Direct Cavity Combiner

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***Abstract*— In order to initiate and maintain controlled fusion reactions, the plasma must be heated to fusion temperatures. For economical, steady state tokamak reactors, efficient current drive is required. Ion Cyclotron Range of Frequencies (ICRF) have been demonstrated in reactor grade plasmas to be effective at plasma heating and central current drive. For high magnetic field fusion devices 60-240 MHz systems are envisioned, which are ideal for solid state devices.**

Diversified Technologies, Inc. (DTI) is building a high power (megawatt class) Direct Cavity Combiner (DCC) Transmitter in a single compact and efficient amplifier under a Department of Energy Small Business Innovative Research (DOE SBIR) grant. DTI has previously demonstrated this DCC solid state transmitter at L-band and UHF. This technology is intended to be an alternative to conventional megawatt-class Vacuum Electron Device (VED) RF sources and overcome the limited frequency range, reliability, and supply chain issues associated with tetrodes and similar VEDs. The DCC transmitter can reduce the cost of high-power RF for fusion and similar plasma heating applications. The basic transmitter technology can be readily tailored to a wide range of frequencies which makes it applicable in a wide range of applications, including high energy physics, radar, and broadcasting.

The cavity and modules are undergoing testing and evaluation to compare the amplifier performance to that predicted by the simulations and calculations performed as part of the design effort. In this paper, DTI will report on the design and test results of the cavity and RF modules at 120 MHz (approximately the center of the ICRF band).

Keywords*— *ion cyclotron range of frequencies, plasma heating, fusion, current drive, solid state transmitter

I. INTRODUCTION

In order to initiate and maintain controlled fusion reactions, the plasma must be heated to great temperatures.[1] For economical, steady state tokamak reactors, efficient current drive is also required. Fast waves (FW) in the Ion Cyclotron Range of Frequencies (ICRF) have been demonstrated in reactor grade plasmas to be both effective at plasma heating (TFTR and JET) and central current drive. For high field devices, 60-240 MHz systems are envisioned, which are ideal for solid state devices.

Fig. 1. Phase I full-scale 120 MHz Direct Cavity Combiner populated with 8 modules achieving 10 kW.

Diversified Technologies, Inc. (DTI) has developed a novel, patented[2], compact, and reliable solid state Direct Cavity Combiner (DCC) transmitter, shown in Fig. 1 with final concept shown in Fig. 2. It is far simpler and compact than a conventional high-power solid state RF amplifier such as the state-of-the-art amplifier at CERN. The DCC transmitter combines hundreds of (1.5 kW) solid-state RF power amplifier transistors into a single high-power source, enabling the efficient heating, current drive, and control of the plasma required in a fusion system. This much more practical RF source can

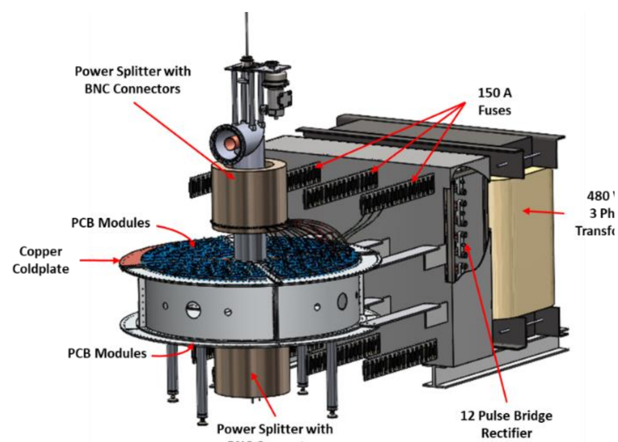

Fig. 2. 90 To 120 MHz, 1.5 MW DCC Transmitter with Transformer/Rectifier set to provide adequate input DC power.

[1] For typical tokamak plasmas, between 100 and 150 million degrees K.

This effort is sponsored by the US Department of Energy under Grant No. DE-SC0022713.

[2] US 10,411,665, Resonant Cavity Combined Solid State Amplifier System; Erik G. Johnson, Marcel P. J. Gaudreau, John Kinross-Wright, Frederick Marvin Niell, III, David B. Cope.

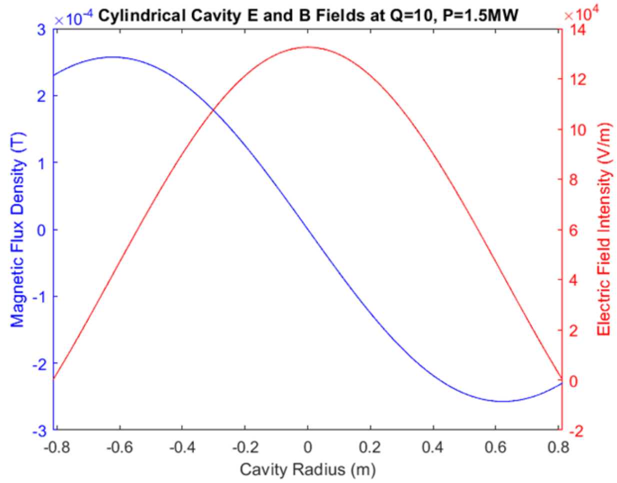

Fig. 3. Field distribution for a cylindrical cavity at Q=10, and P=1.5MW

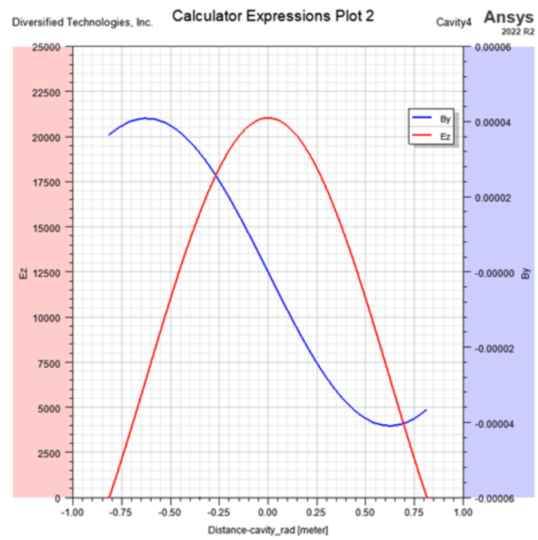

Fig. 4. The cavity magnetic and electric fields for the TM010 mode

dramatically reduce the life cycle cost of ICRF power, while increasing its efficiency, and significantly reducing its footprint.

II. Technical Approach

The approaches taken in this effort were analytical, numerical and experimental. The cavity analysis guided the selection of the geometrical configuration, specific numerical calculations were made to validate expected device performance, and extensive experiments were made on two test beds to optimize components and confirm results.

A. Analytical Basis

The cavity of choice for the DCC amplifier is a cylindrical cavity operating in the TM010 mode, with a magnetic field in the azimuth direction of the cavity and the electric field in the axial direction. To determine the frequency of operation the cavity diameter must be determined using an equation which is based on the premise that the electric field Bessel function of the first kind, zeroth order equals 0 at the wall of the cylindrical cavity.

The cavity was designed to be tunable using a plate with an adjustable height at the bottom of the cavity to perturb the axial electric field, which is analogous to changing the cavity capacitance. Raising the tuning plate increases the cavity capacitance, thus decreasing the resonant frequency, meaning that the cavity much be designed for a greater frequency and then tuned down to cover the desired frequency band. The cavity's resonant frequency was chosen to be 141 MHz (diameter of 1.626 meters), and was tuned to 120 MHz for testing. The height of the cylindrical cavity was 0.457 meters, resulting in a volume of about 0.95 cubic meters.

The target quality factor of the DCC amplifier is of the order of 10 to give a wide bandwidth; at real power of 1.5 MW, this corresponds to 15 MW of reactive power. From there, the peak cavity and subsequently E and H field distributions can be determined.

Fig. 3 shows the electric and magnetic fields for a cavity of radius 0.8128 m at a frequency of 120 MHz and an output power of 1.5 MW.

The peak electric field reaches a maximum value of 132 kV/m over the cavity height of 0.457 meters, which equates to 3.3 kV per inch, well below the conservative design rule of 10 kV per inch for high voltage standoff. The magnetic flux density reaches a maximum value of 2.5 Gauss at the outer radius of the cavity. Since the B-field is evaluated in reference to the X-axis, the field appears negative for one half of the cavity since the fields are in the azimuthal direction. The B-field distribution of the cavity is important because designing a drive loop requires the expected field from the cavity to be present. Proper transistor impedance matching requires the loop to be immersed in a magnetic field Units.

B. Numerical Validation

The approach for cavity analysis had two complementary numerical forms: direct computation of the theoretical equations and finite element analysis (FEA) of the configuration. The former is suitable for numerical calculations of analytical expressions and FEA is suitable for calculation of specific geometries not readily addressable by analysis.

Fig. 4 shows results along a cavity diameter of an FEA calculation of the resonant cavity-internal electric and magnetic fields. The fields follow the predicted analytical forms for J0 and J1, respectively.

To efficiently excite the TM010 mode it would be desirable to locate modules on the cavity plate surface in regions of high magnetic field. Loops in lower field regions will compensate by having loops with larger diameters to remain effective in contributing power to the cavity. The region marked with blue shading covers 87% of the cavity plate surface area and is the region to be occupied by modules in a fully-populated cavity.

III. Conclusions

Fusion devices will require 50 MW to 100 MW CW of RF power each. To affordably provide this RF power requires dramatic improvements in RF sources. DTI has demonstrated technical feasibility through experimental validation, firmly establishing the DCC as a technically feasible and practical ion

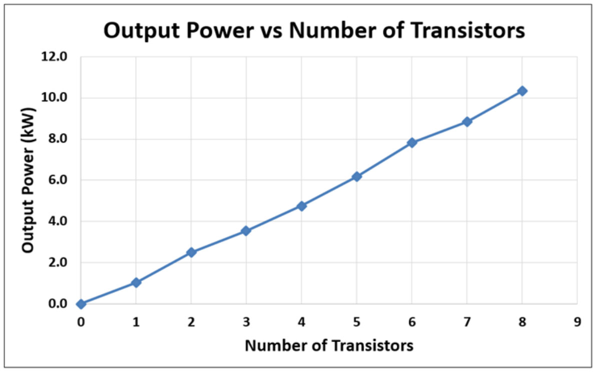

Fig. 5. Module RF input 8.7 W, Pulse length 100 us, frequency 120 MHz, drain bias 60.9 V, gate bias 2.82 V.

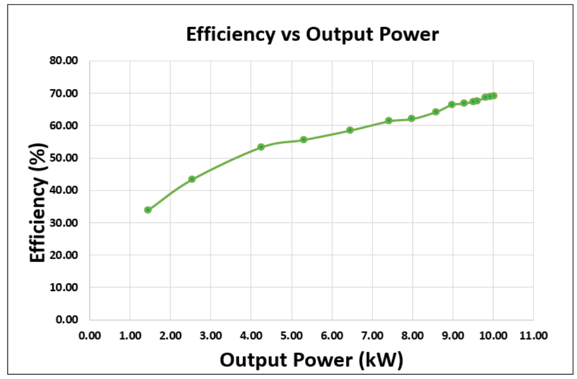

Fig. 6. Efficiency versus output power by varying the RF drive for 8 modules with constant gate and drain bias.

cyclotron resonance heating (ICRH) solution. As expected and shown in Fig. 5, cavity RF output power increases linearly with the number of transistors, indicating that greater power operation is feasible by increasing the number of transistors. The one-transistor-per module production process was streamlined and well-documented in Phase I, so hundreds of refined modules can be fabricated with additional funding to reach high power operation. This technology utilizes stable supply chains which are very important as fusion technology matures. Future fusion pilot plants require technologies which rely on common, abundant parts and materials, and be easily mass-manufactured. The DCC fulfills this imperative.

System efficiency is critical when considering the commercialization of future fusion devices. Efficiency impacts both heat removal and input power. Compared to VEDs, the DCC promises to be more efficient, with the estimated efficiency to be 75%+ (even more with Class E transistors), compared to around 68% for conventional tetrode-based systems. For a 1 MW RF output operating continuously (8760 hours per year) an increase in efficiency from 68% to 75% will result in an electricity savings of approximately 1200 MW-hr. At an average electric power cost of $83.00 per megawatt-hour this translates into a yearly electricity savings of almost $100,000 or $4 million over a 40-year life. This is for each 1 MW RF transmitter in the facility. For ITER, 50 MW of RF heating is required. Using approximately 35 DCCs instead of VEDs for this program would save $200 million over the lifetime of ITER.

Fig. 6 shows DCC Phase I results for efficiency versus RF output power. This plot shows the fixed system losses become an increasingly small fraction of the total as the power is increased.

Graceful degradation was demonstrated by one module being short-circuited, open-circuited, or unpowered while the remaining were powered. Within measurement error, the net measured power in the presence of 7 powered modules and 1 shorted, open, or unpowered module is equal to 7 powered modules. Therefore, if one transistor fails it will not affect the overall efficiency or power output of the unit significantly. This is a very important aspect of the DCC's graceful degradation.

Estimations show that the DCC will allow an order of magnitude improvement in Mean Time Between Failures (MTBF) and reduced Mean Time to Repair (MTTR) as well as reduced physical footprint, especially compared to conventional VED transmitters. In addition, the efficiency is improved and life cycle cost per Watt is considerably reduced compared to existing tetrode-based RF plasma heating systems. The elimination of relatively short lived VED components which need periodic replacement and increased efficiency lead to reduced operational and maintenance costs over the life of the system and greater device availability. The DCC approach is far simpler and more practical than conventional solid state transmitters, especially for high power ICRF.

IV. Next Steps

- Small Scale Demonstration
  - 16 Quad-modules (64 Transistors) Populating Existing Cavity
  - Power Goal = 80 kW @ 120 MHz
  - Short-Pulse Operations
- Large Scale Demonstration
  - Incorporate Module / Cavity Improvements as Needed
  - 104 Quad-modules
  - 26 Quad-modules Per Quadrant (Top Plate Only)
  - 500 kW Of RF Power = 416 Transistors (120 MHz)
  - Full Scale DCC Demo Requires More Funding