INTEGRATION OF THOMSON SCATTERING AND LASER-INDUCED FLUORESCENCE IN ITER DIVERTOR

Engineering and Performance Analysis

E.E.Mukhin[a], G.S.Kurskiev[a], A.V.Gorbunov[b], D.S.Samsonov[a], S.Yu.Tolstyakov[a], A.G.Razdobarin[a], N.A.Babinov[a], A.N.Bazhenov[a], E.B.Berik[c], I.M.Bukreev[a], P.V.Chernakov[d], Al.P.Chernakov[d], An.P.Chernakov[d], A.M.Dmitriev[a], D.I.Elets[a], M.M.Kochergin[g], A.N.Koval[a], A.S.Kukushkin[b,e], M.G.Levashova[b], A.E.Litvinov[a], V.S.Lisitsa[b], S.V.Masyukevich[a], A.N.Mokeev[f], V.A.Solovei[a], V.V.Solokha[a], I.B.Tereschenko[a], L.A.Varshavchik[a], K.Yu.Vukolov[b], P.Andrew [g], M.Kempenaars [g], G.Vayakis [g], M.Walsh [g]

[a] Ioffe Institute, St. Petersburg 194021, Polytekhnicheskaya 26, Russia, [b] NRC Kurchatov Institute, Moscow, 123182, Akademika Kurchatova sq. 1, Russia, [c] ESTLA Ltd., Tartu, 51014, Riia 185, Estonia, [d] Spectral-Tech, ZAO, St. Petersburg 194223, Kurchatova, 10, Russia, [e] NRNU MEPhI, Moscow, 115409, Kashirskoe sh. 31, Russia, [f] Institution 'Project Center ITER' RF DA, Moscow, 123182, Akad. Kurchatova sq. 1, Russia, [g] ITER Organization, CS 90 046, 13067 St. Paul Lez Durance Cedex, France

FIP/1-5

DTS/LIF integration main drivers

DTS and LIF are both laser aided diagnostics and it seems attractive to use common laser and probing optics – the most sophisticated and expensive part of any ITER optical diagnostics. The combined DTS and LIF approaches can simultaneously measure a set of electron, ion and atom parameters (T_e, n_e, T_i, n_i and $n_{He/H/D/T}$) localized in 24 spatially resolved elements arranged nearly parallel to magnetic surfaces.

SOLPS modelling of detachment requires a detailed knowledge of:

(a) Rates of electron processes, including rates of ionization, recombination and electron induced radiation, playing an important role in cooling and recombination of the divertor plasma flows,

(b) ion-neutral collisions, being not directly involved in the reduction of the plasma flux to the target but playing three important roles in the detachment physics:

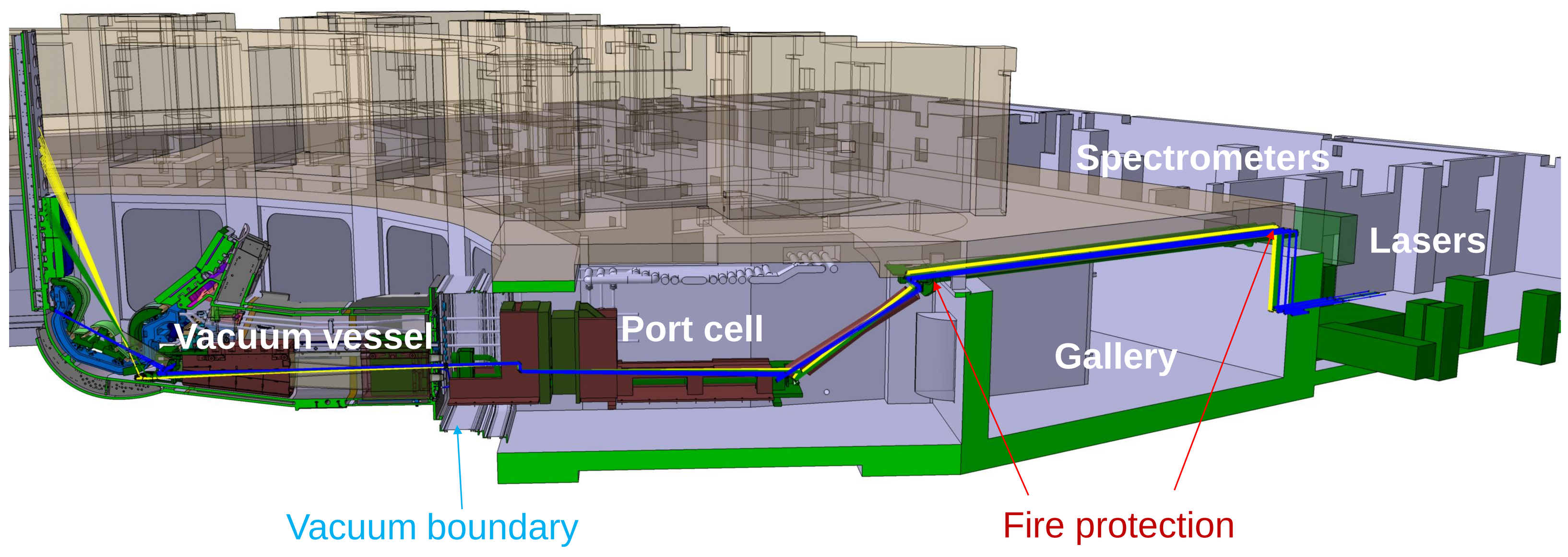
- (1) control effective pressure in the recycling region, with counter-balancing the upstream plasma pressure;
- (2) cool the plasma down to ~1 eV and initiate the recombination processes;
- (3) 'friction' switch the plasma flow from free streaming to diffusion, making the residence time of the electrons and ions sufficient for recombination.

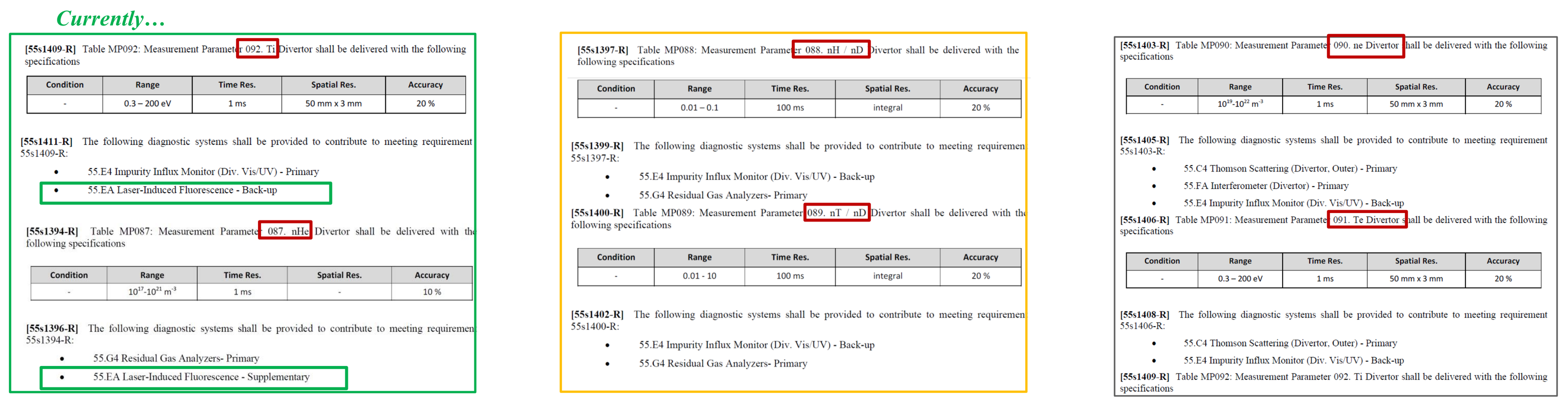
Under detachment, the input plasma flux from the upstream core plasma (free streaming) must be: slowing down from free flow to slow diffusion; cooling down to ~1 eV and finally recombining.

Effective volumetric recombination is possible only at plasma temperatures below ~1 eV, and without recombination, each ion reaching the divertor plate will transfer ~13.6 eV of the recombination energy in the form of heat.

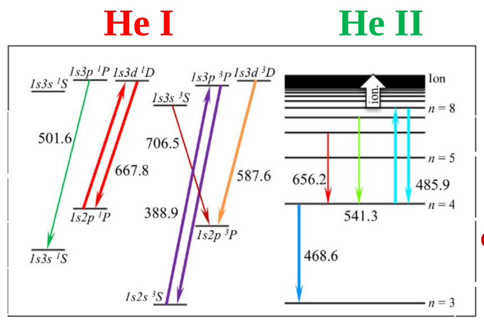
There is an unmet demand for diagnostics able to locally determine plasma characteristics for simulating:

- Ionization balance: rates of ionization and recombination (T_e n_e $n_{He/H/D/T}$);
- Emission intensity (T_e n_e n_i $n_{He/H/D/T}$);
- Frictional force of the plasma flow due to collisions with neutrals (T_i n_i $n_{He/H/D/T}$);
- Pressure of the incoming plasma flow (T_e n_e T_i n_i).





He I | **He II**

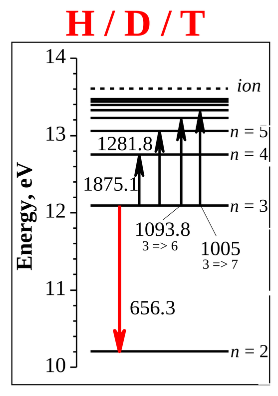


Pumping line	Observation line
388.9	587.6
501.6	667.8
667.8	**587.6**

Pumping: Transition n=4 => n>4

Observation line: **468.6**

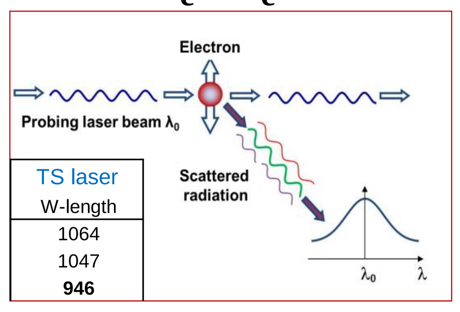
H / D / T



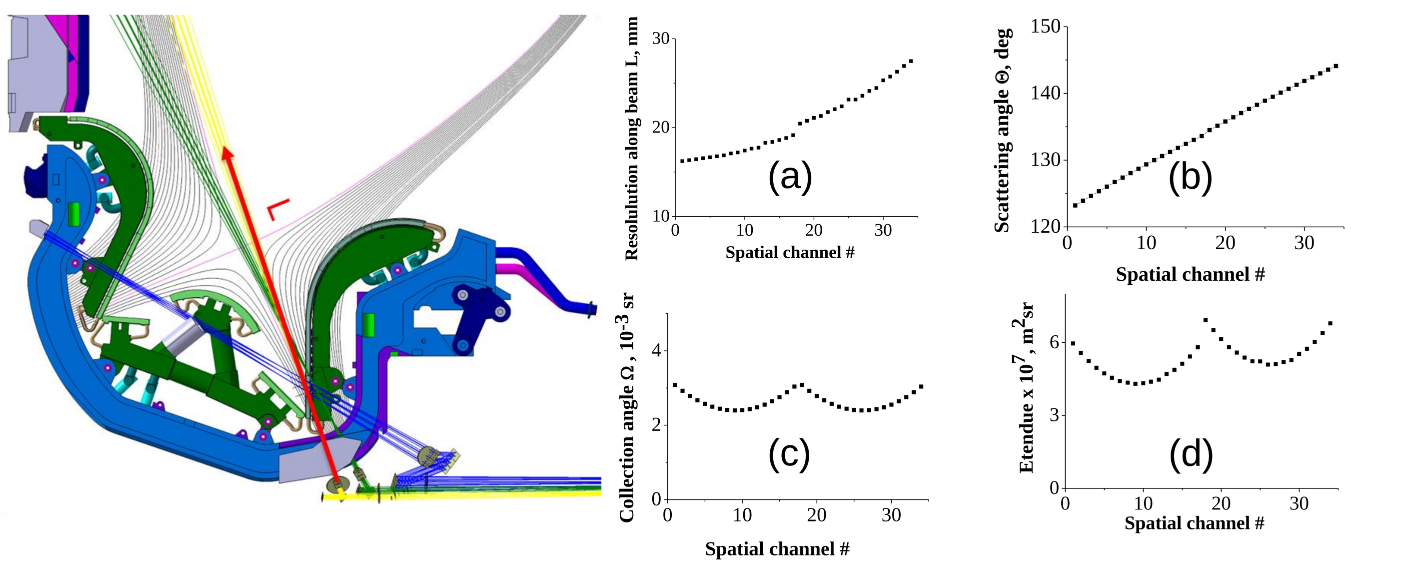
Pumping: Transition n=3 => n>3

Observation line: **656.3 (Hα)**, **656.1 (Dα)**, **656.0 (Tα)**

n_e T_e

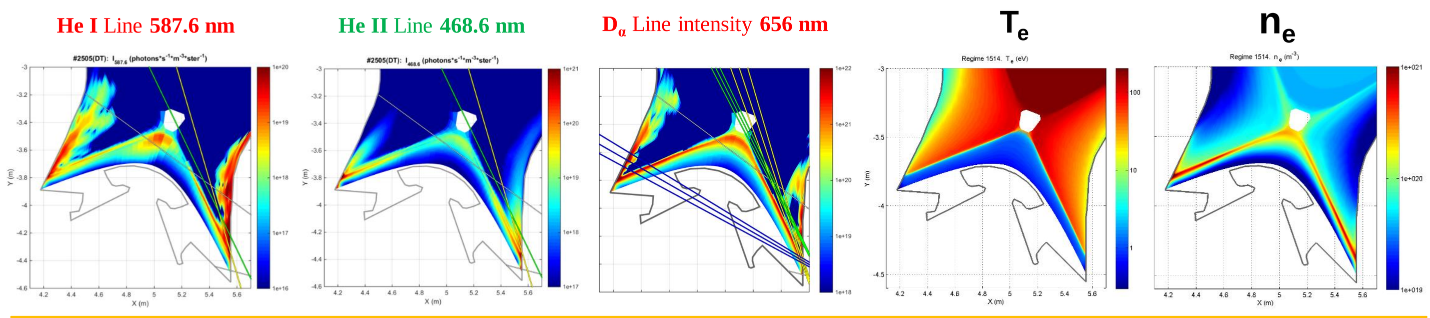


TS laser
W-length
1064
1047
946



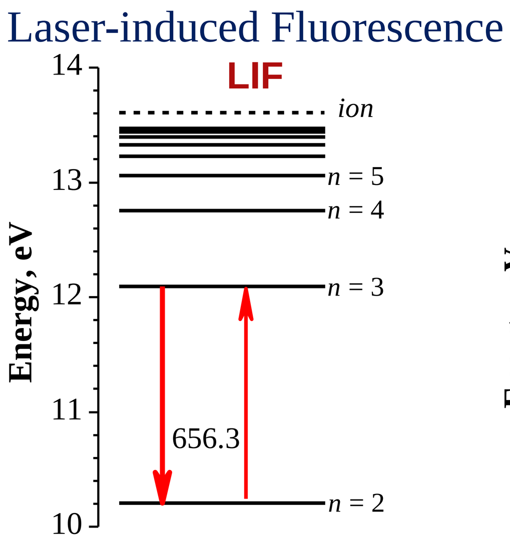
Variation of the collection system optical parameters in different spatial channels. The spatial channel numbers are laid out along the probing chords L from the outer divertor leg bottom: (a) Scattering length, (b) Angle of scattering, (c) Collection angle, (d) Etendue.

He I Line 587.6 nm | He II Line 468.6 nm | D_α Line intensity 656 nm | T_e | n_e

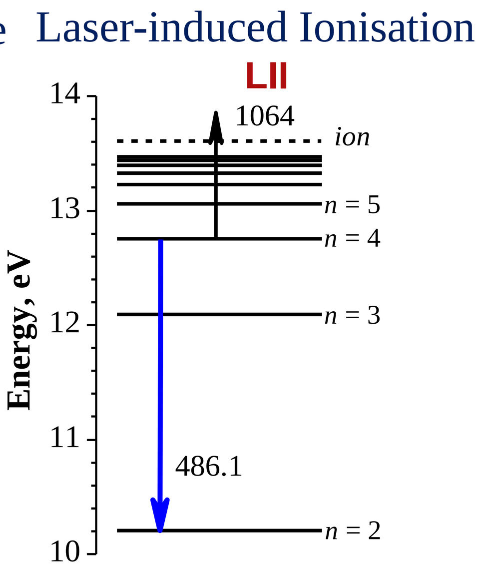


LIF => LII => LIQ H / D / T

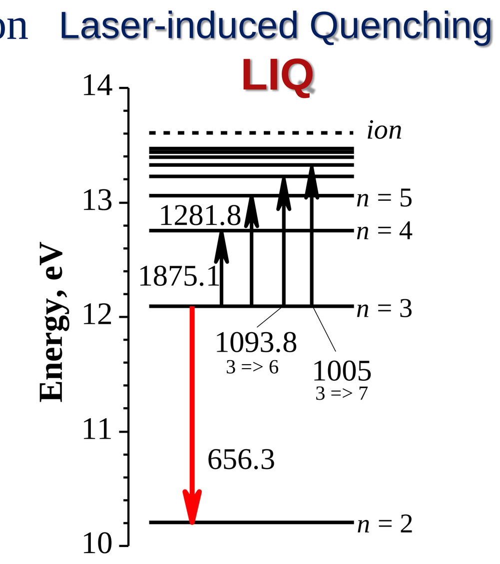
Laser-induced Fluorescence | Laser-induced Ionisation | Laser-induced Quenching



RAZDOBARIN, G., et al, An absolute measurement of neutral density profile in the tokamak plasma by resonance fluorescence on H-alpha line. Nucl. Fusion. 19 (1979) 1439



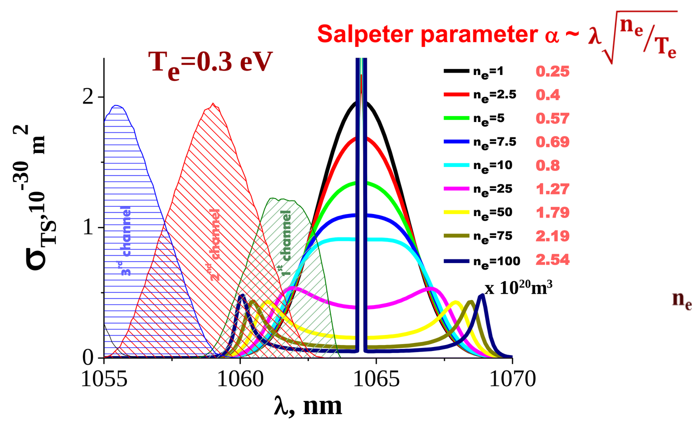
GLADUSHCHAK, V., et al, Measurement of neutral density profile in a tokamak plasma using the principle of laser induced ionization, Nucl. Fusion 35 (1995) 1385



For Helium was suggested in GORBUNOV A. et al, Laser-induced Fluorescence for ITER Divertor Plasma Fusion Engineering and Design Volume 123, November 2017, Pages 695-698

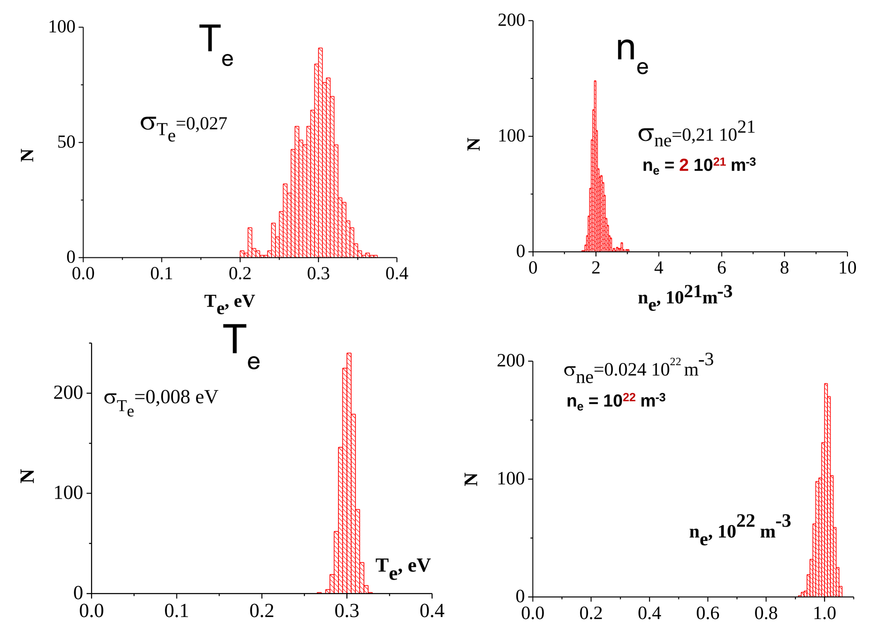
Thomson scattering in ITER divertor

In cool and dense plasma the laser wavelength approaches Debye length and distortions of Gauss shape in scattered spectra become obvious



Gauss shape approximation is valid for $\alpha \lesssim 0.2$

3eV < T_e < 1000eV for $n_e \lesssim 10^{21}$ m^3, no relativistic distortion



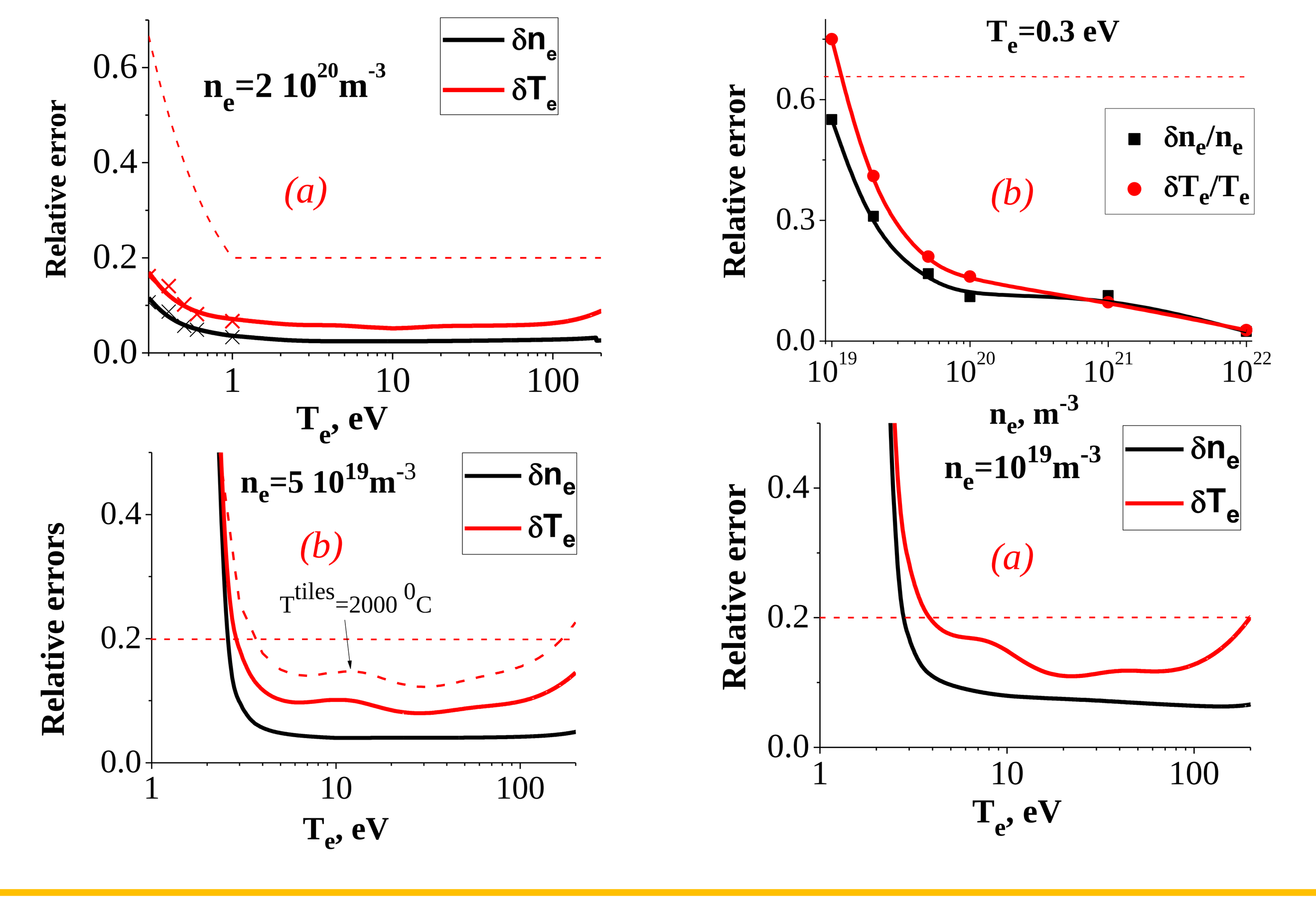
The expected n_e and T_e errors were assessed using the following algorithm:

(a) estimation of signals in spectral channels based on the known engineering parameters and using TS spectra shape;

(b) multiple solution (10^3 runs) of the inverse problem of the recovery of T_e and n_e from the TS signals simulated for given n_e and T_e with allowance for random deviations $\sigma_{N_{fe_i}} = \sqrt{k\left(N_{fe_i} + 2N_{bg_i}\right) + 2N^2_{AMP}}$

where k ~2.5 - APD excess noise, N_{bg} - number of background photoelectrons
N_{amp} ~ 50 -contribution of the detector and amplifier noise reduced to the input of the detector
Measurement accuracy of the TS signal to be not less than 2.5%, assuming probable systematic errors

(c) standard deviation distribution functions of the measured T_e and n_e, with the expected measurement accuracy.



Relative measurement errors of n_e and T_e.

Background radiation - from SOPLS run #1514 matching n_e^2 dependence.
Dashed line marks the acceptable accuracy.

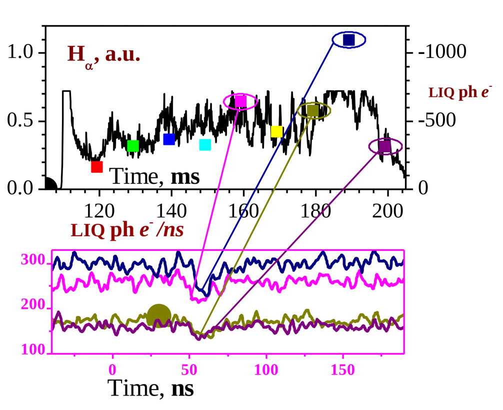
(a) Errors of T_e and n_e for n_e=2 10^{20} m^{-3} solid curves – analytical approximation, crosses – errors (numerical experiment);
(b) Errors of T_e and n_e for T_e=0.3 eV

Relative measurement errors of T_e :

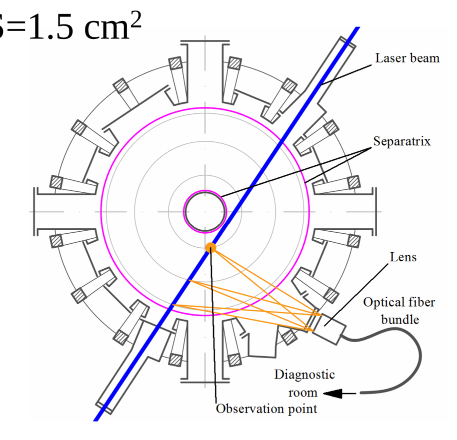
(a)- for n_e=10^{19} m^{-3},
(b)- for n_e=5 10^{19} m^{-3}, which is the minimum density (SOLPS run #1514 yielding peak load ~8 MW/m^2)
Dashed line corresponds to divertor temperature 2000 C.
Continuum background is 5-fold overestimated.

LIF in ITER divertor

Measurement Globus-M
H_α LIQ

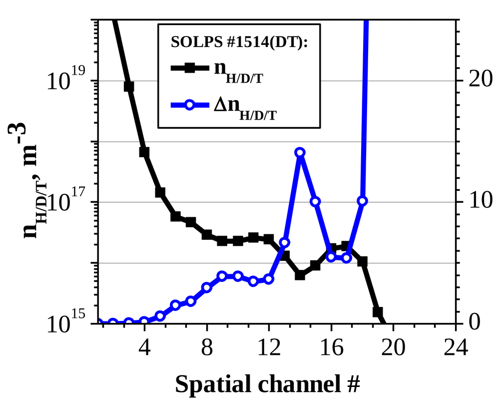


Pumping n = 3 → 7
OPO laser λ =1005 nm
Δλ =2000 pmτ =10 ns
E =2.2 mJ
S=1.5 cm^2



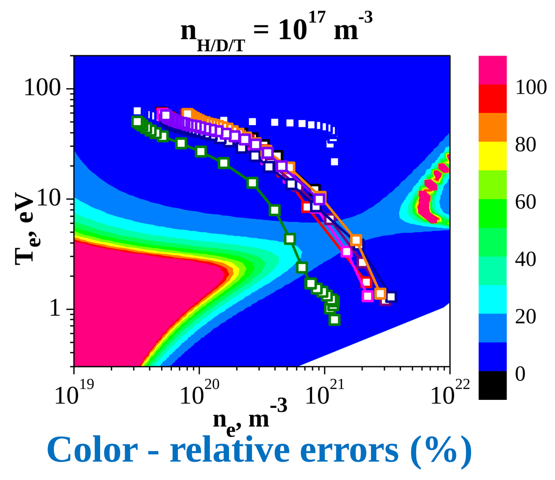
plasma core r/a=0.7

Simulation for ITER divertor
D_α LIQ



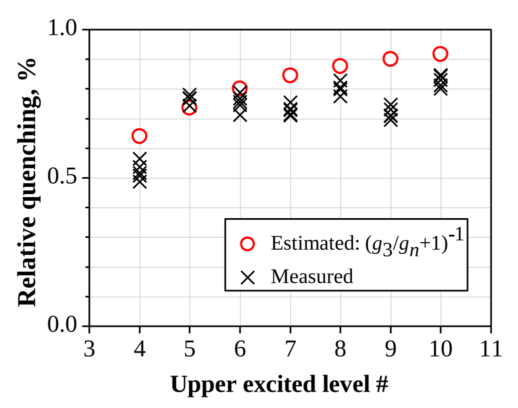
Pumping n = 3 → 5
λ =1281.8 nm,
Δλ =2000 pm,
τ =10 ns, E =2.2 mJ,
S=1.5 cm^2

$n_{H/D/T}$ = 10^{17} m^{-3}

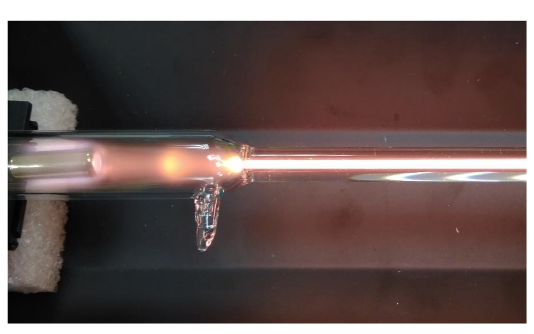


Color - relative errors (%)

Measurement Deuterium lamp
D_α LIQ



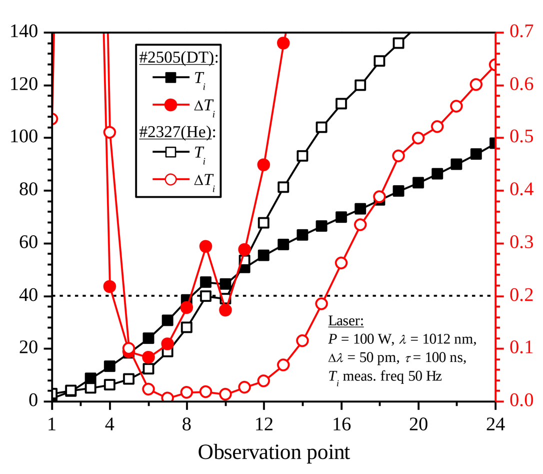
OPO laser λ =1005 nm
Δλ =2000 pmτ =10 ns
E =2.2 mJ
S=1.5 cm^2

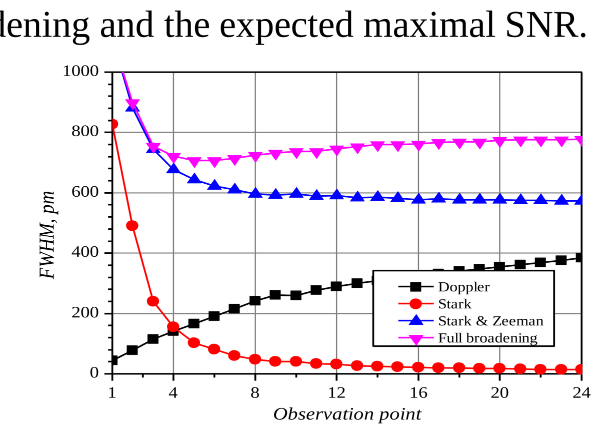


LIQ He II for T_i (see details in GORBUNOV A. et al, Implementation of Laser-induced Fluorescence Diagnostics in ITER, SOFT 2018)

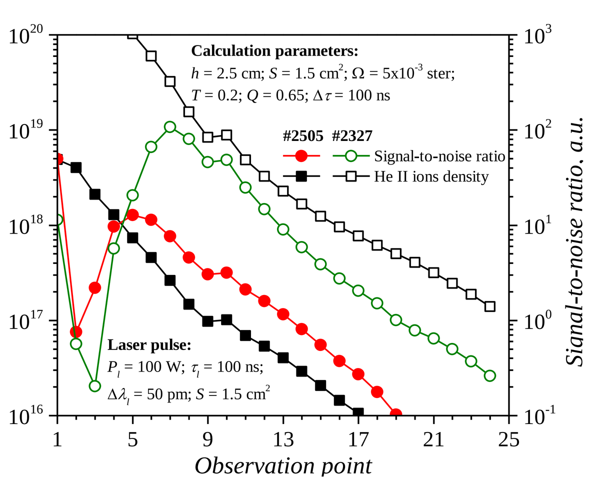
Measurement of T_i is based on scanning excitation line with a narrowband tunable laser and deconvolution of thermal component from entire broadening.

The transition n = 4 → 5 (1012.3 nm) is chosen for 468.6 nm line quenching due to minimal influence of Stark broadening and the expected maximal SNR.



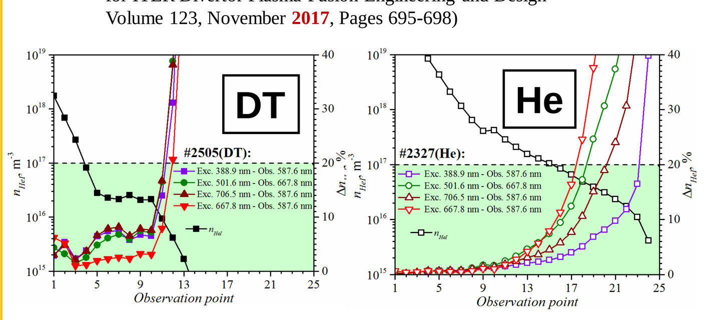


He II 1012.3 nm line broadenings Doppler, Stark and Zeeman



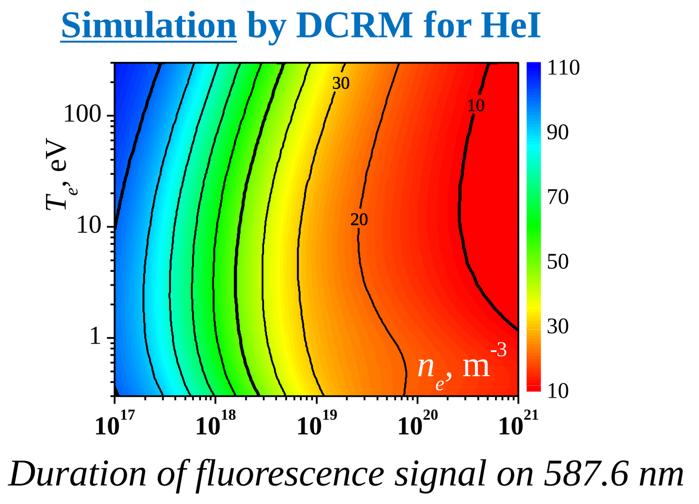
LIF He I for n_{HeI}

(see details in GORBUNOV A. et al, Laser-induced Fluorescence for ITER Divertor Plasma Fusion Engineering and Design Volume 123, November 2017, Pages 695-698)



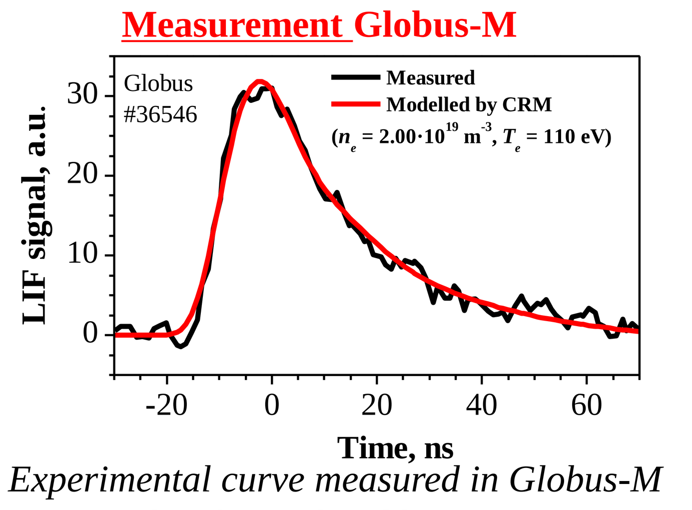
LIF He I for n_e

Simulation by DCRM for HeI



Duration of fluorescence signal on 587.6 nm
Excitation on 388.9 nm
Laser: 10 ns / 1 mJ , Δλ$_l$ =50 pm S = 1 cm^2

Measurement Globus-M



Experimental curve measured in Globus-M compared with simulated by DCRM HeI

Acknowledgement: This report supported in part by Rosatom (contract - N.4a.241.19.18.1027) was prepared as an account of work for the ITER Organization. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.