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ABSTRACT

The electron cyclotron heating system on DIII-D has been supporting experiments with six gyrotrons. The gyrotrons are connected to three power supplies: two have single modulators, each energizing two gyrotrons, while the third has three modulators that can energize three gyrotrons asynchronously. However, only two gyrotrons can be run synchronously due to the limitation of the high voltage dc power supply providing the input voltage to the modulators. These two configurations mimic proposed architectures of power systems for multiple gyrotron systems and demonstrate their advantages or disadvantages, which will be discussed in more detail. A fourth power system is being built as part of an upgrade to eight gyrotrons. The two future gyrotrons will have depressed collectors. A 1.2 MW gyrotron will be delivered in mid-2011 and the design of a 1.5 MW gyrotron has been initiated. This fourth power supply will have two modulators to independently energize the cathode of each gyrotron. Commercially available high voltage amplifiers will provide the body voltage. It will also have a solid-state crowbar instead of an ignitron crowbar. This power supply is described in more detail, as well as the testing performed on the solid-state crowbar to prove its performance.

1.0 INTRODUCTION

The electron cyclotron heating (ECH) system on DIII-D currently has six gyrotrons supporting plasma physics experiments [1]. Each of these non-depressed collector gyrotrons has an 80 kV, 40 A electron beam. The six gyrotrons are connected to three ECH power supplies (ECHPS). ECHPS#1 and #2 have 80 kV, 90 A modulators with a single CQK 200-4A tetrode, each operating two gyrotrons in parallel. ECPS#3 [2] has three modulators, each with a single 4CPW1000KB tetrode. Because of the limitations of the input high voltage dc power supply (HVdc PS), only two of the three gyrotrons can be pulsed simultaneously. The HVdc power supplies are located outdoors and deliver the input voltage to the modulators via high voltage coaxial cables. The gyrotrons routinely run three to five second pulses. Reliability is largely limited by gyrotron dropouts, The power supplies have become reliable to the 90% level.

In order to meet the modulation requirements of up to 10 kHz, tetrode-based modulators are needed for the gyrotrons used in the DIII-D ECH system. If this requirement was reduced to below 1 kHz, or if depressed collector gyrotrons were used on DIII-D, then a solid-state modulator could be used [3]. The proposed architecture for the solid-state power supplies had multiple gyrotrons connected to a single power supply, each with its own modulator to be able to maximize the flexibility and performance of the ECH system and to reduce the cost of the power system. The configurations of the ECH power supplies on DIII-D with multiple gyrotrons on a single modulator in a power supply (as for ECHPS#1 and #2) or with multiple gyrotrons each with its own modulator on a single power supply (as for ECHPS#3) mimic the configurations discussed and demonstrate the disadvantages of the former and the benefits of the latter. This will be described in more detail.

The ECH system on DIII-D is currently being expanded with the addition of a seventh gyrotron, with plans to add an eighth gyrotron in the near future, and more if the long-range plans come to fruition. These gyrotrons will have depressed collectors and generate 1.2 MW, or higher, rf power. A fourth ECHPS is being built for the next two gyrotrons and will have two modulators as in ECHPS#3. A solid-state crowbar [4] is to be installed in ECHPS#4, replacing the ignitron crowbar used in the other power supplies. The solid-state crowbar was temporarily installed in ECHPS#3 and tested to 100 kVdc. It triggered in less than 1.5 μS at full voltage. The solid-state crowbar also successfully went through a set of tests to demonstrate reliable triggering and voltage holding. The tests and results are described in more detail.

2.0 CONFIGURATIONS OF ECH POWER SUPPLIES

2.1 Configuration of ECPS#1 & #2

ECHPS#1 & #2 have a modulator-regulator with a single CQK 200-4A tetrode and have two gyrotrons connected to each as shown in Figure 1. Both gyrotrons see the same voltage and both need to be set up for the same pulse. If the pulse of one gyrotron needs to be terminated early for whatever reason, the pulse of the second gyrotron is also terminated. If one gyrotron needs to be conditioned, the second is usually disconnected. Conditioning usually is done for 16 hours a day. In the few instances when a conditioned gyrotron was also needed for support of physics operations, the conditioning of the gyrotron was performed after physics operation and was reduced to less than 8 hours a day.

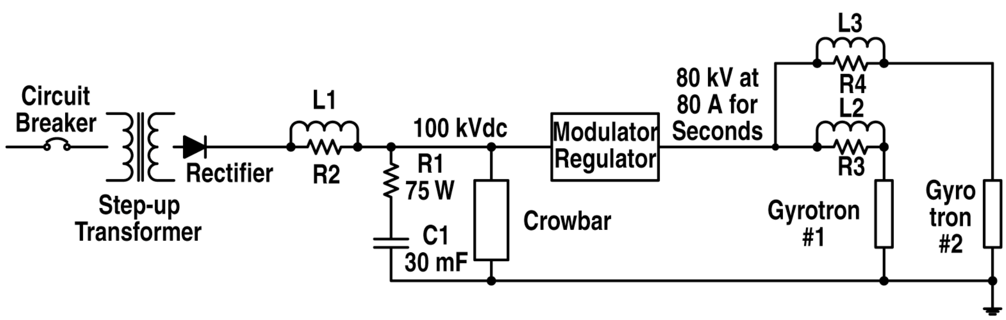

Fig. 1 Configuration of an ECHPS#1 & #2 with two gyrotrons connected to a modulator-regulator.

In support of physics operations, modulation of the rf power generated by gyrotrons is performed, which is done by reducing the voltage applied to the gyrotron. This can lead to excessive power loading in the tetrode. If the tetrode is running two gyrotrons at 80 kV and 80 A of total current, it will need on the order of 5 kV of voltage across the tetrode to be able to regulate the output, which causes 400 kW of dissipation in the tetrode. If the voltage applied to the gyrotrons is reduce to 60 kV to reduce the power, the current will reduce to around 60 A, and the dissipation in the tetrode will increase to over 1.5 MW, well over the 1 MW maximum dissipation limit of the tetrode. The average dissipation can be kept below this limit by properly adjusting the frequency and depth of the rf power modulation. However, the dissipation in the tetrode precludes remaining at low rf power levels during modulation for very long.

The tetrodes in ECPS#1 & #2 have a problem with parasitic oscillations which is aggravated by the non-linear nature of the load presented by two gyrotrons connected in parallel to it. Operation into a purely resistive dummy load does not have these oscillations, nor does it occur at the lower current levels for one gyrotron. This problem has complicated the operation of two gyrotrons. By adjusting the operating parameters of the tetrodes, the operating points of the gyrotrons, and how the gyrotrons are turned on, a small window of operation was opened that allows for operation of the two gyrotrons, but at reduced power.

2.2 Configuration of ECPS#3

ECHPS#3 has three modulator-regulators, each having a single 4CPW1000KB tetrode, and each energizing one gyrotron, as shown in Figure 2. Because of the limitations of the input HVdc power supply, only two of the three gyrotrons that could be connected to ECPS#3 can be pulsed simultaneously. In this configuration, the voltage applied to each gyrotron is independently controlled and there is much more flexibility in their operation. The gyrotrons can be pulsed at different voltage or rf power levels, at different times, and for different durations. The dissipation limit for this tetrode is also 1 MW, which will limit the separation in voltage at which the two gyrotrons can be operated. This should not be too much of a restriction for normal operation, as operation near full power is usually the norm. This is more of an issue during the early stages of gyrotron conditioning. However, conditioning of a gyrotron can occur asynchronous from a pulse of the other gyrotron(s) into the tokamak once the operating voltage levels are close enough together. In addition, the capability for modulation is greater in this configuration due to the lower current load on each tetrode.

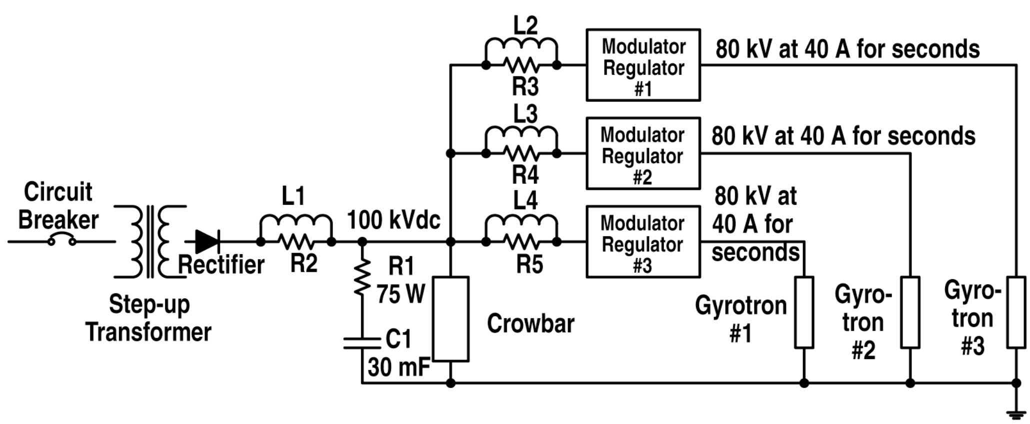

Fig. 2 Configuration of an ECHPS#3 for multiple gyrotrons with a modulator-regulator per gyrotron.

2.3 Future DIII-D ECH Power Supplies

DIII-D is beginning an expansion of the EC system. A seventh gyrotron is being built. It is an upgraded design of a previous 1.2 MW depressed collector gyrotron. The rf design is more efficient with less internal losses and the collector is to be made of dispersion strengthened copper to allow higher power loading and yet achieve long cyclic thermal fatigue life. Long-range plans are being formulated for a 15 MW system of ten gyrotrons, using a new 1.5 MW depressed collector gyrotron. The design of this gyrotron has been initiated and the eighth gyrotron will be the first of the new gyrotrons. To limit the cost of the upgrade, the gyrotron is being specified to be the highest power achievable within the capabilities of the existing power supplies. In the plan, two more gyrotrons would be added to increase the total number of gyrotrons to 10, and the existing six 1 MW gyrotrons would be replaced.

ECPS#4 is being built for the seventh and eighth gyrotrons. It will be similar to ECHPS#3, but with two modulators. The modulators will provide the cathode voltages and the body voltages will be provided by commercially available high voltage amplifiers. Rf power modulation can be performed with either the body power supply or the cathode power supply. Modulation by only the body power supply alleviates the tetrode dissipation issues for modulation, but modeling shows that the collector of the gyrotron will experience excessive power loading unless the it is modulated at frequencies above 100 Hz and for duty cycles greater than 50%. Therefore, modulation must be done with only the cathode power supply or with either one depending upon the desired form of modulation.

A fifth ECHPS will be built when the upgrade to ten gyrotrons is made. The single modulators in ECHPS#1 & #2 will be replaced with two modulators when the gyrotrons connected to them are upgraded to the new 1.5 MW gyrotrons.

Solid-states modulators [3] could be used for the depressed collector gyrotrons instead of the tetrode-based modulators. This would eliminate the operational issues associated with tetrode dissipation. To achieve full range of rf power modulation, modulation with only the cathode power supply can be used from dc to around 1 kHz. For the instances when higher frequency modulation is required, the body power supply can perform the modulation under prescribed conditions of frequency, depth of modulation, and duty cycle within the power dissipation limits of the collector of the gyrotron. General Atomics is developing a solid-state modulator and could use it in future power supplies once the design is proven.

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3.0 SOLID-STATE CROWBAR

Gyrotrons routinely experience high voltage faults and arcs, especially while they are being conditioned to full operating parameters for the first time. Also, the tetrode can arc. A crowbar is needed to protect both the tetrode and the gyrotron. It is imperative that the energy into such faults be limited to prevent major physical damage from the energy available from the power supply. Typical requirements placed upon the power supplies are to remove the source of energy from the gyrotron within 10 µS and to limit the energy into the fault to less than 10 J while doing so. The power supplies usually have a fast acting regulator or switch to apply the voltage to the gyrotron, such as the tetrodes in the ECH power supplies at DIII-D. In the event of a gyrotron fault, the first action is to simply turn off the regulator or switch, which most of the time is sufficient. However, the regulator or switch can fail or arc, which can destroy the regulator as well as the gyrotron. If this occurs, the crowbar is triggered, diverting the energy in the HVdc power supply away from the fault while the circuit breaker is opened. It will take a few microseconds to detect such a failure and trigger the crowbar, so passive circuit elements are needed to limit the energy into the fault while this is happening.

The first three ECH power supplies have ignitron crowbars. Solid-state crowbars are being developed and are being used in place of ignitron crowbars. It can take one to two microseconds to detect a fault and then another few microseconds to fire the crowbar. Therefore, the inherent delay of each device and circuit in the chain is critical. This includes the delay time of the SCR, which can be a significant contributor to the overall circuit delay depending upon the device selected. General Atomics developed a SCR crowbar [4], which is shown in Figure 3. It achieved delay times less than 1.8 µS during initial bench tests at 15 kV with five SCR modules.

The crowbar with 30 SCR modules was assembled and successfully tested for voltage hold-off at 100 kVdc for eight continuous hours. The SCR crowbar was temporarily installed in ECHPS#3 to test it under realistic conditions. Tests were performed up to 100 kVdc with peak currents up to 3 kA. The time delay to fire the crowbar was 1.4 µS as seen in Figure 4.

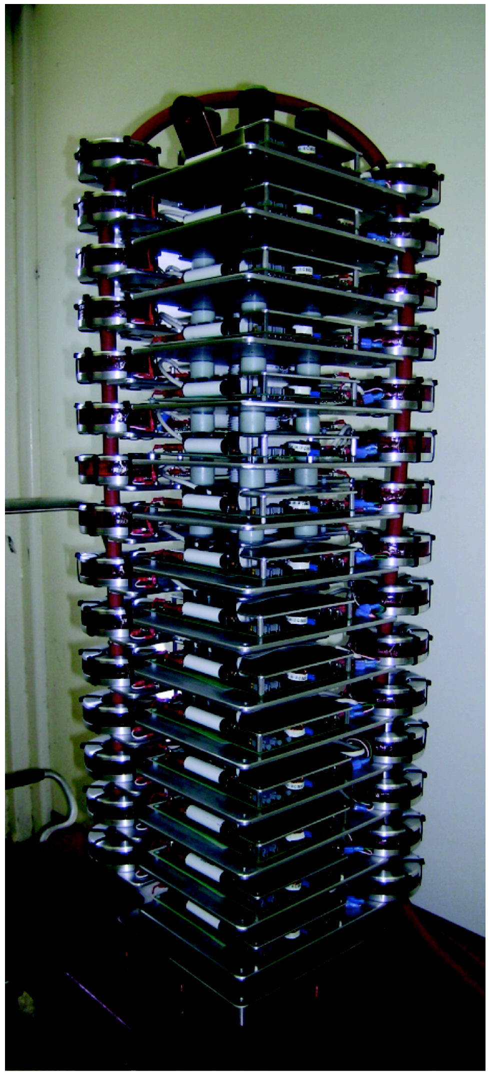

Fig. 3 100 kV crowbar with thirty SCRs

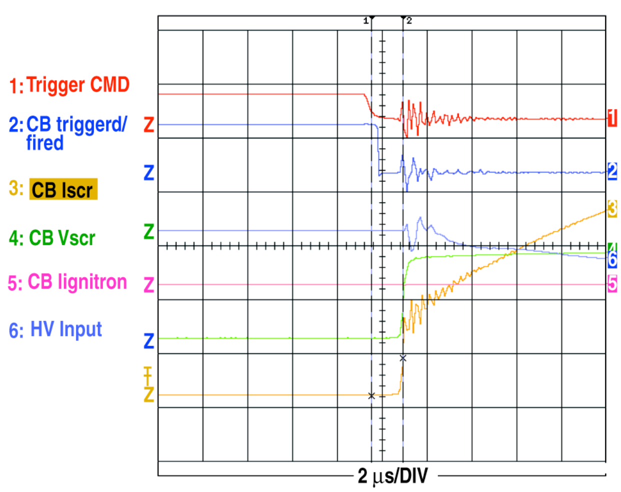

Fig. 4 Crowbar waveforms during 100 kV test showing 1.4 μS delay from trigger command

A "36-gauge wire test" was performed to verify meeting the 10 J limit. In this test the output of ECHPS#3 was connected to one side of a high voltage relay and a 12-inch length of 36 AWG wire was connected from the other side to ground. The power supply was energized and the relay was closed. The power supply must detect the fault and fire the crowbar fast enough to prevent the wire from melting when the test is performed five times in a row. This was successfully done with a 36 AWG wire, as well as with a 38 AWG wire. Figure 5 shows the crowbar current from the discharge of the capacitor filter plus the current from the supply until the circuit breaker opened after 32 mS (two ac cycles). A total system time delay of 3.5 µS was achieved to sense the fault and fire the crowbar, diverting the energy from the power supply and protecting the wire, as shown in Figure 6.

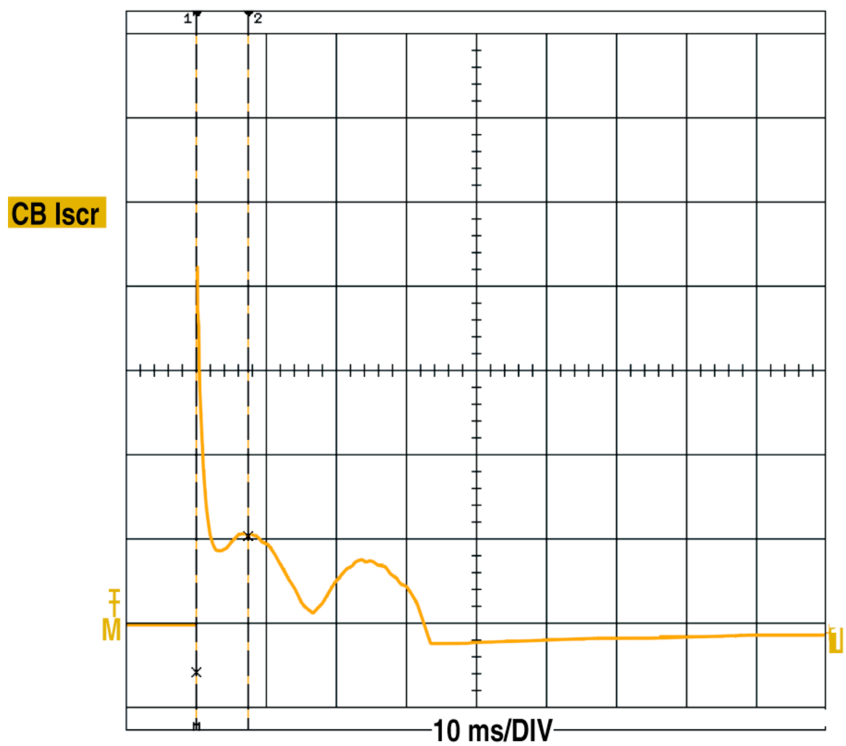

Fig. 5 Crowbar current showing current from HVdc PS until circuit breaker opened

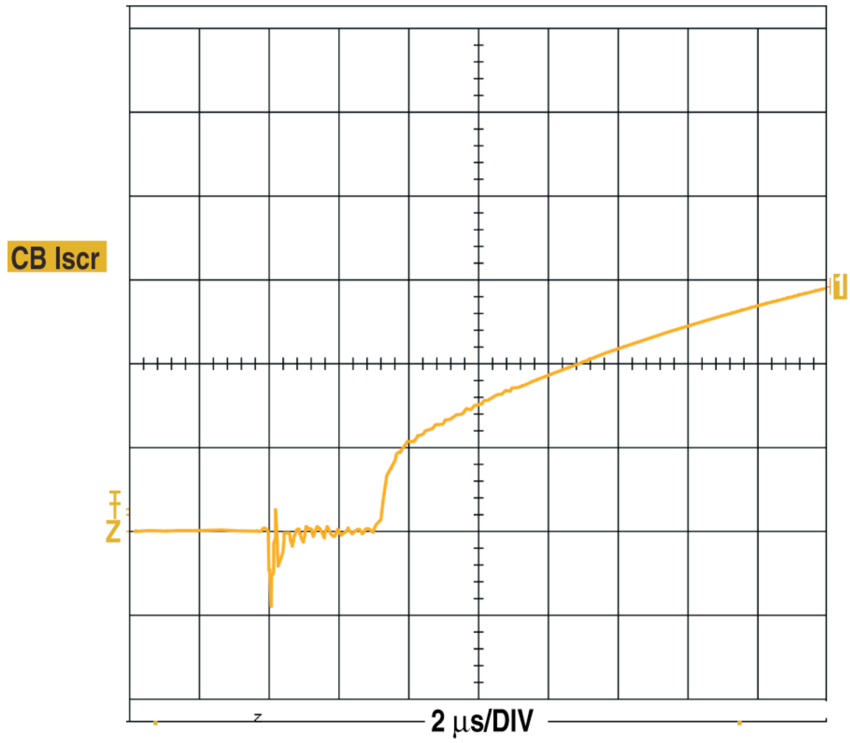

Fig. 6 Expanded view of crowbar current for “36-Gauge Wire Test” showing 3.5 μS system delay

A portion of the crowbar was also tested to demonstrate the long-term reliability of the SCR modules. A shorter nine SCR crowbar was tested at 27 kVdc. A capacitor was charged to this voltage and held at this value for a few minutes before firing the crowbar. The current was limited to 1 kA and the rate of rise of the current was 0.6 kA/μS. This was repeated over 300 times over the span of several days without any failures of the crowbar. This is the estimated number of times that the crowbar will likely be fired in a year of service.

4.0 CONCLUSION

An ECHPS power supply with individual modulators for each of the gyrotrons connected to it has demonstrated greater versatility in the operation of the gyrotrons than one in which multiple gyrotrons are connected to a single modulator. As the EC system is upgraded with more gyrotrons and to higher power, the future power supplies will have a modulator for each gyrotron, and the two supplies with the single modulators will be upgrade to two modulators. Solid-state crowbars will be installed in the new power supplies instead of ignitron crowbars.

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5.0 ACKNOWLEDGMENT

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