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

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on behalf of the tokamak GOLEM team
for the Torino Politecnico, Italy

December 2, 2020

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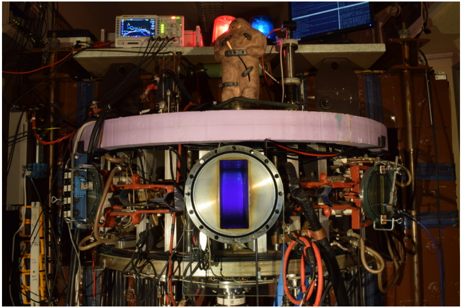
The GOLEM tokamak basic characteristics
The grandfather of all tokamaks (ITER newsline 06/18)



- 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 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.

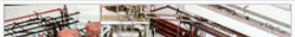
Experimental tokamaks [edit]

Currently in operation [edit]

(in chronological order of start of operations)

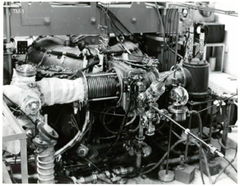
- 1960s: TM1-MH (since 1977 Castor; since 2007 Golem[12]) in Prague, Czech Republic. In operation in Kurchatov Institute since early 1960s but renamed to Castor in 1977 and moved to IPP CAS,[13] Prague; in 2007 moved to FNSPE, Czech Technical University in Prague and renamed to Golem.[14]
- 1975: T-10,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



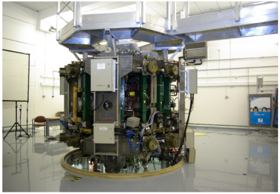
The GOLEM tokamak for education - historical background

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



1974

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

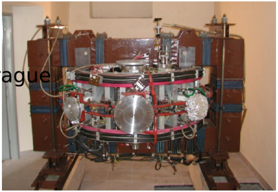


2006

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

2008

Czech Technical University Prague
Czech republic
GOLEM



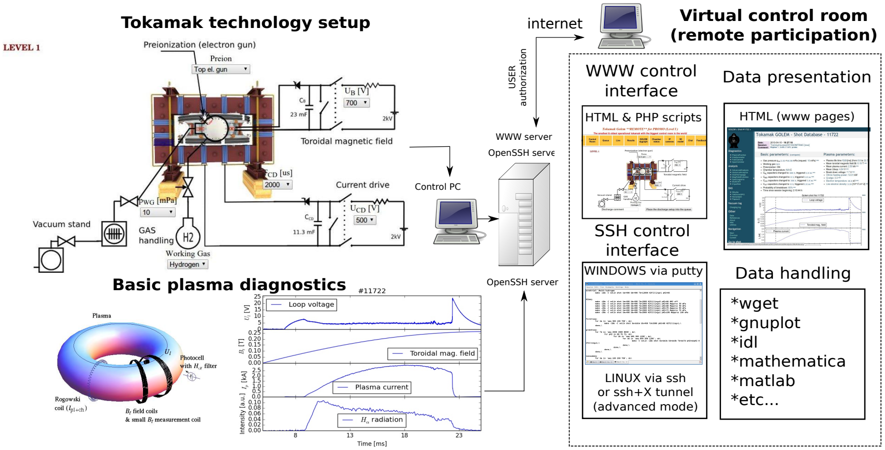
GOLEM

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

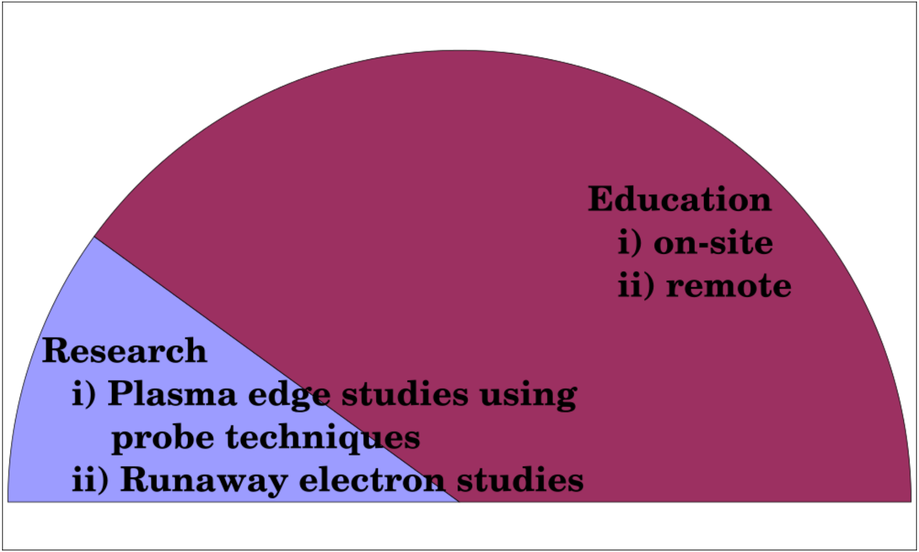
there is hidden indeed "infernal" power. Yet it is the very power of celestial stars themselves. Calmly dormant, awaiting mankind to discover the magic key, to use this power for their benefit...

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. [1].

The global schematic overview of the GOLEM experiment

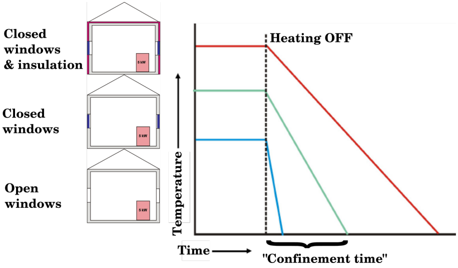


The GOLEM tokamak mission

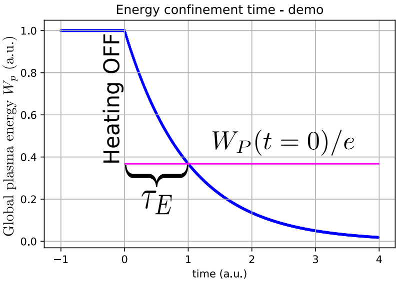


Towards ... Energy confinement time

House



Tokamak



Lawson criterion

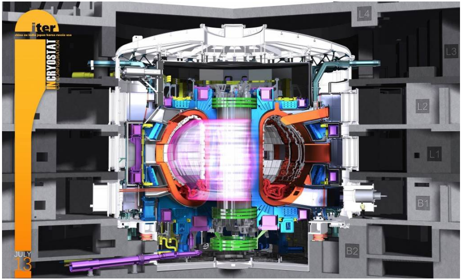
- The confinement time: $\tau_E = \frac{W}{P_{\mathrm{loss}}}$
- Energy density: $W = 3nk_{\mathrm{B}}T$
- Reactions per volume per time of fusion reactions is: $f = n_{\mathrm{d}}n_{\mathrm{t}}\langle\sigma v\rangle = \frac{1}{4}n^2\langle\sigma v\rangle$
- Fusion heating fE_{ch}, where $E_{\mathrm{ch}} = 3.5\,\mathrm{MeV}$ 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)

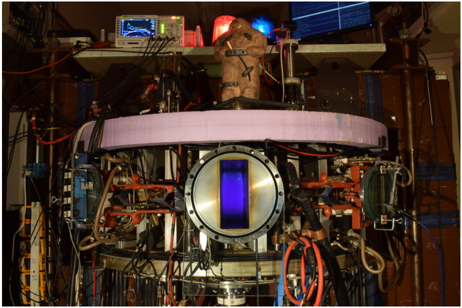
The competition

The ITER: 3.6 s



credit:[3]

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



credit:[4]

Production

- Everything via `http://golem.fjfi.cvut.cz/Torino`
  - 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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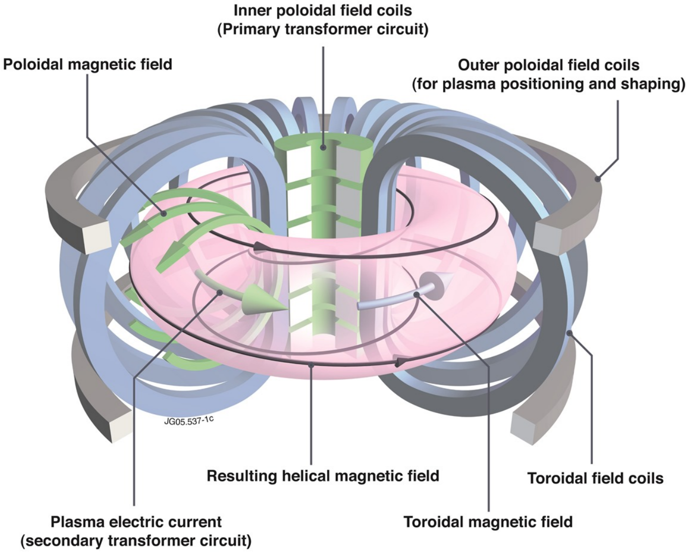
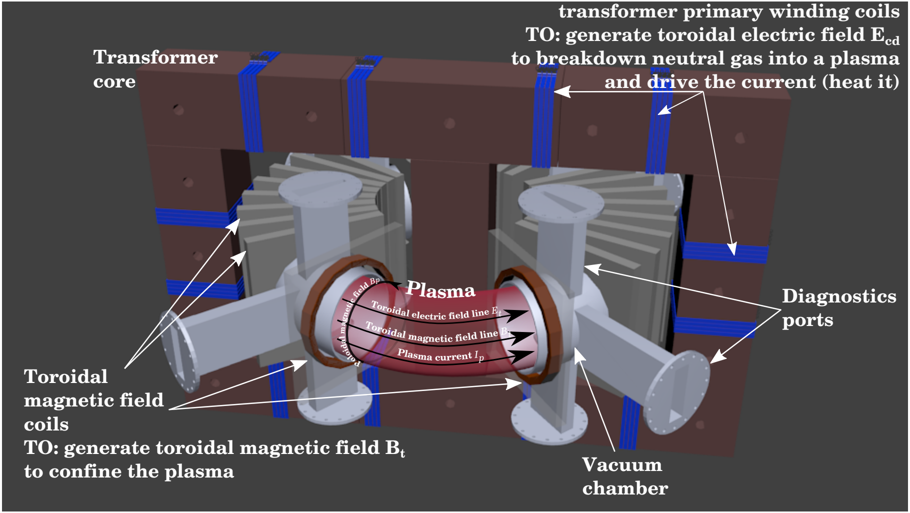
Tokamak magnetic confinement concept



credit:Tokamak concept@Wiki

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



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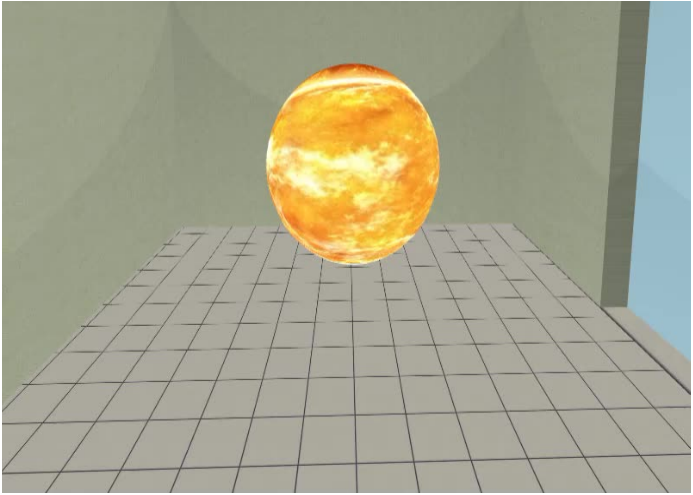
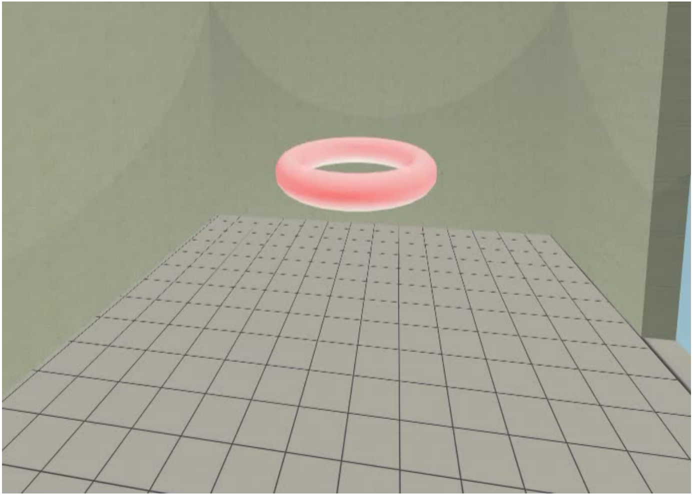
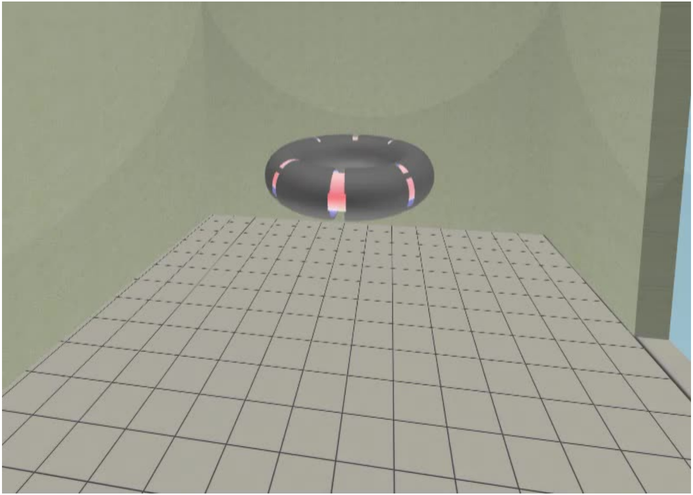
Our goal: the technology to create a μSun on the Earth



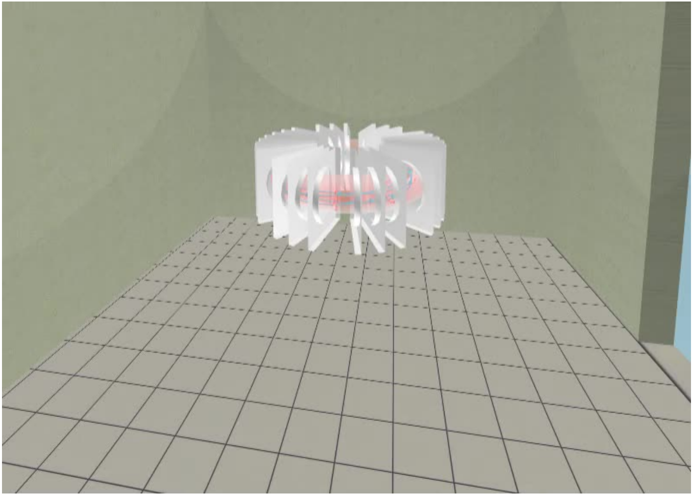
Magnetic confinement requires toroidal geometry



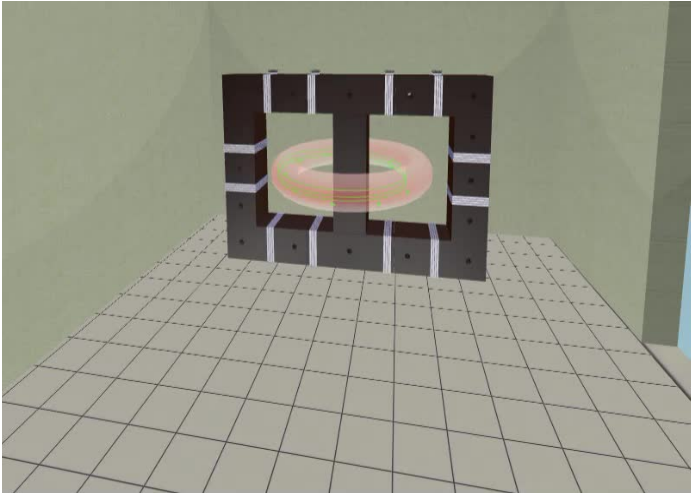
A chamber contains the thermonuclear reaction



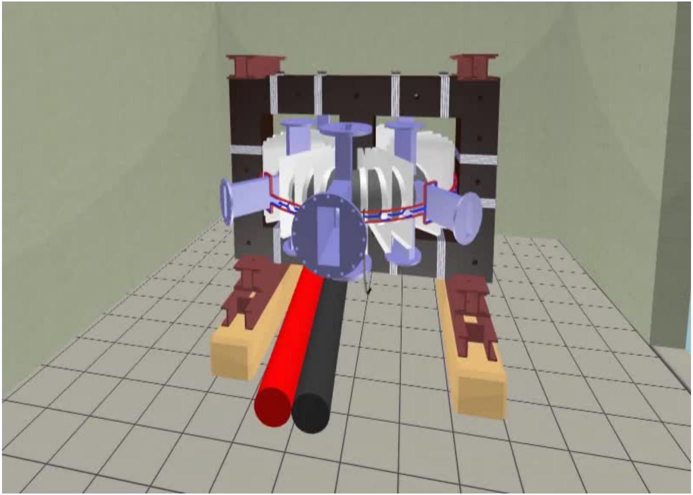
Toroidal magnetic field coils confine the plasma



A transformer action creates and heats the plasma



The final technology altogether



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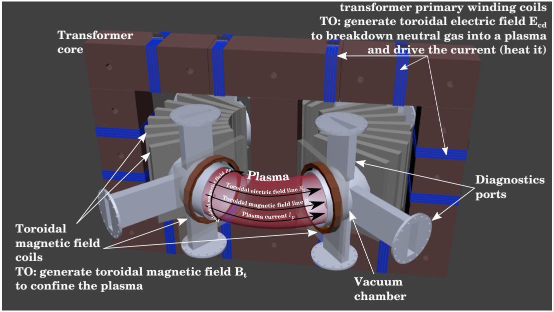
Plasma in Tokamak (GOLEM) - the least to do



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

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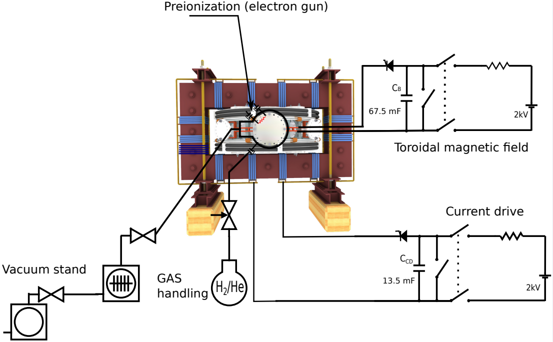

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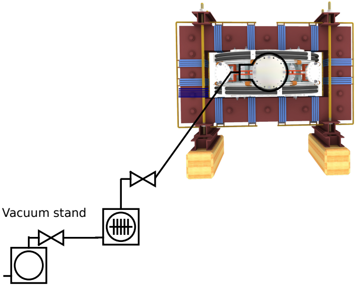

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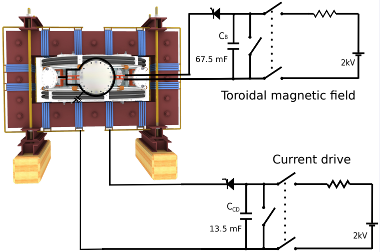

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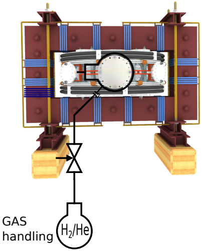

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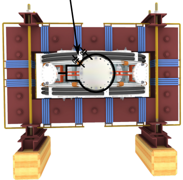

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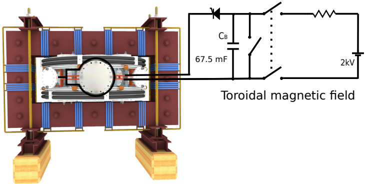

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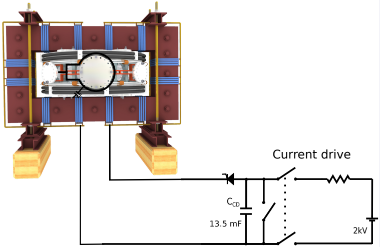

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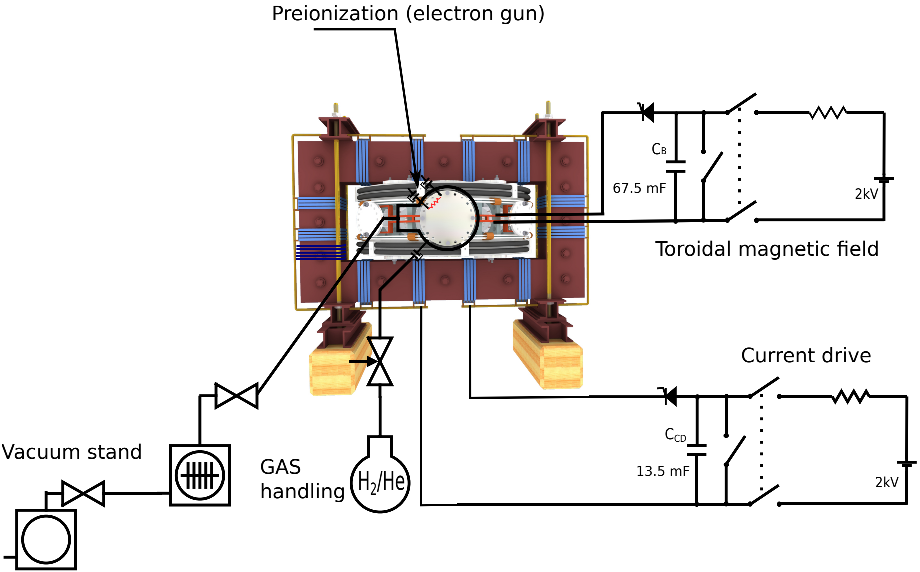
Tokamak GOLEM - schematic experimental setup



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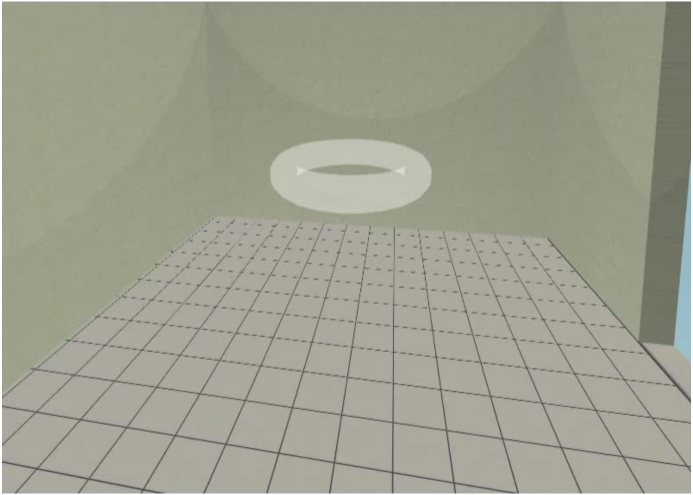
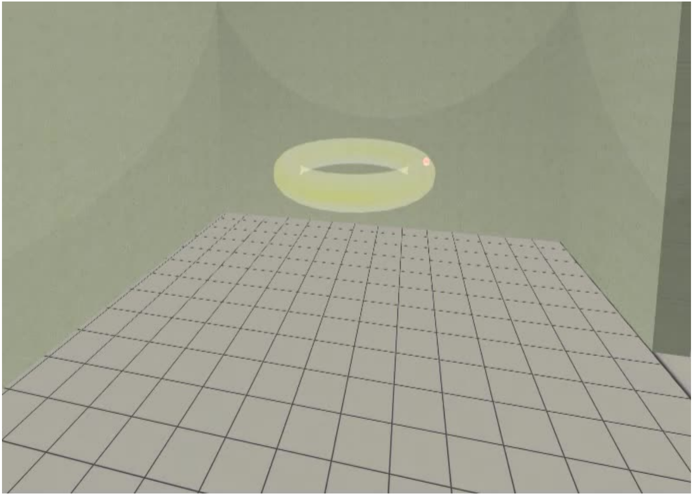
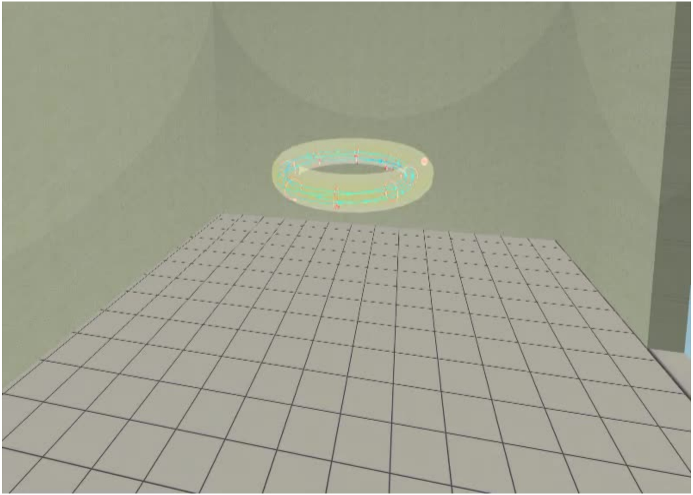
Introduce the working gas (Hydrogen x Helium)



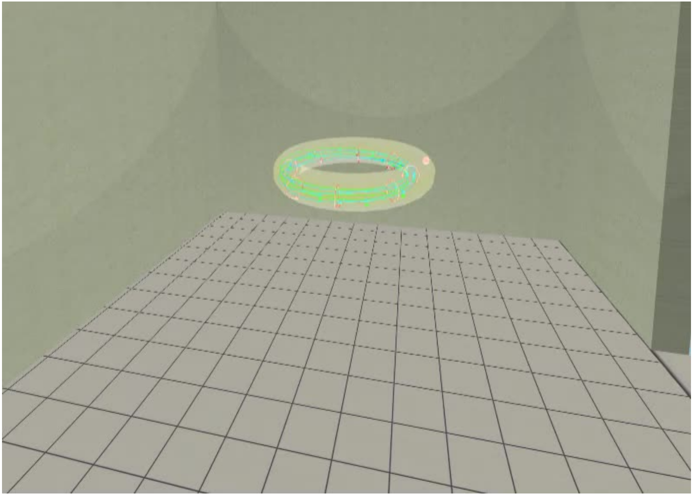
Switch on the preionization



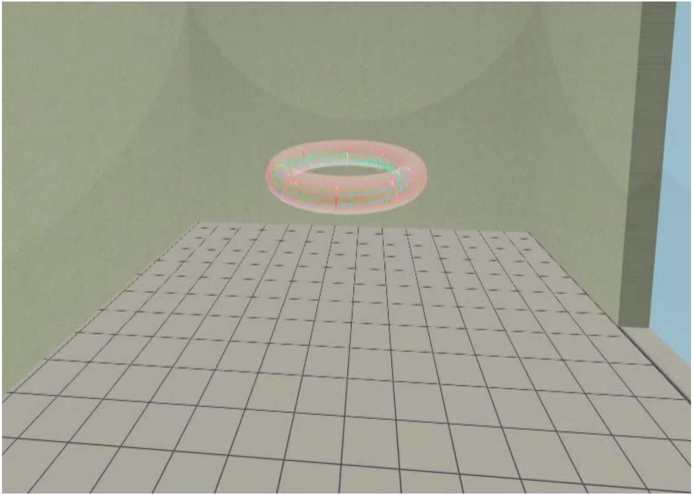
Introduce the magnetic field



Introduce the electric field



Plasma ..



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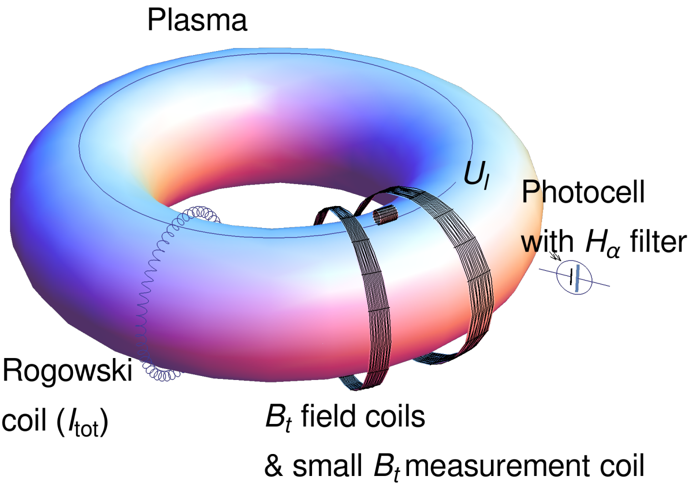
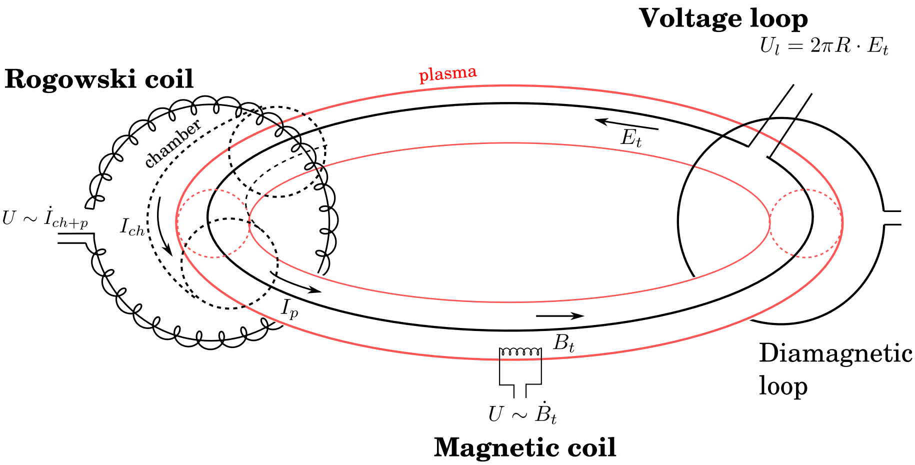
The GOLEM tokamak - basic diagnostics

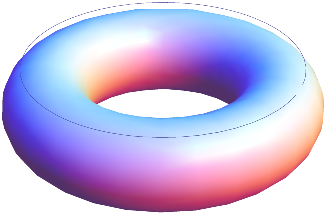


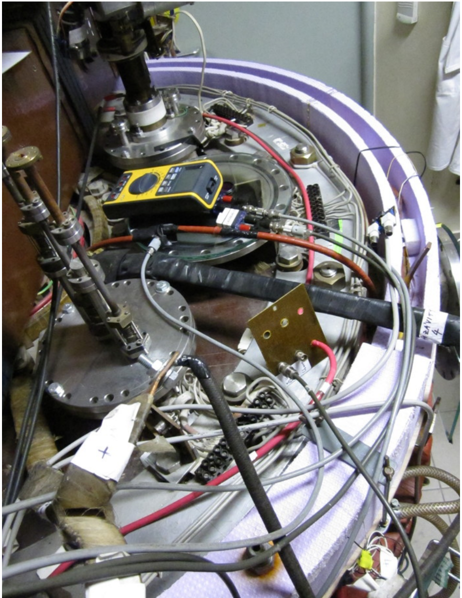
Schematic of electromagnetic diagnostics



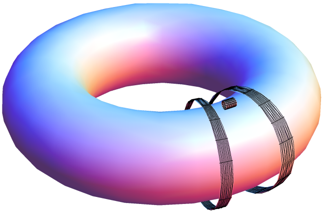
credit:[5]

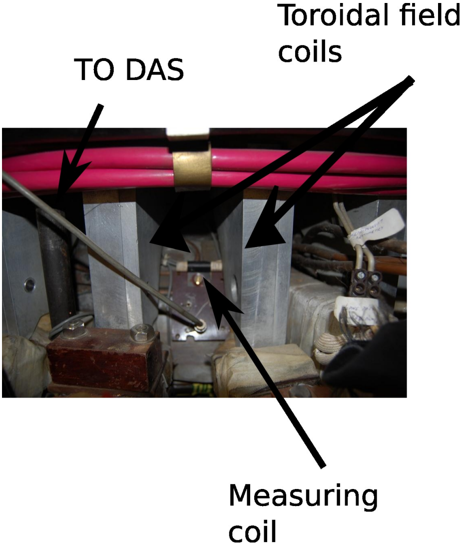
Loop voltage U_l @ the GOLEM tokamak



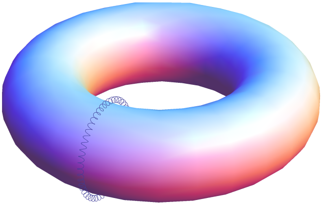


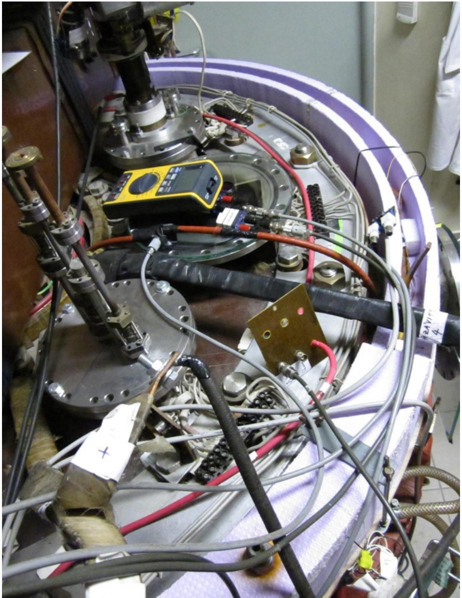
Toroidal magnetic field B_t @ the tokamak GOLEM



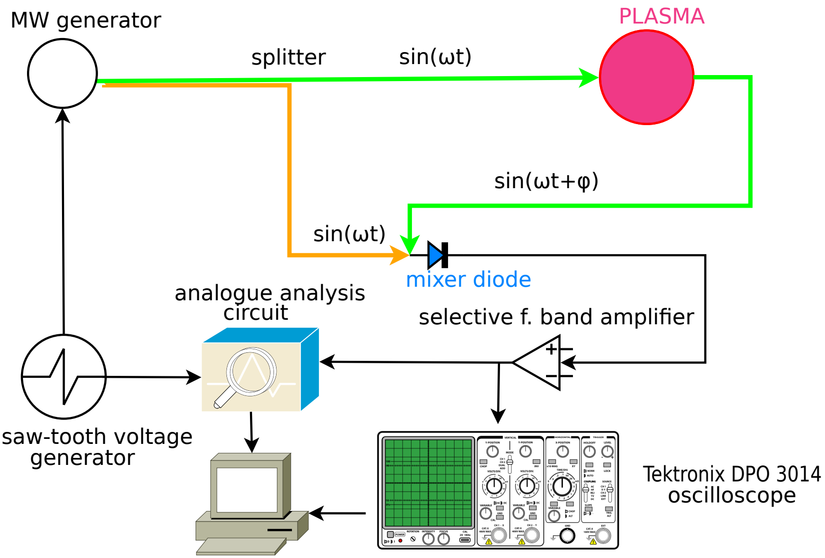


Total current I_{ch+p}

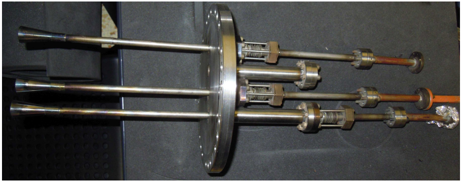




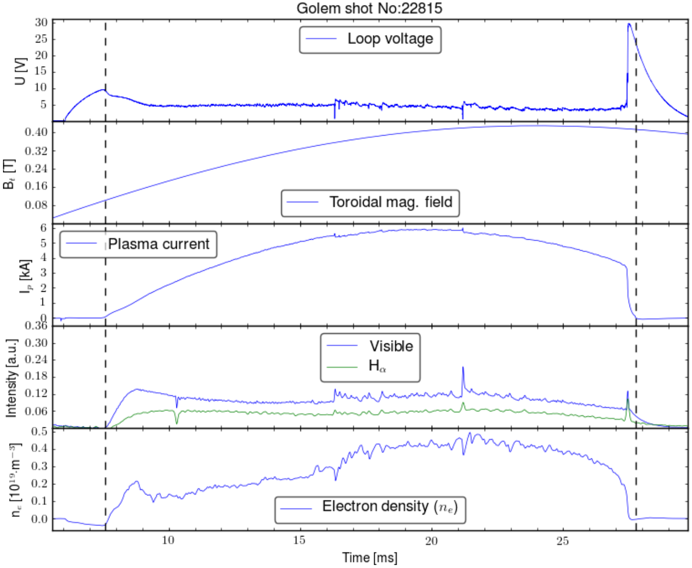
Electron density n_e interferometry measurement scheme



The GOLEM tokamak interferometry HW



"Typical", well executed discharge @ GOLEM



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Infrastructure room (below tokamak) 10/16

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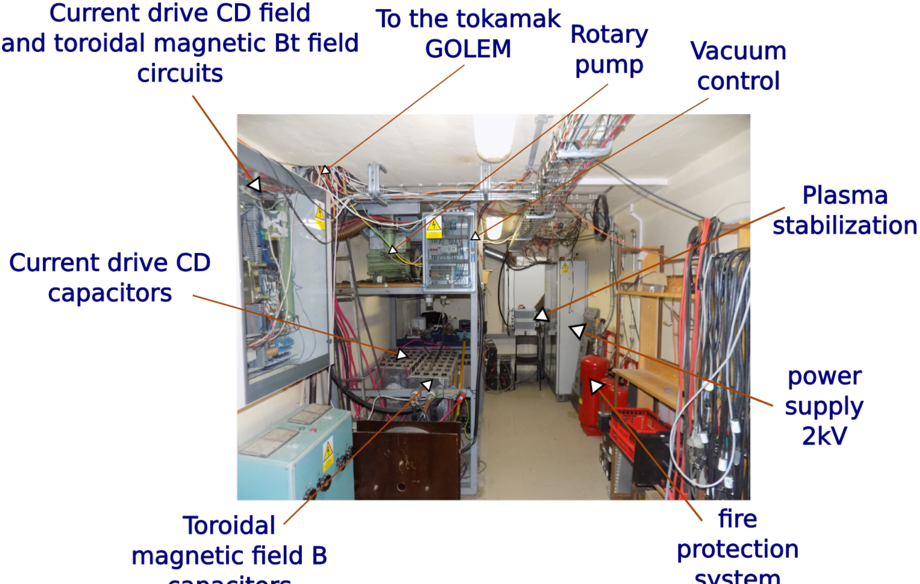
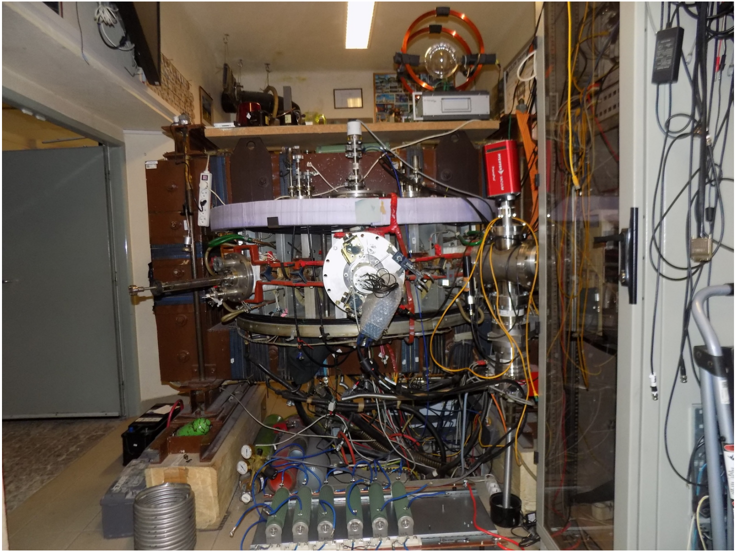
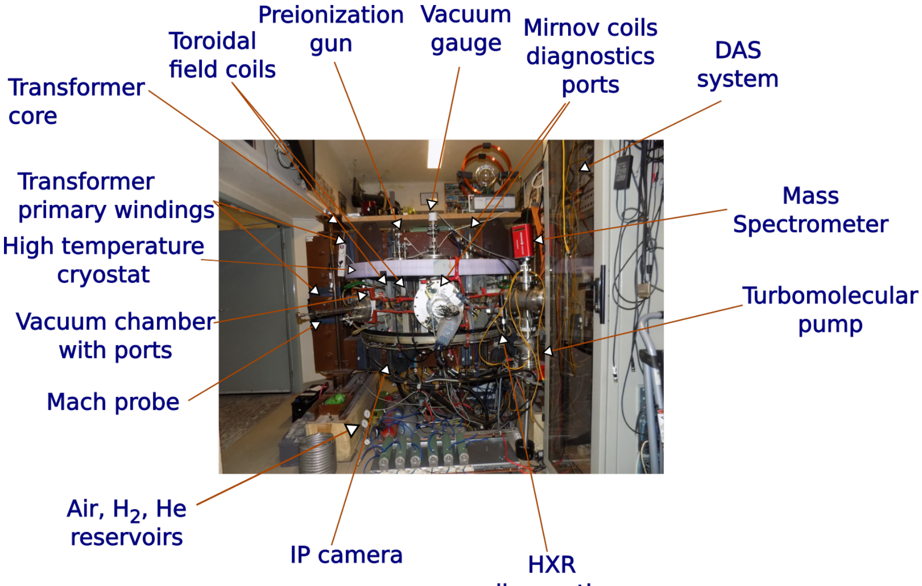


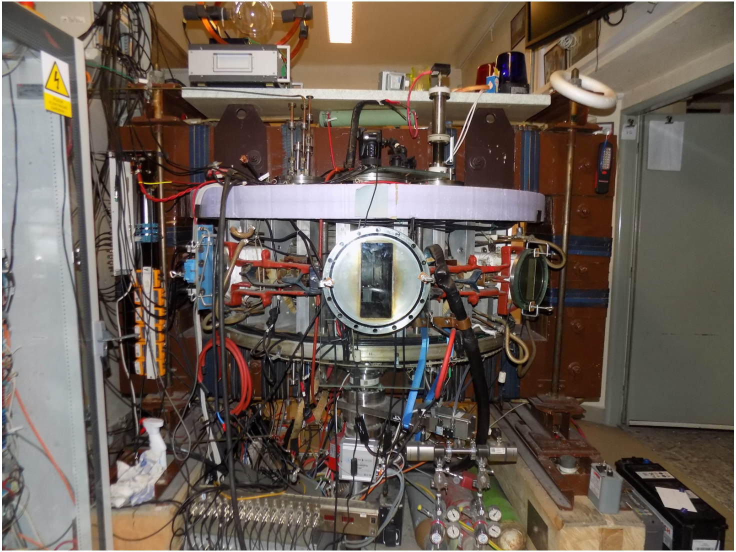
Tokamak room (North) 10/16



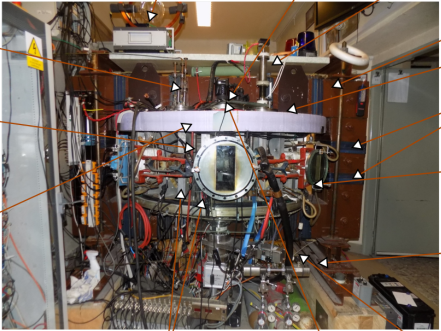
Tokamak room (North) 10/16



Tokamak room (South) 10/16



Tokamak room (South) 10/16



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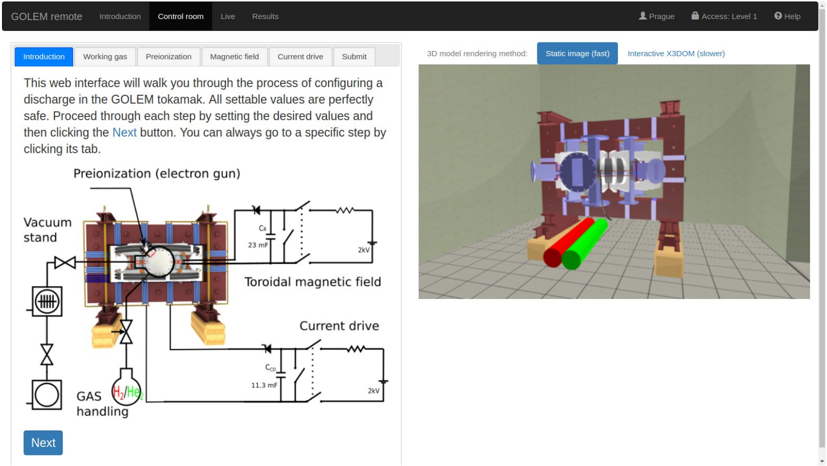
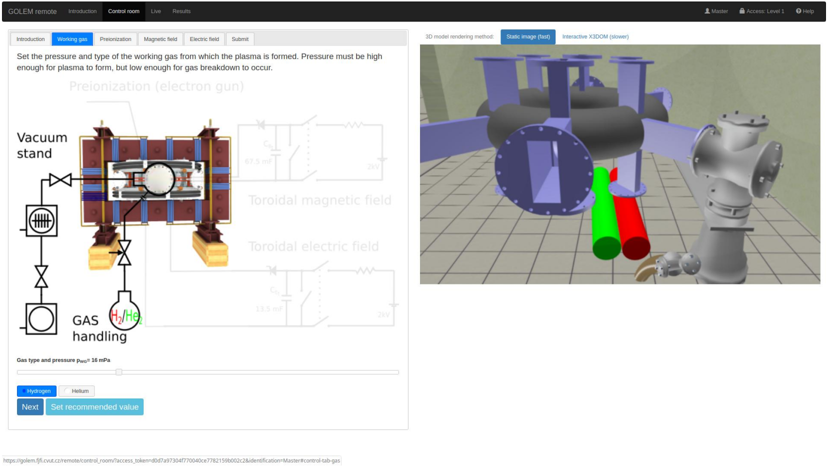
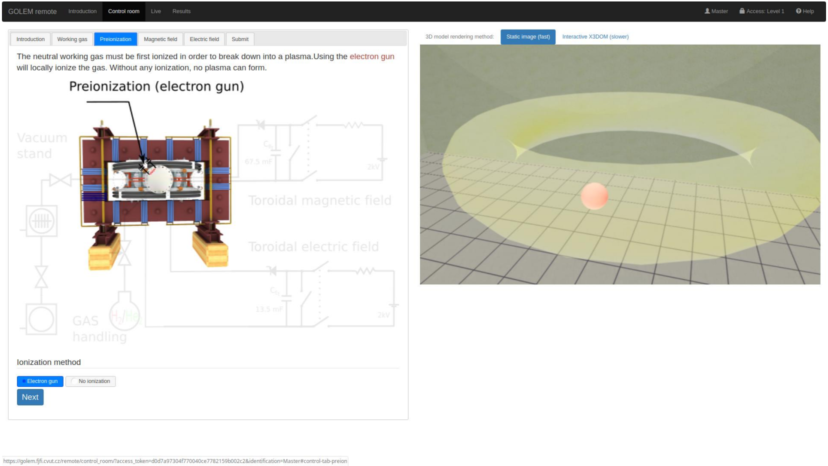
Control room: Introduction



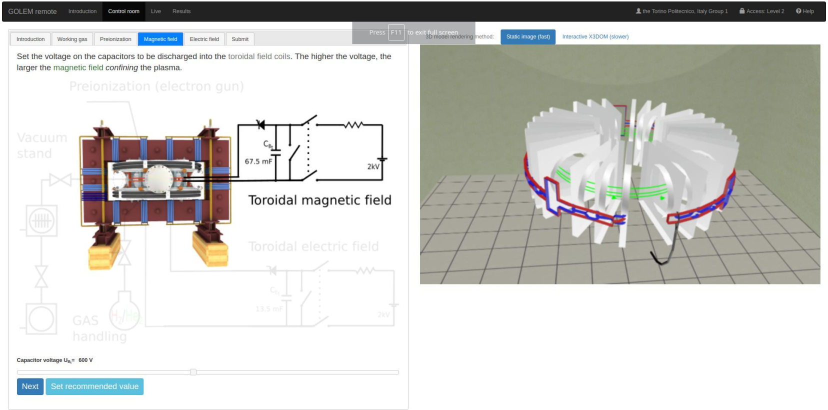
Control room: Working gas



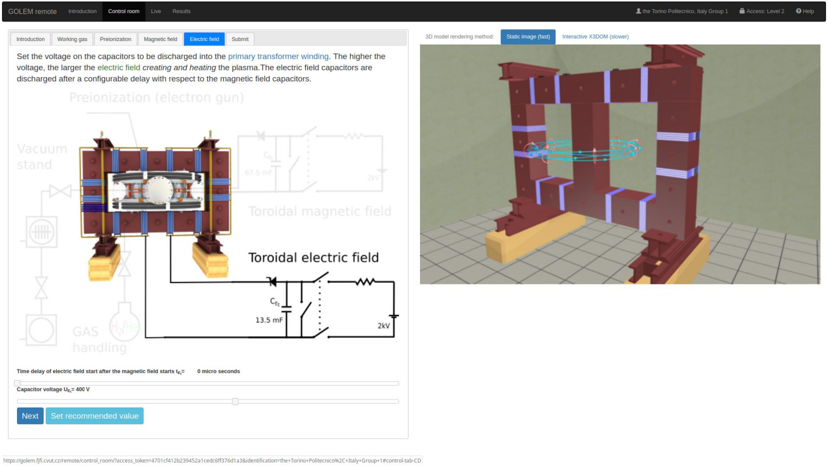
Control room: Preionization



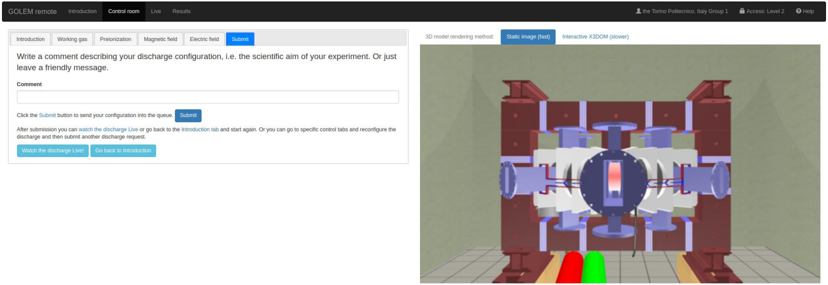
Control room: Magnetic field B_t



Control room: Current drive E_{cd}

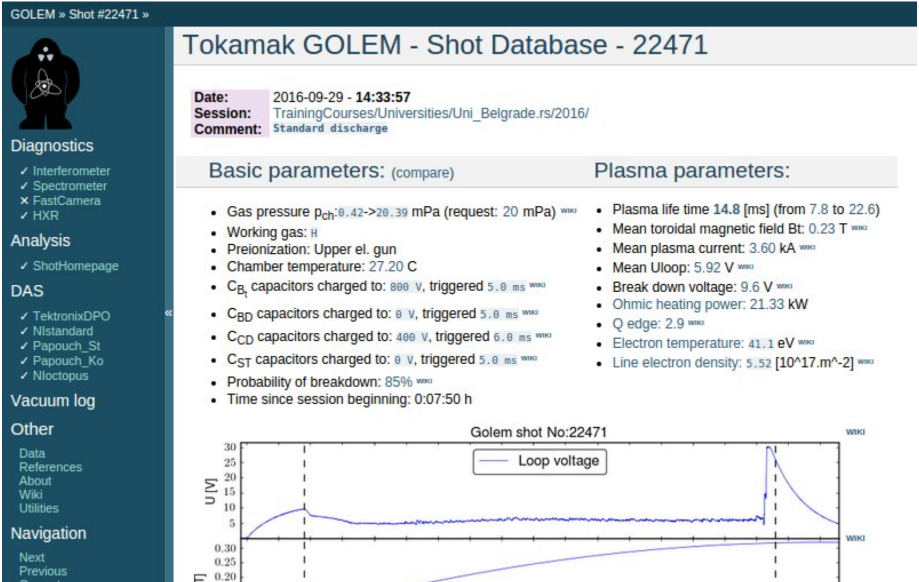


Control room: ... and Submit



https://golem.fjfi.cvut.cz/remote/control_room/?access_token=4701cf412b239452a1cedc6ff376d1a3&identification=the+Torino+Politecnico%2C+Italy+Group+1#control-tab-submit

Shot homepage



GOLEM » Shot #22471 »

Tokamak GOLEM - Shot Database - 22471

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

Diagnostics
- ✓ Interferometer
- ✓ Spectrometer
- × FastCamera
- ✓ HXR

Analysis
- ✓ ShotHomepage

DAS
- ✓ TektronixDPO
- ✓ NIstandard
- ✓ Papouch_St
- ✓ Papouch_Ko
- ✓ NIoctopus

Vacuum log

Other
- Data
- References
- About
- Wiki
- Utilities

Navigation
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- Previous

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_t} 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 Bt: 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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GOLEM **basic** Data Acquisition System (DAS)

- U_l, U_{B_t}, $U_{I_{p+ch}}$, I_{rad}
- $\Delta t = 1\mu s/\ f = 1MHz$.
- Integration time = 40 ms, thus DAS produces 6 colums x 40000 rows data file.
- Discharge is triggered at 5th milisecond after DAS to have a zero status identification.

Data file example, DAS $\Delta t = 1\mu s/f = 1MHz$ (neutral gas into plasma breakdown focused)

t	$\approx U_l$	$\approx U_{\frac{dB_T}{dt}}$	$\approx U_{\frac{d(I_{p+ch})}{dt}}$	$\approx I_{rad}$
⋮	⋮	⋮	⋮	⋮
first	≈	7405	lines ..	
⋮	⋮	⋮	⋮	⋮
0.007383	1.53931	0.390015	0.048828	0.001831
0.007384	1.53686	0.395508	0.067749	0.00061
0.007385	1.54053	0.391235	0.079956	0.00061
0.007386	1.53686	0.38147	0.072632	0
0.007387	1.54297	0.397949	0.059204	0.00061
0.007388	1.54053	0.384521	0.05249	0.00061
0.007389	1.54053	0.39856	0.068359	0.001221
0.00739	1.54053	0.393677	0.082397	0.001221
0.007391	1.53809	0.38208	0.072632	0.001221
0.007392	1.54297	0.400391	0.056763	0.00061
0.007393	1.54419	0.383911	0.053101	0.00061
0.007394	1.53931	0.397339	0.068359	0.001221
0.007395	1.54297	0.391846	0.084229	0.00061
0.007396	1.54541	0.394897	0.074463	0.00061
0.007397	1.54297	0.388184	0.056763	0.001221
0.007398	1.54297	0.391846	0.056763	0.00061
0.007399	1.54297	0.394287	0.06897	0.00061
⋮	⋮	⋮	⋮	⋮
next	≈	32500	lines ..	
⋮	⋮	⋮	⋮	⋮

Data access

All the recorded data and the settings for each discharge (shot) are available at the GOLEM website. The root directory for the files is:

`http://golem.fjfi.cvut.cz/shots/<#ShotNo>/`

The most recent discharge has the web page:

`http://golem.fjfi.cvut.cz/shots/0`

Particular data from DAS or specific diagnostics have the format:

`http://golem.fjfi.cvut.cz/utils/data/<#ShotNo>/<identifier>`

An overview of available data with identifiers, units, description, etc. for each discharge is at

`http://golem.fjfi.cvut.cz/shots/<#ShotNo>/Data.php`

Data access

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GNU Wget

GNU Wget is a free software package for retrieving files using HTTP, HTTPS and FTP, the most widely-used Internet protocols. It is a non-interactive commandline tool, so it may easily be called from scripts, cron jobs, terminals without X-Windows support, etc.

- Runs on most UNIX-like operating systems as well as Microsoft Windows.
- Homepage: `http://www.gnu.org/software/wget/`
- Basic usage:
  - To get U_l: wget `http://golem.fjfi.cvut.cz/utils/data/<#ShotNo>/loop_voltage`
  - To get whole shot: wget -r -nH –cut-dirs=3 –no-parent -l2 -Pshot `http://golem.fjfi.cvut.cz/shots/<#ShotNo>`

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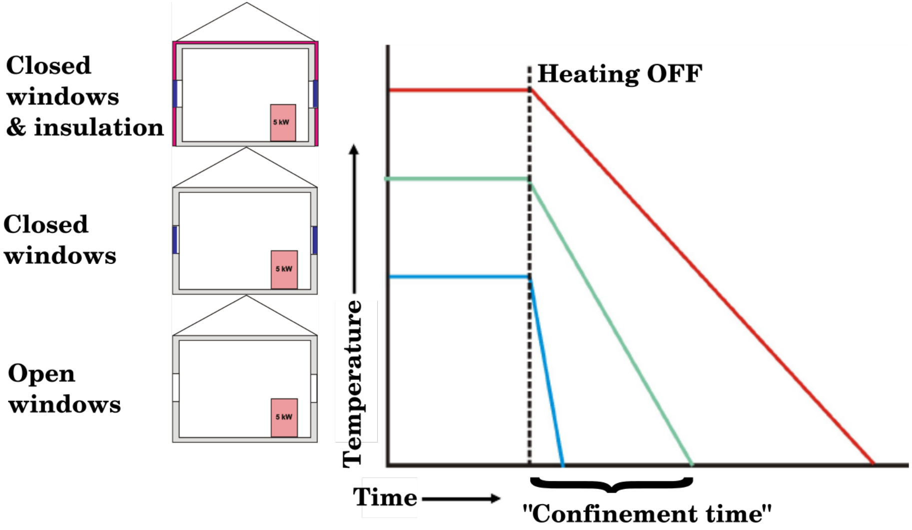
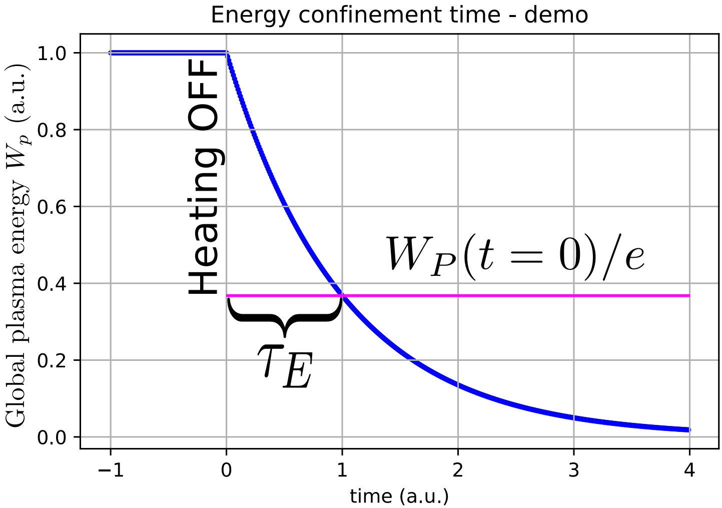
Energy balance of the house



Energy balance of the tokamak



Energy confinement time

Under the assumption of a simplified power balance, the heating power P_H is partially absorbed in the plasma and leads to an increase of the plasma energy W_p and the rest is lost as the loss power P_L

$$P_H = \frac{dW_p}{dt} + P_L$$

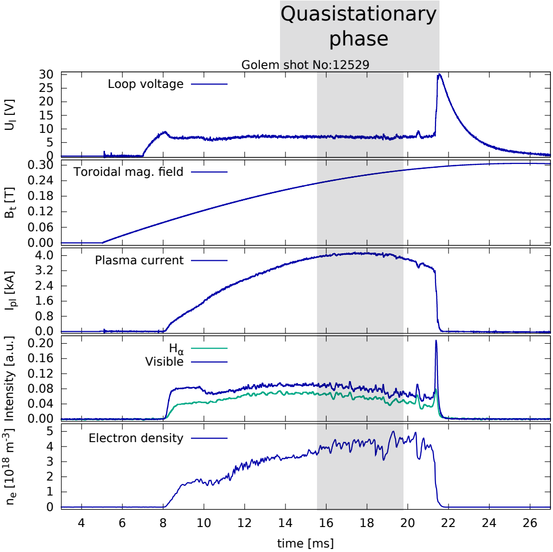
The energy confinement time is defined as the characteristic time scale of the exponential decay of the plasma energy W_p due to the loss power P_L:

$$\tau_E = \frac{W_p}{P_L} = \frac{W_p}{P_H - dW_p/dt}$$

Choosing the quasistationary phase of the plasma discharge, where $\frac{dW_p}{dt} = 0$ gives:

$$\tau_E(t) = \frac{W_p(t)}{P_H(t)}$$

The discharge - quasistationary phase



Plasma heating power

On the GOLEM tokamak the only heating mechanism of the plasma is ohmic heating P_{OH} resulting from the plasma current I_p flowing in a conductor with finite resistivity R_p. The time dependence of the ohmic heating power can be calculated as:

$$P_H(t) = P_{OH}(t) = R_p(t) \cdot I_p^2(t)$$

Plasma Energy

The global plasma energy content W_p can be simply calculated from the temperature estimation $T_e(0,t)$, average density n_e and plasma volume V_p, based on the ideal gas law, taking into account the assumed $T_e(r,t) = T_e(0,t)\left(1-\frac{r^2}{a^2}\right)^2$ temperature profile:

$$W_p(t) = V_p \frac{n_e k_B T_e(0,t)}{3}.$$

The information that the magnetic field reduces the degrees of freedom of the particles to two has been used to derive this formula.

- $V_p \approx 80$ l

Central Electron Temperature estimation (Spitzer Formula)

The time evolution of the central electron temperature $T_e(0, t)$ is calculated from equation based on Spitzer's resistivity formula (see eg. [6],[5]):

$$T_e(0, t) = \left(\frac{R_0}{a^2} \frac{8 Z_{eff.}}{1544} \frac{1}{R_p(t)} \right)^{2/3}, [eV; m, \Omega]$$

For particular case of the GOLEM tokamak it says:

$$T_e(0, t) = 0.9 \cdot \left(\frac{I_p(t)}{U_l(t)} \right)^{2/3}, [eV; A, V]$$

Towards Electron energy confinement time τ_E

Vacuum discharge

ID:irog — ID:loop_voltage

$\int_0^t$

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

Plasma discharge

ID:irog — ID:loop_voltage — ID:electron_density

$\int_0^t$

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

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

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 $R_p = \frac{\overline{U_l}}{\overline{I_p}}$

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

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

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

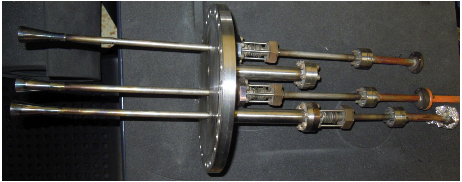
Total electron energy content $W_p = V_p \cdot \frac{\overline{n_e} \cdot k_B \cdot (T_e(0) \cdot eV)}{3}$

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

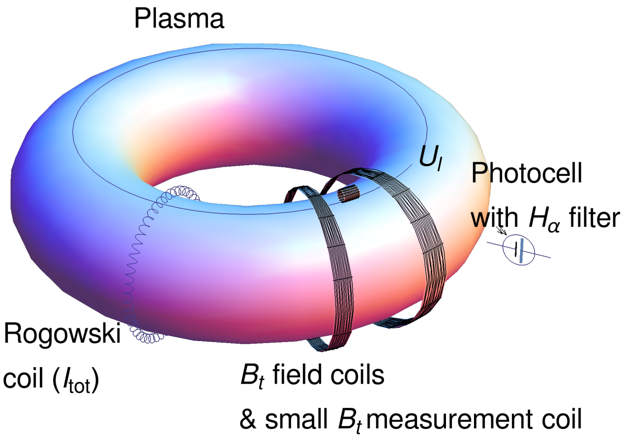
Note: All physical quantities requested in the form of estimated value and associated degree of uncertainty

Hands on the GOLEM tokamak - equipment

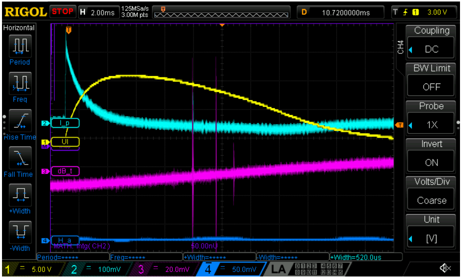
The GOLEM tokamak interferometry HW

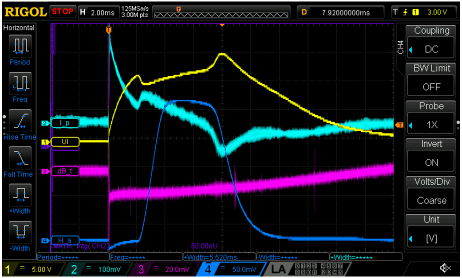


The GOLEM tokamak - standard diagnostics

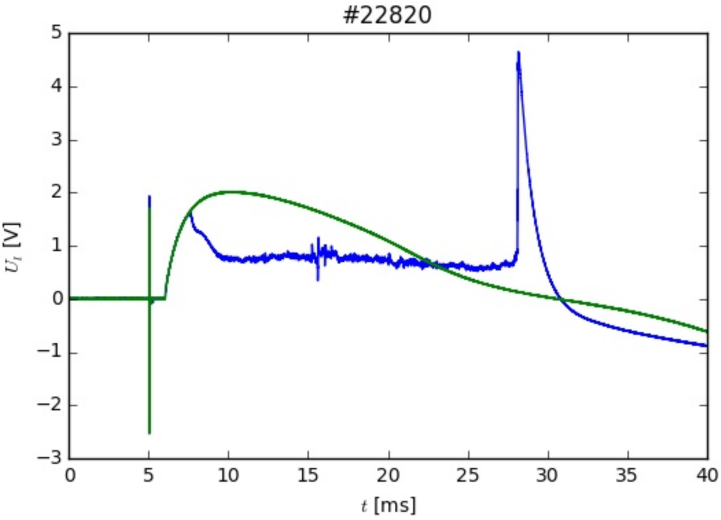


Vacuum x Plasma discharge @ Oscilloscope

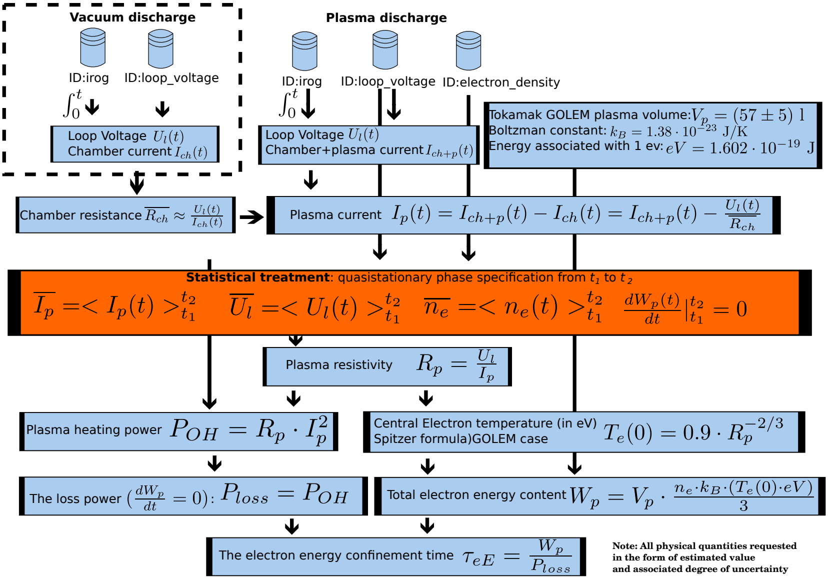




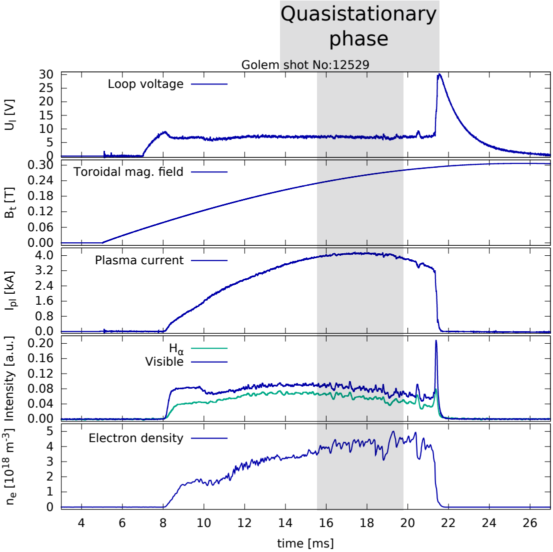
Vacuum x Plasma shot



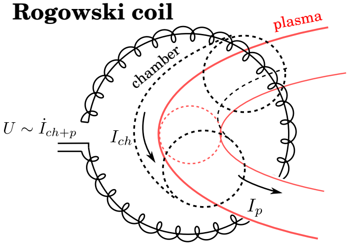
Towards Electron energy confinement time τ_E

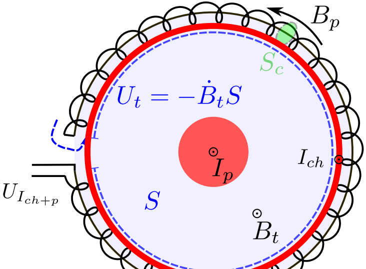


The discharge - quasistationary phase



Rogowski coil for the (chamber & plasma) current I_{ch+p} measurements





- Ampere's Law: $\nabla \times \mathbf{B} = \mu_0 \mathbf{j}$ (neglecting $\dot{\mathbf{D}}$)
- current through (const) surface S: $\int \mathbf{j} \cdot d\mathbf{S} = I_{ch+p}$
- (const) poloidal field along surface border l: $\int \nabla \times \mathbf{B} \cdot d\mathbf{S} = \oint B_p dl = l B_p$
- voltage induced: $U_{I_{ch+p}} + U_t - U_t = -N\dot{B}_p S_c = -\mu_0 \frac{NS_c}{l} \dot{I}_{ch+p}$
- The wire of the coil is back-wounded to ommit a strong toroidal magnetic field B_t signal.

Magnetic measurements generally I

- Raw signals (analog $U_r(t)$ or, respectively, it's discretized digital U_i counterpart form) must be specialy maintained:
  - corrected for the DC bias U_{offset} of the measurement circuit,
  - integrated (pure diagnostics signal voltage $U_d(t)$ is induced by the time derivative of the appropriate magnetic flux),
  - multiplied by calibration factors C_d ($C_B t$, C_{RC}).
- We can express the basic relationship $U_r(t) = U_d(t) + U_{offset}$
- The measured signal $U_d(t)$ is proportional to the time derivative of the original physical quantity $D(t)$ signal (it is a magnetic measurement):

$$U_d(t) \propto \frac{dD(t)}{dt}, \text{ or } U_d(t) = C_d \frac{dD(t)}{dt}$$

Where the linearity coefficient C_d is called a calibration factor.

Magnetic measurements generally II

- To determine the desired physical quantity $D(t)$, we just have to perform an integration over time:

$$D(t) = \frac{1}{C_d}\int_0^t U_d(t')dt' = \frac{1}{C_d}\int_0^t \left(U_r(t) - U_{offset}\right) dt'$$

- In reality, the measurement is not continuous. The system performs a series of measurements U_i separated by with time step $\Delta t = 1$ us.
- In practice, we replace the integral by a sum:

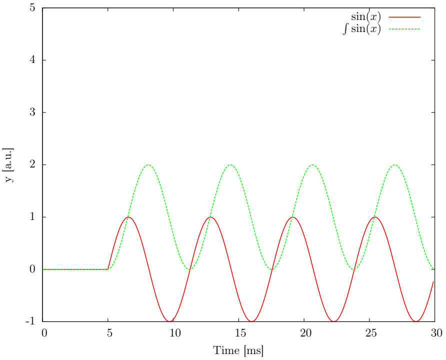
$$D_i = \frac{1}{C_d}\sum_{j=0}^{t/\Delta t} (U_i(t_j) - U_{offset})\Delta t$$

$$D_i = \frac{1}{C_d}\left(\sum_{j=0}^{t/\Delta t} U_i(t_j)\right) - U_{offset}\, t$$

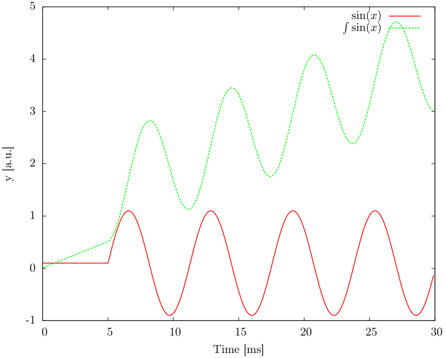
- The offset U_{offset} can be specified from the beggining of the data series before switching on the real experiment.

Magnetic measuremet demo - game with U_{offset}

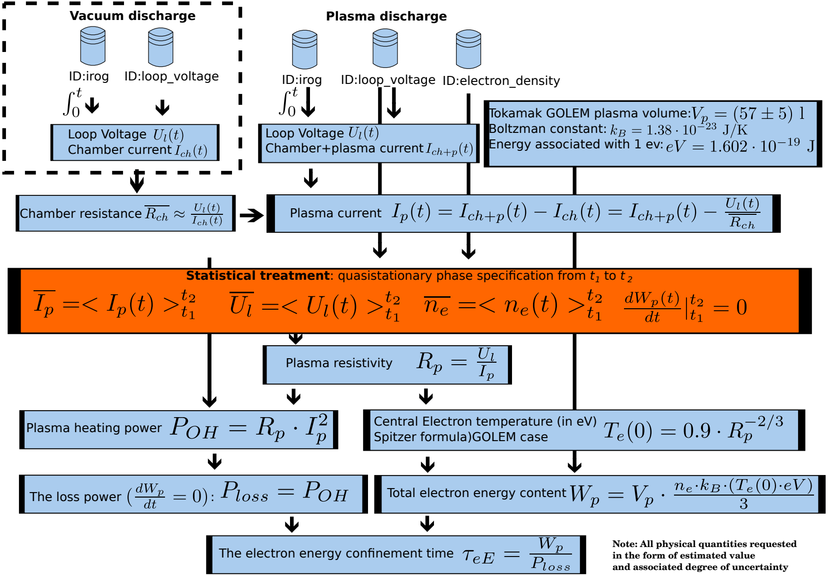
Without U_{offset}



With U_{offset}



Towards Electron energy confinement time τ_E



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

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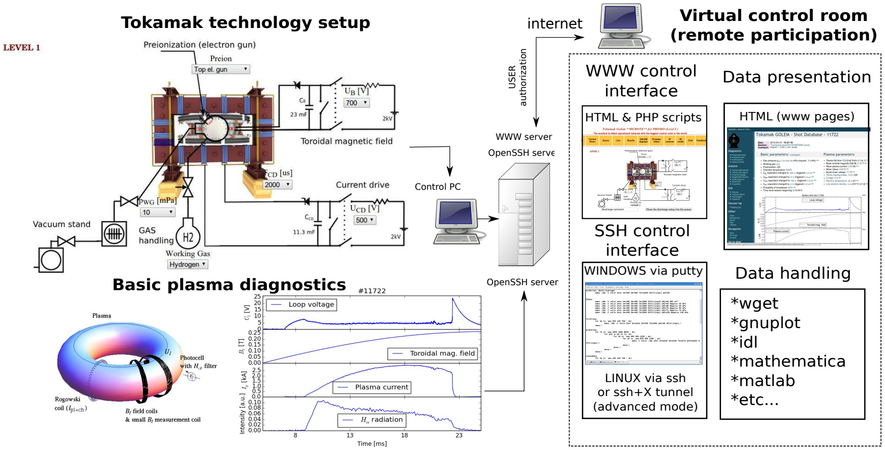
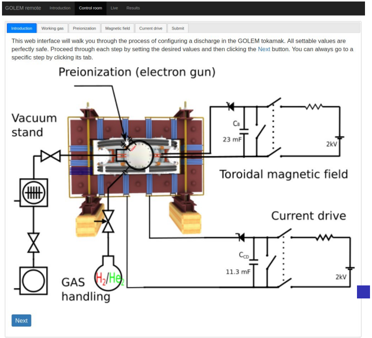
The global schematic overview of the GOLEM experiment



Production

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

Recommended values for the GOLEM tokamak operation



- Preionization: Top electron gunn
- Gas: Hydrogen. Infrastructure/GasManagement/WorkingG
- Infrastructure/CurrentDriveFieldCircuit/C
- Infrastructure/ToroidalMagneticFieldCircu
- Infrastructure/TriggerSystem/USBpulse/Trigge

Fee: postcard from the venue of remote measurements

Acknowledgement

Financial support highly appreciated:

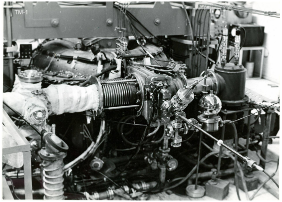
CTU RVO68407700, SGS 17/138/OHK4/2T/14, GAČR GA18-02482S, EU funds CZ.02.1.01/0.0/0.0/16_019/0000778 and CZ.02.2.69/0.0/0.0/16_027/0008465, IAEA F13019, FUSENET and EUROFUSION.

Students, teachers, technicians (random order):

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

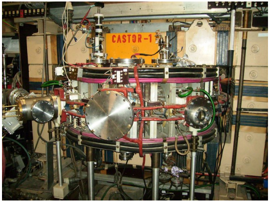
Thank you for your attention

Tokamak TM1
@Kurchatov Institute near Moscow
~1960-1977



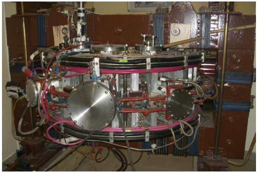
SCIENCE

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



SCIENCE
& education

Tokamak GOLEM
@Czech Technical University, Prague
2007-



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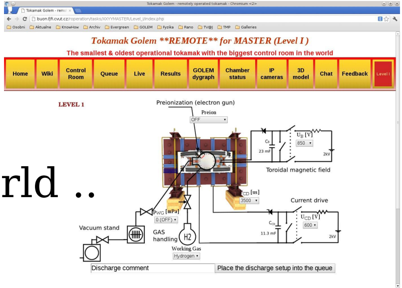

Table of Contents

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] Wikipedia contributors. Lawson criterion — Wikipedia, the free encyclopedia. https://en.wikipedia.org/w/index.php?title=Lawson_criterion&oldid=888000448, 2019. [Online; accessed 6-December-2019].

[3] ITER contributors . ITER. https://www.iter.org, 2007. [Online; accessed 21-December-2018].

[4] Tokamak GOLEM contributors. Tokamak GOLEM at the Czech Technical University in Prague. http://golem.fjfi.cvut.cz, 2007. [Online; accessed December 2, 2020].

References II

[5] J. Wesson. *Tokamaks*, volume 118 of *International Series of Monographs on Physics*. Oxford University Press Inc., New York, Third Edition, 2004.

[6] Brotankova, J. *Study of high temperature plasma in tokamak-like experimental devices*. PhD thesis, 2009.

[7] 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.