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A Preliminary Consideration of Superconducting Rapid-Cycling Magnets for Muon Acceleration

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I. Motivation

An extensive technology development program, Muon Accelerator Program (MAP) [1], aimed at the construction of the Muon Collider is being pursued at Fermilab. There are a number of very difficult accelerator technologies that need to be developed for the successful construction of the Muon Collider. The rapid-cycling synchrotrons for the muon acceleration constitute one of them. At the MAP proposal the normal-conducting magnets are currently considered for the construction of the rapid-cycling synchrotrons. In this Note we outline possible application of High Temperature Superconductor (HTS) based magnets as the low power alternative to the proposed normal-conducting ones.

II. Synchrotron parameters

The μ^+ and μ^- beams after passing through the cooling section are accelerated using combination of linear and circular accelerators. The rapid-cycling synchrotrons are expected accelerate the μ^+ and μ^- beams in a wide energy range, starting at 63 GeV/beam for the precision measurement of the Higgs mass, and up to (1.5 - 3) TeV/beam for the particle physics research beyond the Standard Model.

It is proposed in [2] that the muon acceleration will take place in two subsequent synchrotrons: (I) (30 -> 400) GeV and (II) (400 -> 750) GeV. Due to a very short μ-meson life time these synchrotrons must accelerate both μ^+ and μ^- beam bunches with the shortest possible separation time between them to achieve high luminosity collisions. The main parameters of the proposed Muon Synchrotrons are listed in Table 1. The existing Tevatron ring is used to house these accelerators. The aperture of the synchrotron magnet is determined by both the vertical and the horizontal emittance of the circulating beam. It has been suggested in [2] that a vertical gap of 5-6 mm would allow containment of the beam within +/- 3 σ spread. This is much too small range to suppress the beam scraping on the pipe walls, so the vertical gap should be much higher. Also in the horizontal plane the good field quality should be in no less than (20-30) mm wide to accommodate the changing particle orbits during the acceleration. The rapid-cycling magnets must use a non-conducting ceramic material for the beam pipe to suppress very significant power loss in the pipe's wall. The strength of the elliptical pipe is lower than that of the round one but its strength is improved with the thicker wall provided there is not too large aspect ratio between the horizontal and vertical axes [3]. In addition to the beam scraping problem a larger opening of the beam pipe is detrimental for the proper conductance in the warm beam pipe vacuum pumping system so the accelerator quality vacuum can be achieved. Consequently, for the magnet design we assume the beam gap of 30 mm (vert.) x 100 mm (hor.). The main parameters of the Synchrotrons I and II are listed in Table 1.

Table 1 Main parameters of Synchrotron I and II.

Synchrotron parameter		**I**	**II**
Circumference	[m]	6283	6283
Injection energy	[GeV]	30	400
Extraction energy	[GeV]	400	750
B_{inj} / B_{extr}	[T / T]	0.14 / 1.8	-1.8 / + 1.8
Beam gap (vert. x hor.)	[mm x mm]	30 x 100	30 x 100
Magnet maximum current	[kA-turns]	60	60
Bunch circulation period	[µs]	21	21
Number of orbits		28	44
Acceleration time	[ms]	0.59	0.92
dB/dt rate for acceleration	[T/s]	2800	2000
Bunch cycle time	[ms]	1.5	-
Dual bunch cycle time	[ms]	-	4.6
Bunch frequency	[Hz]	15	15
Duty factor	[%]	1.8	2.8

III. Normal conducting magnets

In order to determine the usefulness of the proposed super-conducting (SC) magnets they need to be compared with the normal-conducting (NC) ones. For this reason we generate new parameters of the NC power cable and the magnetic cores using the design outlined in [2] but with the beam gap increased from 6 mm (vert.) x 30 mm (horiz.) for the Synchrotron I, and 5 mm (vert.) x 50 mm (horiz.) for the Synchrotron II, to 30 mm (vert.) x 100 mm (horiz.) for both. The magnetic core design with the 30 mm gap must be very significantly modified in order to suppress the field descending from the core into the cable space. In Fig. 1a we show the magnetic design with a 1.5 mm gap of ref. [4] used

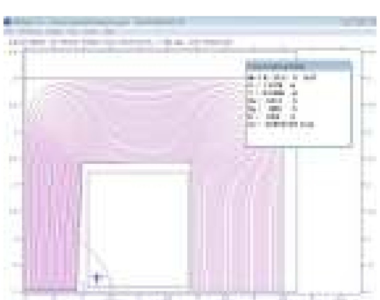

Fig. 1a: 1.5 mm gap, magnet design [4]

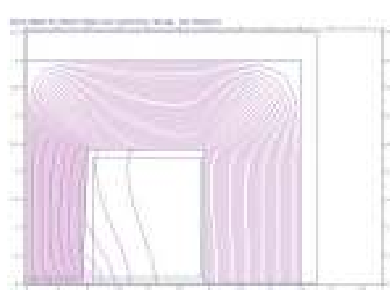

Fig. 1b: 5 mm gap, magnet design [2]

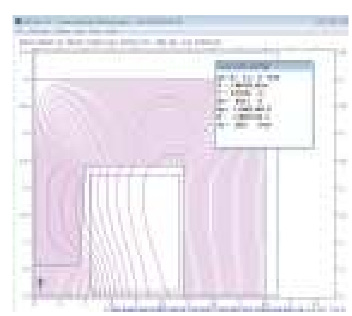

Fig. 1c: 30 mm gap, magnet design [2]

to test a short-sample magnet, Fig.1b and 1c are of the same design but scaled to 5 mm and 30 mm gap, respectively. For the purpose of this illustration we assumed that a very high current density would be possible in the power cable of Fig. 1b and 1c. We observe that the field crossing the conductor with 30 mm gap has increased about 10-fold leading to posssibly 100 times higher eddy power losses. This would increase the projected power loss of the cable in [2] from 6 kW per dipole to 600 kW, and to 840 MW per accelerator. The solution is use a core design where the field crossing conductor is strongly suppressed. As discussed in [5, 6, 7] to achieve this goal the conductor has to be placed in the center of a wide cable gap, and its width should be no more than 20% of that gap, as illustrated in Fig. 2. We scale-up cable design of Ref. 2 to generate 1.8 T field in the 30 mm gap, and we change the magnetic

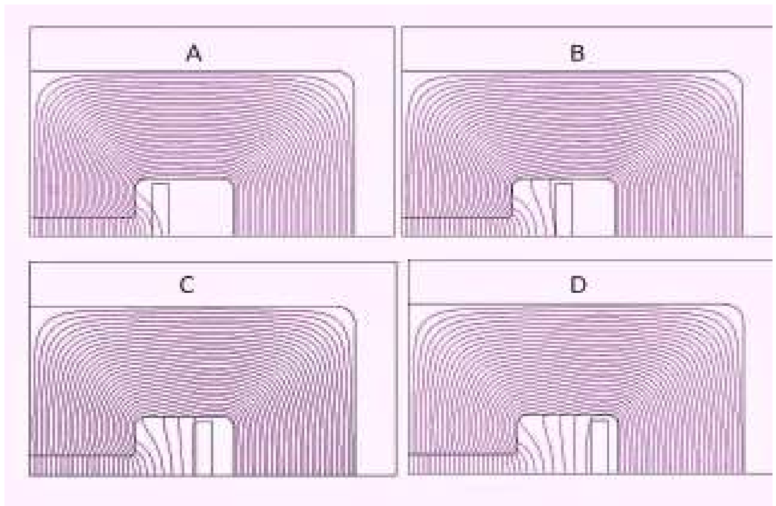

Fig. 2 Dependence of field in the cable gap for various cable horizontal positions

core design to comply with the option "B" of Fig. 2. The total required cable current to generate 1.8 T field in the 30 mm gap is 60 kA. Our preliminary investigation suggests that it would be unpractical, if not impossible, to construct a high frequency (400 – 500 Hz) power supply with 60 kA output current of the half-sine or full-sine wave form, as needed for the Synchrotron I and II, respectively. We tentatively assume that it should be possible to develop a 10 kA current supply, but then the 6-turn conductor will be needed, or six supplies of equal current used in parallel as a single-winding each.

The power cable of Ref. [2, 4] is constructed with thin 2 mm transposed and isolated copper wires to reduce the self-field coupling. In the long multi-strand normal conducting cables the variations in the strand cross-section, length and the strand connecting splices give rise to variations of the strand's resistance and the carried current. This in turn leads to the varying self-fields and the resulting self-field couplings leading to the power loss. In addition, any remnant core field crossing the conductor will generate screen-currents. Such an effect, however, is generally negligible in the cables with transposed and small diameter wire strands.

A sketch of the possible magnet design for the 30 mm (vert.) x 100 mm (horiz.) beam gap and six-turn normal conducting cables is shown in Fig. 3. For the magnetic core we use the non-oriented Fe3%Si laminations of 104 µm width. The cable and magnetic core parameters are presented in Table 2. The 3.75 m and 7.5 m dipoles of the Synchrotron II are combined into one dipole type for the purpose of the power loss estimation.

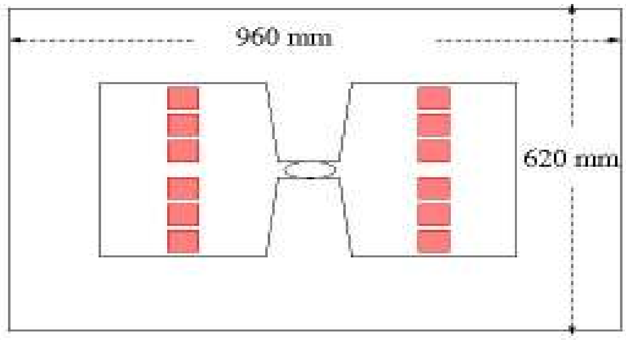

Fig.3 Sketch of a dipole powered with normal-conducting cable

Table 2 NC cable and core parameters for Synchrotron I and II

Power cable		**I**	**II**
Current	[kA-turns]	60	60
Number of turns		6	6
Dipole length	[m]	6.3	7.5
Number of dipoles /accelerator		800	400
Dipole length/accelerator	[m]	5040	3000
Sub-cable length/magnet	[m]	14	16.5
Copper cross-section/sub-cable	[cm^2]	54	54
Copper strand cross-section	[mm^2]	3.1	3.1
Number of strands/sub-cable		1160	1160
Cable mass/magnet	[kg]	1346	1586
Sub-cable resistance	[μΩ]	30	36
Cable resistance @ RT	[μΩ]	180	216
Resistive power loss @ $I_{operation}$	[kW]	18	21
Eddy current loss/cable	[kW]	163	194
Resistive power loss/magnet x DF	[kW]	0.32	0.59
Resistive power loss/accelerator	[kW]	256	236
Eddy current power loss/magnet	[kW]	2.9	5.4
Eddy current loss/accelerator	[MW]	2.32	2.17
Power loss/accelerator	[MW]	2.6	2.7
Magnetic core			
Lamination: Fe3%Si, oriented, 0.1mm			
Overall size (hor. X vert.)	[cm x cm]	96 x 62	96 x 62
Magnetic cross-section	[cm^2]	3600	3600
Magnetic inductance / magnet	[mH]	4	5
Mass per magnet	[ton]	27.6	32.9
Eddy and hysteresis power loss	[W/kg]	8.6	8.6
Power loss/magnet	[kW]	237	283
Power loss/magnet x DF	[kW]	4.27	7.92
Power loss/accelerator	[MW]	3.42	3.17
Consumption power/accelerator	[MW]	6.0	5.9
Consumption power/(I + II) accelerators	[MW]	11.9	

Scaling from the LCW cooling system of the Main Injector a very strong LCW flow (~ 70 % of the Main Injector) will be required to keep the cable temperature rise ≤ 5^0. In the cable design no provision was made for the cooling channels. With the very large number of the copper strands densely packed the appropriate cable design with high cooling capacity will be needed as already suggested [2]. One possible solution is use the cable design presented in [8] but the overall cable size would substantially increase requiring even larger overall cross-section of the magnetic core.

IV. Superconducting magnets

The conceptual design of the super-conducting magnet for the Muon Synchrotrons is based on the work presented in [5, 6, 7]. The main idea for using the HTS, as oppose to the LTS (NbTi), is the possibility of operating with a wide temperature margin, e.g. use the operational temperature of 5 K but set the critical current to 20 K. Such a wide operational temperature margin allows use of temperature sensors in the LHe flow channel to detect the early formation of the quench. This is especially important for the HTS conductors for which the quench propagation velocity is slow making difficult quench detection using the voltage rise across the cable length.

The arrangement of the 344C-2G HTS strands for a power cable is shown in Fig.3. The 2 µm thick

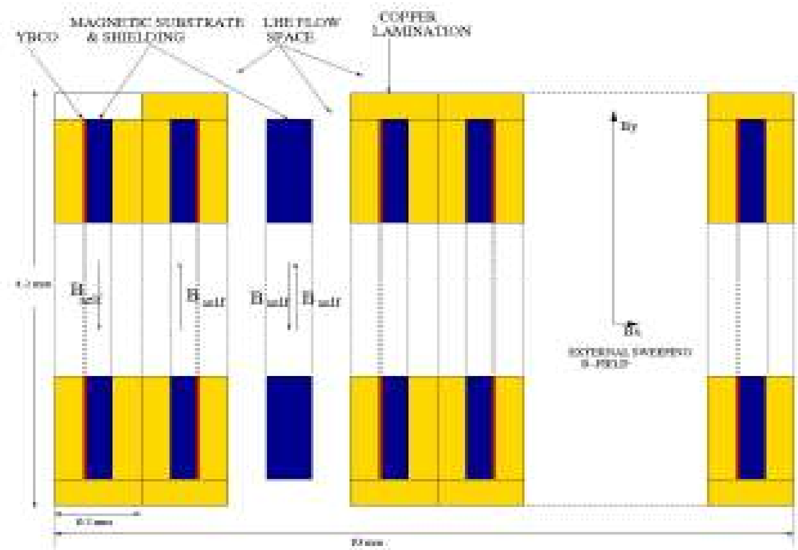

Fig. 3 Arrangement of HTS strands and magnetic substrates in a sub-cable

YBCO layer deposited on the magnetic substrate is encapsulated in the copper lamination. The strands are paired with magnetic substrates facing each other and an additional substrate is placed between each pair with the space left for the liquid helium flow between them. Such an arrangement helps minimize the self-field coupling between the strands. The magnetic core is designed (Fig. 2 B) to create a field-free zone through the cable location, but it cannot be perfect. The stronger B_Y component faces only the narrow (0.2 mm) edge of the strand but the weak B_X component is of concern as it acts on the strand's wide face (4.2 mm) possibly giving rise to the screening currents, as discussed in [5]. Such currents could be eliminated by frequently twisting the HTS tape at 180^0 along the cable path, but this is not practically possible. The multiple magnetic substrates, however, will help minimize the screening currents by absorbing the B_X field through the HTS stack. Consequently, the proposed arrangement of the HTS strands may lead to very low dynamic power losses. The results of the HTS cable test conducted using a sweeping magnetic field of (4 – 20) T/s with the HTS stack orientation toward the magnetic field selected from 0^0 to 8^0 in steps of 1^0, strongly suggests just that [6].

A sketch of the HTS magnet is shown in Fig. 4. The magnetic core design is that of the Fig. 2 B. The core and cable parameters of the HTS magnets for the Muon Synchrotrons I and II are given in Table 3.

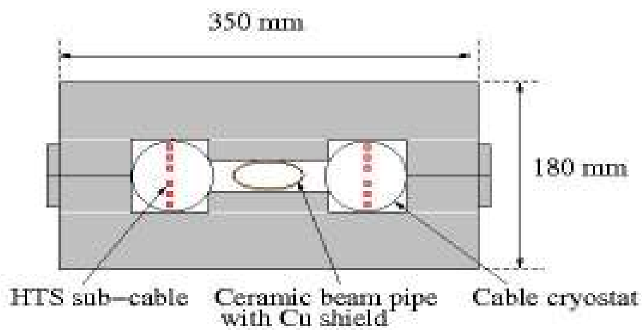

Fig. 4 Sketch of cross-section view of HTS magnet

We constructed power cable considering two types of HTS strands. One is the 344C-2G of the American Superconductor [9] and the other one is that of the Super-Power [10]. Both strands are characterized by about the same critical current and the same dependence on the temperature but the 344C-2G is twice thicker generating proportionally higher hysteresis and eddy losses. For the required 60 kA current at 20 K we use 90 and 48 of each type strand per side to the total of 180 and 96 per magnet. The strands are arranged in 6 vertically stacked sub-cables each with 15 and 8 strands, respectively. The details of the cable construction based on the 344C-2G strands are presented in [7]. The arrangement of the Super-Power strands will be similar except of allowing for wider spaces between the strands, which helps reduce the self-field effect and improves liquid helium cooling. The simulation of the power losses for the complicated structure of the HTS strand is rather difficult and as shown in Ref. [6] the predictions were underestimated by a factor of 2. The analysis of the discrepancy, however, suggested that it was due to a mechanical vibration of the cable caused by the sweeping magnetic field rather than the unaccounted hysteresis, or eddy losses. We will use data from ref. [6] (rather than predictions) to tentatively project cable power losses for the Synchrotrons I and II magnets. Although no field from the core is expected within the cable space, and the strand self-field coupling should be strongly minimized with the magnetic substrate strips between the YBCO conductors, we assume that the remaining effective field in the cable space is at a 1% level of that in the magnet gap. Consequently, the 0.5 T field in the cable space corresponds to 50 T in the beam gap with the dB/dt rate of 2000 T/s. This rate is close to the 2800 T/s required for the Synchrotron I and equals the 2000 T/s of the Synchrotron II. The forthcoming rapid-cycling HTS magnet test [7] will allow for more direct projection of the HTS cable power loss in the Muon Synchrotrons application.

Table 3 Cable and core parameters with HTS-based Synchrotron I and II

Power cable		**I**		**II**	
Current	[kA-turns]	60		60	
Number of turns		6		6	
Cable type		344C-2G	Super-Power	344C-2G	Super-Power
Strands per cable		180	96	180	96
Strands per sub-cable		30	16	30	16
Cable length/magnet	[m]	90		108	
HTS conductor mass/magnet (with Ni5%W)	[kg]	15.2	9.0	18.2	10.7
Cable cryogenic pipe mass/magnet	[kg]	12.7	12.7	15.1	15.1
Total cable mass/magnet	[kg]	27.9	21.7	33.3	25.8
dB/dt rate in cable space	[T/s]	30		20	
Cable power loss @ 5 K	[W/m]	90	60	30	20
Cable power loss @ 5 K x DF	[W/m]	1.6	1.1	0.6	0.4
Power loss/accelerator @ 5 K x DF	[kW]	8.1	5.6	1.8	1.2
Cryogenic line power/accelerator	[MW]	2.4	1.7	0.5	0.36
Magnetic core					
Laminations: Fe3%Si, 0.1 mm, non-oriented					
Overall size (hor. X vert.)	[cm x cm]	35 x 18		35 x 18	
Magnetic cross-section	[cm^2]	538		532	
Magnetic inductance	[μH]	400		500	
Mass per magnet	[kg]	2600		3095	
Eddy and hysteresis power loss	[W/kg]	8.5		8.5	
Power loss/magnet	[kW]	22.1		26.4	
Power loss/magnet x DF	[kW]	0.4		0.74	
Consumption power /accelerator	[MW]	0.32		0.30	
Consumption power/accelerator	[MW]	2.7	2.0	0.8	0.7
Consumption power/(I + II) accelerators	[MW]	3.5	2.7		

V. Power required to ramp magnets

For the rapid cycling magnets the power to ramp magnetic field is determined by the magnetic inductance and the cable resistance. The pulse current voltage rise is $U = L\, dI/dt + I_{max} \cdot R$ and to calculate the required power I_{max} is substituted with $I_{ave} = 0.6\, I_{max}$. In the NC magnets both large cable resistance and large inductance require very high power to ramp the magnets. In addition the power supply of more than 10 kA output current is rather difficult to construct. Although the consumed power for ramping the magnet is recovered at 80 % level the construction and operation of the large capacity power supplies is very expensive. In order to project the required ramping power for the Muon Synchrotrons we limit the magnet current to 10 kA which means that the 6-turn conductors are required increasing six-fold magnetic inductance. The magnet ramping power parameters for the Synchrotrons I and II with 6-turn NC and the SC cables are listed in Table 4. One can see that the use of NC magnets with 30 mm beam gap for the rapid-cycling Muon Synchrotrons is not realistic. In the earlier NC magnet designs the beam gap was only 5 or 6 mm high so the conductor was packed into a minimal space (Fig.1a,1b) within the magnetic core while the field descending from the core was much suppressed. Such an arrangement helped reduce the magnet current and the magnetic inductance to the level acceptable for a practical application.

Table 4 Ramping power parameters for Synchrotron I and II with 6-turn conductor

Parameter/magnet		**Synchrotron I**		**Synchrotron II**	
		NC	**SC**	**NC**	**SC**
Magnet length	[m]	6.3		7.5	
Magnet mass	[kg]	27600	2600	32900	3095
Cable mass	[kg]	1346	27.9	1586	33.3
Cable resistance	[μΩ]	180	< 1	216	< 1
Magnetic inductance	[mH]	4	0.4	5	0.5
RMS current	[A]	6000		6000	
Voltage rise	[kV]	40	4	52	5
Ramping power (inductive)	[MVA]	246	100	315	130
Ramping power (inductive) x DF	[MVA]	4.5	1.1	8.8	3.6
Ramping power (resistive)	[KVA]	6.5	0.01	7.8	0.01
Ramping power (resistive) x DF	[kVA]	0.12	0.0002	0.2	0.0003
Total ramping power x DF	[MVA]	4.6	1.1	9	3.6
Ramping power recovered (80%)	[MVA]	3.7	0.9	7.2	2.9
Ramping power loss	[MVA]	0.9	0.2	1.8	0.4
Ramping power loss/accelerator	[MVA]	720	160	720	160

For the SC magnets the resistive part is strongly suppressed as it is mostly due to splicing of the conductors (typically < 1 nΩ/splice) as well as the resistive leads of the power supply (< few μΩ). In addition, and importantly, the much smaller SC cable space makes the magnet inductance very low. It would be useful, however, to reduce further the magnetic inductance as it dictates the required ramping power. In the proposed HTS magnet design the inductance can only be reduced by using fewer conductor turns. This approach requires development of a high-current (60 kA) rapid-ramping power supply or use of multiple supplies each energizing e.g. a one, two or three turn conductor coil. As example, the ramping power loss with 6 individually powered coils is given in Table 5. One can see that the NC magnet still requires unacceptably high ramping power.

Table 5 Ramping power with six individually powered coils

Magnet coil: Six individually powered coils		Synchrotron I		Synchrotron II	
		NC	SC	NC	SC
Voltage rise	[kV]	6.7	2.7	8.6	3.4
Ramping power	[MVA]	41	17	53	21
Ramping power x DF	[MVA]	0.7	0.3	1.05	0.42
Ramping power lost x DF	[MVA]	0.14	0.06	0.2	0.08
Ramping power / accelerator	[MVA]	560	240	600	240
Ramping power loss/accelerator	[MVA]	112	48	120	48

VI. Rapid-cycling test magnet design

The currently assembled fast-cycling magnet test at E4R will provide information on the magnet performance up to 20 T/s rate with 0.5 T field in the 40 mm beam gap. The magnet is powered with a single-turn HTS cable to a maximum 20 kA pulse current operating at frequency of 10 Hz. In addition the magnetic core and the power cables are placed inside the cryostat eliminating the individual cable cryostats. For the Muon Accelerators the field rate is expected to be of (2000 - 3000) T/s range generating significant heating of the core. For this reason the cables cannot share the cryostat with the core and the core should be both air and water cooled. In order to have more realistic test of the rapid-cycling SC magnet for the Muon Synchrotrons we propose construct a new test magnet. The power supply must ramp magnet current in the 0.59 ms (Synchrotron I) and 0.92 ms (Synchrotron II). The pulse current is of a half-sine wave form (I) and a full-sine wave form (II), both operating at 15 Hz repetition rate. We design test magnet with 5 mm vertical gap and 2-turn conductor requiring 3 kA current supply for 1.8 T field. We will need to construct a 3 kA power supply to test this magnet. Most of the parts are on hand from other constructed supplies which are part of the MI accelerator complex. The MI supply operates with 2 μs pulse at 15 Hz. We will modify it to operate with the ramping times appropriate for the Synchrotrons I and II. The cryogenic support system developed at E4R for the forthcoming magnet test will be reused, with only minor modifications needed for the new test. The magnetic design of the test magnet is shown in Fig. 5, and the basic parameters are given in Table 5. For the conductor we propose use the YBCO based Super-Power strand which can carry nearly the same current as the 344C-

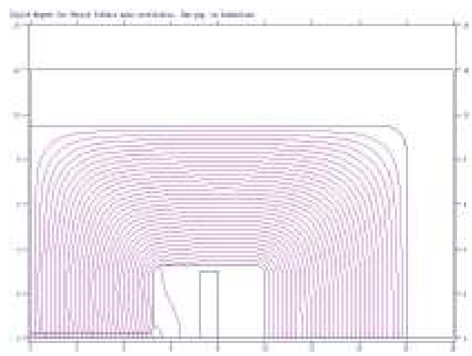

Fig. 5 Test magnet design: beam gap 5 mm (V) x 100 mm (H)

Table 5 Parameters of rapid-cycling test magnet

Core		
Lamination		Fe3%Si non-oriented, 0.1 mm
Cross-section, H x V	[mm x mm]	350 x 180
Length	[mm]	500
Beam gap, V x H	[mm x mm]	5 x 100
Mass	[kg]	206
Cable		
Manufacturer		Super-Power
Cross-section, W x T	[mm x mm]	4 x 0.1
Number of strands / sub-cable		3
Number of sub-cables		6
Strand length / sub-cable	[m]	4.5
Current (operations)	[kA-turns]	6
Number of turns		2
Total strand length	[m]	27
Cable mass (with Ni5%W)	[kg]	2
Critical current @ 20 K	[kA]	1
Current max @ 7 K (operations)	[kA]	1.5
Magnetic inductance	[μH]	9

-2G strand but with only 0.1 mm narrow edge. This allows make wider spaces between the strands for the more efficient helium cooling and also to further lower the self-field induced power losses of the cable. It is also important to note that the Super-Power strand is mechanically stronger than the 344C-2G allowing withstand the shrinkage during the cryogenic cycles without a special mechanical support. The cable on each side of the beam gap will be enclosed in its own cryostat pipe and cooled with the supercritical helium of 7 K, 2.8 bar pressure and the flow rate up to 1 g/s. The helium temperature, pressure and flow rate will be measured to provide data on the power loss. The non-oriented 0.1 mm Fe3%Si laminations will be used for fabrication of magnetic core. The core will be constructed with two half-cores to facilitate cable installation. The LCW flow will be used to provide the core cooling.

The mechanical arrangement of the multi-turn HTS cable is rather difficult. The engineering design of the test magnet cable will allow investigate various options. The return of the conductor, however, takes place only at the beginning and at the end of the magnet string. There are 28 beam orbits in the Synchrotron I and 44 beam orbits in the Synchrotron II. Consequently, the length of the magnet string cannot be longer than about 200 m (6283 m/28) or about 140 m (6283/44) for the Synchrotron I and II, respectively. As the magnetic inductance is low with the SC magnets it should be possible then use only a single power supply per each magnet string.

VI. Summary and conclusions

Our investigation of the muon acceleration magnets indicates that only magnets powered with the HTS cable may prove applicable for the Synchrotrons I and II. As example, a graphic comparison of cost related and technology challenging parameters for the Synchrotron I magnets is shown in Fig. 6.

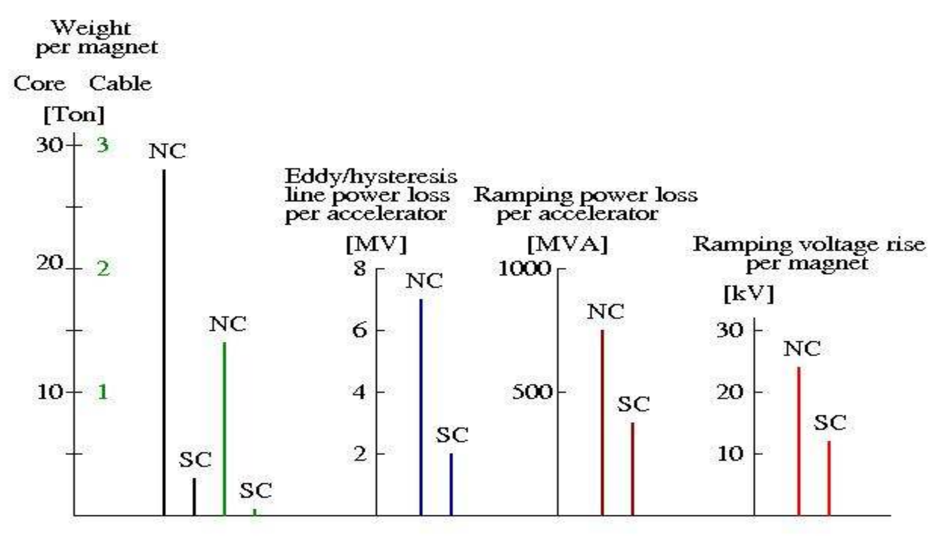

Fig. 6 Cost and power related parameters for magnet and accelerator with NC and SC power cables

We also assumed the lowest possible magnetic inductance by applying six independent single-turn conductors to power the magnet, so they effectively act as a single turn cable. For the NC magnets even such a hardly practical cable arrangement results in a technically very difficult 30 kV range ramping voltage for a single magnet, and an unattainable ramping power for the accelerator. The high ramping voltage rise with the NC cable would not allow power a magnet string but at best only a single magnet using as many power supplies as magnets in the accelerator ring and thus immensely increasing the accelerator construction cost. Contrary to that even the 6-turn SC cable leads to less than 4 kV voltage rise which is easy implementable.

It is also interesting to compare the conductor and magnetic core costs for the magnets powered with NC and SC cables. At present the cost of copper is $3.26/LB and the cost of HTS (344C-2G) is $30/m for small quantities (the claim from the American Superconductor is that for very large orders the HTS cost will drop to the level of the cost of copper carrying the same current at RT). The copper mass for the Synchrotron I magnet is 1346 kg at a cost of $9654. The HTS strand length/magnet is 1350 m and its cost is $40,000 for a small order, so the net cost loss for the SC cable is $30,000. The order of magnitude difference in the core weight, however, is a large gain for the SC magnet. The cost of the standard (0.35 mm) non-oriented electrical steel was $1600/ton in FY10. The re-rolling to the 0.1 mm thick plates at least doubles the cost. We cautiously estimate that the 0.1 mm non-oriented laminated silicon steel is in the range of $4000/ton. As the mass difference between the NC and the SC magnet core is 25 tons the gain is $100 K per 6.5 m magnet. In summary the SC magnet has the net cost gain of at least $70,000, or $90 M for magnets of both Synchrotrons I and II. This cost difference will more than once cover the cost of the cryogenic support system construction for the SC magnets.

The SC cables are primarily considered for the construction of the high-field magnets. But it has been demonstrated (VLHC Stage 1, FAIR, PS2, Super-SPS) that for the large scale accelerators the low-field magnets powered with the SC cable are preferable over those with the NC one as the investment in the cryogenic support system pays off. This includes cost of magnet construction, power requirements and the cryogenic construction and utilization. Even if the construction and utilization costs of the NC and the SC Synchrotrons for the muon acceleration would not differ much the required ramping power with the SC magnets is within the feasible range and thus making them likely to be the only possibly applicable option for the muon acceleration synchrotrons.

We greatly benefited from discussions with Jamie Blowers, Steve Hays and Nikolay Solyak.

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