Ioffe Institute
NATIONAL RESEARCH CENTER
"KURCHATOV INSTITUTE"

Integration in ITER Divertor

FIP/1-5

Thomson Scattering & Laser-induced Fluorescence

Engineering and Performance Analysis

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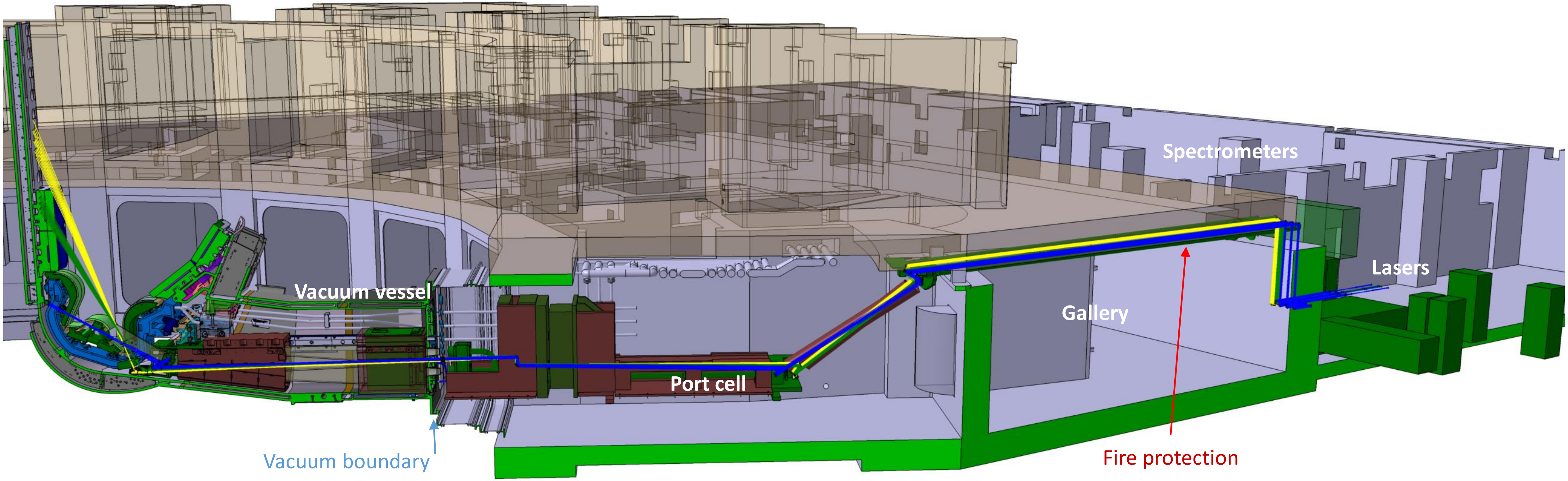
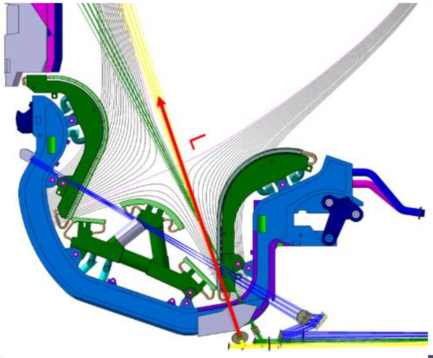


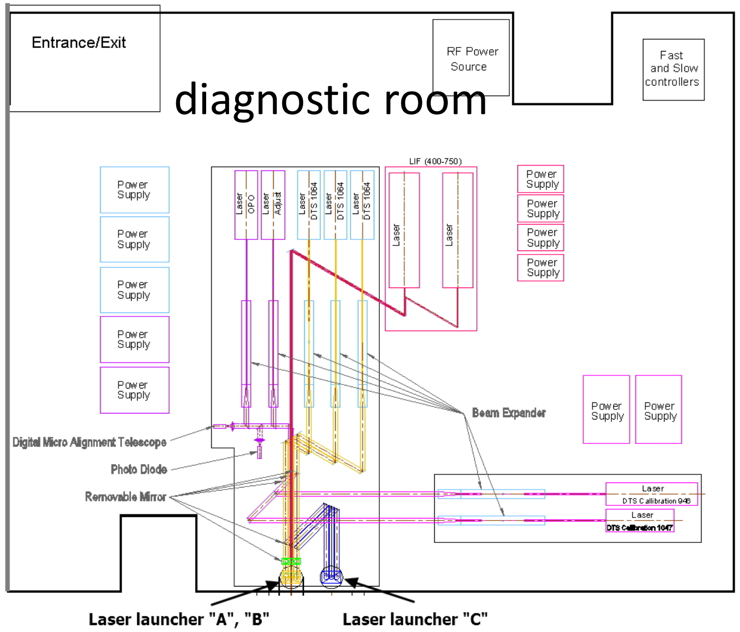
Diagnostic equipment occupies over 40 m, from diagnostic room and gallery to port cell, between bio-shield & vacuum boundary…

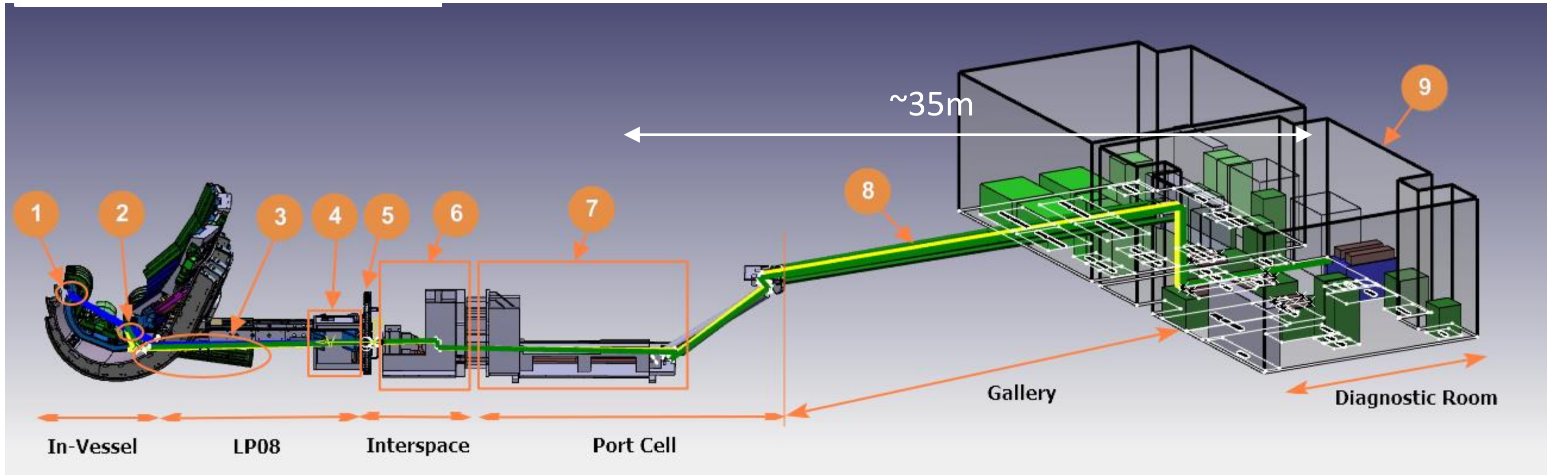
Lasers, relay and injection optics



DTS and LIF have different wavelengths and combine into a single beam path in diagnostic room through several mirrors with selective reflection

The beam path can be switched in diagnostic room between several probing chords, thus improving reliability



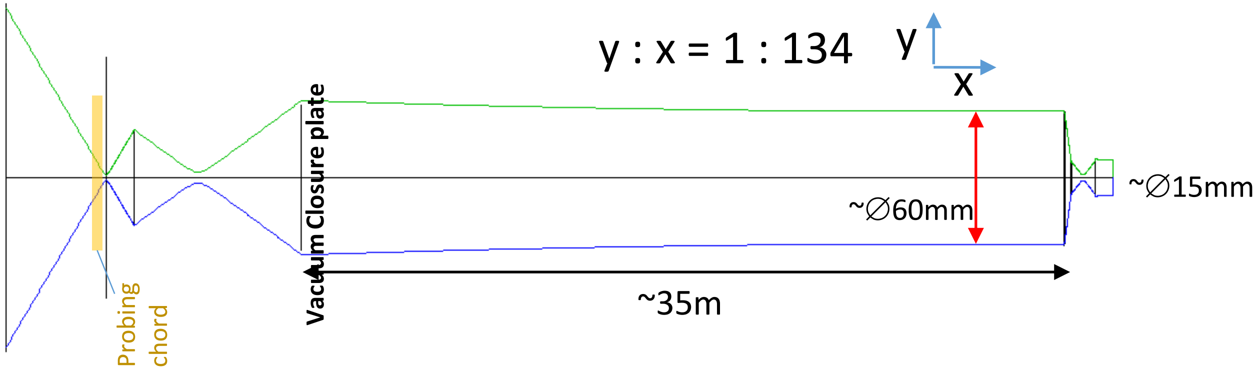


Main DTS laser - Nd:YAG (1064 nm)

(see A.Kornev et al Nd:YAG Lasers for ITER Divertor Thomson scattering SOFT 2018)

Diode-pumped, High beam quality

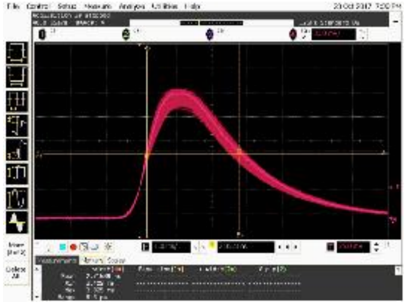
Narrow spectrum, Stable pulse shape



Wavelength	**1064 nm**
Pulse energy	**2 J**
Repetition rate	**50 Hz**
Pulse length	**3 ns**
Beam quality	**1.3×DL**

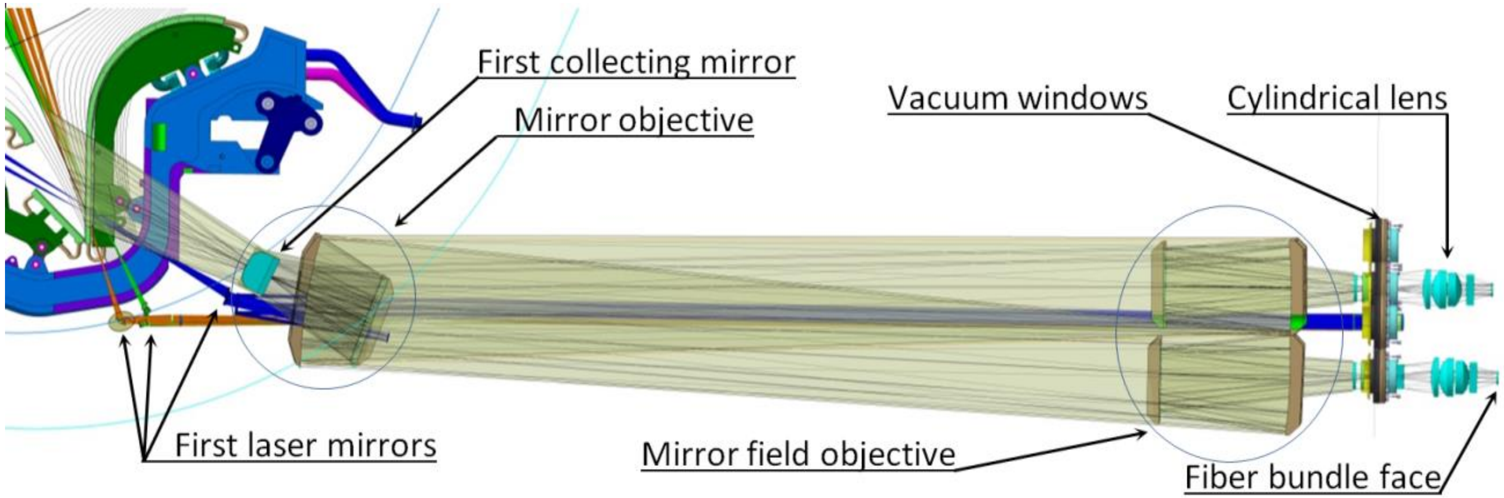
Pulse shape stability > 99.5 %

Energy stability RMS < 1 %



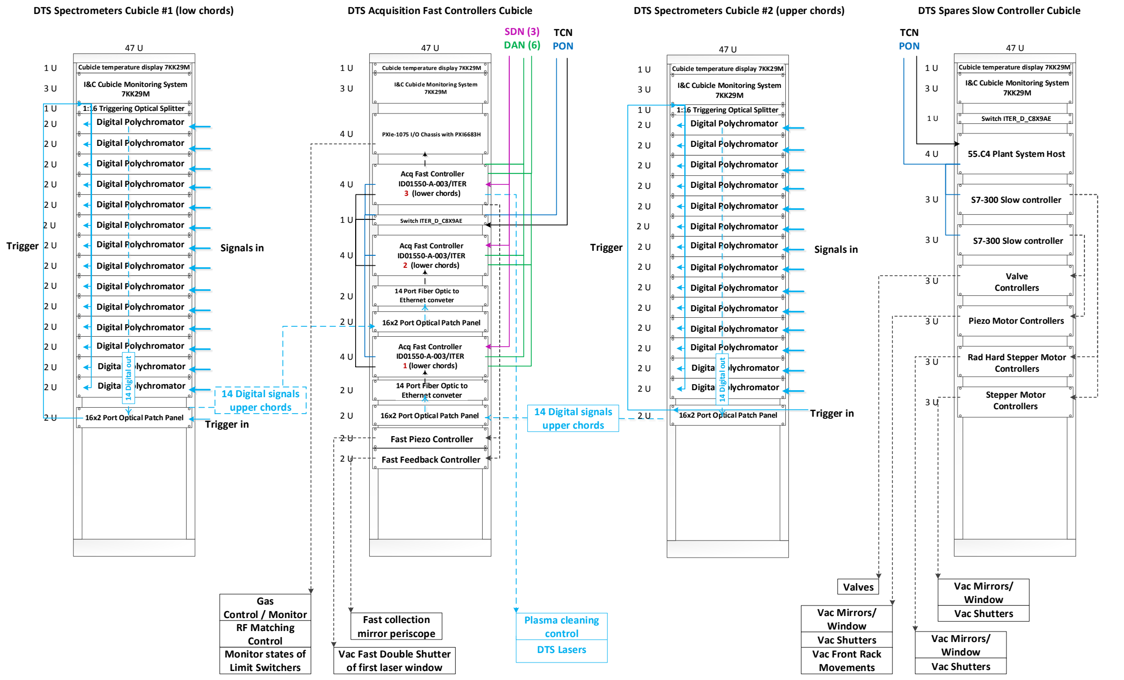
Collection system

The scattered light is collected into a solid angle extended vertically



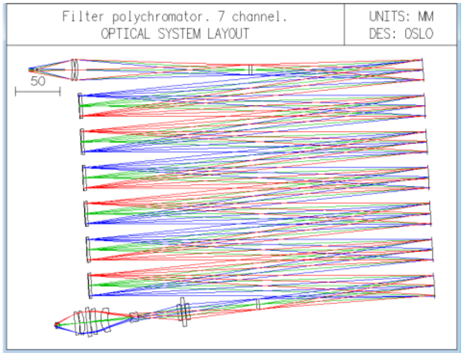
2 cylindrical lenses correct vertical distortions of output collection angles

Control and Data Acquisition system



Digital filter polychromator specially developed for ITER

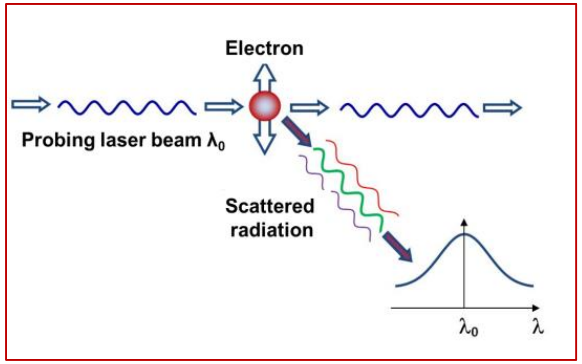
(E.Mukhin et al Hardware solutions for ITER divertor Thomson scattering **123** FED 686 2017)



- Up to 7 optical bandpath filters
- Low-power, no cooling required
- Compact mechanical form-factor 19” 2U
- Digitizing 5 GHz, 12 bit
- APD ∅1.5mm ultra-low noise TIAs with response time ~3ns
- Optical Gigabit Ethernet
- Built-in signal processing
- Polychromator is able to operate independently

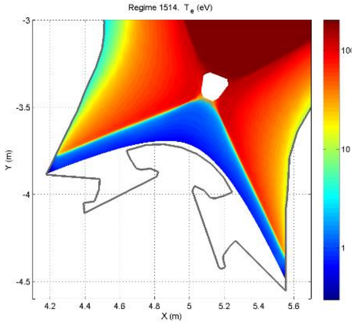
Thomson Scattering & Laser-Induced Fluorescence

Divertor Thomson Scattering 55.C4

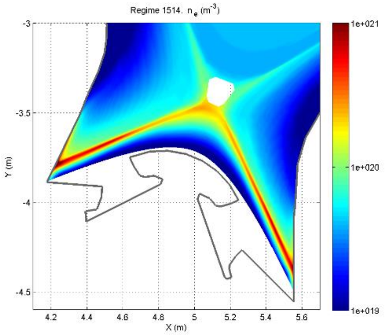


DTS	n_e	10^{19} - 10^{22} m^{-3}	20 ms / 50 Hz	20%
	T_e	1-200eV	20 ms / 50 Hz	20%
		0.3-1eV		0.2eV

T_e

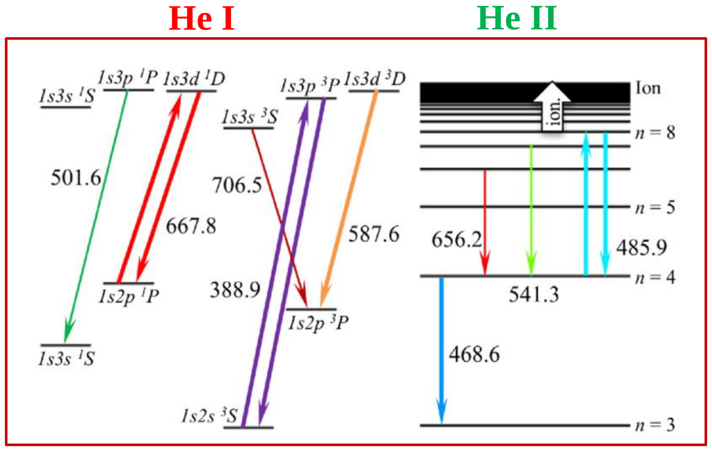


n_e



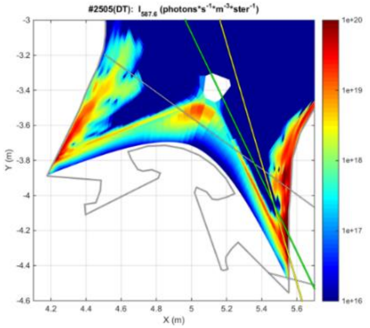
TS on free electrons routinely measures n_e via overall spectrum intensity and T_e via TS spectrum shape / width.

Laser Induced Fluorescence 55.EA

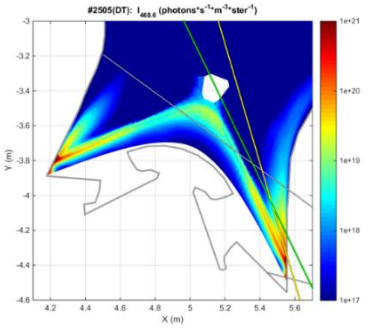


LIF	n_{HeI}	10^{17} - 10^{21} m^{-3}	20 ms / 50 Hz	20%
	T_i	0.3 - 200eV	20 ms / 50 Hz	20%

He I line **587.6 nm**



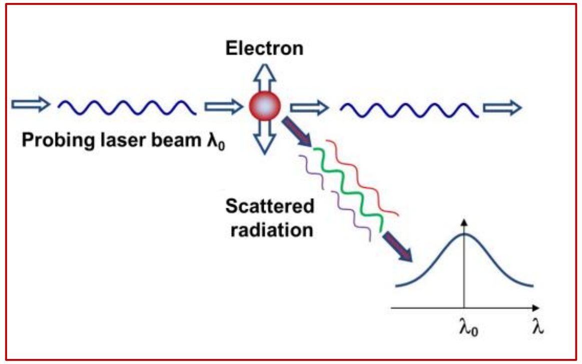
He II line **468.6 nm**



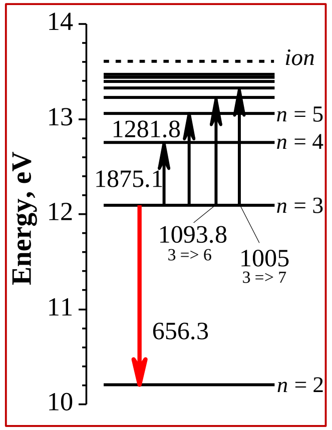
LIF is now responsible for measuring T_i via broadening of hydrogen-like helium ion spectral lines and n_{HeI} based on line radiation of helium atoms.

Thomson Scattering & Laser-Induced Fluorescence + LIQ for H/D/T

Divertor Thomson Scattering 55.C4

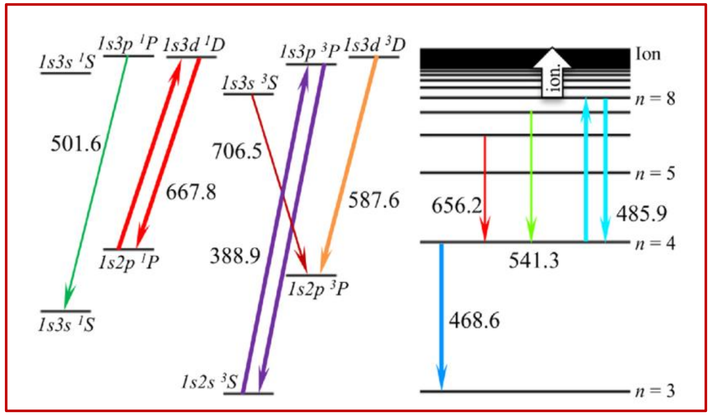


LIF abilities can be extended to measurements of **H/ D/ T**



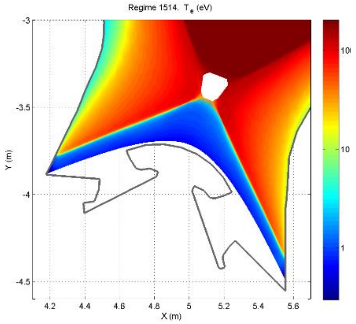
Laser-Induced Fluorescence 55.EA

He I **He II**

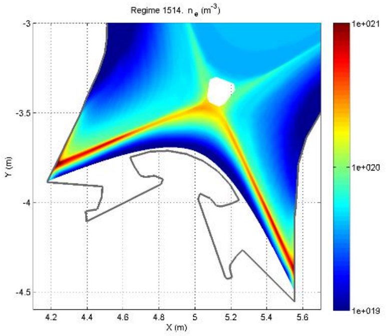


We suggest diagnostics of $n_{H/D/T}$ based on suppression of $H_\alpha/D_\alpha/T_\alpha$ radiation:
Laser-Induced Quenching (LIQ) via pumping transition from 3rd to one of the upper states

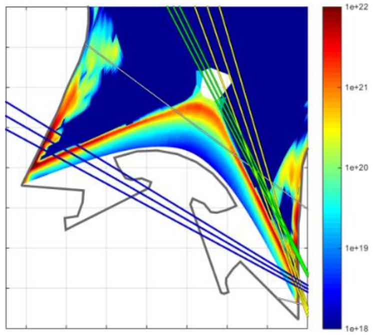
T_e



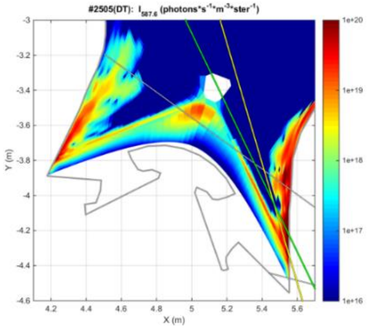
n_e



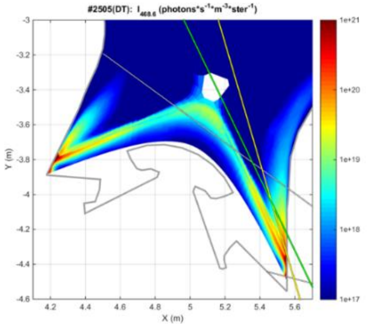
D_α line 656 nm



He I line 587.6 nm



He II line 468.6 nm



Maximum background intensity on the working lines is concentrated in the vicinity of strike point, where loads on divertor targets can reach dangerous levels => the detachment operational mode of ITER divertor needs comprehensive study

Divertor SOL T_e, n_e, T_i, n_i $n_{He/H/D/T}$ measurements

SOLPS modelling of detachment in ITER divertor requires a detailed knowledge of:

- **Electron** processes, including rates of ionization, recombination and radiation,

- **Ion-Neutral** collisions responsible for:

(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; (without recombination each ion reaching the plates will transfer 13.6 eV in the form of heat)

(3)'Friction' switching the plasma flow from free streaming to diffusion, making the residence time of the electrons and ions sufficient for recombination.

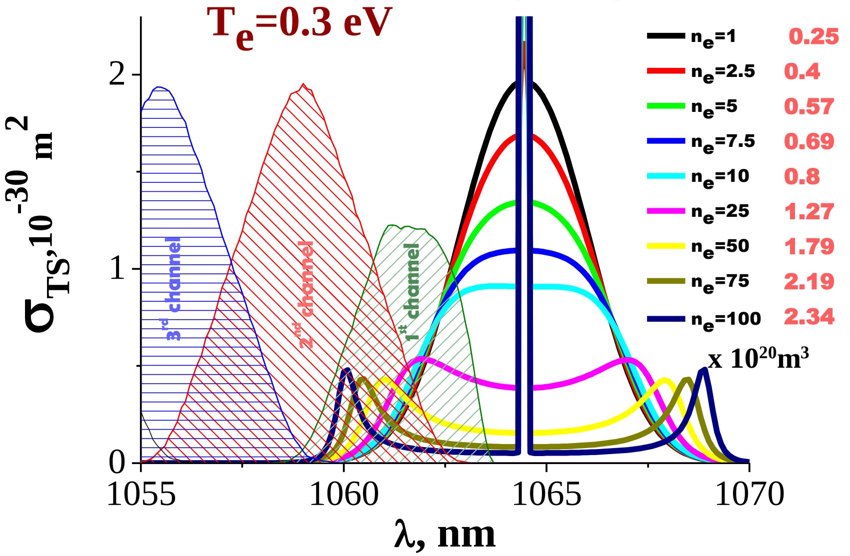
Measuring T_e, n_e, T_i, n_i $n_{He/H/D/T}$ simultaneously, we can calculate in the respective points of the divertor SOL the following important parameters:

- 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 forces determined by 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).

TS cross section

Since the recombination rate increases more rapidly at T_e below ~0.5 eV, this T_e measured **± 0.2 eV** is sufficient for code validation

Salpeter parameter $\alpha \sim \lambda\sqrt{n_e/T_e}$

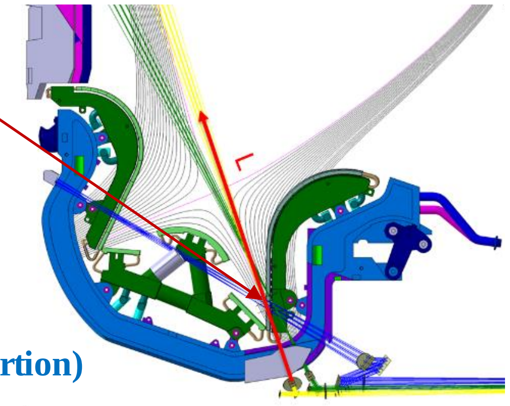


Gaussian approximation is valid for $\alpha \lesssim 0.2$

3eV <T_e <1000eV

(for $n_e \lesssim 10^{21}m^3$)

(no relativistic distortion)



But in cool and dense plasma, the laser wavelength approaches Debye length, and distortions of gaussian shape in scattered spectra become obvious.

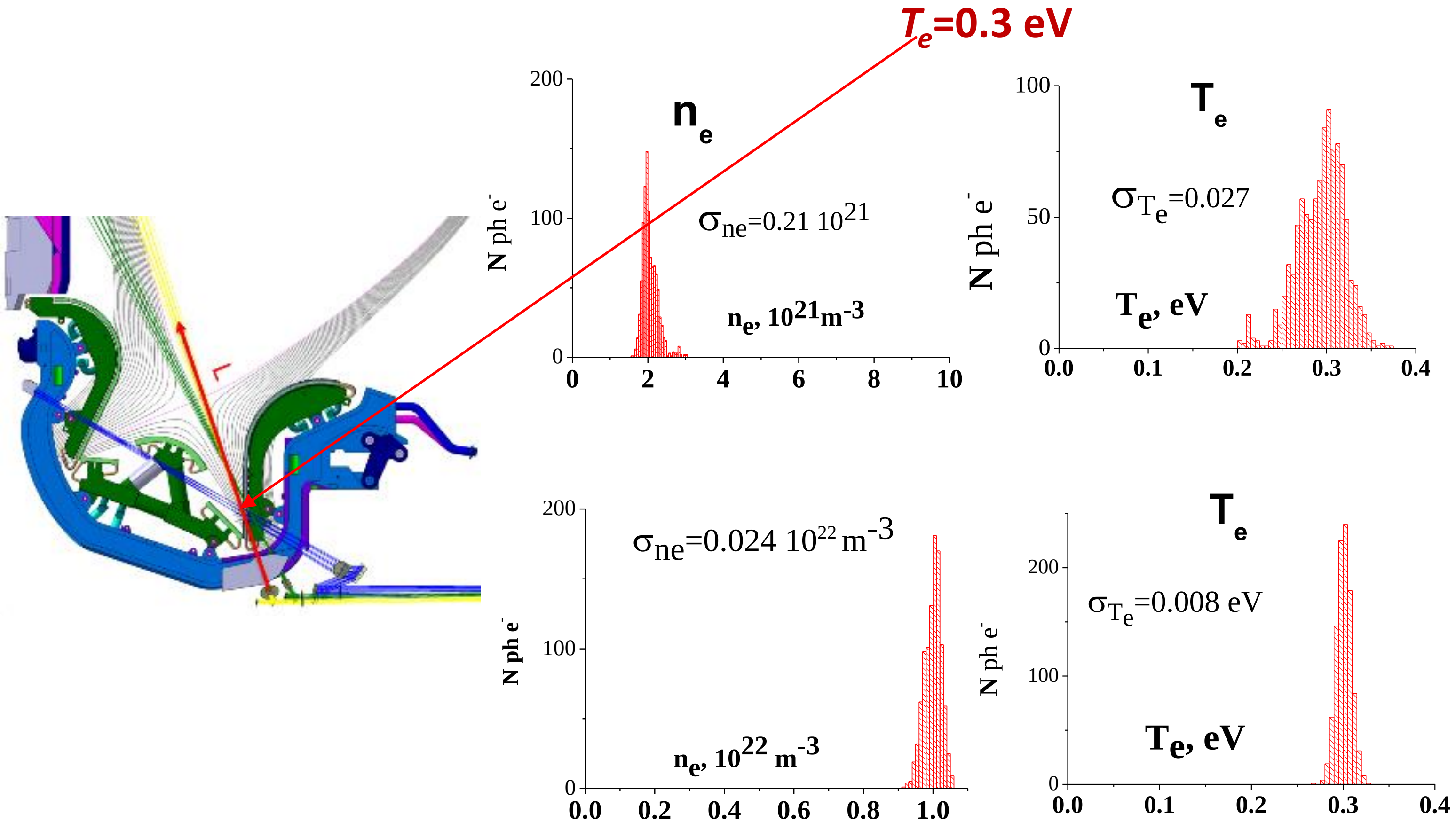
According to Salpeter parameter, the collective effects should be taken into account =>

Conventional analytical calculations of ΔT_e and Δn_e measurement errors are not valid for non-gaussian distribution

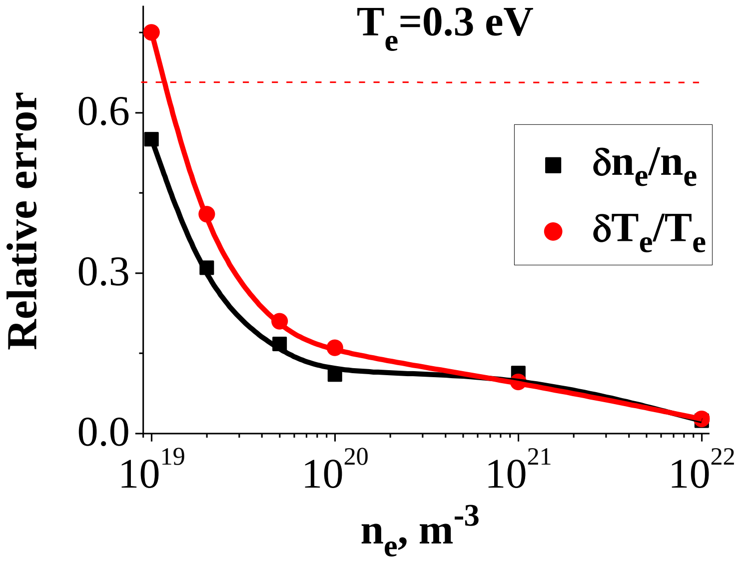
Numerical experiment for n_e and T_e errors assessment

For our non-Gaussian distribution,

we assessed errors via multiple recovery (10^3 runs) of n_e and T_e from random noised signals in spectral channels



The higher density and distortion, the lower errors!



Conclusion: the requirements of 0.2 eV accuracy are met throughout n_e operational range 10^{19} - 10^{22} with slightly worse lower limit (n_e=1.2 10^{19} m^{-3})

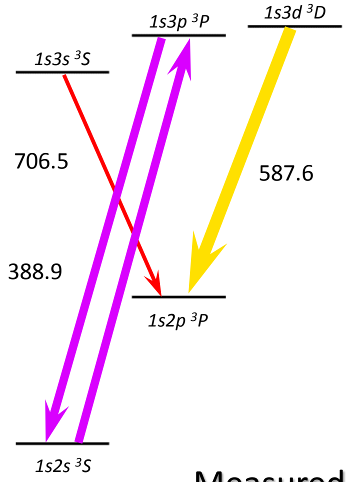
He I LIF pulse duration for measuring n_e

LIF can help measure n_e as low as 10^{18} m^{-3} based on fluorescence pulse duration.

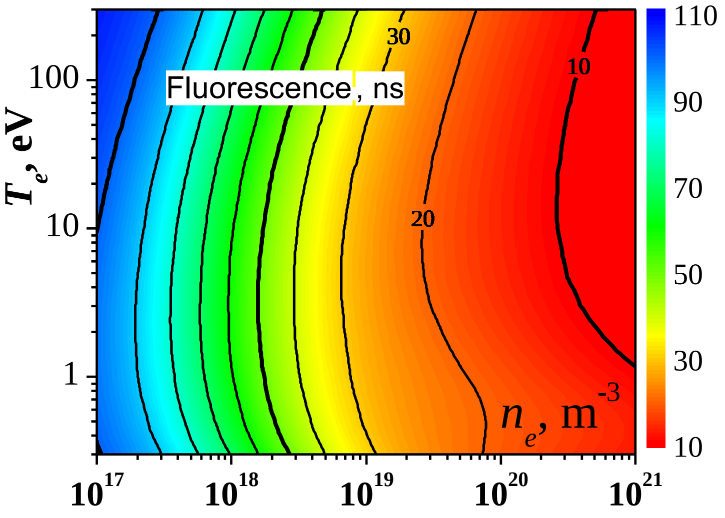
Temporal shape of fluorescence signals depends on parameters of laser, pumping transition and local plasma parameters (n_e & T_e).

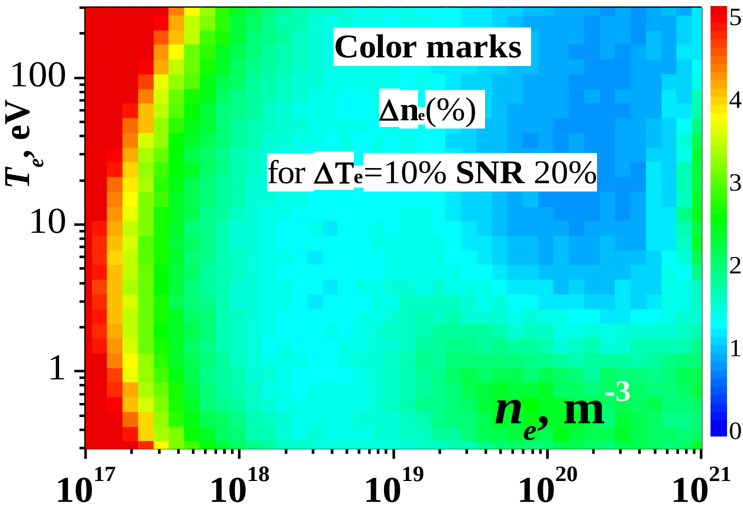
Our Dynamic Collision-radiative Model (DCRM) for **He I** allows fitting calculated temporal shape to the measured fluorescence signals

He I Spectroscopic scheme



Laser	388.9	$1s2^3S$ - $1s3^3P$
Fluor	587.6	$1s3^3D$ - $1s2^3P$

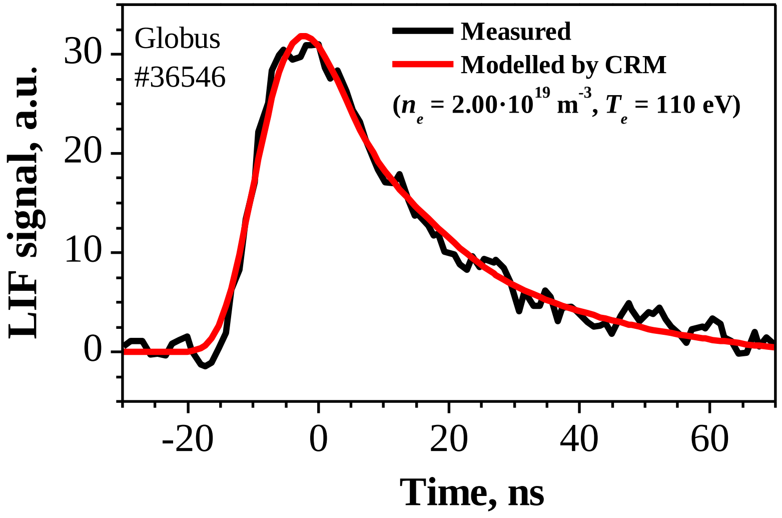




Measured and modelled signals

Globus #36546 discharge

(n_e = $2\cdot10^{19}$ m^{-3} and T_e = 110 eV)



Laser:
10 ns / 1 mJ
$\Delta\lambda_l$ =50 pm S = 1 cm^2

TS vs LIF experiments on Globus-M show good agreement:

Thomson T_e ~ 110 eV

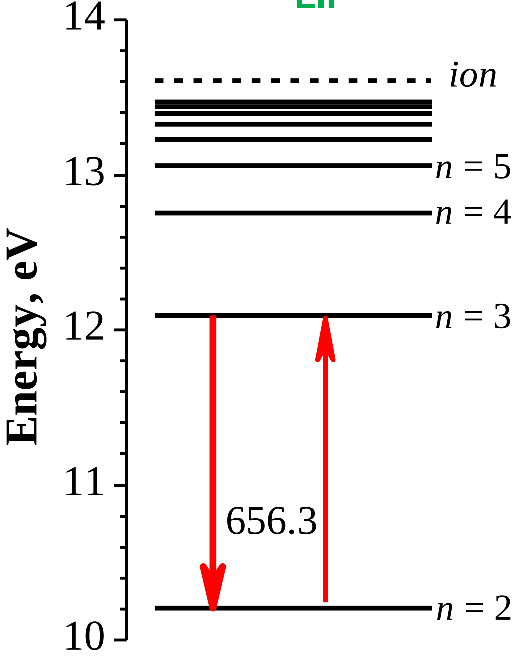
n_e = (2.4±0.2) ×10^{19} m^{-3}

LIF n_e = (2.0±0.6) ×10^{19} m^{-3}

LIF / LII / LIQ for H/D/T density measurements

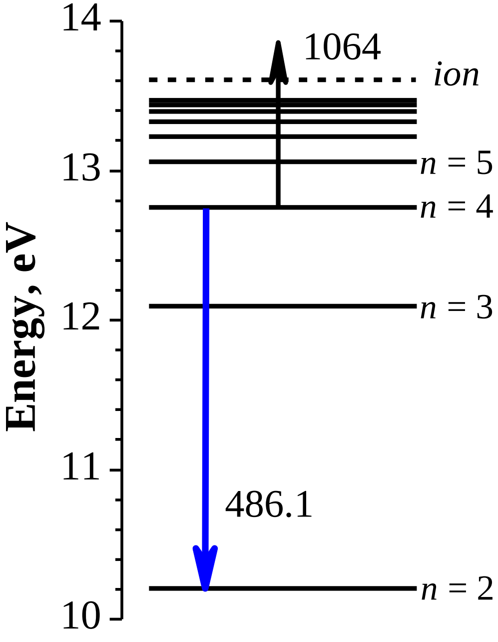
Attempts to establish diagnostics of H/D/T density as a routine one have been made for ~ 40 years:

Laser-induced Fluorescence
LIF



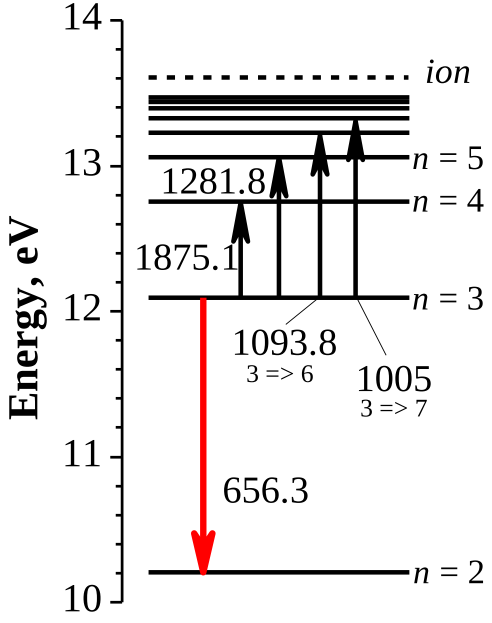
RAZDOBARIN, G., et al, An absolute measurement of the neutral density profile in the tokamak plasma by resonance fluorescence on H-alpha line. Nucl. Fusion. **19** (**1979**) 1439

Laser-induced Ionisation
LII



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

Laser-induced Quenching
LIQ



For He II 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

In 2018, our team has initiated development of LIQ for H/D/T

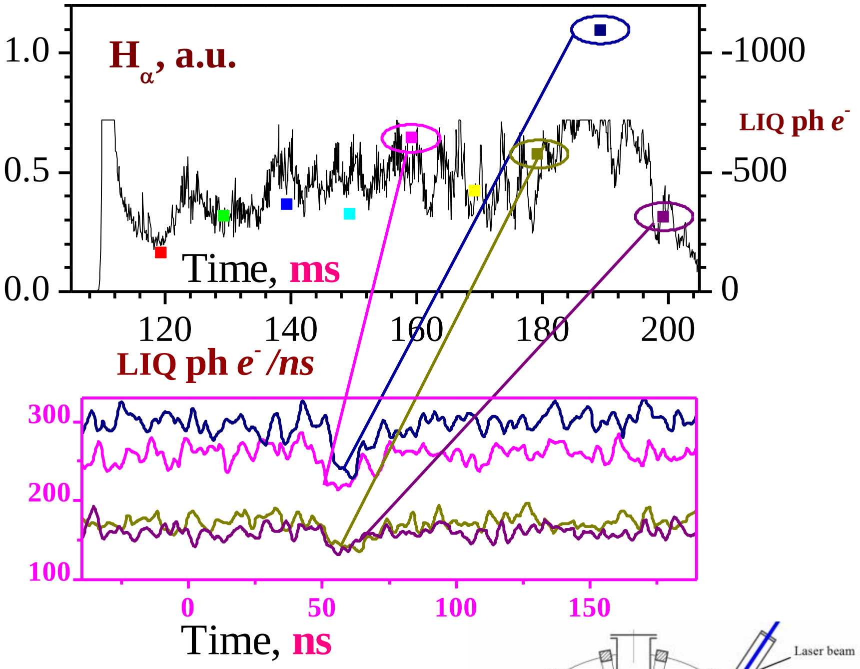
LIQ for H/D/T density benefits:

- pumping wavelengths shifted from the observed one by hundreds of nm as in **LII**
- pumping transition cross-section ~ **LIF** =>laser energy << **LII** and rep rate > **LII** can be achieved
- H/D/T excitation line can be scanned by tunable laser => spectroscopy measurements as in **LIF**

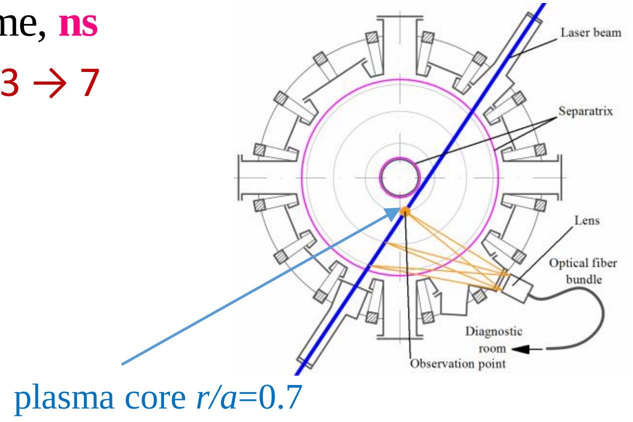
LIQ for H/D/T density measurements

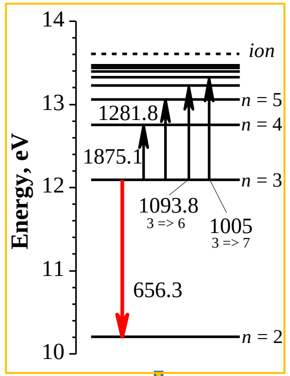
H_{alpha} signal suppression for transition from 3rd to 7th levels only could be distinguished without signal accumulation

Experiment: Globus-M H_α LIQ



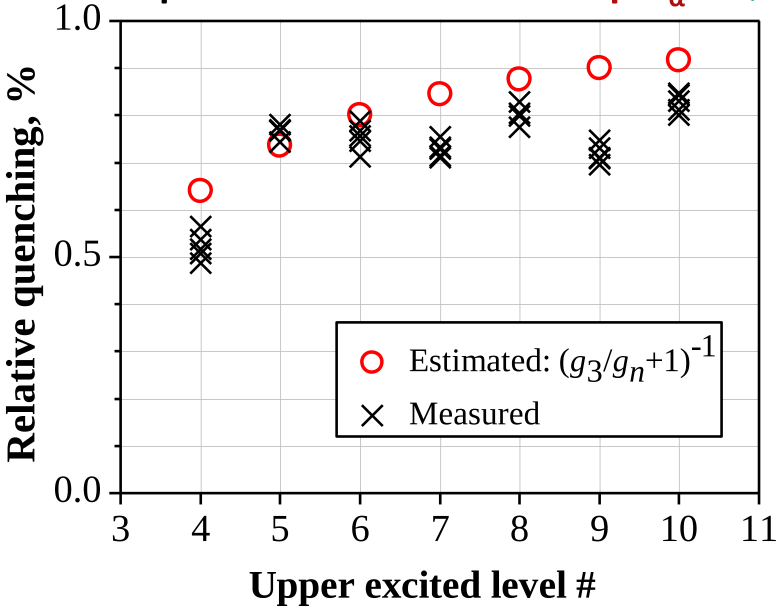
Pumping n = 3 → 7
OPO laser
λ =1005 nm
Δλ =2000 pm
τ =10 ns
E =2.2 mJ
S=1.5 cm^2

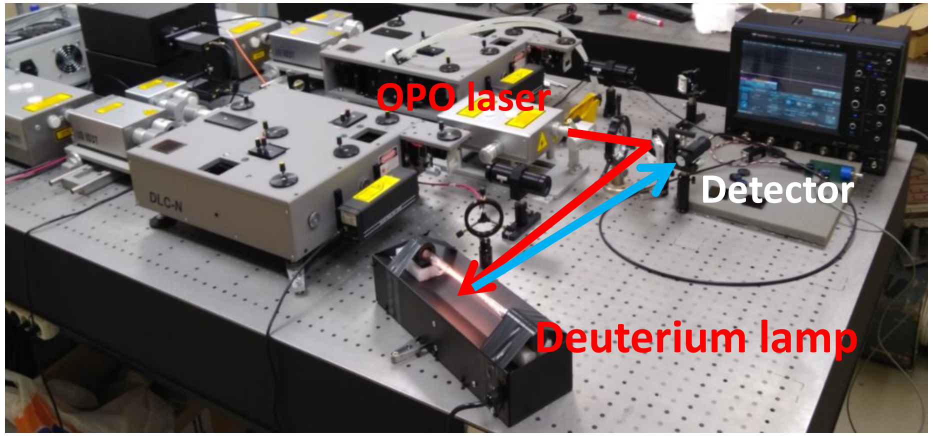




Significant suppression of H_{alpha} was observed for several transitions from 3rd to upper levels in line with predictions

Experiment: Deuterium lamp D_α LIQ





LIQ functionality for ITER divertor (H/D/T)

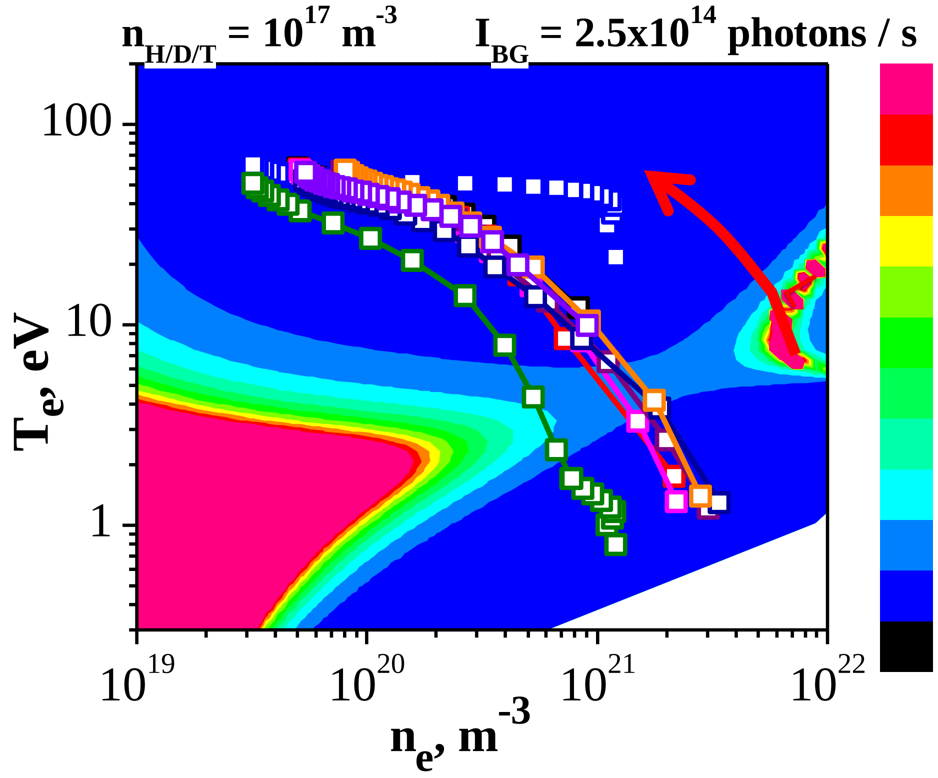
Conditions of accuracy assessments :

Hydrogen density $10^{17} m^{-3}$

Accumulation of 20 pulses

Squares mark positions of spatial channels for several SOLPS runs

Colours mark errors **Δ $n_{H/D/T}$ (%)**



n_e T_e provided by DTS (50 Hz)

1 kHz OPO => accumulation of 20 LIQ signals, better accuracy

Conclusion: most **Δ $n_{H/D/T}$ (%)** < 10%.

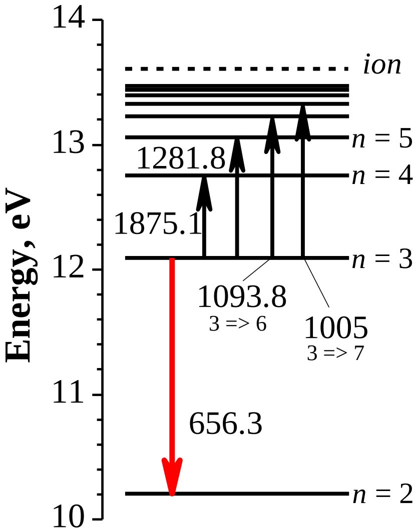
Pumping n = 3 → 5

λ =1281.8 nm,

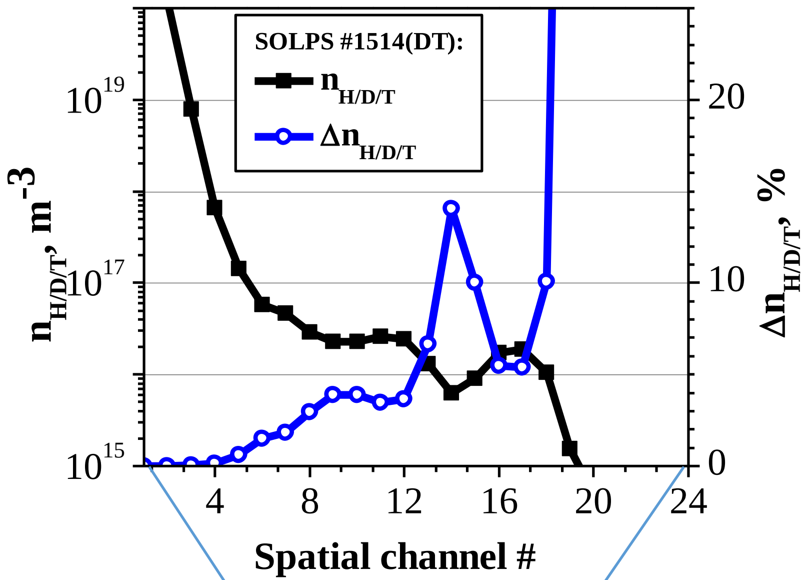
Δλ =2000 pm,

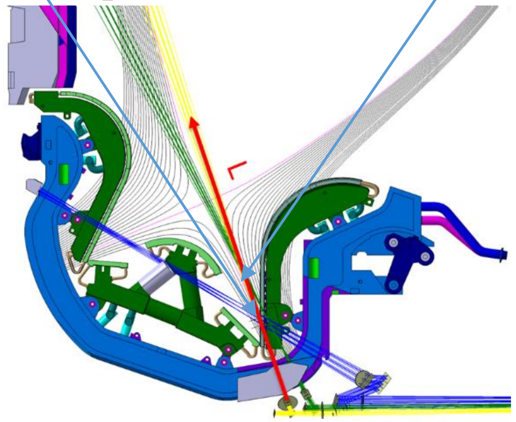
τ =10 ns, E =2.2 mJ,

S=1.5 cm^2



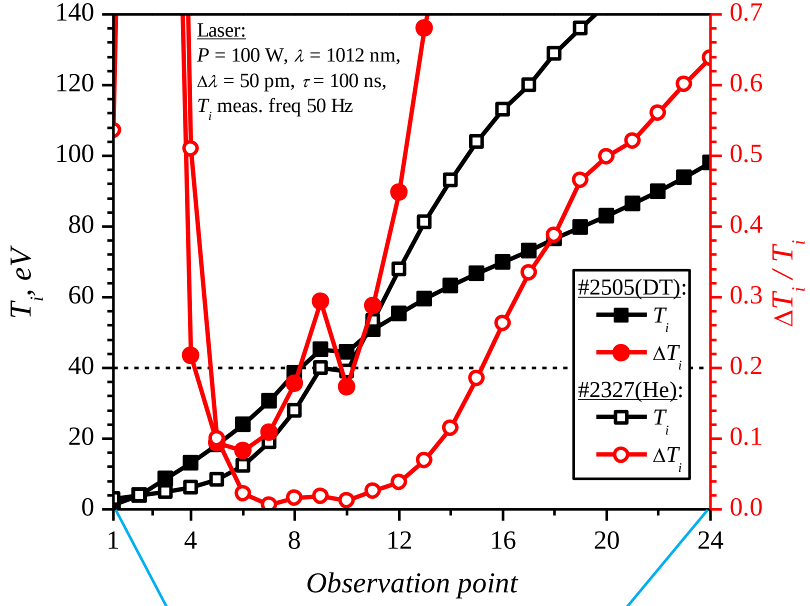
Left and right axes represent $n_{H/D/T}$ and relative accuracy $\Delta n_{H/D/T}$ calculated for SOLPS run #1514 DT:

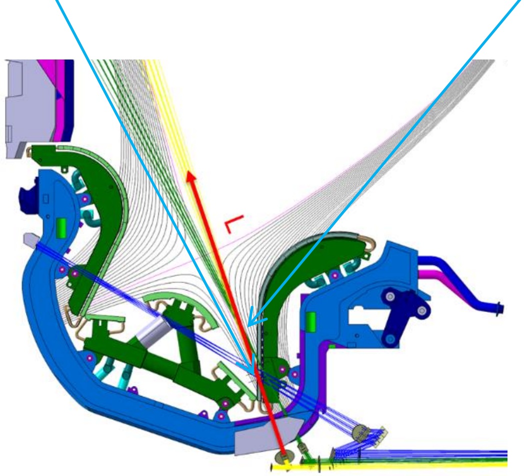




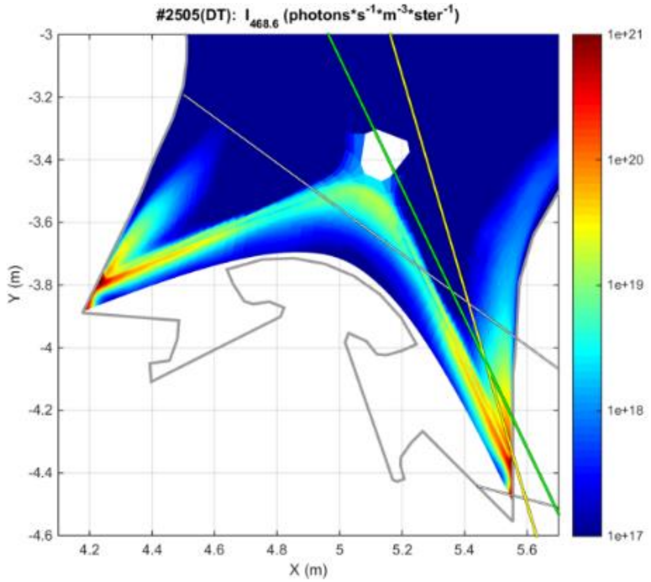
LIQ for He ion T_i measurements

He ion T_i and relative accuracy ΔT_i for SOLPS run #2505 (DT) and #2327 (He):



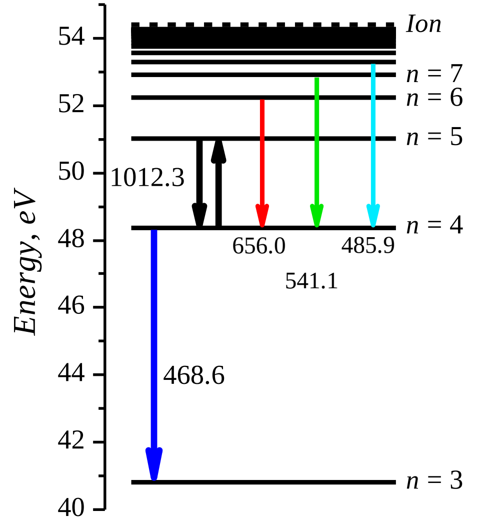


He ion line 468.6 nm

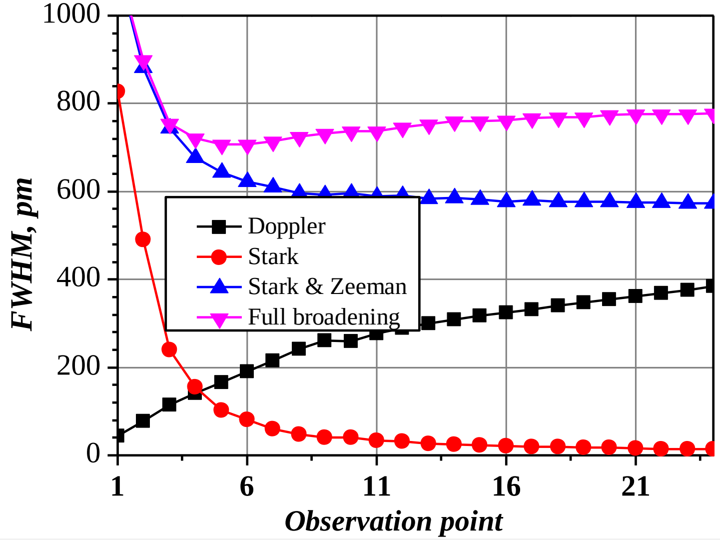


The transition $n = 4 \rightarrow 5$ (1012.3 nm) is chosen for 468.6 nm line quenching due to minimal influence of Stark broadening and the expected maximal SNR.

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

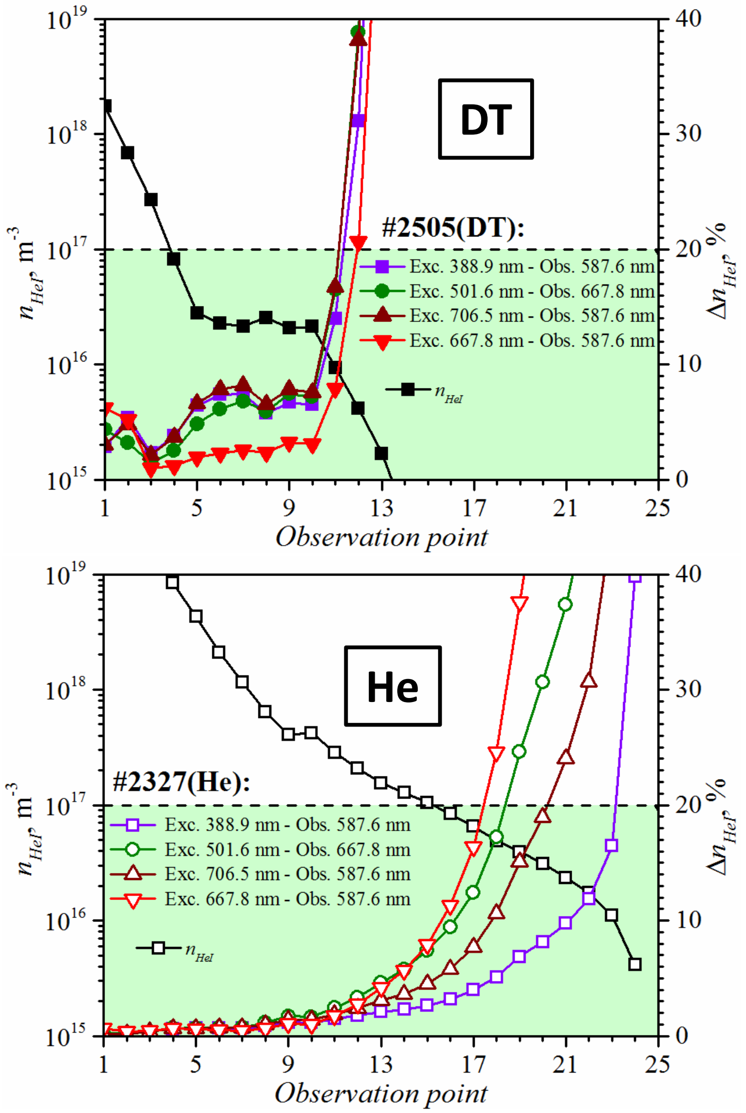


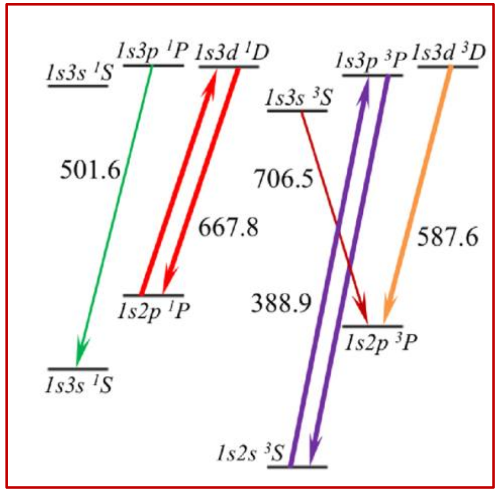
He ion 1012.3 nm line broadenings Doppler, Stark and Zeeman



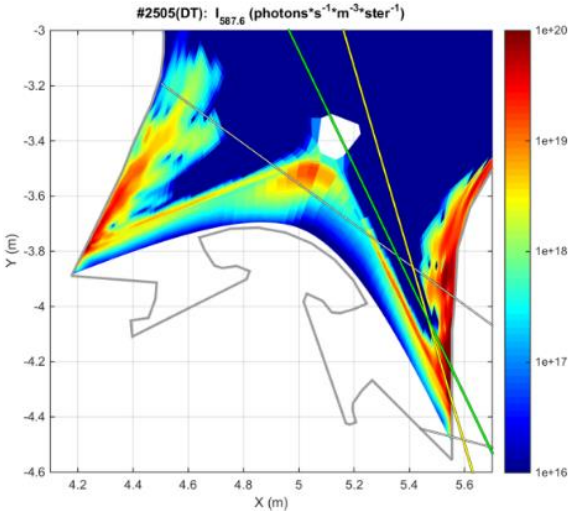
LIF for n_{HeI} measurements

He I density n_{HeI} and relative accuracy Δn_{HeI} for SOLPS runs #2505 (DT) #2327 (He):





He I line 587.6 nm



According to the expected errors, LIF method allows measuring $n_{He\,I}$ with the specified accuracy ($\Delta n_{He\,I}$ < 20%) and temporal resolution (20 ms) using 1 kHz OPO laser

A wide set of the spectroscopic schemes with the laser wavelengths of 388.9 to 706.5 nm and observation lines 587.6 and 667.8 nm allows measuring in both He and DT phases of the ITER operation.

(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)

Conclusions

(1) For T_e=0.3eV & n_e=10^{22}m^{-3}, the laser wavelength approaches Debye length and distortions of gaussian shape in TS spectra become obvious. According to our calculations, the requirements of 0.2 eV accuracy are met throughout n_e operational range 10^{19} - 10^{22} with slightly worse lower limit (n_e=1.2 10^{19} m^{-3})

(2) **He I LIF pulse duration** ($\tau_{fluorescence}$) can be used **for n_e >10^{18} m^{-3}** and **for absolute calibration** ($\tau_{laser} \leq \tau_{excited\ state\ lifetime}$)

Our Dynamic Collision-radiative Model (DCRM) for **He I** allows fitting calculated temporal shape to the measured fluorescence signals. TS vs LIF experiments on Globus-M show good agreement for T_e ~ 110 eV n_e ~ (2.4±0.2) ×10^{19} m^{-3}

(3) Laser-induced Quenching – new technique for H/D/T in ITER divertor

LIQ for H/D/T density benefits:

- pumping wavelengths shifted from the observed one by hundreds of nm as in **LII**
- pumping transition cross-section ~ **LIF** =>laser energy << **LII** and rep rate > **LII** can be achieved
- H/D/T excitation line can be scanned by tunable laser => spectroscopy measurements as in **LIF**

(4) **Measuring** T_e, n_e, T_i, n_i $n_{He/H/D/T}$ **simultaneously, we can calculate in the respective points of the divertor SOL the following important parameters:**

- 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 forces determined by 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).

Next step challenge: combined TS/LIF as a routine diagnostics for SOL plasma