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Quench analysis of a novel compact superconducting cyclotron

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Abstract. Design and analysis of a compact superconducting cyclotron dedicated for medical applications in the fields of nuclear medicine and therapy is presently being pursued in our organization. The novelty of this cyclotron lies in the fact that it does not consist of any iron-pole. The cyclotron magnet will be made of a set of NbTi coils comprising of solenoid and sector coils which are housed in two halves on either sides of the median plane. The average magnetic field is 1.74 T and the maximum extraction energy is 25 MeV, which is sufficient for production of 99mTc from Mo. In this paper, quench analyses of the coils have been discussed in details considering adiabatic condition. The entire cryostat magnet along with coils, formers and support links were modelled for the quench simulation. Self and mutual inductances of all the coils were obtained from a separate magnetic analysis and used in the simulation. Parametric analyses were carried out with different quench initiation energy at various critical locations on the coil surface. The corresponding quench behaviour, i.e. maximum temperature rise, maximum voltage and current decay in each of the coils have been studied.

1. Introduction

One of the major aspects of designing a superconducting magnet is to ensure the safety of its coil against quench. Lot of progress has been made in this field in recent times. Earlier people used to rely on analytical codes for simple geometry where a temperature rise function was defined to predict the maximum temperature in coil from the current decay time [1]. Quench propagation velocity was derived assuming one dimensional heat flow and adiabatic condition. Later people have tried to predict the quench behavior by developing numerical codes using finite difference method. Most of the studies for large accelerator magnets as in RIKEN [2] and LHC [3] were made for cryostable coil, i.e. sufficient cooling was available to take care of quench. However, cryostable design results in lower current density, reducing the advantages of compactness of superconducting magnet. With the advent of powerful computers, nowadays more realistic prediction are made using finite element method as carried out in the study of thermal stability of HTS coils [4]. At the same time more developments in one-dimensional numerical models are still being pursued in the determination of minimum quench propagation zones for different n-values of conductor [5].

In this paper, quench study of a compact superconducting cyclotron conceptualized by a multi-disciplinary group of physicists and engineers at Variable Energy Cyclotron Centre (VECC [6, 7], has been presented. This cyclotron is devoid of any iron-pole which makes it very compact and light weight (~2000 kg). Its magnet consists of thirty-two coils which are housed around Aluminium former in upper and lower half of the cryostat. One half is shown in figure 1. CC1 and CC2 are the central solenoid coils, whereas MC1 and MC2 denote the main solenoid coils at the outer radius. These coils generate an average magnetic field of 1.74 T. In addition, a set of three sector coils in each of four quarters generates the azimuthally varying magnetic field. These coils are denoted by large sector coil (LSC), medium sector coil (MSC) and small sector coil (SSC). This cyclotron is designed for medical applications, especially in the fields of nuclear medicine and therapy. It is designed for maximum extraction energy of 25 MeV which can be utilized to produce 99mTc from Mo. Some of the key parameters of the coils are given in table 1.

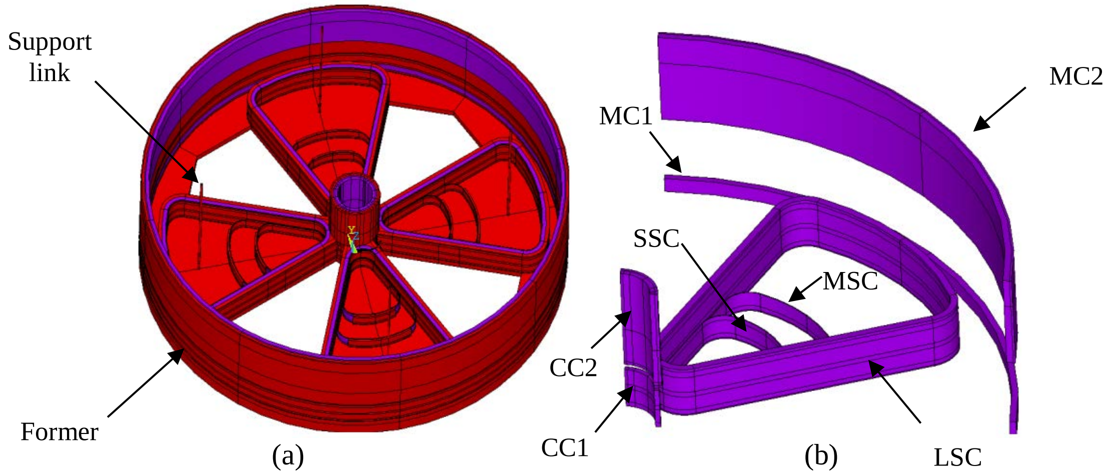

Figure 1. (a) Upper half of cyclotron coil and (b) Quarter symmetry portion of coils in upper half

Table 1. Important coil parameters

Number of circular coils	4 in each half
Number of sectors	4 in each half
Number of sector coils	3 coils in each sector
Average magnetic field	1.735 T
Maximum magnetic field	4 T
Current	500 A
Conductor	NbTi
Copper : Conductor	10.8 : 1
RRR	117
Wire cross-section	1.42 x 2.42 mm^2
Outer radius of former	1.2 m
Overall height	0.72 m
Stored magnetic energy	8.6 MJ

The compactness and low mass of the magnet has posed more challenge in terms of thermal stability against quench. Moreover its complicated network of large number of coils will cause the rate of current decay in a single coil to influence the decay pattern in all the other coils. A detail study of all these factors has been discussed in this paper.

2. Theoretical background

Quench of a superconductor is a phenomenon, which happens when the state of the superconductor lies beyond the superconducting domain, denoted by a function of magnetic field, current density and temperature. It occurs when some energy is dissipated inside the coil due to bad conductor joints, coil movements or developed cracks in epoxy potted coils, etc. It makes the superconductor normal i.e. resistive and results in further heat generation due to Joule heating. Consequently the current through conductors will start to decay and the voltage across the quench region will rise. It is a complex transient coupled electrical thermal problem in which the normal zone can propagate very rapidly within the coils through conduction. It can cause local hot spots of high temperatures which can eventually destroy the coil. The governing equation for quench is basically a transient heat balance equation which can be written as follows [8]:

$$\frac{\partial}{\partial x}\left(k(T)\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k(T)\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k(T)\frac{\partial T}{\partial z}\right)+\dot{q}=d(T)C_p(T)\frac{\partial T}{\partial t} \tag{1}$$

where, k is the thermal conductivity, d is the density, C_p is the specific heat and $\dot{q}$ is the rate of heat generation per unit volume of the coil.

Heat generation can be further written as

$$\dot{q}=\begin{cases} 0\,, if\ T < T_{cs}(t) \\ \rho(T)j(t)^2.\frac{T-T_{cs}(t)}{T_c-T_{cs}(t)}, if\ T_{cs}(t)\le T\le T_c \\ \rho(T)j(T)^2, if\ T > T_c \end{cases} \tag{2}$$

where, t is any time after quench initiation, ρ is the resistivity of coil material, j is the current density, T_{cs} is the current sharing temperature and T_c is the critical temperature of the superconductor.

The current decay i in the coil can be obtained from the following expression [9]:

$$i(t)=i_0\exp\left[-\frac{tR(t)}{L(t)}\right] \tag{3}$$

where i_0 is the initial current, R is the resistance and L is the inductance of coil.

The quench phenomenon is more severe at low temperatures due to very low specific heats of materials at such temperatures and hence will cause more temperature rise for a given energy release. As a measure of protection sometimes a dump resistor is connected across the coils so that the stored magnetic energy can be released outside the coil. This method has been applied in our study in which a separate dump resistor is connected in series in the electrical circuit of each of the coils.

3. Finite element simulation

The large variation of material properties at low temperatures has rendered the governing equation highly non-linear and it is practically difficult to solve it analytically for such a complicated system of coils as in our case. In this present study an attempt has been made to simulate the quench behaviour by developing a parametric code in multi-physics finite element software ANSYS [10]. Two different analyses have been carried out in chronological order and are discussed below in details.

3.1. Magnetic analysis

In the initial step, magnetic analysis is carried out to determine the magnetic field distribution in coils and surrounding air. This step is also required to find out the inductances of coils which will be used in the subsequent thermal analysis. In this analysis the coils are modelled without any former. In order to exploit the symmetrical nature of the problem, one-eighth portion of the solenoid coils and half of one set of three sector coils, belonging to the upper segment, are meshed with electro-magnetic elements. The remaining portions of coils in the upper half and all the coils in the lower half are meshed with current carrying elements. In addition, one-eighth model of free space is modelled to obtain the field distribution around the coils. Normal flux boundary condition is specified at the median plane and parallel flux condition is applied at the vertical planes of free space. The field distribution in coils is shown in figure 2.

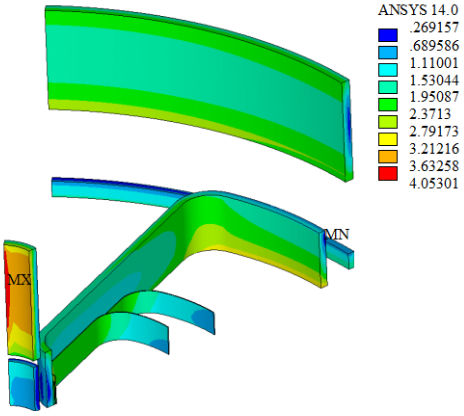

Figure 2. Magnetic field distribution in symmetric portion of coils

3.2. Thermal analysis

The next step is to study the thermal response of the system. Several assumptions have been made for this analysis. Firstly, it has been assumed that no external cooling is available to cool the coils. Although proper cooling will be provided either by direct conduction cooling with cryocoolers or by indirect cooling through natural circulation of liquid helium, this assumption is actually a conservative approach. It will ensure additional buffer for quench protection.

Secondly, the variation of magnetic field with change in current density has been neglected and the maximum magnetic field in the coils i.e. 4T is taken constant in the thermal analysis. This is again a conservative method since a relatively low critical temperature corresponding to this highest field has been imposed as the criteria for quench for all the coil regions irrespective of their field values. The self inductances of the coils lie in the range of 3H to 9x10^{-4} H, whereas the mutual inductances vary between 10^{-1} H to 4x10^{-6} H. The effects of mutual inductances are not considered in the calculation of current decay.

The final assumption is related to the material properties. A typical superconducting coil consists of a number of superconductor filaments imbedded in a copper matrix. However, it is very difficult to model and mesh such a coil. A single equivalent material has been defined for the coil and its thermal and electrical properties have been derived taking into account the volumetric ratio of superconductor and copper in the conductor matrix [11]. In addition, the coils in our cyclotron will be epoxy impregnated. But for the sake of simplicity, the insulation layer has also been neglected for this study.

Symmetric sector of coils, formers and support links are modelled. A special technique has been adopted to mesh the coils. Ideally the coils should be meshed with actual conductor size. But this will lead to a huge number of meshes. In order to make the total resistance R_{Total} of a coil independent of mesh density, the following formula has been developed.

$$R_{Total} = \sum_{i=1}^{n} \rho \frac{V_e}{{A_c}^2} \tag{4}$$

Where, n denotes the number of mesh elements of any coil, ρ is the resistivity of the coil material, A_c is the cross-sectional area of a conductor and V_e is volume of an element. The validity of this formula is illustration with the figure 3.

(a) (b)

Figure 3. (a) Portion of coil consisting of four conductors and (b) a typical mesh element of coil

Four conductors in the left figure, each of length $L/4$, are in series as the same current i will pass through them. The total resistance of these conductors is equal to $\rho\frac{L}{A_c}$. The right figure shows an equivalent mesh element of cross-sectional area A_e, four times that of A_c and of length $L/4$. Using equation (4) the total resistance R_e of the element comes out equal to that of the four conductors in series.

$$R_e = \rho\frac{V_e}{{A_c}^2} = \rho\frac{A_e\, L/4}{{A_c}^2} = \rho\frac{4A_c L/4}{{A_c}^2} = \rho\frac{L}{A_c}$$

However, it should be kept in mind while meshing the coils that very large mesh size will not be able to predict the local hot spots.

Transient thermal run has been given for a certain period of time, say five seconds. It is divided into a number of time steps each of ten milliseconds. Each time step is again sub-divided into smaller time durations which have been chosen judiciously so that the numerical stability of the problem is not disturbed. The symmetric planes are considered as adiabatic surfaces since no heat flow can occur across those planes. At first time step, some Joules of heat are applied as flux on a selected surface area of a coil for ten milliseconds to initiate quench. The applied heat is removed in all the subsequent time steps. When an element has quenched, some amount of heat will be generated inside it which is then applied as body force in the next time step.

Initially the current will pass solely through the superconductor since it is in superconducting state and will offer the least resistance path compared to copper. The operating current density j_{op} through a coil at any particular time step is found out by dividing the total current at that time by the area of superconductor. j_{op} is assumed to be constant for all the mesh elements of a particular coil. It has to be noted that total seven coils are considered in this analysis among which four are solenoid and three are sector coils.

At each time step the temperatures of all elements of the coils are stored in an array in the post-processor. The critical current density j_c of each of the coil elements at the magnetic field B and element temperature T is then found out using the following formula [11]:

$$j_c(B,T) = j_{c0}\left[1 - \frac{B}{B_{c0}}.\frac{1}{1-0.75\left(\frac{T}{T_{c0}}\right)^2-0.25\frac{T}{T_{c0}}}\right]\left(1-\frac{T}{T_{c0}}\right) \tag{5}$$

where, j_{c0} is the critical current density when $B = 0$ and $T = 0$, T_{c0} is the maximum critical temperature when $B = 0$ and $j = 0$ and B_{c0} is the critical field when $T = 0$ and $j = 0$.

The critical temperature T_c at the given B is computed by equating equation (5) to zero. If j_{op} of any coil element is found less than j_c, then there is no heat generation in that element for the next time step. However, if j_{op} is found greater than j_c, then first it is checked whether the element temperature has exceeded T_c or not. If T is found below T_c, it implies that the total current through that particular element will be shared between the superconductor and the copper. In such case the current corresponding to j_c will flow through the superconductor and the remaining current will pass through

IOP Conf. Series: Materials Science and Engineering **171** (2017) 012111 doi:10.1088/1757-899X/171/1/012111

copper. The heat generation in the element will be that generated in the copper. On the other hand, if T exceeds T_c, then a common heat generation term for the element is calculated based on an equivalent resistivity ρ_{eq} given by the following formula[11]:

$$\rho_{eq} = \frac{(1+\alpha)\rho_{Cu}\rho_{Sc}}{\rho_{Cu} + \alpha\rho_{Sc}} \quad (6)$$

where α is the volumetric ratio of copper to superconductor, ρ_{Cu} is the resistivity of copper and ρ_{Sc} is the resistivity of superconductor.

4. Results

Since one quarter portion is taken for simulation and symmetric boundary conditions are applied, the initial heating area is symmetric. Several cylindrical areas at different heights are chosen at the inner radius of CC2 coil around the region of maximum magnetic field. Initial heat flux is applied on those areas. Individual dump resistor across each coil is chosen in such a manner so that the time constant of current decay in each circuit is 2 s if the quench resistance of the coil is ignored. Variations in temperature distributions in the model at different time intervals for a particular combination of input energy and heating area are shown in figure 4. Initially maximum temperature is reached at the region within the CC2 coil where the heat is applied. The high temperature zone then gets shifted with time towards the LSC coil since its current density becomes higher than CC2. The current decay and voltage rise in the coils for this case are shown in figure 5 and 6 respectively.

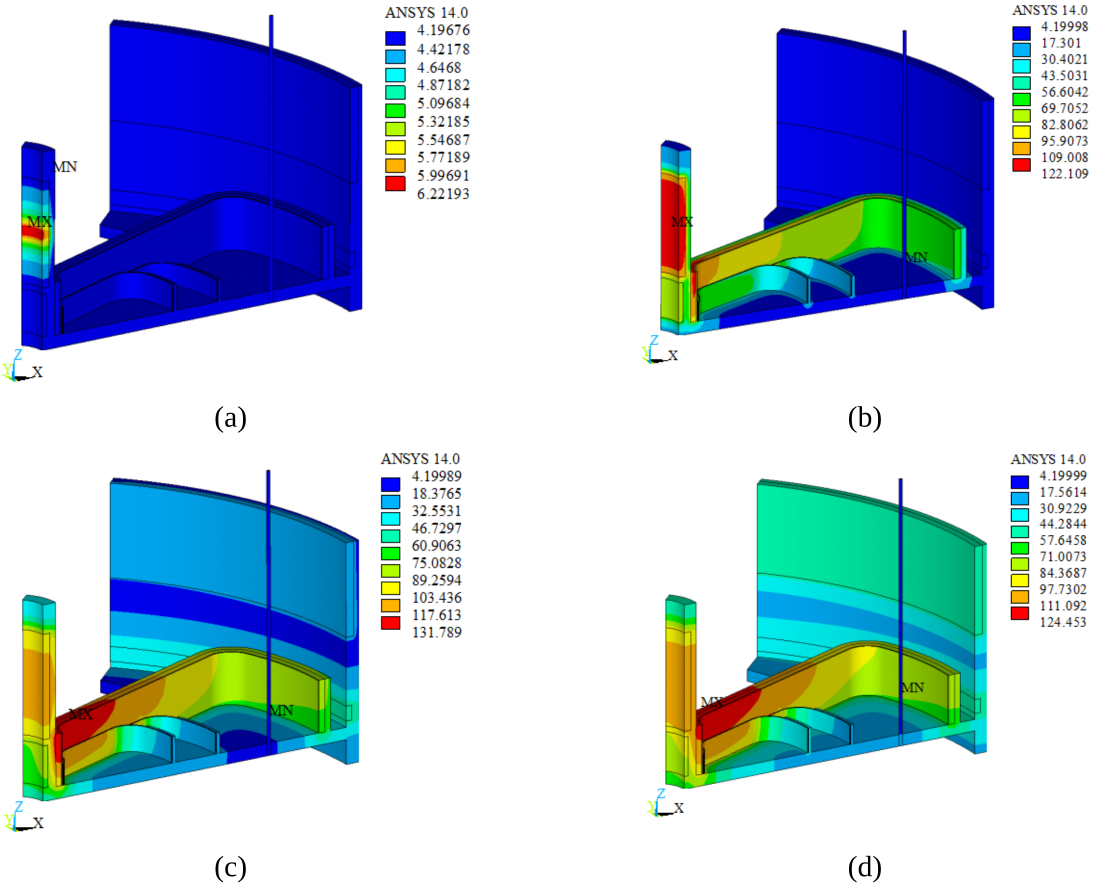

Figure 4. Temperature distribution at various time after application of 2 J of heat energy on a total area of 2896 mm^2 at a height of 220 mm from the median plane; (a) 0.01 s, (b) 0.5 s, (c) 2 s and (d) 4 s

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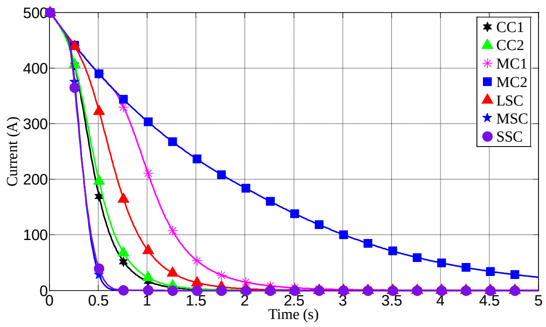


Figure 5. Current decay in coils

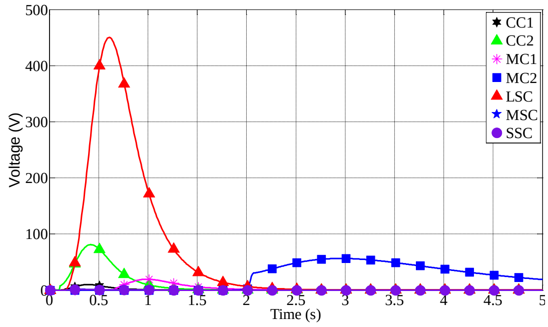
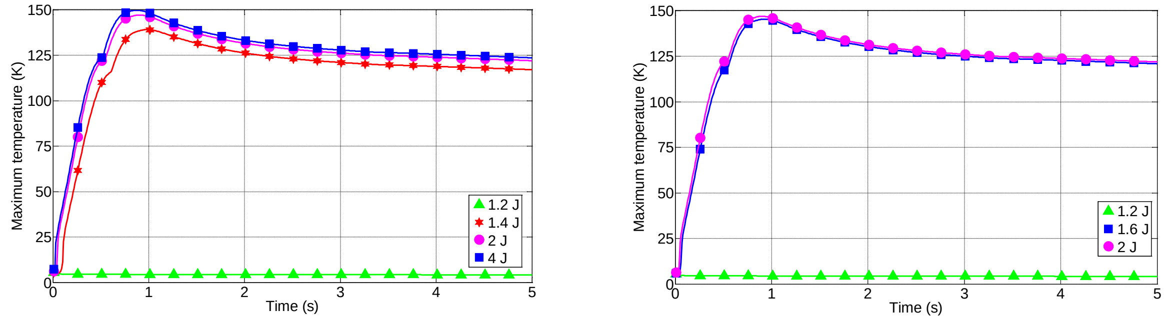


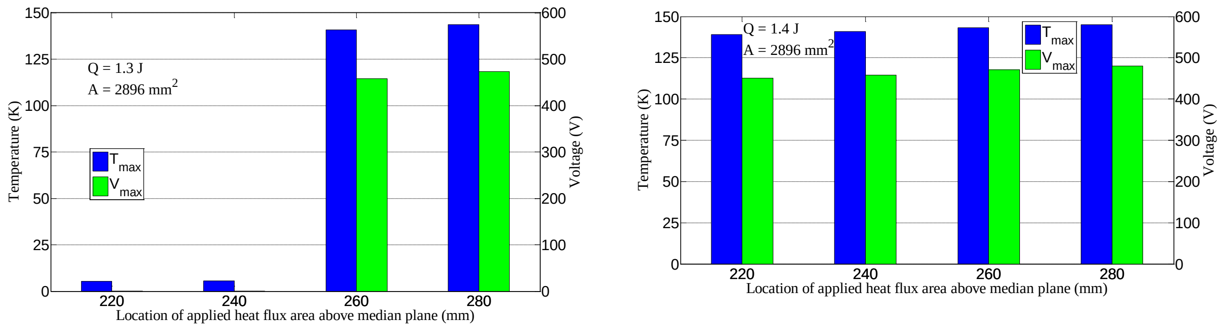
Figure 6. Voltage rise in coils



(a) (b)

Figure 7. Variation of maximum temperature of coil with time after initial heat input on (a) 2896 mm^2 and (b) 1448 mm^2

Another study has been carried out with two different heating areas on CC2 coil at the same height above median plane. The results are compared in figure 7 in terms of maximum temperature rise for different energy inputs. In order to find out the critical locations where the energy required for quench initiation are low, several heating areas are chosen at increasing heights above the median plane on the inner radius of CC2 coil. Two different energy inputs are taken for this study and the results are compared in figure 8. The result shows that the regions away from the median plane will quench at lower energy since they are away from the bulk cold mass.



(a) (b)

Figure 8. Variation of maximum temperature and voltage with changing locations of heating area of 2896 mm^2 for input energy (a) 1.3 J and (b) 1.4 J

5. Conclusion

A detail code using ANSYS parametric design language program (APDL) commands has been developed to study the quench behavior of individual coils of the cyclotron. It is evident from figure 7 that the minimum quench energy (MQE) for the system lies between 1.2 J and 1.4 J and it does not vary much with the size of the initial heating area. MQE may be on the higher side since the chosen heating area is taken as symmetric. For knowing localized temperature rise, complete model should be taken and the heating must be applied to the local regions of interest. The large sector coil (LSC) is more susceptible to quench since it shows the highest temperature and highest voltage rise. More care should be taken while making the conductor joints in LSC. It is also found out that the surface areas on the second central solenoid coil (CC2) are more critical at higher locations above the median plane for the same input heat energy. Effect of eddy current heating on the former and variation of magnetic field with current density are not considered in the present study. They will be included in the code for more realistic results in future plan of work.

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