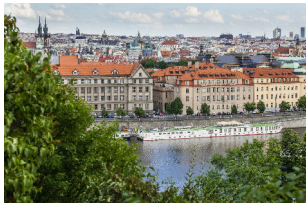


# Jak se v centru Prahy zažehává hvězda

Vojtěch Svoboda  
Korona přednáška - živě na FB

April 23, 2020

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



Hlavní budova FJFI v Praze - Břehová



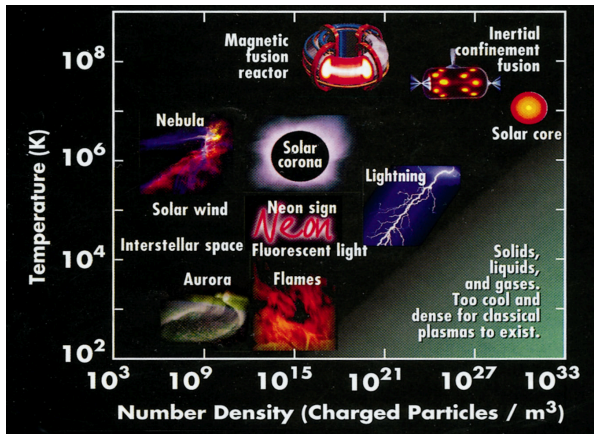
insignie FJFI



Betlémská kaple - slavnostní síň ČVUT

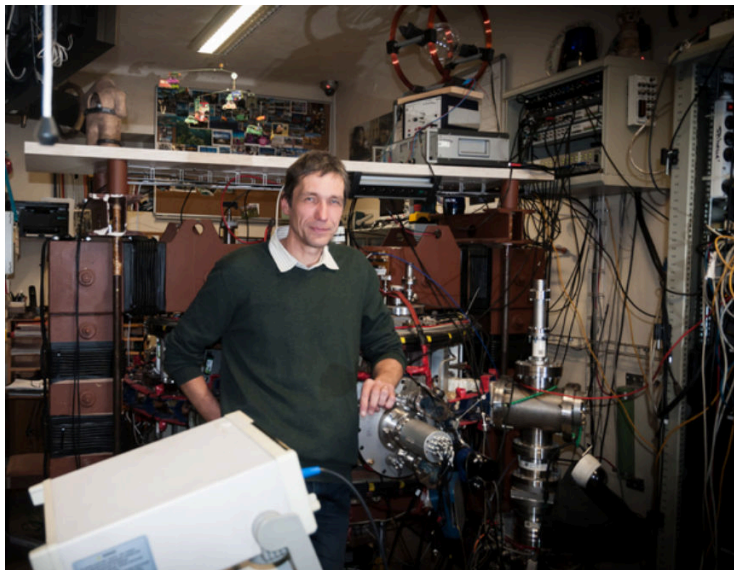
- ČVUT založena roku 1707 císařem Josefem I.
- ČVUT má přibližně 2700 zaměstnanců, 16500 vysokoškolských studentů, 1700 doktorandů. ( $\approx$  2500 zahraničních studentů).
- FJFI byla založena v roce 1955 s posláním vyškolit nové odborníky na vznikající československý jaderný program.
- FJFI je v současné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

# Badatelská skupina / studijní specializace Fyzika plazmatu a termojaderné fúze



99.999 % Vesmíru je v plazmatickém stavu

# Tokamak GOLEM & Vojtěch Svoboda



# Google: Energy

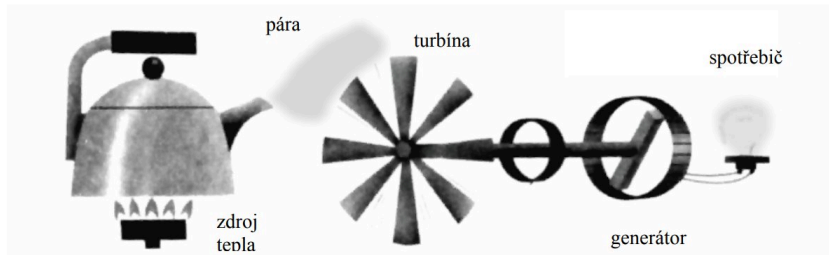
About 2,950,000,000 results (0.60 seconds)

The image shows a Google search interface for the term "energy". At the top, the Google logo is on the left, and the search bar contains the word "energy". To the right of the search bar are icons for "All", "Images", "News", "Maps", "Videos", and "More". Below the search bar is a horizontal menu with icons for "power", "body", "light", "saving", "work", "science", "wave", "heating", "solar", "renewable", "electrical", "conservation", "wind", "nuclear", and "physics".

The main content area is a grid of image search results. Each result consists of a thumbnail image and a caption with a link to the source. The results include:

- Global energy in 2050 - can renewables ...** (Image: Earth with energy lines)
- Understanding and using the Energy Balance ...** (Image: World map with energy lines)
- Siemens signs up to blockchain energy ...** (Image: Lightbulb)
- Using Blockchain in Renewable Energy ...** (Image: Lightning bolt in a circuit)
- New Thermal Battery Could Be A Game ...** (Image: Wind turbines and solar panels)
- Energy and renewable sources. EN's ...** (Image: Sun with energy lines)
- How two IoT startups are changing the ...** (Image: Lightbulb on a circuit board)
- Business Energy - The Leading African ...** (Image: Hand holding a glowing orb)
- Line&Energy** (Image: Energy waves)
- Massachusetts university for clean energy ...** (Image: "ENERGY" text with energy lines)
- WTF is Zero Point Energy and How Could ...** (Image: Energy waves)
- Wilson E. Scott Institute for Energy ...** (Image: Wind turbines)
- Energy Use in Industry - Ener ...** (Image: Pie chart)
- Cracked the Secret to Fusion Energy ...** (Image: Energy waves)
- Alternative energy technology | What we ...** (Image: Glowing particles)
- Energy Trade Surveillance Roadmap ...** (Image: Lightbulb with energy lines)
- Will Energy Offer the Next Market E ...** (Image: Lightbulb with energy lines)
- Energy from Wastewater - ASIO, spot. s r ...** (Image: Pie chart)
- Transformation Ahead for Energy Sector ...** (Image: Wind turbines)
- Mediterranean 2040: How will the energy ...** (Image: "ENERGY" text with energy lines)
- All Forms of Energy Are Important ...** (Image: Energy lines)
- Energy Union Indicators | Energy ...** (Image: Earth with energy lines)
- Green supplier Bulb Energy predict 1n ...** (Image: Solar panels)
- Energy - Wikipedia** (Image: Lightning bolt)
- Related searches**
  - body energy >
  - science energy >
  - energy human >
- Promotion of renewable energy sources ...** (Image: Green energy icons)
- Misc SELECT - Environmental Pathways for ...** (Image: Energy icons)
- Energy Storage | Graphene Flagship** (Image: Energy waves)

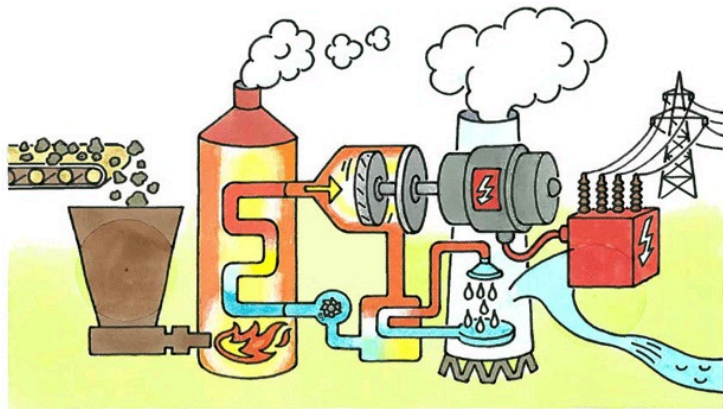
# Základní princip tepelné elektrárny



Základní otázka zní:

?? Čím topit ??

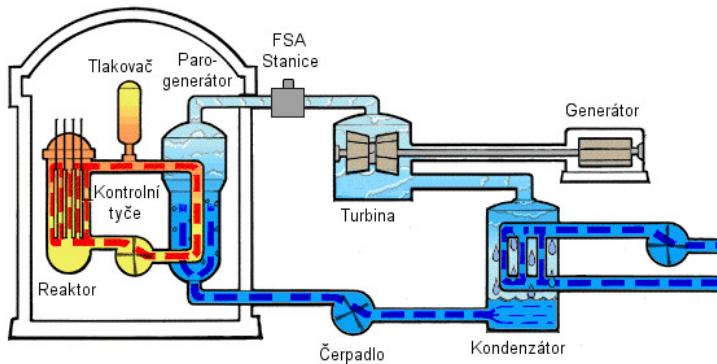
# Uhelná elektrárna



Praha (~ 1 GW): denně ~ vlak uhlí

Emise

# Jaderná elektrárna - štěpná

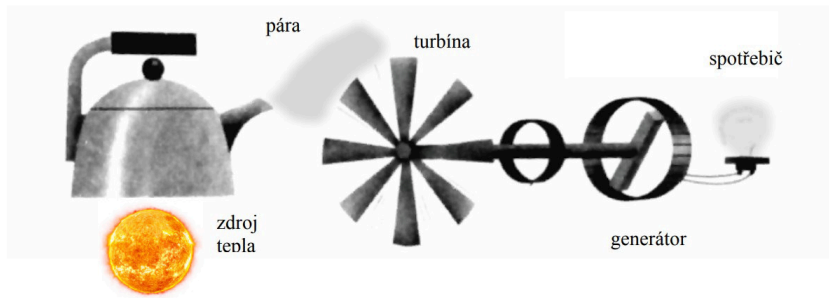


Praha (~ 1 GW): ročně ~ vagón jaderného paliva

Dotáhnout technologii: Suroviny, Odpad, Bezpečnost



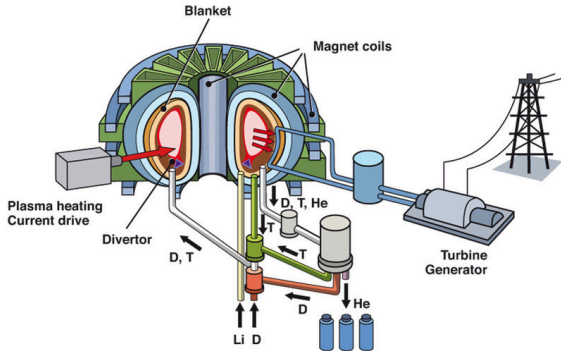
# Topit malým Sluncem/hvězdou ??





Můžeme se zmocnit energie  
která pohání Slunce/hvězdy?

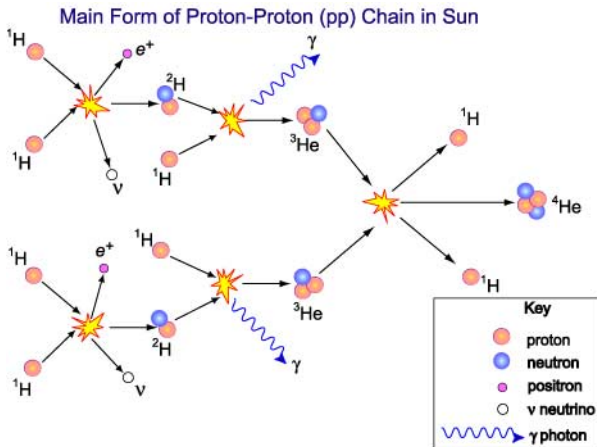
# Vize: Jaderná elektrárna - slučovací/fúzní



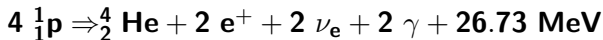
Praha ( $\sim 1$  GW): ročně  $\sim$  dodávka D-T směsi

Vyplat technologii

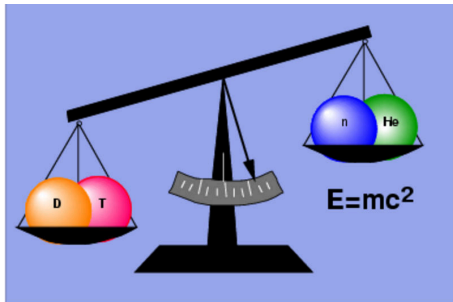
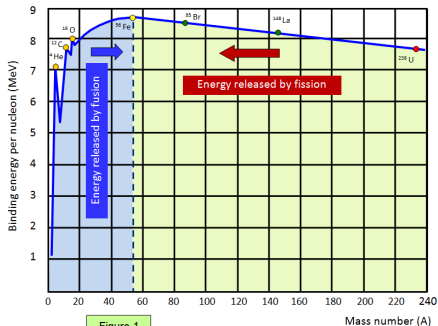
# Inspirace: Slunce - protonový řetězec



credit:CSIRO

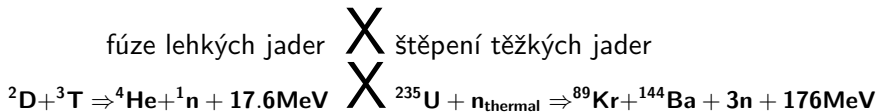
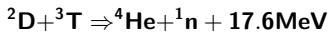


# Uvolnění vazebné energie atomových jader

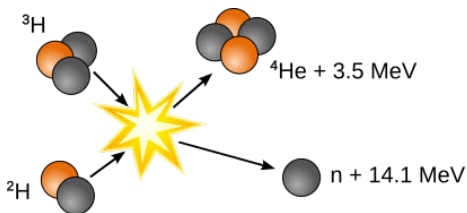


fúze lehkých jader

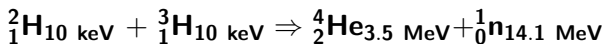
štěpení těžkých jader



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



credit:?



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

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

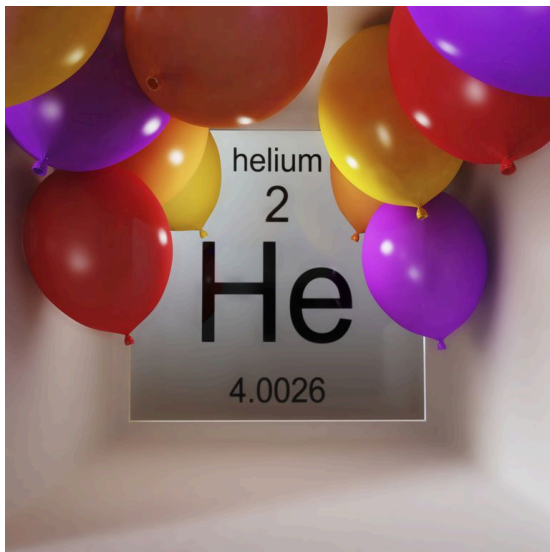
pak hmotnostní schodek  $\Delta m = 0.01888m_u$ .

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

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

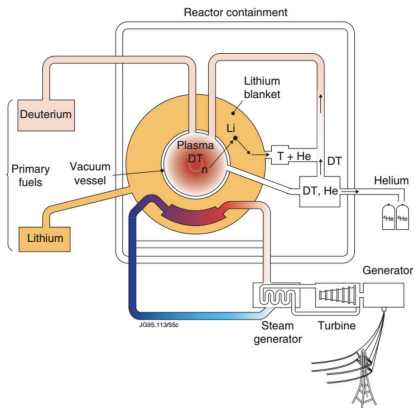
# Palivo: IAEA "Natural water"







# Bezpečnost



\* Nejde o řetězovou reakci.

\* Tritium: slabý  $\beta$  zářič

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

\* Minimalizovaný potenciál aktuálně přítomného D-T paliva.

# 1952 "Operation Ivy - Mike" První test vodíkové bomby



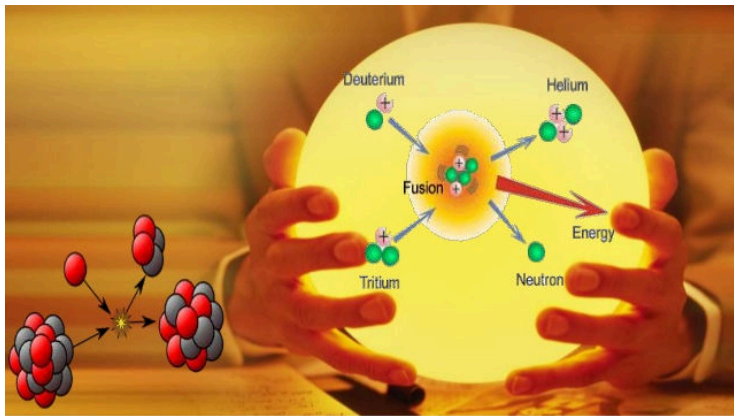
Operation Ivy - Mike

10.4 Megatons

credit:YouTube:Ivy Mike Countdown and detonation

Toto není vhodná technologie

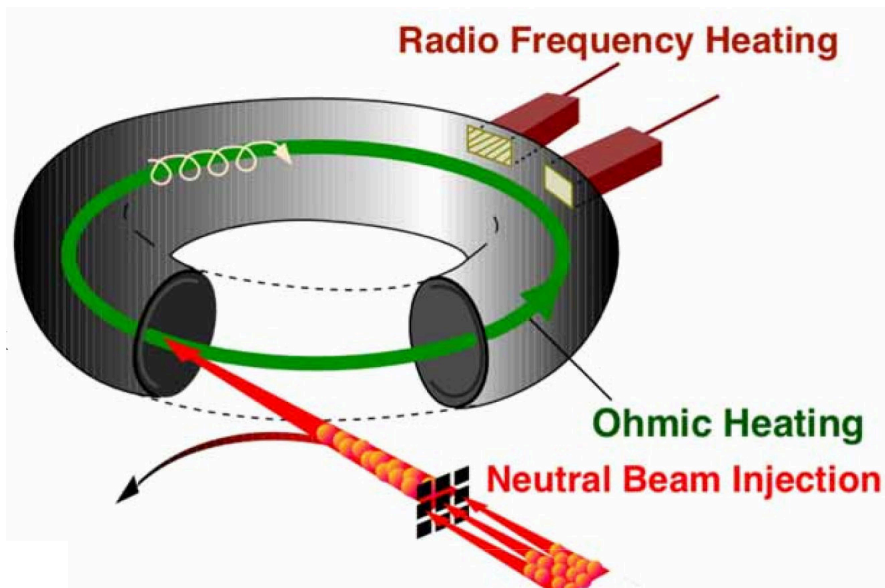
# Hledá se vhodná fúzní technologie



Podmínky:

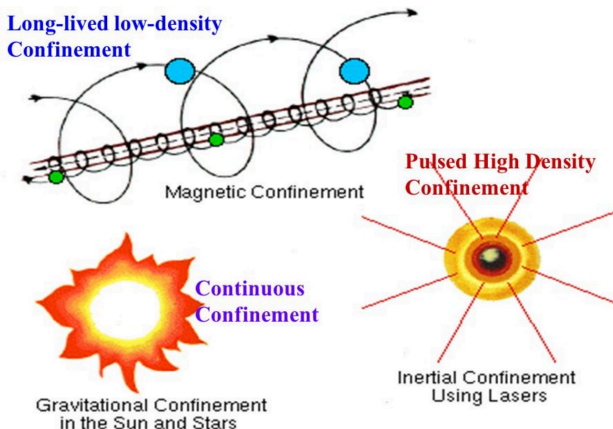
Zahřát na  $\sim 100\,000\,000\text{ }^{\circ}\text{C}$  & **udržet** po dobu  $\sim 30$  let

# Ohřev plazmatu

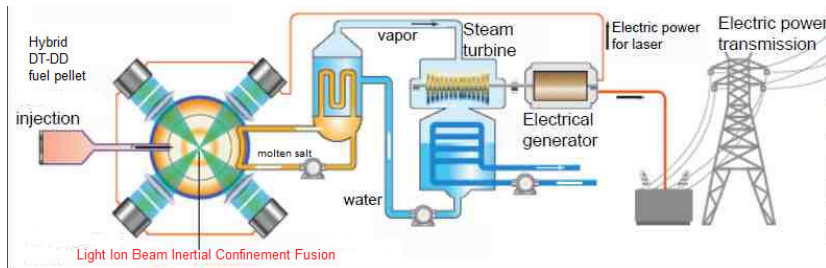


# Tři možné cesty jak udržet plazma pro fúzi

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



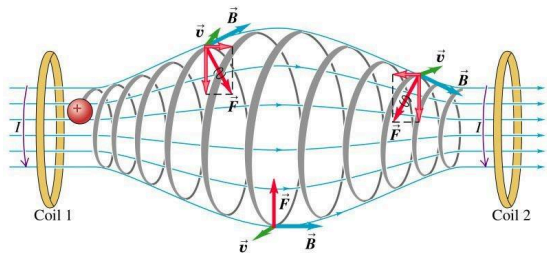
# Inerciální fúze



credit:mext.jp

Velká výzva

# Magnetické udržení: magnetická nádoba

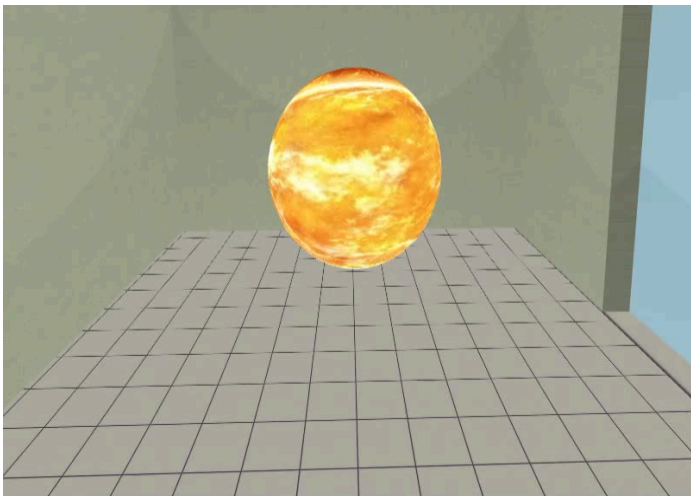


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Musíme ji ale svinout do kruhu (zbavit se podstav)

záchranný kruh/duše pneumatiky/donut

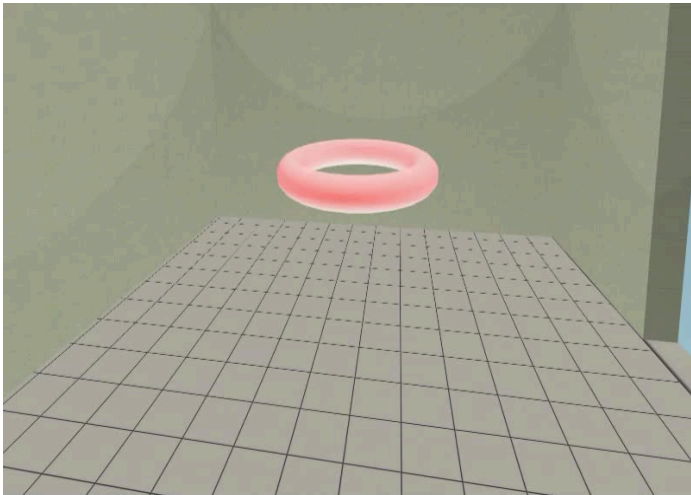
Náš cíl: vytvořit  $\mu$ Slunce v pozemských podmínkách



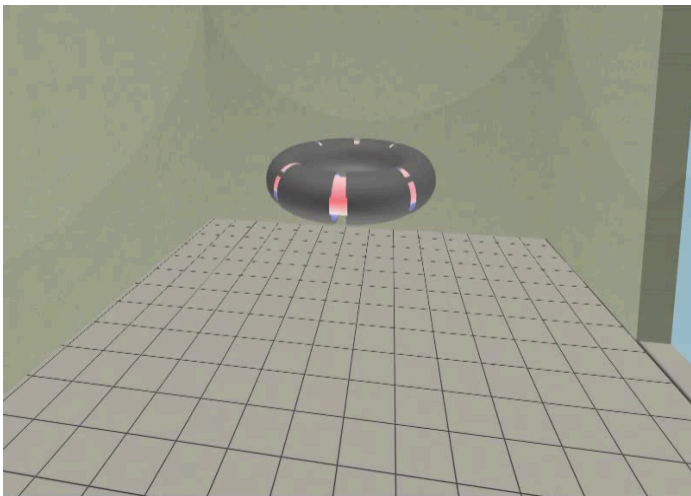


# Magnetické udržení vyžaduje toroidální geometrii

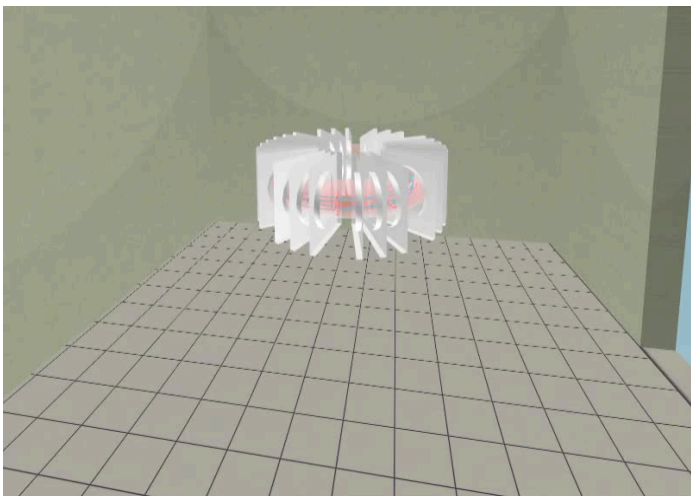
## Svinutá magnetická nádoba



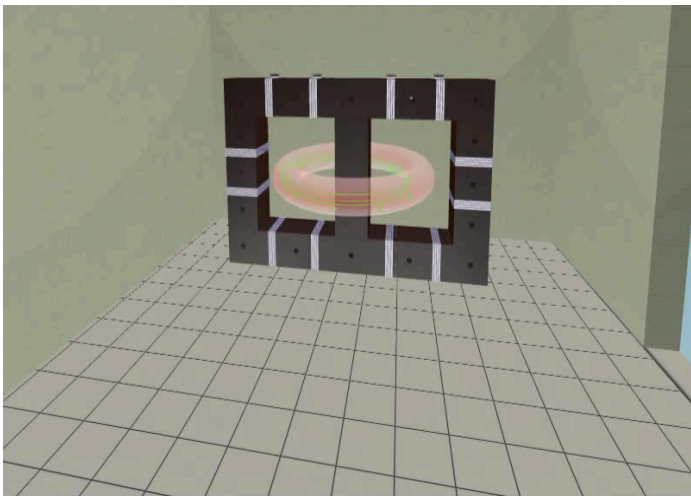
Musíme to celé umístit do reaktorové nádoby - komory



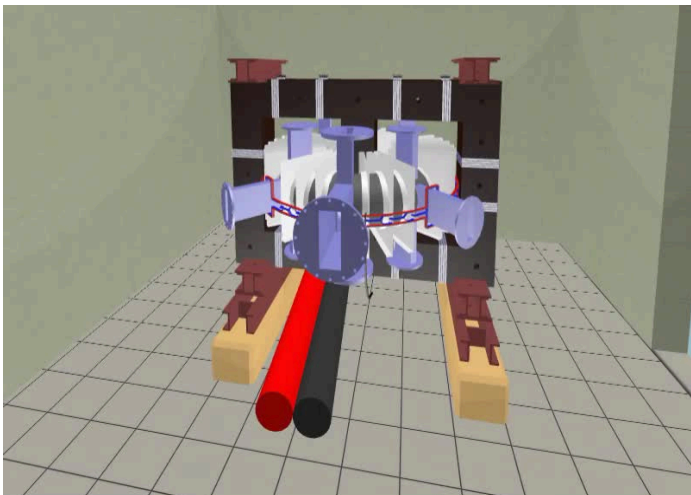
# Toroidální magnetické pole udržuje plazma



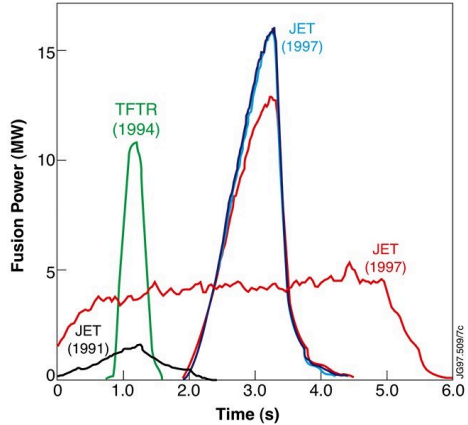
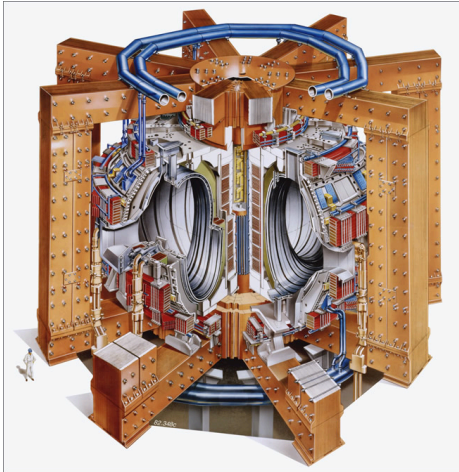
# Transformátorová akce vytvoří a zahřeje plazma



# Vše dohromady - voilà tokamak

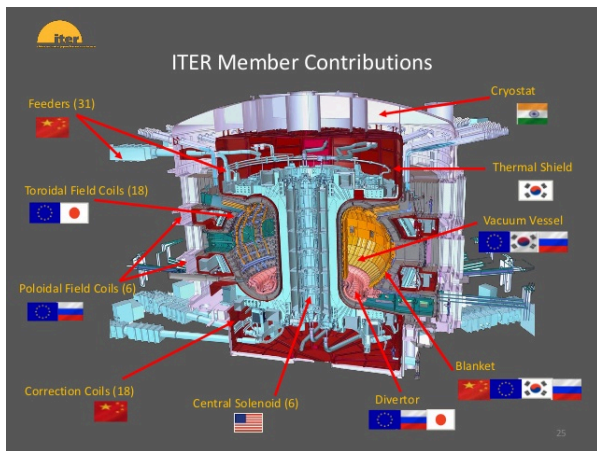


# 1997: Světový fúzní rekord @ JET (EU)



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

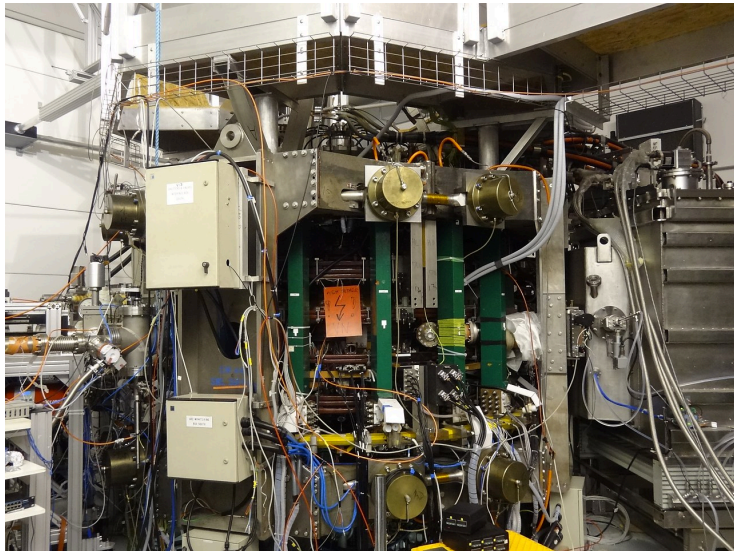
# ITER (jižní Francie) $\approx$ 18 miliard EUR



Mise:

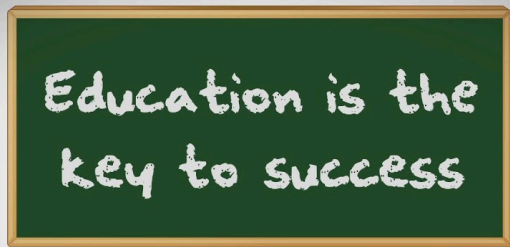
$P \approx 500$  MW,  $Q \approx 10$ ,  $\Delta T \approx 10$  minut, konkurenceschopná cena elektřiny

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

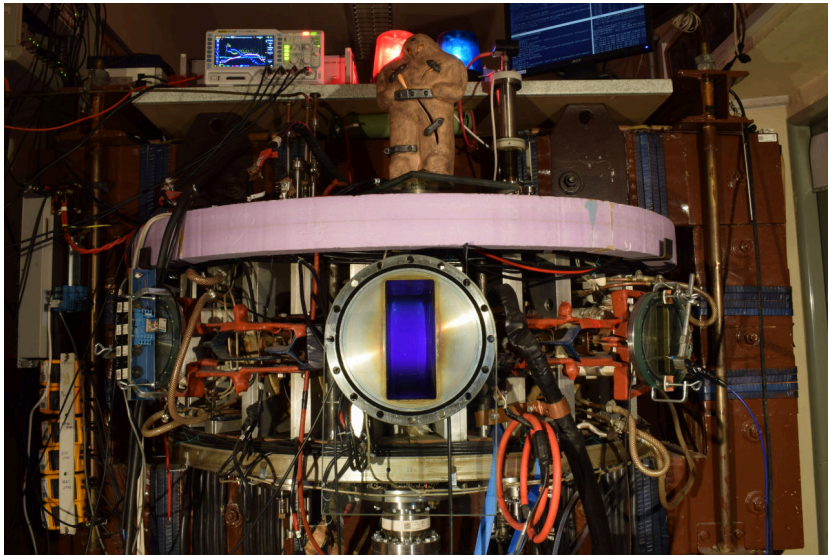




Velké ambice ....



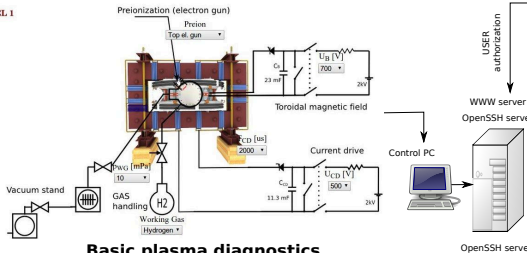
# Tokamak GOLEM



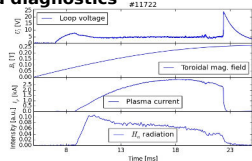
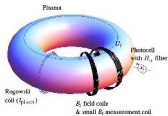
# Tokamak GOLEM - experimentální schéma

LEVEL 1

## Tokamak technology setup



## Basic plasma diagnostics

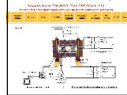


internet

Virtual control room  
(remote participation)

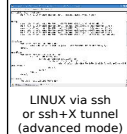
WWW control interface

HTML & PHP scripts



SSH control interface

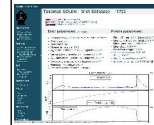
WINDOWS via putty



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

Data presentation

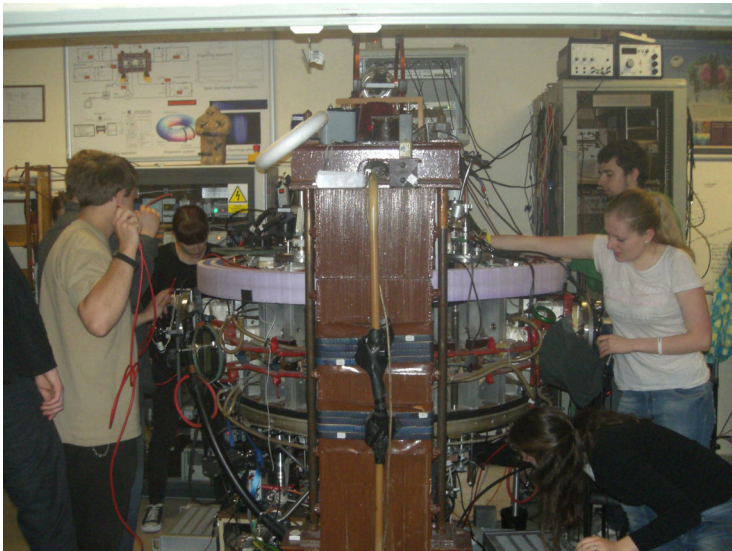
HTML (www pages)



Data handling

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

# 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 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

# Poplatek: pohlednice z místa vzdáleného řízení

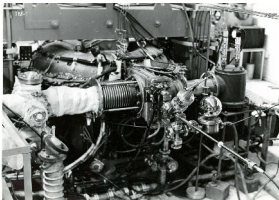


# GOLEM



# Děkuji za pozornost

**Tokamak TM1**  
@Kurchatov Institute near Moscow  
~1960-1977



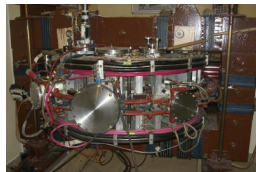
**SCIENCE**

**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 ..

**Tokamak Golem \*\*REMOTE\*\* for MASTER (Level 1)**  
The smallest & oldest operational tokamak with the biggest control room in the world

Home	WiFi	Control Room	Queue	Live	Results	GOLEM diagram	Chamber status	IP cameras	3D model	Chat	Feedback	Logout
------	------	--------------	-------	------	---------	---------------	----------------	------------	----------	------	----------	--------

**LEVEL 1**

Preionization (electron gun)  
Posias

Toroidal magnetic field

Current drive

Vacuum stand  
GAS handling  
Washing Gas

Discharge comment

Place the discharge setup into the queue



# Tokamak GOLEM @ Wikipedia ..

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home Kalendaršř Produkcje Forecast Slovnik Rano

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**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 cusp. 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 ]

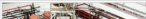
#### Currently in operation [ edit ]

(in chronological order of start of operations)

- 1960s: TM1-MH (since 1977 Castor; since 2007 Golem<sup>[12]</sup>) in Prague, Czech Republic. In operation in Kurchatov Institute since early 1960s but renamed to Castor in 1977 and moved to IPP CAS,<sup>[13]</sup> Prague; in 2007 moved to FNSPE, Czech Technical University in Prague and renamed to Golem,<sup>[14]</sup>
- 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,<sup>[15]</sup> at the CEA, Cadarache, France
- 1989: Aditya, at Institute for Plasma Research (IPR) in Gujarat, India
- 1980s: DIII-D,<sup>[16]</sup> in San Diego, USA; operated by General Atomics since the late 1980s
- 1989: COMPASS,<sup>[13]</sup> 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,<sup>[17]</sup> at the Instituto de Plasmas e Fusão Nuclear, Lisbon, Portugal;
- 1991: ASDEX Upgrade, in Garching, Germany



Alcator C-Mod



# Acknowledgement

Financial support highly appreciated:

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Students, teachers, technicians (random order):

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