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In case of resistive transition of a LHC superconducting magnet ("quench"), the stored energy is dissipated in the winding within a few tenths of a second. A fraction of this energy is transferred to the helium inside the windings and around the beam tubes, causing expansion and axial flow. This results in a fast pressure peak (several MPa) at the midlength of the magnet. We present a one-dimensional thermo-hydraulic model aiming at simulation of the quench pressure peak and study the influence of geometrical parameters, such as magnet length and beam pipe diameter. Results of simulations are compared to measurements performed on a short model and on a quasi-full scale prototype of the LHC dipoles.

INTRODUCTION

The Large Hadron Collider (LHC) at CERN [1] is currently undergoing design studies and development work. The collider, operating in the TeV-range, will consist of a single ring of twin-aperture superconducting magnets using NbTi-conductors and operating in static baths of pressurised superfluid helium at 1.9 K and 0.1 MPa. The present prototype dipole magnets are about 10 m long, 560 mm in diameter with an aperture diameter of 50 mm.

While ramping up the current and during normal operation, a dipole may undergo resistive transition, called quench, where the stored energy, of several MJ per magnet, is dissipated in the windings within a few tenths of a second. A fraction of this energy is transferred to the helium inside the porous windings and to the annular space around the beam tubes (figure 1), causing expansion and axial flow to the end volumes of the cryostat helium vessel, where it is finally discharged through a relief valve. This thermo-hydraulic process gives rise to a pressure peak at the midlength of the magnet with a magnitude of several MPa and a rise time of a few tenths of a second, and is followed by a more gradual pressure rise in the end volumes and later a decline due to opening of the relief valve. Figure 2 shows measurements of these pressure transients provoked by a quench occurring in a 10 m long LHC prototype dipole. Analysis of both pressure transients is important, the initial peak may cause buckling of the beam tube and the pressure rise in the end volumes defines the size and the response time of the relief valve. The magnet length and the radial gap between the beam pipe and the windings, defined by the outer beam pipe diameter, are fundamental geometrical design parameters affecting the pressure transients.

The final design of the LHC dipole magnet is at present not fully finalised, however the current trend is towards increasing magnet length. The effect of magnet length and the radial gap on the pressure peak is presented. The study was made by means of a simulation model, and the results are compared with measurements performed on a short 1 m model and a 10 m long twin aperture dipole prototype.

MEASUREMENTS

Pressure transients due to quench from different excitation currents have been measured on the Twin-Aperture Prototype (TAP) [2,3]. Its magnetic length is 9.1 m and it has aperture diameters of 75 mm and beam pipe diameters of 70.5 mm. During quench, pressure transients were recorded in the annular space at magnet midlength and in the two end volumes (figure 2).

A twin aperture LHC model magnet, 1.21 m long with 50 mm aperture diameters [4] has been equipped with instrumented beam tubes, lowered into a vertical cryostat and cooled to 1.8 K where a series of quenches at different excitation currents and under different rates of energy extraction have been provoked. Each of three stainless steel beam tubes, 1.26 m long with nominal external diameters 42.5 mm, 44.5 mm and 46 mm, were equipped internally with 3 capillaries of equal length and internal diameter 2.5 mm. Emerging radially these tubes are welded flush with the beam tube external surface at locations 275 mm, 630 mm and 990 mm from one end and communicate pressures developed around the beam tubes to Siemens KPY-14 absolute pressure sensors previously calibrated at 1.8 K (table 1).

SIMULATION CODE

The energy dissipation in the dipole winding and the axial helium flow through the annular space around the beam tube into the two end volumes are simulated by an one-dimensional thermo-hydraulic model, as shown schematically in figure 1. Since the spatial propagation of the quench in the windings is not modelled, the windings are considered as lumped, with uniform energy dissipation. The annular space around the beam tube and the winding is modelled as a tube with equivalent hydraulic diameter. The governing equations are partial differential equations of continuity, momentum and energy conservation (1-4), discretized by the finite difference method in an implicit scheme and solved iteratively [5,6].

Helium flow:

Momentum
$$\frac{\partial(\rho u)}{\partial t}+\frac{\partial(\rho u^2)}{\partial t} = -\frac{\partial P}{\partial x}-\frac{\lambda}{D_h}\rho\frac{u}{2}|u| \tag{1}$$

Continuity
$$\frac{\partial u}{\partial t}+\frac{\partial(\rho u)}{\partial t} = 0 \tag{2}$$

Energy
$$\frac{\partial(\rho e)}{\partial t}+\frac{\partial(\rho u e)}{\partial x} = -P\frac{\partial u}{\partial x}+\frac{\lambda}{D_h}\rho\frac{u^2}{2}|u|+h(T_s-T_b) \tag{3}$$

Winding:

Energy
$$-h\alpha A(T_s-T_b)+q' = mc\frac{\partial T_s}{\partial t} \tag{4}$$

The energy dissipation in the winding is calculated from the measured current decay and the voltage developed across the winding, taking into account energy extraction in external resistors. Energy is transferred from the winding to the helium by means of a temperature dependent heat transfer coefficient, depending on the winding temperature and limited by the thermal conductivity of the superconducting cable insulation. The geometrical heat transfer area is the surface of the cylindrical aperture occupied by the superconducting cable. This area is multiplied by a chosen multiplication factor, the only free parameter in the model. The factor combines several uncertainties, the surface of the cable taking part in the heat transfer, the growth of the heat transfer area as a function of time and the thermal conductivity of the cable insulation.

Expulsion of the helium from the porous winding into the annular space around the beam tube is not modelled. Viscous friction due to flow is taken into account, calculated as function of Reynolds number in accordance with measurements of friction factor carried out on the short dipole model. Thermal conduction in the helium is neglected, since the conductivity of supercritical helium is low and the supercritical state prevails almost immediately after the quench. No venting through a relief valve is considered. The thermo-physical properties of helium are determined using HEPAK [7].

RESULTS

The measured and simulated pressure peak for the TAP at a quench current of 9505 A are shown in figure 2. The measured pressure transient in the end volumes and the current decay are also plotted. The rise time, between initiation of quench and peak pressure, was measured at 150 ms, slightly faster than simulated. The multiplication factor of the geometrical heat transfer area was 4.

Table 1 shows measurements compared with simulations on the short dipole model with different radial gaps. I_0 is the quench current, E_{dipole} the stored energy in one dipole, t_{rise} the rise time and P_{max} the peak pressure. The difference in rise time between measurements and simulations is probably due to the fact that the propagation of the quench in the winding is not taken into account. The multiplication factor had the value of 5.2 in all three simulations.

With an multiplication factor of 4.3, which gives a realistic value of the heat transfer area, the pressure peaks in quenches of the long and short magnets can be simulated within an accuracy of 10%.

Table 1 Measurements and simulations on quenches of the short dipole model

Measurements					Simulations		
Radial gap [mm]	*Io* [A]	*Emagn* [kJ]	*trise* [ms]	*Pmax* [MPa]	*Dh* [mm]	*trise* [ms]	*Pmax* [MPa]
1.85	12000	187	40	0.29	3.70	94	0.29
2.60	12000	187	40	0.23	5.20	79	0.24
3.60	12000	187	40	0.19	7.20	76	0.21

The simulated pressure peak as function of the radial gap and the magnet length, scaled from a quench of the TAP magnet at 9505 A, are shown in figure 3 and 4 respectively. The evolution of peak pressure as a function of radial gap shows the same characteristic curve as measured on the short dipole model (table 1). The simulations show that the friction term largely dominates over the acceleration term in the total pressure rise.

CONCLUSIONS

The pressure peak shows a strong dependence on magnet length and radial gap between the beam tube and the winding. The governing equation of the pressure rise, the momentum equation, shows that the frictional pressure drop increases in inverse proportion to the hydraulic diameter and proportionally to the magnet length. The pressure peak can thus be limited by increasing the annular space around the beam tubes. Another possible way to limit the pressure peak in long magnets would be to limit their effective length by adding radial venting channels connecting the annular space around the beam tube with the bulk volume of the helium vessel.

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SYMBOLS

A	geometric heat transfer area	t	time
c	specific heat capacity of winding	T_b	bulk temperature of helium
D_h	hydraulic diameter	T_s	temperature of winding
e	specific internal energy of helium	u	velocity
h	heat transfer coefficient	x	axial coordinate
m	mass of winding		
P	pressure	α	multiplication factor
q'	internal power conversion	λ	flow friction coefficient
Q	power transfer from winding to helium	ρ	density of helium

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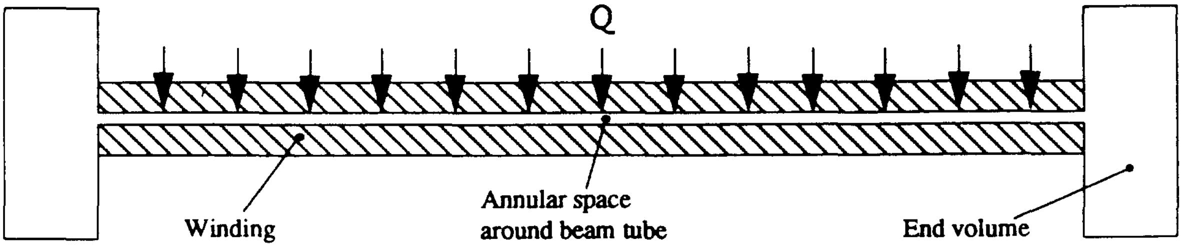


Figure 1 One-dimensional thermo-hydraulic model

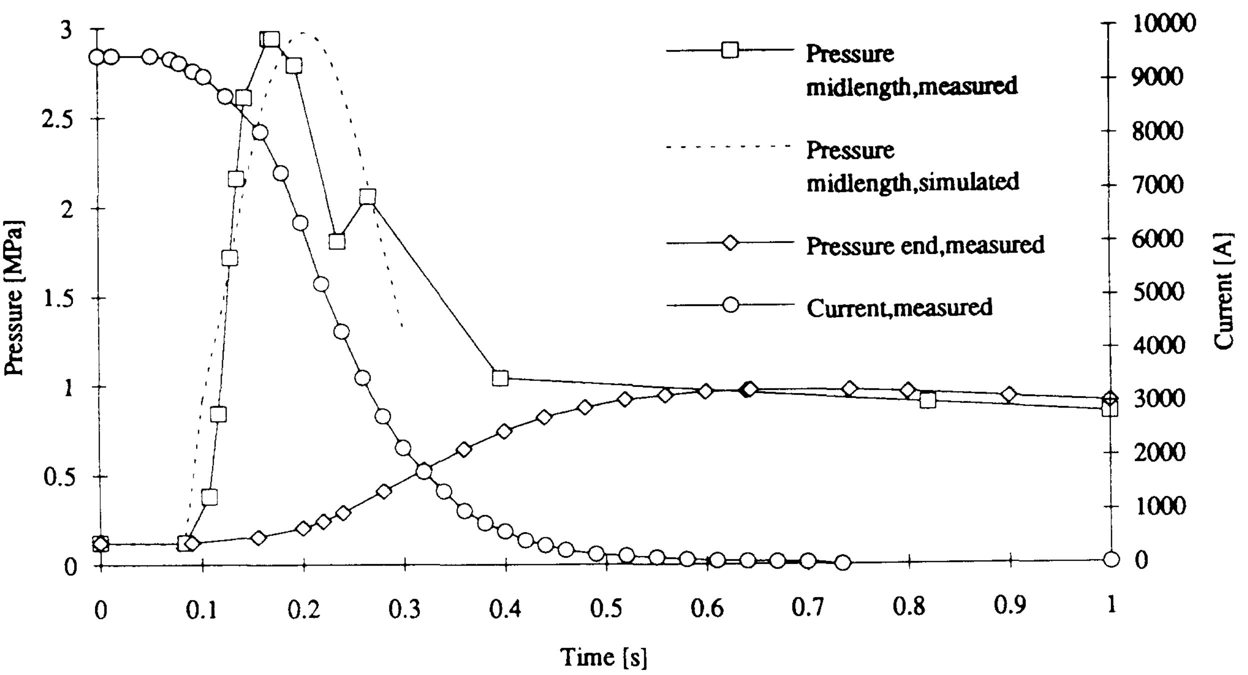
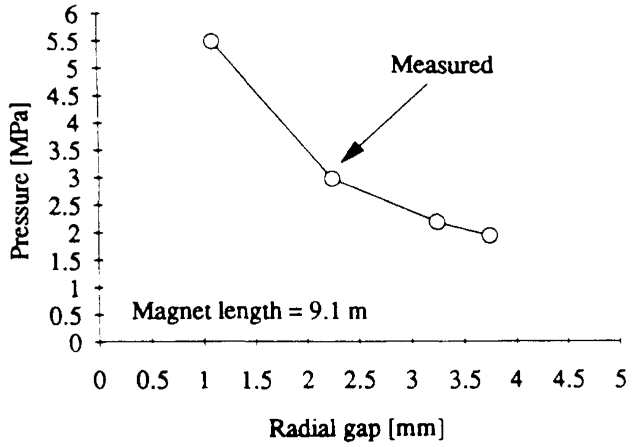


Figure 2 Measurements and simulation on the TAP magnet



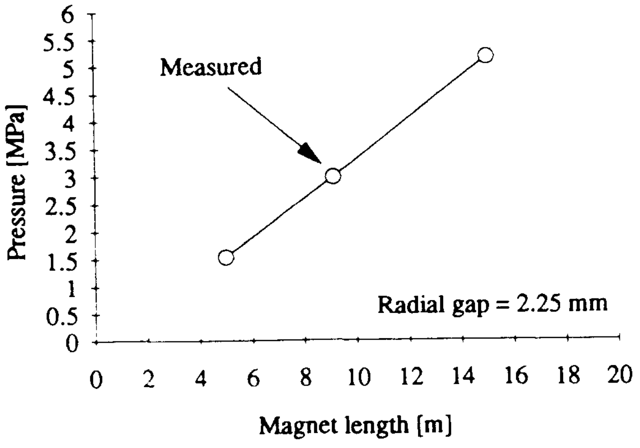


Figure 3 Calculated pressure peak as function of radial gap, scaled from the TAP magnet

Figure 4 Calculated pressure peak as function of magnet length, scaled from the TAP magnet