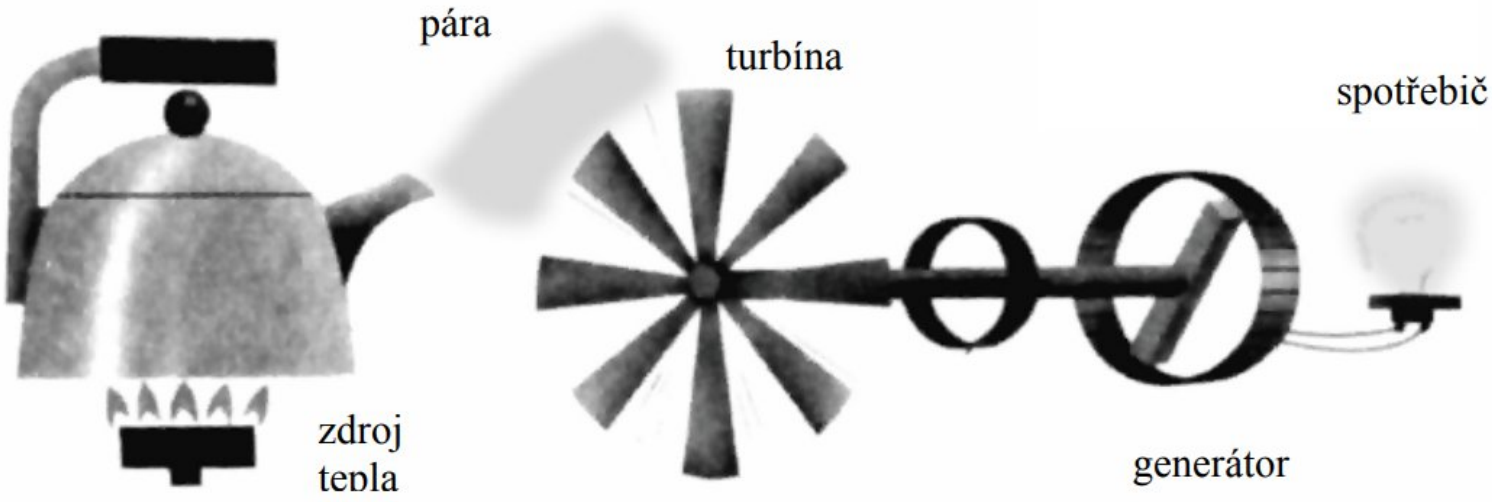
Title

Tokamak GOLEM

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

June 13, 2024

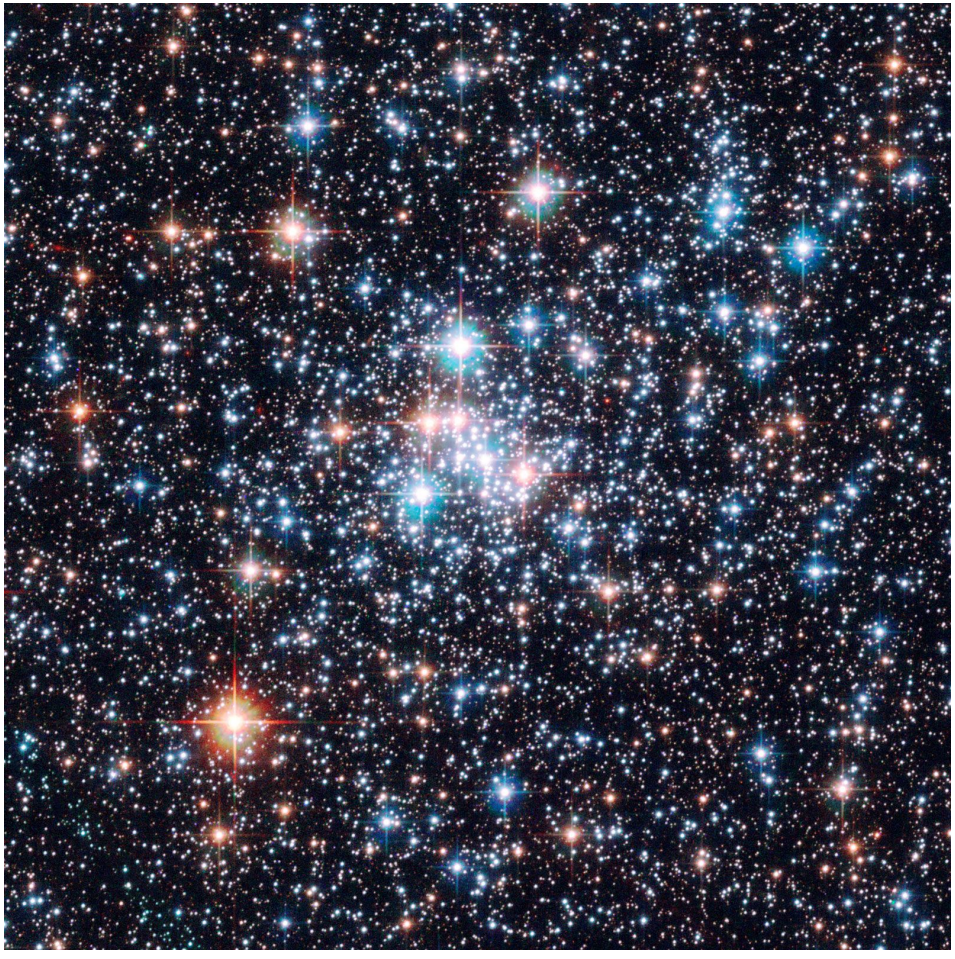
Thermal power plant - basic principle

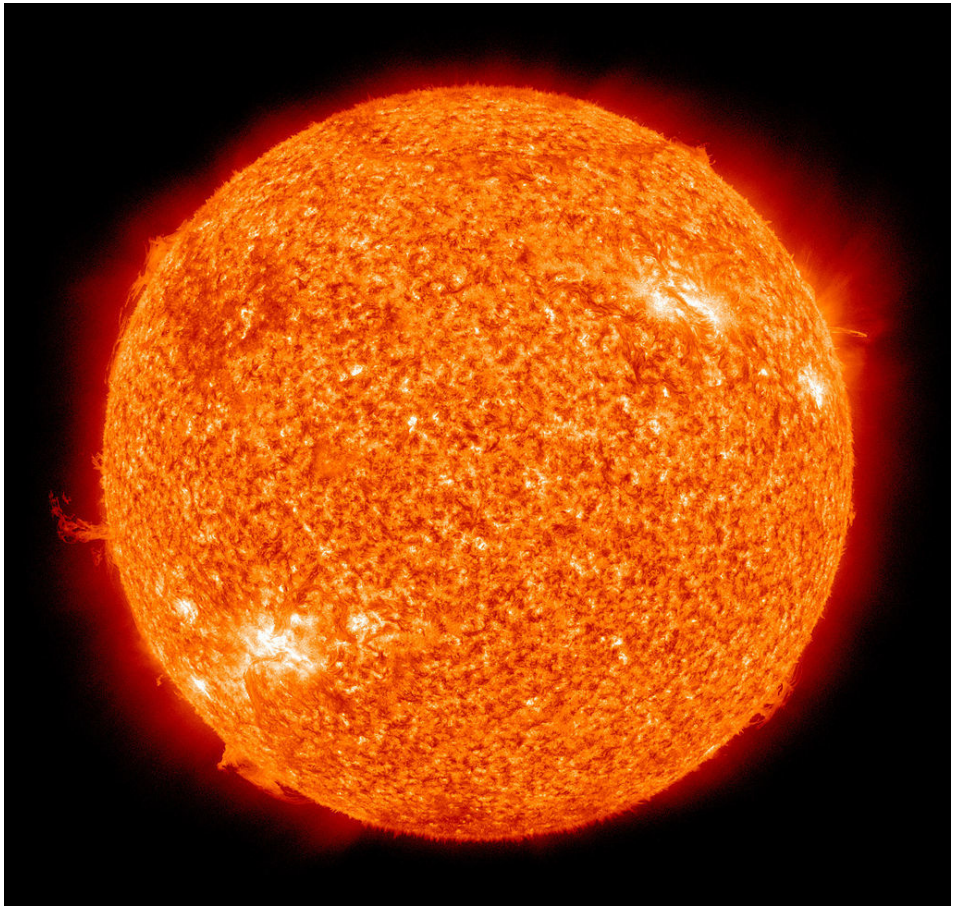


The question:

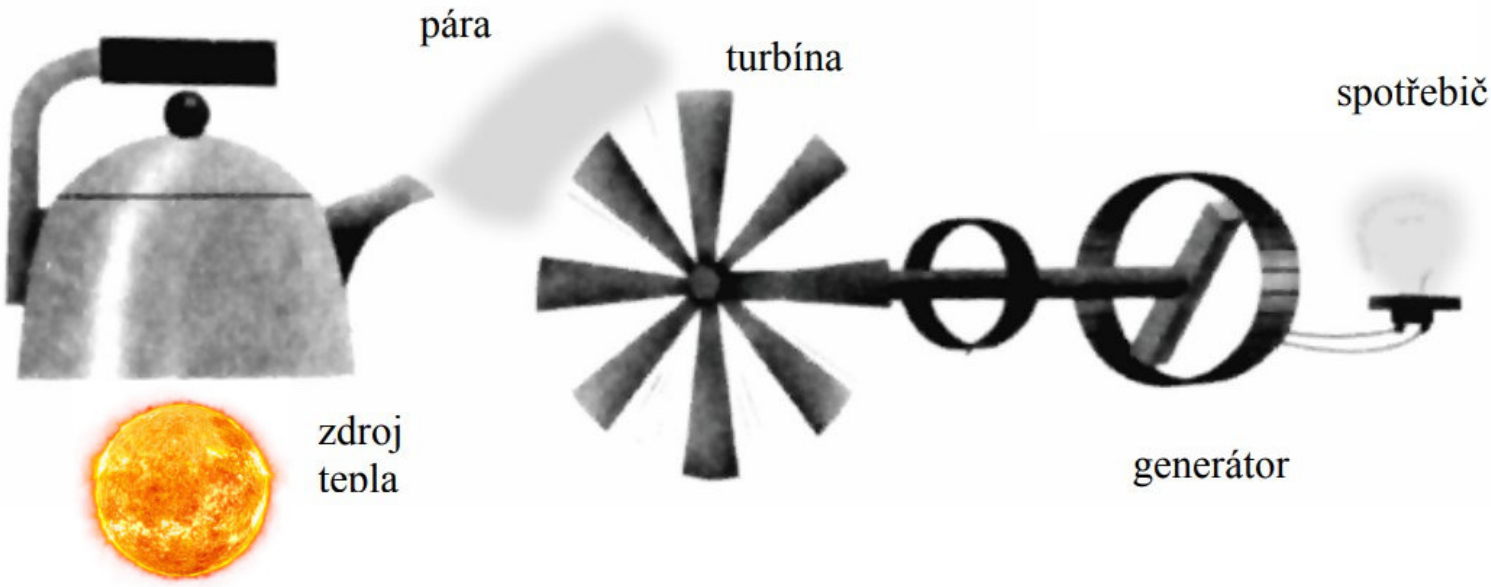
?? WHAT TO BURN ??

What about stars?

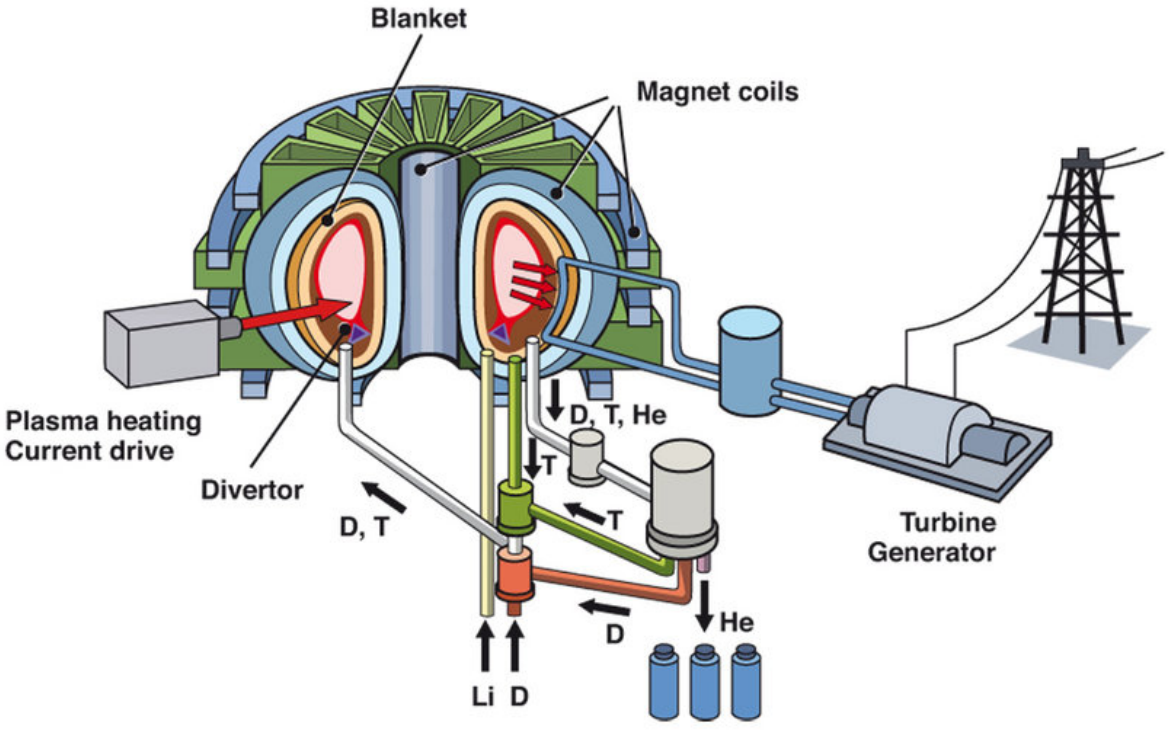




Topit malým Sluncem/hvězdou ??



Vision: Nuclear power plant – a fusion one

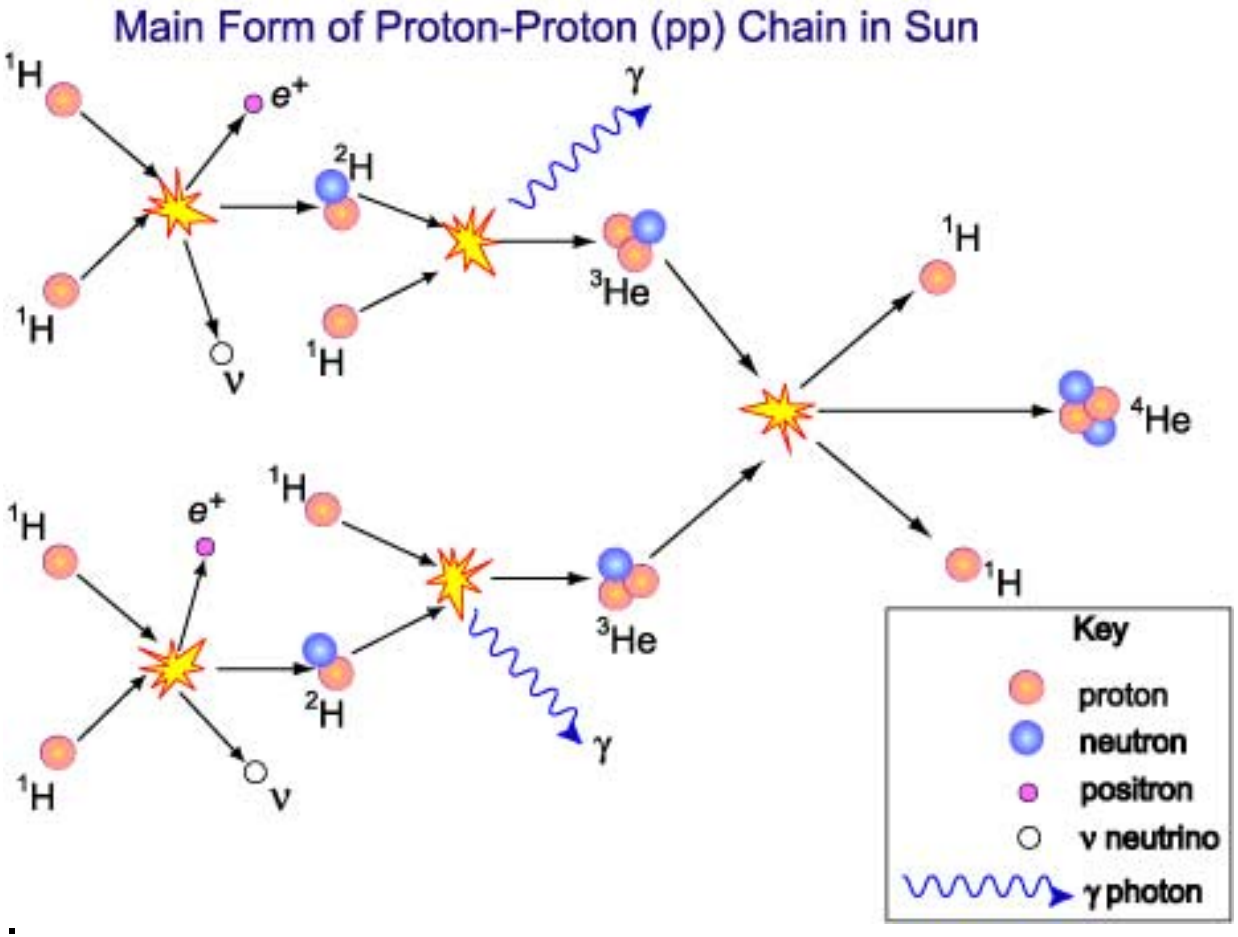


credit:[?]

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

Master the Technology

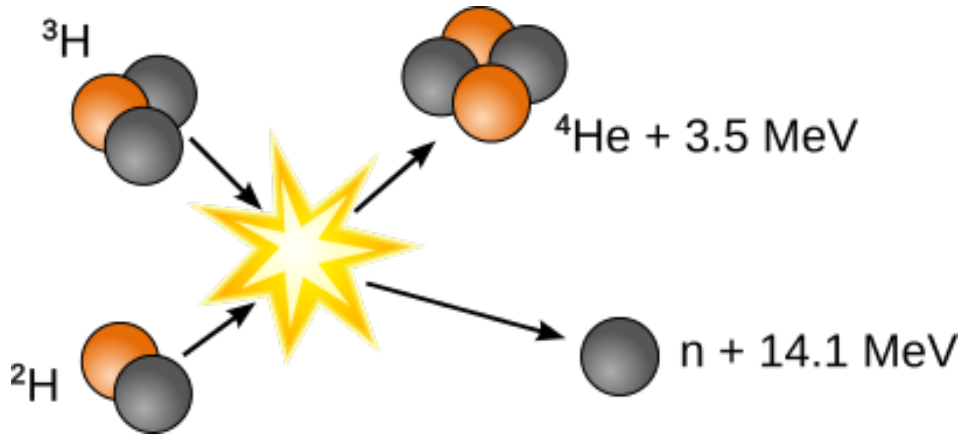
The Sun - Proton proton chain



credit:CSIRO

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

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



credit:[?]

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

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

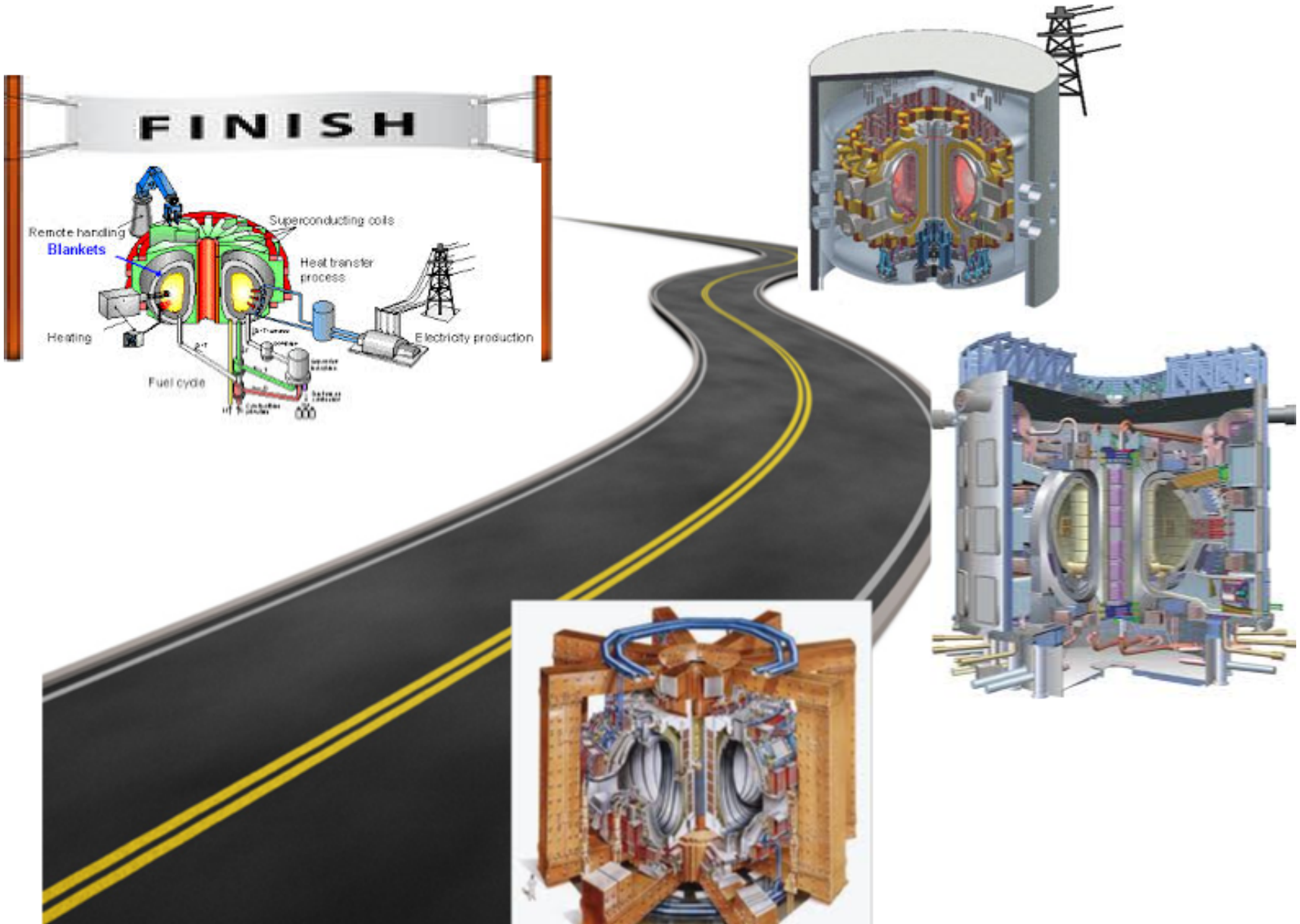
$m_{(^2\mathrm{H}+^3\mathrm{H})} = 5.02905 m_u$, $m_{(\mathrm{He}+\mathrm{n})} = 5.01017 m_u$,

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

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

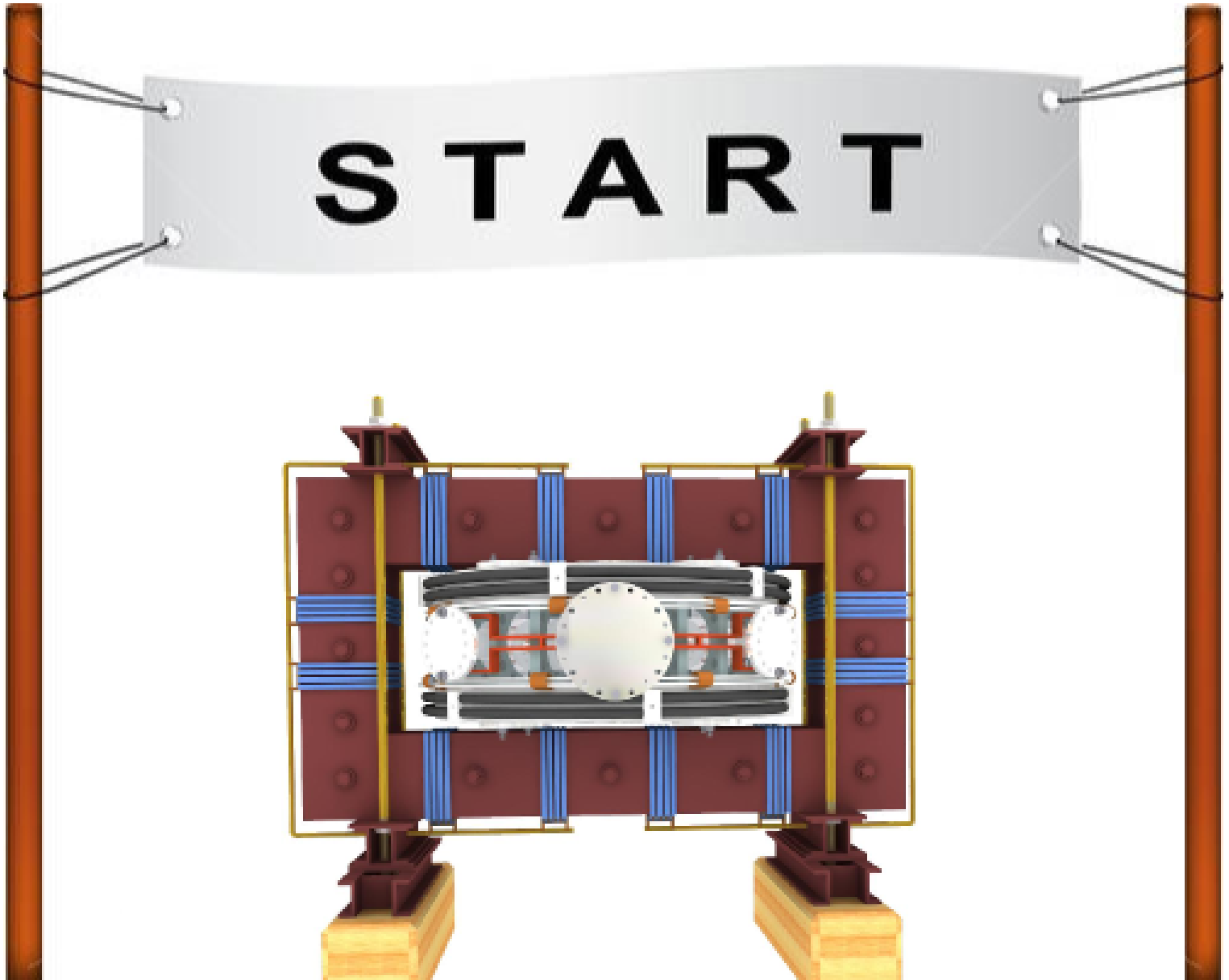
$$1\mathrm{eV} \sim 11600^{\circ}\mathrm{C} \approx \quad \mathbf{^{2}_{1}H_{100\ M^{\circ}C} + {}^{3}_{1}H_{100\ M^{\circ}C} \Rightarrow {}^{4}_{2}He_{35\ G^{\circ}C} + {}^{1}_{0}n_{141\ G^{\circ}C}}$$

Milestones to Fusion Power Plant



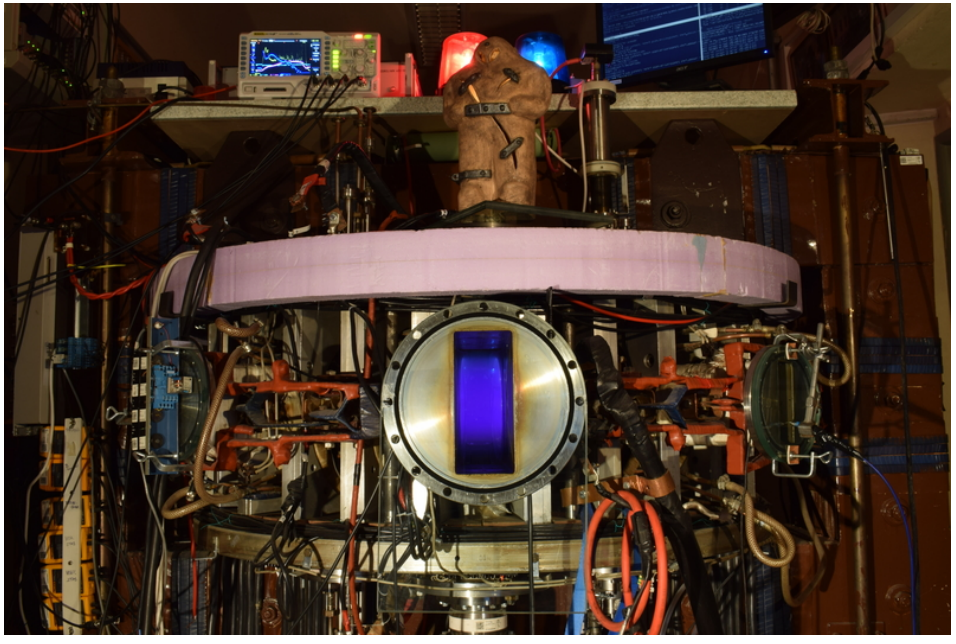
Education importance

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 newsline 06/18)



- Vessel major radius: $R_0 = 0.4$ m
- Vessel minor radius: $r_0 = 0.1$ m
- Maximum plasma current: $I_{\mathrm{p}}^{\mathrm{max}} < 8$ kA
- Maximum toroidal magnetic field: $B_{\mathrm{t}}^{\mathrm{max}} < 0.5$ T
- Typical electron density: $< n_e > \in (0.2, 3) \cdot 10^{19}$ m^{-3}
- Maximum electron temperature: $T_{\mathrm{e}}^{\mathrm{max}} < 80$ eV
- Maximum discharge duration: $\tau_{\mathrm{p}}^{\mathrm{max}} < 25$ ms

Tokamak GOLEM @ Wikipedia ..

File Edit View Go Bookmarks Tools Settings Window Help

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

home Kalendář Produkce Forecast Slovník Rano

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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 shape. Such a helical field can be generated by adding a toroidal field

it decays into a proton and electron with the emission of energy. When the time comes to actually try to make electricity from a tokamak-based reactor, some of the neutrons produced in the fusion process would be absorbed by a liquid metal blanket and their kinetic energy would be used in heat-transfer processes to ultimately turn a generator.

Experimental tokamaks [edit]

Currently in operation [edit]

(in chronological order of start of operations)

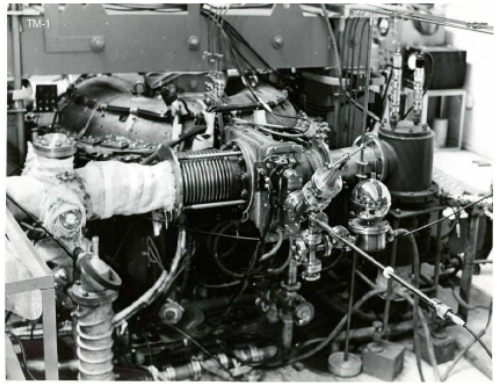
- 1960s: TM1-MH (since 1977 Castor; since 2007 Golem[12]) in Prague, Czech Republic. In operation in Kurchatov Institute since early 1960s but renamed to Castor in 1977 and moved to IPP CAS,[13] Prague; in 2007 moved to FNSPE, Czech Technical University in Prague and renamed to Golem.[14]
- 1975: T-10, in Kurchatov Institute, Moscow, Russia (formerly Soviet Union); 2 MW
- 1983: Joint European Torus (JET), in Culham, United Kingdom
- 1985: JT-60, in Naka, Ibaraki Prefecture, Japan; (Currently undergoing upgrade to Super, Advanced model)
- 1987: STOR-M, University of Saskatchewan; Canada; first demonstration of alternating current in a tokamak.
- 1988: Tore Supra,[15] at the CEA, Cadarache, France
- 1989: Aditya, at Institute for Plasma Research (IPR) in Gujarat, India
- 1980s: DIII-D,[16] in San Diego, USA; operated by General Atomics since the late 1980s
- 1989: COMPASS,[13] in Prague, Czech Republic; in operation since 2008, previously operated from 1989 to 1999 in Culham, United Kingdom
- 1990: FTU, in Frascati, Italy
- 1991: Tokamak ISTTOK,[17] at the Instituto de Plasmas e Fusão Nuclear, Lisbon, Portugal;
- 1991: ASDEX Upgrade, in Garching, Germany

Alcator C-Mod

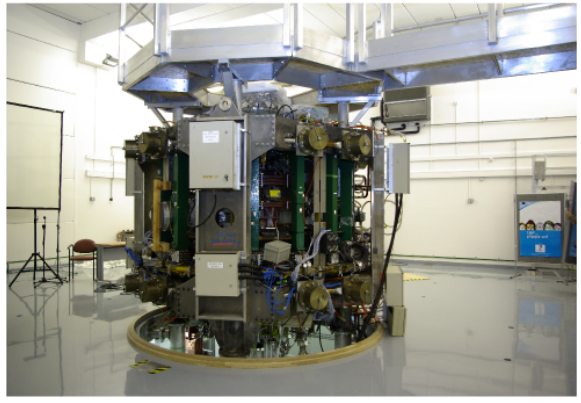
Tokamak - Wikipedia, the free encyclo | (svoboda) buon.fjfi.cvut.cz – Konsole | Krusader | Inbox - svoboda@fjfi.cvut.cz - Mozilla

The GOLEM tokamak for education - historical background

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



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



1974

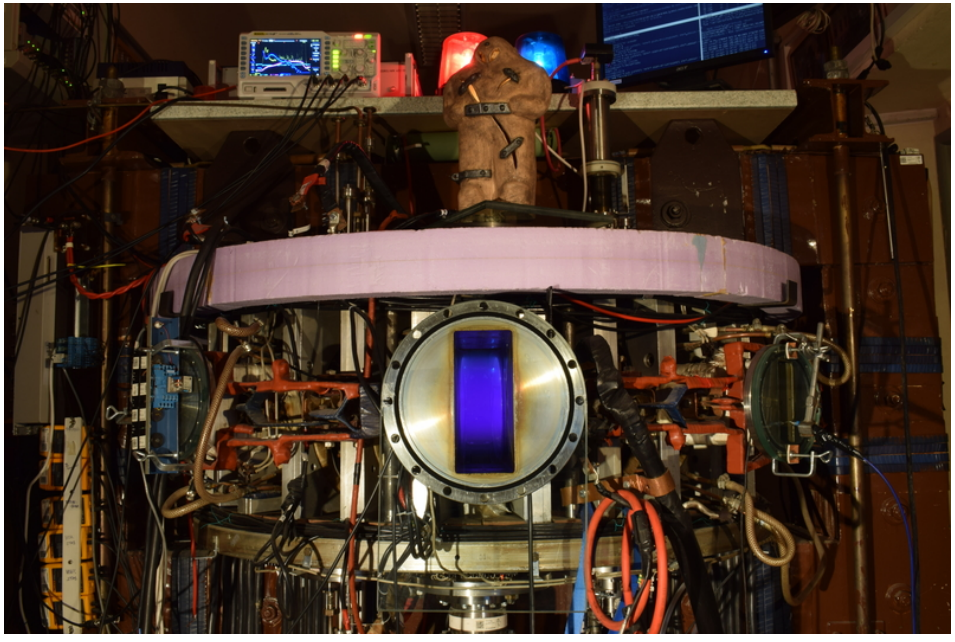
2006

Institute of Plasma Physics
Czech republic
CASTOR **COMPASS**

2008

Czech Technical University Prague
Czech republic
GOLEM

Both, fission and fusion training reactors at the CTU



Fusion:GOLEM

Fission:Vrabec

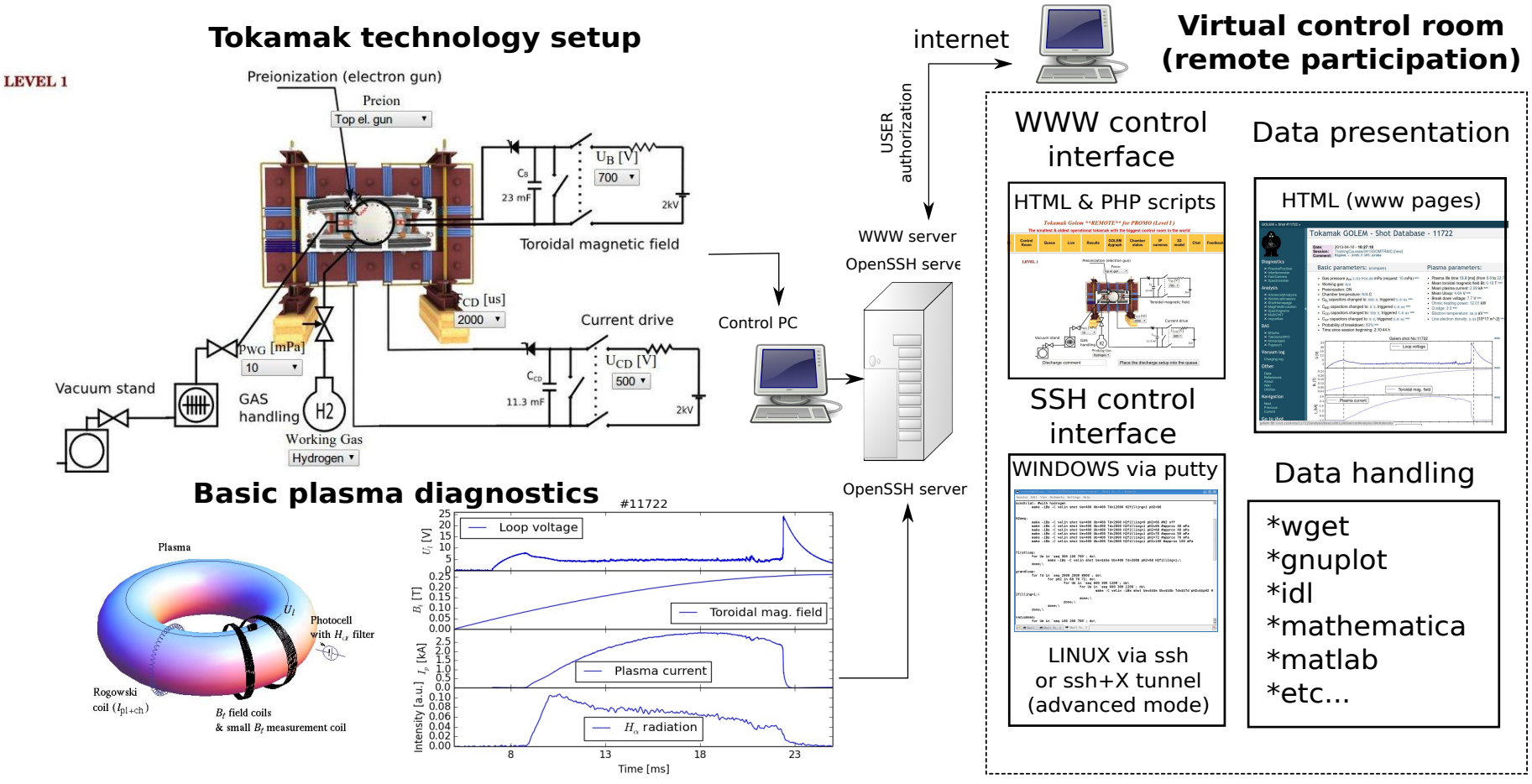
GOLEM

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

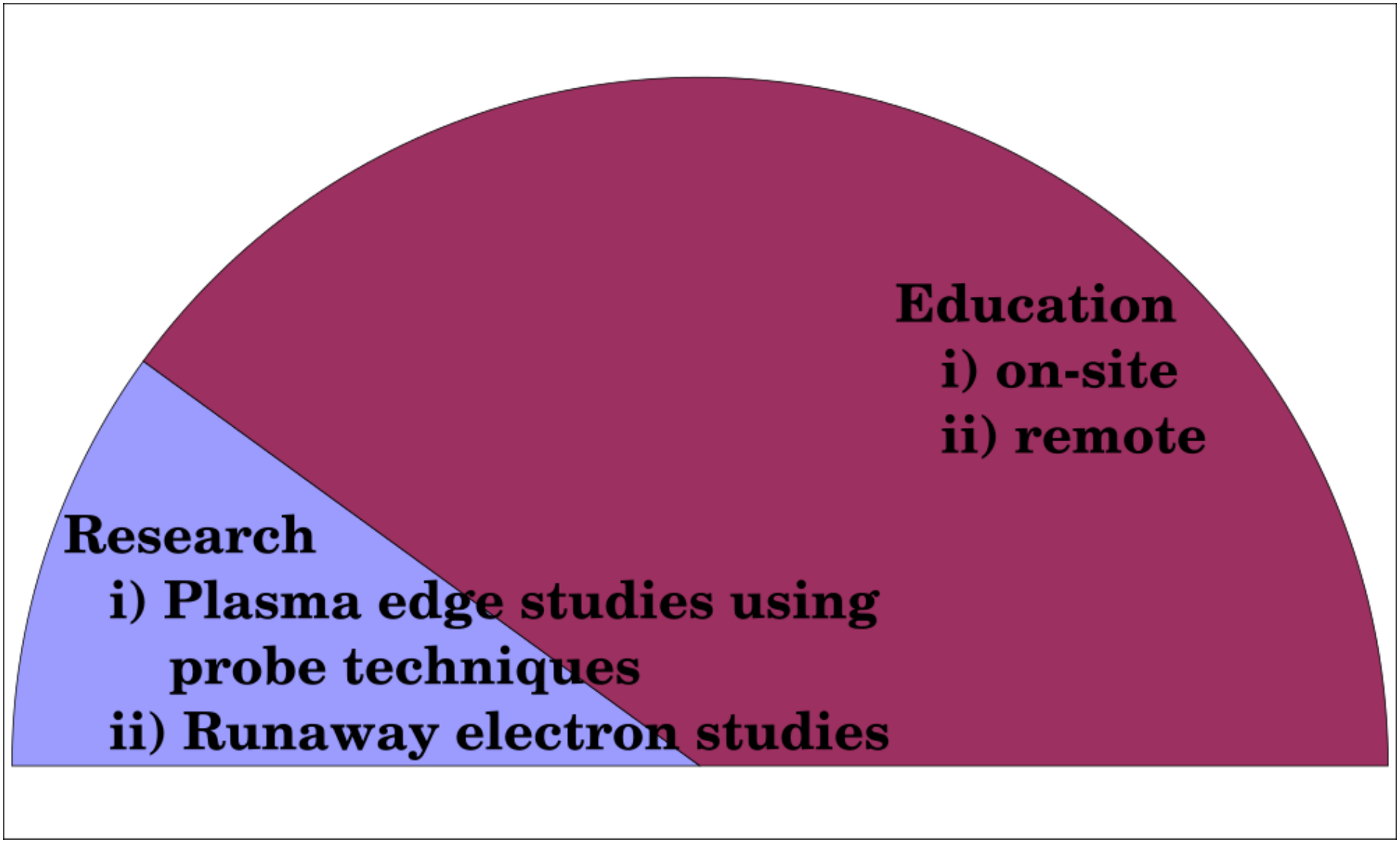
there is hidden indeed "infernal" power. Yet it is the very power of celestial stars themselves. Calmly dormant, awaiting mankind to discover the magic key, to use this power for their benefit...

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. [**?**].

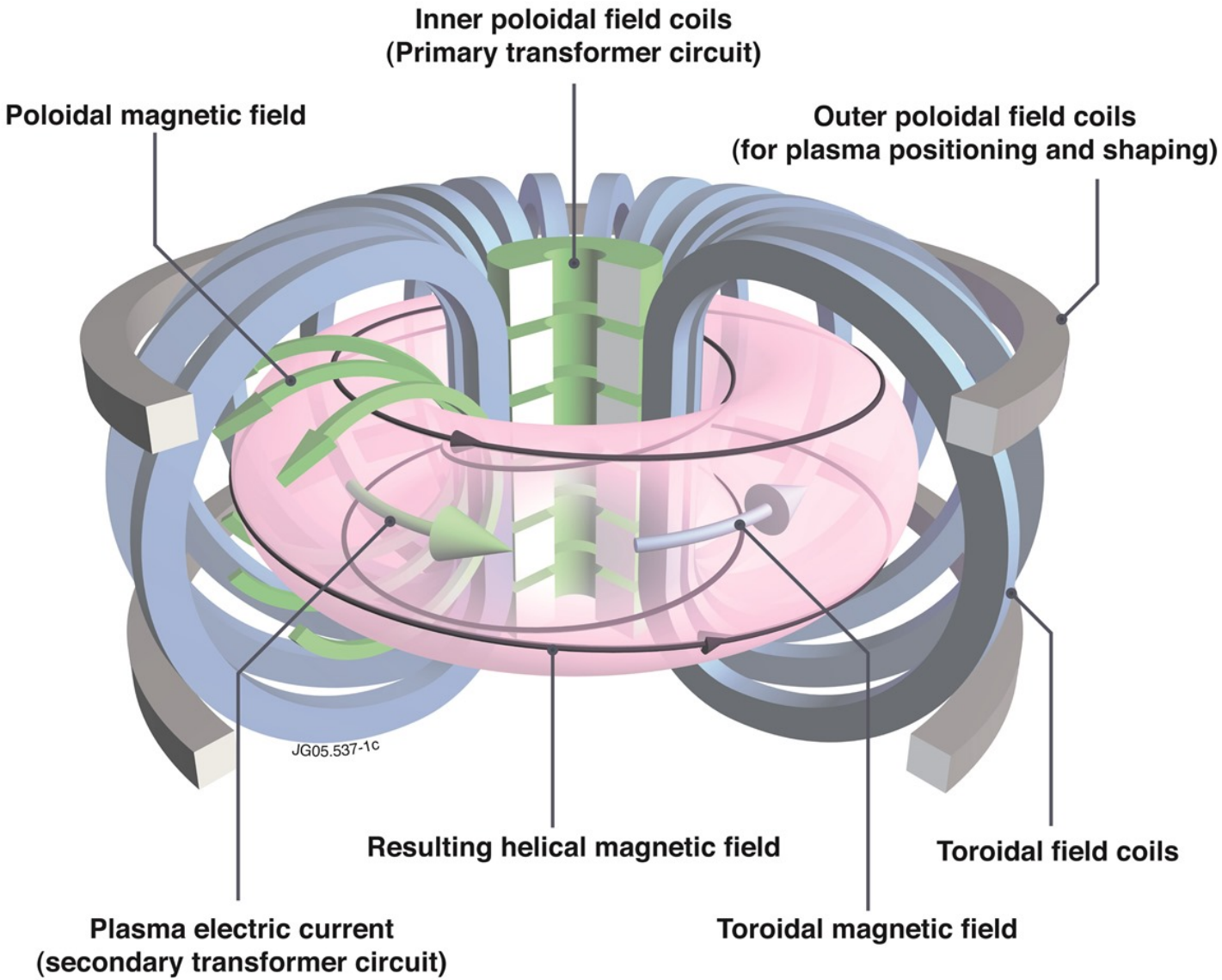
The global schematic overview of the GOLEM experiment



The GOLEM tokamak mission

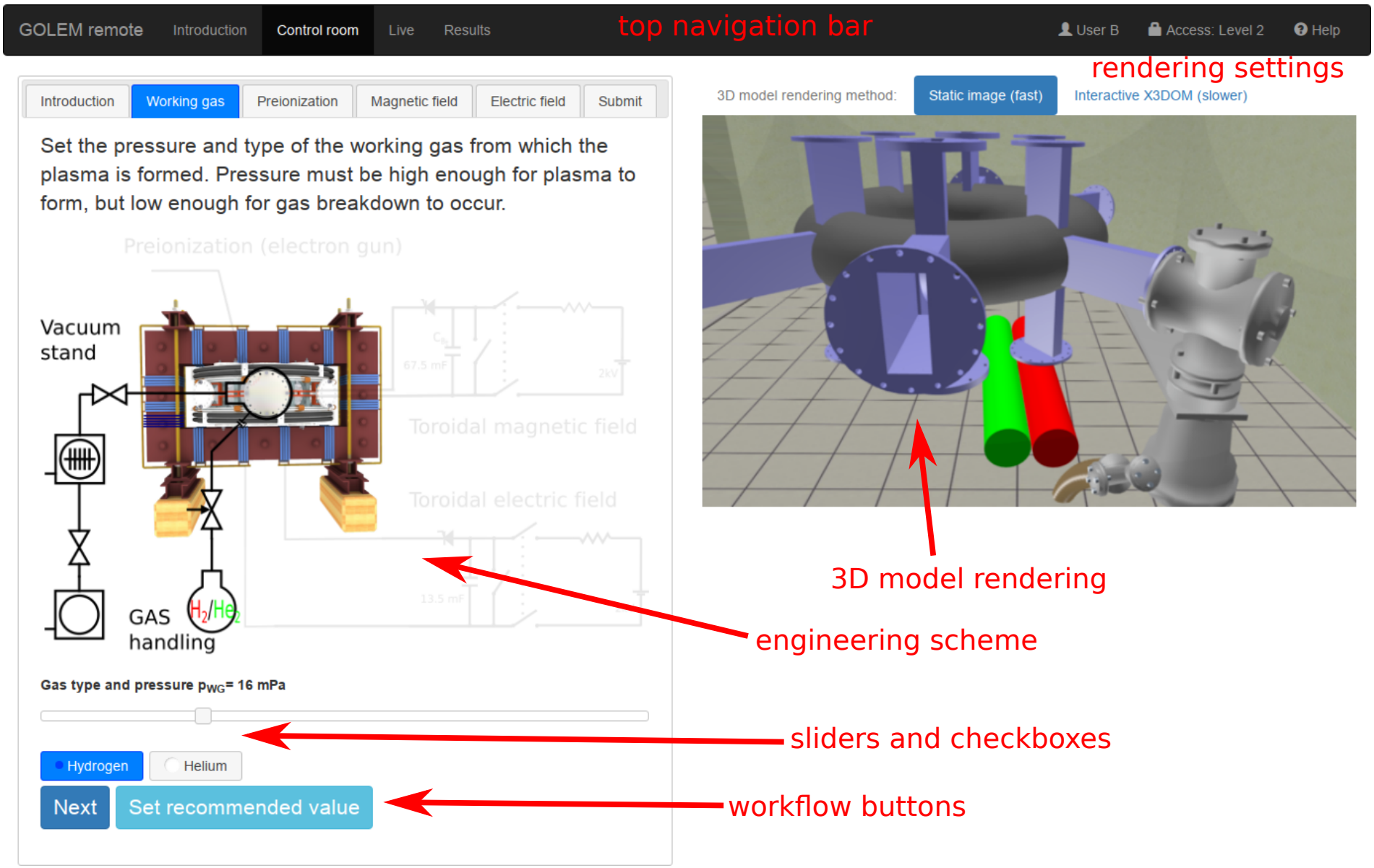


Tokamak magnetic confinement concept



credit:Tokamak concept@Wiki

Remote control interface of the GOLEM tokamak



Shot homepage (≈ 2 minutes after discharge execution)

GOLEM » Shot #40631 »

autoreload: prev

Diagnostics
- BasicDiagnostics
- DoubleRakeProbe
- Interferometry
- LimiterMirnovCoils
- ScintillationProbes

Other
- Wiki
- "Showroom"

Navigation
- Next
- Previous
- Current

Go to shot
40631 Go

Golem utils
- Home
- Plot data
- Shot interval plot
- Manipulators control

Database operations
- Shots listing
- Shots filtering

Tokamak GOLEM - Shot Database - #40631

[Shot logbook]

The date of discharge execution	23-02-07 17:23:54
The session mission	1Final --> Dirigent service
The session ID	40605
The discharge comment	Rake probe 56mm
Discharge command	./Dirigent.sh --discharge --UBt 800 --TBt 0 --Ucd 450 --Tcd 500 --preionization 1 --gas H --pressure 15 --diagnostics.limitermirnovcoils "vacuum_shot=40619" --discharge.preionization "main_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 40629" --comment "Rake probe 56mm"

Technological parameters

- Working Gas: $p_{\text{chamber}}^{\text{discharge,before}}$=2.46 mPa; $p_{\text{chamber}}^{\text{discharge,pre}}$=5.04 mPa ($p_{\text{WG}}^{\text{request}}$= 15 mPa@$X_{\text{WG}}^{\text{request}}$=H)
- Toroidal magnetic field: $U_{\text{B}_\text{t}}^{\text{request}}$=800 V@$t_{\text{B}_\text{t}}^{\text{request}}$=0.0 us
- Current drive field: $U_{\text{E}_\text{cd}}^{\text{request}}$=450 V@$t_{\text{cd}}^{\text{request}}$=500.0 us

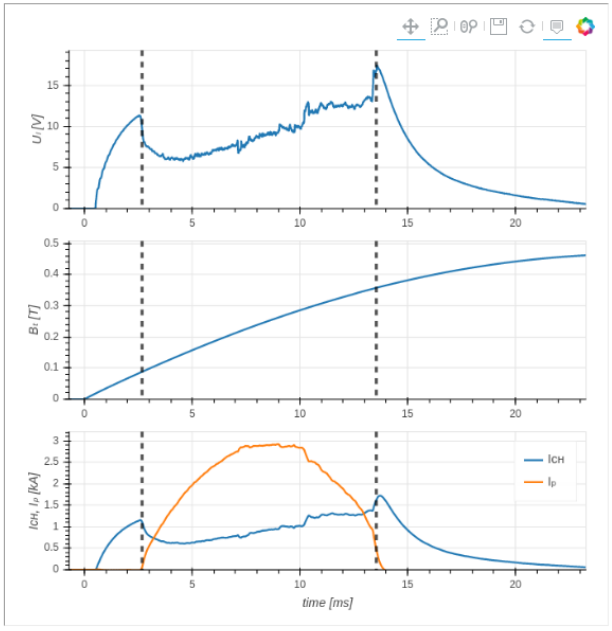
Plasma:

- Plasma: yes or no: ☑
- Time parameters:Δt_{p}=10.88 ms (from:t_{start}=2.67 ms,to:t_{end}=13.54 ms)

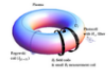
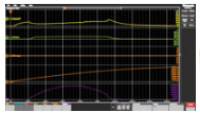
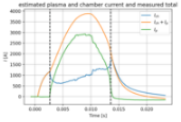
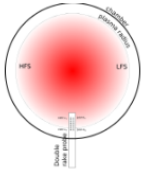
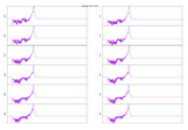
Plasma parameters:

- Loop voltage:$\overline{U_{\text{loop}}}$=8.82 V; $max_{\tau\in[discharge]}U_{\text{loop}}$=16.17 V; $U_{\text{breakdown}}$=0.00 V
- Toroidal magnetic field: $\overline{B_{\text{t}}}$=0.24 T; $\max_{\tau\in[discharge]} B_{\text{t}}$=0.36 T
- Plasma current: $\overline{I_{\text{p}}}$=2.28 kA; $\max_{\tau\in[discharge]} I_{\text{p}}$=2.92 kA; $t_{\text{Ip}}^{\max}$=0.00 ms

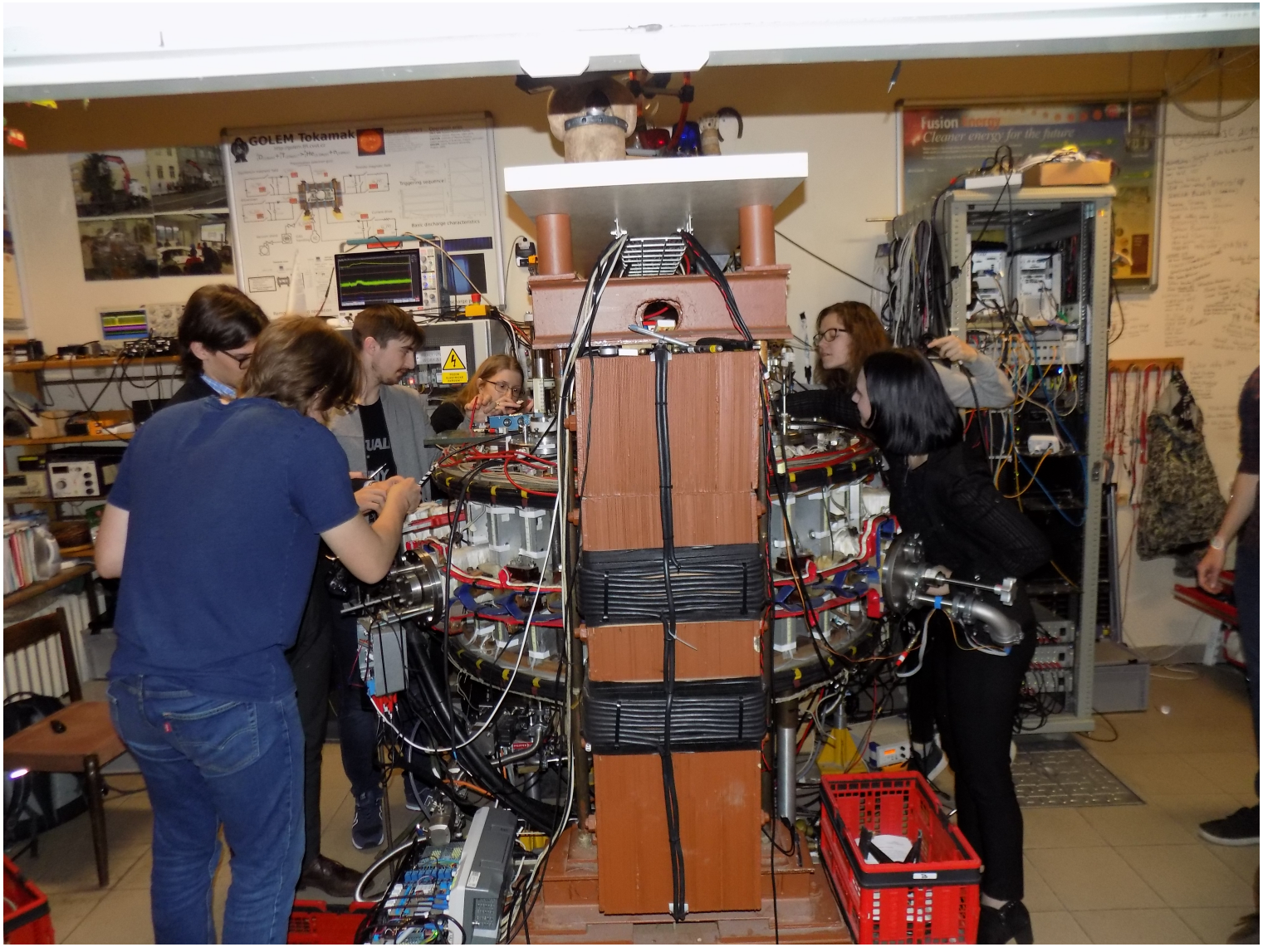
Basic Diagnostics



On stage diagnostics

Data flow	*measurement →*	*digitization →*	*analysis →*	
Name	**Experiment setup**	**Data acquisition system**	**Raw data**	**Analysis results**
Basic Diagnostics				
Double rake probe @ SouthEastBottom port				**Without Analysis**

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 $\approx$ 8000 km from Prague)

Remote education: Data analysis ..

Remote education: Presentations the day after ..

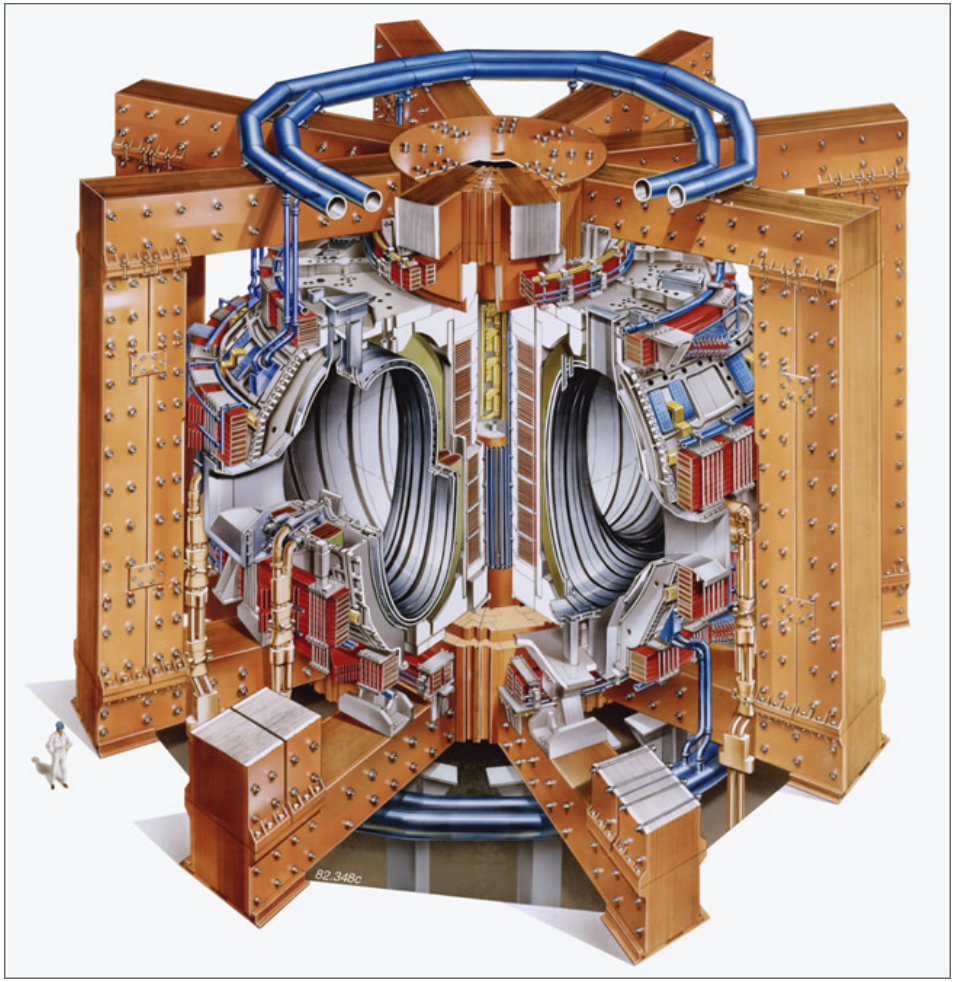
Tokamak GOLEM - vzdálené řízení: 2009-2019 inventura

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

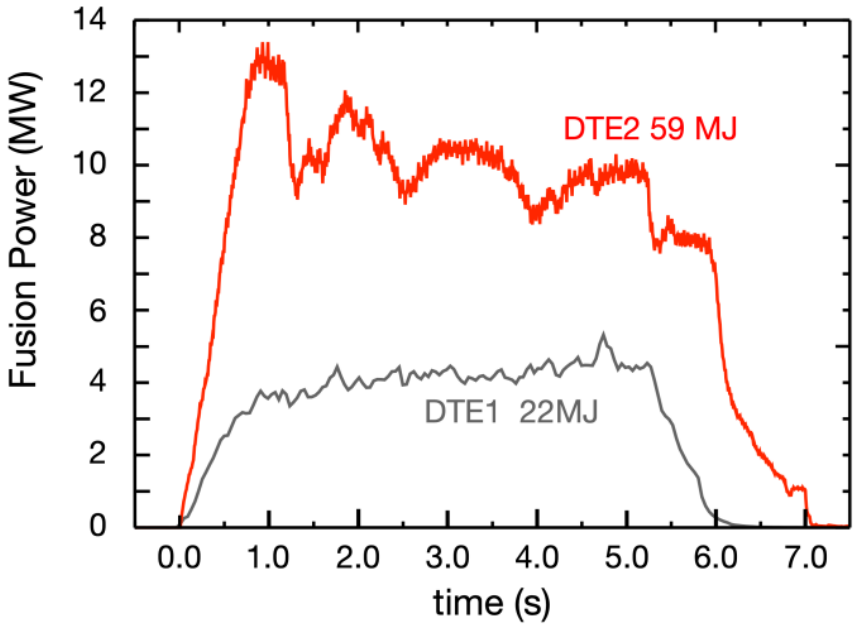
- Demonstrace: Ghent University 09; Bochum University 13; Garching 13; Lemvig High School 14; Instituto Tecnologico Costa Rica 10; Armidale University 17.
- Zimní a letní školy: French Training Course & EM 12-14,16-19; Bangkok 16-19; TU Eindhoven 11,15-19;TU Kobehaven 14,15,18;Grenoble TU 15, University of Belgrade 15-18; BUTE Budapest 10,12-18; University of Padova 14,16,18; TU Torino 16-18, St. Peterburg University 18-19. Kharkov University 19
- Pracovní semináře Kiten: 14,16-18; Observatorium Valasske Mezirici 14; Islamabad

Poplatek: pohlednice z místa vzdáleného řízení

1997: Světový fúzní rekord @ JET (EU)

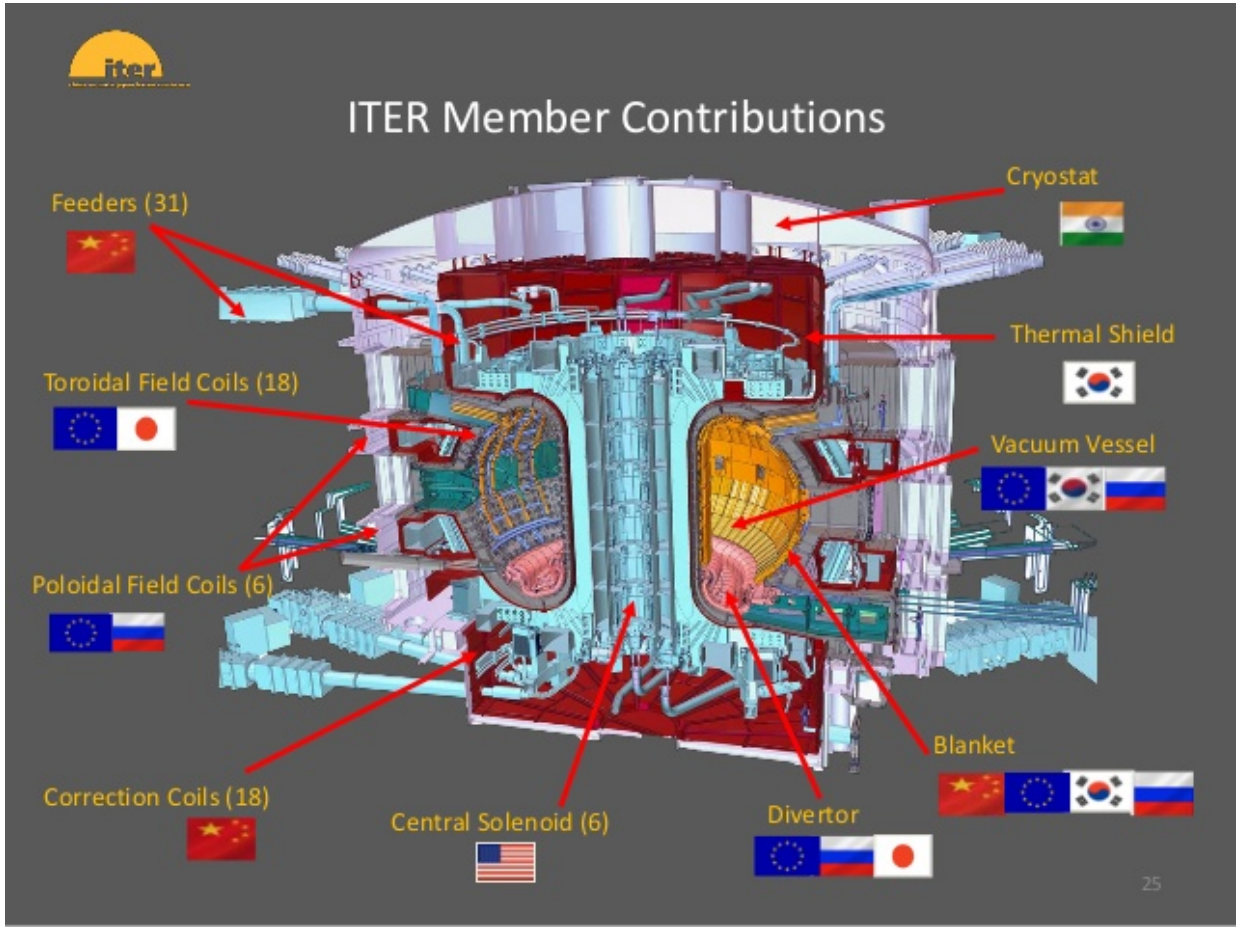


output comparison 1997 and 2021.png



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

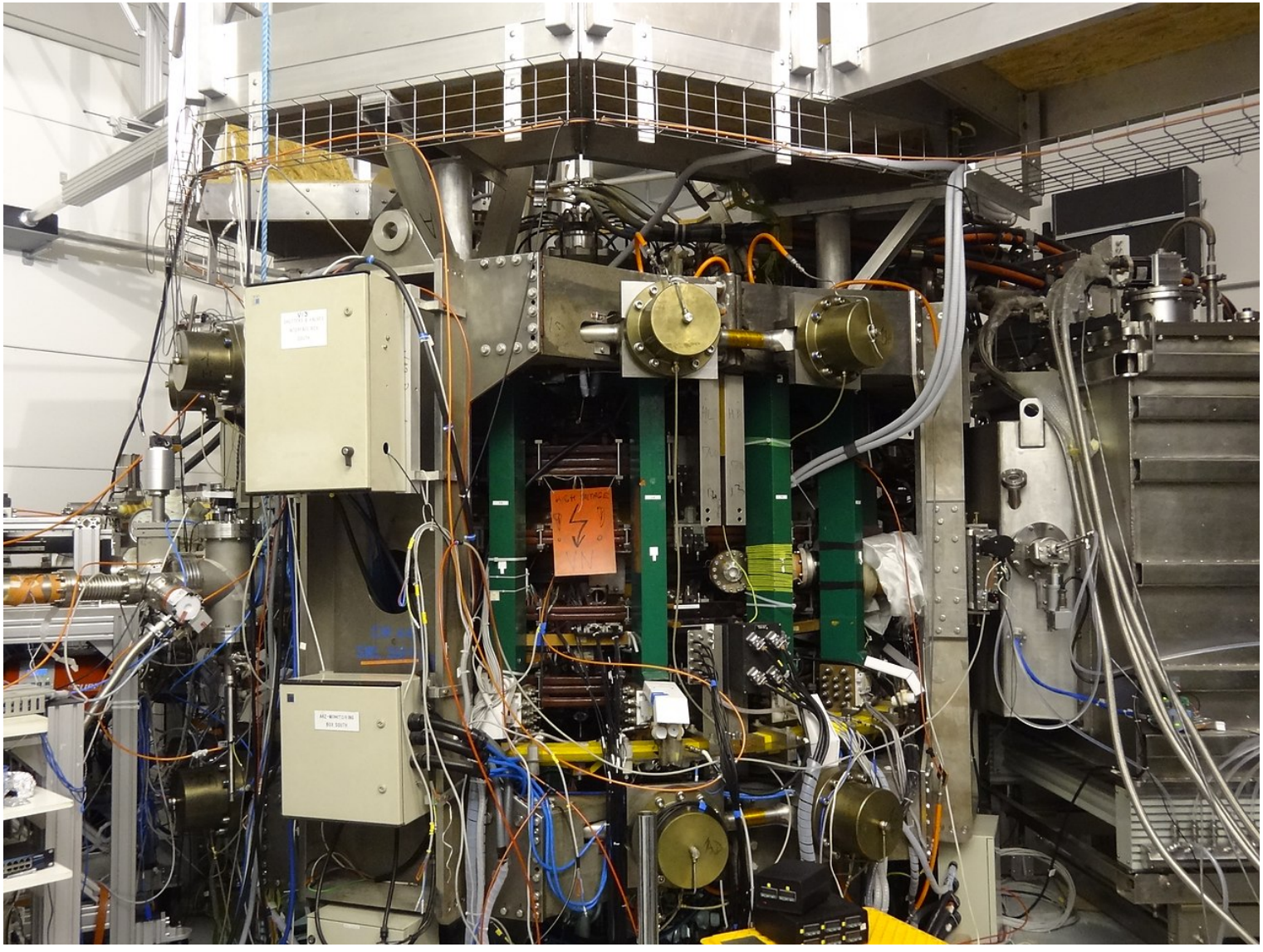
ITER (jižní Francie) $\approx$ 18 miliard EUR



Mise:

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

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



Acknowledgement

Financial support highly appreciated:

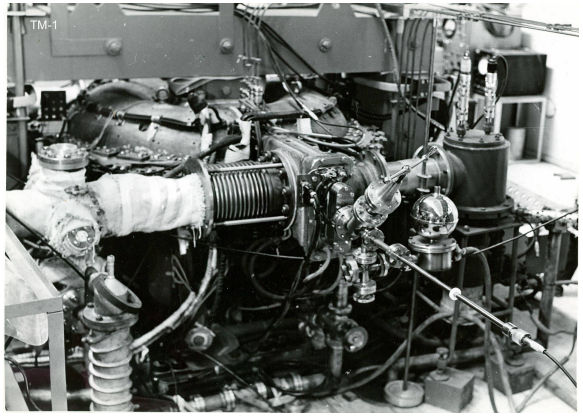
CTU RVO68407700, SGS 17/138/OHK4/2T/14, GAČR GA18-02482S, EU funds CZ.02.1.01/0.0/0.0/16_019/0000778 and CZ.02.2.69/0.0/0.0/16_027/0008465, IAEA F13019, FUSENET and EUROFUSION.

Students, teachers, technicians (random order):

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

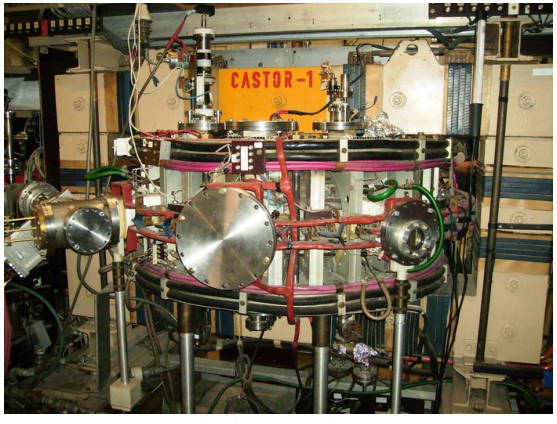
Thank you for your attention

Tokamak TM1
@Kurchatov Institute near Moscow
~1960-1977



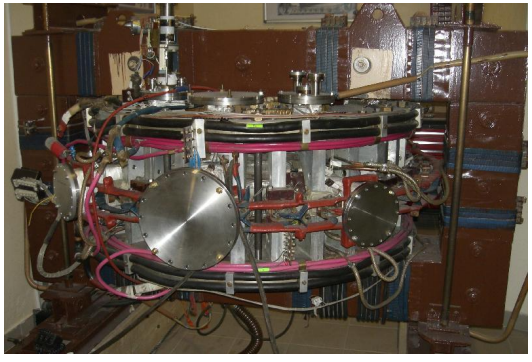
SCIENCE

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



SCIENCE
& education

Tokamak GOLEM
@Czech Technical University, Prague
2007-



EDUCATION
& science

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