The GOLEM tokamak: 10 years of the Fusion education service

Vojtech Svoboda
on behalf of the tokamak GOLEM team
for **Seminar @ UTP Panama**, Panama City

March 11, 2020

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Faculty of Nuclear Sciences and Physical Engineering Czech Technical University in Prague



FNSPE main building in Prague



FNSPE insignia

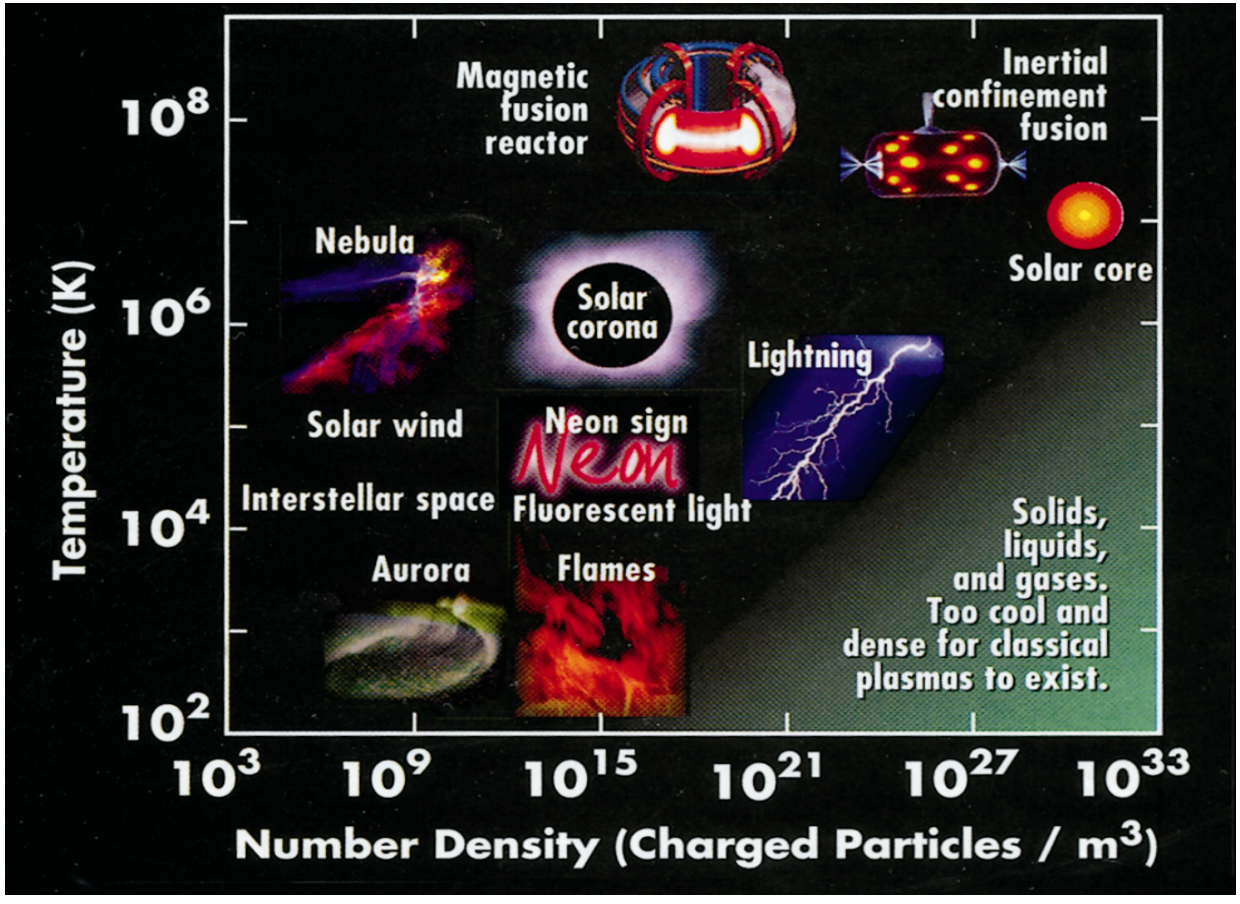


CTU ceremony hall

- CTU founded in 1707 by the emperor Joseph I.
- CTU approximately 2200 staff members, 16000 undergraduate students, 9000 graduate and PhD students. ($\approx$ 2500 foreign students).
- FNSPE established in 1955 with the mission to train new experts for the emerging Czechoslovak nuclear programme.
- FNSPE currently a centre of education and research specialised in boundary fields between modern science and their applications in technologies, medicine, economy, biology, ecology, and other fields.

Scientific group/ education specialization

The Physics of Plasma and Thermonuclear fusion



99.999 % Universe is in the Plasma state of matter

Tokamak GOLEM & Vojtěch Svoboda

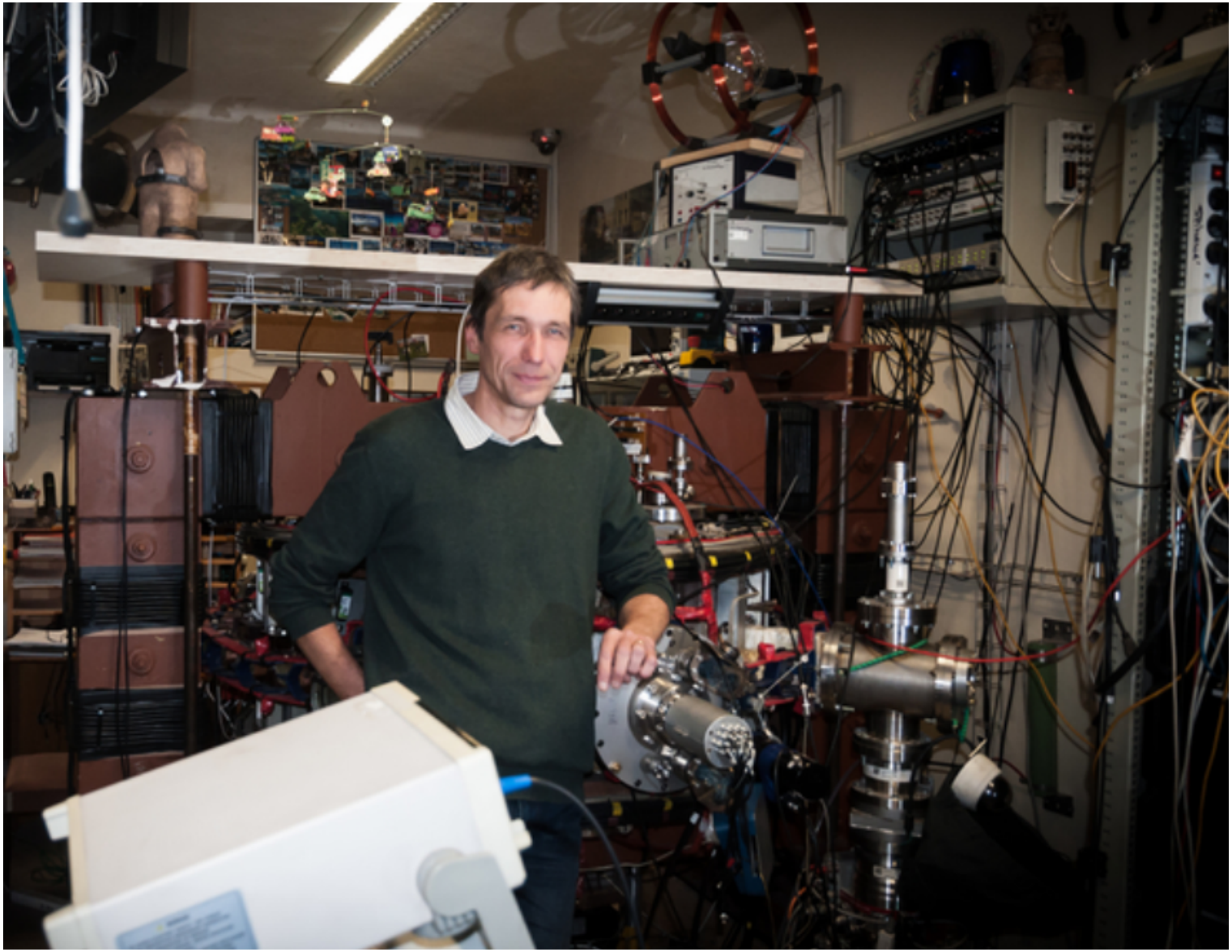


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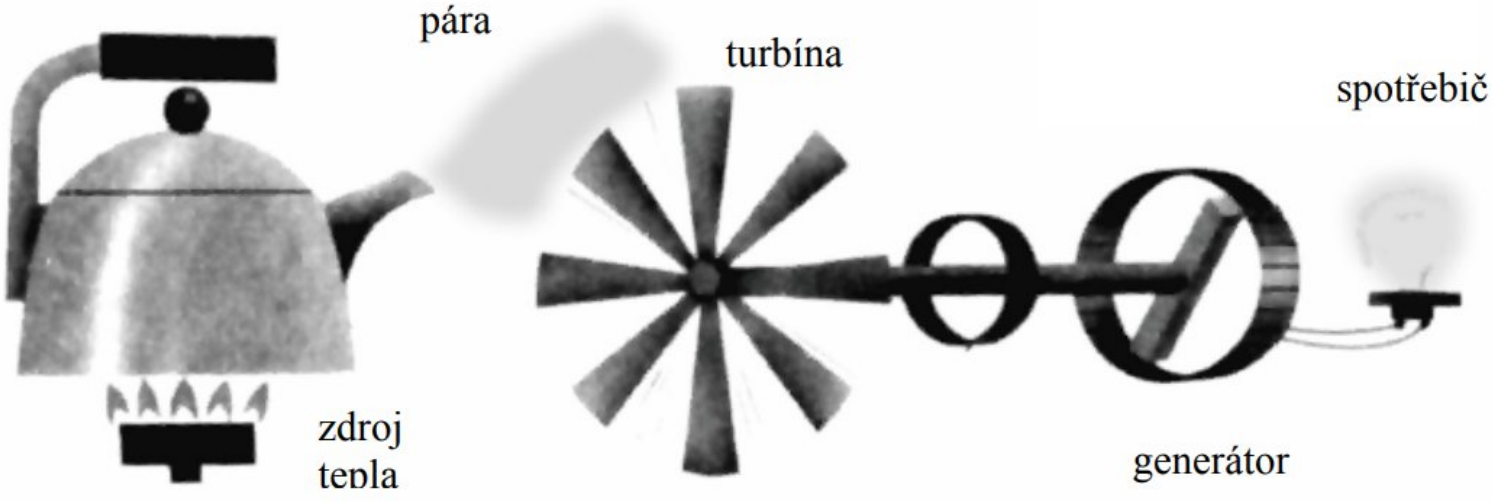
4 Hands on Tokamak experimentation

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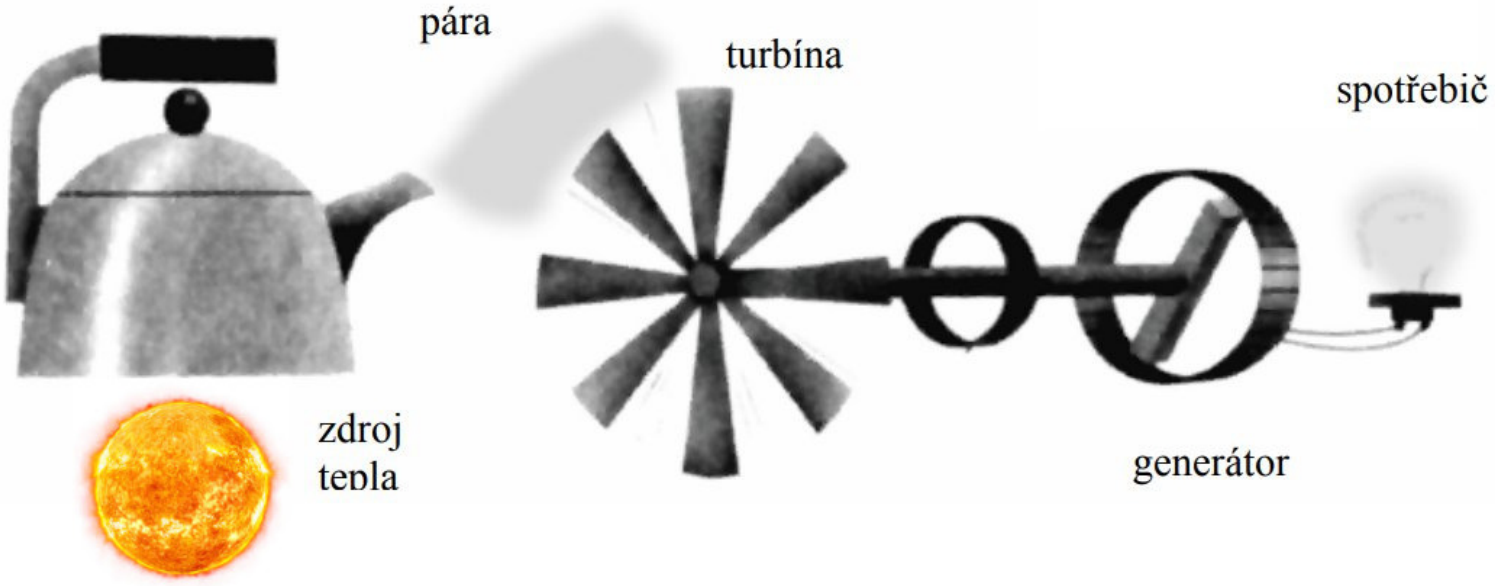
Thermal power plant - basic principle



The question:

?? WHAT TO BURN ??

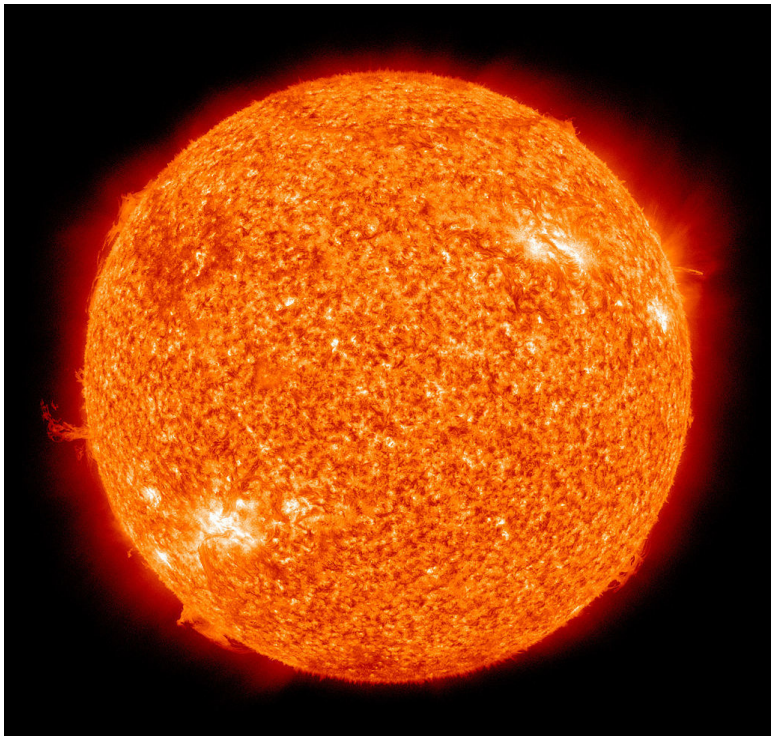
Small μSun in the terestriall conditions ??

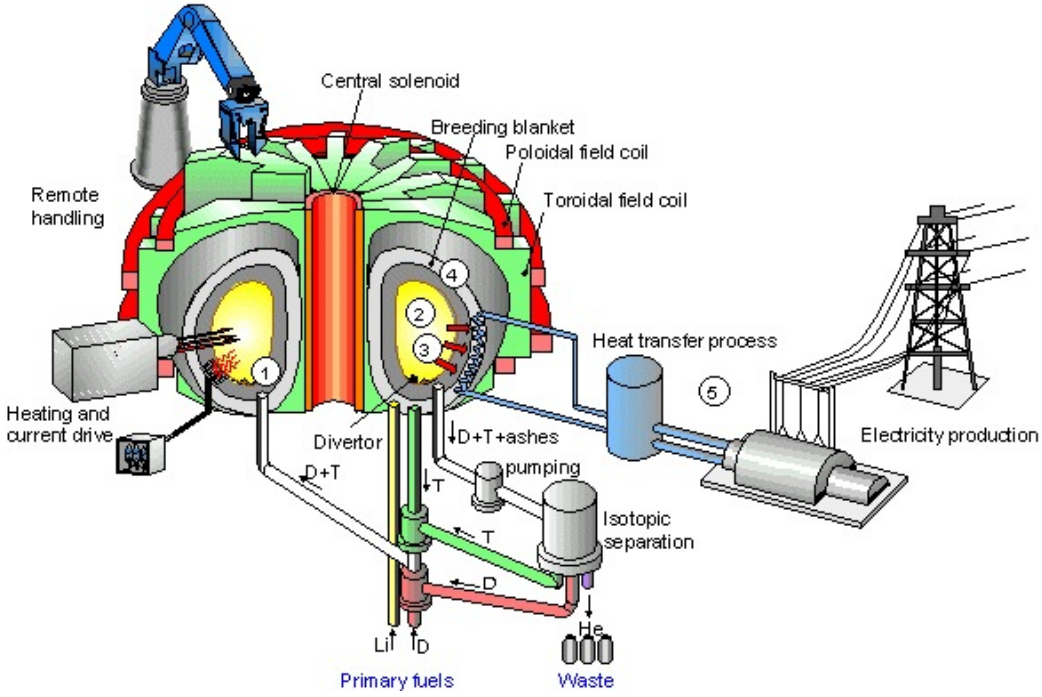


The challenge



Tokamak mission:
to create μSun in the terrestrial conditions

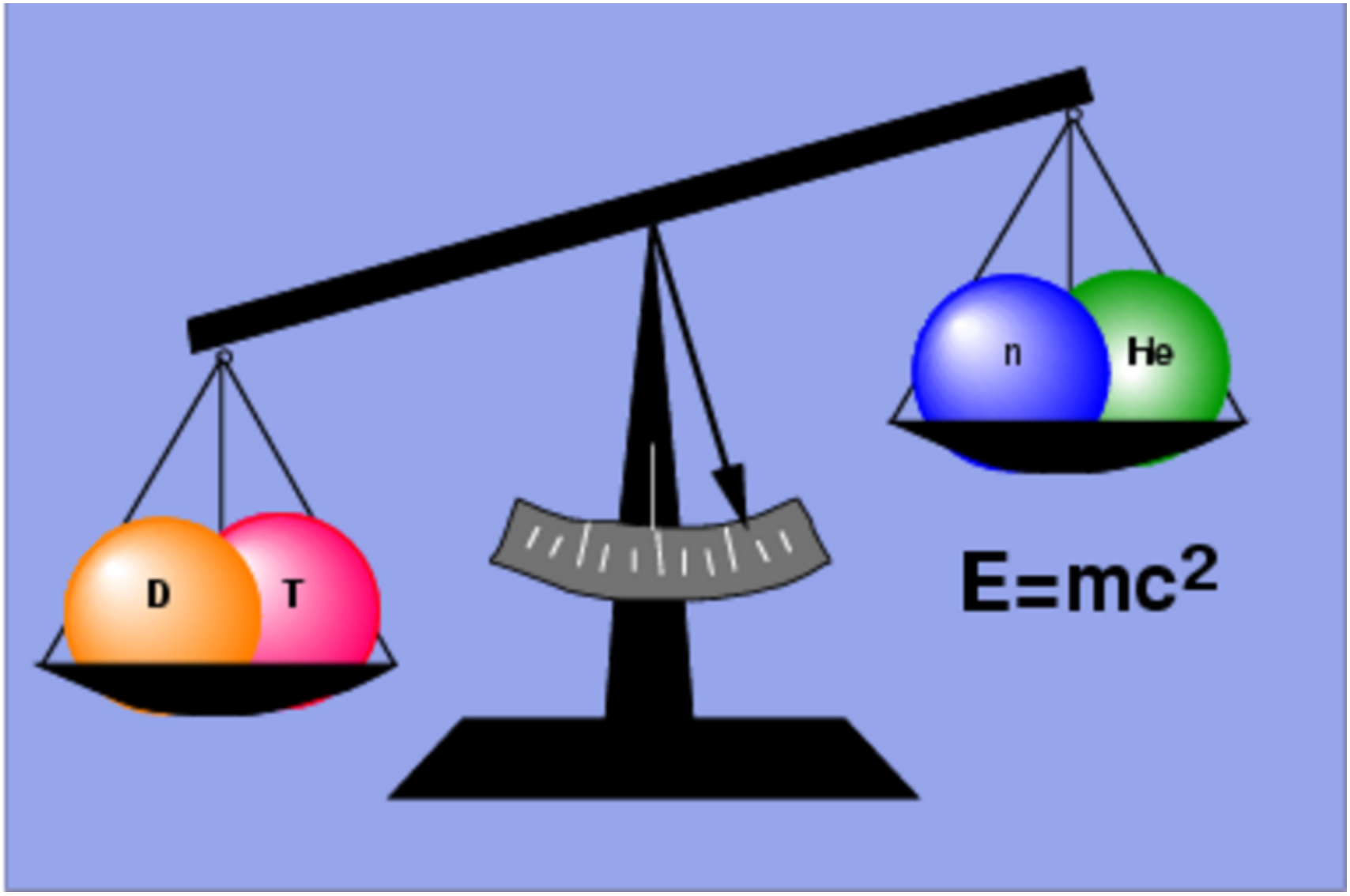




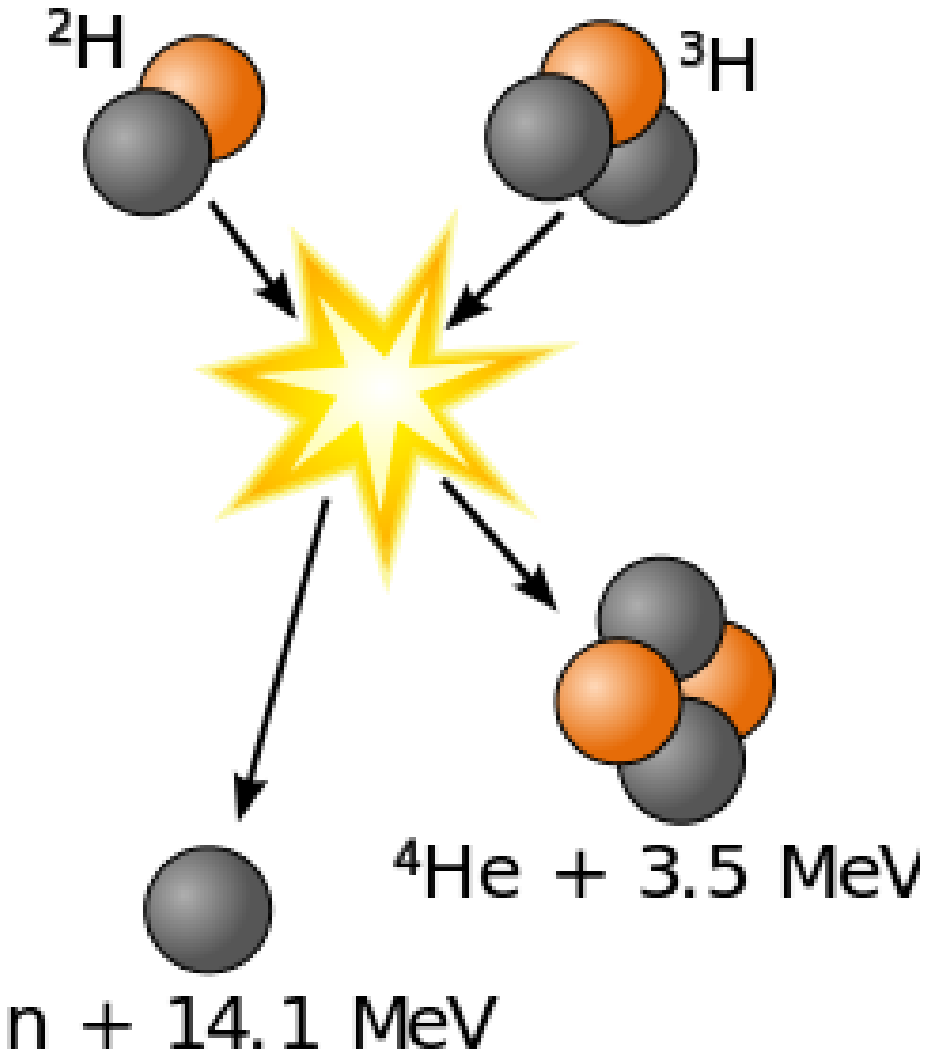
$$^{2}_{1}\mathbf{D}_{(10\mathbf{keV})} + ^{3}_{1}\mathbf{T}_{(10\mathbf{keV})} \Rightarrow ^{4}_{2}\mathbf{He}_{(3.5\mathbf{MeV})} + \mathbf{n}_{(14.1\mathbf{MeV})}$$

The task: to heat (up to 100 million degrees) DT fuel and confine it (up to 30 years) in the high temperature plasma state of matter to produce He & fusion energy.

Binding energy releasing I

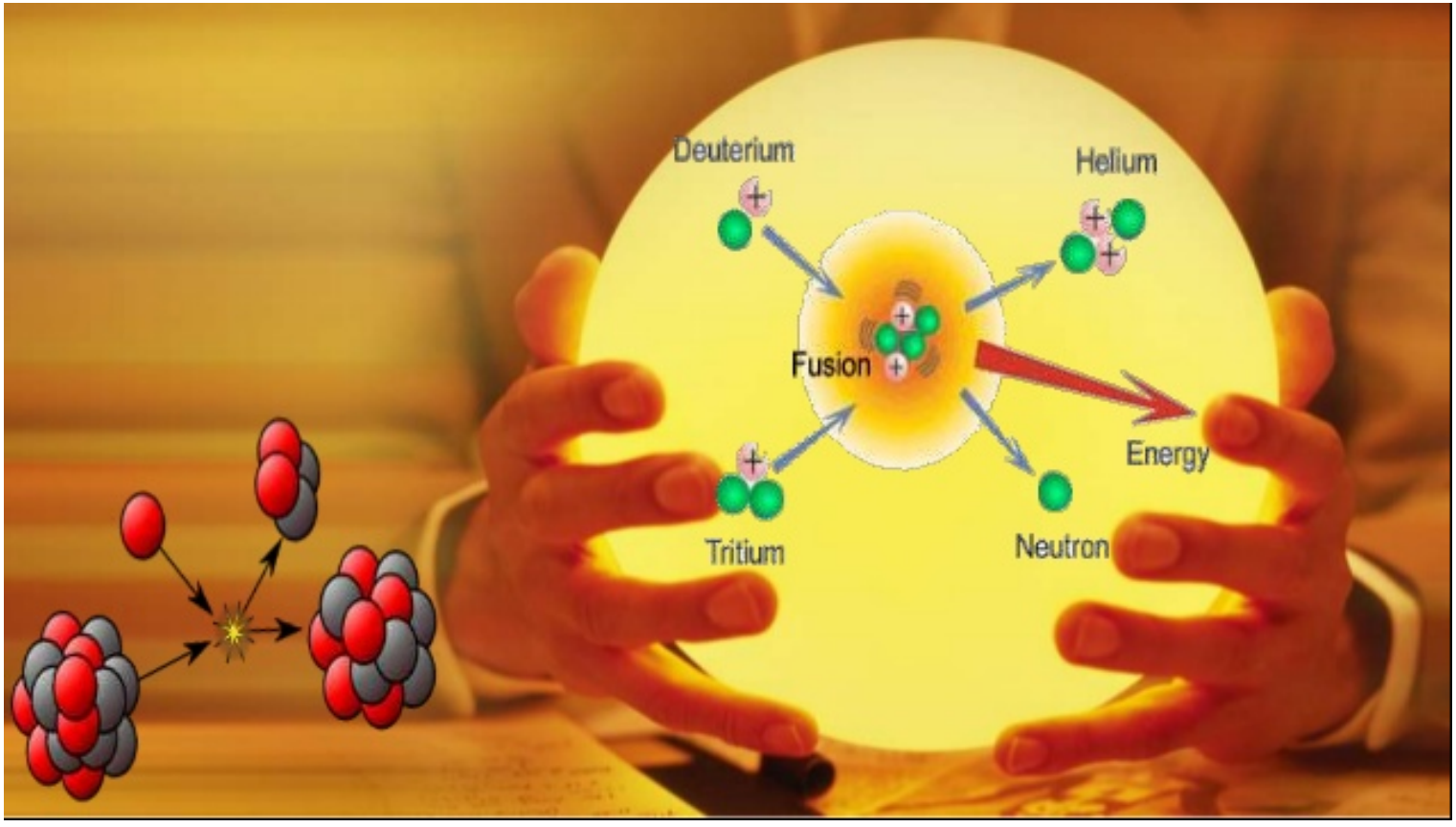


Fusion Reaction



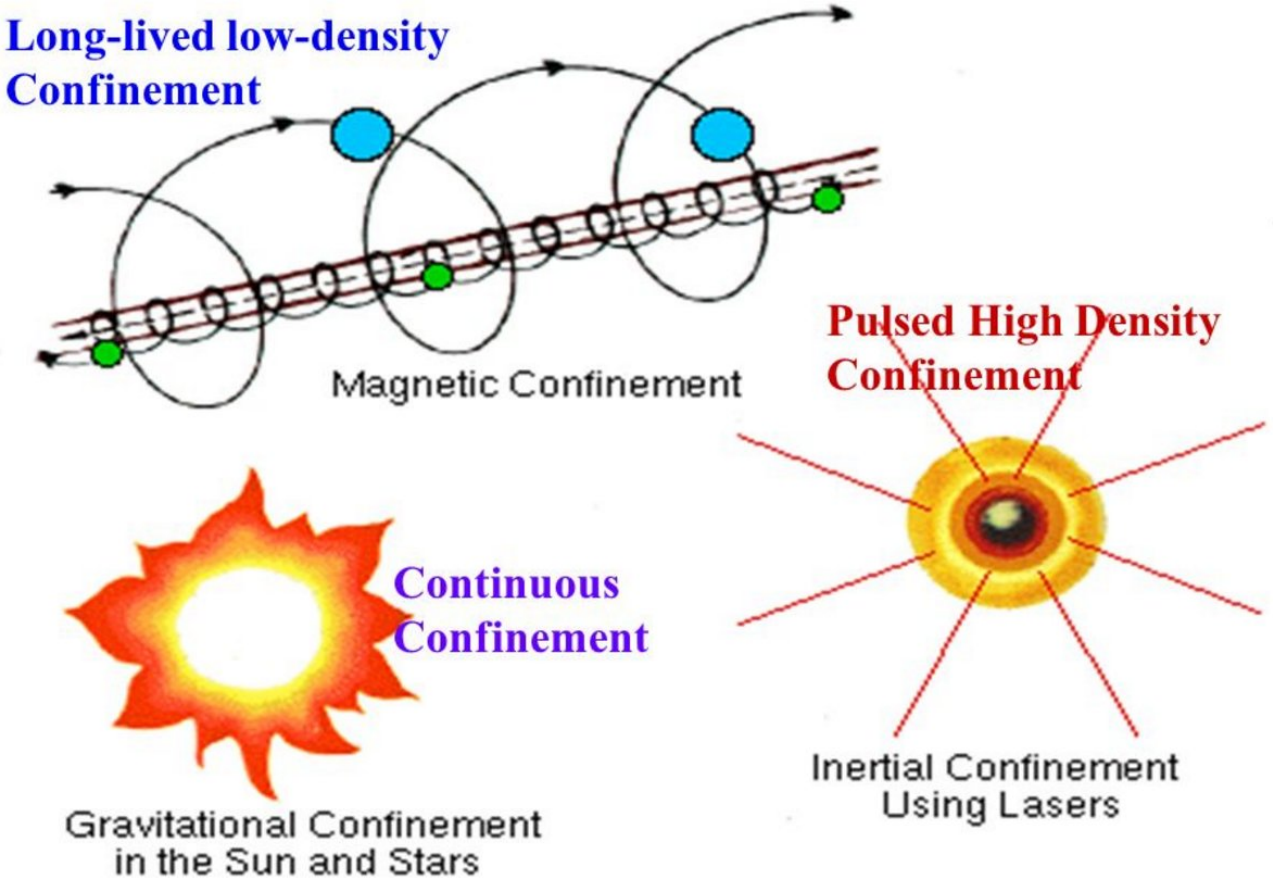
credit:[?]

Looking for feasible fusion technology

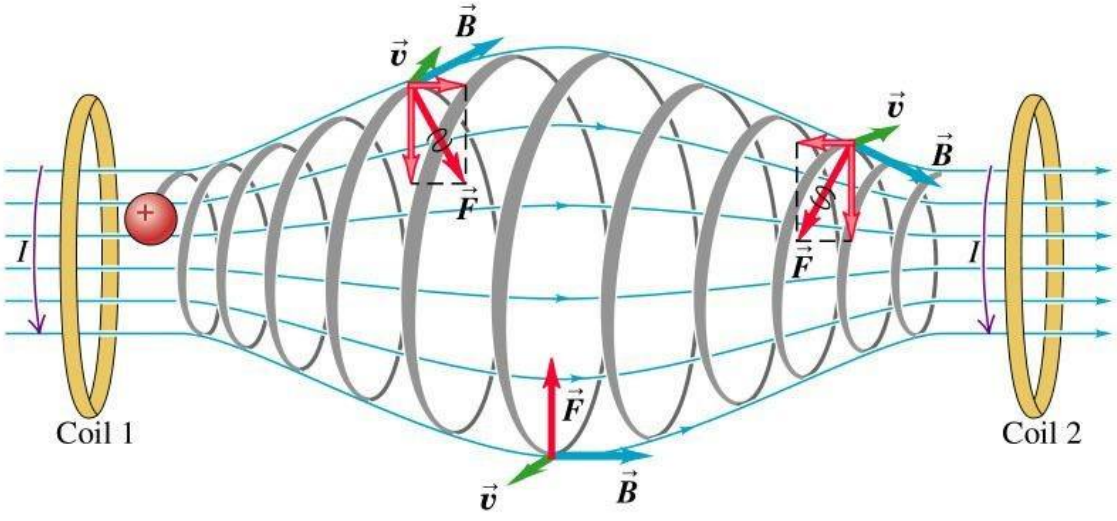


Three ways to confine plasma

Lawson criterion: $n\tau_E \geq 1.5 \cdot 10^{20} \frac{\mathrm{s}}{\mathrm{m}^3}$



Magnetic confinement: magnetic bottle



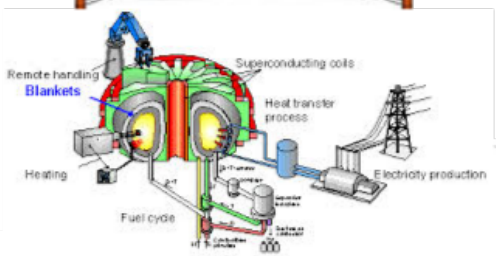


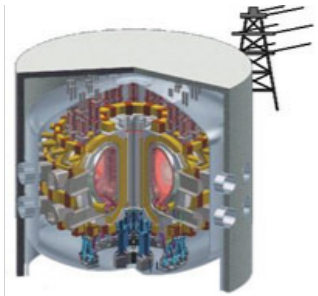
Copyright © 2004 Pearson Education, Inc., publishing as Addison Wesley.

A Roadmap to the Fusion Power Plant

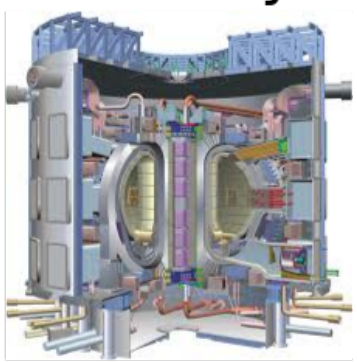
COMMERCIAL
POWER PLANT
???







DEMO (2044?-)
Mission: fusion electricity to the grid



ITER (WORLD)
2025?-
Mission: ~ 400s 500 MW @ Q=10



JET (EU)
1984-present
World record (1997): ~ 2s 16 MW @ Q=0.67

Education importance



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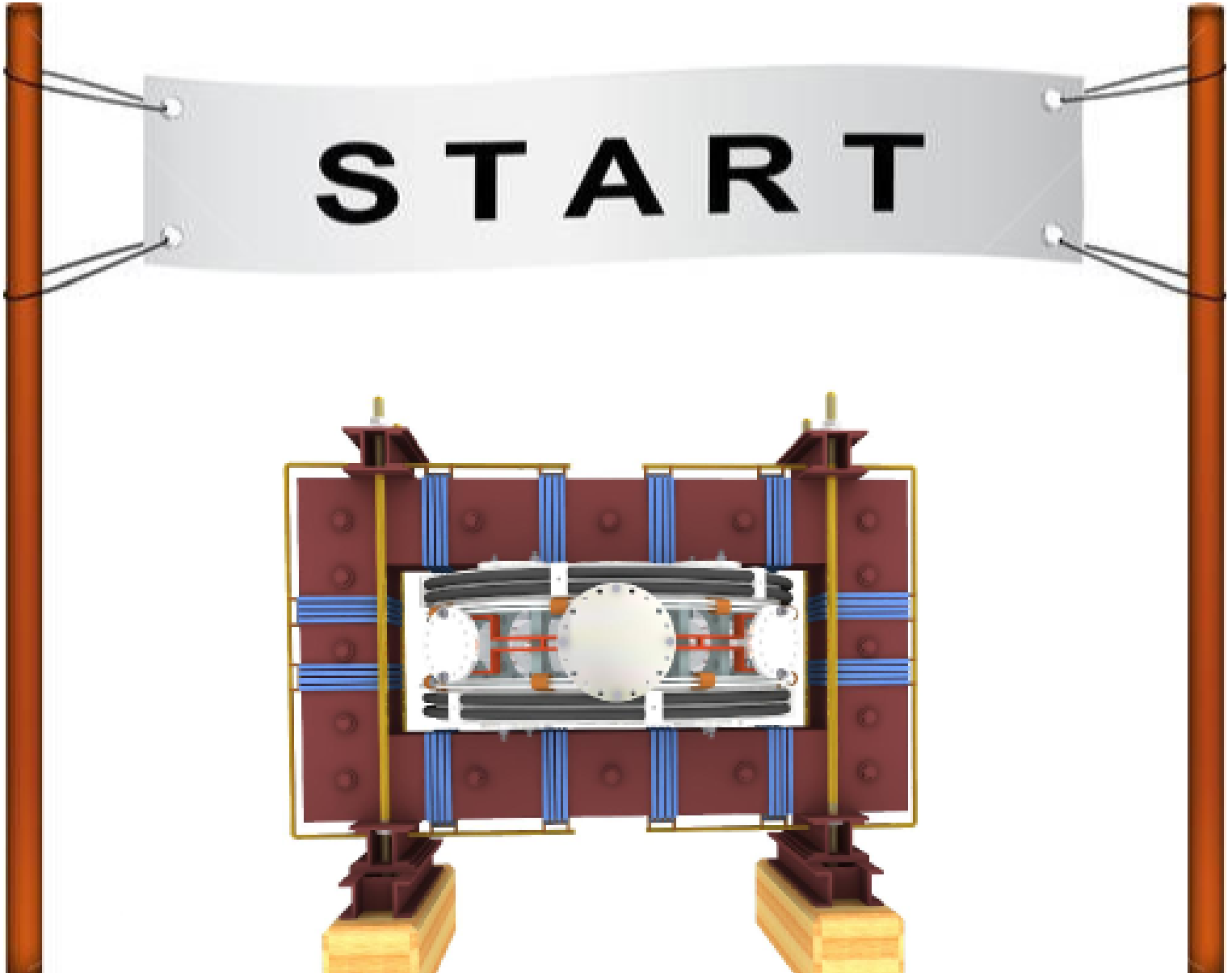
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6 The GOLEM tokamak research (recent issues)

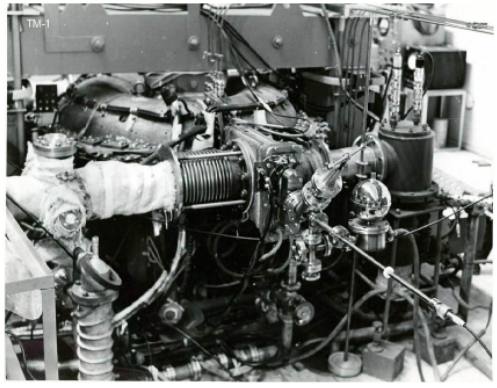
7 Conclusion

Let's start with the tokamak GOLEM - *the smallest tokamak in the World with the biggest controll room*

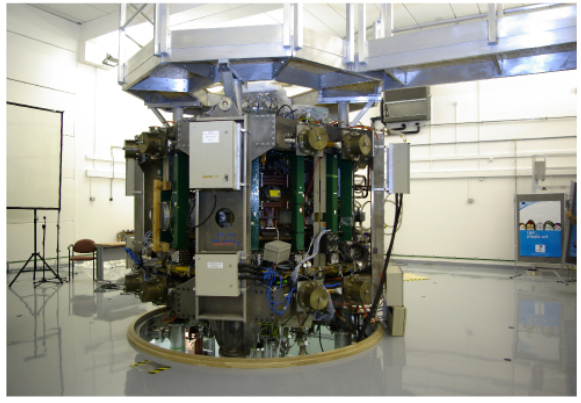


The GOLEM tokamak for education - historical background

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



GOLEM

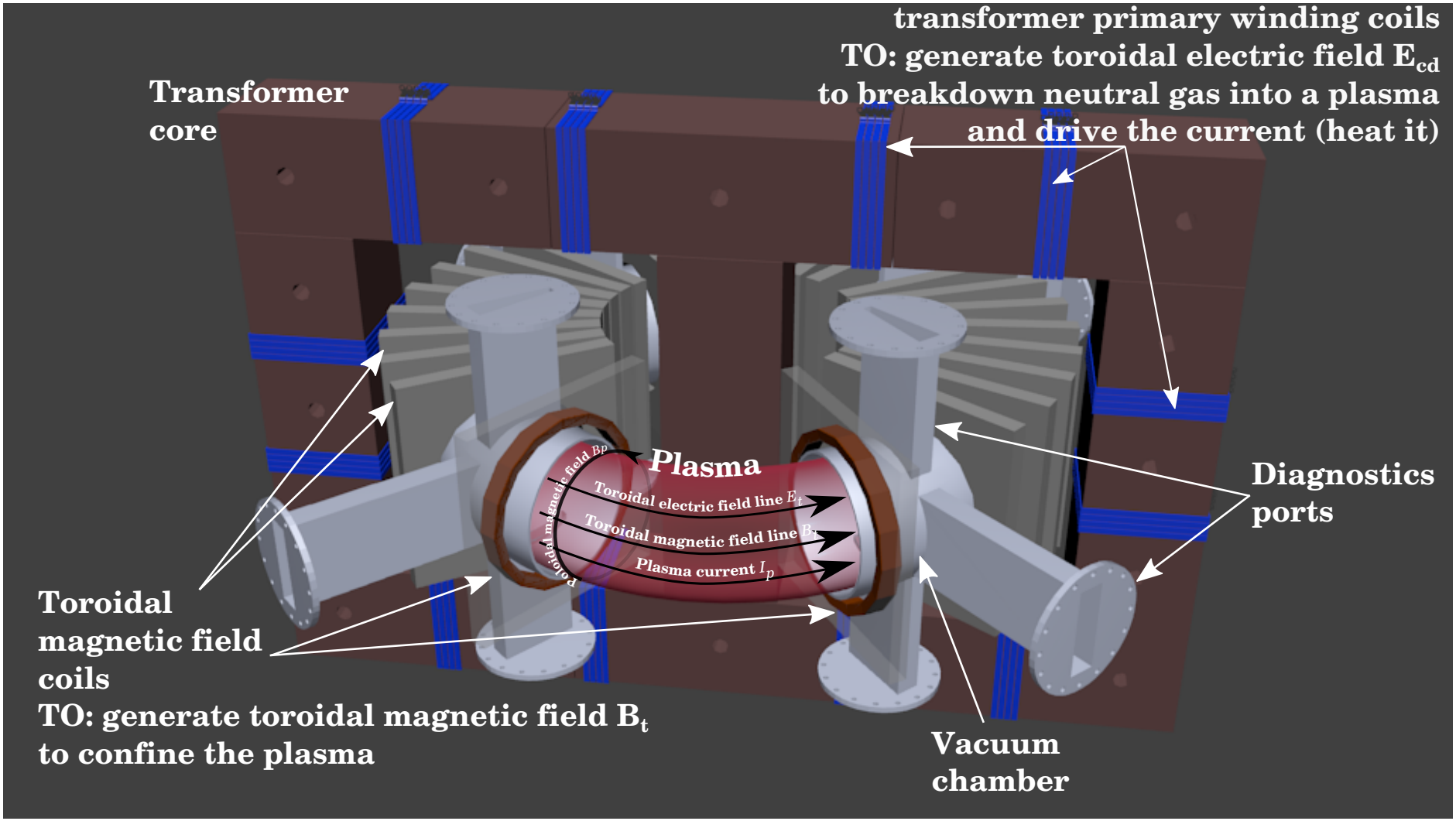
... somewhere, in the ancient cellars of Prague,

there is hidden indeed "infernal" power. Yet it is the very power of celestial stars themselves. Calmly dormant, awaiting mankind to discover the magic key, to use this power for their benefit...



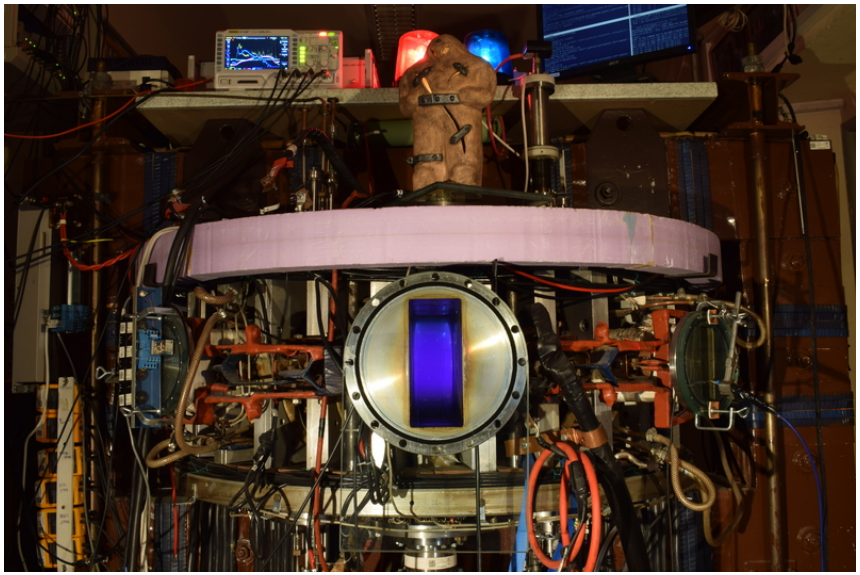
At the end of the 16th century, in the times when the Czech lands were ruled by Emperor Rudolf II, in Prague, there were Rabbi Judah Loew, well known alchemist, thinker, scholar, writer and inventor of the legendary GOLEM - a clay creature inspired with the Universe power that pursued his master's command after being brought to life with a shem, . Golem is not perceived as a symbol of evil, but rather as a symbol of power which might be useful but is very challenging to handle. To learn more of the Golem legend, see e.g. Wikipedia/Golem.

Tokamak (GOLEM) basic concept to confine and heat the plasma



The GOLEM tokamak basic characteristics

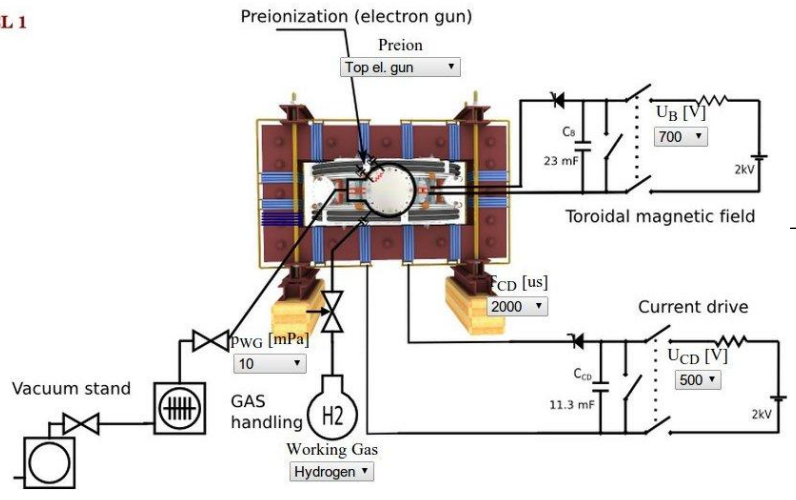
The grandfather of all tokamaks (ITER newsline 06/18)



- Vessel major radius $R_0 = 0.4$ m
- Vessel minor radius $r_0 = 0.1$ m
- Plasma minor radius: $a \approx 0.06$ m
- Maximum toroidal magnetic field $B_t^{max} < 0.5$ T
- Maximum plasma current $I_p^{max} < 8$ kA
- Typical electron density: $< n_e > \approx 0.2 - 3 \times 10^{19}$ m^{-3}
- Effective ion charge: $Z_{eff} \approx 2.5$
- Maximum electron temperature $T_e^{max} < 100$ eV
- Maximum ion temperature $T_i^{max} < 50$ eV

The global schematic overview of the GOLEM experiment

Tokamak technology setup



internet

USER authorization

WWW server

OpenSSH serve

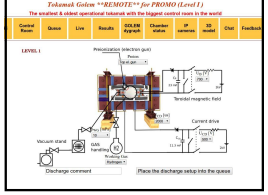
Control PC

OpenSSH server

Virtual control room (remote participation)

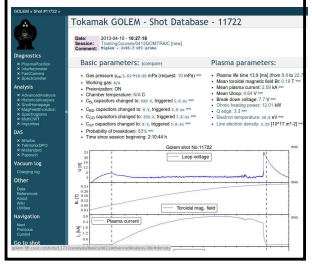
WWW control interface

HTML & PHP scripts



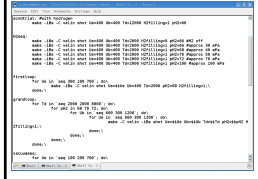
Data presentation

HTML (www pages)



SSH control interface

WINDOWS via putty

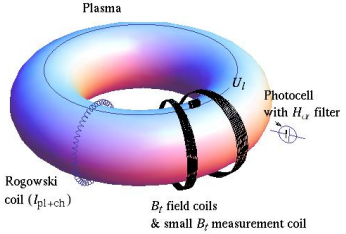


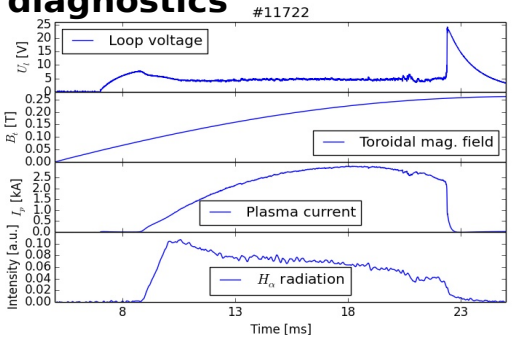
LINUX via ssh
or ssh+X tunnel
(advanced mode)

Data handling

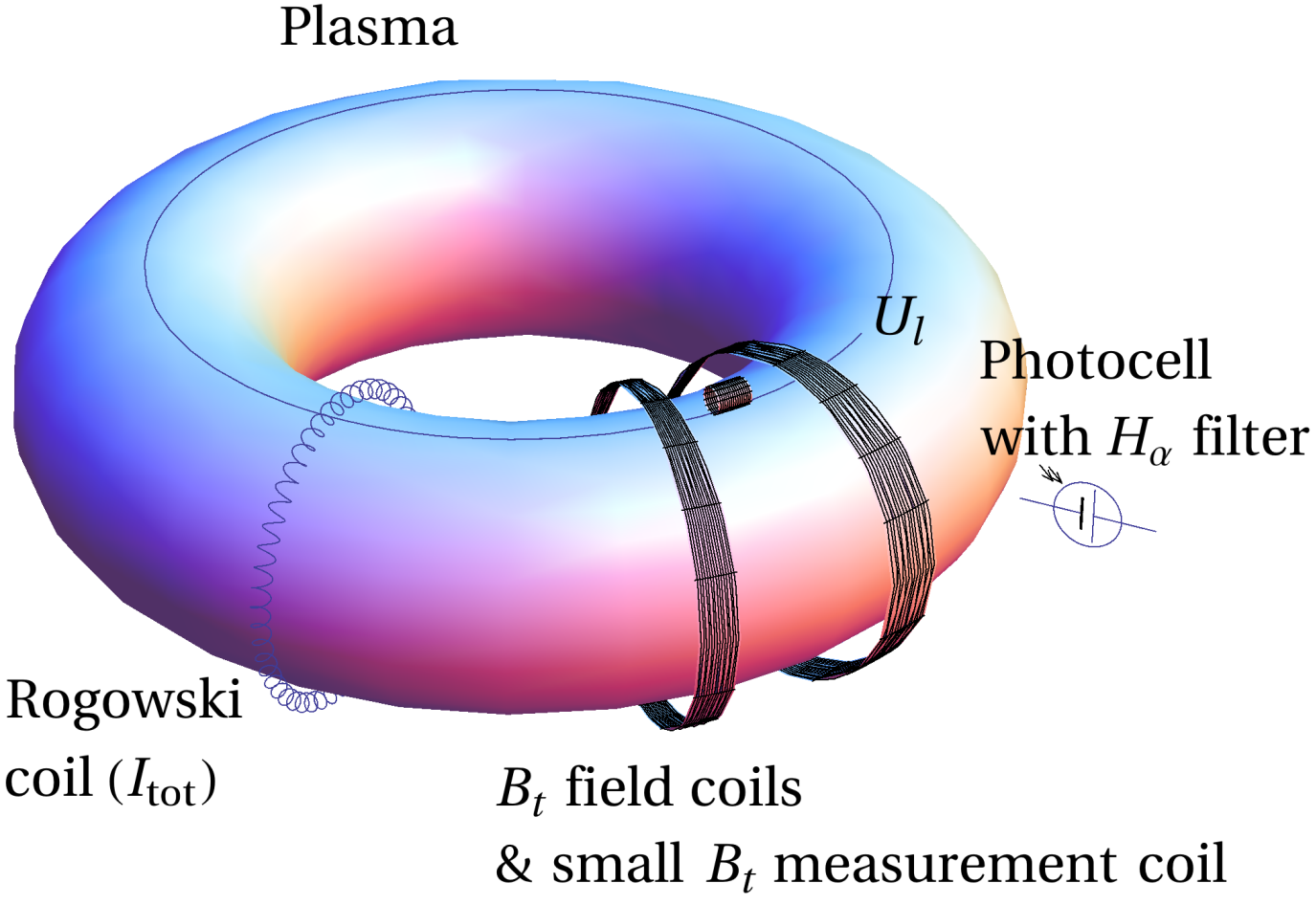
*wget
*gnuplot
*idl
*mathematica
*matlab
*etc...

Basic plasma diagnostics

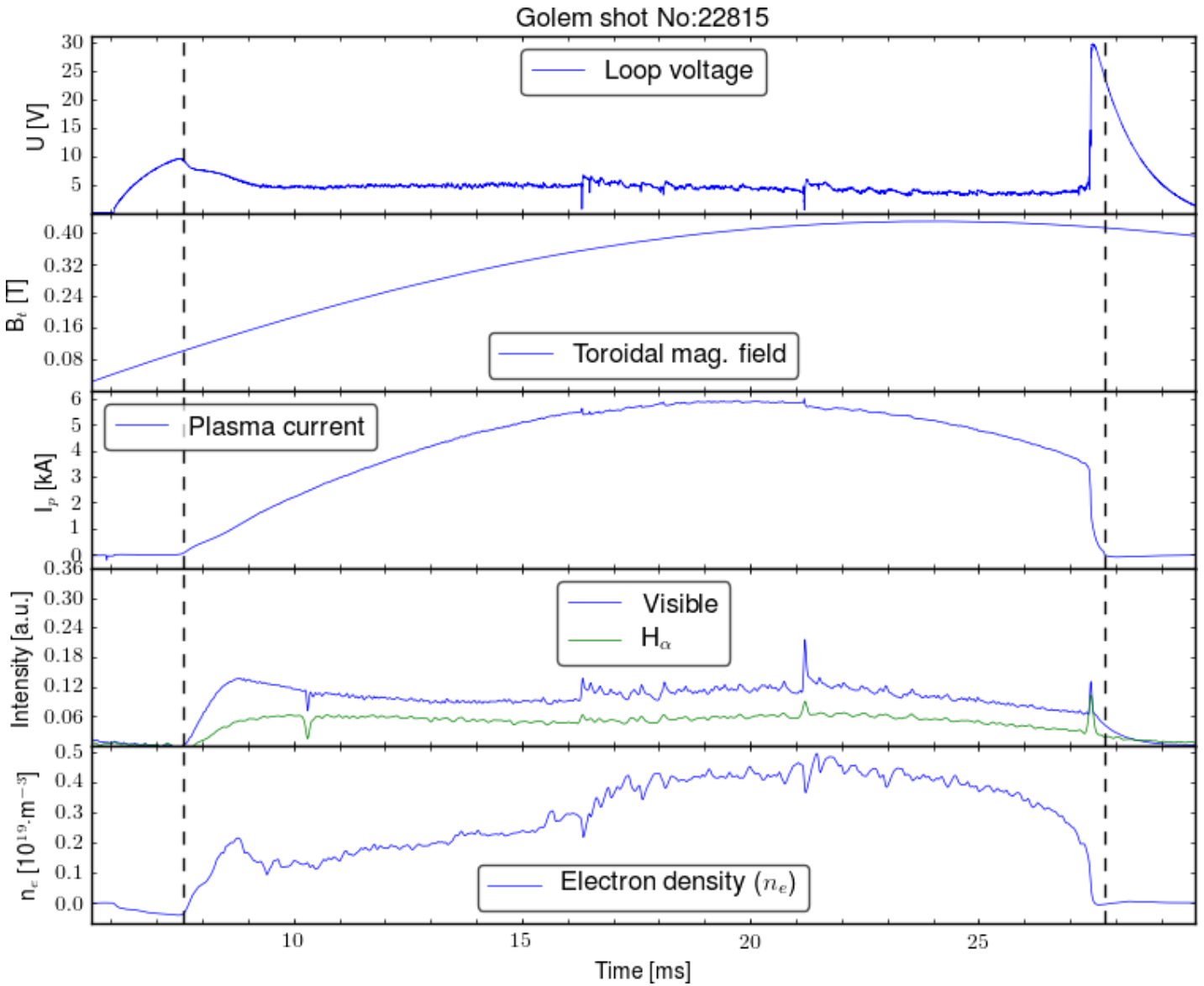




The GOLEM tokamak - standard diagnostics



”Typical”, well executed discharge @ GOLEM



The GOLEM tokamak mission

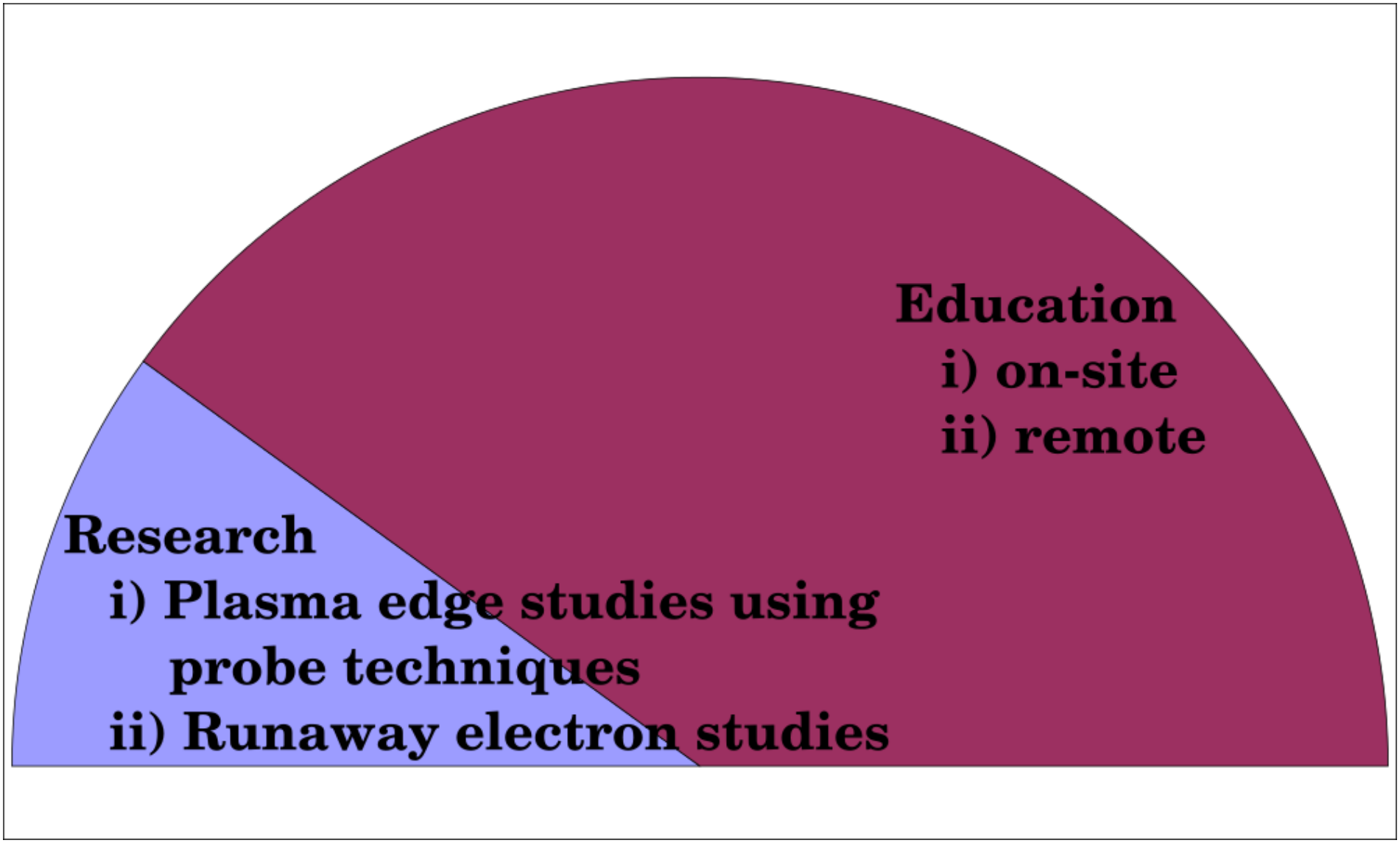


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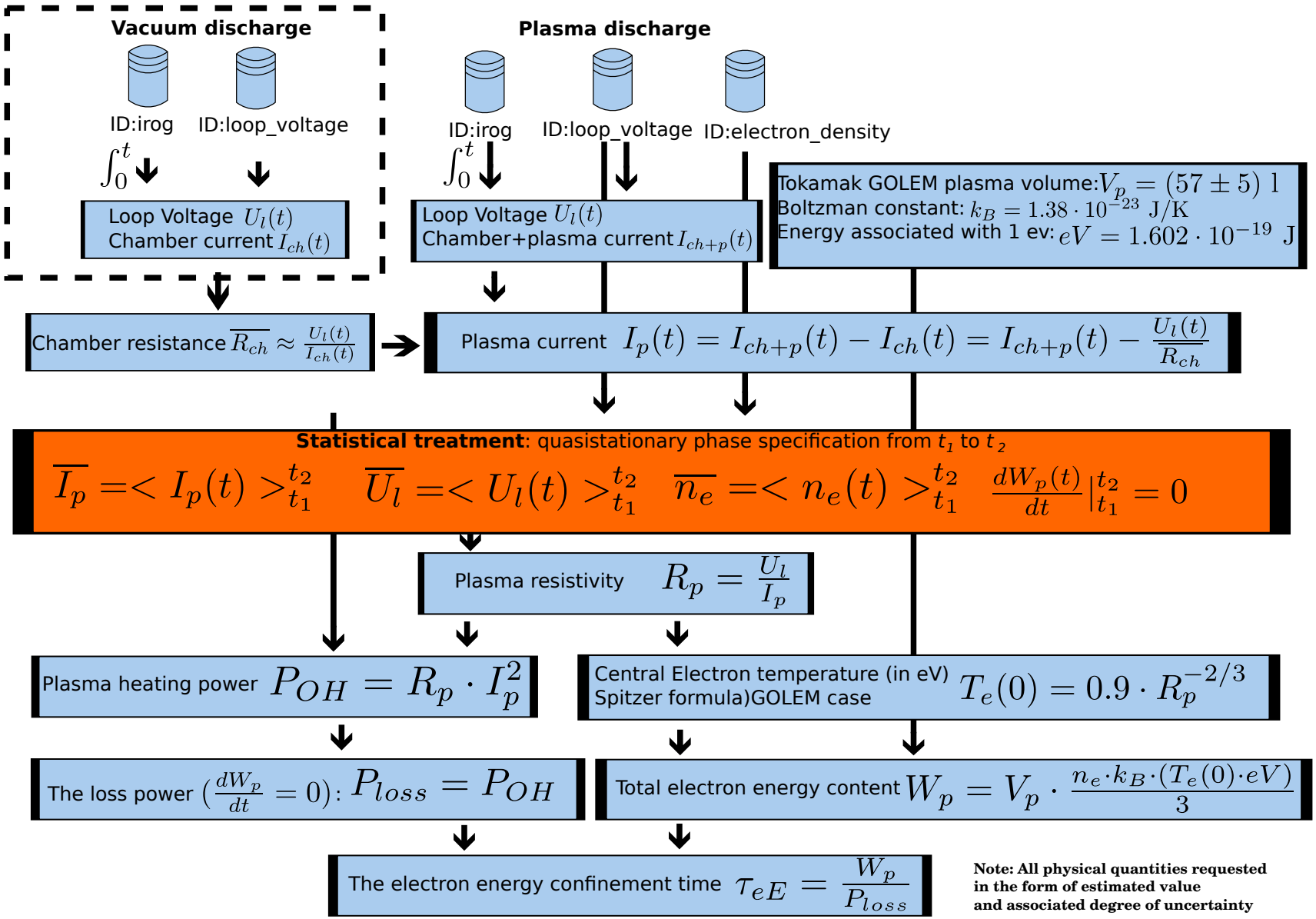
4 Hands on Tokamak experimentation

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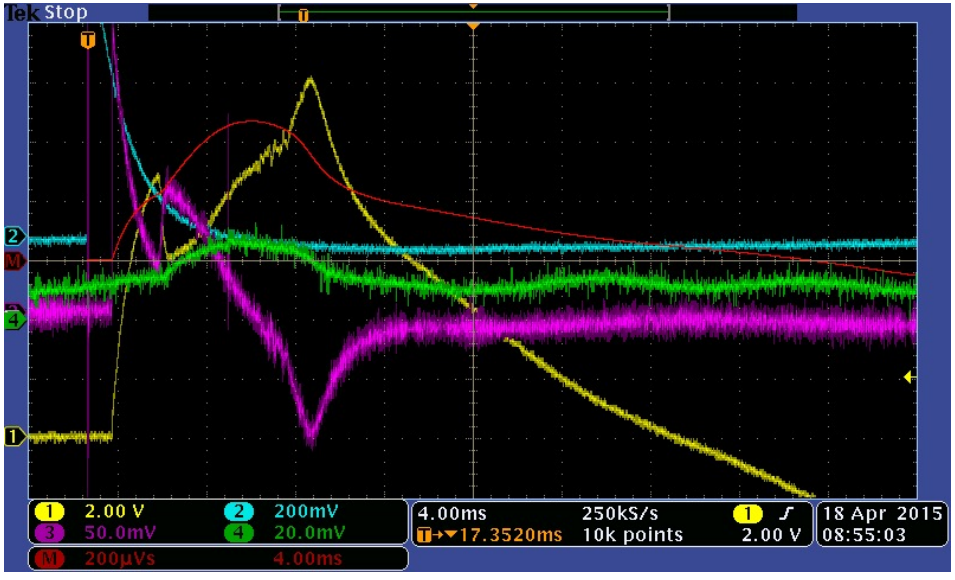
Towards Electron energy confinement time τ_E



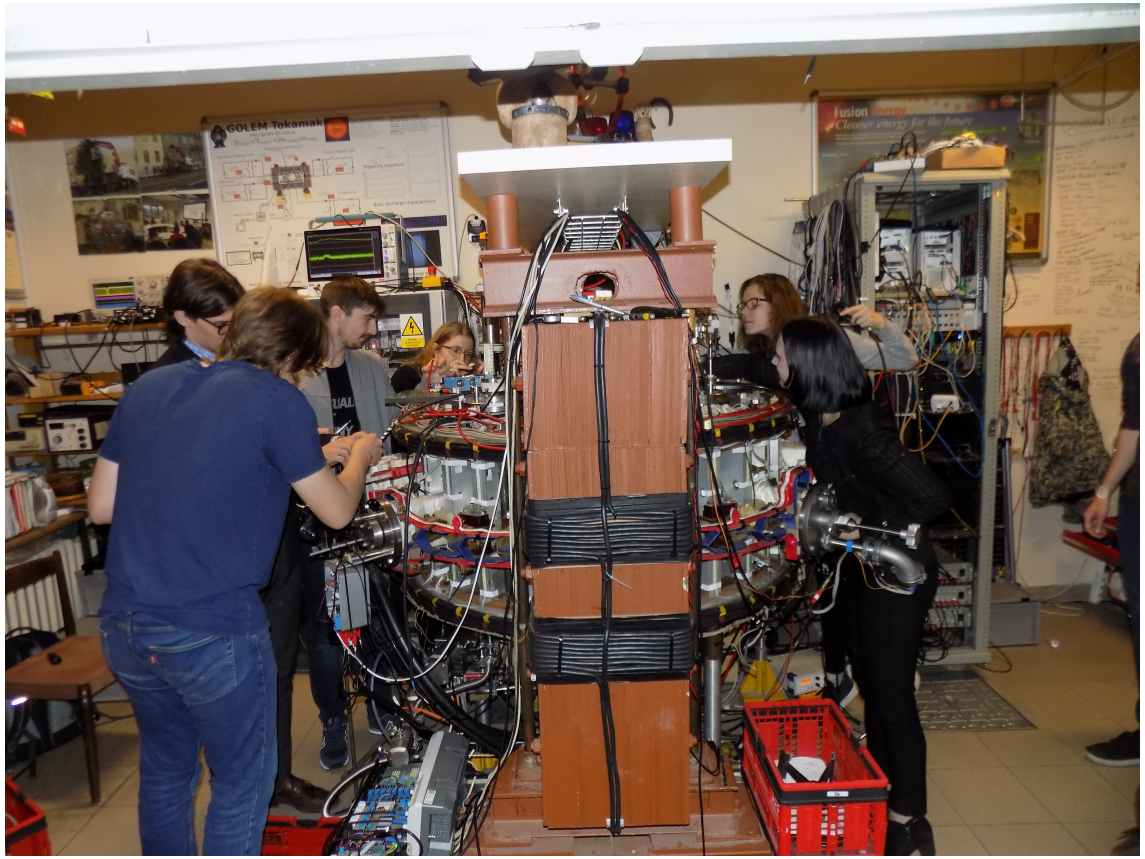
Note: All physical quantities requested in the form of estimated value and associated degree of uncertainty

Hands on the GOLEM tokamak



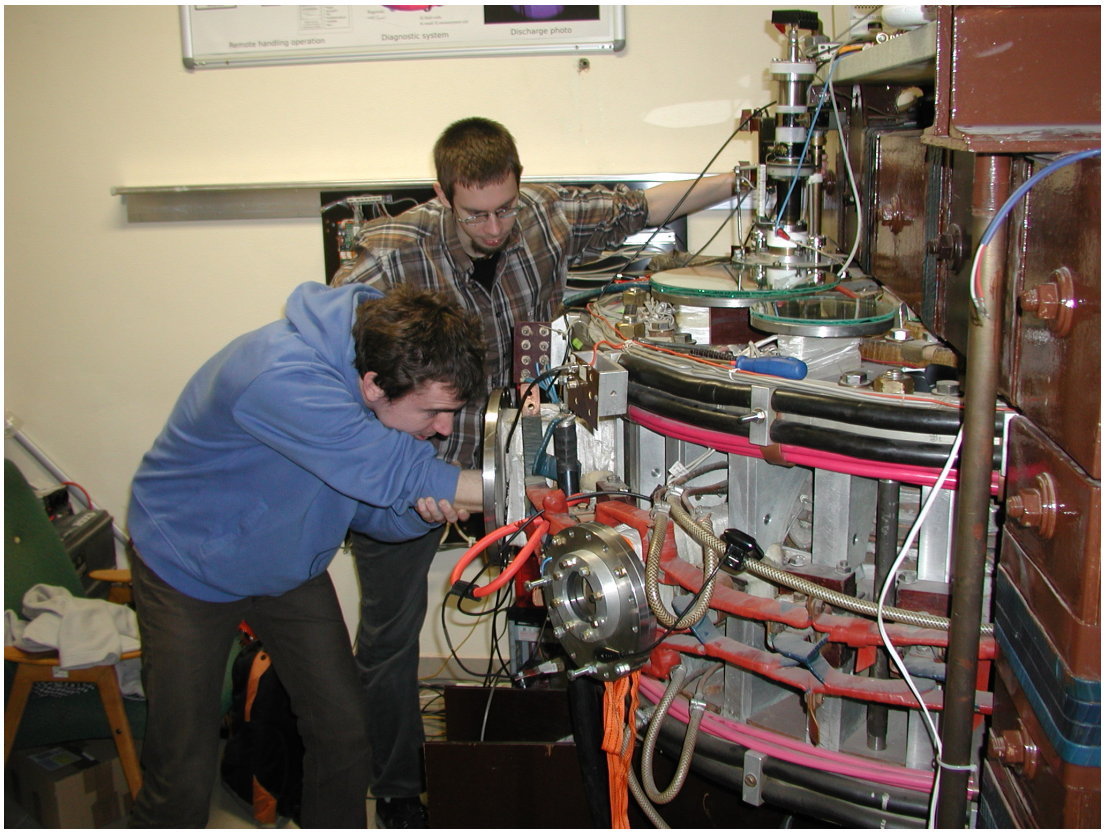


Hands on the GOLEM tokamak



- Laboratory Practice for Basic course of Physics 2015-19 (CT University Bachelor level).
- Advanced plasma training course 2014-19 (CT University Master level).
- Week of scientists 2013-19 (Czech republic High school level).
- International Golem Training Course 2013,2019 (Master and PhD level).

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.

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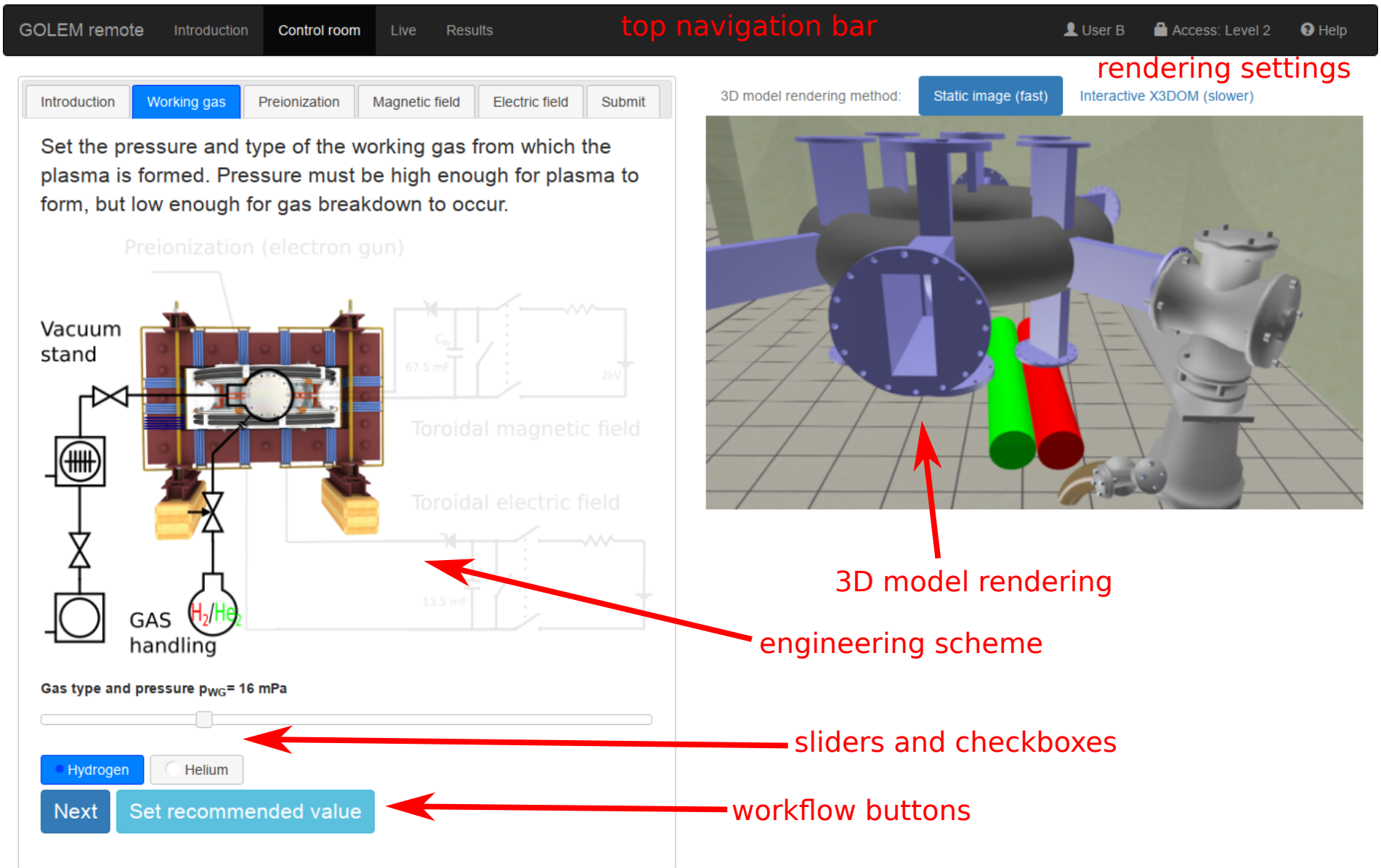
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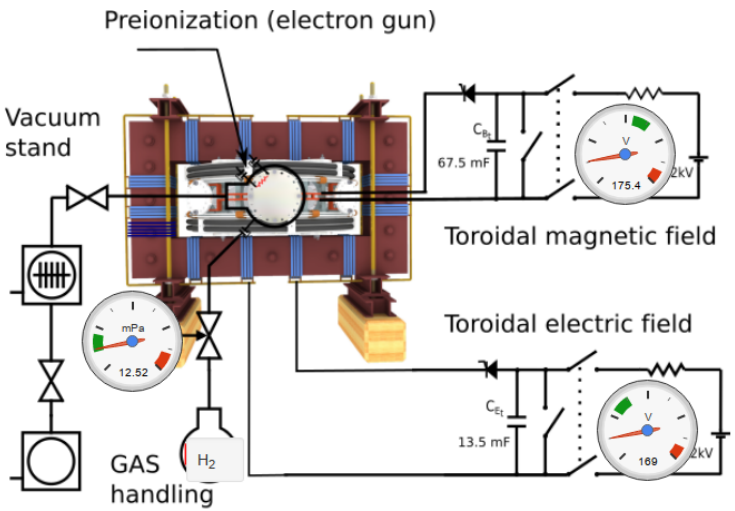
7 Conclusion

Remote control interface of the GOLEM tokamak



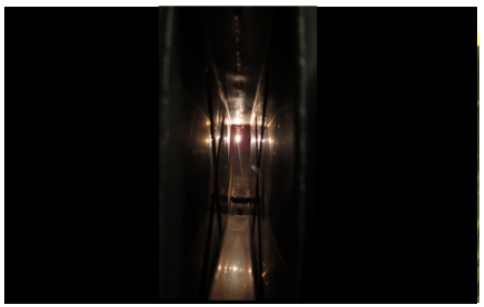
Live real-time view of the experiment

GOLEM remote | Introduction | Control room | **Live** | Results | User B | Access: Level 2 | Help



Charging capacitors, setting working gas pressure

Tokamak chamber camera



Room camera



Discharge request queue

Status	User	Comment	U_{B_t} [V]	U_{E_t} [V]	gas [mPa]
In progress	User A	plasma reference	800	450	16 (H)
Waiting	User A	higher pressure	800	450	20 (H)
Waiting	User B	strong E field	600	500	16 (H)

Shot homepage

GOLEM » Shot #22471 »

Tokamak GOLEM - Shot Database - 22471

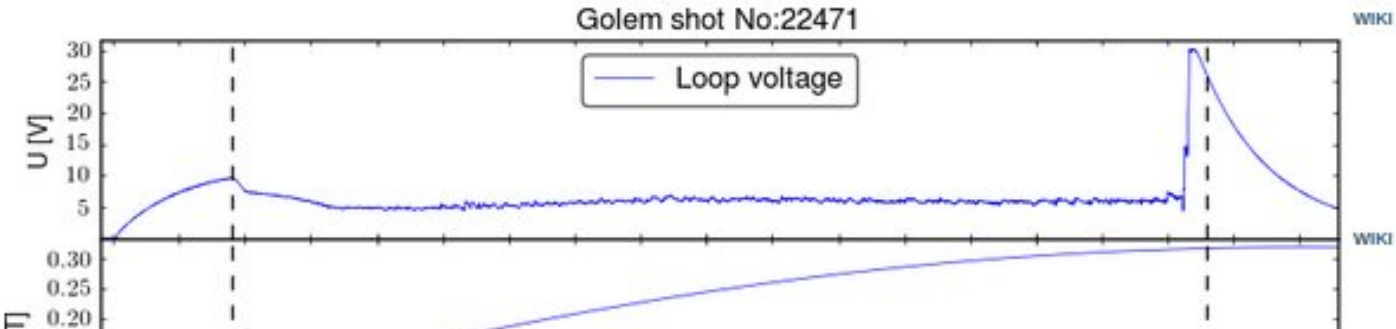
Date: 2016-09-29 - **14:33:57**
Session: TrainingCourses/Universities/Uni_Belgrade.rs/2016/
Comment: `Standard discharge`

Basic parameters: (compare)

- Gas pressure p_{ch}: `0.42`->`20.39` mPa (request: 20 mPa) WIKI
- Working gas: `H`
- Preionization: Upper el. gun
- Chamber temperature: 27.20 C
- C_{B_t} capacitors charged to: `800 V`, triggered `5.0 ms` WIKI
- C_{BD} capacitors charged to: `0 V`, triggered `5.0 ms` WIKI
- C_{CD} capacitors charged to: `400 V`, triggered `6.0 ms` WIKI
- C_{ST} capacitors charged to: `0 V`, triggered `5.0 ms` WIKI
- Probability of breakdown: 85% WIKI
- Time since session beginning: 0:07:50 h

Plasma parameters:

- Plasma life time **14.8** [ms] (from 7.8 to 22.6)
- Mean toroidal magnetic field Bt: 0.23 T WIKI
- Mean plasma current: 3.60 kA WIKI
- Mean Uloop: 5.92 V WIKI
- Break down voltage: 9.6 V WIKI
- Ohmic heating power: 21.33 kW
- Q edge: 2.9 WIKI
- Electron temperature: `41.1` eV WIKI
- Line electron density: `5.52` [10^17.m^-2] WIKI



Diagnostics
- ✓ Interferometer
- ✓ Spectrometer
- ✕ FastCamera
- ✓ HXR

Analysis
- ✓ ShotHomepage

DAS
- ✓ TektronixDPO
- ✓ NIstandard
- ✓ Papouch_St
- ✓ Papouch_Ko
- ✓ NIoctopus

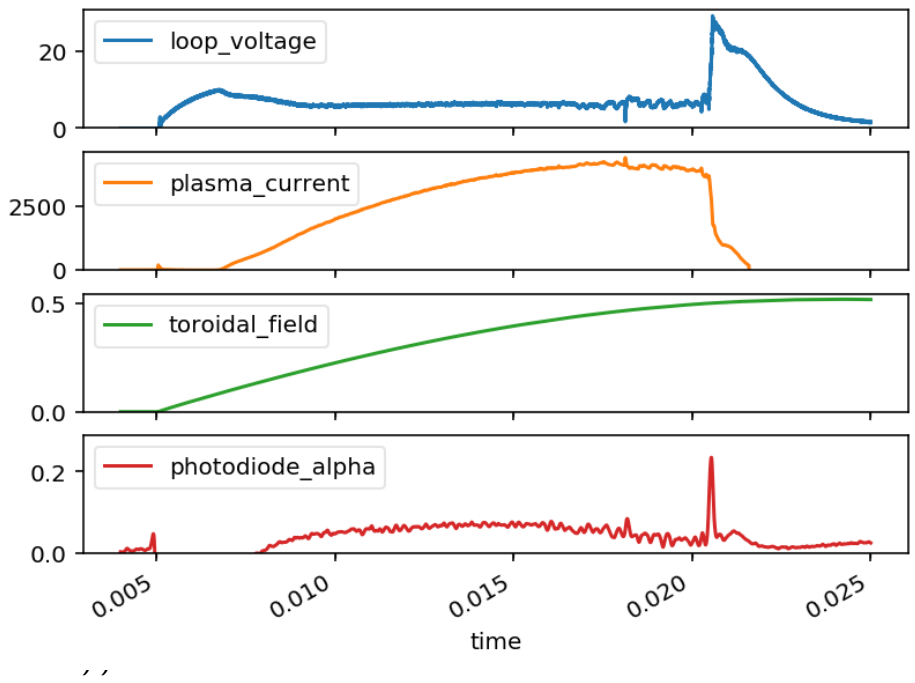
Vacuum log

Other
- Data
- References
- About
- Wiki
- Utilities

Navigation
- Next
- Previous

Remote data access (using a few high level functions)

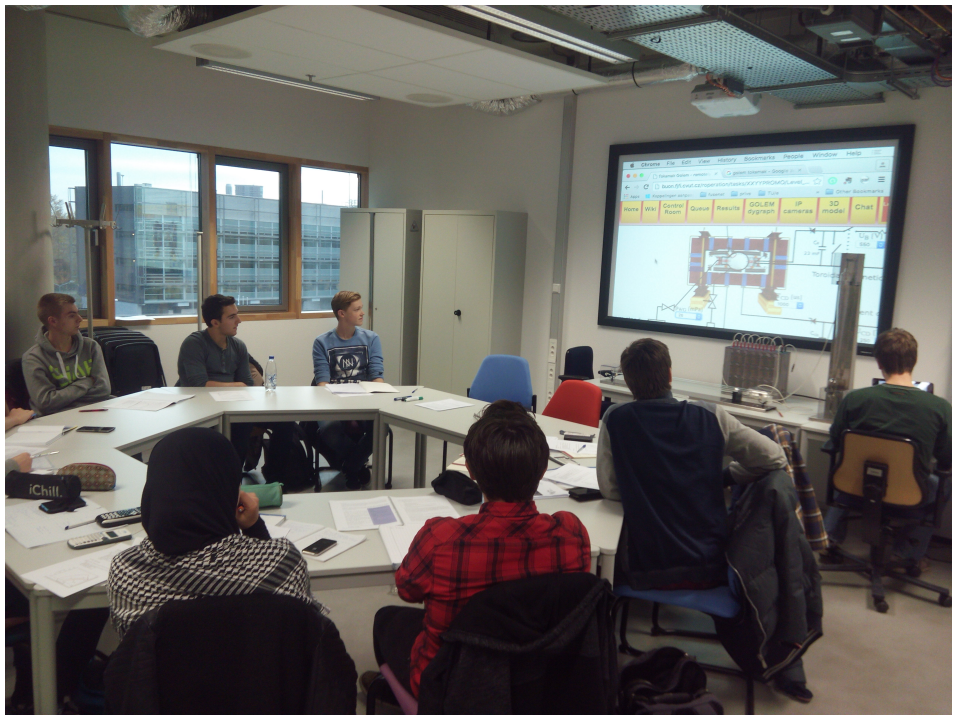
```
import pandas as pd
import matplotlib.pyplot as plt
URL = 'http://golem.fjfi.cvut.cz/utils/data/{}/
# function for reading 1D y(t) signals
def read_signal1d(shot_number, signal_id):
    url = URL.format(shot_number, signal_id)
    return pd.read_table(url,names=['time',sign
                         index_col='time')
# read the specified signals
shot_no = 29395
U_l = read_signal1d(shot_no, 'loop_voltage')
I_p = read_signal1d(shot_no, 'plasma_current')
P_OH = U_l*I_p
# vectorized, time-aligned operation
B_t = read_signal1d(shot_no, 'toroidal_field')
H_a = read_signal1d(shot_no, 'photodiode_alpha'
# combine into a data frame table
df = pd.concat([U_l, I_p, B_t, H_a], axis='colu
# plot the data table in subplots from 4 to 25
df.loc[4e-3:25e-3].plot(subplots=True, ylim=(0,
plt.show()
# display the figure in a window
```



Available topics

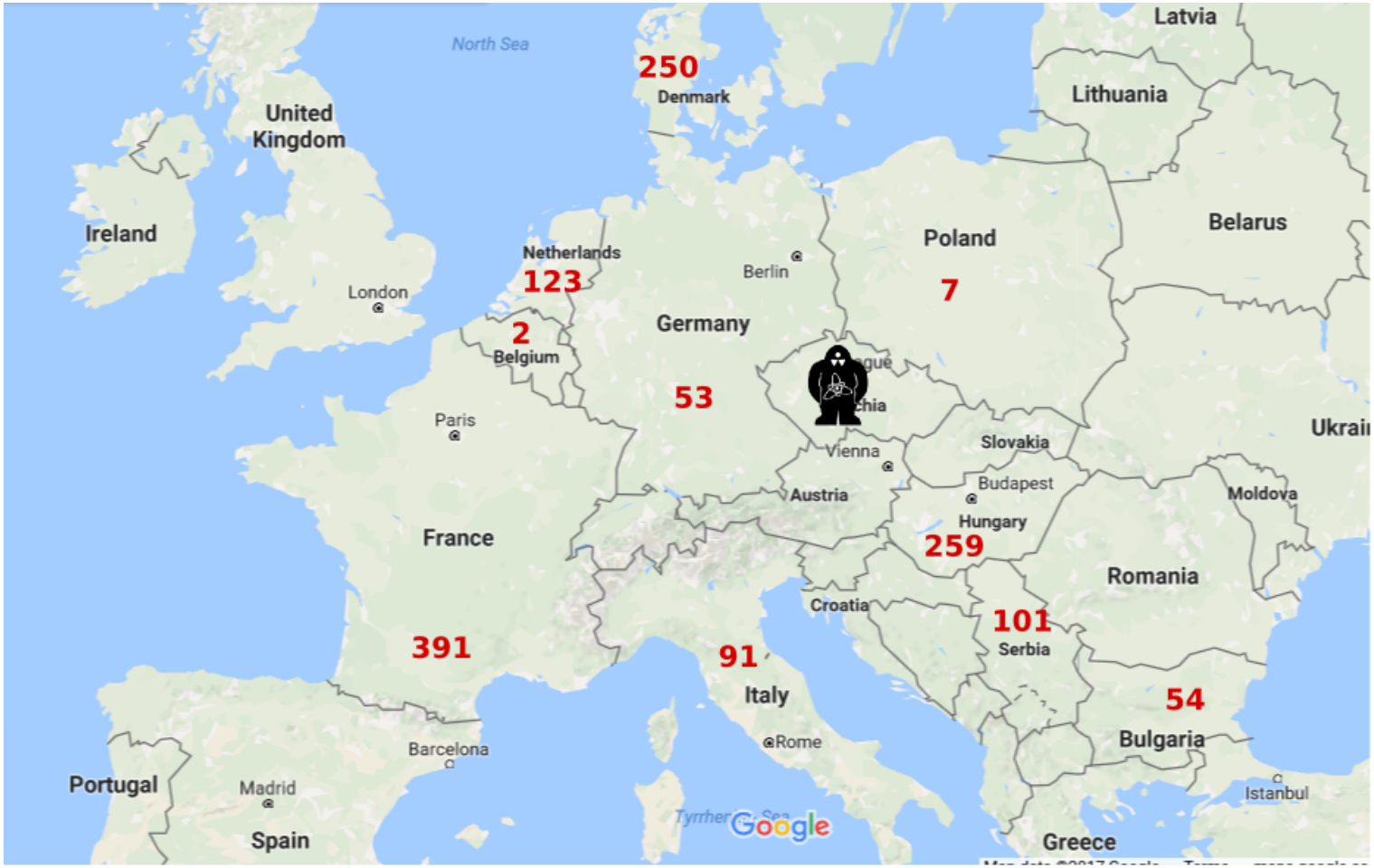
- Level 0 "a game/playground"
- Level 1 "basic"
  - Breakdown studies
  - Energy confinement time τ_E
  - $\mathbf{q} = \mathbf{2}$ disruptions
- Level 2 "data mining"
  - Neo-Alcator confinement scaling law
  - Machine learning
- Level 3 "advanced"
  - Isotopic studies

Remote control 2009-2019 inventory



- Demonstrations: Ghent University 09; Bochum University 13; Garching 13; Lemvig High School 14; Instituto Tecnologico Costa Rica 10; Armidale University 17.
- Training courses: French Training Course & EM 12-14,16-19; Bangkok 16-19; TU Eindhoven 11,15-19;TU Kobehaven 14,15,18;Grenoble TU 15, University of Belgrade 15-18; BUTE Budapest 10,12-18; University of Padova 14,16,18; TU Torino 16-18, St. Peterburg University 18-19. Kharkov University 19
- Workshops Kiten: 14,16,18; Observatorium Valasske Mezirici 14; Islamabad 14.

Remote discharges over the Czech borders (up to 2017)



+ IN ~ 10, + PK ~ 70, + OTHERS ~ 100

Σ(09/12-02/17)~1500

Fee: postcard from the venue of remote measurements



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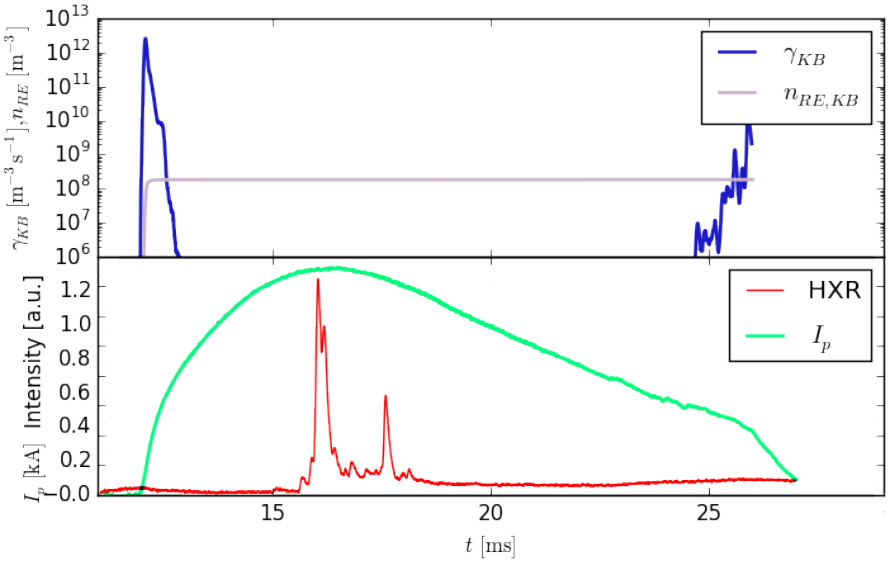
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REs@GOLEM: A basic observation

- A new NaI(Tl) 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)



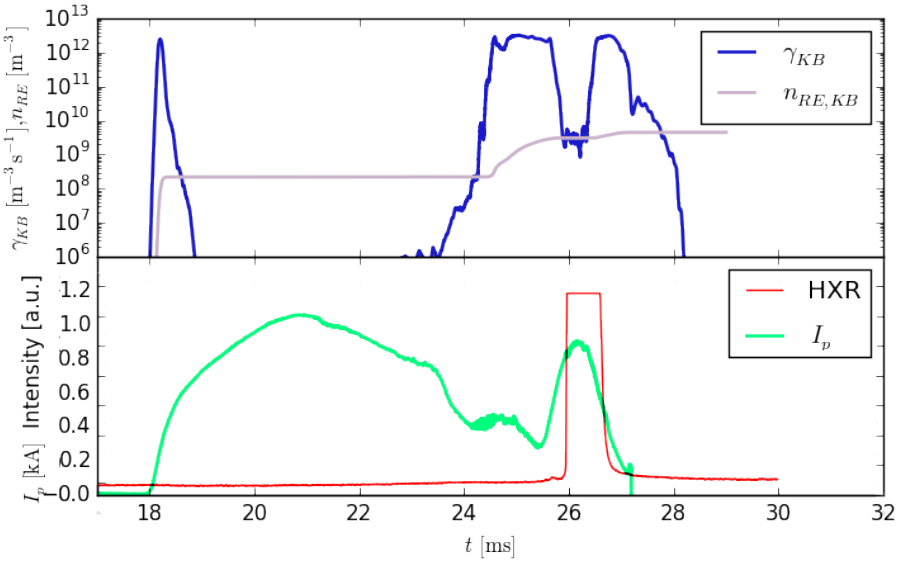


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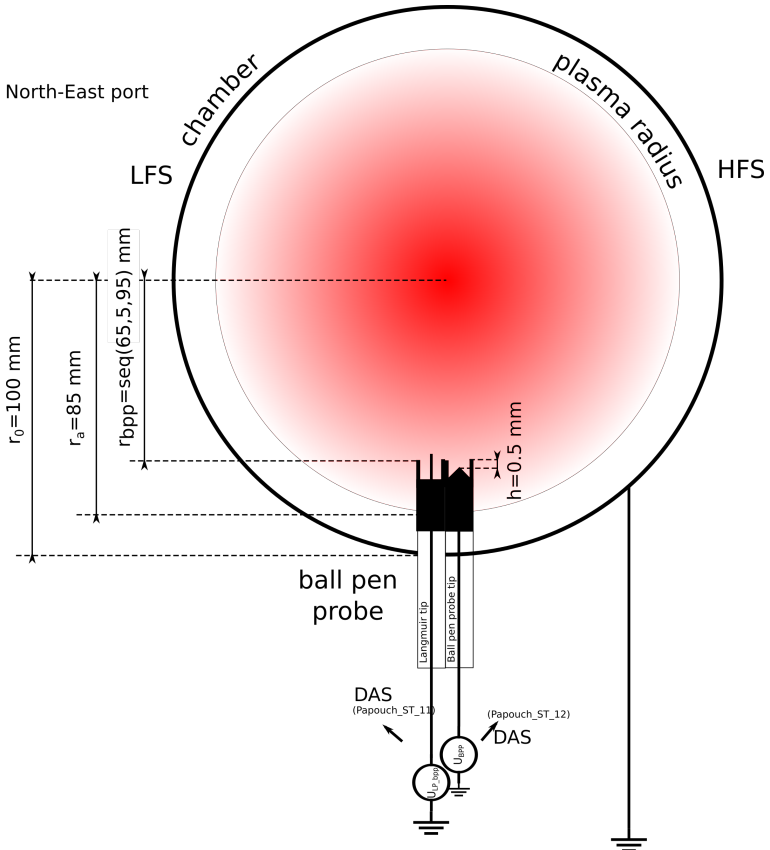
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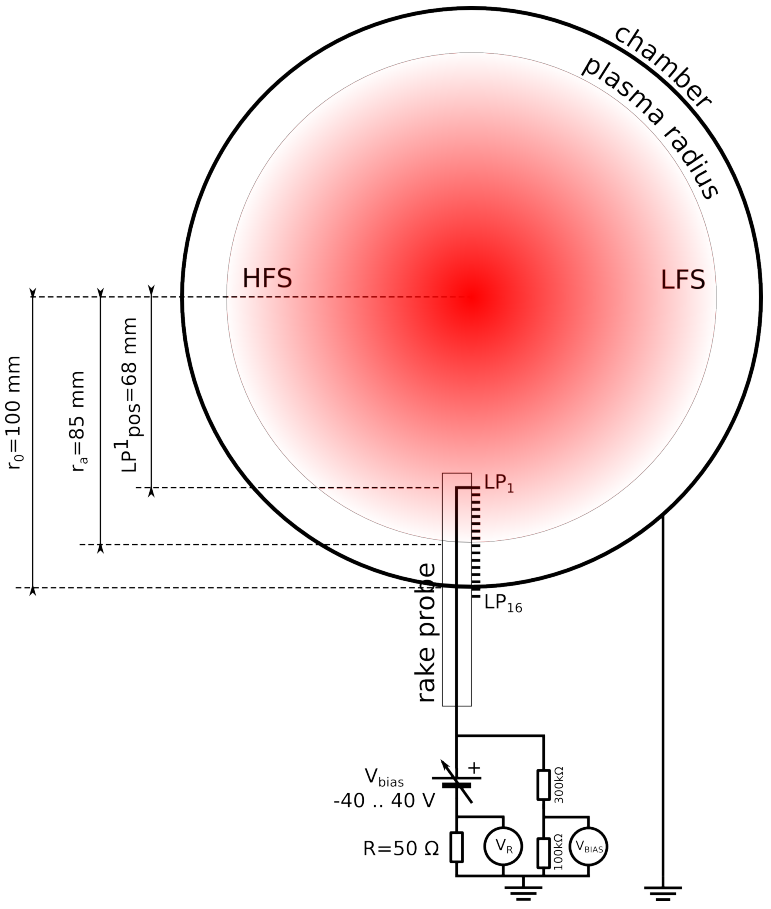
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Electrostatic probes@GOLEM



Combined Ball-pen probe and Langmuir probe @ North-East-Down port



Double rake probe @ South-East-Down port

Probes@GOLEM: Empirical Parametrization of the GOLEM data on the shot-to-shot basis

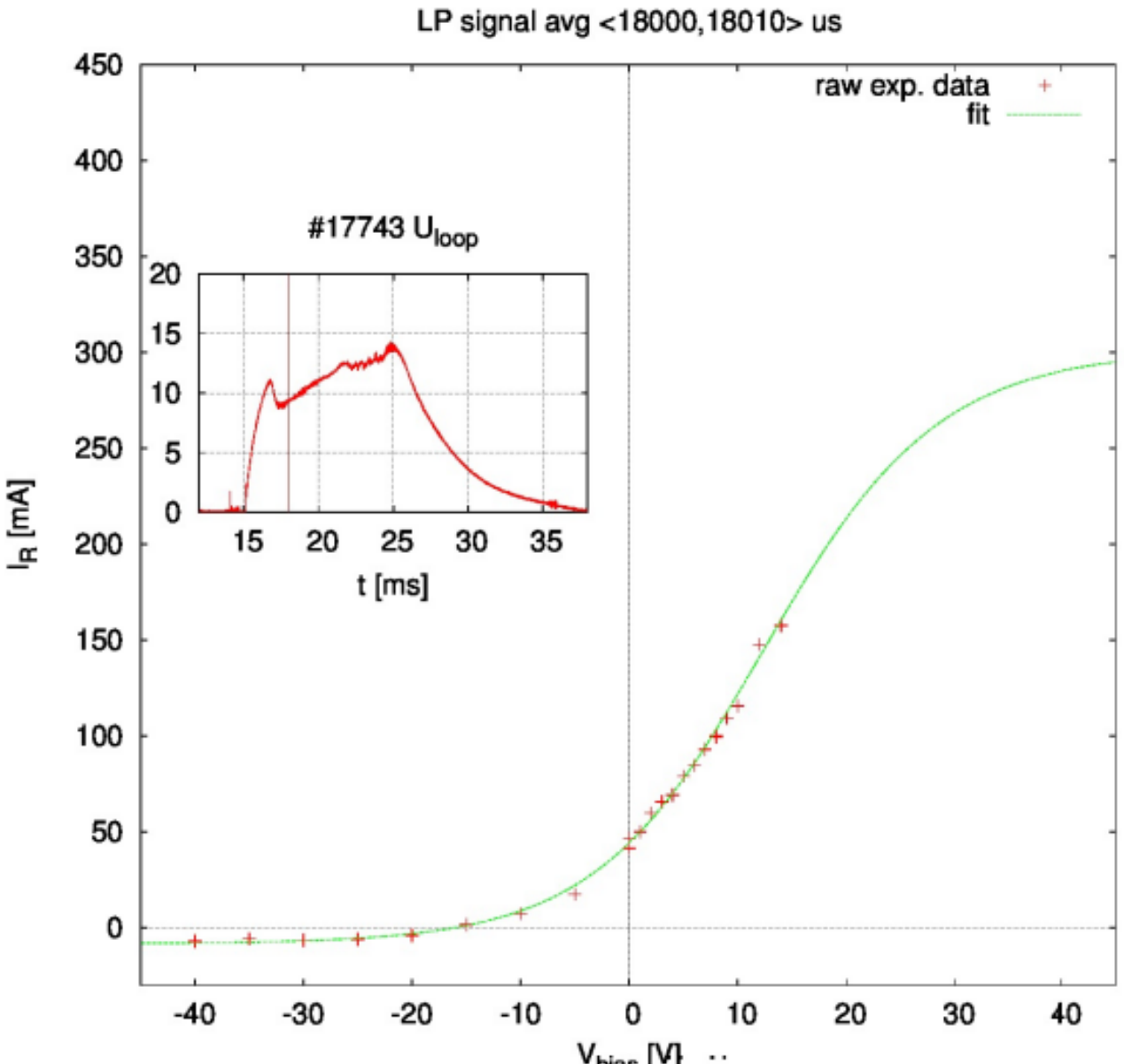


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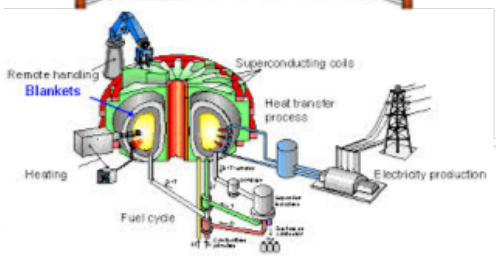
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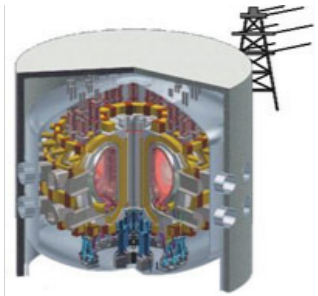
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A Roadmap to the Fusion Power Plant

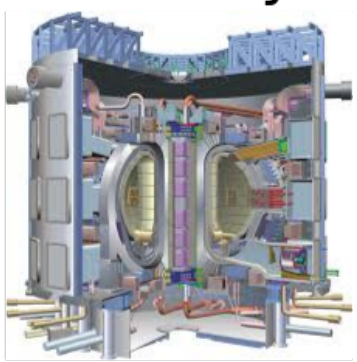
COMMERCIAL
POWER PLANT
???







DEMO (2044?-)
Mission: fusion electricity to the grid



ITER (WORLD)
2025?-
Mission: ~ 400s 500 MW @ Q=10



JET (EU)
1984-present
World record (1997): ~ 2s 16 MW @ Q=0.67

Education importance



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