Fast-ion generation with ICRF at Wendelstein 7-X in high-density regimes

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Experimental aim: prove good fast-ion confinement

- Stellarator-reactor must be designed to provide confinement of fusion-born $\alpha$’s
  - provide sufficient self-heating of the plasma
  - avoid damage to device components

- $\rho_L/a \propto \frac{(mE)^{1/2}}{Z Ba} = \text{const}$

- HELIAS: $\alpha$-particles (3.5 MeV)
  - $W7-X$: protons (60 keV), $^3\text{He}$ (80 keV)

- Fast ion sources for $W7-X$:
  - NBI (55 keV) (see e.g. D. Gradic, NF2015)
  - ICRH

The main goal of ICRH in $W7-X$: source of fast ions ($\sim 50$–$100$ keV), at very high plasma density $n_{e0} \approx 2 \times 10^{20}$ m$^{-3}$

(* also good in view of impurity control, HDH-mode)
Outline

● Short overview of the ICRF system design

● ICRH scenarios for W7-X

● Three-ion \(^{3}\text{He})\)-D-H ICRF heating: 
  fast-ion generation at the largest plasma densities on W7-X

● Summary and conclusions
The dedicated ICRH antenna for W7-X

- TEC is designing a dedicated ICRH antenna for fast-ion generation in W7-X

- A two-strap antenna will be installed
  → different toroidal antenna phasings can be used e.g. (0;\(\pi/2\)), (0;\(\pi\)), (0;0), (0;\(\pi/4\))

- Using the RF equipment and hardware of TEXTOR (frequency range, \(f = 25–38\text{MHz}\))

- ICRH coupled power: 1–2 MW for 10s
  (with current assumptions for positioning of launcher and density profile in front of the antenna)

Design overview of the ICRF antenna

- Standard plasma LCMS
- AEE 3.1 port
- Bellows
- Center of gravity
- Transmission line slider
- RF feedthroughs
- AEE 3.1 flange
- Supporting vertical plate with vacuum sealings
- Adjustable basic support on platform
- Movable truck
- Spindle drive for truck
- Rails

Antenna box: 34cm x 88cm

- Antenna geometry has been optimized to maximize coupled power (see F. Louche et al., FED-2015, e.g. increasing the strap width, 6.8cm $\rightarrow$ 9cm)

Antenna surface (3D) is designed to mimic LCFS for the standard configuration of W7-X

Optimization of ICRF antenna design

<table>
<thead>
<tr>
<th>ICRF frequency, ( f ) (MHz)</th>
<th>Coupled ICRF power, ( P_{\text{ICRF}} ) (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>0.8</td>
</tr>
<tr>
<td>20</td>
<td>1.0</td>
</tr>
<tr>
<td>25</td>
<td>1.1</td>
</tr>
<tr>
<td>30</td>
<td>1.3</td>
</tr>
<tr>
<td>35</td>
<td>1.6</td>
</tr>
<tr>
<td>40</td>
<td>1.7</td>
</tr>
</tbody>
</table>

\( Coupled \text{ power, } P_{\text{ICRF}} \sim 1\text{–}2 \text{ MW} \)

F. Louche et al., FED-2015
● Short overview of the ICRF system design

● ICRH scenarios for W7-X

● Three-ion ($^3$He)-D-H ICRF heating: 
  *fast-ion generation at the largest plasma densities on W7-X*

● Summary and conclusions
ICRF minority heating: \( ^1\text{H} \) and \(^3\text{He} \) resonant ions

\[
B_0 \approx 2.5T \text{ (ECRH 140GHz), TEXTOR RF generators: } f = 25–38 \text{ MHz}
\]

- ICRF minority heating \( (\omega = \omega_{ci}) \): a) \( ^1\text{H} \) ions at \( f \approx 38 \text{ MHz} \), b) \(^3\text{He} \) ions at \( f \approx 25 \text{ MHz} \)
- ICRF second harmonic \( (\omega = 2\omega_{ci}) \): \( ^1\text{D} \) and \(^4\text{He} \) ions at \( f \approx 38 \text{ MHz} \) \( (\omega_{cH} = 2\omega_{cD}) \)
ICRF scenarios: (H)D and (³He)H heating

Single-pass absorption from 1D-TOMCAT code, $n_{e0} = 2 \times 10^{20}$ m⁻³

A concentration of minority ions (H or ³He) of a few percent is required

Hydrogen minority heating in W7-X (SCENIC, EPFL)

1% of H, $n_{e0} = 8 \times 10^{19} \text{ m}^{-3}$, $T_0 = 3 \text{ keV}$, $P_{\text{ICRH}} = 1.5 \text{ MW}$

- The five-fold periodicity is broken due to the antenna localisation
- Equilibrium geometry imposes 3D dependency on the resonant layers, i.e. where the wave transfers energy to the particles.
- Wave damping appears in the toroidal direction and is more important for the standard configuration, for which no resonance-free region exists.

Theory of fast-ion generation with minority ICRF

FAST-WAVE HEATING OF A TWO-COMPONENT PLASMA

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Abstract. The use of the conceptual hydrodynamic mode (also called the magnetoacoustic or, simply, the fast wave) is essential to some extent in the heating of a torus plasma containing a small fraction of high-energy ions. The total absorption of wave energy by the minority component is limited when the electron temperature is much higher than the ion temperature. The general condition for fast-wave heating is given by the relation $\xi_{\text{Stix}} \gtrsim n_{e,20}^{1/2} A_{\text{mino}}^{-1} \langle P_{\text{RF}} \rangle^{1/2}$, where $\xi_{\text{Stix}}$ is the characteristic plasma heating factor, and $\langle P_{\text{RF}} \rangle$ is the average RF power. This condition is satisfied when the fast wave can be absorbed by minority heating, and the wave mode is not too high in frequency to allow resonant absorption to the minority component.

1. Introduction

The need for supplementary heating in a tokamak—supplementary, that is, to the Ohmic heating associated with the toroidal current—has been recognized for a number of years. Originally, however, the special benefits become clear for a specific form of supplementary heating: putting the heat in at a high-energy tail on the ion distribution. In bringing a tokamak (50–60) $\text{E}_{\text{r}}$-relativistic heating, the high-energy ions cross-fusion reactions which release alpha particles and enhance the heating power, while in the two-component fusion device [1], the creation of the ion tail is an essential element of the trial concept. The most direct way to produce the ion tail is evidently by neutral injection. It will be some years, however, before neutral-beam technology allows us to test this heating method at the requisite beam currents and voltages, and the limit on where we can be efficient, penetration, impurities, plasma stability, and beam absorption rates must await such testing. Meanwhile, it is appropriate to look at supplementary heating methods as an alternative process for plasma heating and for ion tail creation. Radiofrequency heating can play a number of roles:

a. Electron heating. A successful two-component fusion experiment needs an electron temperature of 5 keV or more. Neutral injection provides supplementary heat to both the background ions and electrons, and too much background ion heating can be wasteful. In addition, it may turn out that r.f. electron heating is less costly to install than injection heating with similar capability.

b. Supplementary heating. Supplementary ion heating is the traditional role assigned to r.f. heating.

c. Ion tail creation. Selective absorption of r.f. energy by a minority of the plasma ions may be achieved by cyclotron resonance tuned to the minority ions [2–4], or by cyclotron harmonic heating which preferentially delivers power to the high-energy (large Larmor radius) component [5–7].

d. Ion tail enhancement. Radiofrequency heating may be used to enhance neutral injection itself by tuning the r.f. to resonate with the injected beam particles in the plasma. Such heating can easily add and proportionally increase the power and can also increase and maintain the energy distribution of the beam and the fusion reaction rate.

Energies of fast ions generated with minority ICRF

$E_{\text{mino}} \approx T_{\text{e}} \xi_{\text{Stix}}$, \hspace{1cm} $\xi_{\text{Stix}} \approx \frac{0.24 \left[ T_{\text{e}} (\text{keV}) \right]^{1/2} A_{\text{mino}} \langle P_{\text{RF}} \rangle}{n_{e,20} Z_{\text{mino}}^{2} X_{\text{mino}}}$

Good confinement in W7-X requires:

$n_{e0} \approx 2 \times 10^{20} \text{ m}^{-3}$, $T_{0} \approx 3 \text{ keV}$ ($\beta \approx 4\%$)

ICRH goal: $E_{\text{mino}} \approx 50–100 \text{ keV}$

ICRH acceleration factor: $\xi_{\text{mino}} \gtrsim 20–30$

$P_{\text{ICRF}} (\text{MW}) \approx 2.5 X_{\text{mino}} (\%) \left( \frac{Z_{\text{mino}}^{2}}{A_{\text{mino}}} \right) \Delta V (\text{m}^{3})$

$V_{\text{W7-X}} = 30 \text{ m}^{3}$, $\Delta V \approx 5 \text{ m}^{3}$, $X_{\text{mino}} \approx 1\% \quad \rightarrow \quad P_{\text{RF}} > 10 \text{ MW} (!)$ (for full plasma density)

H minority heating – a good option for operation with reduced $n_{e0}$
Challenge of ICRF in W7-X: produce 50-100keV ions in very high density plasmas

High-plasma density: improving wave absorption vs. complicating fast-ion generation

\[ \xi_{\text{mino}}^{(\text{Stix})} \approx \frac{0.24 \left[ T_e(\text{keV}) \right]^{1/2} A_{\text{mino}} \langle P_{RF} \rangle}{n_{e,20}^2 Z_{\text{mino}}^2 X_{\text{mino}}} \sim 20 - 30 \]

Solution: \textit{Decrease the concentration of resonant ions to compensate for the high density plasma}

But what scenario to use ?????
Answer: a novel ICRH scenario using three ion species

ICRF heating of $^3$He ions in 30%D – 70%H or 15% $^4$He – 70% H plasmas with $X[^3\text{He}] < 1\%$

How does it work?
● Short overview of the ICRF system design

● ICRH scenarios for W7-X

● Three-ion \(^3\text{He})\)-D-H ICRF heating: fast-ion generation at the largest plasma densities on W7-X

● Summary and conclusions
Fast wave (excited by ICRF antenna) is elliptically polarized.  
\( E_+ / E_- : \) left/right-hand polarized component (ions / electrons)

- **Left-hand polarized component** \( E_+ \) is responsible for (thermal) ion heating.

\[
p_{\text{ion}}^{(N=1)} = A|E_+|^2 + B(k_{\perp}r_L)^4|E_-|^2
\]  
(see Stix 1975)

- Plasma (mainly) imposes wave polarization.

\[
\frac{E_+}{E_-} \approx \frac{\varepsilon_R - n_i^2}{\varepsilon_L - n_i^2}
\]

- Why not single ion species?

\( E_+ \) (almost) vanishes at the ion cyclotron resonance, \( E_+ \rightarrow 0 \).
Two-ion species plasmas: Minority heating

- Two ion species:
  \[ \frac{E_+}{E_-} \rvert_{\omega=\omega_{c2}} \approx \left| \frac{Z_2 - Z_1}{Z_2 + Z_1} \right| \neq 0 \]

- Two-ion minority heating has a limited capability for ion absorption at very low \( X_{\text{mino}} < 1\% \)

D. Start et al., Nucl. Fusion 39, 321 (1999)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Minority ion</th>
<th>( E_+ / E_- )</th>
<th>Damping</th>
</tr>
</thead>
<tbody>
<tr>
<td>(H)-D</td>
<td>H</td>
<td>( \approx 1/3 )</td>
<td>‘Strong’</td>
</tr>
<tr>
<td>(D)-T</td>
<td>D</td>
<td>( \approx 1/5 )</td>
<td>‘Medium’</td>
</tr>
<tr>
<td>( ^3\text{He} )-H</td>
<td>( ^3\text{He} )</td>
<td>( \approx 1/7 )</td>
<td>‘Weak’</td>
</tr>
<tr>
<td>(Z)-Y-X</td>
<td>Z</td>
<td>( \gg 1 )</td>
<td>How? See [1]</td>
</tr>
</tbody>
</table>

Two-ion ICRF minority heating
- Minority concentrations of \( \sim 5\% \) are typically used in present-day experiments
- Wave polarization and absorption are fully decoupled
- \( X_3 = n_3/n_e \sim 0.1–1\% \) (impurity ions)

Three-ion ICRF minority heating


(Invited talk at the 21st Topical RF Conference, 27-29 April 2015, Lake Arrowhead, USA)
Three-ion ICRF heating: a dedicated tool for fast-ion generation

\[
\min \{(Z/A)_1, (Z/A)_2\} < (Z/A)_3 < \max \{(Z/A)_1, (Z/A)_2\}
\]

(\textsuperscript{3}He)-D-H or (\textsuperscript{3}He)-\textsuperscript{4}He-H plasmas

\begin{align*}
\text{W7-X (baseline conditions):} & \quad P_{\text{ICRF}}(\text{MW}) \gtrsim 2.5 X_{\text{mino}}(\%) \left(\frac{Z_{\text{mino}}^2}{A_{\text{mino}}} \right) \Delta V (m^3) \\
\rightarrow & \quad \text{Reduce the concentration of resonant ions (to } X_{\text{mino}} \sim 0.1-0.5\%\text{)!}
\end{align*}
Three-ion ICRF scenarios: fast-ion generation

Power deposition from TORIC, $X^{[3\text{He}]}=0.1\%$, D:H=29:71

*Flat $p_{\text{abs}}$ dependence in the range $X^{[3\text{He}]}=0.05\% – 1\%$ (very precise $^3\text{He}$ control not required)*

Potential in JET: $X^{[3\text{He}]} = 0.2\%$, $E_{^3\text{He}} \sim 1\text{ MeV/MW}_{\text{inj}}$

Potential in W7-X: $X^{[3\text{He}]} \sim 0.1\%$, $E_{^3\text{He}} \sim 50\text{-}100\text{ keV}$

(dedicated fast-ion source at the largest $n_{e0}$ in W7-X)
Three-ion ICRF heating: $\omega = 2\omega_{ci}$ vs. our proposal


Three ion species: D (majority, ~90%), H (minority, ~10%) + $^{13}\text{C}$, $^{21}\text{Ne}$, $^{7}\text{Li}$, $^{11}\text{B}$, $^{40}\text{Ar}$

Fast Wave $\rightarrow$ IBW (mode conversion) $\rightarrow$ absorption by impurities ($\omega = 2\omega_{c3}$)

Such an impurity RF heating was also observed on TFR, T-10, T11-M, JET, HT-7, ...

- LPP-ERM/KMS proposal

Three ion species: H (majority, ~70%), D (minority, ~30%) + $^{3}\text{He}$

Fast Wave $\rightarrow$ absorption by $^{3}\text{He}$ impurities ($\omega = \omega_{c3}$)
Conclusions

- ICRH will be used in W7-X as a source of fast ions ($E_{\text{fast}} \sim 50\text{–}100 \text{ keV}$)

- A number of ICRF scenarios are available with TEXTOR generators:
  - $H$ or $^3\text{He}$ minority heating in $^4\text{He}$ or $D$ plasmas (good option for reduced $n_{e0}$)
  - Three-ion $^3\text{He}$ minority heating in $D$-$H$ or $^4\text{He}$-$H$ plasmas (for the largest $n_{e0}$ in W7-X)
  - Second harmonic heating of $^4\text{He}$ or $D$ majority ions (at 38 MHz)

- Three-ion ICRF: efficient RF power absorption at very small $X_{\text{mino}} (<1\%)$:
  
  $H$:D $\sim$ 70:30 or $H$:4He $\sim$ 70:15 plasmas

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Future experiments on three-ion ICRF heating:

- ASDEX-Upgrade (10 shots, ~ May 2016)
- JET (selected as a backup experiment for 2015-2016 campaign)
- Alcator C-Mod (preparatory work with C-Mod Team is ongoing)
- Any further collaboration is welcome (LHD, EAST, …)