Introduction to tokamak operation (GOLEM specific)

Vojtěch Svoboda

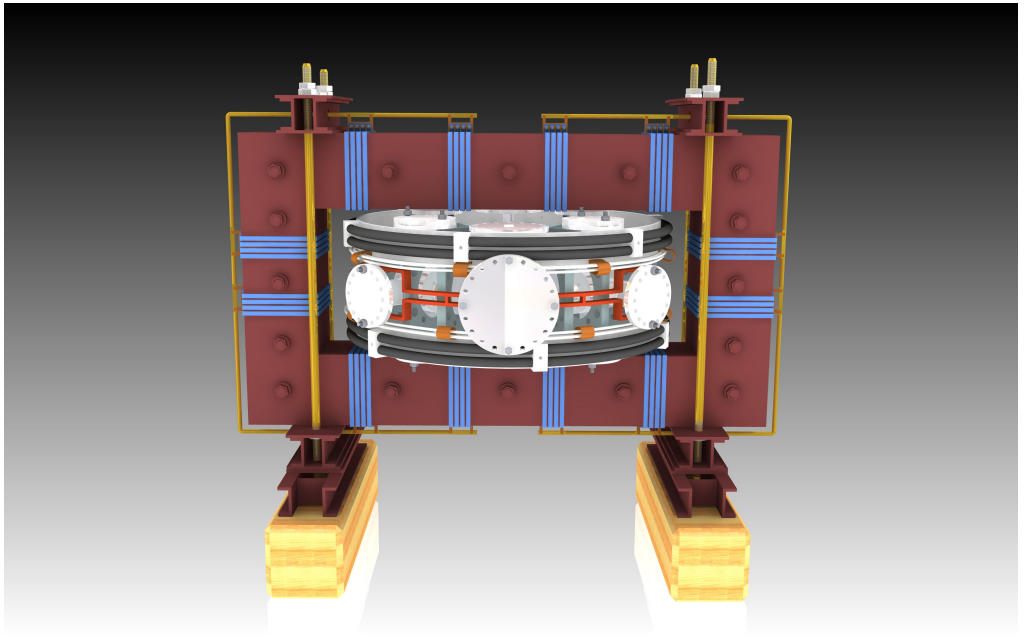
For GOLem reMote TRAIning Course
https://gomtraic.fjfi.cvut.cz

Outline of the talk

Content

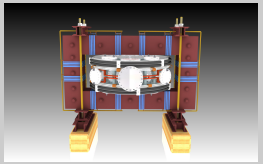
Section begin

Tokamak GOLEM - basic parameters:



- major radius $R = 0.4$
- minor radius $a = 0.085$ m
- plasma current $I_{pl} < 10$ kA
- pulse length $t < 20$ ms
- toroidal magnetic field $B_t < 1$ T
- plasma density $n_e = 0.2 - 3.0 * 10^{19}/m^{-3}$
- electron temperature $T_e(0) < 200$ eV
- ion temperature $T_i(0) < 100$ eV

Tokamak GOLEM - basic parameters:



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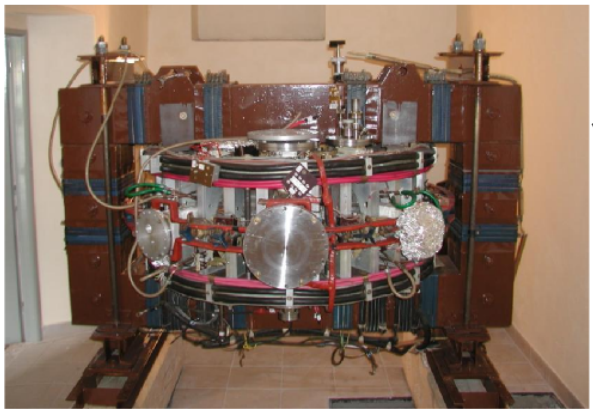
- ion temperature $T_i(0) < 100$ eV

The GOLEM tokamak (formerly CASTOR) at Czech Technical University is demonstrated as an educational device for domestic and foreign students. The reinstalled tokamak (R = 0.4 m, a = 0.085 m) currently operates at a modest range of parameters ($B_t < 0.8$ T, $I_p < 10$ kA, pulse length < 15 ms) which corresponds to a very small fusion triple product. Despite this fact, small tokamaks can produce edge plasma with similar characteristics to large tokamaks and so have general validity [1]. Additionally the remote participation features could be applied to a tokamak of any size.

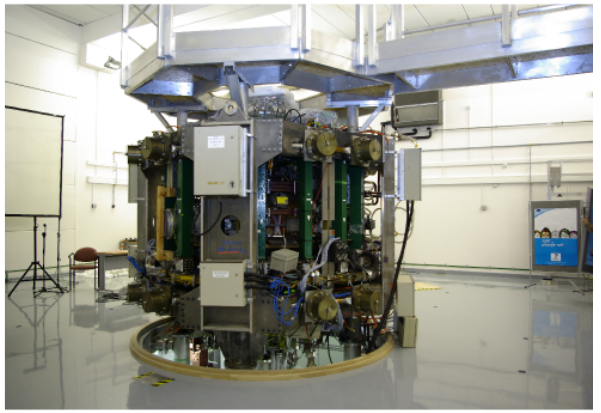
Credit:[2]

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**



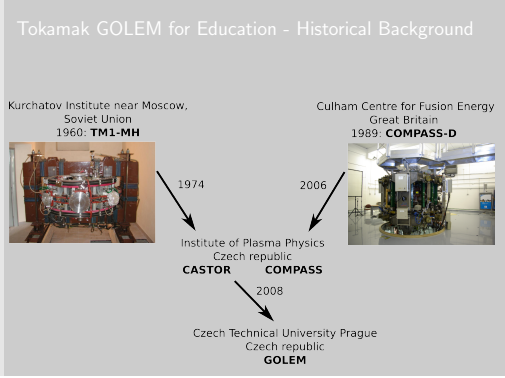
1974

2006

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

2008

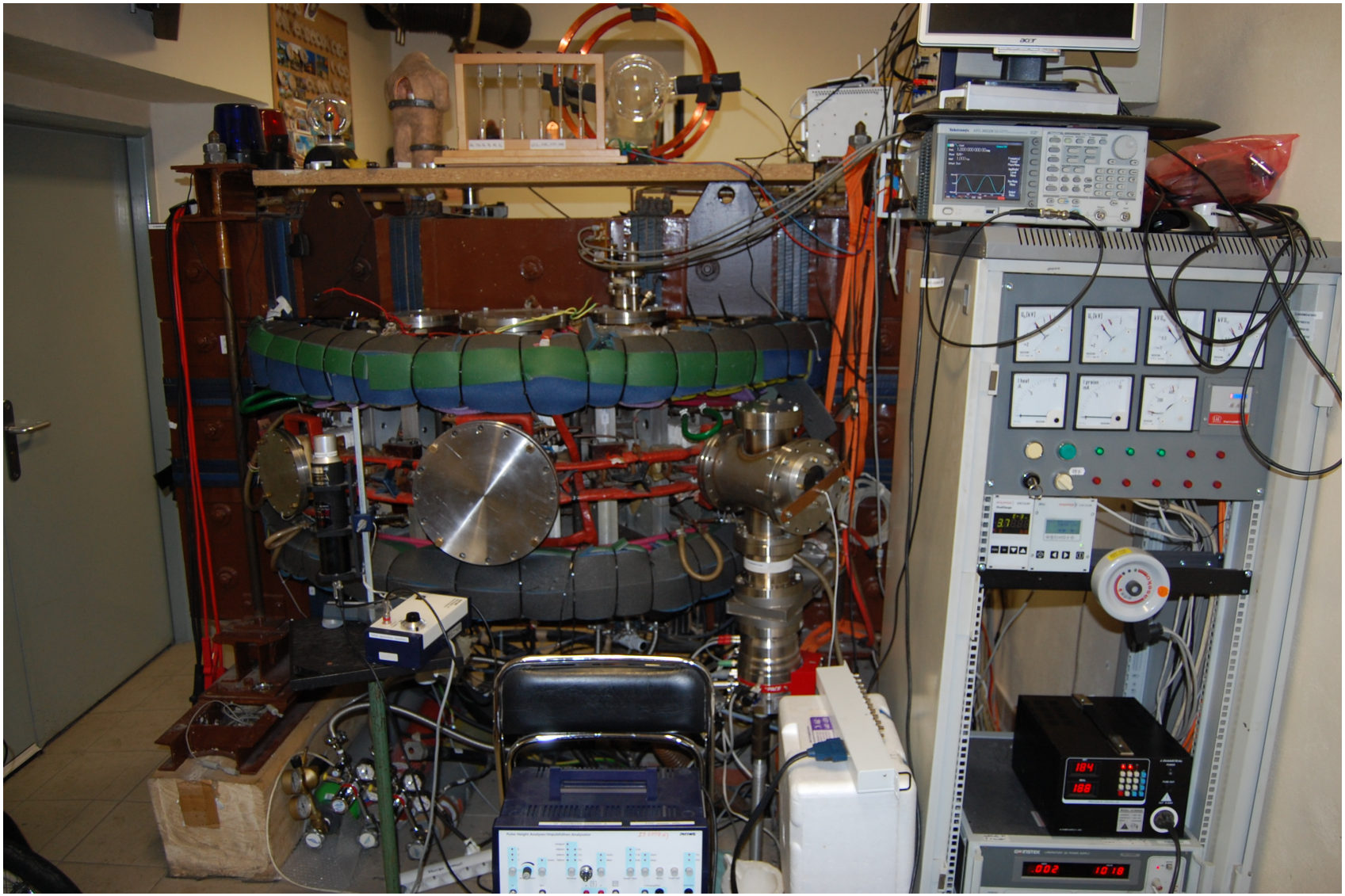
Czech Technical University Prague
Czech republic
GOLEM



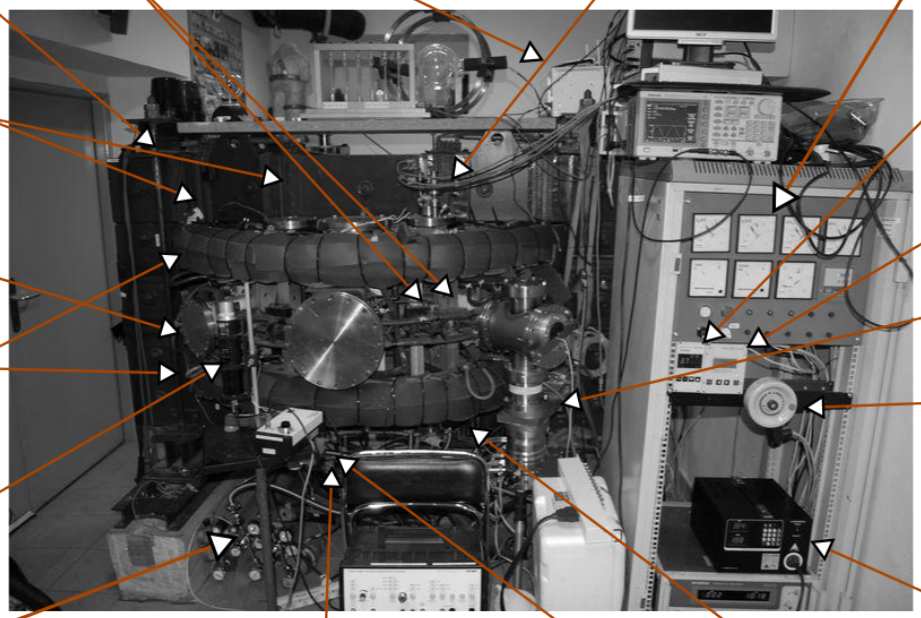
The GOLEM tokamak was built as TM-1 (Tokamak Malyj - meaning "a small tokamak No 1") in Kurchatov institute near Moscow in 1960, so TM-1 was the third tokamak after T-1 and T-2. In late 1960s, this tokamak was offered for free to Czechoslovak republic to test some theories. The machine was reinstalled in Prague in 1977 as TM-1MH and later completely refurbished and started as CASTOR in 1984. Main experimental research was into edge turbulences and RF current drive. It worked in IPP Prague until 2007 but due to its small size and circular, "limiter" plasma its potential for ITER-relevant research was next to nothing. Therefore IPP was happy to get the bigger and modern UK tokamak COMPASS instead. The CASTOR tokamak has been moved to a new location and started a new educational mission under the Czech Technical University, Faculty of Nuclear Sciences and Physical Engineering.

Credit:[**?**]

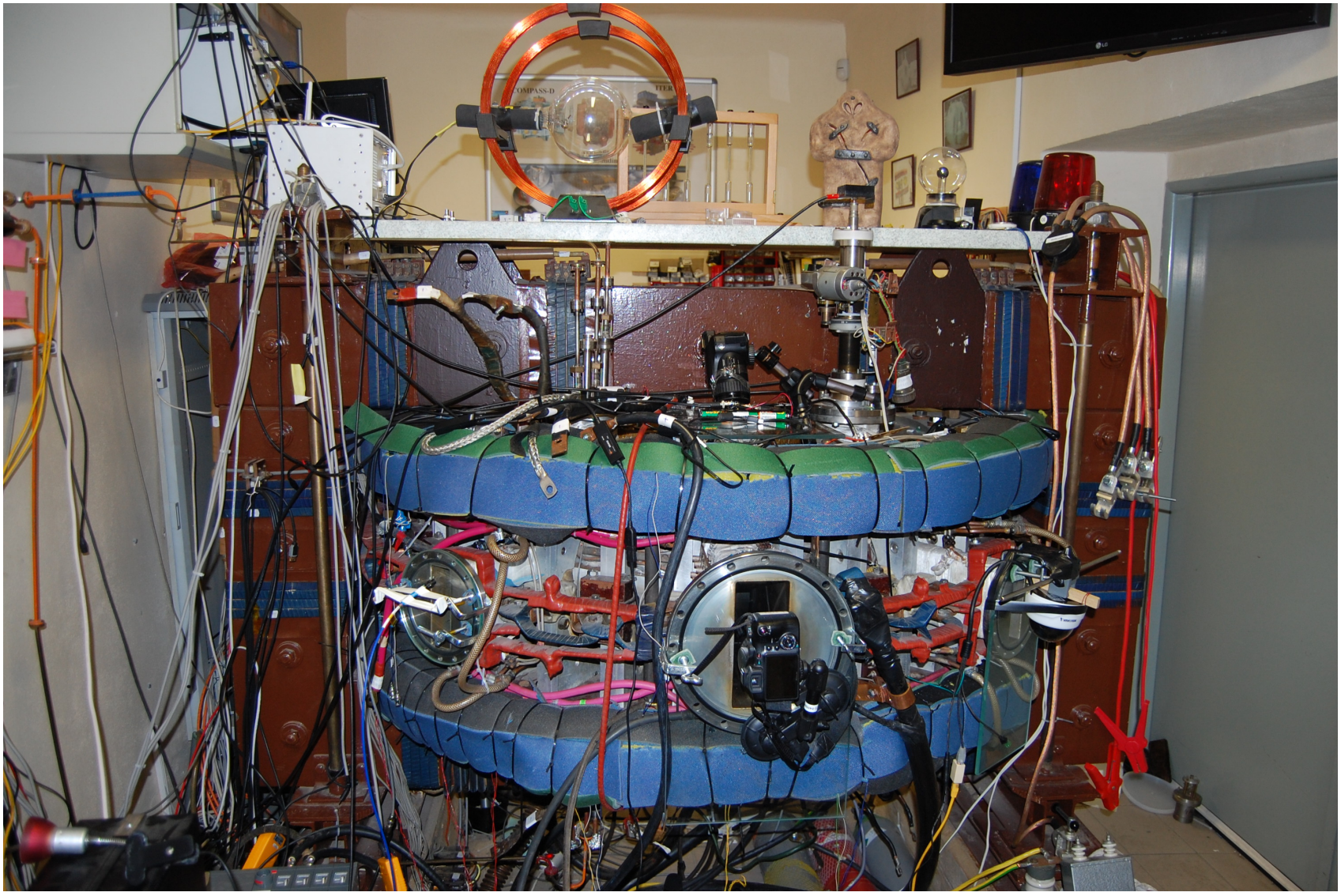
The Golem tokamak - South view (02/12)



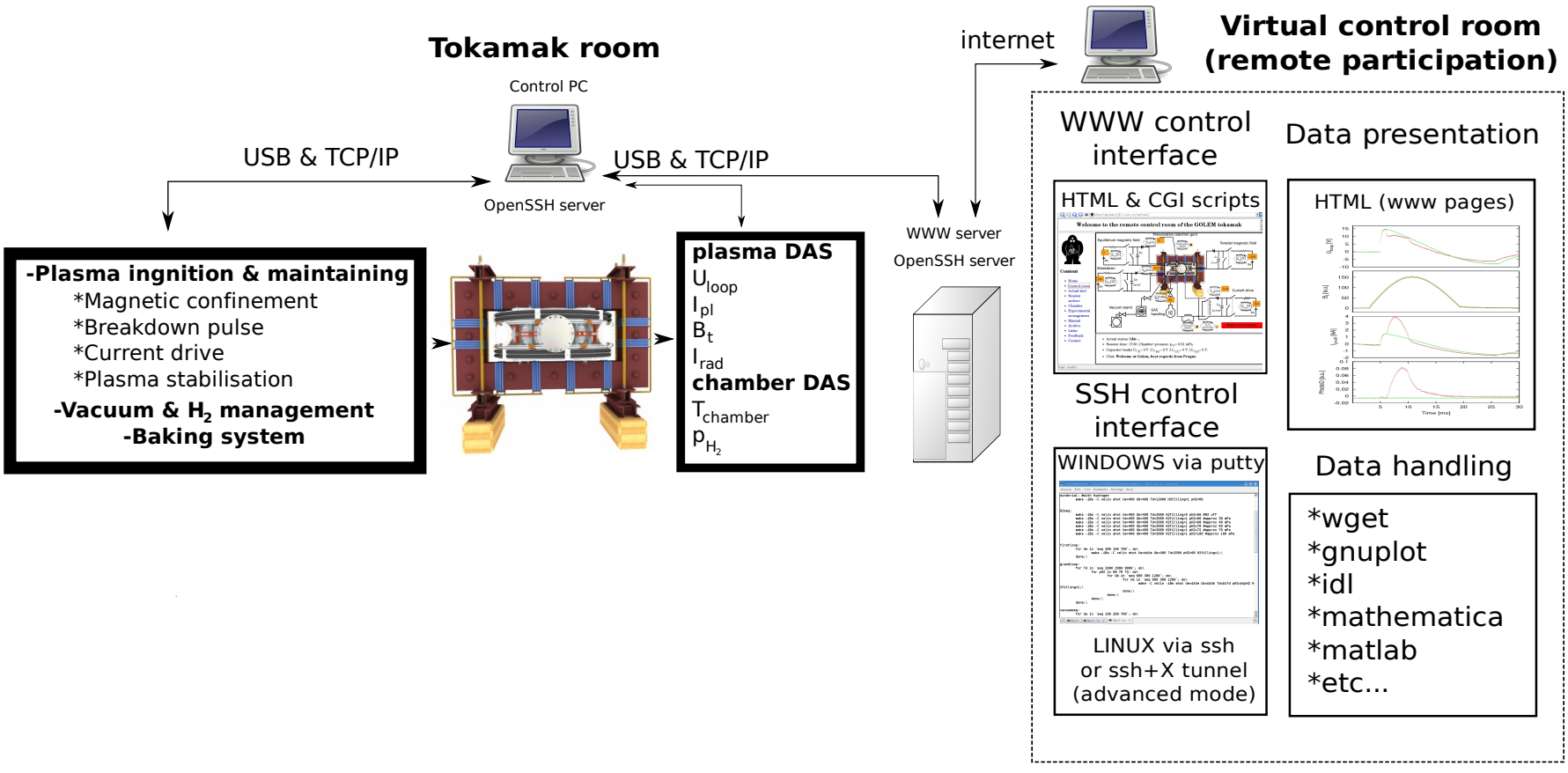
The Golem tokamak - South view (02/12)



The Golem tokamak - North view (02/12)

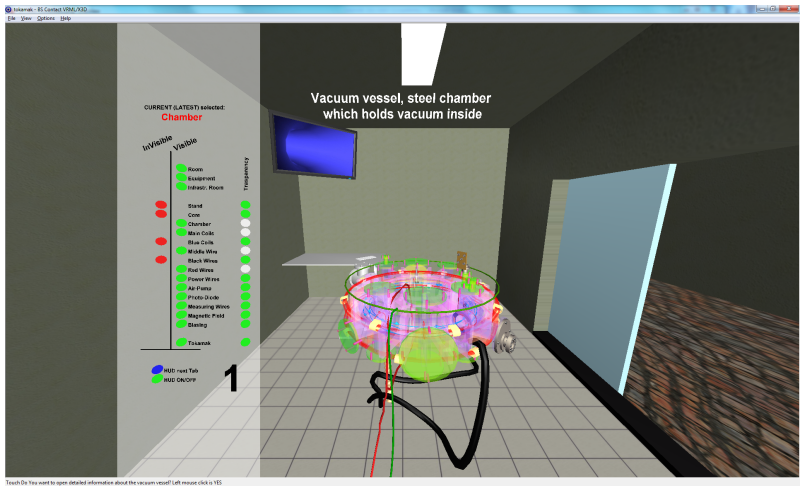


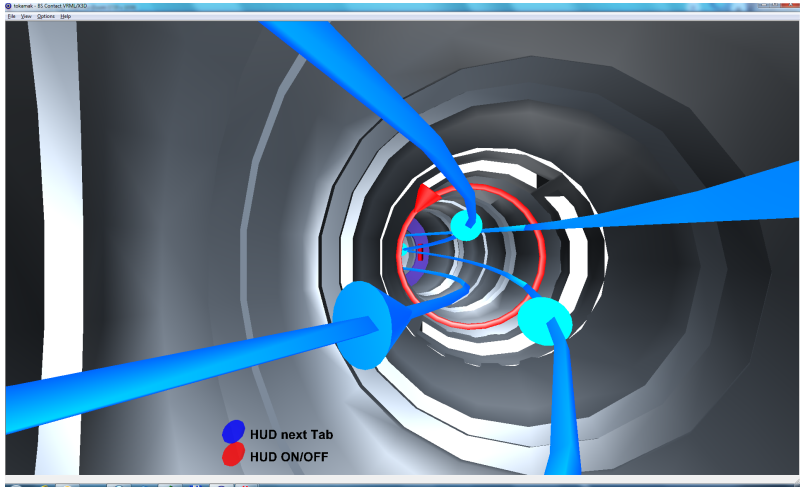
Unique remote operation capability



The GOLEM tokamak virtual model

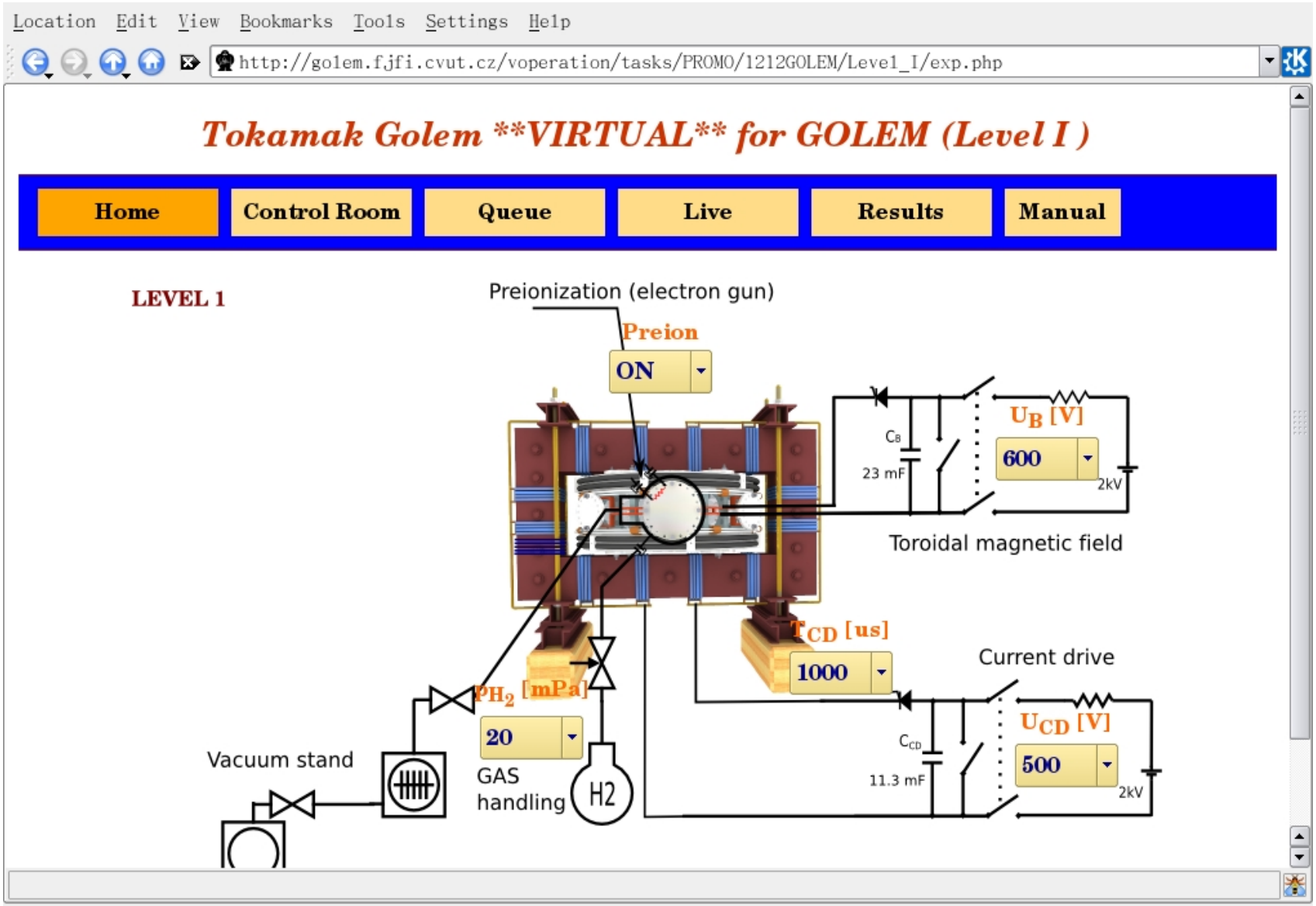
Tokamak Room & Infrastructure Room



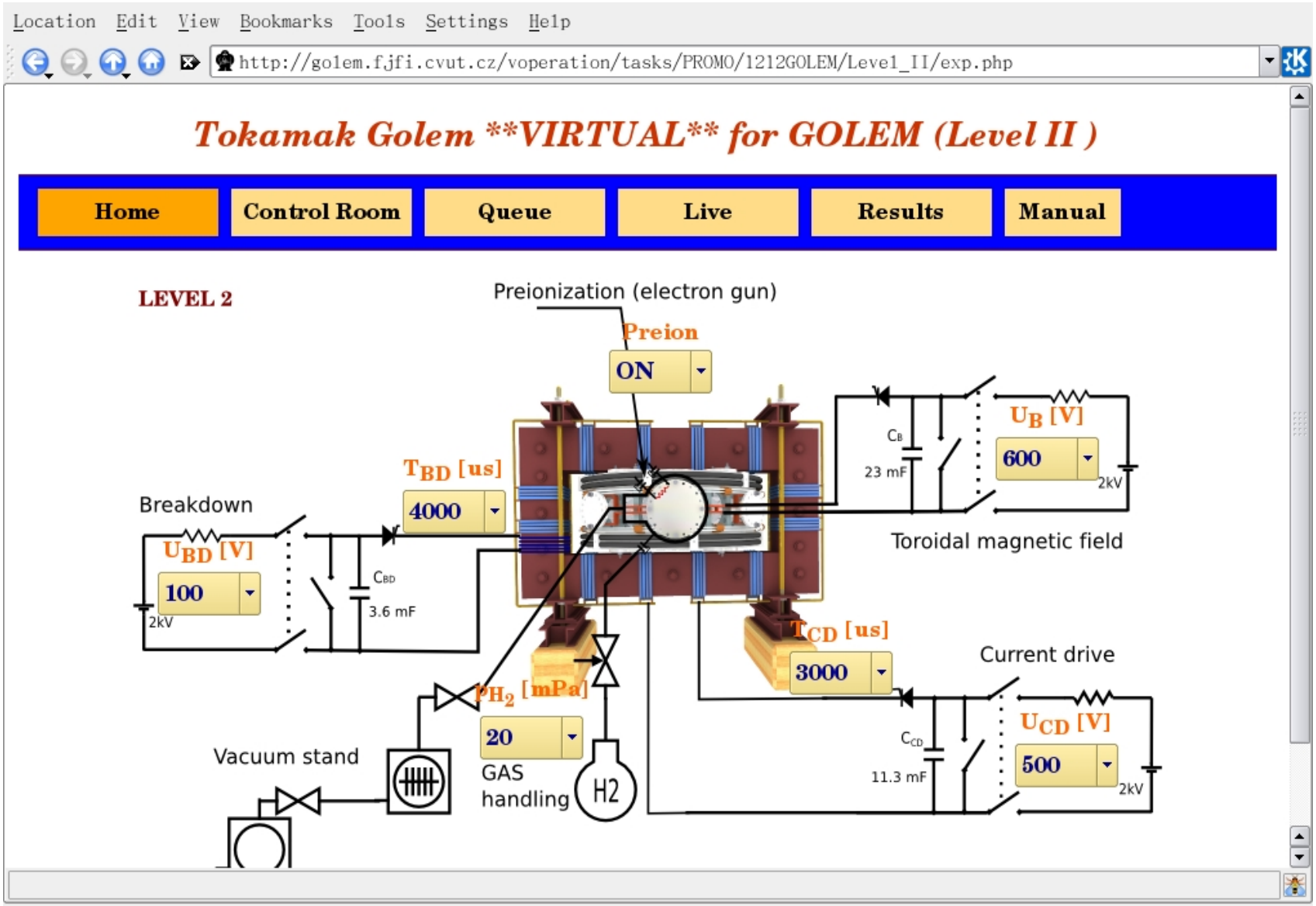


Inner view & Inside chamber

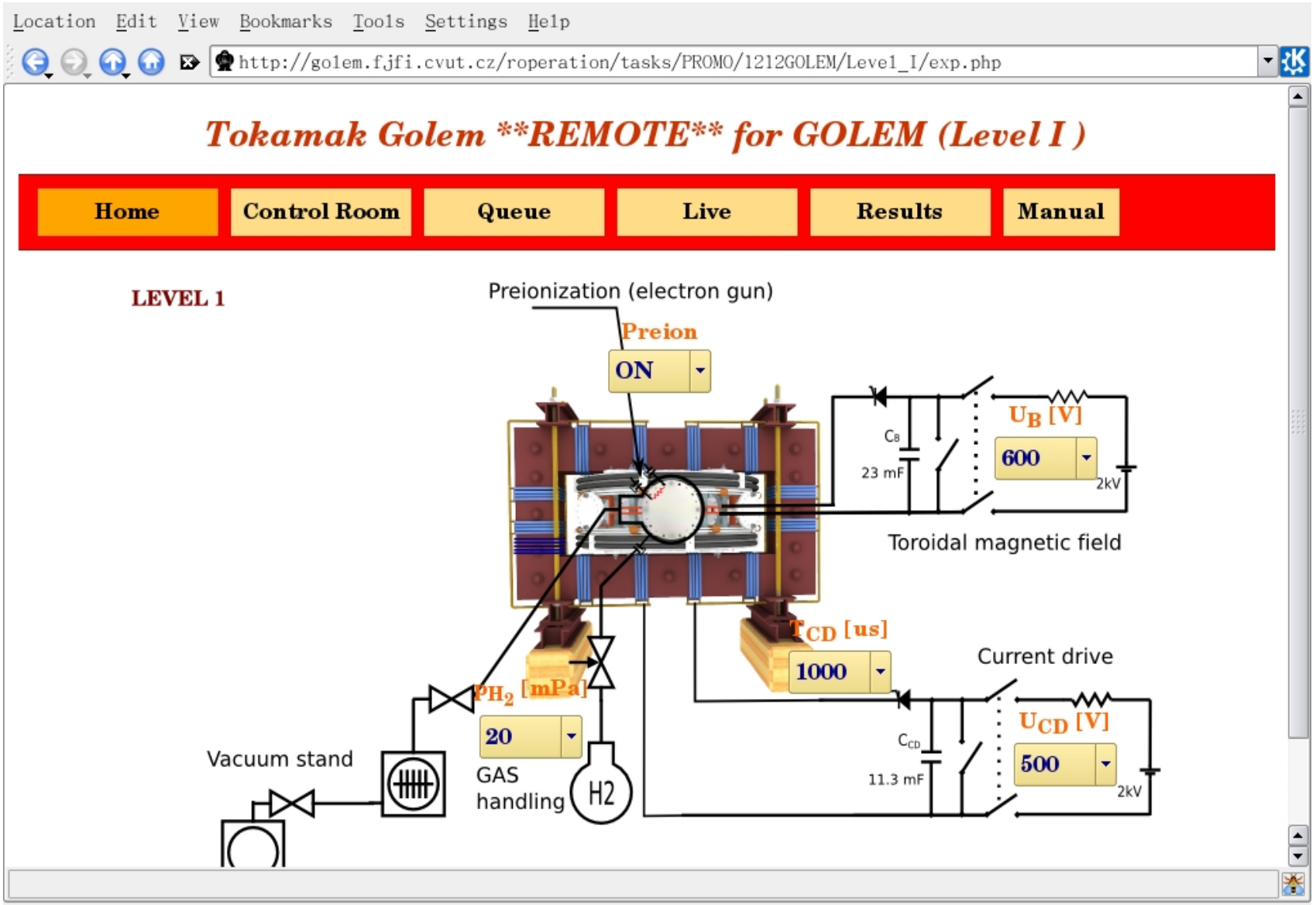
The GOLEM tokamak **virtual** Control Room - level I



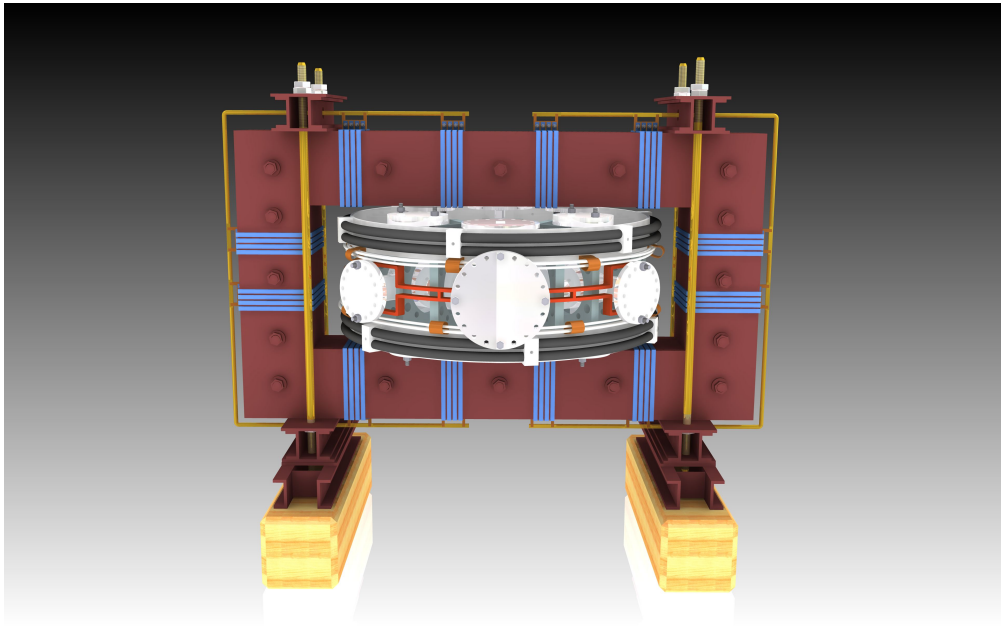
The GOLEM tokamak **virtual** Control Room - level II



The GOLEM tokamak **real** Control Room



Tokamak GOLEM - mission:



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

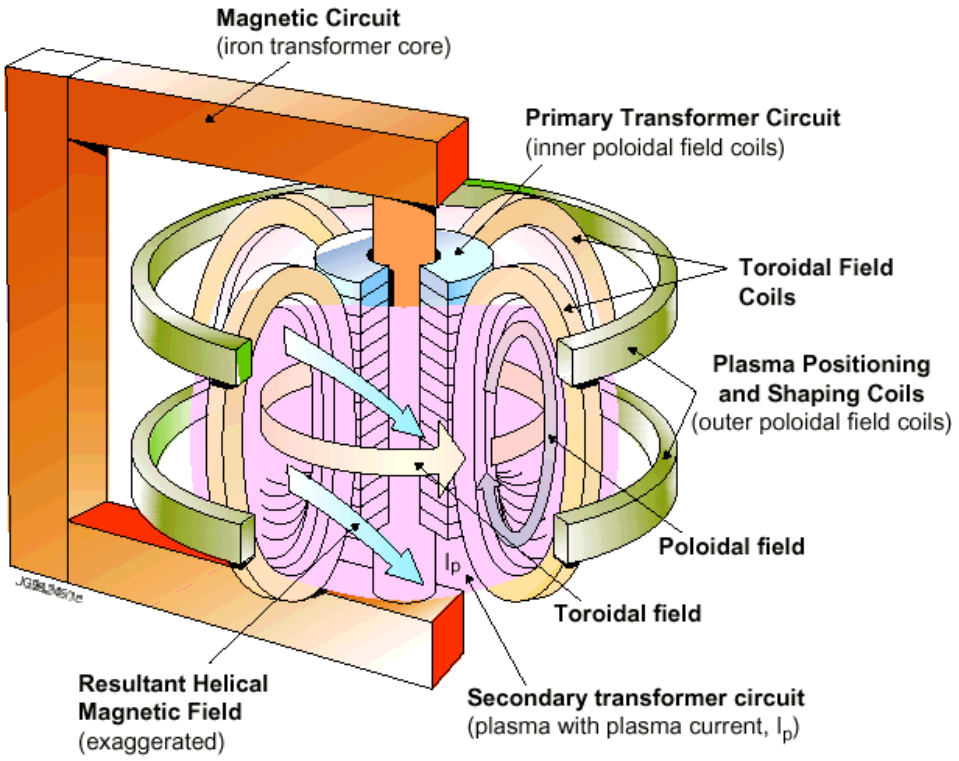
WEB address:

http://golem.fjfi.cvut.cz

Content

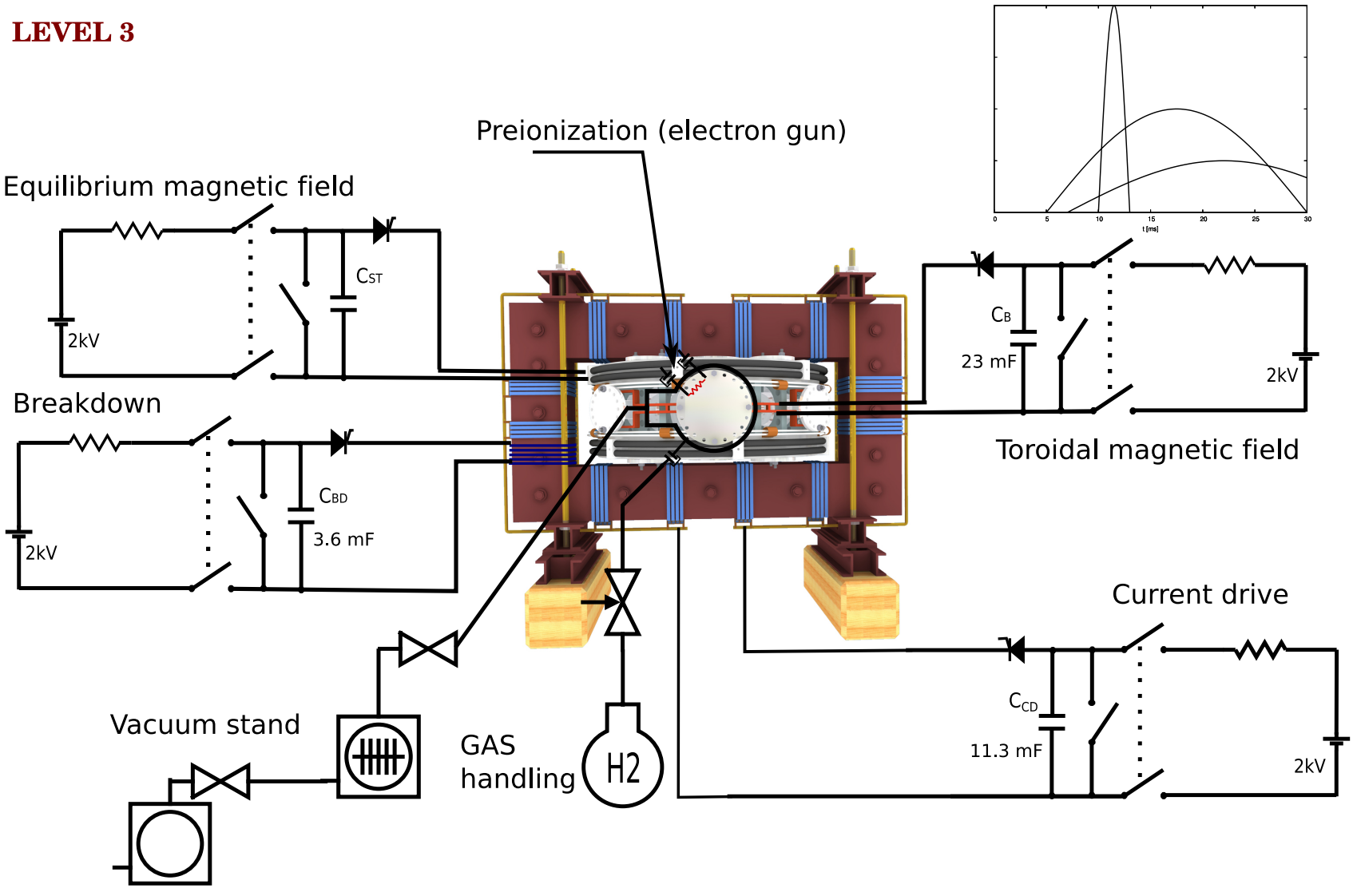
Section begin

Plasma in Tokamak GOLEM - to do



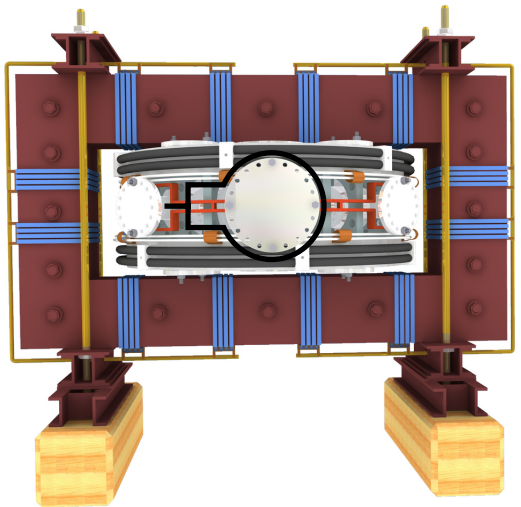
- Vacuum.
- Fill in working gas (H_2 or He).
- Toroidal magnetic field to confine plasma.
- Toroidal electric field to breakdown neutral gas into plasma and consequently heat it.
- Plasma positioning.
- Diagnostics.

Tokamak GOLEM - engineering scheeme



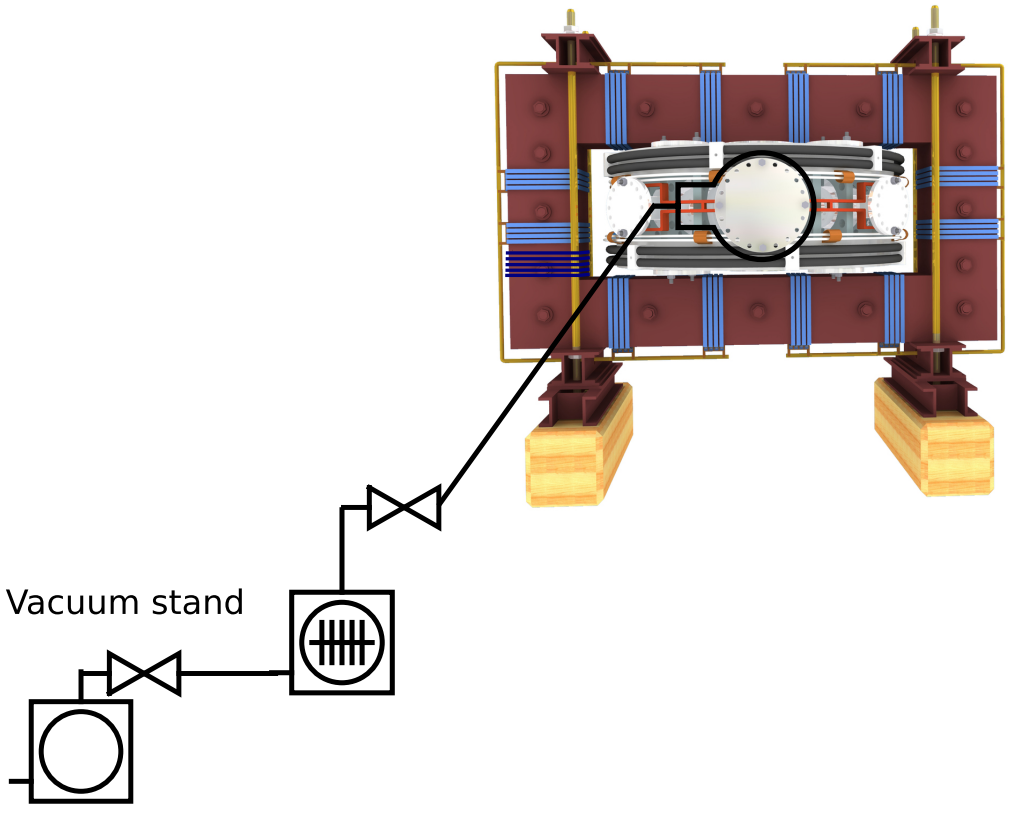
Tokamak GOLEM - basic

LEVEL 0



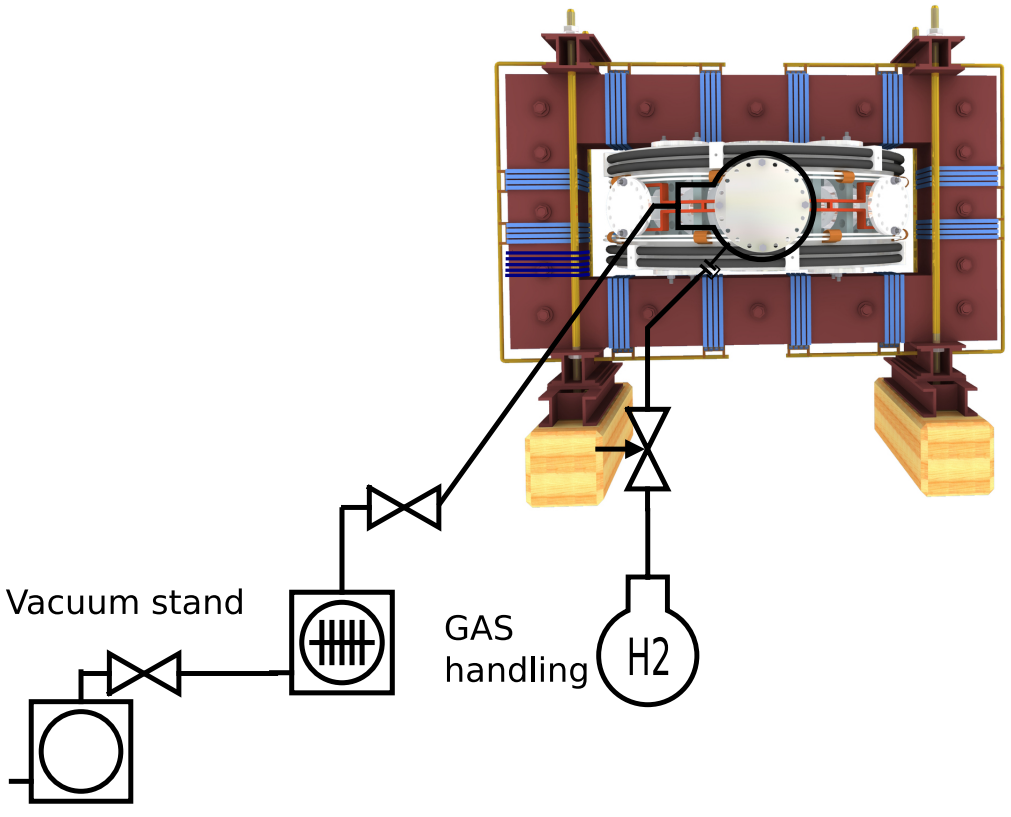
+ vacuum pumping system (100 kPa $\rightarrow \approx$ 1 mPa)

LEVEL 0



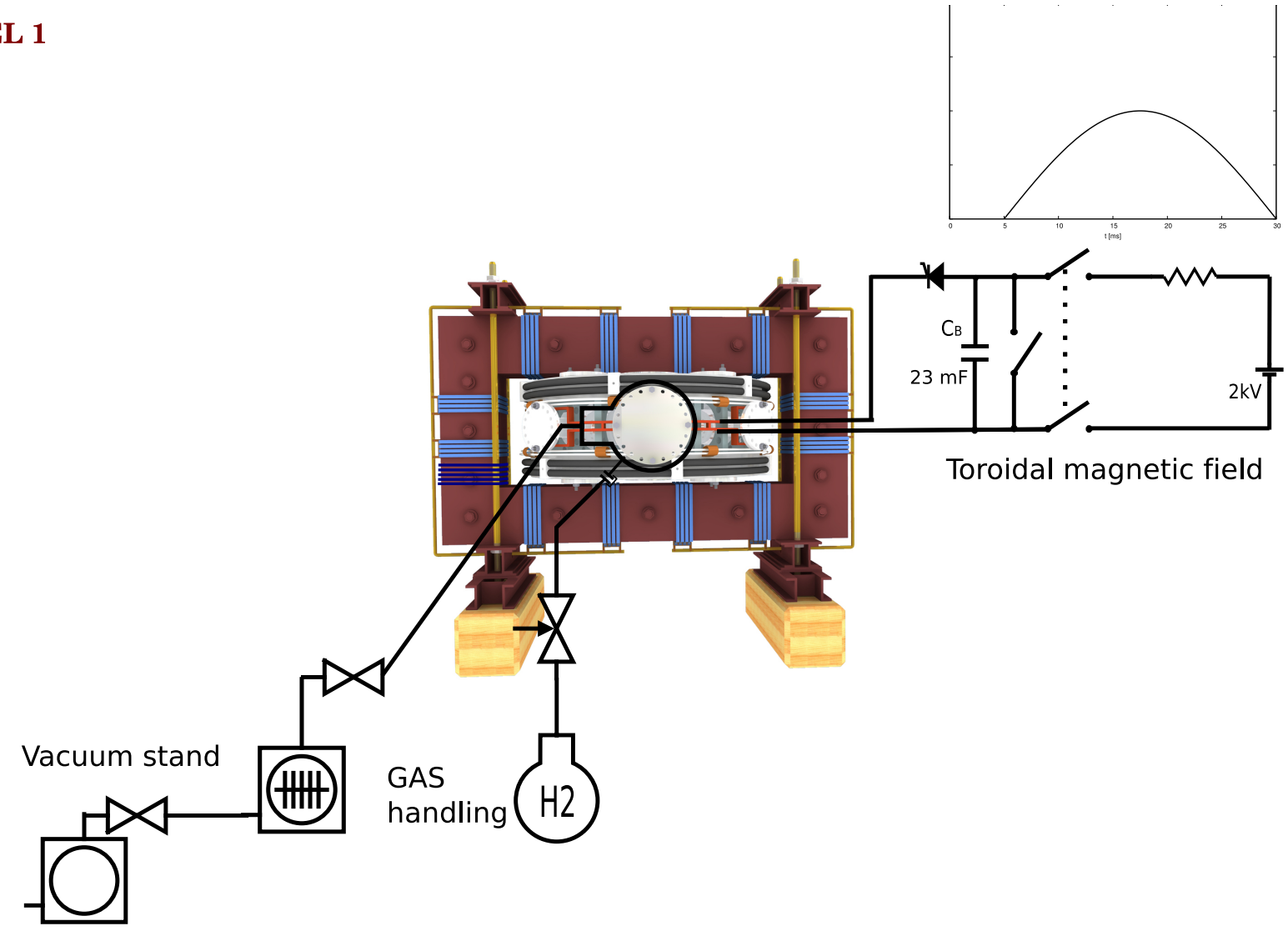
+ working gas management (H_2 or He)

LEVEL 0

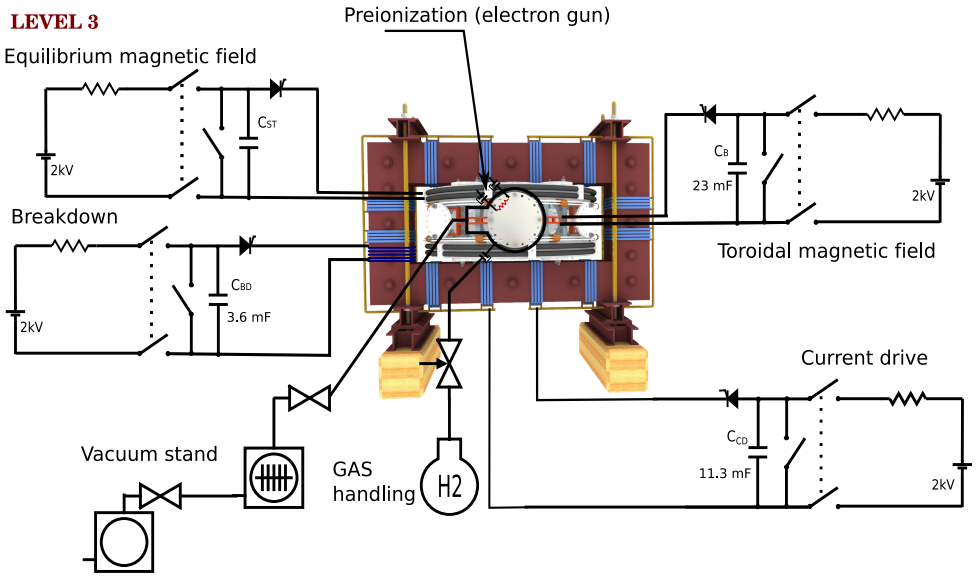


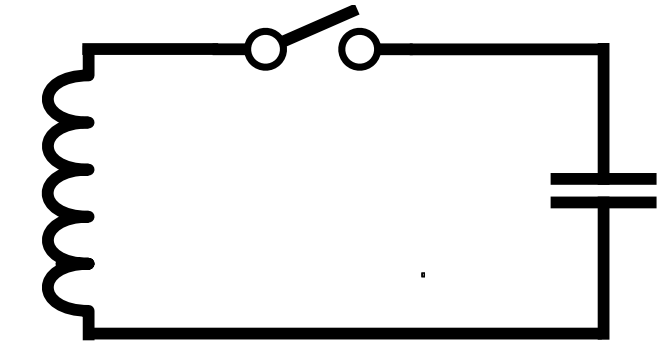
+ toroidal magnetic field B_t .. **plasma confinement**

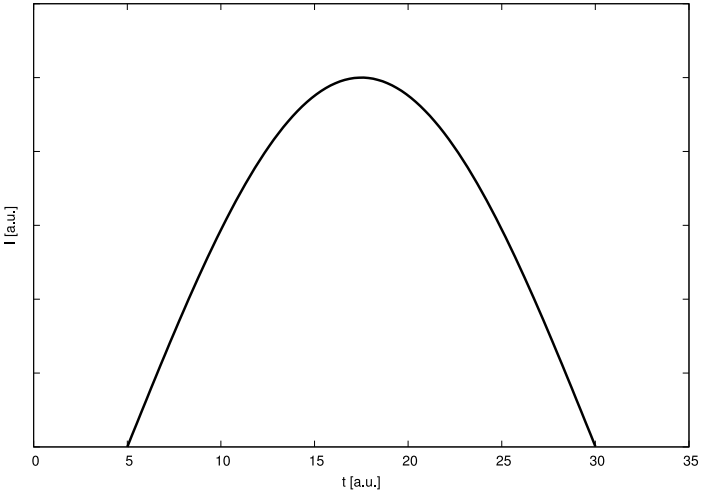
LEVEL 1



Insertion - LC circuit

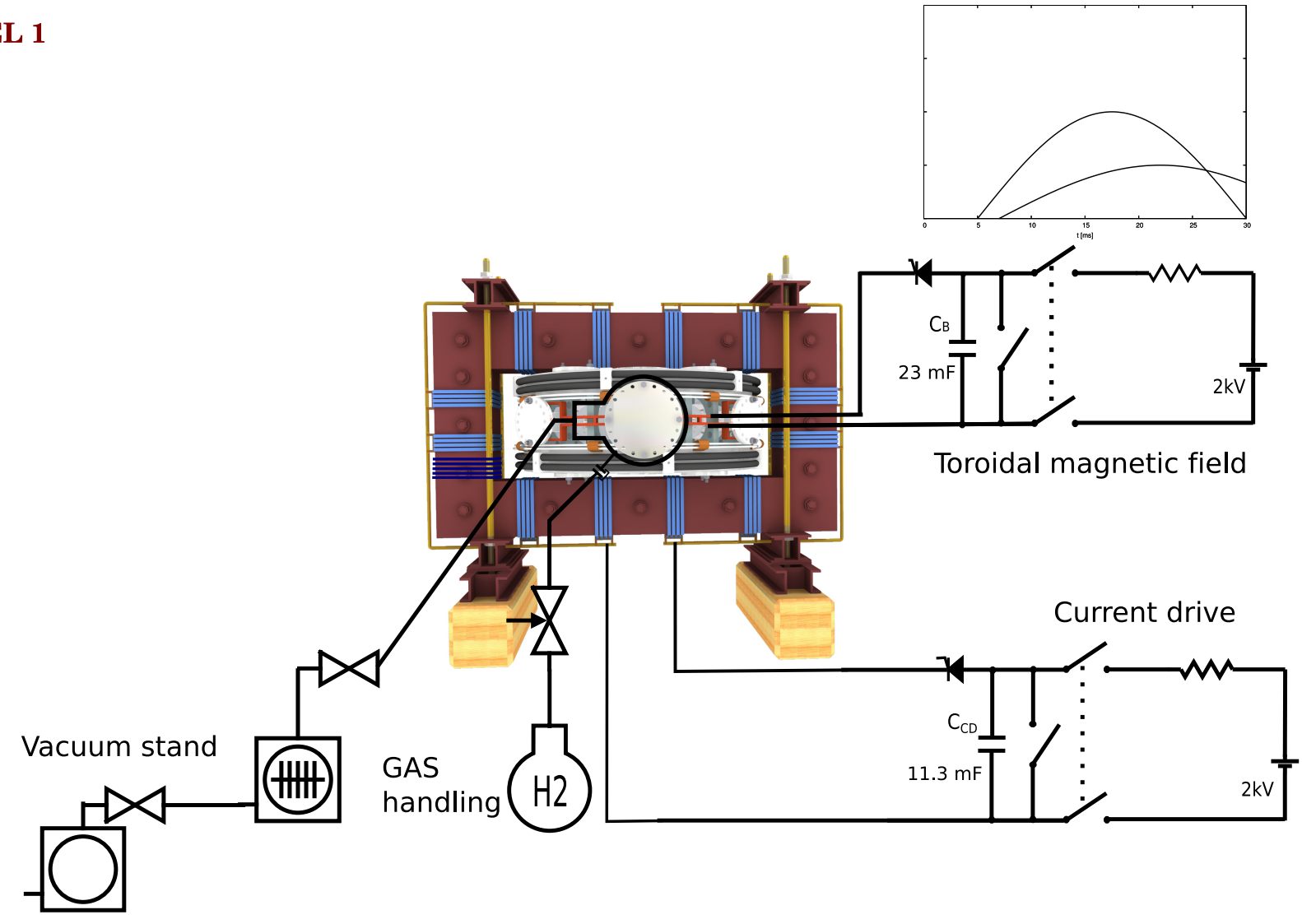






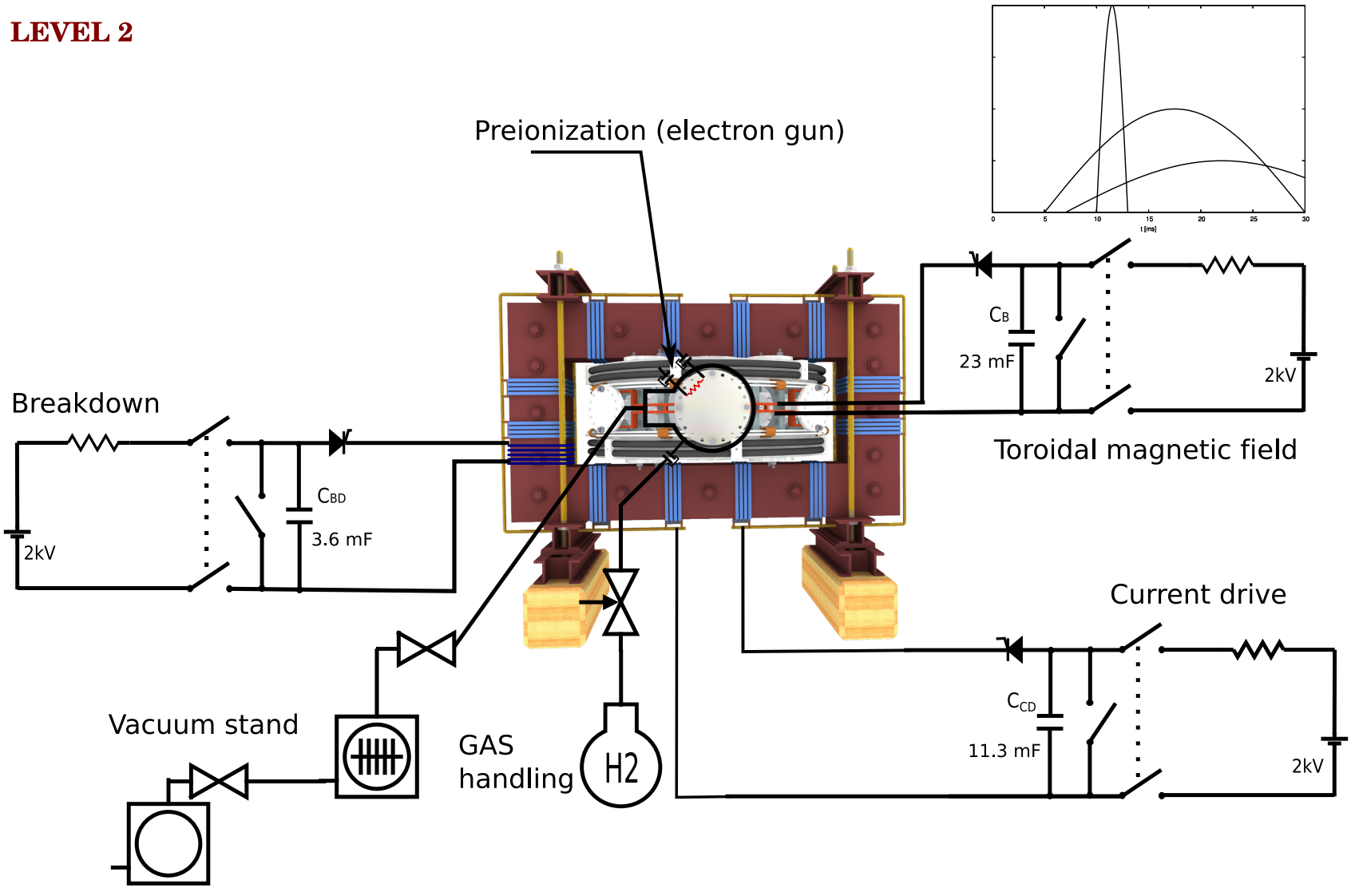
+ toroidal electric field E_{CD} .. **plasma heating**

LEVEL 1



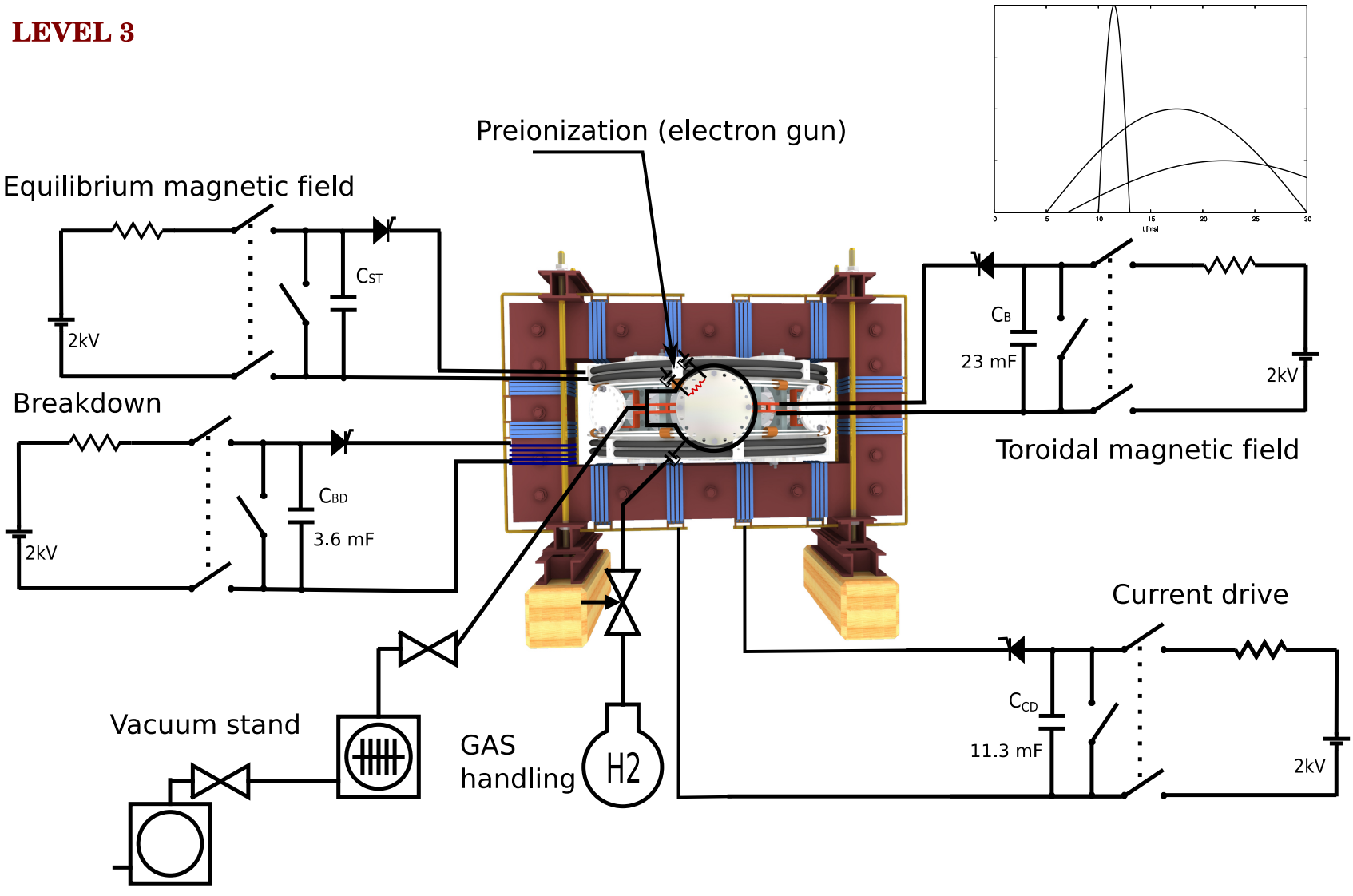
+ toroidal electric field E_{BD} .. **plasma creation**

LEVEL 2

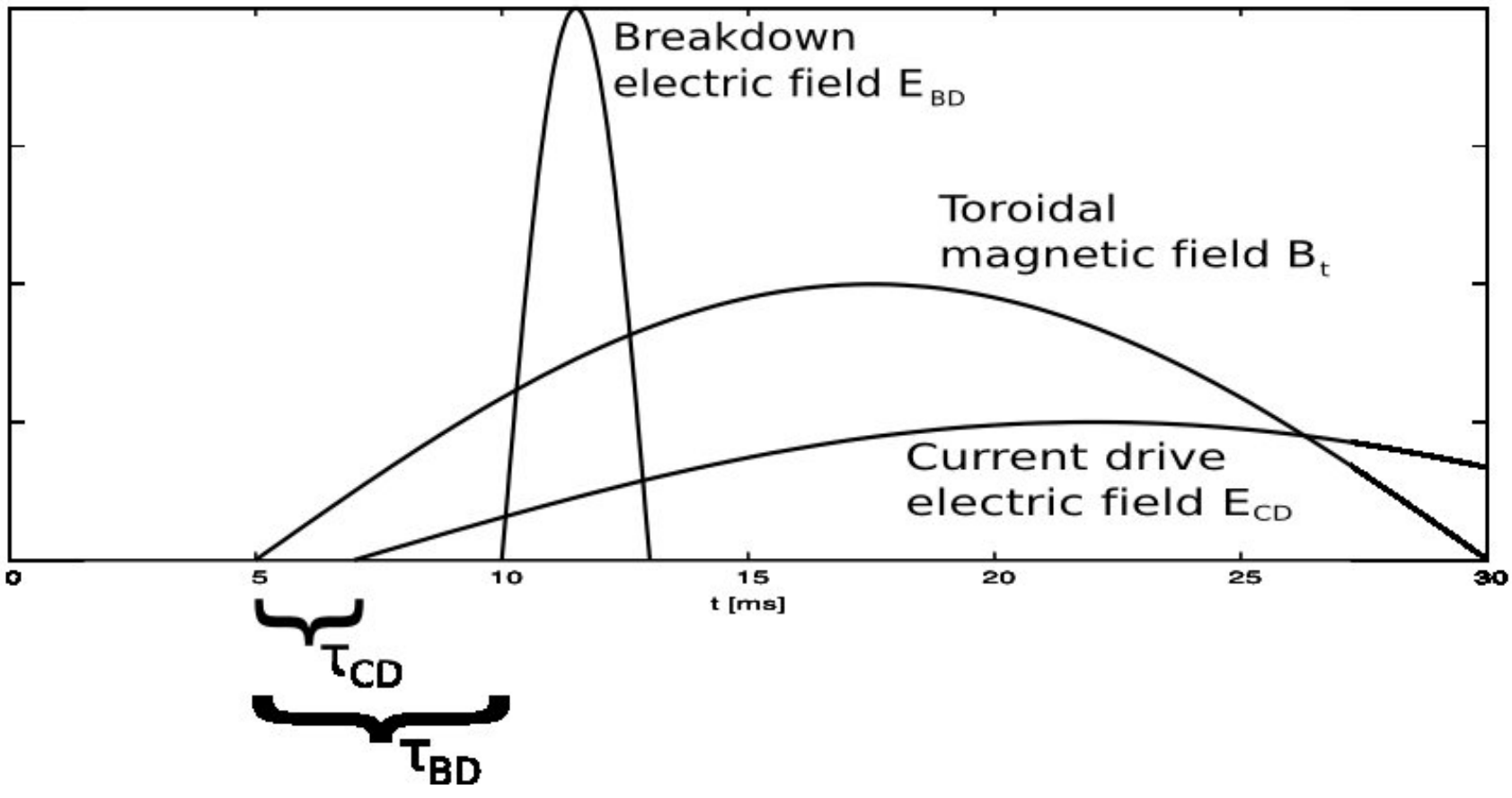


+ equilibrium magnetic field B_{EQ} .. **plasma stabilization**

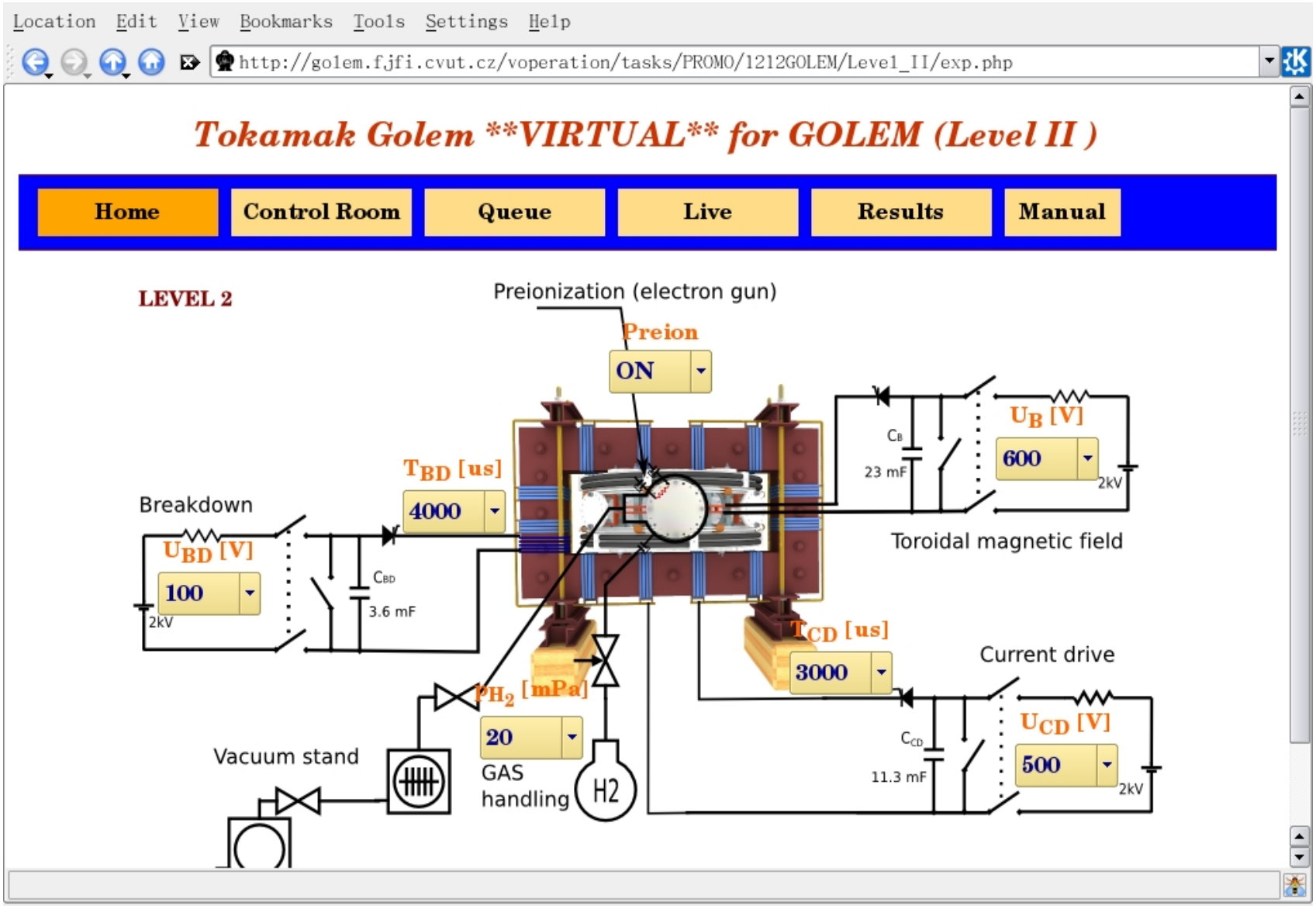
LEVEL 3



Triggering sequence



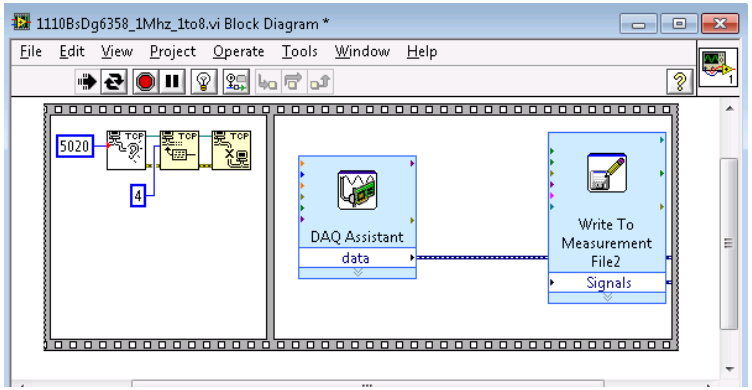
The GOLEM tokamak **virtual** Control Room - level II



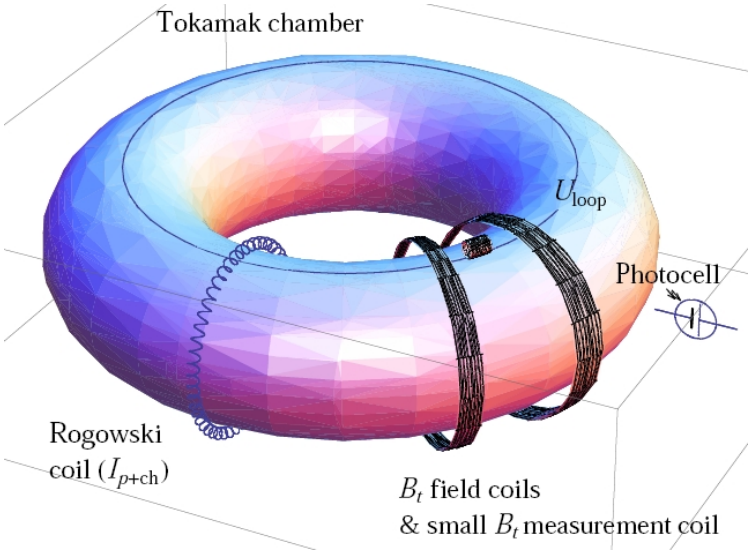
Content

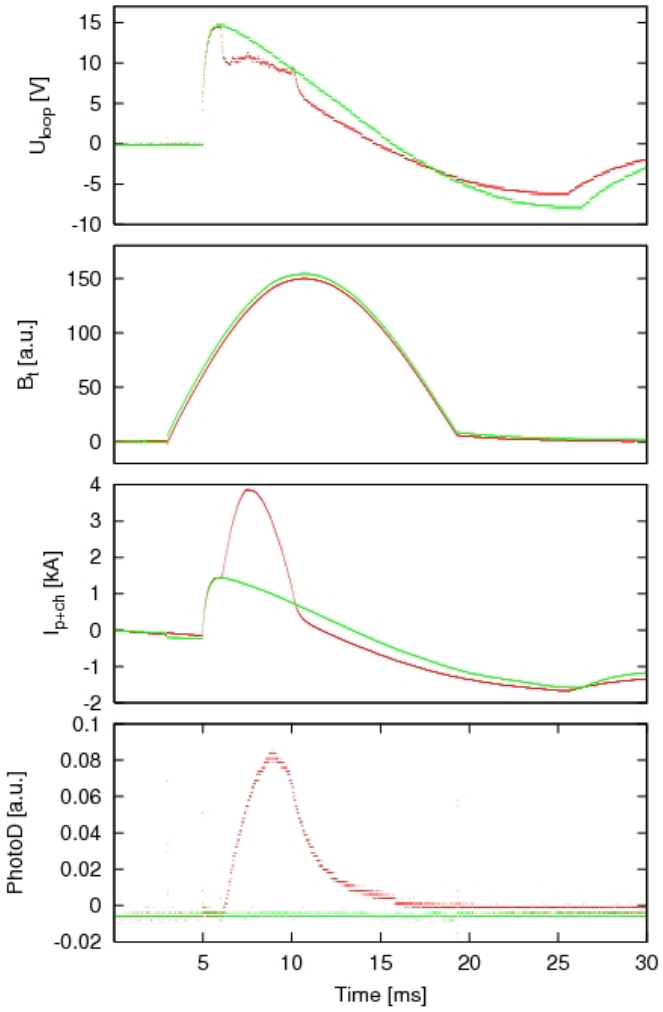
Section begin

Basic plasma diagnostics in tokamak GOLEM



PXI system with PXIe 6358





Data Acquisition System based on: NATIONAL INSTRUMENTS

GOLEM **basic** Data Acquisition System (DAS)

- $U_{loop}, U_{B_t}, U_{I_{pl+ch}}, I_{rad}, I_{H_\alpha rad}, I_{HXR}$.
- $\Delta t = 1\mu s /\ f = 1MHz$.
- 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 $\Delta t = 10\mu s/f = 100kHz$ (neutral gas into plasma breakdown focused)

t	U_{loop}	$U_{\frac{dB}{dt}}$	$U_{\frac{d(I_{pl+ch})}{dt}}$	I_{rad}
:	:	:	:	:
:	:	:	:	:
first	$\approx$	870	lines ..	
:	:	:	:	:
:	:	:	:	:
0,008760	2,062738	0,170025	0,024531	0,003930
0,008770	2,052438	0,163909	0,018415	0,003930
0,008780	2,040528	0,131720	0,020025	0,004252
0,008790	2,028296	0,161012	0,022600	0,004574
0,008800	2,017995	0,168416	0,023887	0,003930
0,008810	2,003510	0,174853	0,028394	0,004252
0,008820	1,984519	0,159081	0,032256	0,004252
0,008830	1,964561	0,128823	0,042557	0,004896
0,008840	1,945892	0,177107	0,033222	0,005218
0,008850	1,928510	0,171634	0,036441	0,004574
0,008860	1,908552	0,161978	0,051892	0,004896
0,008870	1,890848	0,164231	0,047385	0,005540
0,008880	1,876041	0,159403	0,039338	0,005218
0,008890	1,860591	0,178394	0,039982	0,005861
0,008900	1,847071	0,173244	0,049638	0,006183
0,008910	1,834196	0,156506	0,052857	0,006505
0,008920	1,815526	0,162300	0,051248	0,006505
0,008930	1,792672	0,181935	0,059295	0,006827
:	:	:	:	:
:	:	:	:	:
next	$\approx$	3100	lines ..	
:	:	:	:	:

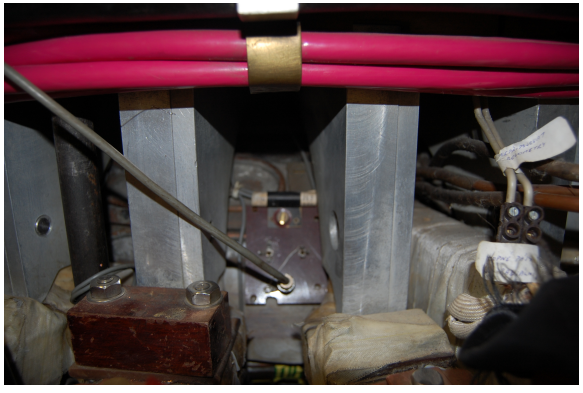
Basic diagnostic - total current I_{total}, I_{pl+ch} respectively

Is deduced from Rogowski coil measurements with three operations:

- offset identification from first 4500 data rows).
- time integration (it is a magnetic diagnostic, where $U_{acquired} \sim \frac{dI_{total}}{dt}$)
- multiplication of calibration factor C_{rog}

$$\left\langle U^{rog}_{offset} \right\rangle = \frac{1}{4500} \sum_{i=0}^{4500} U^{rog}_i; \; I_{total} \approx C_{rog}\left(\sum_{i=0}^{40000} U^{rog}_i \Delta t - \left\langle U^{rog}_{offset} \right\rangle t \right).$$

Basic diagnostic - toroidal magnetic filed B_t

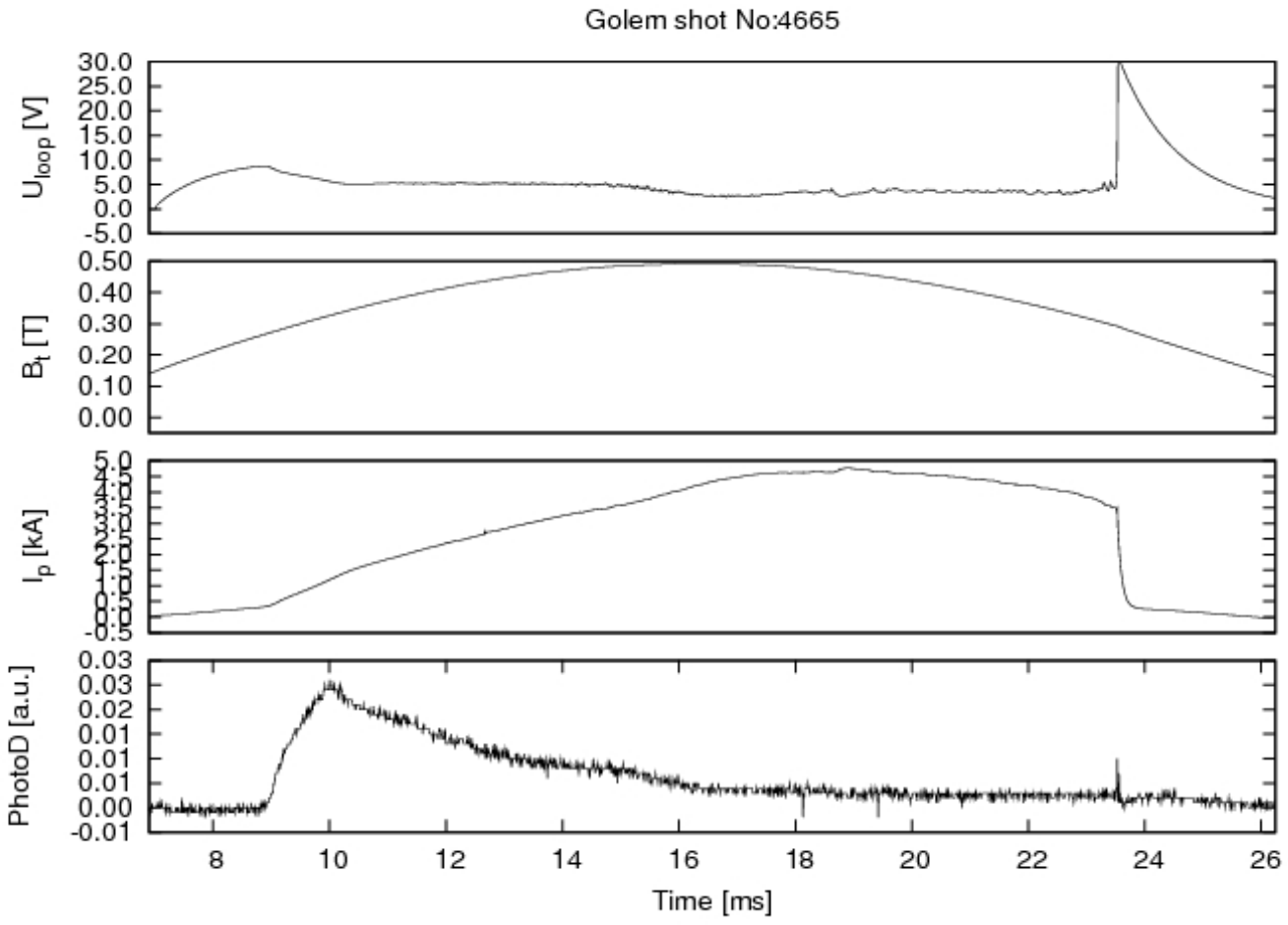


Is deduced from small coil measurements with three operations:

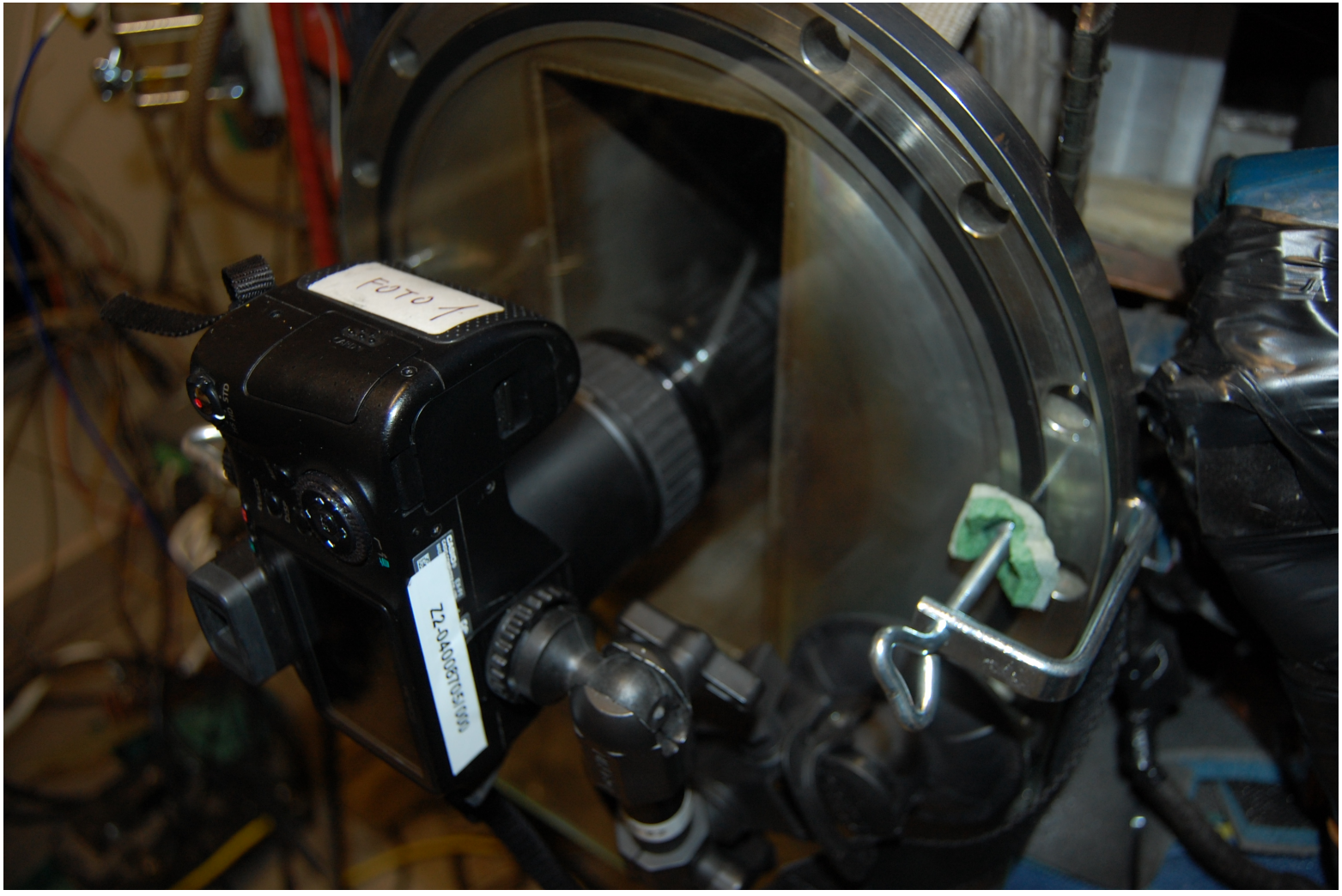
- offset identification from first 4500 data rows).
- time integration (it is a magnetic diagnostic, where $U_{acquired} \sim \frac{dB_t}{dt}$)
- multiplication of calibration factor C_{Bt}

$$\left\langle U^{Bt}_{offset} \right\rangle = \frac{1}{4500} \sum_{i=0}^{4500} U^{Bt}_i; \; B_t \approx C_{Bt}(\sum_{i=0}^{40000} U^{Bt}_i \Delta t - \left\langle U^{Bt}_{offset} \right\rangle t).$$

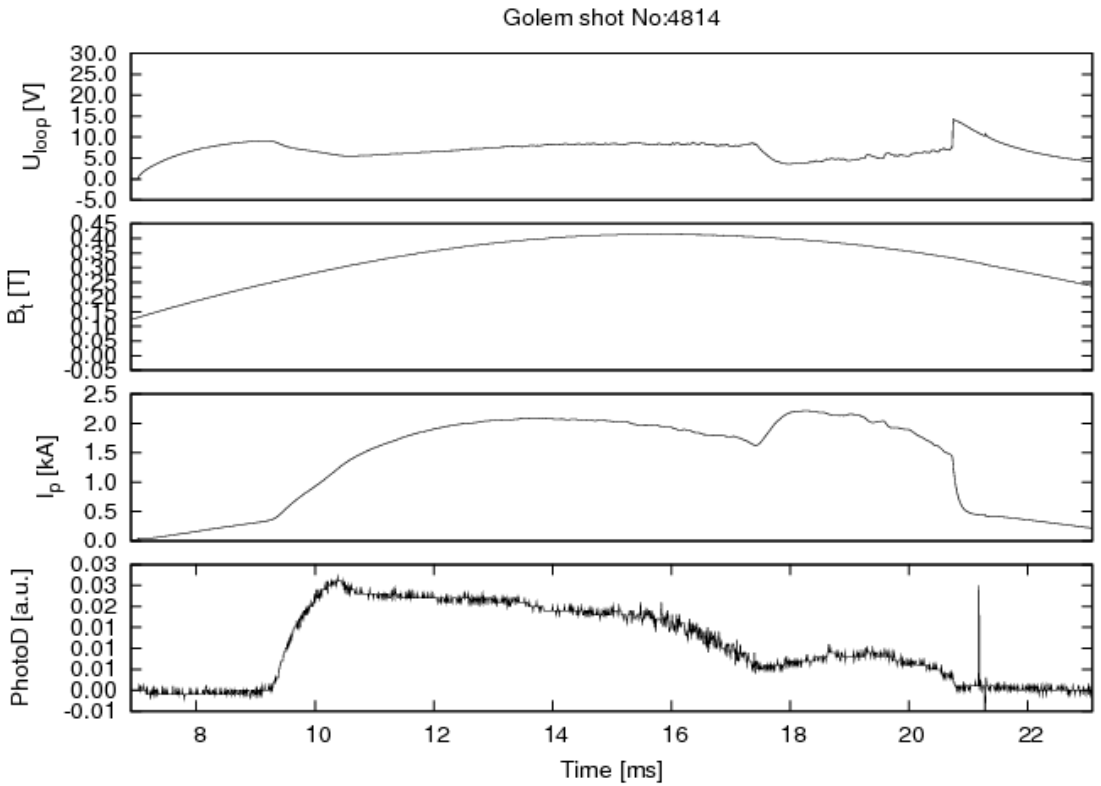
Golem discharge



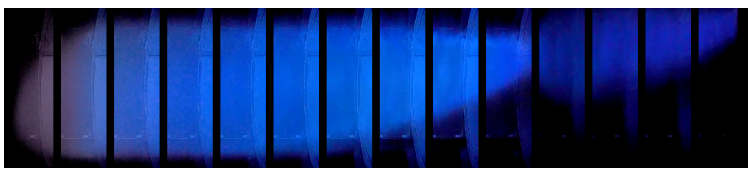
Fast camera CASIO FX1



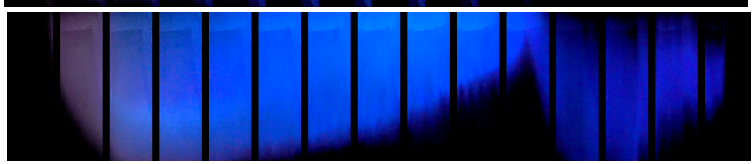
Fast camera CASIO FX1 - results



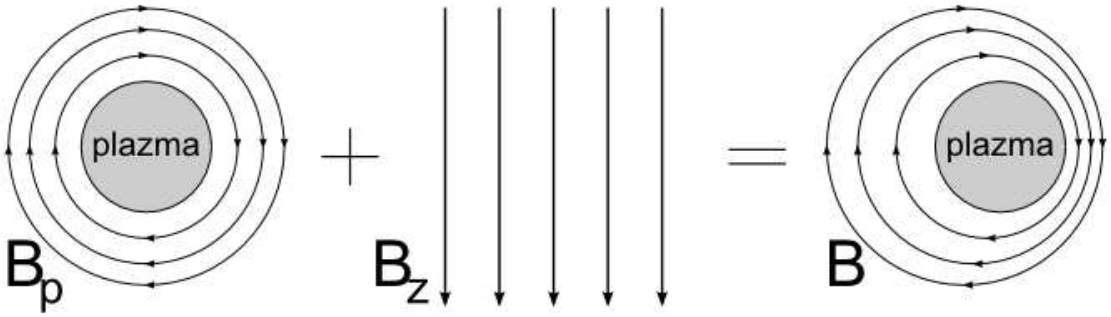
TOP view:

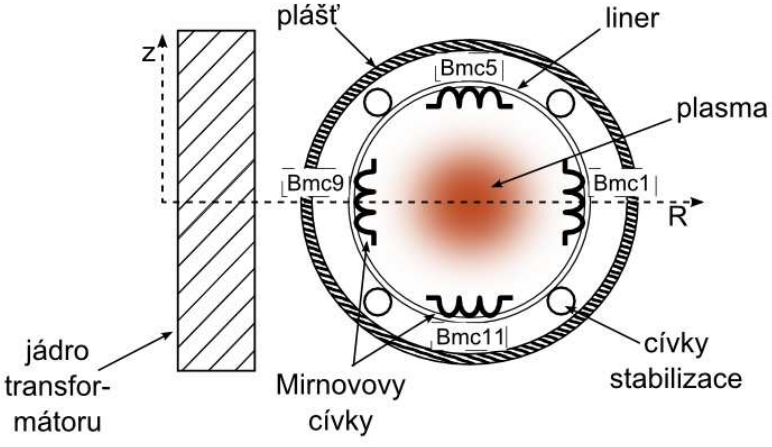


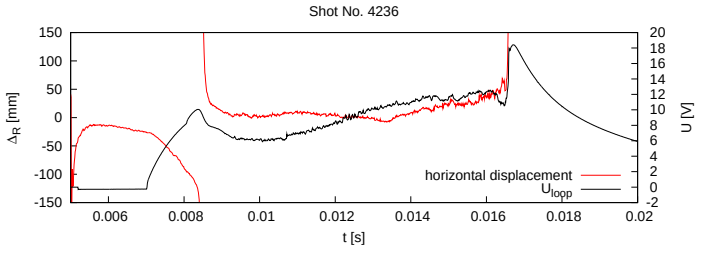
SIDE view:



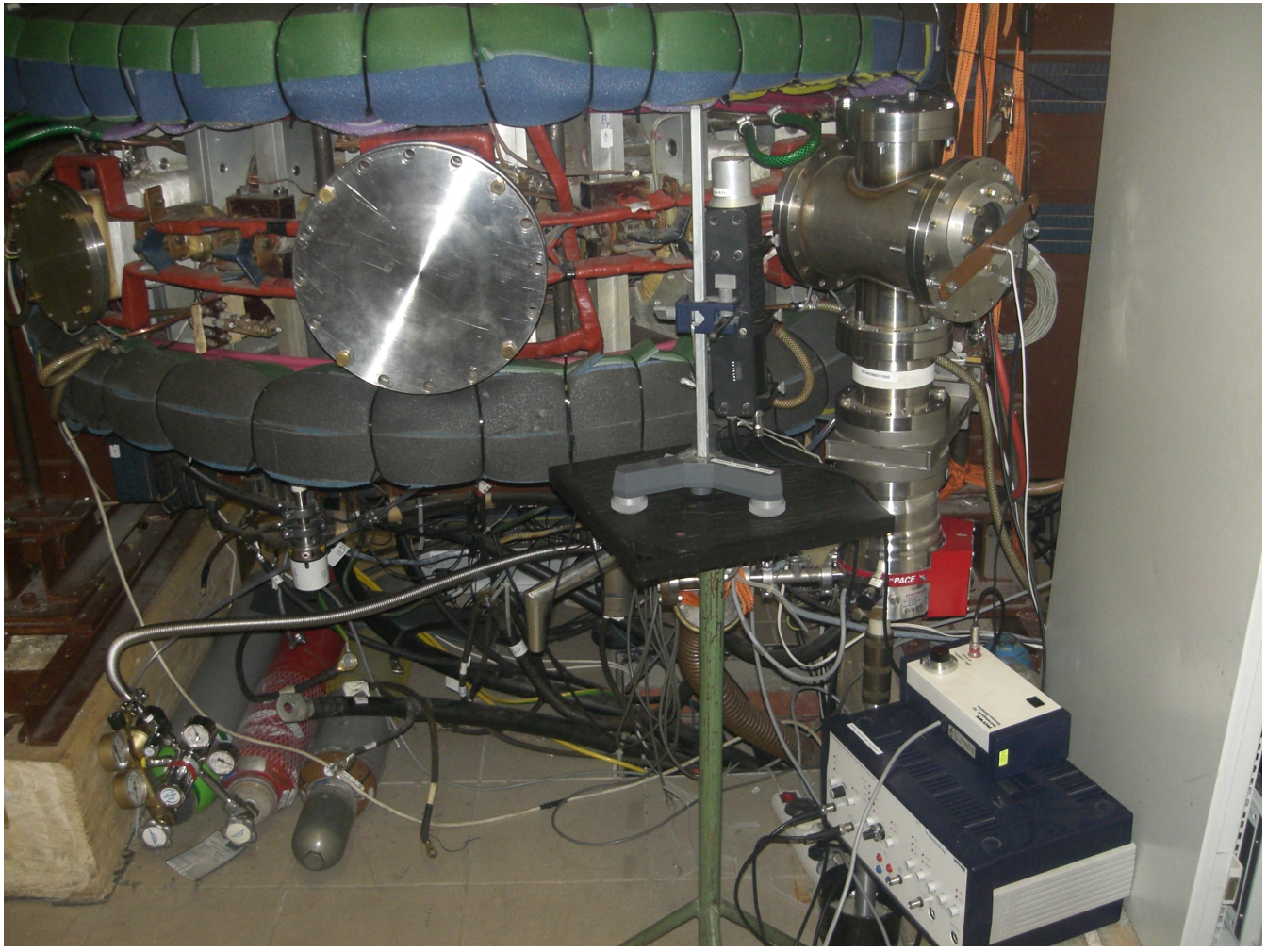
Plasma Position using Mirnov Coils



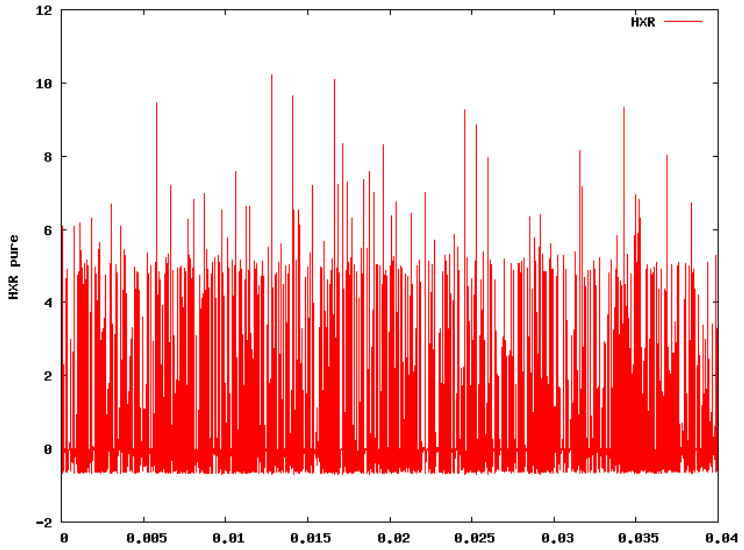


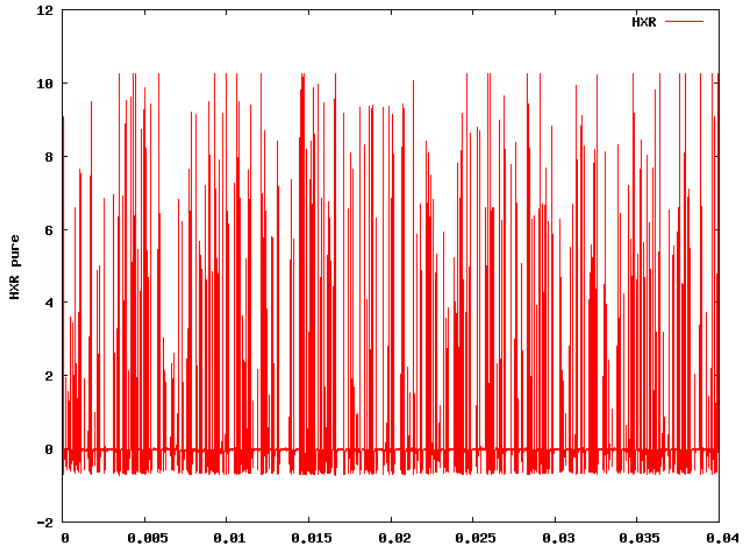


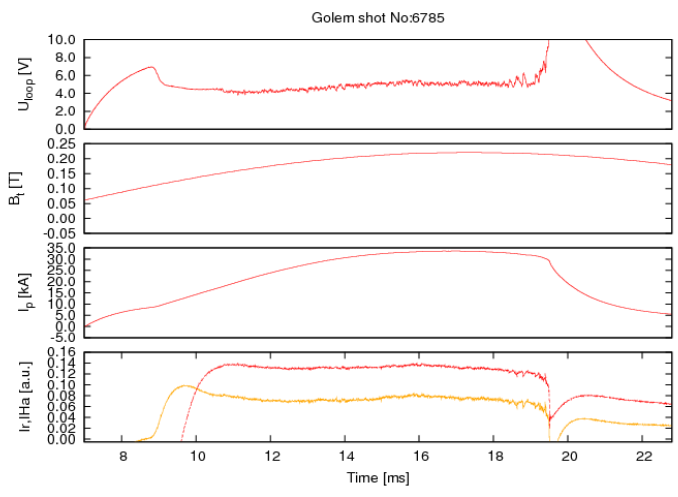
HXR (Lenka Kocmanová) (6780-6787)

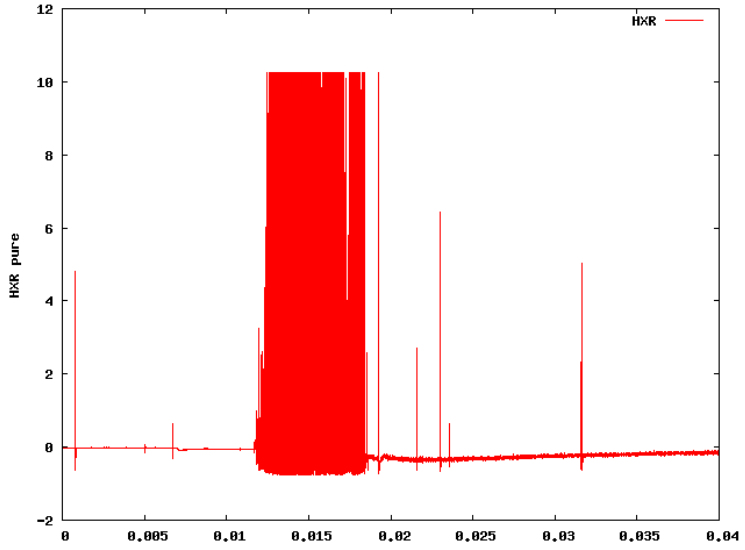


HXR (Lenka Kocmanová) (6780-6787)

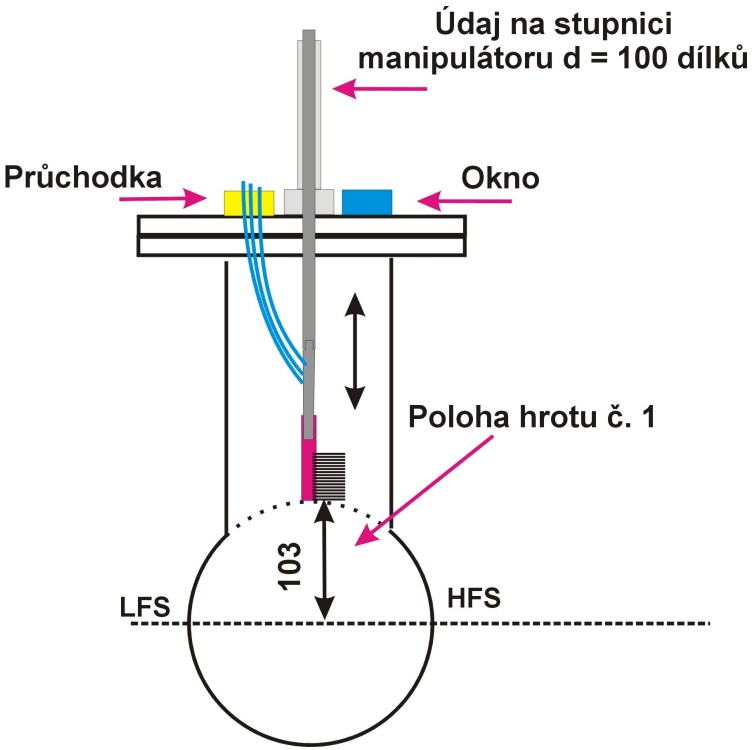


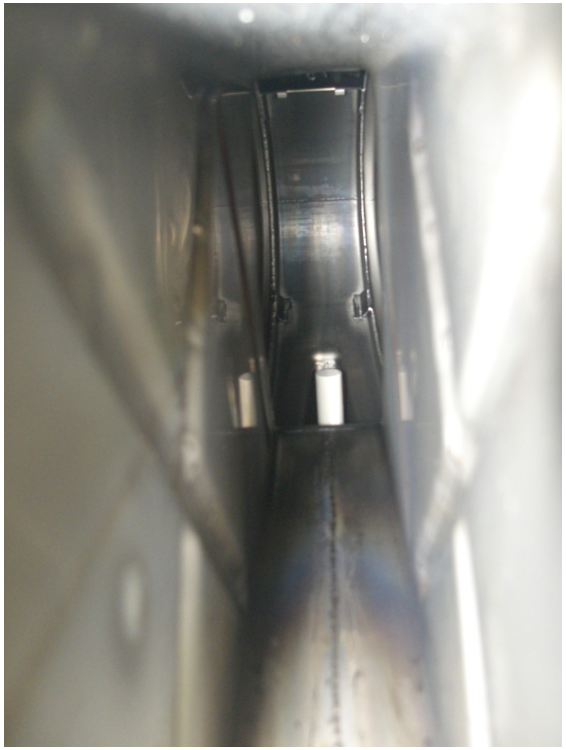


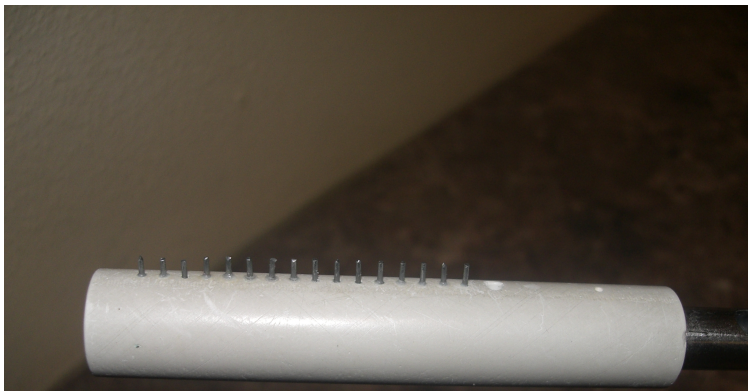




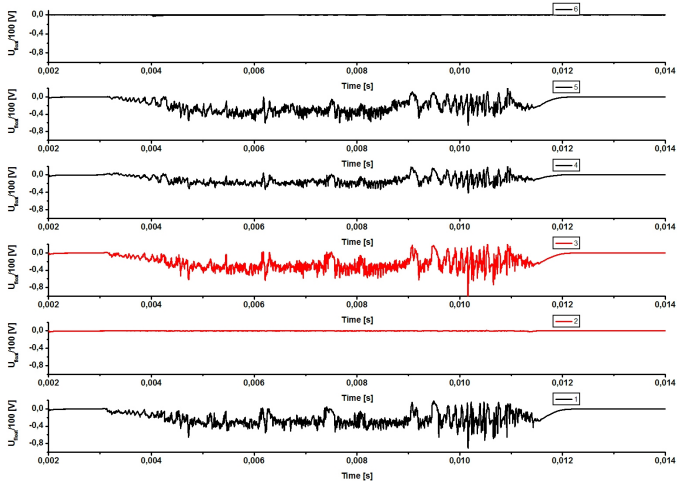
Rake probe (2012)

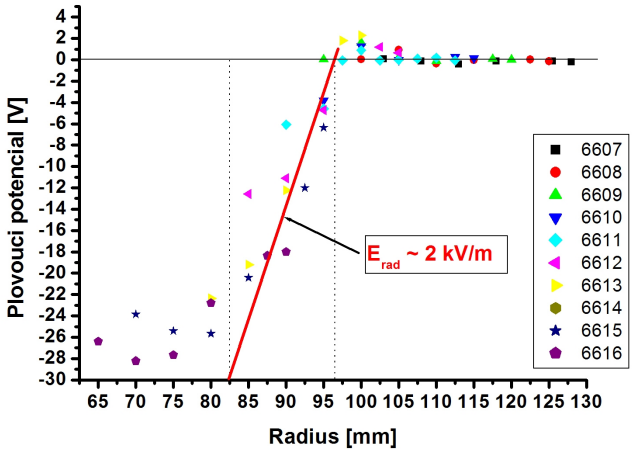


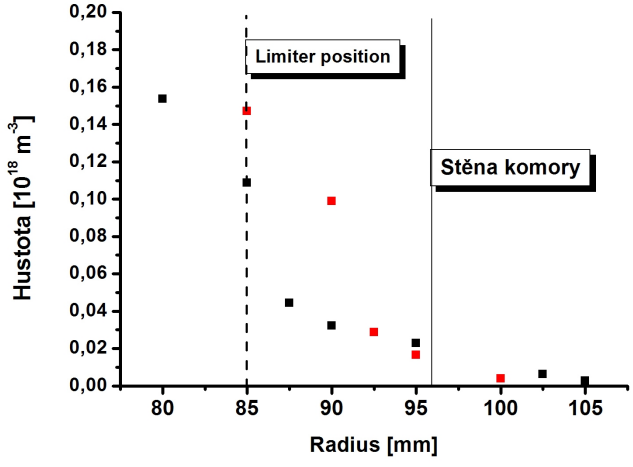




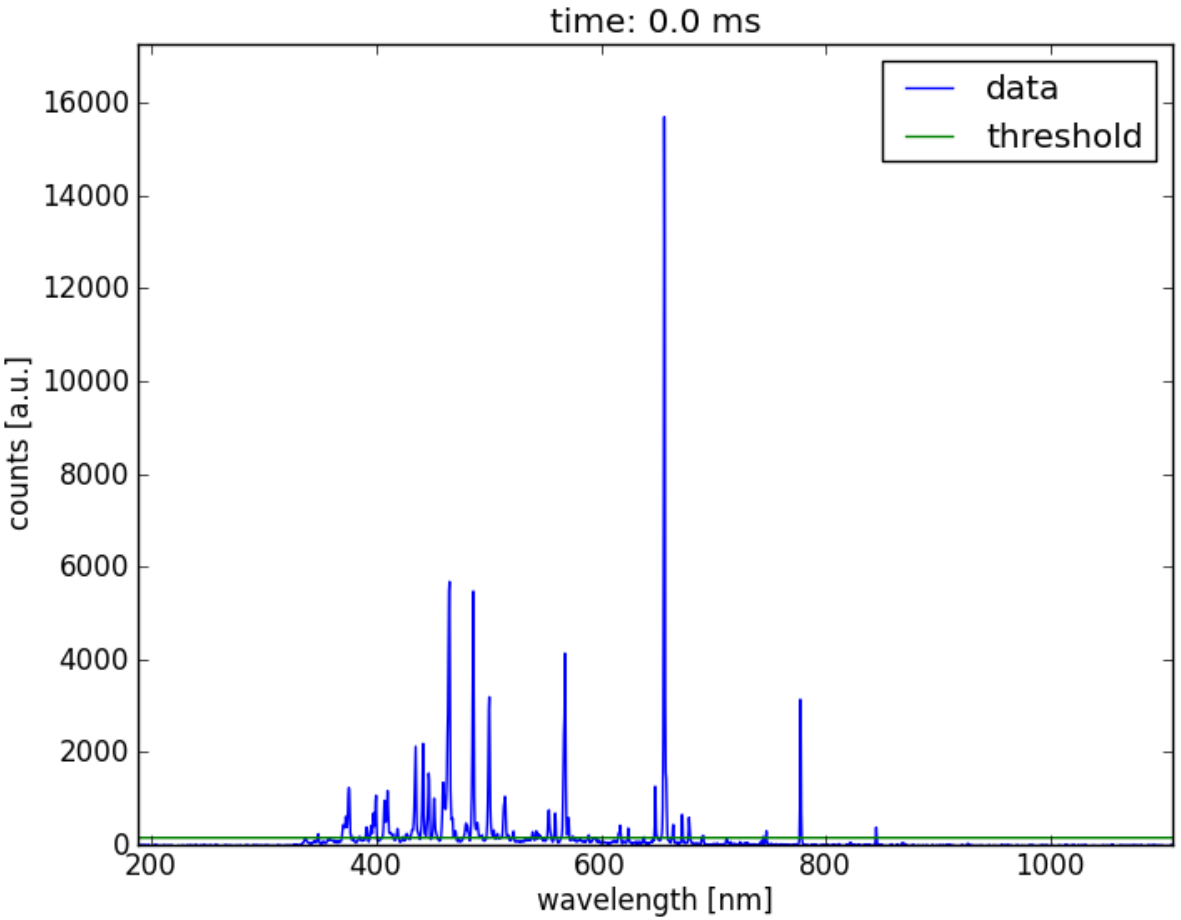
Rake probe (2012) - results







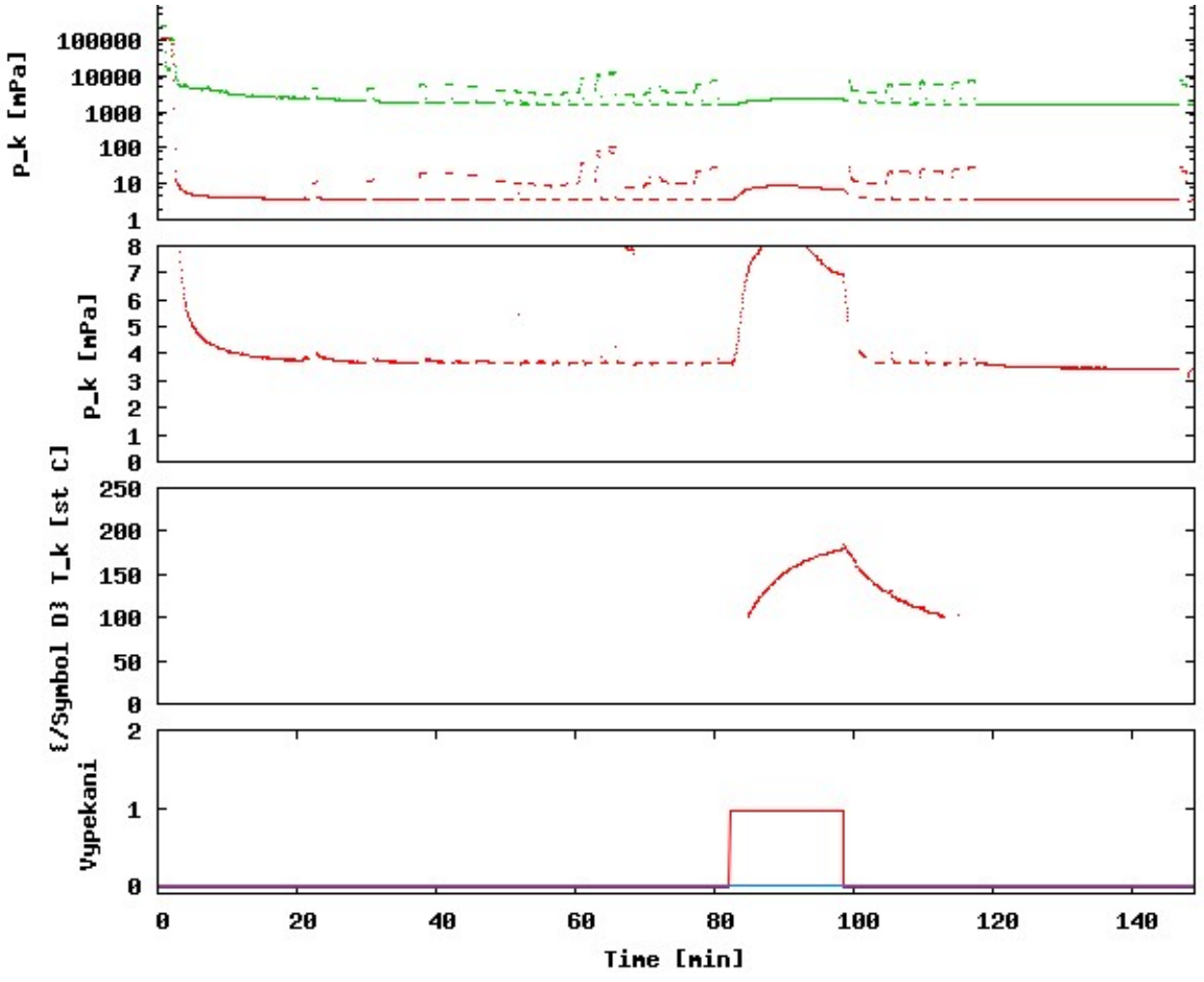
Spectra


time: 0.0 ms
data
threshold
16000
14000
12000
10000
8000
6000
4000
2000
0
counts [a.u.]
200
400
600
800
1000
wavelength [nm]

Content

Section begin

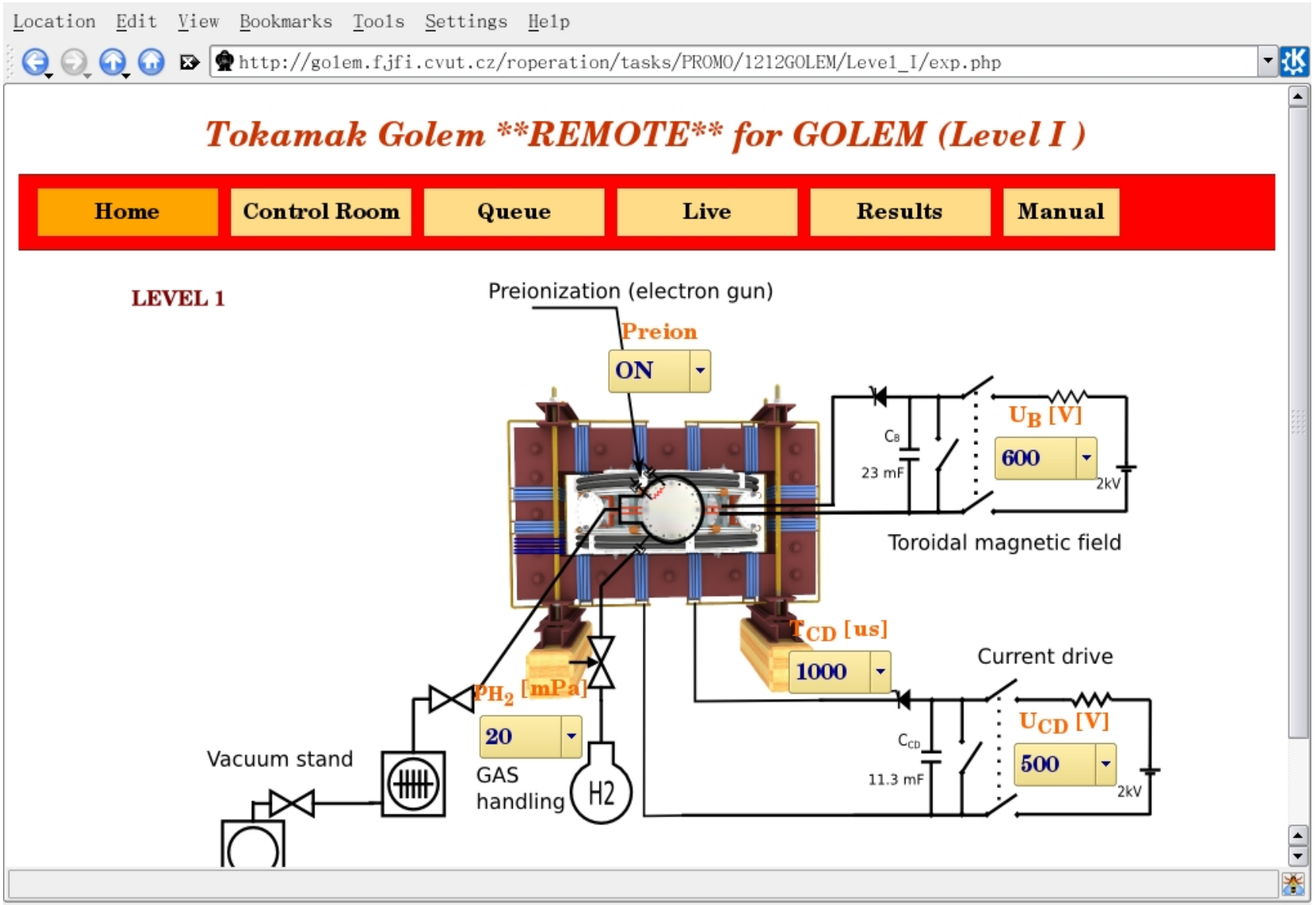
Chamber conditioning



Content

Section begin

The GOLEM tokamak **real** Control Room



Operational parameters and their limits

The parameters to be set remotely:

- Toroidal magnetic field (B_t) through the voltage of the toroidal field capacitor bank U_B, range: $400 - 1300\ \mathrm{V}$.
- Toroidal electric field (E_{CD}) through the capacitor bank for the current drive U_{CD}, range: $200 - 600\ \mathrm{V}$.
- Toroidal electric field (E_{BD}) through the capacitor bank for the breakdown U_{BD}, range: $100 - 200\ \mathrm{V}$.
- The time delay between the triggers of the toroidal magnetic field and the current drive T_{CD}, range: $0 - 20000\ \mu\mathrm{s}$.
- The time delay between the triggers of the toroidal magnetic field and the breakdown T_{BD}, range: $0 - 20000\ \mu\mathrm{s}$.
- Hydrogen or Helium gas pressure p_{WG}, range: $0 - 100\ \mathrm{mPa}$.
- Status of preionization (ON/OFF).
- Requested working gas (H2/He).

Content

Section begin

Central electron temperature estimation I [3]

The current density of plasma is

$$j = E \cdot \sigma \tag{1}$$

where σ is the specific conductivity of plasma given by

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

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

$$E = \frac{U_{loop}}{2\pi R}. \tag{3}$$

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

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

Central electron temperature estimation II [3]

For the electron temperature, we assume a polynomial profile

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

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

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

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

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

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

Content

Section begin

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: Overal 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

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