# Testing of TAMU1 Dipole

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*Abstract.* The NbTi model dipole TAMU1 was successfully tested at Lawrence Berkeley Lab. The dipole reached 84% of short-sample current on the first quench, and trained rapidly to 96%. Notwithstanding a variety of component failures during fabrication and assembly, the dipole still had sufficient provisions for monitoring and quench firing to permit a fairly extensive study of its performance. The quench heaters were capable of inducing quench in <10 msec. The splice resistance was measured to be 0.28 nΩ, consistent with excellent splice contact. AC loss properties were studied during ramp studies. Ramps to 1,000 A/s were sustained. The dipole is a success.

The superconducting magnet TAMU1 is a NbTi block-coil dipole, designed and built at Texas A&M University.[1]. The magnet was built as a learning model, to evaluate construction techniques and materials that will be necessary for subsequent high-field $Nb_3Sn$ dipoles. The coil was fabricated using the insulation materials (S-glass cloth, mica paper), vacuum impregnation, and provisions for stress management that are being developed for use in a 12 Tesla $Nb_3Sn$ dipole[2].

Figure 1 shows the cross-section of the dipole and its flux return. Its principal parameters are given in Table 1. The coil is asymmetric, built in the geometry that would be needed for a flux-coupled dual-bore dipole. The superconducting cable is SSC inner cable, having the properties given in

Table 2.

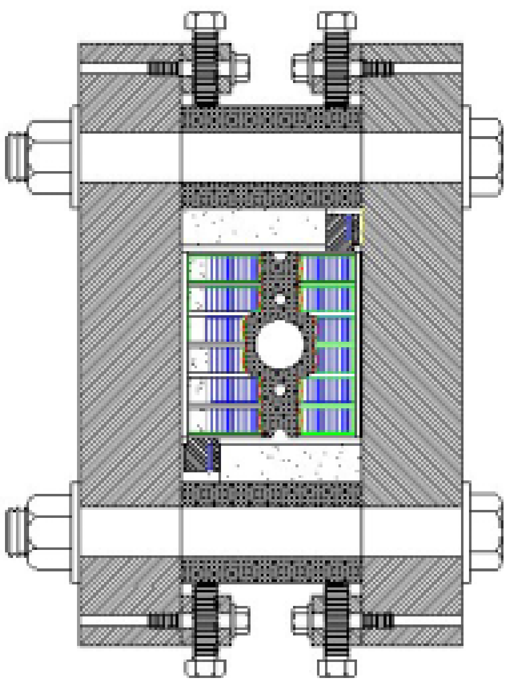


**Figure 1. TAMU1 dipole cross-section.**

**Figure 2. Completed TAMU1 dipole and group that built it.**

**Table 1. Main parameters of the TAMU1 dipole.**

| | | |
|---|---|---|
| Maximum field | 6.88 | Tesla |
| Maximum current | 8.55 | kA |
| Inductance | 3.5 | mH |
| Stored energy | 70 | kJ |
| Overall length | 110 | cm |
| Body length | 50 | cm |
| Beam tube diameter | 2.5 | cm |

**Table 2. Properties of SSC inner cable used in the coil.**

| | | |
|---|---|---|
| Strand diameter | 0.8 | mm |
| $j_{sc}$ @ 4.2 K, 5 T | 2,846 | A/mm$^2$ |
| Cu/SC ratio | 1.3 | |
| # strands | 30 | |
| Cable width | 12.39 | mm |
| Cable thickness | 1.37 | mm |

**Table 3. Properties of the windings.**

| winding | Maximum field @ 8.8 T<br>T | # turns | Self-inductance<br>mH | Total mutual inductance<br>mH |
|---|---|---|---|---|
| 1,2 | 6.48 | 10 | .36 | .27 |
| 3,4 | 7.68 | 15 | .53 | .37 |
| 5,6 | 7.14 | 15 | .62 | .32 |

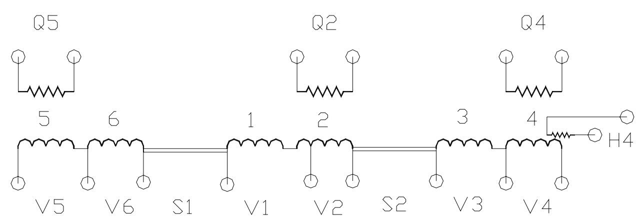



**Figure 3. Schematic showing voltage taps (V), splices (S), quench heaters (Q), and spot heater (S).**

The coil is wound in three double-windings (1,2; 3,4: 5,6 in Figure 3). summarizes the properties of each winding. Each double-winding is wound two-in-hand with an S-transition at the inner boundary. Successive double-windings are connected by a splice ($S_i$). The windings were instrumented with voltage taps $V_i$, quench heaters $Q_i$, and spot heaters $H_i$. Although all windings were instrumented when the dipole was built, a number of the taps and heaters were damaged in impregnation and preloading so that they were either shorted to ground, open, or internally shorted. The surviving elements were located as indicated in Figure 3, and provided an adequate basis to protect the magnet (with $Q_2$, $Q_4$, and $Q_5$ we were able to force quench in each double-winding), monitor the voltage across each winding, and launch a local quench (spot heater $H_4$ one turn in from the outside of winding 4).

The coil was preloaded within its flux return by a pattern of large bolts visible in Figure 2. Unfortunately the coil attained a horizontal bow of ~2 mm during vacuum impregnation. In order to provide uniform contact along the sides of the coil within the flux return, it was necessary to apply a “smart shim” of S-glass-reinforced epoxy. As a consequence it was not possible to close the rib/plate structure that was designed to provide stress management, so that the preload of the flux return is delivered directly to the coil. Several intermittent shorts from coil to case were encountered as we delivered preload. We were able to preload to 50 tons, ~30% of the maximum calculated Lorentz stress, without introducing any shorts. We elected to adopt this as a working preload. As the coil is excited to full field, the Lorentz load will exceed the preload and the retaining bolts will stretch according to their elastic modulus – the total bolt strain is calculated to be ~200 μm. The resulting coil motion could produce quenches at high field.

In preparation for testing, the resistances of all windings were measured to check for turn-to-turn shorts. An imbalance equivalent to two turns was observed between $V_1$ and $V_2$, which was due to the placement of the voltage tap one turn in from the S-transition between coils 1 and 2.

***A turn-to-turn short is discovered and removed.***

The dipole was cooled to 4.5 K, and all windings were checked for turn-to-turn shorts by driving a triangular current waveform through the coil. The rate-of-rise was twice the rate-of-fall, so that the inductance of each winding could be checked independently at two frequencies. Figure 4 shows the voltage response. The voltages across coils 1 and 2 were observed to be mismatched by a ratio ~1.7, much more than the resistive mismatch ratio of 1.22 from the location of the voltage tap, indicating that there was a turn-to-turn short.

The short presumably had high enough resistance that it did not perturb the resistance check at room temperature, but provided a parallel current path in AC response. Such a short could pose a serious hazard in a quench from high-current operation. We decided to attempt to remove it by exercising the coil on a continuous sawtooth ramp to 300 A peak current, and increasing the ramp rate in a succession of steps until the coil quenched from AC heating. The rationale was that a substantial but limited energy would be dumped through the short in an impulse during quench. It was hoped that the impulse would be sufficient to burn out the short without damaging the coil.

Figure 5 shows the temperatures measured at the locations $T_1$, $T_7$, and $T_8$ indicated in Figure 3. The Each succeeding plateau region corresponds to a continuous ramp to 300 A, at a succession of increasing ramp rates: 50 A/s, 100 A/s, 200 A/s, 300 A/s, 400 A/s, 500 A/s, and finally 600 A/s. At 600 A/s, the coil temperature reached the critical temperature $T_c$ = 9.3 K, and the coil quenched. After recovery, the coil *did not quench* during a repeated 600 A/s ramp sequence, but did with a 700 A/s ramp sequence. Something in the coil had changed to produce this change in behavior.

We then measured the voltages across the windings during a ramp to 300 A with 400 A/s up and 200 A/s down. Figure 6 shows the response. All windings exhibited inductances that were consistent with their calculated inductances $L_i$, indicating that the short had been successfully removed.

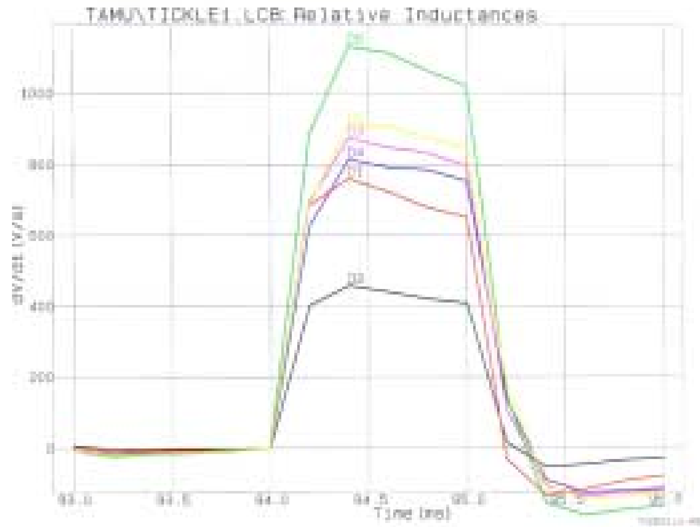



**Figure 4. Voltage response to triangular current ramp (20 A max).**

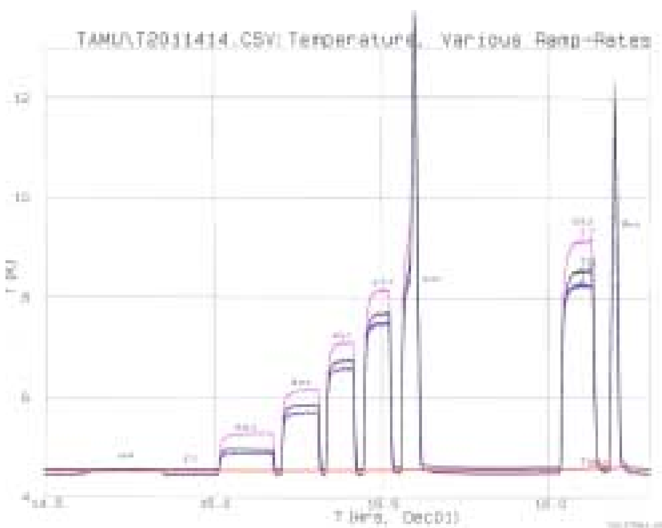



**Figure 5. Temperature response in coil during current ramp sequence.**

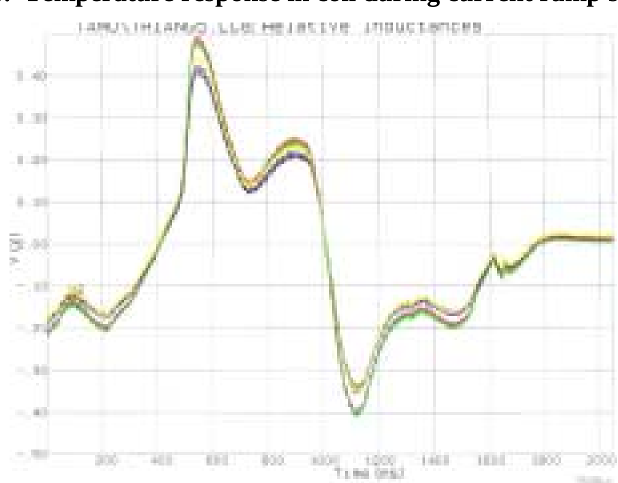


**Figure 6. Voltage response to current ramp after ramp processing.**

### *Evaluation of quench heater operation*

We next increased coil current to 2,000 A, and fired current pulses to the three quench heaters $Q_i$, in order to evaluate their effectiveness in initiating quench in the coils that they contacted. Each heater has a room-temperature resistance of ~1.5 Ω, and is situated to face the edge surfaces of all turns of a winding in the end region, as shown in Figure 7. Although two heaters were installed on each of the six windings, only three were operational by the time of testing. Fortunately the three operational heaters were on windings 2, 4, and 5, so that we were able to fire quench in at least one coil of each double-winding.

At 2,000 A coil current we fired all three heaters, each with a current pulse of ~50 A for ~30 ms, corresponding to an adiabatic temperature of ~200 K. The voltage response across each coil is shown in Figure 8. On the voltage plot, a positive voltage corresponds to a resistive voltage, while a negative voltage corresponds to an inductive response as the coil current decreases. The three windings with heaters were successfully quenched, while the other three windings remained unquenched for ~100 ms and then quenched. We thus validated that the quench heaters worked successfully.

**Figure 7. Quench heater: a) foil heater; b) heater installed with S-glass insulation to coil and mica paper insulation to rib.**

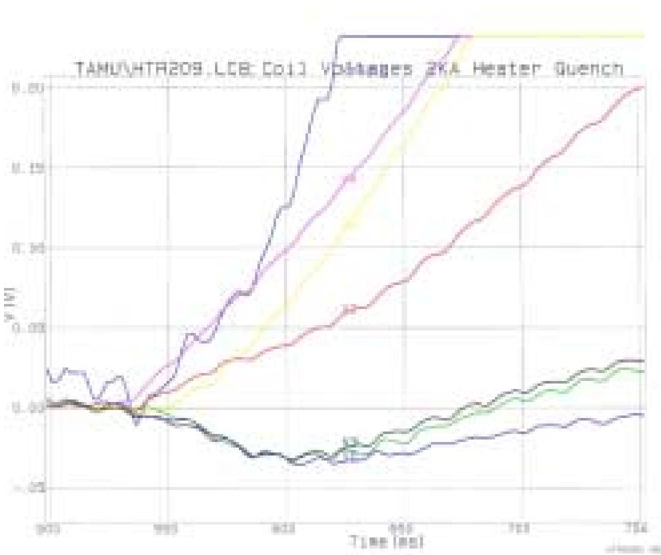



**Figure 8. Voltage response following firing of quench heaters (2,000 A coil current).**

***Protection strategy during high-current testing.***

The magnet was protected by three provisions:

- When a voltage pulse was detected across the voltage taps of any coil, signaling a quench, the power supply was immediately phased back so that no further energy was delivered to the magnet;
- After a delay of 50 ms, the three quench heaters were fired to initiate quench in all three double-windings;
- After a delay of 150 ms, energy was extracted externally by firing a circuit that inserted an external resistor in the coil circuit.

Figure 9 shows the timing of the quench heater firings and energy extraction after detection of a quench. The delays were introduced to enable us to identify which coil quenched and to observe the initial development of quench in that and other coils. $Q_4$ was fired ~10 ms later than $Q_2$ and $Q_5$, as indicated in Figure 9

***High-current testing of the dipole.***

We then increased the coil current to measure the maximum field that could be achieved. The current was ramped at 10 A/s. The first quench occurred at a current of 7,200 A, 84% of short-sample current $j_c$ = 8,550 A. Figure 10 shows the training history during a sequence of 9 quenches. The dipole attained a reproducible quench current of ~8,020 A, 94% of short-sample.

Some of the features of the quench behavior of the TAMU1 dipole are illustrated in Figure 11. Quench 2 appears to have been initiated by a major mechanical motion (the huge spike in all traces). Windings 5 and 6 quenched simultaneously. The other windings remained superconducting until the quench heaters were fired.

In Quench 6 also, a mechanical motion excited all windings, and after a delay of ~3 ms winding 3 quenched. Winding 4 then quenched after a delay of ~28 ms, and then the quench heaters initiated quench in windings 2 and 5

In Quench 8, winding 6 quenched first after a fast transient. In the progression of the quench in winding 6, one can see a particularly clear progression of the quench by jump step from turn to turn. The successive voltage spikes occur when the heat from the quenched region on one turn is conducted through the turn-to-turn insulation sufficiently to quench the same region on its neighboring turns. The jump-step time is ~4 ms.

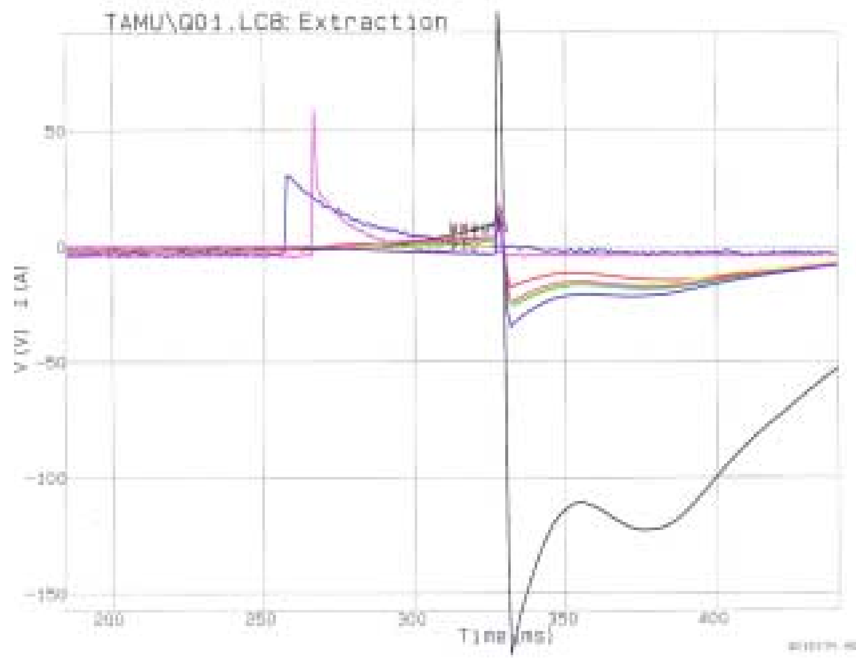



**Figure 9. Timing of quench heater firings and energy extraction following detection of a quench.**

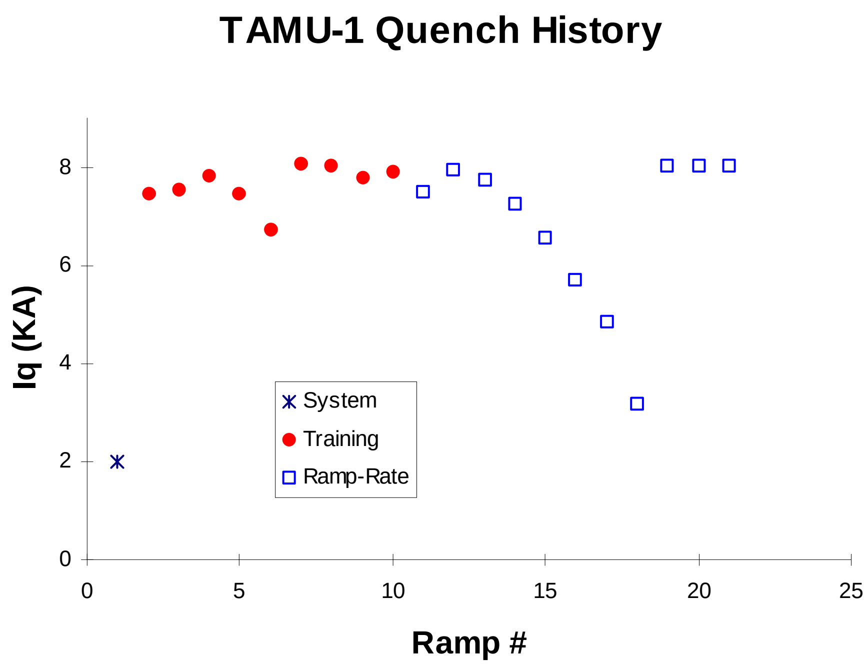
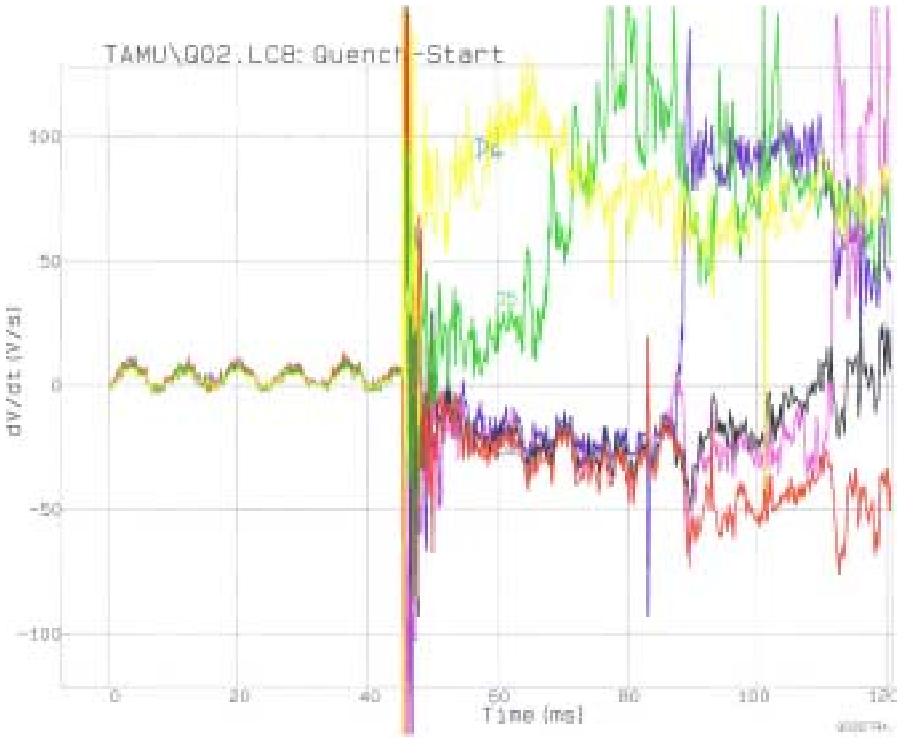
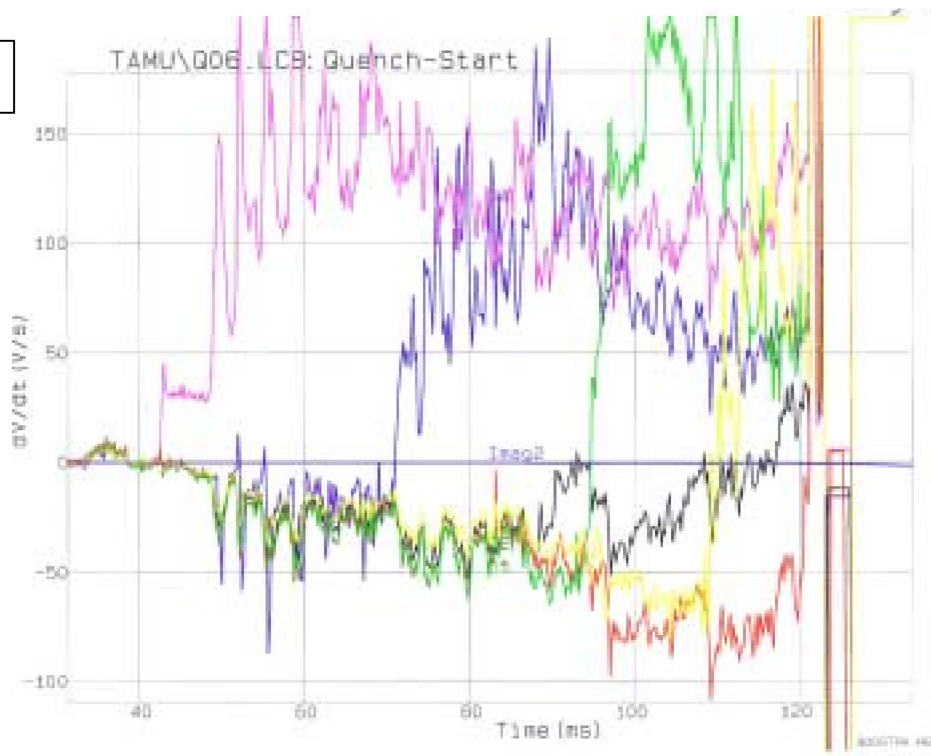



**Figure 10. Training history of TAMU1.**

Quench 2




Quench 6



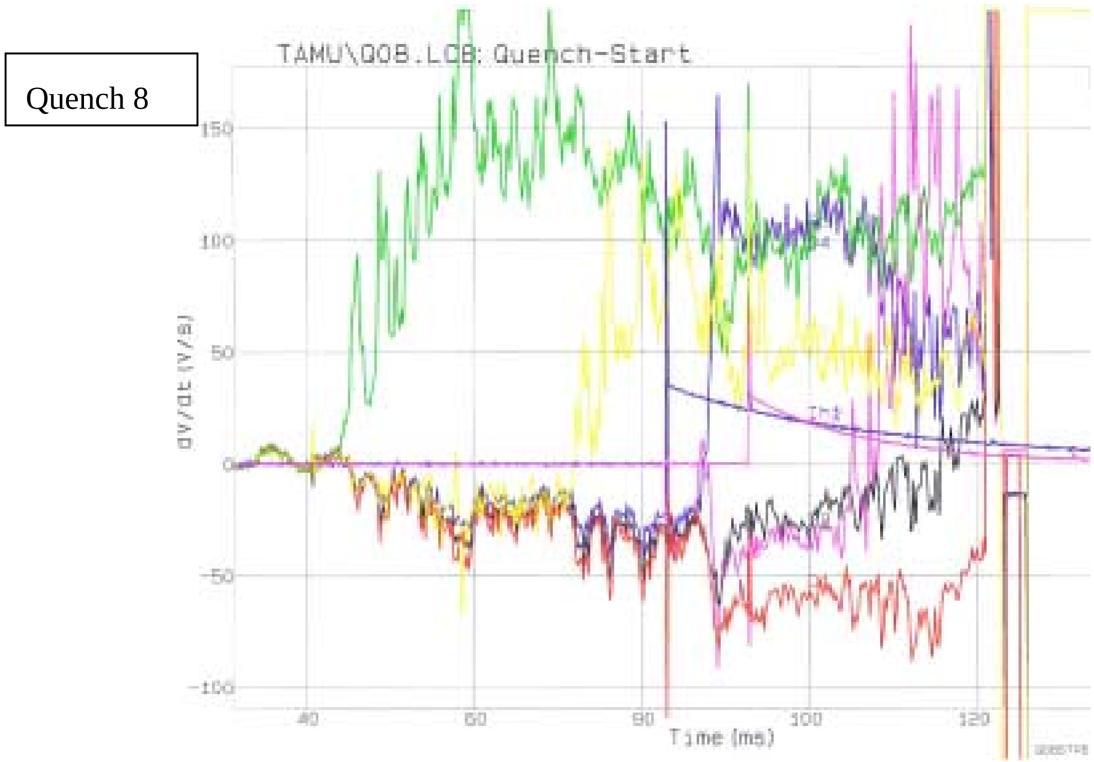



**Figure 11. Voltage response during quench, for three quenches: a) quench 2 @ 7,650 A; b) quench 6 @ 8,050 A; quench 8 @ 8,020 A.**

***Measurement of splice resistance.***

We measured the voltage across the splice joints at a succession of coil currents, in order to determine the splice resistance. The data on splice S1 is shown in Figure 12. For splice S2, the common-mode noise on the voltage taps was too great to make reliable measurements.

On splice S1, there was a thermal gradient offset of ~-1 µV. The measurements were however reproducible and enable an accurate measurement of the slope: R = 0.28 nΩ.

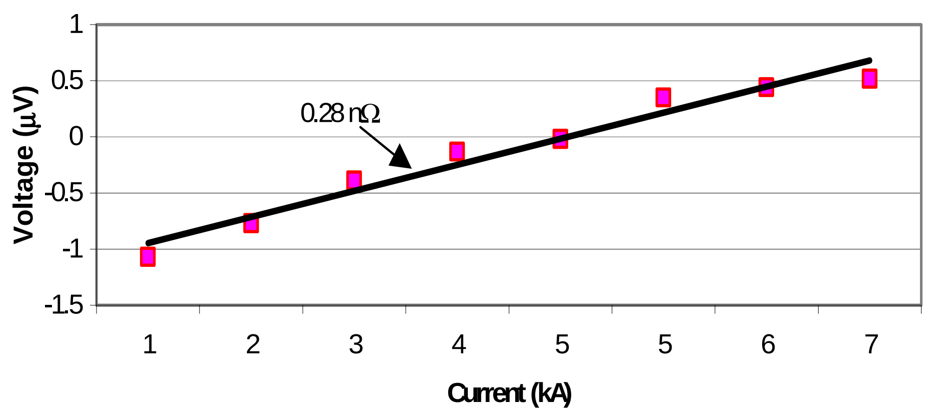



**Figure 12. Measurement of splice resistance for splice S1.**

***Ramp rate studies.***

We studied AC losses by measuring the quench current as a function of ramp rate. The results are presented in Figure 13. Quench current fell to 50% at a ramp rate of ~1,500 A/s.

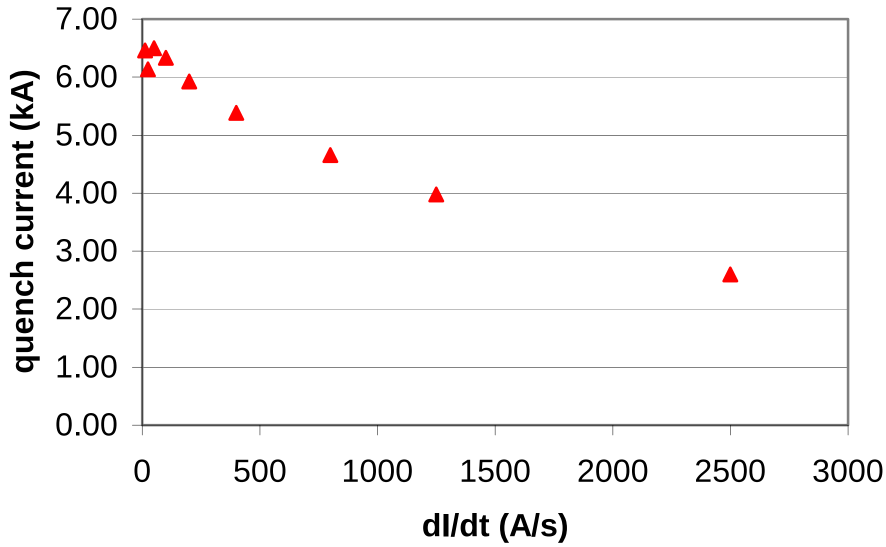



**Figure 13. Dependence of quench current on ramp rate.**

***Spot heater studies.***

We pulsed the spot heater $H_4$ on winding 4, in order to evaluate its operation in initiating a local quench. We excited it with a current pulse of 2 A for 10 ms. This pulse, limited by lead resistance, was adequate, but only barely so, to fire a quench. We will need to re-design the spot heaters for our next dipole.

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[1] Blackburn *et al.*, 12 Tesla hybrid block-coil dipole for future hadron colliders, Proc. Applied Superconductivity Conf., Virginia Beach, VA Sept. 17-22, 2000.

[2] C. Battle *et al.*, Optimized block-coil dipoles for future hadron colliders, Proc. Int'l. Conf. on Magnet Technology, Jacksonville, FL, Sept. 26-30, 1999.