Optimization studies of magnetic confinement of plasma in tokamak GOLEM

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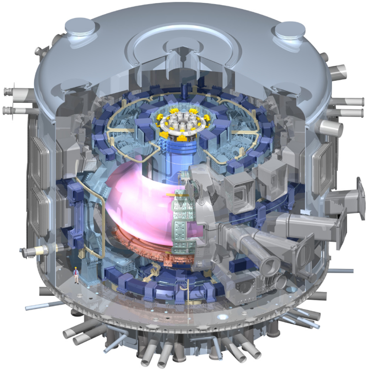
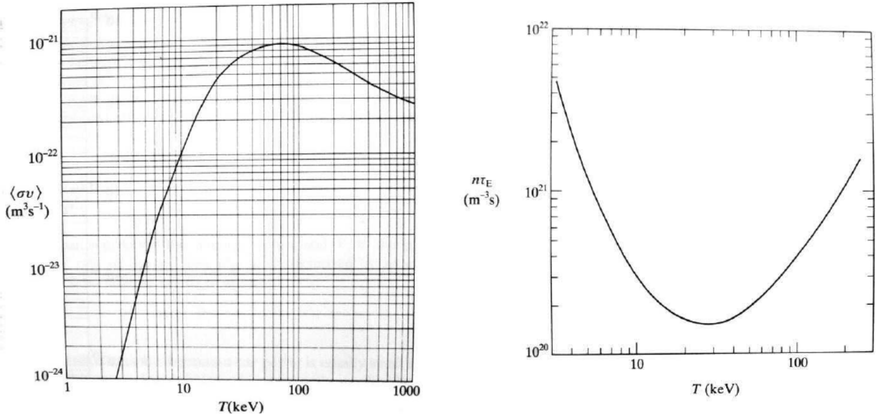
Motivation

- Study the dependence between the energy confinement time and the toroidal magnetic field.
- Identify impurities in the plasma.
- Achieve an efficient fusion reaction in the future, as a clean energy source.



Nuclear Fusion and Confinement Time



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[1] Jana Brotánková. "Study of high temperature plasma in tokamak-like experimental devices", PhD Thesis, 2009

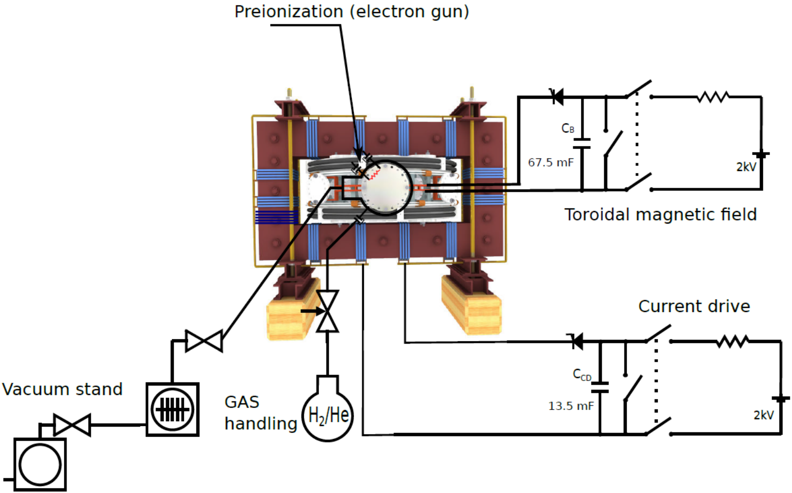
Tokamaks

- Tokamak: *toroidal chamber with an axial magnetic field*.
- Magnetic field with an helical shape is used to confine plasma.
- GOLEM is operated by the Czech Technical University in Prague.
- Remote discharges for research and education.

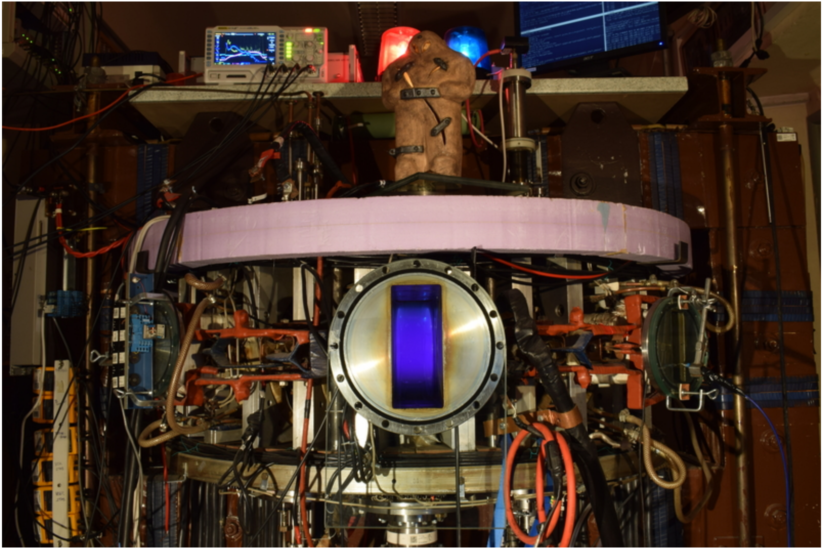
Mayor radius R	40 cm
Minor radius a	8.5 cm
Effective charge Z_{eff}	2.5
Plasma volume V_p	$\approx$ 80 L
Toroidal magnetic field B_t	up to $\approx$ 0.5 T
Plasma current I_p	up to $\approx$ 8kA
Available gases	Hydrogen and Helium

- Steel components and molybdenum obstacle.

GOLEM

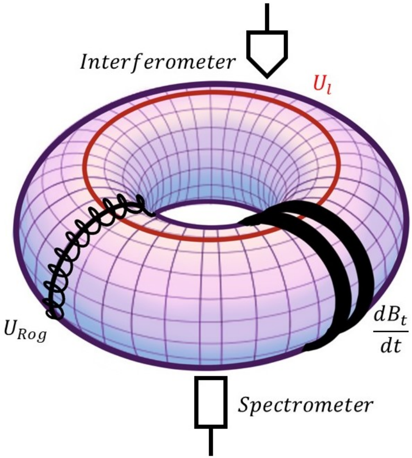

Preionization (electron gun)
C_B
67.5 mF
2kV
Toroidal magnetic field
Current drive
C_{CD}
13.5 mF
2kV
Vacuum stand
GAS
handling
H_2/He

GOLEM



Diagnostics

1. Toroidal coil for loop voltage U_l.
2. Poloidal coils for $\frac{dB_t}{dt}$.
3. Rogowski coil for total current.
4. Spectrometer.
5. Interferometer to measure density.

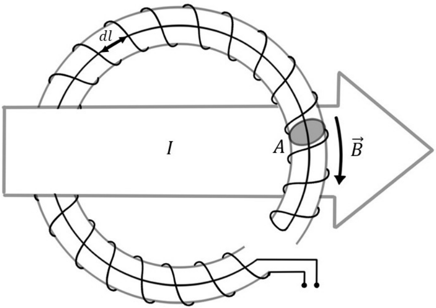


Plasma Current I_p

- Total current is obtained by integrating the signal U_{Rog}.
- Chamber current I_{ch} is subtracted, which satisfies

$$\frac{dI_{ch}}{dt} = \frac{1}{L_{ch}}(U_l - R_{ch}I_{ch}), \quad I_{ch}(t=0) = 0$$

- R_{ch} y L_{ch} are the resistance and inductance of the chamber.



Central Electron Temperature T_e

- Plasma current is related with conductivity

$$I_p = \int j \, dl = \int_0^a E\sigma(r) 2\pi r dr$$

where $E = \frac{U_l}{2\pi R}$

- Spitzer's formula

$$\sigma(r) = 1.544 \cdot 10^3 \frac{T_e(r,t)^{3/2}}{Z_eff}$$

- Polynomial profile is assumed para $T_e(r,t)$
- For GOLEM (a = 78 mm)

$$\Rightarrow T_e(0,t) = 0.898 \cdot \left(\frac{I_p(t)}{U_l(t)} \right)^{2/3}$$

Energy Confinement Time τ_e

- Defined from the energy equilibrium equation

$$\tau_e = \frac{W_p}{P - dW_p/dt}$$

- In the quasistationary phase $dW_p/dt = 0$.
- Global plasma energy

$$W_p = \frac{3}{2}\langle p\rangle V_p = \frac{3}{2}\langle n_e T_e\rangle V_p = \frac{3}{8} V_p n_e(0) T_e(0,t)$$

- Heating Power (Ohmic heating)

$$P(t) = U_l(t) I_p(t)$$

- Confinement time

$$\tau_e(t) = \frac{3}{8}\frac{V_p n_e(0) T_e(0,t)}{U_l(t) I_p(t)}$$

Electron Density n_e (first approach)

- The number of electrons N_e equals the number of neutral hydrogen atoms N_0 (plasma is fully ionized)

$$N_e = N_0 = 2N_{H_2}$$

- Ideal gas law

$$p_0 V_{ch} = N_{H_2} k_B T_0$$

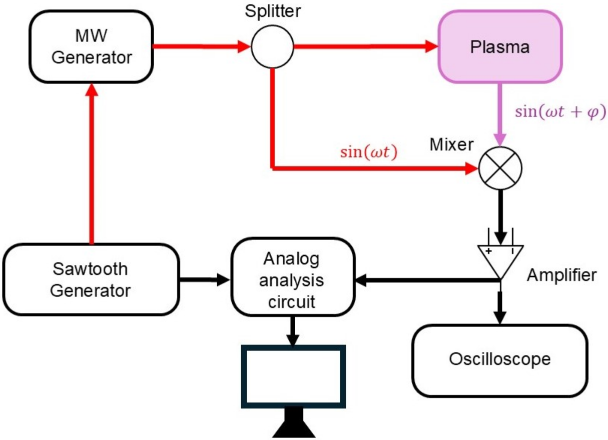
- For GOLEM $T_0 \approx 300\ K$, $V_{ch} = 150\ L$, $V_p \approx 80\ L$.

$$\Rightarrow n_e = \frac{2 p_0 V_{ch}}{k_B T_0 V_p}$$

Electron Density n_e (interferometry)

- Wave experiences a phase shift due to the plasma refractive index

$$\phi = \frac{\omega}{c} \int N(l) dl$$



Electron Density n_e (interferometry)

- The refractive index is related with the electron density:

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

where $\omega_p = \sqrt{\frac{n_e e^2}{\epsilon_0 m}}$ (plasma frequency).

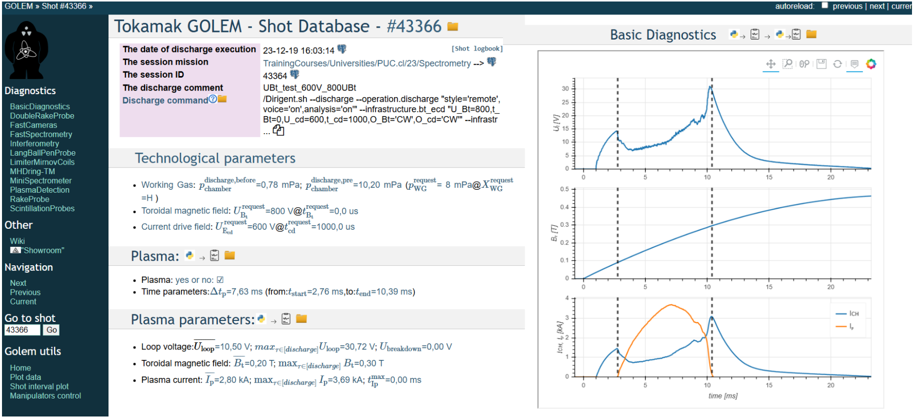
- Phase shift difference with respect to air

$$\Delta\phi = \frac{e^2}{2\omega c \epsilon_0 m_e} \int_L n_e(l) dl$$

First Discharge Session

shot_no	$U_{Bt}(V)$	$U_{Et}(V)$	$p_0(mPa)$
42720	600	600	15
42719	700	600	15
42718	800	600	15
42726	400	400	17
42725	500	400	17
42724	600	400	16
42723	700	400	16
42722	800	400	15
42729	900	400	14
42731	1000	400	16
42728	350	350	14
42738	600	350	16
42737	800	350	16

- Set various U_{Et} and modify U_{Bt}.
- Study the influence of U_{Bt} in different physical quantities.
- Pressure was adjusted manually.
- Hydrogen gas was used.



GOLEM » Shot #43366 »
autoreload: previous | next | current
Tokamak GOLEM - Shot Database - #43366
The date of discharge execution 23-12-19 16:03:14
[Shot logbook]
The session mission TrainingCourses/Universities/PUC.cl/23/Spectrometry -->
The session ID 43366
The discharge comment UBt_test_600V_800UBt
Discharge command /Dirigent.sh --discharge --operation.discharge "style='remote', voice='on',analysis='on'" --infrastructure.bt_ecd "U_Bt=800,t_Bt=0,U_cd=600,t_cd=1000,O_Bt='CW',O_cd='CW'" --infrastr ...
Diagnostics
BasicDiagnostics
DoubleRakeProbe
FastCameras
FastSpectrometry
Interferometry
LangBallPenProbe
LimiterMirnovCoils
MHDring-TM
MiniSpectrometer
PlasmaDetection
RakeProbe
ScintillationProbes
Other
Wiki
"Showroom"
Navigation
Next
Previous
Current
Go to shot
43366 Go
Golem utils
Home
Plot data
Shot interval plot
Manipulators control
Technological parameters
Working Gas: p chamber discharge,before =0,78 mPa; p chamber discharge,pre =10,20 mPa (p WG request = 8 mPa@X WG request =H)
Toroidal magnetic field: U Bt request =800 V@t Bt request =0,0 us
Current drive field: U Ecd request =600 V@t cd request =1000,0 us
Plasma:
Plasma: yes or no: ☑
Time parameters: Δt p =7,63 ms (from: t start =2,76 ms, to: t end =10,39 ms)
Plasma parameters:
Loop voltage: U loop =10,50 V; max τ∈[discharge] U loop =30,72 V; U breakdown =0,00 V
Toroidal magnetic field: B t =0,20 T; max τ∈[discharge] B t =0,30 T
Plasma current: I p =2,80 kA; max τ∈[discharge] I p =3,69 kA; t Ip max =0,00 ms
Basic Diagnostics
U_l [V]
B_t [T]
I_CH, I_p [kA]
I_CH
I_p
time [ms]

Second Discharge Session

shot_no	$U_{Bt}(V)$	$U_{Et}(V)$	$p_0(mPa)$
43366	800	600	10.20
43367	350	350	5.58
43368	400	350	6.03
43369	500	350	6.65
43371	600	350	7.51
43372	800	600	17.70
43373	700	350	10.80
43374	800	350	10.80
43375	900	350	9.51
43378	800	600	11.10

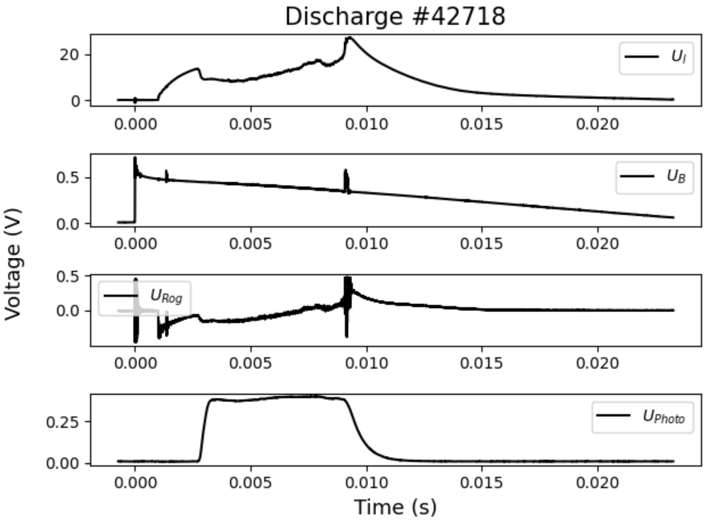
- Corroborate results from the first session.
- Identify impurities using a spectrometer.
- Interferometry diagnostic.

Third Discharge Session

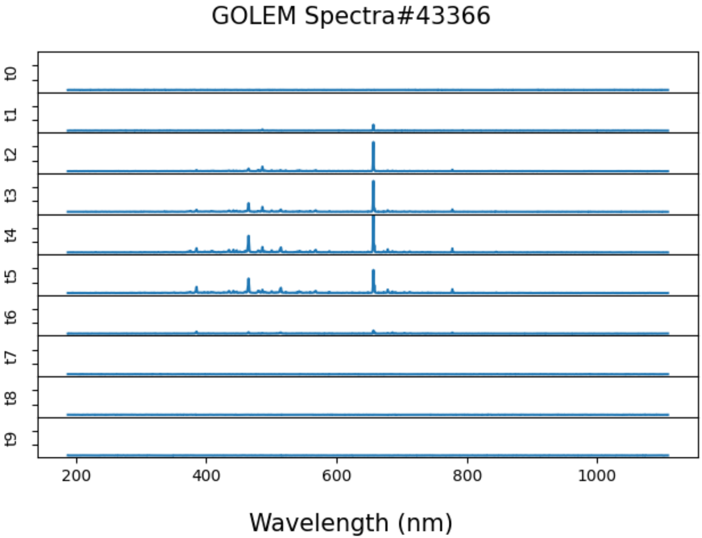
shot_no	$U_{Bt}(V)$	$U_{Et}(V)$	$p_0(mPa)$
45080	400	400	10.5
45081	600	400	14.1
45082	800	400	19.1
45083	1000	400	14.4
45089	600	650	13.4
45091	700	650	14.3
45092	800	650	14.6
45093	900	650	14.9
45094	1000	650	15.1

- Corroborate previous results.
- Helium gas was used in some discharges.

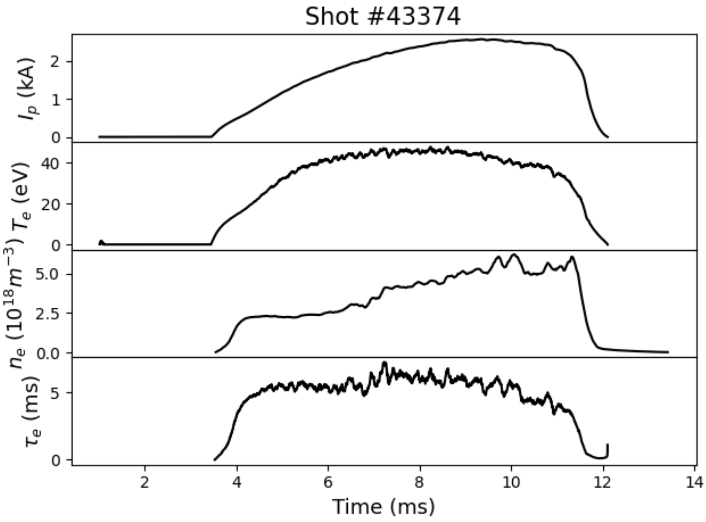
Oscilloscope Output



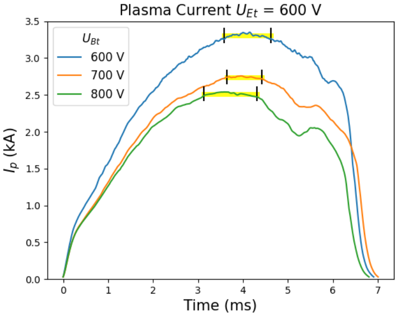
Spectrometer Output

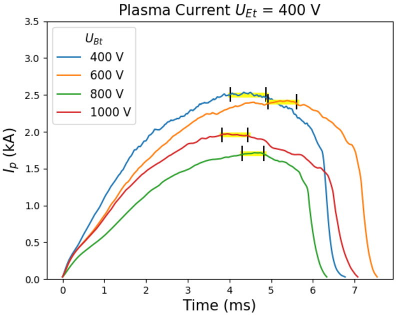


Discharge Evolution Example



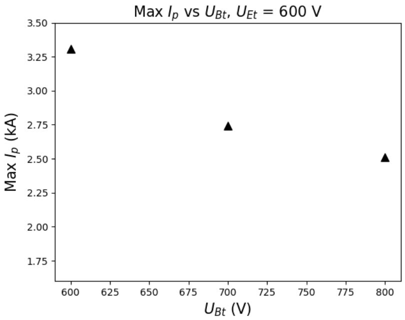
Plasma Current

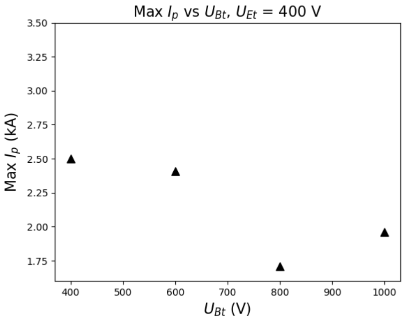




- Current decreases when U_{Bt} is increased.
- It increases with U_{Et}.

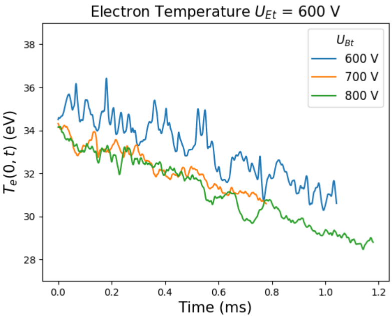
Max Plasma Current

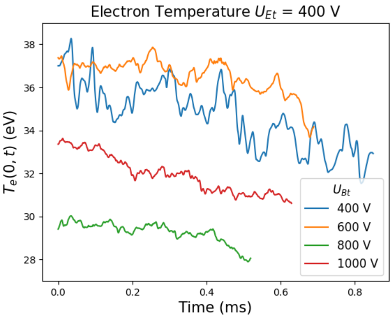




- Plasma current could depend on the gas pressure.

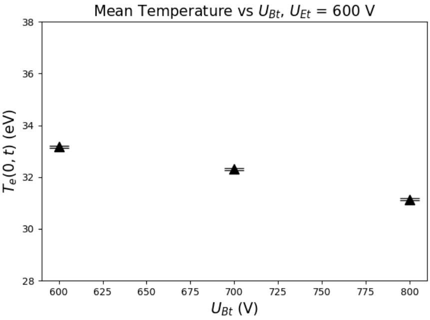
Electron Temperature

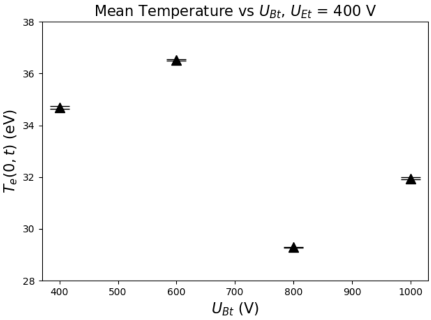




- Temperature tends to be lower when U_{Bt} is increased.

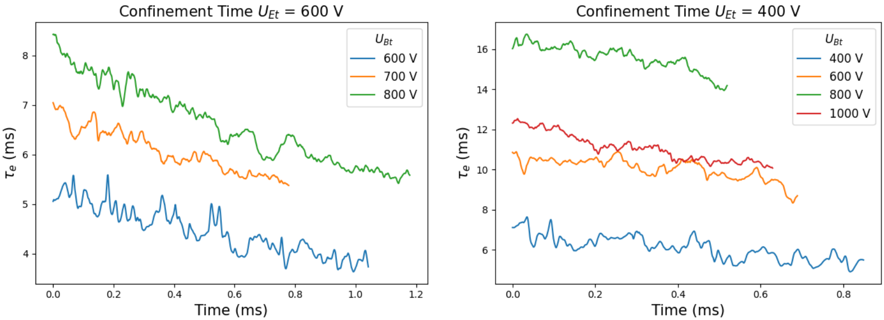
Mean Electron Temperature





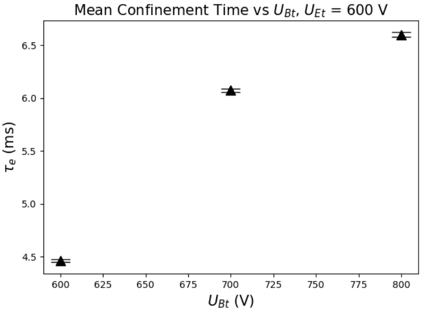
- Temperature depends directly on loop voltage U_l and plasma current I_p

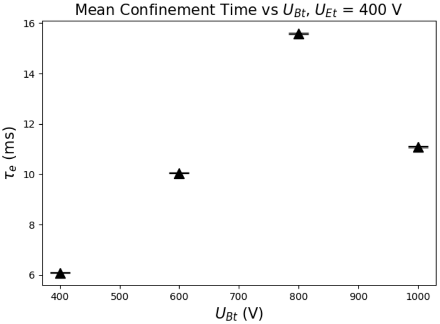
Confinement Time



- Difference in magnitude between using the first approach for density (left) and interferometry (right).

Mean Confinement Time

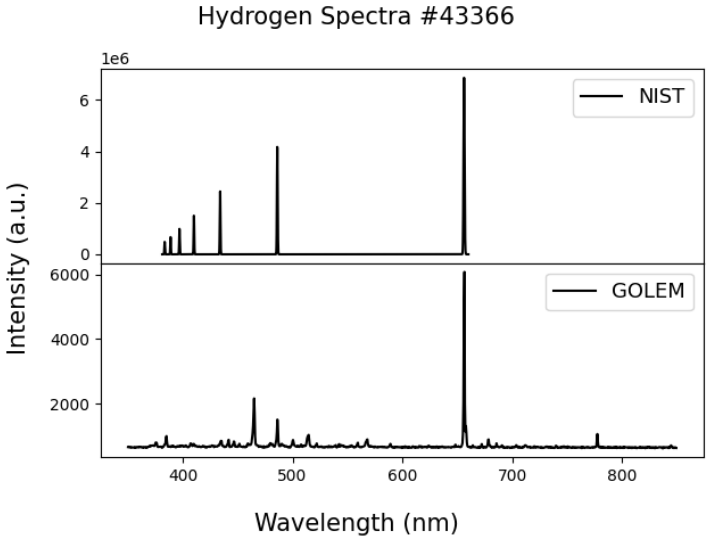




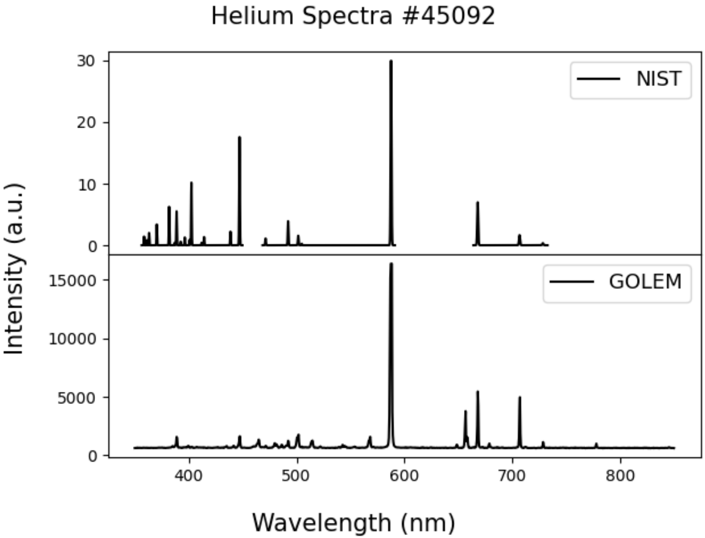
- Confinement time tends to increase with U_{Bt}.
- Consistent with previous studies in other tokamaks $\tau_e \propto Bt^{0.75-0.8}$ (TUMAN-3M) [2]

[2] SV Lebedev y col. “Dependence of energy confinement time on toroidal magnetic field in the TUMAN-3M tokamak”. In: Technical Physics Letters 38 (2012)

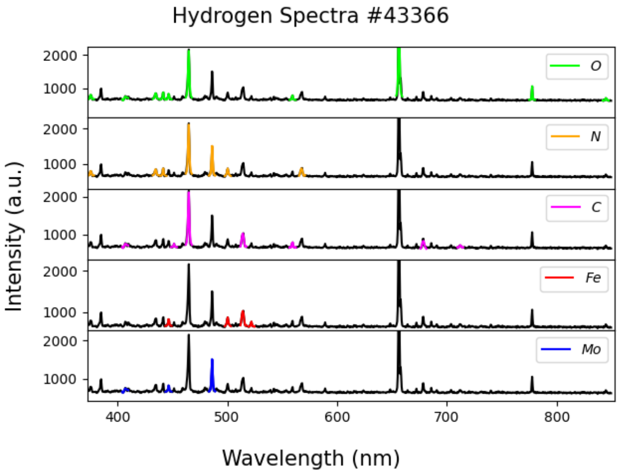
Hydrogen Spectra



Helium Spectra



Found Impurities



Found Impurities

λ (nm)	Impurity	λ (nm)	Impurity
375.87	N_{III}, O_{III}	514.72	C_{II}, Fe_{I}, Fe_{II}
407.08	O_{III}, Mo_{I}, Mo_{V}, C_{II}	522.06	Fe_{III}
409.87	O_{III}	559.56	O_{III}, C_{III}
434.93	O_{II}, N_{III}	568.23	N_{II}
441.88	O_{II}, N_{III}	648.49	N_{II}
446.51	O_{II}, Fe_{I}, Mo_{V}	656.61	O_{II}
451.60	C_{III}	678.65	C_{II}
465.00	C_{III}, O_{II}, N_{II}	712.27	C_{II}
486.21	N_{III}, Mo_{I}	777.72	O_{I}
500.48	N_{II}, Fe_{I}, Fe_{II}	844.77	O_{I}

Conclusions

- Remote operation on a tokamak was achieved, controlling various parameters: U_{Bt}, U_{Et}, p_0 and the used gas.
- Dependency between current, temperature, confinement time and U_{Bt}.
- Confinement time tends to increase with the toroidal magnetic field.
- Plasma current and temperature tend to decrease with U_{Bt}.
- Impurities in plasma: oxygen, nitrogen, carbon, iron and molibden, coming from air and tokamak components.

Future Research

- Increase the number of measurements for more precise results.
- Study the dependency of the parameters with U_{Et} y p_0.
- Study the variation of the impurities when discharges are made.
- Other diagnostics: probes, fast spectrometry, Mirnov coils.
- Possible use of *machine learning* due to the large number of discharges in the Database.