

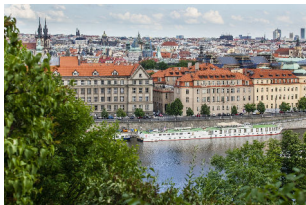
Spoutání energie hvězd v pozemských podmínkách

Vojtěch Svoboda
Základní popularizační přednáška

October 21, 2024

Fakulta jaderná a fyzikálně inženýrská (FJFI)

České vysoké učení technické v Praze



Hlavní budova FJFI v Praze - Břehová



insignie FJFI

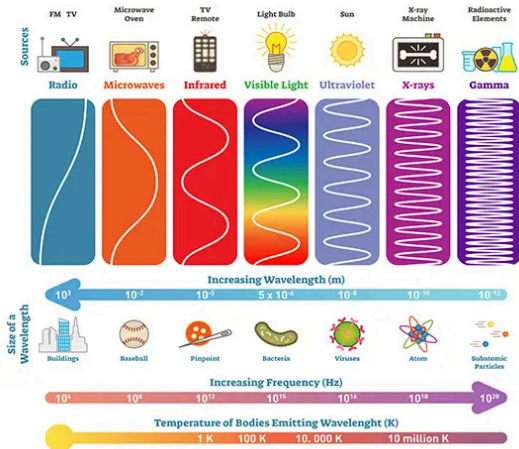


Betlémská kaple - slavnostní síň ČVUT

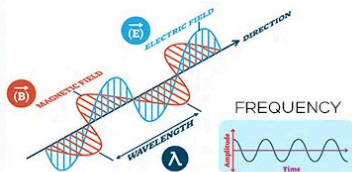
- ČVUT založena roku 1707 císařem Josefem I.
- ČVUT má přibližně 2700 zaměstnanců, 16500 vysokoškolských studentů, 1700 doktorandů. ($\approx$ 2500 zahraničních studentů).
- FJFI byla založena v roce 1955 s posláním vyškolit nové odborníky na vznikající československý jaderný program.
- FJFI je v současné 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.

Aplikované přírodní vědy - Elektřina a magnetismus

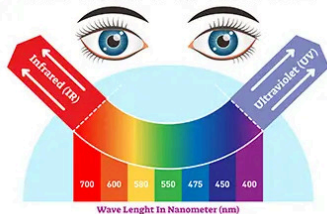
THE ELECTROMAGNETIC SPECTRUM



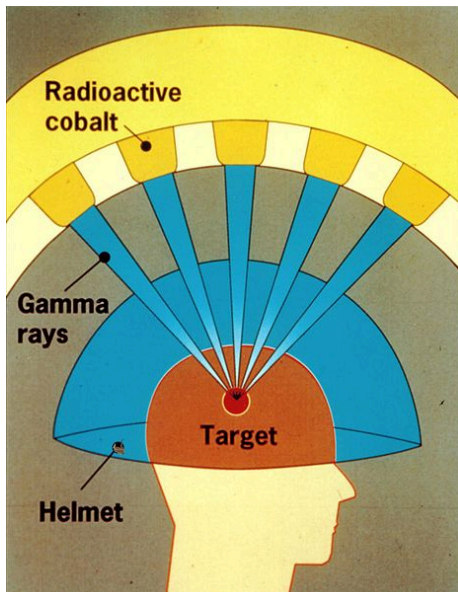
ELECTROMAGNETIC WAVES



THE VISIBLE SPECTRUM



Aplikované přírodní vědy - Leksellův Gamma nůž



Google: Energy

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Energy from Wastewater - ASDO, spol. s r.o.
asdo.cz

Transformation Ahead for Energy Sector ...
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Mediterranean 2040: How will the energy ...
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ec.europa.eu

Green supplier Bubs Energy predict 3m ...
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Energy - Wikipedia
en.wikipedia.org

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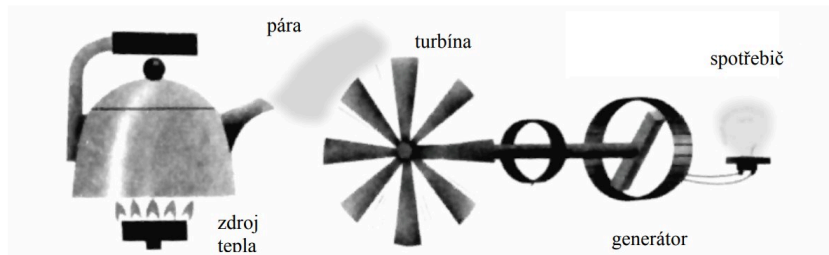
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- science energy
- energy human

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epf.ch/energy

MSC SELECT - Environmental Pathways for ...
mscenergy.com

Energy Storage | Graphene Flagship
graphene-flagship.eu

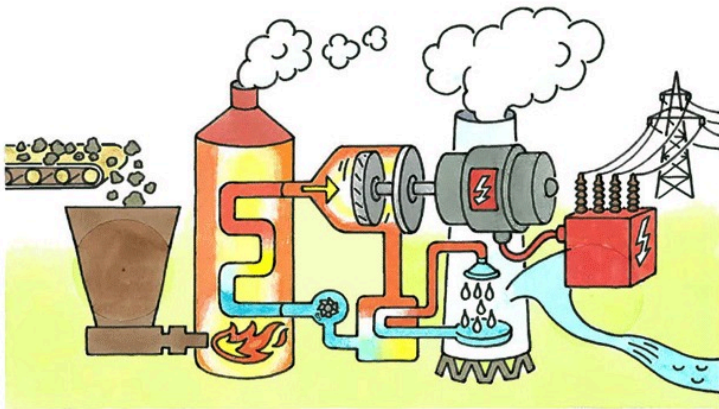
Základní princip tepelné elektrárny



Základní otázka zní:

?? Čím topit ??

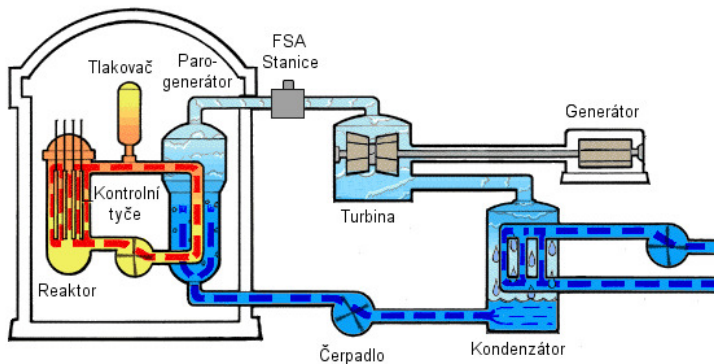
Uhelná elektrárna



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

Emise

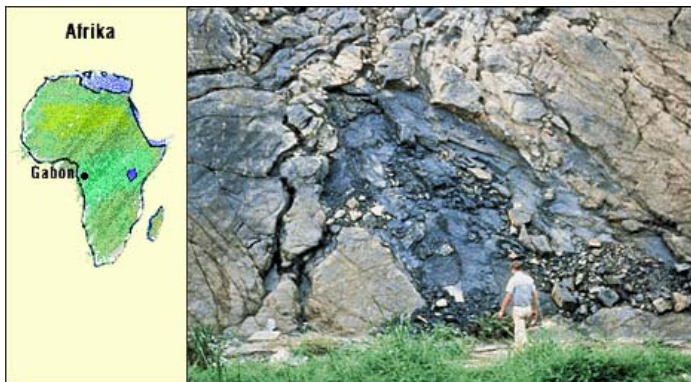
Jaderná elektrárna - štěpná



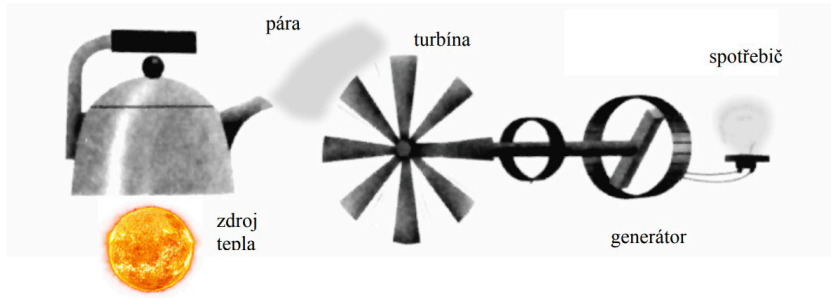
Praha (~ 1 GW): ročně $\sim$ vagón jaderného paliva

Dotáhnout technologii: Suroviny, Odpad, Bezpečnost

Aplikované přírodní vědy - přírodní reaktor Oklo



Topit malým Sluncem/hvězdou ??





Můžeme se zmocnit energie
která pohání Slunce/hvězdy?

1952 "Operation Ivy - Mike" První test vodíkové bomby



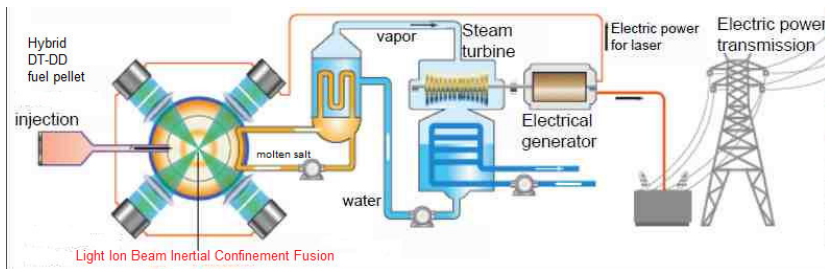
Operation Ivy - Mike

10.4 Megatons

credit:YouTube:Ivy Mike Countdown and detonation

Toto není vhodná technologie

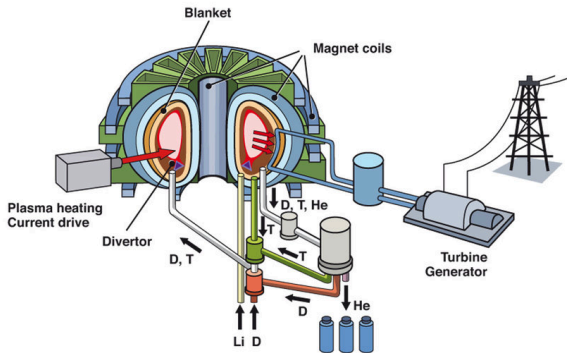
Inerciální fúze



credit:mext.jp

Velká výzva

Vize: Jaderná elektrárna - slučovací/fúzní

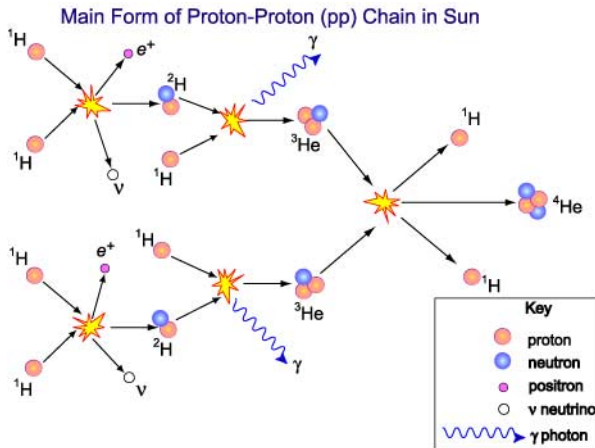


credit:[?]

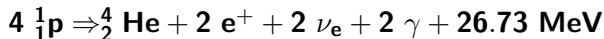
Praha (~ 1 GW): ročně $\sim$ dodávka D-T směsi

Vyplat technologii

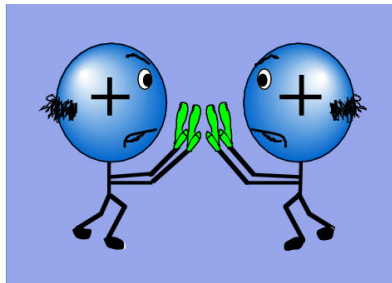
Inspirace: Slunce - protonový řetězec



credit:CSIRO

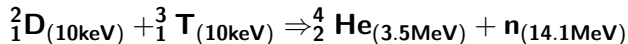


Proč tak obrovské teploty?

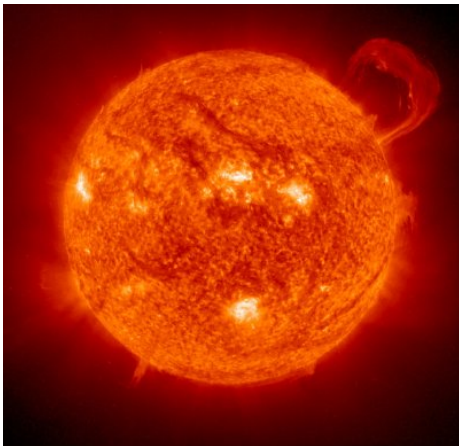


■ Coulomb law:

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



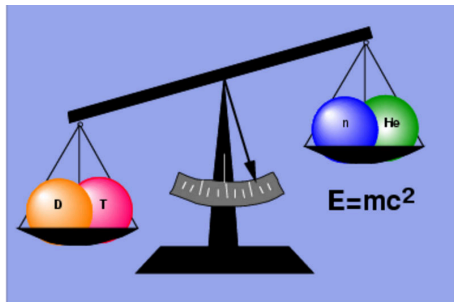
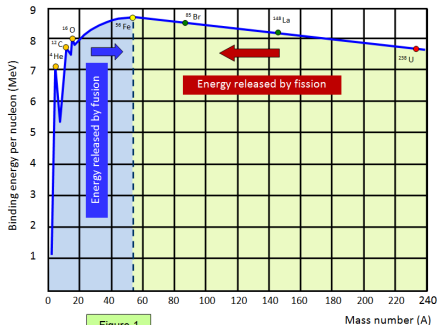
Star burning stages



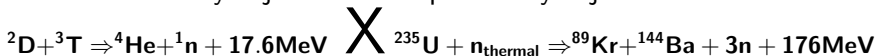
Core Burning Stages in a 25 Solar Mass Star:

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

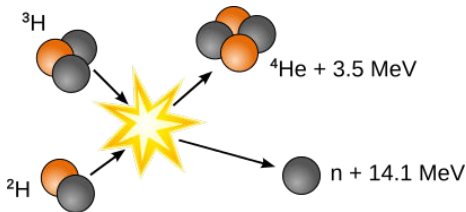
Uvolnění vazebné energie atomových jader



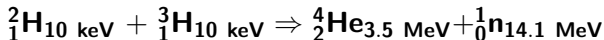
fúze lehkých jader $\times$ štěpení těžkých jader



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



credit:[?]



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

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

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

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

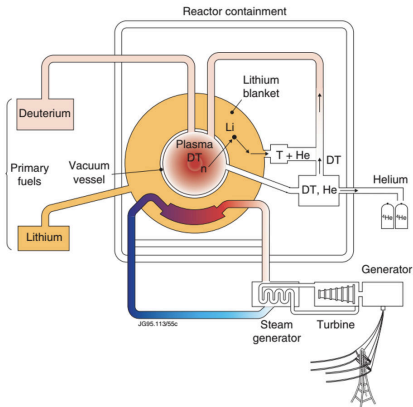
$$1\text{eV} \sim 11600^\circ\text{C} \approx {}^2_1\text{H}_{100 \text{ M}^\circ\text{C}} + {}^3_1\text{H}_{100 \text{ M}^\circ\text{C}} \Rightarrow {}^4_2\text{He}_{35 \text{ G}^\circ\text{C}} + {}^1_0\text{n}_{141 \text{ G}^\circ\text{C}}$$

Palivo: IAEA "Natural water"



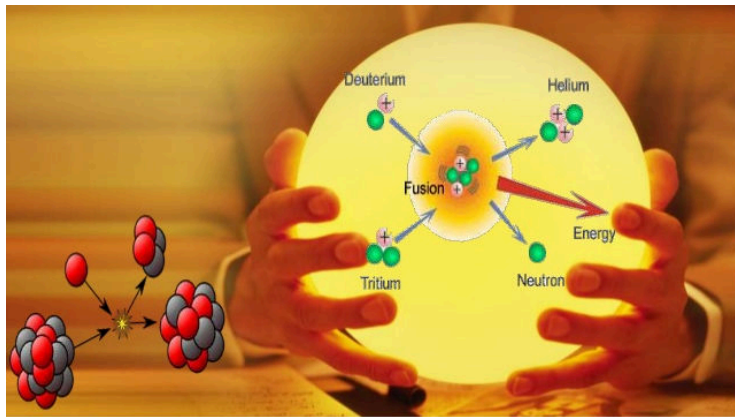


Bezpečnost



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

Hledá se vhodná fúzní technologie

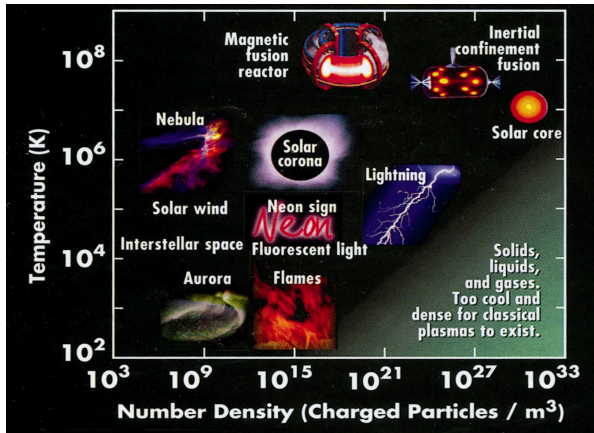


Podmínky:

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

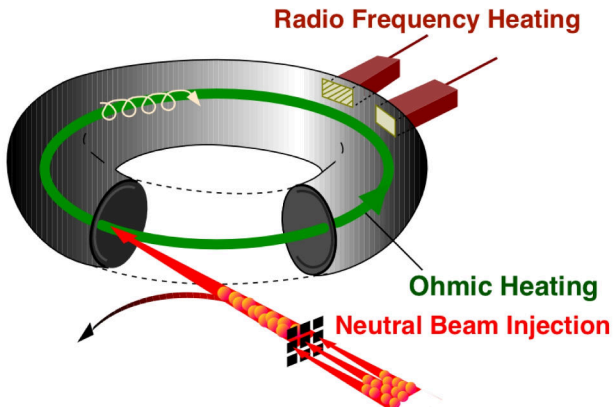
Badatelská skupina / studijní specializace

Fyzika plazmatu a termojaderné fúze



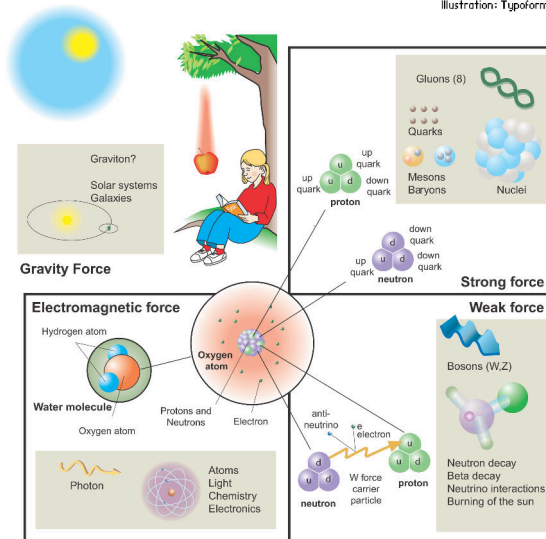
99.999 % Vesmíru je v plazmatickém stavu

Ohřev plazmatu



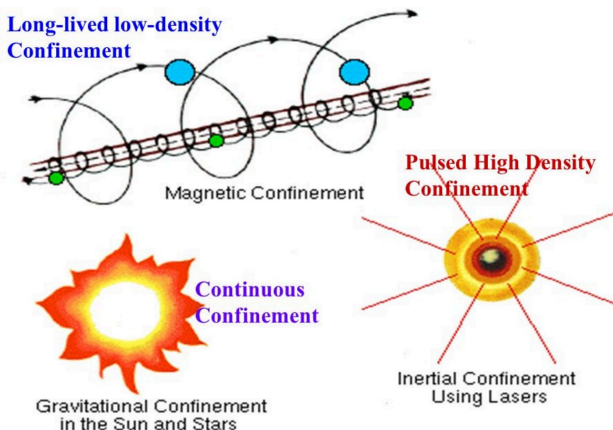
Fundamental forces (to confine?)

Illustration: Typoform

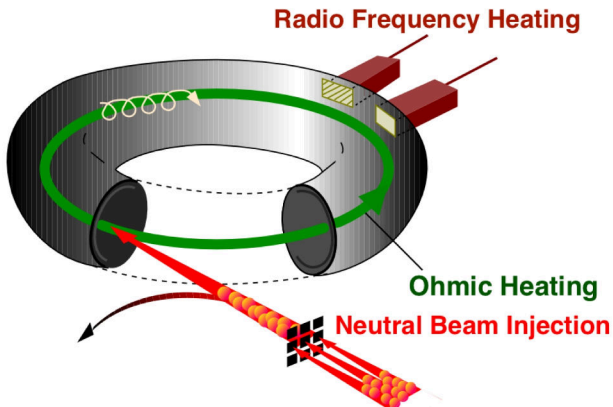


Tři možné cesty jak udržet plazma pro fúzi

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



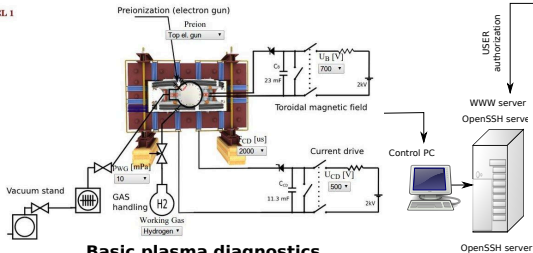
Ohřev plazmatu



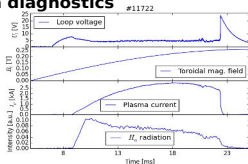
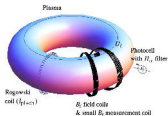
The global schematic overview of the GOLEM experiment

LEVEL 1

Tokamak technology setup



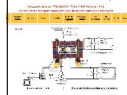
Basic plasma diagnostics



Virtual control room (remote participation)

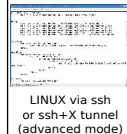
WWW control interface

HTML & PHP scripts



SSH control interface

WINDOWS via putty



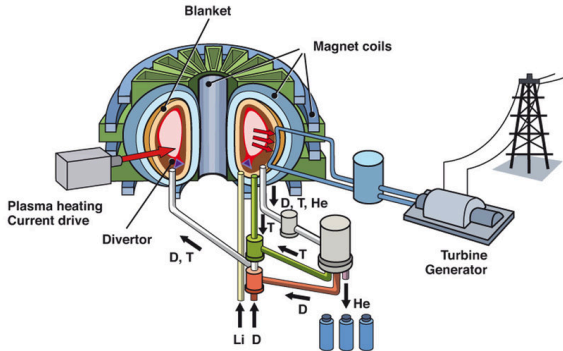
Data presentation



Data handling

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

Vision: Nuclear power plant – a fusion one

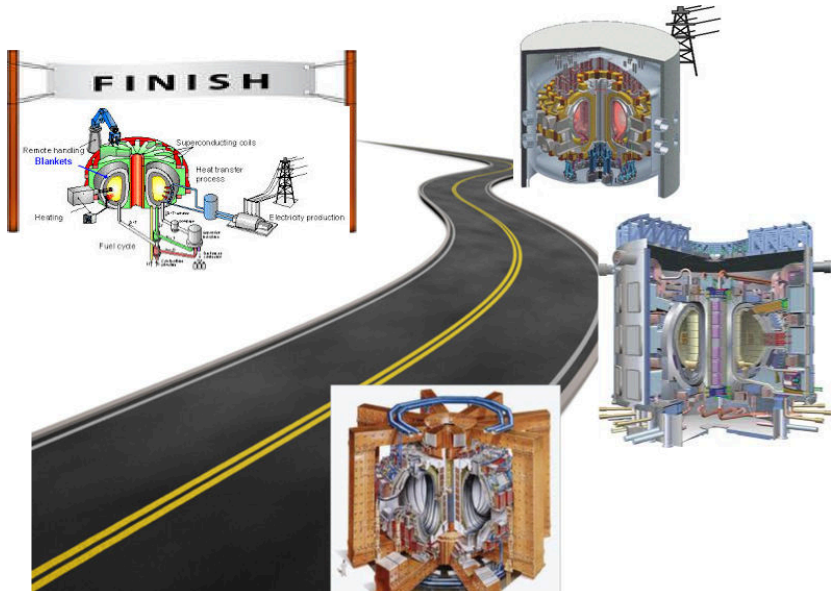


credit:[?]

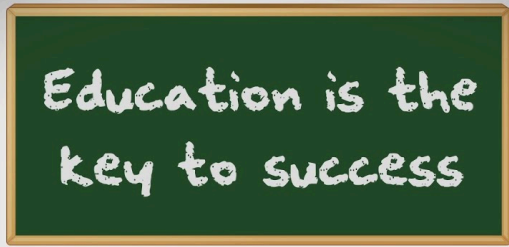
Prague (~ 1 GW): yearly $\sim$ a van of D-T mixture

Master the Technology

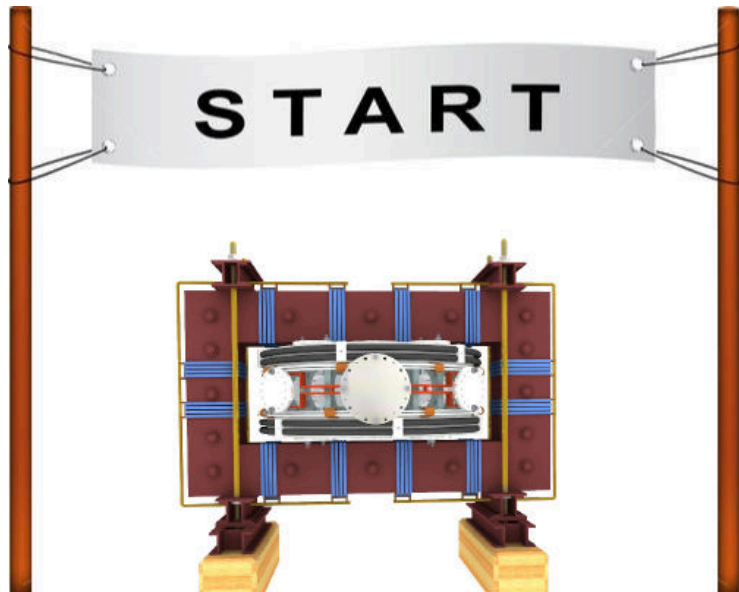
Milestones to Fusion Power Plant



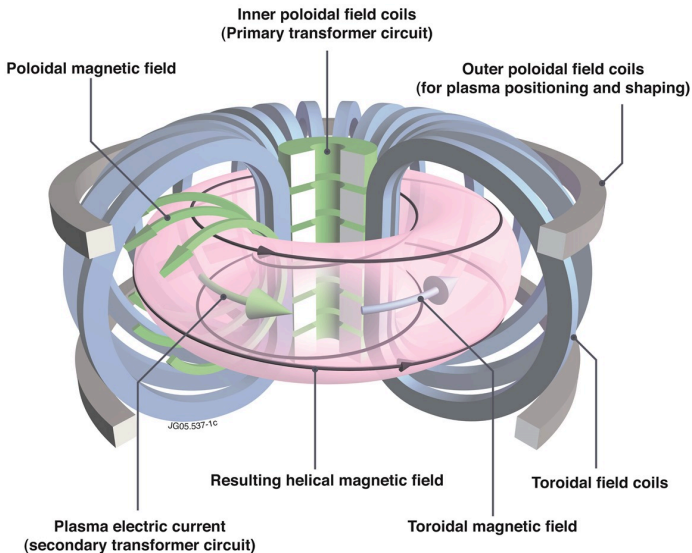
Education importance



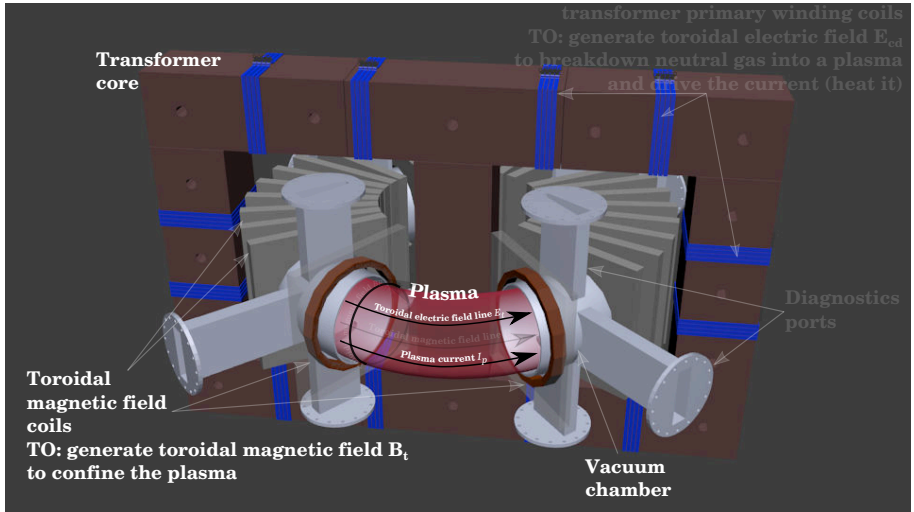
Let's start with the tokamak GOLEM - *the smallest tokamak in the World with the biggest controll room*



Tokamak magnetic confinement concept

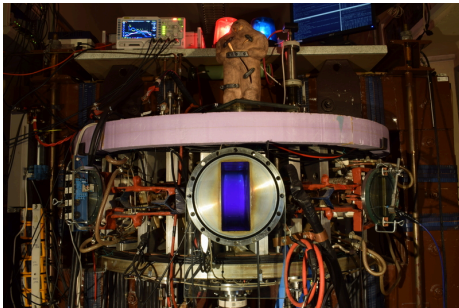


Tokamak (GOLEM) basic concept to confine and heat the plasma



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 GOLEM @ Wikipedia ..



WIKIPEDIA
The Free Encyclopedia

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Article **Talk**

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)

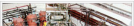
- 1960s: TM1-MH (since 1977 Castor; since 2007 Golem^[122]) in Prague, Czech Republic. In operation in Kurchatov Institute since early 1960s but renamed to Castor in 1977 and moved to IPP CAS,^[13] Prague; in 2007 moved to FNSPE, Czech Technical University in Prague and renamed to Golem.^[14]
- 1975: 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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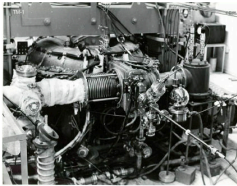
Alcator C-Mod



ida, the free encyclo... W Tokamak - Wikipedia, the free encyclo... [svoboda] brum [fi.cvut.cz - Korošec] [Krusader] [Inbox - svoboda@fi.cvut.cz - Mazič]

The GOLEM tokamak for education - historical background

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



1974

Institute of Plasma Physics
Czech republic

CASTOR

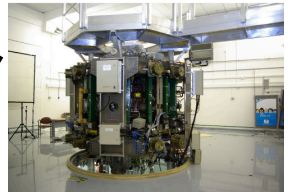
COMPASS

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...

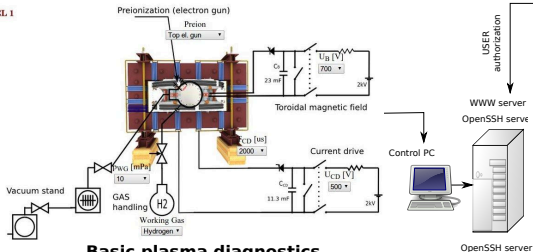


At the end of the 16th century, in the times when the Czech lands were ruled by Emperor Rudolf II, in Prague, there were Rabbi Judah Loew, well known alchemist, thinker, scholar, writer and inventor of the legendary GOLEM - a clay creature inspired with the Universe power that pursued his master's command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

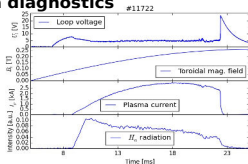
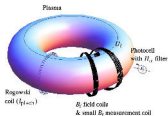
The global schematic overview of the GOLEM experiment

LEVEL 1

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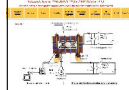
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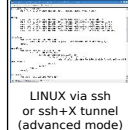
WWW control interface

HTML & PHP scripts



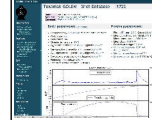
SSH control interface

WINDOWS via putty



Data presentation

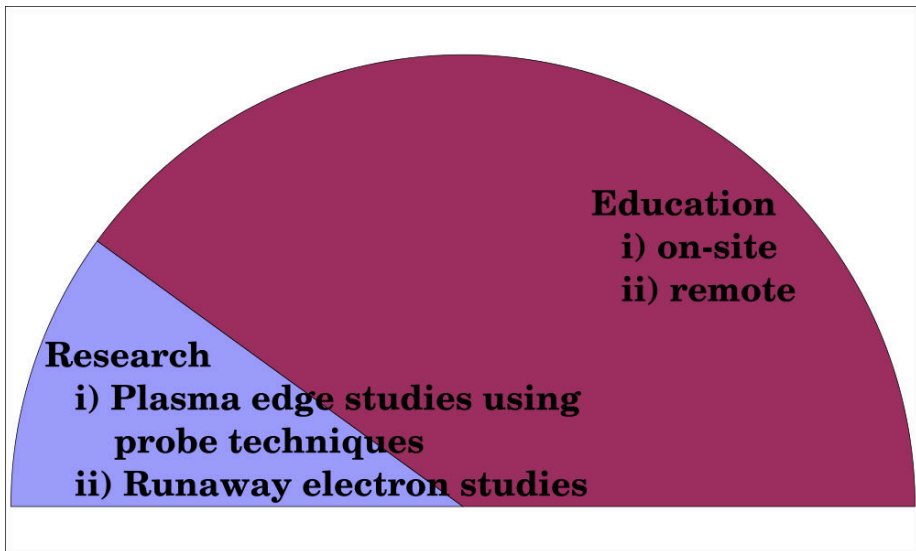
HTML (www pages)



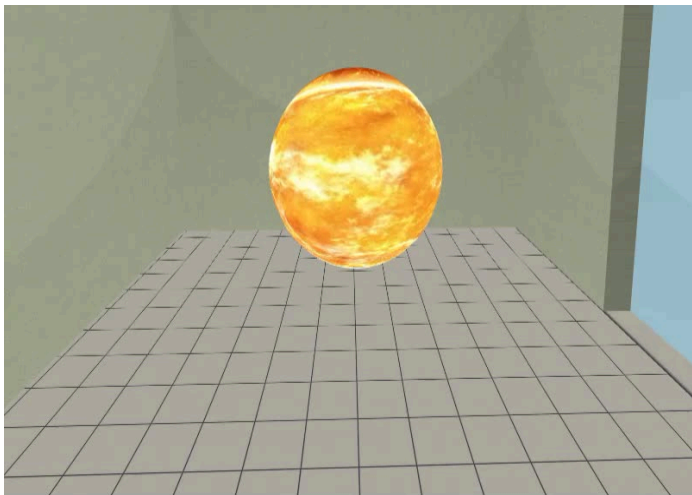
Data handling

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

The GOLEM tokamak mission

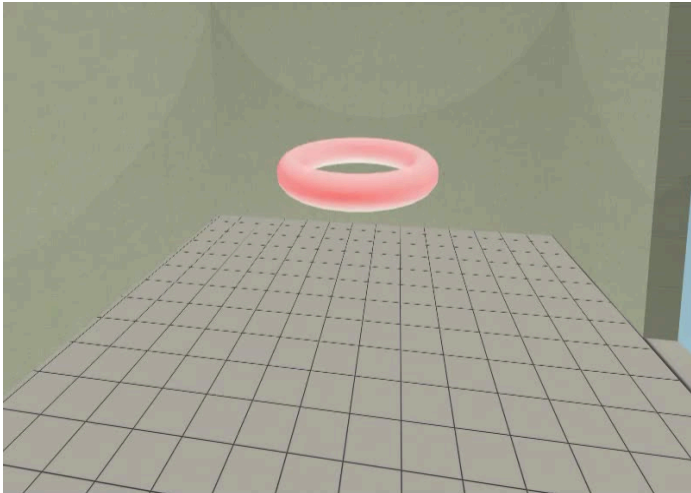


Náš cíl: vytvořit μ Slunce v pozemských podmínkách

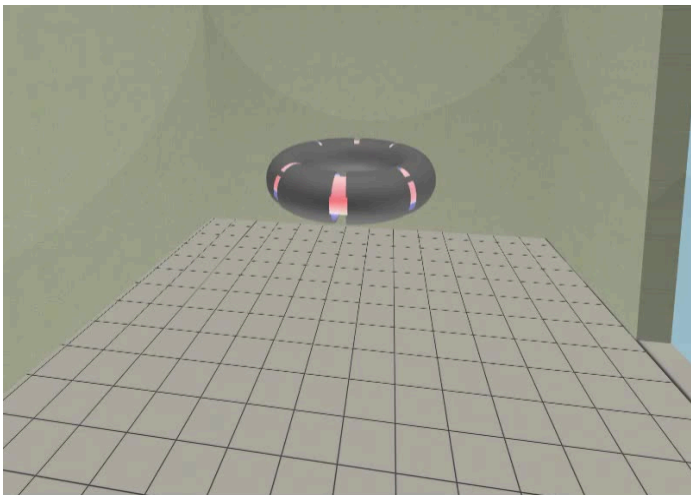


Magnetické udržení vyžaduje toroidální geometrii

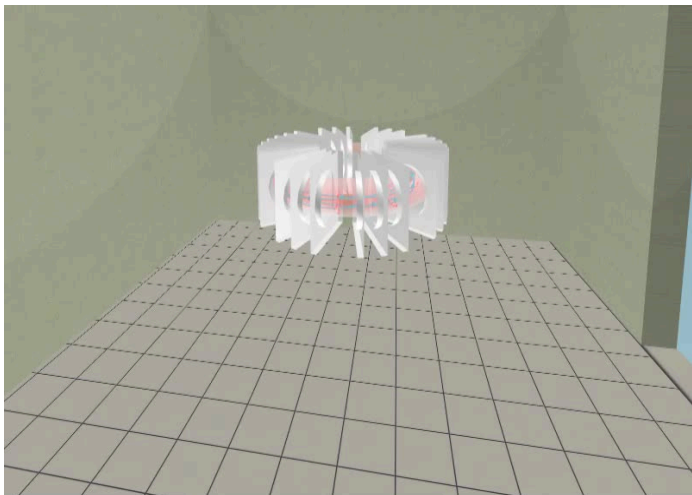
Svinutá magnetická nádoba



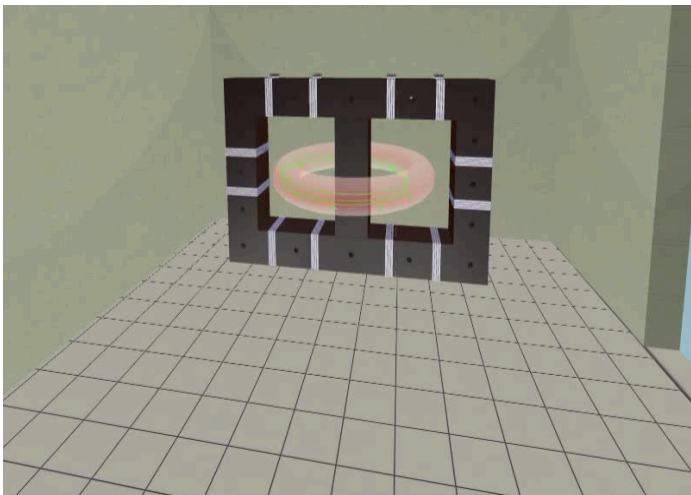
Musíme to celé umístit do reaktorové nádoby - komory



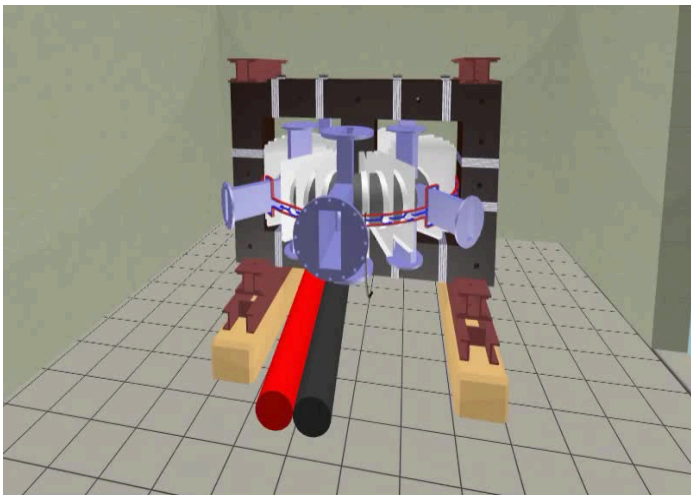
Toroidální magnetické pole udržuje plazma



Transformátorová akce vytvoří a zahřeje plazma



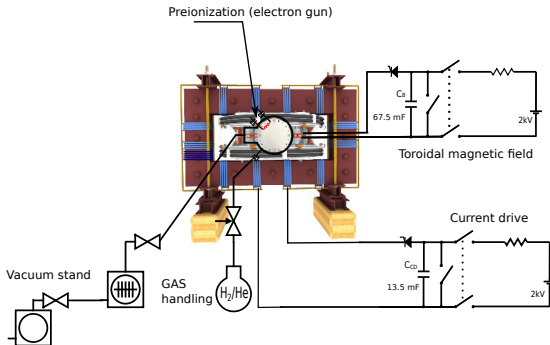
Vše dohromady - voilà tokamak



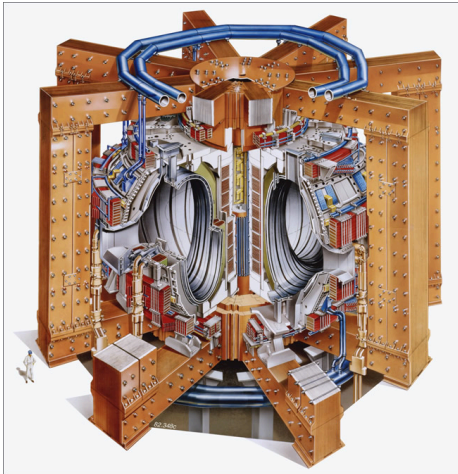
Plasma in Tokamak (GOLEM) - the least to do

To do:

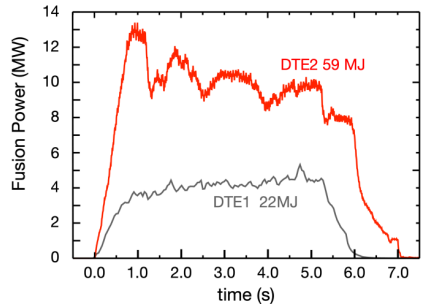
- session start phase:
 - Evacuate the chamber
- pre-discharge phase
 - Charge the capacitors
 - Fill in the working gas
 - Preionization
- discharge phase
 - Toroidal magnetic field to confine plasma
 - Toroidal electric field to breakdown neutral gas into plasma
 - Toroidal electric field to heat the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



1997: Světový fúzní rekord @ JET (EU)



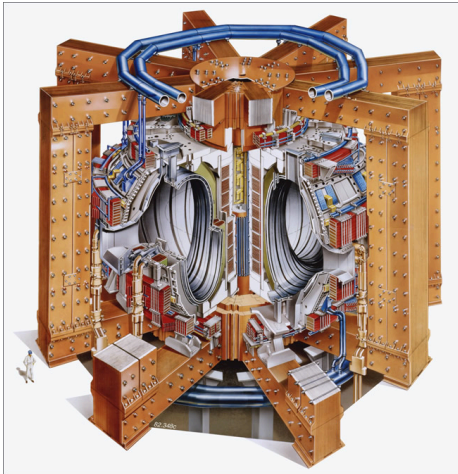
output comparison 1997 and
2021.png



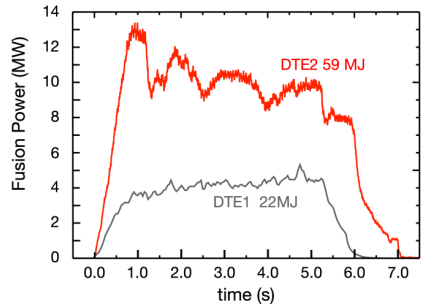
1997: $P \approx 22$ MW, $Q \approx 0.65$, $\Delta T \approx 5$ s,

2022: $P \approx 59$ MW, $Q \approx ?$, $\Delta T \approx 6$ s

1997: Světový fúzní rekord @ JET (EU)



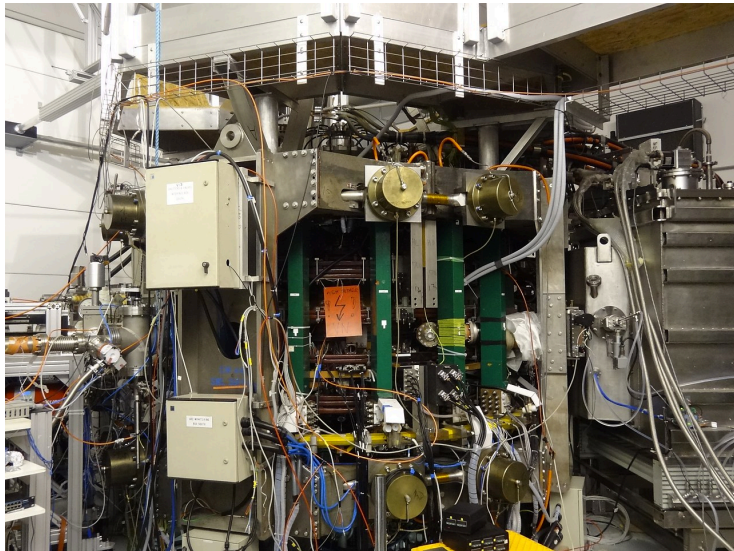
output comparison 1997 and 2021.png



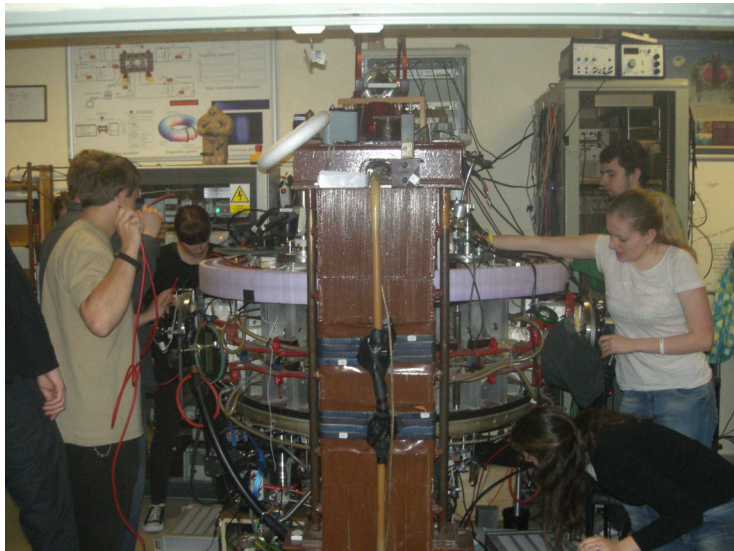
1997: $P \approx 22$ MW, $Q \approx 0.65$, $\Delta T \approx 5$ s,

2022: $P \approx 59$ MW, $Q \approx ?$, $\Delta T \approx 6$ s

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

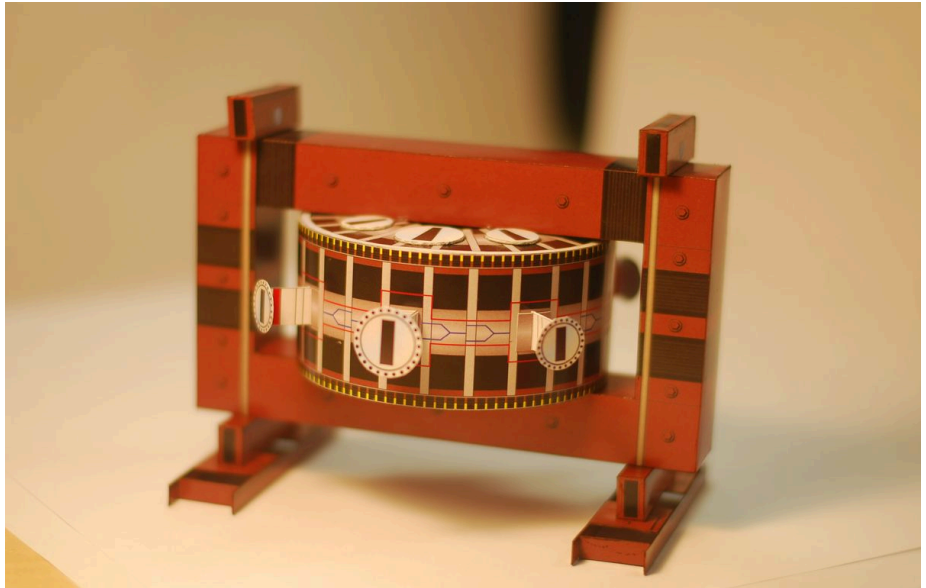
Poplatek: pohlednice z místa vzdáleného řízení



GOLEM

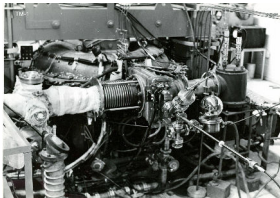


Paper model ABC



Děkuji za pozornost

Tokamak TM1
@Kurchatov Institute near Moscow
~1960-1977



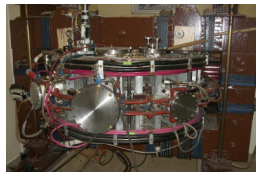
SCIENCE

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

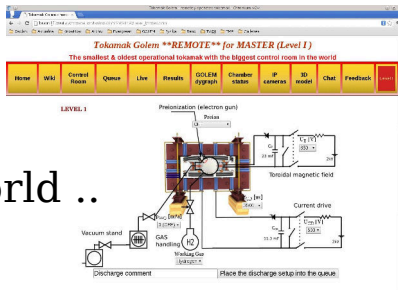


**SCIENCE
& education**

Tokamak GOLEM
@Czech Technical University, Prague
2007-



**EDUCATION
& science**



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

Acknowledgement

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CTU RVO68407700, SGS22/175/OHK4/3T/14,EUROFUSION & MEYS cofund.

Students, teachers, technicians (random order):

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currently **Martin Himmel**, **Petr Mácha**, Filip Papoušek, Martina Lauerová, Jan Buryanec, **Daniela Kropáčková**, Jarda Zajac, Jana Brotánková, Lukáš Lobko, Marek Tunkl, Jakub Chlum, Sara Abbasi, Eliška Pumprlová, Matyáš Pokorný, Vladislav Ivanov Štěpán Malec, Kateřina Jiráková, Jaroslav Čeřovský.

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