What is the MCI in terms of helium discharge in case of a beam driven failure of a magnet enclosure?

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Abstract

The superconducting magnets in LHC function either in a pressurized bath of superfluid helium at about 1.3 bar and 1.9 K or in a pool boiling bath of normal helium at about 4.5 K (1.3 bar saturation pressure). The question of the Maximum Credible Incident (MCI) in terms of helium discharge due to a "beam driven" failure of the magnet enclosure does not have a unique answer. Nevertheless order of magnitude discharge rates for various failure conditions are possible to establish. We will discribe the effect of the main determining factors: thermodymic state of the helium, hole size, magnet geometry. The results derived can serve as a basis for further study of specifically defined cases.

ASSUMPTIONS

Layout

The superconducting magnets in LHC function either in a pressurized bath of superfluid helium at about 1.3 bar and 1.9 K or in a pool boiling bath of normal helium at about 4.5 K (1.3 bar saturation pressure). The volume of helium and the number of magnets contained in it vary considerably: from $5600\,\ell$ at 1.9 K for a typical ARC hydraulic cell (4 optical half-cells giving a total lenght of 214 m, containing 4 quadrupoles, 12 main dipoles and several corrector magnets) to $400\,\ell$ at 4.5 K for a stand-alone quadrupole of about 10 m length. We assume an incident can happen anywhere in any of these hydraulic units.

Incident Scenario

We assume that accidentally a hole in the helium enclosure of the magnets is made by the LHC beam. The hole is made almost instantaneously and the beam is dumped immediately. There are two distinct possible locations for the hole: between beam pipe and magnet cold mass or between insulation vacuum and magnet cold-mass (in case the beam gets astray in the magnet end-caps and/or magnet interconnects). The size of the hole depends on the detailed process by which the beam is lost in the magnets. For the purpose of this article we consider the size of the hole to be arbitrary.

Energy

The energy dumped by the beam is assumed to be expended mainly for making the hole, and the energy fraction transferred to the helium considered negligible.

The magnets may quench, either provoked by the beam or by the quench protection system. The effect of the quench energy release to the helium will be to affect the thermodynamic state of the helium being released.

Mass Discharge Estimator

The discharge flow is limited by a process commonly called "choked flow" due to the high ratio of upstream pressure P_u at the magnet cold mass to downsteam pressure P_d, either at the beam pipe vacuum or the insulation vacuum. This phenomenon appears typically for $P_d \lesssim (0.5 - 0.8)P_u$, a condition easily satisfied since it would take a very long time to pressurize either the full sector length of beam pipe vacuum space or the 214 m long ARC hydraulic cell insulation vacuum space. Even in cases where the space into which one discharges is limited in volume this condition will still hold as long as the safety relief devices can handle the flow. Examples are the (semi-) stand alone magnets or the inner triplets. There the beam pipe vacuum might rise to 1.5 bar absolute, their safety release pressure, due to closing of the vacuum sectorization valves. Their insulation vacuum is as well limited in volume and would rise to 1.5 bar absolute, their safety release pressure.

Choked flow is manifested by no additional increase in flow rate with increasing pressure differential under fixed upstream conditions. The flow becomes limited when the exit plane velocity is at sonic condition [1]. This is the case for homogeneous fluids (no phase change) at adiabatic conditions. In addition cavitation will occur if the downstream pressure is below the vapor pressure at the prevailing liquid temperature. For the purpose of this article we use as discharge flow estimator the flow at sonic conditions and assume a geometry factor of 1 for the hole:

$$m^* = \rho c \,(\mathrm{kg/s \cdot cm^2})\,, \qquad (1)$$

with m^* the specific discharge flow, ρ the helium density at the hole and c the local sound velocity at the hole.

Magnet Specific Flow Restrictions

Hole at End-Caps and/or Magnet Interconnects If a hole is made at the magnet end-caps or interconnects the flow limitation will be given by the thermodynamic conditions of helium at the hole and by its size. The discharge flow rate will ultimately be restricted by the rate at which helium is able to reach the hole location from elsewhere in the hydraulic section. This ultimate limitation comes from the flow impedance in the longitudinal direction along the magnet(-chain) and would become visible only for an excessively big hole as happened during the incident in sector 3-4 in 2008.

Hole between Beam Pipe and Magnet For reasons of electrical insulation the magnet coil blocks are covered by several layers of thick Kapton foil, inpenetrable to helium. If a hole is made between beam pipe and magnet cold mass, the helium from the main volume of the cold mass can only access the beam pipe region by circumventing the coil blocks. There are only two possibilities. One, longitudinal, via the end-caps regions through the beam-pipe - coil spacing annulus. This route has a very high flow impedance and is not capable of sustaining any substantial discharge flow rate [2]. The other, radial, through the yoke and collar spacing and then via the so-called "nose" area to the beam pipe. This will be the main discharge route.

The collars are spaced 0.2 mm per 6.2 mm length. The collar nose is an about 10 mm long fraction of the inner magnet coils circumference. If one considers the collar nose to be opened up completely over its 10 mm circumference fraction, this then makes for a total "slit" area of 3.23 cm^2/m ($\sim$161 slits per meter length). The available discharge area will depend on the assumed damage made by the beam.

"LANDSCAPE" OF SPECIFIC DISCHARGE FLOW

Figure 1 shows the range of possible specific discharge flow values, the "landscape", as function of the thermodynamic state of the helium defined by its pressure P and temperature T. We see that the values cover a full order of maginitude. From $3.5\,\mathrm{kg/s\cdot cm^2}$ at $P = 1.3\,\mathrm{bar}$, $T = 1.9\,\mathrm{K}$, the nominal operating conditions for the ARC magnets, to as high as $5.9\,\mathrm{kg/s\cdot cm^2}$ at $P = 20\,\mathrm{bar}$, $T = 2.9\,\mathrm{K}$ and as low as $0.5\,\mathrm{kg/s\cdot cm^2}$ at $P = 10\,\mathrm{bar}$, $T = 30\,\mathrm{K}$. In general the specific discharge rate rises with rising pressure and goes down with increasing temperature.

The actual encountered specific discharge values will be determined by the state of the helium at the hole location and thus by the physical process taking place in the cold masses. Figures 2 and 3 show the specific discharge for isochoric (closed volume) heating and adiabatic compression of helium in ARC or Inner Triplet magnets. They do not vary much over the whole heating or compression range. Table 1 gives the typical values for 4.5 K pool boiling vapour and liquid phase and for the isochoric heating and adiabatic compression. It shows that except for the vapour phase, which is not a realistic phase, the order of magnitude is the same $\sim 3\,\mathrm{kg/s\cdot cm^2}$ or $\sim 0.06\,\mathrm{kg/s\cdot slit}$.

In order to quantify better what might be the development of the thermodynamic state of the helium in actual cases we'll make use of measured quenches in the LHC ARC.

REALISTIC P-T DEVELOPMENT

Figures 4 and 5 show the measured pressure and temperature development as function of time for a single magnet quench in the LHC ARC at various currents.

If we map these data to a pressure versus temperature phase diagram we can determine where we are situated in the "landscape" of possible specific discharge flow rates. Figures 6 and 7 show the phase diagrams for quenches at 6 kA and 10 kA respectively. For reference the theoretical adiabatic compression line is added in figure 6 and the theoretical isochoric heating line in both. We see that apart from the first 10 - 15 s most of the time the temperature rises faster than even the isochoric heating case.

The specific discharge values when following the P-T development are indicated in table 2. It shows that as long as the energy dumped into the helium is low the specific discharge rates stay in the region of $\sim 3.5\,\mathrm{kg/s\cdot cm^2}$ or $\sim 0.070\,\mathrm{kg/s\cdot slit}$. Only at later times and only for the 10 kA quench do we see that the temperature rise compared to the pressure rise is such that we start to move into the region of lower specific discharge rates.

CONCLUSIONS

The MCI in terms of helium discharge due to a "beam driven" failure of the magnet enclosure depends in details on the size of the hole produced and at its location. For scaling, if the hole is in the magnet end or interconnects the m^* has to be used. Otherwise if the hole is in the beam-pipe to magnet coil area the m^* per slit value has to be used.

The order of magnitude discharge rates for low energy quenches, as deduced from the data of LHC for single quenches, will be in the range of $\sim 3.5\,\mathrm{kg/s\cdot cm^2}$ or $\sim 0.070\,\mathrm{kg/s\cdot slit}$. Only when the system can evolve to higher temperatures will we see a significant, up to an order of magnitude, decrease in discharge rates.

Inducing multiple quenches whenever a beam loss incident is detected would be a way to effect this order of magnitude decrease. It so happens that the new quench protection system, which triggers more neighbouring magnet quenches to avoid the so-called "symmetric quenches" goes already in the right direction. Any major incident is likely to produce as well many simultaneous quenches, as seen the sector 3-4 incident in 2008, with potential to go down to values of $0.5\,\mathrm{kg/s\cdot cm^2}$ ($\sim 0.010\,\mathrm{kg/s\cdot slit}$).

Discharge rates are highest, up to and order of magnitude, for low energy incidents.

The results derived can serve as a basis for further study of specifically defined cases based on feasible beam loss scenarios.

REFERENCES

[1] L.D. Landau and E.M. Lifshitz, "Course of Theoretical Physics, Volume 6, Fluid Mechanics", 2nd edition, Pergamon Press, ISBN 0-08-033932-8.

[2] P. Lebrun, P, T. Wahlstrm, R. van Weelderen, L. Williams, "Investigation of quench pressure transients in the LHC superconducting magnets", 15th International Cryogenic Engineering Conference : ICEC-15, Genoa, Italy, 7 - 10 Jun 1994 - Cryogenics : 34 (1994) - pp.705-708.

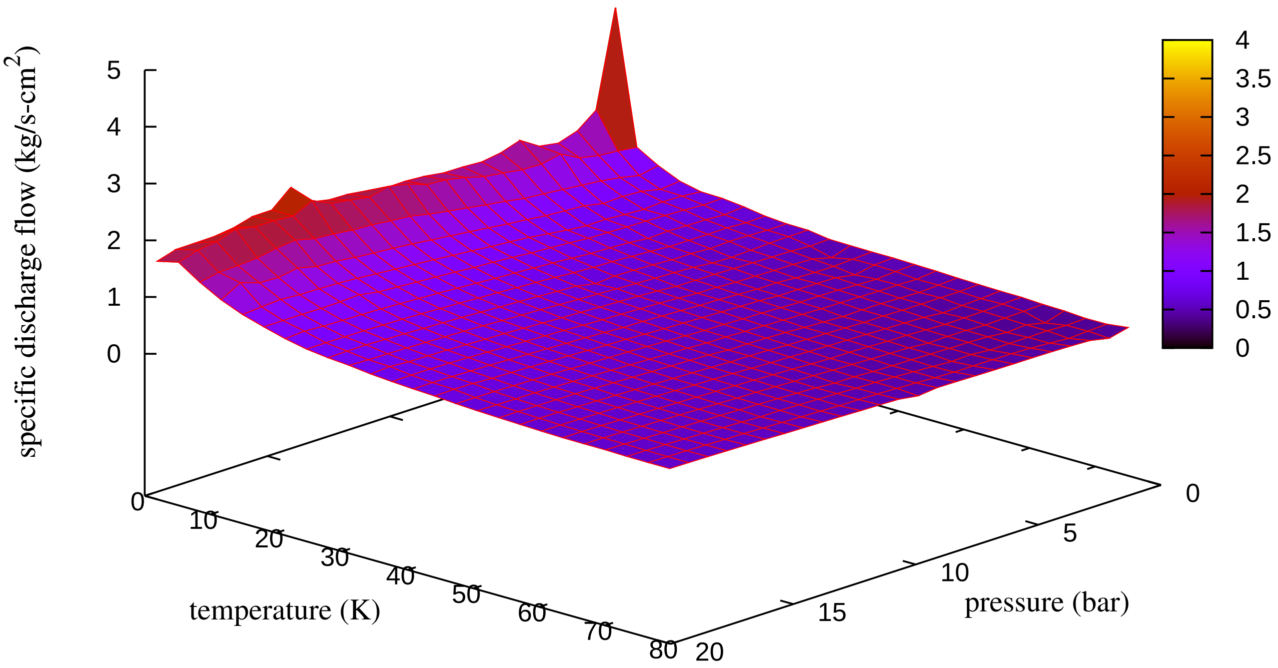

Figure 1: Specific helium discharge flow at random back-pressure and temperature.

Table 1: Specific discharge values

Helium state	**Specific** $(\mathbf{kg/s \cdot cm^2})$	**Per slit** $(\mathbf{kg/s \cdot slit})$	**Per meter collar nose** $(\mathbf{kg/s \cdot m})$
Pool boiling, vapour phase	0.22	0.004	0.71
Pool boiling, liquid phase	2.0	0.039	6.3
Isochoric	3.9	0.078	12.6
Adiabatic	4.3	0.085	13.7
Reality	?	?	?

Table 2: Specific discharge values along the P-T development line for single magnet quenches in LHC

6 kA quench P, T (bar, K)	$\mathbf{m^*}$ $(\mathbf{kg/s \cdot cm^2})$	$\mathbf{m^*}$ **per slit** $(\mathbf{kg/s \cdot slit})$	**10 kA quench P, T (bar, K)**	$\mathbf{m^*}$ $(\mathbf{kg/s \cdot cm^2})$	$\mathbf{m^*}$ **per slit** $(\mathbf{kg/s \cdot slit})$
(1.3, 1.9)	3.6	0.071	(1.3, 1.9)	3.5	0.071
(4.0, 3.0)	3.8	0.076	(4.0, 4.0)	3.3	0.066
(6.0, 4.0)	3.7	0.074	(6.0, 4.5)	3.4	0.068
(8.0, 5.0)	3.5	0.070	(8.0, 5.5)	3.2	0.063
(10.0, 5.5)	3.6	0.071	(10.0, 6.0)	3.2	0.065
-	-	-	(14.0, 7.0)	3.4	0.068
-	-	-	(18.0, 10.5)	2.4	0.048
-	-	-	(22.0, 16.0)	1.9	0.037

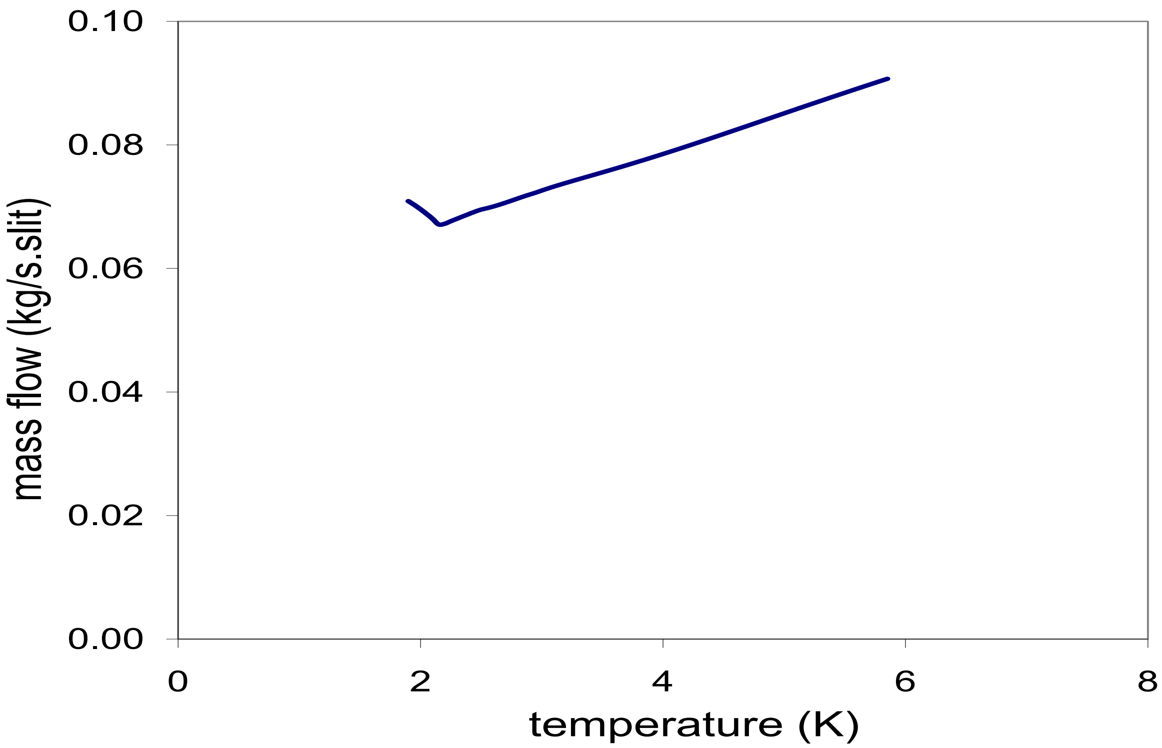

Figure 2: Main dipole discharge mass flow per 0.2 mm wide 10 mm large collar slit under semi isochoric conditions. Average discharge flow 0.078 kg/s per slit

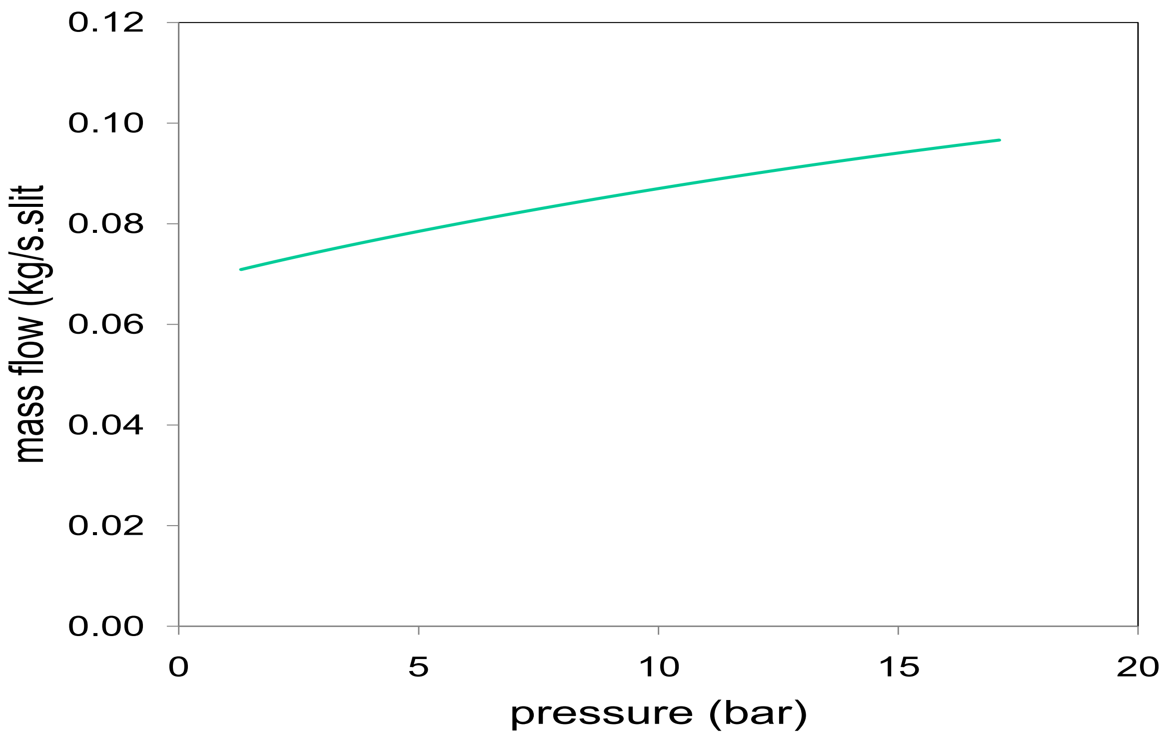

Figure 3: Main dipole discharge mass flow per 0.2 mm wide 10 mm large collar slit under semi adiabatic conditions. Average discharge flow $0.085\,\mathrm{kg/s \cdot slit}$.

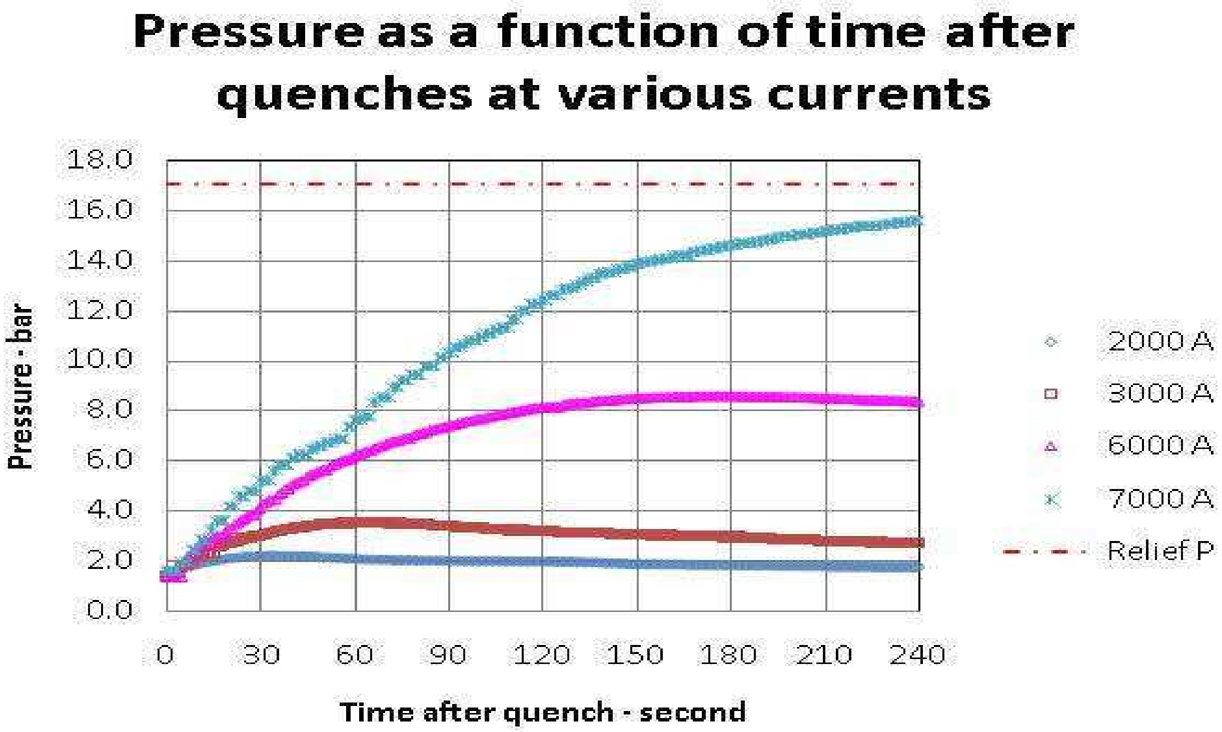

Figure 4: Pressure as function of time after quenches at various currents.

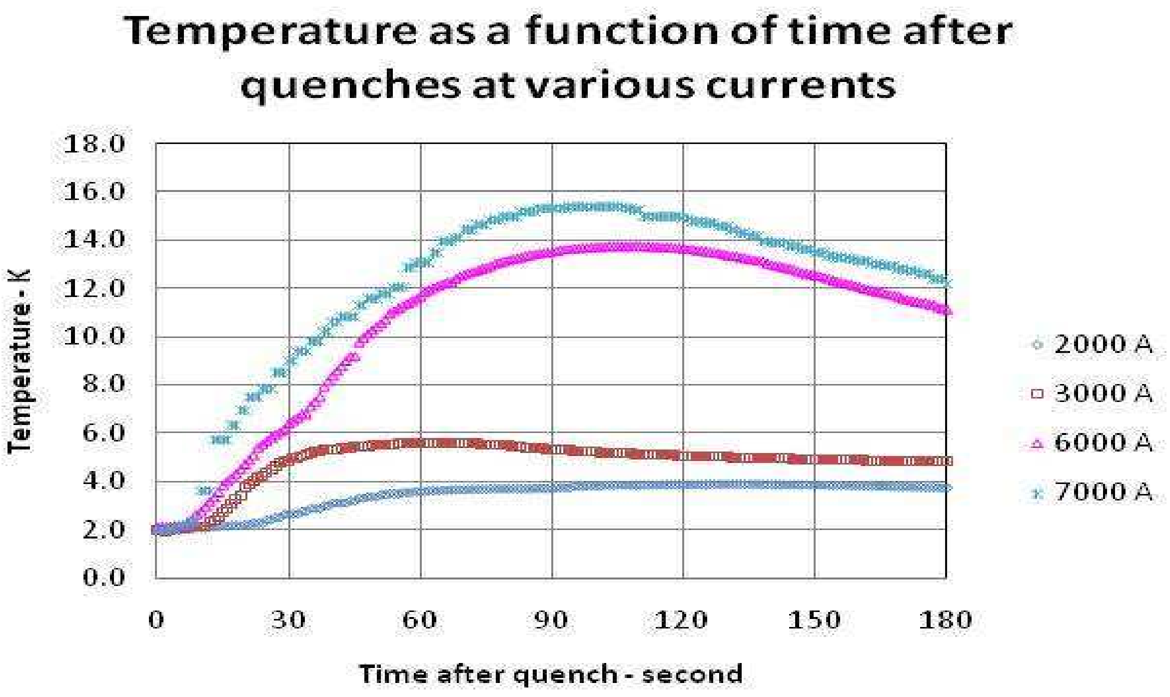

Figure 5: Temperature as function of time after quenches at various currents.

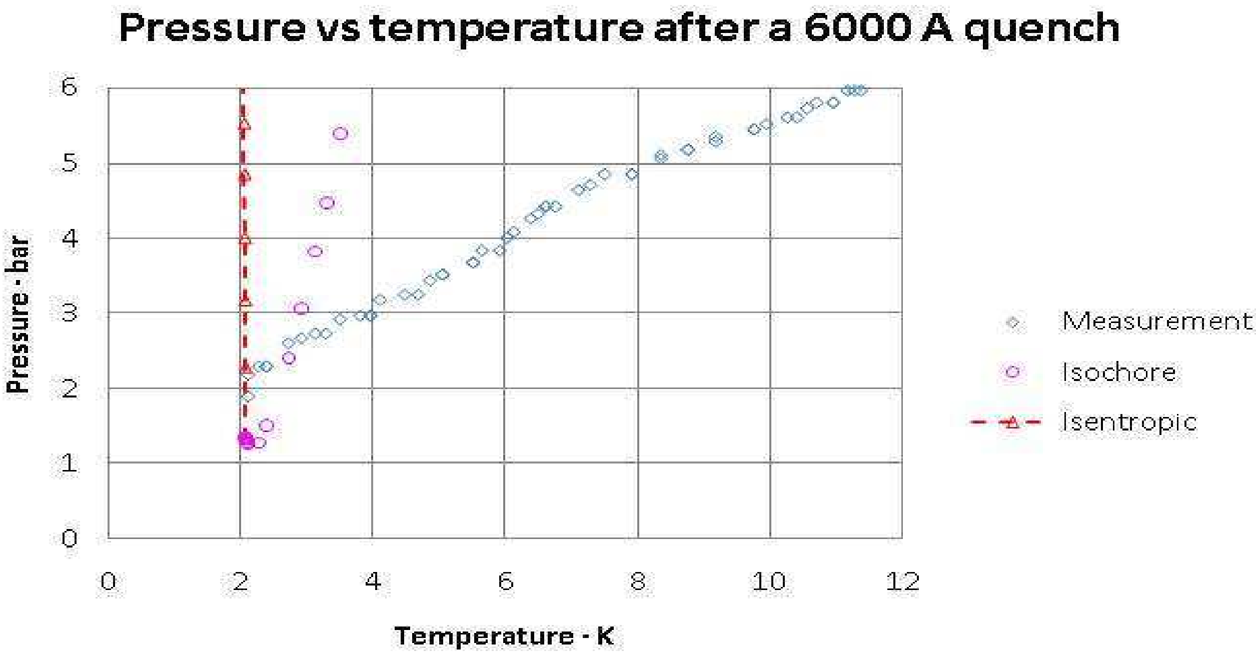

Figure 6: Phase diagram after a 6 kA quench.

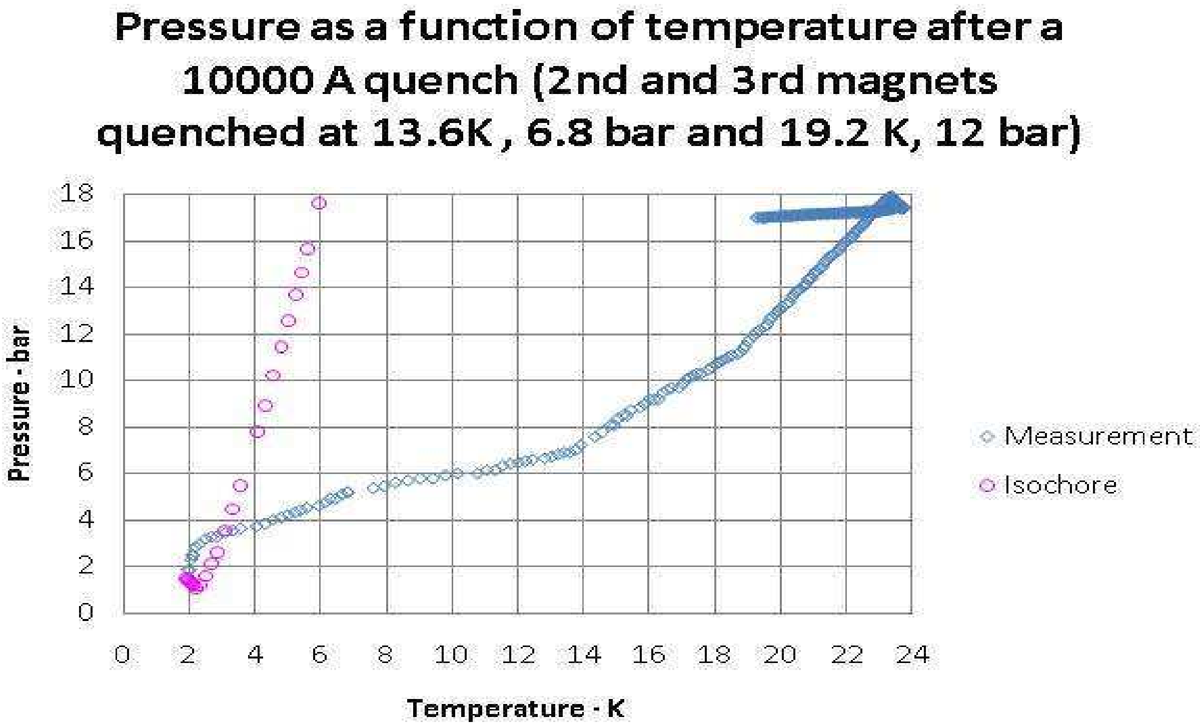

Figure 7: Phase diagram after a 10 kA quench.