The tokamak GOLEM contribution (2x) ..cont.

Vojtěch Svoboda
on behalf of the GOLEM tokamak team

December 13, 2019

http://golem.fjfi.cvut.cz/EXF2

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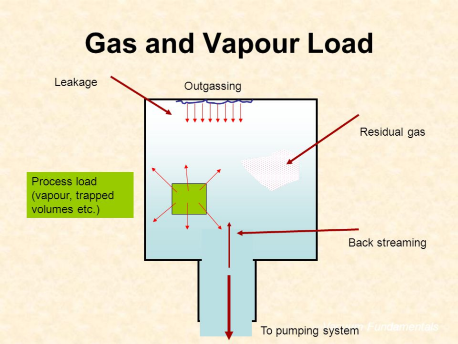
Vacuum IDEAL pump down basic theory

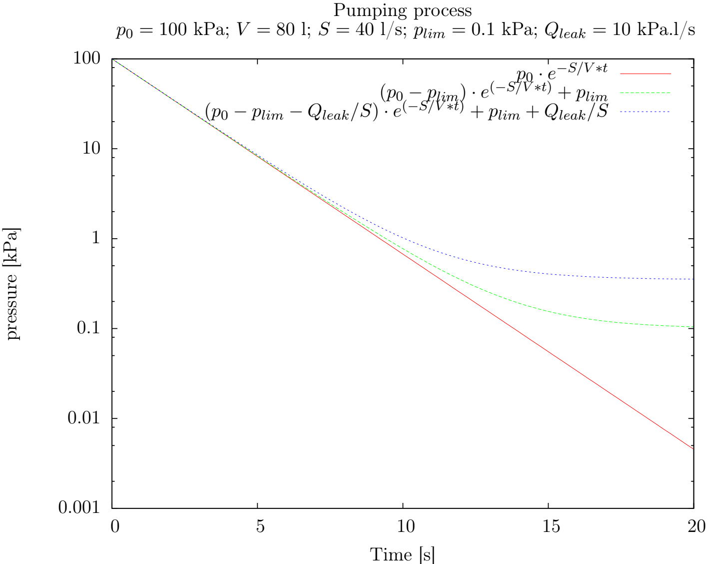


credit:[Nash, 2015]

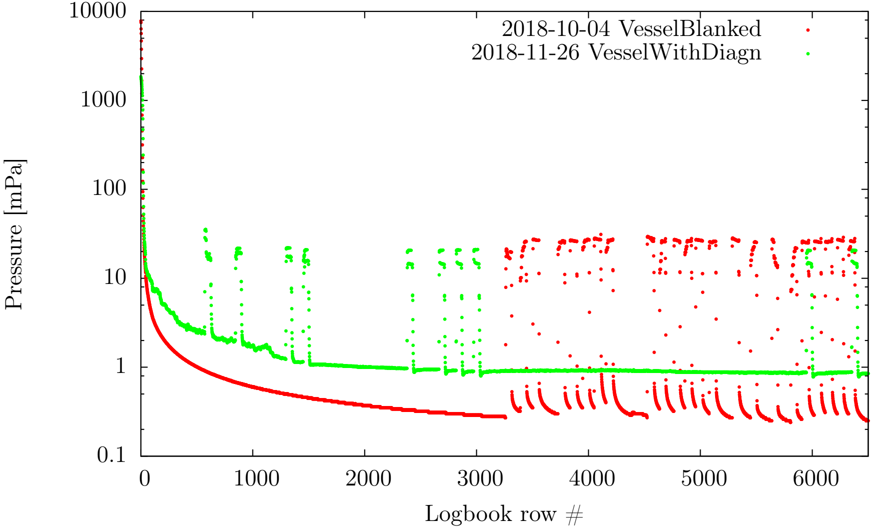
- Volume V [l].
- Pumping speed S [l/s].
- pressure $p(t)$ [Pa].
- initial pressure p_0 [Pa].
- Basic pump-down equation: $V\frac{dp}{dt} = -S \cdot p$.

- Basic pump down time evolution: $p(t) = p_0 \cdot e^{-S/V*t}$
- .. with p_{lim} limite pressure: $p(t) = (p_0 - p_{lim}) \cdot e^{(-S/V*t)} + p_{lim}$
- .. with Q_{leak} leakage:
  $p(t) = (p_0 - p_{lim} - Q_{leak}/S) \cdot e^{(-S/V*t)} + p_{lim} + Q_{leak}/S$

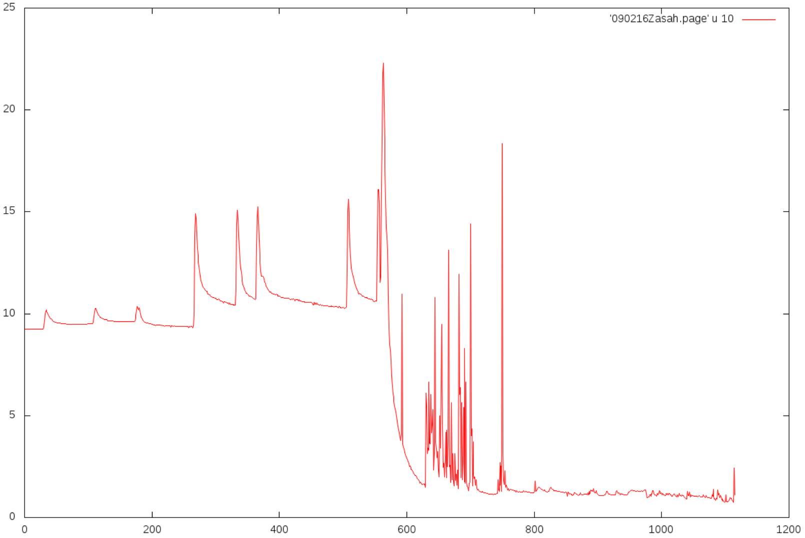
Pump down process - model



Vacuum condition after a DAS addition



Vacuum leakage hit



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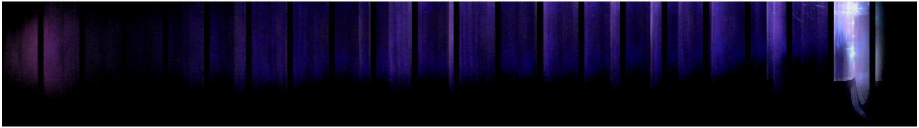
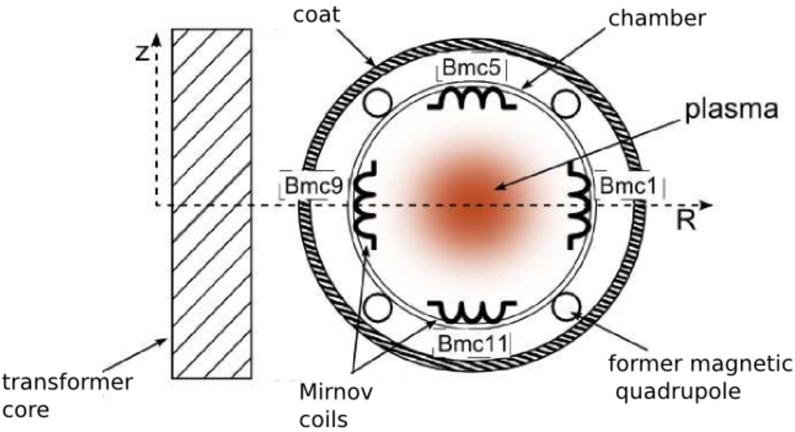
Problem

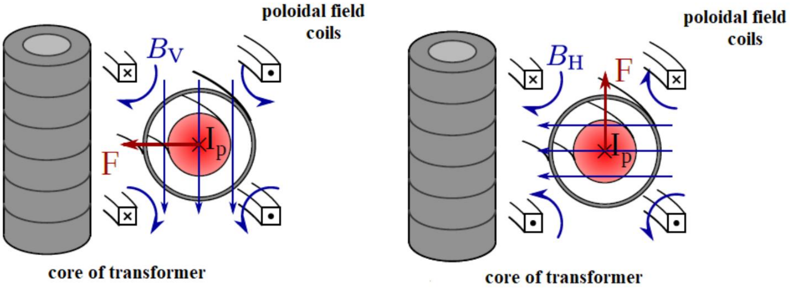


Plasma position /magnetic/ diagnostics



credit:[Kocman, J., 2015]

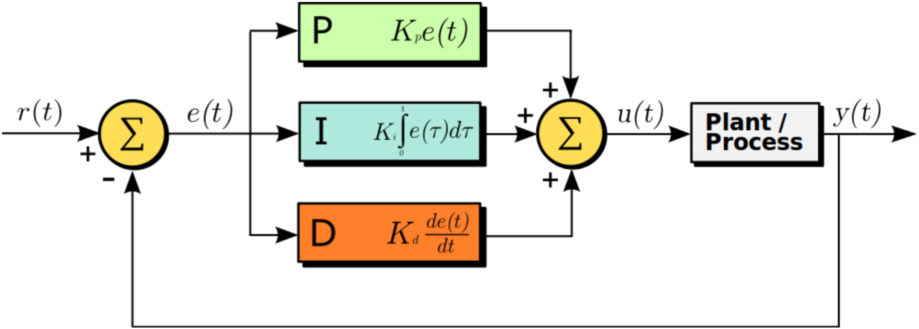
Plasma position stabilization



$$\vec{F} \approx \vec{I}_p \times \vec{B}$$

credit:[Kocman, J., 2015]

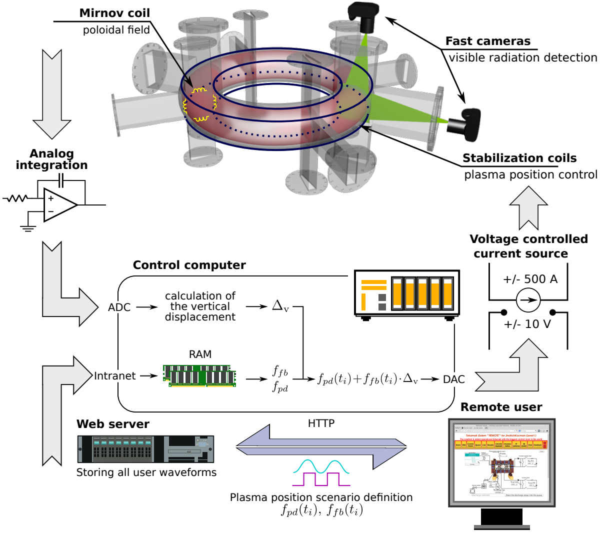
PID



credit:[Wikipedia contributors, 2018]

- $r(t)$: desired setpoint.
- $y(t)$: measured process variable.
- $e(t)$: error value.
- $u(t)$: control variable.

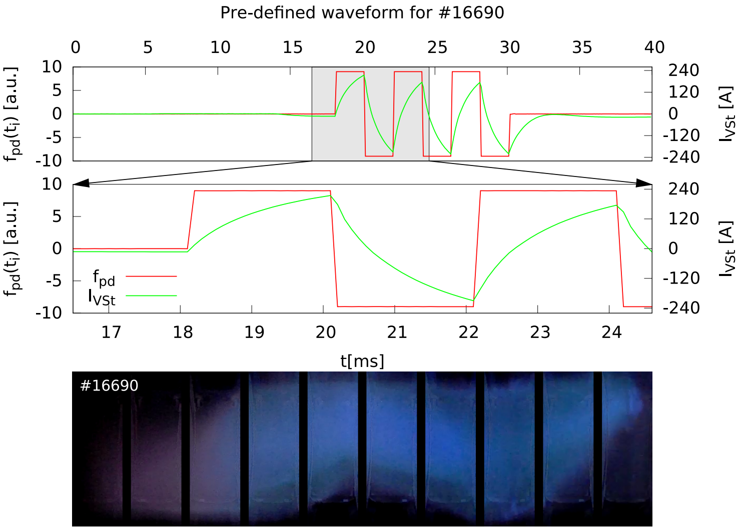
Plasma position stabilization



credit:[Svoboda et al., 2015]

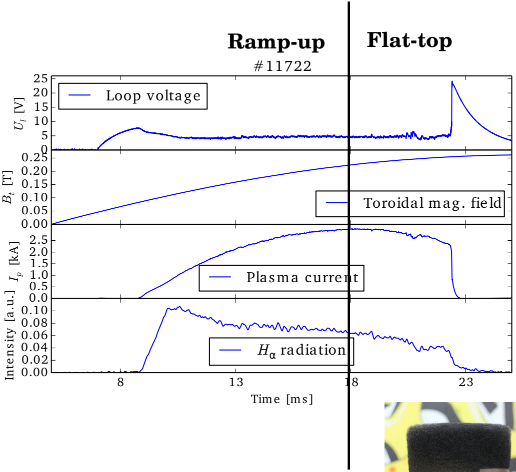
Plasma stabilization ON/OFF

Plasma DisStabilization :-)



credit:[Svoboda et al., 2015]

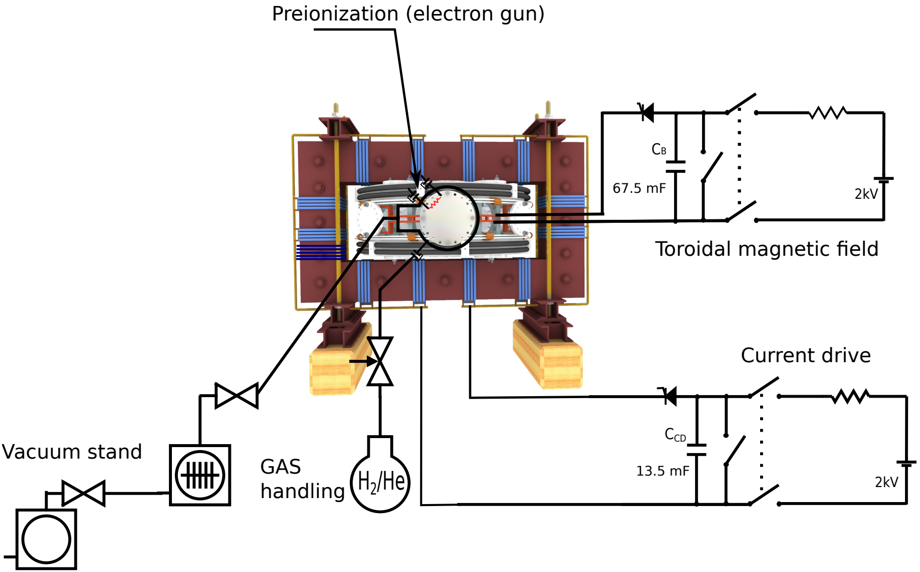
GOLEM horizons



Transformer primary current control

Gas puff control

Tokamak GOLEM - schematic experimental setup



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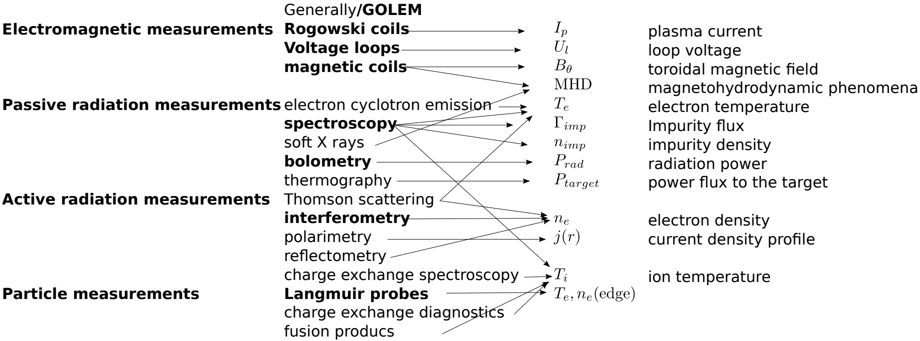
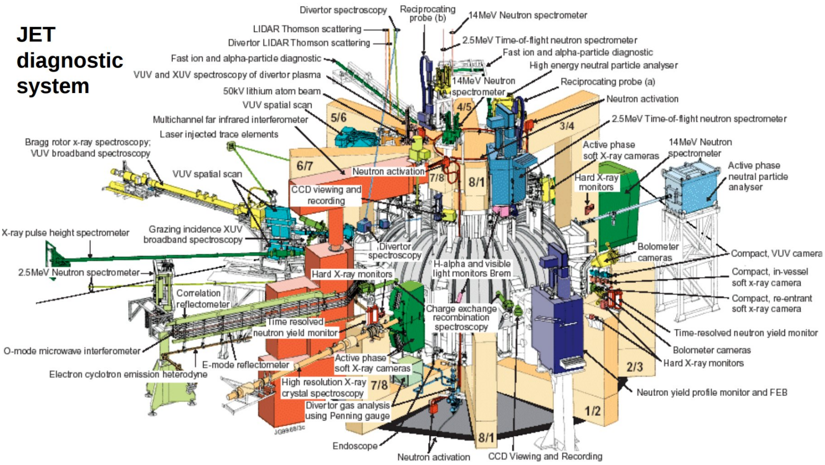
Diagnostics of fusion plasmas - an overview



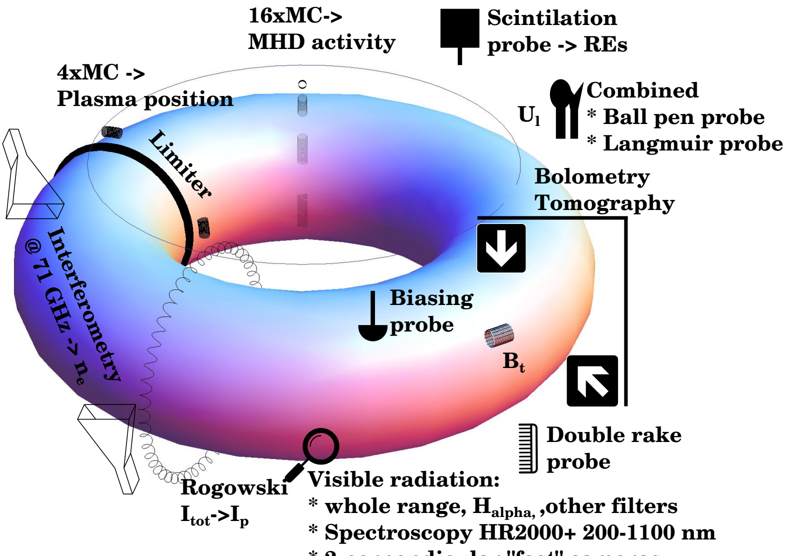
credit:[H.-W.Bartels at al., 1993]

JET tokamak - diagnostic overview

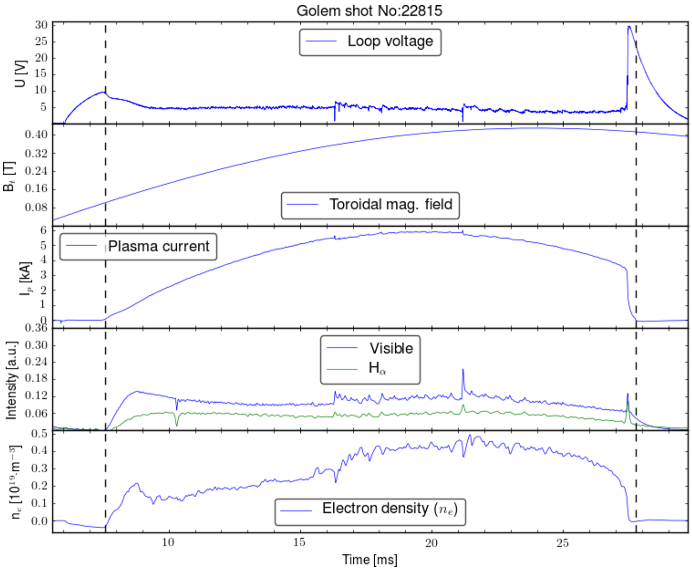


credit:[F4E, 2007]

The GOLEM tokamak - standard diagnostics



"Typical", well executed discharge @ GOLEM



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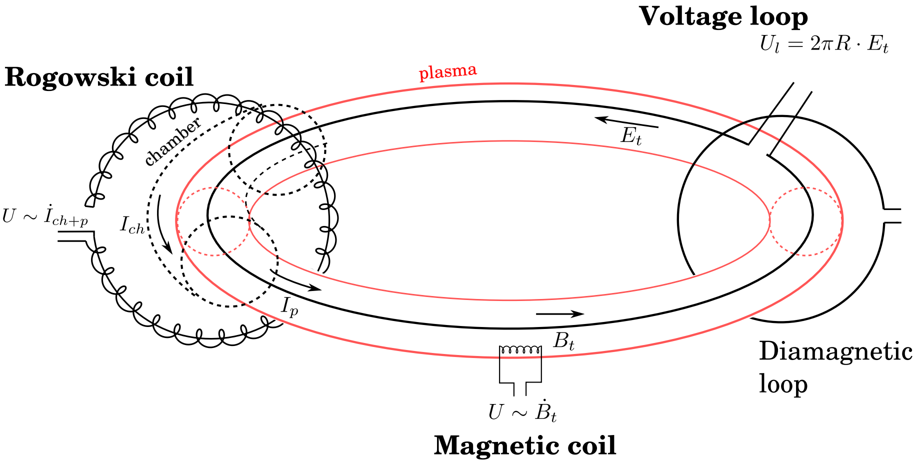
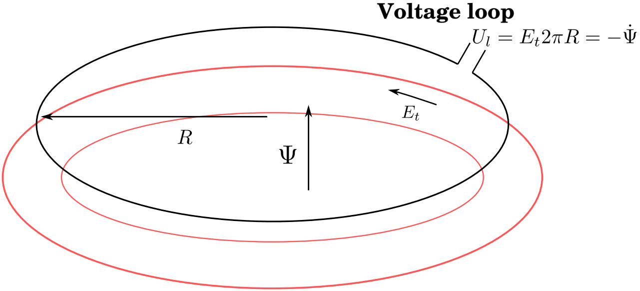
Schematic of electromagnetic diagnostics



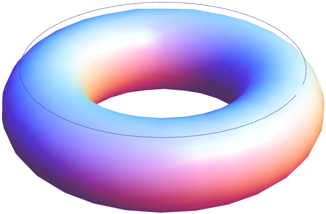
credit:[Wesson, 2004]

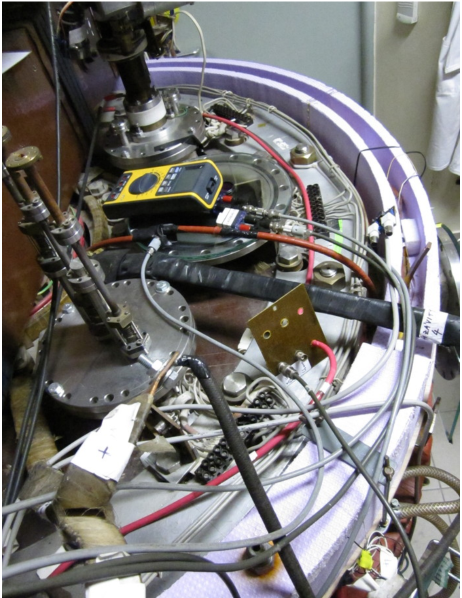
Loop voltage - theoretical introduction



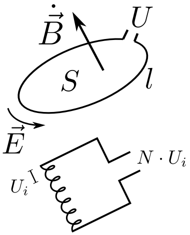
- Corresponds to the toroidal electric field E_t or time variance of Ψ
- Voltage induced in a one loop of wire: $U_l = \oint_l \mathbf{E}_t \cdot d\mathbf{l}$
- On a circular path: $U_l = E_t 2\pi R$
- Kelvin-Stokes theorem transforms closed boundary curve integral $\oint_l \mathbf{E}_t \cdot d\mathbf{l}$ into the "circulations of the fields": $\iint_S \nabla \times \mathbf{E}_t \cdot d\mathbf{S}$
- From Faraday law $\nabla \times \mathbf{E}_t = -\partial \mathbf{B}/\partial t$ the induced voltage $U_l = -\iint_S \partial \mathbf{B}/\partial t \cdot d\mathbf{S} = -\partial/\partial t \iint_S \mathbf{B} \cdot d\mathbf{S} = -\dot{\Psi}$

Loop voltage U_l @ the GOLEM tokamak





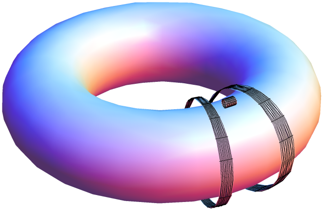
Magnetic coils

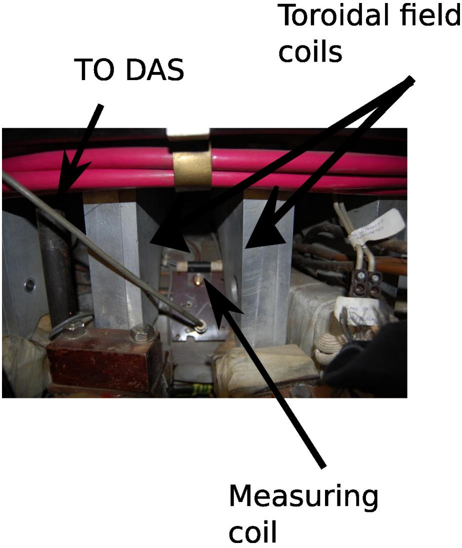


- A small coil of area A with N windings measure time varying magnetic field B.
- Voltage induce in one coil winding: $U_i = \oint_l \mathbf{E} \cdot d\mathbf{l}$
- Kelvin-Stokes theorem transforms closed boundary curve integral $\oint_l \mathbf{E} \cdot d\mathbf{l}$ into the "circulations of the fields": $\iint_S \nabla \times \mathbf{E} \cdot d\mathbf{S}$
- From Faraday law $\nabla \times \mathbf{E} = -\partial \mathbf{B}/\partial t$ the induced voltage $U_i = -\iint_S \partial \mathbf{B}/\partial t \cdot d\mathbf{S}$
- Considering constant surface $\mathbf{S} \perp \mathbf{B}$: $U_i = -S\dot{B}$
- N windings of the coil generate $U = -NS\dot{B}$
- Leads should be twisted to minimize external S.
- Raw signal should be integrated numerically or electrically to get real signal B.

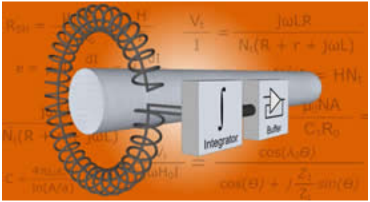
credit:Bartels:IPPlectures.wiki:MaxwEqs

Toroidal magnetic field B_t @ the tokamak GOLEM





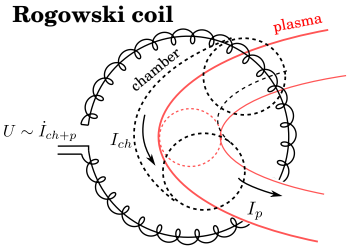
Rogowski coil for the current I measurements

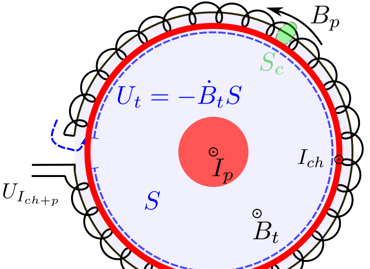


credit:[PEM, 2018]

- Ampere's Law: $\nabla \times \mathbf{B} = \mu_0 \mathbf{j}$ (neglecting $\dot{\mathbf{D}}$)
- current through (const) surface S: $\int \mathbf{j} \cdot d\mathbf{S} = I$
- (const) poloidal field along surface border l: $\int \nabla \times \mathbf{B} \cdot d\mathbf{S} = \oint B_p dl = l B_p$
- voltage induced: $U_l = -N \dot{B}_p S_c = -\mu_0 \frac{N S_c}{l} \dot{I}$
- The wire of the coil is back-wounded to ommit stray magnetic fields from other possible sources.

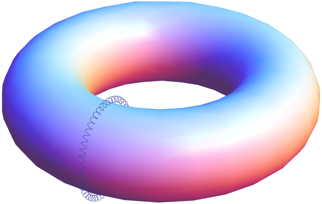
Rogowski coil for the (chamber & plasma) current I_{ch+p} measurements

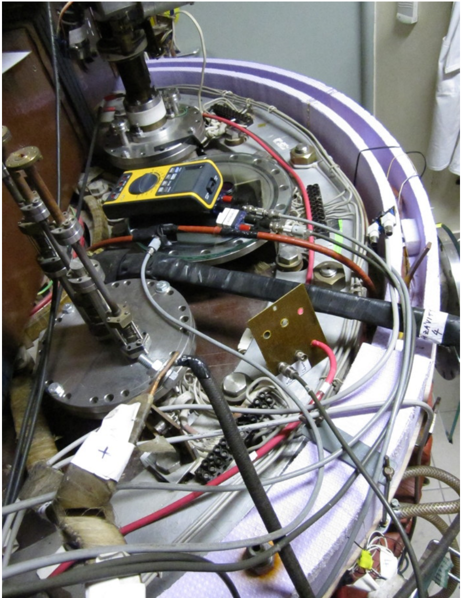




- Ampere's Law: $\nabla \times \mathbf{B} = \mu_0 \mathbf{j}$ (neglecting $\dot{\mathbf{D}}$)
- current through (const) surface S: $\int \mathbf{j} \cdot d\mathbf{S} = I_{ch+p}$
- (const) poloidal field along surface border l: $\int \nabla \times \mathbf{B} \cdot d\mathbf{S} = \oint B_p dl = lB_p$
- voltage induced: $U_{I_{ch+p}} + U_t - U_t = -N\dot{B}_p S_c = -\mu_0 \frac{NS_c}{l} \dot{I}_{ch+p}$
- The wire of the coil is back-wounded to ommit a strong toroidal magnetic field B_t signal.

Total current I_{ch+p}





Magnetic measurements generally I

- Raw signals (analog $U_r(t)$ or, respectively, it's discretized digital U_i counterpart form) must be specialy maintained:
  - corrected for the DC bias U_{offset} of the measurement circuit,
  - integrated (pure diagnostics signal voltage $U_d(t)$ is induced by the time derivative of the appropriate magnetic flux),
  - multiplied by calibration factors C_d ($C_B t$, C_{RC}).
- We can express the basic relationship $U_r(t) = U_d(t) + U_{offset}$
- The measured signal $U_d(t)$ is proportional to the time derivative of the original physical quantity $D(t)$ signal (it is a magnetic measurement):

$$U_d(t) \propto \frac{dD(t)}{dt}, \text{ or } U_d(t) = C_d \frac{dD(t)}{dt}$$

Where the linearity coefficient C_d is called a calibration factor.

Magnetic measurements generally II

- To determine the desired physical quantity $D(t)$, we just have to perform an integration over time:

$$D(t) = \frac{1}{C_d} \int_0^t U_d(t')dt' = \frac{1}{C_d} \int_0^t \left(U_r(t) - U_{offset}\right) dt'$$

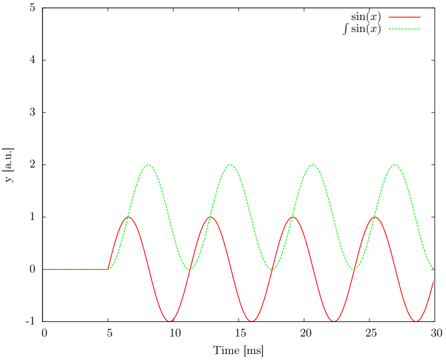
- In reality, the measurement is not continuous. The system performs a series of measurements U_i separated by with time step $\Delta t = 1$ us.
- In practice, we replace the integral by a sum:

$$\begin{aligned} D_i &= \frac{1}{C_d} \sum_{j=0}^{t/\Delta t} (U_i(t_j) - U_{offset})\Delta t \\ D_i &= \frac{1}{C_d} \left(\sum_{j=0}^{t/\Delta t} U_i(t_j) \right) - U_{offset}\, t \end{aligned}$$

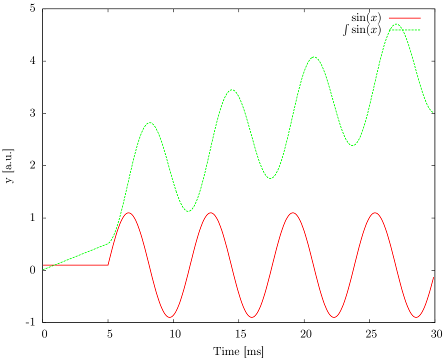
- The offset U_{offset} can be specified from the beggining of the data series before switching on the real experiment.

Magnetic measuremet demo - game with U_{offset}

Without U_{offset}



With U_{offset}



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Spectroscopy

Radiation involving atoms and ions:

- **Free-free** (free electrons in the field of ions) ... continuous spectrum - bremsstrahlung.
- **Free-bound** (free electrons captured by an ion) .. continuous spectrum
- **(GOLEM) Bound-bound** (electrons in an excited or ionized atoms) .. line spectrum
  - Identification of the elements present in the plasma.
  - Measurement of the impurity influx rates from walls and limiters
  - Determination of total impurity concentrations.
  - Investigations of transport processes by comparing measured impurity concentration profiles with transport models.

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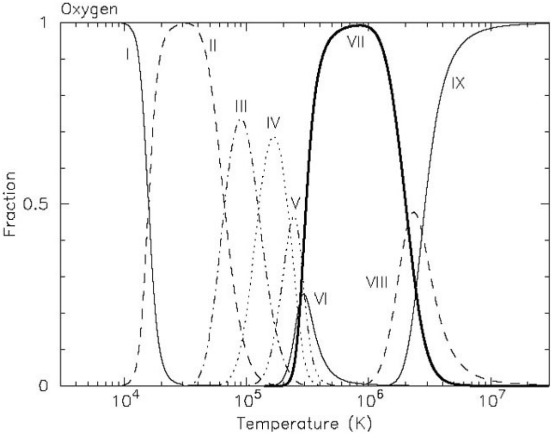
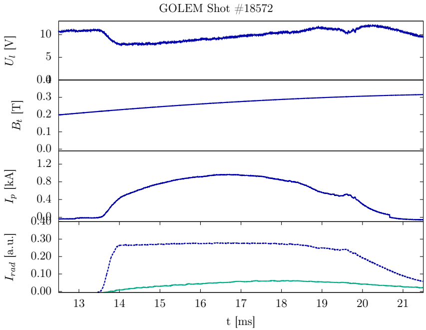
credit:Bartels:IPPlectures

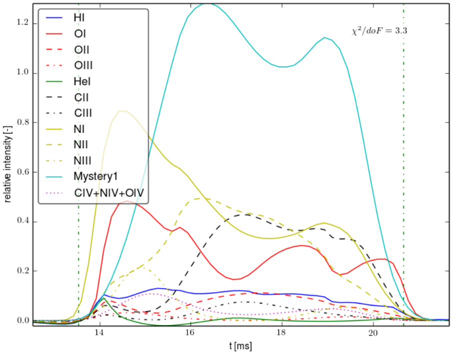
Ionization Balance of the plasma species when heated



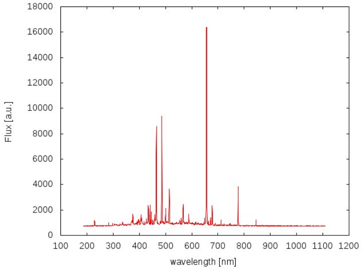
credit:[J.S. Kaastra, 2008]

GOLEM tokamak time evolution of the spectrum





Automated line fitting algorithm ([Alfa, 2018])



4336.68	4338.67	19812.486	0.000	1604.396	11.601	He II	4.10	4f+ 2F*	10g+ 2G	32
4411.09	4413.11	12470.760	0.000	992.836	11.800	Ne II	V57c	3d 4F	4f 1[3]*	4
4628.42	4630.54	11403.713	0.000	865.255	12.381	N II	V5	3s 3P*	3p 3P	5
4636.73	4638.86	31186.416	0.000	2362.020	12.404	O II	V1	3s 4P	3p 4D*	2
4645.29	4647.42	74293.625	0.000	5616.542	12.427	C III	V1	3s 3S	3p 3P*	3
4857.09	4859.32	121851.461	0.000	8810.176	12.993	He II	4.8	4f+ 2F*	8g+ 2G	32
5004.55	5006.84	15754.210	0.000	1105.509	13.388	[O III]	F1	2p2 3P	2p2 1D	5
5666.18	5666.63	14319.603	0.000	979.118	13.739	N II	V3	3s 3P*	3p 3D	3
5675.56	5676.02	16486.086	0.000	1125.389	13.762	N II	V3	3s 3P*	3p 3D	1
6547.57	6548.10	15318.212	0.000	906.404	15.876	[N II]	F1	2p2 3P	2p2 1D	3
6559.57	6560.10	274134.750	0.000	16191.334	15.906	He II	4.6	4f+ 2F*	6g+ 2G	32
6582.97	6583.50	27489.877	0.000	1617.875	15.962	[N II]	F1	2p2 3P	2p2 1D	5
6794.46	6795.00	12099.052	0.000	689.907	16.475	[K IV]	F1	3p4 3P	3p4 1D	3
7750.47	7751.06	35708.781	0.000	481.826	69.623	[Ar III]		3p4 3P	3p4 1D	3
8001.25	8001.86	13357.887	0.000	174.592	71.876	Ar I		3d 2<1>*	8p 2<1>	3

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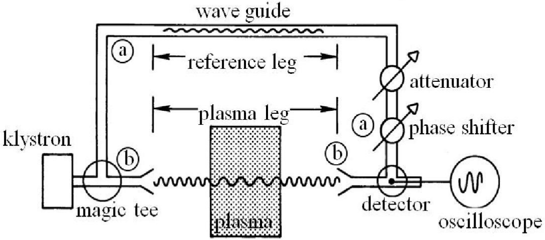
Electron denstity n_e measurement: basic strategy

4.13(2)

- Microwave interferometer for plasma density measurement

index of refraction $\tilde{n} = \frac{c}{v_{ph}} = \frac{ck}{\omega}$ >1 in glass, $=1$ in vacuum, <1 in plasma



A microwave interferometer for plasma density measurement.

1.without plasma, signals from path ⓐ and ⓑ are 180° out of phase.

2.with plasma, the phase in ⓑ changed as $\lambda \uparrow$, (by higher plasma density).

credit:[Unknown, 2016]

Electron density n_e interferometer measurement introduction (extreme simplification $B = 0$)

Electromagnetic transverse wave:
$$E_x(z,t) = E_0 \cos(\omega t + kz)$$

Maxwell Equations@Vacuum:

$$\begin{aligned} \nabla \cdot \mathbf{E} &= 0 \\ \nabla \cdot \mathbf{B} &= 0 \\ \nabla \times \mathbf{E} &= -\partial_t \mathbf{B} \\ \nabla \times \mathbf{B} &= \mu_0 \epsilon_0 \partial_t \mathbf{E} \end{aligned}$$

$\Longrightarrow$

The refractive index: $N = 1$

Maxwell Equations@Plasma:

$$\begin{aligned} \nabla \cdot \mathbf{E} &= \rho/\epsilon_0 \\ \nabla \cdot \mathbf{B} &= 0 \\ \nabla \times \mathbf{E} &= -\partial_t \mathbf{B} \\ \nabla \times \mathbf{B} &= \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \partial_t \mathbf{E} \end{aligned}$$

$\Longrightarrow$ The refractive index:

$$N = \sqrt{1 - \frac{{\omega_p}^2}{\omega^2}} \approx 1 - \frac{ne^2}{2\varepsilon_0 m \omega^2}$$

The phase shift:
$$\Delta\varphi = -\frac{e^2}{2c\varepsilon_0 m\omega} \int_0^L n(l)\, dl$$

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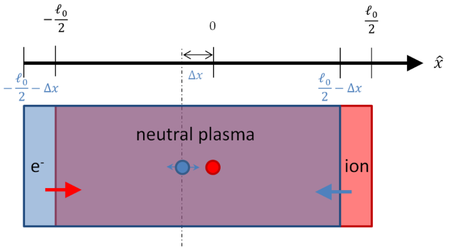
credit:underthehood.blogwyrm:PlasmaWaves, Bartels:IPPlectures, MatenaMT

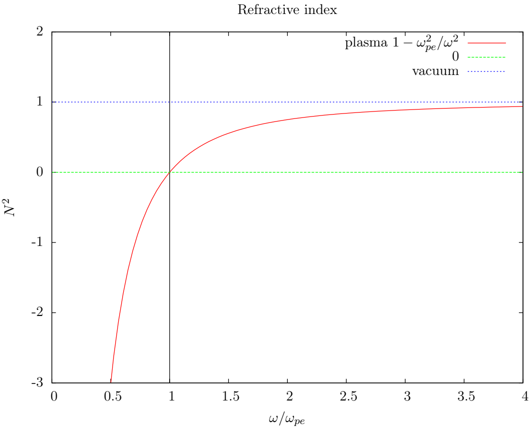
Plasma Oscillations



- Outside agency **(e.g. EM wave)** cause all of the electrons to be displaced by the very small amount of Δx.
- Equation of motion: $m_{tot}\frac{d^2}{dt^2}\Delta x = q_{tot}E$, where $m_{tot} = m_e n_0 V$.
- Integral form of the Gauss law: $EA = \frac{en_0 A\Delta x}{\epsilon_0}$ gives: $E = \frac{en_0}{\epsilon_0}\Delta x$.
- Then: $m_e n_0 V\frac{d^2}{dt^2}\Delta x = -en_0 V\frac{en_0}{\epsilon_0}\Delta x$, typical LHO form with oscillation at **electron plasma frequency** $\omega_{pe} = \sqrt{\frac{e^2 n_0}{m_e\epsilon_0}}$.

credit:underthehood.blogwyrm:PlasmaOscillation

The index of refraction

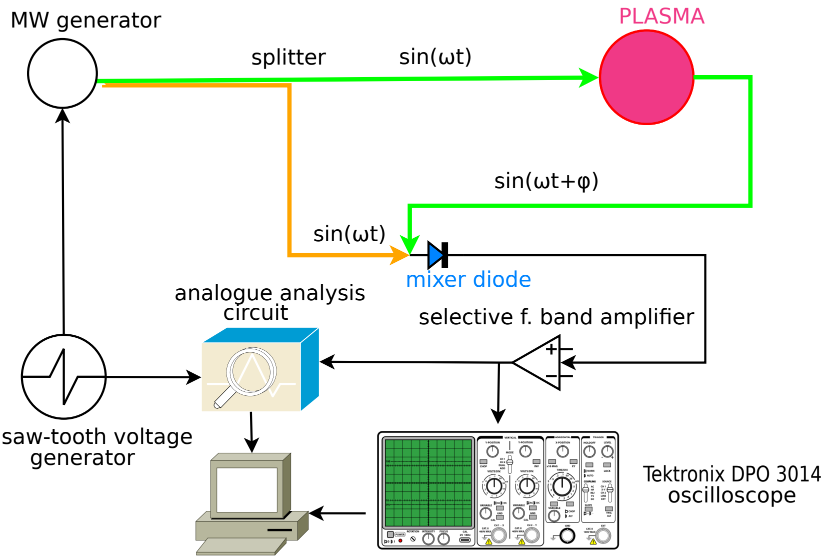


- is always smaller than 1,
- decreases as density increases,
- wave only propagates when $\omega > \omega_{pe}$,
- for every wave frequency ω there is a *critical density*

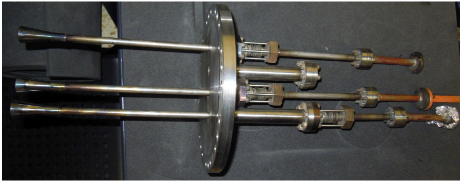
$$n_c = \frac{\varepsilon_0 m}{e^2}\omega^2$$

which is the highest density that allows the wave to propagate.

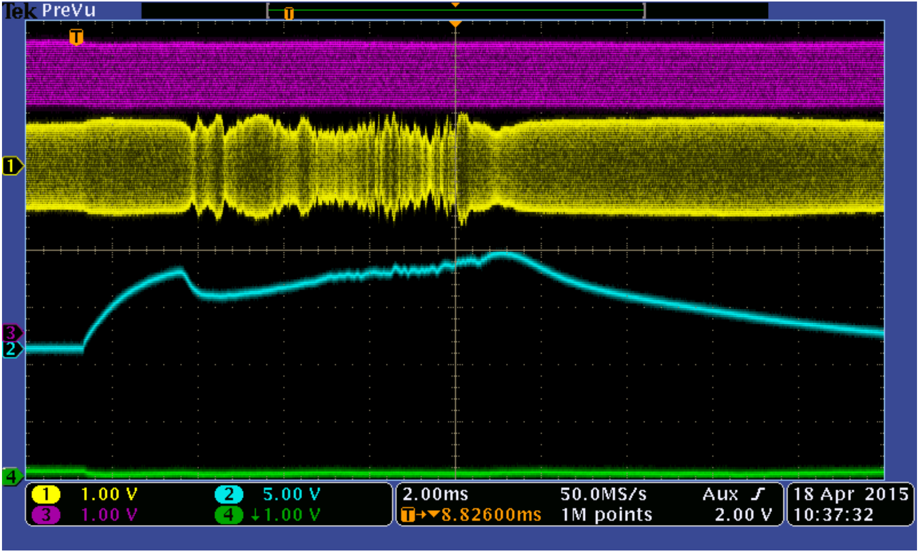
Scheme


MW generator
splitter
sin(ωt)
PLASMA
sin(ωt+φ)
sin(ωt)
mixer diode
analogue analysis circuit
selective f. band amplifier
saw-tooth voltage generator
Tektronix DPO 3014 oscilloscope

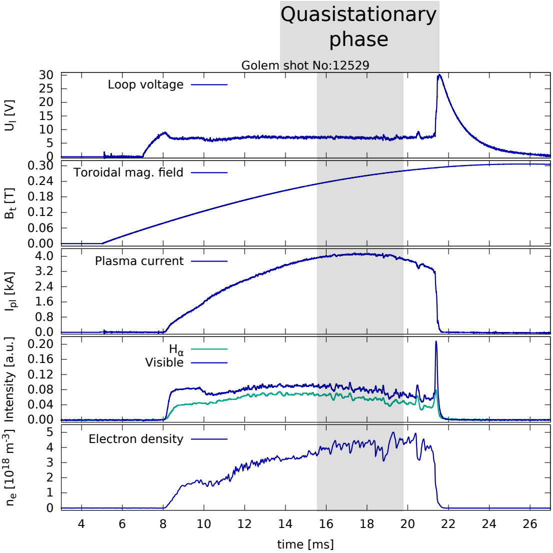
The GOLEM tokamak interferometry HW



Oscilloscope record of interferometry



The discharge - quasistationary phase



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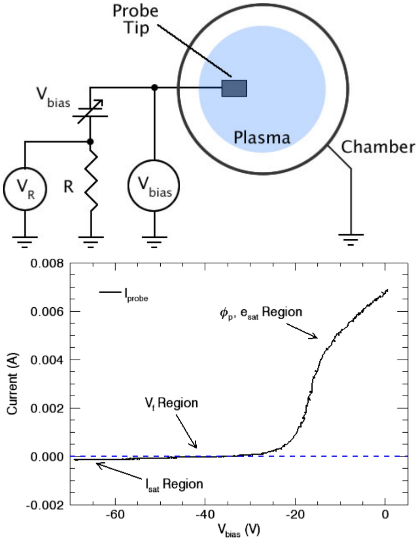
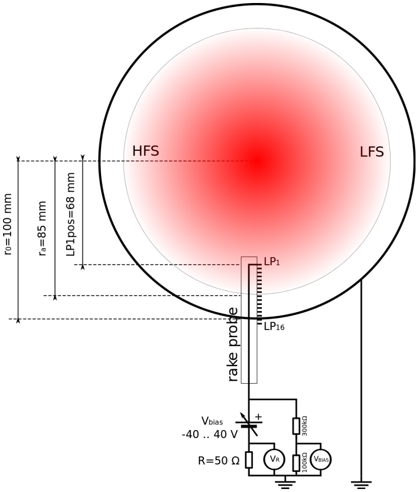
Particle flux measurement with Langmuir probes

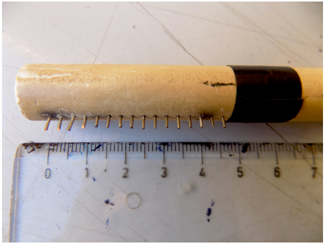


credit:DavidPace:LangProbe

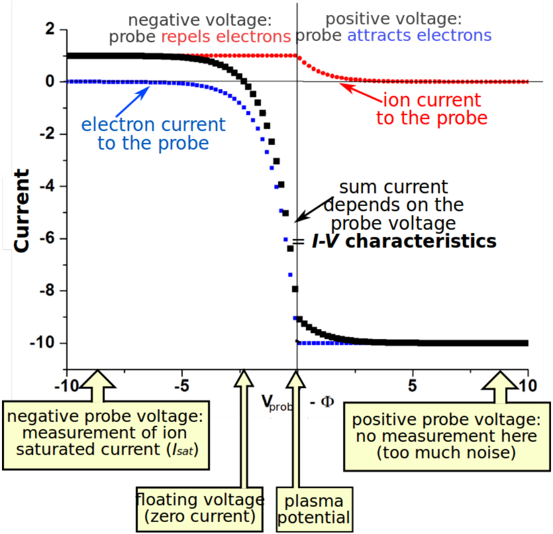
- A small, conductive component in direct contact with plasma.
- The measurement output is determined: i) shape: Langmuir probe, ball-pen probe, tunnel probe, Katsumoto probe, Mach probe ... ii) by the applied voltage.
- Measurement only at the edge of the plasma.
- Measured quantities: plasma potential, electron temperature and density, electric fields, electron distribution functions ...

A set of Langmuir probes: Rake probe

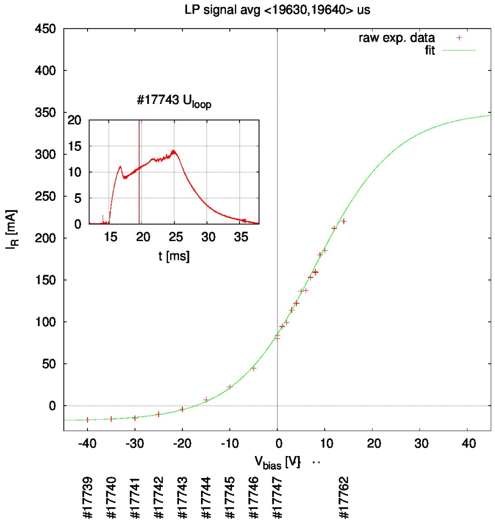


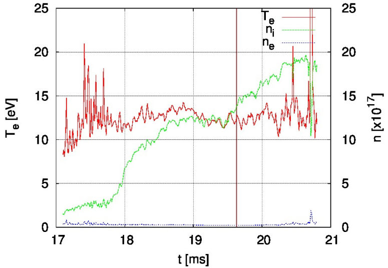


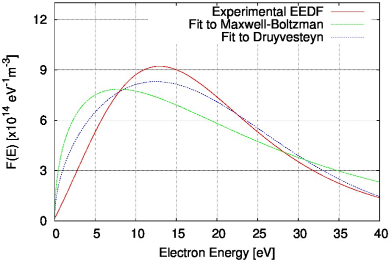
Volt-amper characteristics of the Langmuir probe



VA characteristics at the GOLEM tokamak







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

- $U_l, U_{B_t}, U_{I_{p+ch}}, I_{rad}$
- $\Delta t = 1\mu s / f = 1MHz$.
- 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 $\Delta t = 1\mu s/f = 1MHz$ (neutral gas into plasma breakdown focused)

t	$\approx U_l$	$\approx U_{\frac{dB_T}{dt}}$	$\approx U_{\frac{d(I_{p+ch})}{dt}}$	$\approx I_{rad}$
:	:	:	:	:
:	:	:	:	:
first	$\approx$	7405	lines ..	
:	:	:	:	:
:	:	:	:	:
0.007383	1.53931	0.390015	0.048828	0.001831
0.007384	1.53686	0.395508	0.067749	0.00061
0.007385	1.54053	0.391235	0.079956	0.00061
0.007386	1.53686	0.38147	0.072632	0
0.007387	1.54297	0.397949	0.059204	0.00061
0.007388	1.54053	0.384521	0.05249	0.00061
0.007389	1.54053	0.39856	0.068359	0.001221
0.00739	1.54053	0.393677	0.082397	0.001221
0.007391	1.53809	0.38208	0.072632	0.001221
0.007392	1.54297	0.400391	0.056763	0.00061
0.007393	1.54419	0.383911	0.053101	0.00061
0.007394	1.53931	0.397339	0.068359	0.001221
0.007395	1.54297	0.391846	0.084229	0.00061
0.007396	1.54541	0.394897	0.074463	0.00061
0.007397	1.54297	0.388184	0.056763	0.001221
0.007398	1.54297	0.391846	0.056763	0.00061
0.007399	1.54297	0.394287	0.06897	0.00061
:	:	:	:	:
:	:	:	:	:
next	$\approx$	32500	lines ..	
:	:	:	:	:
:	:	:	:	:

Data access

All the recorded data and the settings for each discharge (shot) are available at the GOLEM website. The root directory for the files is:

`http://golem.fjfi.cvut.cz/shots/<#ShotNo>/`

The most recent discharge has the web page:

`http://golem.fjfi.cvut.cz/shots/0`

Particular data from DAS or specific diagnostics have the format:

`http://golem.fjfi.cvut.cz/utils/data/<#ShotNo>/<identifier>`

An overview of available data with identifiers, units, description, etc. for each discharge is at

`http://golem.fjfi.cvut.cz/shots/<#ShotNo>/Data.php`

Matlab

```
ShotNo=22471;
baseURL='http://golem.fjfi.cvut.cz/utils/data/';
identifier='loop_voltage';
%Create a path to data
dataURL=strcat(baseURL,int2str(ShotNo),'/',identifier);
% Write data from GOLEM server to a local file
urlwrite(dataURL,identifier);
% Load data
data = load(identifier, '\t');
% Plot and save the graph
plot(data(:,1)*1000, data(:,2), '.') ;
xlabel('Time [ms]')
ylabel('U_l [V]')
saveas(gcf, 'plot', 'jpeg');
exit;
```

Jupyter (python)

```
import numpy as np
import matplotlib.pyplot as plt

shot_no = 22471
identifier = "loop_voltage"
# create data cache in the 'golem_cache' folder
ds = np.DataSource('golem_cache')
#Create a path to data and download and open the file
base_url = "http://golem.fjfi.cvut.cz/utils/data/"
data_file = ds.open(base_url+str(shot_no)+'/'+identifier)
#Load data from the file and plot to screen and to disk
data = np.loadtxt(data_file)
plt.plot(data[:,0], data[:,1]) #1. column vs 2. column
plt.savefig('graph.jpg')
plt.show()
```

Gnuplot

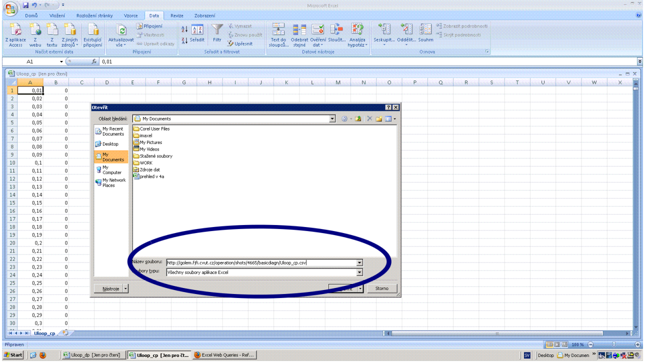
```
set macros;
ShotNo = "22471";
baseURL = "http://golem.fjfi.cvut.cz/utils/data/";
identifier = "loop_voltage";
#Create a path to data
DataURL= "@baseURL@ShotNo/@identifier";
#Write data from GOLEM server to a local file
!wget -q @DataURL;
#Plot the graph from a local file
set datafile separator "\t";
plotstyle = "with lines linestyle -1"
plot 'loop_voltage' using 1:2 @plotstyle;
exit;

# command line execution:
# gnuplot Uloop.gp -persist
```

GNU Wget

GNU Wget is a free software package for retrieving files using HTTP, HTTPS and FTP, the most widely-used Internet protocols. It is a non-interactive commandline tool, so it may easily be called from scripts, cron jobs, terminals without X-Windows support, etc.

- Runs on most UNIX-like operating systems as well as Microsoft Windows.
- Homepage: `http://www.gnu.org/software/wget/`
- Basic usage:
  - To get U_l: wget `http://golem.fjfi.cvut.cz/utils/data/<#ShotNo>/loop_voltage`
  - To get whole shot: wget -r -nH –cut-dirs=3 –no-parent -l2 -Pshot `http://golem.fjfi.cvut.cz/shots/<#ShotNo>`

Excel



File→Open→

`http://golem.fjfi.cvut.cz/utils/data/<#ShotNo>/<identifier>`

Spredsheets (Excel and others)

are not recommended, only tolerated.

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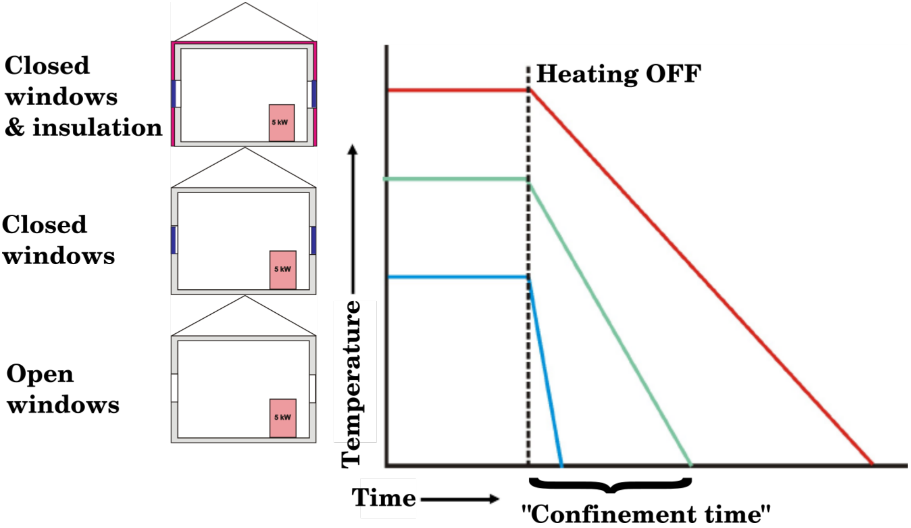
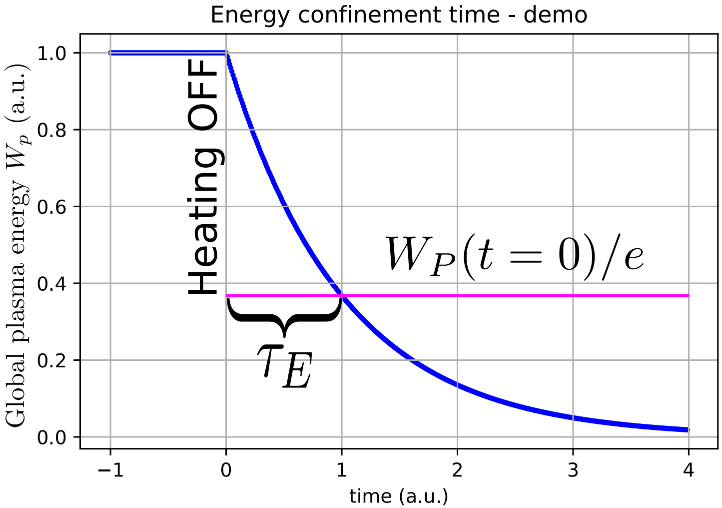
Energy balance of the house



Energy balance of the tokamak



Energy confinement time

Under the assumption of a simplified power balance, the heating power P_H is partially absorbed in the plasma and leads to an increase of the plasma energy W_p and the rest is lost as the loss power P_L

$$P_H = \frac{dW_p}{dt} + P_L$$

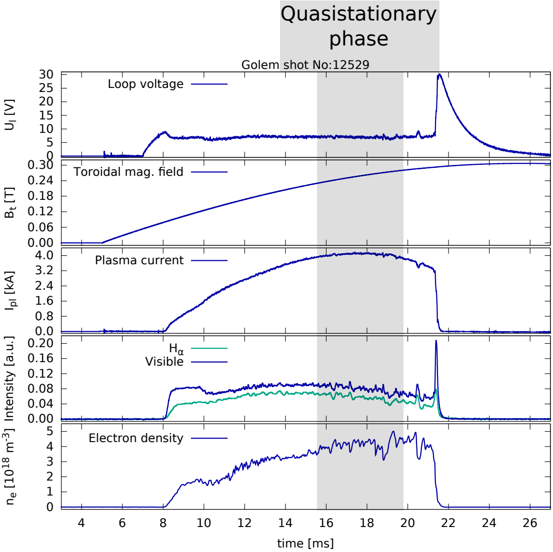
The energy confinement time is defined as the characteristic time scale of the exponential decay of the plasma energy W_p due to the loss power P_L:

$$\tau_E = \frac{W_p}{P_L} = \frac{W_p}{P_H - dW_p/dt}$$

Choosing the quasistationary phase of the plasma discharge, where $\frac{dW_p}{dt} = 0$ gives:

$$\tau_E(t) = \frac{W_p(t)}{P_H(t)}$$

The discharge - quasistationary phase



Plasma heating power

On the GOLEM tokamak the only heating mechanism of the plasma is ohmic heating P_{OH} resulting from the plasma current I_p flowing in a conductor with finite resistivity R_p. The time dependence of the ohmic heating power can be calculated as:

$$P_H(t) = P_{OH}(t) = R_p(t) \cdot I_p^2(t)$$

Plasma Energy

The global plasma energy content W_p can be simply calculated from the temperature estimation $T_e(0,t)$, average density n_e and plasma volume V_p, based on the ideal gas law, taking into account the assumed $T_e(r,t) = T_e(0,t)\left(1 - \frac{r^2}{a^2}\right)^2$ temperature profile:

$$W_p(t) = V_p \frac{n_e k_B T_e(0,t)}{3}.$$

The information that the magnetic field reduces the degrees of freedom of the particles to two has been used to derive this formula.

- $V_p \approx 80$ l

Central Electron Temperature estimation (Spitzer Formula)

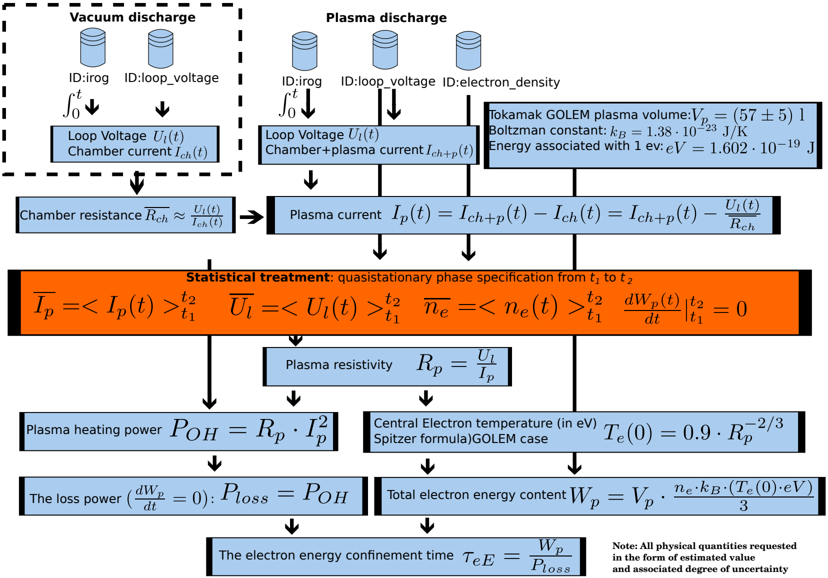
The time evolution of the central electron temperature $T_e(0,t)$ is calculated from equation based on Spitzer's resistivity formula (see eg. [Brotankova, J., 2009],[Wesson, 2004]):

$$T_e(0,t) = \left(\frac{R_0}{a^2} \frac{8Z_{eff.}}{1544} \frac{1}{R_p(t)} \right)^{2/3}, [eV; m, \Omega]$$

For particular case of the GOLEM tokamak it says:

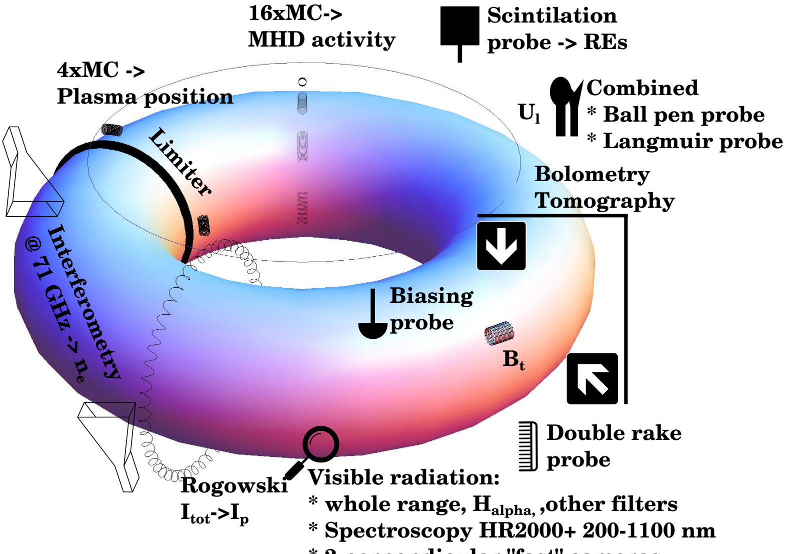
$$T_e(0,t) = 0.9 \cdot \left(\frac{I_p(t)}{U_l(t)} \right)^{2/3}, [eV; A, V]$$

Towards Electron energy confinement time τ_E

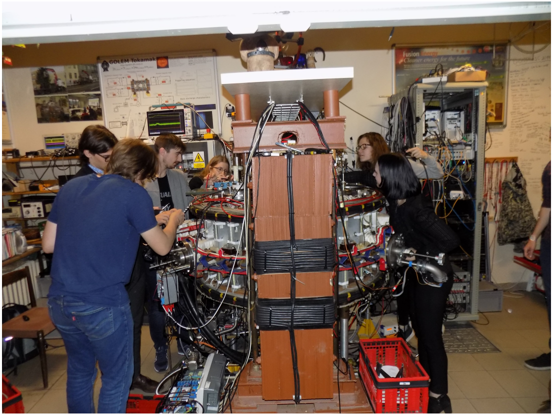


Hands on the GOLEM tokamak - equipment

The GOLEM tokamak - standard diagnostics

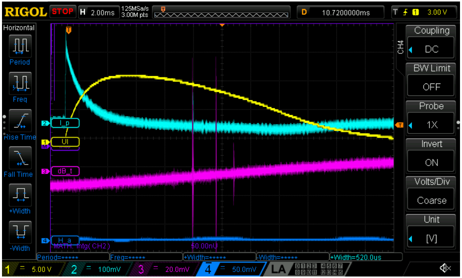


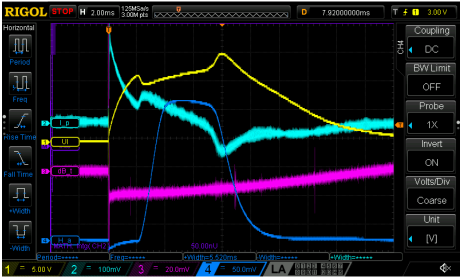
Hands on the GOLEM tokamak



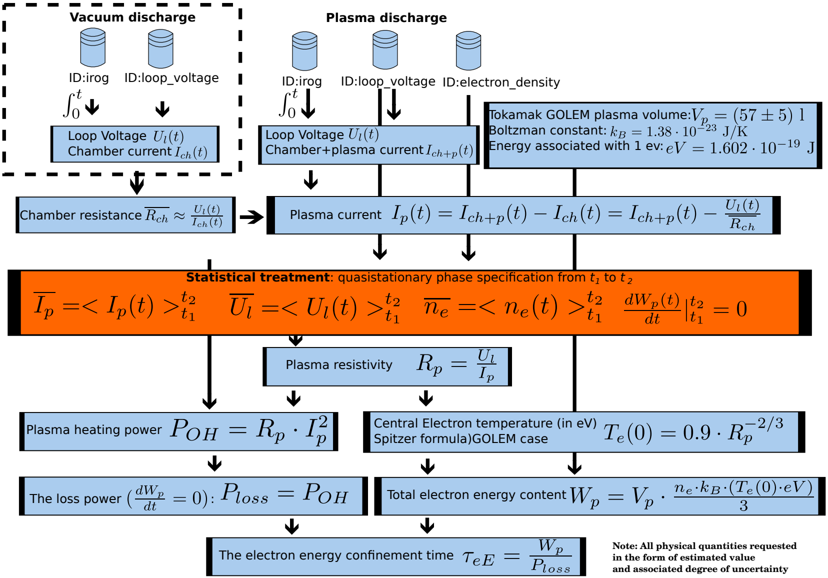
- Laboratory Practice for Basic course of Physics 2015-19 (CT University Bachelor level).
- Advanced plasma training course 2014-19 (CT University Master level).
- Week of scientists 2013-19 (Czech republic High school level).
- International Golem Training Course 2013,2019 (Master and PhD level).

Vacuum x Plasma discharge @ Oscilloscope





Towards Electron energy confinement time τ_E

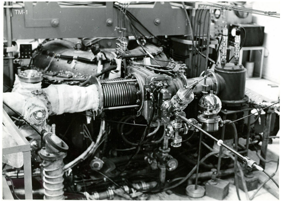


Možno si odnést, či doporučené otázky ke zkoušce.

- Tokamak, jeho mise, základní princip.
- Základy diagnostiky vysokoteplotního plazmatu.
- Základy real-time řízení experimentu.
- Princip měření doby udržení energie v tokamacích.

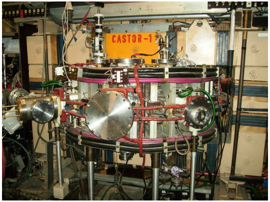
Thank you for your attention

Tokamak TM1
@Kurchatov Institute near Moscow
~1960-1977



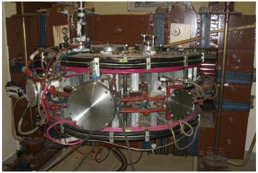
SCIENCE

Tokamak CASTOR
@Institue of Plasma Physics, Prague
1977-2007



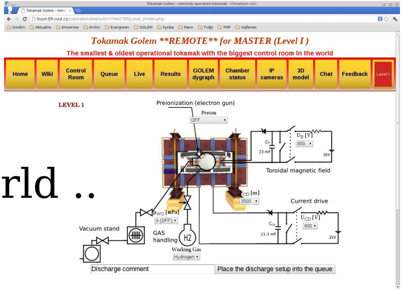
SCIENCE
& education

Tokamak GOLEM
@Czech Technical University, Prague
2007-



EDUCATION
& science

... with the biggest
control room
in the world ..



Acknowledgement

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Students, teachers, technicians (random order):

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