Power Circuit and Quench Protection for the Pipetron Magnet Transmission Line*

K. Koepke, A. Zlobin and W. Foster

Fermi National Accelerator Laboratory, Batavia, IL 60510 USA

ABSTRACT

A double aperture, superferric magnet powered by a transmission line centrally located within the magnet's iron yoke has been proposed as the lattice magnet for a very large hadron collider [1]. The transmission line contains a single superconducting bus carrying 75 kA for a nominal magnetic field of 2 T in each aperture. This paper describes a possible transmission line geometry for this magnet, a power supply circuit to energize the magnets, and a quench protection method that prevents quench damage to the superconducting bus.

I. MAGNET GEOMETRY

A conceptual sketch of the superferric magnet is shown in Figure 1. Close to and far from the superconducting bus, the magnetic field lines are circles centered on the current. In the area of the magnet yoke, the field lines are channeled by the steel and pole tips to yield precision combined function dipoles and quadrupoles in the two magnet apertures. Typical field quality tolerances for accelerator bend magnets limit the maximum field in an iron dominated magnet to approximately 2 T. For this magnet geometry, the peak bus current is determined by the desired 2 T peak dipole field and by the required vertical aperture. The vertical aperture is in turn chosen to limit image current effects. For two apertures with 2.4 cm vertical gaps, the required bus current to reach 2 T is approximately 75 kA. The total inductance, magnet and return bus, is 2 μH/m.

II. TRANSMISSION LINE GEOMETRY

The superconducting transmission line has to satisfy the following requirements:

- The cross sectional area of the superconductor must be sufficient to carry 75 kA with an adequate current density safety margin.
- The superconductor must be stabilized with sufficient normal conductor to limit the maximum quench temperature to a level that prevents damage.
- The cryogen channel should be in direct contact with the superconductor and must have an area sufficient to allow the required cryogen flow rate at an acceptable pressure drop.
- The current bus must be electrically insulated from the cryogen containment pipe and ground.
- An insulating vacuum jacket is required to limit the heat leak into the cryogen.

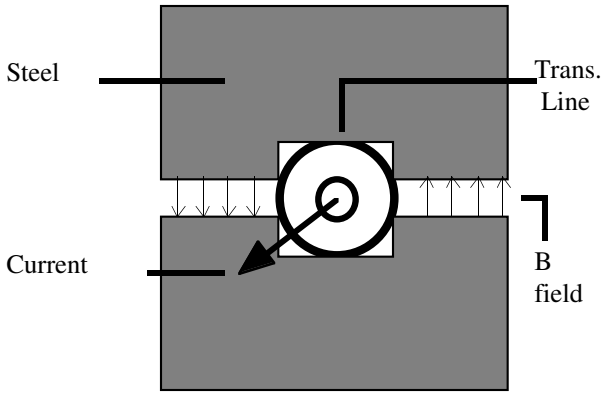

Figure 1: Conceptual sketch of superferric magnet powered by centrally located transmission line.

- The transmission line must tolerate a finite number of thermal cycles.
- Cost considerations dictate that the line be as compact as possible.

A transmission line that satisfies these requirements is shown in Figure 2. The innermost element of the transmission line is a 2.54 cm i.d. copper tube. Its bore transports the cryogen that cools the superconductor. The tube is helically slit to minimize the stresses that occur during cooldown to cryogenic temperature. The slits also allow the cryogen direct contact to the superconductor which is helically applied with a pitch equal to that of the copper slits. The superconductor is soldered to the outer surface of the copper tube for improved thermal contact, current sharing, and mechanical rigidity. This geometry minimizes the self field seen by the superconductor. The cross sectional areas of the superconductor and copper depend on

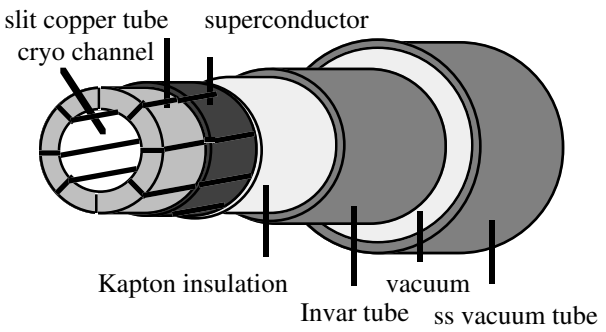

Figure 2: Conceptual sketch of superconducting transmission line.

*Operated by Universities Research Association under contract to the U.S. Department of Energy.

the type of superconductor utilized and the details of the quench protection system. The superconducting layer is electrically insulated with 4 helical wraps of Kapton for a total insulation thickness of 0.5 mm. The next layer is a stainless steel or Invar tube which isolates the cryogen from the vacuum jacket. If stainless steel is employed, periodic convolutions are necessary to reduce cooldown stresses below the yield point. The vacuum volume contains super insulation to improve the thermal insulation of the vacuum barrier. Periodic "fiberglass spider" supports center the cold mass within the outer stainless steel vacuum tube.

III. MAGNET POWER CIRCUIT

A 100 TeV peak energy proton accelerator with 2 T lattice dipoles has a circumference of 10^6 m plus the lengths associated with the required quadrupoles, correctors and straight sections. At 2μH/m, the total ring inductance of the combined function magnet is therefore 2 H. Assuming a ramping time of 20 minutes, acceptable for a collider, and neglecting the magnet current at injection, the required total power supply voltage is ± 125 V for a peak bus current of 75 kA. The accelerator ramp rate is therefore not limited by the total magnet power supply voltage.

Given the low required power supply voltage, several options are available: A single power supply could be used to power the entire circuit, several smaller power supplies could be distributed along the circuit, or as in the case of the SSC [2], the lattice can be divided into separate circuits, each with its own power supply. Current regulation in the latter case is achieved by making one of the supplies the master while the remaining supplies regulate on the current differences measured with differential current monitors located between contiguous circuits.

IV. DUMP CIRCUIT

The required number of resistive dumps depends on how quickly the current needs to be removed from the transmission line after a quench. This current decay rate is limited by the permissible voltage to ground. Existing superconducting accelerators, the Tevatron and HERA, remove the current from a quenched magnet within a fraction of a second with local current bypasses, either cold diode shunts at each magnet or warm thryristors shunting several magnets Warm thyristors make electrical contact with the cold superconductor via warm to cold power lead transitions. Dump resistors simultaneously remove the current from the remaining magnet circuit at a much slower rate but fast enough to prevent failure of the bypass circuit around the quenched magnet. Dump resistors are used instead of inverting the circuit power supply as the dumps can be made to function more reliably.

Current bypass circuits work well with multiturn magnets as the electrical resistance of such a magnet after a quench is high relative to its shunt resistance, assuring that most of the magnet's current transfers to the shunt. In the case of the transmission line magnet, the bypass bus would require a cross section much larger than the transmission line bus to assure adequate current transfer. Also, the high current of the transmission line makes periodic bypass switches unattractive. For this magnet, an alternative to bypass circuits is to add sufficient normal conductor to the current bus of the transmission line to enable the dumps to protect the superconductor directly.

The cross sectional area of copper required to limit the conductor temperature to 500 K after a quench is obtained from conservation of energy for a small volume of conductor centered around the quench origin. In the adiabatic approximation, correct for magnets operating at their peak current, this equation simplifies to the integrals:

$$\int_0^\infty i^2 dt = \sum_n A_n^2 \int_{T_c}^{500K} \frac{\gamma_n}{\rho_{cu}} C_n \, dT \qquad (1)$$

The time integral of the current squared (i^2) is normally expressed as "Miits" when evaluated in increments of 10^6 square amperes per second . The integrals over temperature are performed for each constituent of the composite conductor with A_n the cross sectional area, γ_n the density, C_n the specific heat, and ρ_{cu} the electrical resistivity of copper. The temperature integral needs to be evaluated numerically as ρ and C are strongly dependent on temperature. If the copper to superconductor ratio of the cable is large and the quench resistance is small relative to the dump resistance, Equation 1 reduces to

$$I_0^2 t_{det} + \frac{I_0^2}{2}\frac{L}{R} = 1500\, A_{cu}^2 \qquad (2)$$

where I_0 is the initial quench current (kA), t_{det} is the quench detection delay (sec), L is the total circuit inductance (H), R is total dump resistance (Ω) of the circuit and A is the copper cross sectional area (cm^2) that stabilizes the superconducting bus. The superconductor is assumed to be NbTi with Tc≈10K. An RRR value of 55 was assumed for the copper. The total dump resistance can be subdivided into distributed dumps to limit the peak voltage to ground.

V. QUENCH DETECTION

A quench in a large superconducting magnet circuit is typically detected by measuring the resistive voltage associated with current flowing in the locally normal conductor. This voltage changes with time even at constant current as the normal zone grows with time and the resistivity changes with temperature which itself increases

with time as long the conductor is not cryostable. A minimum quench voltage estimate can be made by neglecting the change in electrical resistivity with time and the minimum propagation zone. The quench voltage V(t) is then given by the equation:

$$V(t)=\frac{I_0 \rho v t}{A_{cu}} \tag{3}$$

where v is the quench velocity. This equation assumes that the quench propagates in only one direction. An approximate relation for the quench velocity[3], assuming only longitudinal heat flow and constant resistivity, conductivity, and specific heat is:

$$v_{adiabatic}=\frac{I_0}{A\gamma C}\sqrt{\frac{\rho\kappa}{T_s-T_0}} \tag{4}$$

T_S is the temperature at which the current starts to transfer to the copper, T_O is the cryogen temperature, and k is the thermal conductivity. Effective values for γ, C, ρ and k are used to evaluate this equation for composite superconducting cables. An approximation for the transmission line with its high copper to superconductor ratio is to neglect all but the copper. For a given quench current, circuit inductance, voltage to ground and quench detection voltage, the required dump resistance and copper cross sectional area can be obtained by simultaneously solving the above equations.

VI. QUENCH CELL

A 40 km tunnel length has been proposed [4] for the Pipetron cryogenic system. A power supply and quench protection circuit equal in length to the cryogenic system is therefore proposed and is shown in Figure 3. The power supply and dump circuit of each cell are located above ground at a tunnel access penetration. Each penetration will feed two cryoloops and two power loops. The electrical return bus is housed within the cryogenic liquid supply line that cools the transmission line at regularly spaced heat exchangers. A 1 V quench detection threshold permits detection of a quench at the power supply output. Table 1 lists the power supply and transmission line parameters required for a 40 km long magnet circuit.

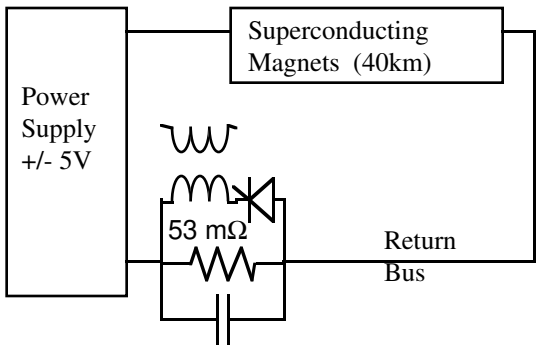

Figure 3: Power supply and quench protection cell.

Table 1: Power supply and quench cell parameters.

Magnet length (km)	40
Inductance (mH)	80
Power supply current (kA)	75
Power supply voltage (V)	5
Dump resistance (mΩ)	53
Dump voltage to ground (± kV)	2
Dump time constant (s)	1.5
Quench detection threshold (V)	1
Maximum quench temperature (K)	500
Copper area (cm^2)	1.8
NbTi critical current density (kA/mm^2)*	7
NbTi area (mm^2)	21

* at 1 Tesla, 5 Kelvin

VII. OPTIMIZATION

The results presented utilized NbTi superconductor as this has been the superconductor of choice in accelerator magnet production. No serious effort has yet been made to optimize the cost, performance and manufacturing of the transmission line, power circuit or quench protection circuit. In that sense, the above represents a feasibility study. Other low temperature superconductors, for example Nb_3Sn, could have been utilized with only minor adjustments in Table 1.

High temperature superconductors have made impressive improvements in current density and may prove suitable in the future. Their obvious advantage is lower refrigeration power. However, their very high critical temperature and specific heat lower the quench velocity and makes it difficult to detect a quench in this material.

Both high temperature and low temperature superconductors can be cryostabilized with some increase in the normal conductor cross section, especially if aluminum with high RRR (≈1000) is employed. However, some means of quench protection will still be required in the event of cryogen loss in the quench zone.

VIII. REFERENCES

[1] W. Foster, Snowmass 96.
[2] SSC Conceptual Design Report, 1986, pg 372.
[3] M. Wilson, (1983),*Superconducting Magnets* Clarendon Press, Oxford, pg 206.
[4] P. Mazur, Snowmass 96.