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Modeling of 2nd Harmonic Electron Cyclotron Heating and Current Drive Solenoid-free Start-up Experiment in QUEST

The QUEST ECH solenoid-free start-up experiment utilizing the 28 GHz gyrotron at 2nd harmonic frequency has demonstrated remarkable efficiency and achieved record start-up current values [1]. The experiment provides rich opportunities to understand and optimize ECH-based tokamak/ST current start-up and ramp-up concept. Another potentially noteworthy aspect of the QUEST 28 GHz experiment is its very high frequency to toroidal magnetic field ratio, which is 28 GHz/0.25T or 112GHz/1T. The higher frequency enables higher density limit and for reactors with several Tesla toroidal field, this start-up scenario can largely avoid the usual density limit often encountered by ECCD. Conversely this higher harmonic scenario would enable utilization of ECH at lower magnetic field as in the case of many ST experiments. This scenario maybe also attractive for the ECH assisted start up for the initial phase of ITER where the toroidal magnetic field maybe relatively low ~ 2 T. To better understand the QUEST experimental results, we initiated a modeling effort at PPPL. Improved modeling should also help develop better predictive capability for future ST and tokamak-based reactors. An ST/tokamak start-up modeling is a highly coupled non-linear problem as the magnetic field topology evolves dramatically from an open vacuum field configuration to a closed configuration. The plasma temperature evolves from a very cold collisional regime to a very hot collision-less regime. For this task, we developed a grid-based start-up code where plasma parameters, generated plasma currents, and resulting poloidal magnetic fields are evolved from the vacuum fields. Initially, 2nd harmonic electron cyclotron heating takes place with multi-pass ECH absorption as the single-pass absorption is relatively small at low temperature. The current generated in this stage is purely pressure driven since the launched wave phase and polarization information is likely lost quickly. The grad-B drift driven current together with the processional currents can then create a closed flux surface configuration and then the bootstrap current in a closed configuration can further enhance the plasma current. The ECH heating efficiency increases with plasma current since the confinement is increased and resulting electron temperature rise would further increase the ECH absorption and plasma currents. Once the plasma temperature becomes sufficiently high ~ 1 keV, a single-pass absorption can rise sufficiently to transition to the ECCD phase. The entire start-up process is therefore a self-amplifying non-linear problem where a very rapid spontaneous plasma current rise (e.g., "current jump") can be expected. An important point to note is that two-component distribution (hot minority and colder bulk) is highly advantageous for hot electrons to be generated for efficient ECCD as observed in the QUEST start-up experiment. The analysis shows that the QUEST experiment was able to generate energetic electrons by heating small hot component ~ 3% to minimize the collisional drag. Once heated to ~ 10 keV, the hot component could be sustained even with the subsequent density rise to 3-4 x 1012cm-3.
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