The tokamak Golem discharges

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pro Žhavé výstřely 2012

Outline of the talk

1. Introduction
2. Tokamak GOLEM - engineering scheme
3. Tokamak GOLEM - diagnostics
4. Tokamak GOLEM - remote operation
5. Electron temperature estimation

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1 Introduction

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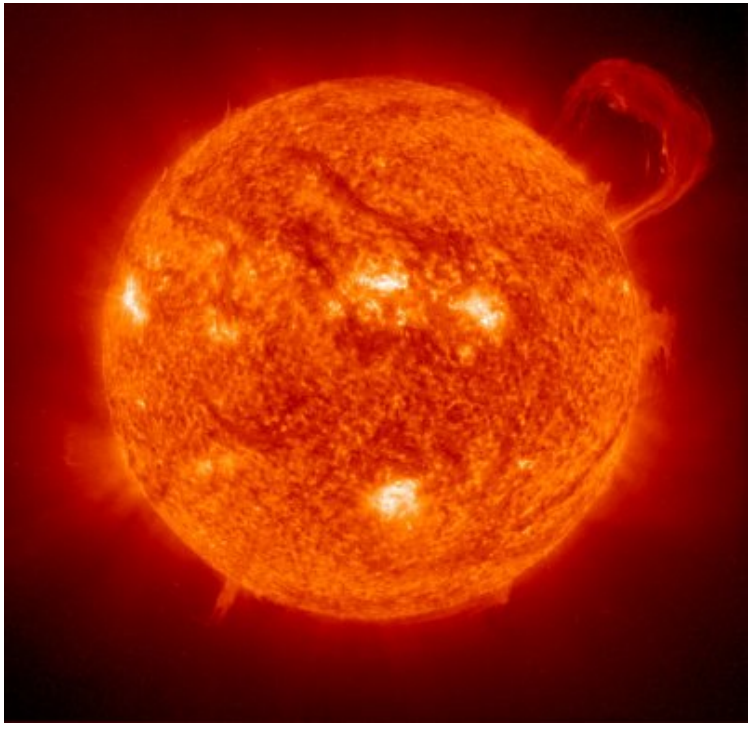
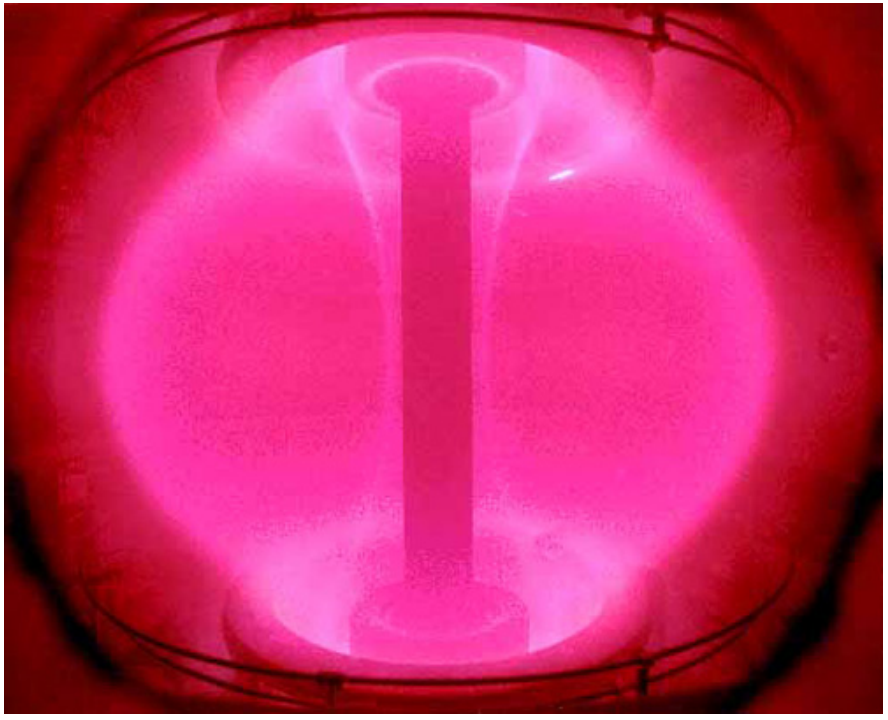
4 Tokamak GOLEM - remote operation

5 Electron temperature estimation

Harnessing the Sun's (star's) energy



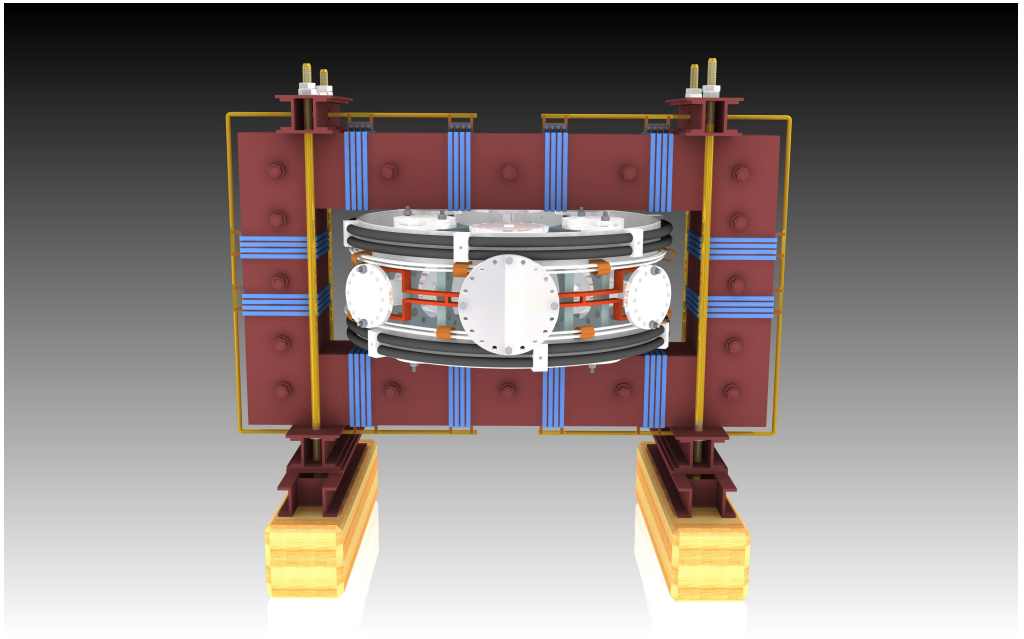


On the Earth the most feasible candidate:

$$ {}^{2}_{1}\mathbf{D}_{(\mathbf{10keV})} + {}^{3}_{1}\mathbf{T}_{(\mathbf{10keV})} \Rightarrow {}^{4}_{2}\mathbf{He}_{(\mathbf{3.5MeV})} + \mathbf{n}_{(\mathbf{14.1MeV})} $$

(??remotelly) $\longrightarrow$ Confine & Heat & Measure $\longleftarrow$ (remotelly??)

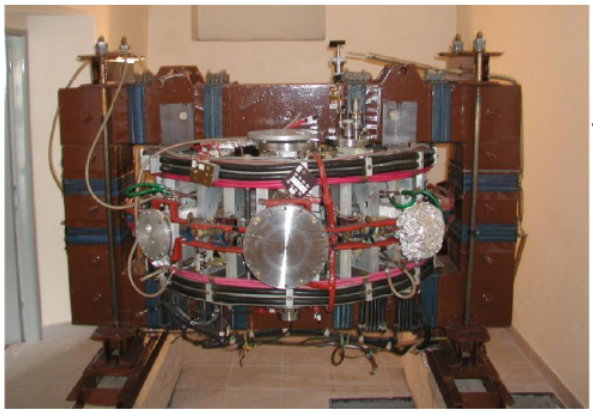
Tokamak GOLEM - basic parameters:



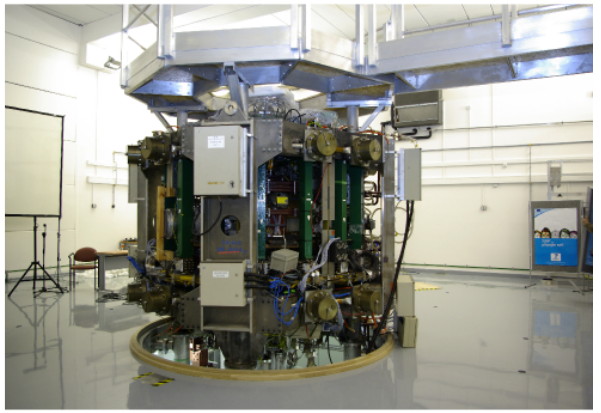
- major radius $R = 0.4$
- minor radius $a = 0.085$ m
- plasma current $I_{pl} < 10$ kA
- pulse length $t < 20$ ms
- toroidal magnetic field $B_{tor} < 1$ T
- plasma density $n_e = 0.2 - 3.0 * 10^{19}/m^3$
- electron temperature $T_e(0) < 200$ eV
- ion temperature $T_i(0) < 100$ eV

Tokamak GOLEM for Education - Historical Background

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



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



1974

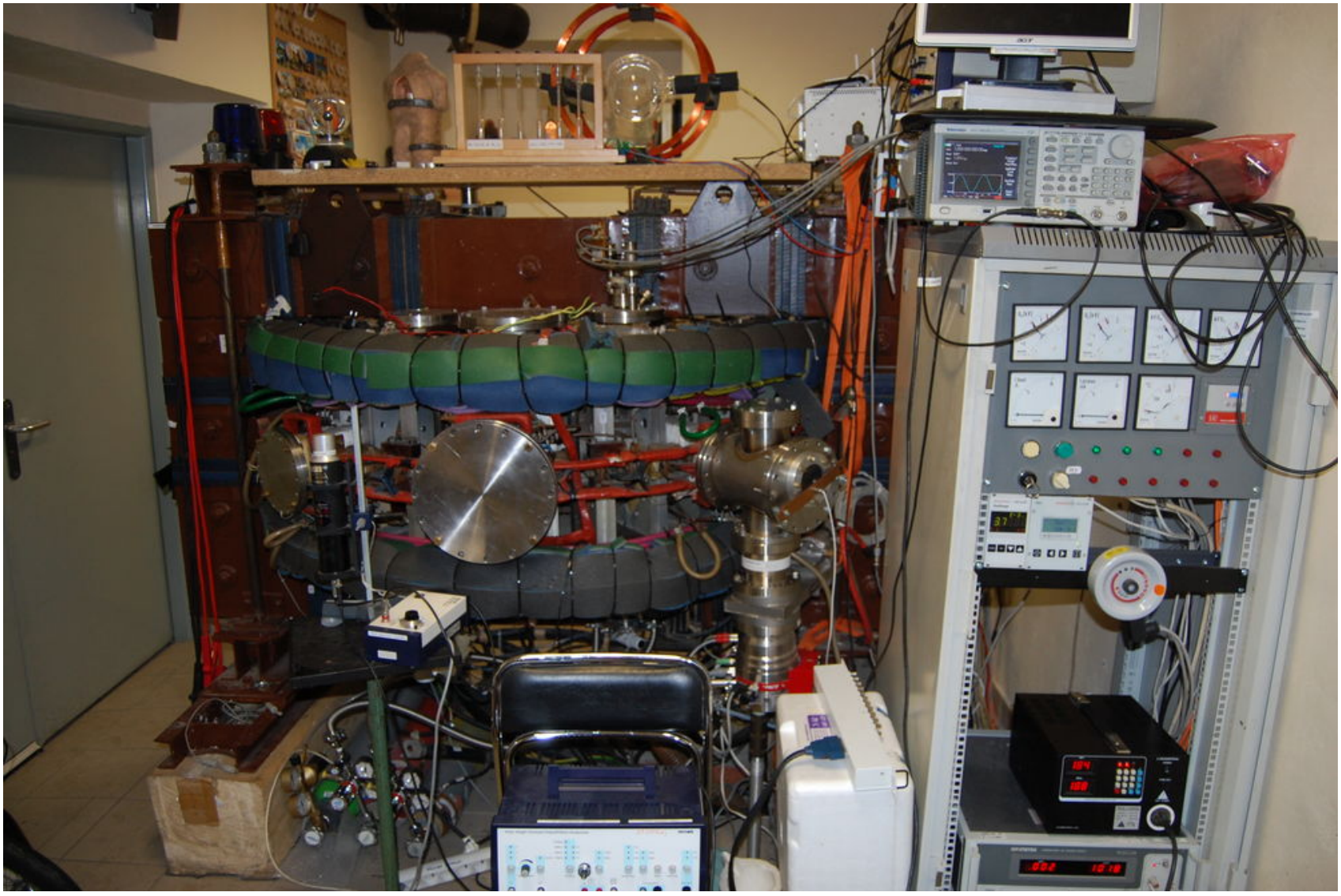
2006

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

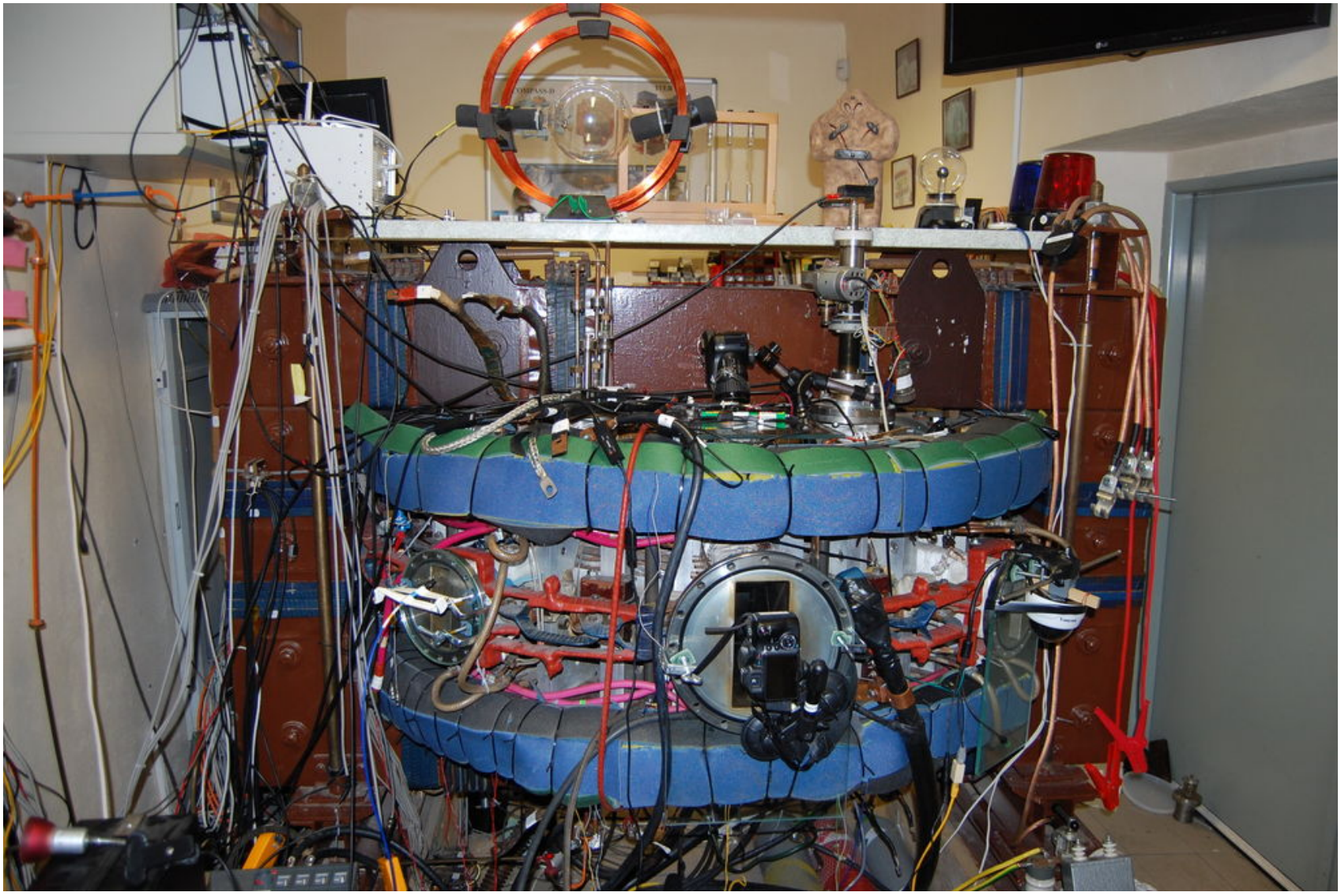
2008

Czech Technical University Prague
Czech republic
GOLEM

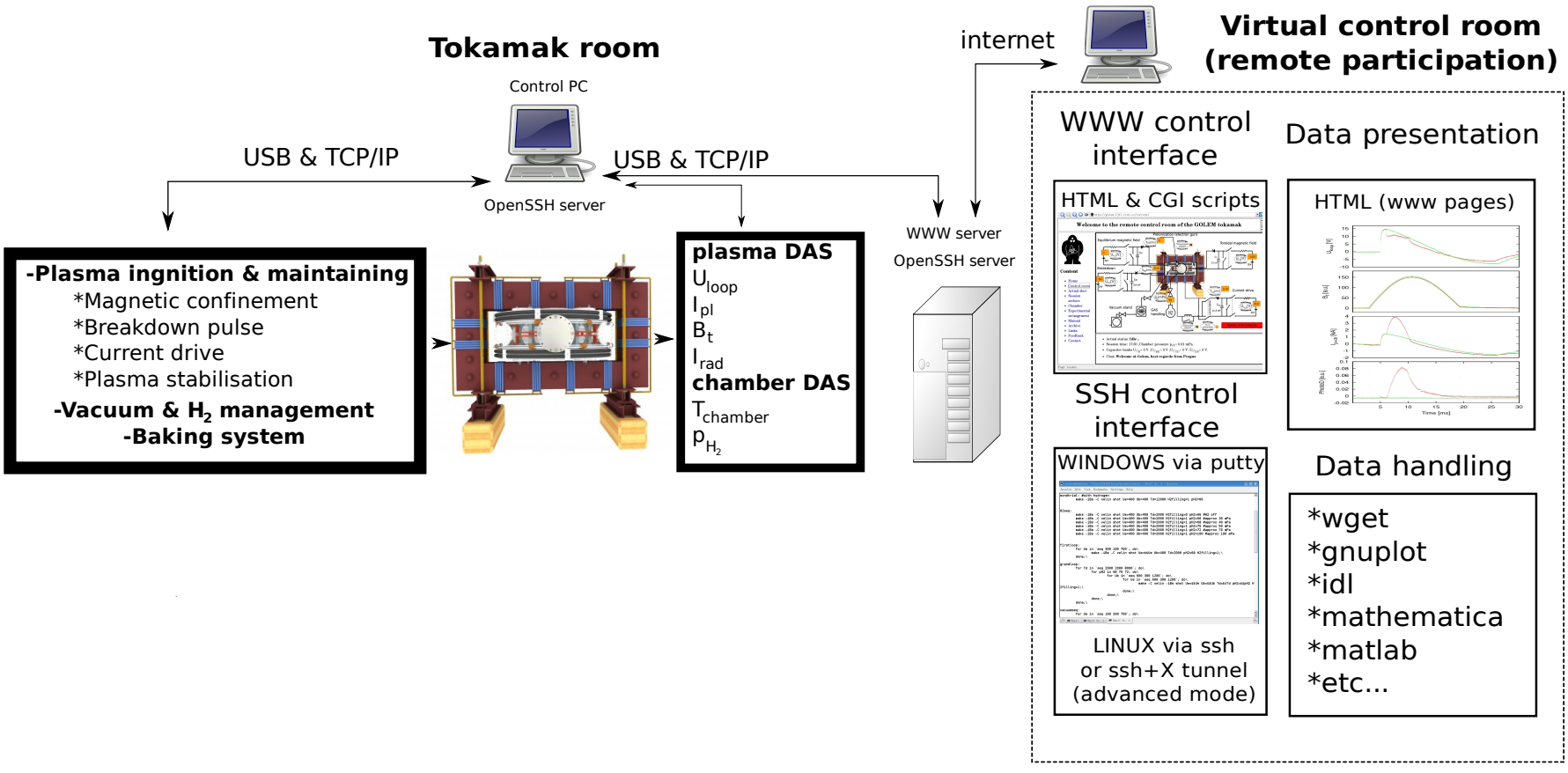
The Golem tokamak - South view (02/12)



The Golem tokamak - North view (02/12)

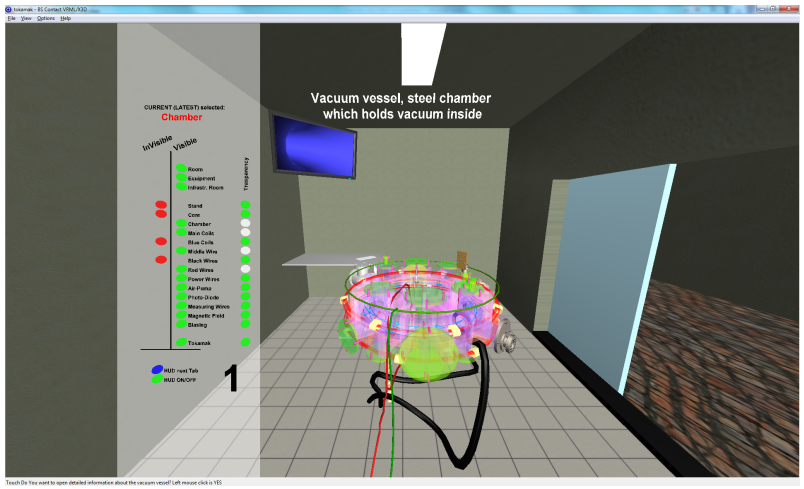


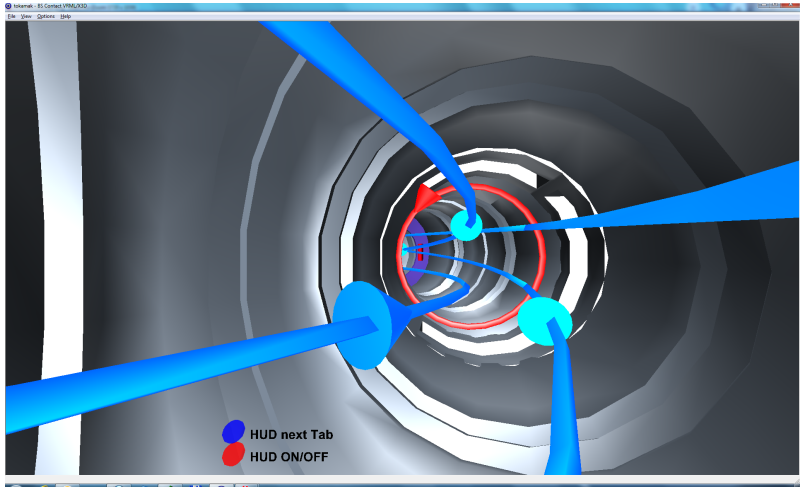
Unique remote operation capability



The GOLEM tokamak virtual model

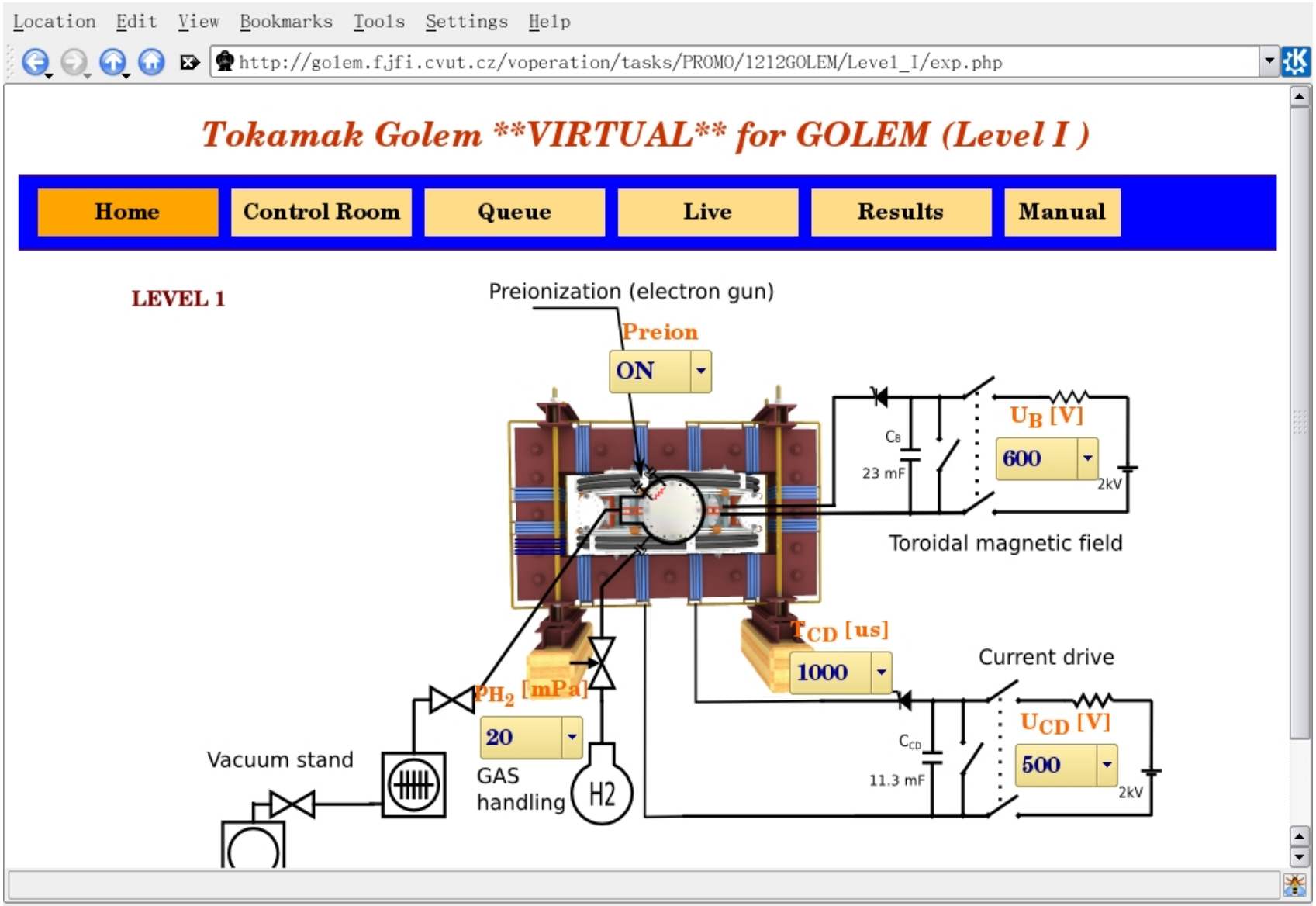
Tokamak Room & Infrastructure Room



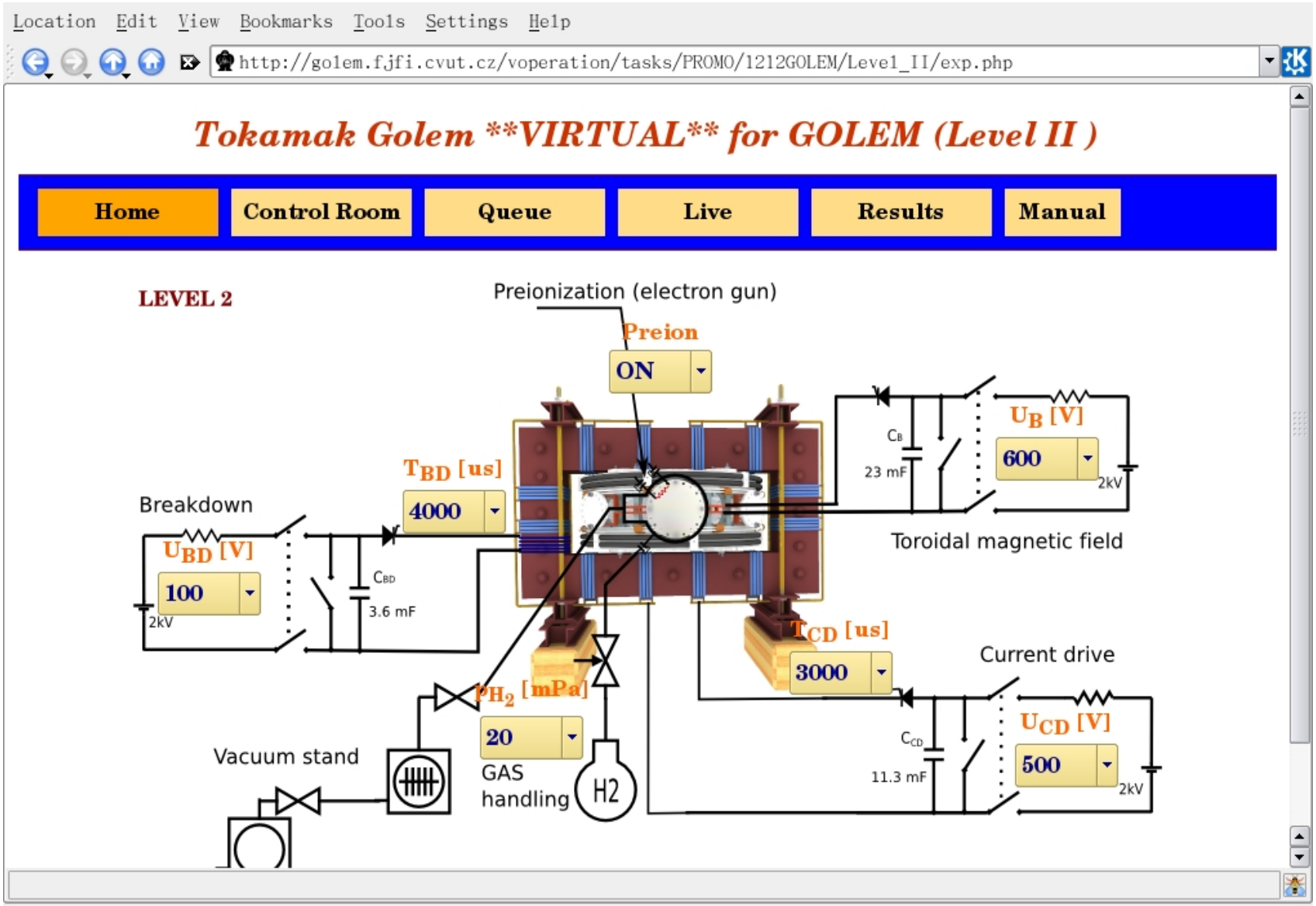


Inner view & Inside chamber

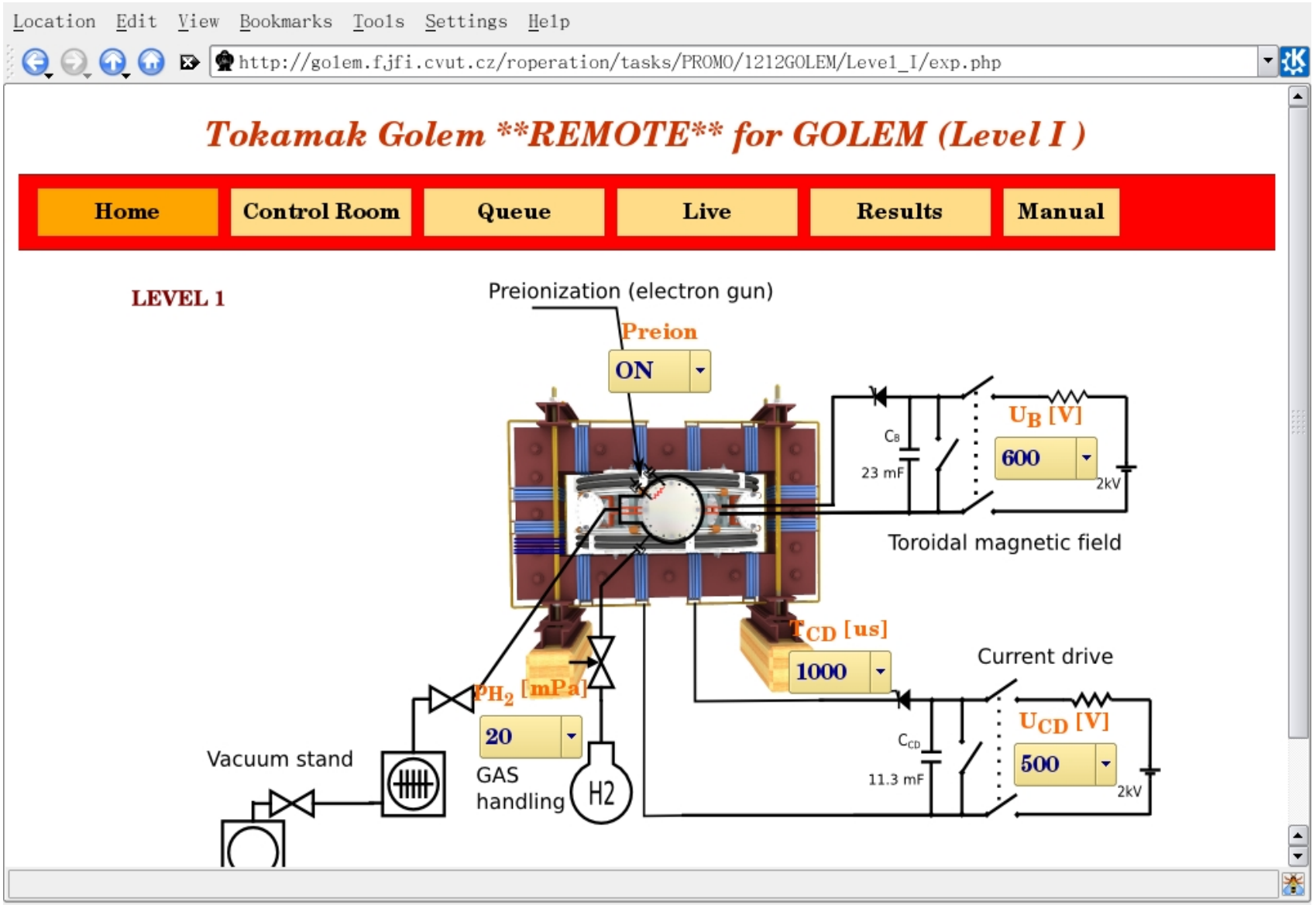
The GOLEM tokamak **virtual** Control Room - level I



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



The GOLEM tokamak **real** Control Room



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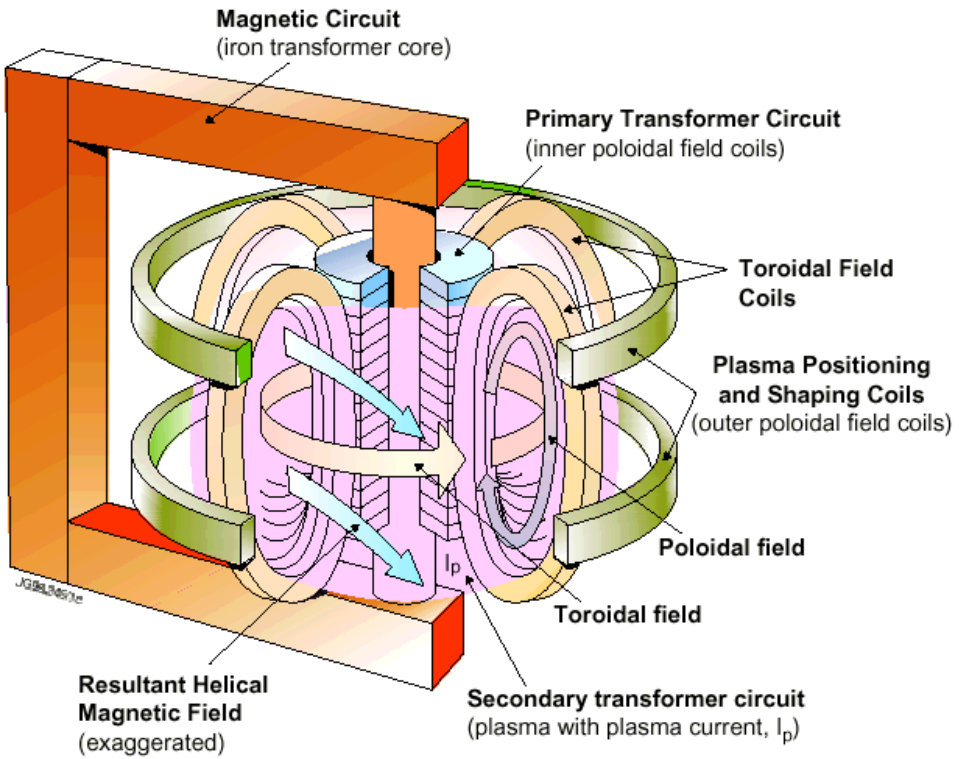
4 Tokamak GOLEM - remote operation

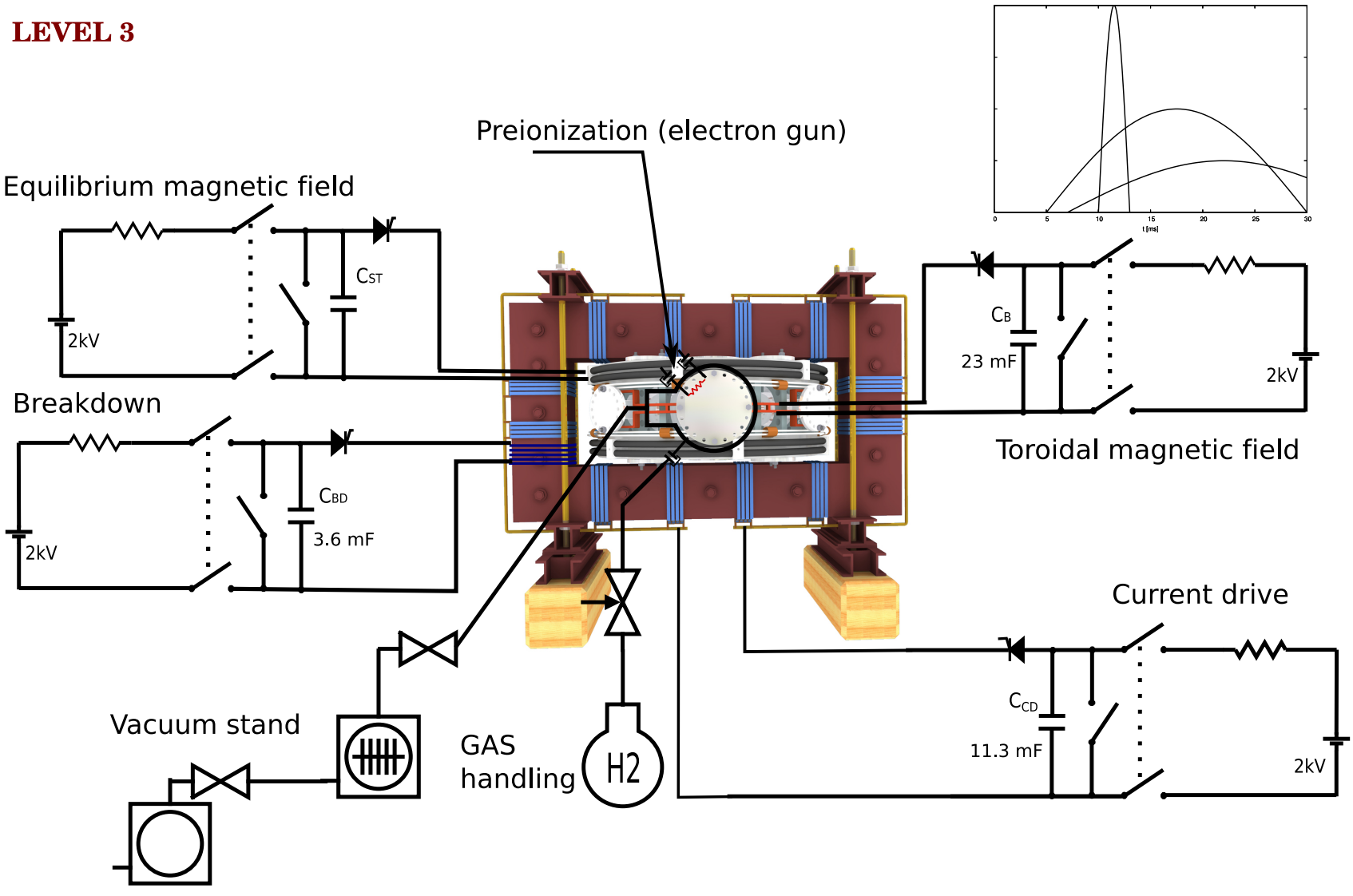
5 Electron temperature estimation

Plasma in Tokamak (GOLEM) - the least to do



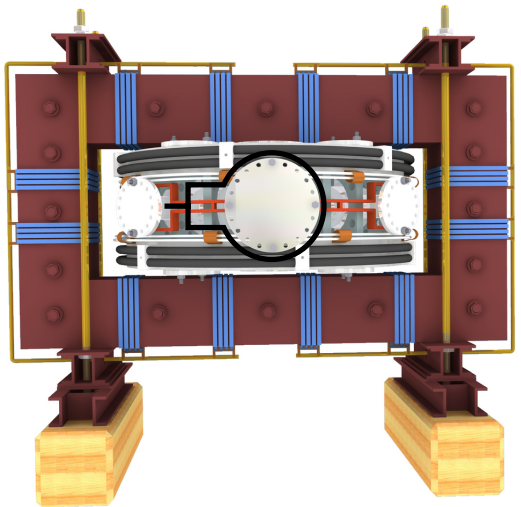
- Evacuate the chamber.
- Fill in the working gas.
- Toroidal magnetic field to confine plasma.
- Toroidal electric field to breakdown neutral gas into plasma.
- Toroidal electric field to heat the plasma.
- Plasma positioning.
- Diagnostics.

Tokamak GOLEM - engineering scheeme



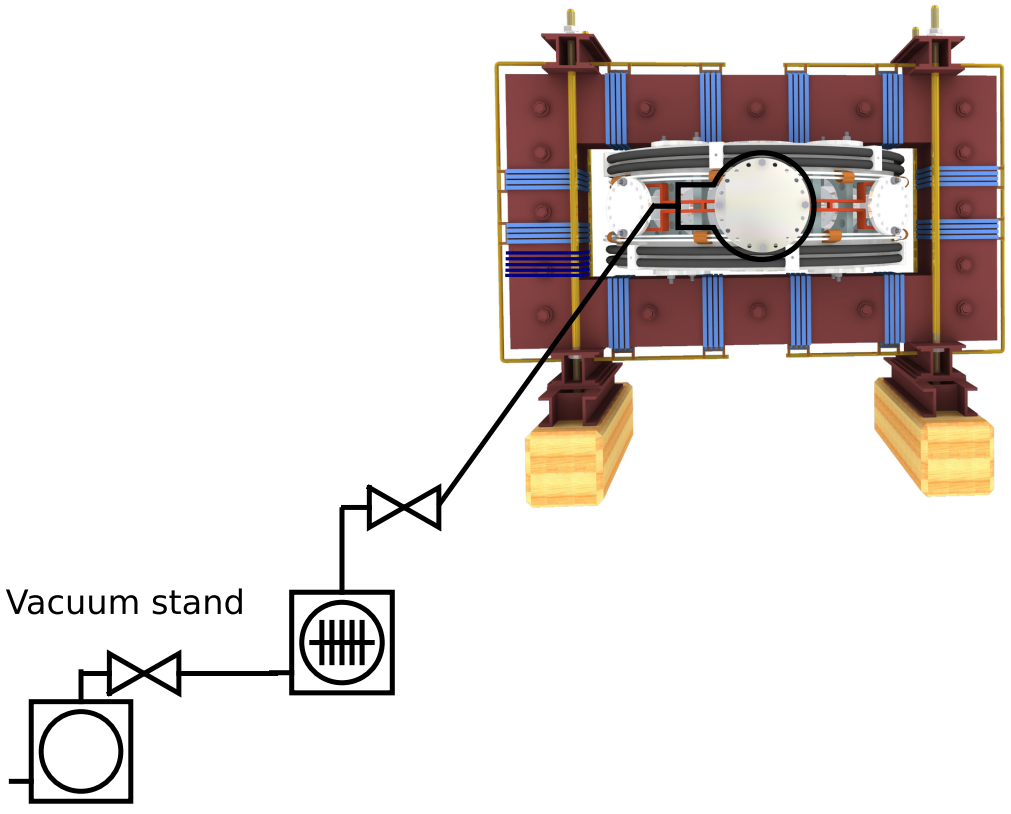
Tokamak GOLEM - basic

LEVEL 0



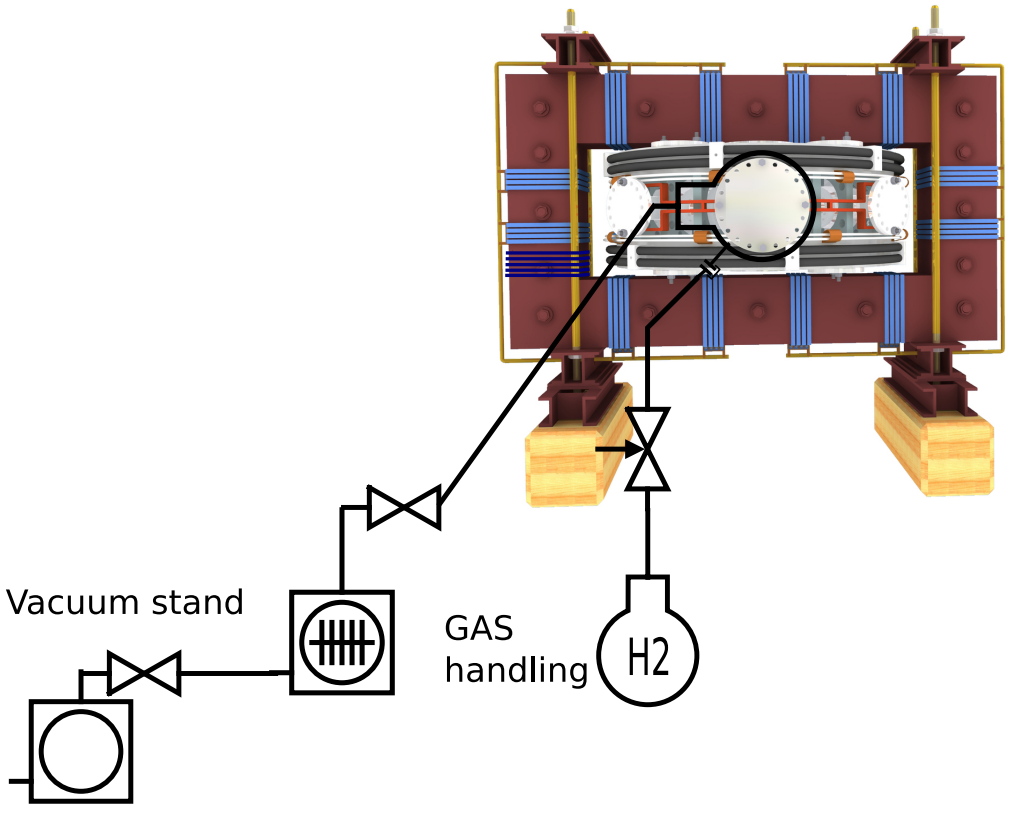
+ vacuum pumping system (100 kPa $\rightarrow \approx$ 1 mPa)

LEVEL 0



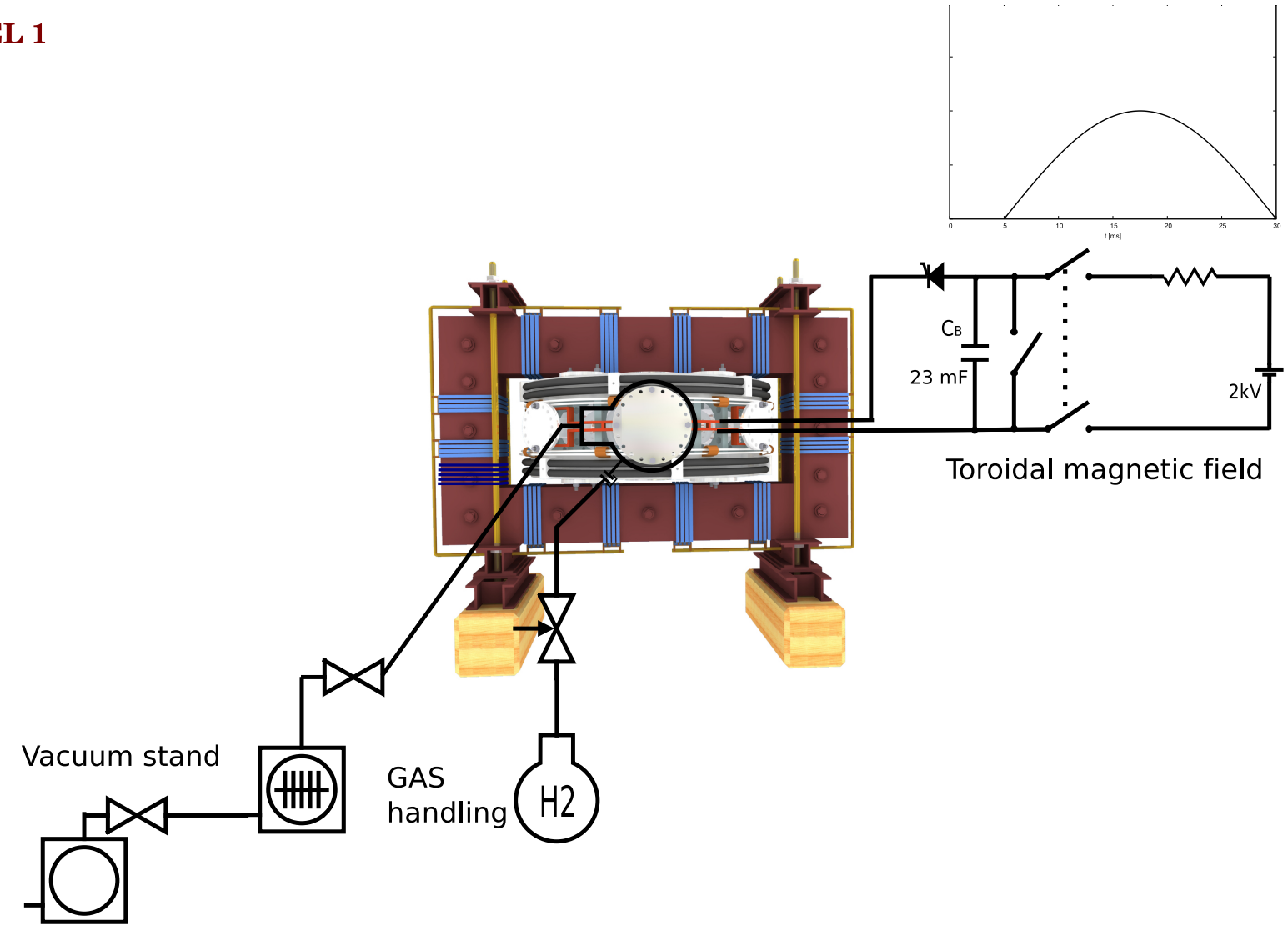
+ working gas management (H_2 or He)

LEVEL 0

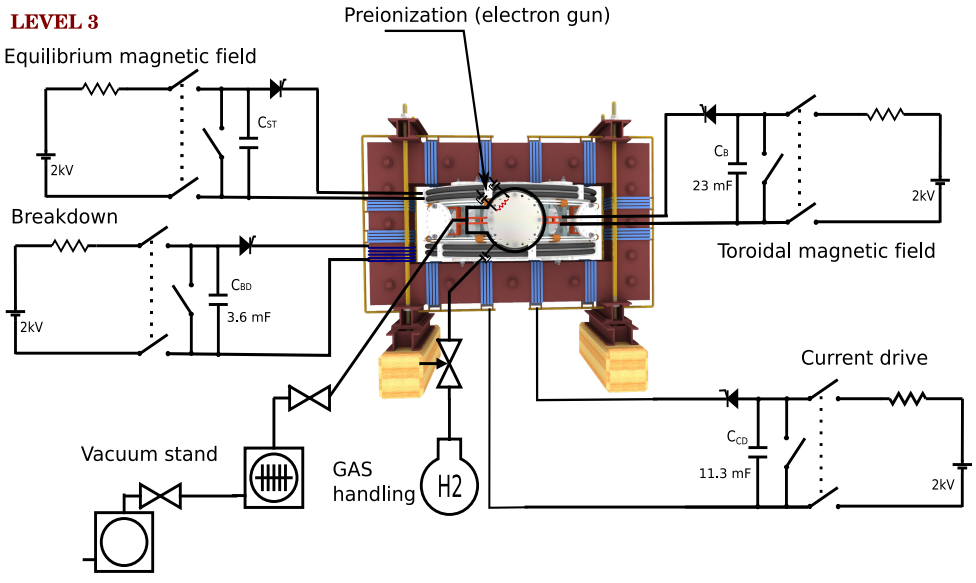


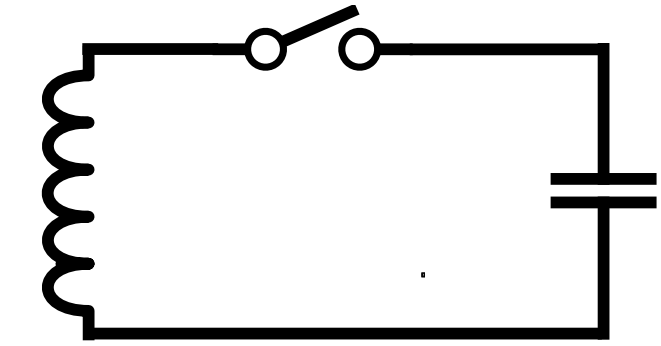
+ toroidal magnetic field B_{tor} .. **plasma confinement**

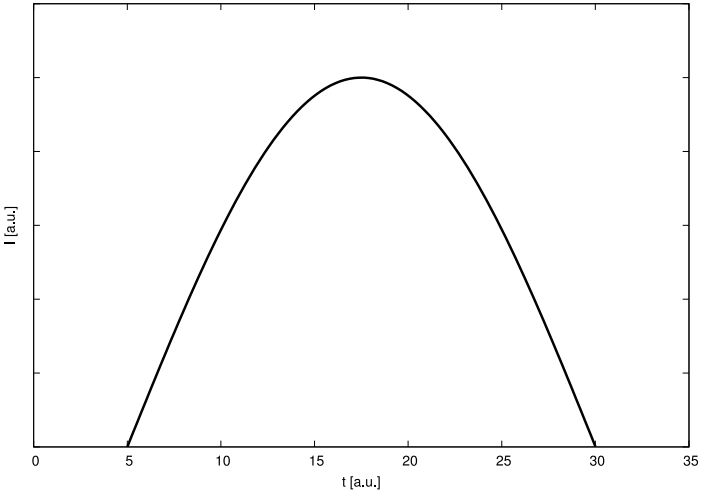
LEVEL 1



Insertion - LC circuit

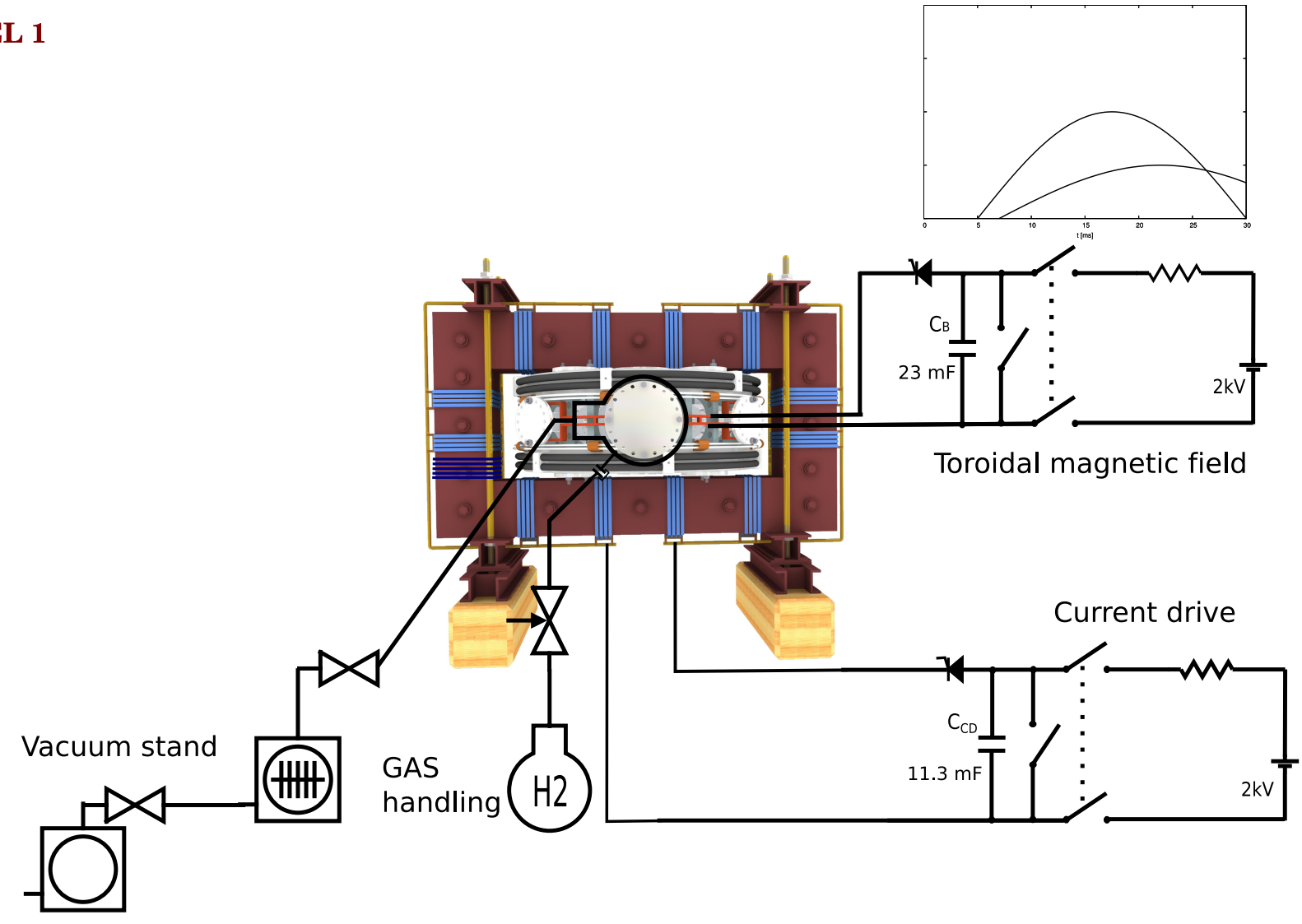






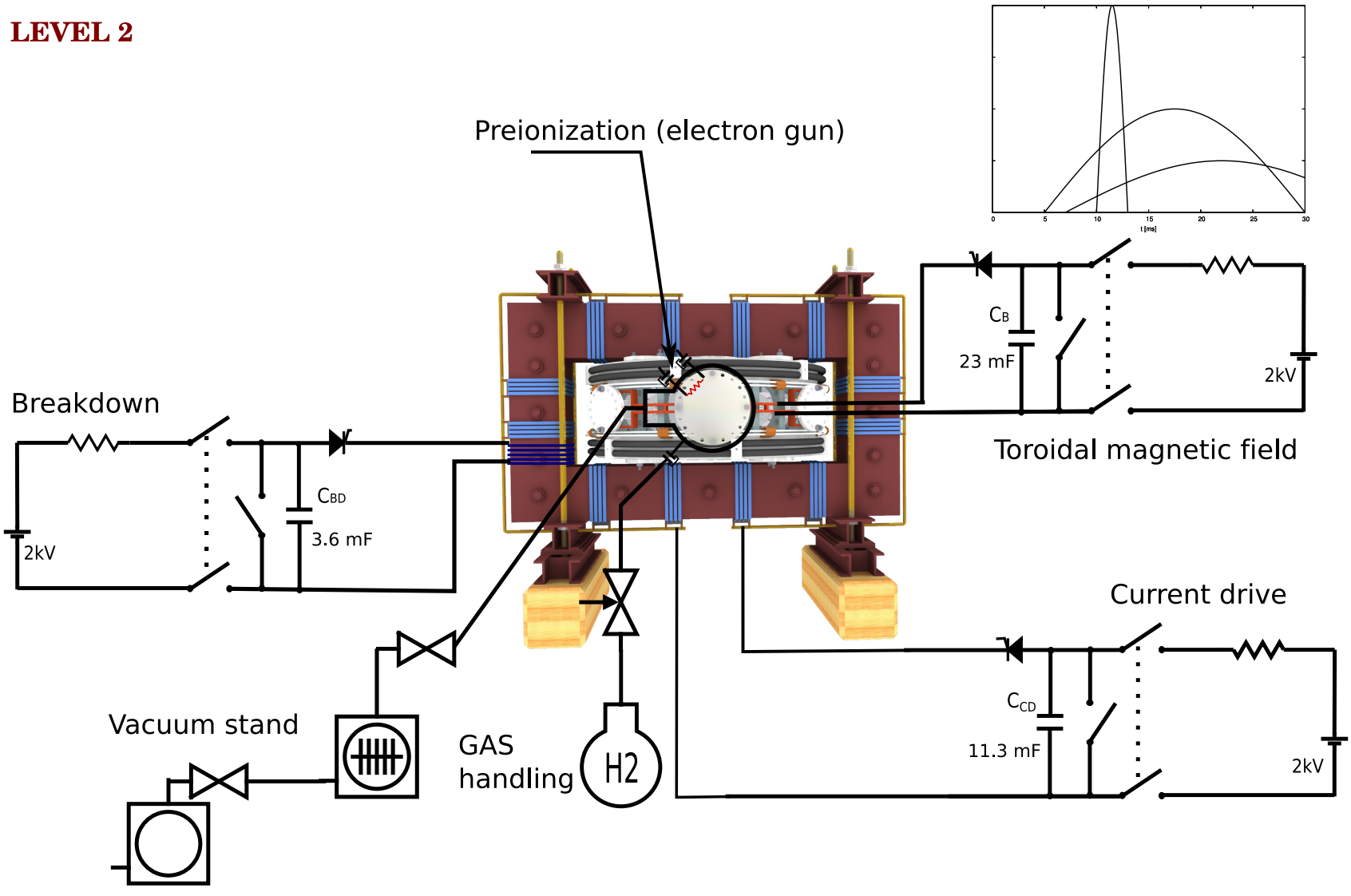
+ toroidal electric field E_{CD} .. **plasma heating**

LEVEL 1



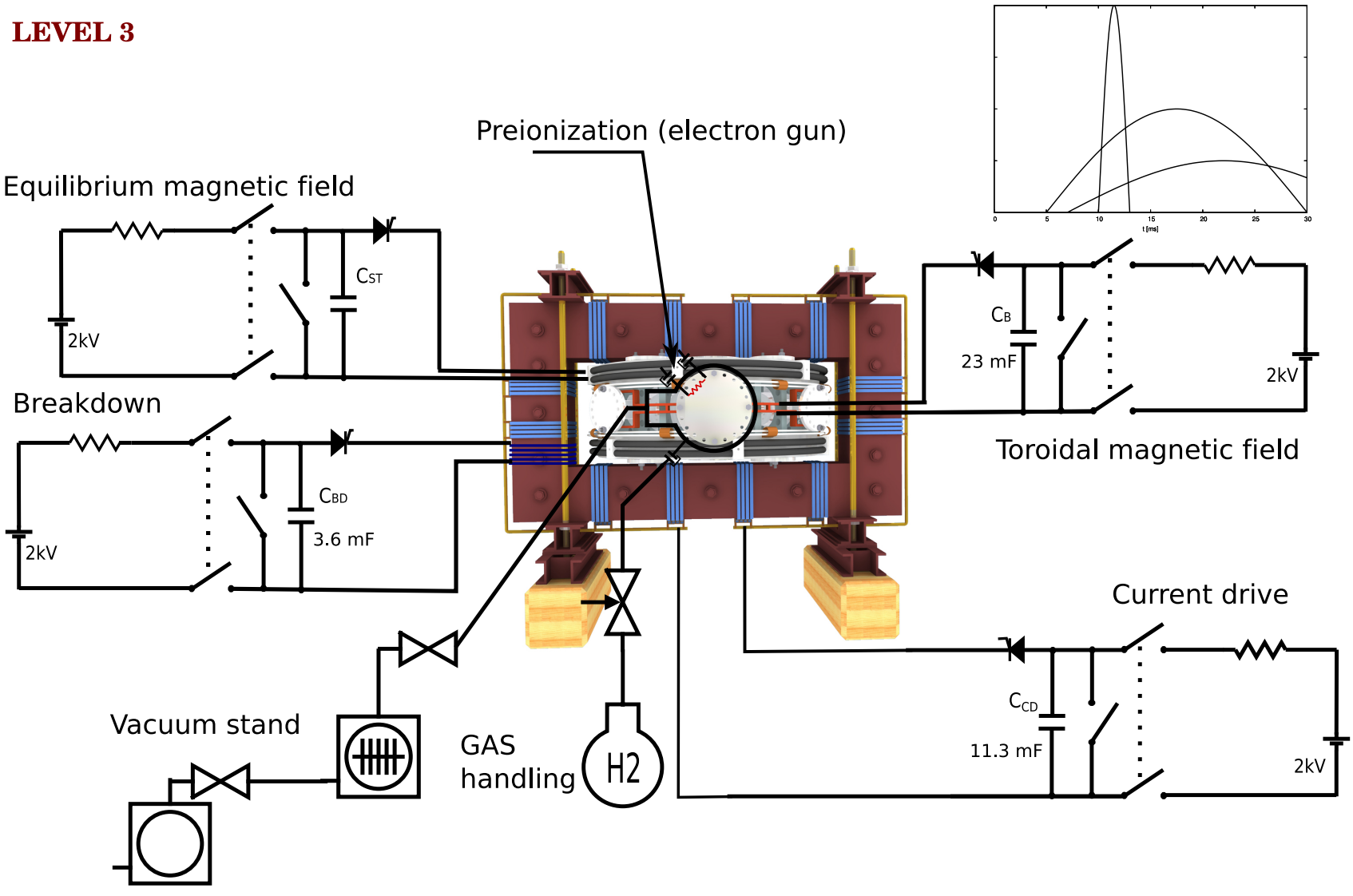
+ toroidal electric field E_{BD} .. **plasma creation**

LEVEL 2

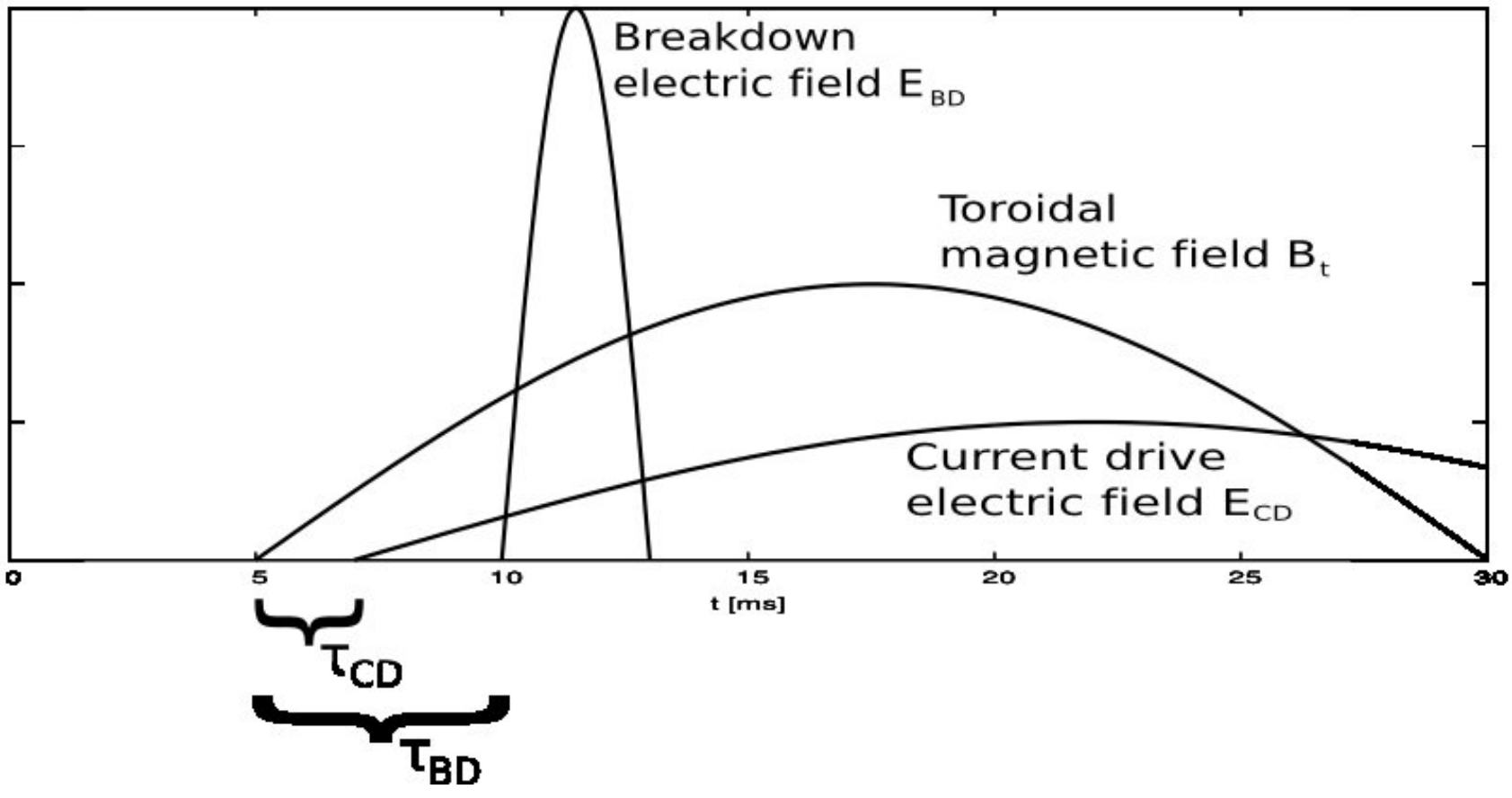


+ equilibrium magnetic field B_{EQ} .. **plasma stabilization**

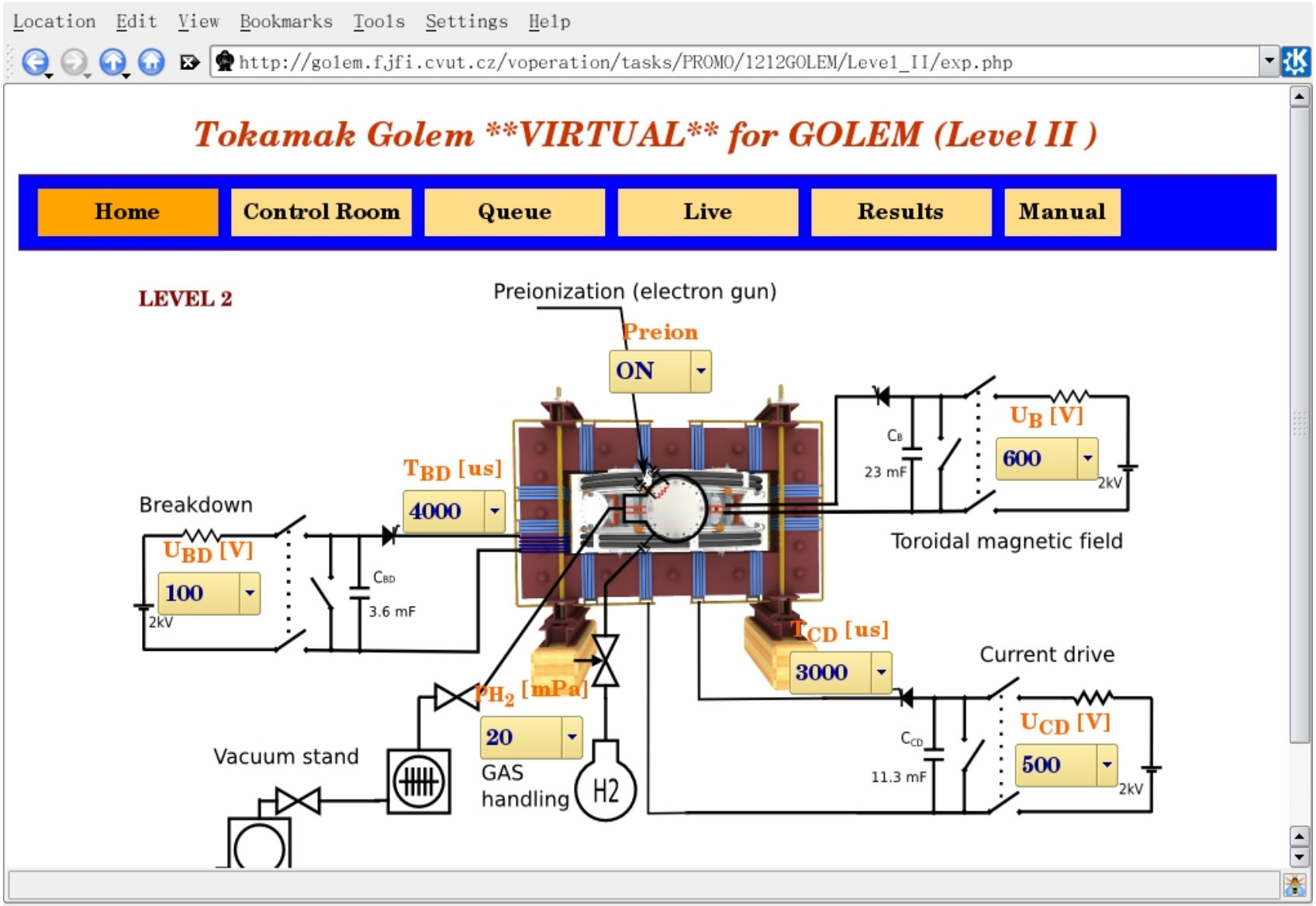
LEVEL 3



Triggering sequence



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



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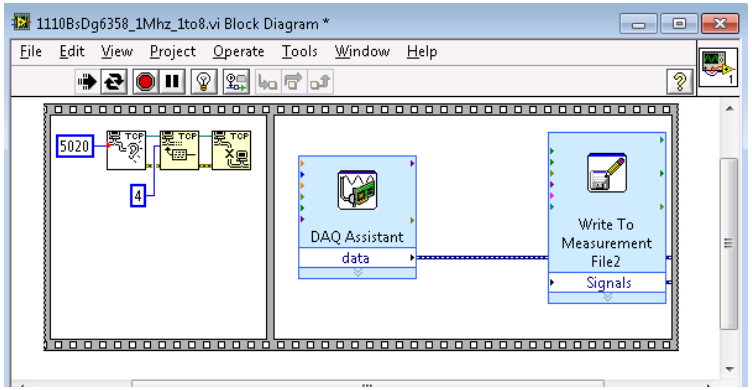
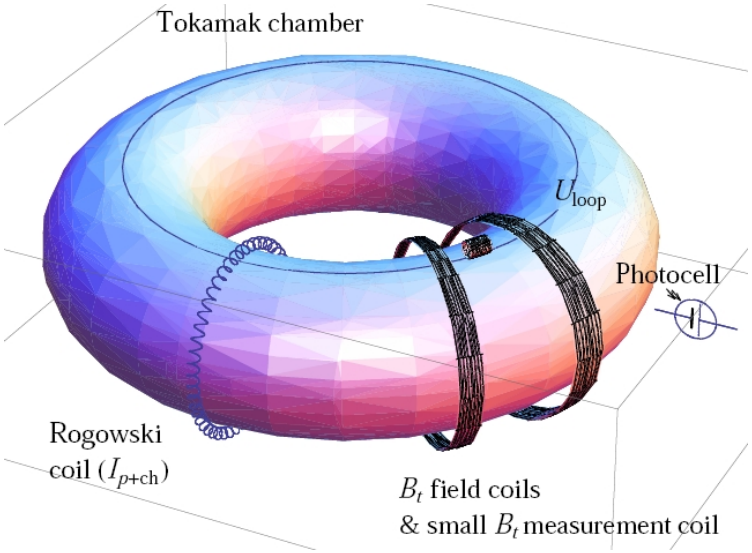
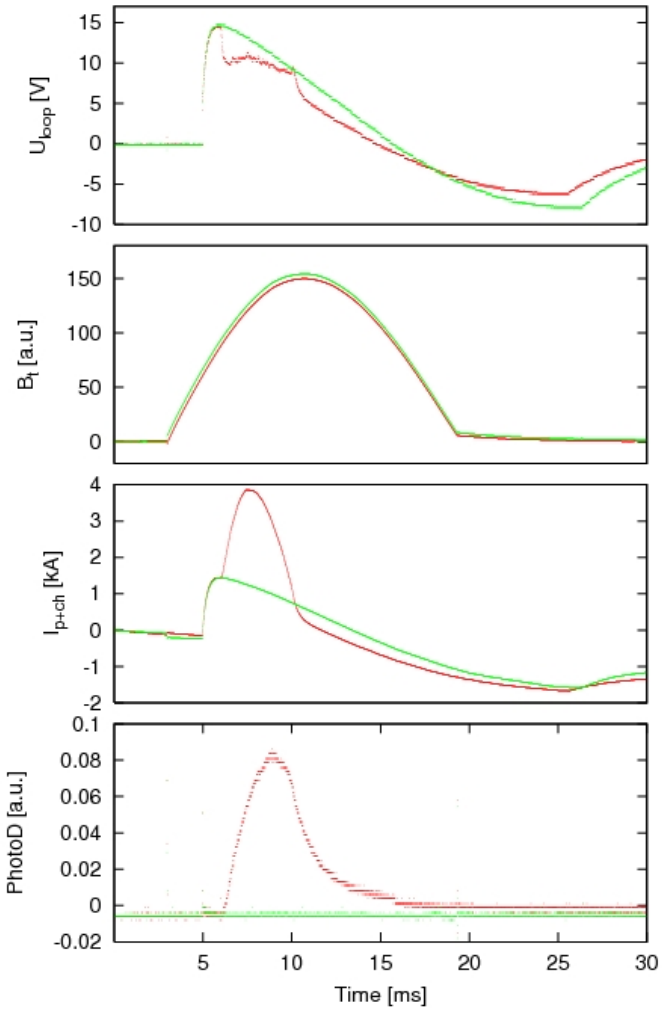
Basic plasma diagnostics in tokamak GOLEM



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}

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

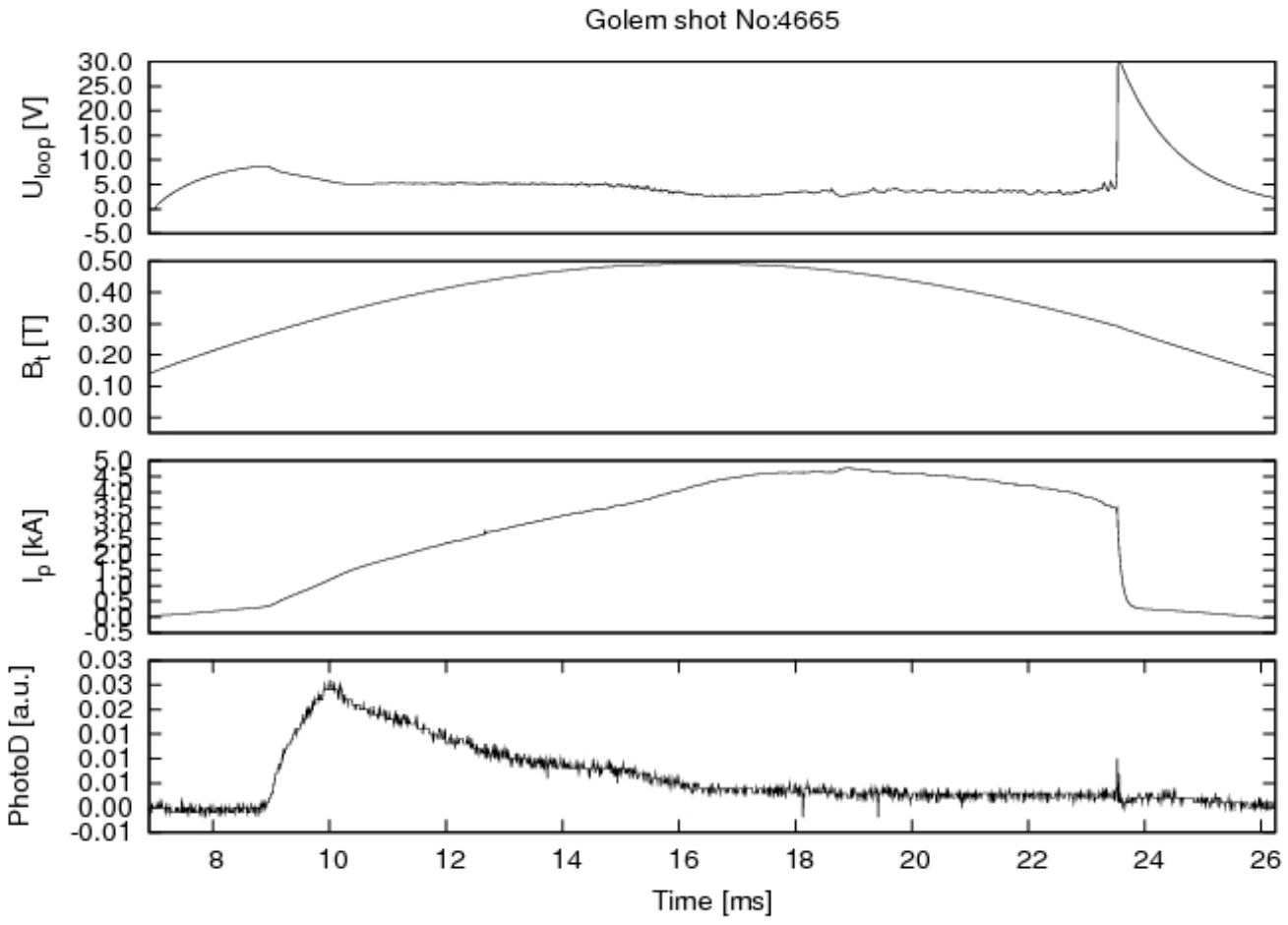
Basic diagnostic - toroidal magnetic filed B_t

Is deduced from small coil measurements with three operations:

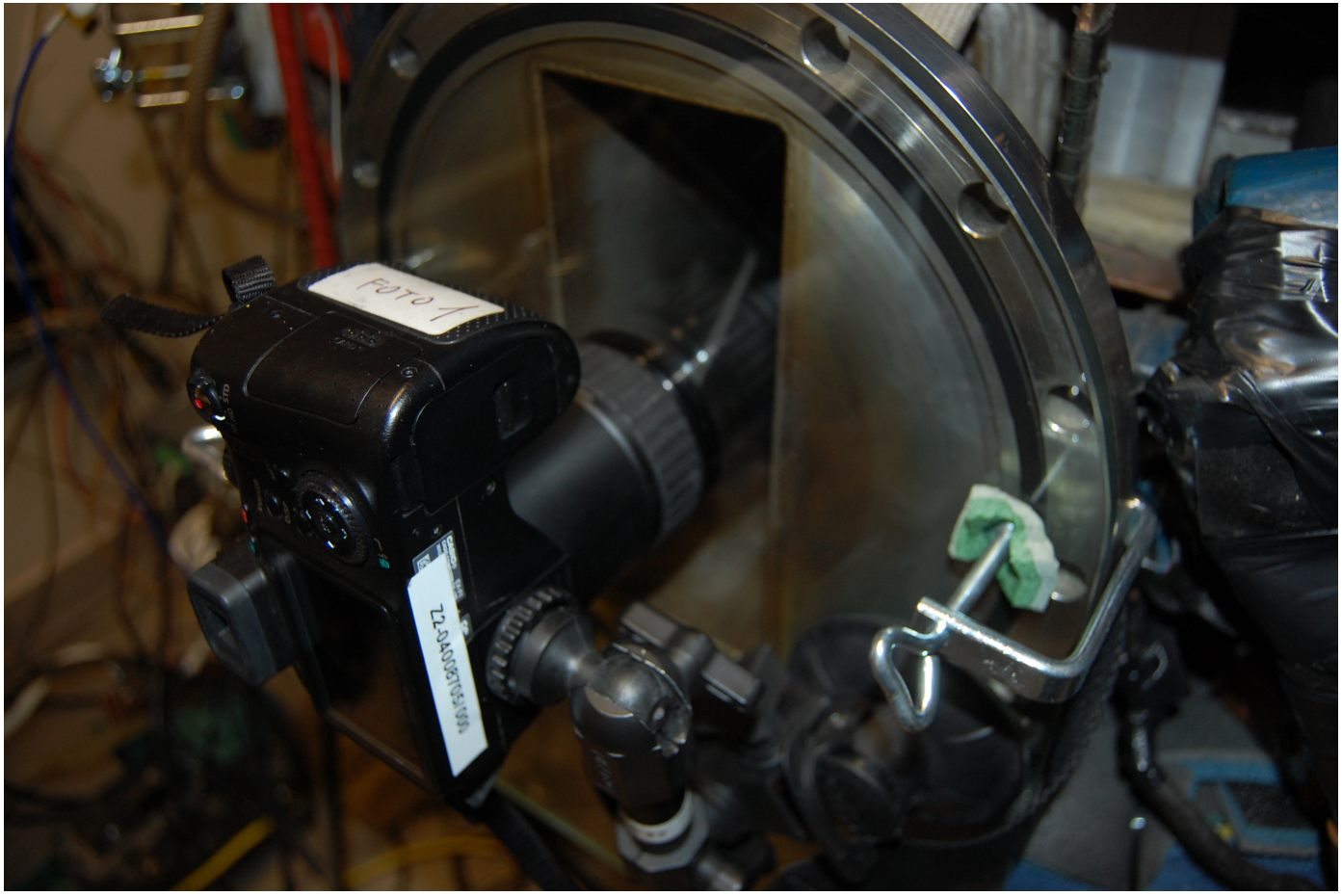
- offset identification from first 4500 data rows).
- time integration (it is a magnetic diagnostic, where $U_{acquired} \sim \frac{dB_t}{dt}$)
- multiplication of calibration factor C_{Bt}

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

Golem discharge

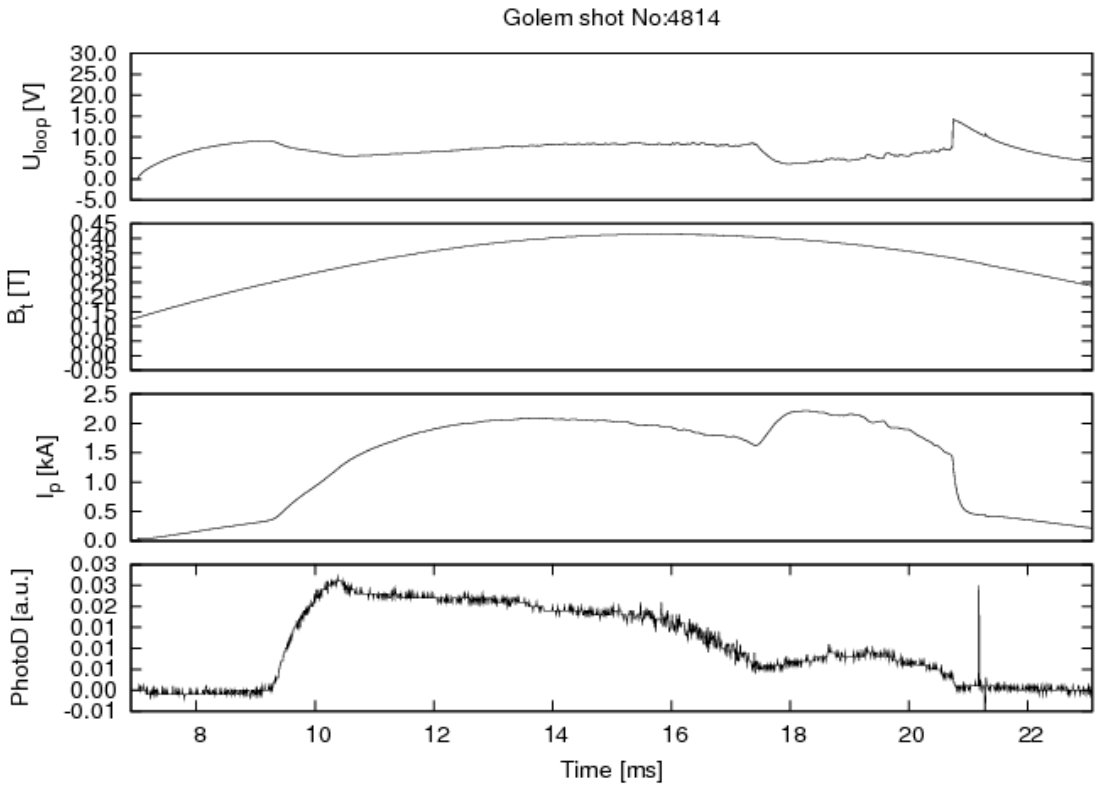


South-Middle port: Fast camera CASIO FX1 I

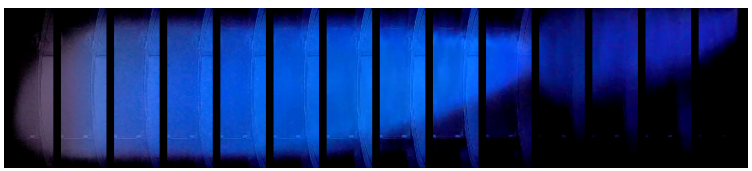


Manual, Graph

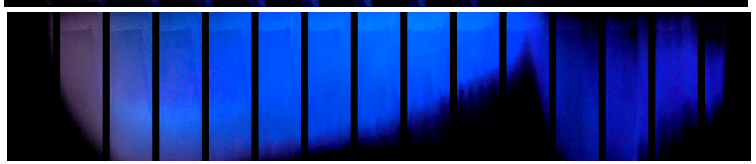
Fast camera CASIO FX1 - results



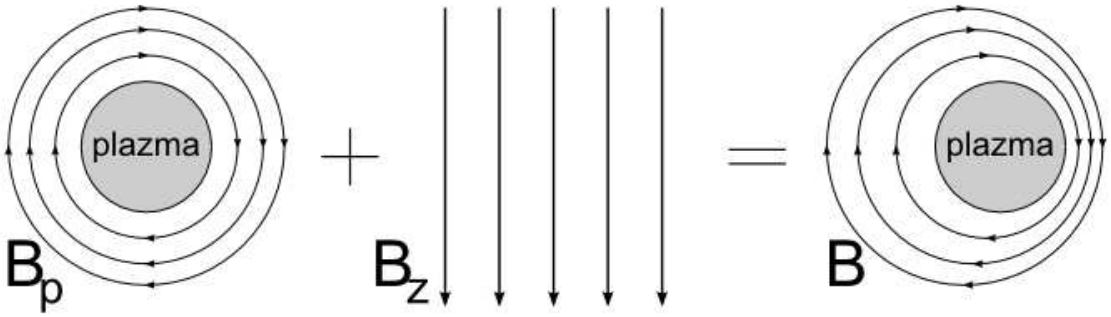
TOP view:

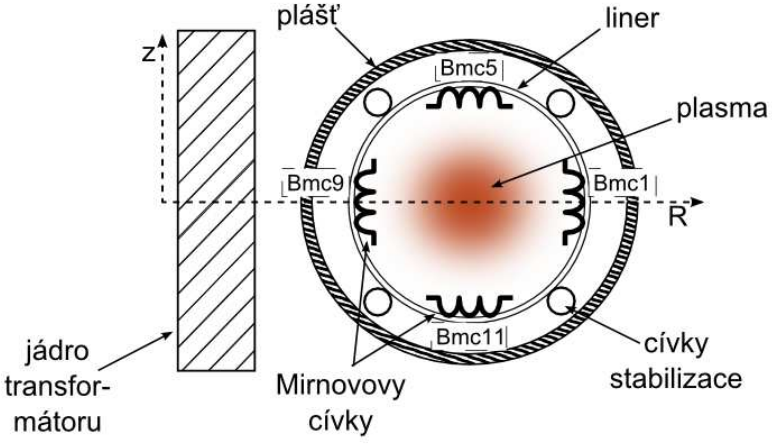


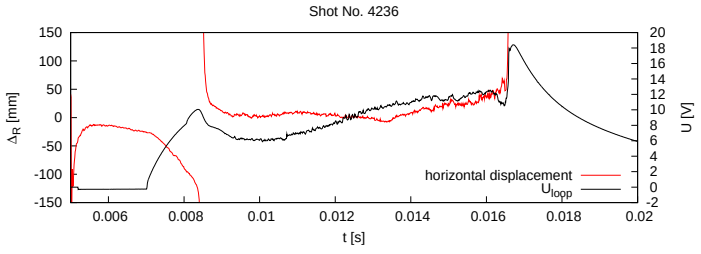
SIDE view:



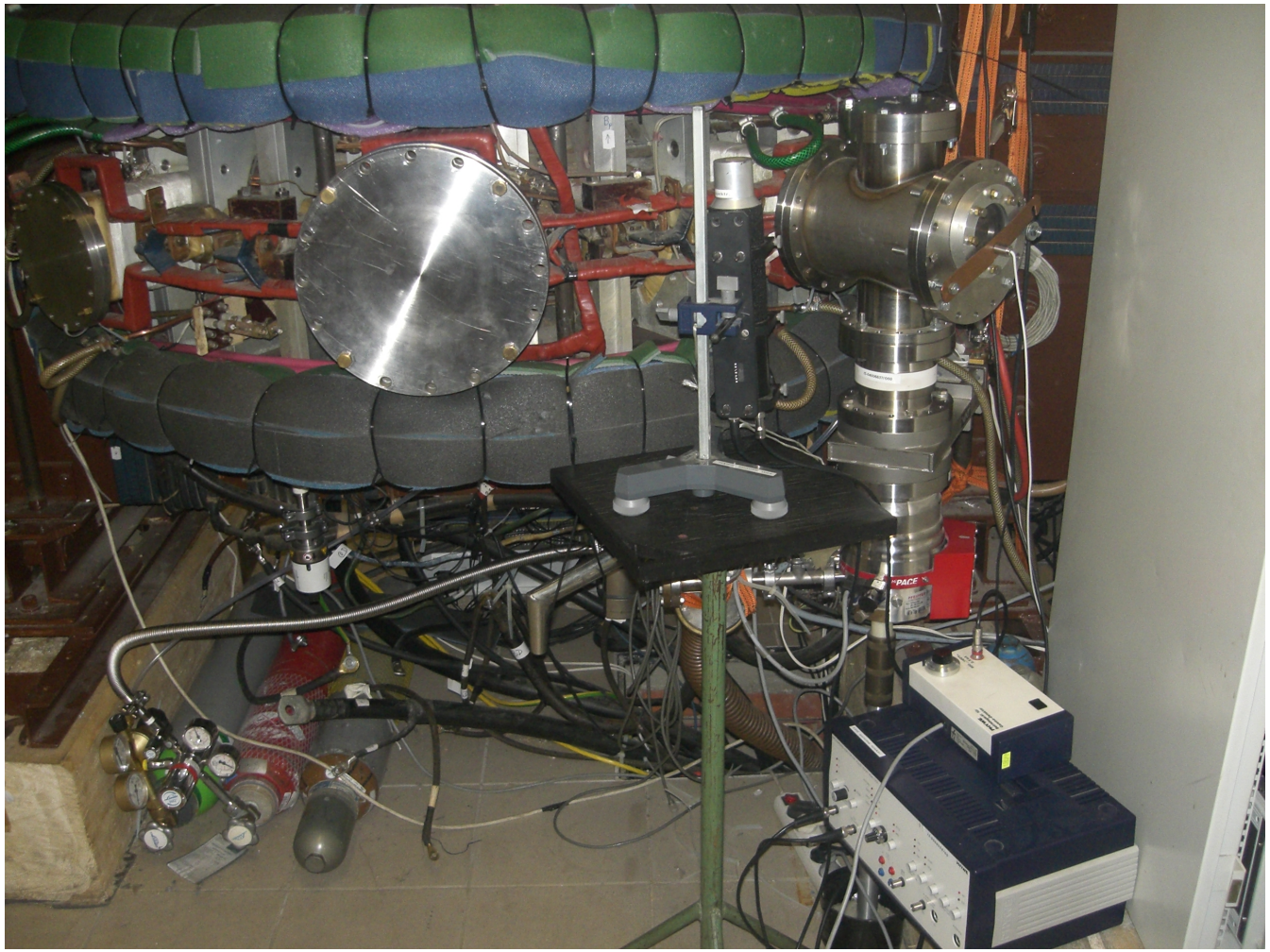
Plasma Position using Mirnov Coils



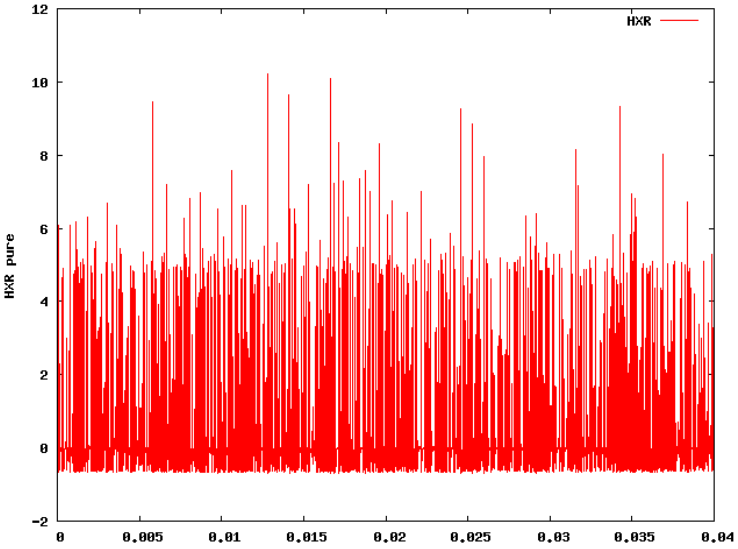


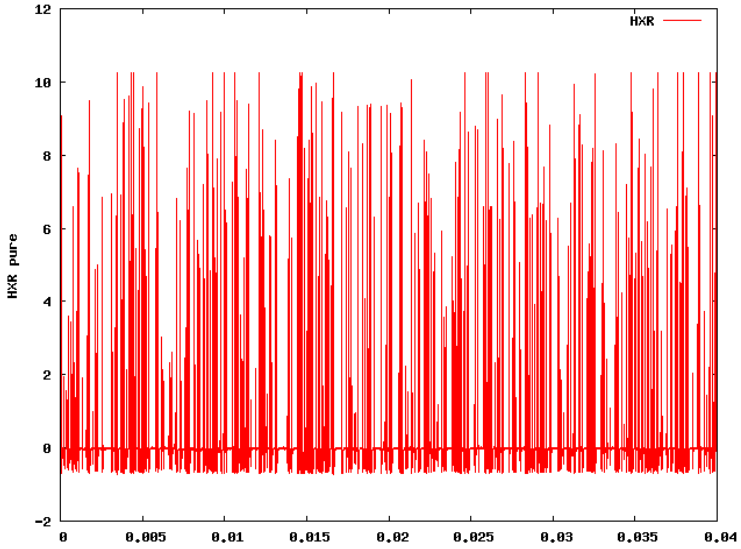


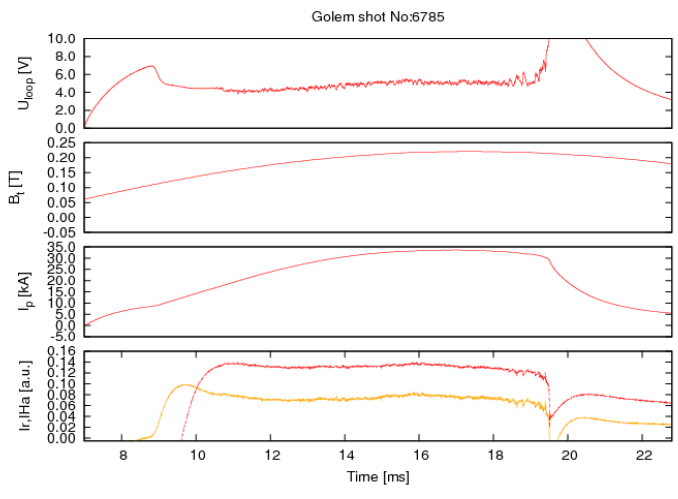
HXR

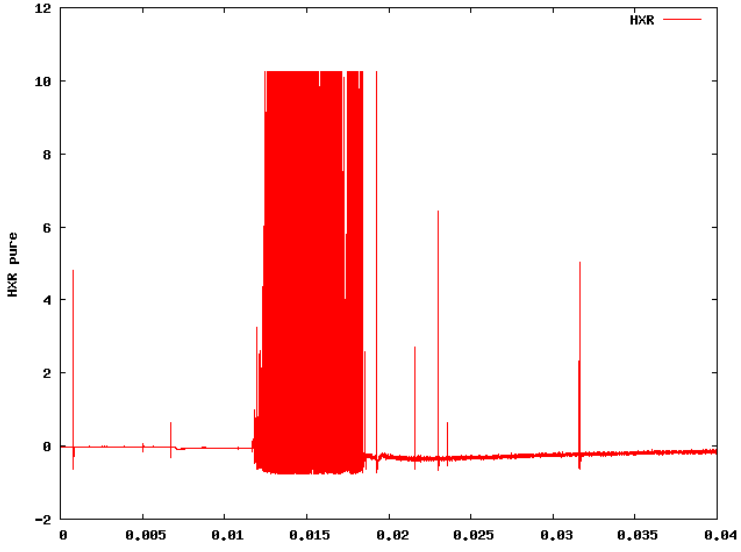


HXR

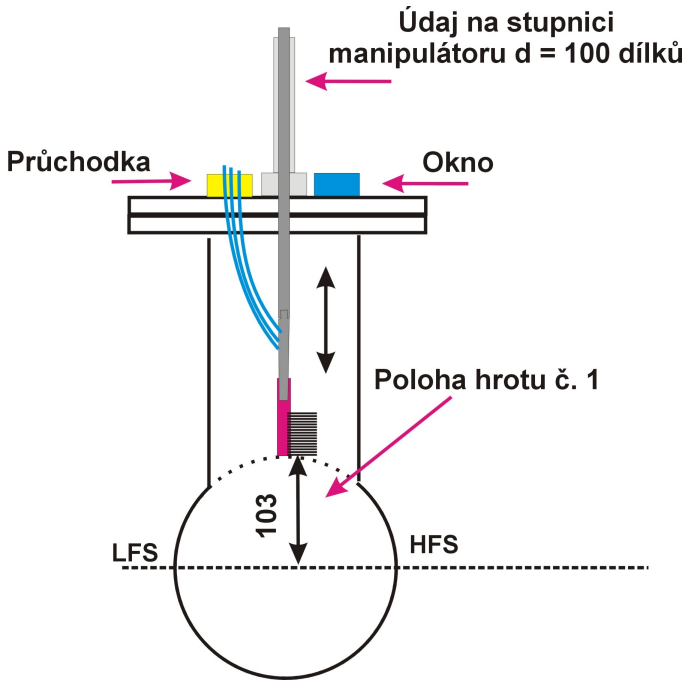

HXR
HXR pure
12
10
8
6
4
2
0
-2
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04

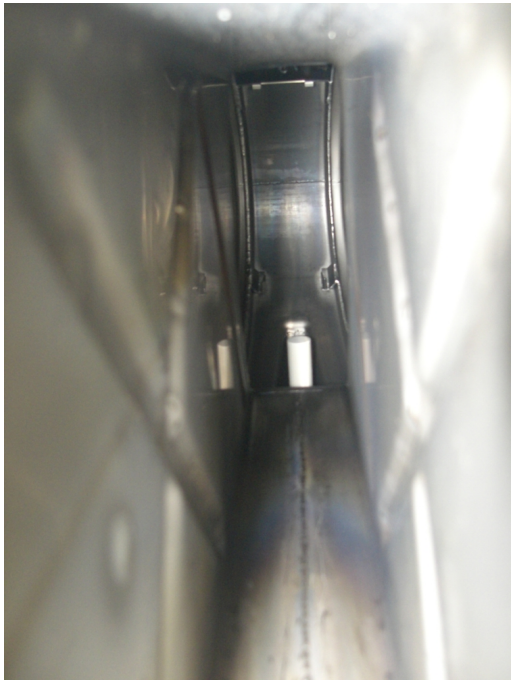

HXR
HXR pure
12
10
8
6
4
2
0
-2
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04

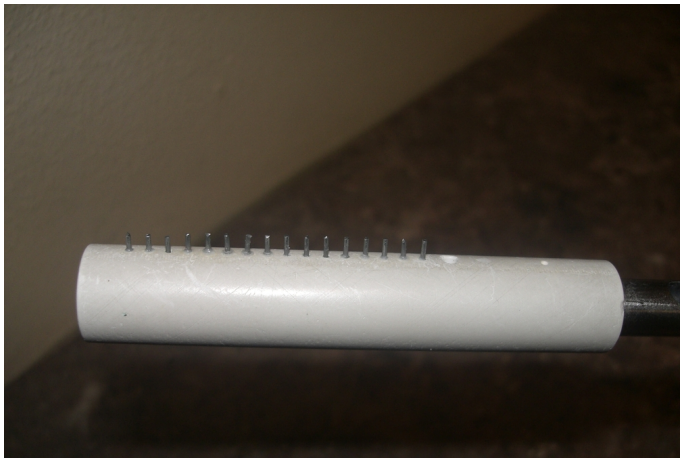

Golem shot No:6785
U_loop [V]
B_t [T]
I_p [kA]
I_r,IHa [a.u.]
Time [ms]
8
10
12
14
16
18
20
22


HXR
HXR pure
12
10
8
6
4
2
0
-2
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04

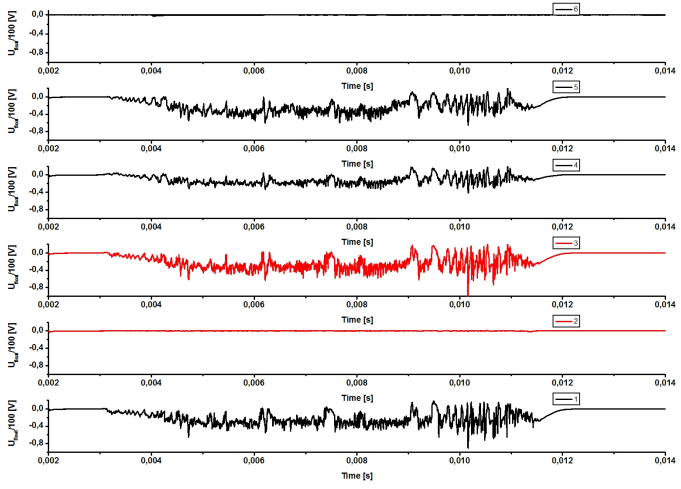
Rake probe (2012)

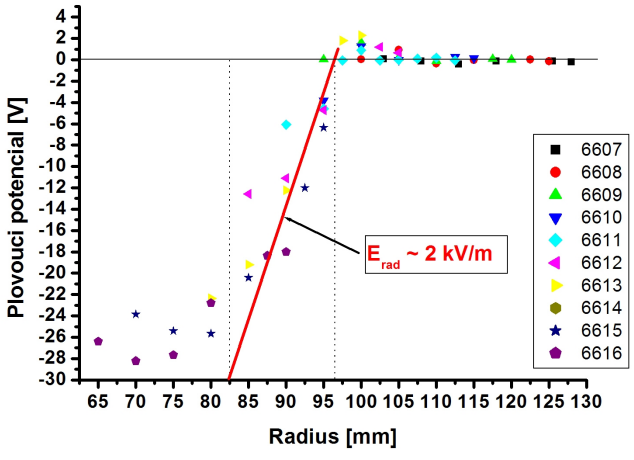


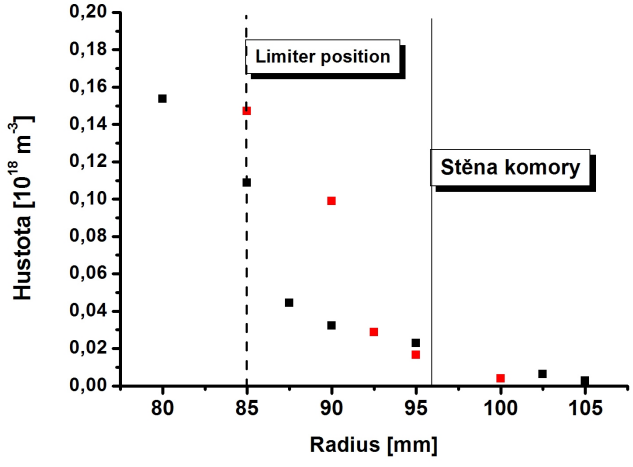




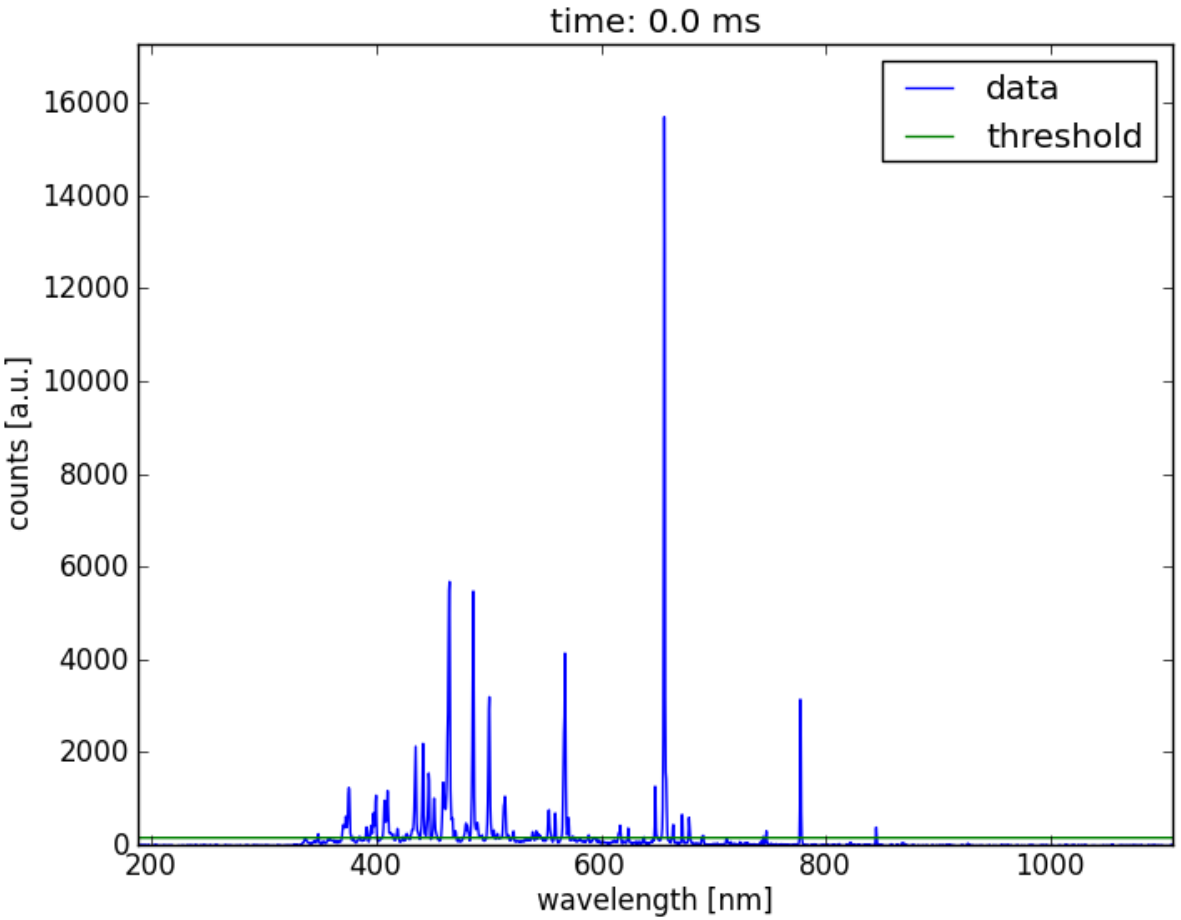
Rake probe (2012) - results







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

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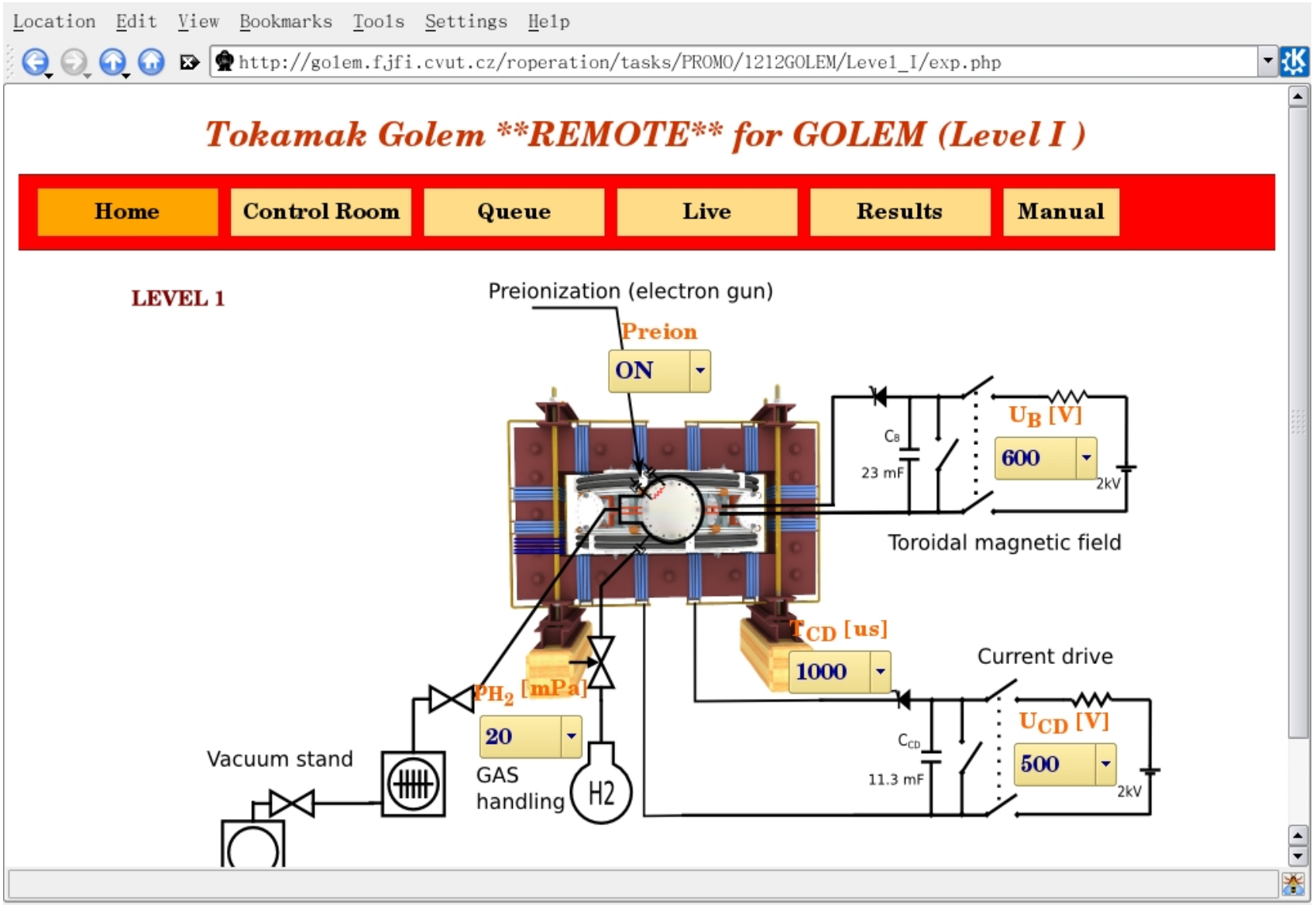
The GOLEM tokamak **real** Control Room



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).

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Central electron temperature estimation I [?]

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 [?]

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 $Z_{eff} = 2.5$.

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References I