NON-INDUCTIVE CURRENT DRIVE AT ZERO LOOP VOLTAGE USING LHCD PAM LAUNCHER ON ADITYA-U

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1. ABSTRACT

For the first time, a steady plasma current of approximately 40 kA has been successfully driven exclusively through lower hybrid waves, without any loop voltage, using a PAM launcher in ADITYA-U. The target plasma is initially formed using an Ohmic transformer, typically lasting around 100 ms. In inductive discharges, the available loop voltage can extend the pulse length up to a maximum of ~150 ms. To further prolong the plasma pulse, lower hybrid waves (LHWs) are injected at 80 ms. The lower hybrid current drive (LHCD) experiment, utilizing a passive-active multijunction (PAM) launcher, is conducted at peak parallel refractive index of -2.5 The plasma pulse is extended up to 320 ms and good coupling of LHW was observed, with the reflection coefficient (RC) remaining below 5% as long as the plasma column remained stably positioned which also confirm the predicted RC values from ALOHA coupling code. The LHCD figure of merit ~0.2×10^{19} A/m².W is achieved in these non-inductive phase of plasma discharges during the flat-off phase of the plasma current. The generation of suprathermal electrons confirmed energy transfer from LHWs to bulk plasma electrons, as demonstrated experimentally through bremsstrahlung emission measurements from these suprathermal electrons. This paper provides an estimate of figure of merit of LH current drive with PAM launcher in ADITYA-U for the first time since stationary, stable and constant plasma current could be maintained with LH only over a reasonable current diffusion time scales without any loop voltage. Additionally, the LHW coupling studies and results obtained from pulse height analysis of hard x-ray energy spectra in the energy range of 20-200 keV obtained from CdTe detector is also presented.

2. INTRODUCTIONS

Lower hybrid current drive (LHCD) plays an important role in steady-state tokamak operations by reducing dependence on Ohmic Heating (OH) flux and enhancing bootstrap fraction [1-3]. Experiments on tokamaks like ALCATOR-CMOD and FTU have demonstrated LHCD's efficiency in driving plasma current at high densities relevant to reactor-scale applications [4]. Recent studies on DIID tokamak focus on high field side (HFS) launching of lower hybrid waves for future reactors relevant studies [5]. The passive-active multijunction (PAM) launcher has been widely adopted in tokamaks such as FTU, TORE SUPRA, EAST, and ADITYA-U due to its superior heat resistance and efficient wave coupling [6,7]. In ADITYA-U, a PAM launcher successfully sustained a steady plasma current of ~40 kA solely using lower hybrid waves with zero loop voltage, extending plasma pulses up to 320 ms with a reflection coefficient below 5%, consistent with theoretical predictions. Experimental results confirmed energy transfer from lower hybrid waves to bulk plasma electrons through bremsstrahlung emission measurements. This paper provides an estimate of figure of merit of LH current drive with PAM launcher in ADITYA-U. Additionally, the LHW coupling studies and results obtained from pulse height analysis of hard x-ray energy spectra in the energy range of 20-200 keV obtained from CdTe detector is also presented

3. EXPERIMENTAL SET UP AND OBSERVATIONS

ADITYA-U is an upgraded version of India's first tokamak, ADITYA, with an aspect ratio of 3 and major and minor radii of 0.75 m and 0.25 m, respectively [8]. It features a circular vacuum vessel enclosed by twenty toroidal field coils, with plasma initiation driven by an Ohmic heating coil. The tokamak is equipped with a range of diagnostics, including magnetic, microwave, spectroscopy, and probe-based systems to measure plasma parameters. Recently a PAM launcher is successfully integrated with ADITYA-U to carry out non inductive current drive experiment using LHWs. The PAM antenna comprises of two modules, each containing two active and two passive waveguides arranged toroidally, with three such rows in the poloidal direction. This setup is realized using two TE_{10} to TE_{30} mode converters, which feed two standard WR284 waveguides into the launcher [9]. The non-inductive CD experiment carried out at launch parallel refractive index ($n_{\parallel}$) of – 2.5 with launching power level in the range of 80-100 kW from the existing klystron sources. The primary results of the non-inductive current drive at 3.7GHz using PAM launcher in ADITY-U tokamak is presented. The good coupling of LH power is observed over many shots and the measured reflection co-efficient (RC) matches well with the predicted RC from ALOHA linear coupling model. Figure-1 highlights the coupling studies of the LHCD PAM launcher over many shots. The plasma current pulse length is extended up to 320 ms solely with LHWs where loop voltages were available up to 70 ms. The non-inductive phase beyond 200 ms is achieved in the recent plasma discharges with LHCD. The LHCD figure of merit has been estimated based on the measured plasma current, density, coupled power over the non-inductive phase of LHCD driven plasma.

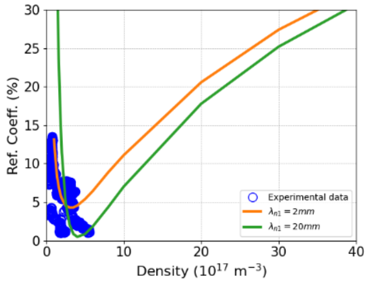

Figure-1: The RC values calculated from ALOHA model vs edge density near PAM mouth. The blue circle represents the experimental RC

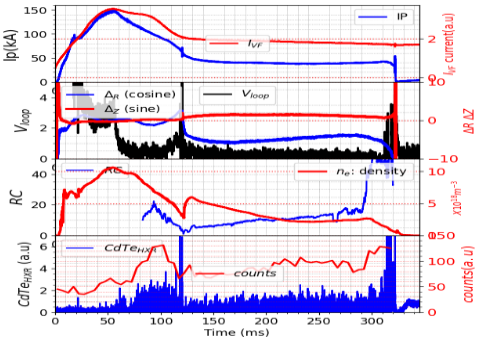

Figure-2: Temporal evolution of plasma current, current of vertical field power supply, loop voltages, position of the plasma column, RC, density, bremsstrahlung emission measurement employing CdTe detector is shown for discharge # 38781

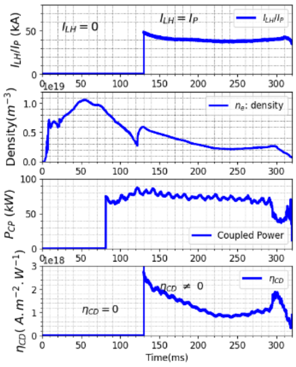

Figure-3: Temporal evolution of driven current (I_{LH}), density ($\overline{n_{e0}}$), coupled power (P_{CP}) and LHCD merit (η_{cd}) are shown.

The non-inductive current drive scenario for the plasma discharge #38781 is displayed in the figure-2. The performance of LHCD in terms of driven current, density, coupled power, and experimental figure of merit over time is shown in the figure-3. LHCD figure of merit $\eta_{cd} \sim 0.2 \times 10^{19}\, A.m^{-2}.W^{-1}$ has been achieved during purely non-inductive phase of the plasma current. The hard x-ray in the energy range of 20 -200 keV has been measured using CdTe detector also establish the generation of supra-thermal electron due to electron landau damping of LHWs. The immediate response of LH pulse to the CdTe signal confirms the same. The pulse height spectrum analysis reveals that the high energy tail extend up to 60 keV before LHCD pulse and it extend up to 170 keV after the application of LH pulse. These LHCD driven fast electron are the main driver to extend the tail of the HXR spectrum up to 170 keV.

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