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DESIGN CONSIDERATIONS OF FAST-CYCLING SYNCHROTRONS USING SUPERCONDUCTING TRANSMISSION LINE MAGNETS*

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Abstract

Fast-cycling synchrotrons are key instruments for accelerator based nuclear and high-energy physics programs. We explore a possibility to construct fast-cycling synchrotrons by using super-ferric, ~2 Tesla B-field dipole magnets powered with a superconducting transmission line. We outline both the low temperature (LTS) and the high temperature (HTS) superconductor design options and consider dynamic power losses for an accelerator with operation cycle of 0.5 Hz. We also briefly outline possible power supply system for such accelerator, and discuss the quench protection system for the magnet string powered by a transmission line conductor.

MOTIVATION: A POSSIBLE NEW ACCELERATOR COMPLEX AT FNAL

Long baseline neutrino oscillation search experiments require high-power proton beams to produce neutrino beams of sufficient intensity. A high-power proton beam can be achieved using both high rate of protons and high energy of protons. The fast-cycling synchrotron can combine both options allowing produce a neutrino beam of intensities comparable to those expected from the Neutrino Factories. At Fermilab, a fast-cycling Dual Super-Ferric Main Ring (DSFMR) accelerator in the Tevatron tunnel is proposed to serve as a high intensity proton source for the long baseline neutrino experiments [1], and in a longer term as an injector to the low energy ring (LER) of the VLHC [2].

The outline of the proposed new accelerator complex at Fermilab is shown in Fig. 1. The ring circumference of ~ 6300 m would allow acceleration of proton beam up to 480 GeV with 2 Tesla dipole magnets. With total beam intensity of $0.5e^{14}$ppp, and the repetition cycle of 0.5 Hz DSFMR can provide up to 4 MW power on two neutrino production targets (total 8 MW). With such a high power, one neutrino beam could be directed to a detector at ~ 7500 km away from Fermilab (e.g. Gran Sasso, Italy), and the other one to a location at ~ 3000 km within the US (e.g. Mt Whitney, CA). Sending neutrino beams into such two detectors is a very attractive option for a firm resolution to the neutrino oscillation physics [3]. The DSFMR will allow the simultaneous operations of NOVA and MINOS experiments but with 10 times higher beam power than presently available at Fermilab.

The DSFMR is also compatible with recently proposed 8-GeV "Project X" SC RF linac which could provide high intensity proton beam to Main Injector.

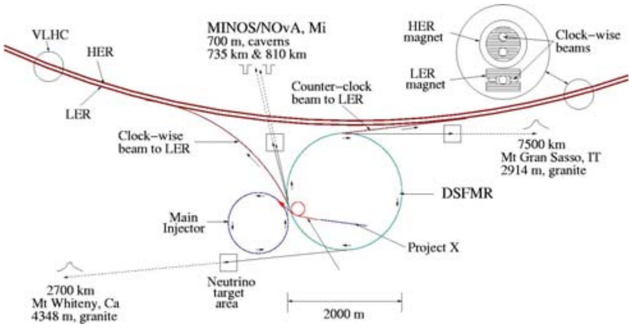

Figure 1: Outline of proposed FNAL accelerator complex

Basic parameters of the DSFMR are listed in Table I, and time sequence for beam stacking, ramping and extraction onto neutrino targets, or into the VLHC LER rings is shown in Fig. 2. The 8 GeV beam batch from Project X is transferred to the Main Injector, accelerated to 48 GeV, and then transferred to one of DSFMR rings where it awaits for a second proton beam batch from the Main Injector to arrive. The DSFMR will accelerate both proton batches up to 480 GeV, and then extract them to two neutrino beam production lines, or to the LER rings of the VLHC. In simultaneous extraction to the LER rings one proton batch is transferred into the clock-wise VLHC circulation, and the other one into the counter-clock circulation facilitating setting the colliding mode of operation.

Table I: Parameters of DSFMR synchrotron

Radius [m]	E_{inj} / E_{extr} [GeV / GeV]	Gap [m]	B [T]	dB/dt [T/s]
1000	48 / 480	40	2.0	2.0

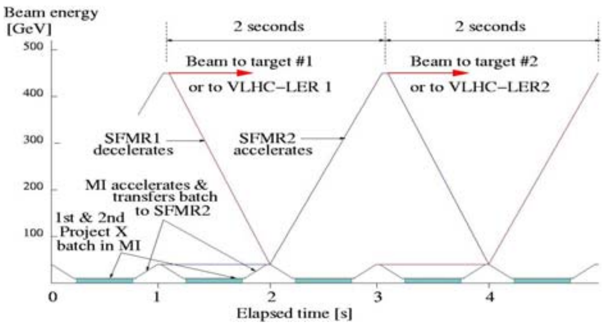

Figure 2: Time sequence for beam stacking, ramping and extraction to neutrino production targets or to LER rings.

DSFMR DESIGN CONSIDERATIONS

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There are two important constraints on the DSFMR accelerator design. The first constraint is the necessity of placing dual accelerator rings inside the Tevatron tunnel. This is only possible if the superconducting magnets are used which allows for the minimization of magnetic cores. The second constraint is due to the cryogenic power limitation of 24 kW that is currently available for the Tevatron. This requires very strong optimization of the superconductor design, so both static and dynamic power losses will be contained to this available cryogenic power.

In the superconducting super-ferric magnets the B-field is determined by the iron core, and not by the conductor making easier to secure a high quality of the magnetic field. This is especially true with a window-frame type core. In principle, there are two options for the arrangement of the conductor in a window-frame core. In Fig. 3A the conductor is located in an extended space for the beam pipe while in Fig.3B the conductor is located in designated cavities. In the first case the conductor is more exposed to the beam losses while in the second one it is better protected from such losses. Most beam losses occur at the beam injection. The higher the injection energy the smaller is the beam phase-space, and potential for the scattered beam to hit conductor is reduced. The beam loss effect can be further minimized by placing a protecting carbon scatter block in front of the conductor. For the lower-energy machines hiding the conductor behind the core walls, as shown in Fig.3B, may be well justified as a larger core is more acceptable. As pointed out in [4] option of Fig.3A allows strong minimization of dynamic power losses with HTS tape of single filament strand by orienting its narrow edge to be parallel to the B-filed in the magnet gap. In a larger bore magnet use of the LTS conductor may be appropriate as the B-field lines will more likely cross conductor at various angles.

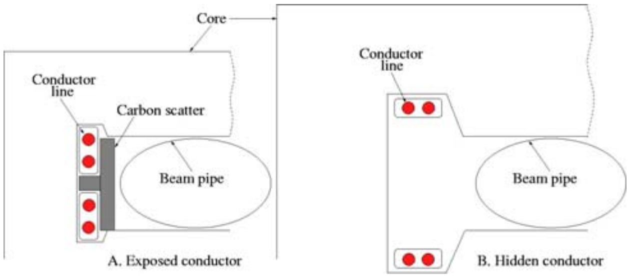

Figure 3: Options for conductor placement within a core

As discussed in [4] the DSFMR magnet would be powered by four subsets of HTS conductor lines in each current flow direction. The updated design of a one subset is shown in Fig.4. There are 35 344S HTS tapes (0.2 mm x 4.5 mm) from the American Superconductor in a subset allowing for a transport current $I_t = \sim 20$ kA (50% of I_c) at 4.5K with 20K margin. These tapes are separated from each other using the 0.1 mm thick and 2 mm wide kapton rings. These rings are also staggered to create access of liquid helium to ~ 50% of strand surface. The proposed LTS conductor line is also shown in Fig.4. It consists of 23 twisted pairs of the NbTi strands (0.65 mm diameter, SSC inner dipole) allowing for a transport current of ~20 kA (80% of I_c) at 4.5K, with temperature margin of 1.5K.

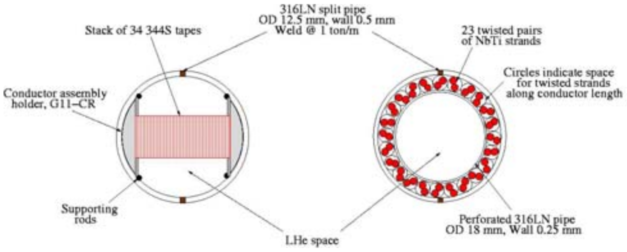

Figure 4: Conceptual designs of HTS and LTS conductors for fast cycling magnets of DFSMR and Booster

The cryogenic parameters of the proposed conductors are listed in Table II. We use these parameters to estimate the available heat transfer from the LHe to the super-conductor, and the LHe flow pressure drop per conductor length.

Table II: Cryogenic parameters of proposed conductors

CICC geometry	HTS	LTS
Pipe outer diameter [mm]	12.5	12.5
Pipe inner diameter [mm]	11.5	11.5
Number of strands	35	46
Single strand area [mm^2]	0.90	0.43
Total strand area [mm^2]	31.5	19.8
Void fraction	0.70	0.81
LHe flow area [mm^2]	73	84
Pipe perimeter [mm]	36	64
Total strand perimeter [mm]	263	120
Cooled perimeter [mm]	300	184
Hydraulic diameter [mm]	0.97	1.83

For ideal heat transfer ΔQ from liquid helium coolant to a CICC conductor we use formula (1) from [5]:

$$Q = 0.0259\ (k/D_h)\ Re^{0.8}\ Pr^{0.4}\ (T_c/T_{He})^{-0716} \qquad (1)$$

where k - heat conductivity, D_h -hydraulic diameter, Re = 4 [(dm/dt)/(k x P_{cool})], dm/dt helium flow rate, $P_{cool,}$ cooled perimeter, Pr = (μ x C_p)/k, μ – viscosity, and T_c , T_{He} – are conductor and LHe temperature. The supercritical helium pressure drop ΔP in the CICC conductor of a length L is estimated using formula (2) from [6]:

$$\Delta P/L = 0.5\ F_f\ [P_{cool} \times (dm/dt)^2\ ]/[\rho \times (A_{flow})^3] \qquad (2)$$

where friction factor $F_f = 0.3164 \times Re^{-0.25}$ for a turbulent flow in a smooth pipe, ρ – helium density, and A_{flow} is the cross-sectional area of helium flow in CICC conductor. As the CICC conductors are not smooth pipes we arbitrarily assume that a more realistic factor is 3 times higher corresponding to some roughness, ε, over pipe diameter D to be ~ 0.1 (e.g. for NbTi twisted pair: 1.3 mm /12.3 mm). The estimated in the above way heat transfer and pressure drop for the LTS and HTS conductors with parameters listed in Table II is shown in Fig.5. We observe that the pressure drop strongly increases with the flow rate while the heat transfer saturates at ~5 g/s to that of helium boiling from the metal surface. This suggests that our CICC conductors should be optimized for low LHe flows, possibly just above a laminar flow regime (> 0.5 g/s). Data [5] suggests that the heat transfer efficiency in CICC conductor may be at ~ 25% of the calculated value with a formula (1). This still would provide heat absorption of ~ 8 W/m^2 for $\Delta T = 0.1$K at 0.5 g/s flow, much exceeding projected power loss of ~ 0.5 W/m^2 for DSFMR magnet with the HTS conductor [4], but being in a close range to (3-5) W/m^2 projected for the LTS conductor [4,7]. Using the transmission line conductor to power the Booster and DSFMR magnets allows consider temperature rise and pressure drop only on the conductor length between the joints of the two magnets; e.g. 6 m length for a 5 m long magnet. In this case the helium supply and return lines run parallel to the magnet ring. Assuming initial LHe of 4.4K @ 2.6 bar, and arbitrarily the pressure drop of 0.1 bar with temperature rises of 0.6 K for the LTS and 0.2 K for the HTS in 6m long conductor, a projected cryogenic cooling power for DSFMR is 34 kW for the LTS option and 8 kW in the HTS option. We plan to perform test measurements of both dynamic and static losses in these conductors [7].

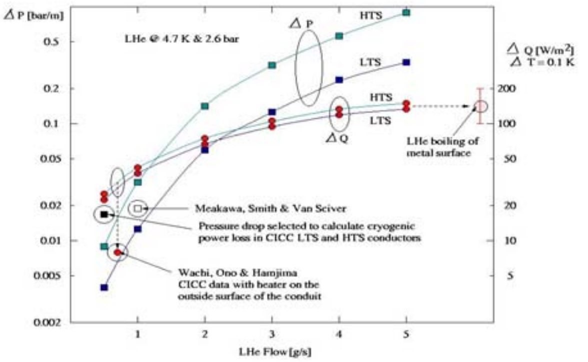

Figure 5: Projected heat transfer and pressure drop in LTS and HTS conductor lines.

POWER SUPPLY AND QUENCH PROTECTION CONSIDERATIONS

The projected inductance of the DSFMR magnets is ~ 3μH/m. This leads to ~18.75mH for a single DSFMR ring producing ~50 MW of stored energy. Supplying this energy can be handled with a single power supply that can then also be used as the primary quench protection system. The power supply ramps up and down in one second and therefore can remove the magnet energy at the same one second from any point in the cycle. In the event of a power system failure the power supply will need to be backed up by a minimum of two dump switches. These should be Superconducting type to avoid the added voltage drop of a room temperature switch system.

As a result of a large operational temperature margin the quench detection with the HTS conductor will be very different than used in classical LTS magnet systems. To illustrate this we show in Table III crudely estimated heat absorption sharing between liquid helium and copper of 344S HTS strands as the temperature rises. We see that up to ~ 30 K, where $I_t \approx I_c$, heat is mostly absorbed by helium coolant, and ~ 100 kJ is required to reach 300K.

Table III: Heat absorption sharing in HTS conductor

T[K]	Q_{Cu} [%]	Q_{LHe} [%]	Q_{total} [kJ/m]
5-30	7	93	3
5-300	76	24	100

Consequently, with DSFMR stored energy of ~ 8 kJ/m we have a time window of ~ 12.5 s to stop the power supply and remove the magnet string energy. The HTS of DSFMR magnet remains superconducting up to 25 K, so the temperature sensors can indicate coming of a quench.

The magnet system will still need to have installed a Quench Protection Monitor (QPM) to ensure that the system energy is managed safely. The difficulty in using a classical Quench Detection Unit (QDU) is the signal levels and speed. The power supply voltage for the Tevatron is 10,000 volts stepping up in 1 second and a ramp rate 240 amps/second. Each DSFMR ring will use a 2000 volt supply and will have the dV/dt of 20,000 volts/second. In addition the ramp current of 68,000 amps/sec required for the DSFMR will make classical quench detection rather difficult. Using a combination of temperature pre-quench warning and classical quench detection with a more tolerant trip level may be possible. During development tests we will have to establish a safe operating level for the conductors and develop a Quench Protection System that will meet the needs of a fast-ramping and fast-cycling accelerator.

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