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# Design considerations for fast-cycling sc transmission-line magnets

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1. **Physics motivation and outline of Fermilab accelerator complex for neutrino physics with possibility of extension to VLHC**
2. **Constraints imposed on accelerator and magnet designs for a new Fermilab accelerator complex**
3. **HTS and LTS conductor designs for fast-cycling dipole magnets**
4. **Estimated cooling power and pressure drop in transmission line LTS and HTS CICC conductors**
5. **Estimated cryogenic power required for Booster, PS2 and DSFMR accelerators based on the proposed LTS or HTS conductors**
6. **Outline of HTS and LTS conductor test arrangement at FNAL**
7. **Summary and plans**

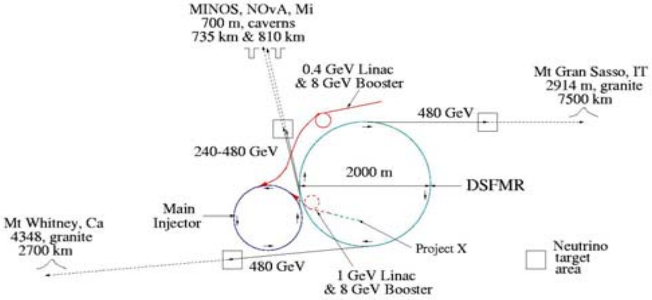
# Physics motivation I

## Provide 2 proton beams of 4 MW power each for two long-baseline neutrino experiments

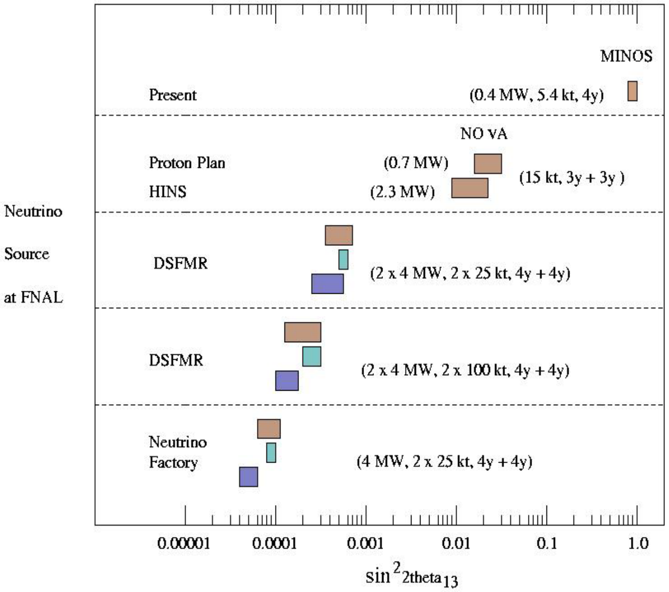
H. Piekarz, S. Hays – FNAL TM-2381-AD-TD, 2007
H. Piekarz – FNAL TM-2402-APC, 2008

Neutrino beam to Gran Sasso- 7200 km

Neutrino beam to Mt Whitney 2800 km



Dual Super-ferric Main Ring in the Tevatron tunnel – two 480 GeV proton beams at 0.5 Hz repetition rate. Neutrino production lines fit well within Fermilab proper.



Sensitivity limits with DSFMR and other neutrino beam facilities (brown – $\sin^2 2\theta_{13}$, green - $\Delta m_{31}{}^2$ , blue – CP violation)

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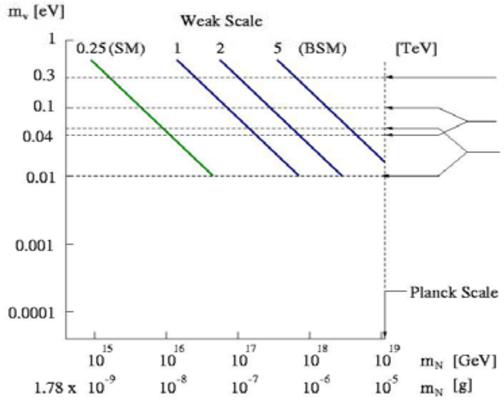
# Physics motivation II

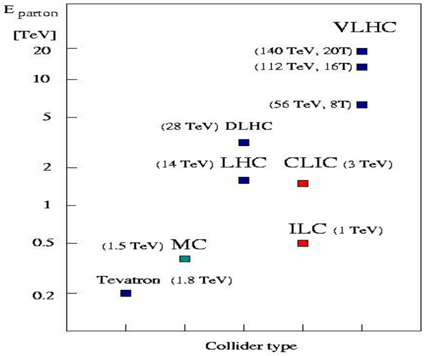
## Prepare Fermilab accelerator center for a possibility of VLHC if new physics from the LHC will justify just that !



In connecting the dark matter and dark energy to the particle physics we look at the upper bound on the scale of Majorana neutrino mass generation [1], $\Lambda_{Maj}$ , as it is determined by the weak scale, V, of the SM particles:

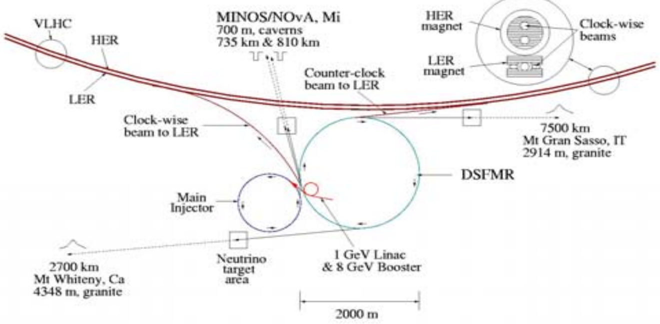
$$\Lambda_{Maj} = 4\pi V^2 / 3^{2/2} m_\nu$$

With $m_\nu \sim 0.01$ eV, the weak scale $V < 5$ TeV allows to reach Majorana neutrino mass up to the Planck scale.



Energy per parton at various colliders

Only VLHC can allow to reach particle masses which compatible with the strength of the weak force responsible for generation of Majorana neutrinos up to the Planck scale mass.

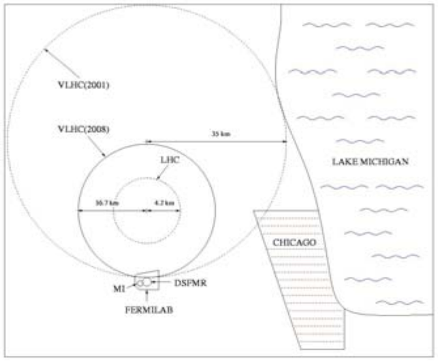


Beam injection scheme to VLHC LER and HER rings. The LER -> LHC beam transfer is assumed as proposed in [3].

DSFMR is a fast-cycling Injector to VLHC LER ring [2].

| Accelerator | Beam energy [TeV] |
|---|---|
| DSFMR | 0.5 |
| LER | 7 |
| HER I | 28 |

[1] J.M. Nicziporuk, IJMP, Nov, 2000
[2] H. Piekarz, FNAL TM 2402, 2008
[3] G. Ambrosio et al., Lumi-06, Valencia



New VLHC in Chicago-land. The LHC and the old VLHC rings are also shown.

# ***Constraints on DSFMR accelerator & magnet designs***

Low cost to build, low cost to operate and simple technology for stability and durability !!!

- **No new large-scale tunnels**
  - **- DSFMR will use Tevatron tunnel**
  - **- New 8 GeV Booster will use Accumulator Ring**
  - **- New 1 GeV Linac will need a tunnel of ~ 200 m**
  - **- Two ~1000 m long, 2m diameter tunnels with shafts are needed for the neutrino production lines**
- **DSFMR must use superconducting magnets to fit 2 rings in the Tev tunnel**
- **It is suggestive to use superconducting magnets for the Booster as well**
- **New Linac can be superconducting, or normal conducting for lower cost**
- **Total cryogenic power for the new accelerator complex is limited to the currently existing 24 kW @ 4.5 K**

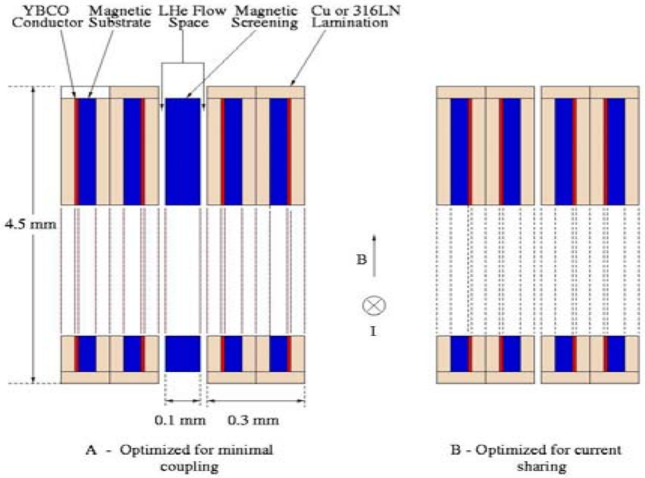
Limitation on the cryogenic power constitutes the most severe constraint on the magnet superconductor design. Hysteretic, eddy currents, intra-strand coupling and static losses must be very strongly minimized to meet the allowable cryogenic power limit.

Basic parameters of the superconducting magnets for DSFMR and Booster

| **Accelerator** | **Gap [mm]** | **B-field [T]** | **Current (single winding) [kA]** | **Rate [Hz]** | **dB/dt [T/s]** |
|---|---|---|---|---|---|
| **DSFMR** | **40** | **2** | **90** | **0.5** | **2** |
| **Booster** | **100** | **0.4** | **90** | **2.5** | **2** |

# ***LTS and HTS conductors for a fast-cycling dipole magnet***

The HTS strands of American Superconductor are 0.2 mm x 4.5 mm cross-section with a single filament of 2 μm x 4 mm. Positioning the narrow side of the strand “edge-on” to the magnetic field lines suppresses all sweeping B-field related losses proportionally to the “exposed” width of the filament. In addition, arranging strands with their magnetic substrate back-to-back strongly suppresses any coupling between the strands further minimizing losses.

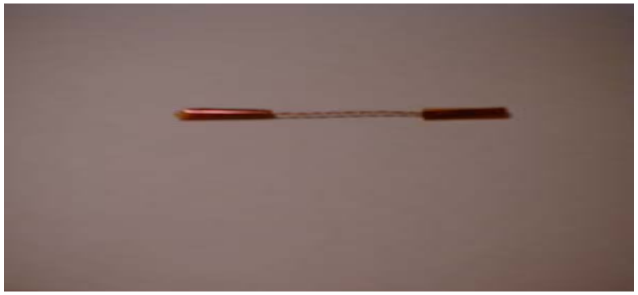


A - Optimized for minimal coupling

B - Optimized for current sharing

Two options for arrangement of the HTS tapes in a superconductor

The LTS strands (e.g. NbTi) are composed of thousands micron-size filaments embedded in a common copper matrix of ~ (0.5-0.8) mm range cross-section. This matrix facilitates current sharing between the filaments increasing stability of a transport current, but in the same time it also increases eddy and hysteretic losses due to coupling of the filaments. Twisting strands and inserting magnetic cores between the strand layers should help to minimize losses.



A twisted pair of NbTi strands. Twist pitch 6 mm, full twist 12 mm.

**Temperature margin for operations:**
**HTS => 20 K, LTS => < 2 K**

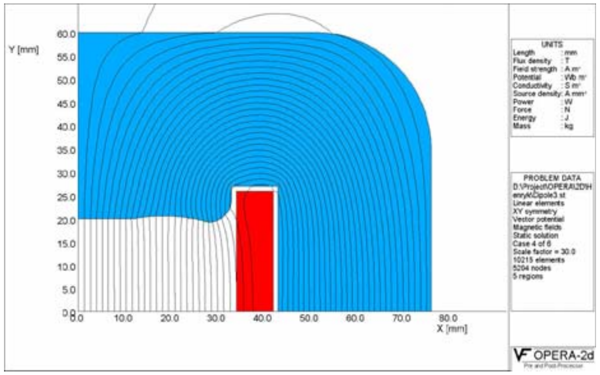
# Estimated power loss in HTS and LTS conductors

The YBCO power loss analysis [1] is based on a paper:
Sumption et al., Superconductor Science Tech., **18** (2005) 122

[1] H. Piekarz, S. Hays, Y. Huang, G. de Rijk and L. Rossi – MT20, 2007
[2] G. Moritz, Apl. Superc. Conf., Houston, 2002

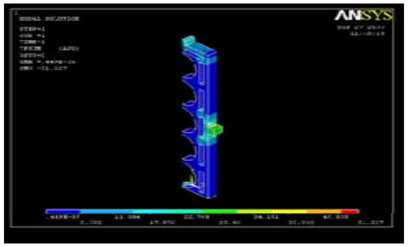
The YBCO losses are hysteretic, over-layer and under-layer are eddy (scale with $(dB/dt)^2$). The magnetic substrate are eddy but scale with dB/dt due to saturation. The Cu and SS losses are eddy. The ac current/self-field and the ac current/ac -field losses depend strongly on the ratio of Ic/It. For the HTS conductor in fast-cycling magnet we have chosen Ic/It ~ 0.5, which gives the operational temperature margin of ~ 20 K.

For the LTS conductor power loss we assumed expected losses with the Nuclotron type of conductor [2], except of using the static loss from the FNAL conductor design.



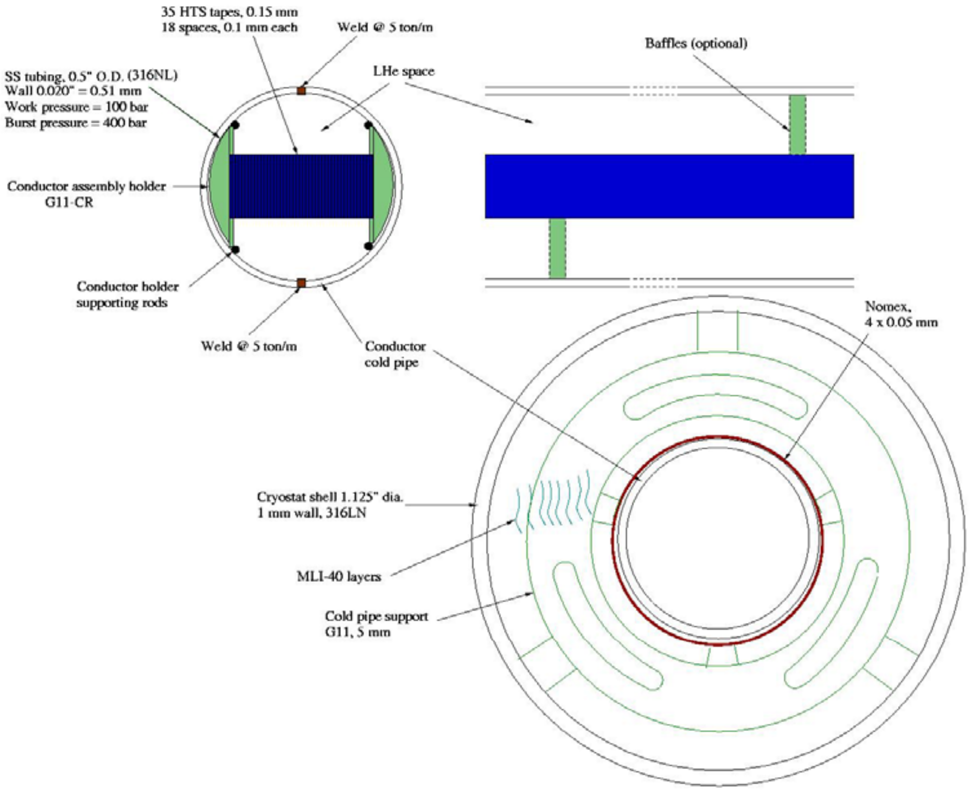
| 344/348 Strand component | B-flux parllel to strand [mW/m] | 50% of 0.5 T flux at 5 ° [mW/m] |
|---|---|---|
| YBCO, 2 um | 0.050 | 0.380 |
| Hustelloy underlayer, 50 um | << 0.0001 | 0.005 |
| Overlayer, Ag, 3 um | <<0.0001 | <<0.0001 |
| Ni5%W substrate and screen, 100 um | 0.136 | 0.136 |
| AC current/self-field, i = 0.5 | 0.088 | 0.088 |
| AC current/AC field, i = 0.5 | <0.0001 | 0.002 |
| Cu lamination, 0.1 mm | 0.0095 | 0.0380 |
| 316LN lamination, 0.1 mm | 0.0167 | 0.067 |
| Toatl with Cu lamination | 0.284 | 0.649 |
| Total with 316LN lamination | 0.291 | 0.678 |

| Magnet type | Coil [W/m] | Static [W/m] | Total [W/m] | Accelerator 7 km, [kW] |
|---|---|---|---|---|
| 348 HTS (ideal) | 0.092 | 0.360 | 0.452 | 3 |
| 348 HTS (compromised) | 0.210 | 0.360 | 0.570 | 4 |
| Nuclotron | 3 | 2 | 5 | 35 |



Thermal flux on G-11 spider in FNAL design

# ***HTS conductor design***



**Will use 35, 344S strands per cable.**

**For $B_{||}$ of 1 Tesla:**

**$I_c$ ~ 40 kA @ 4.5 K**
**$I_c$ ~ 24 kA @ 25 K**
**$I_t$ ~20 kA @ 4.5 K (50% of $I_c$)**

(Ic from D. Turioni et al., CEC/ICMC, 2007)

**Main LHe flow is above and below the conductor stack. A staggered kapton tape of 0.1 mm separates strands allowing for LHe to access 80% of each strand surface. Strand cooling is mostly by convection.**

**The stack is pre-assembled with G11 half-moon holders along entire length.**

**Stack position within the pipe is secured with 4 rods welded to the interior wall of the split pipe, and then by welding the split pipe under 5 ton/m pressure.**

# LTS conductor design

**LTS conductor consists of 2 rings of twisted pairs of NbTi strands (SSC outer dipole 0.65 mm) with total number of strands = 76.**

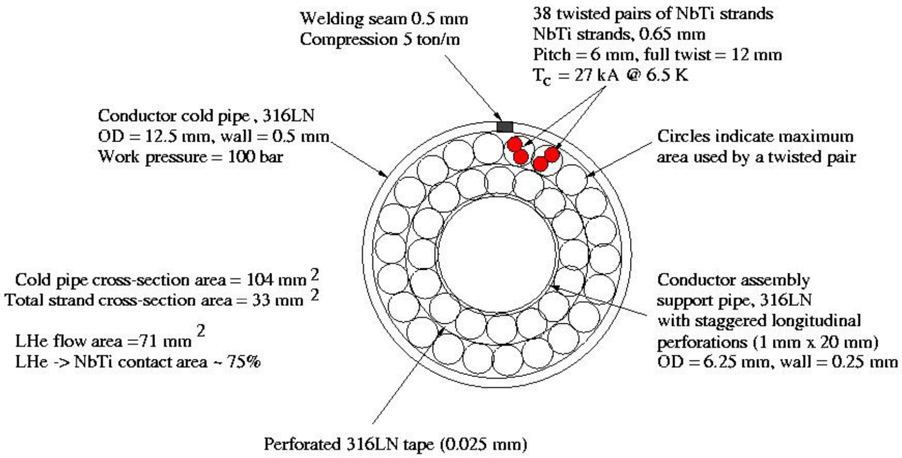
**For B-field of 1 Tesla:**

**$I_c$ ~ 40 kA @ 4.5 K**
**$I_c$ ~ 27 kA @ 6.5 K**
**$I_t$ ~ 20 kA @ 4.5 K (50% of $I_c$)**

**A hollow, longitudinally perforated tube constitutes main helium flow channel, and provides support for the strands.**

**A perforated thin SS tape holds inner layer of strands and helps to suppress intra-layer coupling.**

**Welding under pressure of the slit cold pipe secures strand pairs firmly in position.**



# Cryogenic parameters of proposed LTS and HTS CICC conductors

| CICC geometry | FNAL LTS | FNAL HTS | Ref. # 1 | Ref. #2 |
|---|---|---|---|---|
| Conductor length [mm] | 1300 | 1300 | 3120 | 500 |
| Pipe outer diameter [mm] | 12.5 | 12.5 | 19.1 | 7.5 |
| Pipe inner diameter [mm] | 11.5 | 11.5 | 15.7 | 5.4 |
| Number of strands | 76 | 35 | 588 | 21 |
| Strand area [mm$^2$] | 0.43 | 0.90 | 0.72 | 0.48 |
| Total strand area [mm$^2$] | 33 | 31.5 | 410 | 10 |
| Void fraction | 0.68 | 0.70 | 0.47 | 0.56 |
| LHe flow area [mm$^2$] | 71 | 73 | 364 | 12.75 |
| Pipe perimeter [mm] | 55 | 36 | 97 | 17 |
| Total strand perimeter [mm] | 148 | 263 | 1583 | 51 |
| Cooled perimeter [mm] | 203 | 299 | 1680 | 68 |
| Hydraulic diameter [mm] | 1.40 | 0.96 | 0.87 | 0.75 |

The reference papers are used to compare data with predictions for the pressure drop and heat transfer in the proposed LTS and HTS CICC conductors.

Ref. #1 – R. Meakawa, M.R. Smith and S.W. Van Sciver, IEEE Trans. on Appl. Superc., June 1995, p 741
Ref. #2 - Y. Wachi, M. Ono and T. Hamajima, IEEE Trans. On Appl. Superc, June 1995, p 569

# ***Friction factor for liquid helium flow in a CICC conductor***

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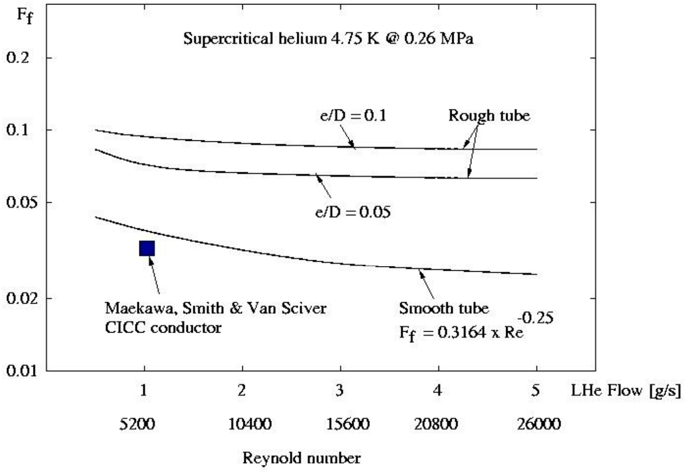

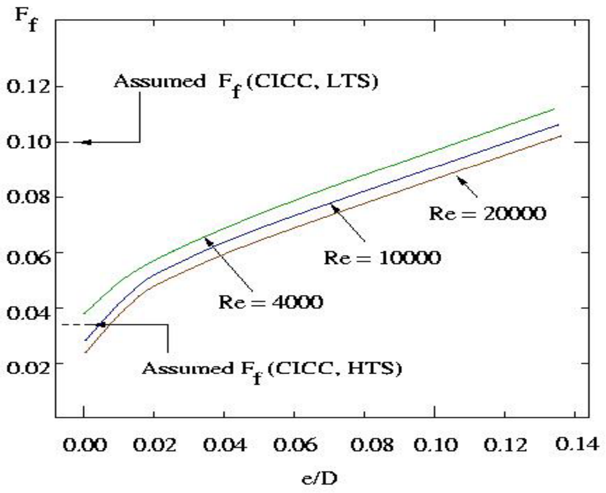

**Pressure drop for a flow of liquid in a pipe is related to friction via formula:**

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

**where L is pipe length, $F_f$ friction parameter, $P_{cooled}$ cooled perimeter, dm/dt flow rate, ρ density and A flow cross-section area.**

**For “smooth” pipe friction factor is approximated:**

$$F_f = 0.3164 \times Re^{-0.25}$$
$$Re = 4\ [(dm/dt)/(k \times P_{cooled}),\ \ k - \text{heat cond.}$$

**For “non-smooth” pipes there are practical graphs of $F_f$ as a function of ratio of ε/D with ε as roughness, and D diameter of the pipe. Using such approach we calculated $F_f$ factors for LHe of 4.75 K and 0.26 MPa and for Re of 2600 to 26000, and for ε/D up to 0.1.**

**Data of Maekawa et al. show no increase of friction with smooth wires inside a conduit pipe. We assumed, however, 3 x higher friction factor for LTS conductor due to twisting of the strands. The strand twist may be seen as “roughness” of €/D ~ 0.12**

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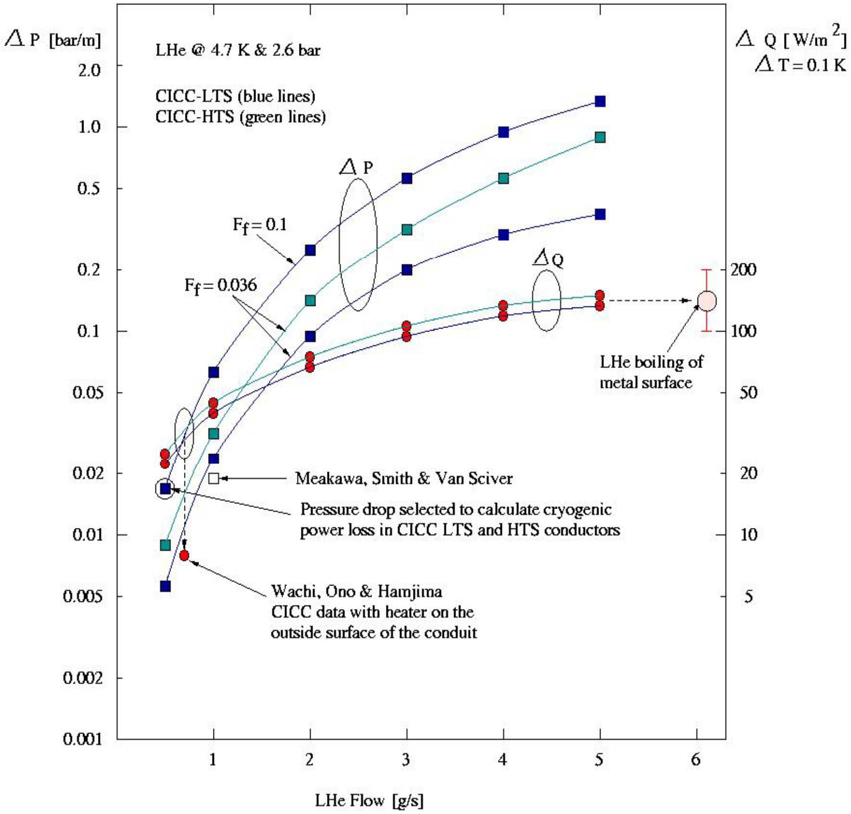
*) Maekawa et al., IEEE Trans. Appl. Superc., vol 5, no 2, 1995

# *Heat transfer from liquid helium to CICC conductor and pressure drop*



**The above graphs indicate that one should optimize operations for a minimal pressure drop rather then for high heat transfer. The lower the flow (or Reynolds number) the less pressure drop but not below some 0.5 g/s when flow changes from turbulent to laminar, and friction rapidly increases again.**

**The steady-state turbulent heat transfer in a smooth pipe is given in [1] by:**

**$Q = 0.0259\ (k/D_h)\ Re^{0.8}\ Pr^{04}\ (T_c/T_{He})^{-0.716})$**
**where $Pr = (\mu \times C_p)/k$, and μ- viscosity [1]**

**Calculated this way ideal heat transfer from LHe of 4.7 K @ 2.6 bar with flow rates of 0.5 To 5 g/s, and temperature rise of 0.1 K is nearly identical for both LTS and HTS CICC conductors, and it increases slowly with flow.**

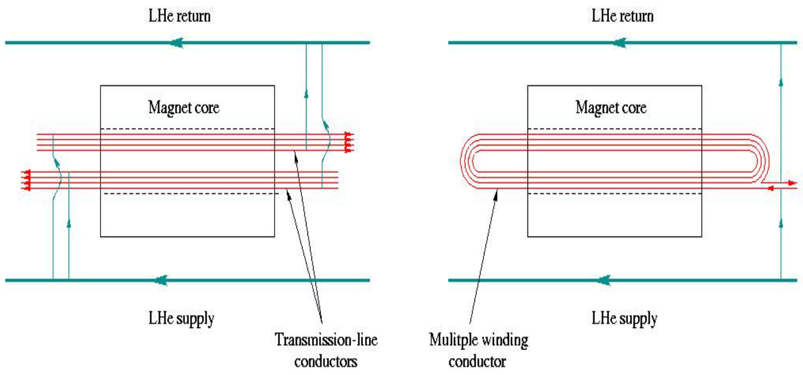
**In practice heat transfer depends on the properties of the contact surface, and there is also a delay in response which may have very adverse effect in a quench situation.**

**Data [1] suggests factor 4 loss in heat transfer efficiency, but it would still provide in our conductors ~ 8 $W/m^2$ at 0.5 g/s flow for 0.1 K temperature rise.**

**Nusselt numbers are large for both HTS and LTS conductors suggesting convection is a dominant process in heat transfer there.**

[1] Wachi et al., IEEE Trans. Appl. Superconductivity, vol 5, no 2, 1995

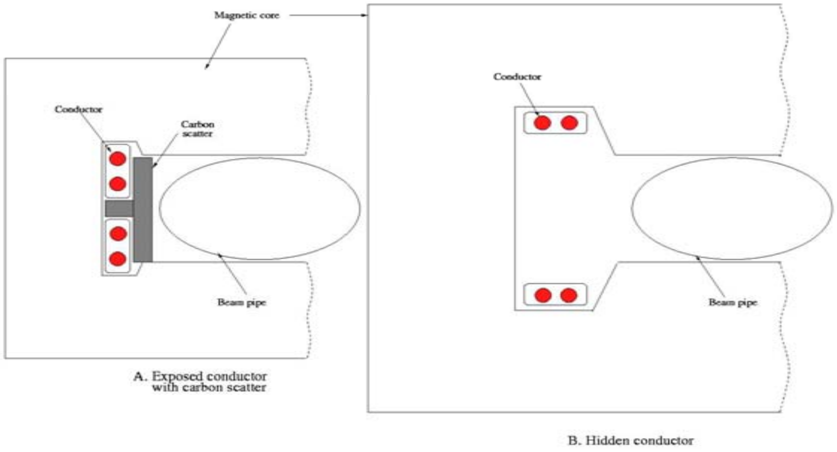
# Considerations of conductor arrangement for fast-cycling accelerator magnet



Two options for conductor winding:

- single turn allows to provide current from a transmission line greatly simplifying magnet assembly but at expense of higher power in a single power supply
- multiple turn allows to use much lower current but at expense of considerable complication of magnet assembly

Single-turn winding minimizes conductor length in a magnet that is required between the “feed” and the “return” LHe lines. Such arrangement suppresses pressure drop (and temperature rise) of liquid helium coolant within the magnet path.



Two options for conductor placement within magnetic core: A – minimizes core size, B- gives better protection from a failed beam

The type “A” conductor-core arrangement is more suitable for higher energy machines such as DSFMR, while type “B” for lower energy ones (PS2, Booster) with large beam gaps. Both, HTS and LTS can be used in “A” , while more likely LTS in type “B”.

# Estimated cryogenic power for accelerators based on LTS and HTS transmission-line magnets

**Assumptions:**

- **Magnet 5 m length with single conductor of 6 m length**
- **8 conductor lines per magnet with individual LHe flow support**
- **Pressure drop per 6 m line ~ 0.1 bar (both LTS and HTS) with 0.5 g/s flow**
- **Temperature rise per 6 m line ~ 0.6 K (LTS) and 0.2 K (HTS)**
- **LHe supply: 4.4 K/2.6 bar ($h_1$ = 1.09284 $e^4$ J/kg, $s_1$ = 3.44214 $e^3$J/kg_K)**
- **LHe return (LTS): 5.0 K/2.5 bar ($h_2$= 1.50288 $e^4$J/kg), $s_2$ = 4.32333 $e^3$J/kg_K)**
- **LHe return (HTS): 4.6 K/2.5 bar ($h_2$= 1.19018 $e^4$J/kg, $s_2$ = 3.67522 $e^3$J/kg_K)**

**Cryogenic cooling power used $P_{cool} = (h_2 - h_1) \times dm/dt$**

**$P_{cool}$ (LTS) = 0.41000 $e^4$ x 0.0005 kg/s = 2.05 W/line_6m**
**→16.4 W/magnet_5m**
**$P_{cool}$ (HTS) = 0.09734 $e^4$x 0.0005 kg/s = 0.49 W/line_6m**
**→ 3.9 W/magnet_5m**

| Conductor | Booster (475 m) | PS2 (1200 m) | DSFMR (6250 m) | |
|---|---|---|---|---|
| LTS | 1.30 kW | 5.80 kW | 34 kW | |
| HTS | 0.31 kW | 1.37 kW | 8.13 kW | |

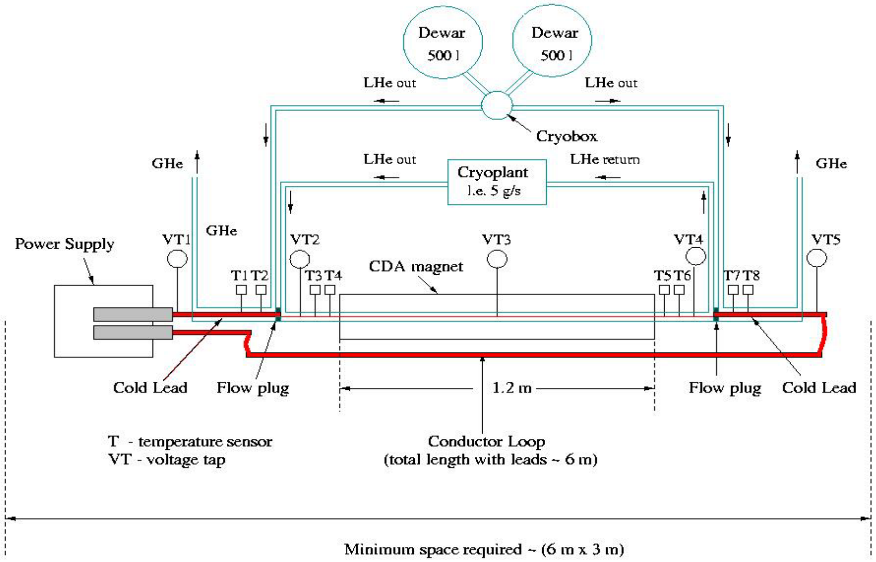
With LTS conductor for Booster and HTS conductor for DSFMR there seems to be a good chance of meeting the imposed cryogenic power limit of < 24 kW.

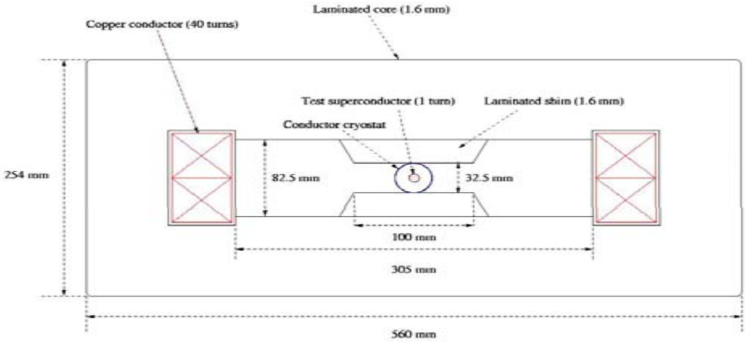
# *HTS and LTS conductor test arrangement*

Fermilab personnel involved in preparations to the conductor test:
J.Blowers, D.Harding, S.Hays, Y.Huang, A.Klebaner, H.Piekarz, J.Theilacker, V.Shiltsev, G.Velev and D.Wolff

**CDA magnet**

- 1.2 m length
- 82.5 mm gap
- $B_{max} = 0.70$ T
  40 turns @ 1.3 kA





**Measure power loss of 1.3 m long conductors (HTS: 16 x 344S tape, and LTS: 38 twisted pairs of NbTi) as a function of:**

- **dB/dt up to 2 T/s, with external sweeping B-field orientation of $(0\text{-}90)^0$ (for HTS only)**
- **di/dt up to 40 kA/s (self B-field, conductor outside magnetic core)**
- **All of the above for the supercritical helium (2.5-3.0) bar, and (4.5-5.0) K with flow rates range of (0.5 – 1.5) g/s**

Will install laminated shim to make magnet gap = 32.5 mm in order to allow for 0.32 T @ ~10 kA.

The field 0.32 T exceeds saturation field of ~ 0.2 T in Ni5%W substrate of HTS, and it is closer to 0.5 T in DSFMR magnet. CDA magnet will operate at ~ 3 Hz to create equivalent of ~ 2 T/s rate.

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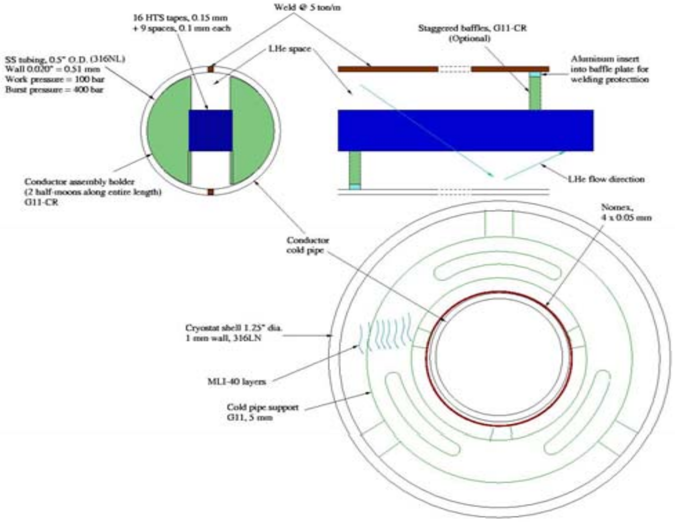
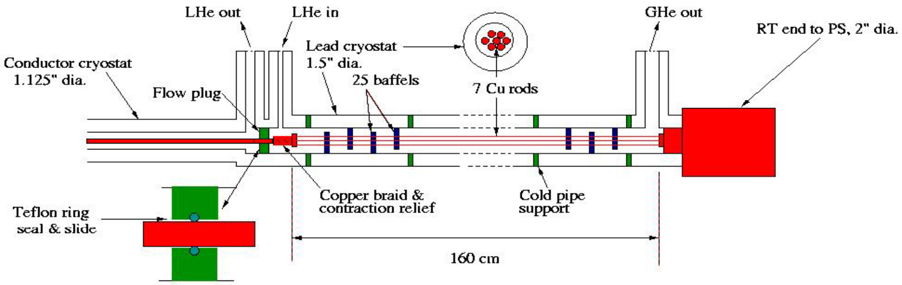
# Test HTS conductor and leads – engineering design in progress





**Test HTS test conductor will consists of 16, 344S tapes with the critical and transport currents:**

**$I_c$ ~ 18 kA @ 4.5 K**
**$I_c$ ~ 11 kA @ 25 K**
**$I_t$ ~ 10 kA @ 4.5 K (55% of $I_c$)**

**The LHe flow cross-section is scaled-down proportionally to match that of the full conductor. The use of “infrequent” baffles to re-direct, or force the flow through the stack is still investigated.**

**Test conductor leads are scaled down from VLHC-LF magnet tests. Each lead is made of seven, ¼”, 160 cm length low resistance copper rods. The overall cross-sectional size of the lead allows passing through the CDA magnet gap making easier to change the test conductors.**

**Each lead consists of seven, ¼” diameter, 160 cm length low resistance copper rods. The overall size of the leads is designed to allow passing of the whole assembly (with conductors) through the CDA magnet gap. This will facilitate changing the test conductors.**

**At RT ends the 2” diameter rods are clamped to the power supply ends facilitating rotation of the conductor relative to the CDA magnet B-field.**

# Summary and plans

- We have shown that there is strong physics cause to develop fast-cycling superconducting accelerator magnets for the future of HEP at Fermilab
- Both LTS and HTS conductors should be considered as they may find application in accelerators of different scales
- Fast-cycling superconducting accelerator magnets have best chance of success if powered by a transmission-line conductor allowing to provide LHe cooling of consistent properties through the entire magnet length
- Our first priority is to complete tests of both LTS and HTS transmission-line conductors by the end of 2008
- Preparations for fabrication of a 1.2 m long magnets powered with HTS and LTS conductors are in progress with tests expected by mid-2009