DEVELOPING HHFW AS AN ENABLING ELECTRON HEATING ACTUATOR FOR AN FRC PLASMA

National Laboratory **Principal Investigator**	Princeton Plasma Physics Laboratory Dr. N. Bertelli nbertell@pppl.gov
Company **Principal Investigator**	TAE Technologies Dr. Xiaokang Yang XYang@tae.com
Award	INFUSE 2019
Period of Performance	May ’20 – May ’21 / Sept. ’21 - Oct ‘21
Final Report Submission Date	01/11/2022

Note: Report may be posted publicly. Do not include proprietary information.

1 Technical Overview

1.1 Problem Statement [Written by TAE Technologies PI]

Describe the TAE Technologies challenges this program is meant to address. Should be adapted from original application, noting any departures / evolutions from that original application.

The advanced beam-driven FRC plasma, such as in the TAE Technologies C-2U/C-2W devices [1, 2], is a simple compact toroid magnetic confinement system, that is, one without toroidal coils linking the plasma, and thus with predominantly poloidal fields. The attractions of such a configuration for a potential fusion reactor are its very high $<\beta_e>$ (near unity) thus allowing for efficient use of magnetic hardware, simple and linear geometry for ease of construction and maintenance, as well as a natural, unrestricted divertor configuration for facilitating energy extraction and fusion ash removal [3].

Over the entire history of FRC research, direct RF based electron heating of the FRC core has never been explored. If an RF based electron heating actuator can be developed for FRC, that would provide a cost effective and technologically attractive solution to the problem of electron heating for FRCs. One unique characteristic of FRCs, is the fact that the plasma is unusually over-dense ($\omega_{pe} > 30\ \omega_{ce}$ inside the separatrix) coupled with the magnetic field quickly dropping to zero (or near zero) inside. This feature makes it extremely challenging to heat the electrons in the FRC core. Conventional electron heating scenarios such as electron cyclotron resonant heating (ECRH) and fast wave mode conversion heating which are widely utilized in tokamaks or stellarators, cannot be adapted in FRC plasmas due to the conflict between wave penetration into core plasmas and the efficiency of power damping on electrons. Since the increase of electron temperature can help enhance the efficiency of neutral beam heating and current drive as well as improve FRC plasma confinement and performance, numerous efforts have been made recently at TAE Technologies to explore various microwave & RF heating scenarios including upper-hybrid resonant waves, electron Bernstein waves, Whistler (helicon) waves [4], and high harmonic fast wave (HHFW) heating [5]. Amongst those scenarios, studies with the GENRAY-C ray-tracing code [6] have demonstrated that HHFW may be a promising path for core electron heating of FRC plasmas. For example, in an optimal regime (waves are launched at midplane of the C-2U at frequency of 10 MHz and external magnetic fields of 1 kG, $N_{//} = \pm 8$), the single pass absorption of HHFW is 100% and most of the power is deposited inside the separatrix of FRC plasmas, with power damping efficiency about 67% on electrons and less than 25% on ions. Motivated by these promising simulation results performed by GENRAY-C and previous experiments in NSTX, a deployment of HHFW heating has been planned on C-2W, TAE Technologies' newly built machine currently under operations.

The HHFW heating concept was conceived at PPPL for the specific purpose of heating electrons for a spherical tokamak which has similar issues with FRC in that it has a very over-dense and high beta plasma core [7]. NSTX/NSTX-U device, located at Princeton Plasma Physics Laboratory (PPPL), is indeed equipped with an HHFW 12-strap antenna which was designed and fabricated by PPPL [8]. HHFW system in NSTX has successfully demonstrated the capability to heat the plasma electrons to temperature larger than 6 keV [9]. However, the HHFW experiments and related theory/modeling have discovered complexity related to the HHFW antenna-SOL plasma interactions [10-20]. The experience gained on NSTX can be immediately applied to the present HHFW heating feasibility study for the C-2W FRC plasma.

During the process of conceptually designing HHFW antennae the C-2W FRC plasma, 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 waves' launching, coupling, and propagation; as a result, HHFWs' utility and efficiency are more uncertain in C-2W FRC plasmas than in tokamaks or stellarators. Furthermore, the simulations are based on the standard ray tracing technique, which could fail in some specific plasma scenarios, and they are performed without considering a realistic antenna geometry. Therefore, for all these reasons, it is of vital importance to perform advanced HHFW full wave simulations with a realistic antenna geometry in a FRC plasma configuration with state-of-the-art RF numerical tools.

The work scope of this proposal is schematically described in the next section. This modeling effort can also benefit from the on-going experimentally study of a phased-array HHFW coupling and wave propagation experiment of the TAE high-power-capable HHFW 4-strap antenna on LAPD facility at UCLA [22]. This antenna was mechanically designed and fabricated by ASIPP (Institute of Plasma Physics, Chinese Academy of Sciences). TAE technologies' HHFW effort on LAPD is a successful international, multi-institutional project including PPPL – an exemplary Public-Private collaboration; the construction of a high quality HHFW antenna has been completed on time (less than a year) as planned.

1.2 Work Scope [Written by Lab PI]

Describe the approach used to achieve the project goals, including the capabilities at the national laboratory or partner facility, as well as the capabilities at TAE Technologies and its subcontractors on this award. Can be informed / adapted from original application, noting departures / evolutions.

The proposed full wave modeling for HHFW electron heating in FRC plasma will be conducted through the collaboration between TAE Technologies and PPPL. Dr. Nicola Bertelli and Dr. Masayuki Ono from RF group at PPPL will lead this collaboration task force. RF PPPL group has a previous experience with several RF tools such as ray tracing (GENRAY [6]), full-wave (AORSA [23]), and RF finite-element method (FEM) code (FW2D [20] and Petra-M [24, 25]). Moreover, PPPL RF group has a strong connection with RF SciDAC project where all these tools are maintained and improved.

The main task of this proposal is to perform HHFW simulation in FRC plasma by using the 4-strap antenna geometry implemented in LAPD under different plasma conditions, for example, at (1) different phasing between straps, (2) different external magnetic field (thus different RF frequency), and (3) different antenna radial position. Furthermore, due to compact and limited space near the midplane of the machine, the impact of the different number of antenna straps will be also explored in order to improve the antenna design and its performance. A study of the low and high power HHFW antenna design will be considered.

A possible verification activity with the experimental data obtained by the HHFW 4-strap antenna in LAPD will be considered.

The main scope of this proposal is directly related to the RF PPPL group due to the previous experimental and modeling efforts for HHFW in NSTX/NSTX-U.

An additional and important scope of this work scope, which is not explicitly present in the original application is the calculation of the S-matrix from the Petra-M simulation using a realistic 2-strap antenna provided by ORNL. This result is indeed crucial for the INFUSE project awarded to TAE Technologies in collaboration with ORNL, which is entitled "Development of phased-array HHFW antenna and load-resilient matching network for the C-2W FRC plasma device" and led by Dr. R. Goulding (ORNL).

1.3 Results [Written by Lab PI]

Describe the tasks accomplished, results obtained, key deliverables, lessons learned.
Do not include proprietary information.

The main scope of this project consists in the investigation of the high harmonic fast waves (HHFWs) propagation in FRC configuration for different plasma scenarios and antenna geometry and parameters. Moreover, additional HHFW simulations have been performed for the 4-strap antenna installed in LAPD. All the HHFW simulations were performed by using Petra-M code, which is a FEM framework able to solve the Maxwell's equations.

Below is the list of the main tasks performed in this project:

- Adopted a FRC magnetic configuration (provided by TAE Technologies) including the electron density profile.
- From this configuration, a 3D geometry of the full machine was generated together with a simplified 2-stap antenna (using Surface current boundary conditions). A corresponding mesh was also created to be able to perform a FEM analysis.
- A series of full wave simulations were performed with (i) different electron density profiles (constant parabolic profiles + rescaled original profile) and edge density values; (ii) different wave frequencies.
- A similar work was done for the HHFW 4-strap antenna installed in LAPD. In particular, a new 4-strap antenna was generated and a few simulations with different antenna phasing and resolution were performed.
- ORNL provided a realistic 2-strap antenna for FRC configuration, which has been imported in the Petra-M code and a mesh was generated.

- A series of simulations were performed with the new antenna (including the edge density scan). The main purpose, though, was to obtain the Scattering matrix (S-Matrix) in order to provide such information to Dr. R. Goulding (ORNL) to use it for his INFUSE RF project (Development of phased-array HHFW antenna and load-resilient matching network for the C-2W FRC plasma device).

Lesson learned / results from these simulations:

- Reasonable agreement with ray tracing results in terms of wave propagation is found.
- The edge density profile and its values are crucial in order to make HHFW propagates from the antenna to the core plasma (or in other words the be able to inject power to the plasma core)
- The full wave simulations in this regime and configuration are extremely challenging because the magnetic field goes to zero in core plasma. As a consequence, there are two regions in the plasma where the wavelength goes to zero requiring an infinite resolution. Kinetic effects may play an important role in these regions. However, the simulations in this project were performed assuming a cold plasma with artificial collisions.
- Radial location of the antenna hopefully can be moved closer to the plasma core (as similarly done on the 4-strap antenna on LAPD) in order to maximize the coupling and as a consequence minimize RF losses in the SOL.

2 Impact

2.1 Use of Project Results [Written by TAE PI]

Describe how the results obtained contributes to TAE Technologies' roadmap. Include a timeline slide pointing out relationships to other DOE programs and C-2W *milestones.*

This modeling effort can also benefit from the on-going experimentally study of a phased-array HHFW coupling and wave propagation experiment of the TAE high-power-capable HHFW 4-strap antenna on LAPD facility at UCLA [22]. This antenna was mechanically designed and fabricated by ASIPP (Institute of Plasma Physics, Chinese Academy of Sciences). TAE technologies' HHFW effort on LAPD is a successful international, multi-institutional project including PPPL – an exemplary Public-Private collaboration; the construction of a high quality HHFW antenna has been completed on time (less than a year) as planned.

The simulation results performed by Dr. Bertelli for fast wave coupling and propagation study with 4-strap HHFW antenna on LAPD, are in good agreement with experimental measurements at both near field and far field of the HHFW antenna. The project results for 4-strap HHFW antenna on LAPD, validated by experimental measurements, clearly demonstrate that Petra-M code is a very powerful tool for fast wave coupling and propagation study.

The full wave Petra-M modeling results of 2-strap HHFW antenna for C-2W FRC plasma, are in reasonable agreement with ray tracing results (previously done by TAE Technologies); this theoretical validation not only alleviates the concerns on HHFW coupling and propagating into the core of FRC plasma, but also makes TAE Technologies more confident to drive their RF project forward to next step – engineering conceptual design of HHFW system for C-2W device.

By using this project results as the guidance, in collaboration with ORNL, TAE Technologies is exploring the engineering design of the phased-array RF antenna with 2 MW power handling capability, and the load-resilient matching network, which can operate at arbitrary relative phasing between antenna straps, at multiple operating frequencies, and with rapid variation of plasma loading. If these concept-and-feasibility studies prove to be successful, it will not only make a breakthrough in achieving a high efficiency of transmitting, launching and coupling RF power into the core of FRC plasma, but also benefit other fusion configurations, including the tokamak/spherical tokamak approach and ITER, as well as the linear devices and mirror machines.

2.2 Fusion Energy Impact [Written by Lab PI]

Describe how this project will contribute to advancing fusion energy development more generally.

Plasma heating and non-inductive current drive will play a crucial role in the ignition and sustainment of burning plasmas. However, the loss of RF power in the SOL can be a real PMI issue for possible RF sheaths and plasma facing component damage. Indeed, many experiments in different fast wave (FW) heating regimes, such as hydrogen minority heating and high harmonic fast waves (HHFW), have found strong interactions between RF waves and the SOL region. Therefore, the study of the antenna design, antenna loading, etc. is a critical step to overcome these issues.

On the other side, from the core plasma point of view, a significant interaction between FW and energetic ions generated by neutral beam injection (NBI), also, plays an important role in the current experiments.

Quite recently, RF simulations are capable to include the SOL plasma and they can be done in three dimensions taking into account realistic antenna and machine geometries. This is the case of this project where the analysis was performed using the Petra-M FEM framework.

This project contributes to advancing the RF modeling effort from one side (improving the current RF modeling capability) and the experimental observations with the installation and operation of the new antenna both in LAPD and C-2W (in the future).

References

1. M. Binderbauer, et al., Phys. Plasmas, **22**, 056110 (2015).
2. H. Gota, et al., Nucl. Fusion, **59**, 112009 (2019).
3. M. Tuszewski, Nucl. Fusion, **28**, 2033 (1988).
4. X. Yang, et al., 21st Topical Conf. On RF Power in Plasmas, AIP Conference Proceedings **1689**, 09008-1 (2015).
5. X. Yang, et al., EPJ Web of Conferences **157**, 03065 (2017).
6. A. Smirnov and R. Harvey, *CompX report*, CompX-2000-01 (2001).
7. M. Ono, *Phys. Plasmas* **2**, 4075 (1995).
8. P.M. Ryan et al., *Fusion Engineering and Design* **56-57** 569 (2001).
9. G. Taylor et al. *Phys. Plasmas* **17**, 056114 (2010).
10. J. C. Hosea et al. *Phys. Plasmas* **15**, 056104 (2008).

11. C. K. Phillips et al. *Nucl. Fusion* **49**, 075015 (2009).
12. E. Mazzucato et al. *Phys. Rev. Lett.***101**, 075001 (2008).
13. H. Yuh et al. *Phys. Rev. Lett.***106**, 055003 (2011).
14. J. C. Hosea et al. *Phys. Plasmas* **15**, 056104 (2008).
15. R. J. Perkins et al. *Phys. Rev. Lett.***109**, 045001 (2012).
16. R. J. Perkins et al. *Nucl. Fusion* **53**, 083025 (2013).
17. R. J. Perkins et al. *Phys. Plasmas* **22**, 042506 (2015).
18. R. J. Perkins et al. *Nucl. Materials and Energy* **12**, 283 (2017).
19. N. Bertelli et al. *Nucl. Fusion* **54**, 083004, (2014).
20. N. Bertelli et al. *Nucl. Fusion* **56**, 016019 (2016).
21. E.-H. Kim et al, *Phys. Plasmas* **26**, 062501 (2019).
22. W. Gekelman, et al., *Rev. Sci. Instr*., **87**, 025105 (2016).
23. E. F. Jaeger et al. *Phys. Plasmas* **8**, 1573 (2001).
24. S. Shiraiwa, et al., *EPJ Web of Conferences* **157**, 03048 (2017).
25. N. Bertelli, et al., *AIP Conf. Proceedings* **2254**, 030001 (2020).