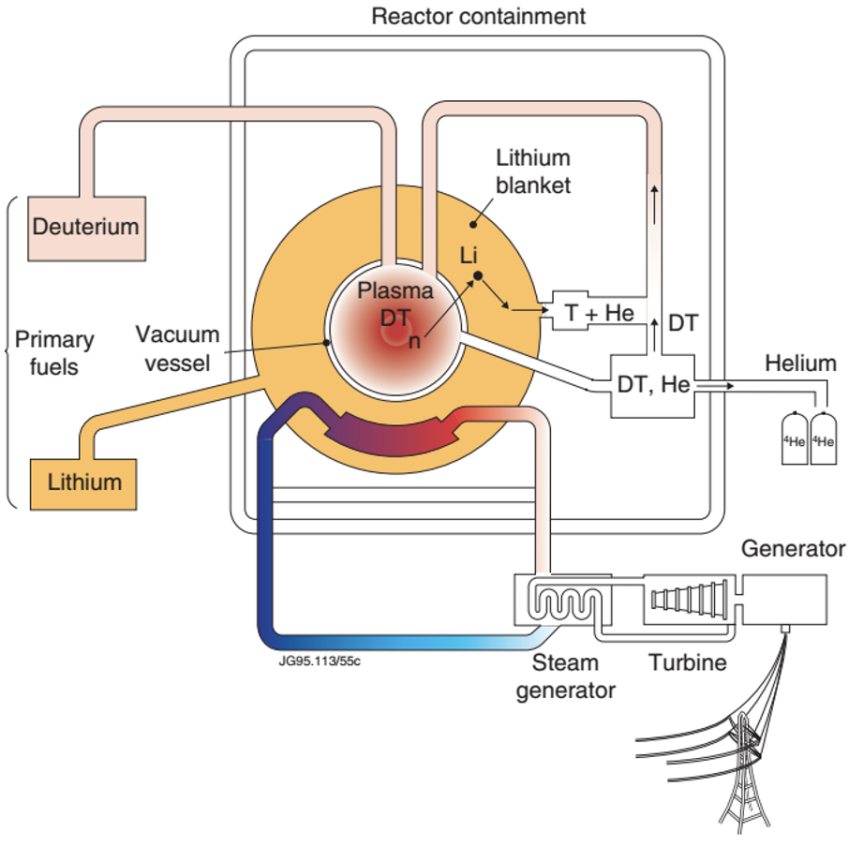
$$1\mathrm{eV} \sim 11600^{\circ}\mathrm{C} \approx \quad \mathbf{^{2}_{1}H_{100\ M^{\circ}C} + {}^{3}_{1}H_{100\ M^{\circ}C} \Rightarrow {}^{4}_{2}He_{35\ G^{\circ}C} + {}^{1}_{0}n_{141\ G^{\circ}C}}$$

Palivo: IAEA "Natural water"

Odpad

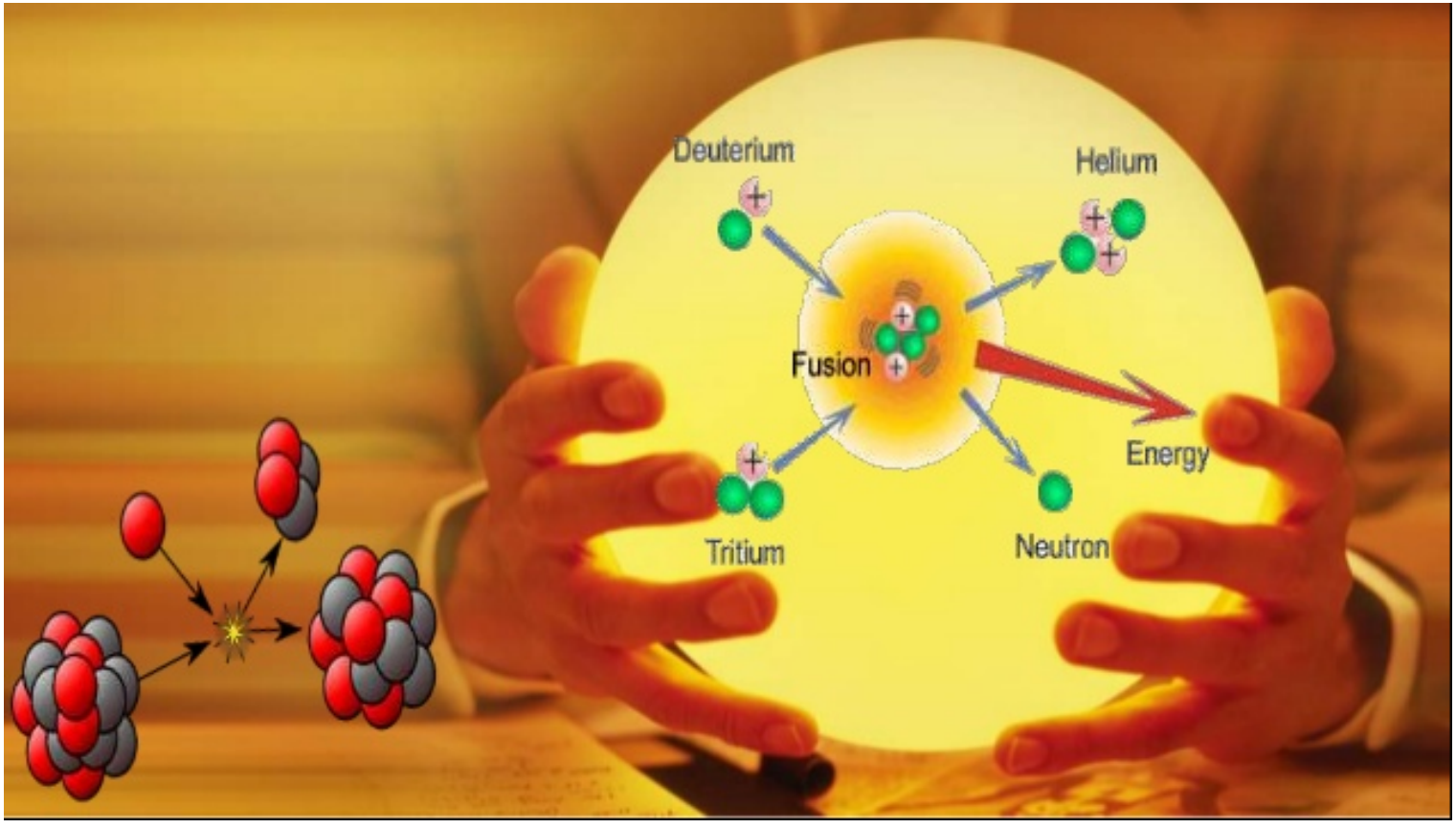


Bezpečnost



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

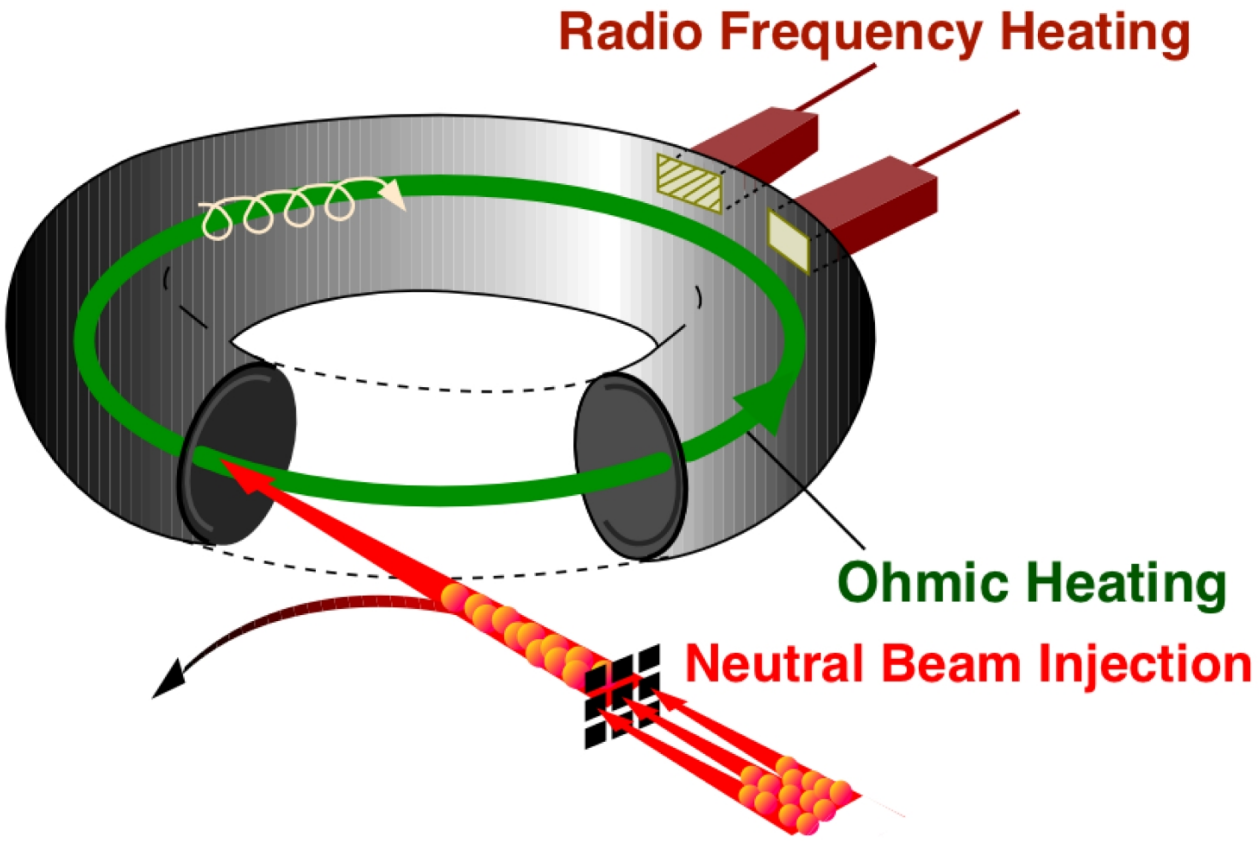
Hledá se vhodná fúzní technologie



Podmínky:

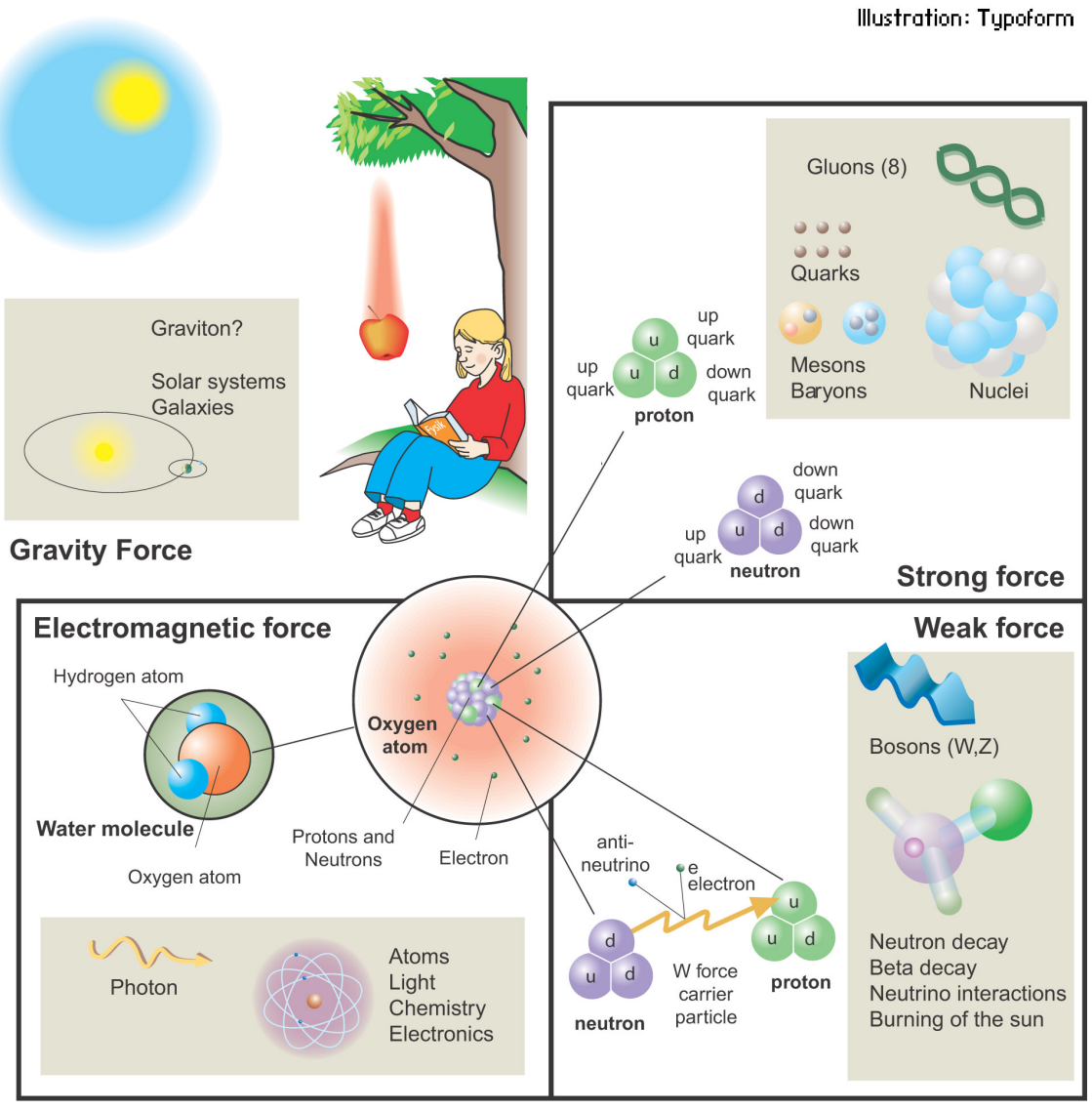
Zahřát na $\sim$ 100 000 000 °C & **udržet** po dobu $\sim$ 30 let + konkurenceschopnost

Ohřev plazmatu



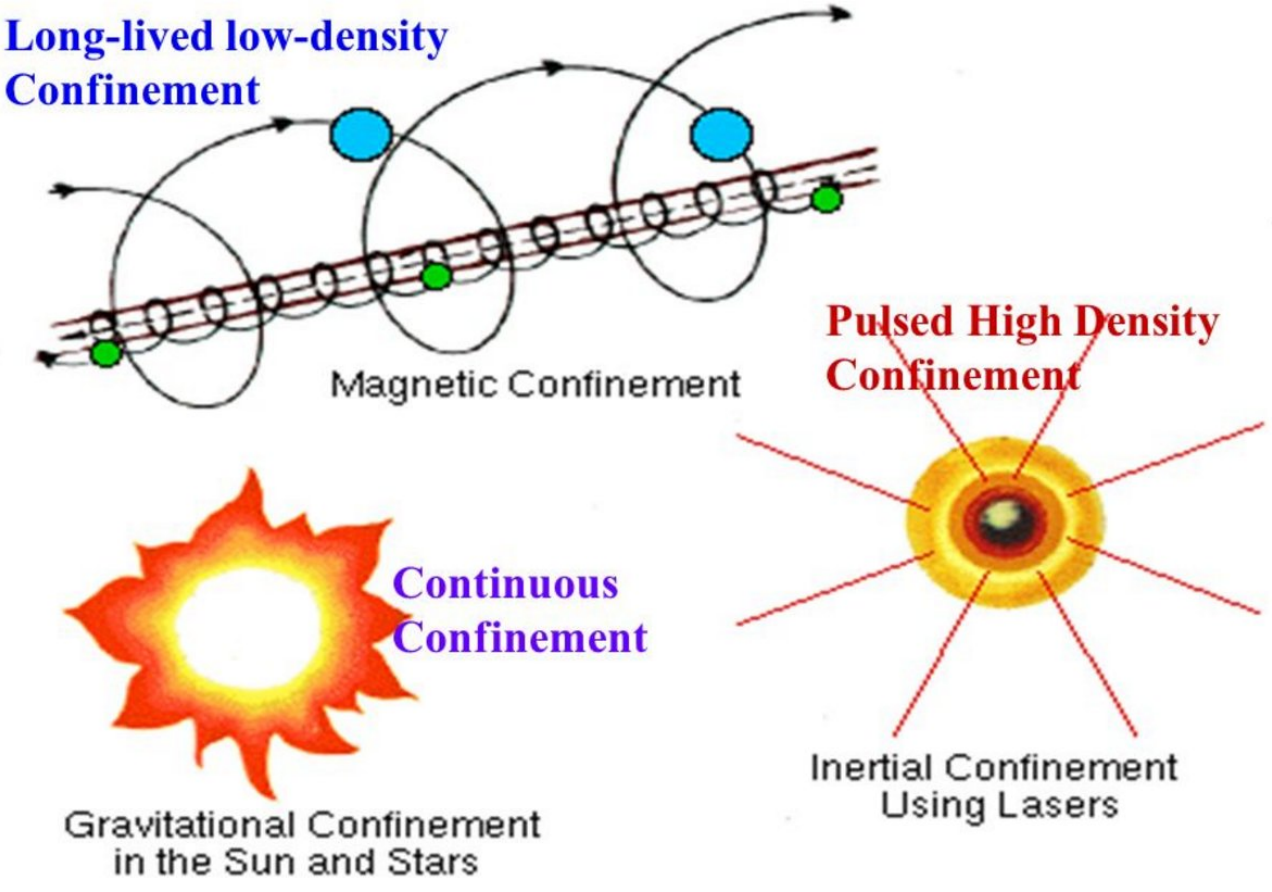
credit:[3]

Fundamental forces (to confine?)

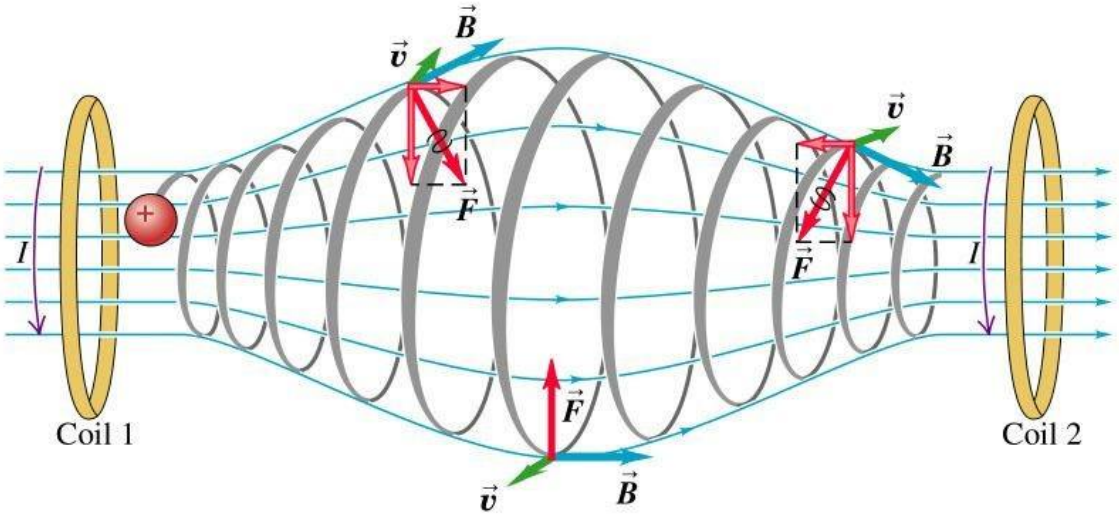


Tři možné cesty jak udržet plazma pro fúzi

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



Magnetické udržení: magnetická nádoba

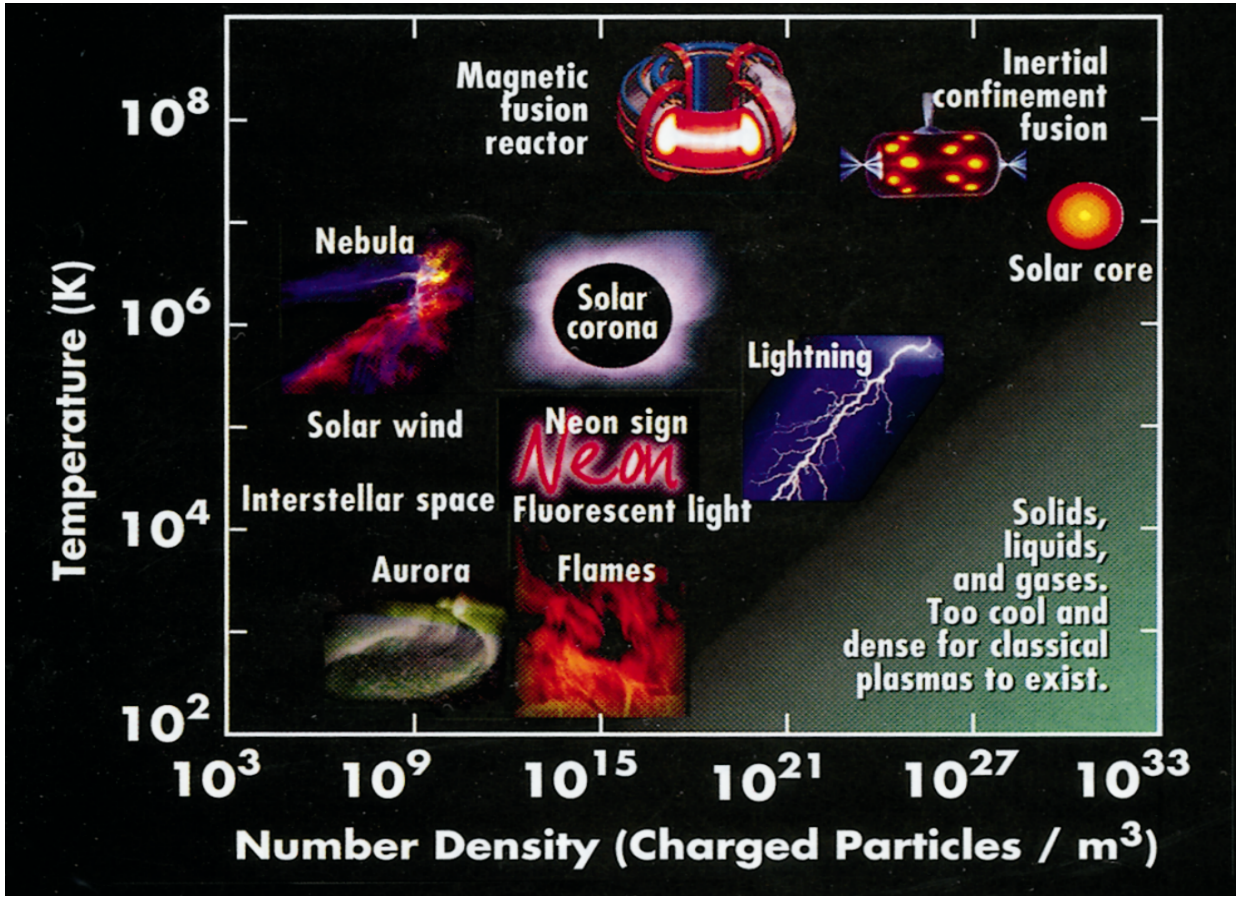


Musíme ji ale svinout do kruhu (zbavit se podstav)

záchranný kruh/duše pneumatiky/donut

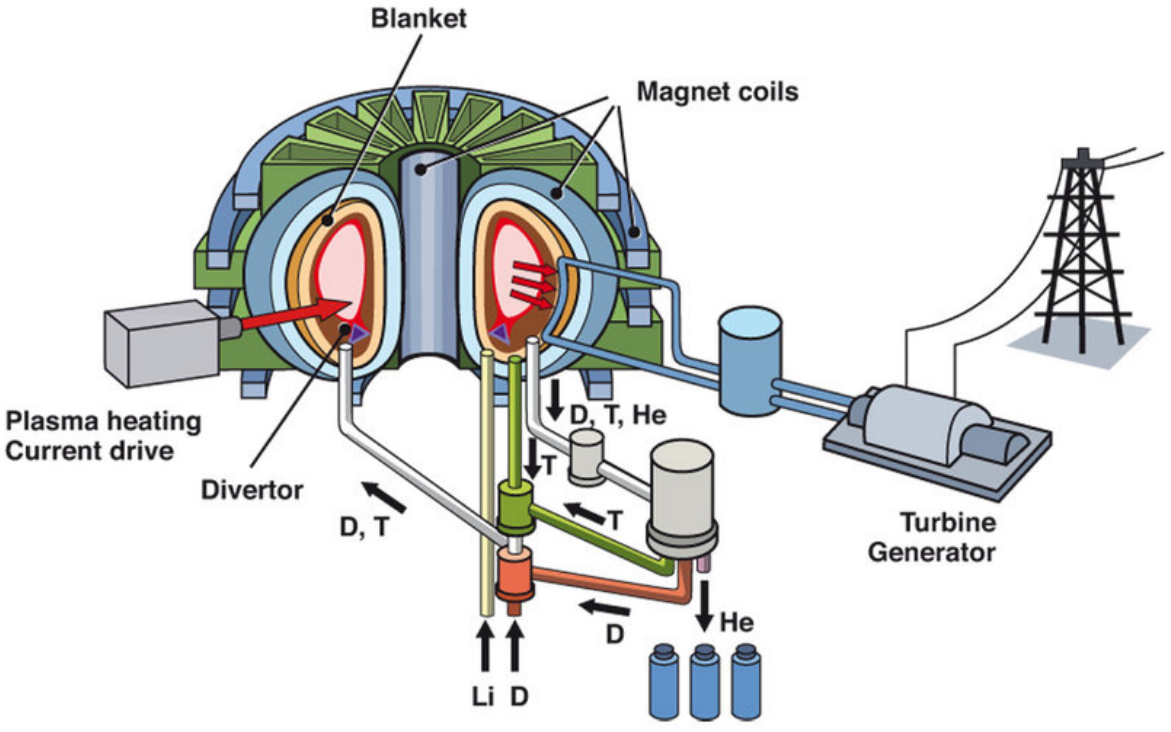
Badatelská skupina / studijní specializace

Fyzika plazmatu a termojaderné fúze



99.999 % Vesmíru je v plazmatickém stavu

Vision: Nuclear power plant – a fusion one

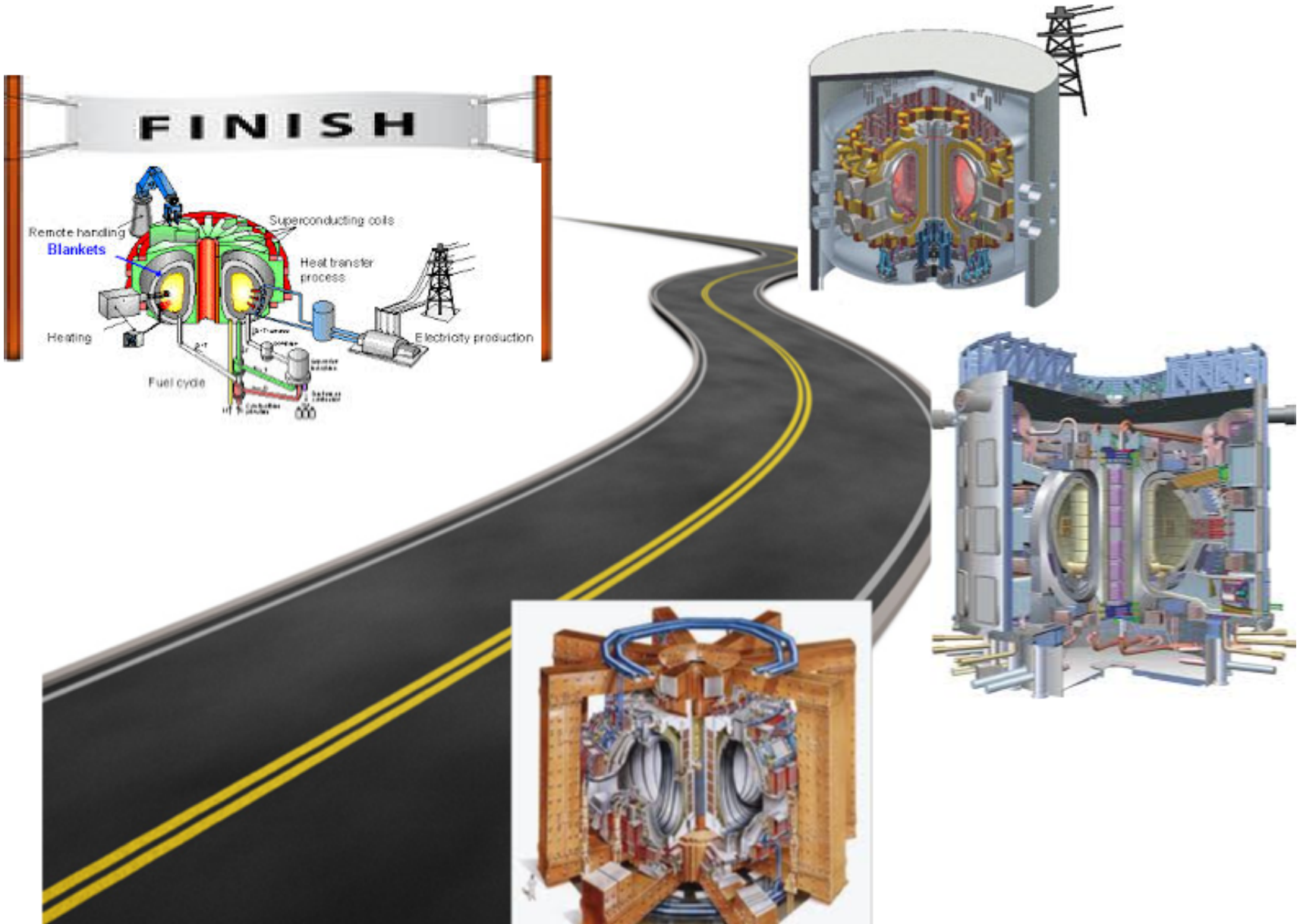


credit:[1]

Prague ($\sim$ 1 GW): yearly $\sim$ a van of D–T mixture

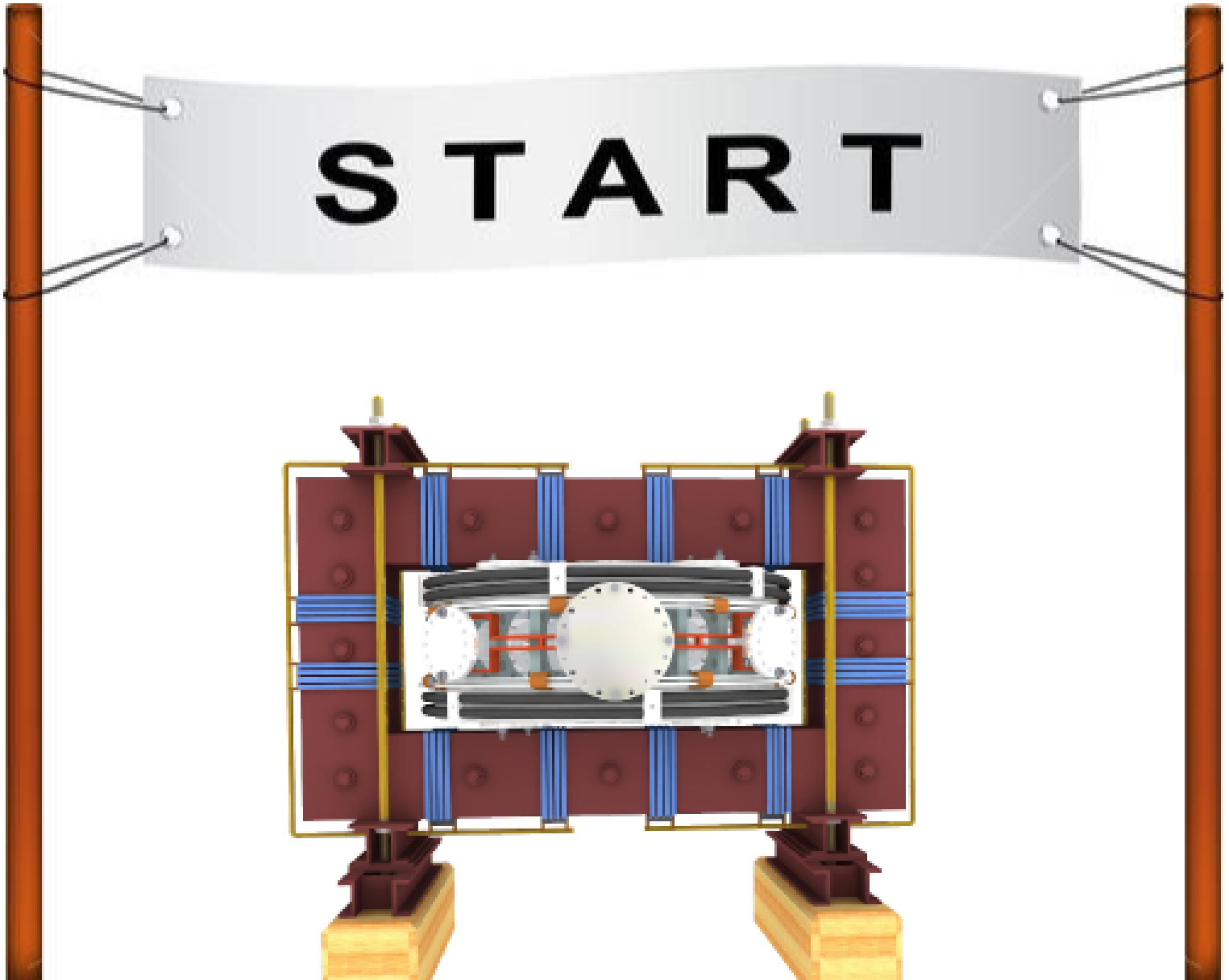
Master the Technology

Milestones to Fusion Power Plant

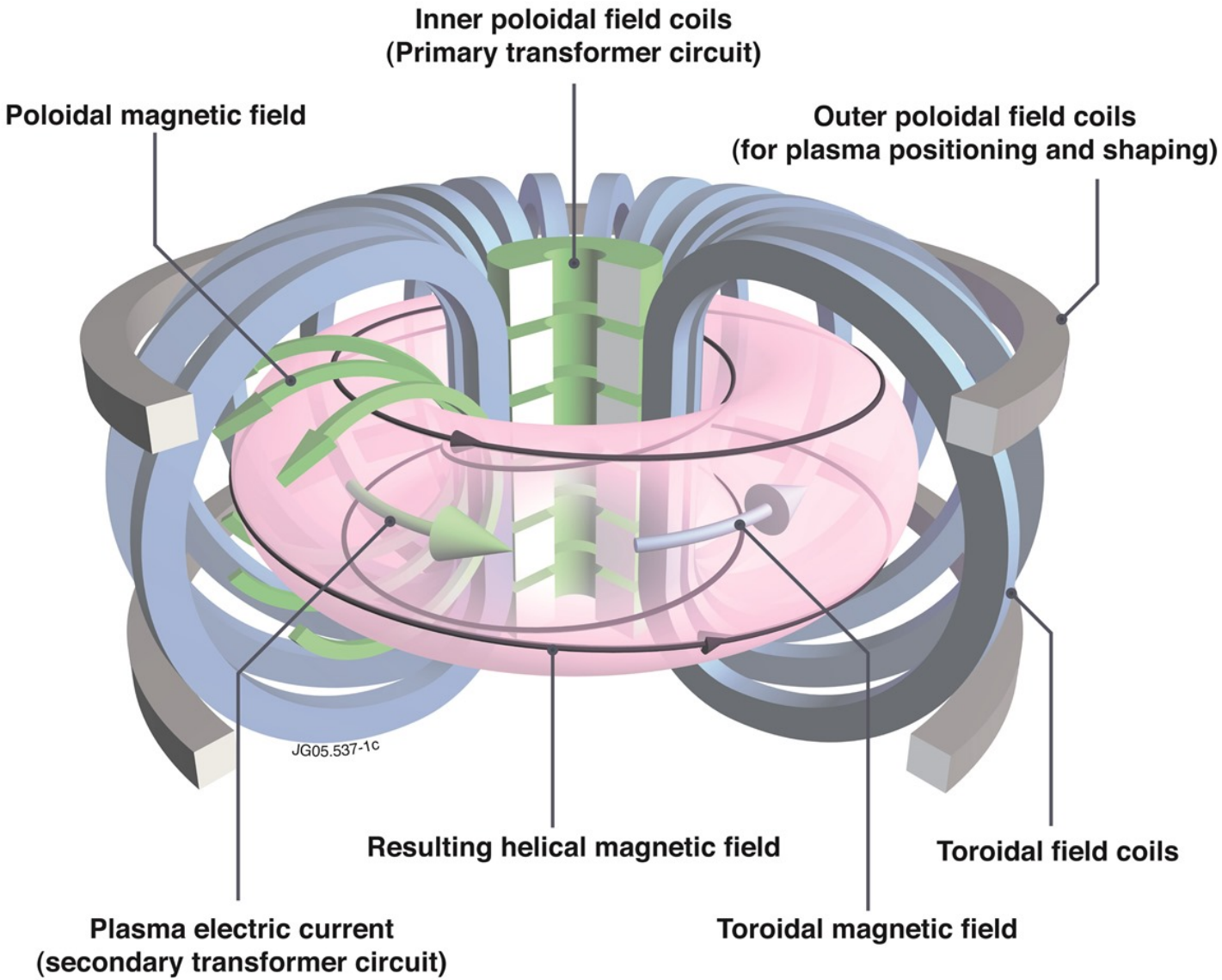


Education importance

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

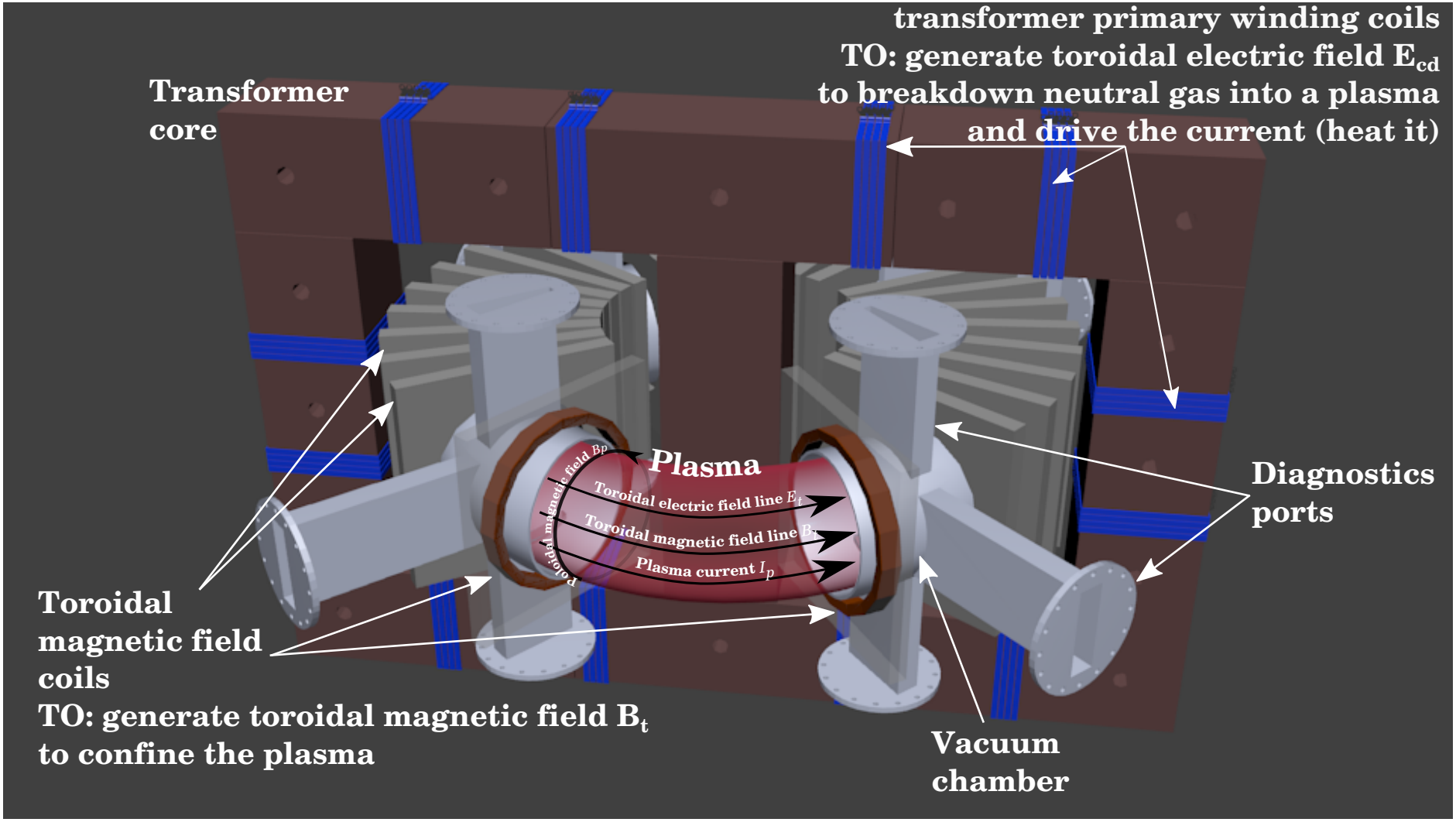


Tokamak magnetic confinement concept



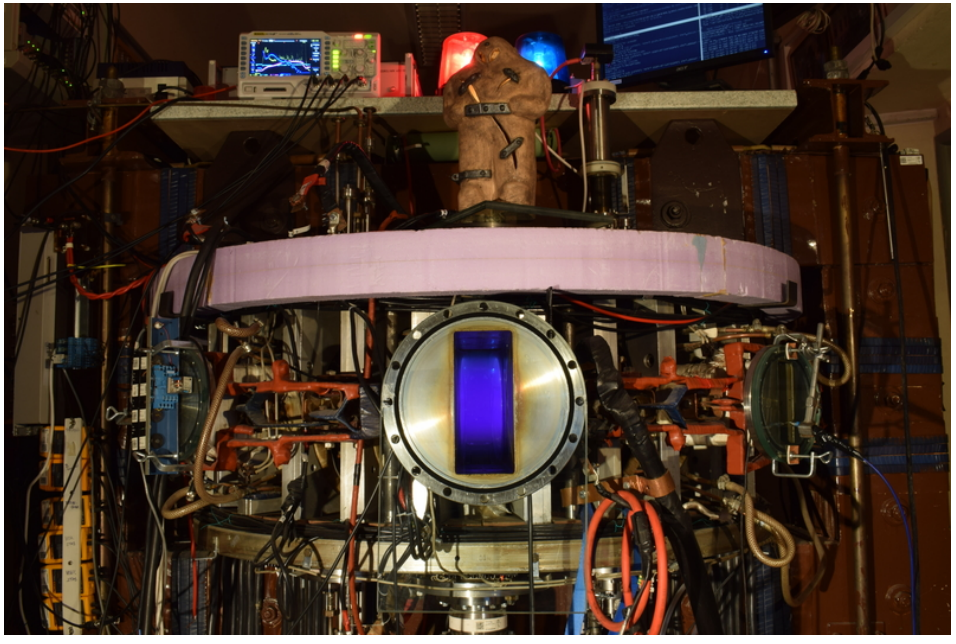
credit:Tokamak concept@Wiki

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



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 ..

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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)

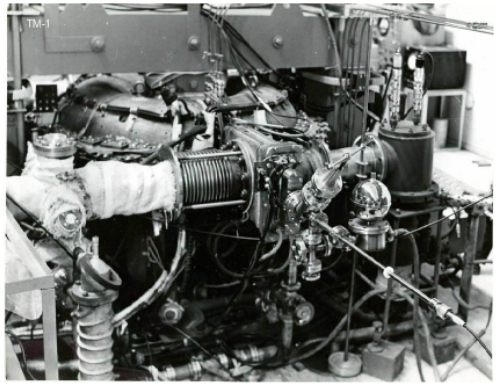
- 1960s: TM1-MH (since 1977 Castor; since 2007 Golem[12]) in Prague, Czech Republic. In operation in Kurchatov Institute since early 1960s but renamed to Castor in 1977 and moved to IPP CAS,[13] Prague; in 2007 moved to FNSPE, Czech Technical University in Prague and renamed to Golem.[14]
- 1975: T-10,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

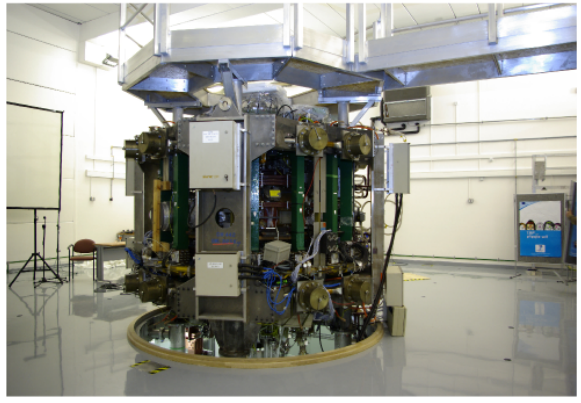
Tokamak - Wikipedia, the free encyclo | (svoboda) buon.fjfi.cvut.cz – Konsole | Krusader | Inbox - svoboda@fjfi.cvut.cz - Mozilla

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

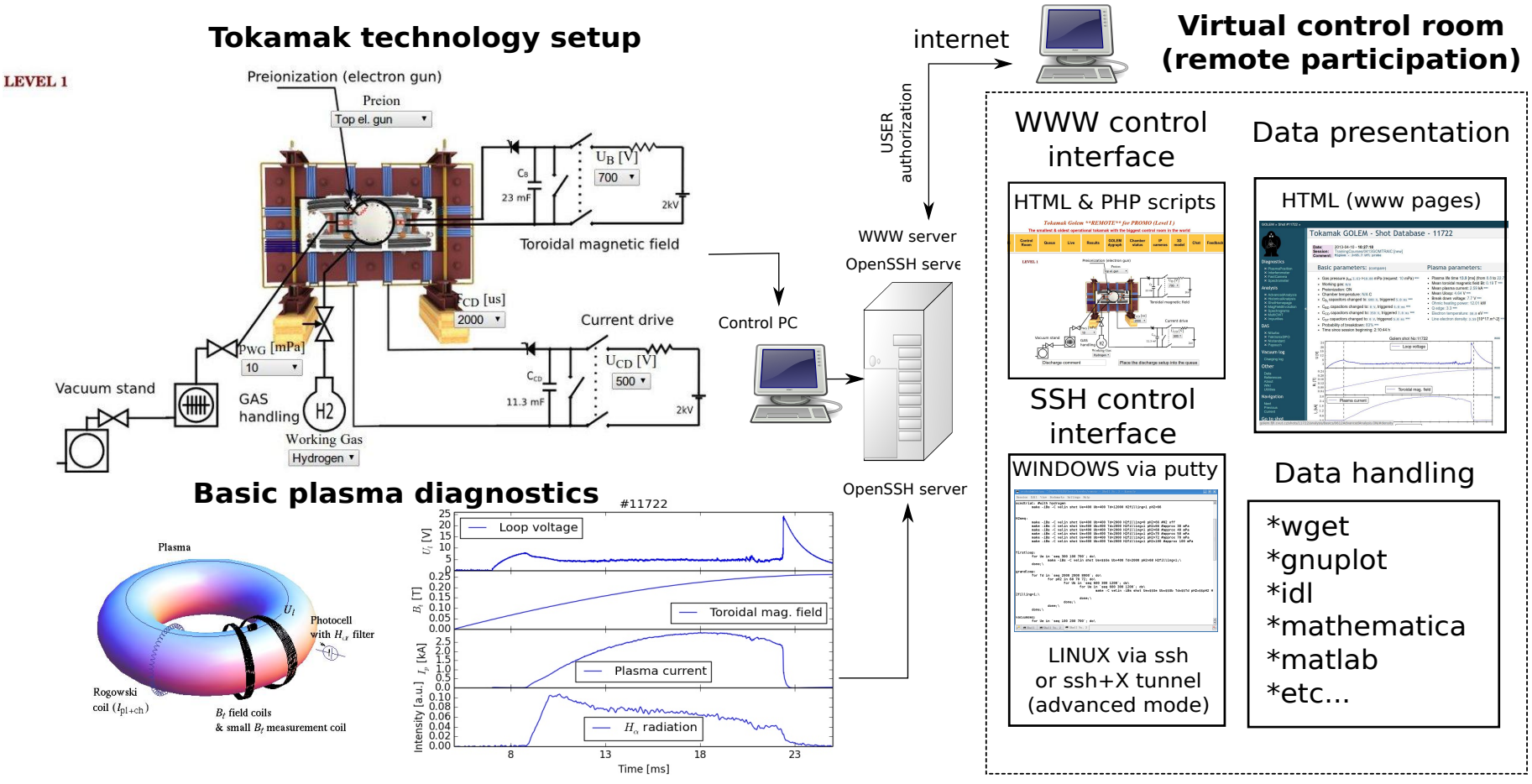
GOLEM

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

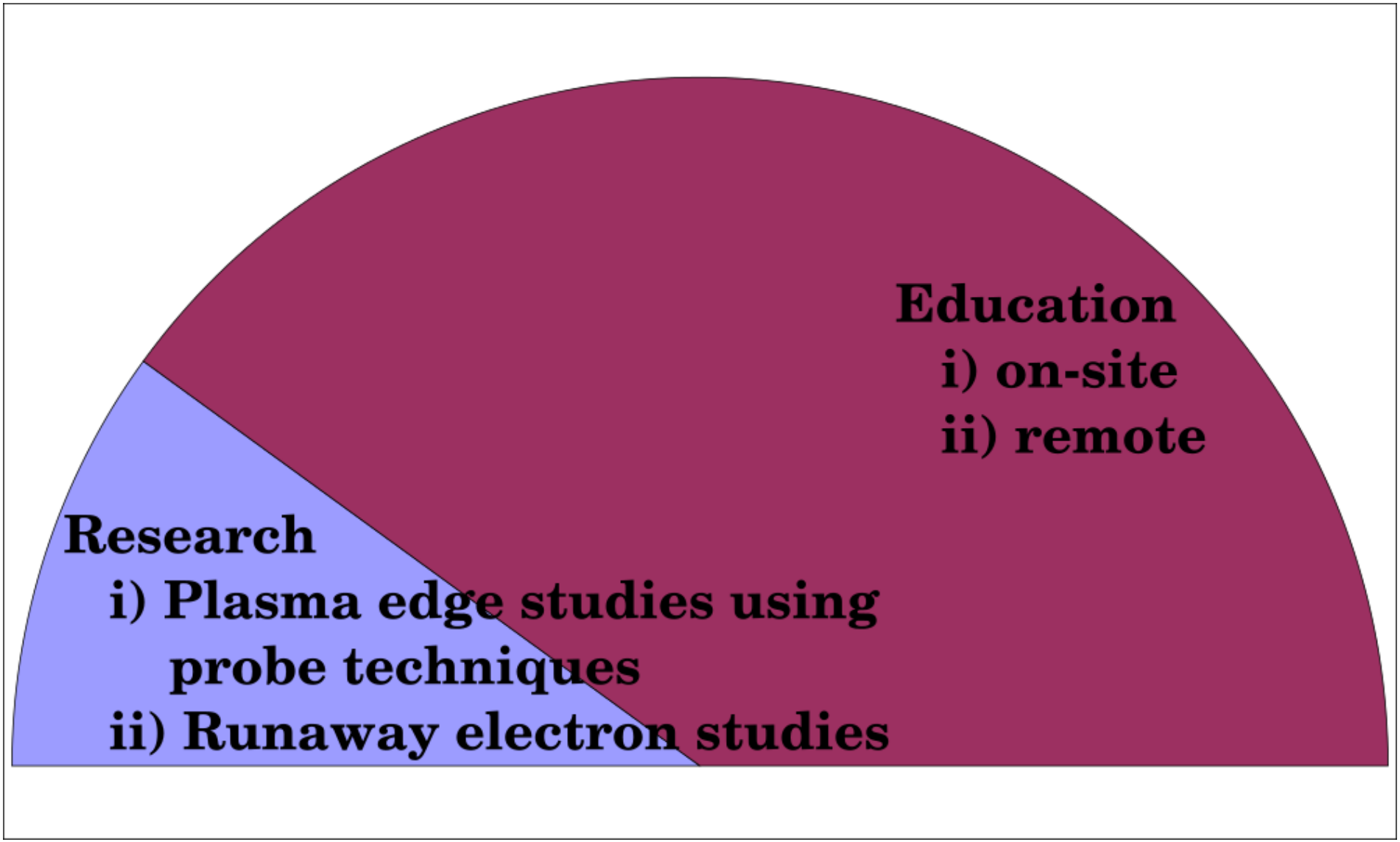
there is hidden indeed "infernal" power. Yet it is the very power of celestial stars themselves. Calmly dormant, awaiting mankind to discover the magic key, to use this power for their benefit...

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. [4].

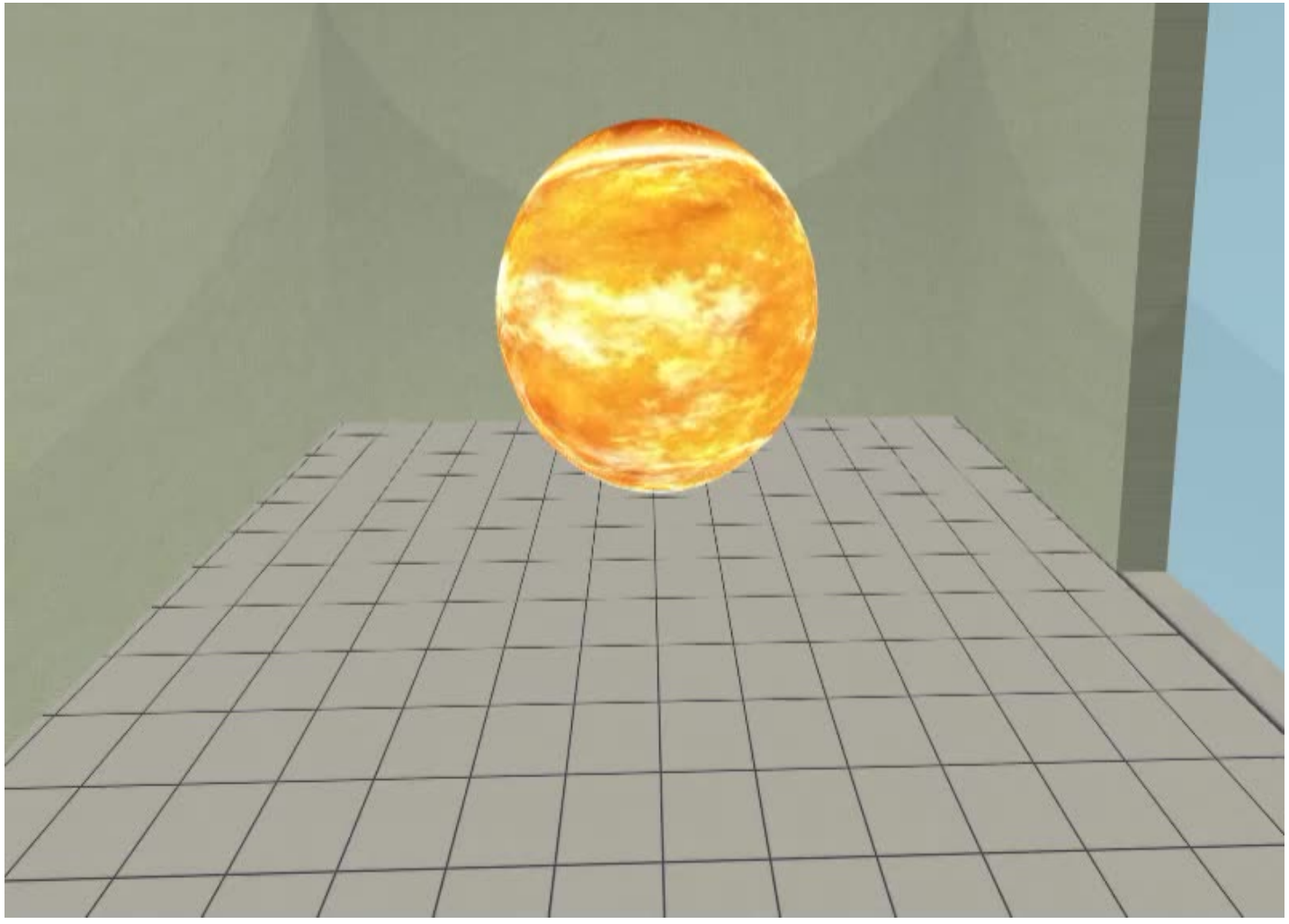
The global schematic overview of the GOLEM experiment



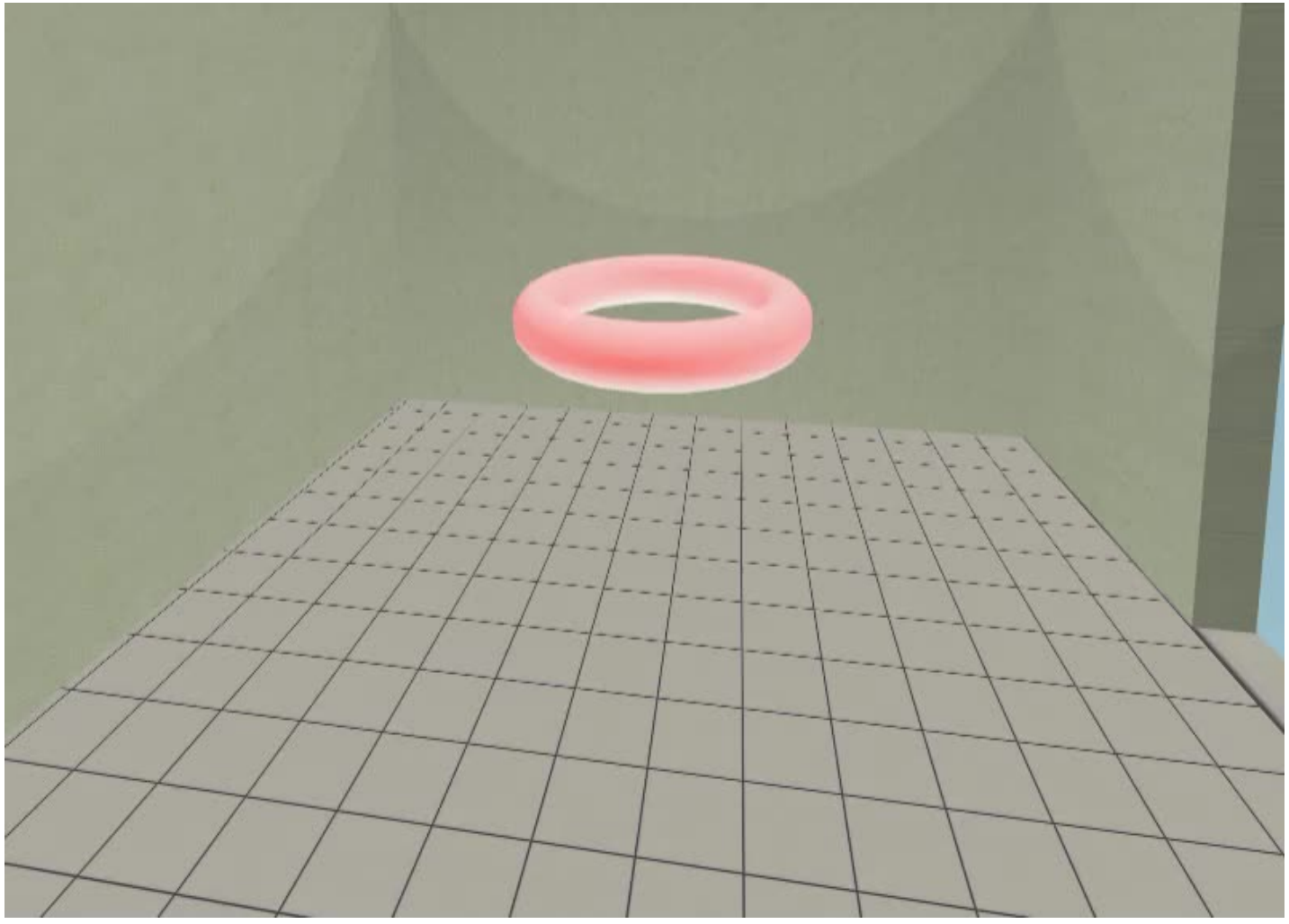
The GOLEM tokamak mission



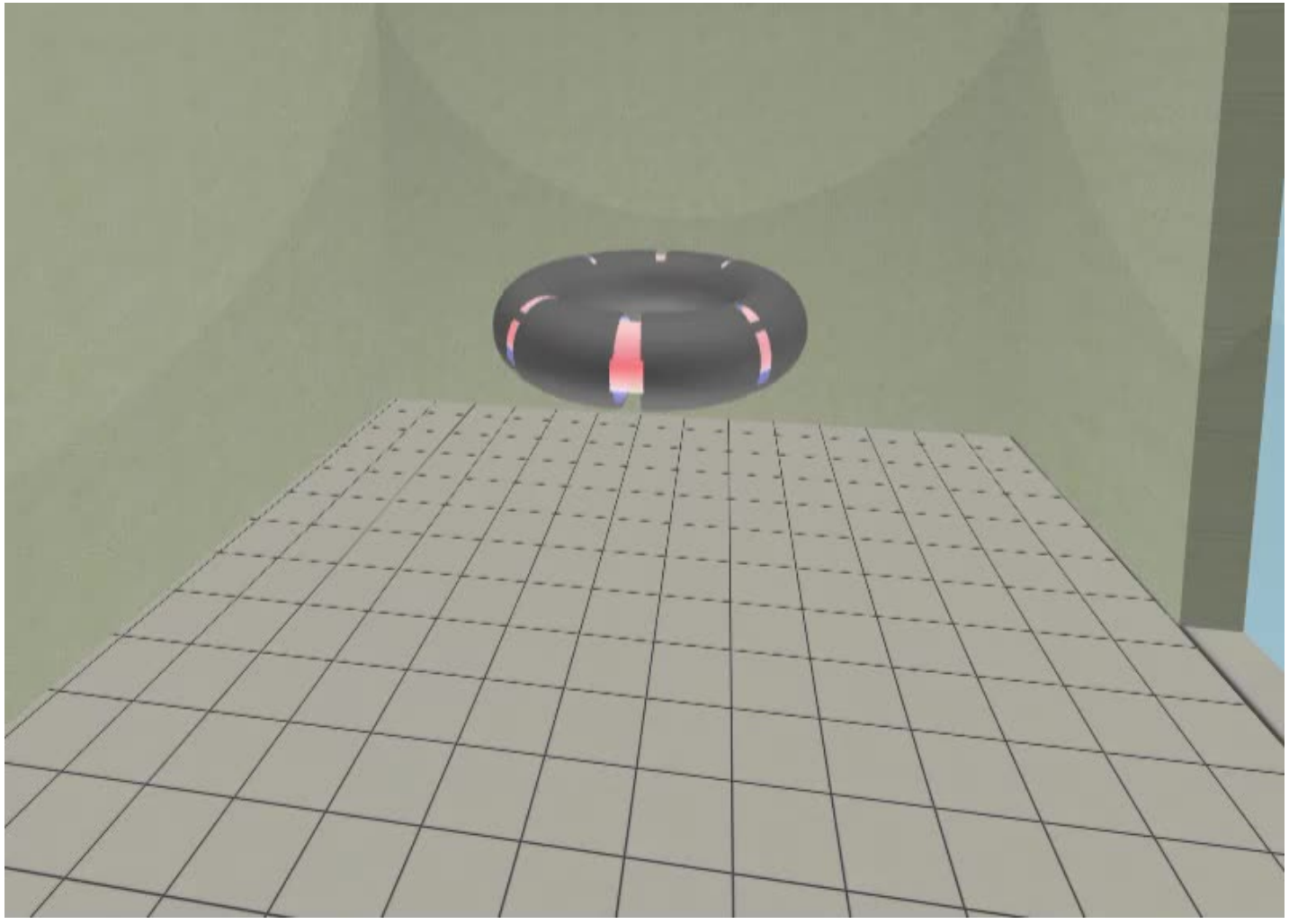
Náš cíl: vytvořit μSlunce v pozemských podmínkách



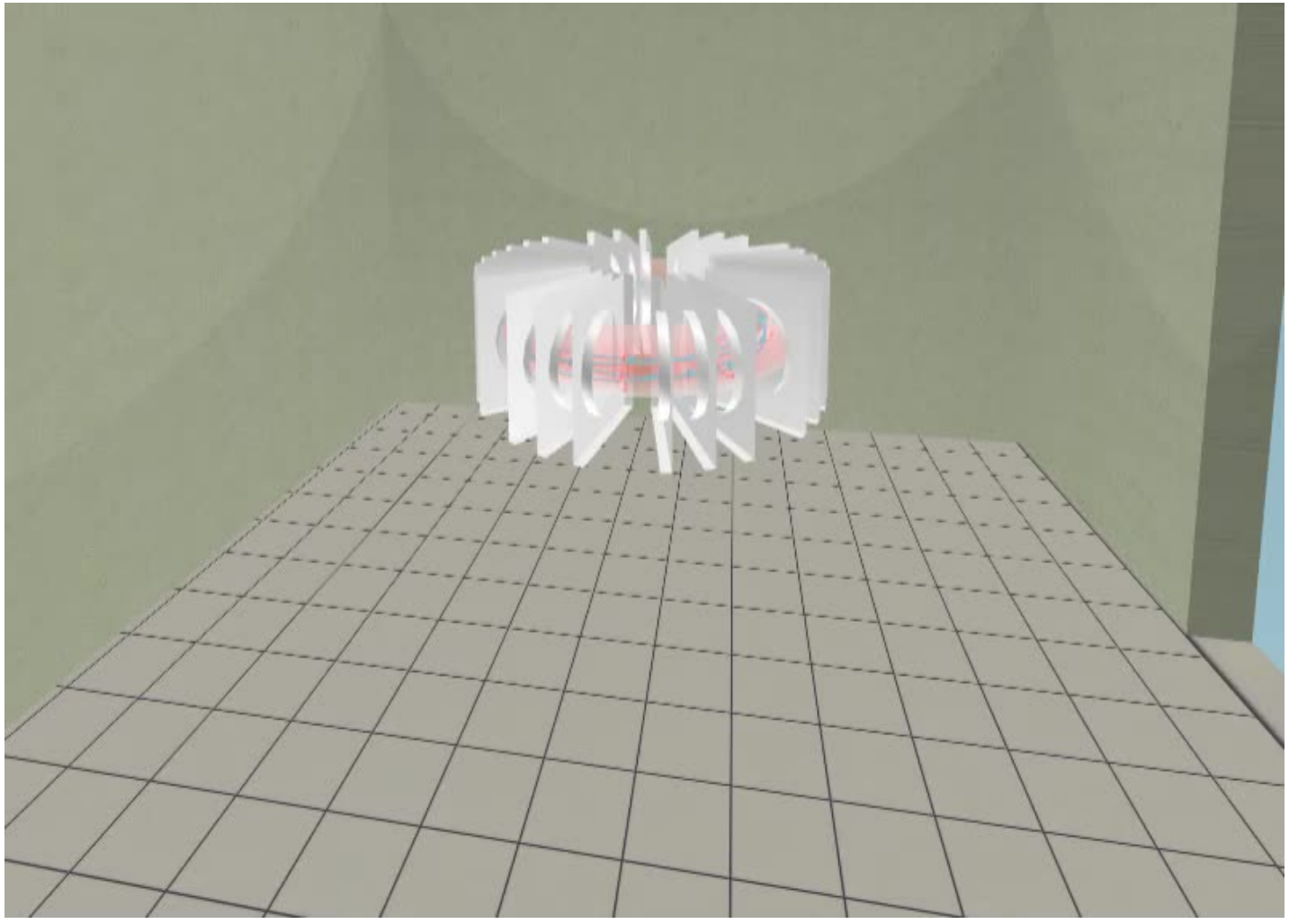
Magnetické udržení vyžaduje toroidální geometrii
Svinutá magnetická nádoba



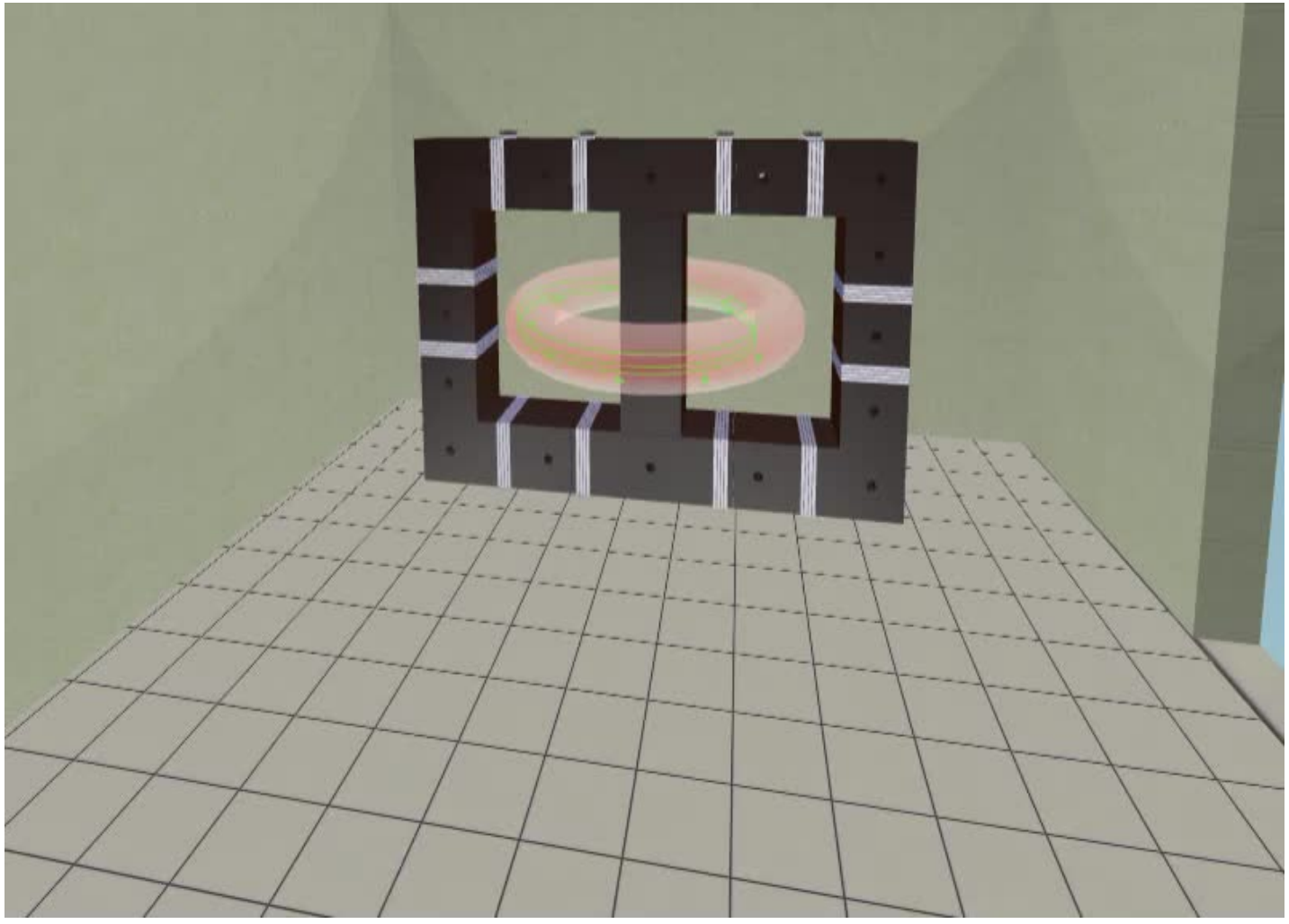
Musíme to celé umístit do reaktorové nádoby - komory



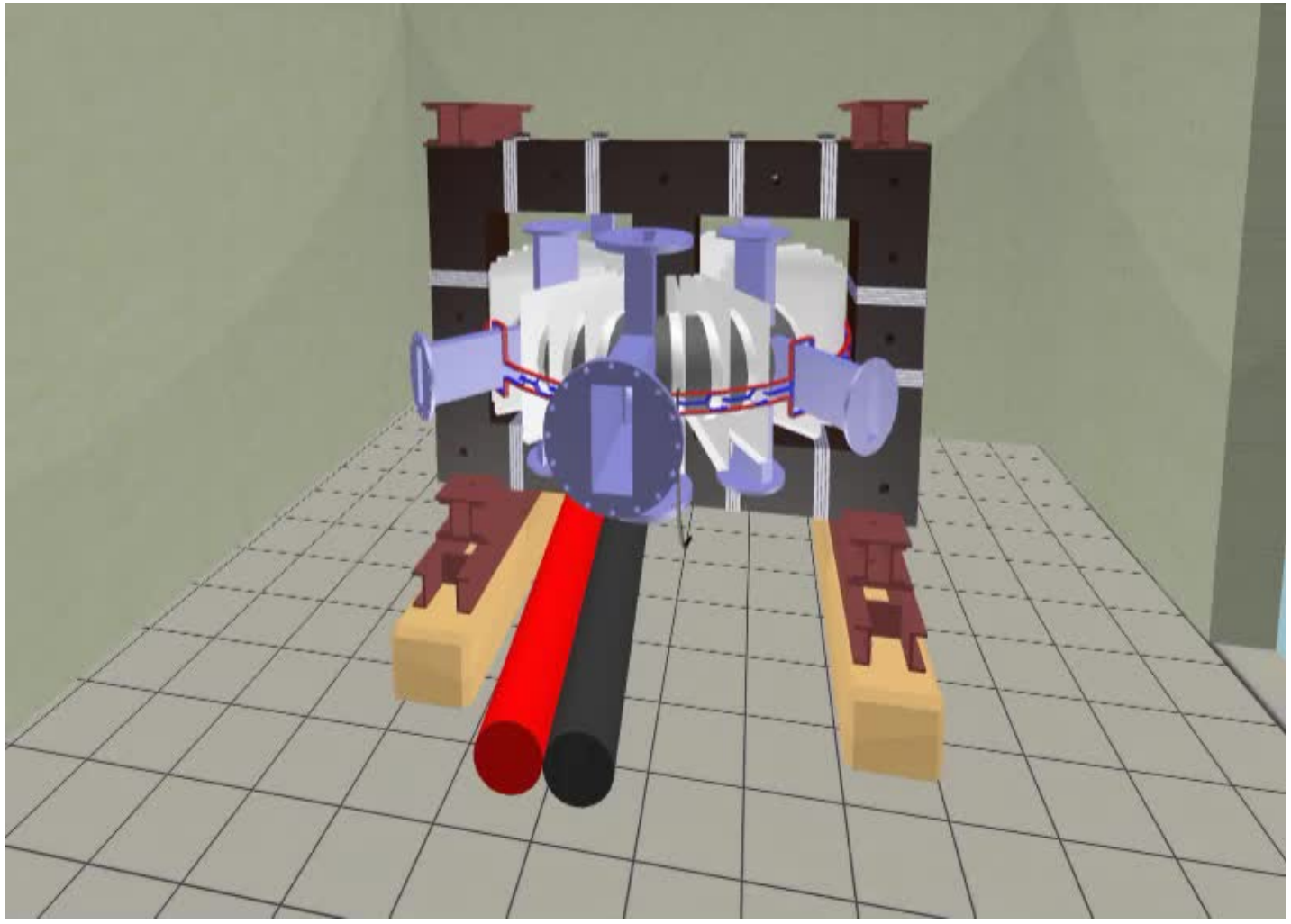
Toroidální magnetické pole udržuje plazma



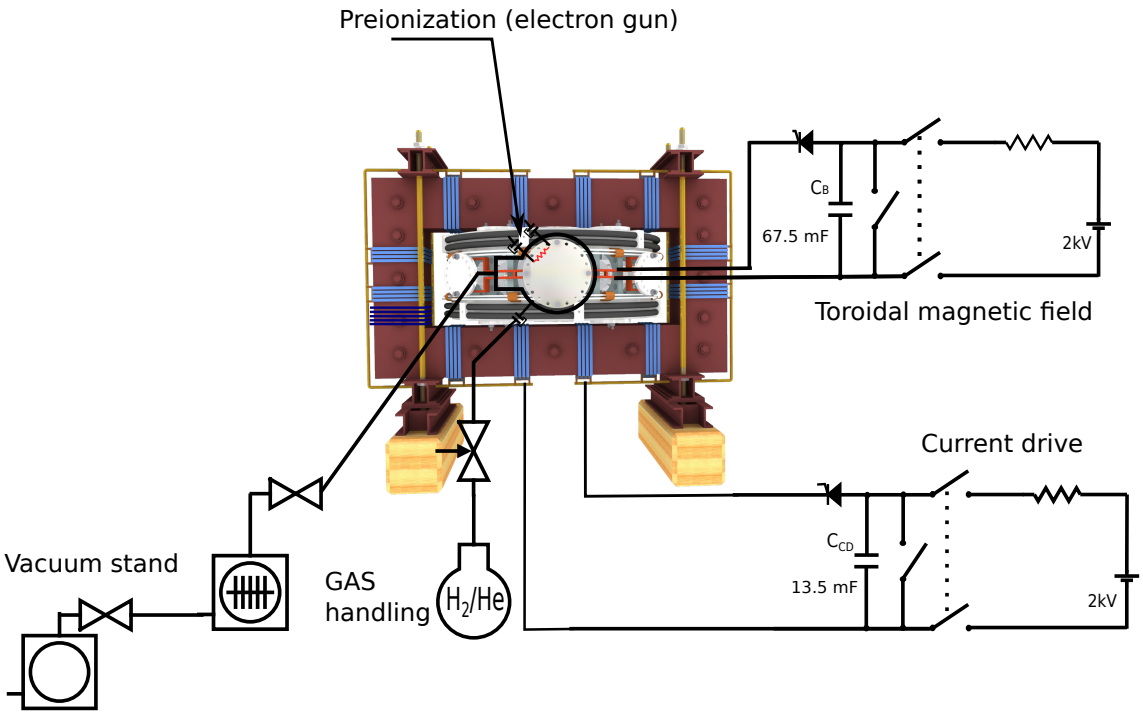
Transformátorová akce vytvoří a zahřeje plazma



Vše dohromady - voilà tokamak



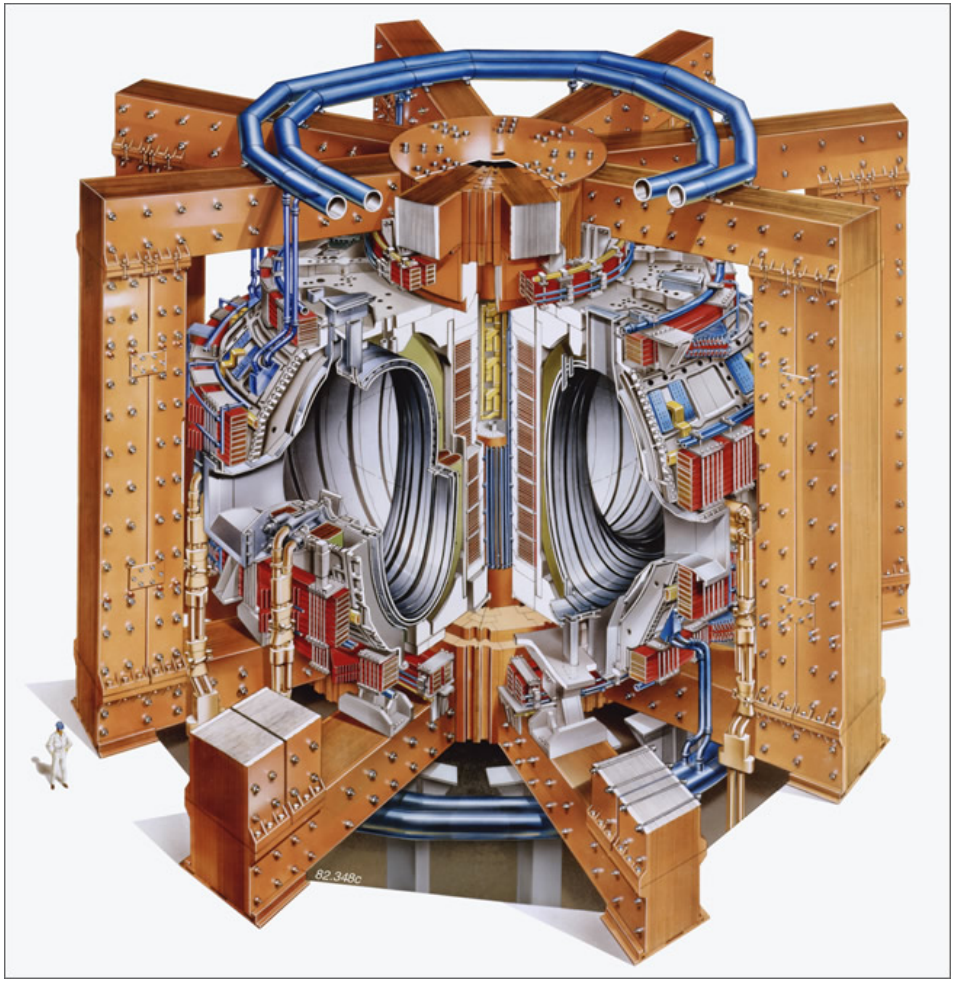
Plasma in Tokamak (GOLEM) - the least to do



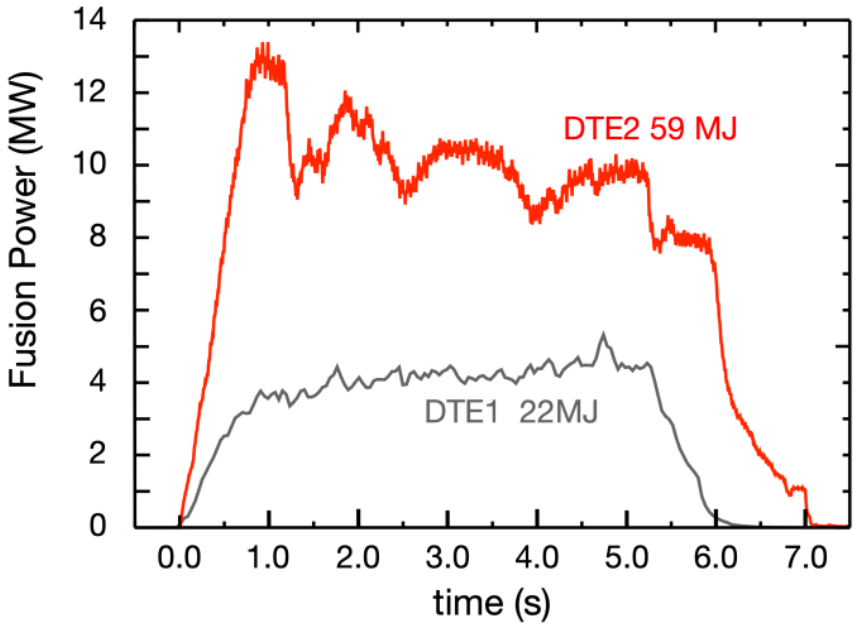
To do:

- 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

1997: Světový fúzní rekord @ JET (EU)

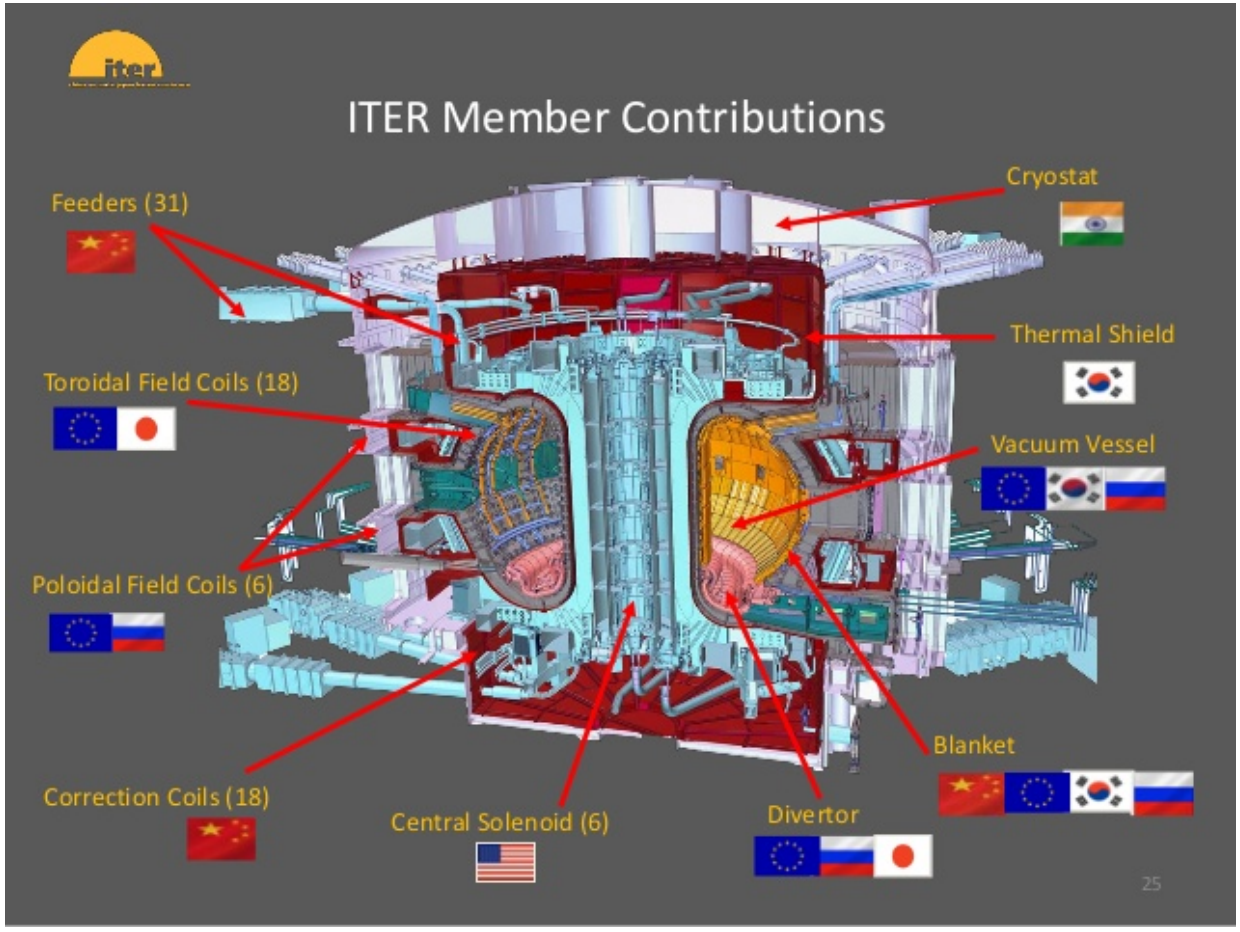


output comparison 1997 and 2021.png



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

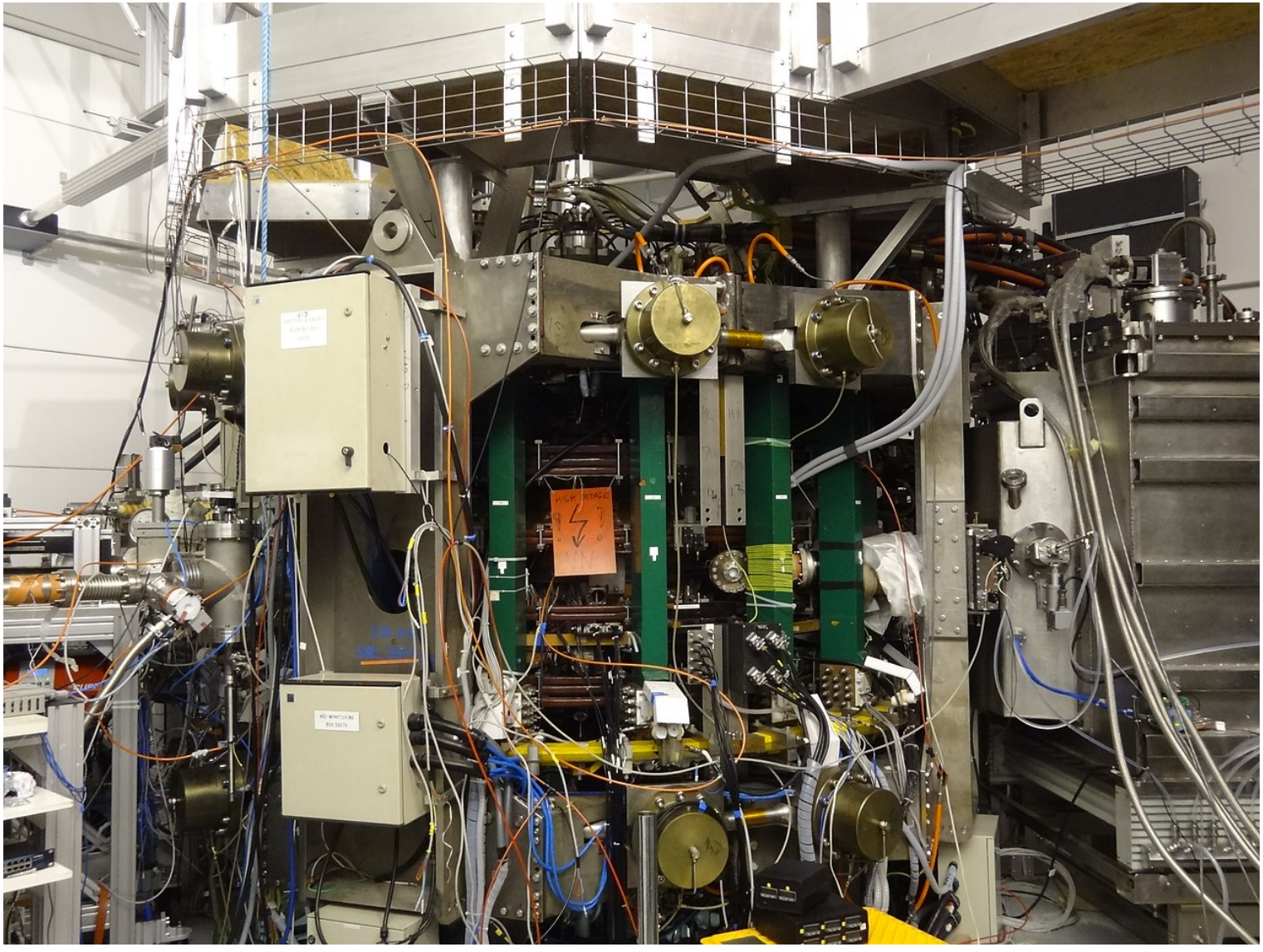
ITER (jižní Francie) $\approx$ 18 miliard EUR



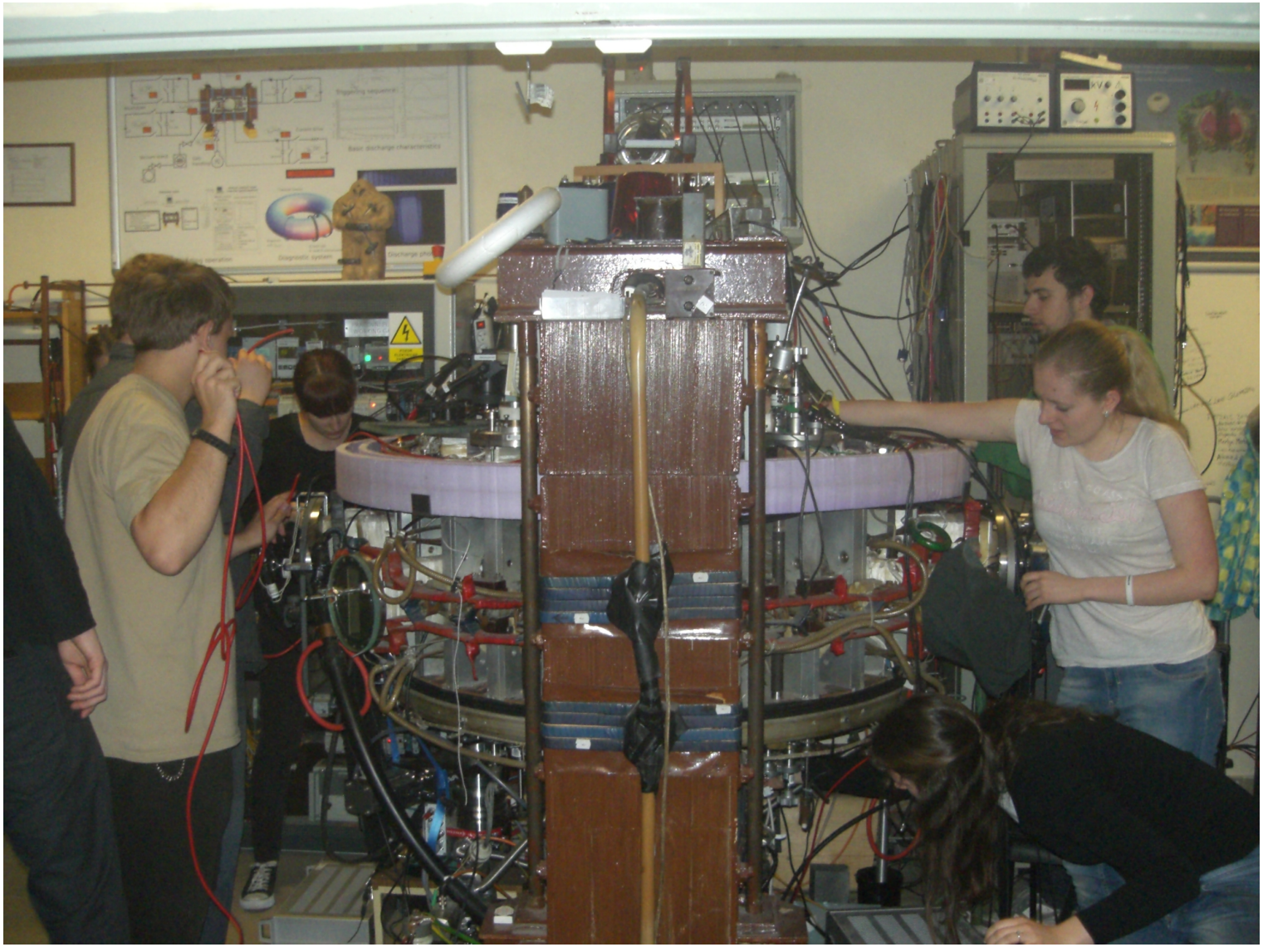
Mise:

$P \approx 500$ 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

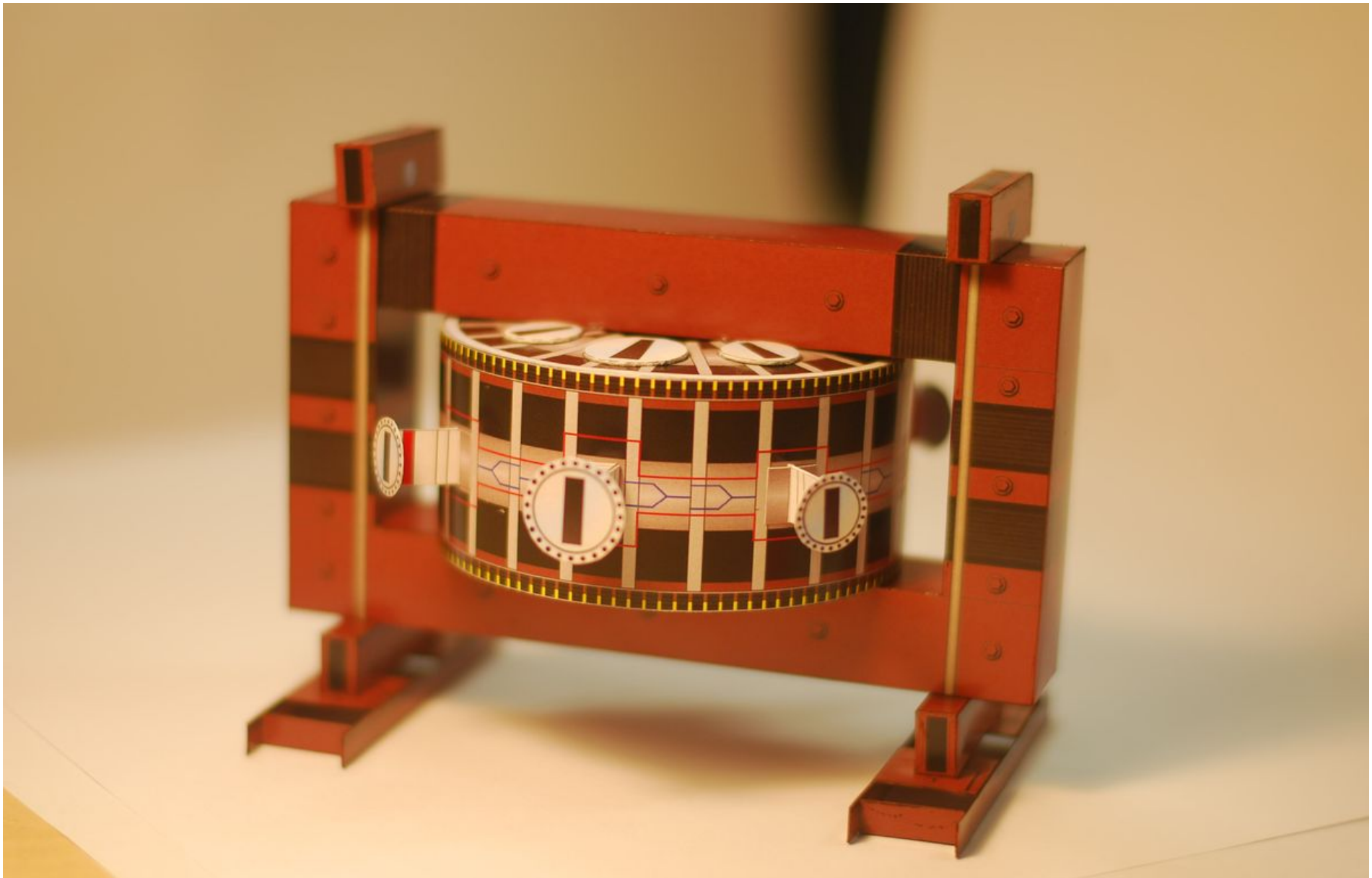
Studenti z TU Eindhoven, operující tokamak, 650 km vzdušnou čarou

- 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

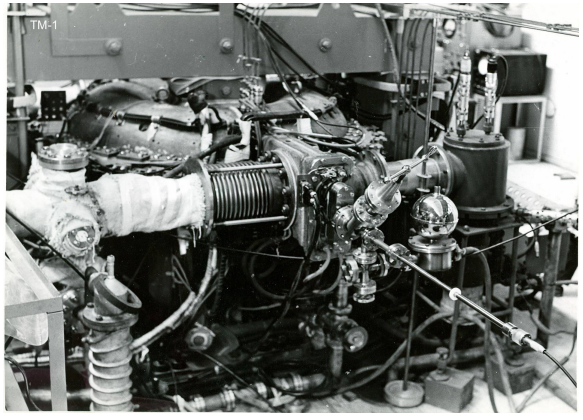
GOLEM

Paper model ABC



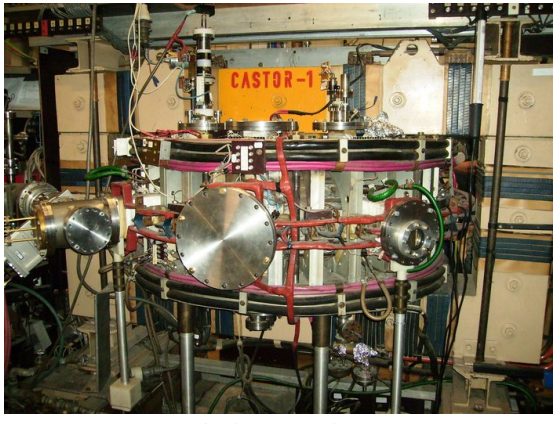
Děkuji za pozornost

Tokamak TM1
@Kurchatov Institute near Moscow
~1960-1977



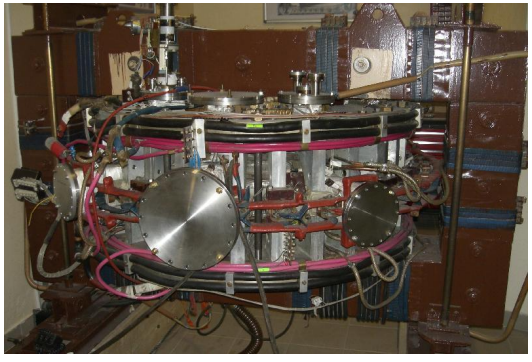
SCIENCE

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



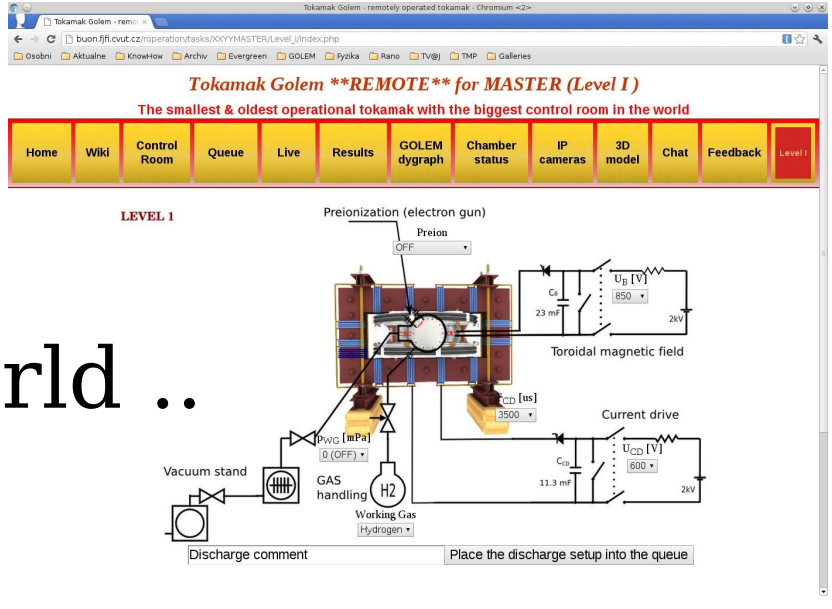
SCIENCE
& education

Tokamak GOLEM
@Czech Technical University, Prague
2007-



EDUCATION
& science

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



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