Observation of MeV range ions in radio frequency heating experiments with the three ion scenarios at JET

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• Theoretical overview: new heating scenarios for mixture plasmas

• Experimental evidence: the D-(³He)-H scenario

• Experimental evidence: the D-(D\textsubscript{NBI})-H scenario

• A quantitative perspective

• Applications to fast ⁴He studies

• Conclusions
Theoretical Overview
What makes ion heating with RF waves effective?

**Requirements**

1) **Accessibility**

2) **Frequency matching** \( (\omega = p \cdot \omega_{ic} \ p=1,2,3\ldots) \)

3) **Polarization** (left handed for ions; \( E_+ \))

_Cold wave theory provides a simplified description of the propagation of a wave in a plasma in the IC frequency range_

\[
\begin{align*}
n_\perp^2 &= \frac{(R - n_\parallel^2)(L - n_\parallel^2)}{S - n_\parallel^2} \\
\left|\frac{E_+}{E_-}\right| &= \left|\frac{n_\parallel^2 - R}{n_\parallel^2 - L}\right|
\end{align*}
\]

- \( n_\perp^2 > 0 \): the wave **propagates**
- \( n_\perp^2 < 0 \): the wave is **evanescent**
- \( n_\perp = 0 \): **cutoff** (wave reflection)
- \( n_\perp \to +\infty \): **resonance** (mode conversion)
D majority heating: $E_+ = 0!$

Here $E_+ = 0!$

$B = 3.16 \, \text{T}$
$n_\phi = 27$
$f = 24 \, \text{MHz}$

- Evanescence
- Cold wave resonance
- Ion cyclotron absorption

Very poor absorption!
Here $E_+ \text{ goes from 0 \emph{exactly at the resonance} to maximum at the L cutoff.}$

**Reference scheme. Good absorption.**
H:D≈70:30 plasma + $^3$He at < 1% concentration

Key idea: place the $L$ cutoff determined by the 2 main ions at the IC layer of a third ion

$E^+ \text{ is maximum at the } L \text{ cutoff}$
Requirements for the 3 ion scheme

**Sandwich criterion**

\[(Z/A)_2 < (Z/A)_3 < (Z/A)_1\]

**Proper concentrations**

Resonant ion at < 1% concentration not to change the wave propagation properties set by the 2 majority ions

**Optimal concentration to fulfill** \(\omega_{iC}(3) = \omega_L(1, 2)\)

\[X_1^* \approx \frac{1}{Z_1} \frac{(Z/A)_1 - (Z/A)_3}{(Z/A)_1 - (Z/A)_2}\]

\[X_2^* \approx \frac{1}{Z_2} \frac{(Z/A)_3 - (Z/A)_2}{(Z/A)_1 - (Z/A)_2}\]
Experimental evidence:
D-(³He)-H

*Fast³He ions in H-D mixtures*
Reference discharges

Three-ion heating pulses on JET: #90753 and #90758

- $B = 3.16$ T, $I_p = 2$ MA, L mode
- $H:D \approx 70:30$
- $X[^9\text{Be}] \approx 0.6\%$
- $X[^3\text{He}] \approx 0.3\%$

**Stabilization of sawteeth**

Enhanced plasma energy

doi:10.1038/nphys4167
Evidence of $^{3}\text{He}$ ions in the MeV range: fast ion driven MHD

For core TAEs assumed to be localised at $r/a \approx 0.2$

$$E_{3\text{He}}[\text{MeV}] \approx 0.047 \frac{f [\text{kHz}]}{n}$$

**Table:**

<table>
<thead>
<tr>
<th>$n$</th>
<th>$E_{3\text{He}}$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>$\approx 2.2$</td>
</tr>
<tr>
<td>6</td>
<td>$\approx 2.6$</td>
</tr>
<tr>
<td>7</td>
<td>$\approx 3.0$</td>
</tr>
</tbody>
</table>

S. Sharapov
Further evidence: gamma-ray emission

**HPGe** and **LaBr₃**

- **HPGe**: best energy resolution (Doppler broadening)
- **LaBr₃**: high rate (MHz) at high energy resolution

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Gammas & Neutrons

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*Diagram showing the layout of the laboratory with HPGe and LaBr₃ detectors.*
$^3$He+$^9$Be nuclear reactions produce gamma-rays
$^{3}\text{He} + ^{9}\text{Be}$ nuclear reactions produce gamma-rays
Gamma-ray emission from $^3$He+$^9$Be reactions

$^9$Be($^3$He,p)$^{11}$B*, $^9$Be($^3$He,n)$^{11}$C* and $^9$Be($\alpha$,n)$^{12}$C* reactions: different peaks at $E_\gamma > 3$ MeV expected; Ions in the MeV range required for significant emission (more details later)

**Richest gamma-ray emission spectrum observed so far in JET-ILW!**

- #90753, 3-ion scenario ($t=8-14$s)
  - $X[^3\text{He}] \approx 0.2-0.4\%$
  - $P_{\text{ICRH}} \approx 4$ MW

- #91323, $^3$He minority ($t=8-15$s)

- #91256
  - ($^3$He minority)
  - $X[^3\text{He}] \approx 1-2\%$
  - $P_{\text{ICRH}} \approx 6$ MW
Response of the fast ion profile to the antenna phasing

**Stix Theory**

\[ T_{\text{mino}} \approx k_0 T_e \xi_{\text{mino}} \]

\[ \xi_{\text{mino}} = \frac{m_{\text{mino}} v_{\text{th},e} \langle P_{\text{RF}} \rangle}{4\sqrt{2\pi}X_{\text{mino}} n_e Z_{\text{mino}}^2 e^4 \ln \Lambda} \]

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Antenna phasing
```

**Tail temperature**

\[ \Delta V \approx 16\pi^2 n_{\text{tor}}^2 v_{\text{th},3\text{He}}^2 k_0 R_0 / \omega^2 \]

**Absorption volume**

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Dipole
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\[ \Delta V \]

\[ <P_{\text{RF}}>_{} \]

```
\[ \pi / 2 \]
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\[ + \text{ pinch effect} \]
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Fast ion gradient expected to increase with \( \pi / 2 \) phasing
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Antenna phasing
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\[ \pi / 2: \quad n_{\text{tor}} \approx 14 \]

\[ \pi / 2: \quad n_{\text{tor}} \approx 27 \]
More intense fast ion driven MHD is excited with $\pi/2$ phasing for the same total ICRH power (4.2 MW).
Experimental evidence:

$D-(D_{\text{NBI}})-H$

*Fast D ions in H-D mixtures*
D-($D_{\text{NBI}}$)-H 3 ion scenario

$\omega = \omega_{IC} + k_\parallel v_\parallel$

$H:D \approx 85:15$

$\omega = \omega_{IC} + k_\parallel v_\parallel$

$R_{ic}(D)$

$R_{ic}(D_{\text{NBI}})$

L cut-off
Reference discharge: #91256
Fast ion driven MHD activity

Modes localised in the core ($R \approx 3.2$ m) based on reflectometry data.
Observation of energetic tails in the neutron spectrum with TOFOR

$E_n \approx 2.5 \text{ MeV}$

$E_n \approx 4 \text{ MeV}$

$E_n \approx 5 \text{ MeV}$

$E_n [\text{MeV}] \approx \frac{10380}{(\text{TOF}[\text{ns}])^2}$

M. Gatu Johnson et al. NIMA 591 (2008) 417
A quantitative perspective
Estimation of the tail temperature

**Stix Theory**

**Tail temperature**

\[ T_{\text{mino}} \approx k_0 T_e \xi_{\text{mino}} \]

\[ \xi_{\text{mino}} = \frac{m_{\text{mino}} v_{th,e} < P_{RF}>}{4 \sqrt{2 \pi} X_{\text{mino}} n_e Z_{\text{mino}}^2 e^4 \ln \Lambda} \]

**Absorption volume**

\[ \Delta V \approx 16 \pi^2 n_{\text{tor}}^2 v_{th,3\text{He}}^2 k_0 R_0 / \omega^2 \]

*\( T_{\text{mino}} \approx \text{several MeV can be estimated for both the } ^3\text{He and D 3 ion scenarios} \)*

*Is this consistent with data?*
He scenario - $^9$Be($^3$He,$p\gamma$)$^{11}$B and excited states of $^{11}$B

$^{11}$B nuclear levels

- L9
- L8
- L7
- L6
- L5
- L4
- L3
- L2
- L1
- GS

Energy levels:
- GS
- 0 keV
- 2124 keV
- 4445 keV
- 5020 keV
- 6741 keV
- 6792 keV
- 7286 keV
- 7978 keV
- 8560 keV
- 8920 keV

Percentage transitions:
- 100%
- 100%
- 86%
- 14%
- 87%
- 6%
- 67%
- 70%
- 67%
- 29%
- 4%
- 87%
- 6%
- 7%
- 46%
- 53%
- 0.9%
- 56%
- 30%
- 59%
- 9%
- 95%
- 5%
D-$^3$He-H: gamma-ray spectrum

Counts

Energy [keV]

- 90753
  t = 9-17 s
D-(\(^3\)He)-H: gamma-ray spectrum

\[^3\text{He}(^9\text{Be},p\gamma)^{11}\text{B}^*\]
\[^3\text{He}(^9\text{Be},n\gamma)^{11}\text{C}^*\]
The reactivity of the different excited states of $^{11}$B changes with $T_{3\text{He}}$.

Lack of cross section data at low energies make predictions for $T_{3\text{He}} < 500$ keV uncertain.

For $T_{3\text{He}}$ in the MeV range we expect a peak ratio of $\approx 3$.

However, we measure a ratio of $0.6\pm0.2$, pointing to $T_{3\text{He}} < 500$ keV.
Advanced modelling with SCENIC


LEMan:
- Low-frequency full-wave 3D code.
- Includes warm contributions to the dielectric tensor.
- No FLR effects are included.
- Suited for ICRF scenarios with dominant fundamental ion cyclotron resonant interaction

VENUS-LEVIS:
- Solves guiding-centre orbit equations in 3D
- Applies Monte-Carlo operators for Coulomb Collisions and ICRF wave-particle interaction

ANIMEC:
- VMEC equilibrium + anisotropic pressure
GENESIS-SCENIC synthetic gamma-ray diagnostics

Core $^3\text{He}$ distribution

Fast $^3\text{He}$ profile

$E \approx 2-3 \text{ MeV}$

$7.28$ and $7.98 \text{ MeV}$ $\gamma$-ray peak shapes

M. Nocente PhD Thesis 2012
7.28/7.98 MeV peak ratio from SCENIC-GENESIS

**Predicted peak ratio \( \approx 2.9 \)**
(vs 0.6 measured!)

TAEs resonate with \(^3\text{He}\) ions at energies between 2-3 MeV

If we believe in the SCENIC results, the significantly lower measured peak ratio may suggest that \(E_{^3\text{He}}=2-3\ \text{MeV}\) are effectively redistributed away from the core

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**Core \(^3\text{He}\) distribution**

![Core ^3He distribution](image)

**# 90753 spectrogram**

![Spectrogram # 90753](image)
$\gamma$-ray counting rate vs MHD activity

Relatively constant plasma parameters up to t=14 s but "bumpy" $\gamma$-ray counting rate
Alfven Eigenmodes lead to fast ion losses

It is clear seen how fast ions interact with modes escaping from the plasma
D-\(\text{D}_{\text{NBI}}\)-H scenario indicates similar results

Expected neutron spectrum

**TOFOR data**

\(T_D(\text{Stix}) \approx \text{some MeV} \quad \text{vs} \quad T(\text{best fit}) \approx 200 \text{ keV}\)

More advanced modelling and production of synthetic diagnostics ongoing
Applications to fast $^4$He studies
A large number of 3 ion scenarios is possible

<table>
<thead>
<tr>
<th>Ion species</th>
<th>( T )</th>
<th>( ^9\text{Be}, , ^7\text{Li}, , ^{22}\text{Ne} )</th>
<th>( \text{D}, , ^4\text{He}, , ^{12}\text{C}, \ldots )</th>
<th>( ^3\text{He} )</th>
<th>( \text{H} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( (Z/A)_i )</td>
<td>1/3</td>
<td>( \approx 0.43-0.45 )</td>
<td>1/2</td>
<td>2/3</td>
<td>1</td>
</tr>
</tbody>
</table>

Fast ion applications at JET and ITER:

\(^4\text{He}\) generation in the MeV range and test of confined \( \alpha \) particle diagnostics, anticipation of fast \(^4\text{He}\) physics

eg. \( T-(^4\text{He})-\text{H} \): generation of an \textit{anisotropic} \(^4\text{He}\) ion population

\( D-(D_{\text{NBI}})-^3\text{He} \): generation of an \textit{isotropic} \(^4\text{He}\) ion population by maximising the \( \text{d}+^3\text{He} \to \alpha+p \) fusion reactivity

Possibility to \textit{tailor the fast ion profile} by the antenna phasing and the pinch effect

Proposals to test these schemes at JET are under way
Conclusions

• The 3 ion species scenarios are efficient techniques for heating mixture plasmas and for fast ion physics studies (key ingredient: optimization of the wave polarization at the resonance)

• **Two 3 ion scenarios** have been tested at JET: $D-(^3\text{He})-H$ and $D-(D_{\text{NBI}})-H$

• All of the qualitative features associated to fast ion generation are observed and demonstrate the success of the scheme: sawtooth stabilization, fast ion driven MHD, pinch effect, gamma-ray emission, suprathermal neutron emission.

• At a quantitative level, we can use the measured gamma-ray and neutron spectra to quantitatively study the fast ion distribution function.

• In general, data indicate lower fast ion energies than expected (without MHD). This might point to the role of fast ion driven MHD in effectively depleting the plasma core from $E_{^3\text{He}} \approx 2-3 \text{ MeV}$ and $E_{D} \approx 1-2 \text{ MeV}$, which are resonant with the observed modes.

• Other applications of the scheme to fast ion generation include studies of $^4\text{He}$ ions (isotropic or anisotropic) at JET and ITER.
Thank you for your attention!