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Superconducting Transmission-Line Magnet Ring in Tevatron Tunnel

Henryk Piekarz

P996 Experiment Meeting

Outline of Presentation

- Possible applications of transmission-line superconducting magnet ring in Tevatron tunnel
- Principles of transmission-line superconducting magnet design
- Beam line construction with transmission-line magnets
- Experience with transmission-line superconducting magnets
- LBNE/P996 magnetic core and power cable arrangement
- Preliminary design of LBNE/P996 gradient dipole
- Conductor for LBNE/P996 dipole magnet
- Arrangement of LTS cable for LBNE/P996 dipole magnet
- LBNE/P996 magnet string power supply and power leads
- Corrector magnets options with superconducting LBNE/P996 beam lines
- Preliminary cost estimate for P996 beam line
- Tasks for P996 beam line design and magnet prototyping
- Fast-cycling superconducting magnet test at E4R and extension to LBNE/P996 magnet tests
- Summary & conclusions

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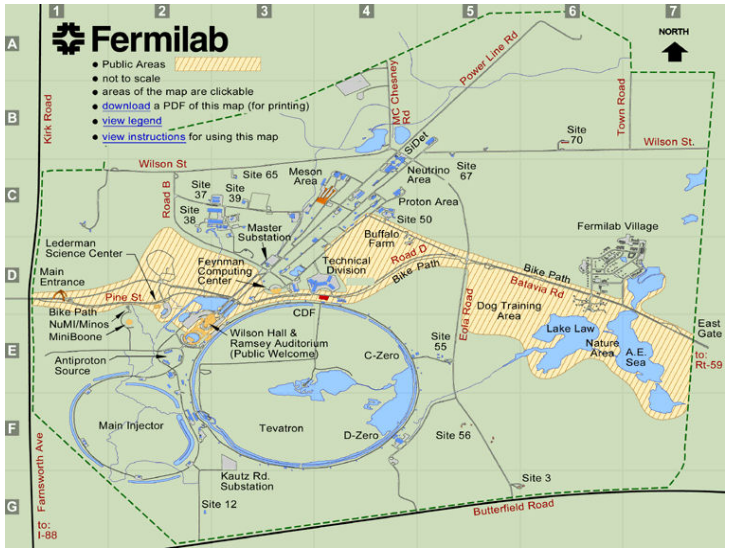
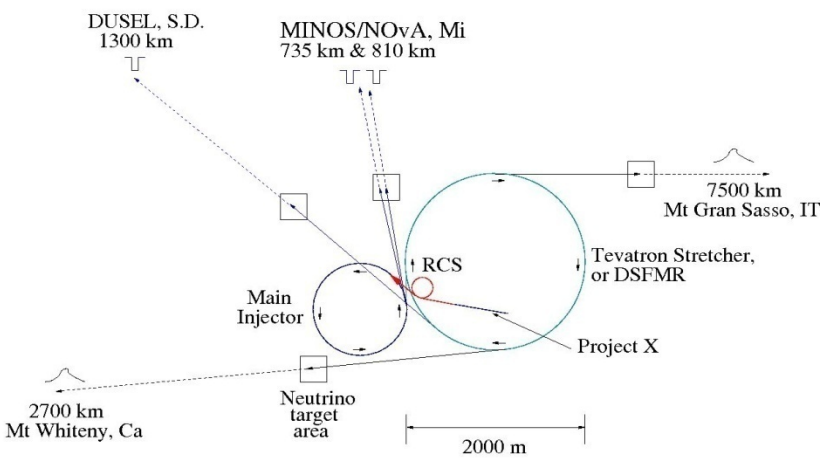
Possible Applications of Transmission-line Superconducting Magnet Ring(s) in Tevatron Tunnel





1. **Stretcher – One 150 GeV proton beam**
   - **Fixed target physics: Kaon decays, Neutrino oscillations, etc..**
2. **DSFMR - Two fast-cycling (2 Hz each) 480 GeV proton beams**
   - **High power Fixed target physics: Neutrino oscillations, Kaon physics**
   - **Dual fast injector to VLHC**

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Principles of Transmission-line Superconducting Magnet Design

- Magnetic field in the magnet beam gap is generated by the current from a single-turn conductor (fig. 1)
- Magnetic field strength in the beam gap is dependent on both the current in the conductor and the magnetic permeability of the core material
- Transverse inclination of magnetic poles within the beam gap space (fig. 2) generates a combined dipole & quadrupole magnetic functions reducing required focusing power in independent quadrupole magnets
- Single-turn conductor requires high currents to generate required B-fields but it much simplifies magnet assembly work reducing the magnet cost
- Single-turn conductor constitutes easiest application of transmission-line power cable concept with the entire magnet string (beam line) being energized with a single power supply

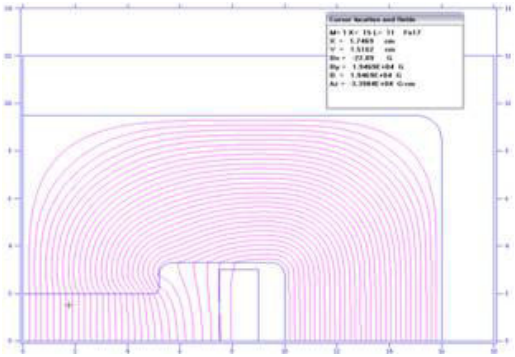


Fig. 1 Example of ¼ of magnetic core for a dipole magnet. Conductor (square) sits in the core cavity outside the beam gap. It runs through the entire magnet length and then continues to the next magnet.

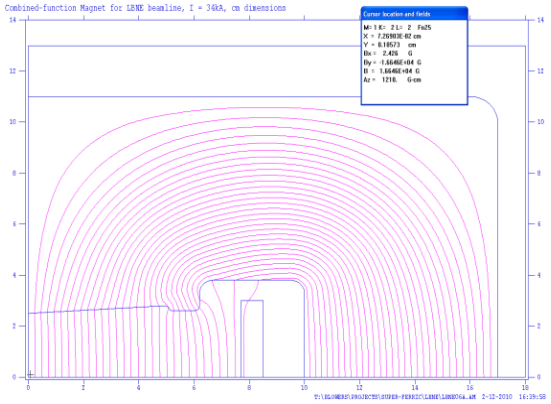
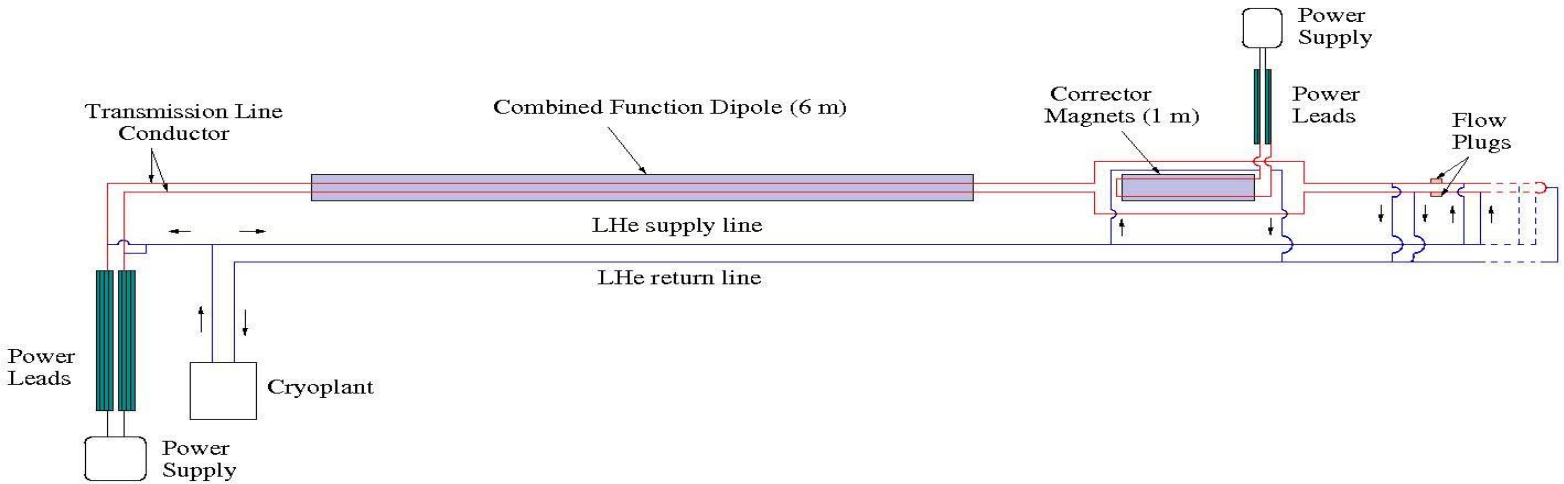


Fig. 2 Example of magnetic core design for a gradient dipole

Beam Line Construction with Transmission-Line Superconducting Magnets



Beam line consists of multiple sets of gradient dipole and correctors (quads, dipoles, sextupoles). All gradient dipoles are powered by a single power supply with a single set of power leads. Correctors require multiple supplies and multiple leads for each set. Correctors can be either normal conducting or superconducting.

Gradient dipoles can be of different length to match the varying requirements along the beam path.

LHe coolant is distributed independently to the individual magnets ensuring high efficiency of heat removal.

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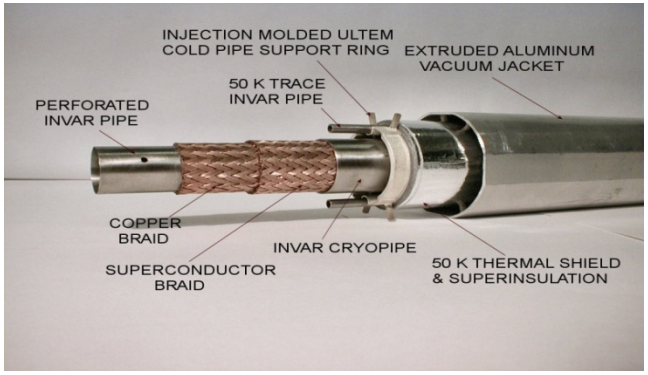
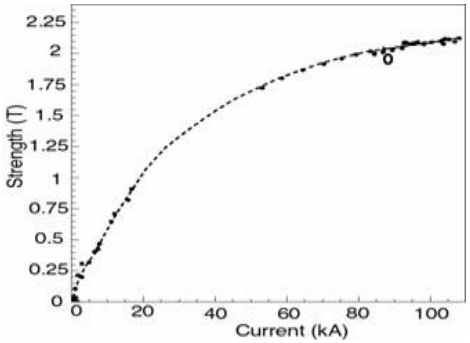
Experience with Transmission-Line Superconducting Magnets

VLHC-LF magnet with 2 beam gaps on the sides and transmission-line conductor in the center.

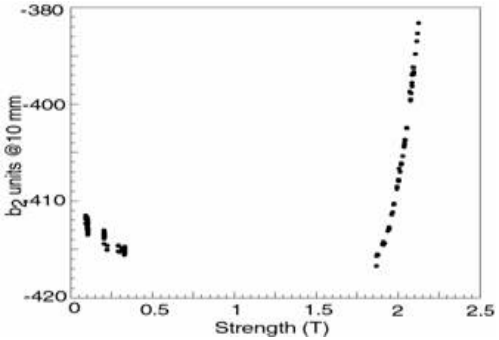


VLHC-LF transmission-line conductor, 100 kA

Final assembly work of VLHC-LF magnet



B-field versus current



Sextupole strength

Five papers published at International Conference on Magnet Technology, MT-19

LBNE Magnet String Power Supply and Power Leads

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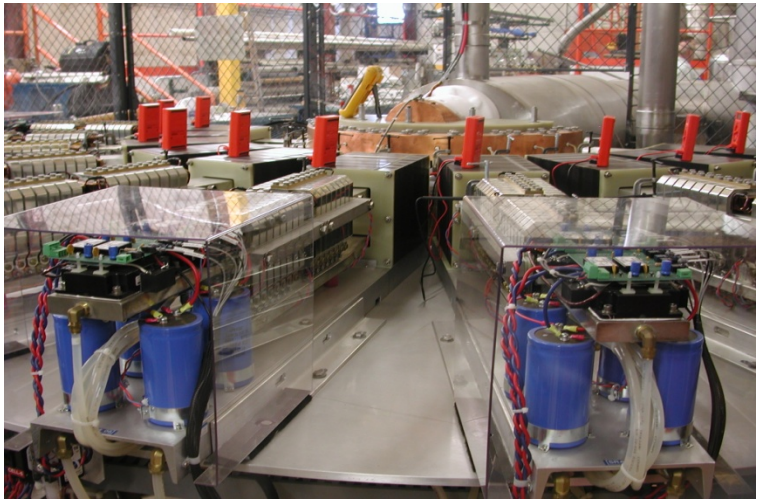
VLHC-Stage 1 magnet test arrangement at MS6



Close-up look at 100 kA power supply at MS6

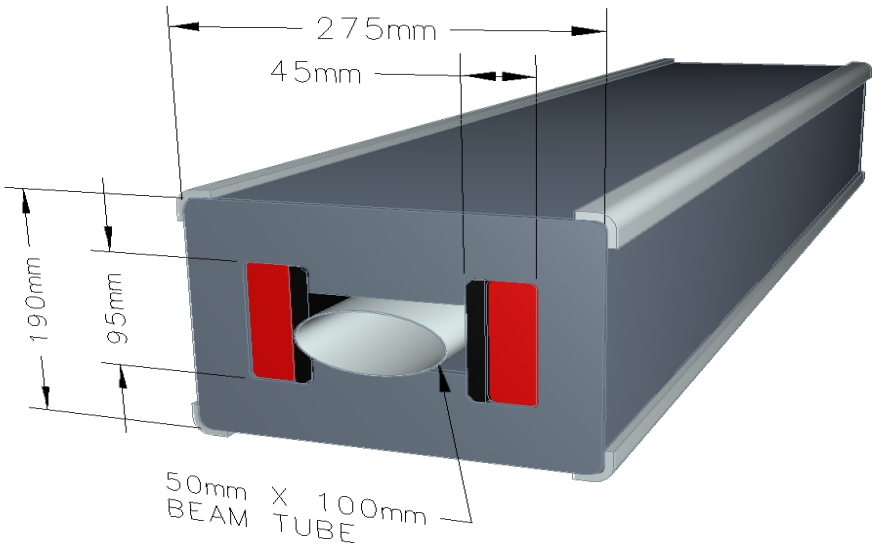
Assembly work on 100 kA power lead

Power supply and power leads exist. They successfully operated up to 104 kA for the VLHC-Stage 1 magnet test at MS6.

They can support the LBNE magnet string.

This system can be relocated as desired.

LBNE/P996 Dipole Magnet Arrangement



Core can be made of two yokes split along the central horizontal plane , and then assembled in-situ over conductor cables and beam pipe.

Magnetic core uses 0.65 mm laminations of Fe3%Si steel, or 1.5 mm AISI 1008. Although LBNE/P996 magnet operates in a DC mode the very fast, μ-second range, B-field decay time in the silicon steel suppresses persistent currents effect caused by ramping. The carbon blocks placed between the beam pipe and conductors absorb and spread over a larger volume the beam loss induced heat into the conductors thus minimizing potential for a quench.

Preliminary Design of Gradient Dipole for LBNE/P996 Beam Lines

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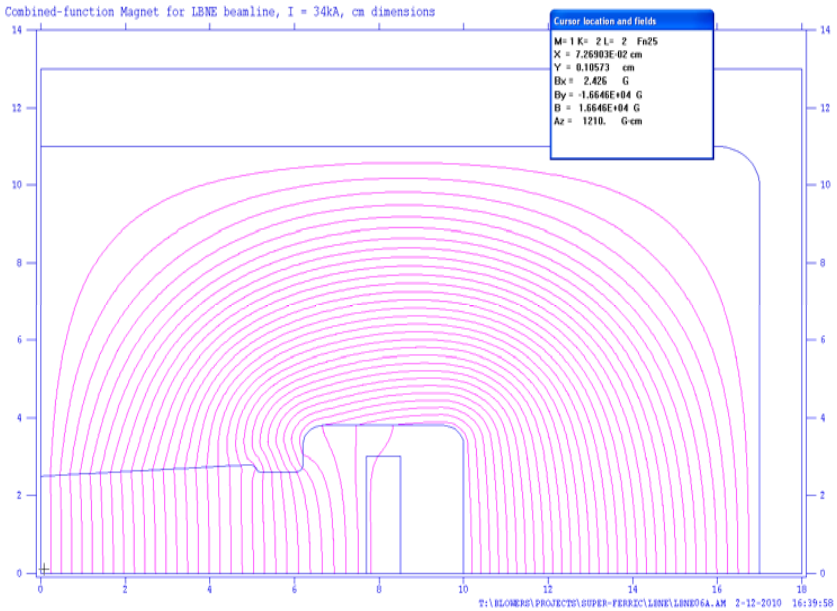

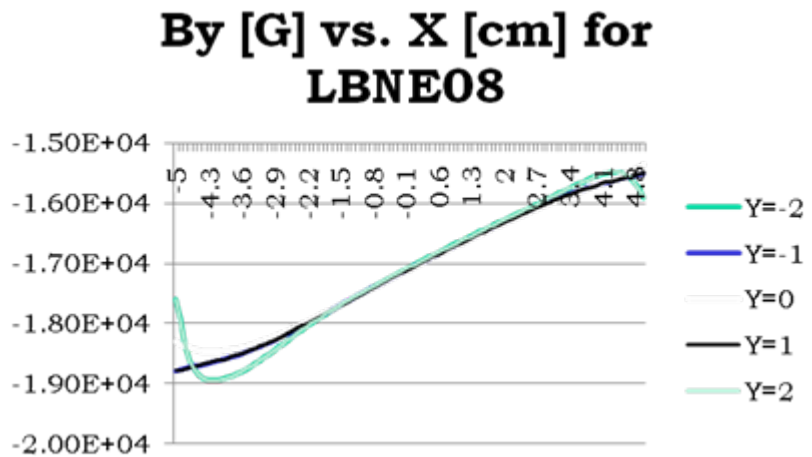

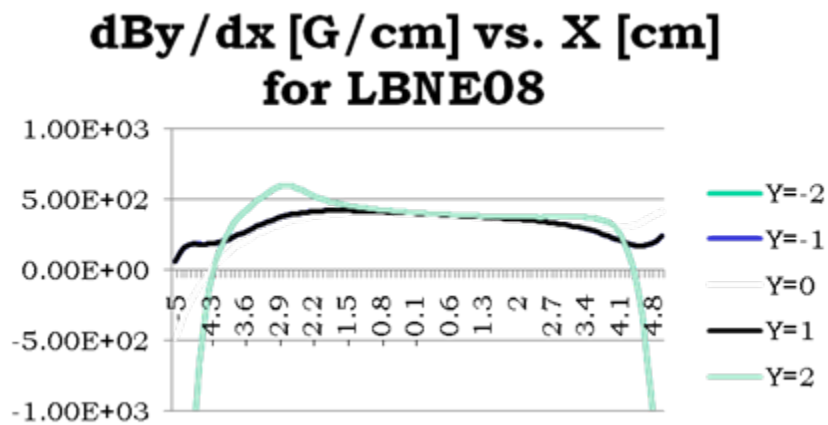

Beam gap = 50 mm (X = 0) x 100 mm
B = 1.7 T @ X= 0, I = 70 kA
B = 0.65 T @ X=0, I 26 kA
dBy/dX = 4 T/m (LBNE)
dBy/dX = 1.5 T/m (P996)

Conductor for LBNE/P996 Dipole Magnets Using Superconductor Wire

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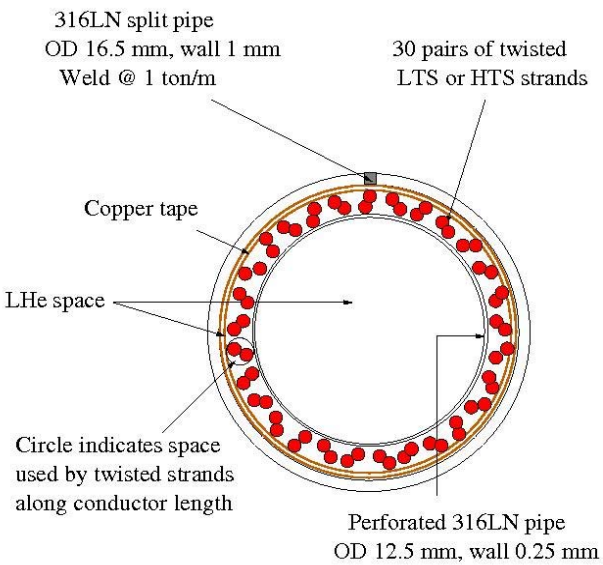
For dc operations at low B-fields the LTS conductor, such as NbTi, is the most proper one as its cost is about 200 times lower than that of the HTS.

The HTS can operate with much wider temperature margin and at higher magnetic fields, properties NOT truly required for the LBNE or P996 magnets.



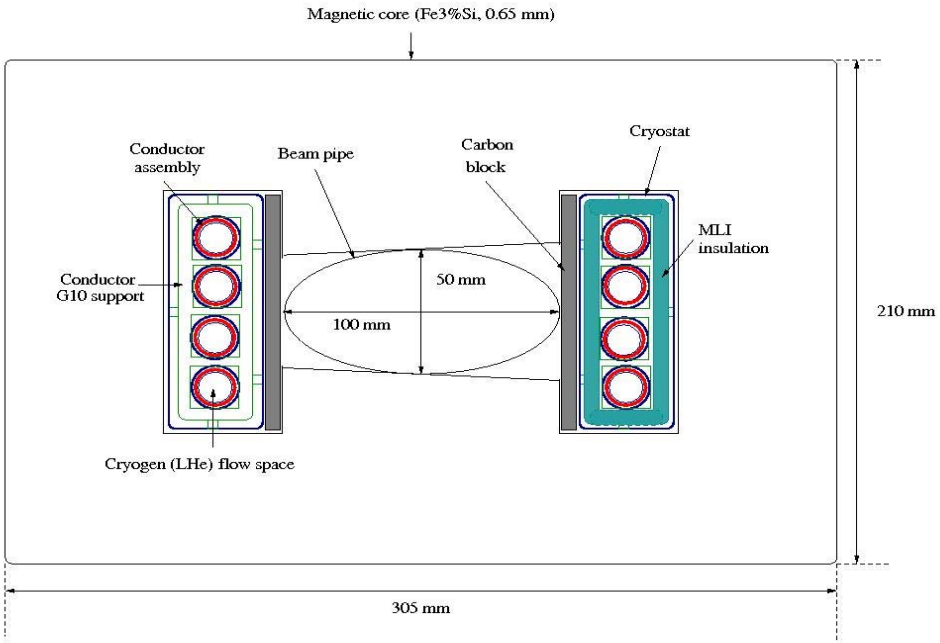
Combined function LBNE/P996 dipole: 50 mm gap
Magnetic core laminations: Fe3%Si, 0.65 mm, or
AISI 1008, 1.5 mm

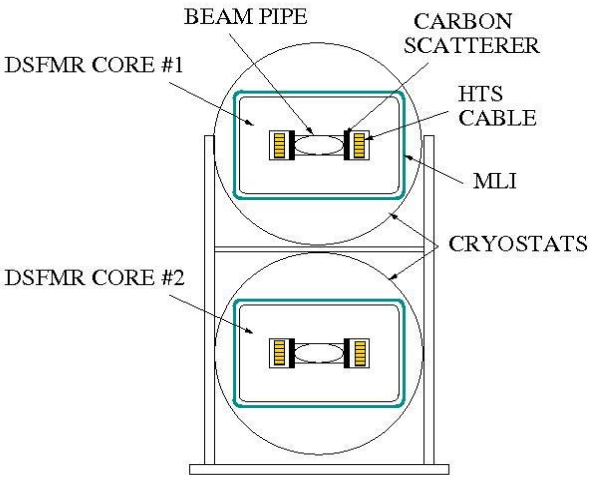
Operating current: 68 kA-turns @ 1.7 T (LBNE)
26 kA-turns @ 0.65 T (P996)

Superconductor: NbTi 0.8 mm wire
Maximum current / mm^2: 1 kA @ 4.2 K _2 T
N strands/cable: 240 (LBNE), 92 (P996)
Maximum current: 150 kA (LBNE), 58 kA (P996)
Operating current: ~ ½ maximum current

30 pairs of twisted superconductor wires are placed on the perforated liquid helium channel pipe. These wires are held together with help of multiple copper tape wraps and inserted into a split cryostat pipe. The pipe is laser welded under 1 ton/m tension to firmly secure strands placement on the supporting pipe.

Arrangement of Superconducting Cable for LBNE/P996 Dipole Magnet





Each power cable consists of 4 independent sub-cables held together by G-10 support rings. Squared cut-outs minimize sub-cables heat leak. The 40 layers of MLI covers assembly of all 4 conductors. Carbon blocks minimize beam loss induced heat in the conductor and in the helium coolant.

Optional arrangement with magnetic cores supported by large cryostat pipe. The MLI can be placed outside the core though the core is not cooled.

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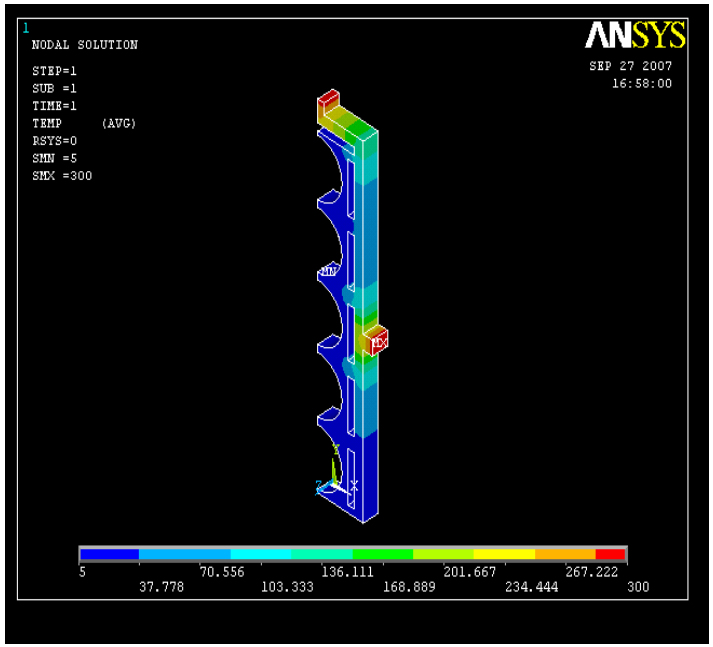
Cryogenic Power Losses for P996 Magnet Ring



Heat loss analysis of a G-10 support ring for a fast-cycling magnet (PS2, 10 conductor lines).
Assumptions for strength: 1 ring/m, 2 T/s, 0.5 Hz, 30 Years of operation at 90% duty factor.
Projected heat loss: Conduction = 0.62 mW/m, Radiation with 40 layers of MLI= 0.03 mW/m.
N rings(dc) < 1/3 N rings(ac) (analysis/tests are required) gives heat loss (dc) < 0.22 mW/m.
We expect then the maximum heat loss for LBNE line < 330 W, and for Stretcher < 2.8 kW.

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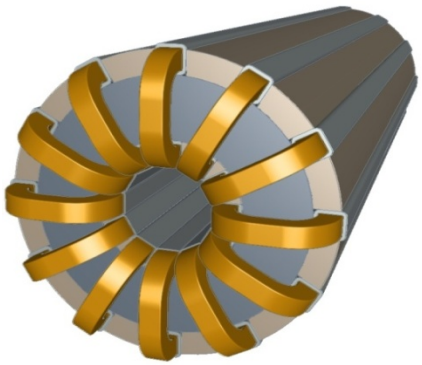
Corrector Magnets Options with Superconducting LBNE/P996 Beam Lines

Multipole corrector magnet may comprise of :

- Vertical or horizontal dipole
- Quadrupole
- Skewed quadrupole
- Sextupole

Not all of them are required at each gradient dipole. Hence the best approach is to have a universal corrector magnet where selected combination of windings will produce desired set of correctors. This combination may change with different beam line stages.



A view of a universal corrector with 12 coils over a hollow cylindrical core. Current leads and cryostat are not shown.

V. S. Kashikhin, IEEE Trans. Superc. Vol 15, 2005

Universal corrector can be both normal or superconducting. For the cost estimate we assumed the superconducting one of 1 m length and with the following parameters:

-Vertical/Horizontal dipole: 0.5 T
-Quadrupole: 2.4 T/m
-Skew quadrupole: 1.2 T/m
-Sextupole: 1.2 T/m

12 coils / corrector
5 supplies / corrector
Operating current: 20 kA-turns
N strands: 80 / coil
Core: Fe3%Si, 0.65 mm, OD/ID = 240 mm /120 mm
Leads: 5 / corrector

Preliminary Cost Estimate – P996 Assumptions

1. There are 774 dipoles of 7 m and 240 quads of 1.35 m inTevatron ring. For P996 Stretcher we use the same number of dipoles but replace quads with 240 correctors.

   Gradient dipole: B -field = 0.65 T, B-field gradient = 1.5 T/m
   Correctors: B (V/H) = 0.5 T, Quad = 2.4 T/m, Sextupole = 100 T/m^2

2. Superconducting transmission-line cable = 2 x 6250 m => 12500 m with total length of superconducting strand = 1156 km.

3. Corrector cables superconducting strand total length = 576 km.

4. Supporting vacuum system for the superconducting cables, power supplies, magnet supporting structure and quench protection system.

5. For all crucial components the M&S cost of the construction of the fast-cycling superconducting dipole for the E4R test was used.

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P996 combined function dipole

Gradient dipole	Strength	Gap [mm]	Length [m]	Integrated strength
B-field	0.65 T	50	7	3.9 T-m
B-field gradient	1.5 T/m	50	7	9 T/m

Power cable conductor	Nominal kA-turns	N strands/coil	Cable strand length [m]
2 x 6280 m = 12560 m			
NbTi 0.8 mm wire	26	92	1,156,000
Ic = 1 kA @ 5 K, It = 0.3 kA @ 5K			

Power cable cryopipes	Length [m]	N units/ magnet	N units/cable
12.5 mm OD, 0.5 mm wall, 316LN	100,000		
16 mm OD, 1 mm wall, 316LN	100,000		
90 mm x 35 mm, 1mm wall, 316LN	12560		
Cold pipe G-10 supports		36	37680
MLI insulation, 40 layers	12560		
LHe distribution lines (supply & return)	exist		
Magnet transfer lines (supply & return)	1.5	2	2000
LHe recoolers	exist		
Controls (temperature, flow, pressure)			772 + 18 + 18

Core laminations	Weight/dipole [ton]	Weight/774 dipoles [ton]
AISI 1008, 1.5 mm		
0.32 m x 0.19 m x 6 m	2.9	2245

Dipole support	Length/dipole [m]	Length/774 dipoles [m]
Pipe, 400 mm OD, 6 mm wall, 304	7	5400

Dipole position adjusting mechanism	N units/magnet	N units/beam line
Vertical	1	774
Horizontal	1	774
Skew	1	774

Power supply		
10 kA rectifier (VLHC Stage 1)	3	3

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P996 multipole corrector magnets

Component	Strength	Gap [mm]	Length [m]	Integrated strength	kA-turns
Vertical & horizontal dipole	0.5 T	80	1	0.5 T-m	20
Quadrupole	2.4 T/m	80	1	2.4 T	3
Sextupole	100 T/m^2	80	1	100 T/m	6
Skew quadrupole	1.2 T/m	80	1	1.2 T	1.5

Coil	kA-turns	N strands/coil	Strands/coil [m]	Coils/magnet	Strands/magnet [m]	Strands/240 magnets [m]
NbTi or Bi-2212 wire						
0.8 mm, Ic = 1 kA @ 4.2 K						
It = 150 A, ~ 15% Ic						
Each corrector type	20	80	200	12	2400	576,000

Core laminations	Outer diameter [mm]	Inner diameter [mm]	Weight/segment [kg]	Weight/magnet [kg]	Weight/240 magnets [ton]
Fe3% Si steel, 0.65 mm laminations	240	120	22	264	64

Cryogenic support	Length [m]	Outer diameter [mm]	Inner diameter [mm]	N units/240 magnets	Length/240 magnets [m]
Vessel	1.2	300	60	240	288
Transfer lines	1.5			480	720
Controls (temperature, flow, pressure)				480 + 4 + 4	

Leads	Length/lead [m]	Cu rods/lead	Vessels/lead	Leads/magnet	Leads/240 magnets	Length/240 magnets [m]
OFHC copper, 1/4" dia.	1.6	2	1	5	1200	1920
Cryovessel						
SS pipe 3/4" dia.	1.7					2040
SS pipe 1-1/4" dia.	**1.7**					2040

Corrector postion adjusting mechanixm	N units/magnet	N units /240 magnets
Vertical	1	240
Horizontal	1	240
Skew	1	240

Power supply	N supplies/magnet	N supplies / 240 magnets
Lambda 300 A / 2.5 V	5	1200

P996 conductor line vacuum system

Vacuum jacket @ E-7 Torr		Length [m]
LHe Supply & Return main lines	exist	
Main lines to magnets, SS pipe 50 mm dia.		2000
Total length		2000
Conductor line, 90 mm x 35 mm		6280
Conductor line, 90 mm x 35 mm		6280
Total length		12560

Vacuum pumps	N units / 100m	N units / LHe Supply/Return	N units /Conductor lines
Turbo pumps - 50 L/s	1		250
Fore-pumps	1		250
Pumpout ports	1		250
Pirani gauge	1		250
Ion gauge	0.2		64
RGA	0.1		32

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P996 transmission-line superconducting magnets - cost estimate

Dipoles	Unit	N units	M&S $ / unit	Labor Hr/unit	M&S $ total	Labor @ $40/hr
Conductor, NbTi (0.65 T)	m	1,156,000	0.35		405 k	
Pipes, 316LN						
12.5 mm OD x 0.5 mm wall	m	100,000	28.74		2874 k	
16.5 mm OD x 1 mm wall	m	100,000	10.75 (estimate)		1075 k	
90 mm x 35 mm x 1mm wall	m	12,560	71.64		890 k	
Bellows		4,000	100		400 k	
G-10 support rings	EA	37,680	50		1884 k	
Cable assembly	EA	774		160		124 k
Core AISI 1008, 1.5 mm						
0.28 m x 0.19 m x 0.65 mm	kg	2,245,000	1.3		2918 k	
Lamination stamping	m	4,644	2000		9288 k	
Core assembly	EA	774		80		2477 k
Power leads	EA	1	250	480	250 k	20 k
Correctors						
Conductor, NbTi	m	576,000	0.35		202 k	
Cable assembly	EA	2,880		40		4608 k
Core AISI 1008 1.5 mm						
240 mm dia. x 0.65 mm	kg	104,000	1.3		135 k	
Lamination stamping	m	292	2000		584 k	
Core assembly	EA	240		80		768 k
Cryogenic vessel	EA	240	2000	40	480 k	384 k
Power leads	EA	1,200				
OFHC Cu rods, 1/4" dia x 1.6 m	EA	2,400	3.6	16	9 k	768 k
Cryogenic vessel	EA	240	50	16	12 k	154 k
Magnets supports						
Dipole holding pipe	EA	774	2000	16	1548 k	495 k
Position adjustable fixture	EA	1,014	2000	16	2028 k	649 k
Dipoles power supply	EA	1	250 k	480	250 k	19 k
Correctors power supplies	EA	1200	1230	16	1476 k	768 k
Conductors vacuum system					1975 k	158 k
Total					**28653 k**	**11392 k**

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Superconducting transmission-line magnet rings in Tevatron tunnel - cost summary

	M&S, k$ [NbTi]	M&S, k$ [344S-2G]	Labor K$
Dipoles			
NbTi, 0.65 T, AISI 1008, 1.5 mm	19,984		2,621
344S-2G, 2.0 T, Fe3%Si, 0.65 mm		116,433	2,621
Correctors	1,422	1,422	6,682
Power supplies			
Dipoles	250	250	19
Correctors	1,476	1,476	768
Quench protection			
4 temp. sensors/magnet	5,000	5,000	80
Controls (1 control unit/12 sesnsors)	1,500	1,500	80
Quench protection @ Tevatron, $30k/4 magnets			
P996 774 magnets	<5,805>	<5,805>	<80>
Conductor vacuum	1,975	1,975	158
Magnet supports	3,576	3,576	1144
Total M&S, P996, NbTi	**35,183**		
Total M&S, P996, 344S-2G		**131,632**	
Total Labor			**11,552**
Grand total M&S + labor, P996	**46,735**	**143,184**	
Grand total M&S + labor, P996, Fe3%Si	**48,735**		
Grand total DSFMR (M&S + Labor)		**286,368**	

Fast-Cycling Magnet Test at E4R and Possible Extension to LBNE/P996 Magnets

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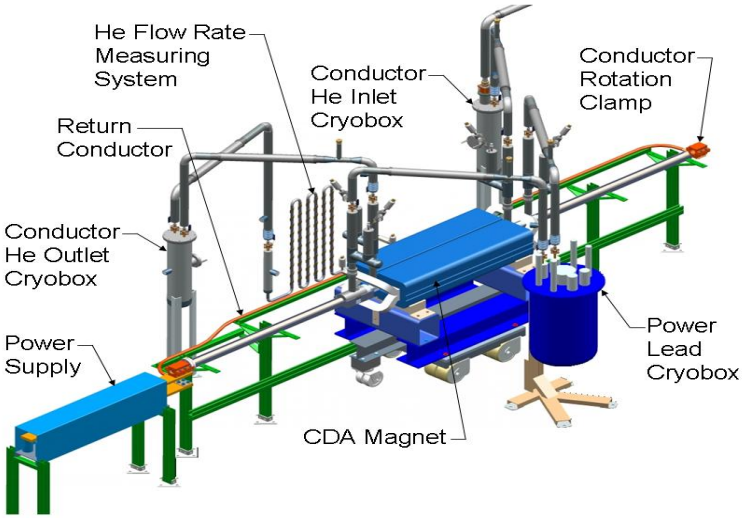
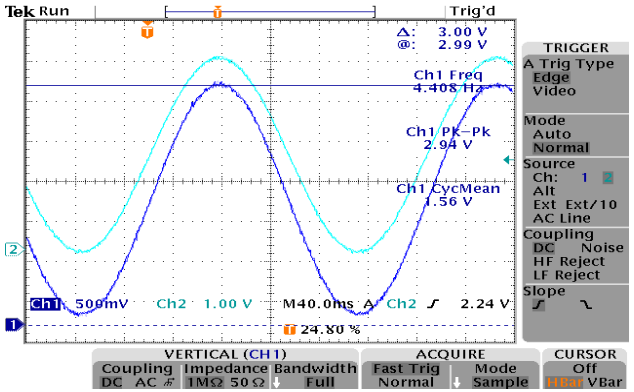


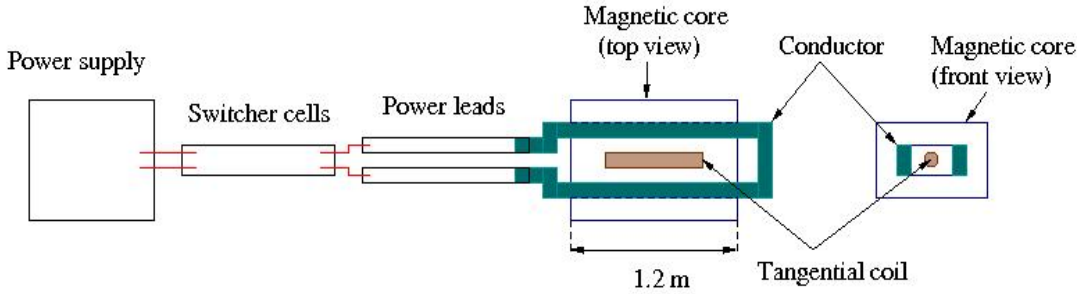
E4R test setup



CDA magnet AC B-field response

E4R test setup is suitable for the LBNE/P996 conductors and magnets tests. Tests will provide data on the transport current induced cryogenic power losses as well as will determine the ramping rate limits.

We have in order a 2nd magnetic core that could be changed to the LBNE/P996 combined function dipole design.

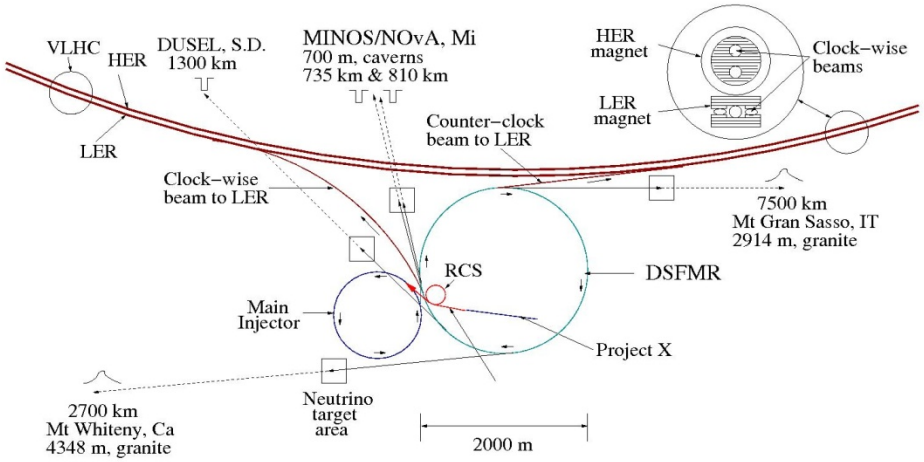


DSFMR, LBNE or P996 magnet test arrangement

Tasks for Superconducting P996 Beam Line Design & Magnet Prototyping

- Stretcher design based on transmission-line gradient dipoles => B, dB/dx, gap size, length and number of magnets
- Optimization of P996 gradient dipole design
- Optimization of P996 correctors design
- Adaptation of E4R setup to P996 magnets tests
- Prototype P996 dipole and corrector fabrication and tests
- Re-assessment of P996 gradient dipole and corrector designs
- Changes to the Stretcher design, if required
- Final P996 prototype dipole and corrector fabrication and tests
- Final Stretcher design and cost projection

Future Outlook



Benefits from the superconducting transmission-line Stretcher ring design and fabrication:

1. Large scale test of superconducting transmission-line accelerator magnet concept including:
   - effect of transmission-line cable shrinkage when passing from room (assembly) to cryogenic temperature (operation)
   - operation with a single supply to power a long string of magnets
   - quench detection and protection systems for long string of magnets energized from a single power supply
   - firm determination of static cryogenic power losses

2. Strong facilitation of a fast-cycling superconducting transmission-line accelerator design for the future (e.g. : RCS, PS2, SF-SPS, DSFMR etc..), if the HTS conductors are used in the Stretcher.

Summary & Conclusions

1. Transmission-line superconducting magnets offer high flexibility for beam line construction and possibly significantly reducing the construction cost.
2. The dc operation of the P996 Stretcher ring is much less demanding as compared to the fast-cycling magnets operation thus allowing instantly to profit from the up-to-date fast-cycling magnet design effort.
3. The preparations for the fast-cycling magnet test at E4R are much advanced. Arrangement at E4R is suitable for the P996 magnet tests.
4. Upgrading the P996 Stretcher to DSFMR in the future would set a stage for a total neutrino beam power of 8 MW, or up to 4 beams @ 2 MW each, with the highly improved benefit/cost ratio relative to the Project X alone, and in the very far future the DSFMR may serve as a dual, fast-injector to the VLHC, if such a project comes to a consideration.

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