High Current Tokamak Protection Switch

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Abstract— One of the major remaining technical hurdles facing tokamaks, a leading architecture for fusion systems, is that plasma disruptions can result in the generation of high current beams of relativistic electrons (10s of MeV). These beams are called Runaway Electrons (RE). In advanced fusion machines, Runaway Electrons can cause severe damage to plasma-facing surfaces of a tokamak structure. This catastrophic destruction includes melt damage, coolant leaks, and loss of vacuum.

High field tokamaks, which will be required for commercial fusion power, will be even more susceptible to damage from RE than present-day systems such as ITER. Even if these events occur rarely, they could hamper fusion machines from reaching commercial viability. To prevent these events from damaging tokamaks, a non-axisymmetric coil can be excited to disrupt the magnetic field and prohibit formation of such relativistic electron beams. Diversified Technologies, Inc. (DTI) is working under a Small Business Innovative Research (SBIR) grant from the Department of Energy [1] (DOE) to develop a fast-acting high current switch and vacuum feedthrough controlling a magnetic coil. When passively switched ON, this will disrupt formation of the relativistic beams, and prevent damage to the plasma facing surfaces. As part of the switch design, protective circuits are integrated to ensure proper switch operation.

The full-scale switch and feedthrough will be installed in a working fusion device for full-scale tests. This effort is in collaboration with MIT and General Atomics (GA) for future installation on the GA fusion device (DIII-D) as a prototype.

Keywords— Relativistic electron beams, runaway electrons, non-axisymmetric magnetic coil, passive switching, high current vacuum feedthrough

I. INTRODUCTION

A Runaway Electron Mitigation Coil (REMC) can be used to quash undesired RE currents by creating a spoiling magnetic field to cause poor plasma confinement, including runaway electrons, thereby preventing a build-up of relativistic beams during a disruption in the tokamak. Perturbative magnetic fields are generated by currents in a non-toroidally symmetric coil inside the tokamak vacuum vessel at either the vessel inner radius or outer radius. These magnetic fields interact with the RE current beam and cause disruptive forces stopping the RE beam before it does damage. The induced current requires only a few milliseconds to reach its design value. A control switch is needed which is capable of very high current integrated with a neutron radiation resistant high-shock resilient vacuum feedthrough for such a coil. The switch controls the current through the non-axisymmetric coil: the magnetic forces generated by the coil interact to disrupt the electron beam.

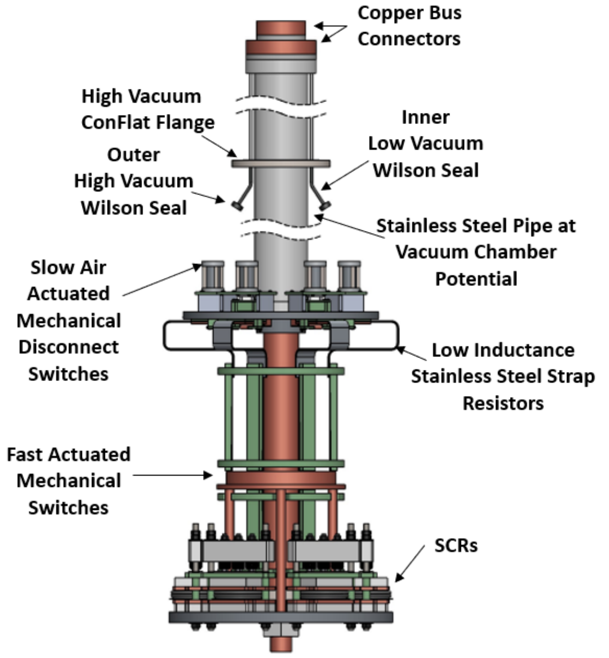

Fig 1. Artist's concept of proposed 350 kA passive, fast-acting, high current solid state, switch and low-inductance coaxial feedthrough for use with an REMC in DIII-D and other future tokamaks. The whole assembly is electrically isolated from the vacuum chamber. The six fast SCR switches are passively triggered and have microsecond turn-on times. A fast-acting mechanical shorting switch is used to unload the SCRs for long pulses. The coaxial feedthrough minimizes electromagnetic forces and can be any length. Disconnect switches can isolate the unit if desired.

Diversified Technologies, Inc. (DTI) designed a 350 kA passive, fast-acting, electrically-isolated, high current switch and vacuum feedthrough (Fig 1). This design was experimentally validated through a scaled-down test of the full system, where 1/6th of the total switch (one "branch" of the design) was successfully demonstrated at 60 kA and 5 kV. High-field tokamaks will require remarkably high-power engineering components and systems that are reliable and have an established supply chain. During Phase I of the SBIR effort DTI identified and resolved multiple issues that could be tokamak operation show-stoppers. If the REMC switch does not operate

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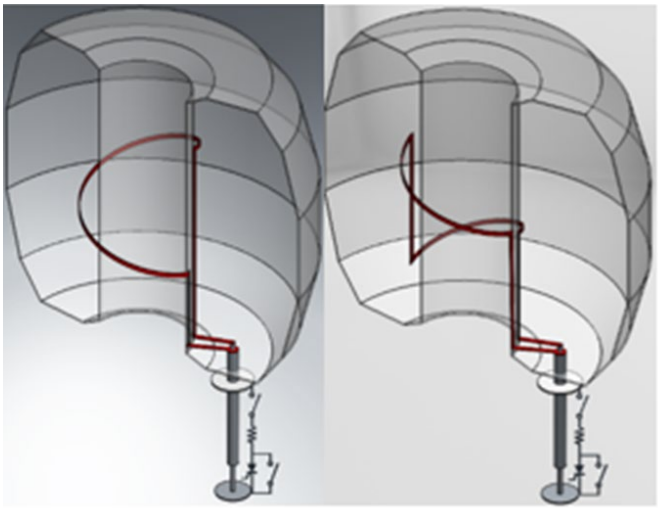

Fig. 2. Two REMC concepts: non-toroidally-symmetric coils shown in a basic concept on DIII-D tokamak. DTI's switch and feedthrough connects to either REMC. The coil could also be on chamber outer diameter for SPARC.

correctly, the whole tokamak could be irreparably damaged. Mitigating the effects of the extreme forces (hundreds of tons) proved to be a challenge, but DTI's experimental efforts provide more information to fusion device designers.

II. SYSTEM OVERVIEW

A. *The REMC Switch*

The REMC switch (Fig. 2) consists of an SCR assembly connected electrically in parallel with a fast mechanical switch which is connected to the REMC via a coaxial feedthrough at the bottom or other edge of the tokamak vacuum vessel. There are six SCRs and six mechanical switches distributed around the coaxial feedthrough to maintain quasi-coaxial current flow external to the tokamak. During a disruption event, the coil loop voltage will increase above a threshold value (~20 V) which initiates each SCR activation. This activation will prevent the build-up of energy in the electrons that leads to a possibly destructive runaway event.

B. *Current Transfer*

The key to understanding the REMC switch operation is the current transfer from the SCR to the mechanical switch. This reduces the integral of I^2t as experienced by the SCR and permits fewer, lower cost devices to be utilized. Each mechanical switch becomes passively engaged as a result of the large forces generated on the bending-beam conductor by the large peak currents through the SCRs. A semi-flexible strap allows for beam movement. These forces close the metal contacts; since the mechanical switch is electrically in parallel with the SCR, it shares the current, and being of lower voltage drop, it relieves the SCR of the majority of its current. There are dissipative resistors in each of the six current paths. The resistors can be designed to intentionally increase in resistance at the higher temperatures during a current pulse, which will reduce the pulse duration. These resistors also guarantee equal current sharing among the SCR paths. Note there is also a fail-safe air-actuated series disconnect switch used to safeguard the system for maintenance or other purposes.

The ~1 kV loop voltage from the plasma disruption which created the runaway electrons also triggers the SCRs and powers the REMC, hence an external power source is not needed.

Fast mechanical bypass switches are used to protect each SCR switch from overheating at high action integrals ($\int_0^t I^2 t$). High forces are created by the repulsion between closely spaced parallel conductors with currents traveling in opposite directions. Each parallel mechanical switch becomes passively engaged by large forces generated on a bending-beam conductor relieving SCR current.

III. EXPERIMENTAL TEST BED

A. *The REMC Switch*

DTI designed and demonstrated all key elements of a passively operated, high current, solid state switch. This switch can operate at 1 kV open circuit and conduct 100 kA to 350 kA for tens of milliseconds through a high strength vacuum feedthrough. DTI experimentally validated this design by testing 1/6th of the total switch (i.e. one "branch" of a 350 kA design) up to 60 kA and 5 kV (Figure 3). Figure 4 shows the simplified electrical simulation for the Phase I experimental set-up. The experimental test set-up consisted of a large capacitor bank in series with a test inductor. A back-biased diode was connected across the capacitor to prevent capacitor voltage reversal. The SCR switch was used to discharge the inductor-capacitor arrangement. The peak current is determined by the inductor-capacitor ratio and the charge voltage; the discharge time is determined largely by the resistance in the circuit.

The new piece of technology being tested is the rapid current transfer between the SCR and mechanical switch. Figure 5

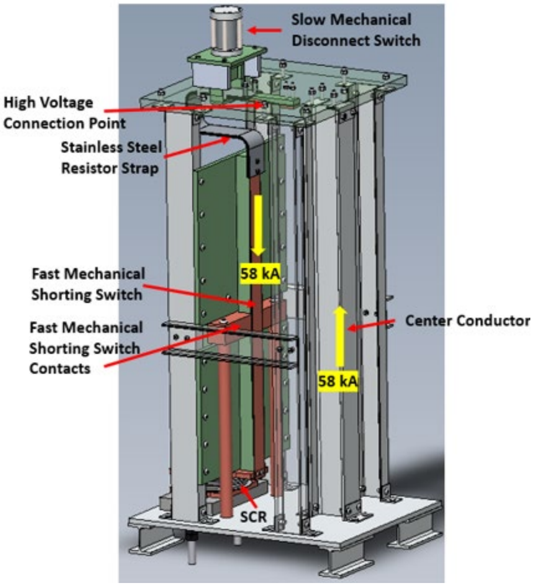

Figure 3. Original SolidWorks design of Phase I test apparatus to test 1/6thof the total switch (i.e. one branch of the 6 SCR final 350 kA system).

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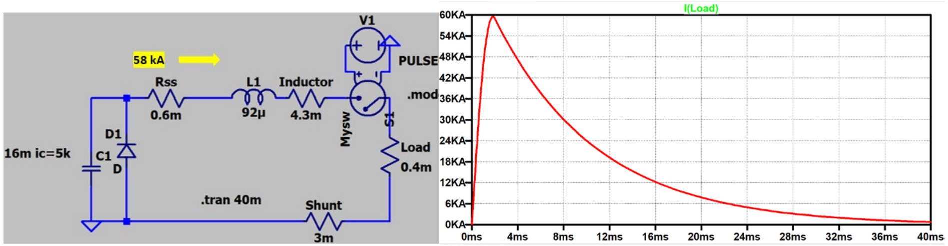

Figure 4. Simplified SPICE simulation for the experimental testbed for Phase I DTI in-house test of 1/6th or one "branch" of the final 350 kA system.

shows the copper-tungsten contacts post-test, which survived extensive high voltage and high current testing and did not weld.

Figure 5. Left: Fast Mechanical Switch flexible copper strap side, with copper-tungsten insert. Right: Fixed side copper-tungsten contact area. Both photographs are after ~30 shots and show a little damage.

B. *Vacuum Feedthrough*

DTI designed the low-inductance, high-strength, high power vacuum feedthrough by studying the shock and energetic forces due to high magnetic field and investigating the effects of neutron dose on state-of-the-art insulating materials. The coaxial feedthrough design is chosen to minimize side forces as the feedthrough enters the toroidal field.

Large (1400 kg) side and flexural loads on the vacuum feedthrough for the electrically insulated sensing coil support are too great for the usual ceramic/metal seals used in typical vacuum feed-throughs. Thin metal seal members will distort and peel, creating local stresses and the tensile strength of ceramic may be exceeded.

An alternative means of support is needed. Requirements are:

- Ability to support side and flexural loads without permanent deformation
- No use of O-rings, oil, plastics or other organic materials due to the high levels of radiation.
- 2500 volt electrical isolation of conductors from ground and each other
- Vacuum-tight construction – helium leak < ~ 10-9 std cc/sec
- Suitable for use with concentric conductors

The design must retain vacuum integrity and low gas blowby while allowing for small displacements due to the extremely large magnetic force on the REM coils and feedthrough connections.

A significant risk involving the feedthrough is the potential for breakdown in the differential pumped O-rings or Wilson seal assembly. The concentric O-rings leave a small space in between the O-rings. This approach is frequently used in high vacuum systems. Due to the high voltages in this area and the possibility of a small amount of gas being present between the seals, there is a potential for plasma breakdown, which would damage the seal. We have addressed this risk by preliminary design. At normal operation, without any plasma disruptions, the O-ring area at a pressure of ~10 milliTorr will experience a small differential voltage (~20 V). During a plasma disruption the voltage differential becomes approximately 1 kV. However, the gap between O-rings is small enough that breakdown will not occur, as secondary electron emission will not have enough space to proceed into an avalanche breakdown. Both voltage regimes (20 V and 1 kV) are past the "breakdown" part of the Paschen curve. If future systems require voltage or pressure changes, DTI can adjust the geometry of the seal to prevent breakdown. For example, the thickness and surface tracking distances of the ceramic rings could be extended or shortened, whichever way prevents breakdown, according to the Paschen curve.

IV. RESULTS

It was crucial to this effort to show the current transfer from the SCR to the mechanical switch, and to accurately measure the currents, so that the system will be reliable and operate correctly when a Runaway Electron event occurs. As the currents are large (up to 60 kA in this effort), ordinary current transformers were not applicable. DTI designed, fabricated, and tested three types of current sensors in Phase I: Hall Effect probes, Rogowski Coils, and shunt resistors. The peak current could also be estimated as the derivative of the 16 millifarad capacitor bank voltage, or from the peak charging voltage divided by the circuit $\sqrt{\frac{L}{C}}$ characteristic impedance. The relatively good agreement of these five methods instilled confidence in the current measurements.

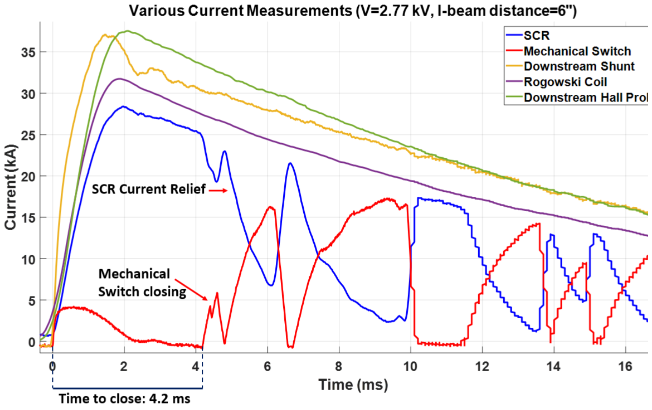

Figure 6. 2.77 kV, 37 kA shot where the mechanical switch took 4.2 ms to initially close. The fast mechanical switch continues to relive a greater portion of the SCR current as the overall system current increased, and therefore force increased.

Figure 6 shows an experimental test shot where there are three Hall Effect Probes used: one downstream of the switch, one to measure SCR current, and one to measure the fast mechanical switch current. This clearly showed the intermittent current transfer from the SCR to the mechanical switch during the pulse. The mechanical switch did bounce as it made contact, but this effect improves as current, and therefore force, increases. Mitigating this effect will be a key Phase II task. In Phase II, a short stainless-steel strap resistor will be added in series with the SCRs, which should greatly improve the current transfer to the mechanical contacts.

In summary, all the key components to the full-scale runaway electron mitigation coil switch were demonstrated: 60 kA, 5 kV current transfer between SCR and mechanical switch, and differentially-pumped movable vacuum rings for feedthrough.

V. NEXT STEPS

DTI's main recommendation is that the 1/6th, 58.3 kA branch tested in Phase I should be expanded and tested as the full 350 kA version, where a center conductor carries 350 kA, and each branch carries 58.3 kA (six branches). The full system has already been designed, and once it is fabricated and experimentally tested at DTI, it will be installed in a fusion machine and tested in conjunction with an REM coil.

Prior to the fabrication process, DTI and MIT will test several SCRs with varying degrees of radiation shielding to inform the design. For example, if the switch was placed in the SPARC basement, radiation becomes a concern for the SCRs. The neutron flux in this location is anticipated to be 1010 cm^2/s, where 10% of the neutrons are fast neutrons with an energy of 14 MeV. This information was calculated by MIT and CFS, and the basement is 1 m of concrete away, but the RF pipes also come from the tokamak to the basement, allowing more neutrons through. There is concern that the radiation could damage the SCRs or cause them to falsely fire. This area has not been studied thoroughly, as SCRs are not commonly used in space environments (which is why transistors have been studied pretty well in radiation environments). The few studies[2] that have been performed suggest that the level of radiation in the SPARC basement will be an issue for the SCRs. DTI and MIT have planned to study this, by exposing the exact SCRs used in this work to similar radiation doses, and with fast neutrons, and then measuring the ion saturation voltage and other performance characteristics afterward. Various methods of shielding will also be employed during some of the testing, to see which methods are most effective in this environment. Boron carbide is a go-to material here for neutron radiation shielding, but other options include steel and concrete.

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[2] https://ntrs.nasa.gov/api/citations/19920019189/downloads/19920019189.pdf