High Current Tokamak Protection Switch

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***Abstract*— One of the major remaining technical hurdles facing tokamaks, a leading architecture for fusion devices, are plasma disruptions which 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 devices. 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 (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.

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 conducting 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.

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. 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 correctly, the tokamak vacuum vessel could be irreparably damaged.

II. System Overview

A. The REMC Switch

The REMC switch 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 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 copper-tungsten 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.

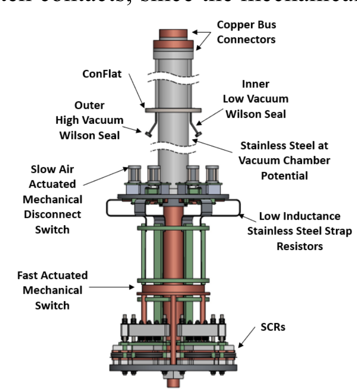

Fig 1. SolidWorks model of proposed 350 kA passive, fast-acting, high current solid state, switch and low-inductance coaxial feedthrough for use with an REMC in future tokamaks. The whole assembly is electrically isolated from the vacuum chamber. The six fast SCR switches are passively triggered and 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.

The ~1 kV loop voltage from the plasma disruption

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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 – 60 kA Demonstration*

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. 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. When the mechanical switch contacts closed in the Phase I experimental testing the contacts bounced, thereby only intermittently relieving the SCR current since there was no method to dissipate the kinetic energy imparted by the Lorentz forces. This approach worked adequately, and no deleterious effects occurred, but this performance is undesirable and risks damage to the SCR. To reduce risk, a more persistent method of keeping the switch closed throughout the event was implemented. During impact, the resistance of the mechanical switch is very low, but as the forces reduce, the voltage across the contact becomes greater, and the current transfers back to the SCR. To mitigate this effect, resistance was added in series with the SCR to ensure continuous current flow through the contacts, even with a higher voltage drop at lower pressure, raising the voltage potential across the SCR for timely current relief. In the Phase I scaled-down test set-up (representing a 1/6th branch of the full 350 kA system), half of the copper mechanical switch has been replaced with stainless steel, increasing series resistance with the SCR, allowing successful testing and confirmation of a significant reduction in mechanical bounce before progressing to the full-scale system, thereby reducing risks.

B. *The REMC Switch – 350 kA Demonstration*

To test the full 350 kA switch system, a new experimental testbed must be constructed. The original 350 kA testbed design plan was to design and build one large 350 kA inductor, but in the beginning design portion of Phase II, it became clear that it would be simpler to build six 58.3 kA inductors instead. As force increases with the square of the current, the 350 kA inductor would have had significantly more force than the 58.3 kA inductors, which presented a much larger amount of risk to the experimental test campaign. Six high current free-wheel diodes, one for each inductor, will be used to prevent voltage reversal on the capacitors. The large capacitor bank will be comprised of twelve x 8 mF capacitors in parallel. However, in the event of a fault, more than a mega-amp of current could be produced. Therefore, the capacitor bank will be split up, so that each inductor and diode is connected to only two capacitors. The end of the inductors connects to the top of the switch, at the coaxial bus, and the currents combine to provide the required 350 kA. Each individual SCR will experience only 60 kA, as they are in parallel.

C. *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 feed-through 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. 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. 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.

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. 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.