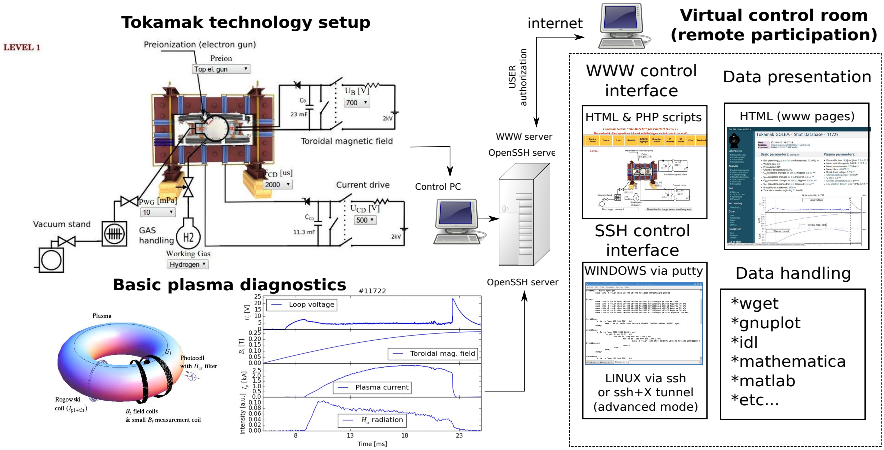
Title

The tokamak GOLEM ...for fusion education Scientific activities)

Vojtěch Svoboda
on behalf of the tokamak GOLEM team

July 29, 2017

The global schematic overview of the GOLEM experiment



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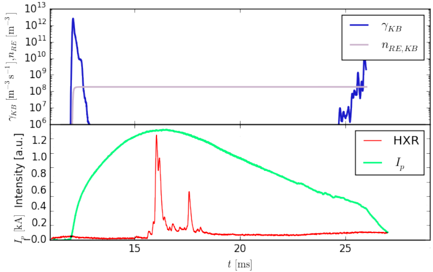
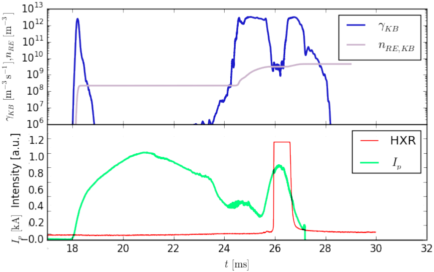
Runaway electrons

- A new NaI(TI) scintillation detector with a photomultiplier tube was installed
- Kruskal-Bernstein criterion used for estimating the RE generation rate
- RE generation observed during the breakdown phase as well as during position instabilities
- Plasma recreation observed after the loss of RE (probably due to secondary electrons)





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MHD plasma activity via poloidal ring of 16 Mirnov coils

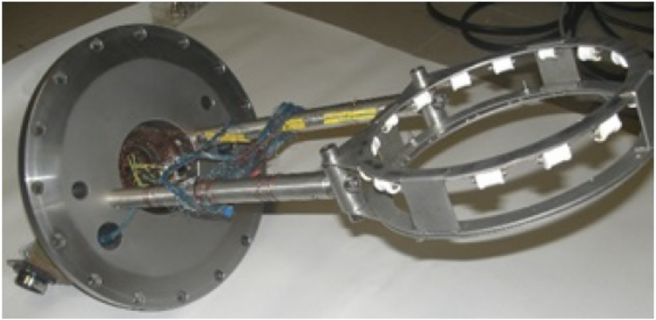
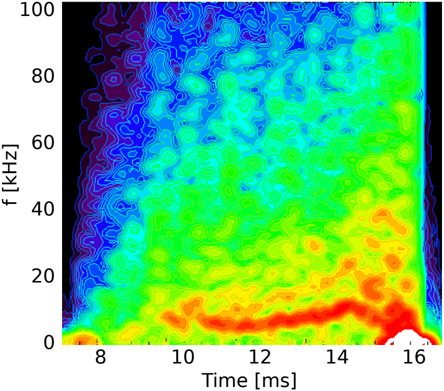
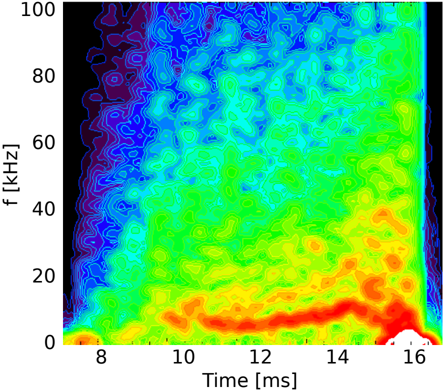


Figure 1: *Set of 16 Mirnov coils mounted in a poloidal ring to work like sensors of local magnetic field.*

Magnetohydrodynamic studies

Array of 16 Mirnov coils has been instaled. Magnetic islands detected at low q regime of tokamak $m = 3$ magnetic island – shown by cross-correlation analysis of $14 - 15$ ms interval





Spectrogram of B_θ perturbations detected by a Mirnov coil located on $\theta = \pi/2$, Cross-correlation coefficients of B_θ perturbation signal on an array of 16 Mirnov coils. Reference coil chosen on $\theta = \pi/2$

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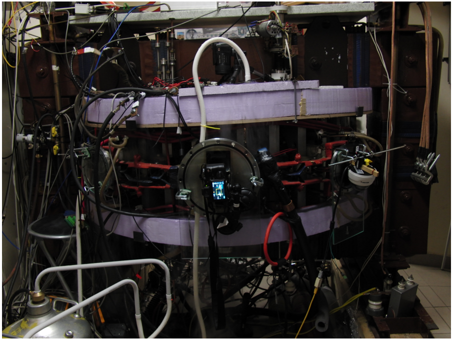
HTS @ tokamak GOLEM

.. as a test bed (or forerunner)

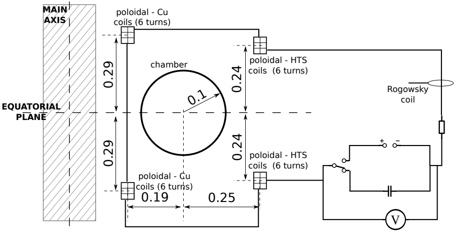
for application of High Temperature Superconductors in Fusion Devices

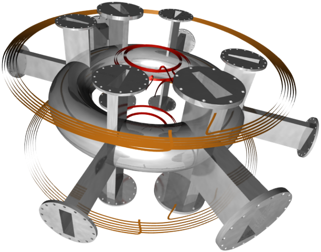


Broad collaboration:

- Tokamak Solutions UK,
- Oxford Instruments UK,
- Czech Technical University in Prague,CR,
- Institute of Plasma Physics, CR,
- Saint Petersburg State University, RF.

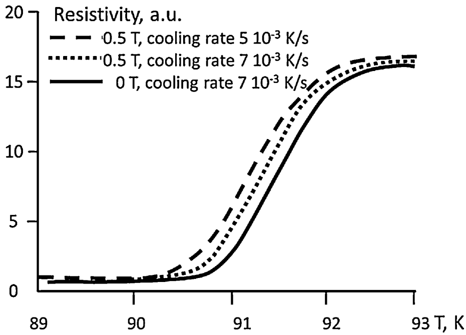
HTS@GOLEM





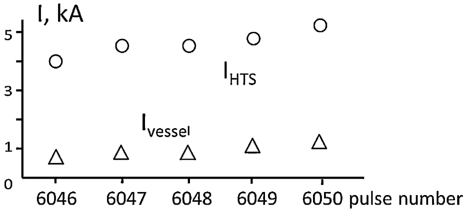
- Investigation of performance of HTS magnets during tokamak operations.
- Provide experimental data for the development of new concept of advanced magnets in fusion devices, based on High Temperature Superconductors.
- Studies of properties of HTS in tokamak environment: critical current dependence on magnetic field, temperature, stresses, etc.

HTS resistivity (table-top experiment)

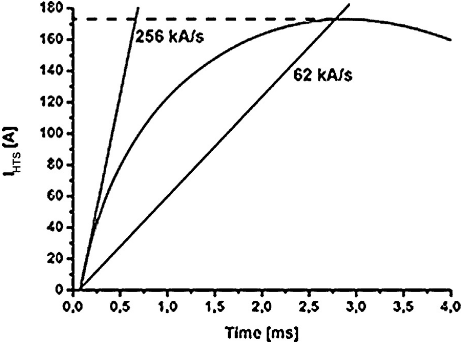


Resistance of a HTS sample vs temperature at different external field and cooling speed.

HTS current benchmark tests (real tokamak experiment)

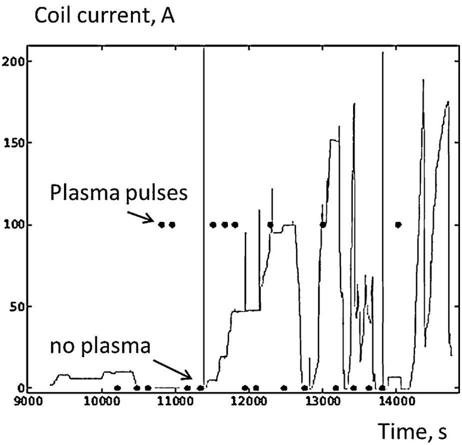


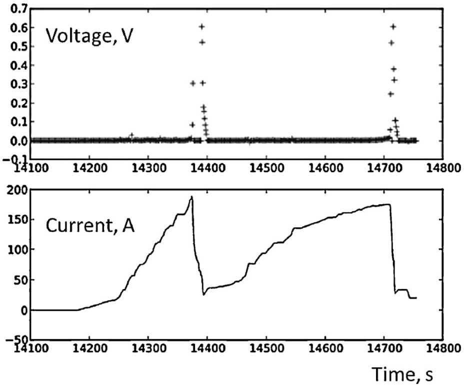
Maximum current in the HTS coil in different pulses. Current up to 0.84 kA through the tape (5 kA × turns) has been achieved.



Current in the HTS coil. Current ramp-up speed 100 kA/s.

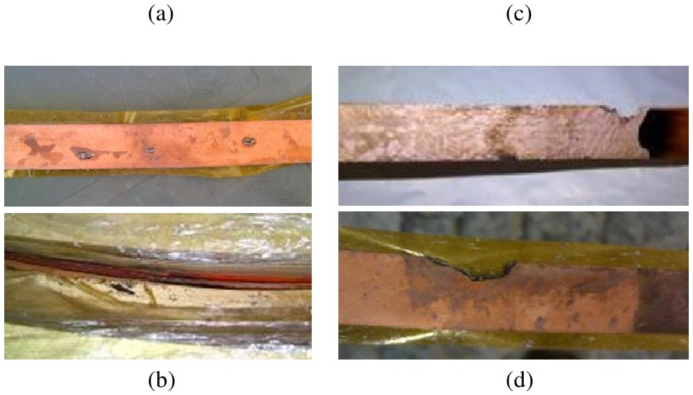
HTS performance during series of quenches





Voltage drop on HTS coil and current in HTS tape.

HTS tape damage after quenches



Hot spots (a,b) and arc damaged tapes, (c,d)

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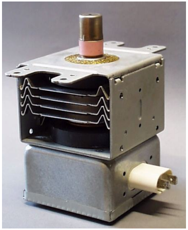
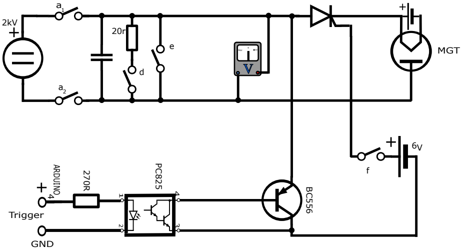
Experimental Setup

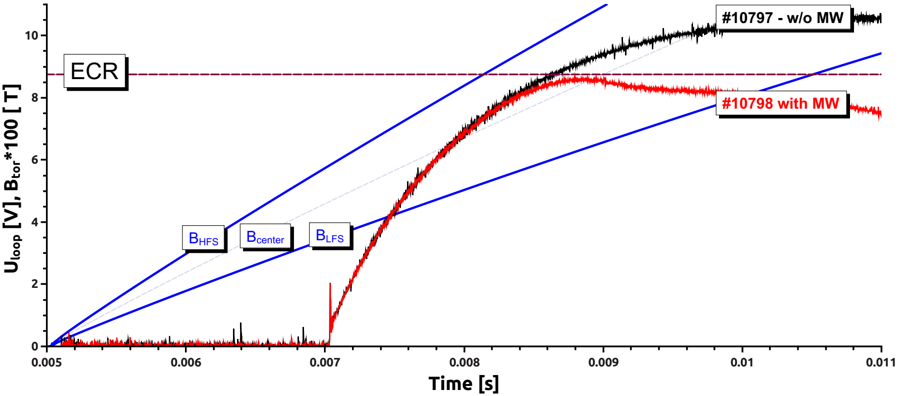




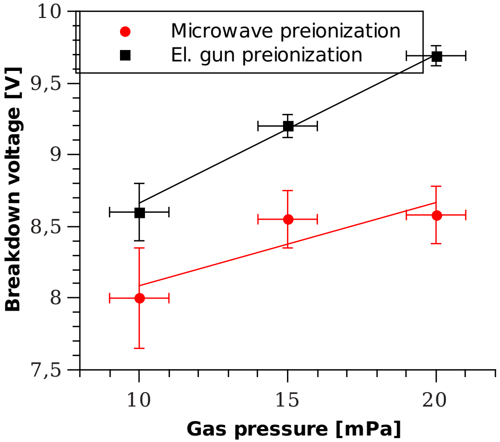
Motivation

- HTS PF coils application requires modifications to the discharge scenario.
- To reduce AC losses during current ramp-up in HTS coils, reduction in the current ramp-up speed is needed.
- Reduction in the loop voltage needed for the plasma breakdown.

ECRH assisted breakdown



MW versus Electron gun preionization



Paschen curve

Reduction in the loop voltage achieved for the plasma breakdown

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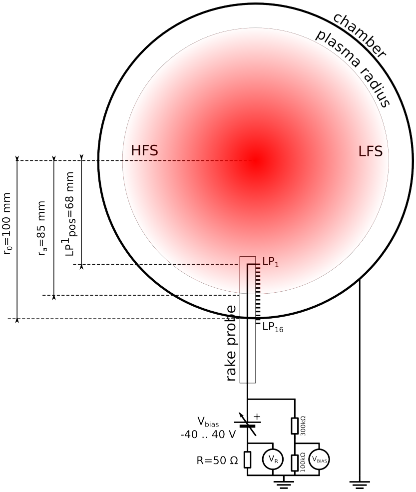
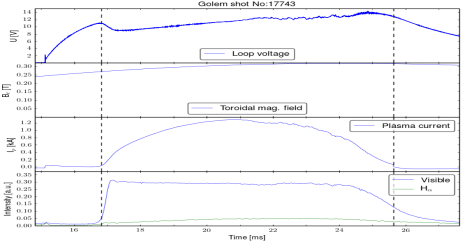
Experimental setup



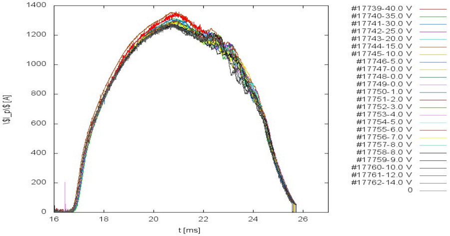
- Radial array of 16 Langmuir tips is immersed in the plasma from the bottom of the tokamak vessel, movable on the shot to shot basis.
- Tokamak discharge: Cylindrical probe diameter 0.7 mm, probe length 2 mm. Load resistance = 50 Ω
- MW plasma: Planar probe 5 x 5 mm Load resistance RL = 50 kΩ (because of much lower plasma densities)
- The DC voltage (from -40 to + 40 V) is applied to a probe (No 1) on the shot to shot basis and the temporal evolution of the probe current is recorded with sampling frequency 1 MHz i.e. with temporal resolution 1 us.

Probe measurements performed in two different plasmas

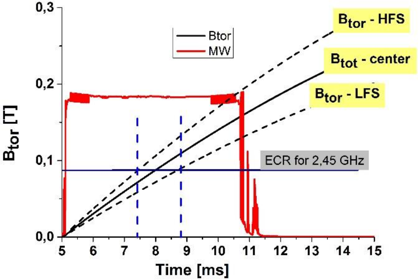
Reference discharge #11743



Reproducibility

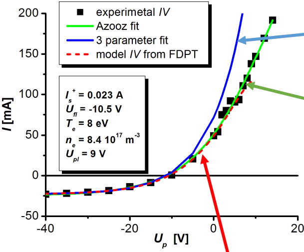


Microwave plasma used for breakdown of the working gas



Probe measurement in tokamak discharge - 2

Experimental IV characteristics are processed by three techniques:



1. Classical technique (3 parameters fit)

$I_p = I_{sat}$ (1-exp[(U_{fl} - U_p)/T_e]

The electron branch is not taken into account ($V_{probe} < V_{fl} + T_e$)

2. Empirical fit according empirical formula proposed by Azooz)

I_p = exp[a_1 * tanh (U_p + a_2)=a_3] + a_4

where a_1-a_4 are linked to plasma parameters

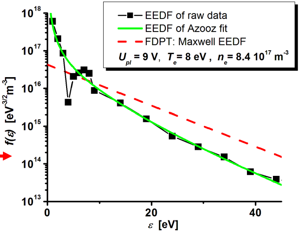
A. Azooz, *Four free parameter empirical parametrization of glow discharge Langmuir probe data*, Review of Sci. Instr. 79. 2008, 103501

3. First derivative technique according (see talk of Tsv. Popov)

$$I_e(U) = -\frac{2eS}{3\sqrt{2m_e}} \int_{eU}^{\infty} \frac{(\varepsilon - eU) f(\varepsilon) d\varepsilon}{\gamma(\varepsilon)\left[1 + \frac{(\varepsilon - eU)}{\varepsilon}\psi(\varepsilon, B)\right]}$$

$$f(\varepsilon) = \frac{3\gamma\sqrt{2m}}{2e^3 S} \cdot \frac{\psi(\varepsilon, B)}{U} \cdot \frac{dI_e(U)}{dU}$$

Tsv. K. Popov et al, *Electron energy distribution function, plasma potential and electron density measured by Langmuir probe in tokamak edge plasma* Plasma Phys. Control. Fusion, 51 (2009)

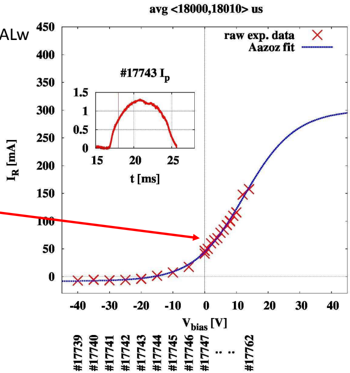


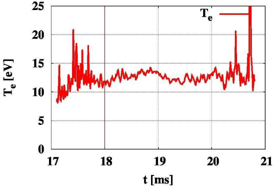
Probe measurement in tokamak discharge - 3

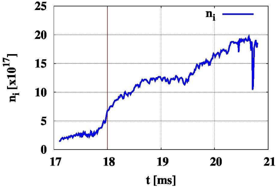
Temporal evolution of the shape of the IV characteristics during the series of reproducible discharges #17 739- 17 762 with the temporal resolution 10 μs (video)

https://youtu.be/AGaqU0q2ALw

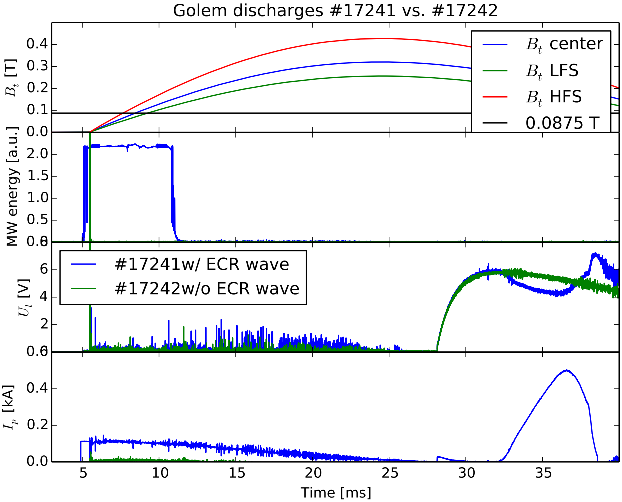
Fit of IV characteristics according the Azooz empirical formula





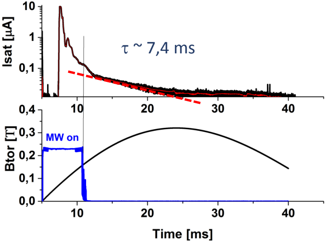


Breakdown conditions persistence



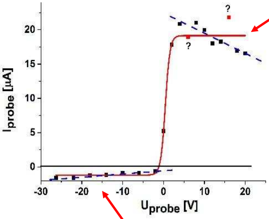
Probe measurements in microwave plasma – 1

Evolution of the toroidal magnetic field/MW power and the ion saturation current



- MW plasma is confined during whole duration of the toroidal magnetic field!
- The ion saturation current decays with the time constant ~7,4 ms after switching of the MW power
- **What are the plasma parameters??**

The typical IV characteristic recorded at t = 12 ms, when the MW power is already switched off



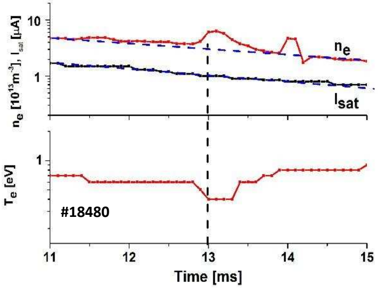
4 parameter fit – A.A Azooz

The electron saturation current decreases with the probe voltage – no explanation yet
Speculation: large probe acts as the biasing electrode => vertical electric field => ExB drift towards the Low field Side

The ion saturation current increases with the probe voltage – probe sheath expansion

Probe measurements in microwave plasma – 2

B_{tor} is still on, but MW power switched off



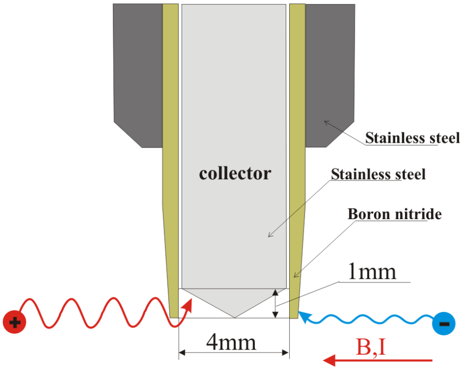
Evolution of the electron density and temperature during MW plasma decay in toroidal magnetic field

- n_e decays with a characteristic time constant 7,4 ms
- T_e is constant, remaining at < 1 eV

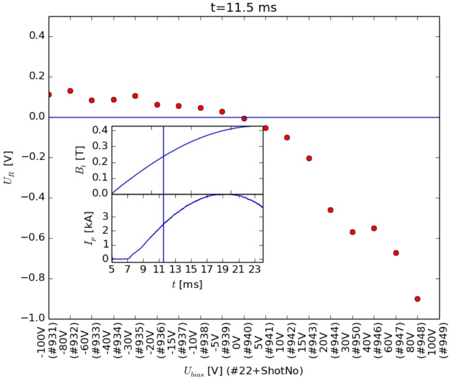
-> Low temperature plasma can be confined in toroidal magnetic field for a relatively long time (in the range of 1 -10 ms), if the electron temperature is sufficiently low.

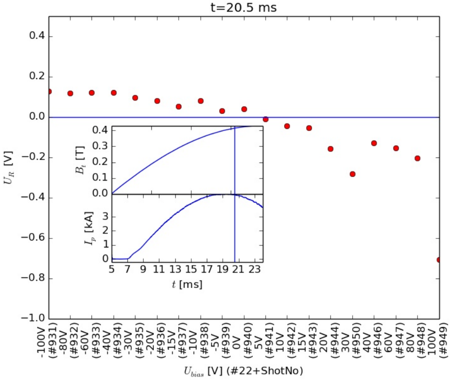
-> Particle losses due to the centrifugal and **B** x **grad B** losses in inhomogeneous magnetic field are reasonably low in this case

Ball pen probe



Ball Pen probe VA characteristic symmetry with B_t





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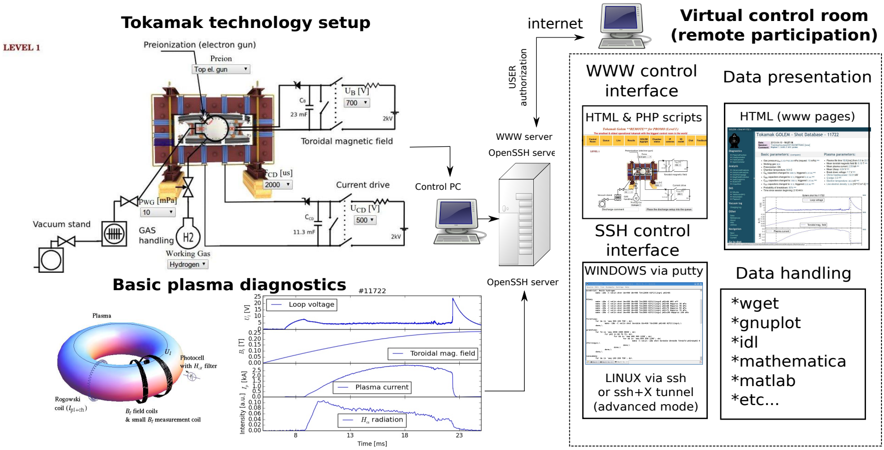
The global schematic overview of the GOLEM experiment



Production

- Everything via `http://golem.fjfi.cvut.cz/XXYY`
- All the resources at the `http://golem.fjfi.cvut.cz/wiki`
  - This presentation
  - Control rooms 4 Wednesday
  - Contact: Vojtech Svoboda, +420 737673903, svoboda@fjfi.cvut.cz

Acknowledgement

Acknowledgement

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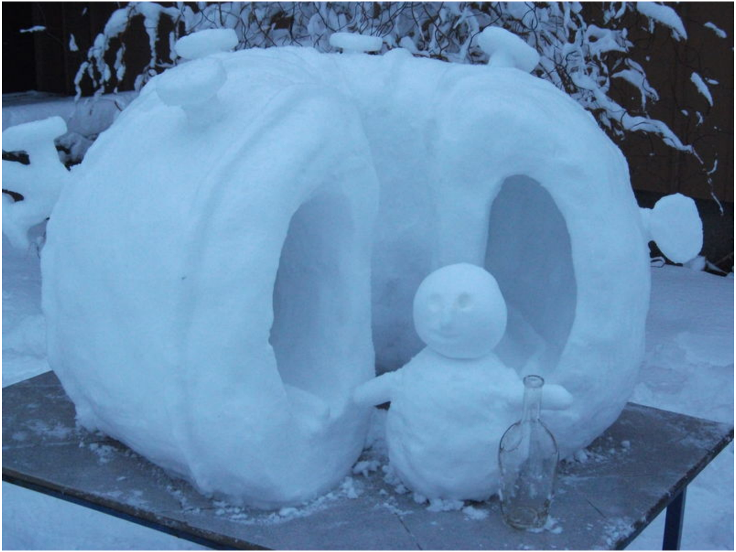
2010 Tokamak GOLEM



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