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Developing attractive radio frequency actuators for fusion reactors*

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The radio-frequency (RF) plasma waves are viewed as critically needed actuators for heating and current drive of magnetic fusion reactor systems, as alternatives such as NBI are increasingly becoming technically challenging for dense, hot reactor plasma core. A wide variety of relatively efficient RF sources are available and the transmission of the RF power to reactors is well understood and technically developed. The RF systems are also generally compatible with the nuclear boundaries of fusion reactors. There are also many types of plasma waves which can be coupled and access the hot-dense fusion reactor core via antennas or launchers. Even with those attractive features, there are a number of questions and issues which must be resolved before the RF systems can be deployed in fusion reactors. For example, can antenna or waveguide launcher radiate a sufficient amount of RF power without generating excessive impurities? Can the waves thus launched propagate through the highly turbulent plasma edge region and reach the plasma core without adversely being affected? Can the hot plasma waves such as electron and ion Bernstein waves be utilized to access the hot-dense reactor plasma core? Can the RF current drive start-up and ramp-up to full current non-inductively thus significantly simplify the tokamak-based reactor design? To resolve those questions, the RF researchers around the world have been working actively in the past decades. At PPPL, we have been also working to resolve those issues. Taking advantage of advent of modern computing tools, a flexible 3D electro-magnetic simulation platform Petra-M has been developed which can incorporate the CAD-grade antenna and plasma boundary into the plasma-RF-wall interaction physics [1]. Petra-M code was recently improved to calculate the 3D RF-sheath and edge turbulences which can be used to optimize the antenna design to minimize the impurity generation and improve heating and current drive efficiency. Also recently, Petra-M was extended to solve full wave equation of kinetic waves where the coupling to electron and ion Bernstein waves was resolved to all orders of Larmor radius.

In the area of non-inductive start-up, the elimination of the need for an Ohmic heating solenoid may be the most impactful design driver for the realization of economical compact tokamak reactor systems. However, this would require fully non-inductive start-up and current ramp-up from zero plasma current and low electron temperature of sub-keV range to the full plasma current of ~ 10 - 15 MA at 20 - 30 keV electron temperature. To address this challenge, an efficient solenoid-free start-up and ramp-up scenario utilizing a low-field-side-launched extraordinary mode at the fundamental electron cyclotron harmonic frequency (X-I) is proposed, which has more than two orders of magnitude higher electron cyclotron current drive (ECCD) efficiency than the conventional ECCD for the sub-keV start-up regime [2]. A time dependent model was developed to simulate the start-up scenarios. For the Spherical Tokamak Advanced Reactor (STAR), it was found that to fully non-inductively ramp-up to ~ 13 MA, it would only take about 25 MW of EC power at 170 GHz. This level of ECH power is less than that of the ECH power source already anticipated for the plasma sustainment phase so essentially eliminating the capital cost of the non-inductive start-up and ramp-up. Because of the relatively large plasma volume of STAR, radiation losses must be considered. It is important to make sure that high *Z* impurities are kept sufficiently low during the early current start-up phase where the temperature is in sub-keV range. Since the initial current ramp up takes place at a factor of ten lower density compared to the sustained regimes, it is important to transition into a higher bootstrap fraction discharge at lower density to minimize the ECCD power requirement during the densification. For the sustainment phase an array of eight gyrotron launchers with a total of about 60 MW of fundamental O-mode was found to be sufficient to provide the required axis-peaked external current drive. High efficiencies between 19 – 57 kA/MW were found with optimal aiming, and these were resilient to small changes in aiming angles and density and temperature profiles.

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References

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