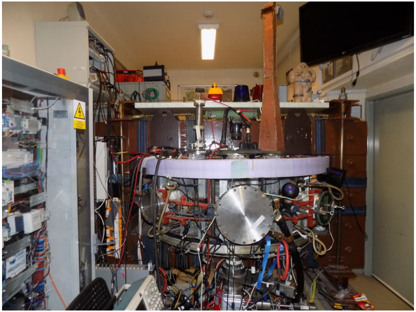
The tokamak GOLEM contribution to the IAEA programme

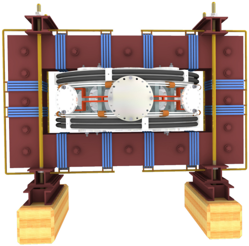


- As a test bed for High Temperature Superconductors usage in the tokamak technology.
- Probe measurement @ tokamak GOLEM.
- ECRH assisted preionization.
- **Education**.

Vojtech Svoboda on behalf of broad collaboration.

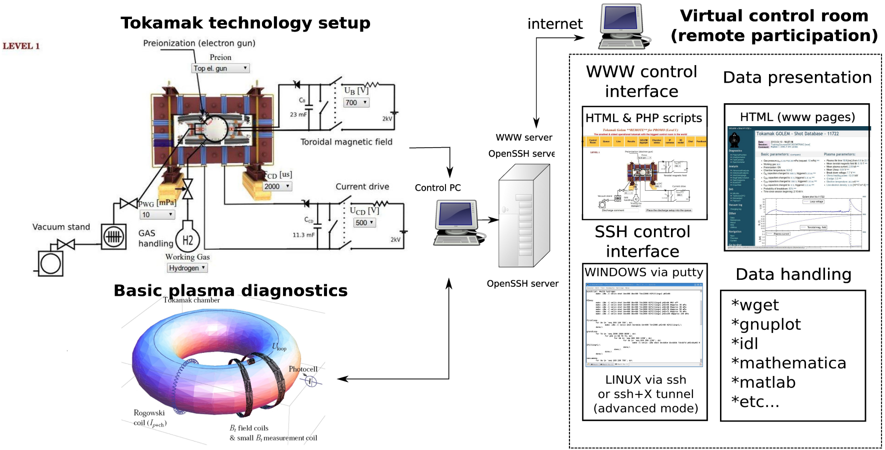
Outline

Basic characteristics



- Major radius $R_0 = 0.4$ m
- Minor radius $r_0 = 0.1$ m
- Plasma radius $a = 0.085$ m
- Toroidal magnetic field $B_t < 0.5$ T
- Plasma current $I_p < 8$ kA
- Plasma density $n \approx 0.2 - 3 \times 10^{19}/\mathrm{m}^{-3}$
- Electron temperature $T_e < 100$ eV
- Ion temperature $T_i < 50$ eV
- Length of the discharge $\tau < 20$ ms

The global overview of the tokamak GOLEM experiment

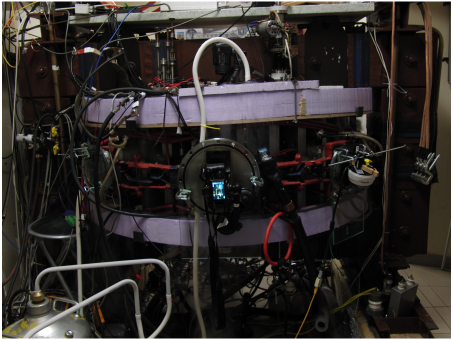


Outline

HTS @ tokamak GOLEM

.. as a test bed

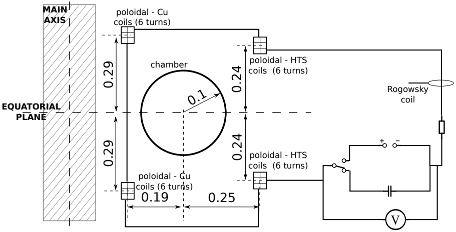
for application of High Temperature Superconductors in Fusion Devices

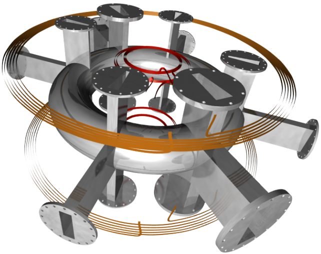


Broad collaboration:

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

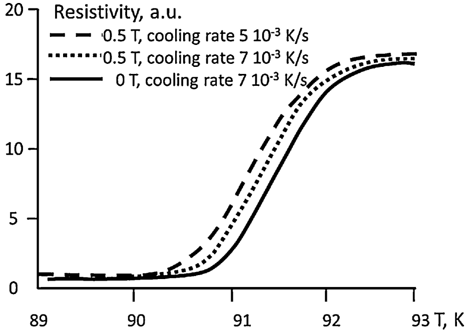
HTS@GOLEM





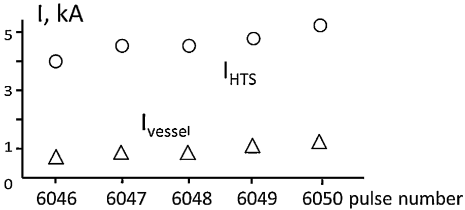
- Investigation of performance of HTS magnets during tokamak operations.
- Provide experimental data for the development of new concept of advanced magnets in fusion devices, based on High Temperature Superconductors.
- Studies of properties of HTS in tokamak environment: critical current dependence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

HTS resistivity (table-top experiment)

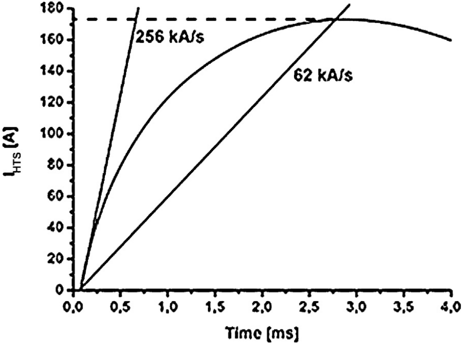


Resistance of a HTS sample vs temperature at different external field and cooling speed.

HTS current benchmark tests (real tokamak experiment)

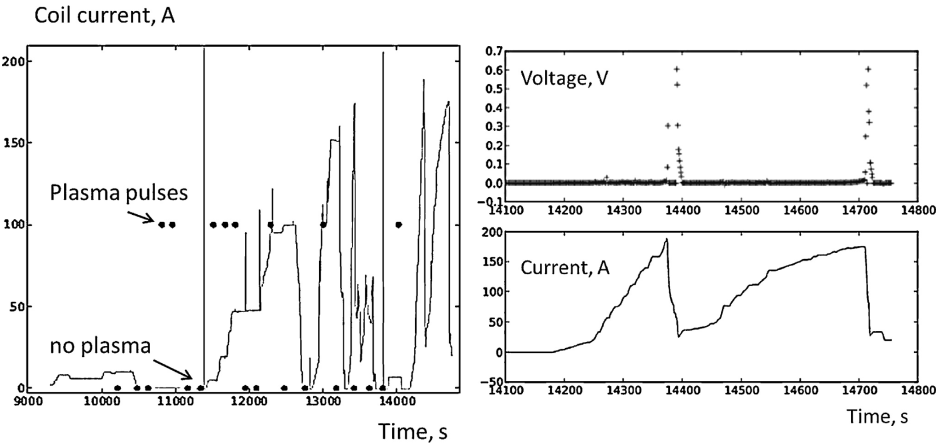


Maximum current in the HTS coil in different pulses. Current up to 0.84 kA through the tape (5 kA $\times$ turns) has been achieved.



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

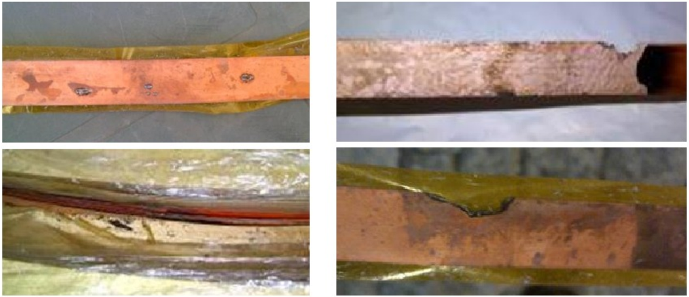
HTS performance during series of quenches



Voltage drop on HTS coil and current in HTS tape.

HTS tape damage after quenches

(a) (c)



(b) (d)

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

HTS outcome

Conclusions:

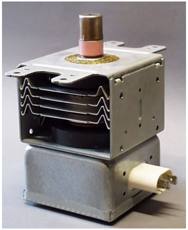
- Bench tests, maximum current and quench studies were conducted on tokamak GOLEM.
- Plasma operation with HTS coils was demonstrated.
- Damages of the tape were analyzed.

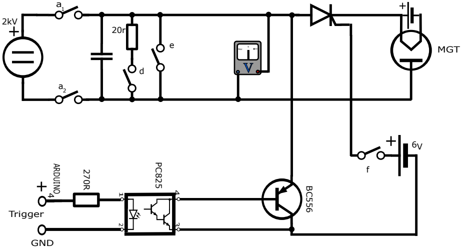
Publications and Conference Contributions:

- M. Gryaznevich et.al: Contribution to fusion research from IAEA coordinated research projects and joint experiments. Nucl. Fusion 55 (2015)
- M. Gryaznevich et.al: Progress in application of high temperature superconductor in tokamak magnets. Fusion Engineering and Design 88 (2013)
- 39th EPS Stockholm 2012, 27th SOFT Liege 2012

Outline

Experimental Setup

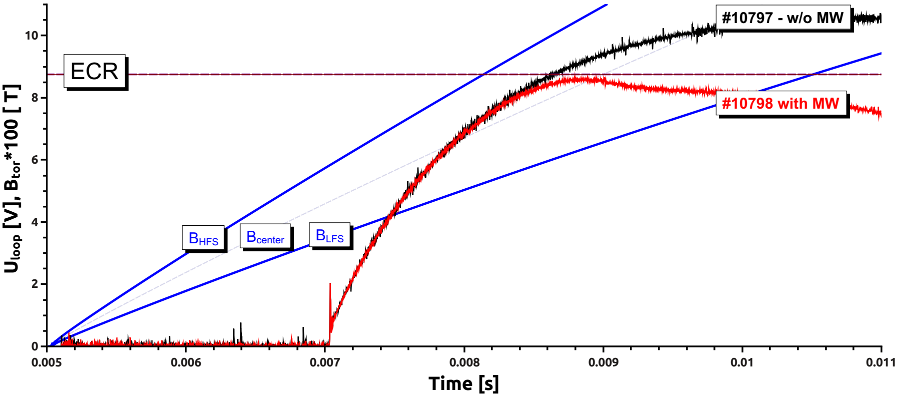




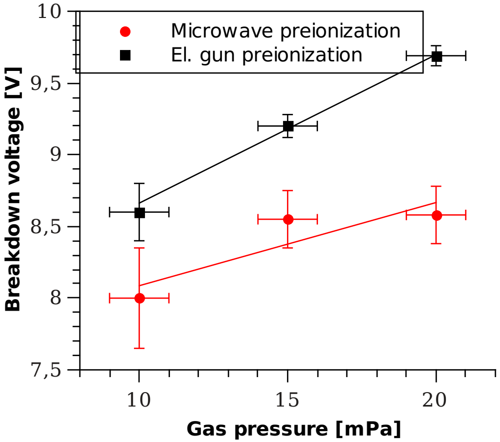
Motivation

- 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

ECRH assisted preionization @ tokamak GOLEM outcome

Conclusions:

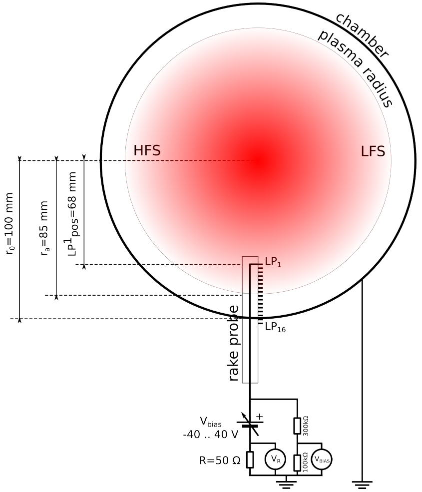
- MW driven preionization - reduction in the loop voltage achieved for the plasma breakdown with respect to Electron Gun preionization.

Publications and Conference Contributions:

- M. Gryaznevich et.al: Contribution to fusion research from IAEA coordinated research projects and joint experiments. Nucl. Fusion 55 (2015)
- 41st EPS Berlin 2014.

Outline

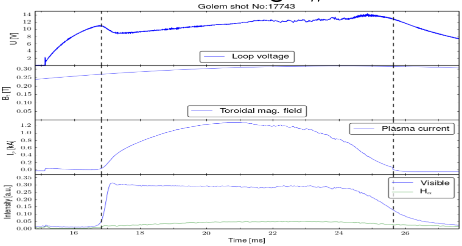
Experimental setup



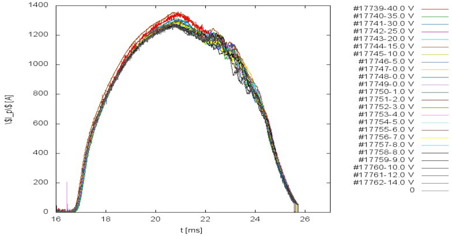
- Radial array of 16 Langmuir tips is immersed in the plasma from the bottom of the tokamak vessel, movable on the shot to shot basis.
- Tokamak discharge: Cylindrical probe diameter 0.7 mm, probe length 2 mm. Load resistance = 50 Ω
- MW plasma: Planar probe 5 x 5 mm Load resistance RL = 50 kΩ (because 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

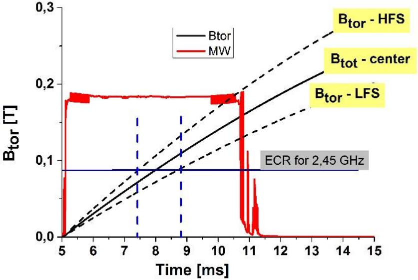
Reference discharge #11743



Reproducibility



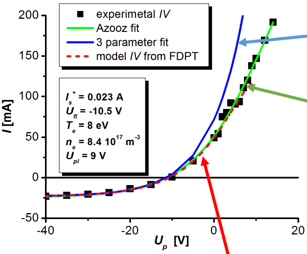
Microwave plasma used for breakdown of the working gas



Outline

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

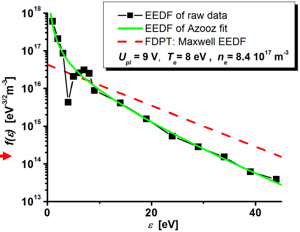
A. Azooz, *Four free parameter empirical parametrization of glow discharge Langmuir probe data*, Review of Sci. Instr. 79. 2008, 103501

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)

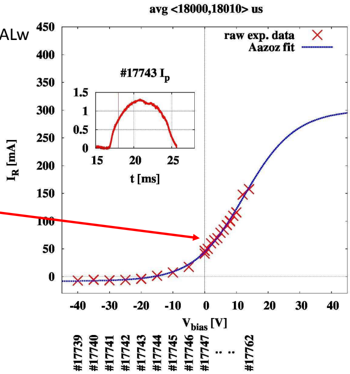


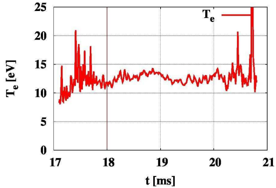
Probe measurement in tokamak discharge - 3

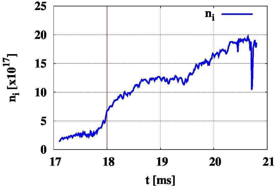
Temporal evolution of the shape of the IV characteristics during the series of reproducible discharges #17 739- 17 762 with the temporal resolution 10 μs (video)

https://youtu.be/AGaqU0q2ALw

Fit of IV characteristics according the Azooz empirical formula

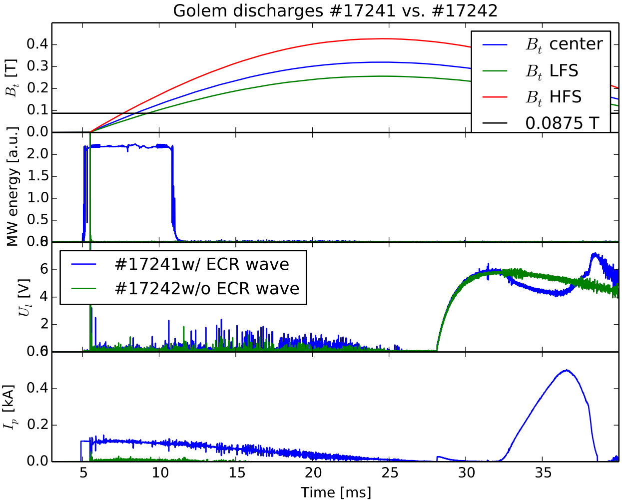






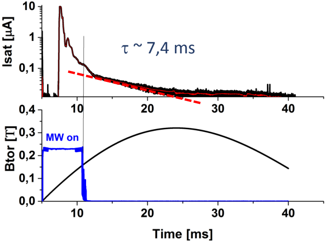
Outline

Breakdown conditions persistence



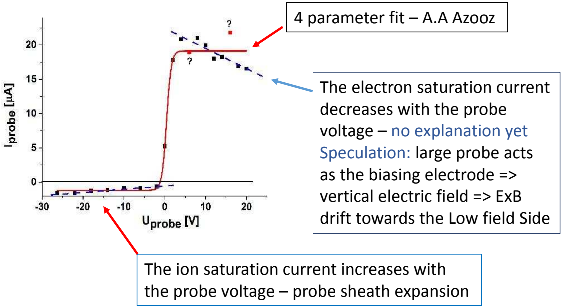
Probe measurements in microwave plasma – 1

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



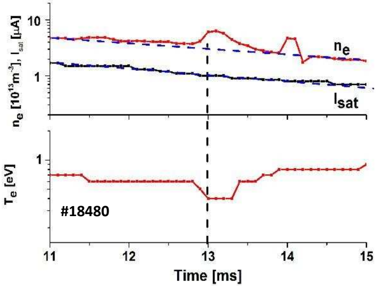
- MW plasma is confined during whole duration of the toroidal magnetic field!
- The ion saturation current decays with the time constant ~7,4 ms after switching of the MW power
- **What are the plasma parameters??**

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



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

Probe measurements @ tokamak GOLEM outcome

Conclusions:

- Discharges on the GOLEM tokamak are quite reproducible =¿ IV characteristics of a single Langmuir probe can be recorded on shot to shot basis
- Temporal evolution of the plasma parameters is determined with a high temporal resolution (10 us)
- Surprisingly, the whole IV characteristics are very well fitted by the empirical analytical expression proposed by Azooz
- Probe date are very well fitted by the empirical analytical expression proposed by Azooz and the T_e , n_e, U_{pl} and the Electron Energy Distribution Function can be determined
  - Tokamak discharge edge electron temperature 10 eV, densities 10^{17} /m^3, Electron Energy Distribution Function is Maxwellian
  - MW plasma used for breakdown: Electron temperature ¡ 1 eV, plasma density ne 10^{13} /m^3 after switching off the MW power, plasma is confined in toroidal magnetic field for tens of milliseconds, EEDF is Maxwellian

Publications and Conference Contributions:

- 39th EPS Stockholm 2012, 42nd EPS Lisbon 2015.

Outline

Outline

On site tokamak GOLME controll

- Summer Training Course 2009-2015
- Erasmus Mundus Training Course 2013-2015
- Science week 2010-2014

Outline

Remote controll

- Ghent University 2009, TU Eindhoven 2011,2015,2016, Bochum University 2013, Garching 2013, Lemvig High School 2014, TU Kobehaven, TU Denmark 2015,2016, University of Belgrade 2015, BUTE Budapest 2010,2012-2014, Instituto Tecnologico Costa Rica 2010, University of Padova 2014.
- French Training Course & EM 2012-2014,2016.
- Workshops Kiten 2014, Observatorium Valasske Mezirici 2014, Islamabad 2014,
- Global Tokamak Experiment 2010,

Outline

1 Introduction

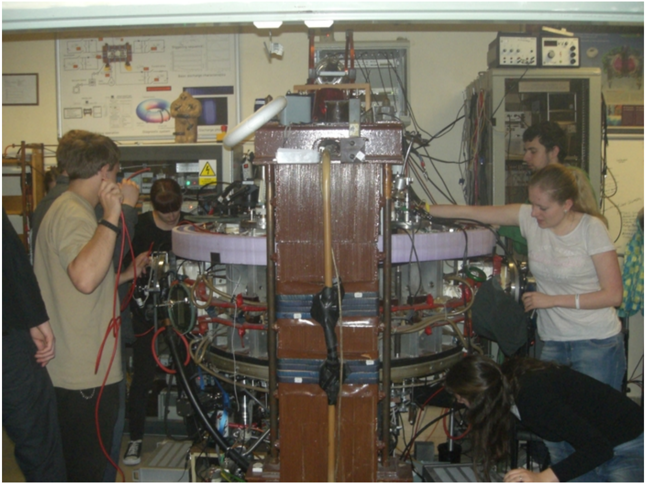
2 HTS

3 ECRH assisted preionization

4 Probe measurement @ tokamak GOLEM
- Tokamak plasma
- MW plasma

5 Education
- On-site controll
- Remote controll
- Tokamak hands-on
- Bachelor & Diploma thesis
- Special events

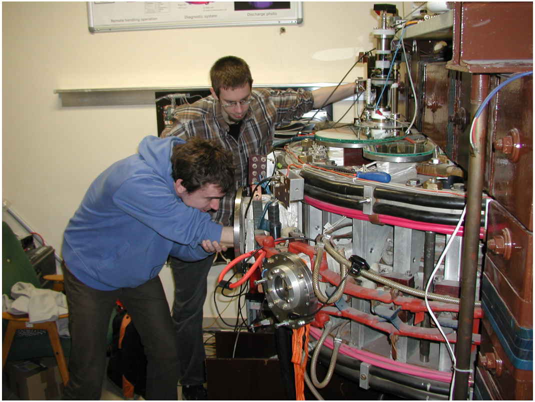
Hands on tokamak



- Laboratory Practice 4 Basic course of Physics 15,16
- Golem Training course 13

Outline

Bachelor & Master thesis made @ tokamak GOLEM



- **Bachelor thesis:** Magnetic field configurations and their measurement, Interactive model, Plasma flow velocity measurements using Mach probe arrays, Virtual model, Bolometric measurements, Breakdown studies, Vertical plasma stabilization.
- **Master thesis:** Microwave interferometry, Remote operation of the vertical plasma stabilization, Measurements of magnetic fields.

Outline

PhD event @ Prague 2015

- 135 PhD students.
- 4 days: social & scientific programme.
- Success.

Education @ tokamak GOLEM outcome

Conclusions:

- Tokamak GOLEM have proven to be used as an (remote as well on-site controll and hands-on) educational device

Publications and Conference Contributions:

- M. Gryaznevich et.al: Contribution to fusion research from IAEA coordinated research projects and joint experiments. Nucl. Fusion 55 (2015)
- V. Svoboda et.al: Remote operation of the GOLEM tokamak for Fusion Education. Submitted to Fusion Engineering and Design.
- 39th EPS Stockholm 2012, 40th EPS Espoo 2013, 41st EPS Berlin 2014, 42nd EPS Lisbon 2015.

Acknowledgement

- **Leaders:** Jan Stockel, Mikhail Gryaznevich
- **Collaborators:** , Gabriel Vondrasek, Gennadij Vorobljev
- **Students:** Ondrej Grover, Michal & Tomas Odstrcilovi, Jindrich Kocman, Tomas Markovic, Lukas Matena
- **Institutions:** Fusenet, Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Institute od Plasma Physics, Czech Academy of Sciences, Ministry of Education, Czech Republic.

Presentations/publications I

- E. Bromova et al. "The GOLEM Tokamak for Fusion Education ". In: *Europhysics Conference Abstracts. 38th EPS Conference on Plasma Physics (online: http://ocs.ciemat.es/EPS2011PAP/pdf/P1.021.pdf).* Vol. 35G. 2011. ISBN: 2-914771-68-1.
- Brotankova, J. "Study of high temperature plasma in tokamak-like experimental devices". In: (PhD. thesis 2009).
- V. Svoboda et al. "Former Tokamak CASTOR becomes remotely controllable GOLEM at the Czech Technical University in Prague ". In: *Europhysics Conference Abstracts. 37th EPS Conference on Plasma Physics (online: http://ocs.ciemat.es/EPS2010PAP/pdf/P2.111.pdf).* Vol. 34A. 2010. ISBN: 2-914771-62-2.

Presentations/publications II

- V. Svoboda et al. "Multi-mode Remote Participation on the GOLEM Tokamak". In: *Fusion Engineering and Design* 86.6-8 (2011), 1310–1314. ISSN: 0920-3796. DOI: {10.1016/j.fusengdes.2011.02.069}.
- The GOLEM team. " Recent results from GOLEM tokamak. 'Indeed, you can teach an old dog some new tricks. " In: *39th EPS Conference on Plasma Physics, Stockholm*. 2012.
- The GOLEM team. "The GOLEM Tokamak for Fusion Education ". In: *38th EPS Conference on Plasma Physics, Strasbourg*. 2011.
- Tokamak GOLEM team. *Tokamak GOLEM at the Czech Technical University in Prague*. http://golem.fjfi.cvut.cz. 2007.

Thanks

Thank you for your attention ..