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# ICRF heating schemes for HL-2M

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Ion Cyclotron Resonance Frequency (ICRF) is the only auxiliary heating method which can heat directly the fuel ions in the future fusion reactors. The HL-2M tokamak has been successfully commissioned at SWIP in 2020. Two key missions that HL-2M is going to achieve are the 10keV ion temperature and investigating the burning plasma physics. It is envisaged to equip 6MW ICRF in the next phase, in addition to the 15MW NBI [1].

Before going to the engineering design of the ICRF system for HL-2M, it is important to conduct physics analyses to explore all the possible heating schemes and set limits on the operation parameters. ICRF can either heat electrons via directly power damping on electrons, by the mode conversion and by recently discovered three ion scheme, or heat ions through minority heating and harmonic heating. This work will investigate all the above heating schemes under typical HL-2M plasma scenarios, i.e. Baseline and Steady-state [2].

To have an efficient ion heating, the first priority is to have the ICRF system optimized for H and $^3$He minority heating, e.g. with a RF frequency in between 18-33MHz and $k_{//}>6m^{-1}$. A good Single Pass Absorption (SPA) can consequently be guaranteed under the conditions of Table 1. An ICRH heating scheme generally performs well if it has a high SPA and the absorption region is located on axis. In D(H) plasmas, the 2nd harmonic D heating along with the H minority heating can both contribute to the ion power absorption. If additional budget is available, the 2nd harmonic H heating can also be a candidate, which requires a distinct frequency range, i.e. 55-70MHz. Unlike the minority heating, harmonic heating is insensitive to the wave polarization, minority concentration and $k_{//}$, but generally requires a higher bulk ion temperature, in which the synergy between NBI and ICRF can be important.

Table 1. SPA analyses of H and $^3$He minority heating in a Deuterium plasma under three plasma scenarios

| Min ion | Baseline (2.0MA/2.2T) | Baseline (1.4MA/2.0T) | Steady-state (1.0MA/1.8T) |
|---|---|---|---|
| H | SPA>0.7<br>*f*=33MHz<br>X(H)~2-8%<br>$T_i$>6keV<br>$k_{//}>7m^{-1}$ | SPA>0.7<br>*f*=30MHz<br>X(H)~2-8%<br>$T_i$>5.5keV<br>$k_{//}>6.7m^{-1}$ | SPA>0.7<br>*f*=27MHz<br>X(H)~2-10%<br>$T_i$>5.4keV<br>$k_{//}>6.5m^{-1}$ |
| $^3$He | SPA>0.9<br>*f*=22MHz<br>X($^3$He)~2-12%<br>$T_i$>3keV<br>$k_{//}>6.2m^{-1}$ | SPA>0.9<br>*f*=20MHz<br>X($^3$He)~2-15%<br>$T_i$>2.5keV<br>$k_{//}>6m^{-1}$ | SPA>0.9<br>*f*=18MHz<br>X($^3$He)~2-18%<br>$T_i$>2keV<br>$k_{//}>6m^{-1}$ |

If one needs to further predict the power allocations on each plasma species from different heating schemes, full wave simulations must be conducted. The TORIC code solves the full wave equations with the kinetic dielectric tensor of the hot plasmas in a 2D radial-poloidal cross section of a real 3D tokamak [3]. Simulation adopts typical magnetic equilibrium and plasma profiles of HL-2M as inputs. The former is provided by EFIT and the latter is obtained by iterating relevant transport and heating codes. Figure 1 shows the power deposition and current drive profiles for the D(H) minority heating scheme with *f*=27MHz, $B_0$=1.8T. Most of the power is absorbed at the H cyclotron resonance. Besides, the 2nd harmonic D heating also accounts for part of ion heating. The electron power absorption and current drive are dominated by the directly damping of the fast wave.

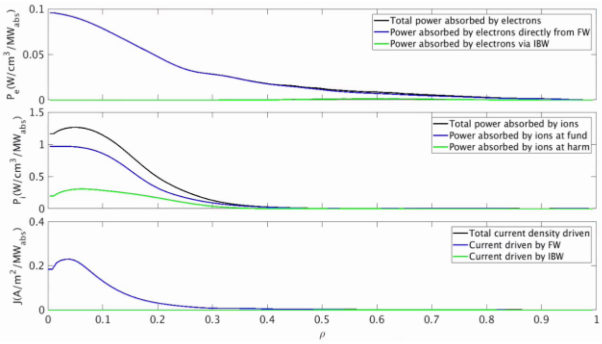

Figure 1. TORIC simulations of power deposition and wave-driven current profiles in D(H) minority heating

Other electron heating schemes have also been investigated, e.g. the D-$^3$He mode conversion heating and the D-H-$^3$He three ion heating. The heating and current drive profile in mode conversion heating are very localized, making this heating scheme an alternative way to control current profile, MHD instabilities and drive plasma flow. The three ion scheme is very efficient in terms of generating energetic particles. Modeling of the energetic particle is incorporated by iterating between TORIC and the Steady-State Fokker-Planck Quasilinear solver (SSFPQL) [4]. Simulation shows the perpendicular energy of the third ion could reach 800keV with only 1MW ICRF. The energetic ion then transfer most of the power to electrons during its slow down.

In conclusion, all of the ICRF heating schemes are analyzed for the HL-2M tokamak and corresponding parameters to achieve the best performance for each heating scheme are proposed. D(H) and D($^3$He) minority heating can be the main ion heating mechanisms in the start-up phase. The second harmonic D heating can then take over when the bulk ion temperature is already high. In the most cases, the fast wave direct damping plays a dominant role on electron heating. Preliminary analyses of the energetic ions produced by the three ion scheme are provided. The results of this study can give guidance to the engineering design of the HL-2M ICRF system.

References

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