

Tokamak GOLEM

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

February 2, 2023

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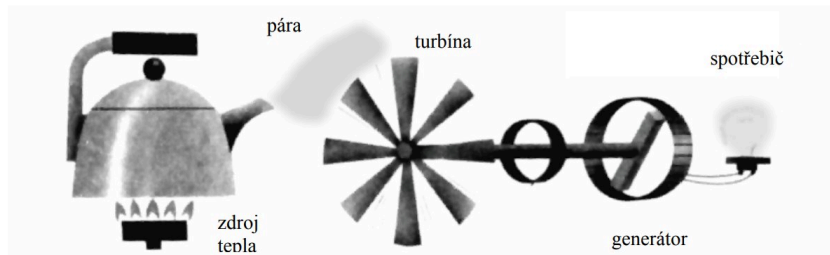
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2 The Tokamak (GOLEM)

3 Conclusion

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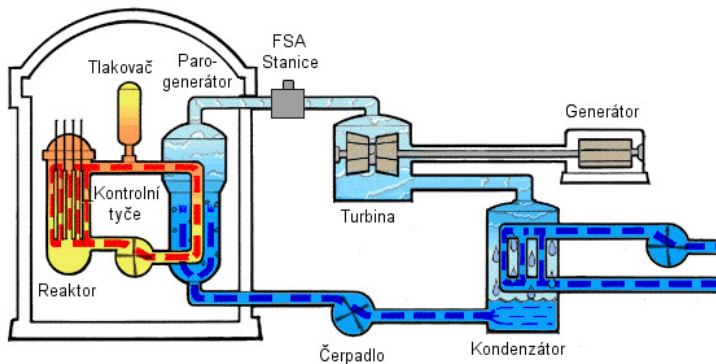
Thermal power plant - basic principle



The question:

?? WHAT TO BURN ??

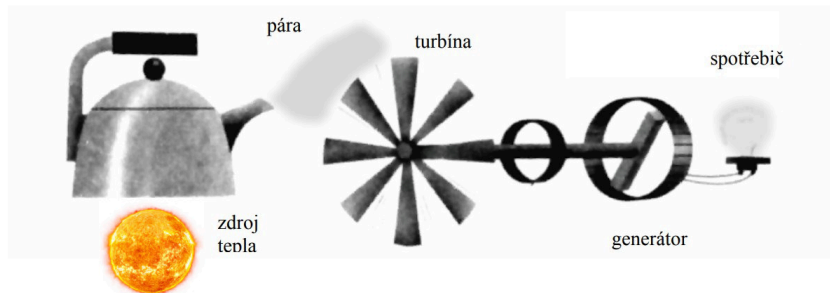
Jaderná elektrárna - štěpná



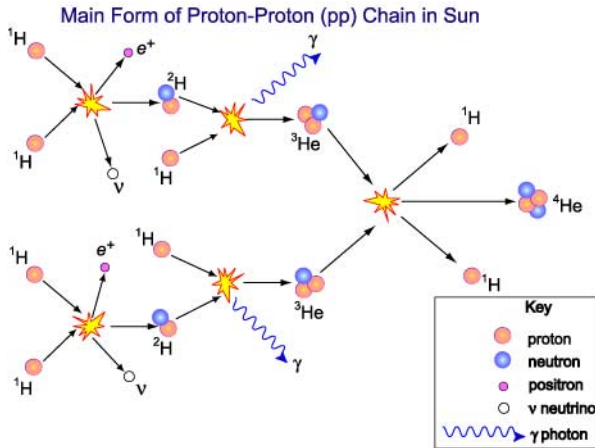
Praha (~ 1 GW): ročně $\sim$ vagón jaderného paliva

Dotáhnout technologii: Suroviny, Odpad, Bezpečnost

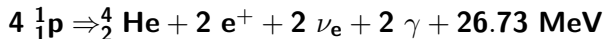
Topit malým Sluncem/hvězdou ??



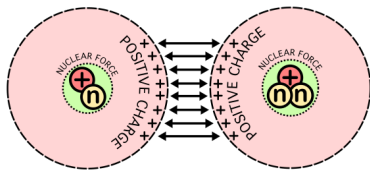
The Sun - Proton proton chain



credit:CSIRO

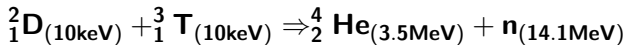


Electrostatic force - like charges repel

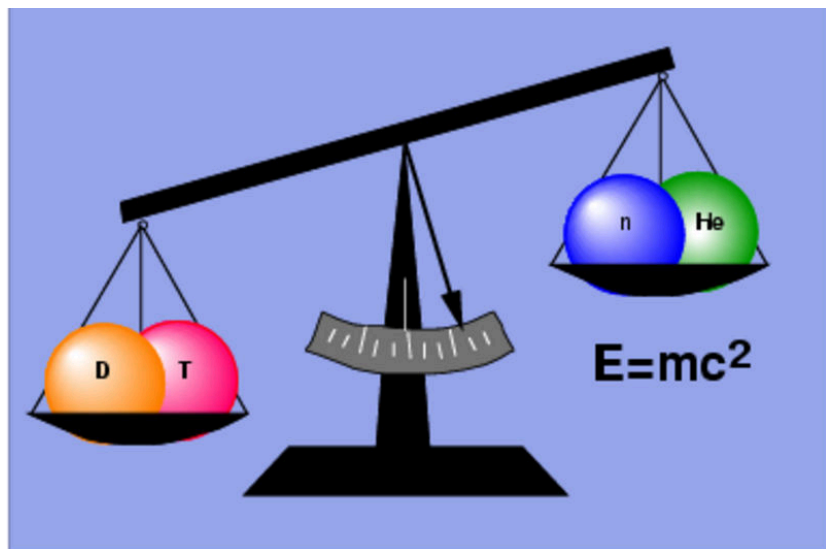


■ Coulomb law:

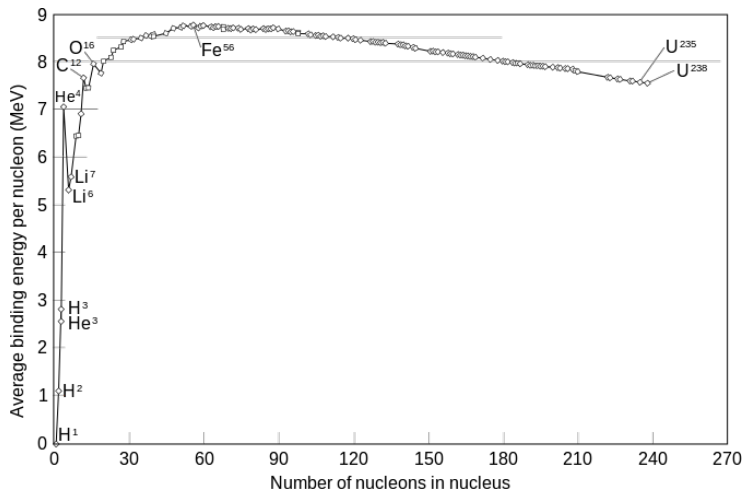
$$F_E = \frac{1}{4\pi\epsilon_0} \frac{Q_1 Q_2}{r^2}$$



Binding energy releasing I

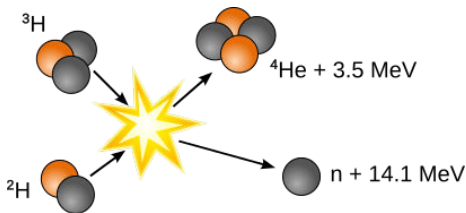


Binding energy per nucleon

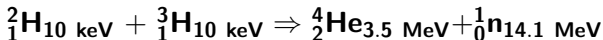


credit:[1]

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



credit:[1]



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

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

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

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

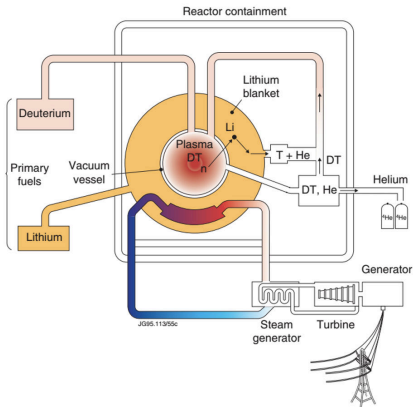
$$1\text{eV} \sim 11600^\circ\text{C} \approx {}^2_1\text{H}_{100 \text{ M}^\circ\text{C}} + {}^3_1\text{H}_{100 \text{ M}^\circ\text{C}} \Rightarrow {}^4_2\text{He}_{35 \text{ G}^\circ\text{C}} + {}^1_0\text{n}_{141 \text{ G}^\circ\text{C}}$$

Palivo: IAEA "Natural water"





Bezpečnost



* Nejde o řetězovou reakci.

* Tritium: slabý β zářič

$T_{1/2} = 12.5$ roku. Minimální nebezpečí.

* Minimalizovaný potenciál aktuálně přítomného D-T paliva.



Můžeme se zmocnit energie
která pohání Slunce/hvězdy?

1952 "Operation Ivy - Mike" První test vodíkové bomby



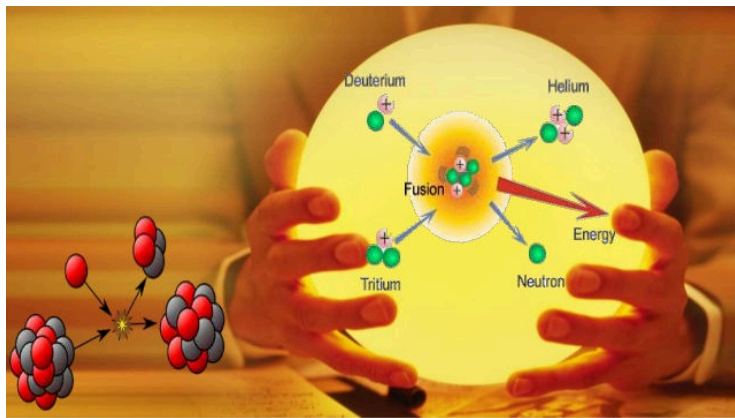
Operation Ivy - Mike

10.4 Megatons

credit:YouTube:Ivy Mike Countdown and detonation

Toto není vhodná technologie

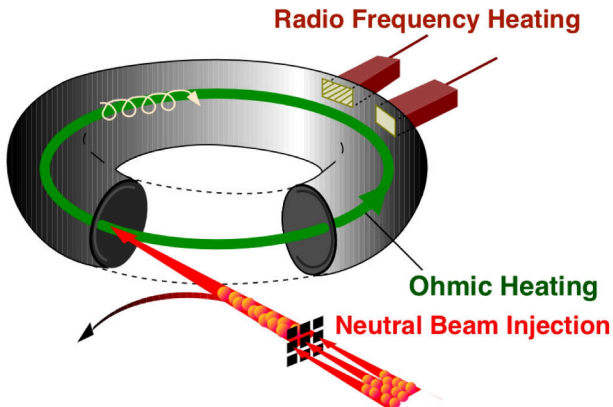
Hledá se vhodná fúzní technologie



Podmínky:

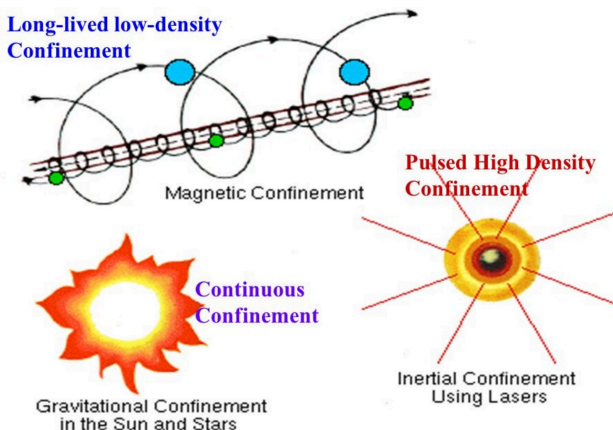
Zahřát na $\sim 100\,000\,000\,^{\circ}\text{C}$ & **udržet** po dobu ~ 30 let

Ohřev plazmatu

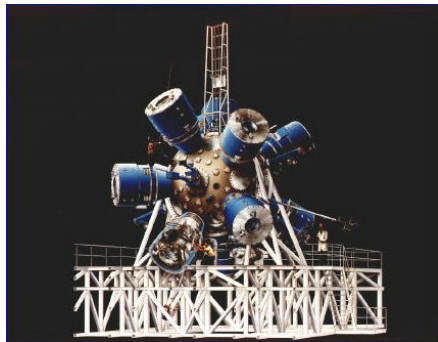
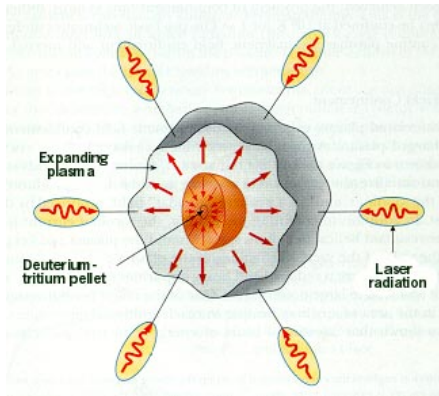


Tři možné cesty jak udržet plazma pro fúzi

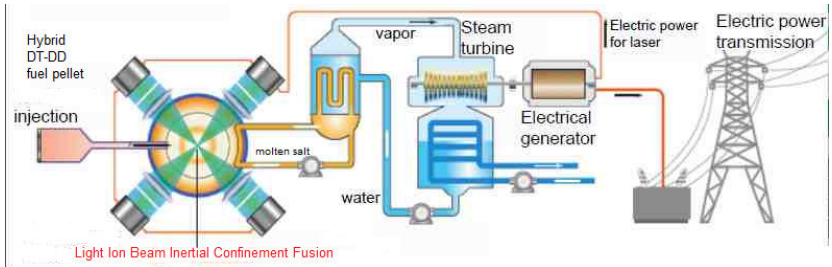
Lawsonovo kritérium: $n\tau_E \geq 1.5 \cdot 10^{20} \frac{\text{s}}{\text{m}^3}$ ($2 \times 6 > 11 \parallel 6 \times 2 > 11$)



Inertial fusion



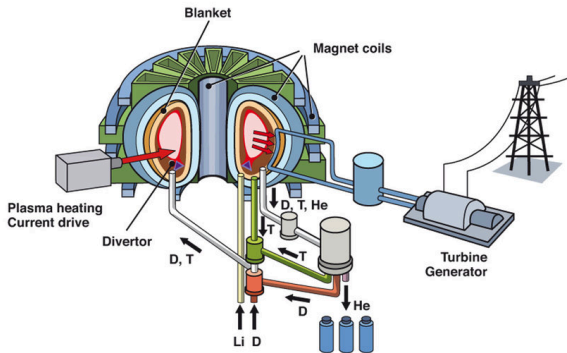
Inertial fusion



credit:mext.jp

Challenge

Vize: Jaderná elektrárna - slučovací/fúzní

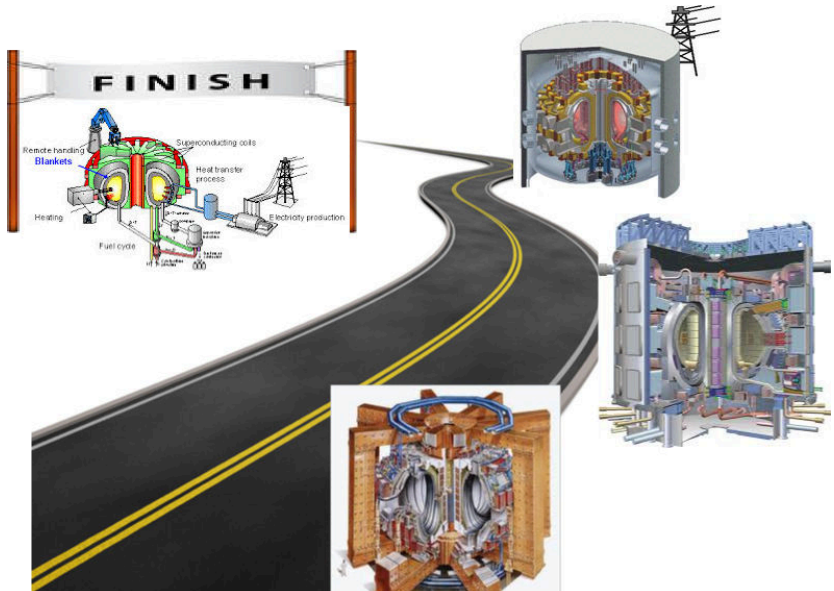


credit:[3]

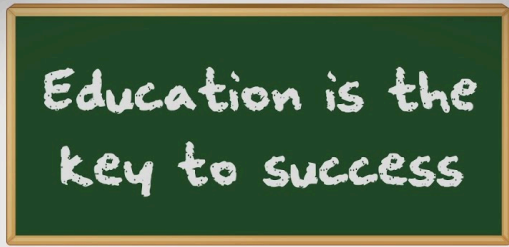
Praha (~ 1 GW): ročně $\sim$ dodávka D-T směsi

Vyplat technologii

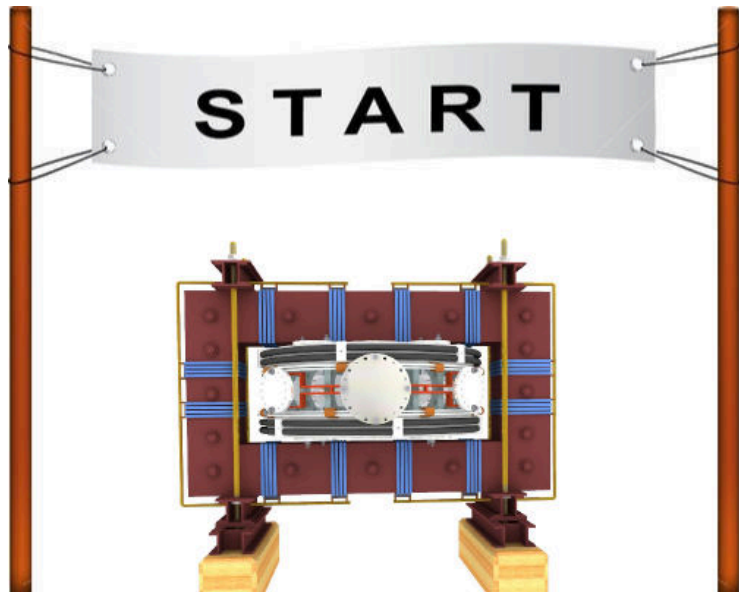
Milestones to Fusion Power Plant



Education importance

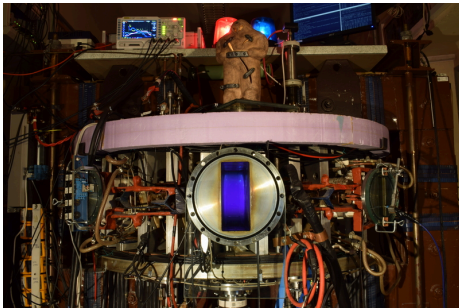


Let's start with the tokamak GOLEM - *the smallest tokamak in the World with the biggest controll room*



The GOLEM tokamak basic characteristics

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



- Vessel major radius: $R_0 = 0.4$ m
- Vessel minor radius: $r_0 = 0.1$ m
- Maximum plasma current:
 $I_p^{\max} < 8$ kA
- Maximum toroidal magnetic field: $B_t^{\max} < 0.5$ T
- Typical electron density:
 $\langle n_e \rangle \in (0.2, 3) \cdot 10^{19} \text{ m}^{-3}$
- Maximum electron temperature:
 $T_e^{\max} < 80$ eV
- Maximum discharge duration:
 $\tau_p^{\max} < 25$ ms

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 ISTOK,^[17] at the Instituto de Plasmas e Fusão Nuclear, Lisbon, Portugal;
- 1991: ASDEX Upgrade, in Garching, Germany



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Article Talk

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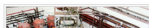
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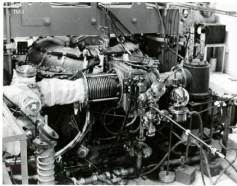


Alcator C-Mod



The GOLEM tokamak for education - historical background

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



1974

Institute of Plasma Physics
Czech republic

CASTOR

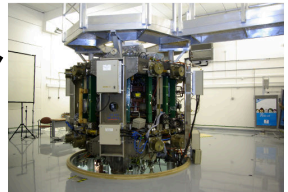
COMPASS

2008

Czech Technical University Prague
Czech republic
GOLEM



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



2006



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...

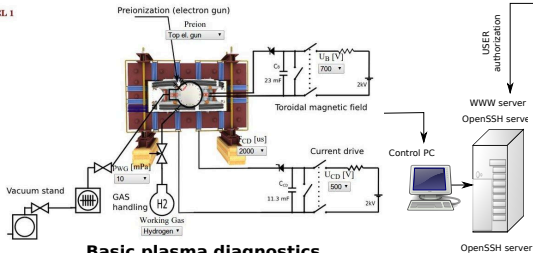


At the end of the 16th century, in the times when the Czech lands were ruled by Emperor Rudolf II, in Prague, there were Rabbi Judah Loew, well known alchemist, thinker, scholar, writer and inventor of the legendary GOLEM - a clay creature inspired with the Universe power that pursued his master's command 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].

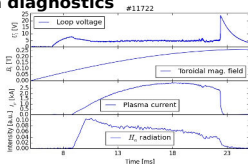
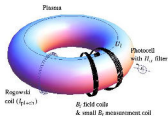
The global schematic overview of the GOLEM experiment

LEVEL 1

Tokamak technology setup



Basic plasma diagnostics



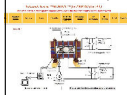
internet



**Virtual control room
(remote participation)**

WWW control interface

HTML & PHP scripts



SSH control interface

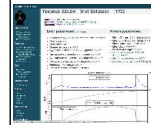
WINDOWS via putty



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

Data presentation

HTML (www pages)



Data handling

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

The GOLEM tokamak mission

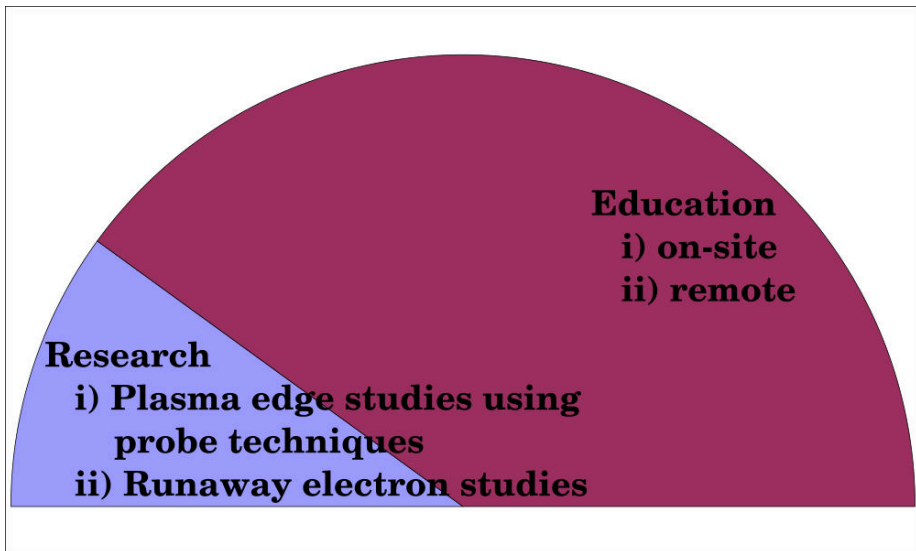


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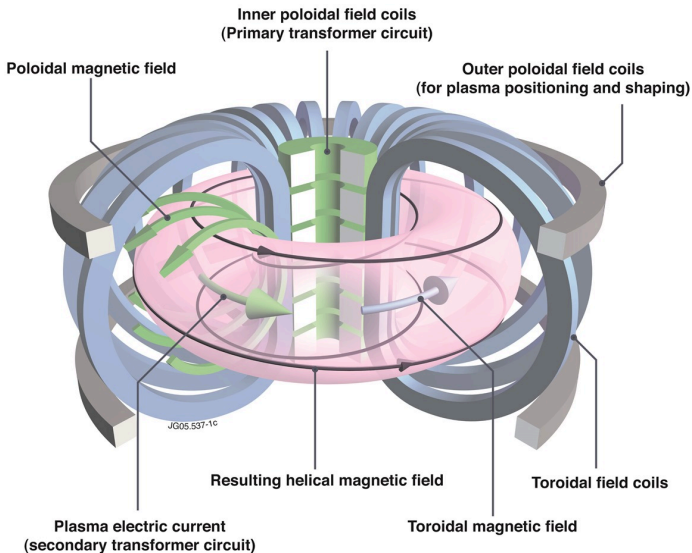
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Tokamak magnetic confinement concept



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

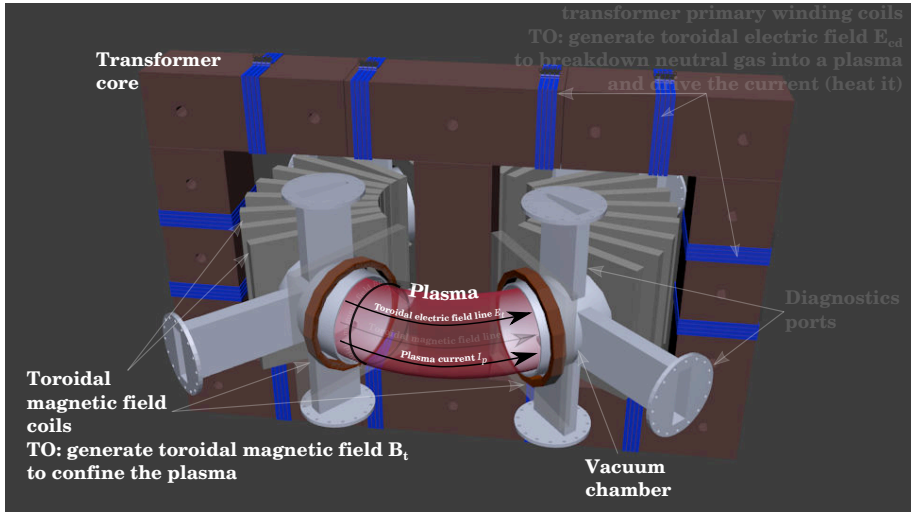


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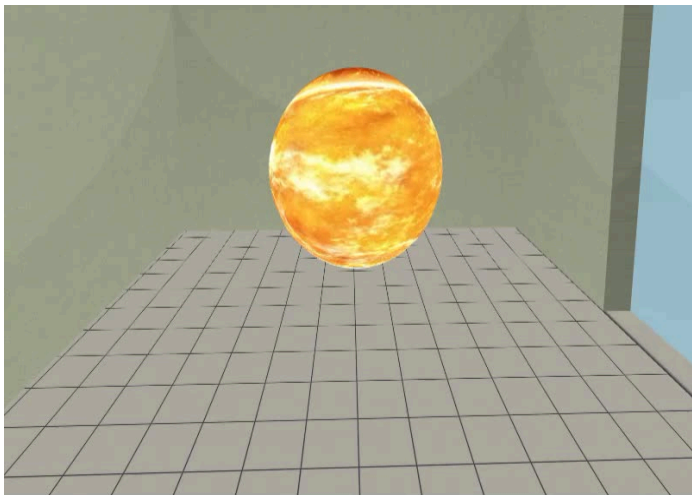
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- The GOLEM tokamak concept
- The scenario to make the (GOLEM) tokamak discharge
- The scenario to discharge virtually
- The GOLEM tokamak basic diagnostics

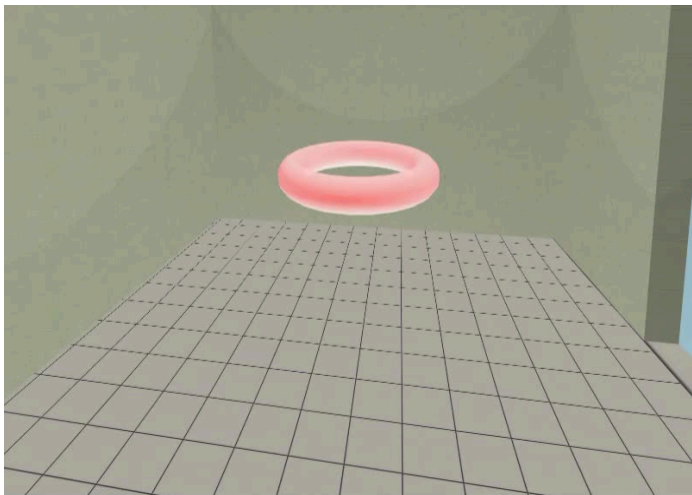
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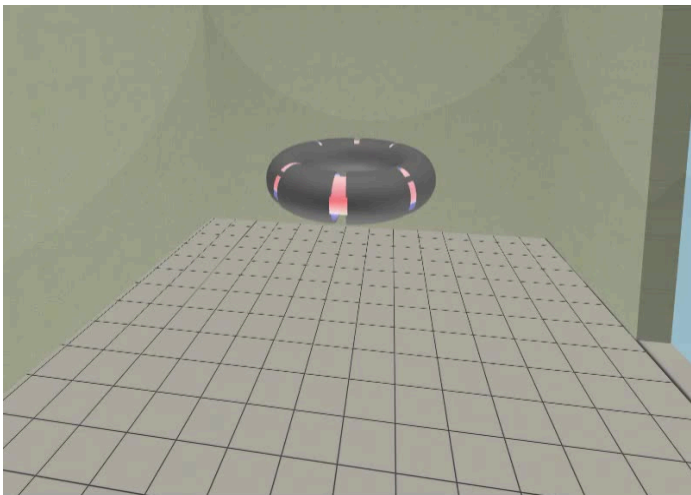
Our goal: the technology to create a μ Sun on the Earth



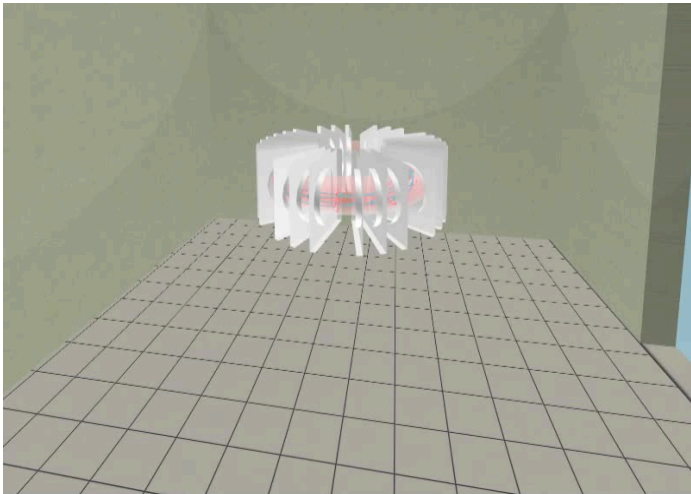
Magnetic confinement requires toroidal geometry



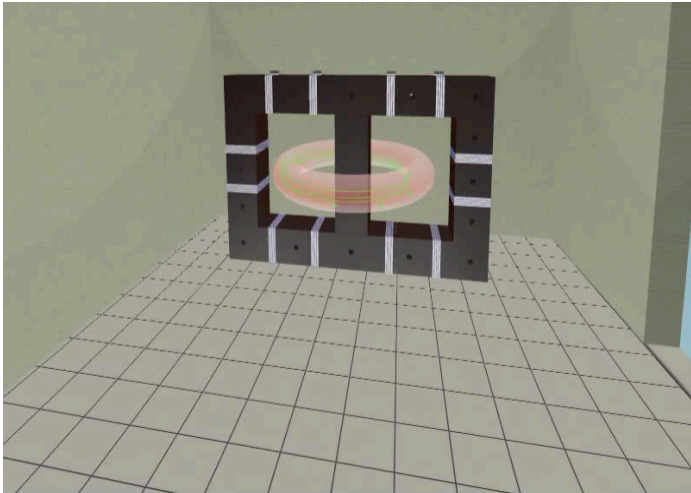
A chamber contains the thermonuclear reaction



Toroidal magnetic field coils confine the plasma



A transformer action creates and heats the plasma



The final technology altogether

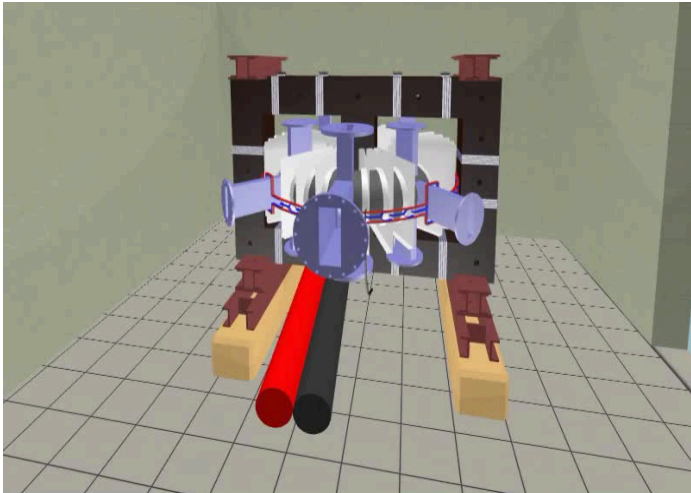


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Plasma in Tokamak (GOLEM) - the least to do

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

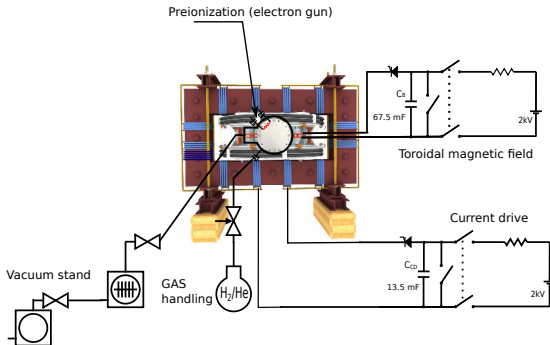


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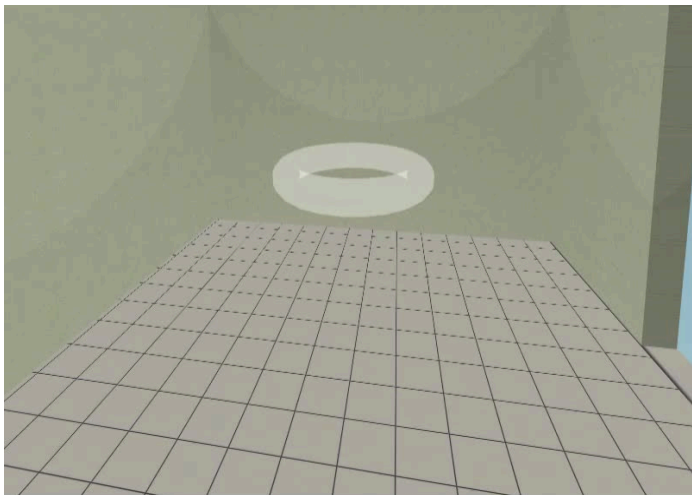
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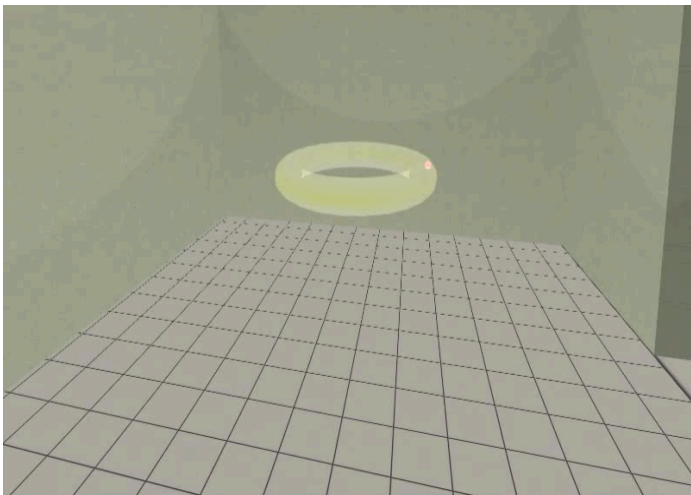
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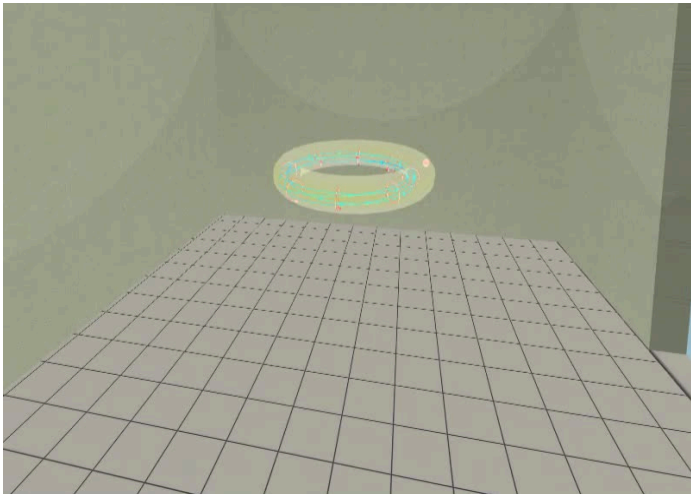
Introduce the working gas (Hydrogen x Helium)



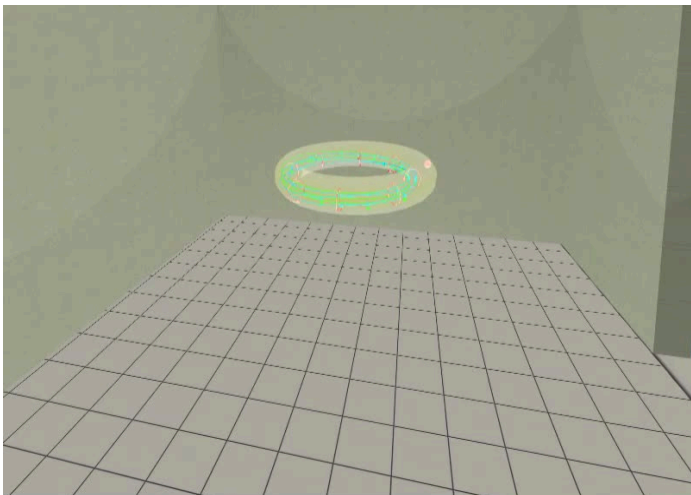
Switch on the preionization



Introduce the magnetic field



Introduce the electric field



Plasma ..

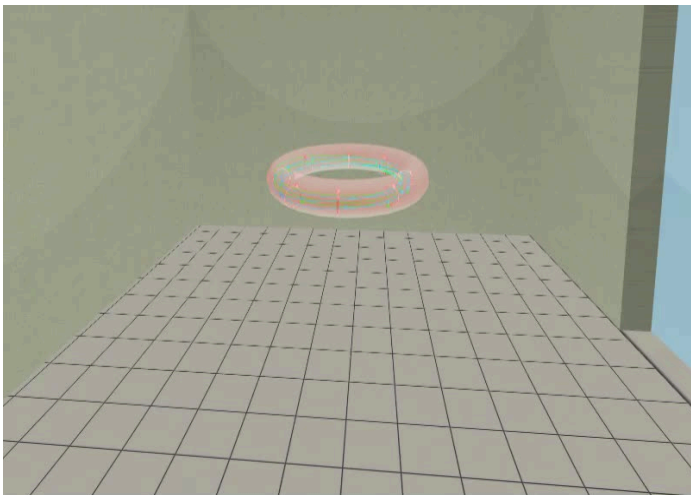


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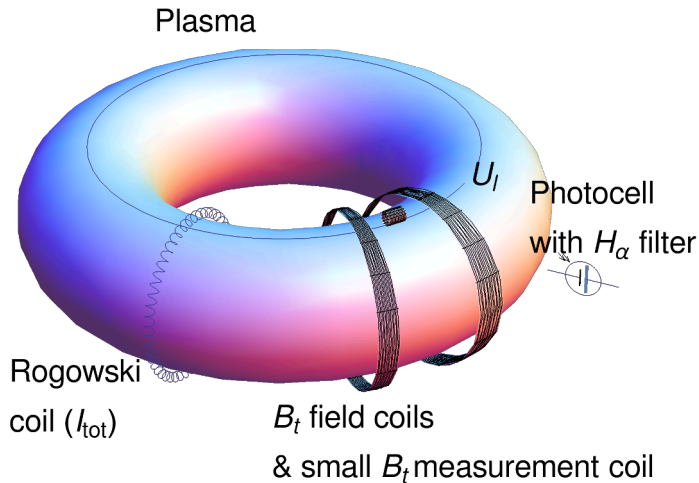
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The GOLEM tokamak - basic diagnostics



"Typical", well executed discharge @ GOLEM

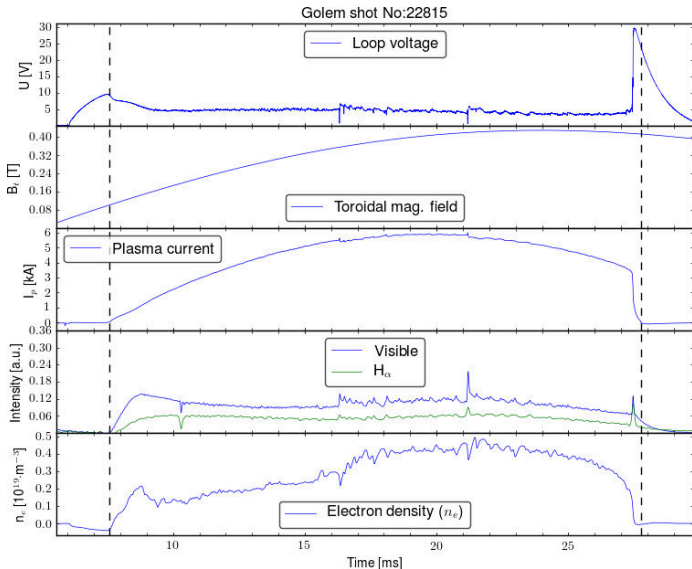


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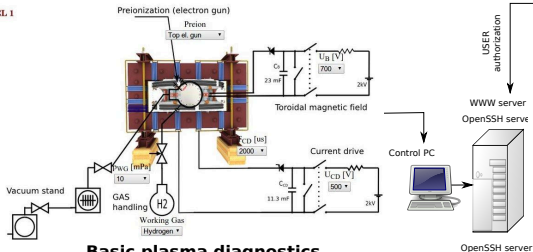
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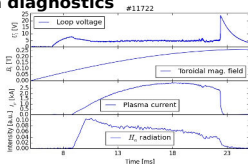
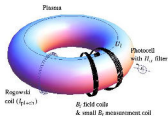
The global schematic overview of the GOLEM experiment

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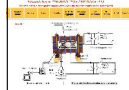
Basic plasma diagnostics



Virtual control room (remote participation)

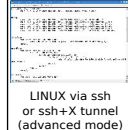
WWW control interface

HTML & PHP scripts



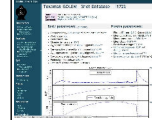
SSH control interface

WINDOWS via putty



Data presentation

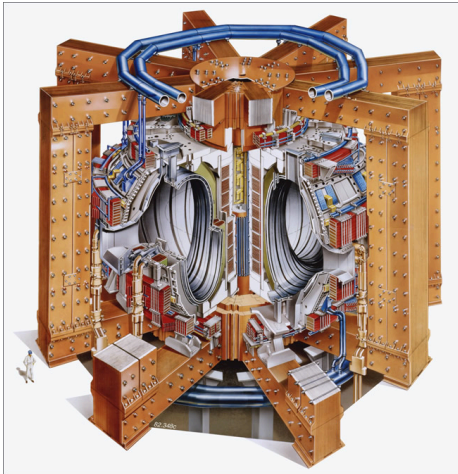
HTML (www pages)



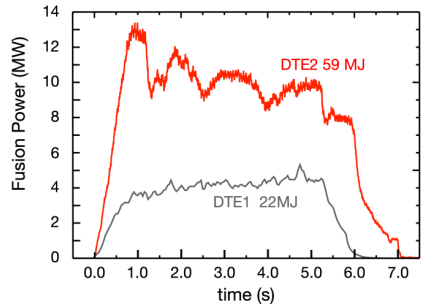
Data handling

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

1997: Světový fúzní rekord @ JET (EU)



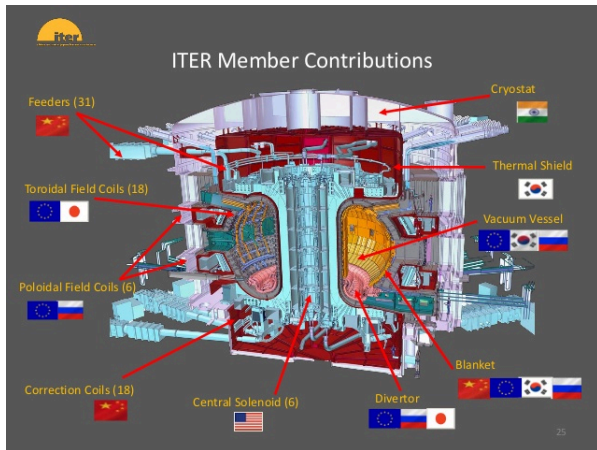
output comparison 1997 and 2021.png



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

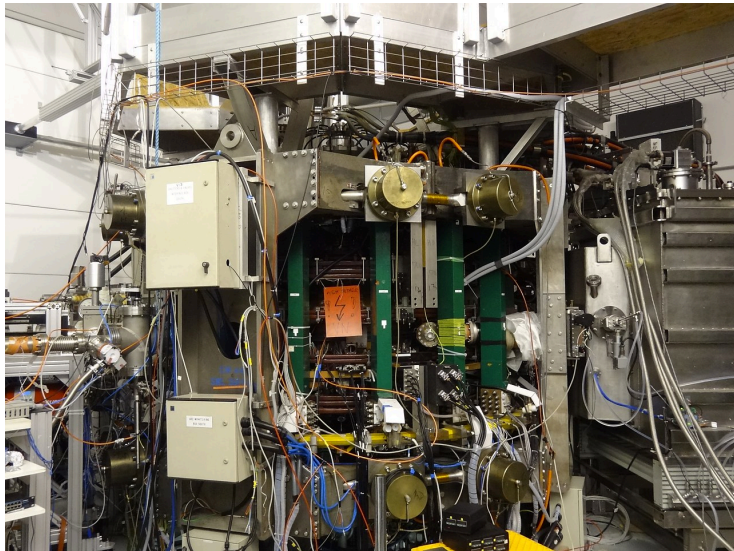
ITER (jižní Francie) $\approx$ 18 miliard EUR



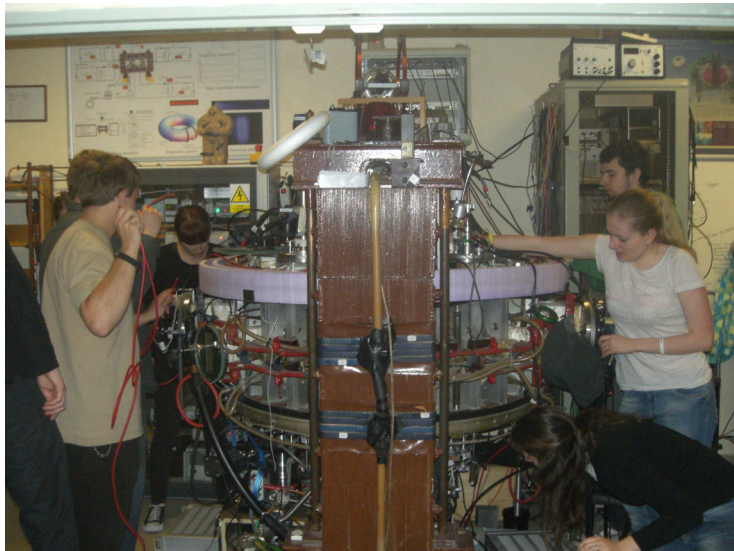
Mise:

$P \approx 500$ 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

- Demontrace: Ghent University 09; Bochum University 13; Garching 13; Lemvig High School 14; Instituto Tecnológico 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 Kobenhavn 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: Kitzing 14,16,18; Observatorium Valaiska Merinzi 14; Islamabad

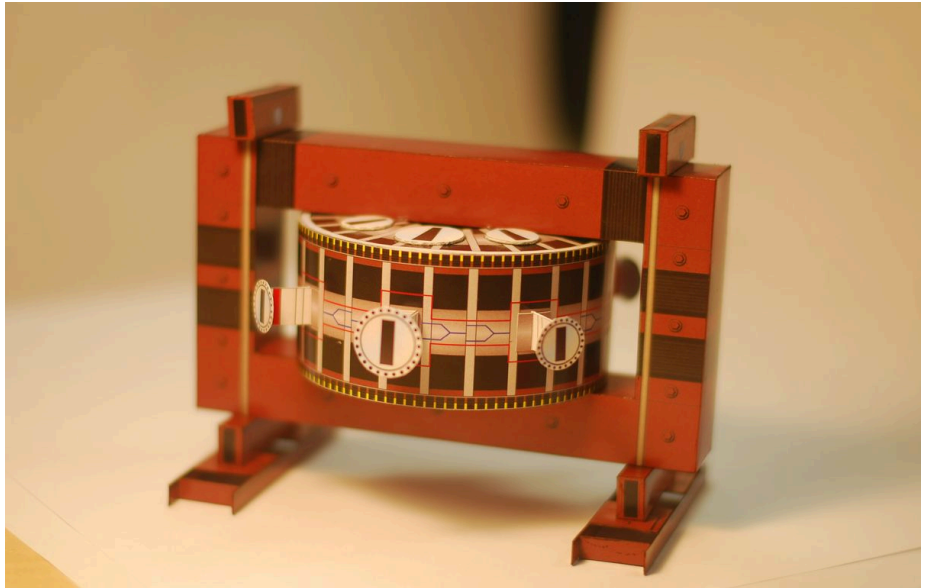
Poplatek: pohlednice z místa vzdáleného řízení



GOLEM



Paper model ABC



Acknowledgement

Financial support highly appreciated:

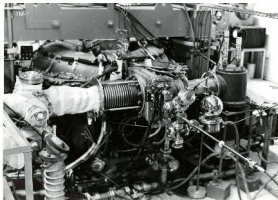
CTU RVO68407700, SGS 17/138/OHK4/2T/14, GAČR GA18-02482S, EU funds CZ.02.1.01/0.0/0.0/16_019/0000778 and CZ.02.2.69/0.0/0.0/16_027/0008465, IAEA F13019, FUSENET and EUROFUSION.

Students, teachers, technicians (random order):

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

Thank you for your attention

Tokamak TM1
@Kurchatov Institute near Moscow
~1960-1977



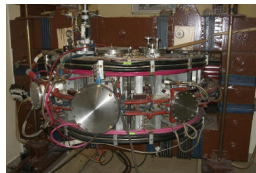
SCIENCE

Tokamak CASTOR
@Institute 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 ..

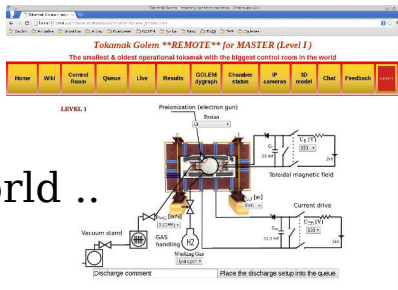


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3 Conclusion

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