

Quench Calculation Software

Jayati Vijaywargiya
Mody University, India

Abstract- FAIR - the Facility for Antiproton and Ion Research is a new accelerator complex which is currently under construction in Darmstadt, Germany. Superconducting magnets are the key components of modern particle accelerators. A superconducting magnet is an electromagnet in which the coils are wound from a superconducting cable instead of a classical copper cable.

Superconducting materials are characterized by zero resistivity under given conditions of temperature, magnetic field induction and transport current. Rise in temperature of Superconducting material results in increase in its resistivity. This change in material from superconducting state to normal resistive state is termed as quenching. A development of a resistive zone during the operation of a superconducting machine may cause a temperature increase, over voltage and pressure raise in the cooling channels to the levels that exceeds the design limits. In that case a severe damage of the machine is expected. In order to properly design a superconducting magnet, quench cases shall be studied and analysed. Therefore detailed quench calculations are required. A special quench calculation tool dedicated to superconducting magnets of FAIR was developed at GSI. The aim of this work is to optimise the code and to create an intuitive graphical user interface (GUI) in SCILAB environment.

Keywords- Quench, current decay, Quench velocity, Temperature profile

I. INTRODUCTION

1.1 FAIR Project

The Facility for Antiproton and Ion Research (FAIR) is an International accelerator facility, built in Darmstadt, Germany. The GSI facility (on upgradation and together with a new proton linear accelerator) will serve as pre-accelerator and injector for the new experiments. It is a double-ring accelerator (SIS100 heavy ion synchrotron) with a circumference of 1100 meters, together with a complex system of cooler and storage rings and experimental setups. The synchrotron will deliver ion beams of unprecedented intensities and energies. Thus also intensive secondary beams can be produced, providing antiprotons and exotic nuclei for future experiments.

1.2 Quench

Superconducting Magnets are used in SIS100 accelerator at FAIR. Superconducting magnets successfully operates under an optimal condition in which superconducting state is enabled. The operating point of the superconductor must be kept below the critical current surface. When the operating point is above the critical current surface, the superconductor becomes resistive and thus loses their superconductivity. The transition from the superconducting state to the resistive state of superconductor is called quench. It occurs mostly because of increase in temperature of superconductor which is a result of conductor movement (friction), eddy currents in the conductor, poor cooling or beam losses (in particle accelerators and fragment separators).

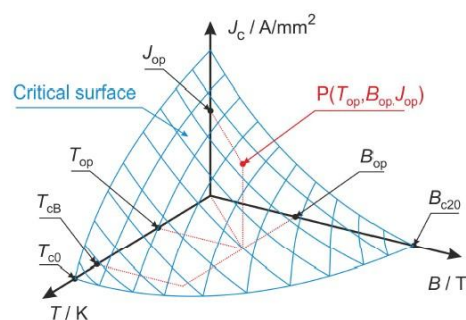


Fig. 1. Influence of RRR on the resistivity of Cu [1]

1.3 Overview

The GSI quench calculation software is developed in order to study quench cases in superconducting magnet circuits of FAIR. The aim of this work is to code and create an intuitive graphical user interface (GUI). Development of GSI code is in the SCILAB environment (free and open source software) for easy accessibility and usability of the software. This will provide knowledge concerning to software details, program limitations and free access to the User Interface to all. The GUI will input the physical parameters and will then analyze change in temperature and current with respect to time. Quench velocity is also an important parameter to be analyzed and thus it is also calculated. After the introductory section the fundamentals of superconductivity is described. It

is followed by physical model of superconducting material, Heat equation , current equation and Quench Velocity. Next section deals with the Model implementation using Implicit and Explicit Numerical approach. The last section concludes with the summary and outlook.

II. QUENCHING AND SUPERCONDUCTIVITY

2.1 Superconductivity

Superconductivity is the phenomenon in which a superconducting material is characterized by negligible resistance below a critical temperature. It was first observed by Heike Kamerlingh Onnes in pure mercury at the temperature below 4.2 K. When temperature of a superconducting material is below critical temperature it loses its resistivity. There are two types of superconducting materials Type I and Type II. The superconductor of type I remain superconducting below a certain critical magnetic field B_c . That means if such a superconductor at $T < T_c$ is immersed into an external magnetic field B_a which is greater than B_c , its superconducting properties are not preserved. Superconductors of type II are characterized by two critical fields: a lower B_{c1} and an upper B_{c2} . At temperatures $T < T_c$ and for $B_a < B_{c1}$, a superconductor of type II is in a superconducting state like an superconductor of type I. When the external magnetic field exceeds B_{c1} , the superconductor of type II enters a mixed state. At $B_a > B_{c2}$ the mixed state is destroyed and the material gets normal conducting.

2.2 NbTi Wires

Niobium Titanium, is the most popular superconductor which is used to construct the superconducting magnets of the FAIR machines. In order to describe the critical current surface of a particular NbTi wire, one can use one of the available empirical fitting functions. The most popular and used is Botturas fit.

2.3 Botturas Fit for the Critical Surface

In order to take into account the nonlinear dependence of J_c , critical current density on B , Bottura proposed the following formulation for the critical surface. The figure below shows the graph of Bottura's fit.

2.4 Superconducting Magnets

An electromagnet in which the coils are wound from a superconducting cable instead of a classical copper cable is termed as superconducting magnet. For the construction of a superconducting machine, the requirement of operating

current is higher than the critical current of a single superconducting wire. The superconducting wires are connected in parallel, in order to increase the current, and thus they form a cable. Superconducting magnets are of two types coil dominated and Super-ferric (yoke dominated). Coil dominated magnets are used for high magnetic field applications (operate at high fields ($B < 2$ T)) and the magnetic field depends on conductor arrangement. On contrary superferric (yoke dominated) magnets for fields up to 22.5 T and are iron dominated magnets in which the field shape depends on the magnetic yoke, Fig. 3.

Superconducting Magnets at FAIR, SIS100 accelerator requires a nominal magnetic field of a dipole 1.9 T. It uses super-ferric windowframe magnets.

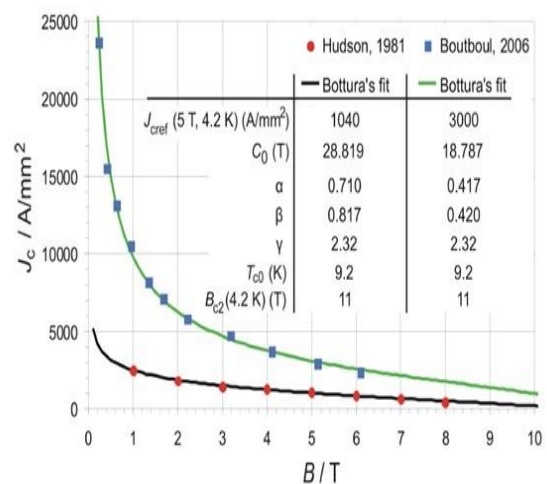


Fig. 2. Botturas fits [1]

2.5 Quenching

For the successful working of superconducting magnet, superconducting material has to be placed in operating conditions in which superconductivity is retained. Operating point of the superconducting material needs to be below the critical current surface. If the case is not so, superconductivity losses and superconducting material gains resistivity. The process in which a superconducting material gains resistivity and transits from superconducting state to normal state, is called Quenching. The major reason for quench development is increase in temperature. This increase in temperature is the result of friction due to conductor movement, eddy currents in the conductor, poor cooling or beam losses (in particle accelerators and fragment separators).

Let us look at the effect of resistivity with increase in temperature of the primary materials used for superconducting wires, copper and niobium-titanium. In order to understand the

development of the resistive zone (conductor quenching), first let us have a closer look at the resistivity of primary materials used for superconducting wires, that are copper and niobium-titanium. The resistivity of Cu decreases with temperature. When the temperature approaches absolute zero, resistivity of Copper does not vanish. It settles at a constant value called residual resistivity, which is dependent on the impurity level. The ratio of the resistivity at 300 K to the resistivity at 4 K (at zero applied magnetic field) is called the residual resistivity ratio (RRR). The purer the copper is (higher RRR), the lower resistivity it has.

Quench Propagation In a superconducting wire, heat is generated due to Joule effect. This causes increase in temperature of material and quench starts within a certain conductor length. If the generated heat power is more than the conduction power, the normal zone expands and if the generated power is less than the conduction power, the normal zone shrinks and finally disappears. The shrinking of the normal zone is called quench recovery. The case in which the generated heat power is equal to the conduction power, the initial normal zone is termed as the minimum

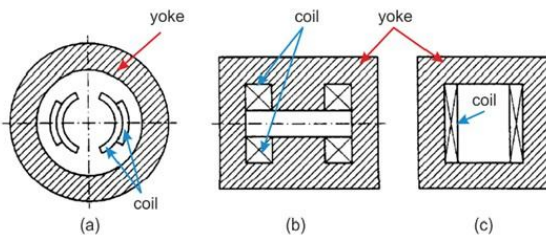


Fig. 3. Superconducting dipole magnet configurations (a) coil-dominated costype, (b) superferric Htype and (c) superferric windowframe [1]

propagation zone(MPZ). The corresponding energy is called the minimal quench energy (MQE). Figure 2.4 shows Normal zone expansion and the temperature profiles.

The velocity of the normal front propagation of Quench is termed as quench propagation velocity v_{fp} . The quench origin is the hotspot and is featured by a temperature *Hot-spot*. A resistive voltage is developed as a result of quench in a superconducting magnet. Once a current i is injected into the coil, it is supposed to circulate there for a very long time but if a quench occurs, it results in development of quench resistance R_q . Thus the current starts to decrease according in the quenched magnet.

where L is the magnet inductance

$$L(i) \frac{di(t)}{dt} + R_q(t)i(t) = 0 \quad (1)$$

III. PHYSICAL MODEL

3.1 Heat Balance Equation

In a 1 dimensional setup, a rod of non uniform heat distribution, heat flows from higher temperature region to lower temperature region.

Now we look at the physical properties of heat transfer. Heat energy of a body with uniform properties

$$Q = cmT \quad (2)$$

where Q is the Heat energy, m is the body mass, T is the temperature, c is the specific heat, Fourier Law of heat transform states that rate of heat transfer is propotional to negative of heat gradient

$$\frac{Q_{transfer}}{area} = -K_0 \frac{dl}{dx} \quad (3)$$

where $Q_{transfer}$ is the heat transfer and K_0 is the thermal conductivity.

Conservation of energy says, let us Consider a uniform rod of length l with non-uniform tem-perature lying on the x-axis from $x = 0$ to $x = l$. By uniform rod, we mean the density, specific

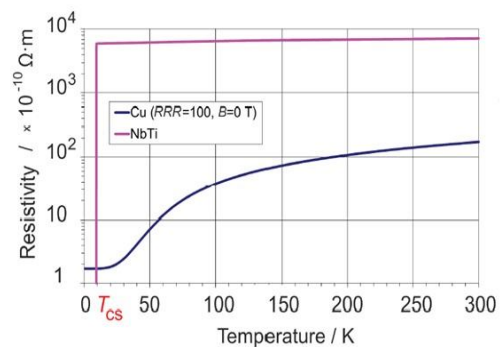


Fig. 4. Critical surface of a superconductor [1]

heat c, thermal conductivity K_0 , cross-subsectional area A are all constant. Assume the sides of the rod are insulated and only the ends may be exposed. Also assume there is no heat source within the rod. Consider an arbitrary thin slice of the rod of width x between x and $x+x$. The slice

is so thin that the temperature throughout the slice is $u(x,t)$. Thus,

$$Q_{dx} = c \cdot r \cdot A \cdot dx \cdot T = c \cdot r \cdot A \cdot dx \cdot T(x, t) \tag{4}$$

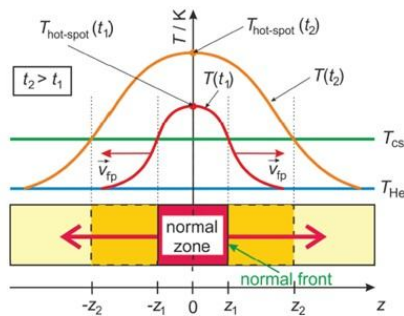
where Q_{dx} is the Heat energy of segment.

3.2 Initial conditions and boundary elements

To use the heat equation for simulation we need to know about the initial condition and boundary condition.

Initial condition corresponds to the initial Temperature distribution of the 1 dimensional setup, which is represented by Temperature(Temperature of element x, x). This Temperature profile changes as the heat propagates.

Boundary elements are complicated to deal with. Broadly elements are divided in 2 categories. Middle elements and boundary elements. Boundary elements are $x=0$ and $x=x_{max}$. These represent the elements at the start and end of the 1 dimensional rod. As the elements for the ends of 1 dimensional setup thus is expected to have insulated boundaries which allow no heat flow.



[1]

Fig. 5. Normal zone expansion and the temperature profiles during a quench [1]

3.3 Theoretical approach to Heat Equation

The heat equation is a parabolic partial differential equation that describes the distribution of heat(or variation in temperature) in a given region over time.

Suppose one has a function u that describes the temperature at a given location (x, y, z) . This function will change over time as heat spreads throughout space. The heat equation is used to determine the change in the function u over time. The rate of change of u is proportional to the "curvature" of u . Thus, the sharper the corner, the faster it is rounded off.

Over time, the tendency is for peaks to be eroded, and valleys filled in. If u is linear in space (or has a constant gradient) at a given point, then u has reached steady-state and is unchanging at this point (assuming a constant thermal conductivity).

One of the interesting properties of the heat equation is the maximum principle that says that the maximum value of u is either earlier in time than the region of concern or on the edge of the region of concern. This is essentially saying that temperature comes either from some source or from earlier in time because heat permeates but is not created from nothingness.

Another interesting property is that even if u has a discontinuity at an initial time $t=t_0$, the temperature becomes smooth as soon as $t > t_0$. For example, if a bar of metal has temperature 0 and another has temperature 100 and they are stuck together end to end, then very quickly the temperature at the point of connection will become 50 and the graph of the temperature will run smoothly from 0 to 50.

The heat equation is used in probability and describes random walks. It is also applied in financial mathematics for this reason.

The heat equation is a consequence of Fourier's law of conduction. If the medium is not the whole space, in order to solve the heat equation uniquely we also need to specify boundary conditions for u . Solutions of the heat equation are characterized by a gradual smoothing of the initial temperature distribution by the flow of heat from warmer to colder areas of an object. Generally, many different states and starting conditions will tend toward the same stable equilibrium.

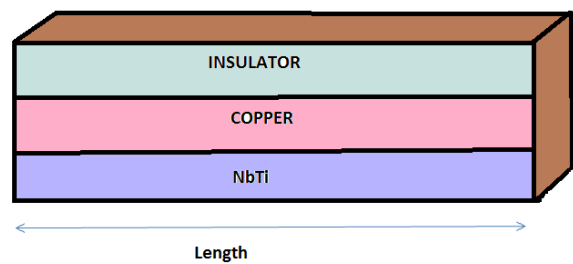


Fig. 6. 1 Dimensional setup of Copper and NbTi superconducting rod

The Heat balance Equation for 1 Dimensional setup is stated below:

$$\rho \cdot c \cdot \frac{dT(x, t)}{dt} = \frac{d(K_x(T) \frac{dT(x, t)}{dx})}{dx} \tag{5}$$

3.4 Current decay

A quench in a superconducting magnet results in development of a resistive voltage, temperature increase due to Joule heating. For a standalone magnet in a helium bath, once a current i is injected into the coil, it circulates there for a very long time (the time constant of the current decay is in the range of years). If a quench occurs, a normal zone featured with a quench resistance R_q develops. The current in the quenched magnet starts to decrease according to

where L is the magnet inductance.

$$L(i) \frac{di(t)}{dt} + R_q(t)i(t) = 0 \quad (6)$$

The implementation of this property of current in computing is done as: $I_{new} = I(t) * (1 - Resistance(t) * dt / L_{mag})$

3.5 Quench velocity

Quench velocity refers to the rate of propagation of quench in the 1 dimensional bar. As the temperature of an element reaches above T_{cs} , that is its critical temperature, the element is said to be Quenched. Quench velocity initially forms an irregular curve but later tends to reduce and become constant gradually.

Quench velocity is computed as follows:

$$speed = (d * dx) / \text{real time}$$

IV. MODEL IMPLEMENTATION

4.1 Explicit scheme

Propagation of heat in a 1 directional homogenous wire carrying some electrical current is governed by the heat balance equation stated below:

$$\frac{d(K_x(T) \frac{dT(x,t)}{dx})}{dx} = C_v \rho \frac{dT(x,t)}{dt} \quad (7)$$

The rate of change of temperature takes the following form, temperature matrix changes with the course of time and with respect to the element.

$$\frac{dT(x,t)}{dt} = \frac{T_{x,t+dt} - T_{x,t}}{dt} \quad (8)$$

$$\frac{dT(x,t)}{dx} \text{ forward} = \frac{T_{x+dx,t} - T_{x,t}}{dx} \quad (9)$$

$$\frac{dT(x,t)}{dx} \text{ backward} = \frac{T_{x,t} - T_{x-dx,t}}{dx} \quad (10)$$

Simplifying the equation 4.1 and rewriting it in the below form:

$$eJ^2 + K \frac{T_{x-dx,t} - T_{x,t}}{dx^2} - K \frac{T_{x,t} - T_{x+dx,t}}{dx^2} = C_v \rho \frac{T_{x,t+dt} - T_{x,t}}{dt} \quad (11)$$

We want to obtain a formula for time moment $t+dt$ where dt is the elementary time step.

And, introducing the indices for discrete space elements $j=1,2,3,4,5,\dots$ and for discrete time moment $n=1,2,3,4,\dots$. One gets a numerical explicit solution of considered 1D problem. The temperature profile at time n is known and we calculate the temperature profile at time $n+1$.

4.2 Implicit scheme

General Heat Balance Equation In implicit approach of heat balance equation, the heat conduction term is calculated at time step $n+1$. And, hence the heat equation takes the form as below:

$$eJ^2 + K \frac{T_{x-dx,t+dt} - T_{x,t+dt}}{dx^2} - K \frac{T_{x,t+dt} - T_{x+dx,t+dt}}{dx^2} = C_v \rho \frac{T_{x,t+dt} - T_{x,t}}{dt}$$

V. CONCLUSION

Superconducting accelerator magnets being important components in construction of experimental setup, need to be designed and constructed efficiently. Analysis, measurement and comparison of properties of Superconducting material thus becomes a necessity. Superconducting materials are characterized by negligible resistivity under given conditions of temperature. Rise in temperature of Superconducting material results in increase in its resistivity. This change in material from superconducting state to normal resistive state is termed as Quenching. A development of a resistive zone during the operation of a superconducting machine may cause a temperature increase, overvoltage and pressure raise in the cooling channels to the levels that exceeds the design limits. In that case a severe

damage of the machine is expected. Comprehensive study and detailed analysis of quench cases and behavior is required.

The GSI quench calculation software was developed in order to study quench cases in superconducting magnet circuits of FAIR. The aim of this internship project was to optimize the existing code and create an intuitive graphical user interface (GUI) in SCILAB. The software developed, measures the effect of initial current, magnetic field and many more parameters on change in temperature profile. Depletion of current and Quench velocity is also measured at each time step. The smallest time step after each iteration is calculated by adaptive time stepping. The developed GUI is capable to plot the temperature profile at required time step. This approach makes it easy to analyze the Quench cases and thus help in design of superconducting magnets. This project is programmed in SCILAB, which is free and open source software. This provides easy accessibility and usability of the software.

3D, three dimensional analyses software can be build as an extension of this 1D, one dimensional Quench calculation software. This project was restricted to Copper with Niobium Titanium but can further be extended in the same environment for other superconducting material or their combination.

REFERENCES

- [1] P. Szwangruber, Quench Study for FAIR Magnets, Ph.D. thesis, TEMF/Technical University Darmstadt, Germany, estimated defence 11/2017.
- [2] Website FAIR-center, www.fair-center.eulink, 2016.
- [3] E. Fischer, P. Schnizer, K. Sugita, J. P. Meier, A. Mierau, A. Bleile, P. Szwangruber, H. Müller, C. Roux, Fast-Ramped Superconducting Magnets for FAIR. Production Status and First Test Results, IEEE Transactions on Applied Superconductivity, vol. 25, no. 3, June 2015.
- [4] A. C. Rose, E. H. Roderick, Introduction to Superconductivity, Pergamon Press, ISBN 0-08-021652-8, 1978.
- [5] M. N. Wilson, Superconducting Magnets, Oxford University Press, ISBN 0-19-854805-2, New York, 1983.
- [6] F. Sonnemann, Resistive Transition and Protection of LHC Superconducting Cables and Magnets, Ph.D. thesis, CERN, 2001.
- [7] P. H. Kes, 100 Years of Superconductivity, CRC Press, ISBN 978-1-4398-4946-0, 2012.
- [8] H. J. Muller, The Upper Critical Field of Niobium-Titanium, Ph.D. thesis, University of Wisconsin-Madison, 1989.
- [9] P. H. Bellin, V. Sadagopan, H. C. Gatos, Ternary Superconductors Alloys of the Titanium-Niobium-Vanadium System. Transition Temperature Variation, Journal of Applied Physics, vol. 40, no. 10, pp. 3982-3984, 1969.
- [10] M. Suenaga, K. M. Ralls, Some Superconducting Properties of Ti-Nb-Ta Ternary Alloys, Journal of Applied Physics, vol. 40, no. 11, pp. 4457-4463, 1969.