Overview of TAE Technologies' HHFW Project on LAPD

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Abstract. Simulation survey performed at TAE Technologies, has demonstrated that high harmonic fast wave (HHFW) heating is a promising scenario to heat core electrons of FRC plasma. To prepare the proposed experimental study of HHFW antenna-plasma coupling and wave propagation on LAPD machine at UCLA, a high-power-capable 4-strap antenna has been calculated and designed through collaboration among TAE, ORNL, ASIPP, and UCLA. This antenna was mechanically designed and fabricated by ASIPP and it has been installed recently on LAPD. Meanwhile, by using the Petra-M code, a newly developed generic electromagnetic simulation tool for modeling RF wave propagation, the RF-SciDAC team starts 3D full wave simulations. Detailed information on antenna electromagnetic simulations and mechanical design, as well as preliminary experimental results of wave propagation study with the newly installed phased-array antenna, will be presented in this paper.

INTRODUCTION

Over the past decades of field-reversed configuration (FRC) plasma research, the topic of efficient RF wave electron heating has rarely been explored. Simulation survey [1] recently performed at TAE Technologies has found for the first time that high harmonic fast wave (HHFW), which has been adapted successfully to high beta, overdense spherical tokamak (ST) for the experiments of core electron heating and off-axis current drive [2 - 4], can be also used to heat the core electrons of FRC plasmas.

Motivated by these promising simulation results, a deployment of HHFW heating has been planned on C-2W, an advanced beam-driven FRC device recently built at TAE. During the process of conceptually designing HHFW antenna, multiple technical challenges are encountered: (a) compact and limited space near the midplane of the machine, (b) fast ions' large betatron orbits extending well outside the separatrix of the FRC plasma, and (c) possible radial or axial shifting and or shrinking of the "football-shaped" FRC plasma during the discharge. These elements create major challenges for fast waves' launching, coupling, and propagation; as a result, HHFWs' utility and efficiency are more unpredictable in C-2W FRC plasmas than in tokamaks or spherical tokamaks. Therefore, it is of vital importance to experimentally study HHFW antenna-plasma coupling and wave propagation on a reliable test bench equipped with sophisticated diagnostics. Our survey has found that in terms of similar machine configuration, highly reproducible plasmas, broad range of operational conditions, available ports and vessel space for a phased-

array antenna, and a variety of plasma diagnostics that allow volumetric measurements with computer-controlled probes, the LAPD facility [5] at UCLA is uniquely and ideally positioned for the proposed experimental studies.

The topics to be addressed on LAPD include: (a) launching of HHFW with desired wave spectra of $k_{//}$ (or $n_{//}$ parallel refractive index) by precisely controlling relative phasing between antenna straps; (b) experimentally validating fast wave coupling and propagation predicated by cold-plasma full wave modeling; (c) optimizing wave coupling by exploring the effects of edge density profiles, antenna-plasma distance, and phasing between straps.

HHFW ANTENNA SIMULATION, DESIGN, FABRICATION, AND INSTALLATION

Based on available ports and operational parameters of LAPD, a high-power-capable phased-array (4-strap) antenna has been calculated and designed through collaboration amongst TAE, ORNL, ASIPP, and UCLA. Antenna 3D electromagnetic simulations with MicroWave Studio (MWS) software was performed by ORNL RF group. For high power operation (200 kW for each strap), the key parameters of antenna geometric structure that need to be optimized include strap length and width, distance between straps, septa thickness and gap, Faraday screen transparency and element sizes, slot height and length, and gap between strap backplane to back wall.

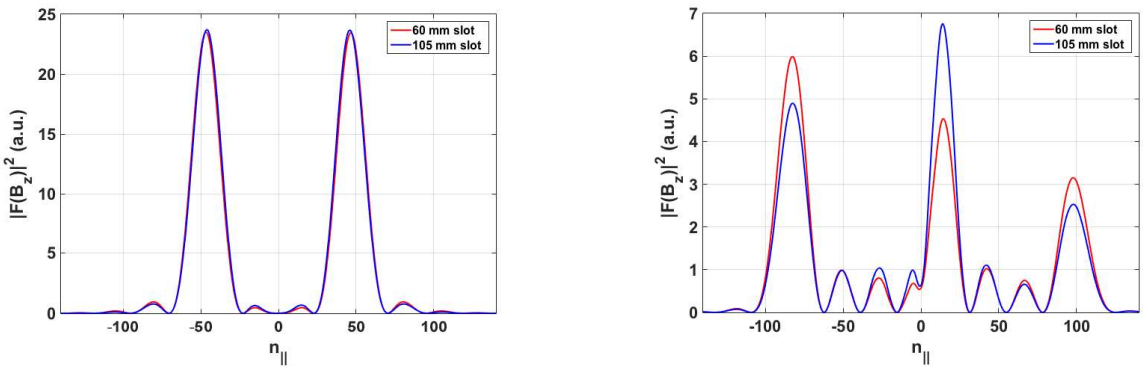


FIGURE 1. Calculated antenna vacuum spectrum at 10 MHz for the phasing of (a) [0, π, 0, π]; (b) [0, π/6, π/3, π/2].

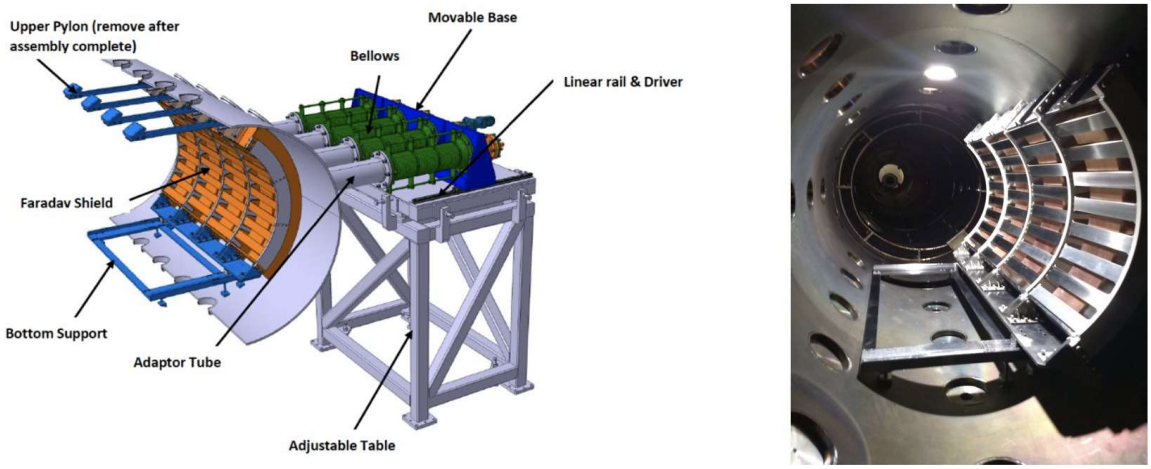


FIGURE 2. Newly built phased-array (4-strap) HHFW antenna for LAPD (a) outline of antenna mechanical design; (b) photo of HHFW antenna installed in LAPD vacuum vessel.

There is a trade-off between the choice of wave frequency and relative phasing. As shown in Figure 1, for a given frequency (10 MHz at 1 kG), antenna *k*-spectrum can be tailored by varying phasing between straps. To obtain a

desired value of $|n_{//}|$, for example $|n_{//}| = 10$ for wave's good penetration into FRC plasma, a low phasing is needed; however, low relative phasing can cause significant impurity generation in high power operation. Comparing with other relative phasing, dipole phasing has a better heating efficiency but its $|n_{//}|$ is too large. Therefore, in order to use diploe phasing while maintaining $|n_{//}| = 10$, wave frequency has to be increased. Slots at septa or sidewall can increase wave's power coupling to plasma but they can also cause the mutual coupling between straps, which may make impedance matching more difficult. As shown in Fig. 1(a), slot length has no effect for the spectrum at dipole phasing, but it has significantly more effect for 30^0 phasing, as indicated in Fig. 1(b). MWS calculation of mutual coupling at 10 MHz indicates >4% coupling with 105 mm long slots, <3% coupling with 60 mm long slots. For antenna operation above 10 MHz, incorporating a nearest neighbor decoupling network into the feed and matching network is necessary.

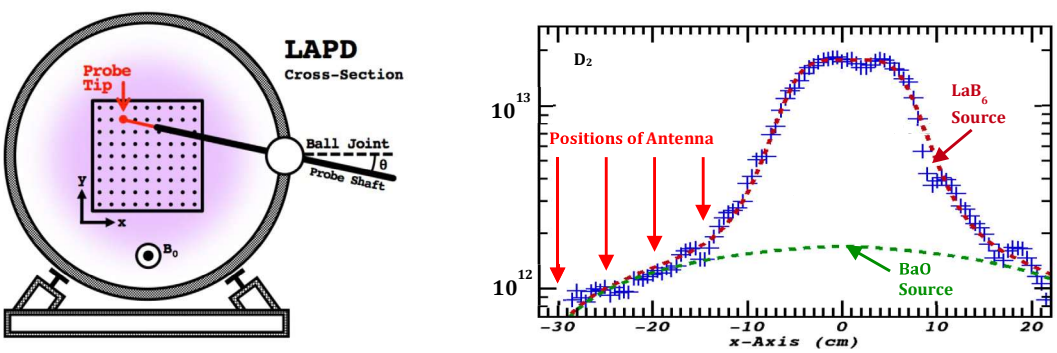
A broadband matching network and decoupler are currently under design by ORNL RF group. This matching network allows antenna operation at 10 MHz and 30 MHz for arbitrary phasing, over a wide range of loads (from vacuum to several Ohms).

Antenna mechanical design has been performed by ASIPP based on the geometry parameters through 3D EM MWS calculation, and it took less than 3 months to complete this mechanical design work. The outline of antenna structure inside and outside LAPD vacuum vessel is shown in Figure 2(a). Antenna has been fabricated at the workshop of ASIPP in Hefei, China, and it has been delivered to UCLA and installed on LAPD on schedule. Figure 2(b) is the photo of phased-array antenna recently installed on LAPD machine. In summary, TAE's HHFW antenna for LAPD is an international, multi-institution, well-coordinated, and successful project; the construction of a high quality 4-strap antenna has been completed on time (less than a year) as planned.

PRELIMINARY RESULTS OF FAST WAVE PROPAGATION STUDY

In the experiments of wave propagation study, main diagnostics include Langmuir probes, B-dot probes, and emissive probes. The LAPD utilizes a **x-y** (vertical plane, as shown in Figure 3 (a)) and **x-z** (horizontal plane) probe drive system capable of collecting data at thousands of points over a few hours. Wave ***B*** and ***E*** fields sampled in **x-y** and **x-z** plane (31 × 31 points) at 1 cm spacing and 10 shots/probe position. LAPD can run 24 hours per day.

The experimental setup for RF systems includes (1) four broadband (1 – 35 MHz) RF amplifiers at 1 kW output power each unit; (2) antenna relative phasing control driver (180^0, 90^0, 60^0, 45^0, and 30^0); (3) directional couplers for RF power measurements; (4) antenna radial positions (distance of antenna front surface to LAPD axis: r = -35 cm, -30 cm, -25 cm, -20 cm, and -15 cm) along edge plasma density gradient (Figure 3(b)).



(a) (b)

FIGURE 3. (a) Diagnostics data sampling setup for **x-y** plane scan; (b) Measured radial electron density profile (z = 0).

As an example of measured HHFW (at 10 MHz) magnetic field pattern, Figure 4 shows an **x-y** plane (at z = -16 cm) of the B_z component of wave field launched by the antenna from left side. For a given antenna phasing (180^0), all measured field patterns shown in Fig. 4 look similar, which means the direction of wave propagation is well-controlled by antenna phasing. Moreover, as expected, when antenna moves further into plasma (r = -15 cm) and close to denser plasma created by LaB_6 source, the coupling becomes stronger. One promising result shown in Fig. 4 is that even when antenna is fully retracted to vessel wall (r = -35 cm), wave coupling to plasma is still observed.

Figure 5 shows measured wave magnetic field pattern in **x-z** plane at 5 different phasing. Antenna is positioned at r = -25 cm; dashed lines indicate denser plasma. As clearly demonstrated in Fig. 5, phasing between straps changes

the direction of fast wave propagation; wave length becomes shorter when edge density n_e is in the range of 2.0×10^{18} $m^{-3} \sim 2.8 \times 10^{18}$ m^{-3}, which seems to be the n_{onset} density for perpendicular fast wave propagation.

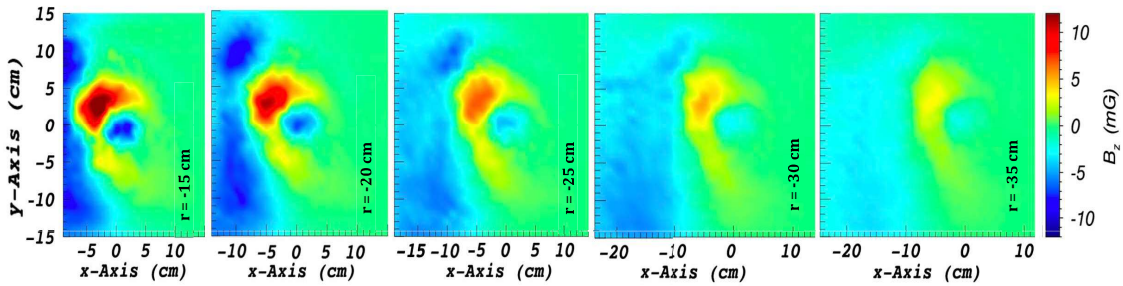


FIGURE 4. Measured HHFW magnetic field pattern (180^0 phasing) in **x-y** plane at different antenna positions.

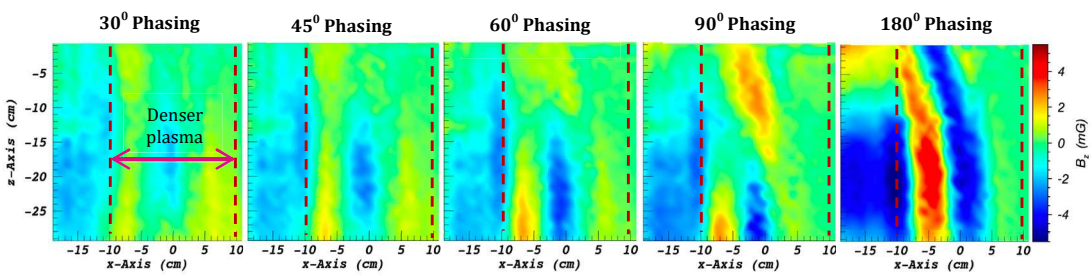


FIGURE 5. Measured HHFW magnetic field pattern in **x-z** plane at different phasing. Antenna is at r = -25 cm.

FUTURE PLAN

For simulations, RF SciDAC team starts 3D full wave modeling with the Petra-M code [6], which is a newly developed generic electromagnetic simulation tool for modeling RF wave propagation; direct comparison of HHFW magnetic fields obtained from 3D simulations with *B*-dot probe measurements is on the way. Meanwhile, TAE theory group currently works on expanding TAE's RF_Pisa code [7] for HHFW regime; validating HHFW modeling results against the experimental measurements is also planned.

For experiments, the following RF campaigns are planned in series on LAPD: (1) wave propagation study at 30 MHz, 2.5 kG; (2) wave coupling studies at both 10 MHz and 30 MHz with a matching network for arbitrary phasing and a wide range of loads; (3) wave coupling and propagation studies at different magnetic configuration (mirror and/or cusp); (4) RF sheath and heating studies at high power (4×200 kW) operations.

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