FERMILAB-SLIDES-23-332-AD

Rapid-Cycling HTS-Based Magnets for Muon Acceleration

Henryk Piekarz

Accelerator Research Department
Fermilab, Batavia, Illinois 60510, USA

OUTLINE;

1. *Why SC RCS magnet (High electric cooling power of NC RCS magnets)*
2. *Placement of test HTS magnet conductor within core & cable parameters*
3. *Scaling-up test HTS magnet conductor to muon RCS's*
4. *AC resistance of test HTS magnet system*
5. *AC resistance of test HTS magnet current leads & options for improvement*
6. *Possible muon RCS HTS magnet arrangement & tentative RCS's parameters*
7. *RCS magnet current wave-form options*
8. *Feasibility of high-quality B-field with super-ferric magnet*
9. *Issues for R&D*

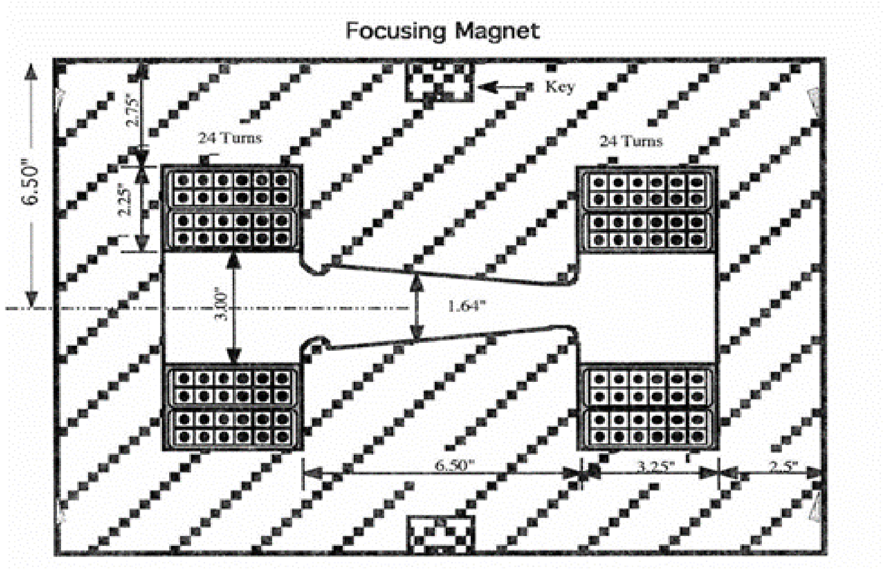
Meeting on Rapid-Cycling HTS Magnet Technology for Muon Acceleration, CERN, October 5, 2023

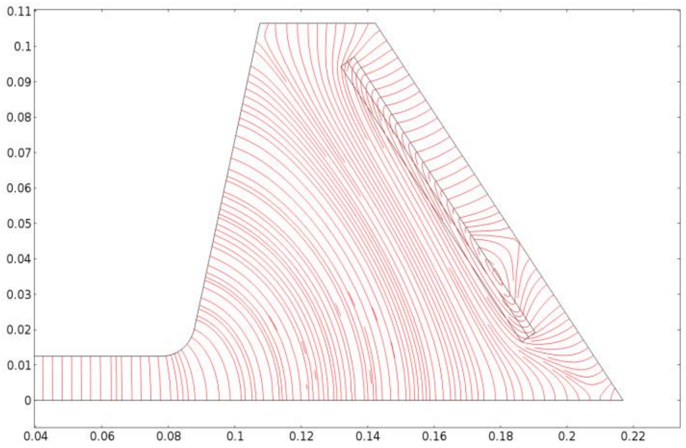
This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

Why SC RCS magnets (High electric cooling power of NC RCS magnets)

FNAL Booster dual function magnet:

https://beamdocs.fnal.gov>Booster V3_0 (1998)





From [1]: 3.5% of 1.75 T B-field in gap passes perpendicularly wide conductor side. Core mass is 3 x the "standard" window magnet.

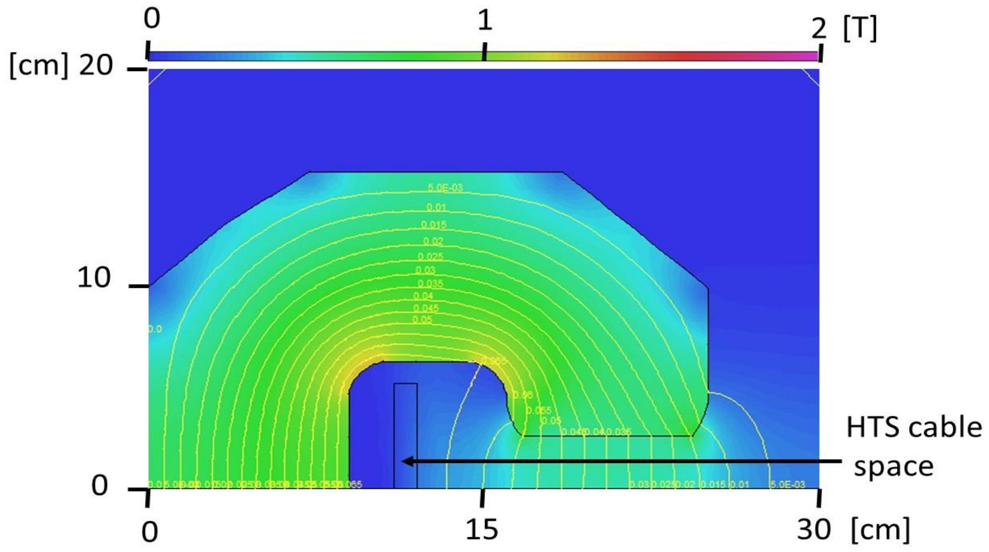
B = (0.07 - 0.7) T, f = 15 Hz, ω = 94.2 $s^{-1,}$ dB/dt = 30 T/s
Cable: 4 bus bars, each of 24 Cu wires (8 mmx 8 mm) with 1/8" LCW cooling channels.
P_{ac} (magnet) = 1.36 kW/m
LCW electric power (magnet) = 8.6 kW/m
P_{LCW} (electric) / P_{ac} (magnet) = 6.4
LCW requires heat exchangers in water pool & compressors.
P_{LCW} / P_{ac} (magnet) will increase with higher P_{ac} (magnet).

Eddy power loss in thin (h), wide (d), length (l) conductor bar [2,3]:
P_{eddy} (bar) = $1/12 \cdot d^3 \cdot l \cdot h \cdot 1/\rho \cdot (dB/dt)^2$,
From [1]: B_{gap} =1.75 T, B_{slab} = 0.06 T , d = 0.19 m, h = 2.4 mm, f = 1 kHz
B- field enters perpendicularly conductor slab side d.
P_{eddy} (4 bars) = 0.66 MW/m @ 1% duty factor (10^{-3}s @ 10 Hz)
Cu conductor temperature rise = 280 K/s-m. Cu melting temp.: 1084^0 C.

[1] J.S. Berg, H. White, *"Pulsed synchrotrons for very rapid acceleration"*, AIP Conf. Proc. Vol. 1777, AIP Publishing LLC (2016)
[2] G. Moritz, *"Eddy currents in accelerator magnets"* [11a 03.1800], https://arxiv.org>physics (2009)
[3] J. McWhirter, M. Thomas, *"Eddy Current Loss in Conductor Slabs"*, IEEE Transactions on Power Apparatus and Systems, Corpus ID: 110570389 (1970)

Placement of test magnet conductor within core & cable parameters [4]

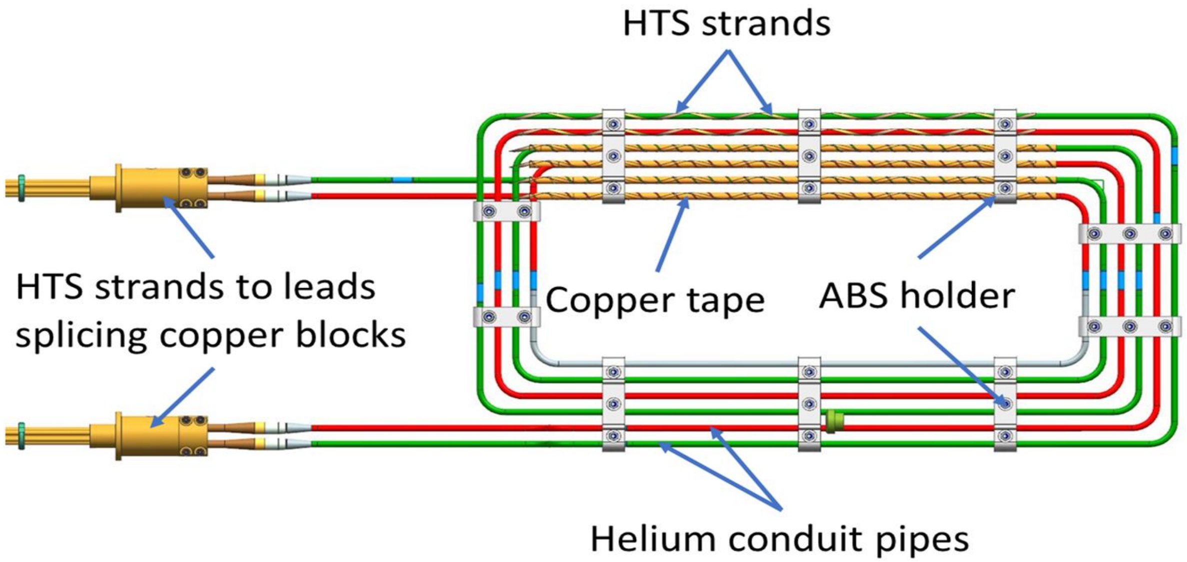
C-shape Fe3.5%Si core design & conductor placement.



A 10 mm thin conductor slab is placed vertically in the magnet cable space. With conductor slab slightly off center, about 5% of B-field in 40 mm beam gap passes through the conductor space.
Conductor slab horizontal placement within magnet cable space can be optimized to allow for as low as possible fraction of core descending magnetic field at different heights of beam gap .

[4] H. Piekarz, S. Hays, B. Claypool, M. Kufer, V. Shiltsev "Record High Ramping Rates in HTS Based Superconducting Accelerator Magnet", MT-27, IEEE Trans. Appl. Superconductivity, 32 (2022). 6, 4100404

Test HTS magnet 3-turn conductor coil.



- ❑ *Two YBCO strands (2.5 mm x 0.1 mm) wrapped at 10 cm pitch over liquid helium conduit pipe (316L, OD 9 mm, wall 0.5 mm) form a sub-cable.*
- ❑ *Two sub-cables form a 3-turn magnet conductor.*
- ❑ *Copper tape (12.5 mm x 0.1 mm) wrapped under tension at 5 cm pitch over HTS strands secures their firm attachment to SS pipe.*
- ❑ *ABS holders/spacers hold firmly together cable structure and secure its unmovable position within magnet core.*
- ❑ *MLI is wrapped over entire cable between ABS holders.*
- ❑ *LHe coolant: Vol. = 0.94 L/m, P = 0.28 MPa, T = 5.5 K, Flow: 2.4 g/s*

Scaling-up test HTS magnet conductor power loss to Muon RCS's

Dual-gap test magnet with 3-turn HTS power cable

Test magnet parameters & power cable cryogenic power loss:
Core: 0.5 m, Dual gap 100 mm (H) x 10 mm (V), I = 2 kA, I (3-turn) = 6 kA, B = 0.4 T, dB/dt = 300 T/s, Rep. Rate 10 Hz.
Measured cryogenic power loss upper limit: < 0.06W/m.

Projected fractions of HTS cable cryogenic power loss:
- *YBCO magnetization power loss: $P_{hys} \sim B \cdot w^2 \cdot f$ [5] where B - external field, w- HTS tape width, f - ramping frequency. With HTS tape wrapped 360 ^{0} around cryogenic pipe w_{eff} = ½ w, reducing P_{hys} by factor 4.*
- *SS cryogenic pipes power loss: $P_{eddy} = B^2 \cdot r^2 \cdot f \cdot ½ \cdot \rho^{-1} \cdot \pi \cdot d \cdot l$ [2] does not depend on direction of B-field.*

Using scaling based on P_{hys} (YBCO) in [5] and P_{eddy} (SS pipes) in [2], the estimated fractions of HTS test cable power losses are:
Eddy in SS pipes- 78 %, Hysteresis is YBCO – 22 %, leading to:
P_{cryo} (SS pipes) < 0.047 W/m, P_{cryo} (YBCO) < 0.013 W/m.

Note: MgB_2 magnetization power loss $P_{hys} \sim B^2 \cdot \Lambda \cdot f$ [5], where Λ is superconducting fraction of wire. Dependence on B^2 and large cross-section make MgB_2 prone to high cryogenic power loss at rapid cycling.

*[5] H. Zan et al., "Alternating Current Loss of Superconductors", Energies 2021, **14***
https://doi.org/10.3390/en14082234

Very tentative cable power loss estimate for Muon RCS's based on the test HTS rapid-cycling magnet:

RCS2 & RCS1 magnet parameters vs test magnet:
Single gap = 25 mm (V) x 100 mm (H), B = 2 T, I = 24 kA @ 3-turns
$N_{strands}$ (2T, 25 mm gap) = 12 x $N_{strands}$ (test magnet)
$N_{cryo-pipes}$ (2T, 300 & 9000 T/s) = $N_{cryo-pipes}$ (test magnet)

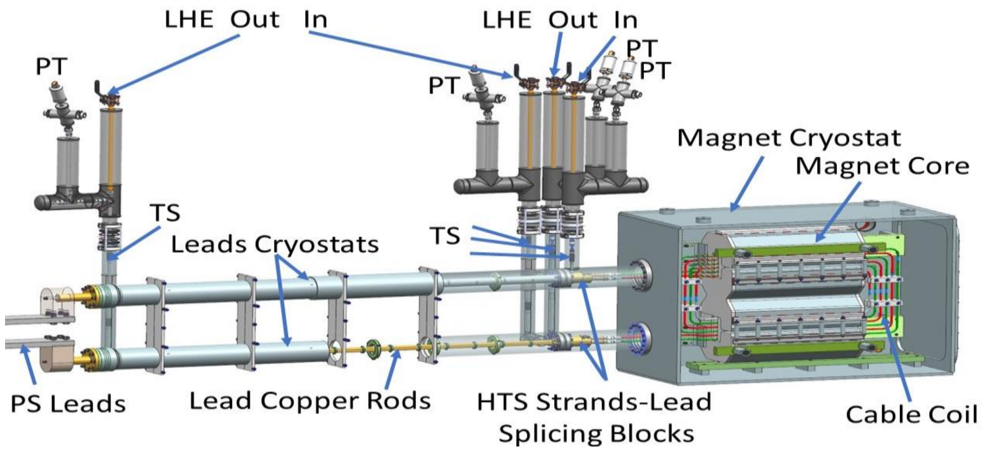
RCS 2
dB/dt = 300 T/s, t_{rise} (B) = 5 10^{-3} s @ 10 Hz, d. f. = 5%
P (YBCO hysteresis) < 12 x 0.013 W/m < 0.156 W/m
P_{cryo} (SS pipes) < 0.047 W/m
P_{cryo} (magnet) < 0.2 W/m, $P_{electric}$ < 15.4 W/m

RCS 1
dB/dt = 9000 T/s, t_{rise} (B) = 0.2 10^{-3} s @ 10 Hz, d. f. = 0.5%
(YBCO hysteresis, 9000 T/s) < 12 x 30 x 0.013 W/m < 4.7 W/m
P_{cryo} (SS pipes) < $(9000/300)^2$ x 0.047 W/m < 42.3 W/m
P_{cryo} (magnet) < 47 W/m, $P_{electric}$ < 3.6 kW/m

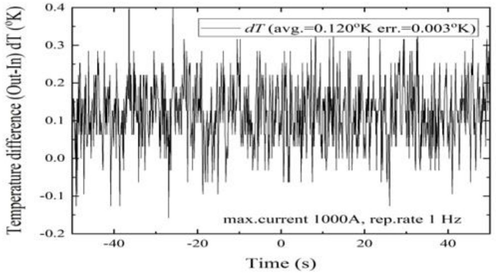
At 9000 T/s power loss in cryogenic pipes is strongly dominant. SS pipe wall can be reduced 5-fold for LHe pressure of 2.8 Bar: Working pressure (SS, d= 9 mm, wall = 0.1 mm) = 1400 bars, then $P_{electric}$ (magnet, 9000 T/s) < 1 kW/m

AC resistance of test HTS magnet system

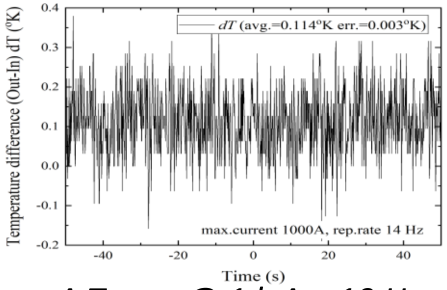
Test magnet arrangement: Conductor & leads are cooled with separate LHe flows



Conductor temperature rise



ΔT_{Out-In} @ 1 kA – 1 Hz



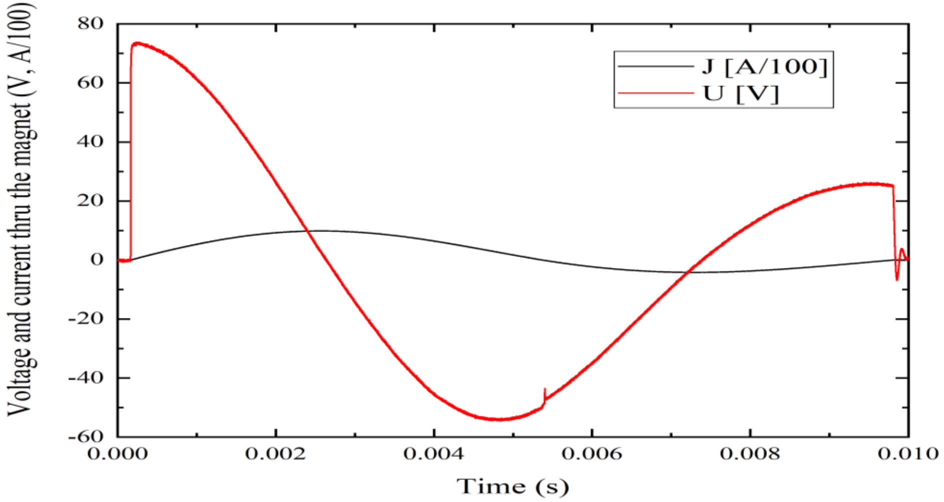
ΔT_{Out-In} @ 1 k A – 10 Hz

ΔT_{Out-In} did not change within 0.003 K error for rep. rates 1 – 10 Hz setting an upper limit on cryogenic power loss at 0.06 W/m with helium of 5.5 K, 2.6 Bar and 2.4 g/s flow.

Magnet conductor coil resistance from temperature rise

HTS strands are wrapped with single layer of 12.5 mm x 0.1 mm Cu tape. If cable was not superconducting, the current would flow through copper tape with expected power dissipation of 180 W and LHe temperature would rise to 40 K. With measured 0.003 K temperature rise upper limit power coil was perfectly superconducting, and so having zero resistance.

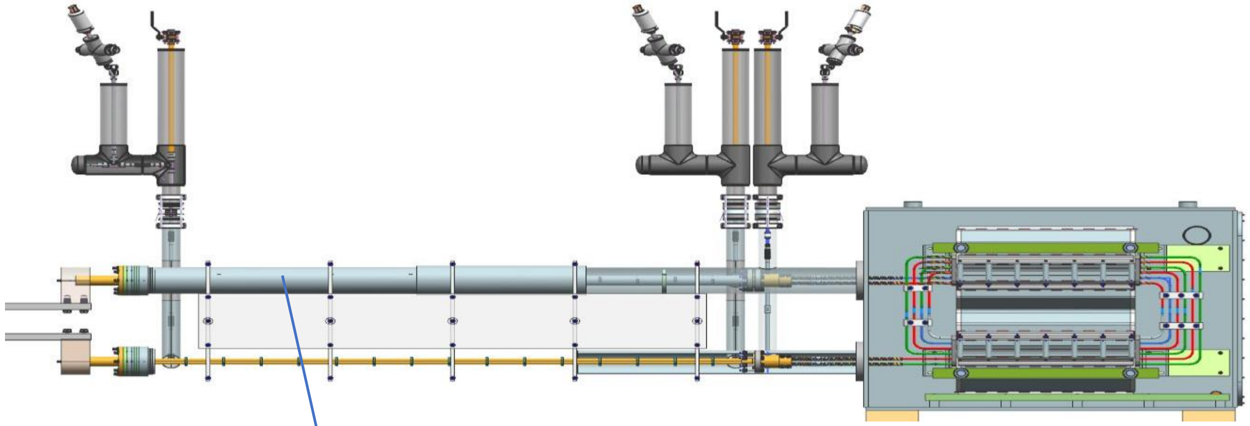
Magnet system resistance from current wave-form analysis

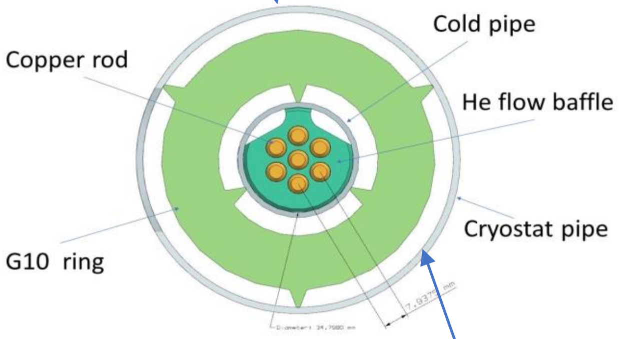


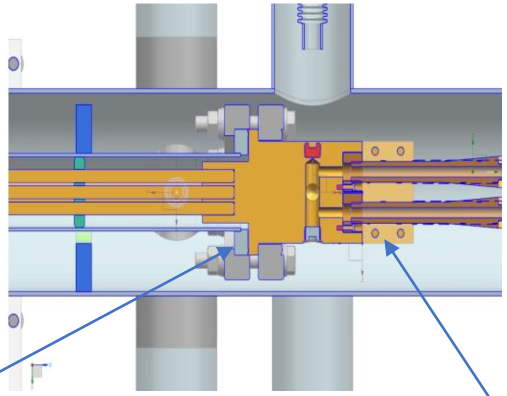
From the integral ∫U(t)dt vs J(t) magnet system resistance is $5.3\ 10^{-3}\ \Omega$ exceeding by 2 orders of magnitude dc resistance. The system inductance of (111 +/- 0.01) μH matches expectation. As magnet cable resistance is zero, the high magnet system resistance comes then solely from the current leads.

AC resistance of test HTS magnet current leads & options for improvement

Current lead: 7 CDA202 Cu rods: ¼ "dia., 1.65 m length.
ρ (Cu, RT) = 1.6 10^{-8} Ω-m, ρ (Cu, 5 K) = 2 10^{-10} Ω-m .







Lead cross-section. Cryostat pipe is determined by the copper block connecting lead rods to HTS cable.

Lead to HTS cable connection. The Cu-SS pipe formed by Magnetic Pulse Welding joins HTS cryo-pipe to lead cold-end copper block.

Sources of leads resistance in test magnet operation:

I_{peak} = 1000 A, f = 100 Hz, ω = 628 Hz

(1) Effect of skin depth in the copper rods
Skin depth δ (5 K, 628 Hz) = 0.27 mm
R (2 x 7 rods) = 2.26 10^{-3} Ω

(2) Screen currents in leads cryostat walls
R (wall) = $(\rho \cdot l) / (2\pi \cdot r \cdot t)$
ρ (RT) = 74 $\mu\Omega$-cm, l = 330 cm, r= 4.6 cm, t = 1.6 mm
R (cryostat walls) = 3.54 10^{-3} Ω

Leads estimated resistance = 5.8 10^{-3} Ω
Leads measured resistance = 5.3 10^{-3} Ω

Improvements for test magnet system

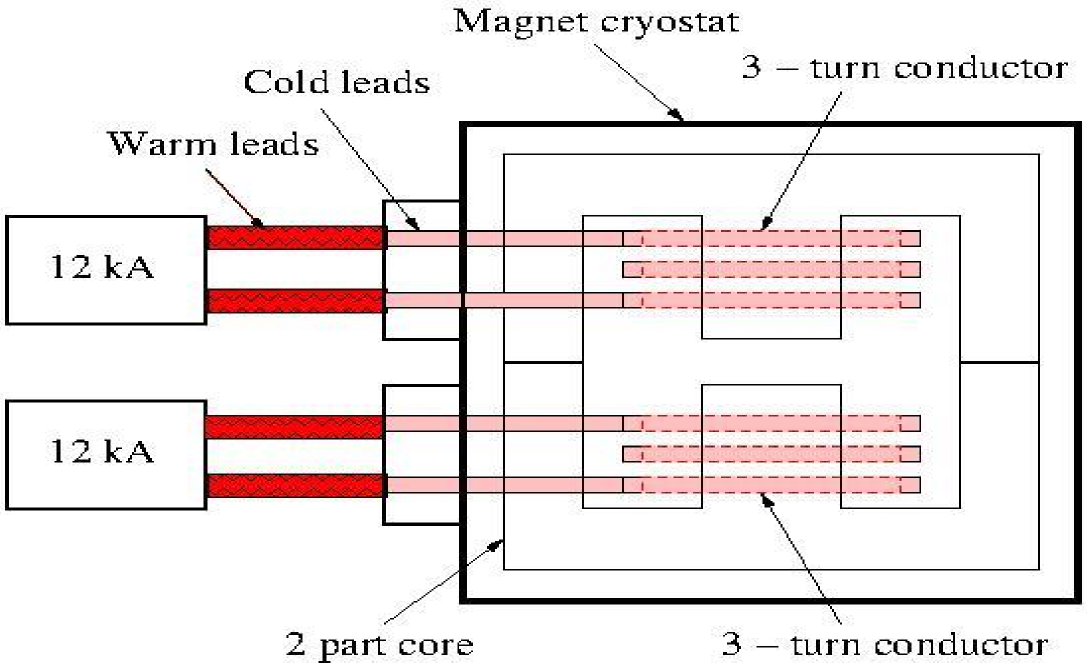
1. Replace CDA202 rods with CDA150 pipes (1/2"-1/16")
R (skin depth) = 0.21 10^{-3} Ω
2. Replace 316L cryostat pipe with Al-6061
R (screen currents) = 0.12 10^{-3} Ω
Total test magnet leads resistance = 0.33 10^{-3} Ω

Leads for accelerator application

- *Keep leads at RT except of HTS cable-lead splice*
- *Use CDA150 pipes for leads splicing area - low pipe mass facilitates low temperature HTS splicing*
- *Place both cold lead ends in common cryostat - eliminates screen currents induced AC resistance*

Possible muon RCS HTS magnet arrangement & tentative RCS's parameters

Window-frame magnet: 25 mm (V) x 100 mm (H) beam gap



- *Conductors are protected from muon decays & beam losses*
- *Magnet core inside cryostat eliminates cryostats for the conductors – potential source of very large eddy losses.*
- *Cables arrangement with 2 sub-cores facilitates assembly.*
- *Very short acceleration period minimizes beam circulation time before extraction so with high level vacuum there may be no need for ceramic vacuum beam pipe.*

Selected parameters of Muon RCS1 & RCS2 accelerators

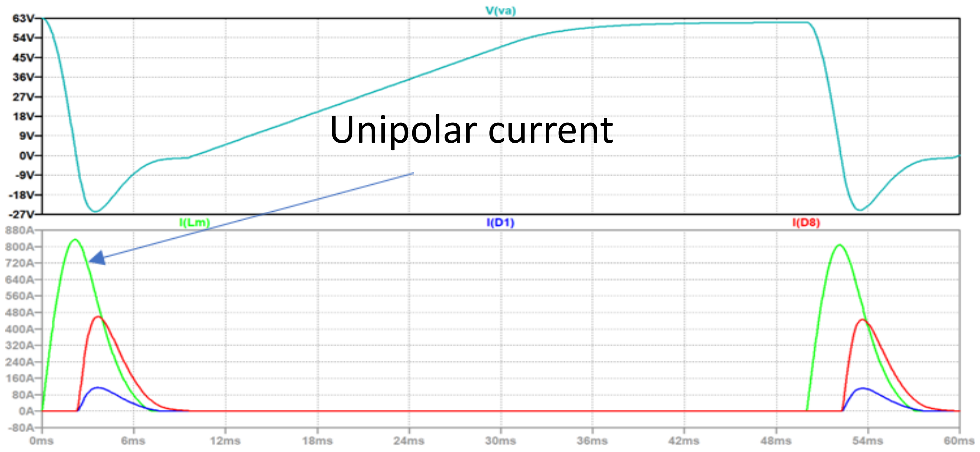
- *Two 12 kA currents from 2 supplies (or from single 24 kA supply) energize two 3-turn magnet conductors providing 72 kA current generating 2 T field in 25 mm beam gap.*
- *Discharge voltage of 960 μF capacitor bank is 400 V/m for RCS 1 and 16 V/m for RCS2. HTS cables and current leads can be made to withstand > 1 kV.*

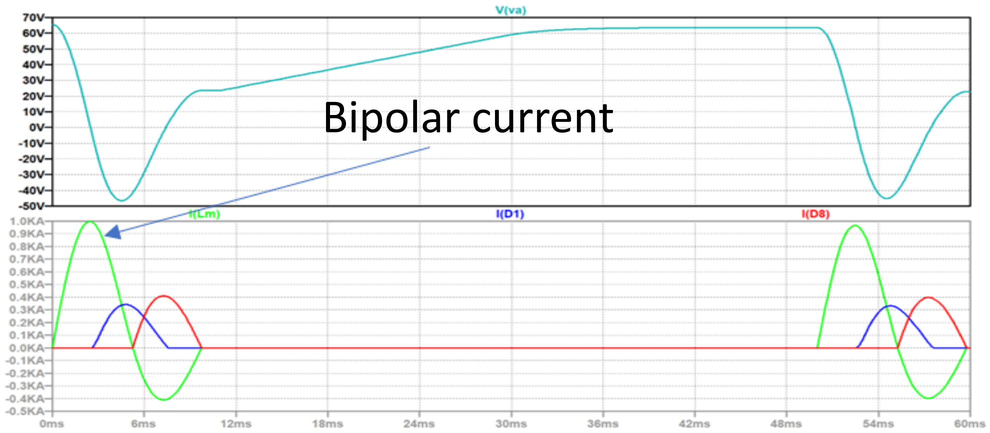
Accelerator parameters	RCS 1	RCS 2
Circumference	2 km	20 km
B-max / B-linear	2 T /1.75 T	2 T / 1.75 T
Beam gap [V x H]	25 mm x 100 mm	25 mm x 100 mm
Conductor turns	3	3
Current/turn @ 2T	2 x 12 kA	2 x 12 kA
Magnet Inductance	20 μH/m	20 μH/m
B-field rise time	$0.2\ 10^{-3}$ s	$5\ 10^{-3}$ s
B-field ramp rate to 1.75 T	9000 T/s	360 T/s
Discharge voltage @ 960 μF	400 V/m	16 V/m
Beam rep. rate	10 Hz	10 Hz
Duty factor	0.5 %	5 %
Cryogenic power	47 W/m	0.2 W/m
Electric power *)	3.6 kW/m **)	15.4 W/m
Electric power / RCS	7.9 MW	0.3 MW

**) Power loss in current leads not included.*
***) About 40% of Fermilab Booster*

RCS magnet current wave-form options

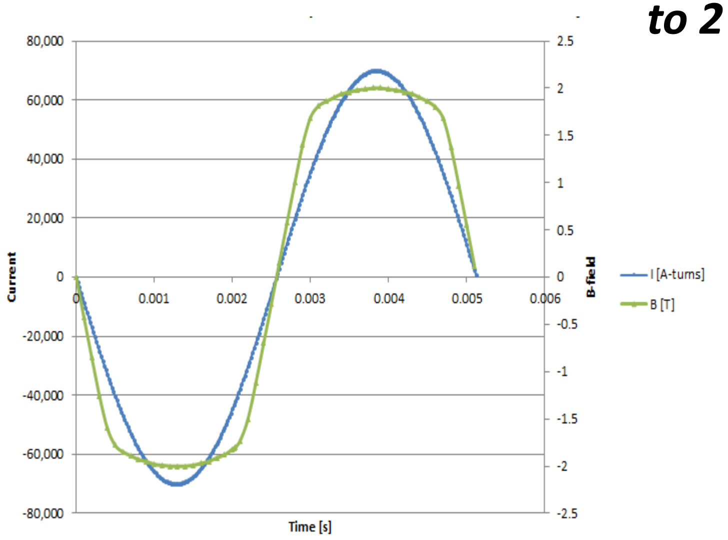
Current wave-forms used for HTS magnet test.





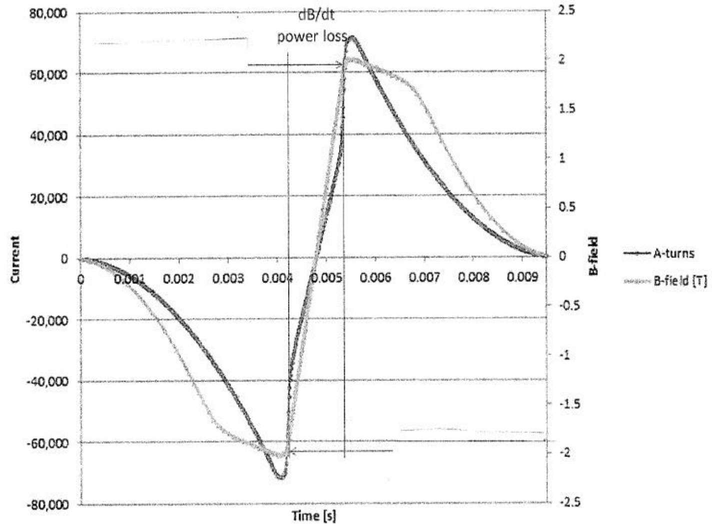
1 kA current was generated with 960 μF capacitor bank discharged at 80 V. Pulse repetition rate 10 Hz.

Expanding linear B-field response to 2 T with Fe3.5%Si core



Standard sine-wave current. B/I linear to 1.75 T. Current 66 kA-turns @ 25 mm gap.

J. Blowers, H. Piekarz, MAP, APC/TD Dep. Fermilab (2017)



Modified sine-wave current. B/I linear to 2.0 T. Current 66 kA-turns @ 25 mm gap.

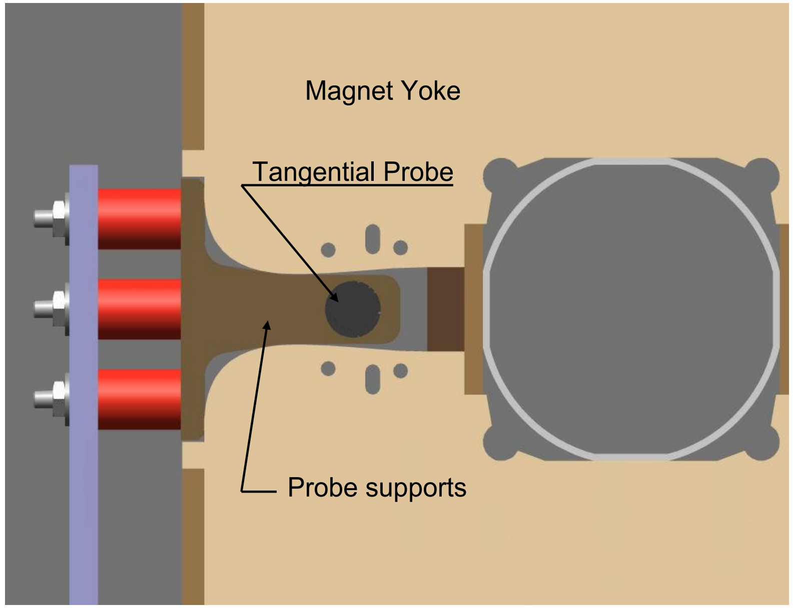
J. Blowers, H. Piekarz, MAP, APC/TD Dep. Fermilab (2017)

Power supply feasible but potentially high cost, needs significant R&D.

S. Hays, M. Kufer, EE., Fermilab (2023)

Feasibility of high-quality B-field with super-ferric magnet

The VLHC 2T magnet was constructed using 1008 AISI laminations. The designed slots in magnet poles eased B-field saturation allowing achieve very high-quality B-field in (0.1-1.966) T. The measurements were done using tangential rotating coil [1] & 102 sensors Hall Station [2].



Slots in magnet poles of combined function VLHC-low field magnet.

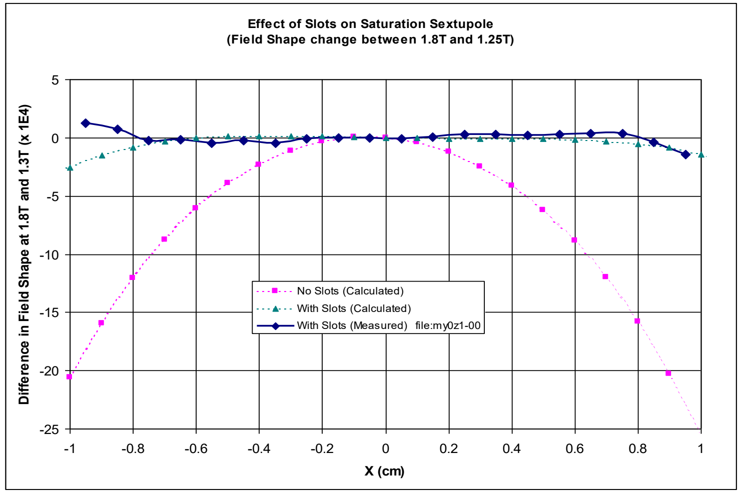
[1] *G. Velev et al., "Field quality measurements of a 2-Tesla Transmission Line Magnet for VLHC", IEEE Trans. of Applied Superconductivity, Vol. 10, No 1 (2000)*

[2] *V. Kashikhin et al., "Test results of a 2 Tesla Superconducting Transmission Line Magnet obtained with 102 Sensors Array of Hall Station", IEEE Trans. of Applied Superconductivity, Vol. 10, No 1 (2000)*

TABLE I
FIELD HARMONICS (IN UNITS AT 10 MM) AT ~3.2 KA INJECTION CURRENT (LEFT) AND AT ~87.5 KA COLLISION CURRENT (RIGHT)

Harmonic	Injection (0.1 T)		Collision (1.966 T)	
order	b_n^{inj}	a_n^{inj}	b_n^{col}	a_n^{col}
1	10000	0.	10000.	0.
2	-412.7	-0.1	-413.6	-2.4
3	2.8	2.6	2.56	-0.7
4	-3.6	-0.6	0.4	1.6
5	2.5	-0.8	6.3	-0.3

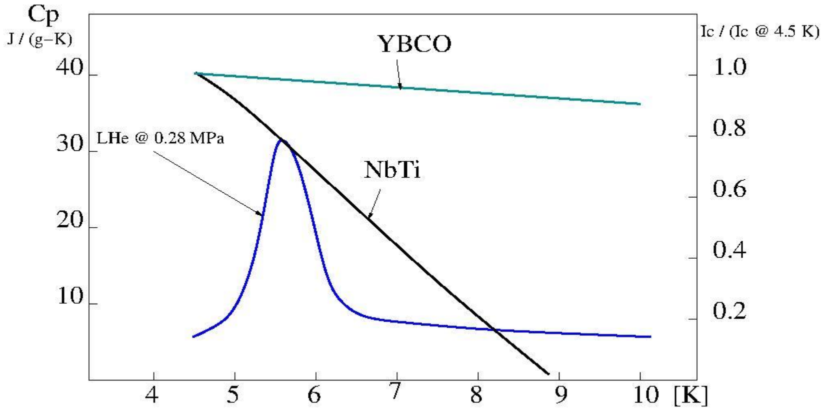
B-field harmonics from tangential rotating coil.



Effect of slots on B-field sextupole component.

Issues for R&D

1. Options for magnet core:
   - Window frame with drive/return conductors within core space.
   - C-shape with return conductor within or outside magnet cryostat.
2. Choice of SC strands:
   YBCO: Tape 2 mm x 0.1 mm , $S = 0.2\ mm^2$,
   MgB_2: Wire dia. 1 mm, $S = 0.8\ mm^2$
   Investigate feasibility of:
   - 1 mm YBCO strand.
   - Adding (0.1 – 0.2) mm copper layer over YBCO tape– facilitates splicing to current leads, safer wrapping around cryogenic pipe and helps quench protection.
3. Design, fabricate and power test various current leads options.
4. Design and test splicing system of SC strands to copper leads.
5. Design, construct & power test 2 m long, 30 mm gap magnet to derive accurate cryogenic & electrical power losses up to 9000 T/s.
6. Investigate feasibility of PS for linear current/B-field response to 2 T.
7. Investigate use of multiple Re-coolers inside accelerator tunnel to lower cryogenic power loss with potentially long transfer lines.



C_p (LHe @ 0.28 MPa) vs YBCO & NbTi critical current change.

Cryocooler: Linde LR280
For (4.5 – 5.8) K @ 600 W, LHe flow = 27 g/s,
Electric power = 200 kW, Cost: $ 4M.
B. J. Hansen, Cryogenic Dep ., Fermilab (2023)