Design and commissioning of a novel LHCD launcher on Alcator C-Mod

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Abstract. The design, construction, and initial results of a new LH launcher (LH2) on Alcator C-Mod is presented. LH2 is based on a novel four way splitter concept which evenly splits the microwave power in four ways in the poloidal direction. This design allows the simplification of feeding structure, while keeping the flexibility to vary the peak launched toroidal spectrum from -3.8 to 3.8. Good plasma coupling over a wide range of edge densities and a clean spectrum were predicted by an integrated model using TOPLHA and CST microwave studio, in which the antenna plasma coupling problem and the vacuum side EM problem were solved self-consistently. Poloidal variations of the edge density were found to affect mainly the evenness of power splitting in the poloidal direction. In order to characterize the coupling performance, LH2 is equipped with a variety of dedicated diagnostics such as 16 sets of RF probes, six Langmuir probes, and three X-mode reflectometer horns. LH2 was successfully commissioned in July 2010 including these dedicated diagnostics. The measured transmission loss is about 30 % lower than the previous launcher and the clean spectrum has been confirmed. The power handling capability exceeding an empirical weak conditioning limit was demonstrated, and so far, the reliable operation upto 0.8 MW net LHCD power has been achieved.

1. Introduction

The goal of the LHCD experiment on the Alcator C-Mod tokamak is to demonstrate and study full non-inductive high performance tokamak operation using the parameters close to that envisioned for ITER in terms of LHCD frequency, density, and magnetic field [1]. Previously, up to 1.2 MW of microwave power at 4.6 GHz has been successfully launched for 0.5 s using a traditional grill launcher (LH1). Modification of current profile by off-axis current drive [2], plasma rotation induced by LHCD, and the modification of edge pedestal has been observed [3]. The LHCD Density limit [4] was also revisited and a new hypothesis was proposed [5].

To explore a wider parameter space using higher power and longer LHCD pulse, a second LHCD launcher (LH2) was designed and constructed. The goal is to realize 2s LHCD with 4MW source power level using two LHCD launchers. LH2 employs a four way splitter as a final stage of power splitting. Different from a commonly used multi-junction type launcher, this component splits the microwave power in four ways evenly in the poloidal direction. This design ensures a clean launched spectrum over a wide range of N_{toroidal} as LH1 (from -3.8 to 3.8), while greatly simplifying the feeding structure (jungle gym).

A challenge in designing LH2 is to predict how the four way splitter behaves when it is loaded with a plasma. To address this issue, we carried out an integrated modeling of LH2 using TOPLHA and CST microwave studio [6]. TOPLHA solves the antenna-plasma coupling problem assuming a stratified plasma, and CST microwave studio solves

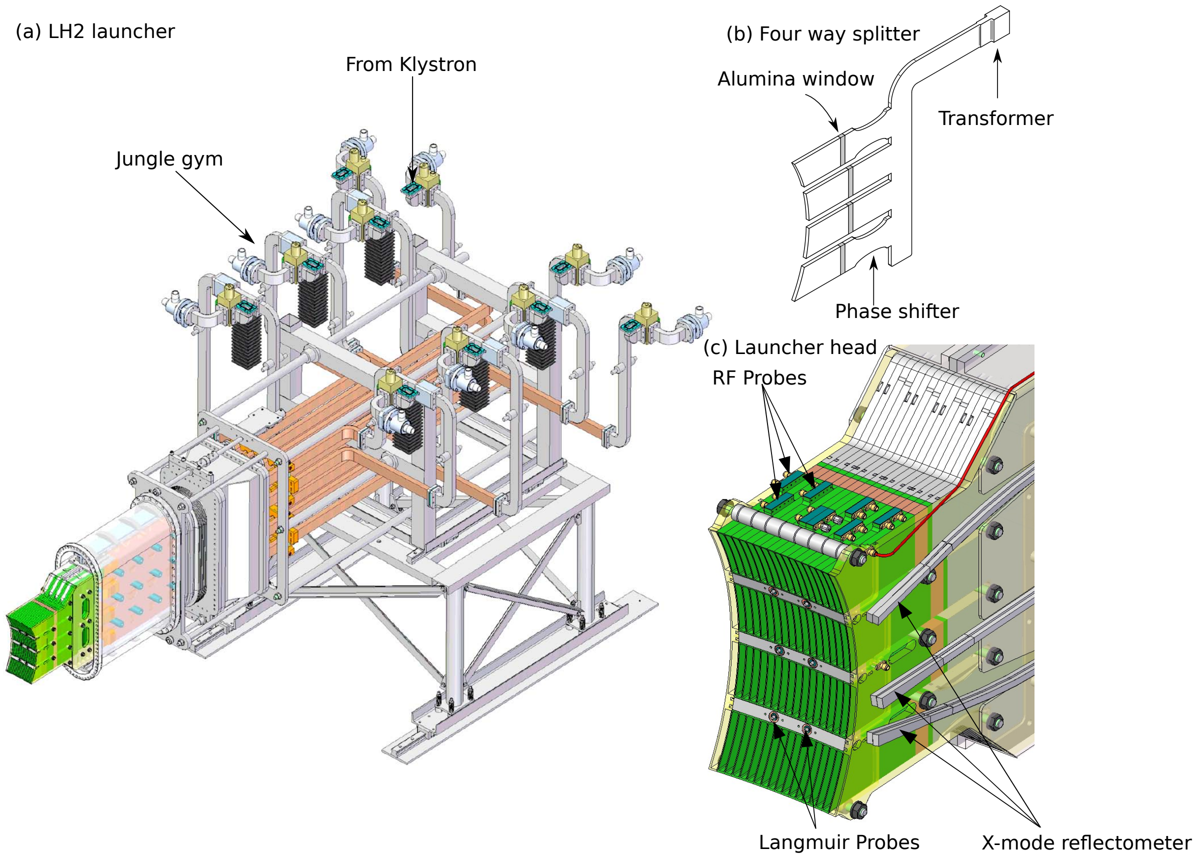

FIG. 1. Schematics of (a) the LH2 launcher, (b) four way splitter, and (c) the coupler waveguide assembly and dedicated diagnostics.

the EM problem in the vacuum region. The RF characteristic of LH2 is calculated by cascading the S matrices from these simulations. Particularly due to the relative size of the launcher to a plasma, we surveyed carefully the impact of having a different plasma impedance on each row of the launcher. And, motivated by this study, we installed a dedicated diagnostic suite to characterize the antenna performance experimentally.

LH2 was installed in May 2010 and all the dedicated diagnostics and a new control system were successfully commissioned in the experimental campaign which started in June. Low transmission loss, reliable high power handling capability, and clean launched spectrum have been confirmed experimentally. In this paper, we present the design of the LH2 launcher, the integrated plasma-launcher coupling modeling, and the initial experimental results, in particular, the survey of the antenna-plasma coupling characteristics.

The plan of the paper is as follows. First, the LH2 design is presented. Second, the RF simulation method and results are described. Third, experimental results from the first run-campaign are presented. Finally remaining issues and future plan will be discussed.

2. LH2 launcher

Figure 1 shows a schematic of LH2. The launcher consists of the forward waveguide assembly and the rear side waveguide assembly (jungle gym). The plasma facing part of the forward waveguide assembly (the coupler assembly) is made of 16 four way splitter components. Each four way splitter, shown in Fig. 1 (b), splits the microwave power equally into four output waveguides spread in the poloidal direction. Each splitter is made from stainless steal and has four short sections of copper on which Alumina vacuum windows are brazed. The air side inner-wall of the splitter is copper plated to reduce the transmission loss. The height and width of the output waveguides are 7 mm and 60 mm, respectively. 16 splitters are stacked in the toroidal direction, for a total of 16 columns and 4 rows of active waveguides. Two inconel plates, one on each side of the stacked splitters, have a total of 8 passive waveguides to reduce the reflection on the edge columns. The coupler assembly is connected to the jungle gym with standard WR-187 copper waveguides via transformers.

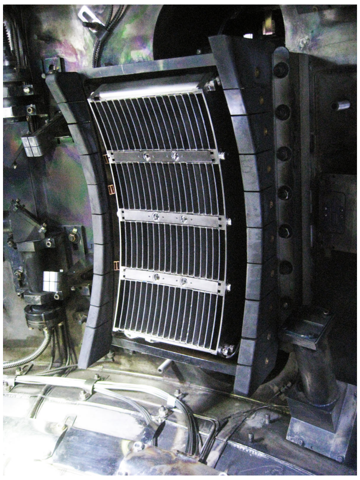

FIG. 2. Plasma side view of the LH2 launcher installed on Alcator C-Mod. The 16-by-4 active waveguides, 8 passive waveguides, and the surrounding launcher protection limiter can be seen.

At the jungle gym, the forward waveguide assembly and the waveguides from klystrons are connected. The standard connection configuration is to power two adjacent four-way splitters by one klystron. The phasing between the two columns are determined by a phase shifter in the jungle gym. During the first run campaign, central 4 columns are directly powered by four klystrons to test the four way splitter power handling capability. Consequently, LH2 was powered by 10 klystrons (250kW source power for each).

The major objective of LH2 construction was to reduce the transmission losses and to improve the over-all reliability. The fabrication process was revised and optimized for this purpose. Poor electric contact, which resulted in the increase of dissipation of high frequency surface current on LH1, was carefully eliminated, and the number of components, joins, and gaskets were significantly reduced. Moreover, all waveguides are pressurized to a higher pressure than LH1 to prevent the arcing. These efforts result in the reduction of transmission losses by 30 %, smooth commissioning and reliable LHCD operation as discussed in Sec. 4.

Since the use of four way splitters is a new approach for a LHCD launcher, LH2 has been equipped with rich diagnostic tools to characterize its performance experimentally. As shown in Fig. 1 (c), 32 RF waveguide probes were installed on a selected set of output wavegudes and passive waveguides in order to measure the forward and reflected power and phase. A total of six Langmuir probes are installed between rows of the waveguides and their pins have a different length to measure both electron density and density scale length in front of the launcher. On the side of the launcher, three X-mode reflectometer waveguides are also installed to measure the density profile. The X-mode reflectometer covers the frequency range from 100 GHz to 140 GHz, providing density profiles with the sweep time of 0.01-1 ms.

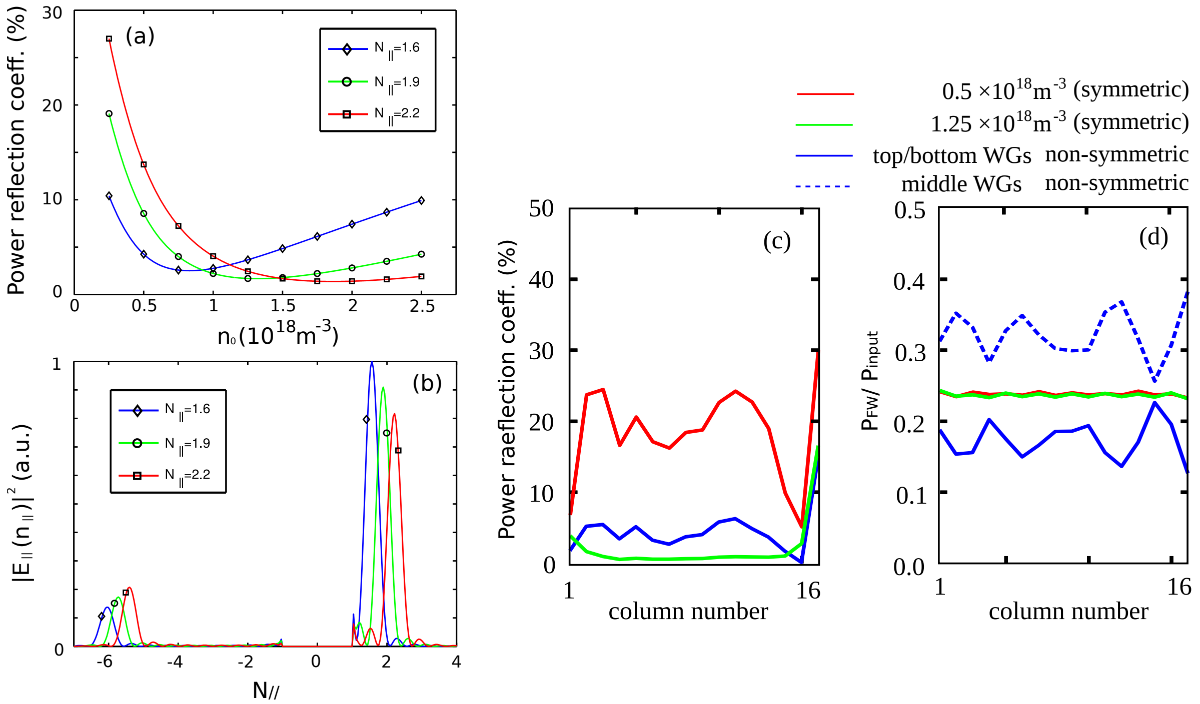

FIG. 3. (Left) the power reflection coefficient (%) as the function of n_0, and the launched spectrum (b), when the plasma load is uniform in the poloidal direction ($n_0 = 1.25 \times 10^{18} m^{-3}$). (Right) the impact of poloidal asymmetry of the density in front of the grill. The power reflection coefficient (%) at the input port of four way splitter on each column (c), and the normalized forward power on rows (d). ($N_{\parallel} = 1.9$)

3. RF characteristic simulation

A design challenge of LH2 was to predict how the four way splitter would behave when facing a plasma. We carried out an integrated modeling of the four-way splitter by using TOPLHA and CST microwave studio [5]. In this approach, TOPLHA solved the antenna-plasma coupling problem assuming a stratified plasma, and CST microwave studio solved the EM problem of the vacuum region. The two codes solved the two problems separately and the overall self-consistent solution (S-matrix) was obtained by cascading the S-matrices from the two codes by using the relation:

$$S = N + XS_p(MS_p - I)^{-1}X, \quad (1)$$

where M, N, and X are partial matrices of the 80-by-80 S-matrix of the coupler assembly and S_p is 64-by-64 S matrix representing the plasma-launcher coupling. In design stage, we used a simple linear density profile, defined by $n(x) = dn/dx(x - x_0) + n_0$ (for $x > x_0$) and $n(x) = 0$ (for $x < -x_0$), where n_0 is the minimum density, x_0 is the vacuum region thickness and x is the distance from the launcher. By changing these parameters, we tested the robustness of coupling.

Figure 3 (a) shows the predicted reflection coefficient as a function of n_0 for different launched $N_{\parallel}$. In this case, $dn/dx = 10^{20}\mathrm{m}^{-4}$ is used. The code predicted a good coupling (less than 10% reflected power) over a wide range of n_0. Figure 3 (b) shows the associated $N_{\parallel}$ spectrum for n_0 of $1.25 \times 10^{18}\mathrm{m}^{-3}$.

In Fig. 3, the density profiles in front of all four rows of launcher are assumed to be the same. In a real experimental condition, the density in front of the launcher was often

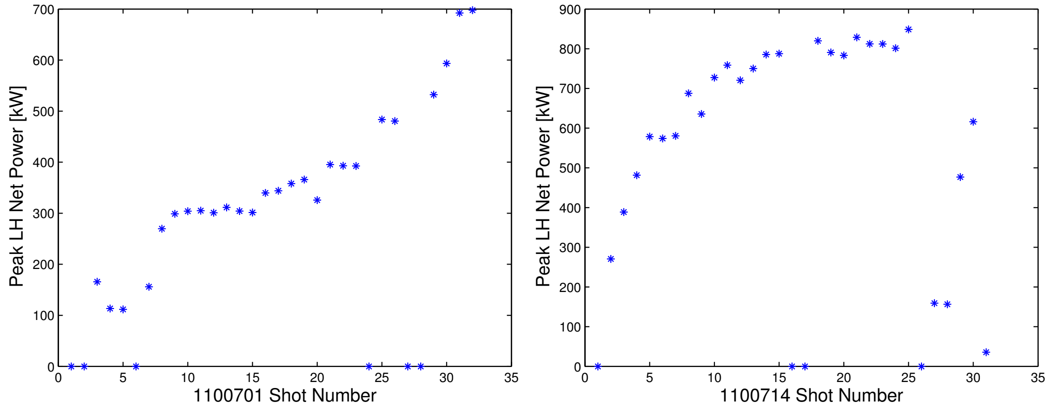

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FIG. 4. The shot history of the net LH power to plasmas on the first and the second day of the high power LH operation.

observed to be non-uniform in the poloidal direction. We tested this effect by assuming different density profiles in front of different rows. A typical case is shown on the right of Fig. 3. As an example of non-uniform density profile, $n_0 = 0.5 \times 10^{18}\mathrm{m}^{-3}$ for top and bottom rows and $n_0 = 1.25 \times 10^{18}\mathrm{m}^{-3}$ for the middle rows were used. Very little adverse effect was found on the reflection at the four way splitter input (Fig. 3 (c)). Even with this fairly large difference of n_0, the reflection coefficient of the non-uniform case (blue) is in-between the two uniform cases (red and green), and the $N_\parallel$ spectrum was also not affected (not shown). The major impact of the poloidal asymmetry of the density is the uneven power splitting in the poloidal direction (Fig. 3 (d)). In this case, more power was injected from the middle rows. This result suggests the importance of measuring the forward and the reflected powers at the mouth of output waveguides.

4. Initial experiments

The LH2 launcher was installed on Alcator C-Mod (Fig. 2) and the run campaign started from the end of June. The initial conditioning operation was performed fairly smoothly. Figure 4 shows the net LH power in the first two days, showing its steady increase up-to 800 kW level, at which a technical issue on a klystron protection circulator prevented further increase of the power. As mentioned before, the central four columns were configured to be driven directly from four klystrons in this initial campaign. Using this configuration, we tested the power handling capability of LH2. The maximum forward power so far achieved is 140 kW source power (the pulse length was 0.4 s). The power

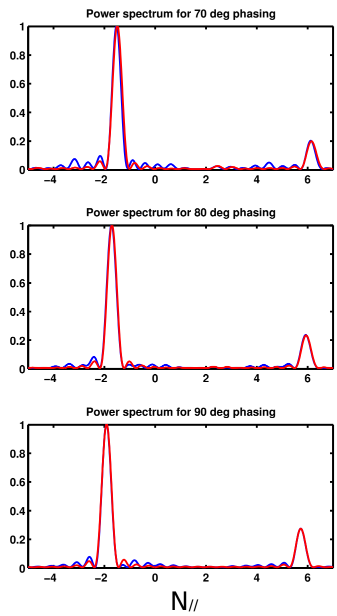

FIG. 5. Comparison of parallel spectra of launched power. The spectra calculated based on the phase measurements of the RF probes (blue) and ideal spectra based on the phase setting of the waveguide (red)

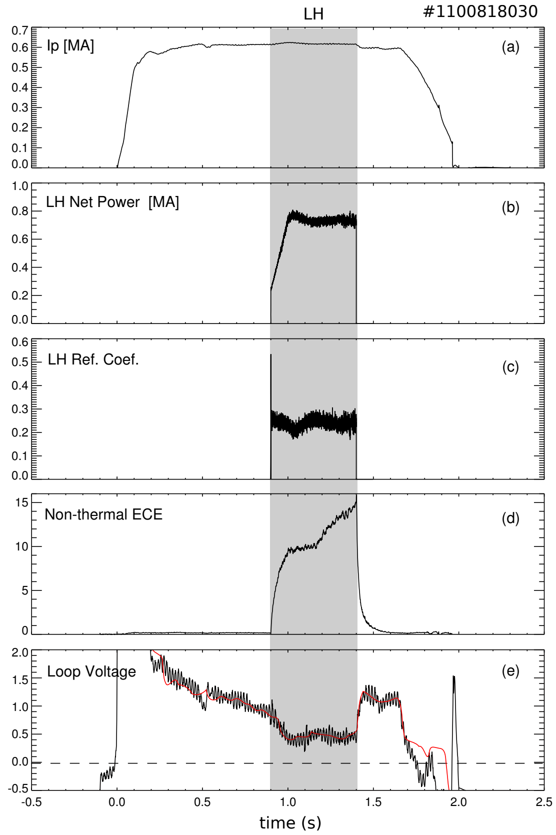

FIG. 6. Temporal evolution of (a) the plasma current, (b) the LH power, (c) the LH coefficient evaluated at the front side of the launcher, (d) non-thermal ECE emission, and (e) loop voltage measured at a flux loop and at the plasma surface (red).

density at the launcher was 5.7 MW/cm^2, which exceeds an empirical weak conditioning limit given by $0.32f^2b$, where f is the source frequency in GHz and b is the waveguide height in cm. This power level extrapolates to a total of 2.3 MW injection from two LH2 launchers.

Besides the power handling capability, the purity of the launched power spectrum is important for LH physics study. We measured the launched spectrum (the spectrum of the forward power) directly using the RF probes. These probes are a pair of small waveguide-coaxial coupler separated by $\lambda/4$ distance, and the power and the phase of the forward and the reflected waves can be decomposed from the quadrature measurements of the these signals. Figure 5 compares the parallel wave number spectra obtained from these RF probe measurements and what is expected from the phase setting of the launcher. It can be seen that the clean spectra are launched in all phasing cases.

Figure 6 shows an example of a typical LHCD discharge using LH2. For this discharge, the relatively low density (the central electron density of about $8 \times 10^{19}\mathrm{m}^{-3}$) is chosen for a better current drive efficiency. The LH power of about 0.75 MW was injected and upon the turn-on of the LH power, clear increase of the non-thermal ECE emission and the decrease of the loop voltage from 1 V to 0.5 V is observed. These observations are qualitatively similar to the previous results using LH1.

However, as shown in Fig 6 (c), the reflection coefficient estimated at the launcher surface is about 30%. This estimation was made from the forward and reflected power measurements at the rear side waveguide assembly and the power losses between the the measurement location and the front side of the launcher were compensated using pre-installation calibration measurements. Although the reflection can be reduced as low as about 10% in optimized conditions, it is generally higher than the simulations shown in Fig. 3 and experiments using LH1 [7]. In order to investigate this unfavorable observation, we surveyed the reflection coefficient in a wide range of the electron density in front of LH2, the antenna phasing, and the position of the launcher with respect to the position of the launcher protection limiter, dR. Figure 7 summarizes a part of this survey. Two sets of three discharges at 70, 90 and 110 degrees phasing are presented, one for the launcher being 0.1 mm behind the protecting limiter, the other 1 mm. The simulation of plasma-launcher coupling was also carried out using experimental measurements of the edge density and the density gradient measured by Langmuir probes on the launcher. It was found that the wide range of experimental observation can be reproduced if the presence of a millimetric vacuum gap between the plasma and the launcher is assumed (black circles in the figure). However, the presence of such vacuum gap has not yet been confirmed experimentally, and we are investigating this issue including the possible reason of the gap, and other explanations and solutions.

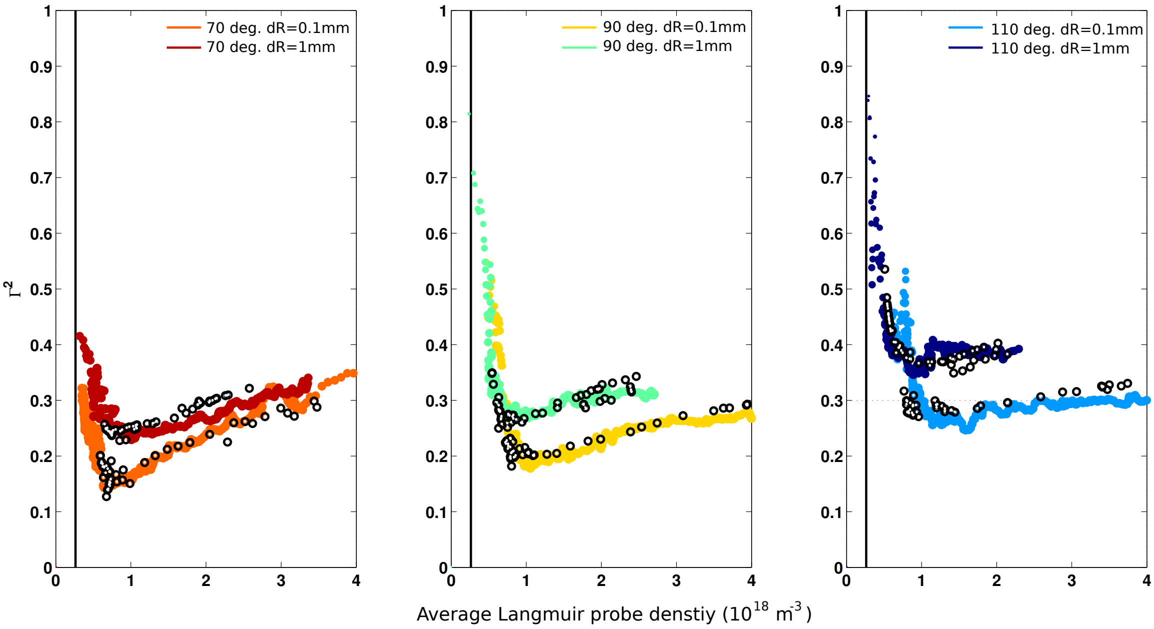

FIG. 7. (Color symbols) The survey of plasma-launcher coupling using different density, antenna phasing, and the distance between the launcher position and the protecting limiter (dR). The plasma equilibrium was kept constant while the density was swept. The low LH power was used. (Black circles) Simulation results of the reflection coefficient. The vacuum gap of 1 mm and 1.3 mm is used for dR = 0.1 mm and dR = 1 mm cases, respectively. Here, calculations of the plasma-launcher coupling matrix was performed using the GRILL code [8] and combined with the CST simulation in the same way as described in Sec. 2.

5. Conclusion

The new LHCD launcher on Alcator C-Mod (LH2) employs a four way splitter concept, which splits the microwave power in four way in the poloidal direction. This concept allows to launch a clean wave spectrum in a wide range of the toroidal wave number ($-3.8 < N_{\text{toroidal}} < 3.8$). At the same time, it allows significant simplification of the feeding structure, which is favorable for reliable high power LHCD operation. Integrated modeling of the plasma - launcher coupling problem predicted that the clean spectrum and equal power splitting is possible unless a plasma load is significantly uneven. LH2 is installed on Alcator C-Mod and successfully demonstrated its more reliable operation at high power compared to the previous launcher. The transmission losses in the launcher were reduced by 30 % and the power handling capability readily exceeded an empirical weak conditioning limit. The achieved power level extrapolates to the total 2.3 MW injection from two LH2 launchers. The predicted clean wave spectrum is confirmed experimentally by RF probe measurements, and up-to 800kW net LHCD power has been injected to plasmas. Despite these encouraging results, LH2 presently exhibits higher power reflection than the previous experiments and simulations. The experimental survey of the reflection coefficient and the plasma-launcher coupling simulations suggest a small vacuum gap between the plasma and the launcher, and we are investigating the source of the gap, other possible explanations and solutions.

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