Non-ohmic ignition scenarios in Ignitor

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Abstract

In the reference Ignitor scenario (B. Coppi et al. (2001) Nuclear Fusion 41, 1253), extensively investigated by 1 1/2-D equilibrium-transport simulations, ignition was found to be reachable with ohmic heating only. Nevertheless, an auxiliary heating system at the ion cyclotron frequency delivering up to 18-24 MW, that is an amount comparable to the expected alpha heating, has been included in the machine design. Time dependent simulations show that the application of ICRH during the current ramp can accelerate the attainment of ignition, and it can help to control the evolution of the current profile, for example by keeping the value of the central $q$ above 1. The present work carried out by the JETTO code aims at establishing the amount of power effectively required for ignition, in the standard limiter configuration. Although relatively low levels of RF power are appropriate to optimize the process of reaching ignition, these will be needed during a phase of varying magnetic field, requiring antennas tuned at various frequencies to operate in sequence. An overview of the possible heating procedures for the most significant phase of the Ignitor experiment is presented.
Ignitor reference parameter


<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major radius</td>
<td>$R_0$ 1.32m</td>
</tr>
<tr>
<td>Minor radii</td>
<td>$a 	imes b$ 0.47 $\times$ 0.86</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>2.8</td>
</tr>
<tr>
<td>Elongation</td>
<td>$k$ 1.8</td>
</tr>
<tr>
<td>Triangularity</td>
<td>$\delta$ 0.4</td>
</tr>
<tr>
<td>Toroidal field</td>
<td>$B_T(R_0)$ 13T</td>
</tr>
<tr>
<td>Toroidal current</td>
<td>$I_p$ 11MA</td>
</tr>
<tr>
<td>Poloidal current</td>
<td>$I_\theta$ 8 MA</td>
</tr>
<tr>
<td>Plasma Volume</td>
<td>$V$ 10 m$^3$</td>
</tr>
<tr>
<td>Plasma Surface</td>
<td>$S_a$ 36 m$^2$</td>
</tr>
<tr>
<td>Safety factor</td>
<td>$q_\Psi$ 3.6</td>
</tr>
<tr>
<td>Plasma duration</td>
<td>$t$ (4 + 4)s</td>
</tr>
</tbody>
</table>

Simulations start at this time
The updated version of the JETTO code is used (Airoldi and Cenacchi, NF (1997) 37, 1117)

Free-boundary axysymmetric equilibrium
Diffusion equations for:
- toroidal current density
- electron thermal energy
- ion thermal energy
- primary ion densities (D-T)
- impurity ion densities (C-O)

Neoclassical electrical resistivity

Losses due to:
- impurity radiation
- bremsstrahlung emission
- synchrotron radiation
Electron thermal diffusion

- Coppi-Mazzucato + Coppi ubiquitous modes contribution
  \[ \chi_e = c_E \chi_e^{CMG} + c_{UB} \chi_e^{UB} \]  

- Mixed Bohm-gyro-Bohm model
  \[ \chi_e = \alpha_B \chi_e^{Bohm} + \alpha_{gB} \chi_e^{gB} \]  
  [Vlad et al., NF (1998) 38, 557]

Ion thermal diffusion:  \[ \chi_i = \chi_i^{NC} + c_{ei} \chi_e \]
Particle transport:

\[ \Gamma_i = -D_p \left( \frac{\partial n_i}{\partial \rho} \left \langle |\nabla \rho|^2 \right \rangle + \alpha_{\text{inv}} \frac{S^2(\rho)}{V_{pl} dV / d\rho n_i} \right) \]

with \( D_p = \alpha_p \chi_e \)

Alpha heating source in the form:

\[ S_{\alpha(e,i)} = n_D n_T W_\alpha <\sigma v_{DT}> f_{e,i}(T_e) \gamma \]

RF power source by the simple expression

\[ P_{RF} = P_0 \exp\{-[(\rho_c - \rho) / \Delta \rho]^2\} \]
Non-ohmic ignition scenarios

The Ignitor ICRH system will be able to provide 18-24 MW in the frequency range 70-140 MHz through six 2-strap antennas.

The application of ICRH during the current ramp up phase is complicated by the fact that, during part of that time, the toroidal field is also ramping up, from 8 to 13 T.

Various heating schemes can be adopted - H or $^3$He minority heating can be used in a 50:50 D-T plasma.

The JETTO transport simulations indicate that the achievement of ignition can be accelerated by the application of relatively modest amounts of auxiliary heating. This allows considering staggered frequencies (up to 3)
Two-frequencies, $^3$He minority heating

- **115 MHz**
- **95 MHz**
Three-frequencies, $^3$He minority heating

- 120 MHz
- 105 MHz
- 90 MHz
Two frequencies, $H$ minority heating

- 130 MHz
- 140 MHz
The more centered deposition profile gives the major boost to the ignition achievement.
Energy confinement time - ohmic case and RF case

\[ \tau_{E}^{\text{CODE}} = \frac{(W_e + W_i)}{(P_\Omega + P_\alpha + P_{\text{AUX}} - dW_{\text{tot}}/dt)} \]

\[ \tau_{E}^{\text{ITER97L}} = 0.023A_i^{0.2}k^{0.64}I_p^{0.96}\bar{n}_i^{0.4}a^{-0.06}R^{1.89}B^{0.03}P_{\text{IN}}^{-0.73} \]

\[ \tau_{E}^{\text{ITER97L}^*} = 0.023A_i^{0.2}k^{0.64}I_p^{0.96}\bar{n}_i^{0.4}a^{-0.06}R^{1.89}B^{0.03}P_{\text{NET}}^{-0.73} \]

\[ P_{\text{IN}} = P_\Omega + P_\alpha + P_{\text{AUX}} \]

\[ P_{\text{NET}} = P_\Omega + P_\alpha + P_{\text{AUX}} - dW/\text{dt} \]
3MW from 4.3s to 5.3s

B-gB model for $\chi_e$

3MW are sufficient to prevent the triggering of sawteeth and ignition is achieved
Energy confinement times

Ohmic case

3 MW applied at 4.3s
Conclusions

• A limited level of RF power, injected during the current ramp, can significantly shorten and optimize the time to reach ignition

• RF power may also be used to control the current density profile so as to avoid MHD instabilities

• See poster QP1.077 for the RF application in the case of an advanced scenario associated with X-point configurations