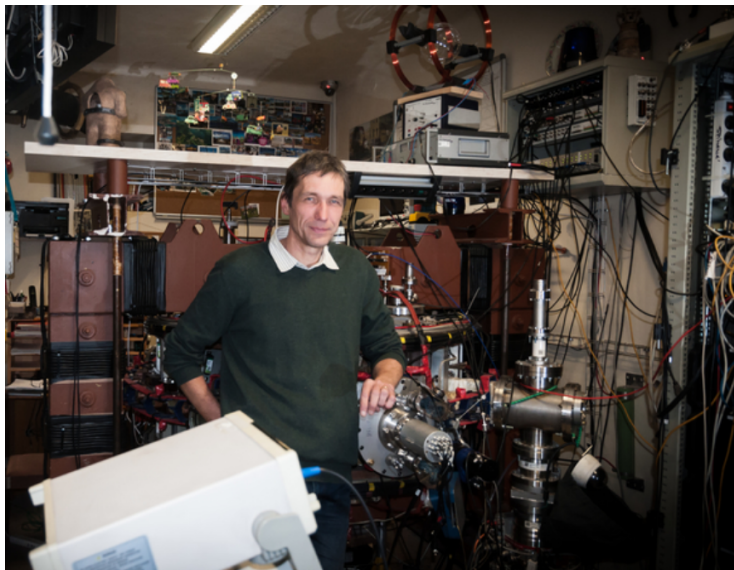


Tokamak GOLEM

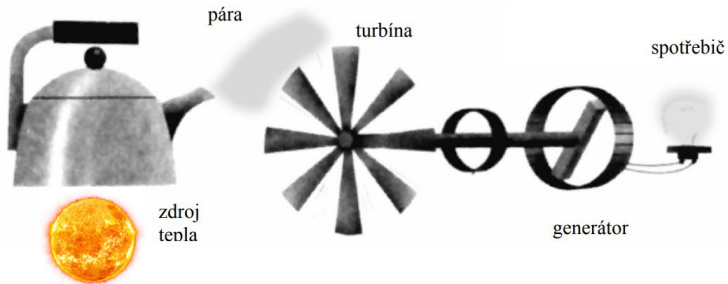
Vojtěch Svoboda
Přednáška pro FS (C#19 kompenzace)

October 21, 2020

Tokamak GOLEM & Vojtěch Svoboda



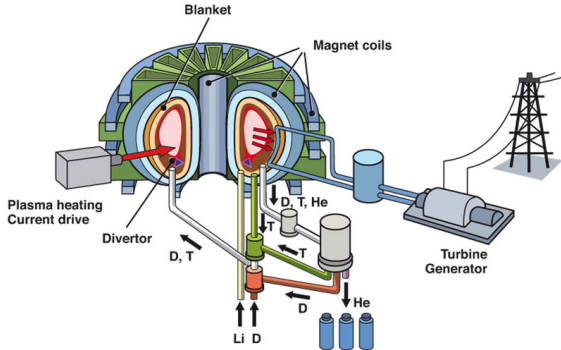
Topit malým Sluncem/hvězdou ??





Můžeme se zmocnit energie
která pohání Slunce/hvězdy?

Vize: Jaderná elektrárna - slučovací/fúzní



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

Vyplát technologii

1952 "Operation Ivy - Mike" První test vodíkové bomby



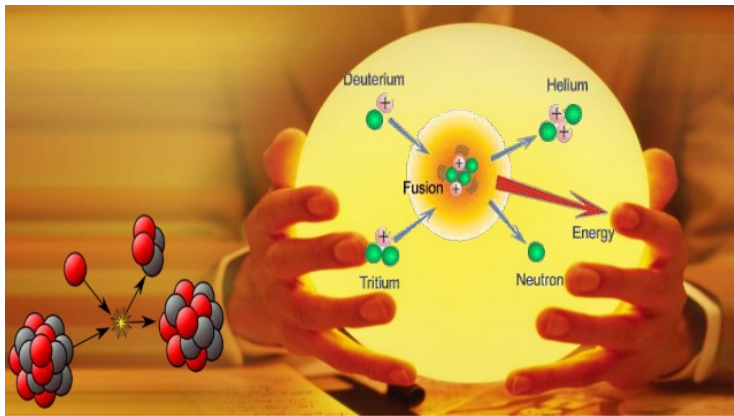
Operation Ivy - Mike

10.4 Megatons

credit:YouTube:Ivy Mike Countdown and detonation

Toto není vhodná technologie

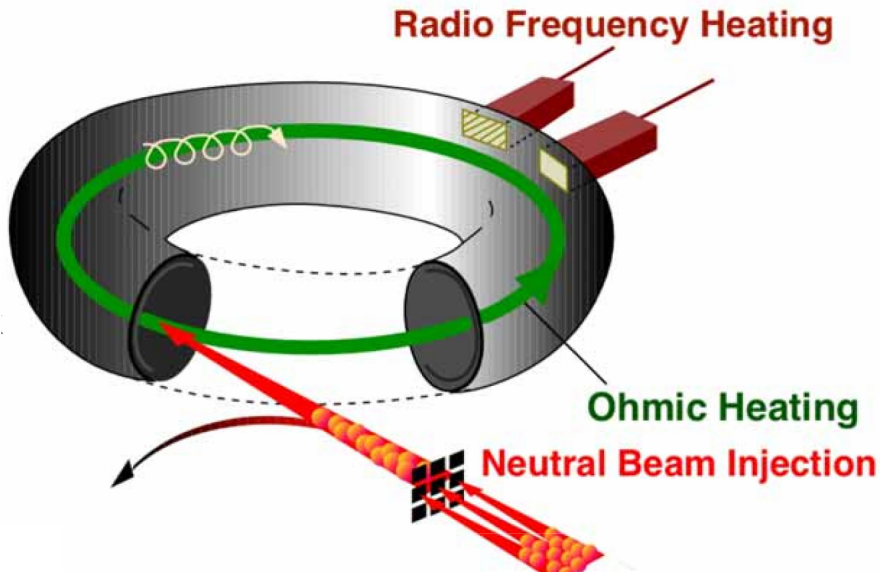
Hledá se vhodná fúzní technologie



Podmínky:

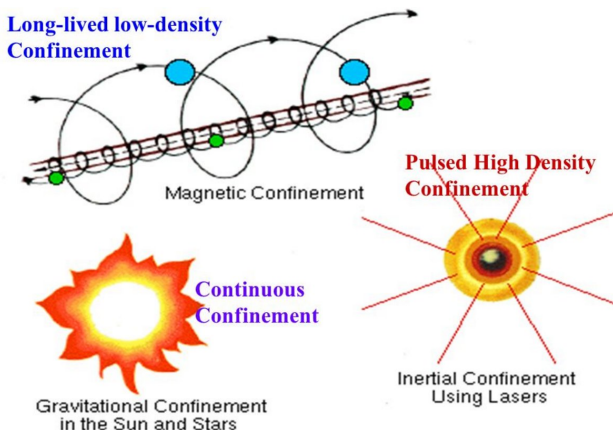
Zahřát na $\sim 100\,000\,000\text{ }^{\circ}\text{C}$ & **udržet** po dobu ~ 30 let

Ohřev plazmatu

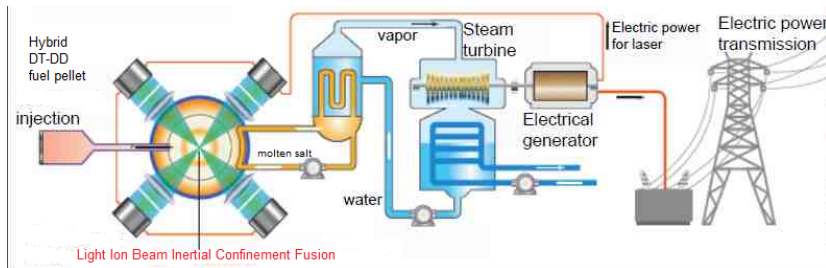


Tři možné cesty jak udržet plazma pro fúzi

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



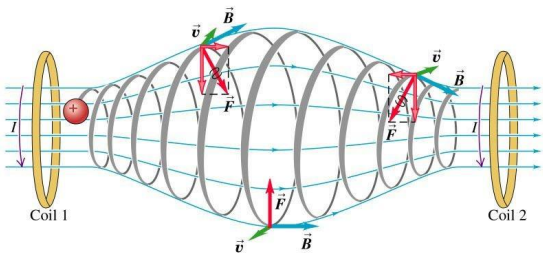
Inerciální fúze



credit:mext.jp

Velká výzva

Magnetické udržení: magnetická nádoba

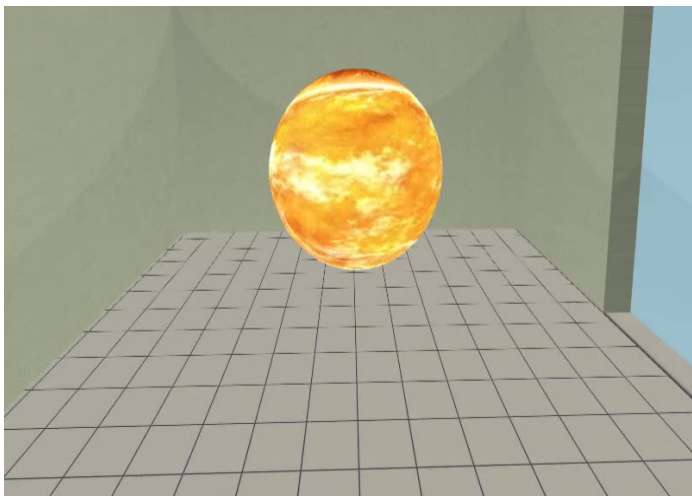


Copyright © 2004 Pearson Education, Inc., publishing as Addison Wesley.

Musíme ji ale svinout do kruhu (zbatvit se podstav)

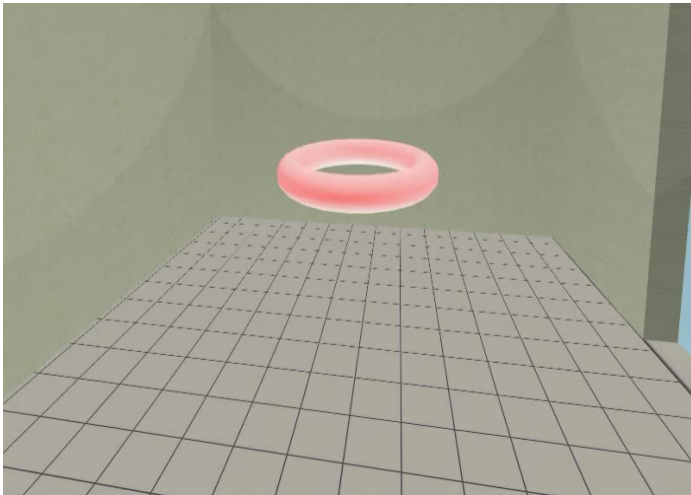
záchranný kruh/duše pneumatiky/donut

Náš cíl: vytvořit μ Slunce v pozemských podmínkách

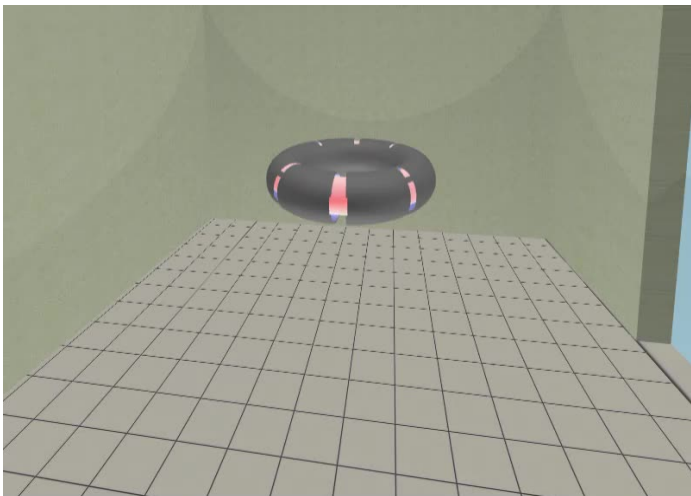


Magnetické udržení vyžaduje toroidální geometrii

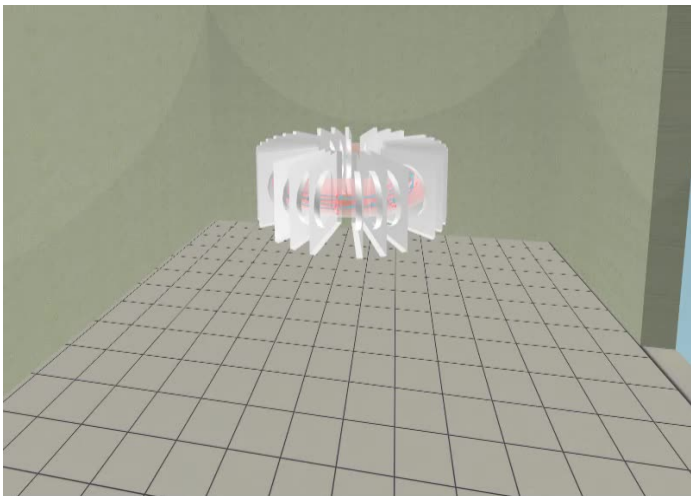
Svinutá magnetická nádoba



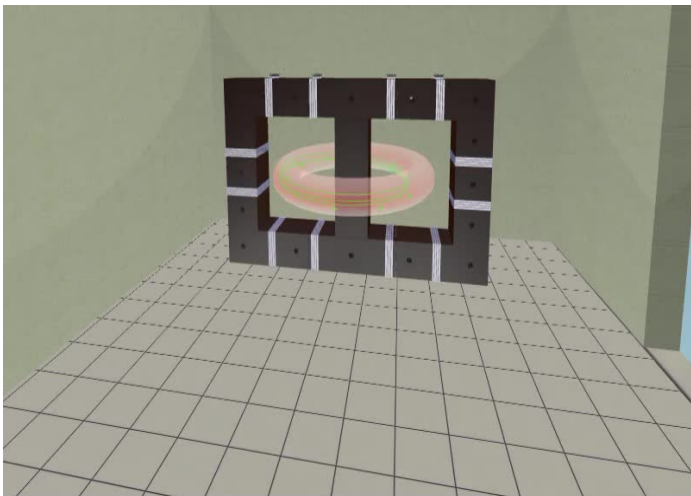
Musíme to celé umístit do reaktorové nádoby - komory



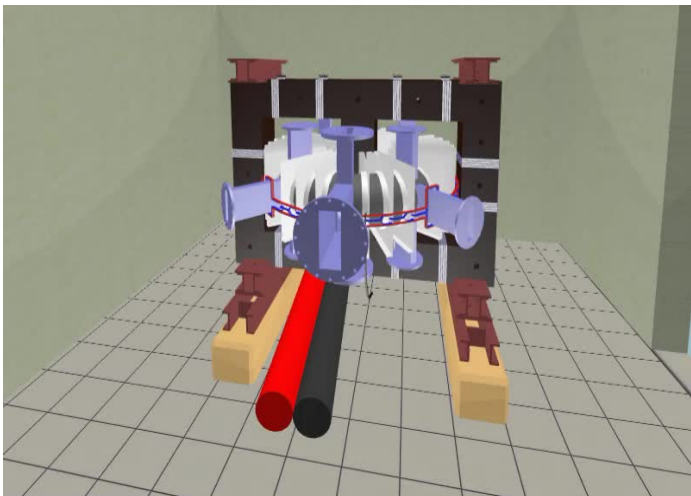
Toroidální magnetické pole udržuje plazma



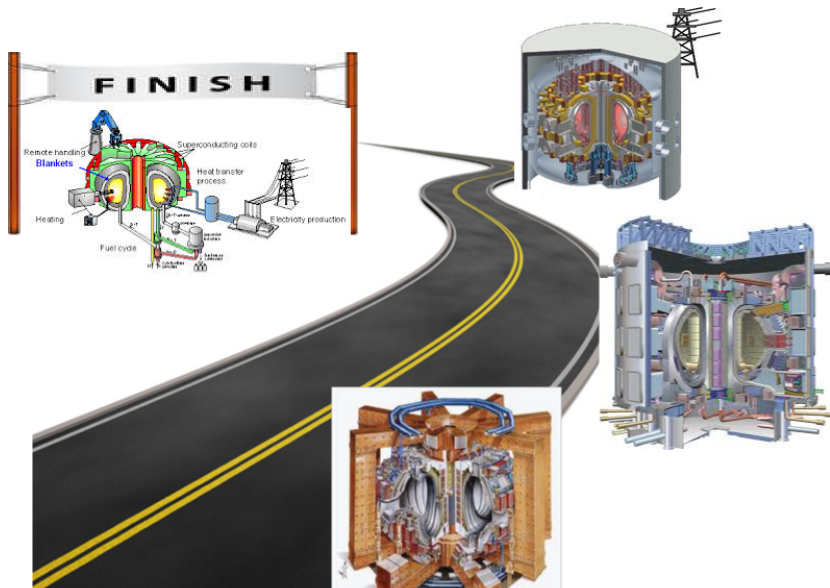
Transformátorová akce vytvoří a zahřeje plazma



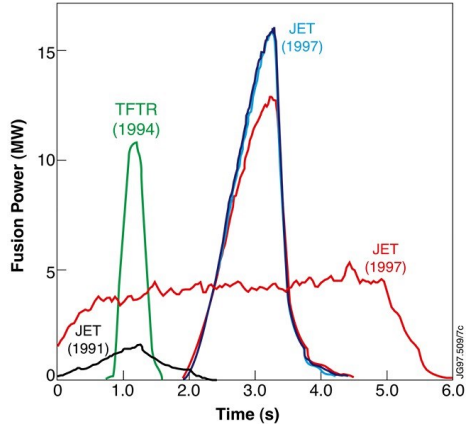
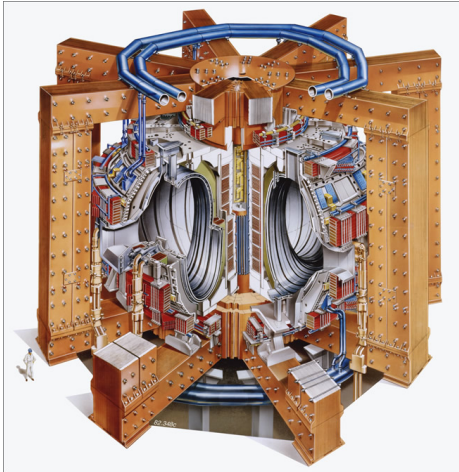
Vše dohromady - voilà tokamak



Milestones to Fusion Power Plant

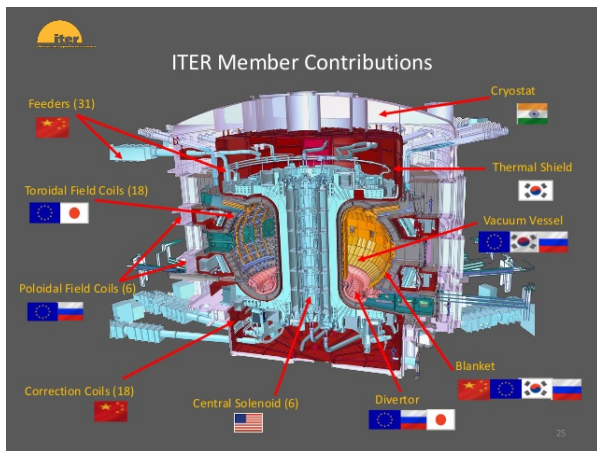


1997: Světový fúzní rekord @ JET (EU)



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

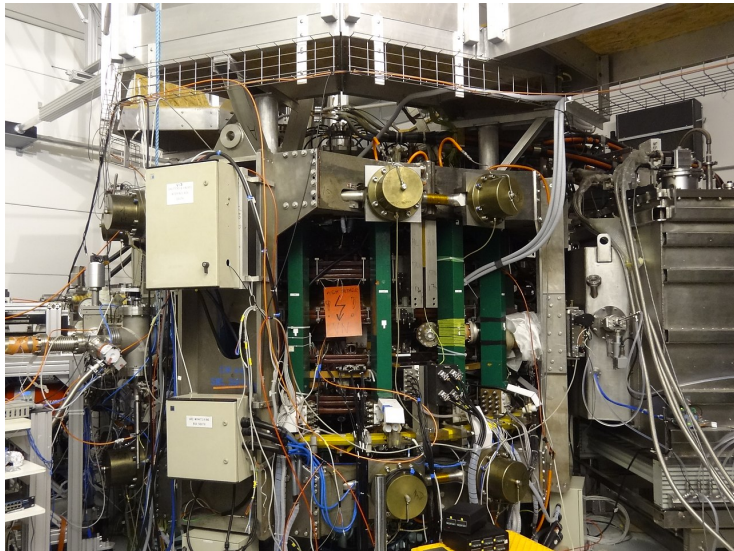
ITER (jižní Francie) \approx 18 miliard EUR



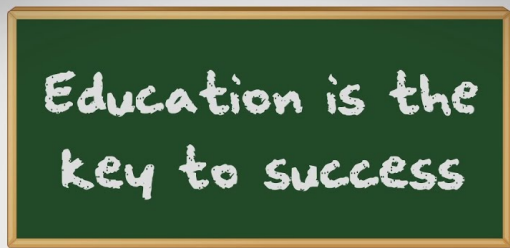
Mise:

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

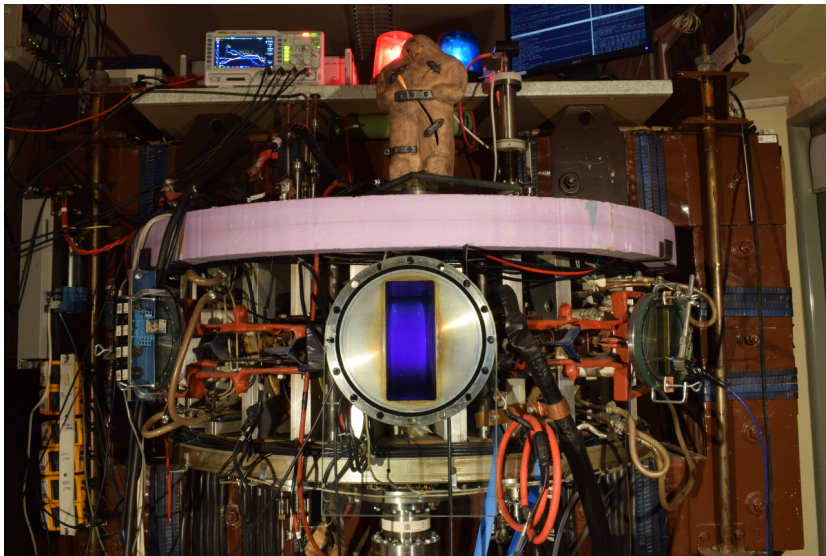
Příspěvek České republiky: tokamak COMPASS@IPP.CAS.CZ



Velké ambice

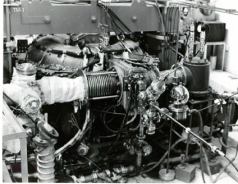


Tokamak GOLEM



The GOLEM tokamak for education - historical background

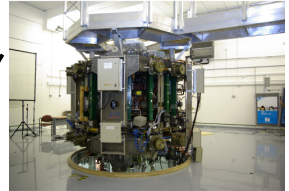
Kurchatov Institute near Moscow,
Soviet Union
1960: **TM1-MH**



1974



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



2006



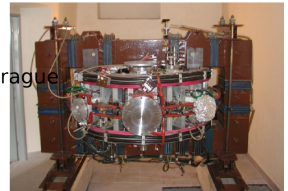
Institute of Plasma Physics
Czech republic
CASTOR **COMPASS**



2008



Czech Technical University Prague
Czech republic
GOLEM



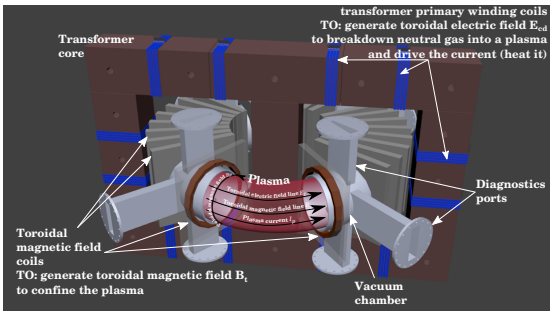
GOLEM



Plasma in Tokamak (GOLEM) - the least to do

To do:

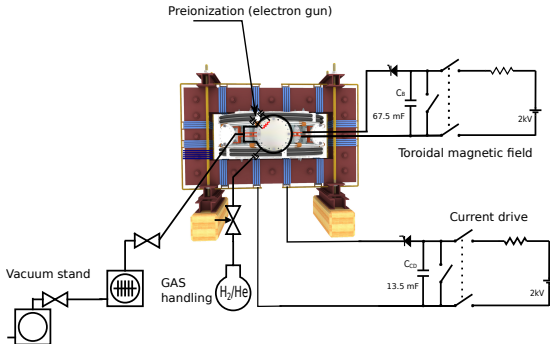
- session start phase:
 - Evacuate the chamber
- pre-discharge phase
 - Charge the capacitors
 - Fill in the working gas
 - Preionization
- discharge phase
 - Toroidal magnetic field to confine plasma
 - Toroidal electric field to breakdown neutral gas into plasma
 - Toroidal electric field to heat the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



Plasma in Tokamak (GOLEM) - the least to do

To do:

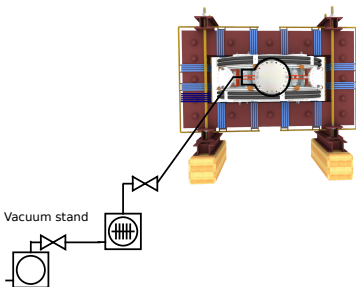
- session start phase:
 - Evacuate the chamber
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 - Charge the capacitors
 - Fill in the working gas
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- discharge phase
 - Toroidal magnetic field to confine plasma
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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



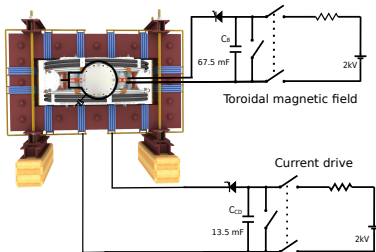
Plasma in Tokamak (GOLEM) - the least to do

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



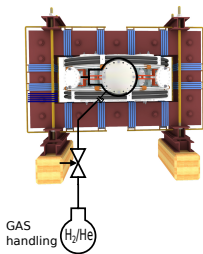
Plasma in Tokamak (GOLEM) - the least to do



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
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- post-discharge phase

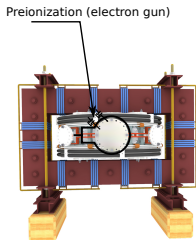
Plasma in Tokamak (GOLEM) - the least to do



To do:

- session start phase:
 - Evacuate the chamber
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 - Toroidal magnetic field to confine plasma
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 - Toroidal electric field to heat the plasma
 - Plasma positioning
 - Diagnostics
- post-discharge phase

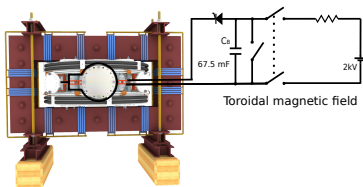
Plasma in Tokamak (GOLEM) - the least to do



To do:

- session start phase:
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 - Toroidal electric field to breakdown neutral gas into plasma
 - Toroidal electric field to heat the plasma
 - Plasma positioning
 - Diagnostics
- post-discharge phase

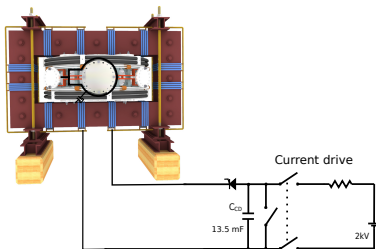
Plasma in Tokamak (GOLEM) - the least to do



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

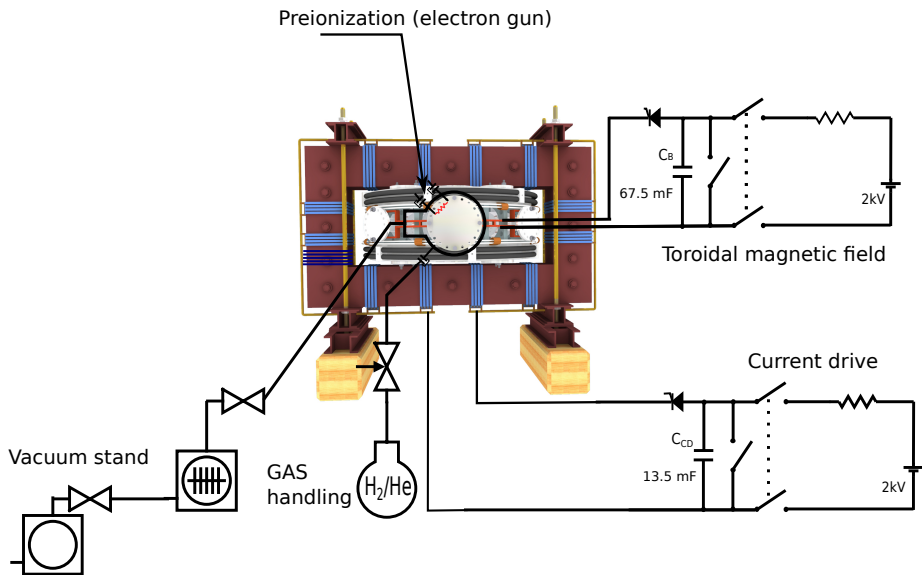
Plasma in Tokamak (GOLEM) - the least to do



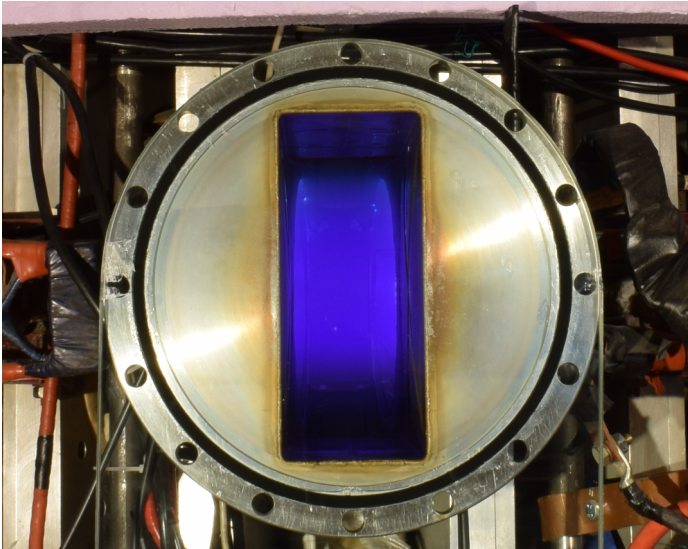
To do:

- 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

Tokamak GOLEM - schematic experimental setup



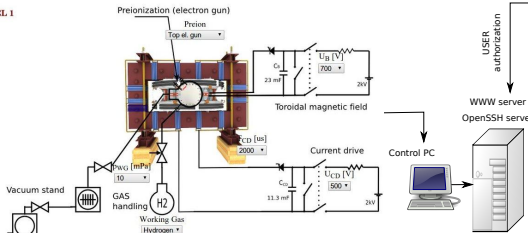
Let's make a discharge



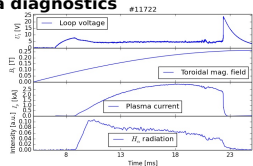
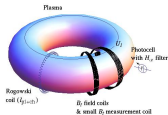
Tokamak GOLEM - experimentální schéma

LEVEL 1

Tokamak technology setup



Basic plasma diagnostics



internet

Virtual control room (remote participation)

USER authorization

WWW server
OpenSSH server

WWW control interface

HTML & PHP scripts

SSH control interface

WINDOWS via putty

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

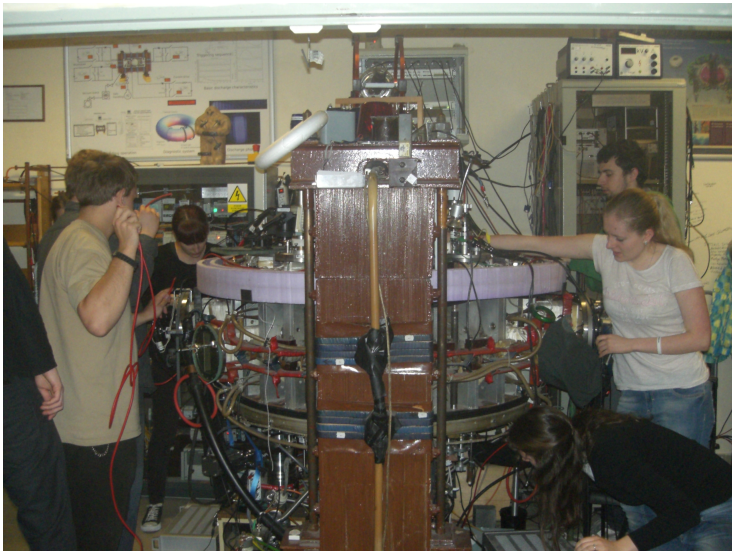
Data presentation

HTML (www pages)

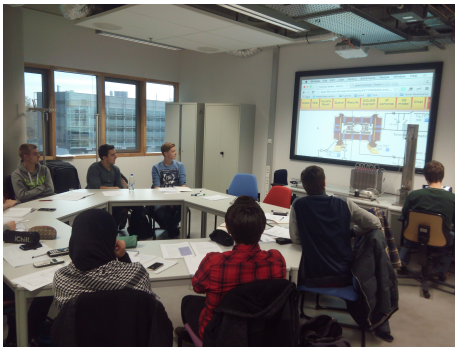
Data handling

- *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

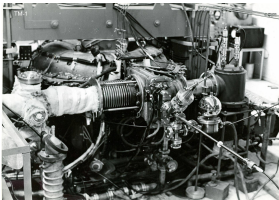


GOLEM



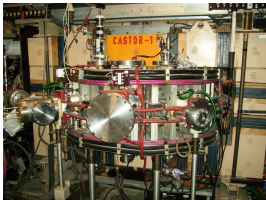
Děkuji za pozornost

Tokamak TM1
@Kurchatov Institute near Moscow
~1960-1977



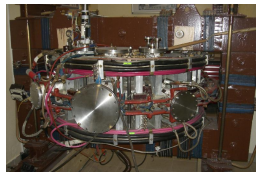
SCIENCE

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 earliest & oldest operational tokamak with the biggest control room in the world

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

LEVEL 1

Preionization (electron gun)
Preion:

Toroidal magnetic field

Current drive

Discharge comment:

Place the discharge setup into the queue

Tokamak GOLEM @ Wikipedia ..

File Edit View Go Bookmarks Tools Settings Window Help

home Kalendaršif Produkce Forecast Slovnik Rano

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Article **Tokamak** Talk Read Edit View history Search

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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 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]

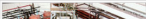
Currently in operation [edit]

(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



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.

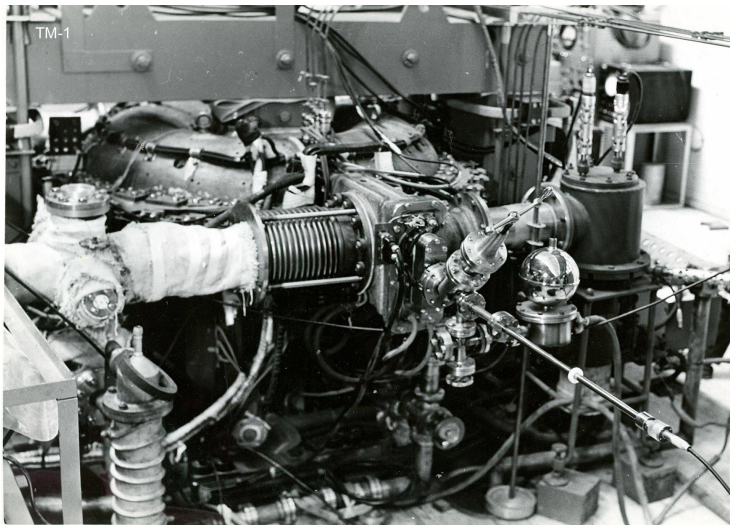
Students, teachers, technicians (random order):

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

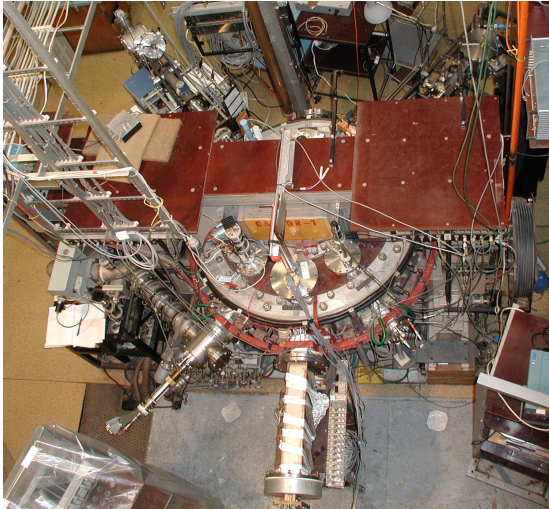
References I

- [1] Brené Brown . The power of vulnerability, 2010. [Online; accessed October 21, 2020].
- [2] V. Svoboda, B. Huang, J. Mlynar, G.I. Pokol, J. Stockel, and G Vondrasek. Multi-mode Remote Participation on the GOLEM Tokamak. *Fusion Engineering and Design*, 86(6-8):1310–1314, 2011.
- [3] Brotankova, J. *Study of high temperature plasma in tokamak-like experimental devices*. PhD thesis, 2009.
- [4] Tokamak GOLEM contributors. Tokamak GOLEM at the Czech Technical University in Prague. <http://golem.fjfi.cvut.cz>, 2007. [Online; accessed October 21, 2020].
- [5] J. Wesson. *Tokamaks*, volume 118 of *International Series of Monographs on Physics*. Oxford University Press Inc., New York, Third Edition, 2004.

XX/YY: TM-1



XX/YY: CASTOR



12/07: Last minutes at the IPP Prague

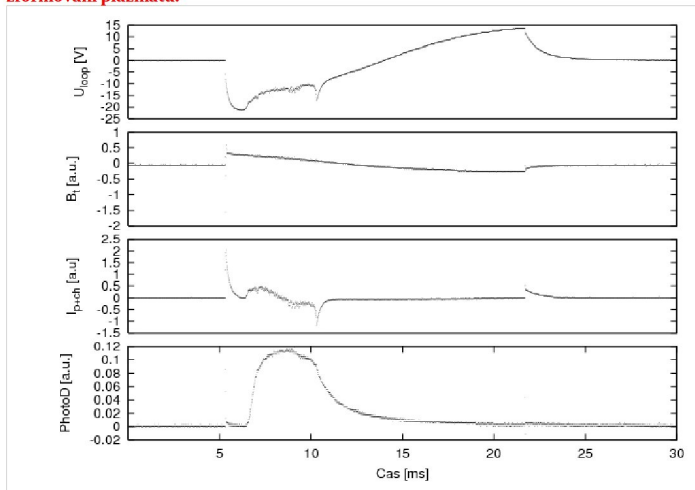


12/07: First minutes at the CTU Prague



07/09: First plasma in the tokamak GOLEM

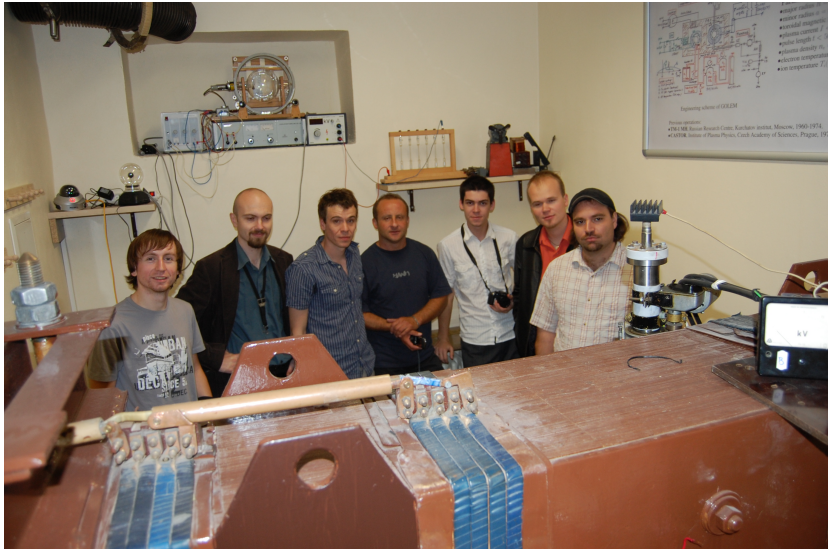
Časové průběhy signálů zřetelně ukazují, že došlo k průrazu neutrálního plynu a k zformování plazmatu.



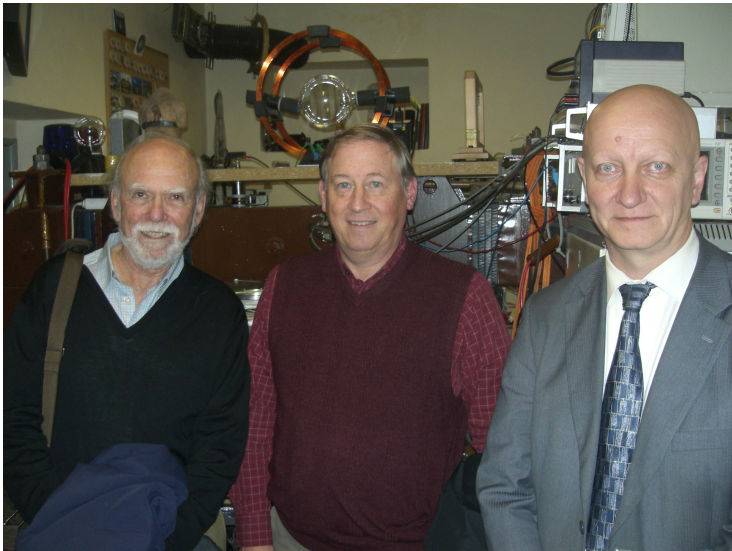
O tom svědčí:

1. Rychlý pokles napětí na závit v čase $t = 6-7$ ms a jeho malé fluktuace, které lze vidět až

09/09: Tokamak and tokamak



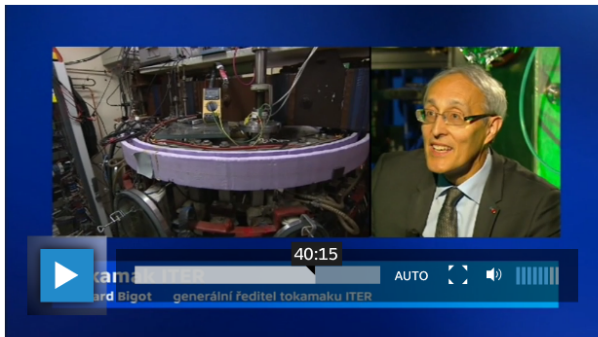
11/11: NP laureat at tokamak GOLEM



05/16: The youngest tokamak (GOLEM) operator, Adam (7 years).



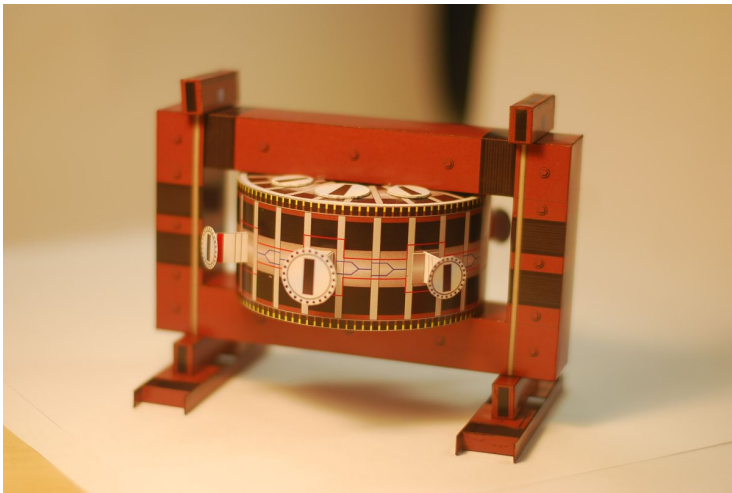
0916: ITER DG, Mr. Bernard Bigot (Shot #22185)



Quotation from Czech Television Hydepark

I am very pleased with the GOLEM ...

09/19 Paper model ABC



2010: Tokamak GOLEM



2011: The tokamak COMPASS with NBI



2016: ITER segment



2017: First Spitzer Stellarator



10/15: Trojan horse - #20000

GOLEM » Shot #20000 » previous | next | current

Tokamak GOLEM - Shot Database - 20000

[TempLate source] [Weblog]

Date: 2015-10-22 - 16:09:25
Session: SessionPreparation
Comment: 20k

Diagnosics

- ✓ PlasmaPosition_TO
- ✗ Flukes
- ✗ Spectrometer
- ✓ FastCamera
- ✓ HXR

Analysis

- ✓ HistoricalAnalysis
- ✓ ShotHomepage
- ✓ AdvancedAnalysis
- ✓ Spectrogramm_TO
- ✗ MultiCWT_TO
- ✓ MWPrezincization
- ✗ Impurities_TO

DAS

- ✓ TektronixDPO
- ✓ Papouch_3l
- ✓ Nlstandard
- ✓ Papouch_Za
- ✓ Papouch_St

Vacuum log

Charging log

Other


Data
References
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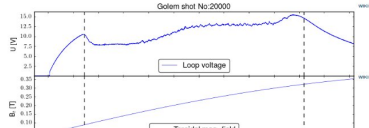
Go to shot
20000

Congratulation, you have reached nuclear fusion.
The following explosion destroyed half of Prague and radioactive fallout contaminated whole Europe.
Have a nice day



Basic parameters: (compare) **Plasma parameters:**

- Gas pressure p_{CH} : 10.20 → 15.38 mPa (request: 5 mPa) ^{Wiki}
- Working gas: H ^{Wiki}
- Preionization: Upper et. gun
- Chamber temperature: 20.00 C
- C_{α} capacitors charged to: 1000 V, triggered 5.0 05 ^{Wiki}
- $C_{\beta 0}$ capacitors charged to: 0 V, triggered 5.0 05 ^{Wiki}
- $C_{\beta 0}$ capacitors charged to: 500 V, triggered 6.0 05 ^{Wiki}
- $C_{\beta 1}$ capacitors charged to: 0 V, triggered 5.0 05 ^{Wiki}
- Probability of breakdown: N/A ^{Wiki}
- Time since session beginning: 0:19:25 h
- Plasma life time 8.7 [ms] (from 7.5 to 16.2)
- Mean toroidal magnetic field Bt: 0.22 T ^{Wiki}
- Mean plasma current: 1.42 kA ^{Wiki}
- Mean Uloop: 12.41 V ^{Wiki}
- Break down voltage: 10.5 V ^{Wiki}
- Ohmic heating power: 17.59 kW
- Q edge: 0.9 ^{Wiki}
- Electron temperature: 13.5 eV ^{Wiki}
- Line electron density: N/A [10⁻¹⁷ m⁻²] ^{Wiki}



Golem shot No:20000

Y-axis: U [V] (0 to 15.0), Bt [T] (0.10 to 0.35)

X-axis: Time

Legend: Loop voltage, Toroidal magnetic field

11/17: GOLEM tokamak "mapping"

Tokamak GOLEM



Základní (řádová) statistika k 30.11.2012

Počet dní od instalace: 1815.

Počet operačních dní: ≈ 438 .

Počet hodin: ≈ 1954

Počet shotů: 10417.

Počet shotů – $>$ plazma: ≈ 7600 .

Průměrná délka výboje: ≈ 7 ms.

Celková délka trvání plazmatu: < 60 s.