

Introduction to tokamak operation (GOLEM specific)

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February 13, 2012

Tokamak operation - engineer and operator point of view

Theodore Von Karmen (The father of supersonic flight):

"The scientist seeks to understand what is;
the engineer seeks to create what never was.

Outline of the talk

- 1 Introduction
- 2 Tokamak GOLEM - engineering scheme
- 3 Tokamak GOLEM - diagnostics
- 4 Tokamak GOLEM - parameter analysis
- 5 Tokamak GOLEM - remote operation
- 6 GOMTRAIC - GOLEm reMote TRAIning Course

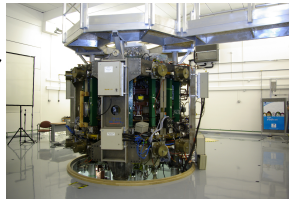
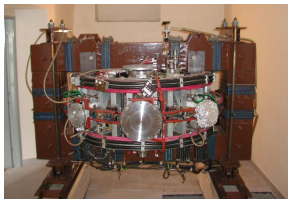
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Tokamak GOLEM for Education - Historical Background

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

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



1974

2006

Institute of Plasma Physics
Czech republic

CASTOR

COMPASS

2006: new curricula at FNSPE:
**Physics and Technology
of Thermonuclear Fusion**

2008

Czech Technical University Prague
Czech republic

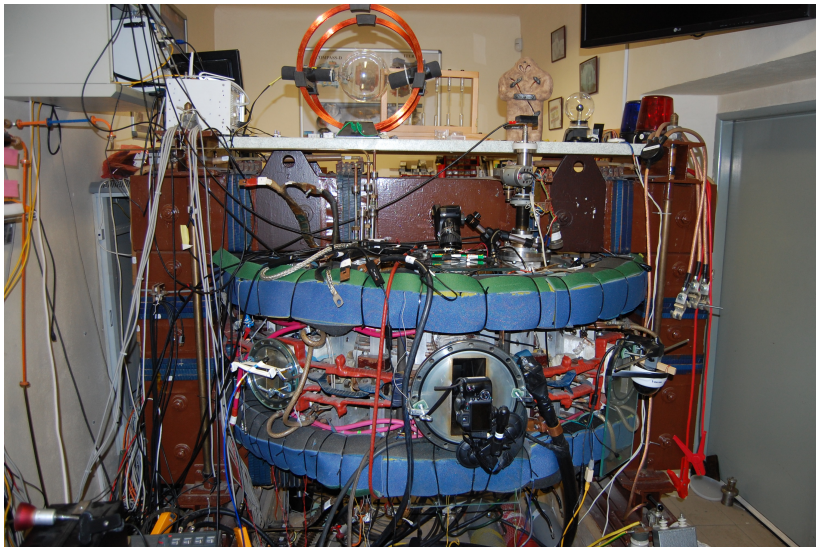
GOLEM

?virtual or real experiments?

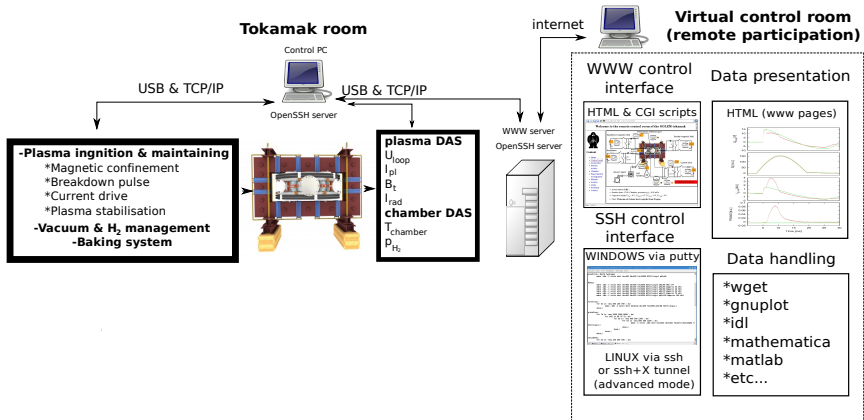
The Golem tokamak - South view (02/12)



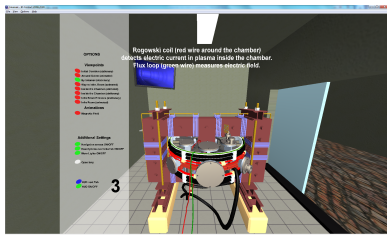
The Golem tokamak - North view (02/12)



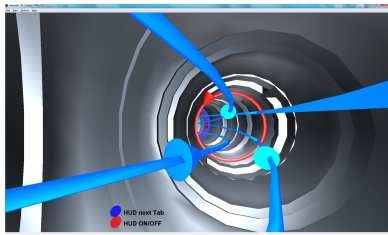
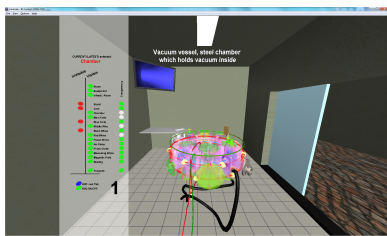
Unique remote operation capability



The GOLEM tokamak virtual model



Tokamak Room & Infrastructure Room



Inner view & Inside chamber

The GOLEM tokamak **virtual** Control Room - level I

Location Edit View Bookmarks Tools Settings Help

http://golem.fjfi.cvut.cz/voperation/tasks/PROMO/1212GOLEM/Level_I/exp.php

Tokamak Golem ****VIRTUAL**** for GOLEM (Level I)

Home Control Room Queue Live Results Manual

LEVEL 1

Preionization (electron gun)

Preion ON

U_B [V] 600 2kV

23 mF

Toroidal magnetic field

t_{CD} [us] 1000

Current drive

U_{CD} [V] 500 2kV

11.3 mF

P_{H_2} [mPa] 20

Vacuum stand

GAS handling

H₂

The diagram illustrates the physical components and their electrical connections. A central tokamak chamber is connected to a Preionization (electron gun) system, a Toroidal magnetic field system, and a Current drive system. The Preionization system includes a capacitor C_p (23 mF) and a switch. The Toroidal magnetic field system includes a capacitor C_B (23 mF) and a switch. The Current drive system includes a capacitor C_{CD} (11.3 mF) and a switch. The Gas handling system includes a vacuum stand, a gas handling unit, and an H₂ source. The interface also shows a navigation menu with buttons for Home, Control Room, Queue, Live, Results, and Manual. The browser address bar shows the URL: http://golem.fjfi.cvut.cz/voperation/tasks/PROMO/1212GOLEM/Level_I/exp.php.

The GOLEM tokamak **virtual** Control Room - level II

Location Edit View Bookmarks Tools Settings Help

http://golem.fjfi.cvut.cz/voperation/tasks/PROMO/1212GOLEM/Level_II/exp.php

Tokamak Golem ****VIRTUAL**** for GOLEM (Level II)

Home Control Room Queue Live Results Manual

LEVEL 2

Preionization (electron gun)
Preion ON

Breakdown
 U_{BD} [V] 100 2kV
 C_{BD} 3.6 mF
 T_{BD} [us] 4000

Toroidal magnetic field
 C_s 23 mF
 U_B [V] 600 2kV

Current drive
 C_{CD} 11.3 mF
 U_{CD} [V] 500 2kV
 T_{CD} [us] 3000

Vacuum stand
 P_{H_2} [mPa] 20
GAS handling H₂

The GOLEM tokamak real Control Room

Location Edit View Bookmarks Tools Settings Help

http://golem.fjfi.cvut.cz/roperation/tasks/PROMO/1212GOLEM/Level_1/exp.php

Tokamak Golem ****REMOTE**** for GOLEM (Level I)

Home Control Room Queue Live Results Manual

LEVEL 1

Preionization (electron gun)

Preion ON

Vacuum stand

GAS handling

P_{H_2} [mPa] 20

H_2

Toroidal magnetic field

C_b 23 mF

U_B [V] 600 2kV

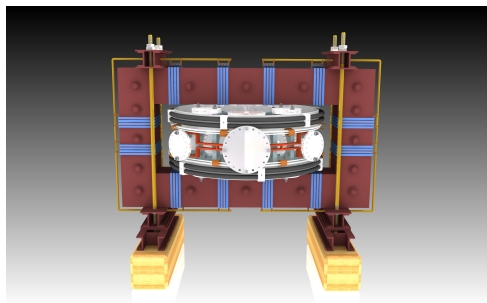
Current drive

C_{cd} 11.3 mF

U_{CD} [V] 500 2kV

I_{CD} [us] 1000

Tokamak GOLEM - mission:

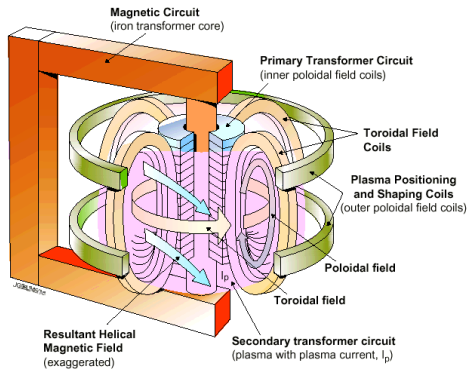


- Educational device.
- As simple as possible.
- Low cost.
- Some scientific goals.
- (-: Bombenfest :-)
- (-: Idiotensichre :-)

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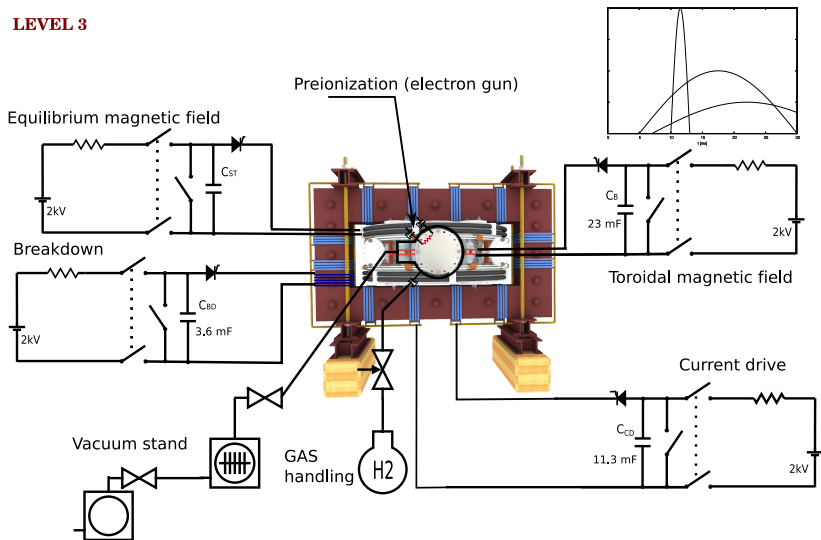
Plasma in Tokamak GOLEM - to do



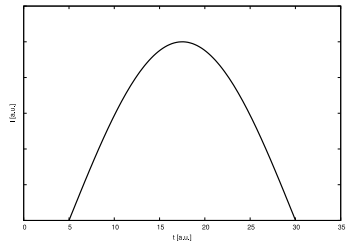
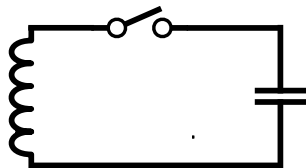
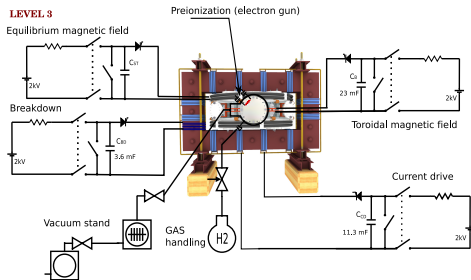
- Vacuum.
- Fill in working gas.
- Toroidal magnetic field to confine plasma.
- Toroidal electric field to breakdown neutral gas into plasma.
- Toroidal electric field to heat the plasma.
- Plasma positioning and maintaining (not ready yet).
- Diagnostics.

Tokamak GOLEM - engineering scheme

LEVEL 3

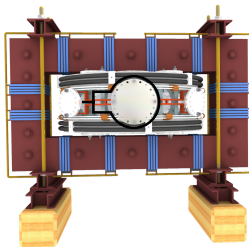


Insertion - LC circuit



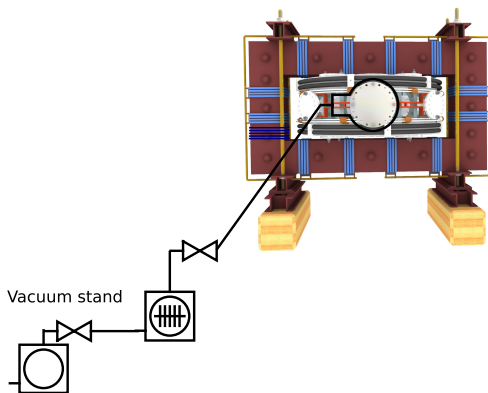
Tokamak GOLEM - basic

LEVEL 0



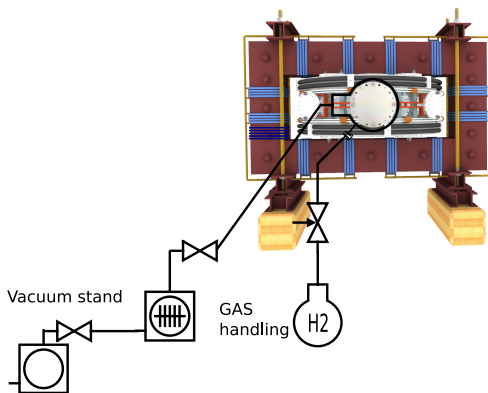
+ vacuum pumping system ($100 \text{ kPa} \rightarrow \approx 1 \text{ mPa}$)

LEVEL 0



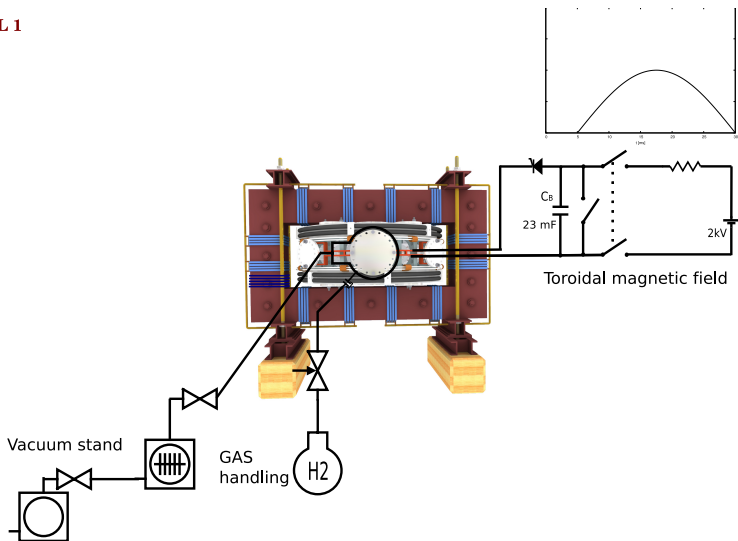
+ working gas management (H_2 or He)

LEVEL 0



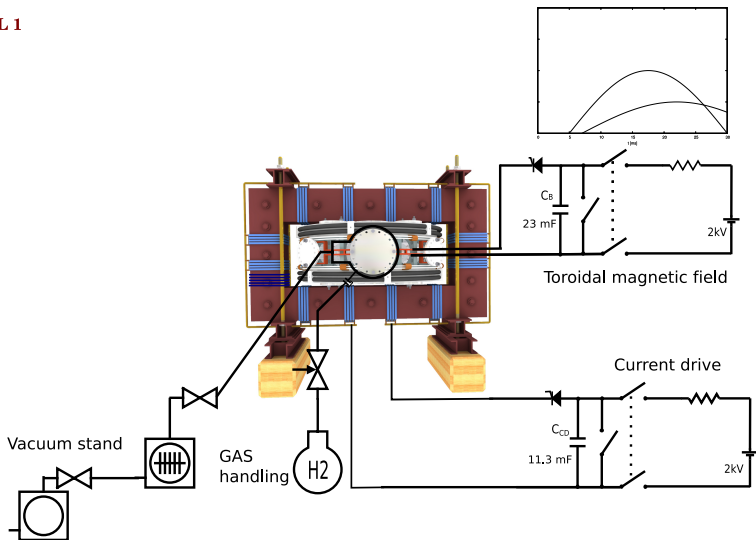
+ toroidal magnetic field B_t .. plasma confinement

LEVEL 1



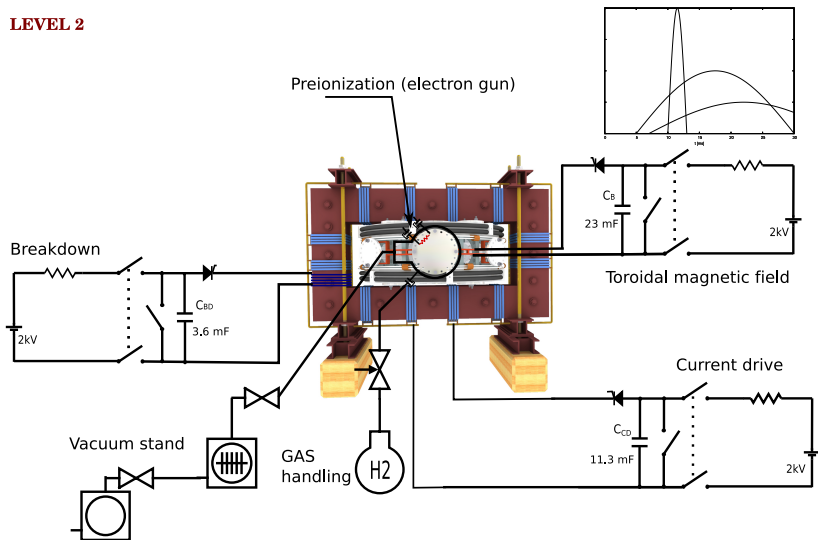
+ toroidal electric field E_{CD} .. plasma heating

LEVEL 1



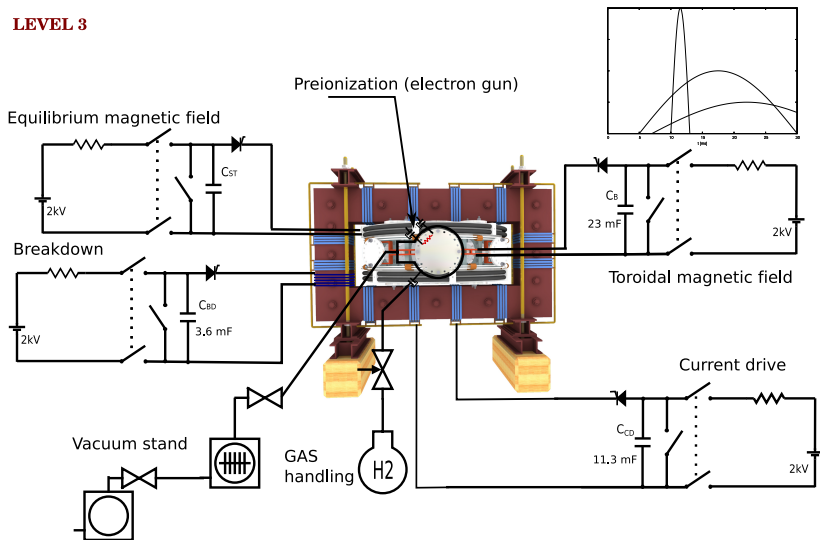
+ toroidal electric field E_{BD} .. plasma creation

LEVEL 2

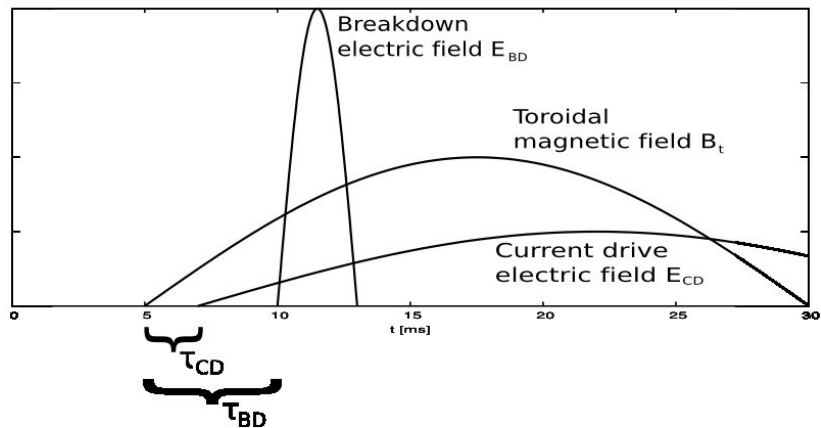


+ equilibrium magnetic field B_{EQ} .. plasma stabilization

LEVEL 3



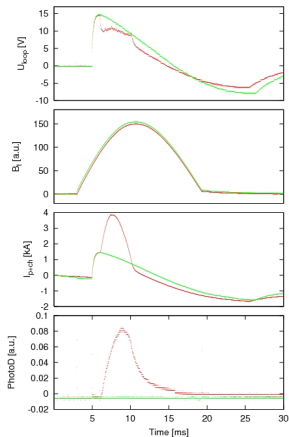
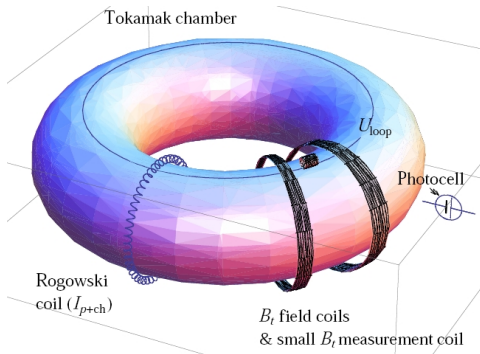
Triggering sequence



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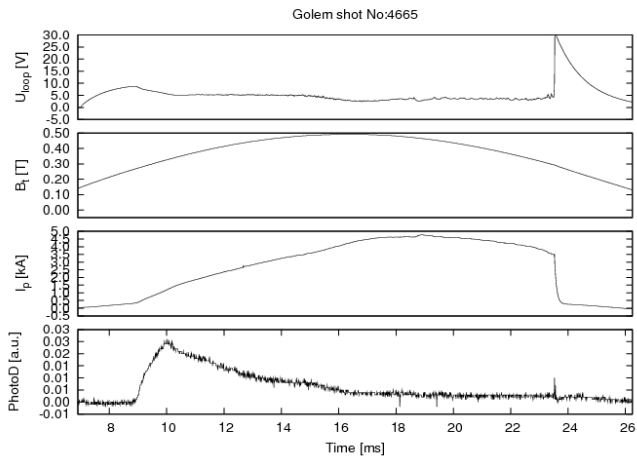
Basic plasma diagnostics in tokamak GOLEM



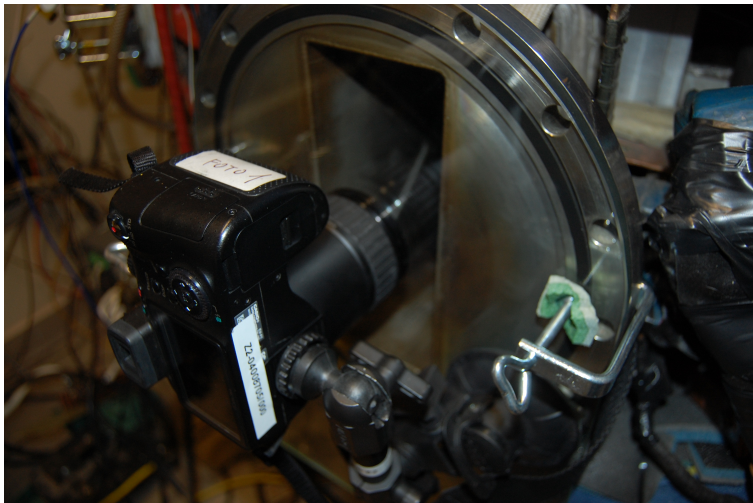
Data Acquisition System based on:



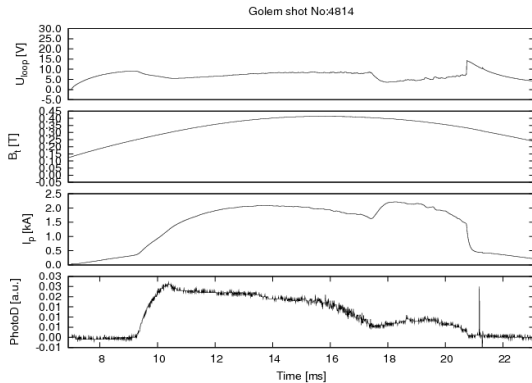
Golem discharge



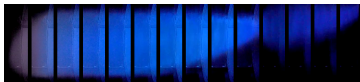
Fast camera CASIO FX1



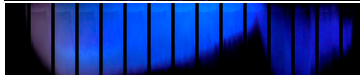
Fast camera CASIO FX1 - results



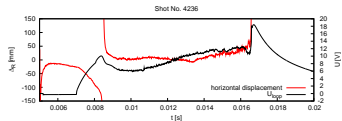
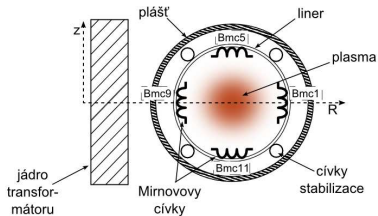
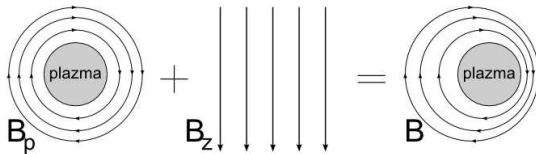
TOP view:



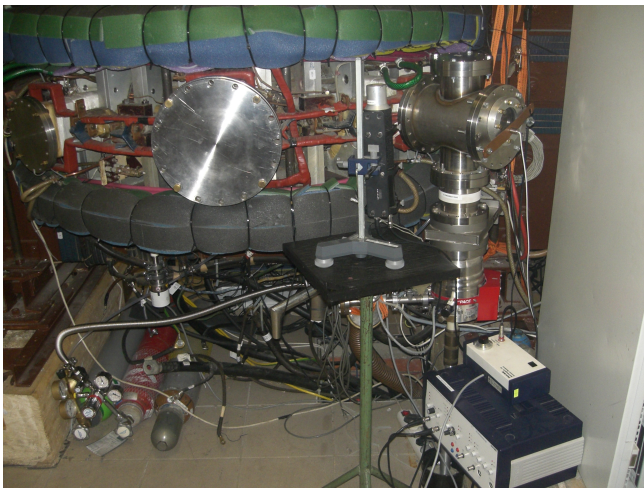
SIDE view:



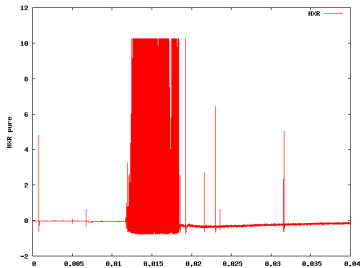
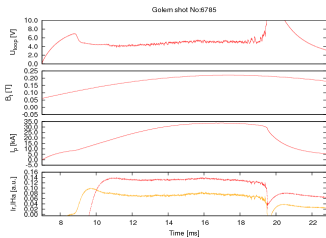
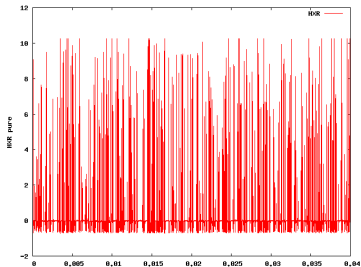
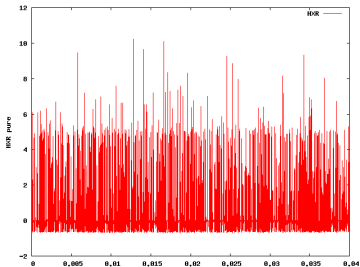
Plasma Position using Mirnov Coils



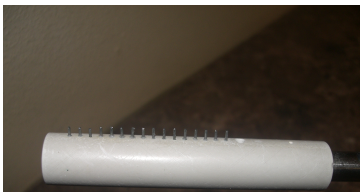
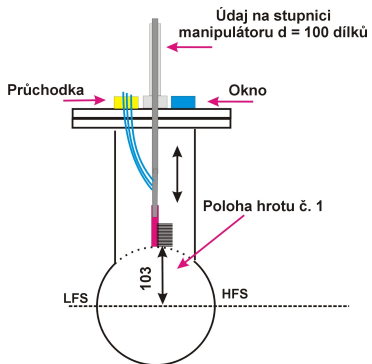
HXR (Lenka Kocmanová) (6780-6787)



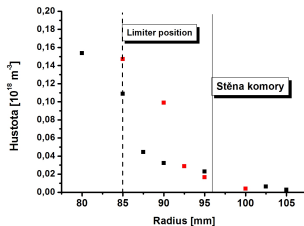
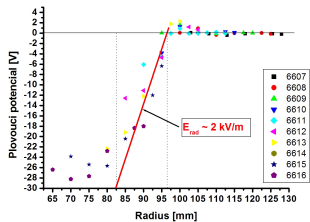
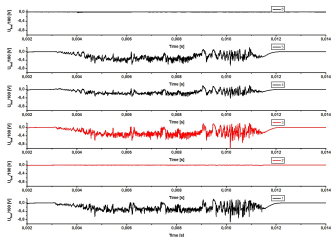
HXR (Lenka Kocmanová) (6780-6787)



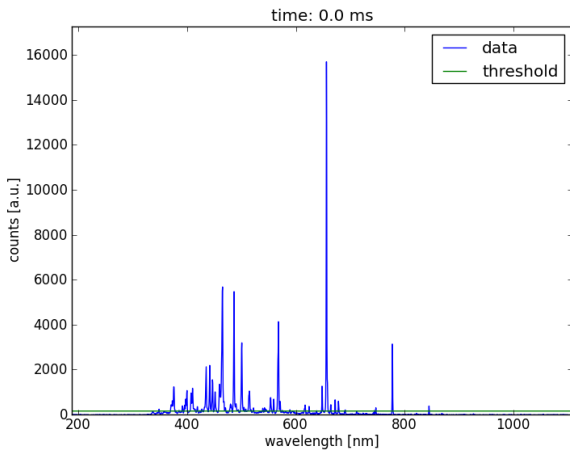
Rake probe (2012)



Rake probe (2012) - results



Spectra



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Central electron temperature estimation I [?]

The current density of plasma is

$$j = E \cdot \sigma \quad (1)$$

where σ is the specific conductivity of plasma given by

$$\sigma(r) = 1.544 \cdot 10^3 \cdot \frac{T_e(r)^{3/2}}{Z_{eff}}, \quad [\Omega^{-1}\text{m}^{-1}, \text{eV}] \quad (2)$$

and the electric field E is assumed constant in the poloidal cross-section:

$$E = \frac{U_{loop}}{2\pi R}. \quad (3)$$

Plasma current is obtained by integrating current density over the plasma column:

$$I_{pl} = \int_0^a E \cdot \sigma(r) 2\pi r dr. \quad (4)$$

Central electron temperature estimation II [?]

For the electron temperature, we assume a polynomial profile

$$T_e(r) = T_e(0) \left(1 - \frac{r^2}{a^2}\right)^\alpha \quad (5)$$

where a is the minor radius and $T_e(0)$ is the central electron temperature. Substitution gives us the formula for the central electron temperature

$$T_e(0) = \left(\frac{R}{a^2} \frac{8 \cdot Z_{eff}}{1.544 \cdot 10^3}\right)^{2/3} \cdot \left(\frac{I_{pl}}{U_{loop}}\right)^{2/3} \quad (6)$$

For the CASTOR/GOLEM tokamak geometry with $a = 78$ mm :

$$T_e(0) = 89.8 \cdot \left(\frac{I_{pl} [kA]}{U_{loop}}\right)^{2/3} \approx 230 \text{ eV}. \quad (7)$$

The effective ion charge is assumed as $Z_{eff} = 2.5$.

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The GOLEM tokamak real Control Room

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http://golem.fjfi.cvut.cz/roperation/tasks/PROMO/1212GOLEM/Level_1/exp.php

Tokamak Golem ****REMOTE**** for GOLEM (Level I)

Home Control Room Queue Live Results Manual

LEVEL 1

Preionization (electron gun)

Preion
ON

Vacuum stand

GAS handling

P_{H_2} [mPa]
20

H_2

Toroidal magnetic field

C_s
23 mF

U_B [V]
600
2kV

Current drive

C_{cd}
11.3 mF

U_{CD} [V]
500
2kV

CD [us]
1000

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GOMTRAIC outline

- **GO**lem re**M**ote **TRAI**ning **C**ourse.
- Course oriented on basic understanding of experimental tokamak physics and control.
- The basis of GOMTRAIC is remote operation of the GOLEM tokamak operated at the Czech Technical University in Prague.
- Organized for undergraduate and postgraduate students interested in experimental tokamak physics.
- Participants do not need to leave their country to get experienced in tokamak operation. They can participate even from their home. No fee.

GOMTRAIC participants

- Each participant (individual or group) has the following opportunities:
 - Unlimited number of virtual discharges in the tokamak GOLEM simulator.
 - 5 remote off-line sessions with 10 real discharges per task on tokamak GOLEM (1 session per week).
 - 2 remote on-line session with 10 real discharges per task on tokamak GOLEM.
 - optionally 1 in-situ on-line session with 20 real discharges per task on tokamak GOLEM (for those who are willing to travel to Prague).
- Participants (individuals or groups) should report their experimental results and publish them in the GOMTRAIC book of proceedings.

GOMTRAIC calendar, March to May 2012

- 1. week: 2 days kick-off event - Introduction, lectures
- 2. week: The GOLEM tokamak VIRTUAL game - virtual discharges in the simulator.
- 3. week: The GOLEM tokamak REAL game - real on-line remote discharges in the tokamak.
- 4. week: Specifying session I aims for each task, remote off-line session I.
- 5.-8. week: Previous session results analysis, specification next session aims, remote off-line sessions II-V.
- 9. week: on-line in-situ session VI.
- 10. week: Overall results discussion and analysis.
- 11. week: Reporting results.
- 12. week: Videoconference presentations of the results, closing.

Tasks

- Breakdown studies:
- Radial profile of floating potential and plasma density (determination of radial electric field and poloidal plasma velocity)
- Determination of plasma resistivity and electron temperature, variation with different discharge regimes
- Plasma position studies with Mirnov coils diagnostics.
- Role of vertical magnetic field on plasma performance.
- Spectroscopy studies
- First wall conditioning (baking of the vessel and glow discharge) on plasma performance.
- Comparison of tokamak discharges in H and He working gases.
- Generation of runaway electrons at different discharge regimes by means of hard X ray radiation.

Acknowledgement

Acknowledgement

The financial support by FUSENET, MSM 6840770039, MSM 6840770014 and A1581 is acknowledged.

Special thanks to the GOLEM team (students, teachers, technicians)

Edita Bromova, Zdenek Cespiro, Ivan Duran, Vladimir Fuchs, Ondrej Grover, Pavel Hacek, Billy Huang, Igor Jex, Michal Kazda, Jindrich Kocman, Martin Kubic, Ondrej Kudlacek, Petr Liska, Tomas Markovic, Jan Mlynar, Michal Odstrcil, Tomas Odstrcil, Ondrej Pluhar, Gergo Pokol, Ondrej Sebek, Adam Sindlery, Michal Smid, Gabriel Vondrasek, Frantisek Zacek, and Jiri Zara.