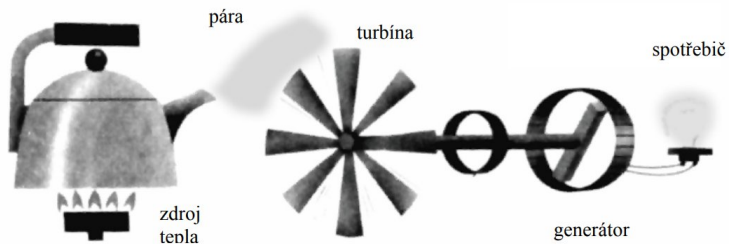


Tokamak GOLEM

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

January 13, 2025

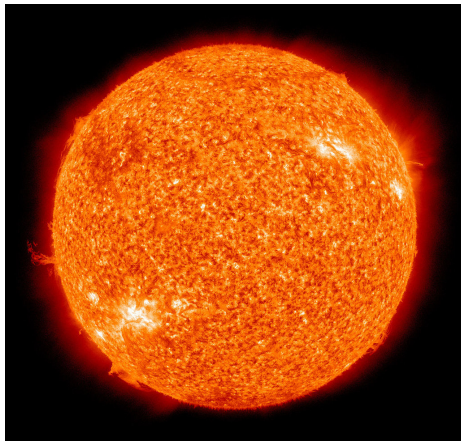
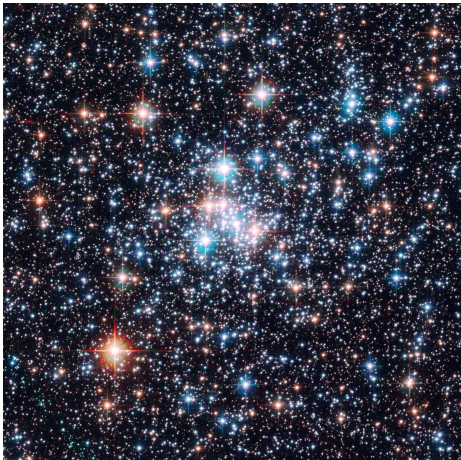
Thermal power plant - basic principle



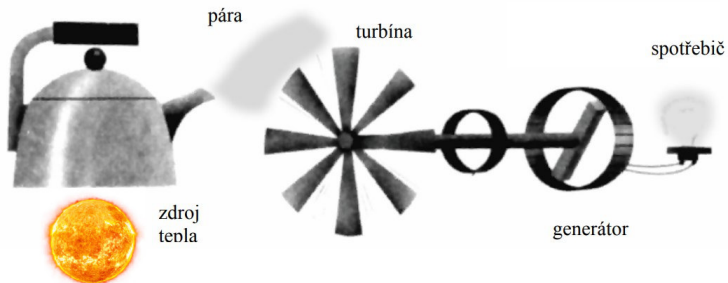
The question:

?? WHAT TO BURN ??

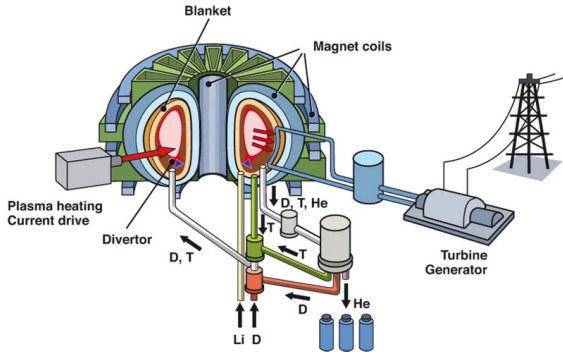
What about stars?



Topit malým Sluncem/hvězdou ??



Vision: Nuclear power plant – a fusion one



credit:[?]

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

Master the Technology

The 1GW (approx. Prague) annual power requirement

Coal

250 trains



Oil

11 super tankers



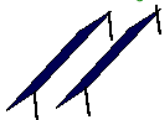
Fission

1.5 rail car load
Uranium Oxide



Solar

5000 acres of collectors
plus energy storage for
night and cloudy days

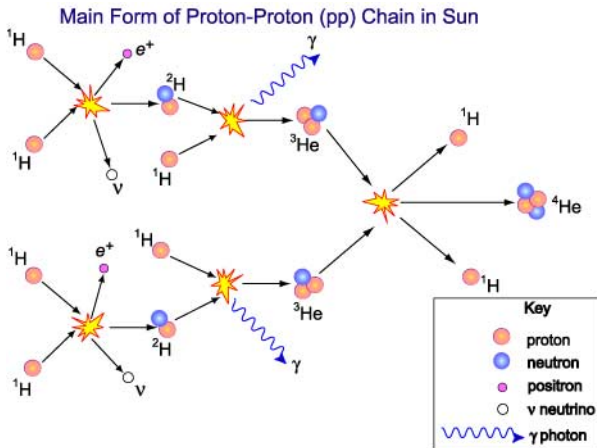


Fusion

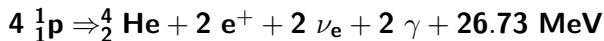
1/2 ton pickup truck
Deuterium & Tritium



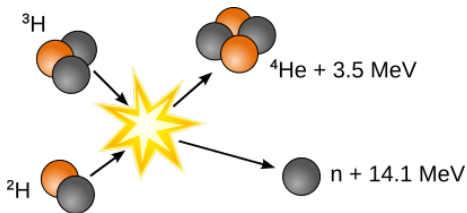
The Sun - Proton proton chain



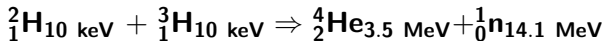
credit:CSIRO



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



credit:[?]



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

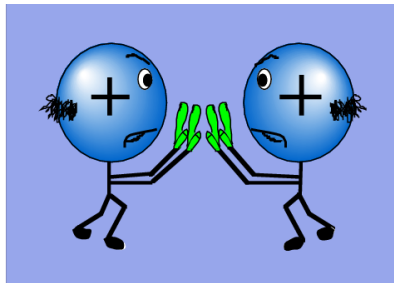
$$m_{(2\text{H}+3\text{H})} = 5.02905m_u, m_{(\text{He}+\text{n})} = 5.01017m_u,$$

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

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

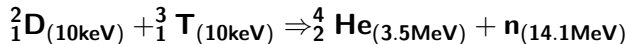
$$1\text{eV} \sim 11600^\circ\text{C} \approx {}^2_1\text{H}_{100 \text{ M}^\circ\text{C}} + {}^3_1\text{H}_{100 \text{ M}^\circ\text{C}} \Rightarrow {}^4_2\text{He}_{35 \text{ G}^\circ\text{C}} + {}^1_0\text{n}_{141 \text{ G}^\circ\text{C}}$$

Proč tak obrovské teploty?

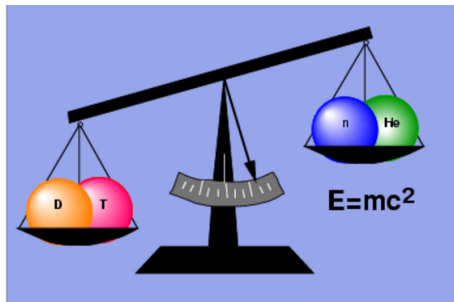
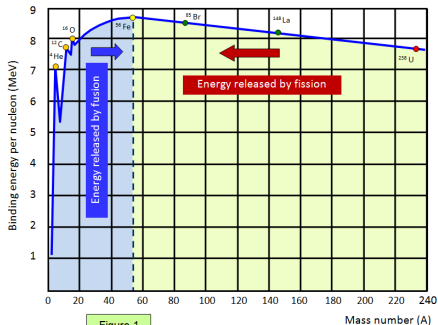


- Coulomb law:

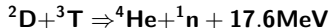
$$F_E = \frac{1}{4\pi\epsilon_0} \frac{Q_1 Q_2}{r^2}$$



Uvolnění vazebné energie atomových jader



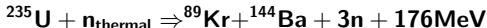
fúze lehkých jader



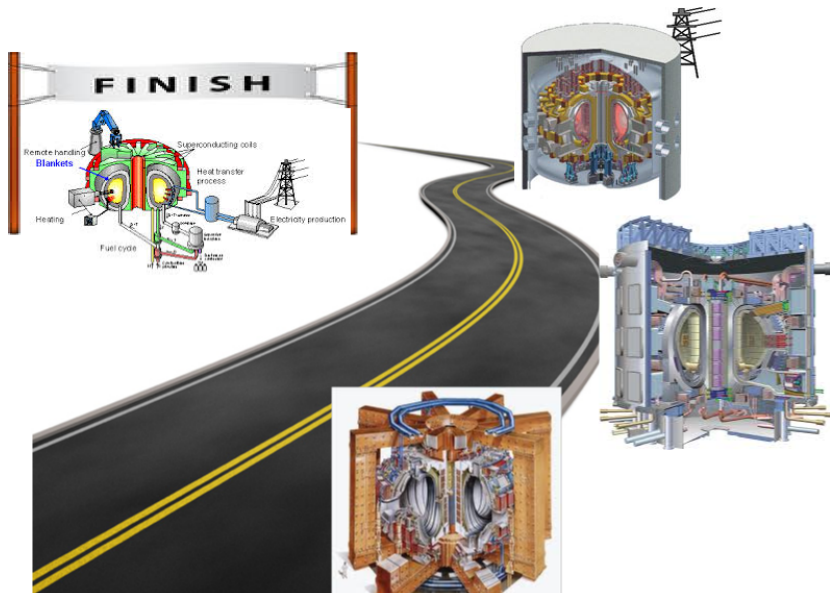
X

štěpení těžkých jader

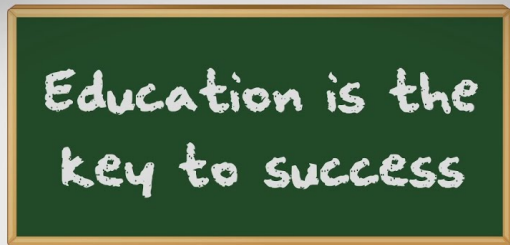
X



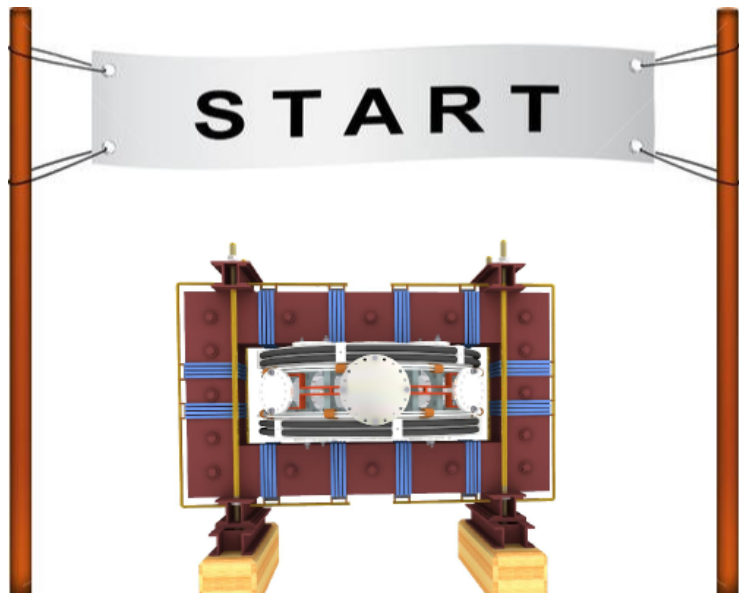
Milestones to Fusion Power Plant



Education importance

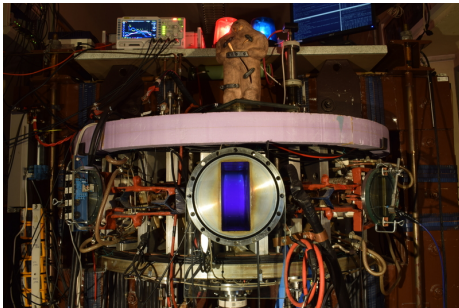


Let's start with the tokamak GOLEM - *the smallest tokamak in the World with the biggest control room*



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 GOLEM @ Wikipedia ..


File Edit View Go Bookmarks Tools Settings Window Help

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

home Kalendarj Produkce Forecast Slovník Itano

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Article [Talk](#) [Read](#) [Edit](#) [View history](#)

 **WIKIPEDIA**
The Free Encyclopedia

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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



ida, the free encyclo... W Tokamak - Wikipedia, the free encyclo... [svoboda] buon@fi.cvut.cz - Kosside [Krusader] Inbox - svoboda@fi.cvut.cz - Mail

The GOLEM tokamak for education - historical background

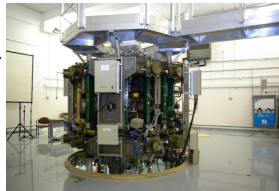
Kurchatov Institute near Moscow,
Soviet Union
1960: **TM1-MH**



1974



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



2006



Institute of Plasma Physics
Czech republic

CASTOR

COMPASS



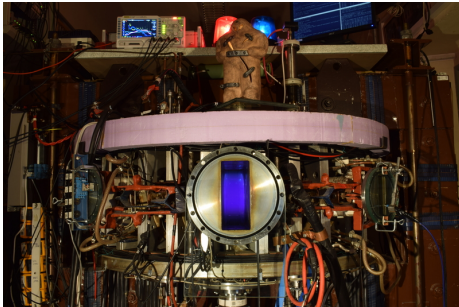
2008



Czech Technical University Prague
Czech republic
GOLEM



Both, fission and fusion training reactors at the CTU



Fusion:GOLEM



Fission:Vrabec

GOLEM

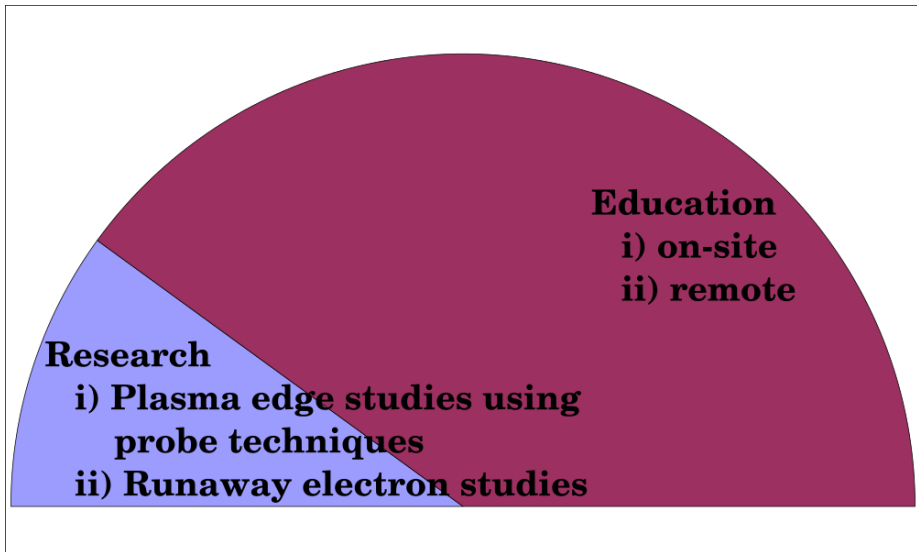
... somewhere, in the ancient cellars of Prague,

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...

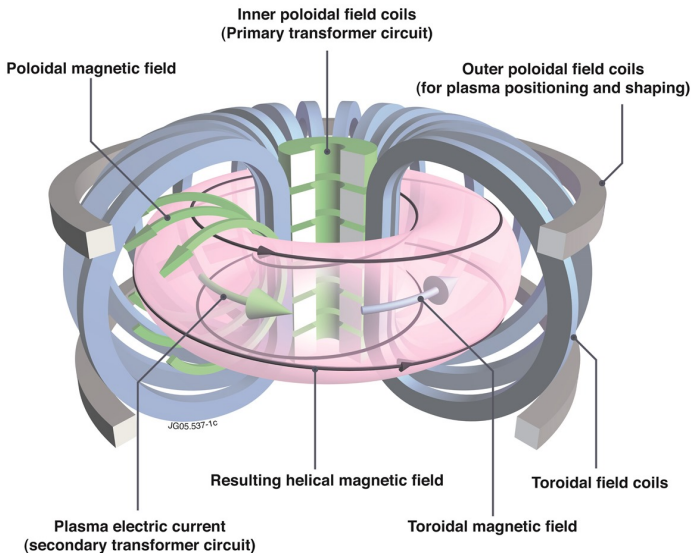


At the end of the 16th century, in the times when the Czech lands were ruled by Emperor Rudolf II, in Prague, there were Rabbi Judah Loew, well known alchemist, thinker, scholar, writer and inventor of the legendary GOLEM - a clay creature inspired with the Universe power that pursued his master's command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

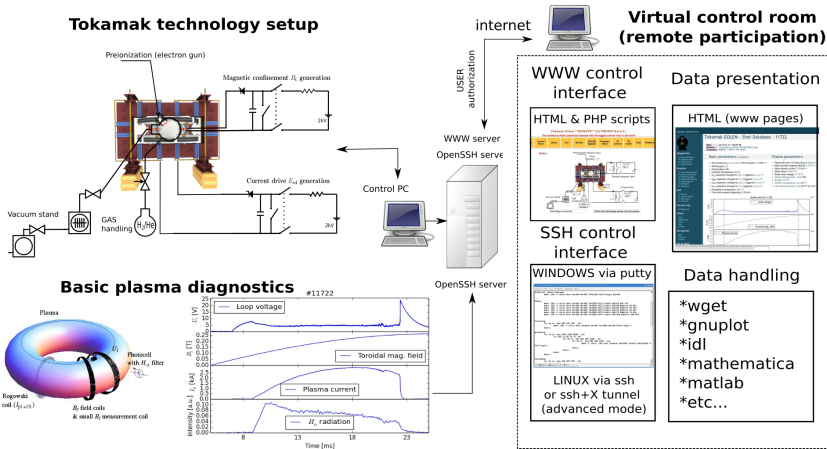
The GOLEM tokamak mission



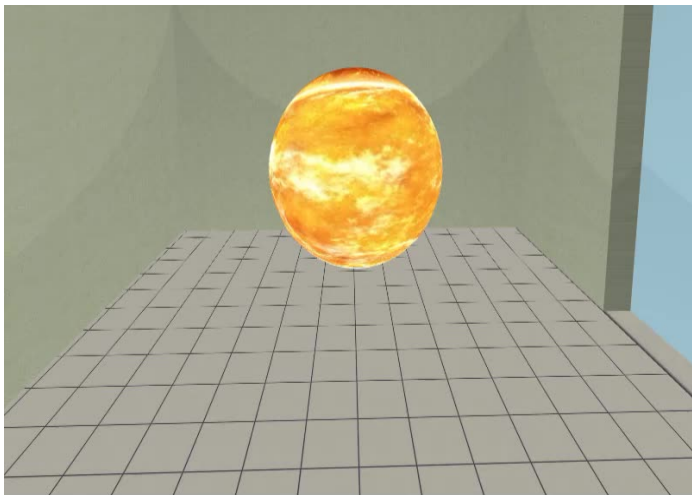
Tokamak magnetic confinement concept



The global schematic overview of the GOLEM experiment

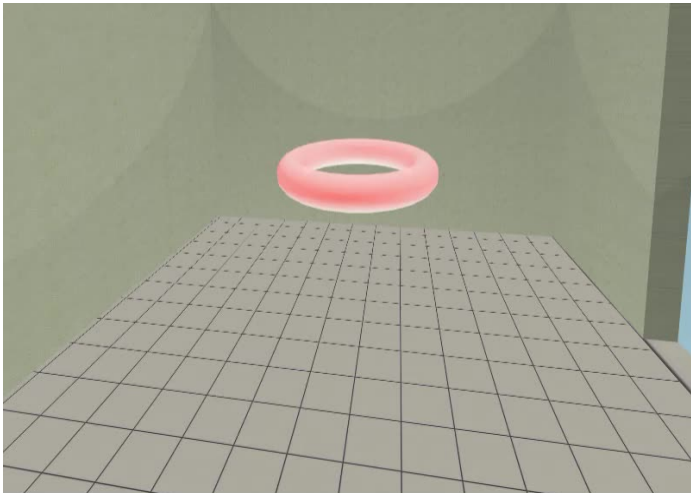


Náš cíl: vytvořit μ Slunce v pozemských podmínkách

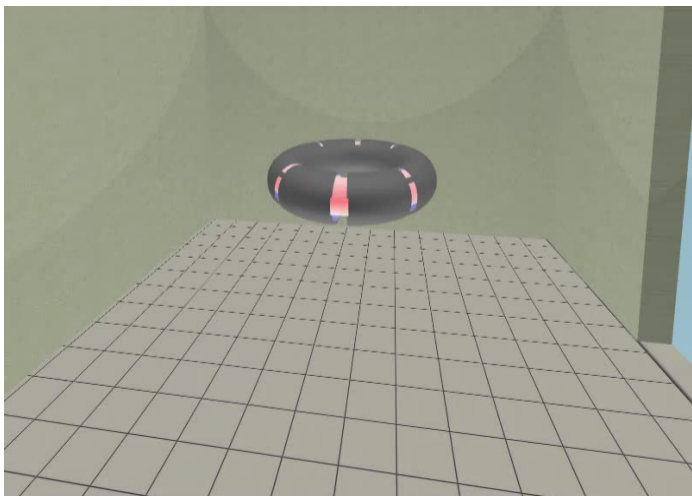


Magnetické udržení vyžaduje toroidální geometrii

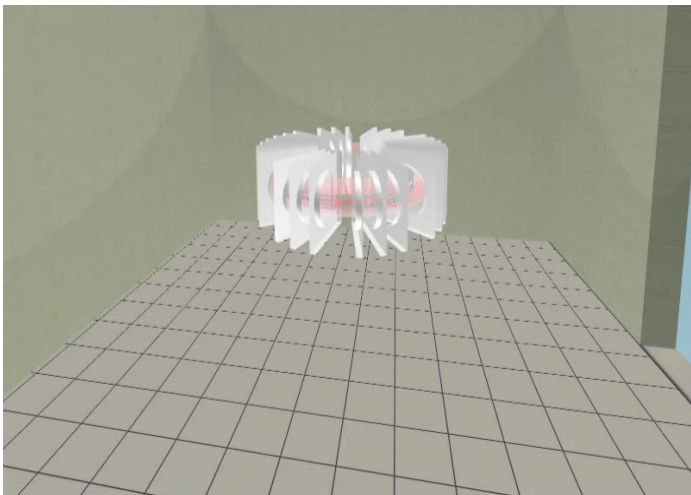
Svinutá magnetická nádoba



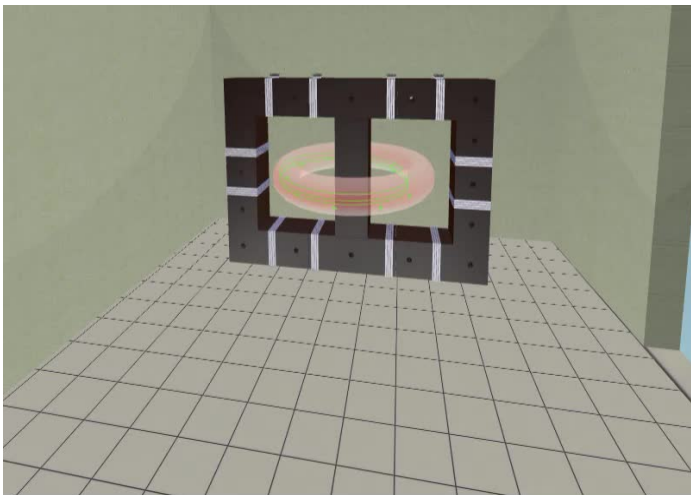
Musíme to celé umístit do reaktorové nádoby - komory



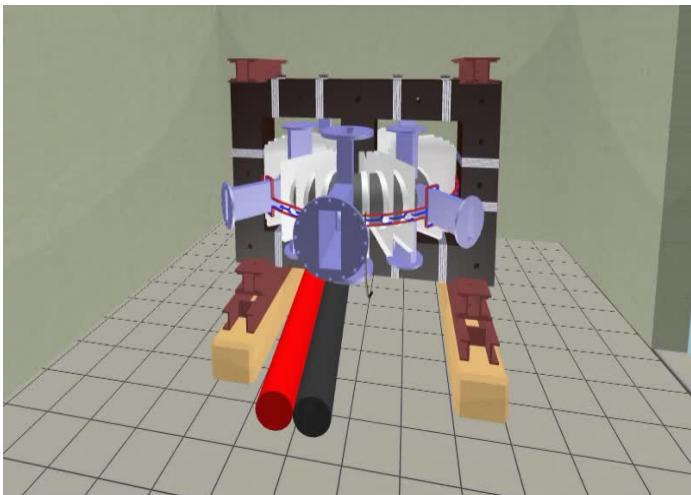
Toroidální magnetické pole udržuje plazma



Transformátorová akce vytvoří a zahřeje plazma



Vše dohromady - voilà tokamak

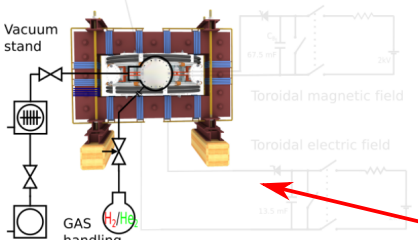


Remote control interface of the GOLEM tokamak

Introduction Working gas Preionization Magnetic field Electric field Submit

Set the pressure and type of the working gas from which the plasma is formed. Pressure must be high enough for plasma to form, but low enough for gas breakdown to occur.

Preionization (electron gun)



Vacuum stand

GAS handling H_2/He

Toroidal magnetic field

Toroidal electric field

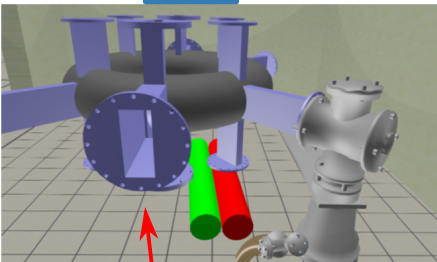
Gas type and pressure $p_{WG} = 16 \text{ mPa}$

Hydrogen Helium

Next Set recommended value

rendering settings

3D model rendering method: Static image (fast) Interactive X3DOM (slower)



3D model rendering


engineering scheme

sliders and checkboxes

workflow buttons

Shot homepage (≈ 2 minutes after discharge execution)

GOLEM # Shot #40631
autoreload



Diagnostics

BasicDiagnostics
DontUseRakeProbe
Interferometry
LimiterMicroCoils
ScribbleRakeProbes

Other

View
Showroom

Navigation

Next
Previous
Current

Go to shot
40631

Golem utils

Home
Plot data
Shot manual plot
Manipulators control

Database operations

Shots listing
Shots filtering

Tokamak GOLEM - Shot Database - #40631

The date of discharge execution 23-02-07 17:23:54

The session mission 1Final -> Dringit service

The session ID 40605

The discharge comment Rake probe 50mm

Discharge command jDringit.sh --discharge --UBt 800 --Tbt 0 --Utd 450 --Tod 500 --preionization 1 --gas H --pre issue 15 --diagnostics.limitermicrocoils.vacuum_shot=40615F --discharge.preionization "m air_switch=on;powsup_heater=80;powsup_accel=100" --infrastructure.position_stabilization "main_switch=on;radial_switch=on;vertical_waveform=1000,0.8000,-20,10000,-25,12000,-10,30000,0;vertical_switch=on;radial_waveform=2000,0.3000,0.7000,-20,9500,-25,10000,-20,30000,2,25000,0" --ScanDefinition 40625 40629F --comment "Rake probe 50mm"

[Shot Logbook]

Technological parameters

- Working Gas: $P_{discharge,befest}=2.46$ mPa; $P_{discharge,pre}=5.04$ mPa ($P_{WG}^{request} = 15$ mPa@ $\Delta_{WG}^{request} = H$)
- Toroidal magnetic field: $U_{B_t}^{request}=800$ V@ $I_{B_t}^{request}=0.0$ us
- Current drive field: $U_{Ecd}^{request}=450$ V@ $I_{Ecd}^{request}=500.0$ us







Plasma:

- Plasma: yes or no:
- Time parameters: $\Delta T_p=10.88$ ms ($t_{onset,stat}=2.67$ ms, $t_{end,stat}=13.54$ ms)

Plasma parameters:

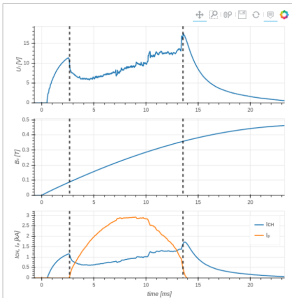
- Loop voltage: $\bar{U}_{loop}=6.82$ V; $max_{T_{inj}}(I_{discharge}) U_{loop}=16.17$ V; $U_{loop,downtime}=0.00$ V
- Toroidal magnetic field: $B_t=0.24$ T; $max_{T_{inj}}(I_{discharge}) B_t=0.36$ T
- Plasma current: $I_p=2.28$ kA; $max_{T_{inj}}(I_{discharge}) I_p=2.92$ kA; $t_p^{max}=0.00$ ms

On stage diagnostics

Data flow	measurement	digitization	analysis
Name	Experiment setup	Data acquisition system	Raw data
Basic Diagnostics			
Double rake probe			

Without Analysis

Basic Diagnostics



On site education - basic laboratory training (Hands on tokamak experiment)



Remote education: CEA France & Czech Technical University for Chiang Mai university on February, 2018)



Remote education (Chiang Mai university students operating tokamak GOLEM ≈ 8000 km from Prague)



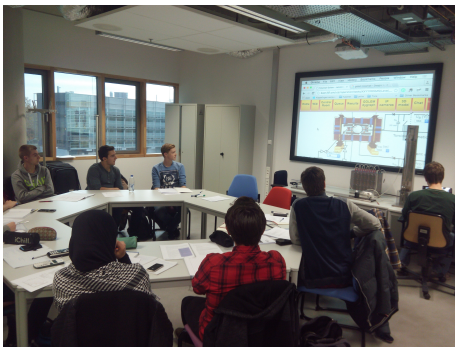
Remote education: Data analysis ..



Remote education: Presentations the day after ..



Tokamak GOLEM - vzdálené řízení: 2009-2019 inventura



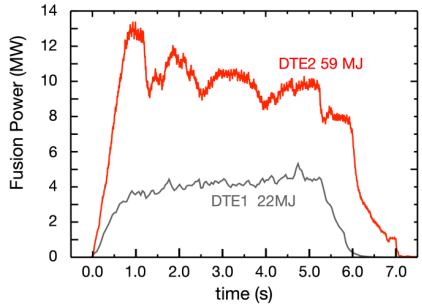
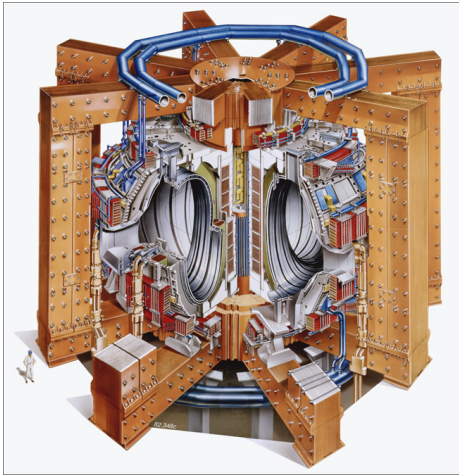
Studenti z TU Eindhoven, operující tokamak, 650 km vzdušnou čarou

- 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
- Pracovní semináře: Kitanu 14,16,18; Observatorium Valovska Mezirici 14; Islamabad

Poplatek: pohlednice z místa vzdáleného řízení



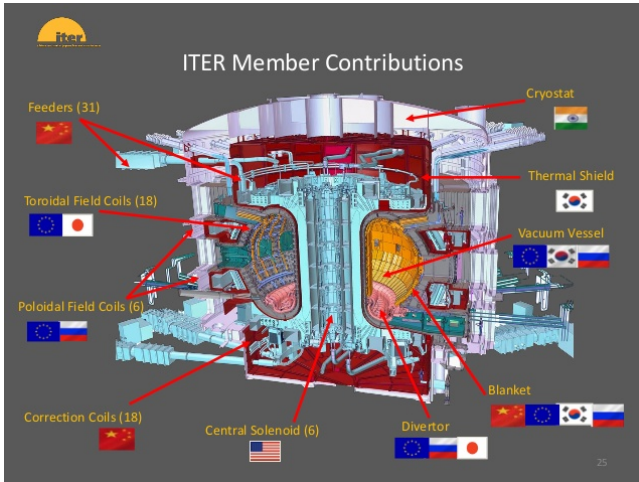
1997: Světový fúzní rekord @ JET (EU)



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 \approx 17 billion euros



- Fusion power 0.5 GW for 10 min.
- $Q = 10$.
- Feasibility.

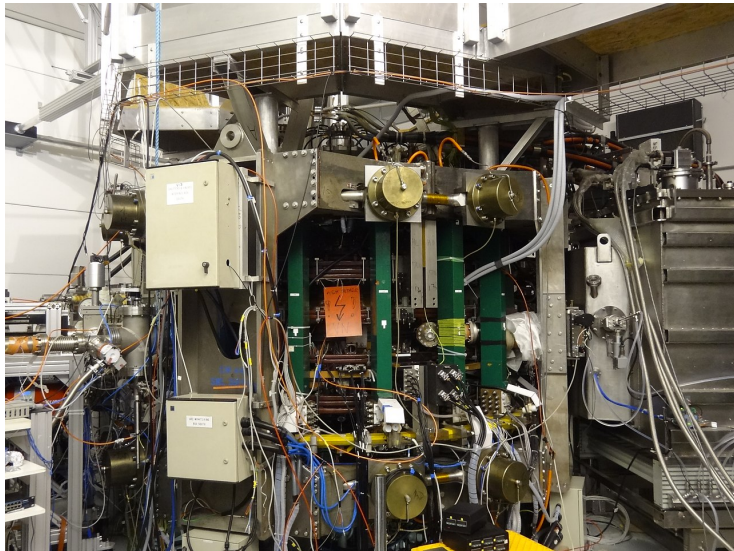
ITER status update 07/24 \approx 22 miliard EUR



Odklad dosažení plného výkonu o 4 roky na 2039 + navýšení nákladů o 5 mld. EUR na 22 mld. EUR:

COVID, RUxUA, chyba Korejců v rozměrech segmentů reaktoru, naleptání heliového chladicího potrubí, kompletní výměna první stěny z beryllia na wolfram, znásobení mikrovlnného ohřevu plazmatu.

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



Acknowledgement

Financial support highly appreciated:

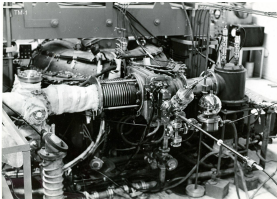
CTU RVO68407700, SGS 17/138/OHK4/2T/14, GAČR GA18-02482S, EU funds CZ.02.1.01/0.0/0.0/16_019/0000778 and CZ.02.2.69/0.0/0.0/16_027/0008465, IAEA F13019, FUSENET and EUROFUSION.

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 Leitl, Martin Himmel. Petr Švihra, Petr Mácha, Vojtěch Fišer, Filip Papoušek, Sergei Kulkov, Martin Imříšek.

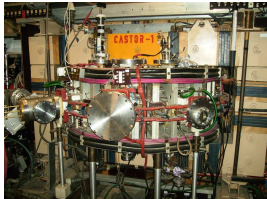
Thank you for your attention

Tokamak TM1
@Kurchatov Institute near Moscow
~1960-1977



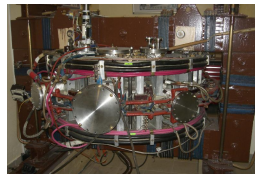
SCIENCE

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 ..

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

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LEVEL 1

Preionization (electron gun)
Thresh

Toroidal magnetic field

Current drive

Vacuum stand

GAS handling

Working Gas (Deuterium)

Discharge comment

Place the discharge setup into the queue