



## Simultaneous H/D/T and <sup>3</sup>He/<sup>4</sup>He absolute concentration measurements

S. Vartanian<sup>1</sup>, E. Delabie<sup>2</sup>, C.C. Klepper<sup>2</sup>, I. Jecu<sup>3</sup>, P. Jacquet<sup>4</sup>, E. Lerche<sup>5</sup>, B. Lomanowski<sup>2</sup>, L. Colas<sup>1</sup>, R. Dumont<sup>1</sup>, D. Douai<sup>1</sup>, A. Widdowson<sup>4</sup> and JET Contributors\*

<sup>1</sup>CEA, IRFM, 13108 Saint Paul-lez-Durance, France

<sup>2</sup>Oak Ridge National Laboratory, Oak Ridge, TN 37831-6304, USA

<sup>3</sup>National Institute for Laser, Plasma and Radiation Physics, Magurele, 077125, Romania

<sup>4</sup>UKAEA/CCFE, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK

<sup>5</sup>LPP-ERM/KMS, Royal Military Academy, 30 Avenue de la Renaissance B-1000, Brussels, Belgium

\*See the author list of E. Joffrin et al. 2019 Nucl. Fusion 59 112021

### Motivation

- Optical Penning gauge is almost universally used for the measurement of H<sub>2</sub>/D<sub>2</sub>/T<sub>2</sub> fuel isotopic composition [1] and He/D<sub>2</sub> concentration [2] in the neutralized particle exhaust of fusion devices.
- An Optical Penning detection system has already been used in JET on Tritium campaigns [DTE1] and has been chosen by ITER.
- Recent studies have shown that, through spectroscopic detection optimization, He/D<sub>2</sub> detection is feasible down to at least 0.1% . [3]
- **Simultaneously measure H/D/T and <sup>3</sup>He/<sup>4</sup>He species, particularly for ICRH scenarios with 3 ions will be essential in JET [DTE2] and ITER [4].**

### 1. The JET Sub-Divertor Neutral Gas Analysis Diagnostic [5] including Optical Penning Gauge

#### Pressure Measurement

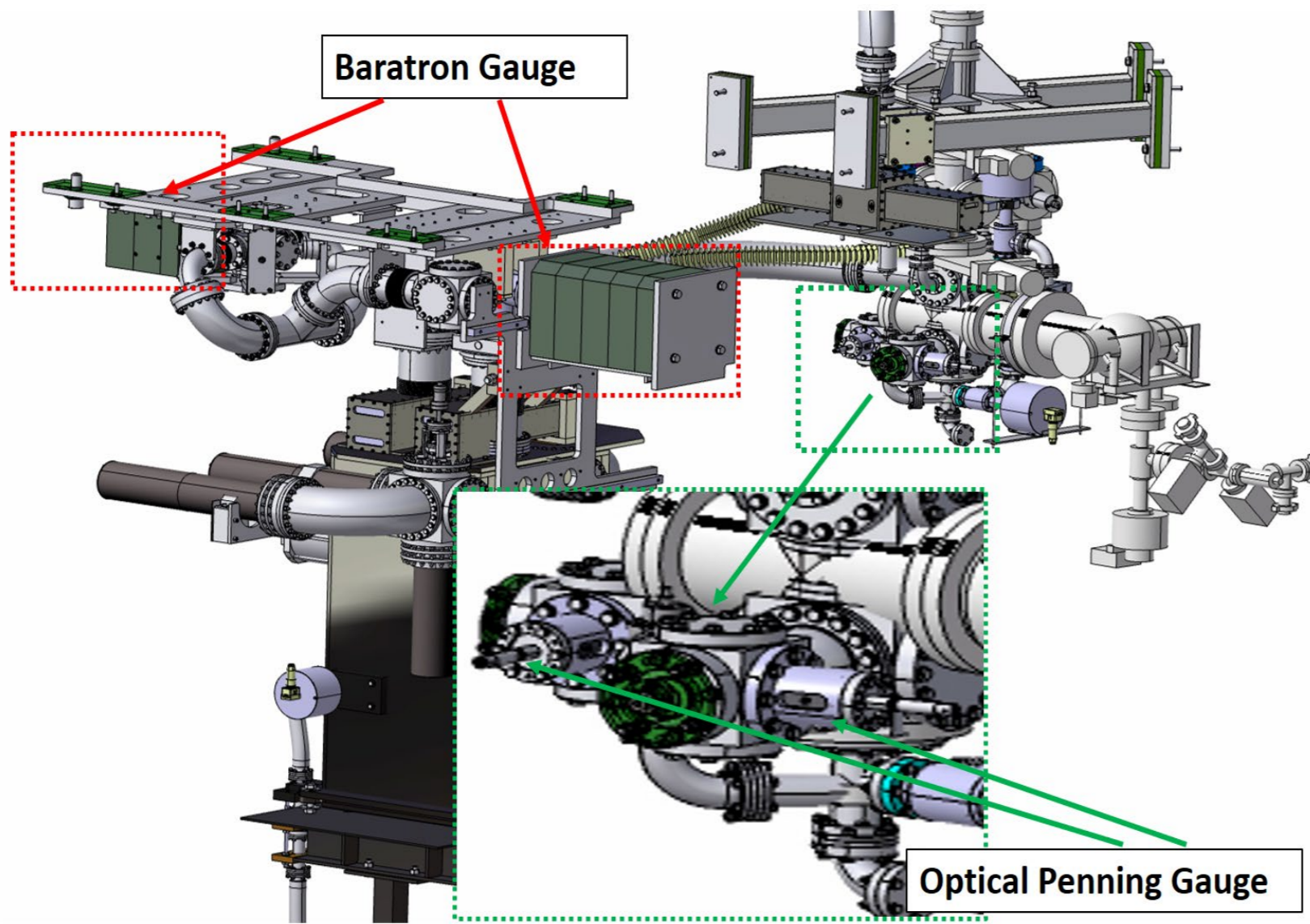
- Absolute pressure – Capacitive gauges
- Partial pressure – Cold cathode gauges

#### Optical Gas Analysers

- Specially developed cold cathode gauge with optimized Penning discharge light detection
- Connected to spectrometer

#### Mass spectrometer

- Best on commercial Quadropole Mass Spectrometers (QMS, not shown in the figure).
- All sensors shielded for stray magnetic field for operation DURING plasma pulse

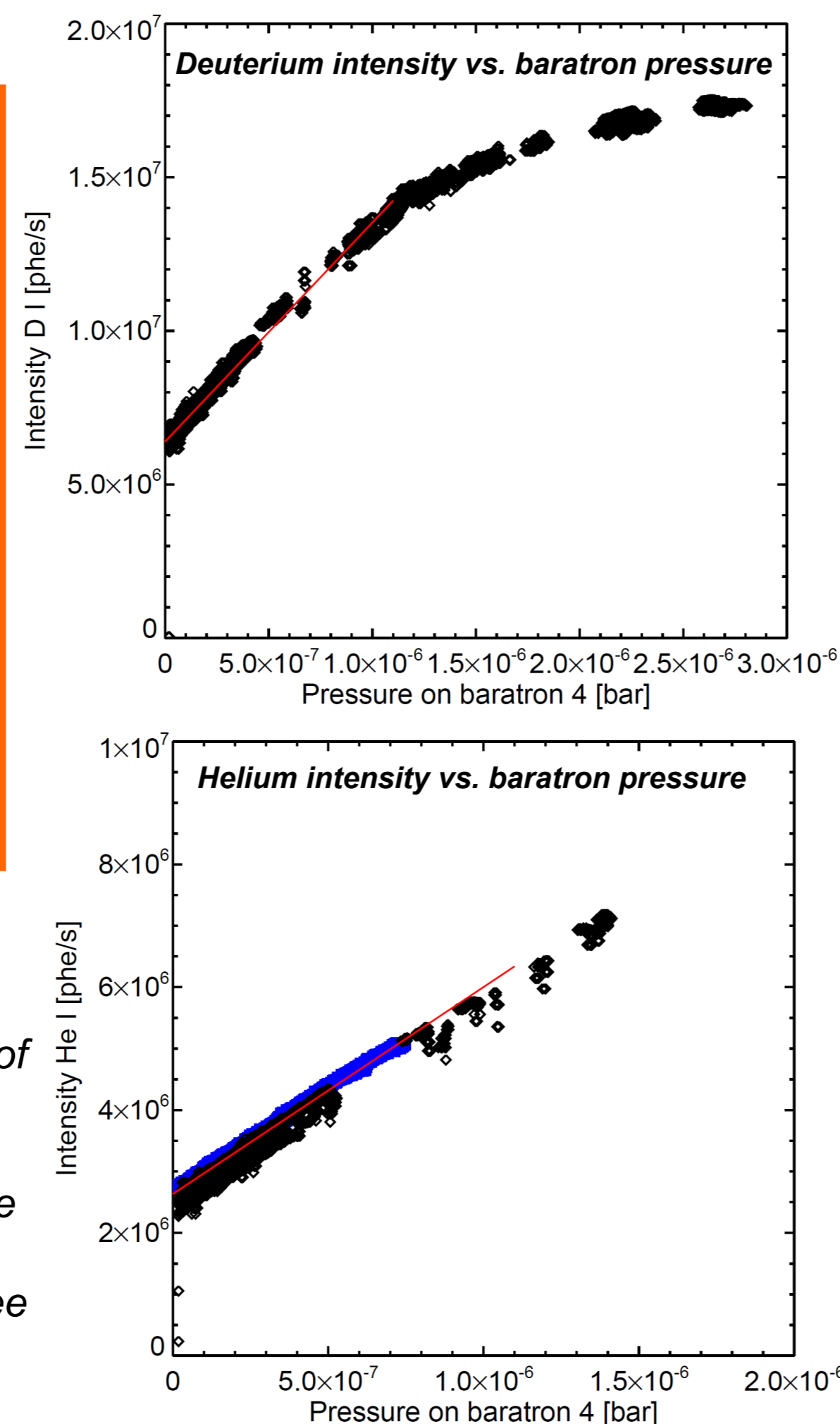


### 3. Calibration of the helium concentration

In order to convert the line intensities of the He I and D I lines in the Penning gauges into a helium concentration, we need to convert the intensities into partial pressures. We use the absolute pressure measurements from a nearby Baratron as reference and carry out a calibration for pure He and D<sub>2</sub>. Then we assume that for mixtures this conversion still holds, or at least that the intensity ratios are conserved. A calibration using gas mixtures, is planned to be carried out in the future.

The helium concentration is calculated as if the gas in the Penning gauge and baratron would be fully ionised, i.e.  $c_{He} = n_{He}/n_e = p_{He}/2(p_{He} + p_{H_2+D_2+T_2})$ .

Right: D I (top) and He I (bottom) line intensities as function of pressure measured on a nearby baratron. The black data points come from stable phases of JET discharges, the blue helium data points come from gas injected into the torus. The fit only considers the linear phase as we have not operated helium discharges at high enough sub-divertor pressure to see the roll over.



### 4. Utilisation limit and recommendation

- <sup>3</sup>He concentrations down to 0.1% have been detected, consistent with ITER study of Ref. [3] for He/D<sub>2</sub> detection with  $\lambda$ -resolved OPG
- <sup>4</sup>He detection limit depends on presence of neon. For JET-ILW, charge exchange spectroscopy (CXs) requires the use of neon (Ne) injection.
  - The Ne I: 6678.28Å emission line is very close to the <sup>4</sup>He I: 6678.152Å line ( $\Delta\lambda = 0.128\text{\AA} \rightarrow$  unresolved even with the hi-res spectrometer !).
  - Long-term, one can extend the spectral range to include the He I line at 7065.190Å, which is free of Ne I 7059.108Å line interference
- Total pressure needs to be less than 5E-1Pa to avoid non-linear behavior of spectroscopic signals from the Penning plasma source.

### References

- [1] D.L. Hillis et al., 1999 Rev. Sci. Instrum. 70, 359  
 [2] D.L. Hillis et al., 2003 J. Nucl. Mater. 313–316, 1061  
 [3] C.C. Klepper et al., 2016 Rev. Sci. Instrum. 87, 11D442  
 [4] Y. Kazakov et al., 2018 in 27th IAEA FEC - IAEA CN-258, Gandhinagar, India  
 [5] U. Kruetz et al 2020 JINST 15 C01032

### 2. Spectroscopic analysis of emission from the Optical Penning Gauge

Fibers from the Penning Gauge are connected to a high resolution spectrometer and a low resolution survey instrument aimed at concentration measurements from line ratios.

#### Optical Penning Jet Design

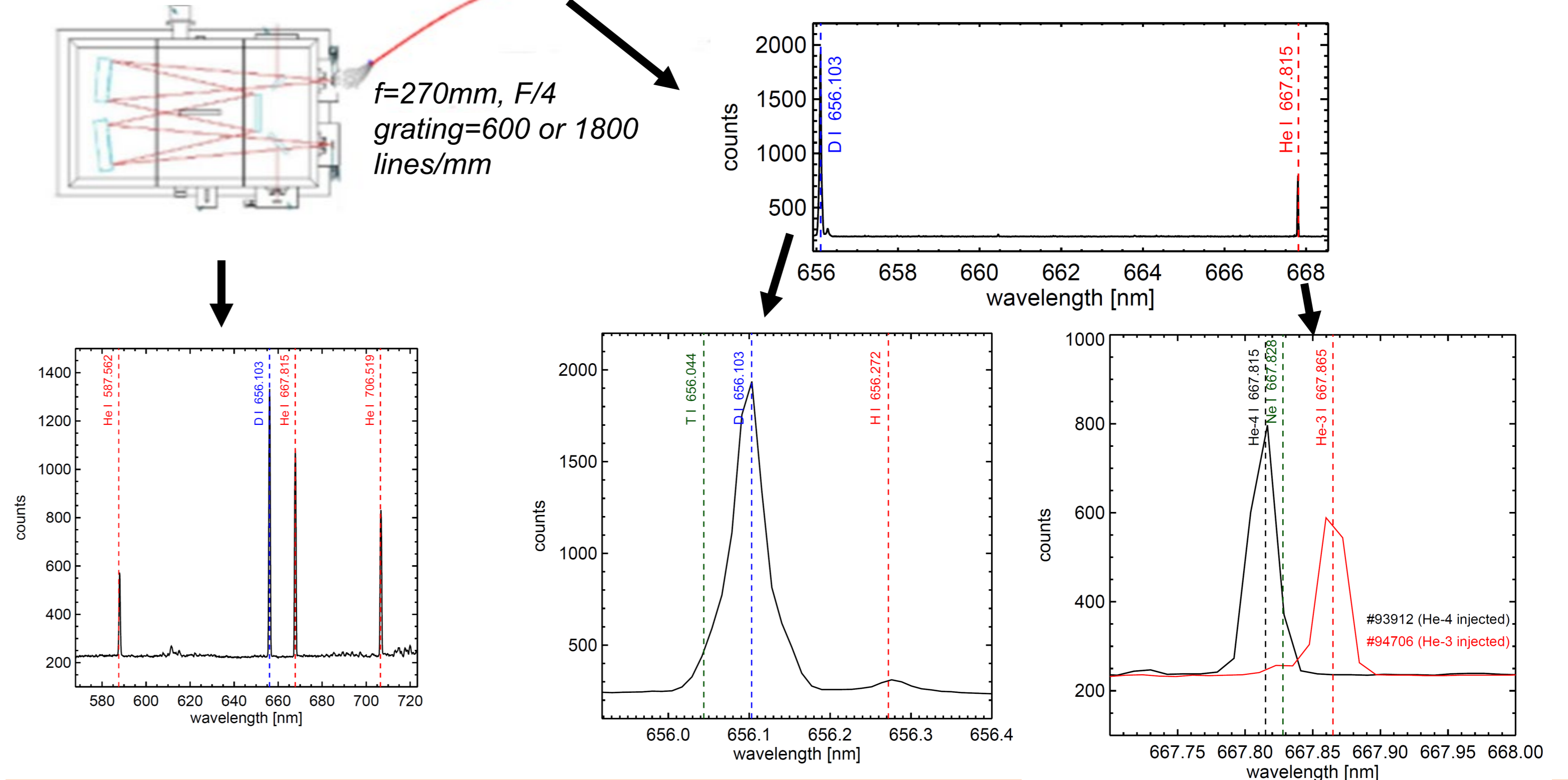
#### High resolution spectrometer

$f=1000\text{mm}$ , F/8  
 grating=1800 lines/mm  
 camera=1024 pixels at  $26\mu\text{m}/\text{pixel}$   
 dispersion= 0.11 Å/pixel



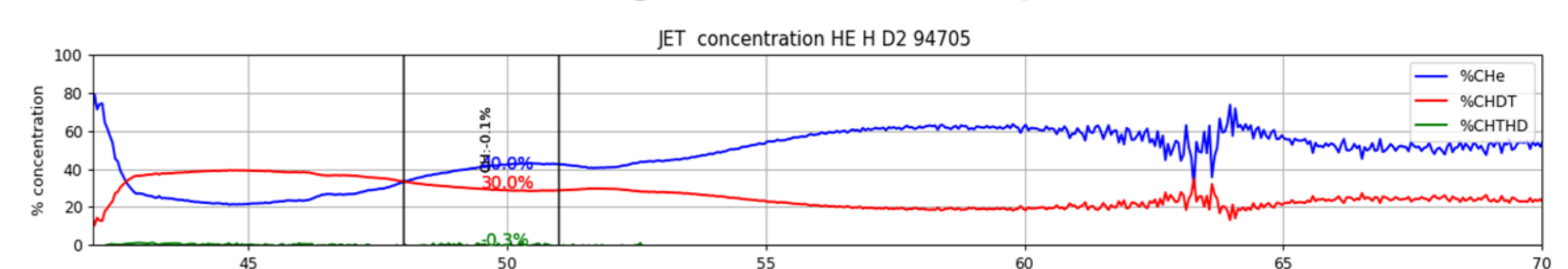
#### Survey spectrometer

$f=270\text{mm}$ , F/4  
 grating=600 or 1800 lines/mm

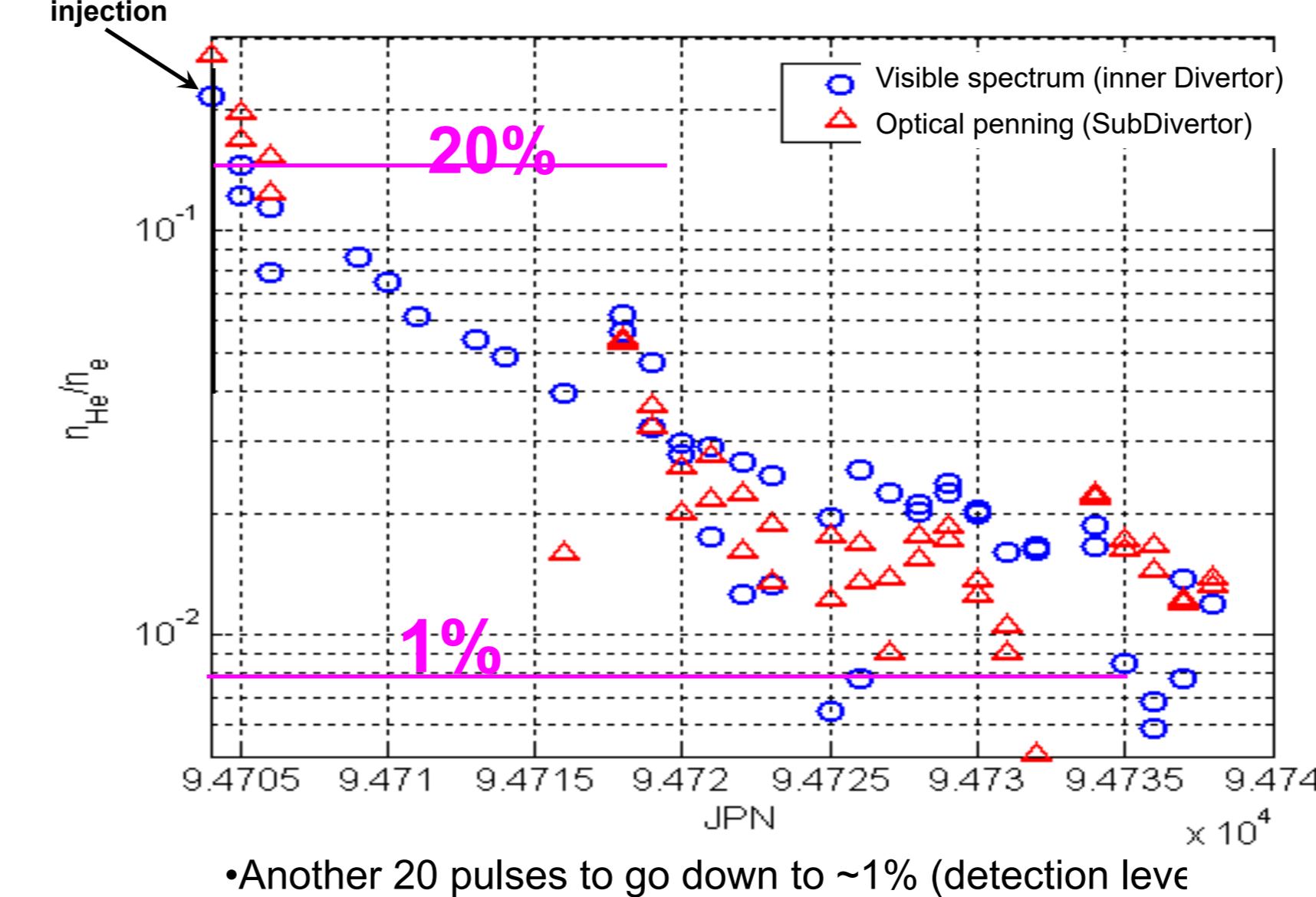


- Low resolution but high optical throughput instrument used for absolute helium concentration measurements. Detection limit set by blending with grassy molecular background (1-2%).
- Increased spectral band covered by the high-resolution spectrometer covers H/D/T-alpha and the neutral <sup>3</sup>He/<sup>4</sup>He line at 667nm simultaneously.
  - H and D well separated. D and T resolved, but will require fitting of the hotter molecular component.
  - Overlaying two pulses with <sup>3</sup>He and <sup>4</sup>He injection shows that the isotopic shift (0.5 Å) can be resolved.
  - Detection limit of <sup>4</sup>He dependent on presence of neon (see Section 4) and intensity. Detection limit of <sup>3</sup>He is only signal limited.

### 3. Measurement during 2019 JET <sup>3</sup>He experiment



#### 3He measurement JET Aug 2019 campaign



The first absolute measurements of the <sup>3</sup>He partial pressure were performed during the JET 2019 and 2020 campaign in mixed D/<sup>3</sup>He plasmas with the three-ion scheme ICRH experiments.

### Conclusion

The present arrangement on JET, prepared to extend into DT operation, allows to simultaneously measure the hydrogen and the He isotopes, thus getting maximum measurement capability during the valuable plasma pulses of the DTE2 campaign. This is the first known use of the Optical Penning technique for such simultaneous measurement.

- **This method will enable scenarios with combined H/D/T & <sup>3</sup>He/<sup>4</sup>He in JET DTE2 and will pave the way for ITER on this same type of ICRH-heated scenarios**