# ADVANTAGES OF SECOND-GENERATION HIGH TEMPERATURE SUPERCONDUCTORS FOR PULSED POWER APPLICATIONS*

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## *Abstract*

Within the past few years a newer, more robust type of superconductor known as Second-generation (2G) High Temperature Superconductor (HTS) wire, has become available in sufficient quantity and length for developers to build prototype devices and test their capabilities. This new material offers the potential for revolutionary changes in magnet technology, enabling more compact and higher performance systems that can meet the stringent demands of different pulsed power technologies, particularly for those in high energy density, nuclear, fusion and plasma applications.

This manuscript will discuss the latest advantages and superior performance of the new 2G HTS superconductors [1]. We will discuss the principal advantages over First-Generation (1G) HTS, Low Temperature Superconductors (LTS) and conventional conductors. We also discuss how pulsed power applications can benefit from their use and their suitability. We will show a wide range of extreme low and high temperature tests performed with currents up to 40kA with 2G HTS that demonstrate superior performance and new capabilities. We also will illustrate different applications where 2G HTS can be the key to improving the performance, compactness and other capabilities of present pulsed power applications D-ROM.

## I. INTRODUCTION

Nowadays, the stringent demand for the generation of high magnetic fields has become essential for a large number of high power and pulsed power applications. Many of these applications are typically related with the generation of very large magnetic fields, which can be categorized in the following groups;

- Non-destructive magnetic fields/conductor development
- Non-destructive production of pulsed magnetic fields
- High magnetic fields in small volumes
- Plasmas, magnetized plasmas, fusion
- Rail-guns, launchers, and related topics
- Experiments for high-energy density in physics

Generation of high magnetic fields for long pulse durations and/or high repetition rates up to continuous or steady state operation becomes more challenging since large energy is deposited on the conductors by resistive heating losses generated over the time. Essentially, the limiting factors become more relevant when the time duration of the pulsed magnetic field increases or when the periodicity, high repetition rates or pulses are required to be steady for long periods of time, which can eventually over heat and destroy the conductive material. Whether short or large pulse durations are required, the larger the conductor current density that can be produced, the larger the magnetic field is achieved. Some of the relevant features of 2G HTS conductors may provide solutions to those challenging issues:

- Current density of 1kA in 1cm width x 50μm thickness.
- Compact dimensions from 50-100μm thickness.
- 2G HTS conductors over 1000m length [2-3];
- Superior electro-mechanical properties [3-4];
- High n-values (20-40) for fast dI/dt, dV/dt transitions.

Superconducting magnets have been an enabling technology for many advanced applications and opening opportunities for advancements in condensed matter physics, biology, chemistry, material sciences, physiology and psychology [5]-[8]. The development of high magnetic field superconducting magnets has driven many of the developments in magnetic resonance (NMR/MRI), particle accelerators and colliders and fusion devices [9]-

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[11]. Superconducting magnets offer a number of advantages including smaller footprint (weight, volume) allowing more freedom in the configuration of the rest of the device especially for most of pulsed power applications where compactness is one of the main design drivers, and consuming much less power.

The availability of high performance superconducting materials has facilitated the development of high field superconducting magnets. Superconducting magnets are typically made of low temperature superconductors (LTS), principally NbTi and $Nb_3Sn$. The highest magnetic field achieved by Nb3Sn-based LTS magnet is 22.3 T [5].

With the growing availability of REBaCuO-based second generation high temperature superconductors (2G HTS), revolutionary and novel electric machines and devices such us powerful and compact electric motors, generators, transformers, transmission lines, and more including high field magnets [5], [9]-[11], are now being considered. The high engineering critical current density, high strength and high critical magnetic field of 2G HTS (critical values refer to the limit where no resistive losses are generated), on the order of 70 Tesla or more, have the potential to breach the limit of today's superconducting magnets using LTS and first generation HTS.

Today, the manufacture of high performance 2G HTS wire is underway. The fabrication technologies for 2G HTS materials have been progressing dramatically in the past few years [12]-[15] with remarkable advancements in the metrics of critical current, wire length, in-magnetic-field performance and production throughput and costs.

We will also discuss some intrinsic characteristics of 2G HTS superconductors useful for pulse shaping stages as well large impedance rising for the protection of electric devices. 2G HTS superconductors offer very unique dual impedance phases thanks to their intrinsic quenching characteristics during the transition from no resistance during the superconducting phase to the normal resistive phase developing very sharp dI/dt's and dV/dt's. This rapid rise of impedance offered by 2G HTS superconductors makes them very unique and useful for fault current protection of electric devices where the impedance can be raised by several orders of magnitudes within a few milliseconds as well for pulsed power applications where impedance matching between different phases is required to increase the efficient transmission of energy from one stage to the other. Therefore, we focus our discussion in non-destructive high magnetic field generation and conductor development for production of high steady and pulsed magnetic fields.

## II. 2G HTS WIRE PROPERTIES

The applicability of a superconducting wire for a high field magnet is principally determined by its current density and mechanical properties to handle the stresses encountered during fabrication, cool-down and operation. In addition, long lengths of wire are needed for the magnet fabrication.

### *A. Structure of the SuperPower 2G HTS Wire*

Table 1 displays a typical SuperPower 2G architecture.

**Table 1.** Typical architecture of a Superpower® 2G HTS.

| Architecture | Process Method |
|---|---|
| 2x20 µm Surround Cu | Electroplating |
| 2 µm Ag | Sputtering |
| 1~5 µm REBCO HTS<br>~150 nm Buffer Stack | MOCVD<br>IBAD / Sputtering |
| 50~100 mm substrate | Electro-polishing |

The substrate serves to provide the mechanical backbone of the conductor and for growing the subsequent layers. The nickel alloy substrate (typically Hastelloy® C276) is typically either 50 or 100 microns thick. Multiple conductor configurations are available using this process, although the most common standard SuperPower® 2G HTS production wire is called SCS4050 consisting of a 50 micron substrate, ~0.2 micron buffer stack, ~1 micron REBCO layer, ~ 2 microns of Ag with 40 microns total thickness of surround copper stabilizer.

### *B. Current-Carrying Capabilities of 2G HTS Wire*

The applicability of a superconducting wire for magnet use is mainly driven by the electrical current density, which is characterized by the engineering critical current density as a function of the operating temperature and the magnetic field seen by the windings, $J_e(B, T)$. The high current density of Superpower's 2G HTS wire results in high $J_e$ values compared to other available wires. For example, for a 4 mm wide wire with a 50 micron substrate and 40 micron total thickness of copper stabilizer, the conductor engineering current density $J_{e\text{-}cond}$ is ~266 $A/mm^2$ at 100 A of operating current. In a coil configuration with a 65% conductor packing factor, this gives a winding engineering current density $J_{e\text{-}wind}$ of ~ 173 $A/mm^2$ at 100 A of operating current.

The performance of the 2G HTS material in field, including the field orientation with respect to the tape (superconductor), is of critical importance. Fig. 1 is a plot of $I_c$ vs. field orientation for a variety of tapes with varying REBCO compositions. In this plot, standard production tape composition is represented by the green line.

In a coil application, the performance of the coil is typically dominated by the $I_c$ vs. B performance at field angles from 15 to 30 degrees. With the standard composition, the drop off in $I_c$ is significant in this angle range, often approaching the perpendicular (90 degree) $I_c$ value. However, the magnetic fields in this region of the coil are still relatively high when compared to the peak field in the windings. This combination of high relative magnetic field and depressed $I_c$ pinpoints the region of the coil that is first subject to transitioning from the superconducting state. Figure 1 shows the critical current as a function of angle between magnetic field and film surface at 77 K, 1 T for 12 mm wide samples with same film thickness but different film compositions. The green line is representative of current standard production tape with Sm doping. The black and red lines are representative of improved conductors with Gd and/or Zr substitution into the REBCO structure. The critical region for coil performance is given in blue.

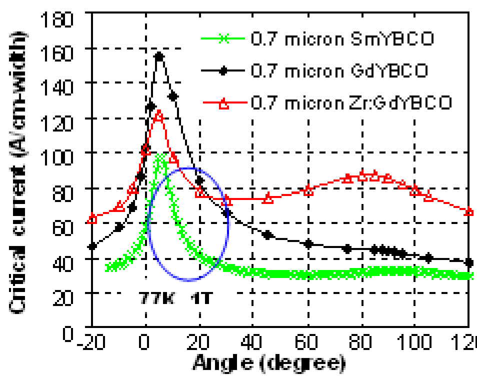


**Figure 1.** *Critical current as a function of angle.*

Recently, improvements have been made in the Ic vs. magnetic field angle performance of the 2G HTS wire through the replacement of Sm with Gd in the REBCO composition, as well as the inclusion of Zr into the REBCO structure. This has resulted in enhanced pinning and improved Ic vs. magnetic field angle performance, particularly in the critical 15-30 degree range where a factor of 2 improvement has been seen. This improved 2G HTS will greatly enhance the future performance of coils built out of this conductor with advanced pinning. Splice joints between segments of 2G HTS wire are routinely fabricated using a simple lap joint technology which has recently been automated. The lowest resistance joints are made with the REBCO sides facing each other using a thin intermediate solder layer. For example, 100 mm solder lap joints between two 4 mm wide SCS4050 wires have typical joint resistances of 30-50 nano-Ω.

### *C. Mechanical Properties of 2G HTS Wire*

The 2G HTS wire fabricated by SuperPower has the inherent advantage of a built-in structural element with its Hastelloy® C276, eliminating the need for added external reinforcement to properly maintain thermal and magnetic stresses the coil experiences keeping the current density high. Recent axial stress-strain measurements conducted at the Naval Research Laboratory on standard 4 mm wide SCS4050 production wire gave a yield stress for the wire of 970 MPa at 0.92% strain. The high strength of the wire is demonstrated in the $I_c$ vs. stress properties shown in Fig. 2 indicating a stress level of 700 MPa can be sustained in the wire before there is irreversible degradation of the critical current. In addition, axial cyclic loading tests (min/max =0.1) out to 100,000 cycles were conducted for various stress levels.

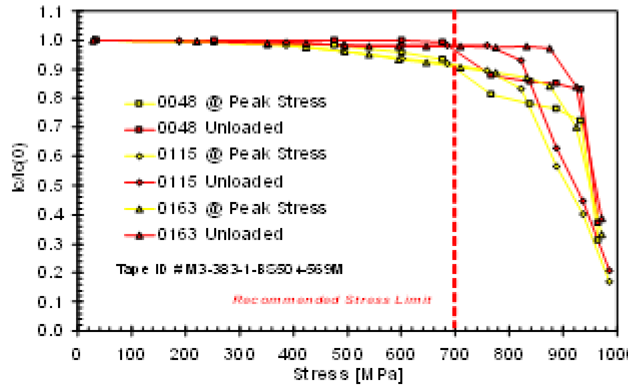


**Figure 2.** *Normalized ($I_c/I_c(0)$) vs. axial stress on 4 mm tape. Stress recommended 700 MPa (data: R Holtz, NRL)*

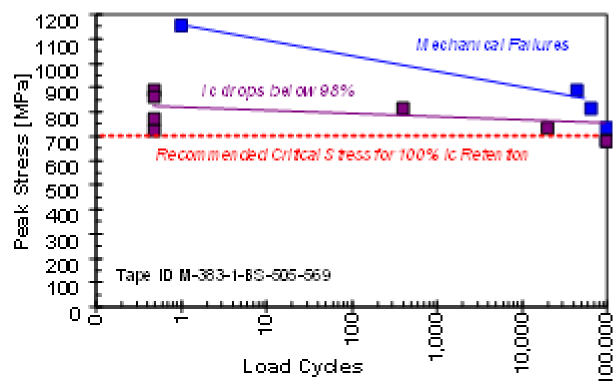


**Figure 3.** *Peak stress vs. load cycles (min/max = 0.1) on 4 mm wire. Below 700 MPa, there is no Ic degradation out to the 100,000 cycle test limit (data from R Holtz, NRL)*

At levels up to the 700 MPa limit, there was no degradation up to the 100,000 cycles tested (Fig. 3). Above the 700 MPa limit there is gradual degradation of the $I_c$ performance until irreversible damage sets in. This shows that for all practical purposes, the 2G HTS wire has fatigue strength comparable to the irreversibility stress limit of the tape. This high strength is essential considering the high stresses that are often encountered in applications such as high field insert coils or high speed rotating machinery. The advantage of this material for high stress applications is clearly seen in Fig. 4 comparing the operating windows for various LTS and HTS conductors. Thermal stresses in the coil structure are developed during the cool down of the coil as well as any thermal transients that may be experienced during fault or quench situations. SuperPower 2G HTS wire has thermal expansion characteristics well suited for inclusion with typical structural materials used in coil construction as shown in Fig. 5.

### *D. Other Considerations for Using 2G HTS Wire*

For most coil applications, long lengths of wire are required to reduce the number of splices in the coil. Continuous piece lengths of up to 1300 m have been fabricated of the 2G HTS material. Piece lengths of several hundred meters typically show very uniform Ic properties and high n-values of ~30.

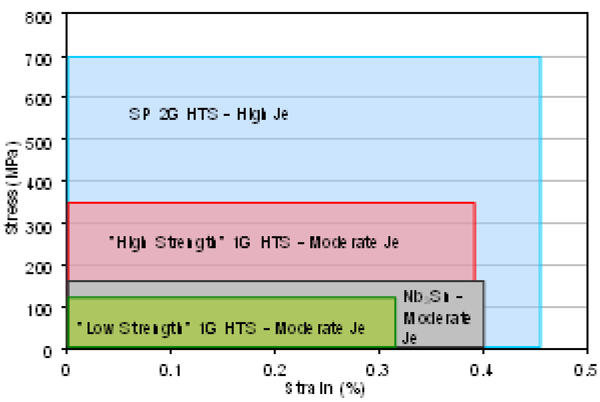


**Figure 4.** *Comparative operating stress-strain windows for LTS and HTS superconductors at 4.2 K.*

For applications operating in an AC environment, low AC loss conductor will be required. Multifilament tapes with channels cut along the length are fabricated to reduce AC loss with discrete filaments. With these types of structures, the 2G HTS tapes see an AC loss reduction on the order of 5 times or more in the 50–100 Hz range. The eddy current loss in the tape is minimized since the Hastelloy® C276 has very high resistivity of 125 μΩ /cm.

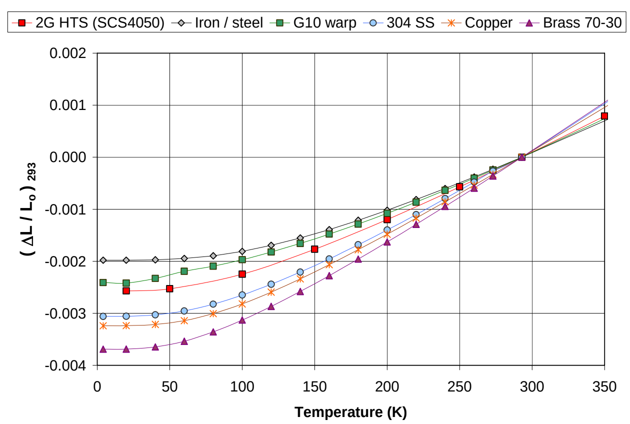


**Figure 5.** *Thermal expansion of (SCS4050) SuperPower 2G HTS wire compared with common magnet materials.*

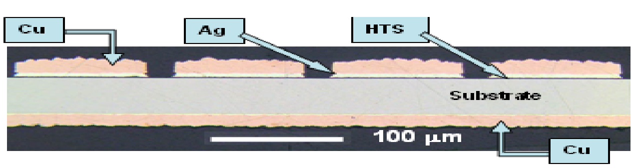


**Figure 6.** *Cross-section of SuperPower multifilament tape of 100 µm wide filaments and 20 µm wide channels.*

## III. HIGH FIELD 2G HTSMAGNET

Using ~460 m of standard production 4 mm wide SCS4050 wire, we constructed a pancake wound solenoid coil for test as a high field insert coil. The REBCO HTS layer was 1 micron thick and the critical current of the wire used in the coil ranged from 70A to 90A at 77K and self field. The coil was dry wound (without epoxy) using co-wound Kapton® polyimide insulation. The coil used a double pancake construction with copper or silver jumper connections between the individual pancake layers. Some basic construction parameters for the magnet are listed in Table 2. A photo of the magnet is displayed in Fig. 7.

**Table 2.** Construction parameters of 2G insert coil.

| Parameter | Value |
|---|---|
| Coil ID | 9.5 mm (clear) |
| Winding ID | 19.1 mm |
| Winding OD | ~87 mm w/ over-banding |
| Coil Height | 51.6 mm |
| Number of Pancakes | 12 (6x double) |
| 2G Wire Used | 462 m total |
| Number of turns | 2772 |
| Coil Winding Je | 1.569 A/mm$^2$ per A |
| Coil Constant | 44.4 mT / A |

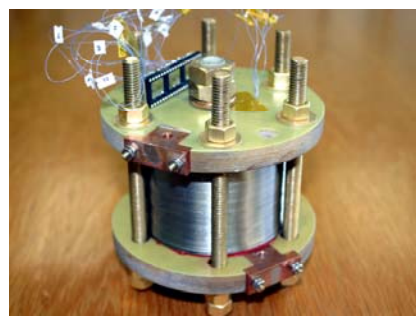

**Figure 7.** *High field insert coil fabricated at SuperPower with standard SCS4050 2G HTS wire. At 4.2K, the coil generated a self field of 9.8T and a center field of 26.8T*

At 77K, the coil generated a 0.733 T central field operating at a critical current of 16.5 A and voltage of 1.0 µV/cm. The magnet was subsequently tested at the National High Magnetic Field Laboratory (NHMFL) at Florida State University in their unique 20 cm wide bore, 20 MW, 20 T Bitter test magnet. At 4.2K, the coil generated a 9.81 Tesla self field operating at a critical current of 221 A. With an axial background field of 19T, the coil generated an additional 7.8 T for total central fields of 26.8 T. Operating parameters of the coil are given in Table 3. Peak operating stress within the coil is estimated to be ~215 MPa, well within the strength limitations of the SuperPower standard 2G HTS wire. when placed in a 19 T axial background field. Flange diameter is 127 mm.

**Table 3.** Operating parameters of the 2G insert coil.

| Parameters at 4.2 K | Value |
|---|---|
| Coil $I_c$ | 221 A |
| Amp-turns @ Coil $I_c$ | 612,612A-turn |
| Coil Winding Je | 346.7 A/mm$^2$ |
| Peak Radial Field | 3.2 T |
| Peak Central Field | 9.81 T |
| Coil $I_c$ (19T axial background) | 175 A |
| CoiAmp-turns (19T axial background) | 485,100 |
| Coil Je(19T axial background) | 274.6 A/mm$^2$ |
| Peak Radial (19T axial background) | 2.7 T |
| Peak Central (19T axial background) | 26.8 T |

## IV. PULSED POWER TEST SETUP

The schematic diagram of the test circuit for a series of fault current tests is shown in Fig. 8. The pulsed power tests were performed by producing a short circuit faulted current between the terminals of the load for a short duration of time (typically 5 periodic sinusoidal pulses or cycles with a repetition period of 60Hz). Therefore, fault current limiting modules were constructed with a set of 12 mm wide 2G HTS tapes in parallel with a copper wound shunt coil. Shunt has X/R ratio 30.

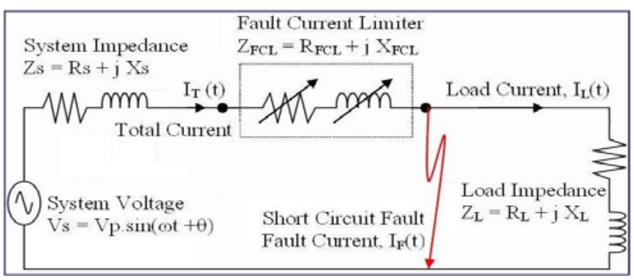


**Figure 8.** *Schematic of power system representation.*

The current leads, HTS material and shunt coils are immersed in liquid nitrogen ($LN_2$) during the test. The short circuit faults were generated and controlled by a bipolar thyristor switch. Larger setups were tested at an outside high-power test facility with faults up to 37-40kA asymmetric peak and loads up to 1700A of peak current.

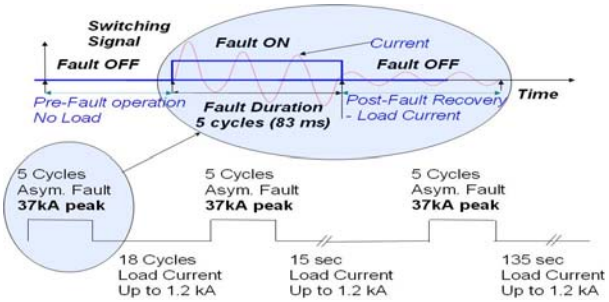


**Figure 9.** *AEP reclosure sequence for the first (3) faults.*

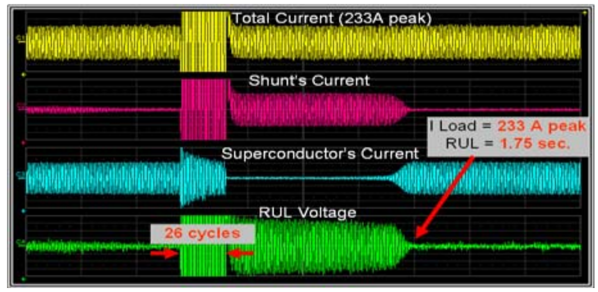


**Figure 10.** *26 cycles of 7kA recover 230A in 1.75 sec.*

The faults and loads were applied following an American Electric Power (AEP) reclosing sequence shown in Fig. 9. The HTS material is able to recover after a fault while the load current is still flowing through the circuit. This recovery process is what we call recovery under load (RUL). Due to the proximity in time between the three first faults of the AEP reclosing sequence and the short time between them for the SFCL to recover from each fault, the worse case scenario for RUL is found between the second and the third faults of Fig 10. In addition to the AEP sequence, a stuck breaker scenario may last an additional 11 cycles after any of the individual 5 cycle faults. In order to test our device under the worst case conditions, the duration of the faults varied from 5 to 26 cycles. Therefore, for this application, a total number of 26 cycles was tested as shown in Fig.9, corresponding to the three first 5 cycle faults of the AEP sequence, together with the 11 cycles of fault of stuck breaker. After applying a fault of 7kA for 26 continuous cycles the recovery of the superconductor under a load current of 230A peak takes about 1.75 sec to come back to the initial superconducting stage, which is where the voltage waveform in Fig. 10 returns back to zero. If no load is applied after the fault, the recovery of the superconductor is faster.

## V. PULSED POWER TEST SETUP

Two prototypes were tested at an outside high-power test facility with faults up to 37-40kA asymmetric peak and loads up to 1700A peak current. The range of temperatures changes from -196C to more than 400C corresponding to superconducting stage and normal resistive stage respectively. At the left of Fig. 11 is shown the test module we used. At the right of Fig. 11 is illustrated the magnetic field distribution of a matrix setup composed of multiple 8 tape modules. At the top left corner, an 8 tape module was highlighted with a circle. All the tests and results shown were taken in open bath, which is not the ideal case scenario for heat transfer under $LN_2$. Fig. 12 illustrates the current flowing through the shunt coil, indicating that 90% of the total power was already flowing though the superconductors as can be observed between the second and third faults of this sequence. However, with optimal bath conditions, the recovery time will decrease while increasing the RUL performance in 20-30%, with full 100% recovery expected.

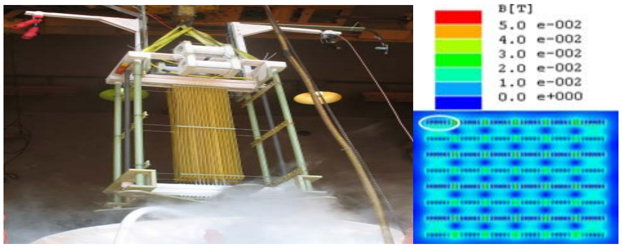


**Figure 11.** *At the left, the test module during testing at the outside power test facility. At the right, magnetic field of a matrix composed of 48 x 8 modules.*

Once we obtained all the RUL operating points, we defined different mapping surfaces where RUL is achievable versus the variables driving its performance. At the left of Fig. 13 is shown the maximum recovered current versus impedance, voltage and groups of different number of tapes. At the right is shown the maximum recovered current per tape, impedance, and voltage for each group. The current recovered per tape is constant for all groups.

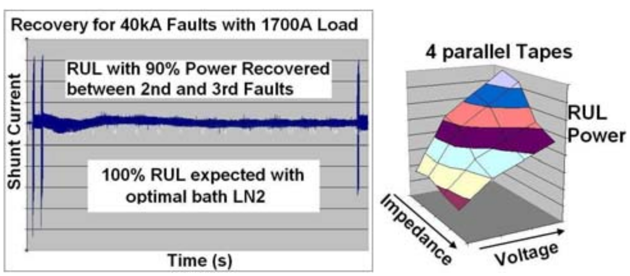


**Figure 12.** *Left, RUL of 40kA faults, 1700A load. Right, recovered power vs. voltage and impedance.*

This mapping provides us the ability to predict RUL over a wide design space. Therefore, we can design any system to follow a determined impedance dynamic change for a wide range of load current/voltage at any specific times.

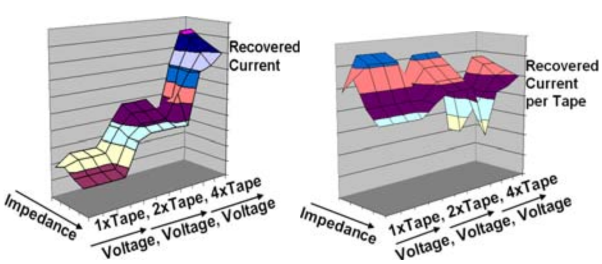


**Figure 13.** *Left, maximum recovered current per group of tapes, impedance and voltage. Right, maximum recovered current per tape, impedance and voltage.*

As shown in the tests, the intrinsic quenching characteristics of the superconductors allows to dynamically change the impedance of the circuit by controlling one or more of its critical parameters, such us the critical current, critical temperature or magnetic field applied to it. These intrinsic characteristics are useful for circuits with stages requiring impedance matching or very steep rise in current and/or voltage typically found in most of the pulsed power applications. The quenching dynamics shown in the previous tests were used for a device able to follow a voltage transition from superconducting stage with a voltage drop in the order of milliVolts to 138kV within a time interval of few milliseconds while driving a current of 40kA peak. This performance was achieved without the destruction of the superconductor with recovery times as short as few milliseconds when no load is applied afterwards or few seconds with load currents allowing in this manner repetition rates from 100s Hz to several kHz.

## VI. SUMMARY

2G HTS wires with high engineering critical current density have been developed and manufactured in long lengths. In field performance of the 2G HTS wires has been remarkably improved through REBCO composition adjustment, high-$T_c$ rare-earth element substitution, Zr-doping and growth condition optimization. A coil wound of 2G HTS wire generated 26.8 Tesla magnetic field. We have not reached the limit of 2G HTS capacity. 30 Tesla and beyond is, we believe, within our grasp using the recently improved 2G HTS wires. The performance obtained at the high powered test facilities satisfies AEP's requirements for 37 kA peak limiting the fault from 40-75% while recovering to the initial superconducting stage. Further optimization on the bath conditions and 2G HTS conductor structure such as stabilizer and substrate, and assembly structure will yield better performance. Recovery under load can be also optimized by using higher Ic superconductors able to recover higher load currents. This provides the ability to use less superconducting material, reducing the overall volume of the device, cryogenics and overall conduction losses. Currently 2G superconductors are available in lengths up to 1000 meters, reducing the number of connections in the devices, as well the resistive losses associated with them.

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