Reducing the Uncertainties in Fusion Fuelling at JET

CCFE
CULHAM CENTRE FOR FUSION ENERGY

HIDEN ANALYTICAL

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The Joint European Torus (JET)

Plasma physics closest to ITER

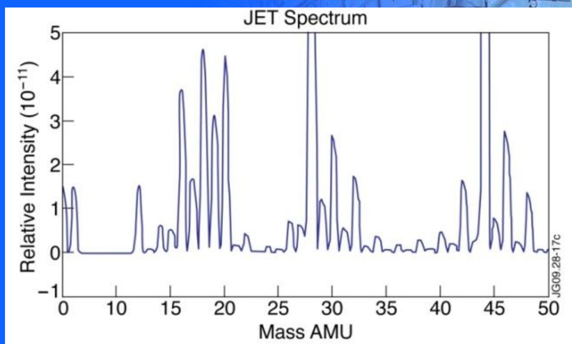
Torus radius	3.1 m
Vacuum vessel	3.96m high x 2.4m wide
Plasma volume	80 m^3 - 100 m^3
Plasma current	up to 5 MA in present configuration
Main confining field	up to 4 Tesla

Unique technical capabilities :

- Tritium
- Beryllium

⇒ Optimise the use of JET in support of ITER by making use of its unique capabilities

8th RGA (Culham); Outlined problems at JET with analysis of primary fuels for fusion process



Spieces	Major m/z	% Abundance
H_2	2	100
He	4	100
D_2	4	400
CH_4	16	100
H_2O	18	100
D_2O	20	100
CD_4	20	100
Ne	20	100
Air	28	100
CO	28	100
C_2H_6	28	100
C_2D_2	28	100
C_3H_8	28	100
C_2H_4	28	100
N_2	28	100
C_2D_4	32	100
C_2D_6	32	100
O_2	32	100
C_3D_8	34	100
Ar	40	100
C_3H_4	40	100
C_3H_6	42	100
C_4H_{10}	43	100
CO_2	44	100
C_3D_4	44	100
C_3D_6	46	100
C_4D_{10}	50	100

JG09 28-18c

RGA: JET quantitative analysis is always difficult;

3 types of Hydrogen isotope: Hydrogen, Deuterium and Tritium.

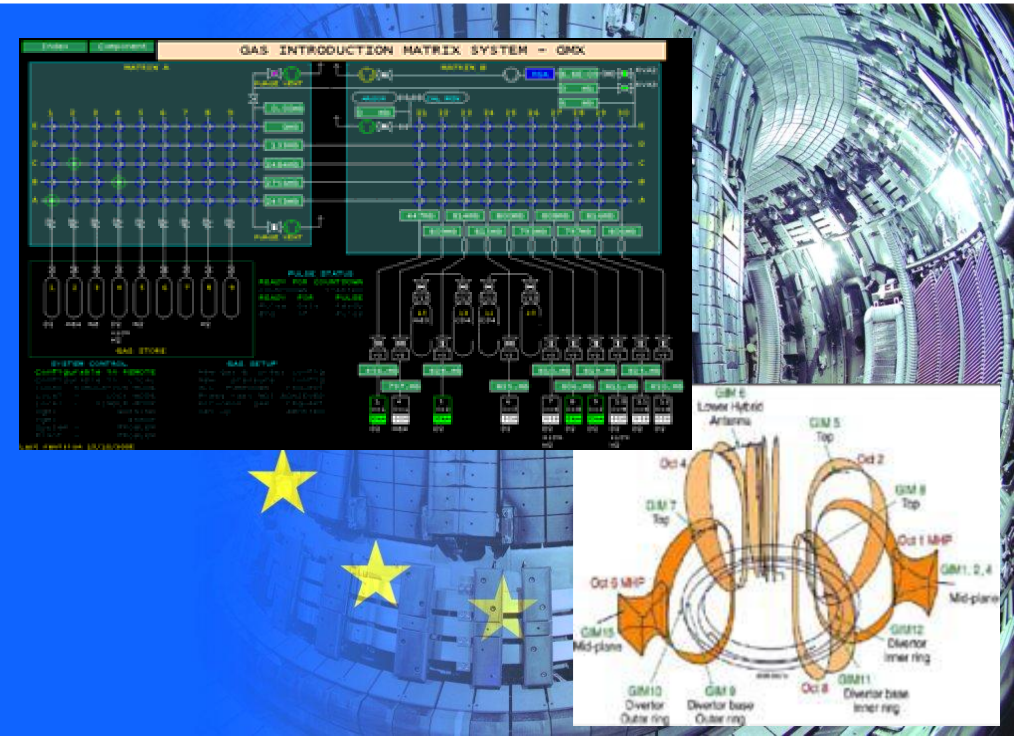
- **2 types of Helium: ^3He, ^4He**
- **3 types of Water, H_2O/ Heavy Water, D_2O / Super Heavy Water, T_2O.**
- **6 Tonnes of Carbon tiles, complex Carbon / Hydrogen isotope interactions.**

Baking the vessel to temperatures in excess of 300 degrees Celsius further complicates an already difficult task due to the dissociation of C_xH_y and C_xD_y species from the vessel wall.

⟹ Of most importance, validation of primary fuel purity is vital to ensure the data obtained from plasma pulses is in line with the strict experimental requirements and that pulse recipe repeatability is not compromised ⇒

Validation of JET primary fuel purity; Why is it difficult?

Fusion fuel most commonly used in the JET Tokamak is Deuterium (D_2);



•**Fundamental Problem** ⇒

• Suspicions of Helium (^4He) contamination in Primary Gas Introduction fuelling modules (GIM).

• Validation of primary fuel is complicated due to D_2 and ^4He having the same atomic mass (4 amu), specifically a mass separation of just 0.0254amu.

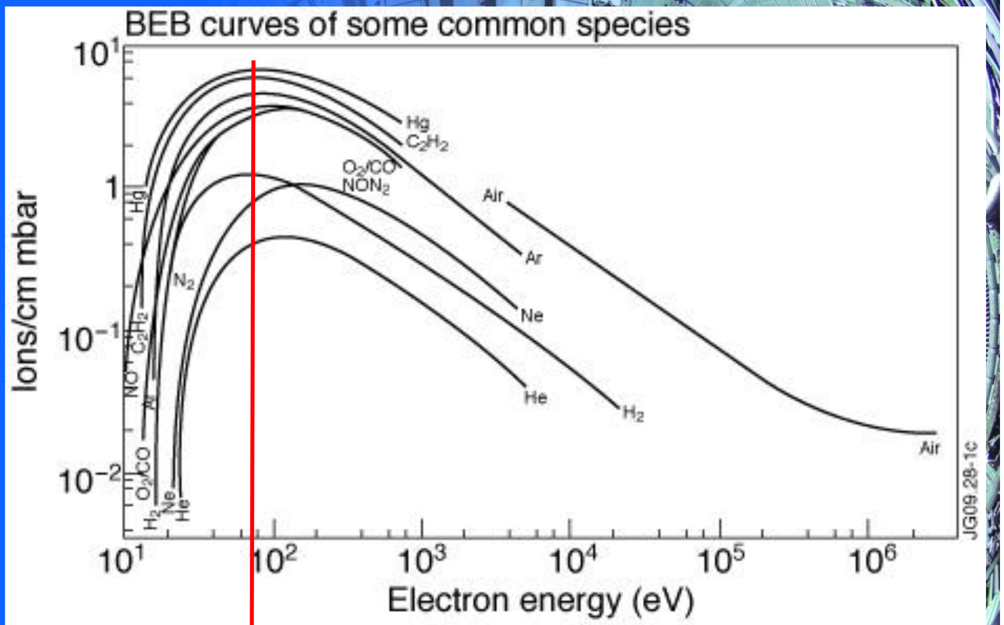
• Validation not possible using conventional mass spectrometry RGA techniques.

• Potential solution ⇒ other analytical techniques considered for quantitative gas analysis at JET; TOF, optical spectroscopy and advanced QMS RGA techniques.

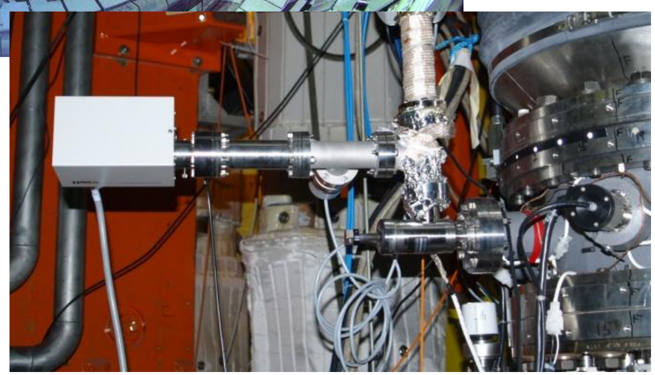
⇒ Solution: Advanced QMS RGA Technique; validation of primary fuel purity using a complimentary quadrupole mass spectrometry technique (TIMS). ⇒

Validation of JET primary fuel purity; TIMS qRGA

Threshold Ionization Mass Spectrometry (TIMS)



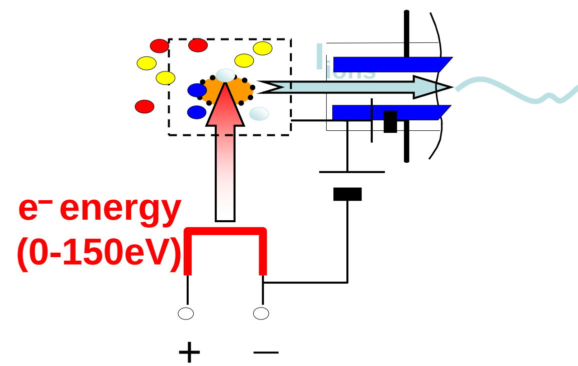
Electron energy set at 70eV



•TIMS: Hiden Analytical qRGA can be operated in a mode allowing control over the energy of the electrons emitted within the ionization source. (0.5eV electron energy resolution)

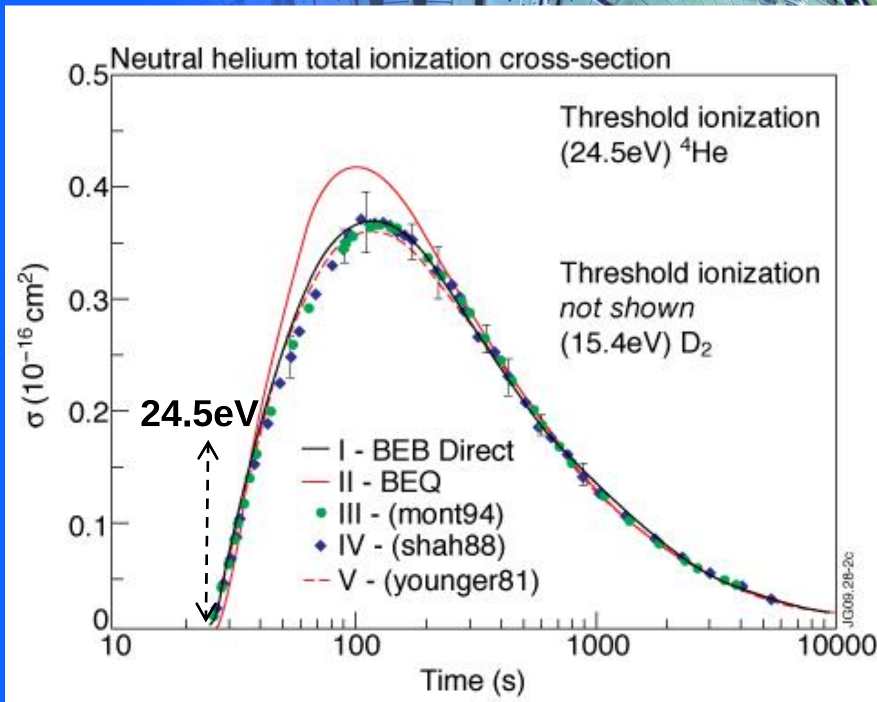
• Different species have defined unique ionization energies, dependent on the electron orbital configuration: outer shell electrons ⇒ weaker ionization energies due to greater distance and lower electrostatic forces from the nucleus.

• Ionization process of neutral particles commences at a minimum (threshold) energy of the impacting electrons ⇒ each species has unique fingerprint



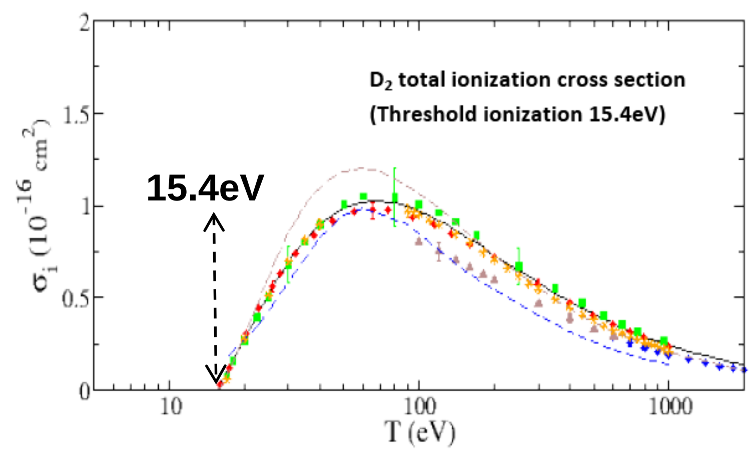
Validation of JET <u>primary</u> fuel purity; TIMS qRGA

Threshold Ionization Mass Spectrometry (TIMS)



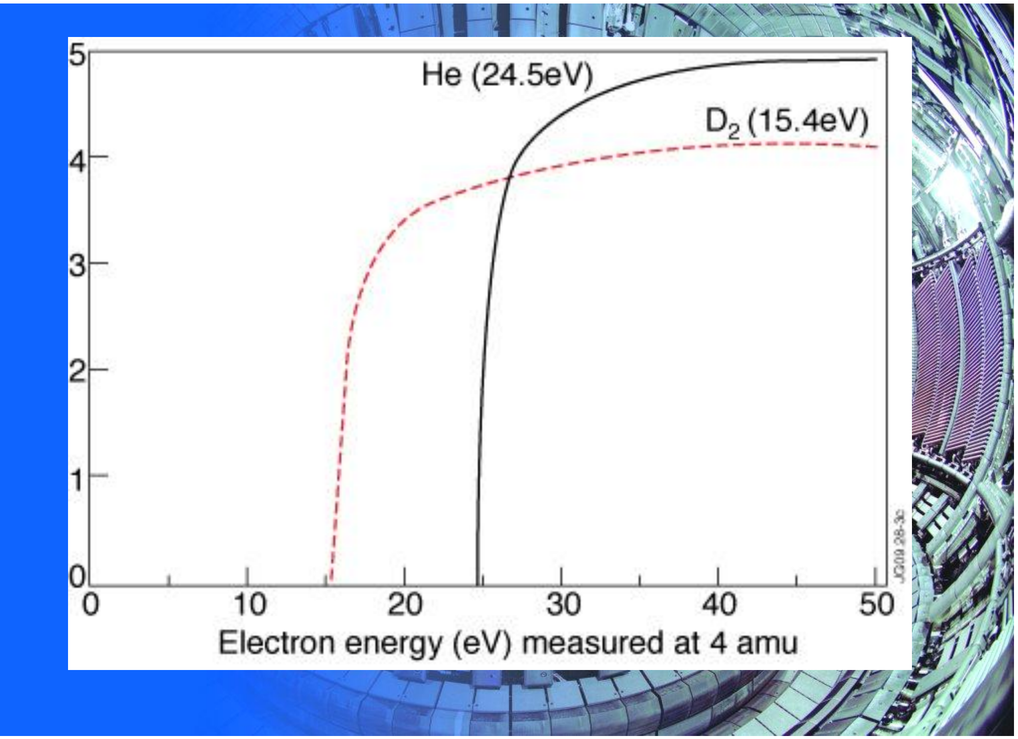
•TIMS: Hiden Analytical qRGA can be operated in a mode allowing control over the energy of the electrons emitted within the ionization source.

• D_2 and ^{4}He have overlapping atomic mass (4 amu), but Binary Encounter Bethe (BEB) theory and experimental data have shown threshold ionization energies (electron impact) are separated at 15.4eV and 24.5eV respectively.



How do the electron impact threshold ionization curves appear in the real qRGA with the (TIMS) technique? ⇒

Validation of JET primary fuel purity; TIMS qRGA

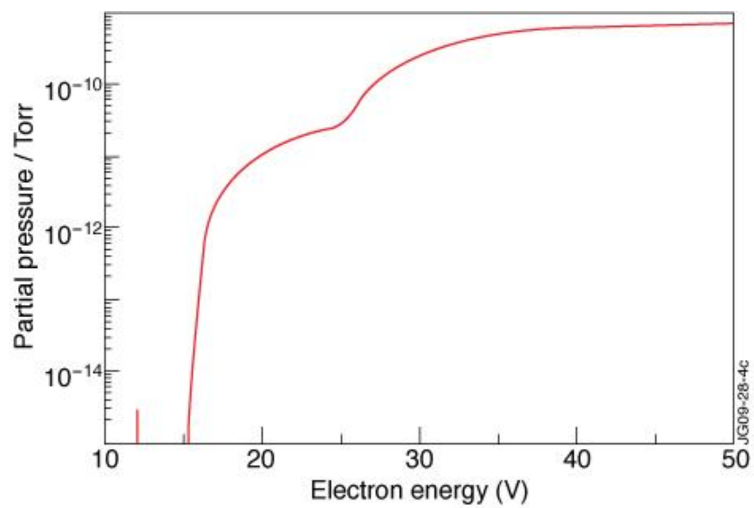


Threshold Ionization Mass Spectrometry (TIMS)

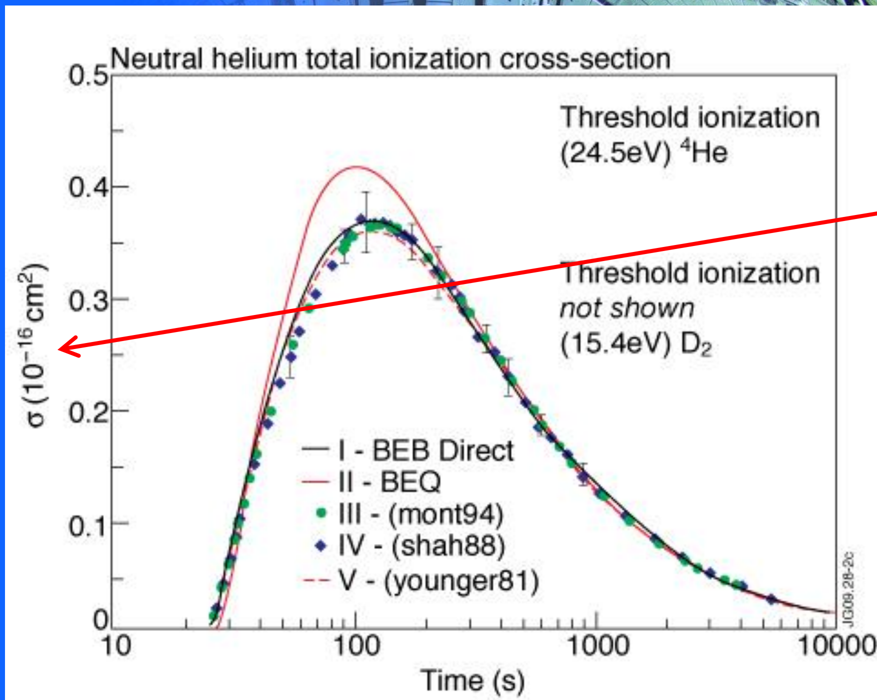
- TIMS on the left shows how an example spectra appears with the QMS if we scan ^{4}He and D_2 separately at 4amu. Threshold Ionization onset in excellent agreement with BEB values (0.5eV).

- TIMS data below shows a real curve when we sample the convoluted ^{4}He and D_2 gas mixture (simultaneously) 0-50eV range.

- The partial pressure gradient prior to the inflection represents just D_2 (in this case), with the gradient at higher electron energies representing (D_2 + ^{4}He)



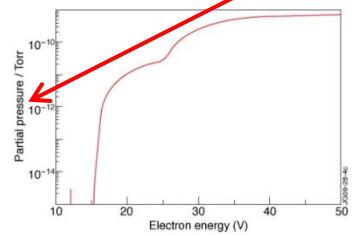
We have shown spectral de-convolution of D_2 & ^4He ; But how to quantify?



D_2 + ^4He: Quantification process with Hiden qRGA (Apply BEB theory to qRGA data) :

• BEB theory literature values gives the total ionization cross section coefficients (σ) for the gas species under consideration as function impact electron energy (*eV*):

•Relate (σ) to the qRGA measured partial pressure of the gas species (let it be denoted as (N_x) in this case)



•Express the true abundance level of the gas species (η_x) as a function of (σ_x) and the measured partial pressures of the qRGA (N_x) . So in the case of the D_2 only and (D_2 + ^4He) regions in the TIMS spectra above, we can express the following two equations (*in this case we choose to measure at the 19eV and 31eV points on the curve*):

$$N(D_2) = A_i \left(\sigma^{\{19eV\}}(D_2)\right) \cdot \eta(D_2)$$

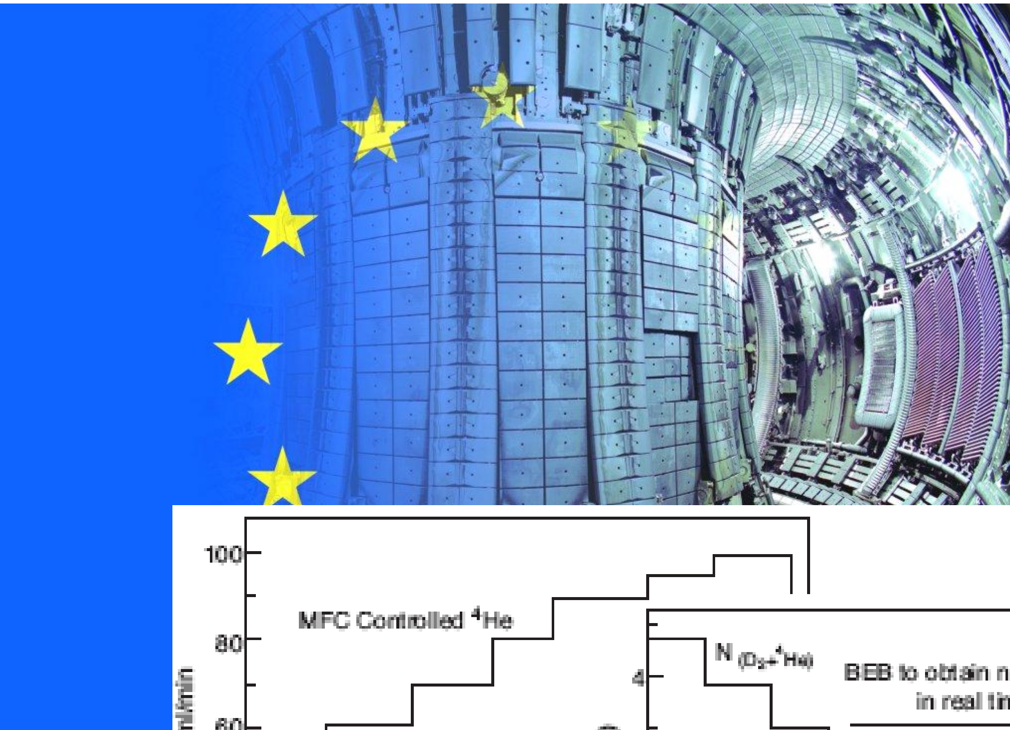
Eqn 1: (D_2)

$$N(D_2 + {}^4He) = A_i \left\{ \left(\sigma^{\{31eV\}}(D_2)\right) \cdot \eta(D_2) + \left(\sigma^{\{31eV\}}({}^4He)\right) \cdot \eta({}^4He) \right\}$$

Eqn 2: (D_2 + ^4He)

TIMS De-convolution of $D_2/^4He$ at JET:

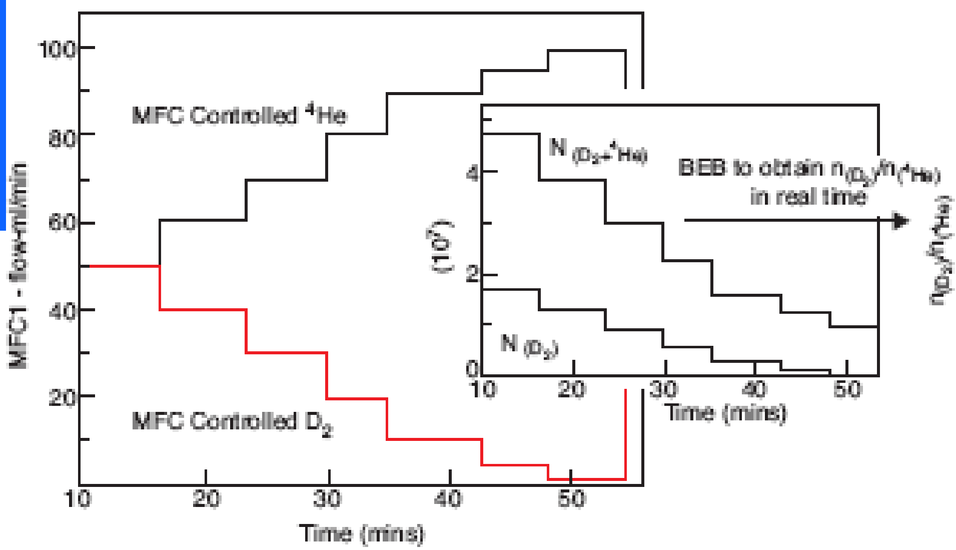
Testing the Model: Real time quantification of a changing $D_2/^4He$ mix with qRGA

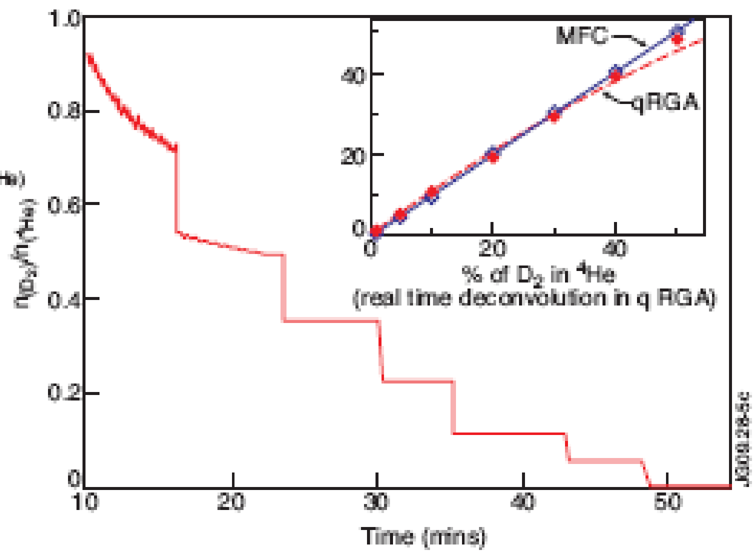


- First: Solve eqns (1&2) for true $D_2/^4He$ abundance ratio, then implement into qRGA Hiden software

- Controlled the ratio of the $D_2/^4He$ mix by MFC method. Over a 60 minute period, the % of D_2 /^4He ratio was varied from 50/50 to 0.1/99.9

- The qRGA data is shown below (left to right); Raw MFC data, raw TIMS data, and corrected TIMS after BEB model. The inset shows a plot of the D_2 % in ^4He. (The qRGA data is in good agreement with the MFC data).

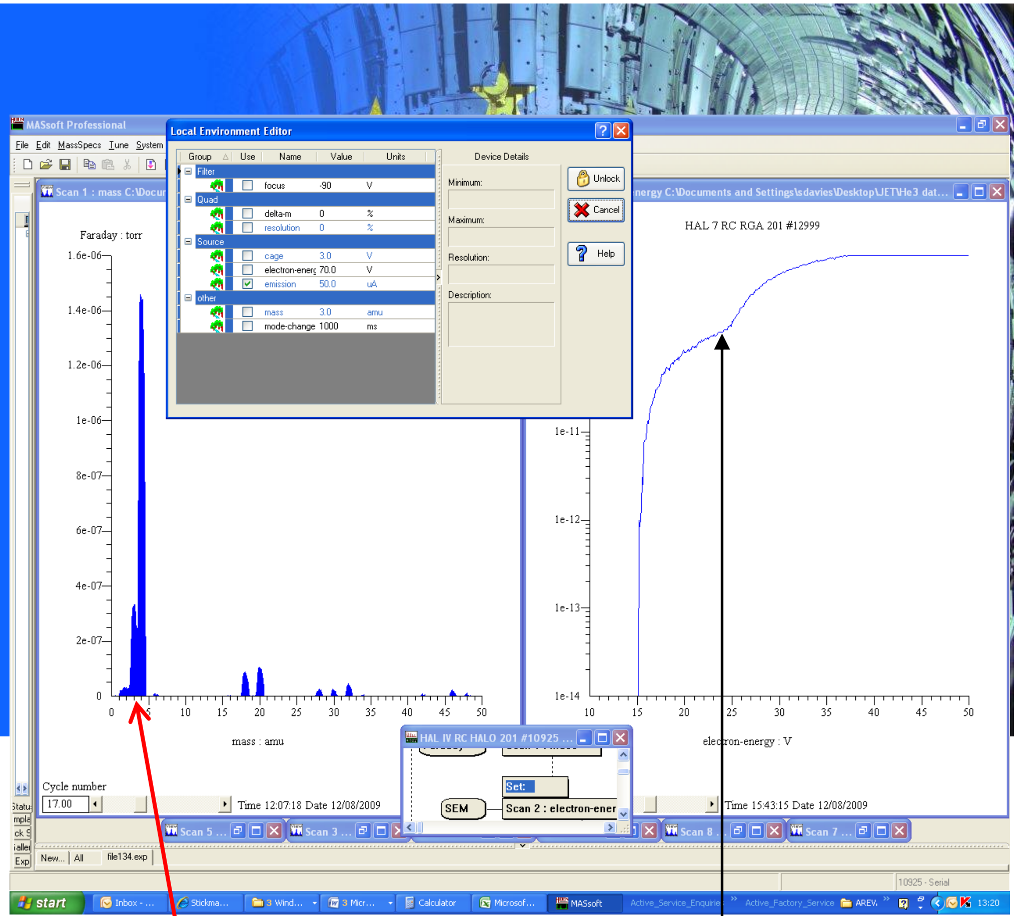




Realising the potential of TIMS at JET:

Not just $D_2/^4He$ de-convolution!

Realising the possibilities, TIMS was used during ^3He operations at JET;



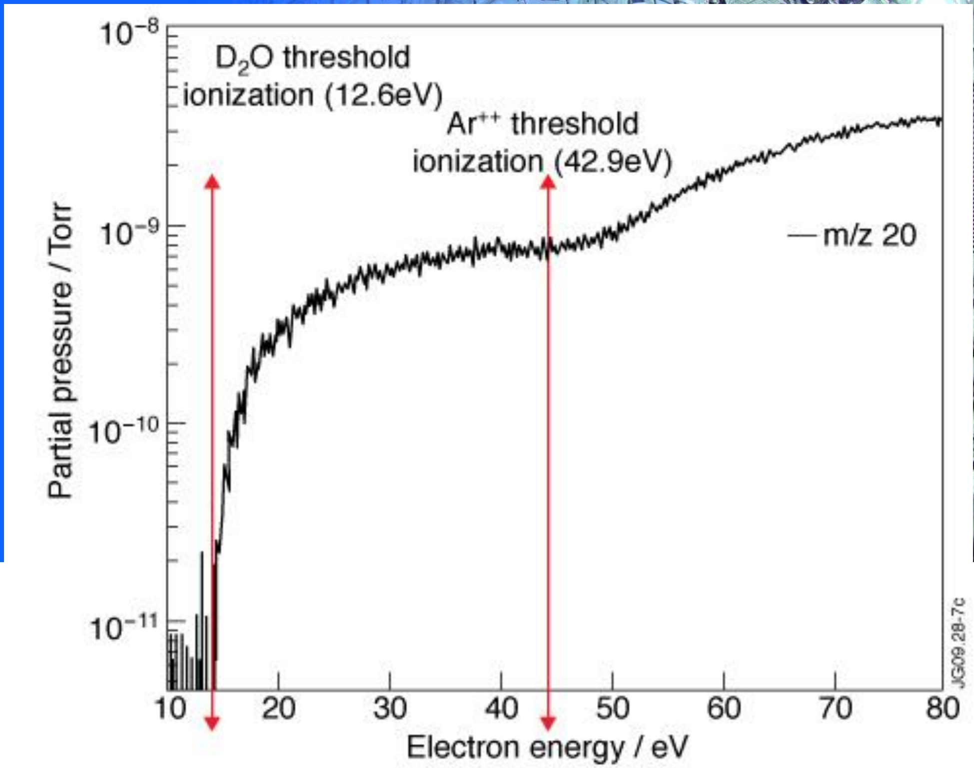
Transition from HD to (HD + ^3He)

2, 3 & 4 amu peaks

- The data follows a Ion Cyclotron heating cycle using ^3He as the minority gas. Varying amounts of ^3He was injected into the plasma.
- In standard quadrupole MS mode, the mass profile scan shows complex gas spectrum from the Torus. 2, 3 & 4 amu peaks are evident (a mix of hydrogen, deuterium and helium isotopes which cannot easily be de-convoluted)
- The qRGA spectra in TIMS mode shows a scan at 3 amu, clearly de-convoluting the ^3He from HD.
- The atomic mass separation of ^3He and HD is just 0.0058 amu; difficult for any mass spectrometer to resolve – EASY in TIMS!

Realising the potential of TIMS at JET:

Not just $D_2/^4He$ de-convolution!



- The TIMS data shows small quantities (≤ 1%) of chamber residual heavy water D_2O, as shown by the electron impact threshold ionization energy at 12.6eV

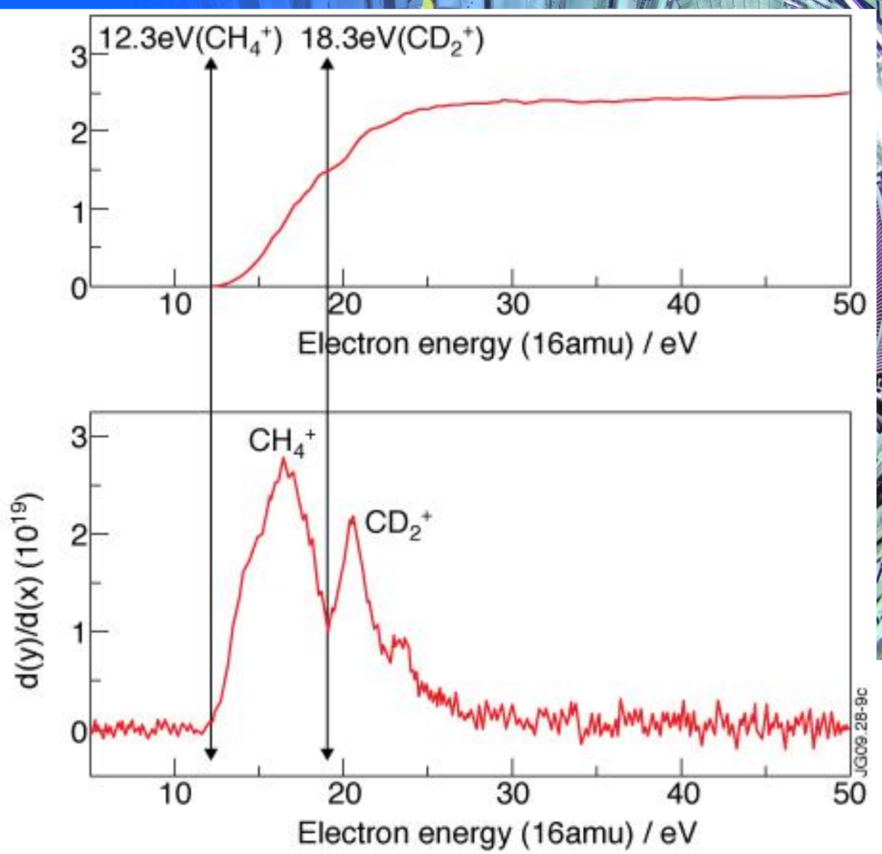
- Any chamber residual Argon (40 amu), will always have a secondary doubly ionized Argon peak (Ar^{++}) present at 20 amu. This is due to the conventional MS operating at an electron energy of ≥ 70ev. (Ar^{++} is formed at 42.9eV)

- Using conventional mass profile scans, D_2O is indistinguishable from chamber residual Argon, and difficult for any conventional mass spectrometer.

- But not with TIMS!

- This de-convolution of gases at 20 amu can have an important role for monitoring vacuum quality conditions in the JET Torus (*To be discussed elsewhere!)*

Realising the potential of TIMS at JET:



Not just D_2/^{4}He de-convolution! What about hydrocarbons and primary fuel contamination:

•It is known that hydrocarbons outgas from the Torus vessel wall, affecting the optimum fuelling conditions. Preliminary TIMS data shows interaction of Deuterium and hydrocarbons: CxHy ⇒ CxDy

• Example of TIMS data: at 16 amu, overlapping species C_2H_4 & CD_2

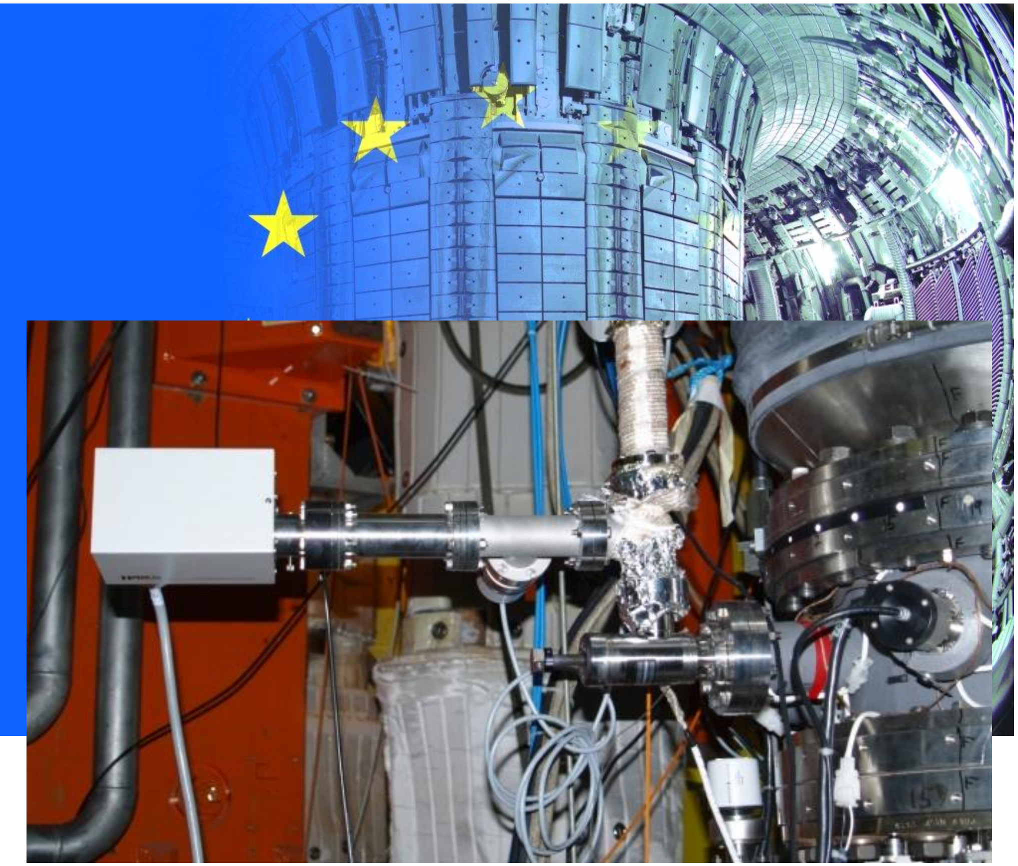
•Using conventional mass profile scans, again these species are virtually indistinguishable, and difficult for a conventional mass spectrometer.

• TIMS can help circumvent this problem!

•In the figure shown, the hydrocarbon level is at 0.5% of the primary gas level, demonstrating the potential in low level impurity detection

•This technique can be applied to any hydro and deuterated-hydrocarbon species within the mass range of the qRGA

Realising the potential of TIMS at JET: What have we learned?



Conclusions & Future Work:

•De-convolution of the mass spectra could lead the way to providing a better understanding of the chemistry within the Torus, and provide invaluable diagnostic information during vessel conditioning.

• Initial results prove encouraging, demonstrating discrimination of $D_2/^4He$ and $HD/^3He$. We have applied BEB to TIMS data to generate algorithms in the qRGA software to automatically determine $D_2/^4He$ ratio concentrations.

•This has provided stimulus to apply TIMS during future Tritium campaigns. Discrimination of T^+ from $HD^+/^3He^+$ ions should prove within the scope of qRGA. The separation of T^+ from $^3He^+$ The separation of 0.00002 amu is challenging for any mass spectrometer.

•We have seen de-convolution of D_2O/Ar^{++} , and initial data of CH_4^+ and CD_2^+. This has encouraged future work, currently ongoing.

•2010 brings the installation of the Beryllium plasma facing wall at JET and an opportunity to accurately determine the vessel chemistry during commissioning.