Dual utilization of X-I and O-I ECCD for fully solenoid-free operations for a fusion reactor

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The elimination of the need for an OH solenoid maybe the most impactful design driver for the realization of economical compact fusion tokamak reactor systems. This is particularly true for lower aspect ratio tokamaks such as spherical tokamaks (STs) to access higher beta regimes. Among many solenoid-free start-up approaches [1], the ECH (electron cyclotron heating) approach is generally considered to be favorable as a reactor compatible technology, since high power gyrotrons are available and ECH components can be compatible with the nuclear environment. Also ECH waveguide coupling, propagation, and absorption physics are well understood. In Fig. 1, we show a schematic of the solenoid-free operations including the plasma densification phase which occurs after the plasma temperature T_{e0} and plasma current I_p are ramped up. In a Spherical Tokamak Advanced Reactor (STAR) [2] study, the O-mode EC current drive (ECCD) at fundamental resonance (O-I) is utilized for the current profile control to sustain high beta, high performance discharges. Utilizing poloidally distributed waveguide system, a desired non-inductive current profile was obtained. As for the non-inductive start-up scenarios, the X-mode ECCD at fundamental resonance (X-I) was proposed [3]. This is because X-I at lower density of ~ 1/10 that of the sustained phase is predicted to have much higher ECCD efficiencies compared to the O-I ECCD particularly as it is going through the lower T_{e0} regime [4]. The ramp-up time can be shortened with lower T_{e0}. While the X-I current ramp-up at the lower density regime provides a logical path for the current ramp-up to a full current level with high ECCD efficiency, the plasma density still needs to be increased by a factor of 10 to reach the sustainment phase. Moreover, at some point, the X-I which can only function at the lower density regime must be switched to the O-I for the higher density sustainment phase. Previously, we investigated the current ramp-up phase at low plasma density [4]. In the present work, we investigate this densification process where the plasma density is increased by a factor of 10 continuously from the low density X-I start-up regime to the high density O-I sustainment phase. A relevant question is if the ECCD by either X-I or O-I can be provided continuously as the density is ramped up.

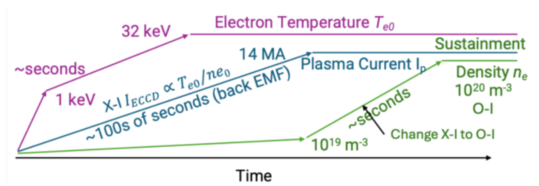

FIGURE 1. STAR solenoid-free operation including current start-up, ramp-up and densification.

For investigating the densification regime, we use a normalized density n_{eN} defined as the ratio of the plasma density compared to the sustainment phase. Here, only the normalized density is changed from 0.1 to 1.0 while other parameters including plasma profiles are assumed to remain constant. It is assumed that the sustainment target electron temperature profile with $T_{e0} \sim 32$ *keV* is achieved during the start-up phase, then it is maintained steadily during the densification phase. As shown in Fig. 2, the ECCD efficiency, while decreasing with ~ 1/ n_{eN}, remains relatively continuous with the X-I and O-I transition near

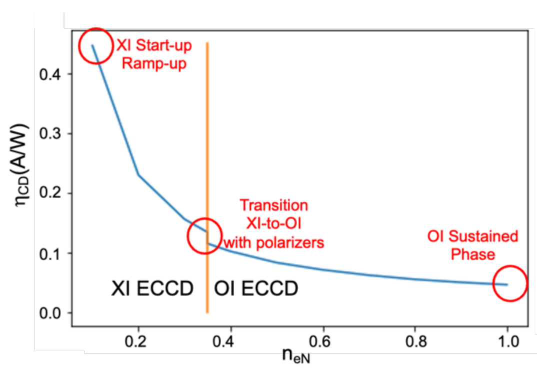

FIGURE 2 ECCD efficiency vs normalized density n_{eN}.

n_{eN} ~ 0.35. The X-I to O-I polarization changes can be done with a polarizer in each of many waveguides. Since there will be a large number of polarizers, the polarization changes can be done incrementally perhaps one at a time. With the given ECCD efficiency as a function of n_{eN}, it is now possible to estimate the required P_{ECCD} as a function of n_{eN}. We considered two cases. The first obvious case is the constant current scenario where I_p is ramped up to the full 13 MA at n_{eN} =0.1 and then I_p is held constant while n_{eN} is increased from 0.1 to 1.0. For the constant I_p case, the boostrap current fraction f_{BS} is linearly proportional to n_{eN} as shown in Fig. 3(a). The required P_{ECCD} for this scenario is shown in Fig. 3(b) which peaks at ~ 100 MW at n_{eN} =0.6 which significantly exceeds the available ECH power of ~ 65 MW. The second scenario is a high f_{BS} scenario starting at a lower I_p of ~ 8 MA which would enable higher f_{BS} as it is inversely proportional to I_p^2. I_p is kept at 8 MA until n_{eN} ~ 0.35, then increased with I_p and n_{eN} toward the sustainment phase as shown in Fig. 3(c) with the required power in Fig. 3(d). As shown in the figure, the required power remains below the available 65 MW level which is desirable from the facility cost point of view. We will now analyze the overall power balance for the high f_{BS} case.

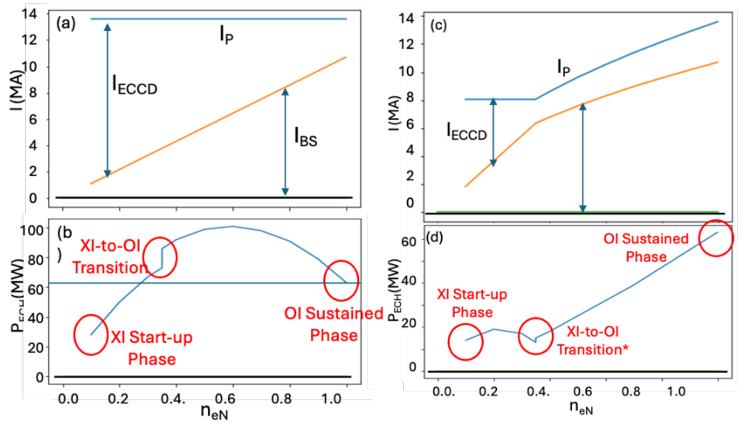

FIGURE 3. Plasma current and required ECCD power during densification. (a) I_{ECCD} and I_{BS} for the constant Ip scenario. (b) The required ECH power for the constant Ip scenario. (c) I_{ECCD} and I_{BS} for the high BS current scenario. (d) The require power for the high BS current scenario.

The power balance schematic is shown in Fig. 4. The electrons have several power loss channels. In addition to the usual transport losses, there are radiative loses including synchrotron and bremsstrahlung and various impurity radiations. The radiative losses are relatively well understood, and can become excessive if the high Z impurity level is high. In this exercise, we found an acceptable impurity level for lower Z carbon to be 2.5 %, for higher Z iron to be 2.5×10^{-2} % and for very high Z tungsten to be 2.5×10^{-3} % which gives the Z-effective of ~ 2. In addition, there is a power loss to ions. The electron loss to ions are computed with Coulomb collisions. The ion temperature rise is balanced by the ion transport loss which could be close to ion neo-classical values. For H-factor ~ 2, the ions thus heated can produce fusion power if the 50:50 mixture of D-T is used. The resulting fusion alpha-heating power could reach ~ 100 MW level (or ~ 500 MW fusion power) at n_{eN} =1.0 which could compensate for the electron power loss channels.

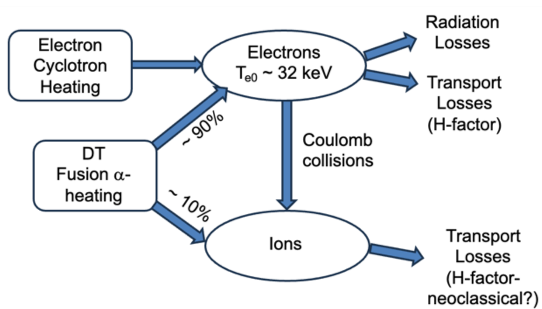

FIGURE 4. A schematic of the power balance for the ECCD densification process.

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