Title

Spoutání energie hvězd v pozemských podmínkách

Vojtěch Svoboda

Pokročilejší popularizační přednáška

October 24, 2024

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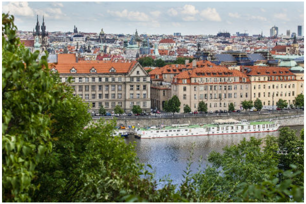
Fakulta jaderná a fyzikálně inženýrská (FJFI)
České vysoké učení technické v Praze



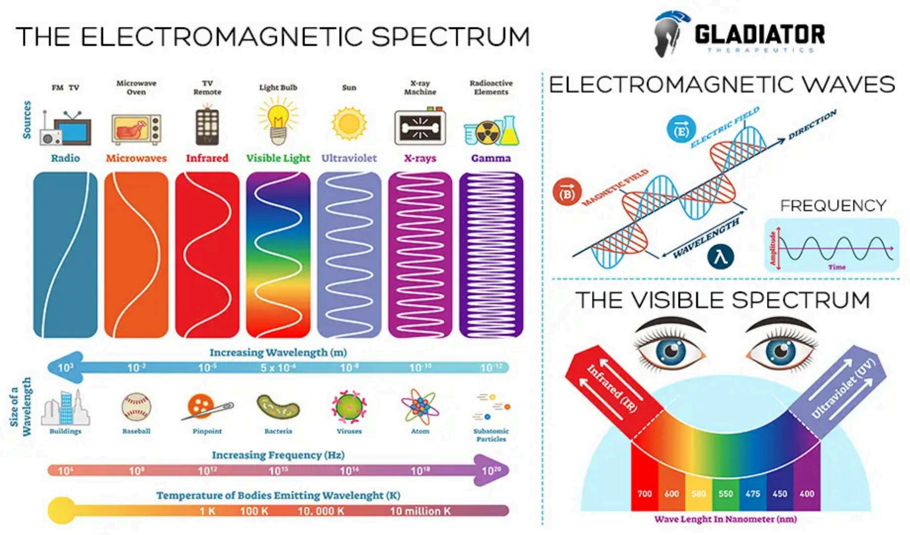
Hlavní budova FJFI v Praze - Břehová

insignie FJFI

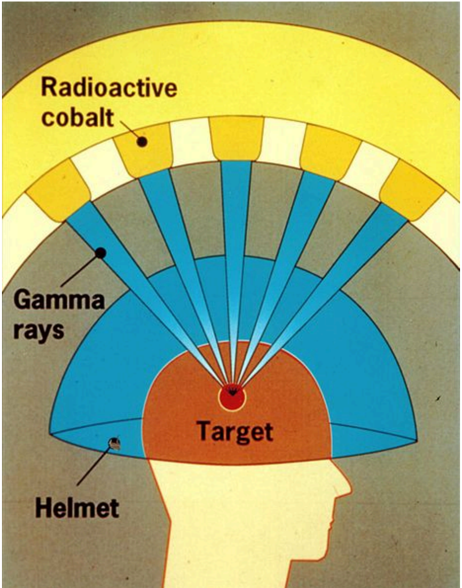
Betlémská kaple - slavnostní síň ČVUT

- 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.

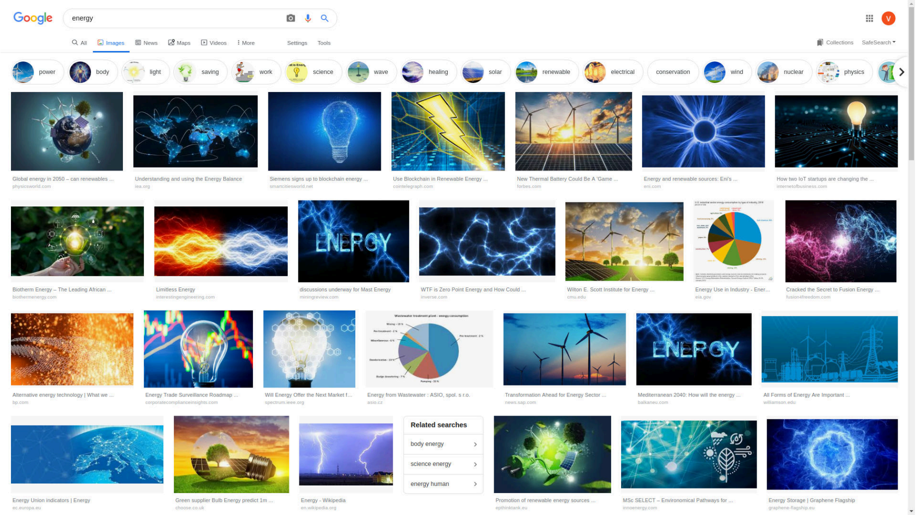
Aplikované přírodní vědy - Elektřina a magnetismus



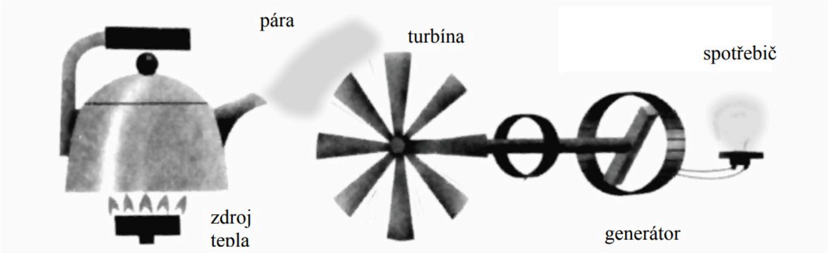
Aplikované přírodní vědy - Leksellův Gamma nůž



Google: Energy
About 2,950,000,000 results (0.60 seconds)



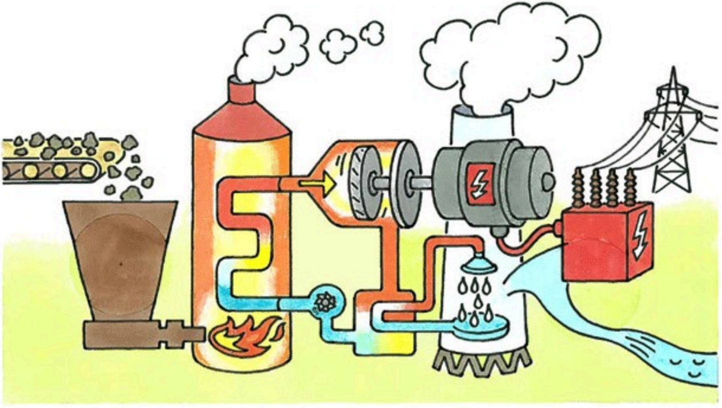
Základní princip tepelné elektrárny



Základní otázka zní:

?? Čím topit ??

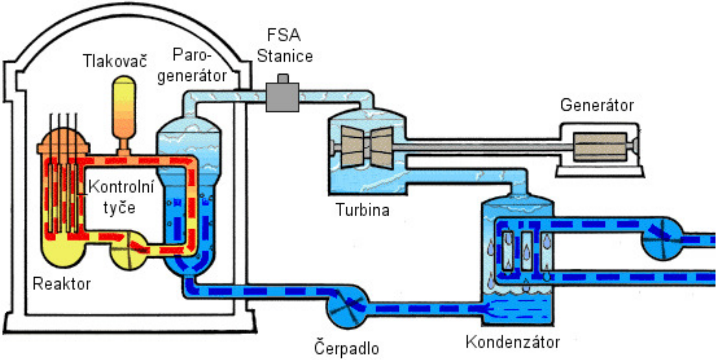
Uhelná elektrárna



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

Emise

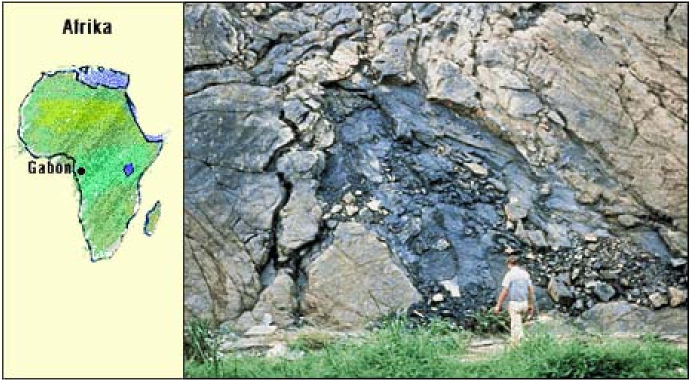
Jaderná elektrárna - štěpná



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

Dotáhnout technologii: Suroviny, Odpad, Bezpečnost

Aplikované přírodní vědy - přírodní reaktor Oklo



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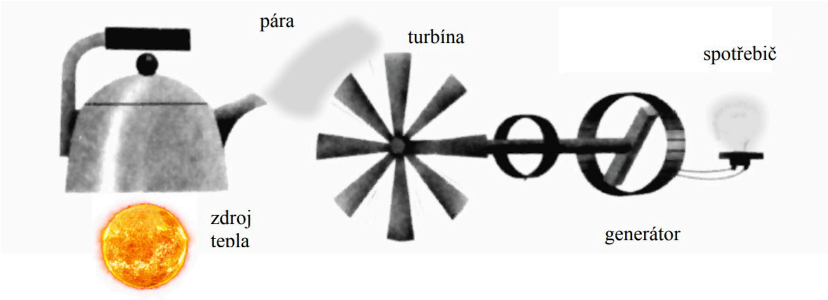
Topit malým Sluncem/hvězdou ??



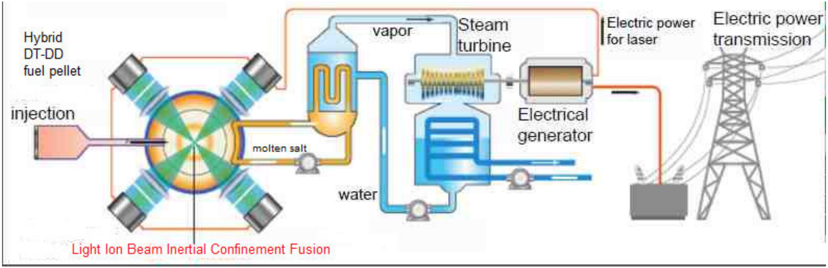
Výzva

1952 "Operation Ivy - Mike" První test vodíkové bomby

credit:YouTube:Ivy Mike Countdown and detonation

Toto není vhodná technologie

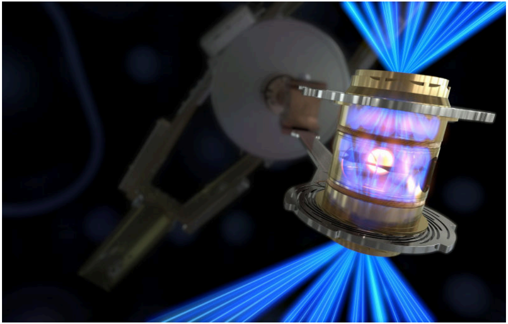
Inerciální fúze



credit:mext.jp

Velká výzva

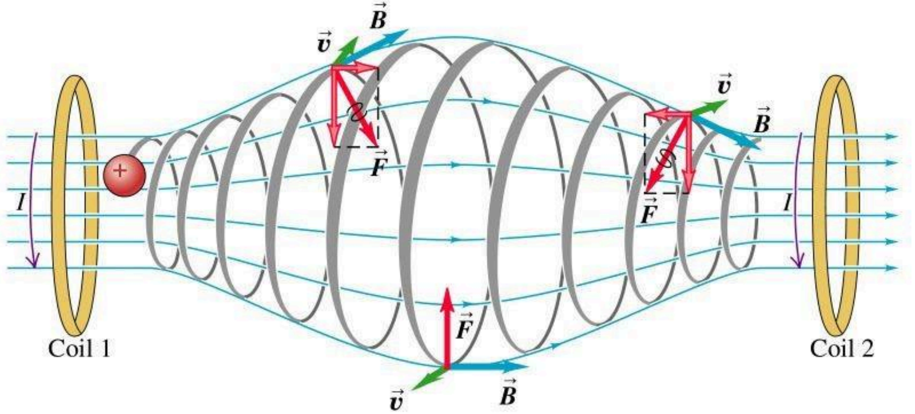
NIF@LLNL 12/22



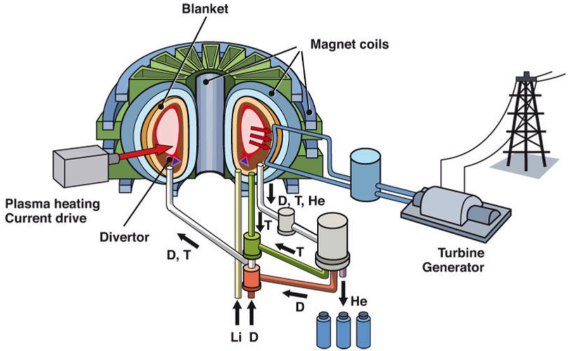
Zážeh (ignition)

Vyprodukování více ≈ 150 % energie z fúze (3.15 MJ), než kolik bylo zapotřebí energie v podobě laserového impulzu (2.05 MJ) do experimentu dodat.

Magnetic confinement: magnetic bottle



Vize: Jaderná elektrárna - slučovací/fúzní

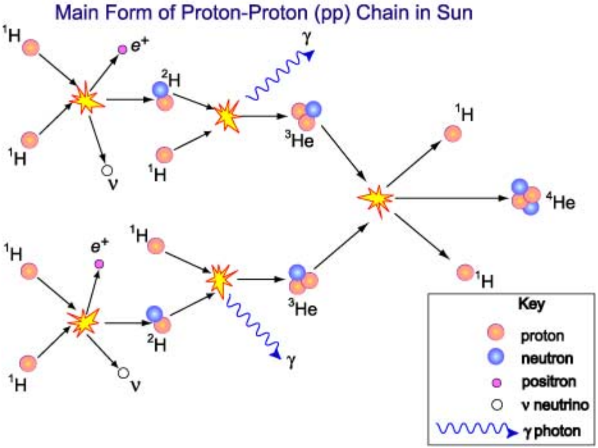


credit: Max-Planck-Institute

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

Vypiplat technologii

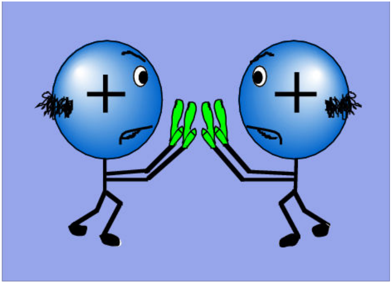
Inspirace: Slunce - protonový řetězec



credit:CSIRO

$$4\ {}^1_1\mathbf{p} \Rightarrow {}^4_2\,\mathbf{He} + 2\ \mathbf{e}^+ + 2\ \nu_\mathbf{e} + 2\ \gamma + 26.73\ \mathbf{MeV}$$

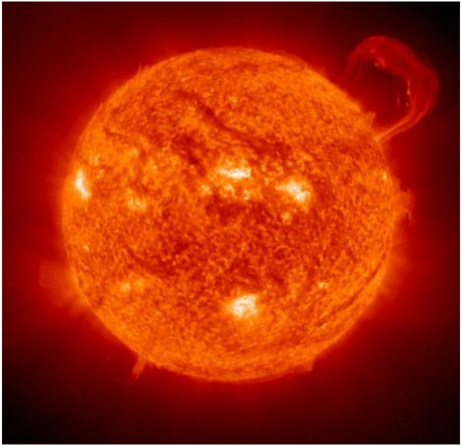
Proč tak obrovské teploty?



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

$${}_1^2\mathbf{D}_{(\mathbf{10keV})} + {}_1^3\,\mathbf{T}_{(\mathbf{10keV})} \Rightarrow {}_2^4\,\mathbf{He}_{(\mathbf{3.5MeV})} + \mathbf{n}_{(\mathbf{14.1MeV})}$$

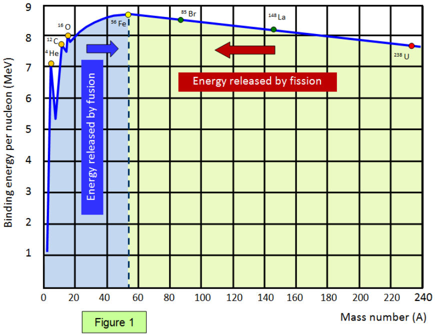
Star burning stages

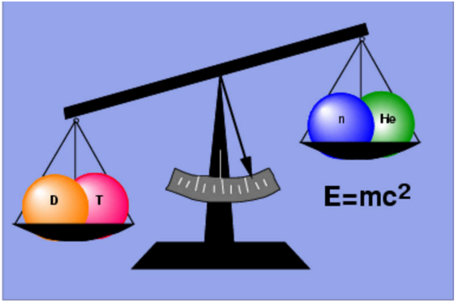


Core Burning Stages in a 25 Solar Mass Star:

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

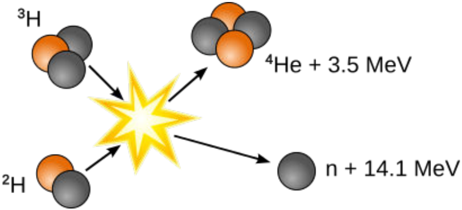




fúze lehkých jader X štěpení těžkých jader

$^{2}D + {}^{3}T \Rightarrow {}^{4}He + {}^{1}n + 17.6 MeV$ X $^{235}U + n_{thermal} \Rightarrow {}^{89}Kr + {}^{144}Ba + 3n + 176 MeV$

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



credit: Wikipedia contributors

$$^2_1\mathbf{H}_{10\ \mathbf{keV}} + {}^3_1\mathbf{H}_{10\ \mathbf{keV}} \Rightarrow {}^4_2\mathbf{He}_{3.5\ \mathbf{MeV}} + {}^1_0\mathbf{n}_{14.1\ \mathbf{MeV}}$$

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

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

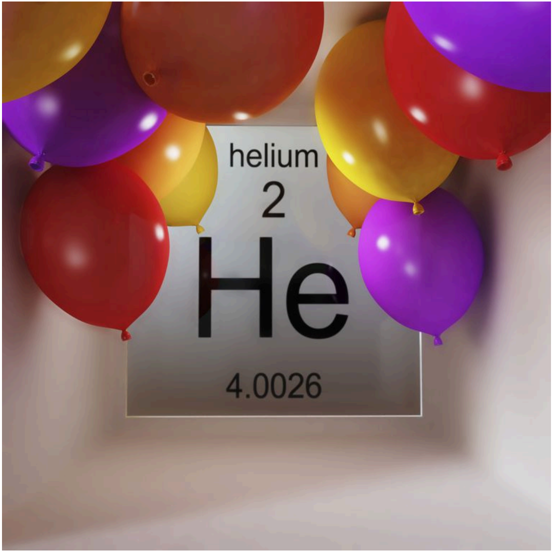
pak hmotnostní schodek $\Delta m = 0.01888 m_u$.

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

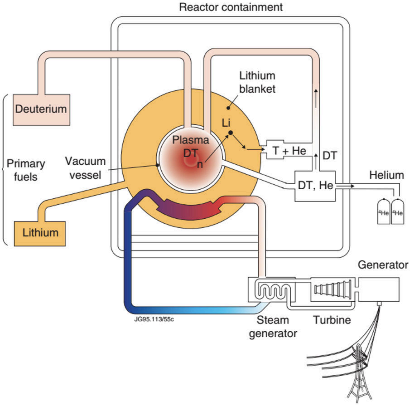
$$1\mathrm{eV} \sim 11600°\mathrm{C} \approx\ {}^2_1\mathbf{H}_{100\ \mathbf{M°C}} + {}^3_1\mathbf{H}_{100\ \mathbf{M°C}} \Rightarrow {}^4_2\mathbf{He}_{35\ \mathbf{G°C}} + {}^1_0\mathbf{n}_{141\ \mathbf{G°C}}$$

Palivo: IAEA "Natural water"

Odpad

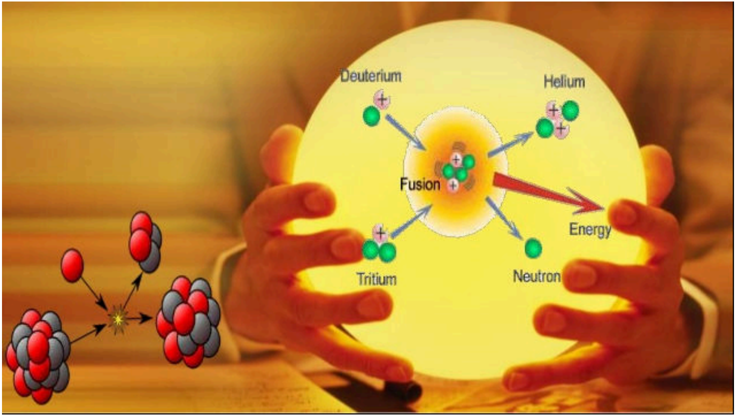


Bezpečnost



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

Hledá se vhodná fúzní technologie

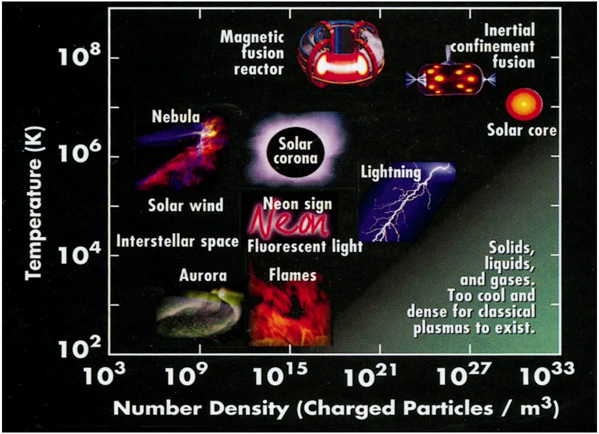


Podmínky:

Zahřát na $\sim$ 100 000 000 °C & **udržet** po dobu $\sim$ 30 let + konkurenceschopnost

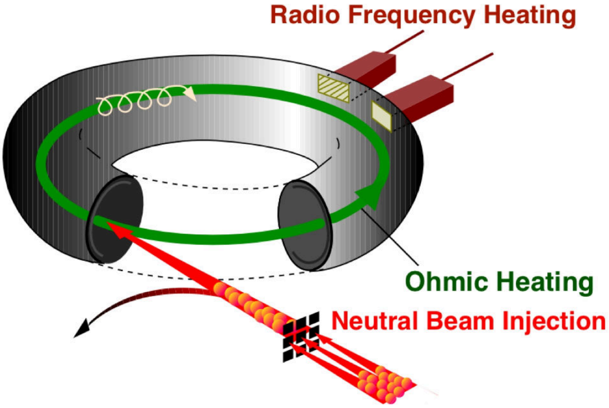
Badatelská skupina / studijní specializace

Fyzika plazmatu a termojaderné fúze



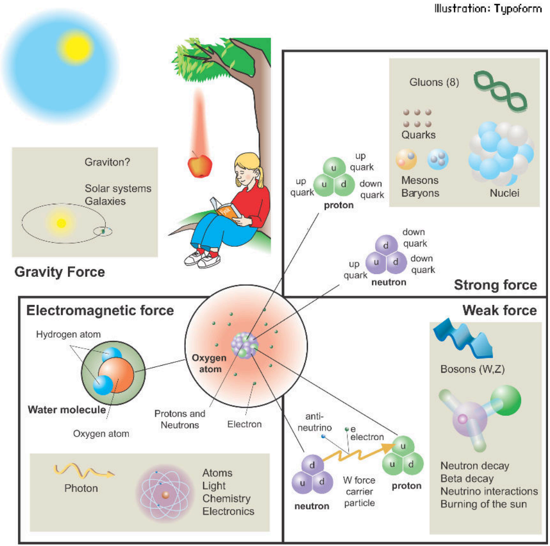
99.999 % Vesmíru je v plazmatickém stavu

Ohřev plazmatu

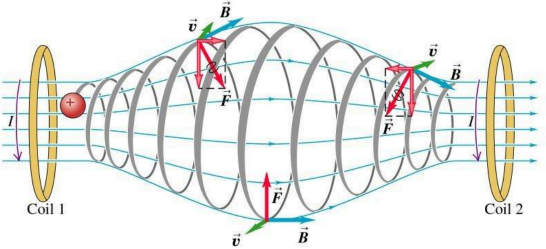


credit: Eurofusion

Fundamental forces (to confine?)



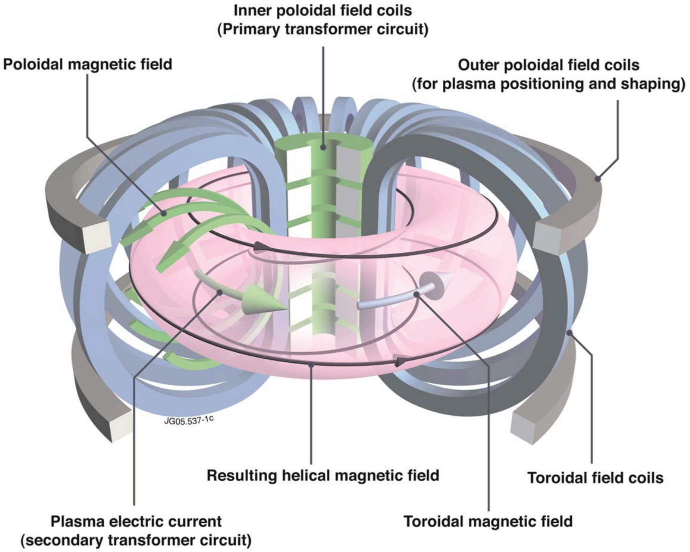
Magnetické udržení: magnetická nádoba



Musíme ji ale svinout do kruhu (zbavit se podstav)

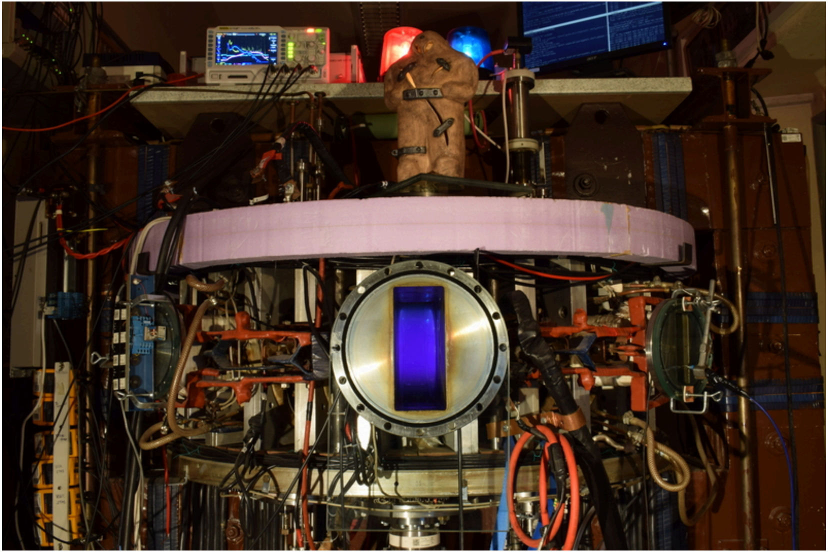
záchranný kruh/duše pneumatiky/donut

Tokamak magnetic confinement concept

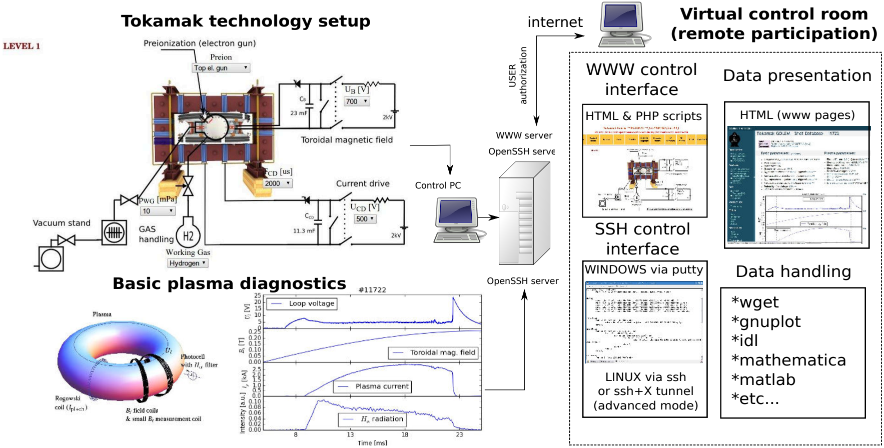


credit:Tokamak concept@Wiki

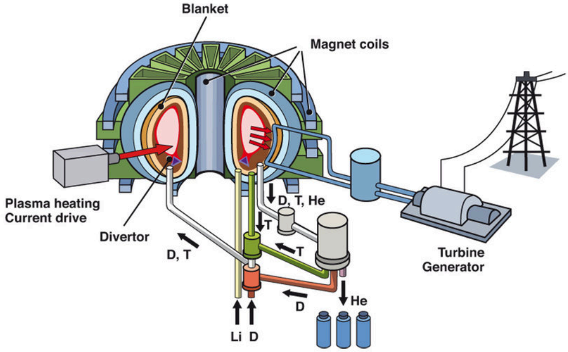
Let's make a discharge



The global schematic overview of the GOLEM experiment



Vision: Nuclear power plant – a fusion one

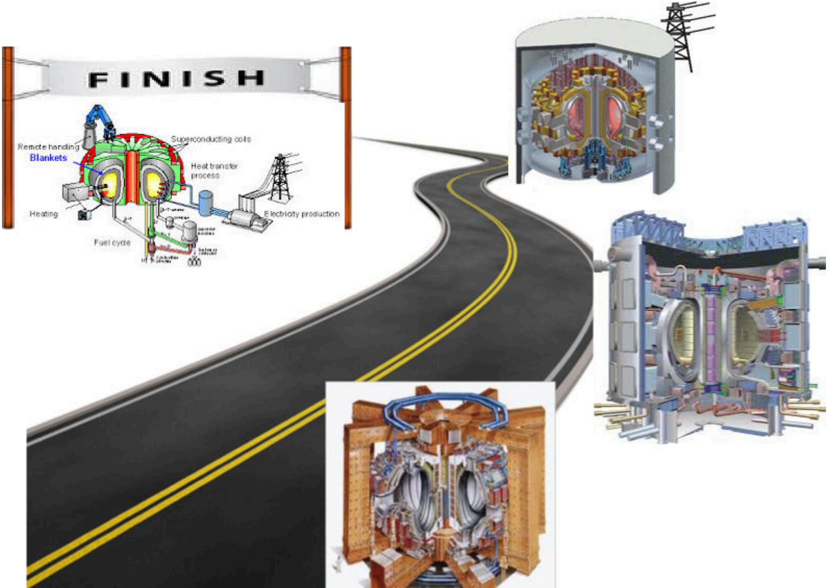


credit: Max-Planck-Institute

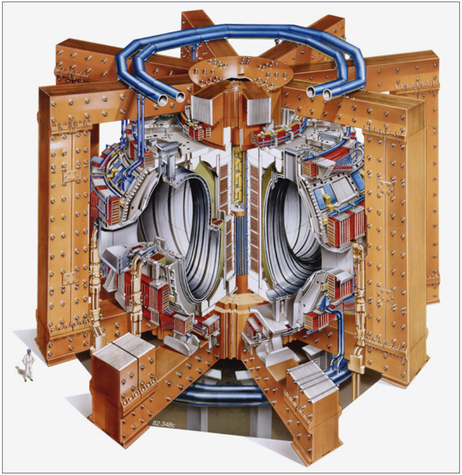
Prague (~ 1 GW): yearly $\sim$ a van of D–T mixture

Master the Technology

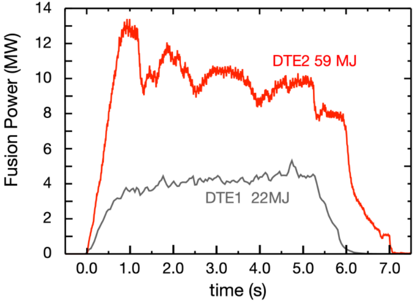
Milestones to Fusion Power Plant



1997: Světový fúzní rekord @ JET (EU)



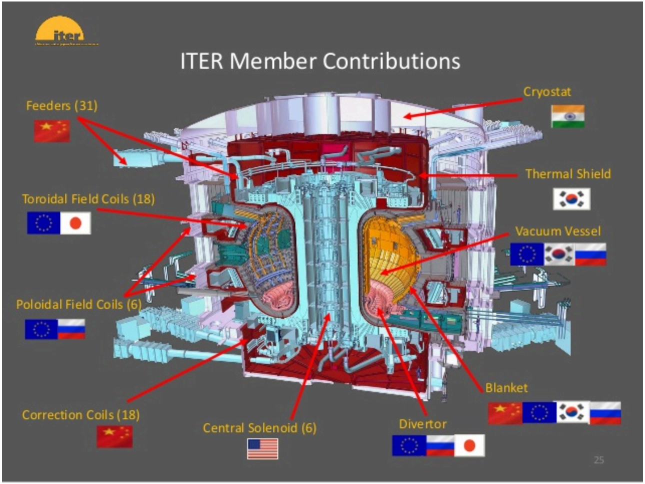
output comparison 1997 and 2021.png



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 ≈ 17 billion euros



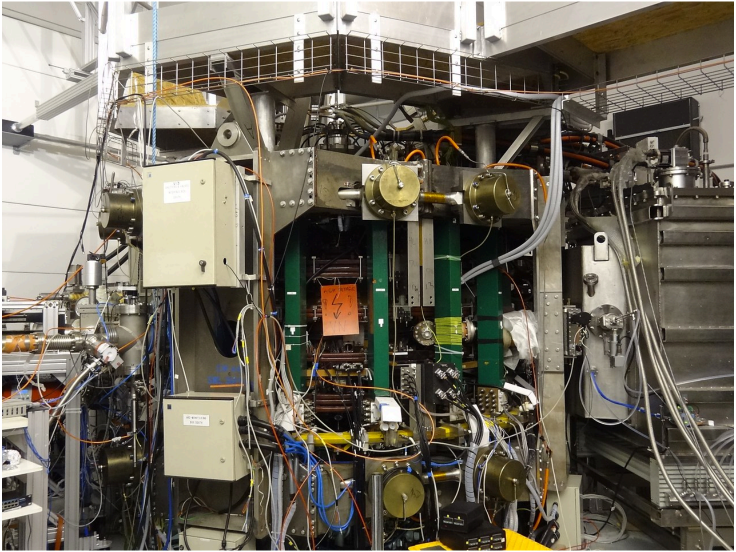
- Fusion power 0.5 GW for 10 min.
- $Q = 10$.
- Feasibility.

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 vyměna první stěny z beryllia na wolfram, znásobení mikrovlnného ohřevu plazmatu.

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



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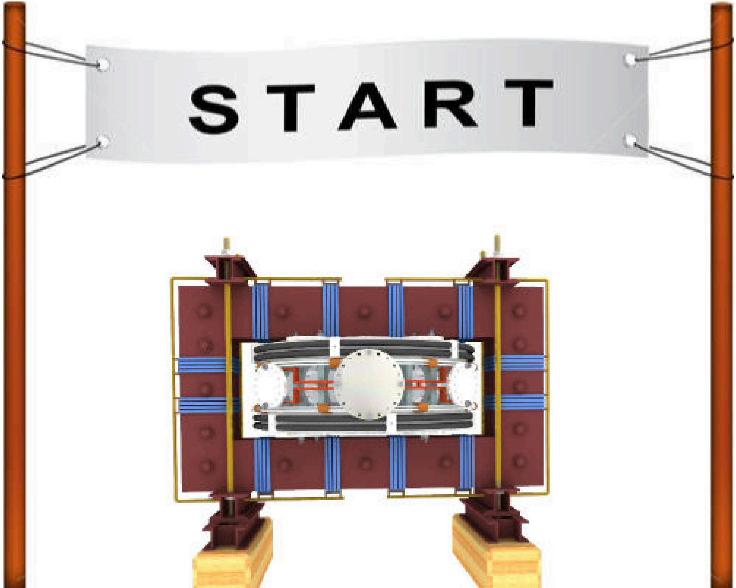
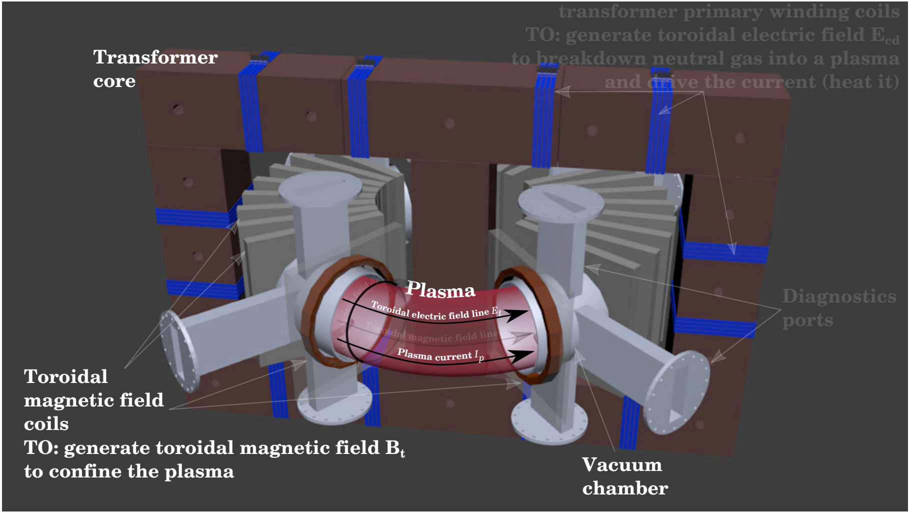
Education importance

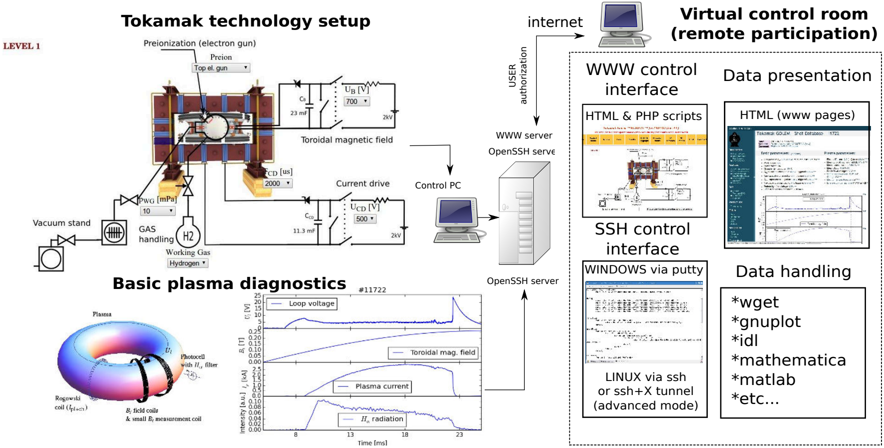
Let's start with the tokamak GOLEM - *the smallest tokamak in the World with the biggest controll room*



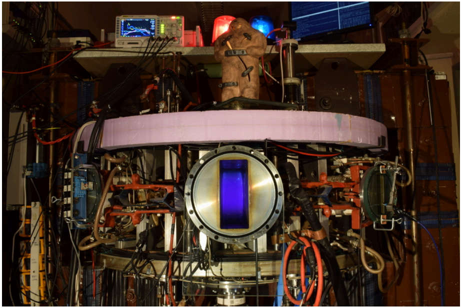
Tokamak (GOLEM) basic concept to confine and heat the plasma



The global schematic overview of the GOLEM experiment

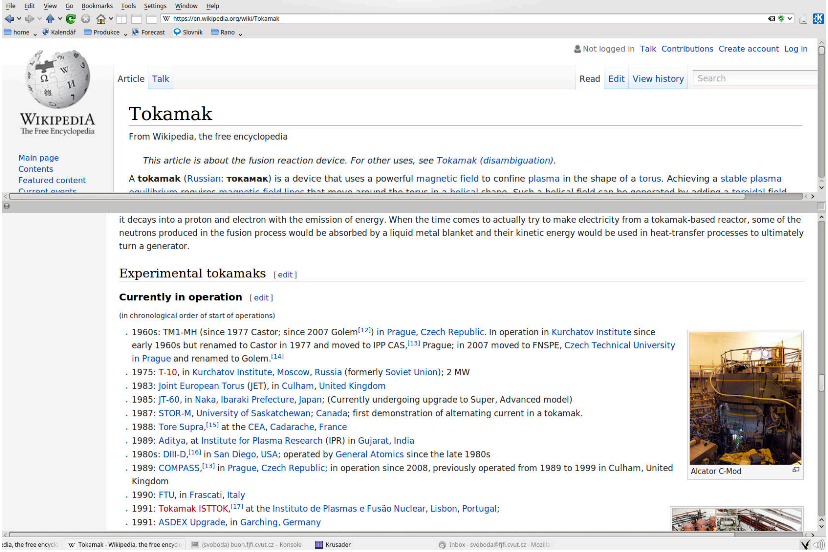


The GOLEM tokamak basic characteristics
The grandfather of all tokamaks (ITER newsline 06/18)



- 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 ..



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

home Kalendář Produkce Forecast Slovnik Rano

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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

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)

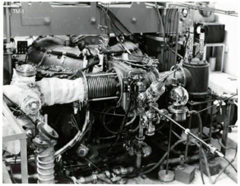
- 1960s: TM1-MH (since 1977 Castor; since 2007 Golem[12]) in Prague, Czech Republic. In operation in Kurchatov Institute since early 1960s but renamed to Castor in 1977 and moved to IPP CAS,[13] Prague; in 2007 moved to FNSPE, Czech Technical University in Prague and renamed to Golem.[14]
- 1975: T-10, 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**



1974

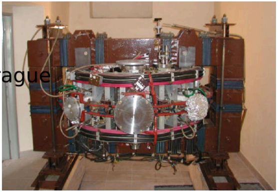
Culham Centre for Fusion Energy
Great Britain
1989: **COMPASS-D**

2006

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

2008

Czech Technical University Prague
Czech republic
GOLEM



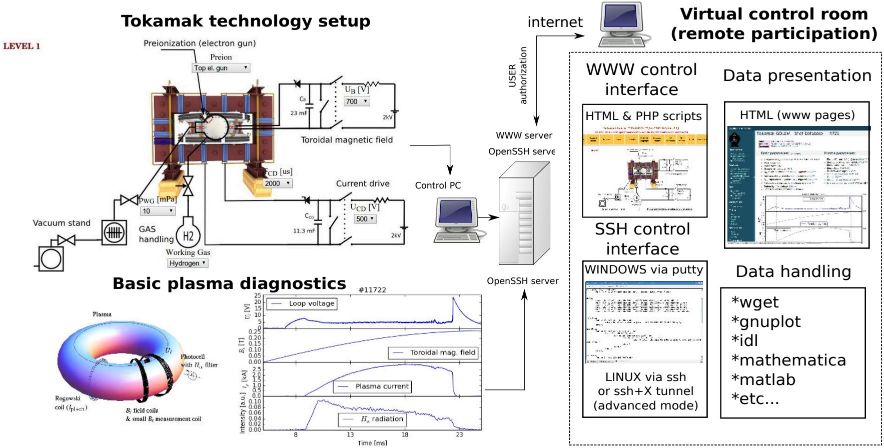
GOLEM

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

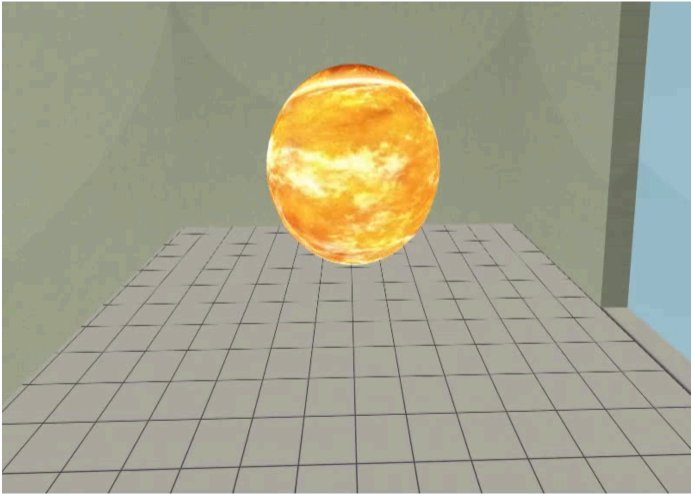
there is hidden indeed "infernal" power. Yet it is the very power of celestial stars themselves. Calmly dormant, awaiting mankind to discover the magic key, to use this power for their benefit...

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. Wikipedia contributors .

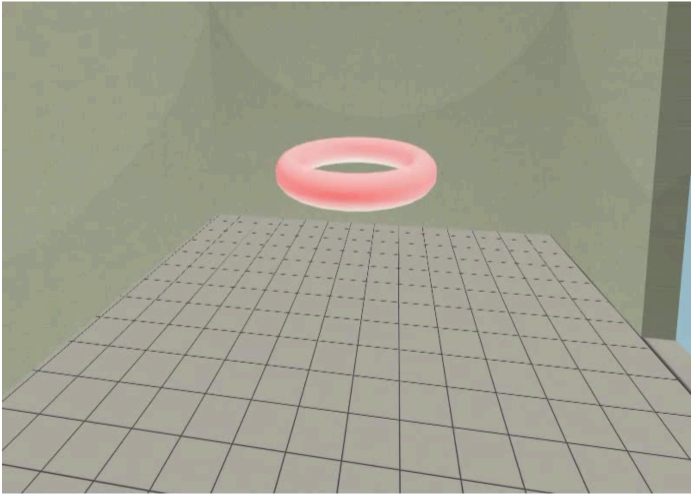
The global schematic overview of the GOLEM experiment



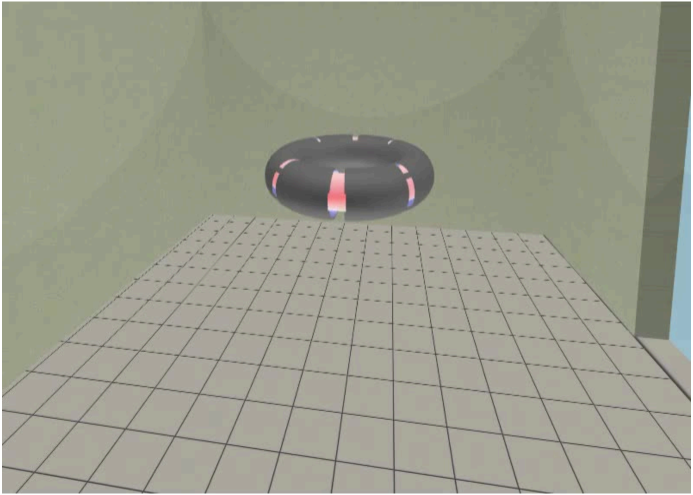
Náš cíl: vytvořit μSlunce v pozemských podmínkách



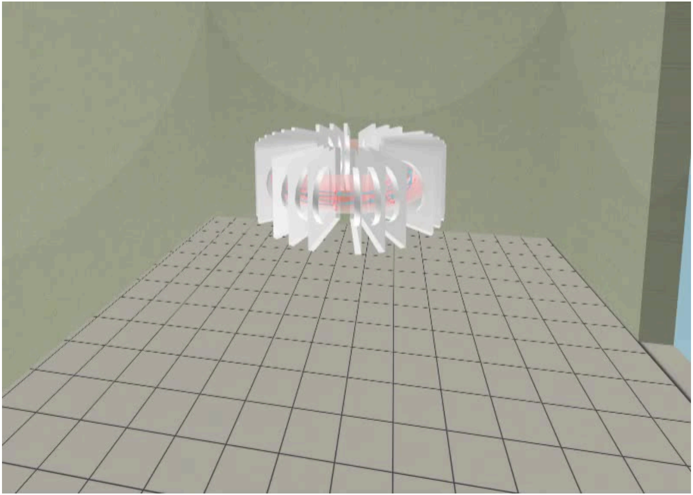
Magnetické udržení vyžaduje toroidální geometrii
Svinutá magnetická nádoba



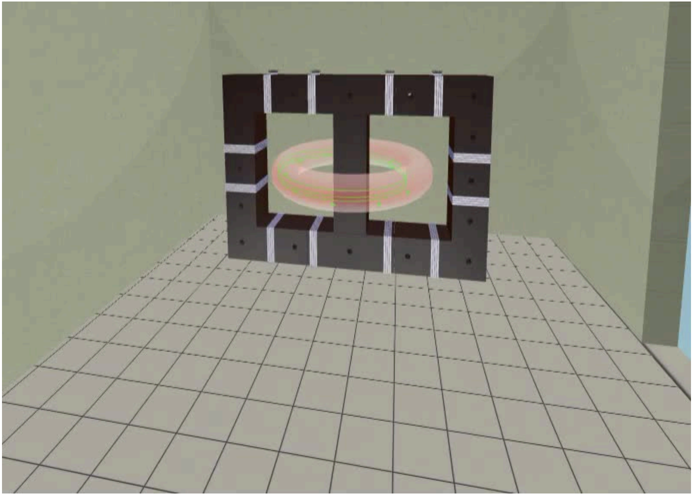
Musíme to celé umístit do reaktorové nádoby - komory



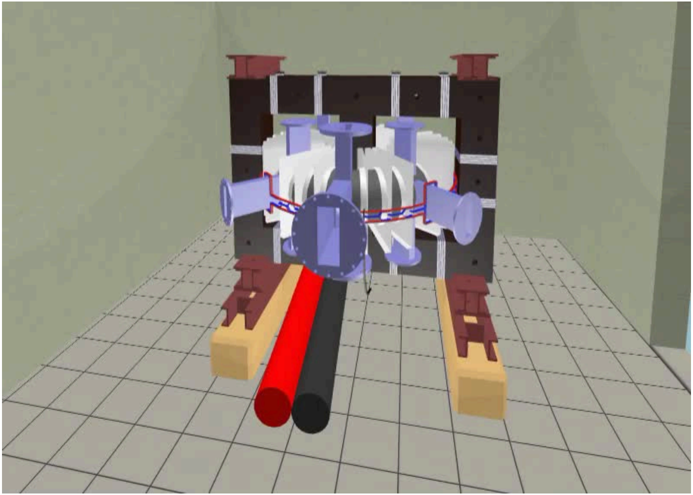
Toroidální magnetické pole udržuje plazma



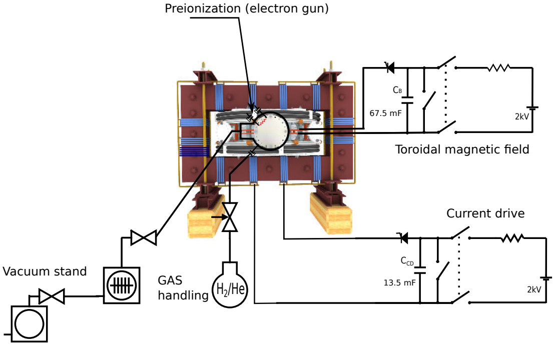
Transformátorová akce vytvoří a zahřeje plazma



Vše dohromady - voilà tokamak



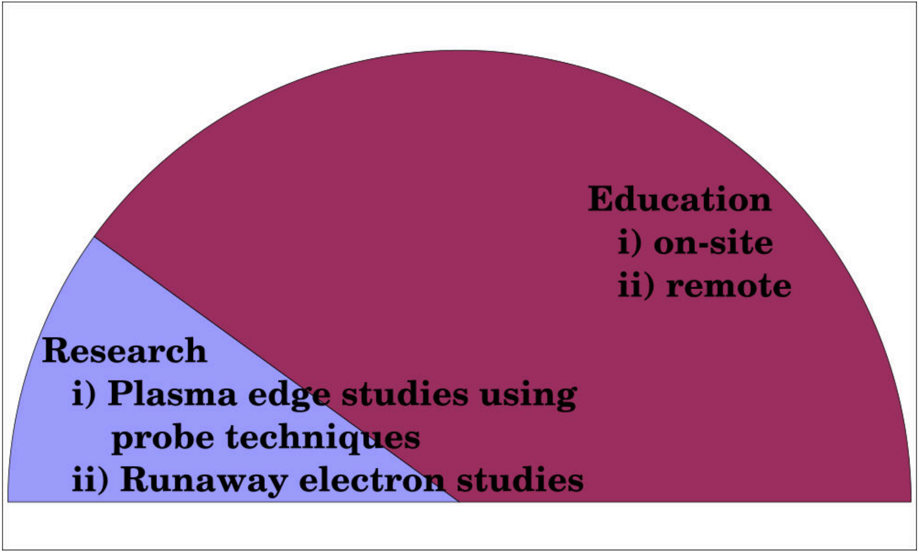
Plasma in Tokamak (GOLEM) - the least to do



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

The GOLEM tokamak mission



Lawson criterion

credit:Lawson criterion @ Wiki Wikipedia contributors

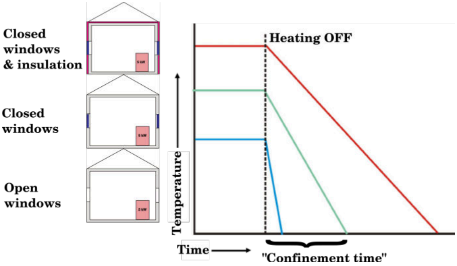
- Net power $=$ Efficiency $\times$ (Fusion - Radiation loss - Conduction loss)
- The confinement time: $\tau_E = \frac{W}{P_{\mathrm{loss}}}$
- Energy density $W = 3nk_{\mathrm{B}}T$ & rate of radiation and conduction energy loss per unit volume P_{loss}
- Reactions per volume per time of fusion reactions is: $f = n_{\mathrm{d}}n_{\mathrm{t}}\langle\sigma v\rangle = \frac{1}{4}n^2\langle\sigma v\rangle$
- Fusion heating fE_{ch}, where $E_{\mathrm{ch}} = 3.5\,\mathrm{MeV}$ should exceeds the losses: $fE_{\mathrm{ch}} \geq P_{\mathrm{loss}}$

$$n\tau_{\mathrm{E}} \geq L \equiv \frac{12}{E_{\mathrm{ch}}}\frac{k_{\mathrm{B}}T}{\langle\sigma v\rangle} \geq 1.5\cdot 10^{20}\frac{\mathrm{s}}{\mathrm{m}^3}$$

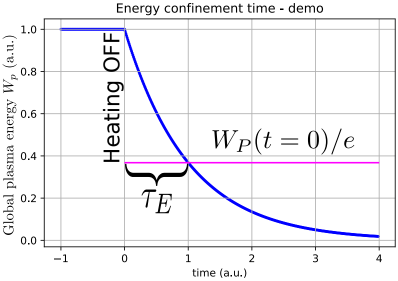
(DT reaction@minimum $\approx$ 26 keV)

Towards ... Energy confinement time

House

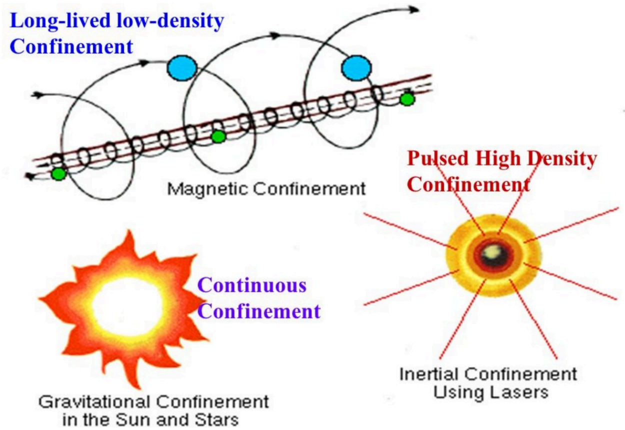


Tokamak

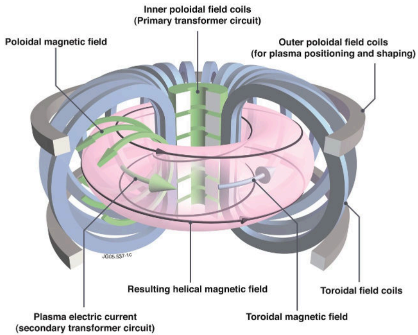


Tři možné cesty jak udržet plazma pro fúzi

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



Runaways electrons - Brief introduction

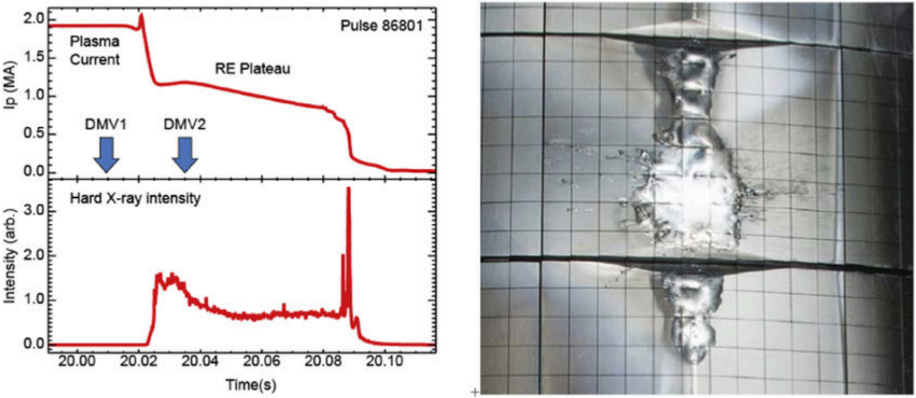


credit: Wikipedia contributors

- Strong guide field generated by toroidal field coils.
- Plasma current induced by transformer coils is needed to establish stable magnetic field configuration

- Each electron is affected by the electric field and by collisions.
- The force of the electric field accelerates the electrons, whereas the friction force decelerate them.
- When the force of the electric field tops the friction force, the electron is accelerated.
- The cross section of collisions falls and the electron achieves almost a speed of light.
- As the electron is accelerated the radius of its trajectory increases.
- The electron emits photons due to synchrotron radiation, bremsstrahlung, collisions with the vessel (most electrons hit the limiter)

Runaway electrons, a brief intro

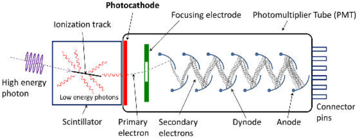


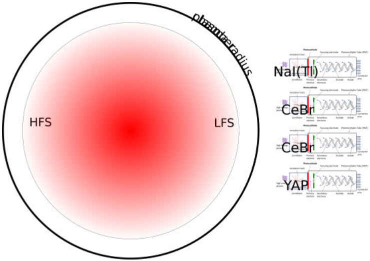
(a) (b)

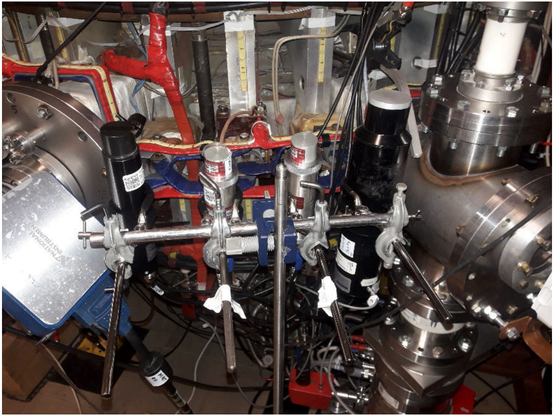
Figure: In-vessel image of melt damage due runaway electrons in JET

Matthews *et al.* 2016 *PhysScr* **T167** 014070

Scintillation probes at the tokamak GOLEM

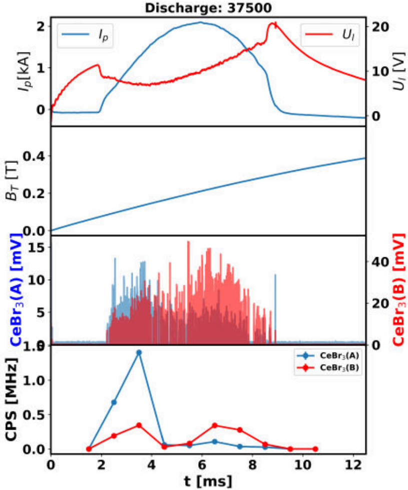






Focus on $CeBr_3$ scintillation crystals with fast decay time (18-25 ns), superior energy resolution (4% FWHM at 662 keV), light yield $\approx$ 60 photons/keV and density ≈ 5.1 g/cm^3.

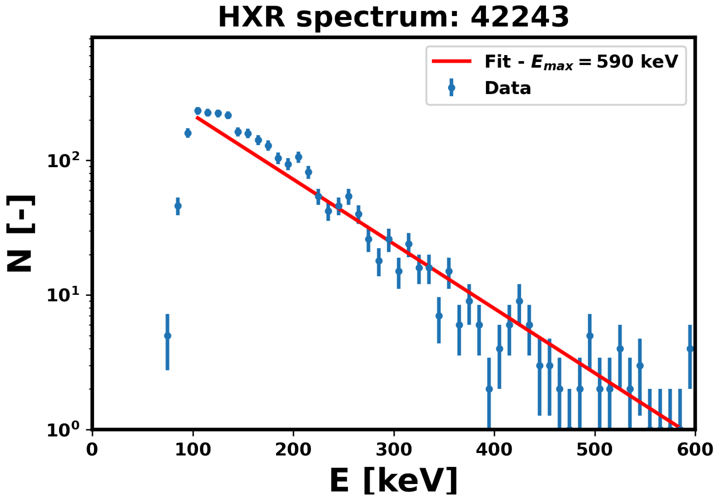
Bremsstrahlung radiation by $CeBr_3$ scintillation detector



- Favorable conditions for runaway electron generation
  - high loop voltage ($E \approx 2 - 5\ \mathrm{V/m}$)
  - low density ($n_e \approx 10^{18}\ \mathrm{m}^{-3}$)
- Density of plasma could be partially controlled by initial pressure of working gas

Cerovsky-2023-ECPD

Bremsstrahlung spectrum by $CeBr_3$ scintillation detector

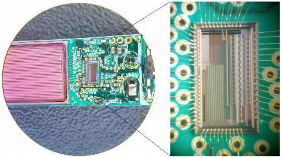


Chlum-2023-ECPP

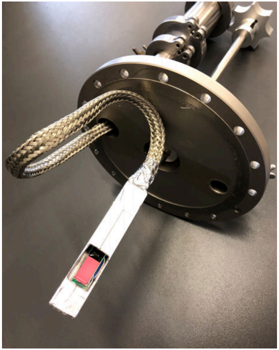
Runaway electron diagnostics using silicon strip detector

In collaboration with the experimental particle group (diagnostics branch)

The silicon n+ -in-p sensor consists of 32 AC coupled 250 um x 18 mm x 525 um strips.



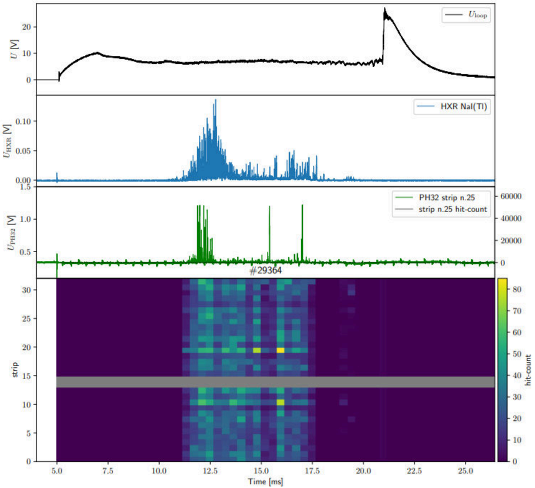
The silicon strip sensor connected to the PH32 readout chip



PH32 detector attached to a radial manipulator.

SvihraFUSENGDES18

Runaway electron diagnostics using silicon strip detector

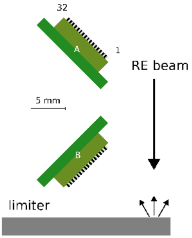


- Loop voltage of plasma discharge.
- HXR scintillation,
- Analog signal voltage in the 25th strip
- Number of hits in all strips.

#29364, the PH32 detector in the LGM collected a number of hits,

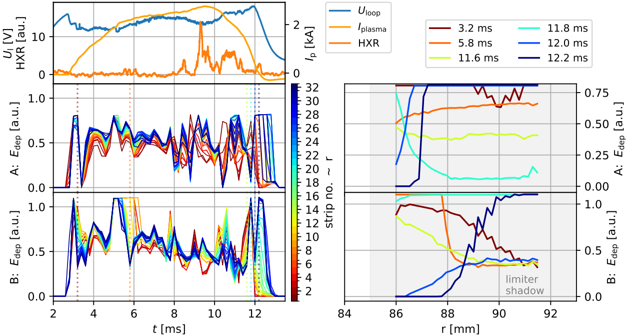
NovotnyJINST20

The distribution of REs in SOL



Two opposite-oriented sensors to observe:

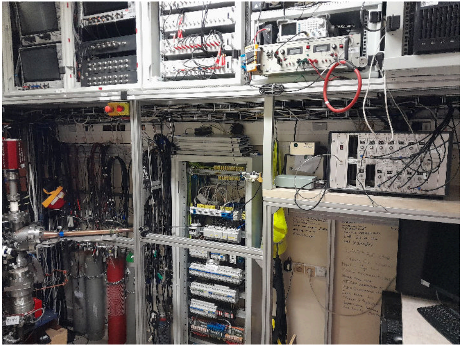
- trapped particles,
- RE backscattering from the limiter.



- During the discharge, REs are usually detected near the limiter edge or with a uniform distribution.
- At the end of the discharge, most of the energy is typically deposited on the LFS side of the limiter.

Chlum-2023-ECPP

26.5 – 40 GHz ECE radiometer

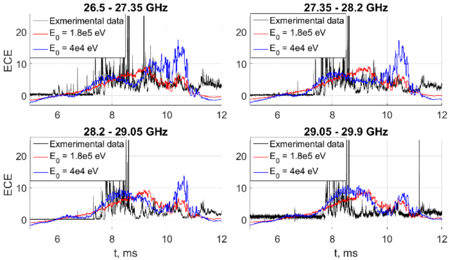


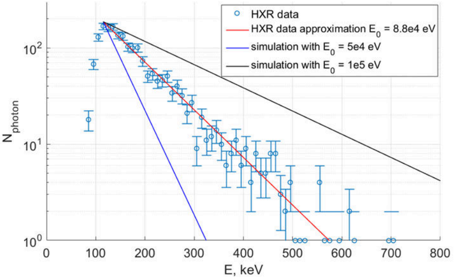
- Due to low electron temperature and density, the ECE radiometer cannot be used for electron temperature measurements.

- The radiometer is sensitive to non-thermal high energy electrons
- Allows simulating radiation from plasma as a combination of single electron radiation.
- Matching model to experimental signal via variation of electron energy distribution function gives possibility to estimate the distribution function.

Ivanov-2023-ECPP

ECE simulation for optically thin plasma

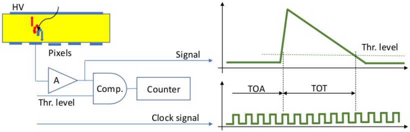


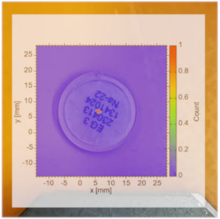


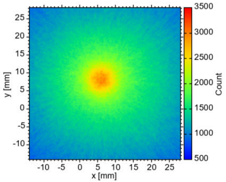
Left) Comparison of thin plasma model and experimental #42245 ECE signal. Right) Comparison of HXR energy distribution and electron energy distribution from ECE measurements. **Ivanov-2023-ECPP**

Timepix3 detection module

- Compton camera has the ability to detect the direction of gamma rays produced by radioisotopes.
- The Compton camera was created from a Timepix3 detector with a sensor from Cadmium-Telluride with a thickness of 2 mm.
- Ongoing improvements of the camera resolution and location.



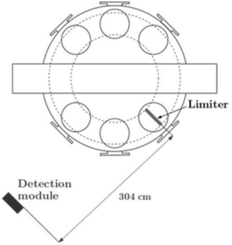


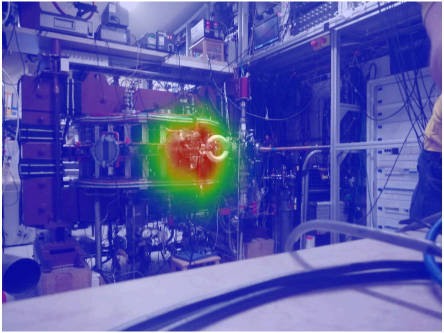


- Example with Na radioisotope radiation detection.

Malec-2023-MastThes,Malec-2021-IEEE

Compton camera on the GOLEM tokamak #39048 to #39097





- Compton camera has the ability to detect the direction of gamma rays produced by radioisotopes.
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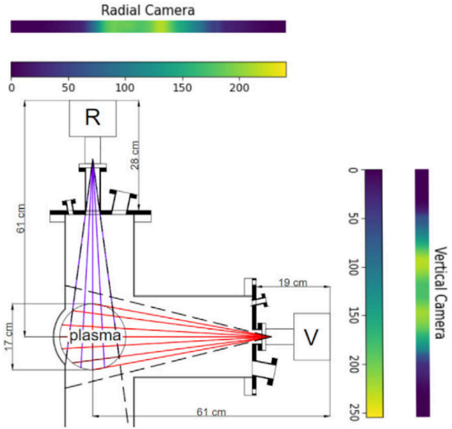
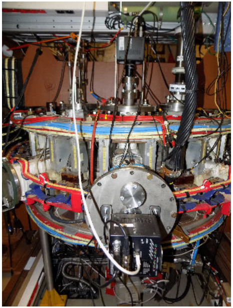
- Ongoing improvements of the camera resolution and location.

Malec-2023-MastThes

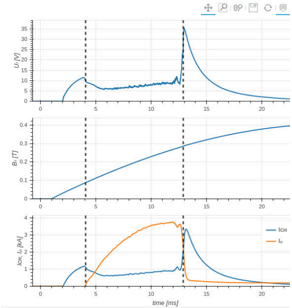
Fast cameras at the GOLEM tokamak

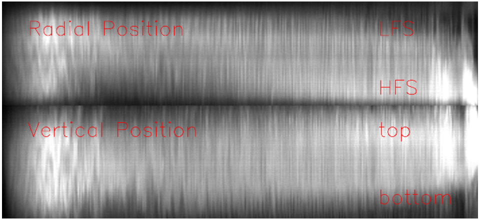




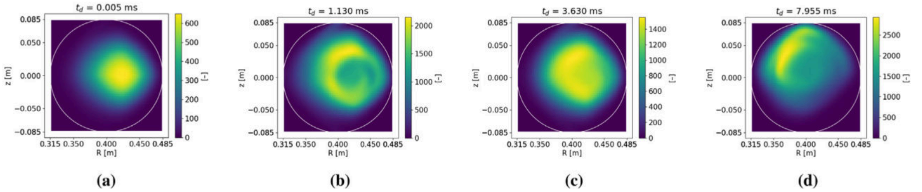
Abbasi-2023-FUSENGDES

Tomographic reconstruction #39304



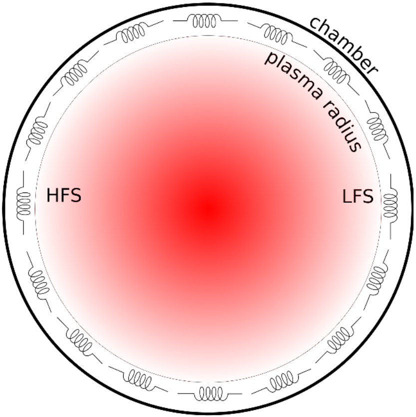


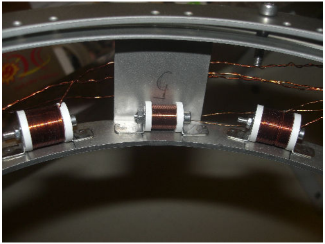
Abbasi-2023-FUSENGDES



(a) $t_d = 0.5$ ms, (b) $t_d = 1.13$ ms, (c) $t_d = 3.63$ ms, (d) $t_d = 7.96$ ms.

MHD ring @ tGOLEM





Magnetic turbulence and long-range correlation studies

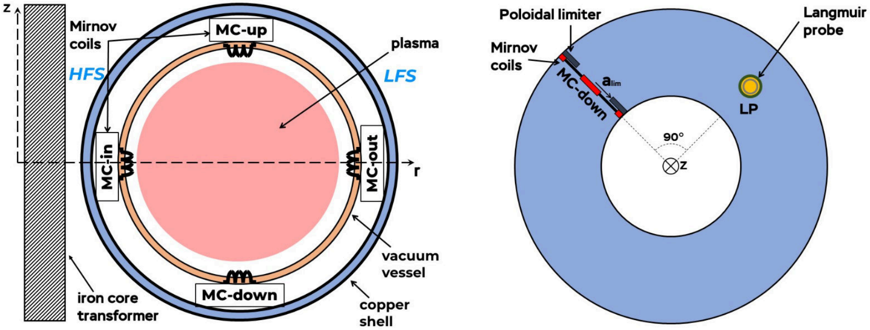


Figure: Arrangement of the GOLEM probe diagnostics (left) side view, (right) bottom view. Mirnov coils are installed behind the circular limiter, $a_{lim} = 0.085$ m. The Langmuir probe is shifted toroidally with respect to the Mirnov probes by 90^o.

Sarancha-JPCS-2021

Magnetic turbulence and long-range correlation studies

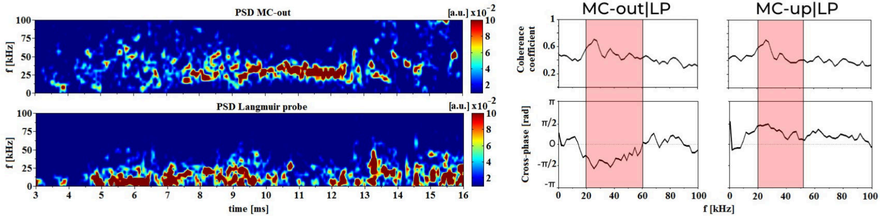
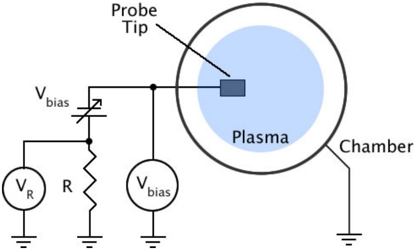
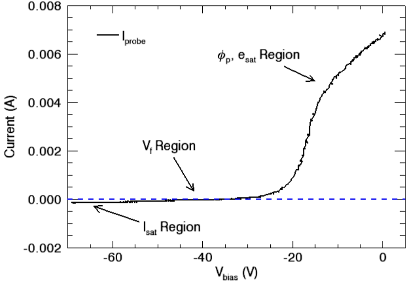


Figure: (left) Power spectral density of the signals of the MC-out (top) and Langmuir (bottom) probes and (right) quadratic coherence coefficient (top) and cross-phase between the signals of the magnetic and Langmuir probes (bottom).

Sarancha-JPCS-2021

Particle flux measurement with Langmuir probes

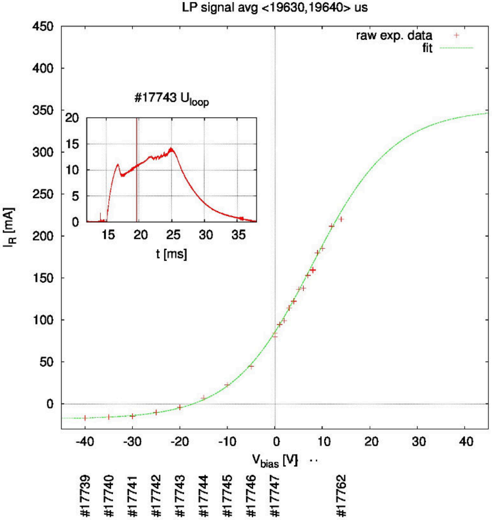


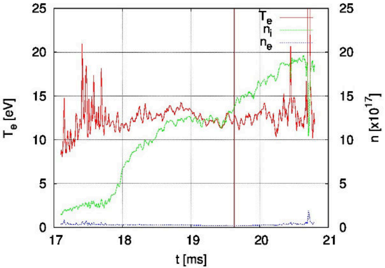


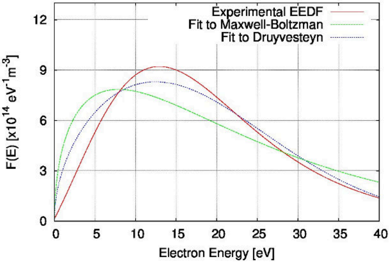
credit:DavidPace:LangProbe

- A small, conductive component in direct contact with plasma.
- The measurement output is determined: i) shape: Langmuir probe, ball-pen probe, tunnel probe, Katsumoto probe, Mach probe ... ii) by the applied voltage.
- Measurement only at the edge of the plasma.
- Measured quantities: plasma potential, electron temperature and density, electric fields, electron distribution functions ...

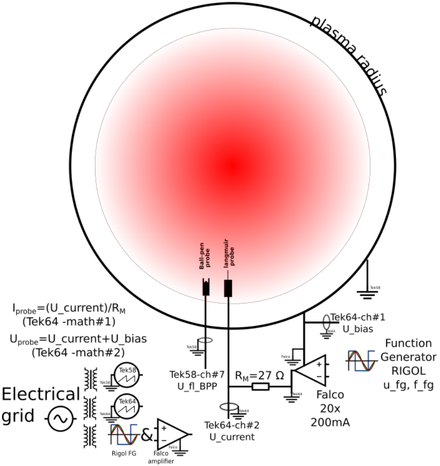
VA characteristics at the GOLEM tokamak





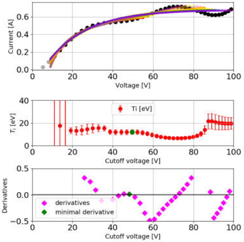


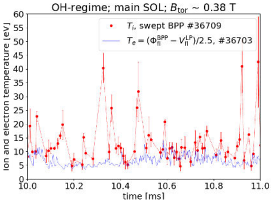
Fast T_i measurement with 5μs temporal resolution

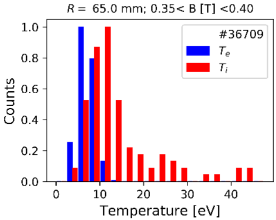


J. Adamek, D. Cipciar, Macha *et al.* 2021 ECPP conf

Fast T_i measurement with $5\mu s$ temporal resolution







- Measurement based on the electron branch IV characteristics of a BPP.
- The probe collector is biased with a voltage swept between -30V to +130 V at a frequency of 100 kHz.
- Cut-off fitting technique is applied to all the IV characteristics (left).
- Fluctuations of the T_i ranging between 5 eV up to 40 eV (middle).
- NON-Gaussian shaped histograms of T_i and T_e are observed (right).

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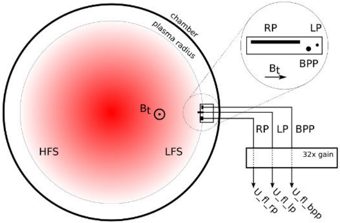
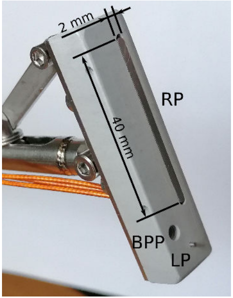
The rail probe concept





- A probe head consists of a rail probe (RP, length = 40 mm, wide = 2 mm), Langmuir probe (LP, length 1.5 mm, diameter 1 mm), and ball-pen probe (BPP).
- Special manipulator with changable inclination to B_{t} within $\pm 10^{\circ}$.

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The rail probe concept

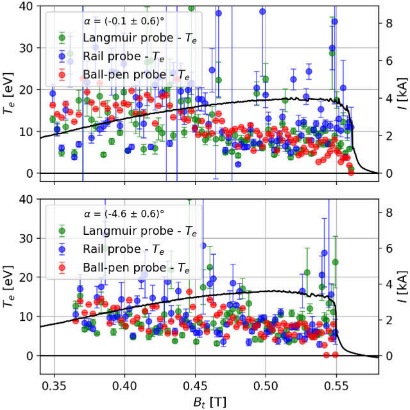
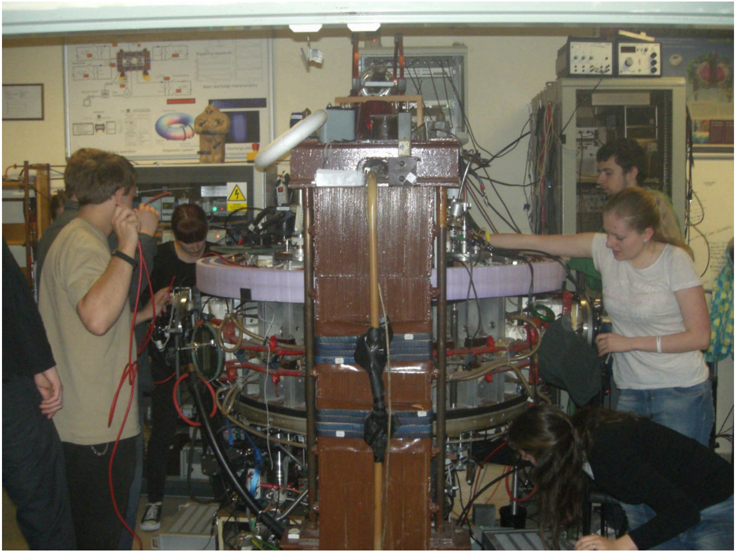


Figure: Comparison of T_e measured by LP, RP and BPP+LP.

- The RP concept can sustain exceptionally high heat flux and reduce the sheath expansion effect.
- T_e is measured using a swept LP and RP (f = 5 kHz) and a floating BPP.
- Capability of RP to reduce the sheath expansion effect was confirmed.
- Good agreement between LP, RP and BPP T_e measurements for large B_t.

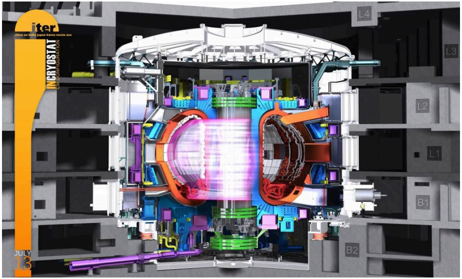
J. Adamek, J. Malinak, Macha *et al.* 2021 ECPP conf

Hands on tokamak



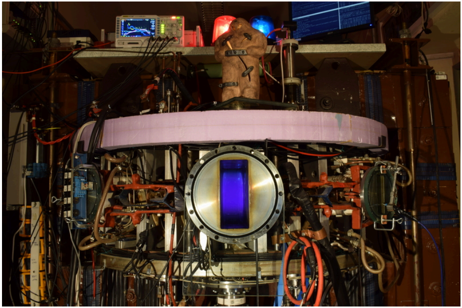
The competition

The ITER: 3.6 s



credit: ITER contributors

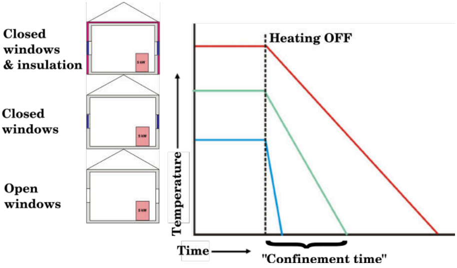
The GOLEM: ??? s or ms or us ??



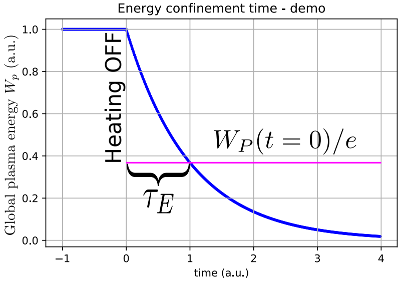
credit: Tokamak GOLEM contributors

Towards ... Energy confinement time

House



Tokamak



Towards Electron energy confinement time τ_E

Vacuum discharge

ID:irog $\int_0^t$

ID:loop_voltage

Loop Voltage $U_l(t)$
Chamber current $I_{ch}(t)$

Chamber resistance $\overline{R_{ch}} \approx \frac{U_l(t)}{I_{ch}(t)}$

Plasma discharge

ID:irog $\int_0^t$

ID:loop_voltage

ID:electron_density

Loop Voltage $U_l(t)$
Chamber+plasma current $I_{ch+p}(t)$

Tokamak GOLEM plasma volume: $V_p = (57 \pm 5)$ l
Boltzman constant: $k_B = 1.38 \cdot 10^{-23}$ J/K
Energy associated with 1 ev: $eV = 1.602 \cdot 10^{-19}$ J

Plasma current $I_p(t) = I_{ch+p}(t) - I_{ch}(t) = I_{ch+p}(t) - \frac{U_l(t)}{\overline{R_{ch}}}$

Statistical treatment: quasistationary phase specification from t_1 to t_2

$$\overline{I_p} = < I_p(t) >_{t_1}^{t_2} \quad \overline{U_l} = < U_l(t) >_{t_1}^{t_2} \quad \overline{n_e} = < n_e(t) >_{t_1}^{t_2} \quad \frac{dW_p(t)}{dt}\Big|_{t_1}^{t_2} = 0$$

Plasma resistivity $R_p = \frac{U_l}{I_p}$

Plasma heating power $P_{OH} = R_p \cdot I_p^2$

Central Electron temperature (in eV) Spitzer formula)GOLEM case $T_e(0) = 0.9 \cdot R_p^{-2/3}$

The loss power $(\frac{dW_p}{dt} = 0)$: $P_{loss} = P_{OH}$

Total electron energy content $W_p = V_p \cdot \frac{n_e \cdot k_B \cdot (T_e(0) \cdot eV)}{3}$

The electron energy confinement time $\tau_{eE} = \frac{W_p}{P_{loss}}$

Note: All physical quantities requested in the form of estimated value and associated degree of uncertainty

Tokamak GOLEM - vzdálené řízení: 2009-2019 inventura

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

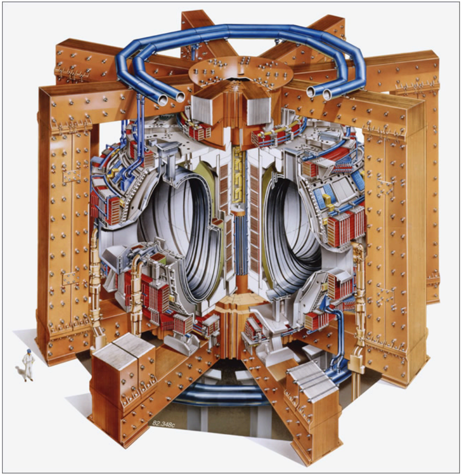
- Demonstrace: Ghent University 09; Bochum University 13; Garching 13; Lemvig High School 14; Instituto Tecnologico Costa Rica 10; Armidale University 17.
- Zimní a letní školy: French Training Course & EM 12-14,16-19; Bangkok 16-19; TU Eindhoven 11,15-19;TU Kobehaven 14,15,18;Grenoble TU 15, University 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

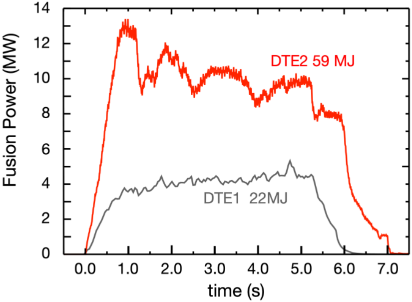
GOLEM

Table of Contents

1997: Světový fúzní rekord @ JET (EU)

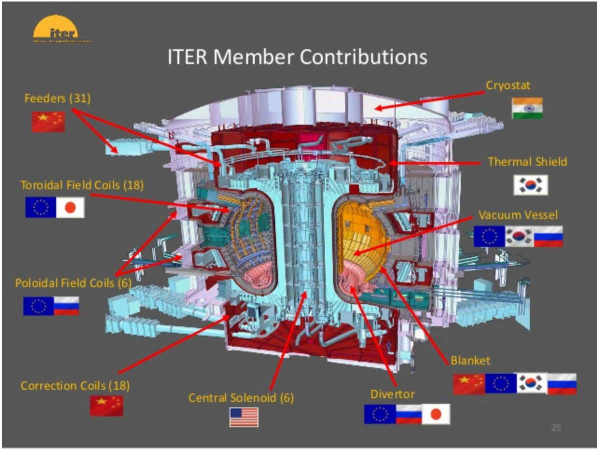


output comparison 1997 and 2021.png



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) $\approx$ 17 miliard EUR



Mise 2035:

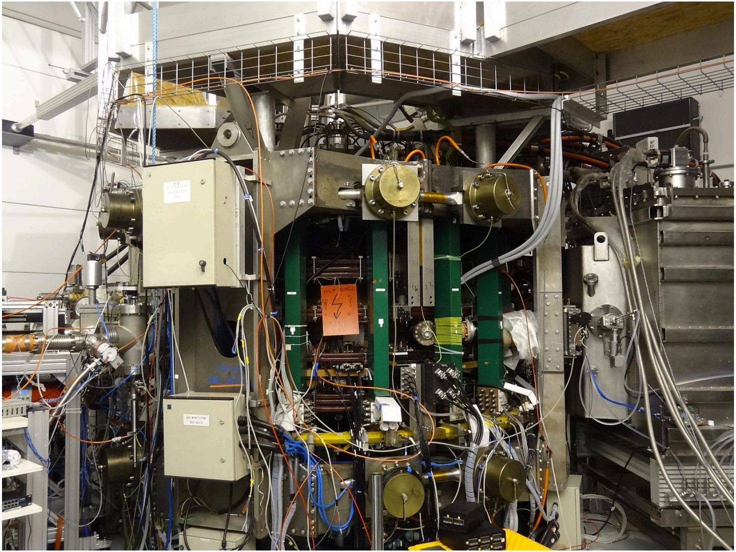
$P \approx 500$ MW, $Q \approx 10$, $\Delta T \approx 10$ minut, konkurenceschopná cena elektřiny

ITER status update 07/24 $\approx$ 22 miliard EUR

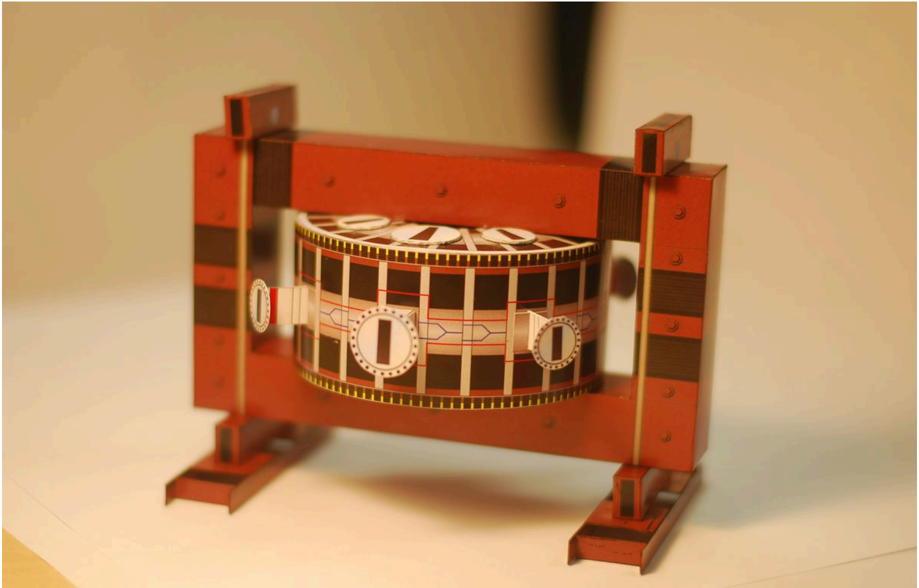
Odklad dosažení plného výkonu o 4 roky na 2039 + navýšení nákladů o 5 mld. EUR na 22 mld. EUR:

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

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

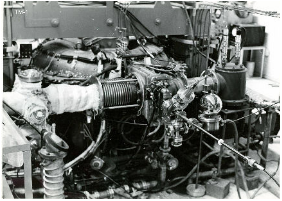


Paper model ABC



Děkuji za pozornost

Tokamak TM1
@Kurchatov Institute near Moscow
~1960-1977

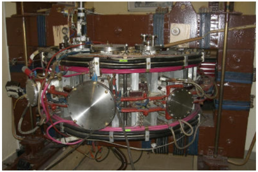


SCIENCE

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

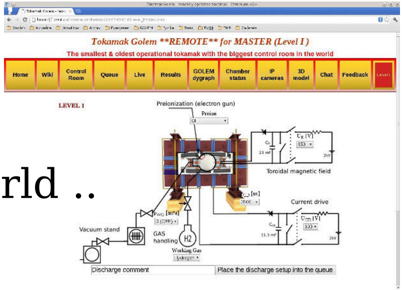
SCIENCE
& education

Tokamak GOLEM
@Czech Technical University, Prague
2007-



EDUCATION
& science

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



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Students, teachers, technicians (random order):

Honorary
: Vladimír Fuchs, **Ondřej Grover**, Tomáš Odstrčil, Gergo Pokol, **Gabriel Vondrášek**, **Jan Stockel**, **Jan Mlynář**, Tomáš Markovič

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 Štepán Malec, Kateřina Jiráková, Jaroslav Čeřovský.

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Macha, P. *et al.* (2021). "Tokamak Golem for fusion education - chapter 12". In: vol. 45A. Europhysics conference abstracts, P4.1028. ISBN: 979-10-96389-13-1. URL: http://ocs.ciemat.es/EPS2021PAP/pdf/P4.1028.pdf.