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HIGH POWER, HIGH FREQUENCY TETRODE DEVELOPMENT WITH REVITALIZATION SUPPLY CHAIN

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Abstract

Tetrode-based amplifiers are well-established, and now have a revitalized supply chain after their demise looked imminent. High power tetrodes have shown a greater power density and frequency range than solid state amplification, making them a robust choice for future accelerators and fusion devices. Recently, the MIT PSFC spearheaded an effort to source new pyrolytic graphite grids, to re-establish the supply chain for the Communication and Power Industries (CPI) high power 4CM2500KG tetrode. This allows Vacuum Electron Device (VED) amplification methods to be seriously considered for the next generation accelerators [2].

Development and experimental validation[1] of a 120 MHZ, 2.5 MW tetrode is described. The tetrode Final Power Amplifier (FPA) was excited with both a (1) tetrode-based Driver, and (2) Solid-State-Amplifier (SSA), utilizing a cavity power system, and protective circuitry developed at DTI. The experimental electrical schematic, setup, and measured results of the Driver and FPA output power, gain, bandwidth, efficiency, and frequency range are discussed and differences in performance between Driver- and SSA-excitation of the FPA are shown.

INTRODUCTION

Future fusion pilot plants, such as ARC, will require reliable, efficient, and cost-effective plasma heating to obtain and sustain thermonuclear conditions. Ion Cyclotron Range of Frequencies (ICRF), has been identified as a potential auxiliary plasma heating source for several reasons. Many future fusion devices plan to use a high magnetic field for plasma confinement, which requires proportionally higher plasma resonance frequencies. Therefore, multi-megawatt ICRF systems that operate above 90 MHz are desired. ICRF transmitters can be accomplished using either of two technologies: solid state amplifiers, which have great promise, but little experimental high-power validation in this field, or tetrode-based amplifiers, which are well established, but now have a fragile supply chain. High power tetrodes have been validated experimentally [1, 2] to show a higher power density and frequency range than solid state amplification, making it a robust choice for future fusion devices. Recently, the Massachusetts Institute of Technology Plasma Science and Fusion Center (MIT PSFC) has reestablished the supply chain for the Communication and Power Industries (CPI) high power 4CM2500KG tetrode, which allows Vacuum Electron Device (VED) amplification methods to be considered more seriously for the next generation fusion devices[2]. However, the 4CM2500KG tetrode remained largely untested at frequencies greater than 80 MHz. The original 80 MHz FMIT installed on Alcator C-MOD consisted of a three-stage amplifier system utilizing an ~8 kW solid state Initial Power Amplifier (IPA) and two consecutive resonant-cavity-matched, tetrode-based amplifier stages to generate RF power up to 125 kW and 2 MW, respectively. These two cavities were built around the 4CW100,000E (Driver) and 4CM2500KG (FPA) CPI tetrode VEDs. In order to reliably modify and test the tetrode quickly while protecting one of the few last functional 4CM2500KG tetrodes, DTI built series fast opening switches, which were then added to the tetrode's plate and screen supplies in order to quickly interrupt high voltage and current arcs. These switches open in less than 1µs, and if desired, can reclose in under 10 µs, allowing transmitter operation to continue virtually uninterrupted. Originally, mercury-based ignitrons provided the crowbar current diverting circuit for the Fusion Materials Irradiation Test amplifiers (FMIT), which required a long system interrupt time, and therefore are not ideal for experimental testing, or future high-uptime fusion devices.

MATCHING AND MODIFICATION PHYSICS

A crucial part of Final Power Amplifier (FPA) cavity study was to develop a realistic surrogate of the tetrode (Fig. 1), which was designed and fabricated to accurately emulate the electron beam resistance and coaxial transmission line reactance between the cathode, grids, and plate of the 4CM2500KG tetrode. This allowed analysis with a network analyzer on the actual FPA cavity stand to explore existing cavity frequency range and guide the 120 MHz input and output modifications prior to operating the tetrode at high voltage and power.

Figure 1: Surrogate tetrode made to the mechanical dimensions of the actual 4CM2500KG tetrode (left) and the added resistances to emulate the electron beam currents (right) photo of 2.5 MW high power 4CM2500KG tetrode.

DTI modified the Driver and FPA output and input cavities to allow the system to operate at 120 MHz. After the first round of modifications, it became clear through experimental testing that the plate impedance was ~130 Ω. This is undesirable, as higher plate impedance requires higher plate voltage to obtain the same output power due to

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comparatively large plate to screen capacitance. Screen RF losses are also proportional to plate resistance. Higher screen I^2R losses increase the temperature of the screen grid. The effects of high plate impedance are also slightly worsened by the skin depth of the pyrolytic graphite. Independently, the direct current (DC) screen grid current is aggravated by the higher RF peak negative plate voltage. In anticipation of long pulse operation, the FPA output cavity was modified again to reduce the plate impedance to ~97 Ω, and should be modified further to lower the plate impedance again to achieve the lowest screen power. From first principals, the desired lowest plate impedance will be when the cathode is about to become emission limited at the reasonable cathode temperature. However, higher cathode emission can negatively affect tetrode lifetime, and the lower the plate impedance, the lower the transmitter efficiency. Lower plate impedance is a compromise to reduce the effects of RF screen heating.

PERFORMANCE CHARACTERIZATION

Experimental Setup

Figure 2 depicts a simplified electrical schematic of the driver and FPA. As shown, the FPA is the 4CM2500KG being driven by a 4CW100,000, which both have fast opening plate and screen solid state insulated gate bipolar transistor (IGBT) switches and 120 MHz frequency modifications to their input and output cavities. The driver input is powered by a 10 kW Solid State Amplifier (SSA). Following successful testing with the driver tetrode, the driver and low power SSA was replaced by a 175 kW Cryoelectra SSA.

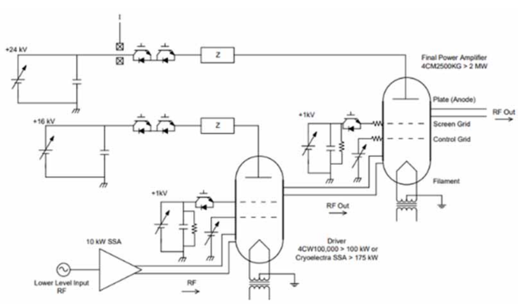

Figure 2: Simplified amplifier system diagram showing tetrodes and solid-state fast plate and screen opening switches.

EXPERIMENTAL RESULTS AND DISCUSSION

The FPA (Fig. 3) was initially driven at 120 MHz using the original 4CW100,000E driver tetrode with modified cavities. This produced excellent results: 2 MW was achieved at 120 MHz in short pulse testing (Table 1).

Although high-power solid-state technology is the likely candidate for ICRF in future tokamak systems due to new device/module development, tetrode-based heating is proven, and represents the best near-term solution. In the interest of realizing a fully solid state ICRF, while maintaining the reliability that tetrodes provide, an incremental step was to replace the driver with solid state technology, while the FPA remains tetrode-based. The main advantage and disadvantage to the tetrode-based driver system is the ability to vary frequency. There is some added complexity in tuning, but gives the ability to operate between 80-120 MHz.

Figure 3: FPA assembly at DTI with short pulse water load attached to front coaxial output.

Over the past several years high-power solid state RF technology has become more viable as costs decrease and reliability increases. While replacing the FPA with solid state technology would be considerably difficult, it is possible to buy a solid-state driver replacement stage commercially. One such vendor is Cryoelectra, GmbH from whom a solid-state unit capable of outputting 175 kW was procured. Classically, VED have provided greater efficiency than solid state units for these power levels, but with an efficiency of ~60%, the Cryoelectra SSA is comparable. The tetrode-based FPA was then driven with the Cryoelectra SSA, and in Fig. 4, the data is compared with the data taken with the tetrode driver. As the Cryoelectra SSA was initially able to drive the FPA with more power than the tetrode-based driver, more FPA output power, was achieved (Table 1).

Table 1 Test Parameters for FPA Operation, Driven by the Tetrode-based Driver Amplifier or the Cryoelectra SSA

Parameter	Driver	Cryoelectra SSA
Frequency	120 MHz	120 MHz
Unit Output Power	120 kW	175 kW
FPA Output Power	2 MW	2.5 MW
Bandwidth	2.5 MHz	2 MHz
FPA Amplifier Gain	13	14
FPA Plate Efficiency	68%	74%
FPA Screen Current	2.5 A	2.7 A
FPA Anode Voltage	24 kV	24 kV
FPA Screen Voltage	1 kV	1 kV
Control Grid Voltage	-580 V	-580 V
Pulse Length	<1 ms	<1 ms

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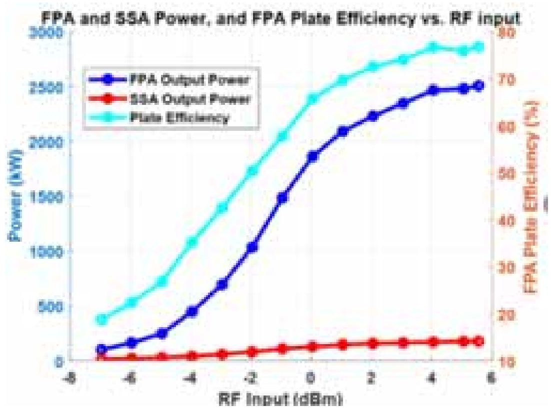
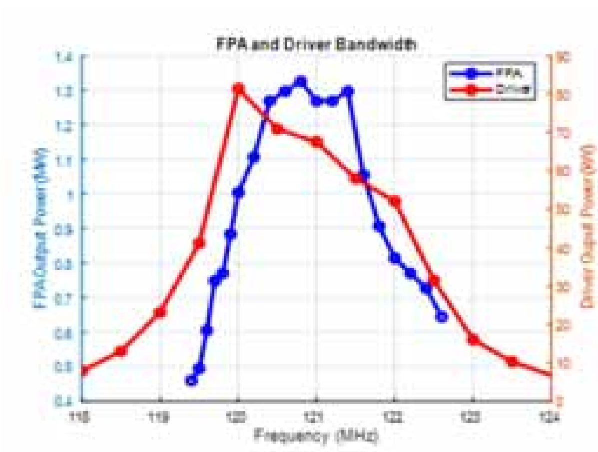
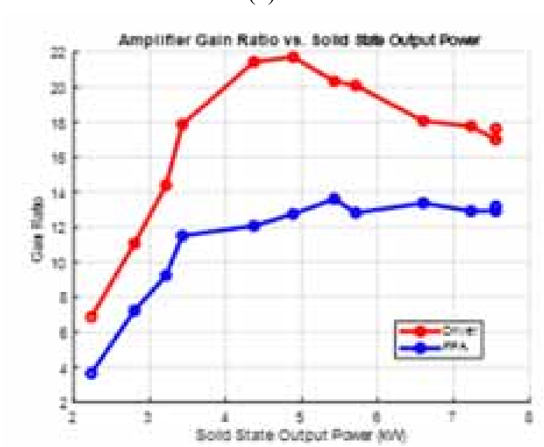


(a)



(b)



(c)

Figure 4: b), and (c) represent performance characterization of the FPA when driven by the driver tetrode, whereas (a), represents performance characterization of the FPA when driven by the Cryoelectra SSA.

Figure 4 (a) shows FPA and SSA output power and FPA plate efficiency as a function of RF input into the Cryoelectra SSA. (b) shows reasonable bandwidth for the FPA and driver, and FPA and Cryoelectra SSA. Note that the driver bandwidth data was taken when the driver was connected to a Fig. 4 50 Ω water load, as was the FPA in both graphs Fig. 4 (c) shows amplifier gain for the FPA and driver, and FPA and Cryoelectra SSA.

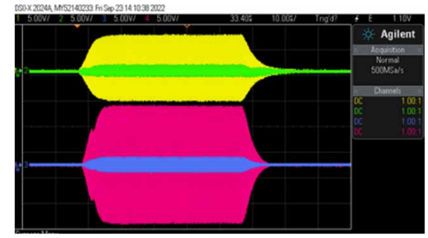


Figure 5: High frequency oscilloscope picture of SSA match into FPA (yellow=forward, green=reflected) and FPA match into water load (red=forward, blue=reflected). The scale is 5 V/division, and all traces are approximately on the same scale, except for the red trace, as it was very large, and so a 6 dB attenuator was added.

As shown in Fig. 5 the match from the Cryoelectra SSA into the FPA has a VSWR of 1.4, and the match from the FPA into the water load has of course a VSWR of about 1. The reasonable match from the Cryoelectra SSA into the FPA input with full power out validates the surrogate strategy for modifying the physical cavity.

NEXT STEPS

Further modification of the driver cavity would improve its performance at 120 MHz, and the FPA could be driven by either the tetrode-based driver or the Cryoelectra SSA. It is important also that long pulse testing of the system occurs to prepare the system for real operation. A new "Beta" transmitter should be fabricated and tested, with a new significantly smaller FPA output cavity (Fig. 6).

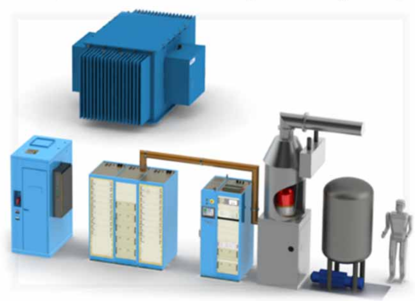


Figure 6: Solid State RF Driver, Screen, Grid, Heater, and RF controls, the FPA. Top row: transformer rectifier set.

CONCLUSION

Development of a short-pulse, 2.5 MW transmitter operating at 120 MHz was described. The 4CM2500KG tetrode FPA can be excited either with a tetrode-base Driver or a Solid-State-Amplifier. The FPA was modified from an 80 MHz, fixed frequency FMIT amplifier. Substantial analyses and experimental modifications to the cavity were made to match and operate the transmitter at high power at 120 MHz. The experimental schematic, setup and results of the Driver and FPA output power, gain, bandwidth, also considered including development of a long pulse system.

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