Integration in ITER Divertor
Thomson Scattering & Laser-induced Fluorescence
Engineering and Performance Analysis


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 $1.3 \times DL$

Pulse shape stability > 99.5 %
Energy stability RMS < 1 %
Digital Polychromator

Up to 7 optical bandpass 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

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

First collecting mirror
Mirror objective
Vacuum windows
Cylindrical lens
First laser mirrors
Mirror field objective
Fiber bundle face

Digital filter polychromator specially developed for ITER
(E.Mukhin et al Hardware solutions for ITER divertor Thomson scattering 123 FED 686 2017)
Divertor Thomson Scattering 55.C4

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

LIF Induced Fluorescence 55.EA

LIF is now responsible for measuring $T_i$ via broadening of hydrogen-like helium ion spectral lines and $n_{Hel}$ 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**

We suggest diagnostics of $n_{\text{H/D/T}}$ based on suppression of $H_\alpha/D_\alpha/T_\alpha$ radiation:

Laser-Induced Quenching (LIQ) via pumping transition from 3$^{rd}$ to one of the upper states

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
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 $\sim 1$ 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 ($T_e$ $n_e$ $T_i$ $n_i$).
Since the recombination rate increases more rapidly at $T_e$ below $\sim 0.5$ eV, this $T_e$ measured $\pm 0.2$ eV is sufficient for code validation.

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 $\Rightarrow$

Conventional analytical calculations of $\Delta T_e$ and $\Delta n_e$ 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 ($n_e=1.2 \times 10^{19} \text{ m}^{-3}$)
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.

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

**Thomson** $T_e \sim 110$ eV

$$n_e = (2.4 \pm 0.2) \times 10^{19} \text{ m}^{-3}$$

**LIF** $n_e = (2.0 \pm 0.6) \times 10^{19} \text{ m}^{-3}$
Attempts to establish diagnostics of H/D/T density as a routine one have been made for ~ 40 years:

**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 $\sim$ LIF $\Rightarrow$ laser energy $<<$ LII and rep rate $>$ LII can be achieved
- H/D/T excitation line can be scanned by tunable laser $\Rightarrow$ spectroscopy measurements as in LIF


For He II was suggested in


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

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

Experiment: Globus-M $H_{\alpha}$ LIQ

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

Estimated: $(g_3/g_n+1)^{-1}$

Measured

Upper excited level #

Relative quenching, %

Time, ms

H$\alpha$, a.u.

LIQ $ph\ e^-$

LIQ $ph\ e^-/ns$

Time, ns

Pumping $n = 3 \rightarrow 7$

OPO laser

$\lambda = 1005$ nm

$\Delta \lambda = 2000$ pm

$\tau = 10$ ns

$E = 2.2$ mJ

$S = 1.5$ cm$^2$

plasma core $r/\alpha = 0.7$
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 $\Delta n_{H/D/T}$ (%)

Pumping $n = 3 \rightarrow 5$
$\lambda = 1281.8$ nm,
$\Delta \lambda = 2000$ pm,
$\tau = 10$ ns, $E = 2.2$ mJ,
$S = 1.5$ cm$^2$

$n_e, T_e$ provided by DTS (50 Hz)
1 kHz OPO => accumulation of 20 LIQ signals, better accuracy
Conclusion: most $\Delta n_{H/D/T}$ (%) $< 10%$. 

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

Energy, eV
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 I density $n_{\text{He I}}$ and relative accuracy $\Delta n_{\text{He I}}$ for SOLPS runs #2505 (DT) #2327 (He):

According to the expected errors, LIF method allows measuring $n_{\text{He I}}$ with the specified accuracy ($\Delta n_{\text{He I}} < 20\%$) 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 $T_e=0.3\text{eV}$ & $n_e=10^{22}\text{ m}^{-3}$, 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 ($n_e=1.2\times10^{19}\text{ m}^{-3}$)

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

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 $T_e \sim 110\text{ eV}$ $n_e \sim (2.4\pm0.2)\times10^{19}\text{ m}^{-3}$

(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 $\sim$ 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 $T_e$, $n_e$, $T_i$, $n_i$ $n_{\text{He/H/D/T}}$ simultaneously, we can calculate in the respective points of the divertor SOL the following important parameters:
- Ionization balance: Rates of ionization and recombination ($T_e\ n_e\ n_{\text{He/H/D/T}}$);
- Emission intensity ($T_e\ n_e\ n_i\ n_{\text{He/H/D/T}}$);
- Frictional forces determined by collisions with neutrals ($T_i\ n_i\ n_{\text{He/H/D/T}}$);
- 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