

Introduction to the tokamak operation (GOLEM specific) - Level 1

Vojtěch Svoboda
on behalf of the tokamak GOLEM team
for the BUTE University, Hungary

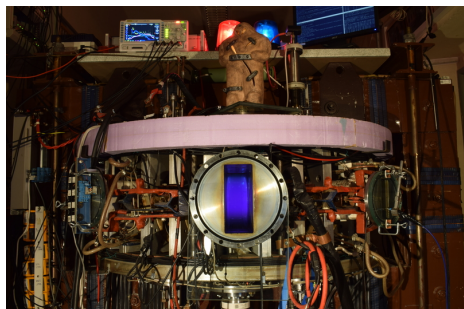
November 2, 2020

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- 1 Introduction
- 2 The Tokamak (GOLEM)
- 3 The Tokamak GOLEM (remote) operation
- 4 Conclusion
- 5 Appendix

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 ..

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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]

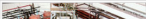
Currently in operation [edit]

(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

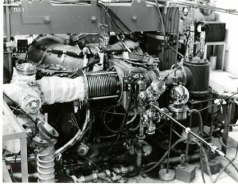


Alcator C-Mod



The GOLEM tokamak for education - historical background

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



1974

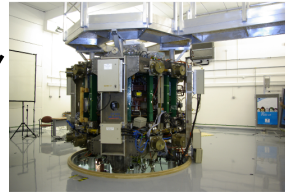


Institute of Plasma Physics
Czech republic
CASTOR **COMPASS**

2006



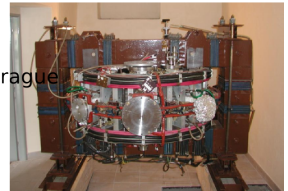
Culham Centre for Fusion Energy
Great Britain
1989: **COMPASS-D**



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...

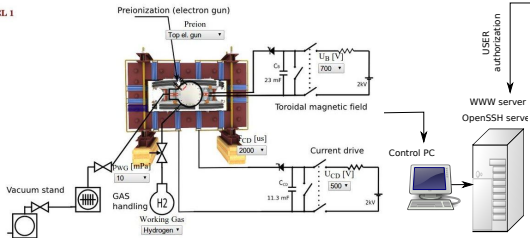


At the end of the 16th century, in the times when the Czech lands were ruled by Emperor Rudolf II, in Prague, there were Rabbi Judah Loew, well known alchemist, thinker, scholar, writer and inventor of the legendary GOLEM - a clay creature inspired with the Universe power that pursued his master's command 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. [1].

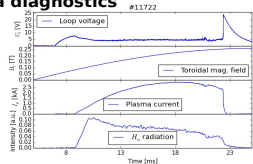
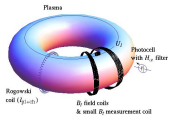
The global schematic overview of the GOLEM experiment

LEVEL 1

Tokamak technology setup



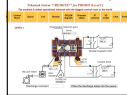
Basic plasma diagnostics



Virtual control room (remote participation)

WWW control interface

HTML & PHP scripts



SSH control interface

WINDOWS via putty



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

Data presentation

HTML (www pages)



Data handling

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

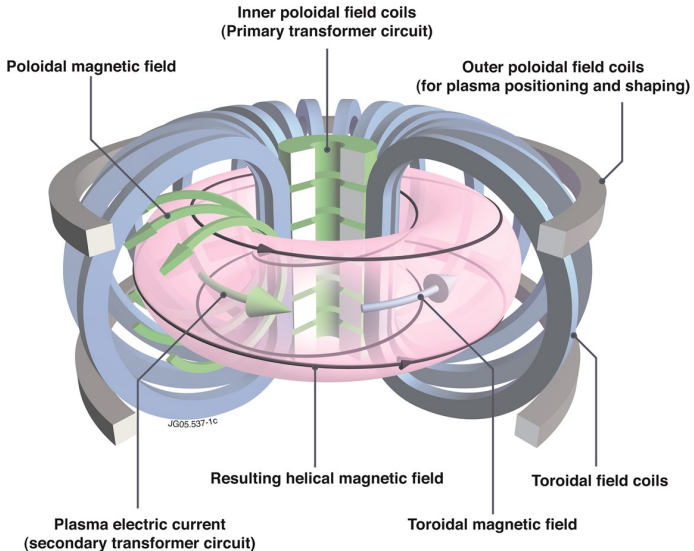
- Everything via <http://golem.fjfi.cvut.cz/Budapest>
 - This presentation
 - Control rooms
 - Contact: Vojtech Svoboda,
+420 737673903,
svoboda@fjfi.cvut.cz
 - Chat:
tokamak.golem@gmail.com or
skype: tokamak.golem



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Tokamak magnetic confinement concept



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

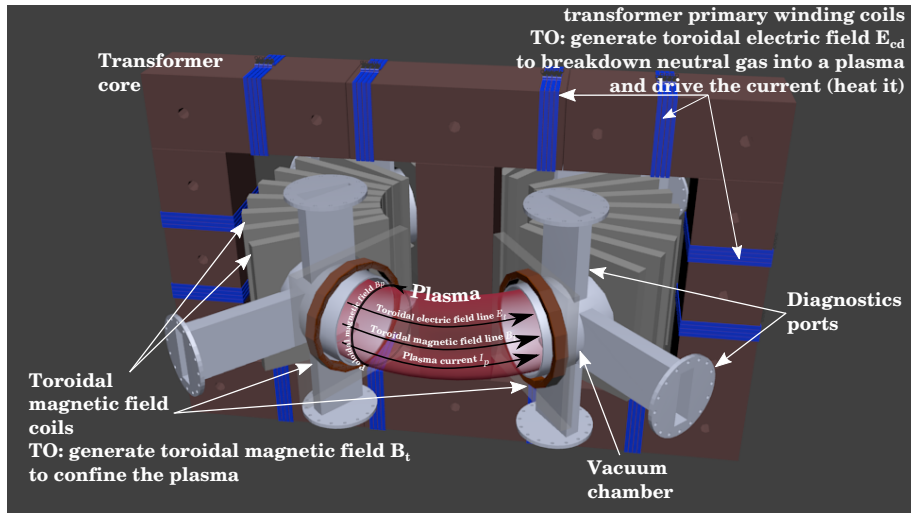


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- The scenario to make the (GOLEM) tokamak discharge
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- The GOLEM tokamak - guide tour

3 The Tokamak GOLEM (remote) operation

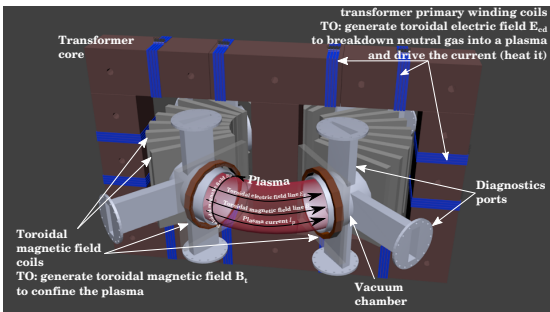
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Plasma in Tokamak (GOLEM) - the least to do

To do:

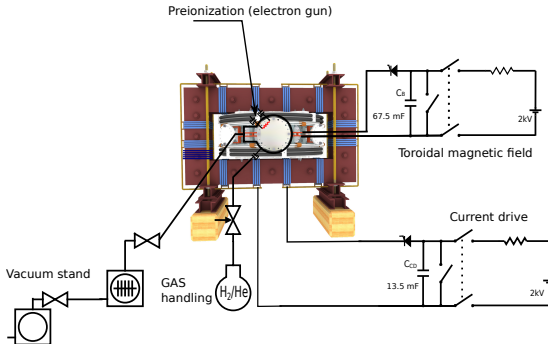
- session start phase:
 - Evacuate the chamber
- pre-discharge phase
 - Charge the capacitors
 - Fill in the working gas
 - Preionization
- discharge phase
 - Toroidal magnetic field to confine plasma
 - Toroidal electric field to breakdown neutral gas into plasma
 - Toroidal electric field to heat the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



Plasma in Tokamak (GOLEM) - the least to do

To do:

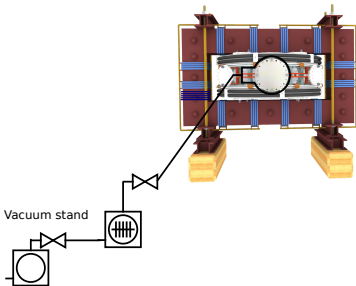
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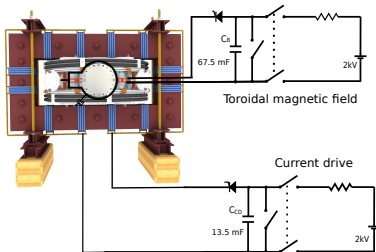
Plasma in Tokamak (GOLEM) - the least to do

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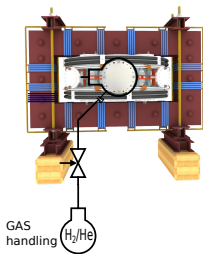
Plasma in Tokamak (GOLEM) - the least to do



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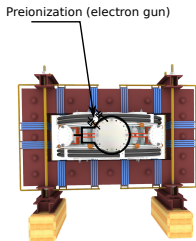
Plasma in Tokamak (GOLEM) - the least to do



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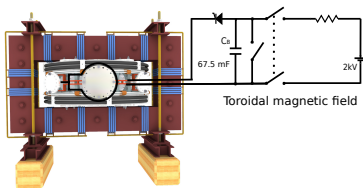
Plasma in Tokamak (GOLEM) - the least to do



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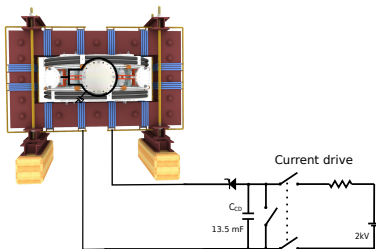
Plasma in Tokamak (GOLEM) - the least to do



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Plasma in Tokamak (GOLEM) - the least to do



To do:

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Tokamak GOLEM - schematic experimental setup

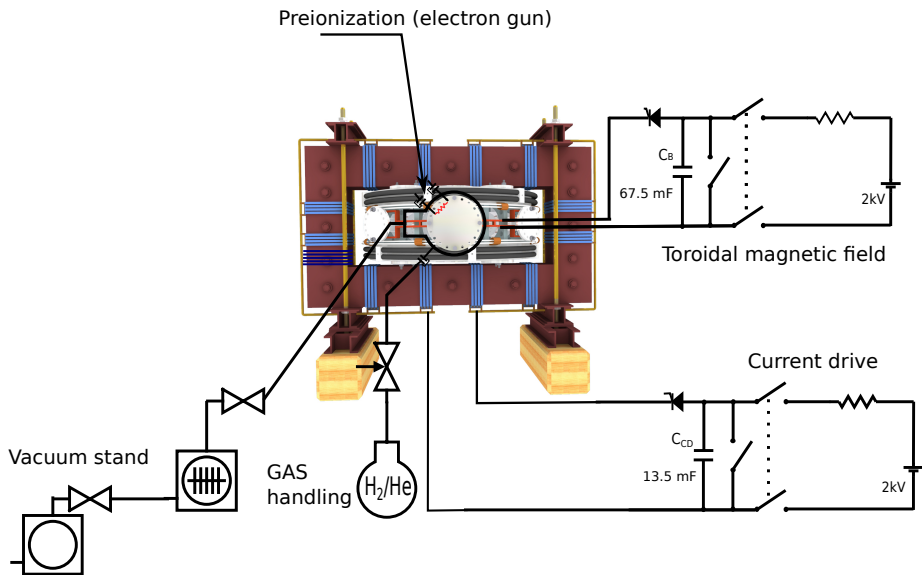


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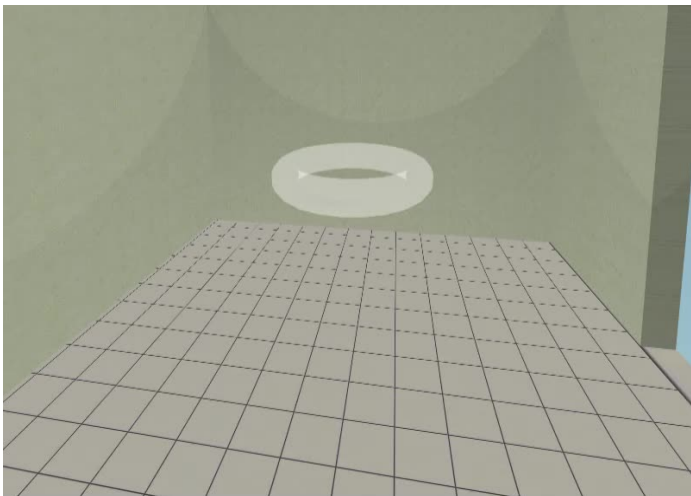
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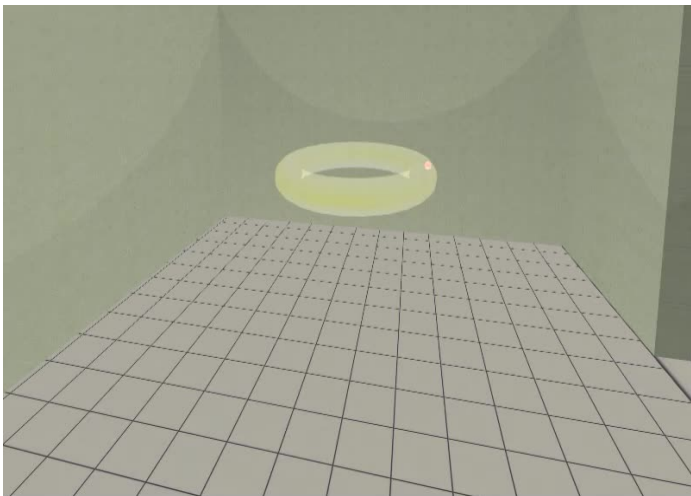
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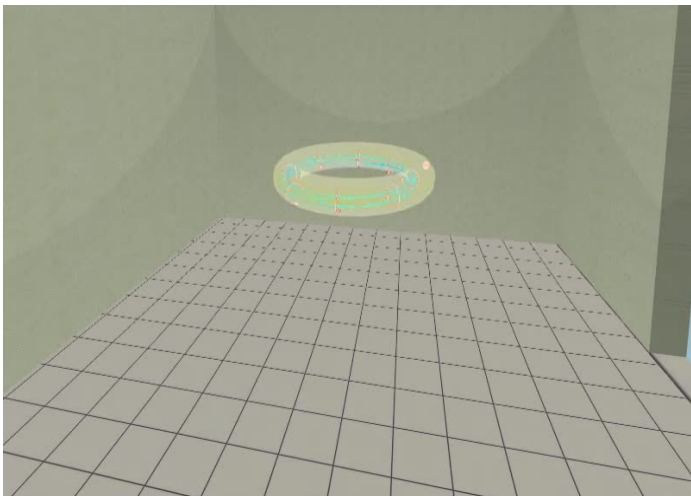
Introduce the working gas (Hydrogen x Helium)



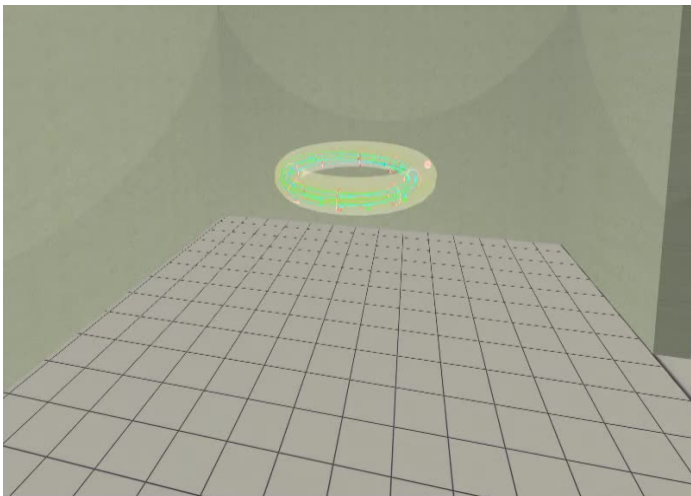
Switch on the preionization



Introduce the magnetic field



Introduce the electric field



Plasma ..

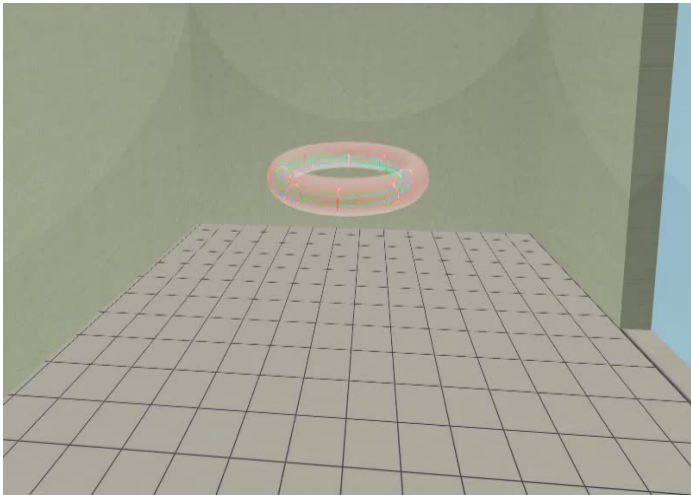


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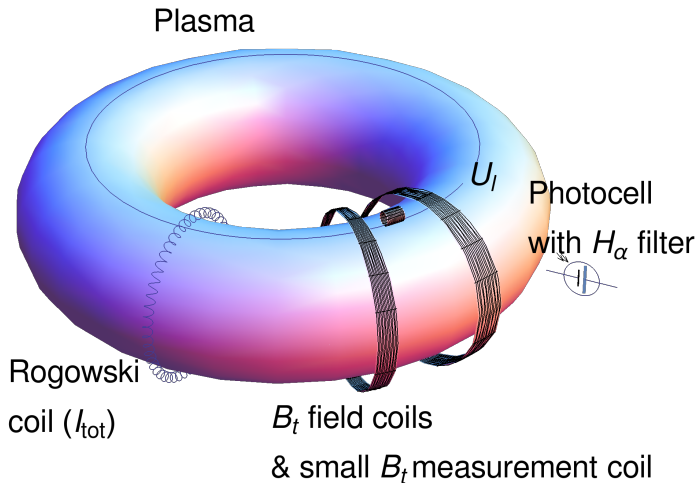
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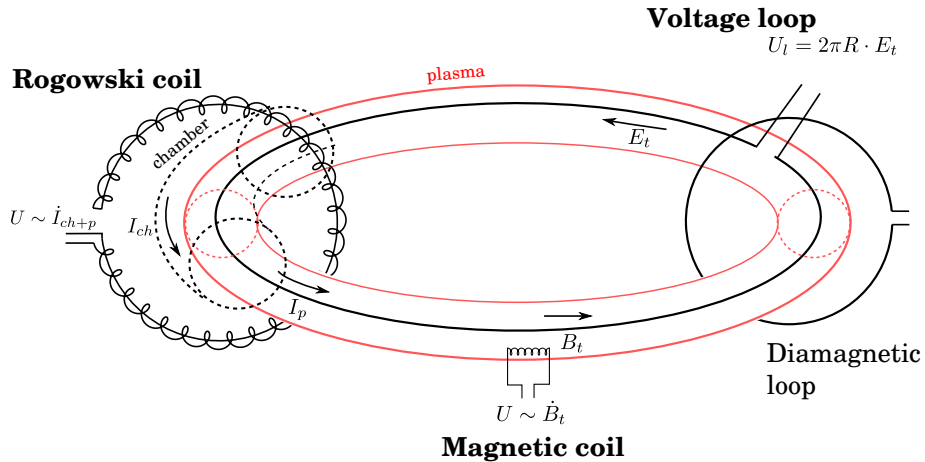
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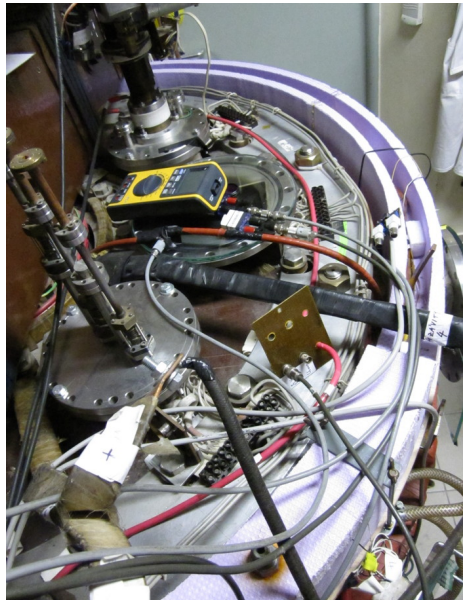
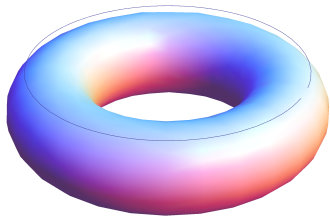
The GOLEM tokamak - basic diagnostics



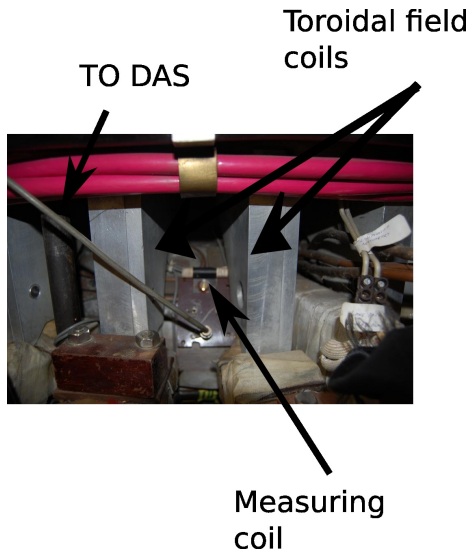
Schematic of electromagnetic diagnostics



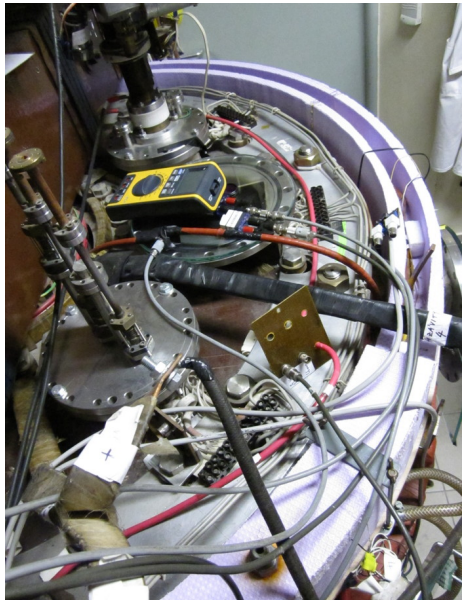
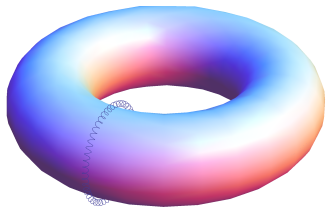
Loop voltage U_l @ the GOLEM tokamak



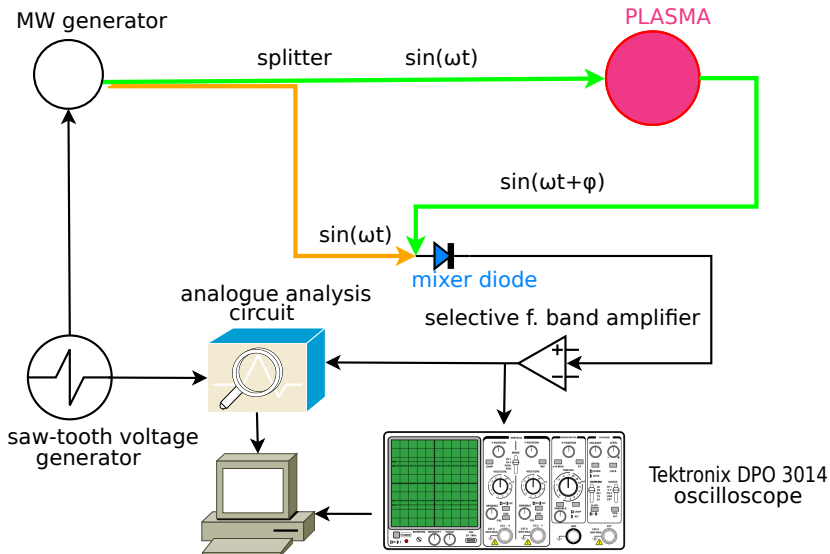
Toroidal magnetic field B_t @ the tokamak GOLEM



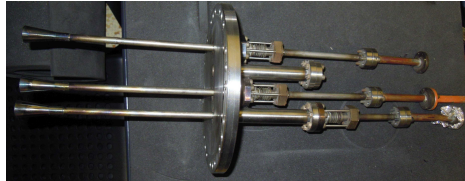
Total current I_{ch+p}



Electron density n_e interferometry measurement scheme



The GOLEM tokamak interferometry HW



"Typical", well executed discharge @ GOLEM

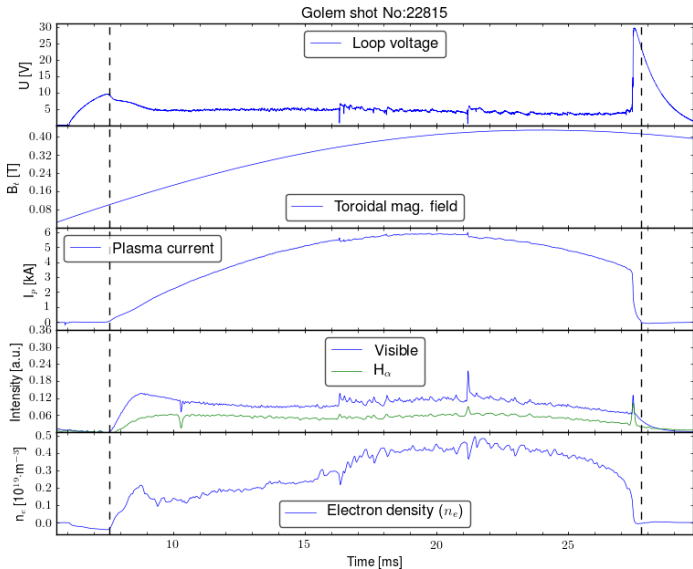


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Infrastructure room (below tokamak) 10/16



Infrastructure room (below tokamak) 10/16

Current drive CD field
and toroidal magnetic Bt field
circuits

To the tokamak
GOLEM

Rotary
pump

Vacuum
control

Current drive CD
capacitors

Plasma
stabilization

power
supply
2kV

Toroidal
magnetic field B
capacitors

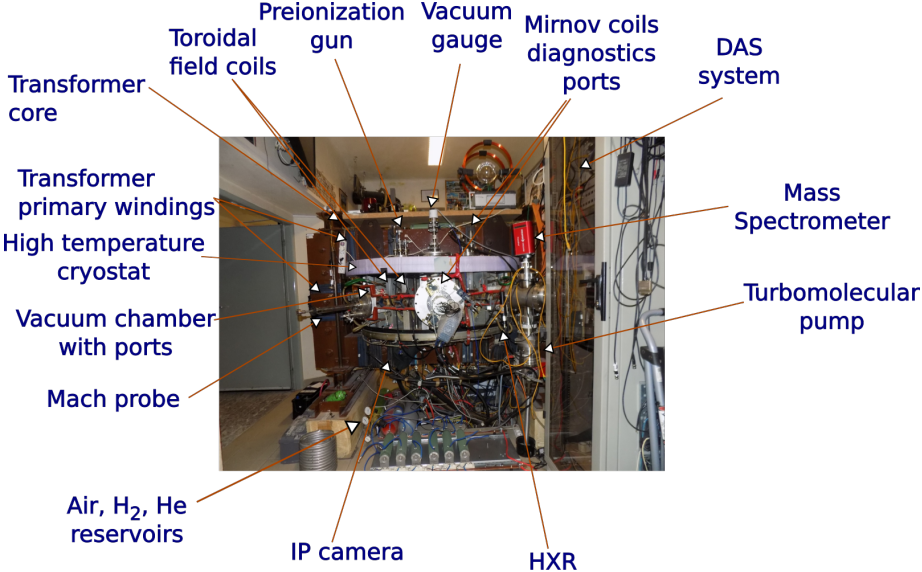
fire
protection
system



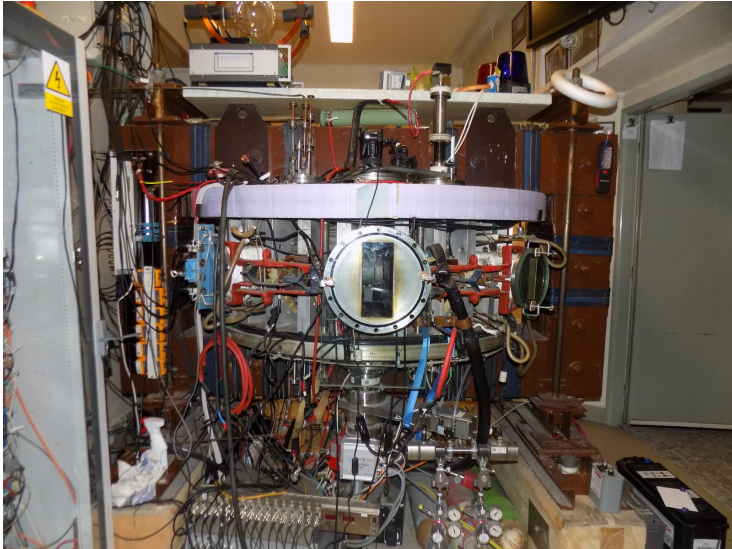
Tokamak room (North) 10/16



Tokamak room (North) 10/16



Tokamak room (South) 10/16



Tokamak room (South) 10/16

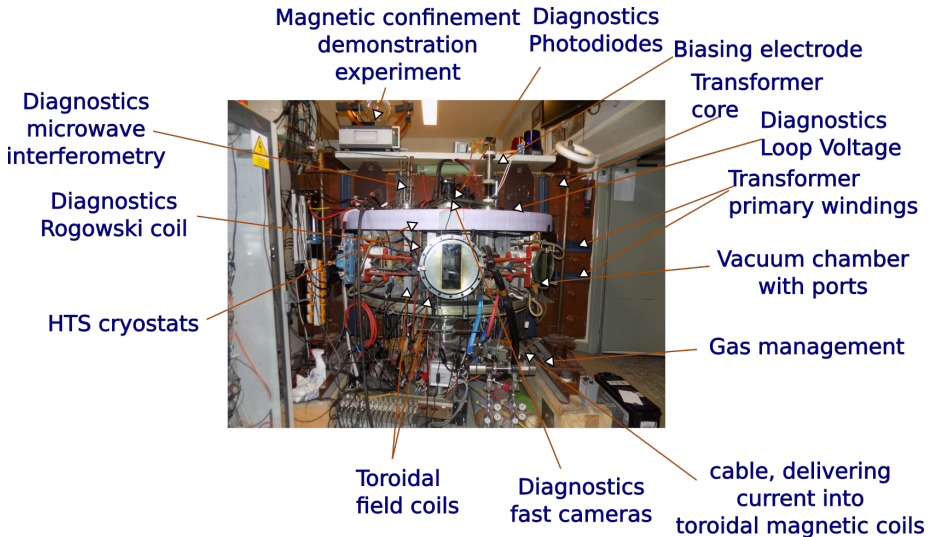


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Control room: Introduction

GOLEM remote Introduction **Control room** Live Results

Prague Access: Level 1 Help

Introduction Working gas Preionization Magnetic field Current drive Submit

This web interface will walk you through the process of configuring a discharge in the GOLEM tokamak. All settable values are perfectly safe. Proceed through each step by setting the desired values and then clicking the [Next](#) button. You can always go to a specific step by clicking its tab.

Preionization (electron gun)

Vacuum stand

23 mF C_p

2kV

Toroidal magnetic field

Current drive

11.3 mF C_{cp}

2kV

GAS handling H_2/H_3

[Next](#)

3D model rendering method: [Static image \(fast\)](#) [Interactive X3DOM \(slower\)](#)

Control room: Working gas

GOLEM Remote Introduction **Control room** Live Results

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

Toroidal magnetic field

Toroidal electric field

Gas type and pressure p_{gas} : 38 mPa

Hydrogen Helium

Next Set recommended value

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

Control room: Preionization

GOLEM remote PREIONIZATION Control room Live Results

Introduction Working gas **Preionization** Magnetic field Electric field Submit

The neutral working gas must be first ionized in order to break down into a plasma. Using the electron gun will locally ionize the gas. Without any ionization, no plasma can form.

Preionization (electron gun)

Vacuum stand

GAS handling

Toroidal magnetic field

Toroidal electric field

67.5 mF

13.5 mF

230V

230V

ionization method

Steady gas No ionization

[Next](#)

3D model rendering method [Static image \(left\)](#) [Interactive X3DOM \(right\)](#)

Control room: Magnetic field B_t

GOLEM interface: Introduction, Preionization, **Magnetic field**, Electric field, Submit

Press F11 to exit full screen
3D model rendering method: **Static image (fast)** Interactive X3DOM (slower)

Set the voltage on the capacitors to be discharged into the toroidal field coils. The higher the voltage, the larger the magnetic field confining the plasma.

Preionization (electron gun)

Vacuum stand

Toroidal magnetic field

Toroidal electric field

GAS handling

Capacitor voltage $U_{C_1} = 600 \text{ V}$

Next Set recommended value

The 3D rendering shows a complex, multi-segmented toroidal structure representing the magnetic field coils. The structure is composed of numerous white, curved segments arranged in a circular pattern. A red and blue ring is visible around the structure, likely representing the electric field coils. The entire assembly is mounted on a grey grid floor.

Control room: Current drive E_{cd}

GOLEM Interface Introduction Control room Live Results

the Torion Politecnico, Italy Group 1 Access: Level 2 Help

Introduction Working gas Preionization Magnetic field **Electric field** Submit

Set the voltage on the capacitors to be discharged into the **primary transformer winding**. The higher the voltage, the larger the electric field creating and heating the plasma. The electric field capacitors are discharged after a configurable delay with respect to the magnetic field capacitors.

Preionization (electron gun)

Vacuum stand

Toroidal magnetic field

Toroidal electric field

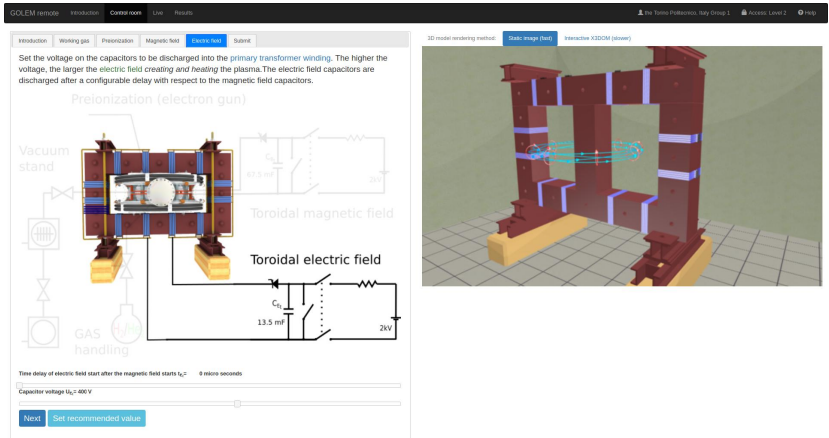
GAS handling

Time delay of electric field start after the magnetic field starts t_d : 0 micro seconds

Capacitor voltage U_c : 400 V

Next Set recommended value

3D model rendering method **Static image (fast)** Interactive X3DOM (slow)



The screenshot displays the 'GOLEM Interface' with a navigation bar at the top. The main content area is titled 'Control room' and features a 'Preionization' section. This section includes a 3D model of a toroidal device with a central vacuum stand and gas handling system. The model is rendered in a static image format. To the right of the model, there are two circuit diagrams: one for the 'Toroidal magnetic field' with a 67.5 mF capacitor and a 2kV source, and another for the 'Toroidal electric field' with a 13.5 mF capacitor and a 2kV source. Below the diagrams, there are two sliders: one for 'Time delay of electric field start after the magnetic field starts t_d ' set to 0 micro seconds, and another for 'Capacitor voltage U_c ' set to 400 V. A 'Next' button and a 'Set recommended value' button are located at the bottom of the control panel. On the right side of the interface, there is a 3D model rendering method selector with 'Static image (fast)' selected and 'Interactive X3DOM (slow)' as an alternative.

Control room: ... and Submit

GOLEM Interface Introduction **Control room** Live Results

the Torneo Politecnico, Italy Group 1 Access: Level 2 Help

Introduction Working gas Preionization Magnetic field Electric field **Submit**

Write a comment describing your discharge configuration, i.e. the scientific aim of your experiment. Or just leave a friendly message.

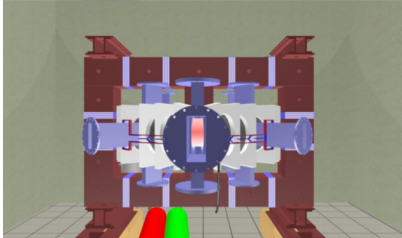
Comment

Click the **Submit** button to send your configuration into the queue. **Submit**

After submission you can switch the discharge **Live** or go back to the Introduction tab and start again. Or you can go to specific control tabs and reconfigure the discharge and then submit another discharge request.

[Watch the discharge Live!](#) [Go back to Introduction](#)

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



Shot homepage

GOLEM » Shot #22471 »



Diagnostics

- ✓ Interferometer
- ✓ Spectrometer
- ✗ FastCamera
- ✓ HXR

Analysis

- ✓ ShotHomepage

DAS

- ✓ TektronixDPO
- ✓ NIstandard
- ✓ Papouch_St
- ✓ Papouch_Ko
- ✓ Nloctopus

Vacuum log

Other

- Data
- References
- About
- Wiki
- Utilities

Navigation

- Next
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Tokamak GOLEM - Shot Database - 22471

Date: 2016-09-29 - 14:33:57
Session: TrainingCourses/Universities/Uni_Belgrade.rs/2016/
Comment: Standard discharge

Basic parameters: (compare)

- Gas pressure p_{ch} : 0.42 → 20.39 mPa (request: 20 mPa) ^{WIKI}
- Working gas: H
- Preionization: Upper el. gun
- Chamber temperature: 27.20 C
- C_B capacitors charged to: 800 V, triggered 5.0 ms ^{WIKI}
- C_{BD} capacitors charged to: 0 V, triggered 5.0 ms ^{WIKI}
- C_{CD} capacitors charged to: 400 V, triggered 6.0 ms ^{WIKI}
- C_{ST} capacitors charged to: 0 V, triggered 5.0 ms ^{WIKI}
- Probability of breakdown: 85% ^{WIKI}
- Time since session beginning: 0:07:50 h

Plasma parameters:

- Plasma life time 14.8 [ms] (from 7.8 to 22.6)
- Mean toroidal magnetic field B_t : 0.23 T ^{WIKI}
- Mean plasma current: 3.60 kA ^{WIKI}
- Mean Uloop: 5.92 V ^{WIKI}
- Break down voltage: 9.6 V ^{WIKI}
- Ohmic heating power: 21.33 kW
- Q edge: 2.9 ^{WIKI}
- Electron temperature: 41.1 eV ^{WIKI}
- Line electron density: 5.52 [$10^{17} m^{-2}$] ^{WIKI}

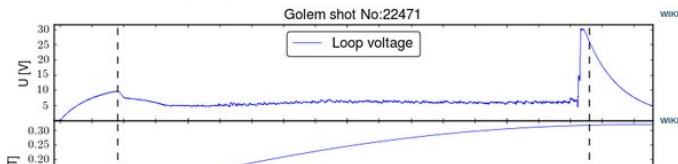


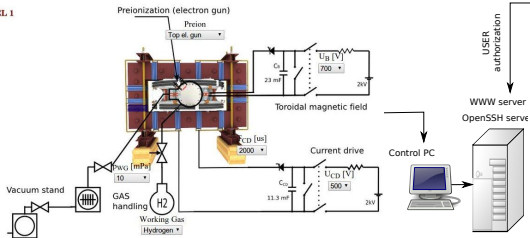
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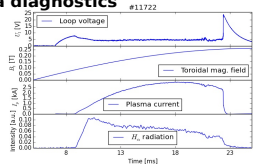
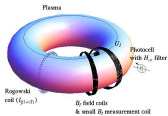
The global schematic overview of the GOLEM experiment

LEVEL 1

Tokamak technology setup



Basic plasma diagnostics



internet

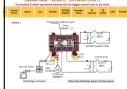
Virtual control room (remote participation)

WWW control interface

Data presentation

HTML & PHP scripts

HTML (www pages)



SSH control interface

WINDOWS via putty

Data handling



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

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



- Everything via <http://golem.fjfi.cvut.cz/Budapest>
 - This presentation
 - Control rooms
 - Contact: Vojtech Svoboda,
+420 737673903,
svoboda@fjfi.cvut.cz
 - Chat:
tokamak.golem@gmail.com or
skype: tokamak.golem



Acknowledgement

Financial support highly appreciated:

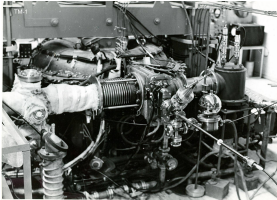
CTU RVO68407700, SGS 17/138/OHK4/2T/14, GAČR GA18-02482S, EU funds CZ.02.1.01/0.0/0.0/16_019/0000778 and CZ.02.2.69/0.0/0.0/16_027/0008465, IAEA F13019, FUSENET and EUROFUSION.

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

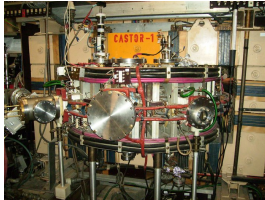
Thank you for your attention

Tokamak TM1
@Kurchatov Institute near Moscow
~1960-1977



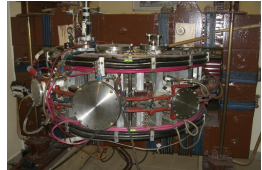
SCIENCE

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 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
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LEVEL 1

Preionization (electron gun)
Preion:

Toroidal magnetic field

Current drive

Discharge comment

Place the discharge setup into the queue

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References I

- [1] Wikipedia contributors. Golem — Wikipedia, the free encyclopedia. <https://en.wikipedia.org/w/index.php?title=Golem>, 2020. [Online; accessed 29-March-2020].
- [2] J. Wesson. *Tokamaks*, volume 118 of *International Series of Monographs on Physics*. Oxford University Press Inc., New York, Third Edition, 2004.
- [3] 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.
- [4] Brotankova, J. *Study of high temperature plasma in tokamak-like experimental devices*. PhD thesis, 2009.
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