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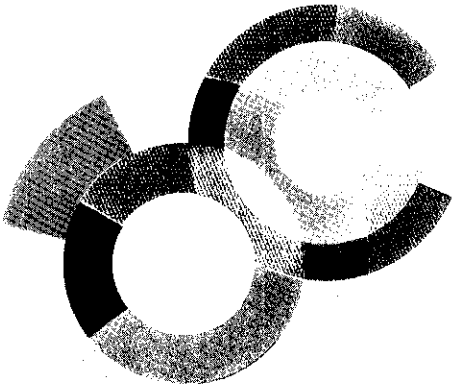

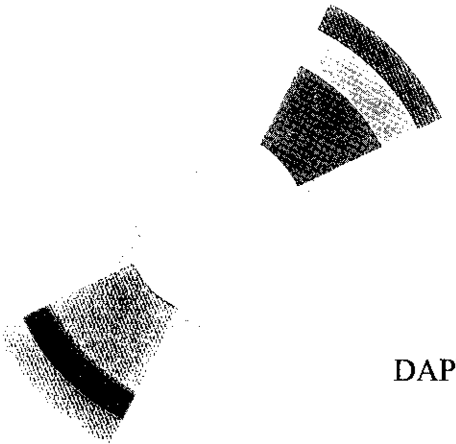

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Stability and Quench Propagation Velocities Measurements on the 'Racetrack' Mock-up of ATLAS Toroid Coil

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Abstract --**A mock-up of ATLAS toroid coil, which is one of the 3 detectors presently under construction for the future Large Hadron Collider at CERN, had been tested at Saclay. Various experiments have been led to check the validity of important technical options for the magnet. This paper focuses on thermal stability and quench propagation velocities measurements. For a 70×7 mm^2 aluminum-stabilized conductor carrying a 20 kA current, a 4-5 joule minimum quench energy and a 20 m/s longitudinal quench propagation velocity were found. We also studied the dependence of those features according to the operating current in the 5-20kA range.**

I. INTRODUCTION

The ATLAS Barrel Toroid (cf. ref. [1]) is composed of 8 racetrack shape coils of overall dimensions 25.1 m × 5.2 m. The so-called 'Racetrack' coil is a mock-up of one of these coils. Its overall dimensions are 2.7m × 0.7 m. The cold mass is composed of two racetrack-shaped double pancakes glued inside an aluminum alloy casing (cf. fig 1). It is indirectly cooled by circulation of saturated liquid helium (T=4.4 K) in 10 tubes glued on the casing.

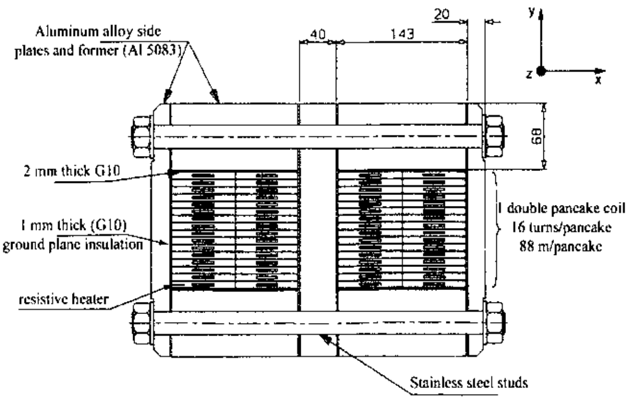

Fig. 1. Racetrack cross-section

The magnetic field generated by the nominal 20 kA operating current is a good approximation of the one expected in the Barrel toroid and so, the forces, the enthalpy and the stability margins are a representative model of the final toroid environment.

This paper focuses on the stability margins with regard to the thermal disturbances and on the longitudinal and transversal quench propagation velocities, which are features of great importance in the final coil protection design.

TABLE I. RACETRACK MAIN CHARACTERISTICS

Sc Cable type	Rutherford	Operating Current	20000 A
Strand No	32	Peak field	4.1 T
Cu/Sc ratio	1.35	Turns/layer No	16
Strand diameter	1.3 mm	Inter layer insul.	0.5mm
Stabilizer	Aluminum	Ground plane insul.	1.0 mm
Aluminum area	446 mm^2	Cooling mode	Indirect
RRR @ 4.1 T	572	2-ph. helium temp.	4.4 K
Bare conductor	70 × 7 mm^2	Auto inductance	6.08 mH
Cond. Insulation	0.25 mm	Stored energy	1.22 MJ

II. STABILITY MARGINS

In order to measure the stability of the magnet against thermal perturbations, a 304L stainless steel heater was embedded in a 0.5-mm-width slot machined in one of the conductors. The resistance of the heater is 70 mΩ, it is supplied with a programmable DC source. It can provide square heat pulses over a length of 10 cm during a time varying from 5 to 500 ms. A special care had been taken to assure a good thermal coupling with the conductor: the measured thickness of the glass-fiber reinforced epoxy resin insulation between the heater and the conductor is only 50 µm leading to a thermal diffusion characteristic time of few milliseconds.

The heater is placed in the inner conductor at the edge of a straight part of the racetrack. At that location, the average field on the superconductor is 2.9 T, the peak field 3.4 T, corresponding to respectively 8.1 and 7.9 K critical temperatures and 7.0 and 6.7 K current sharing temperatures. That field is nearly constant all along the straight part.

The operating mode is the following: for a chosen pulse duration, the current intensity injected in the heater is

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increased step by step until the magnet quenches, the quench energy is therefore comprised between that experimental quench energy and the highest pulse energy which does not lead to a quench. Two sets of measurements were made: the dependence versus the pulse duration at 20 kA nominal current and the dependence versus the magnet operating current for a fixed pulse duration.

A. *Quench energy versus pulse duration at 20 kA*

The results are shown on Fig. 2 and table II.

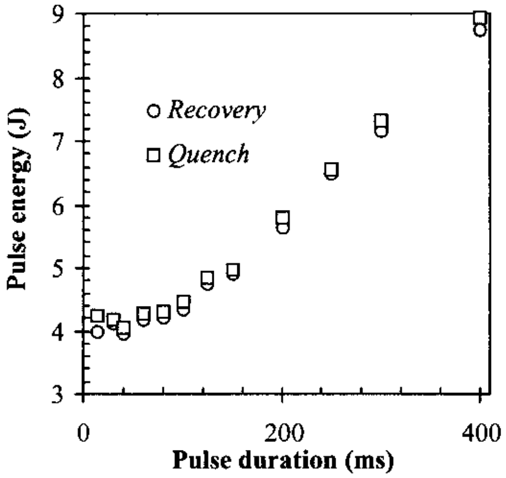

Fig. 2 Quench and recovery energies versus pulse duration.
I = 20 kA

TABLE II. Fig.2 Values

t_p (ms)	15	30	40	60	80	100	125	150	200	250	300	400
E_r (J)	3.98	4.11	3.96	4.16	4.21	4.35	4.76	4.92	5.63	6.49	7.16	8.74
E_q(J)	4.23	4.17	4.05	4.26	4.30	4.45	4.84	4.96	5.79	6.56	7.32	8.93

E_r : highest measured pulse energy leading to recovery
E_q : lowest measured pulse energy leading to a quench
t_p : heat pulse duration

We can make the following remarks:

1. Up to 50-100 ms, the quench energy is not dependent upon the pulse duration. This duration value is related to the time required to form the Minimum Propagating Zone ('MPZ', cf. [2] and [3]). The coil tension evolution enables to evaluate that characteristic formation time, it has been valued at about 50-100 ms. As expected, the measured quench energy is essentially independent of the input pulse duration as long as the duration is lower than that characteristic time. It is important to note that the flat part of the curve cannot be due to the thermal coupling with the heater.
2. The measurements show that the MPZ is limited to one conductor. It is the longitudinal heat diffusion in the pure aluminum to the cold ends of the magnet which allows to recover. Due to current diffusion effect in the aluminum matrix (characteristic time t_d of several seconds), the voltage measurements do not allow do determine the length of the MPZ. Nevertheless, very primary evaluations lead to MPZ of about 0.3-0.5 meter.
3. The minimum quench energy of a magnet can be theoretically found only with a punctual and instantaneous heat pulse. In real life, it is measured with heat pulses whose length and duration are shorter than respectively MPZ extension and formation time. The second condition is fulfilled, we are quite confident that further computations will confirm that the first one is fulfilled too and therefore that **4 joules is the minimum quench energy** of the racetrack coil.
4. At 20 kA normal operating current, the typical 100 ms above mentioned value is significantly lower than the time required for heat to diffuse to the cooling pipes: the phenomena can be considered as adiabatic.

B. *Minimum Quench Energy versus operating current*

The measurements described in that section are made with pulse durations lower than 50 ms to assure that the quench energies which are found are the minimum ones. The results are shown on Fig. 3 and table III.

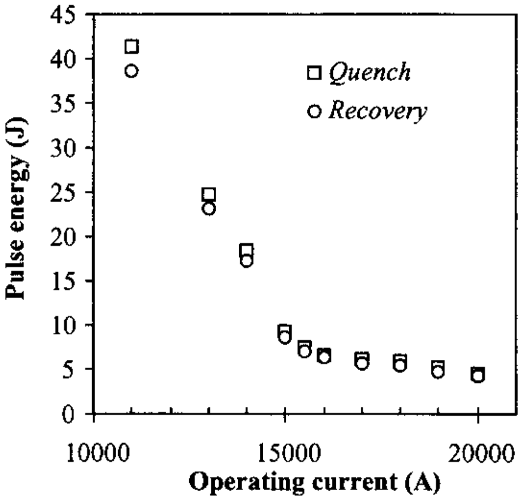

Fig. 3 Quench and recovery energies versus operating current.
Pulse duration < 50 ms

TABLE III. Fig. 3 values.

I (kA)	5	9	11	13	14	15	15.5	16	17	18	19	20
Er (J)	-	83	34.4	22.8	15.9	8.35	6.93	6.15	5.64	5.35	4.75	3.98
Eq(J)	1900	230	38.7	23.2	17.2	8.65	6.98	6.25	5.74	5.44	4.84	4.23

Same notations as TABLE II.

We can make the following remarks:

1. The slope of the curve of the quench energy versus the operating current radically changes for 15-16 kA current values. If the current is higher than 16 kA, the remarks of the previous sections are still valid. As current decreases, the MPZ size and characteristic formation time grow up. When that formation time is large enough compared to the characteristic thermal

diffusion time t_i through the conductor insulation (typically 50 ms), the transverse heat conduction to adjacent conductors or to the coil casing becomes a efficient mechanism to evacuate the power generated by a transition. The curve therefore exhibits two main regions : above 16 kA, the phenomenon is dominated by the longitudinal thermal diffusion, below 15 kA both longitudinal and transverse diffusion play a part, which spectacularly increases the MQE.

2. Below 15 kA, the resistive excursions may last for several seconds before recovery to superconducting state. Consequently, the recovery or quench processes are no more adiabatic and strongly depend on the mass flow rates in the cooling pipes and their implantation.

III. QUENCH PROPAGATION VELOCITIES

A. Measurements

The longitudinal quench propagation velocities are measured on the heated double pancake by means of 5 pick-up coils located on the inner heated conductor and on the inner adjacent conductor, as indicated on fig. 5.

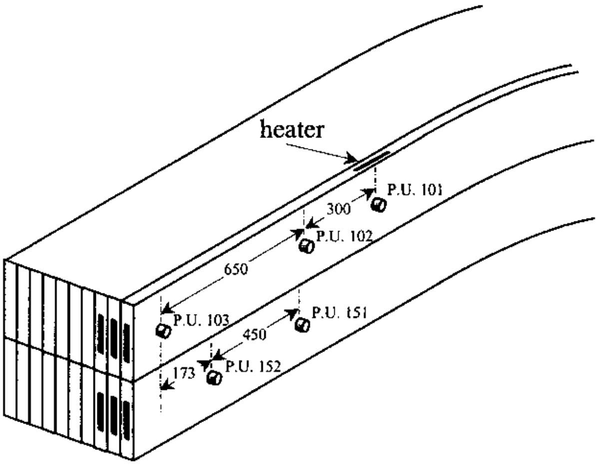

Fig. 5 Pick-up coils implantation scheme

The flux variation in those coils due to the quench propagation leads to very sharp front signal (cf. [6]), which makes it easy to determine the propagation velocity V_z (Oz axis, cf. Fig. 1) along the first heated conductor. It is also possible, but in a less precise way, to calculate V_z in the adjacent conductors.

A given sensor is also sensitive to the successive transitions of the adjacent conductors, which allows to determine the transverse quench propagation V_y (Oy axis) and the time taken t_x by the quench to go through insulation from one single pancake to the other (O_x axis). We study the dependence of V_z, V_y and t_x versus the operating current. The results are summarized in table IV and plotted on Fig.4. The plotted V_z velocity concerns only the first conductor.

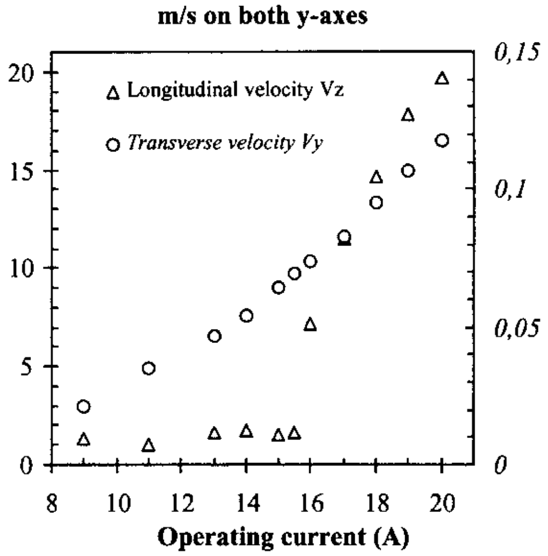

Fig. 4. Quench propagation velocities versus operating current.

TABLE IV. Fig. 4 values

I (kA)	5	9	11	13	14	15	15.5	16	17	18	19	20
V_Z (m/s)	-	1.34	1.02	1.61	1.71	1.49	1.60	7.18	11.5	14.7	17.8	19.6
V_y(cm/s)	0.9	2.2	3.5	4.7	5.4	6.5	7.0	7.4	8.3	9.5	10.7	11.8
t_X (s)	-	-	2.8	1.7	1.4	1.1	0.94	0.71	0.49	0.36	0.28	0.24

B. Longitudinal quench propagation velocity V_Z at 20 kA

At nominal 20 kA operating current, **the longitudinal quench propagation velocity**, which strongly depends on the stabilizer characteristic, **is about 20 m/s.**

This value is notably higher than any computation neglecting the current diffusion effect (typically 5-10 m/s): in the vicinity of the propagation front, the current is not uniformly distributed in the stabilizer, but still concentrated in a small region around the cable, the effective power by unit length generated by the transition is therefore higher than the one computed under the uniform current density assumption. A characteristic time of the propagation process is $t_c \approx D_t/v^2 \approx 5$ ms (D_t : thermal diffusivity of Al. ≈ 2 m^2/s), it represents the order of magnitude of the time required to lead an initially cold point of the magnet to normal resitive state when it is 'reached' by the propagation front. This time is much lower than t_d (§ II-A, remark 3).

It is also lower than t_i (§ II-B, remark 1). This indicates that the adjacent conductors and the coil casing do not participate to the **propagation** process that is therefore **adiabatic** at the 20 kA operating current.

The propagation velocities measured on the adjacent conductors (40-50 m/s) are significantly higher than those measured on the first one because they are preheated by the quench of the other inner conductors.

Longitudinal quench propagation velocities V_Z below 20 kA

As operating current diminishes, the quench propagation velocities decrease for several reasons:

1. The current sharing and critical temperatures increase and as a consequence the enthalpy margin of the materials increases.
2. The time t_c increases and the mean penetration depth of the current in the aluminum stabilizer in the vicinity of the propagation front too. The overheating due to current diffusion effect is thus reduced, this effect adding further of the direct consequence of the current decreasing on the usual Joule effect.
3. As t_c increases, the initially cold surrounding medium (insulation, adjacent conductors, coil casing) takes a more and more important part in the stabilization and so in the slowing of the propagation velocity.

Considering the measurements above 16 kA, we could have believed in an extrapolated recovery current comprised between 15 and 16 kA, corresponding to the current range where the MQE drastically increases as a result of the transverse heat transfer contribution. It is not the case and we can present two explanations for this:

1. It is always possible to quench a finite-size and indirectly-cooled magnet. The cooling system becomes completely inefficient when the liquid helium is evaporated. A heat pulse whose energy is higher than the sum of the total latent heat of the helium contained in the tubes and the enthalpy margin of the magnet between its initial temperature and the critical temperature at zero-field and zero-current, necessarily drives the magnet to normal resistive state.
2. In the current range investigated, the transverse quench propagation velocity is never null (or low enough). As soon as the quench propagates in the adjacent conductors, they do not act any longer as a cold source and prevent the inner conductor from recovery.

Above 15-16 kA, at the location where the measurements are made (determined by the pick-up coils position), the propagation front of the heated conductor is not influenced by the propagation in the first adjacent conductor. Below, $t_c \geq t_i$ and the propagation fronts, the typical size of which ($\approx D_t/v$) grows up as current decreases, interact. We can explain the erratic values of V_z below 15 kA by the fact by the pick-up coils are not located in a zone where the asymptotic propagation regime is achieved.

C. *Transverse quench propagation velocity V_y*

The **transverse quench propagation velocity** is essentially determined by the insulation characteristics. The measured value at 20 kA operating current is **12 cm/s**. In other words, the quench transversally develops to a nearly constant rythm (± 5%) of 1conductor each 64 ms. As that time is lower than the time taken to longitudinally quench a conductor along a complete turn (260 ms for the first one, 100-130 ms for the others), we can say that we really measure a transverse propagation velocity without any significant bias due to longitudinal propagation. With greater reason, this is true as well since current decreases because the ratio V_z/V_y also quickly decreases.

The V_y measurements in the 5-11 kA range 'suggests' an extrapolated recovery current of about 1-2 kA. This value corresponds to the computed maximum current at which the heat generated by the transition of the whole magnet can be evacuated by the cold sources without exceeding the current sharing temperature of the conductors.

IV. CONCLUSION AND PROSPECTS

The stability margins and quench propagation velocities measurements carried out on the Racetrack coil have been mostly understood and the main mechanisms involved have been mostly identified. Both stability margin and propagation velocity dependencies according the operating current show a radical change below 15-16 kA , which has been interpreted as the result of the transverse heat transfer contribution.

Our goal is now to reproduce the achieved results by computation in order to valid our codes and to estimate the stability margins and quench propagation velocities of ATLAS Barrel Toroid, the conductor of which differs from the Racetrack one by the following two important design parameters: the aluminum-stabilizer cross-section and the conductor insulation thickness.

V. ACKNOWLEDGEMENT

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