HTS pulsed magnet concept & detailed studies

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OUTLINE:

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2. *Arrangement of HTS power cable*
3. *Power test of FNAL fast cycling HTS magnet*
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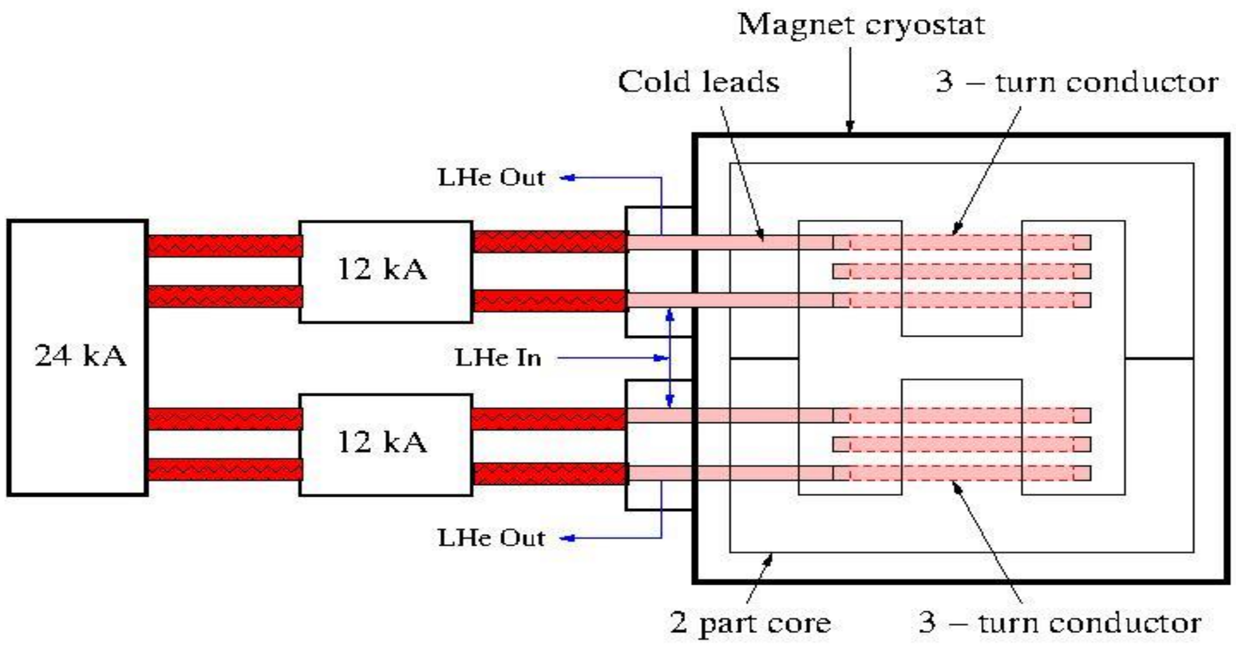
MuCol Mini-Workshop on Rapid-Cycled Synchrotrons, May 15, 2024

RCS HTS magnet conceptual design

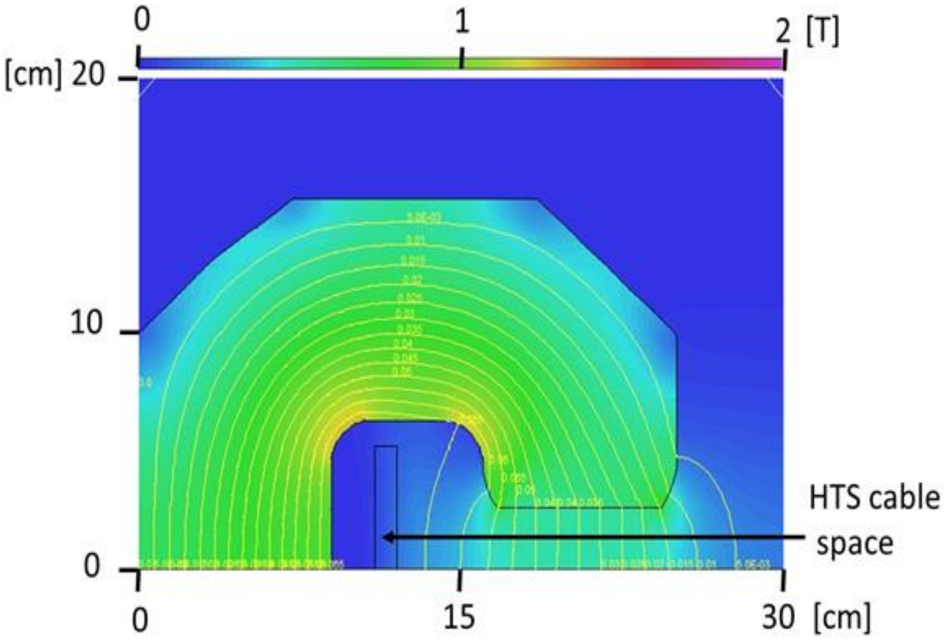


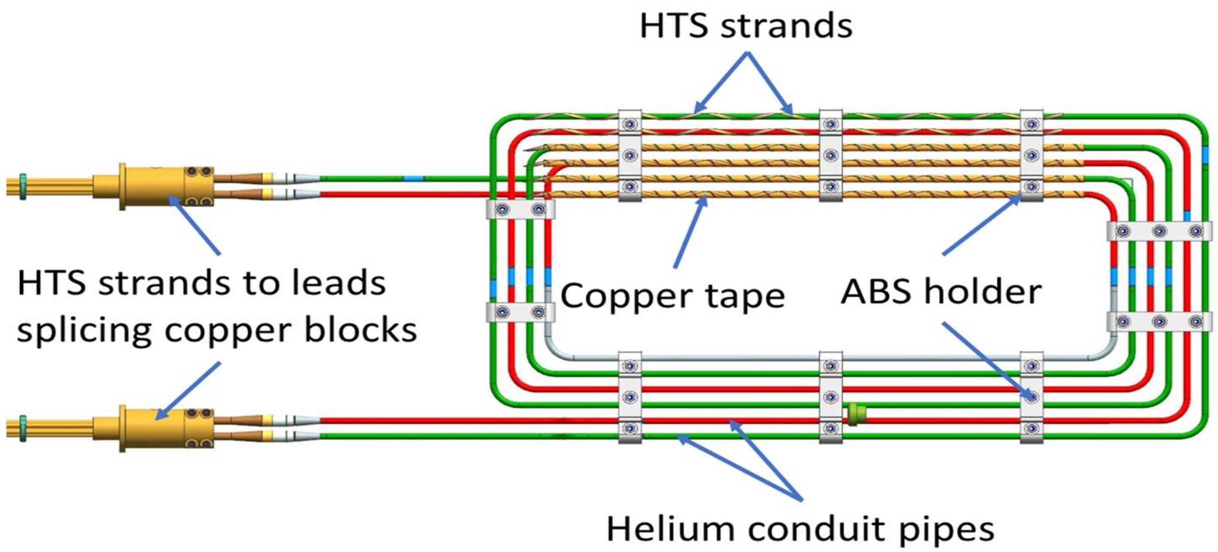
- *12 kA current supplies energize dual 3-turn conductor to 36 kA generating 1.8 T in the 30 mm beam gap.*
- *With power supply based on 960 μF capacitor bank the discharge voltage is 400 V @ 6000 T/s. Both, conductors and current leads can be made to withstand > 1 kV.*

Magnet main characteristics

- *Magnet core inside the cryostat*
- *Dual 3 – turn HTS coil cooled with supercritical helium*
- *Current lead ends with spliced HTS tapes cooled through heat conduction from the conductor coil*
- *Magnet core LCW cooling is provided into interior of magnet cryostat*
- *No vacuum beam pipe:*
  For oval SS vacuum pipe: 30 mm x 100 mm, 1.65 mm wall (Main Injector, Fermilab) eddy currents heat is 9.5 kW/m with 1.8 T @ 5 ms-5 Hz pulse. Temp. rise ~ 7 K/s-m.
- *Ceramic vacuum pipe option:*
  Typical wall 5 mm increases gap/current 30 % and power loss 80 %.

Arrangement of FNAL HTS Fast Cycling Test Magnet

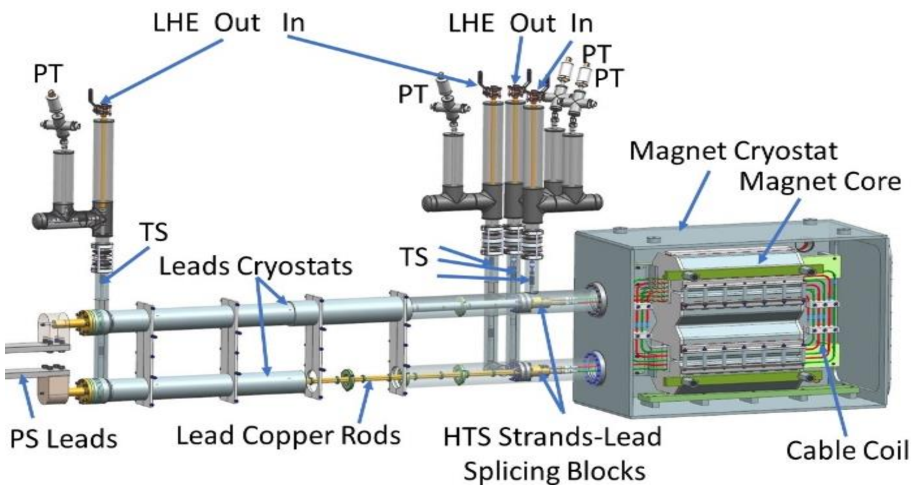


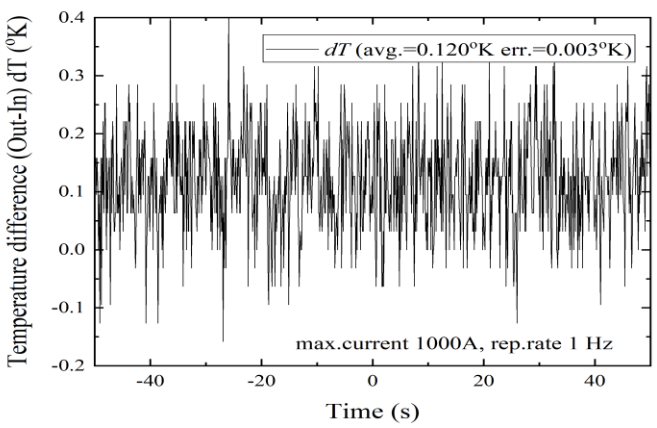


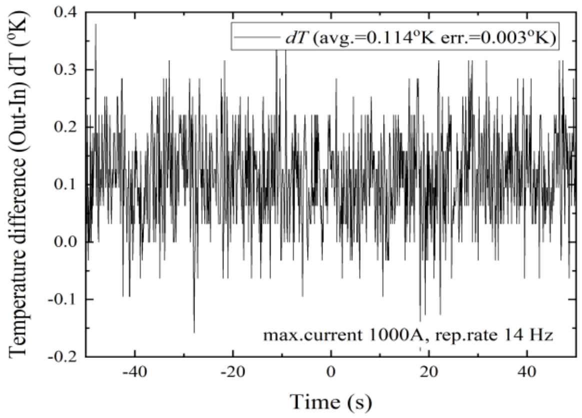
Conductor coil placed within magnet core cable space of magnetic field less than 5% of that in the beam gap. The 0.4 T beam gap field leads to 0.02 T through cable space.

- *Power cable split to 2 parallel sub-cables, each 0.5 kA*
- *YBCO tapes (2.5 mm x 0.1 mm) wrapped at 10 cm pitch over helium conduit pipe (316LN, OD 9 mm, wall 0.5 mm).*
- *Copper tape (12.5 mm x 0.1 mm) wrapped @ 5 cm pitch.*
- *ABS holders/spacers hold together cable structure and secure its position within magnet core cable space.*
- *MLI wrapped over cable assembly between ABS holder.*

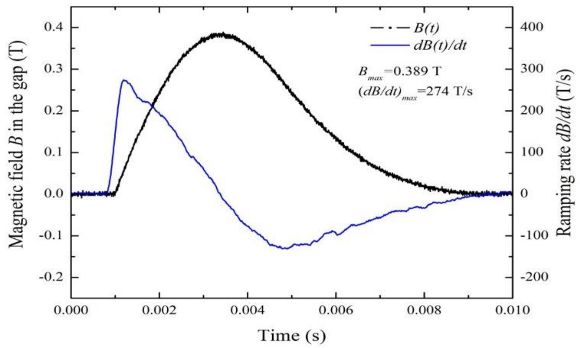
FNAL HTS Fast Cycling Magnet Power Test

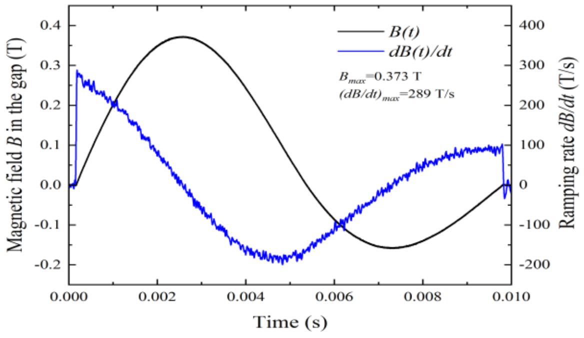






Measured: ΔT_{He} (Out – In), P_{He} & F_{He} @ 1 Hz & 10 Hz.
ΔT_{He} (10 Hz – 1 Hz)) < 0.003 K (measurement error).



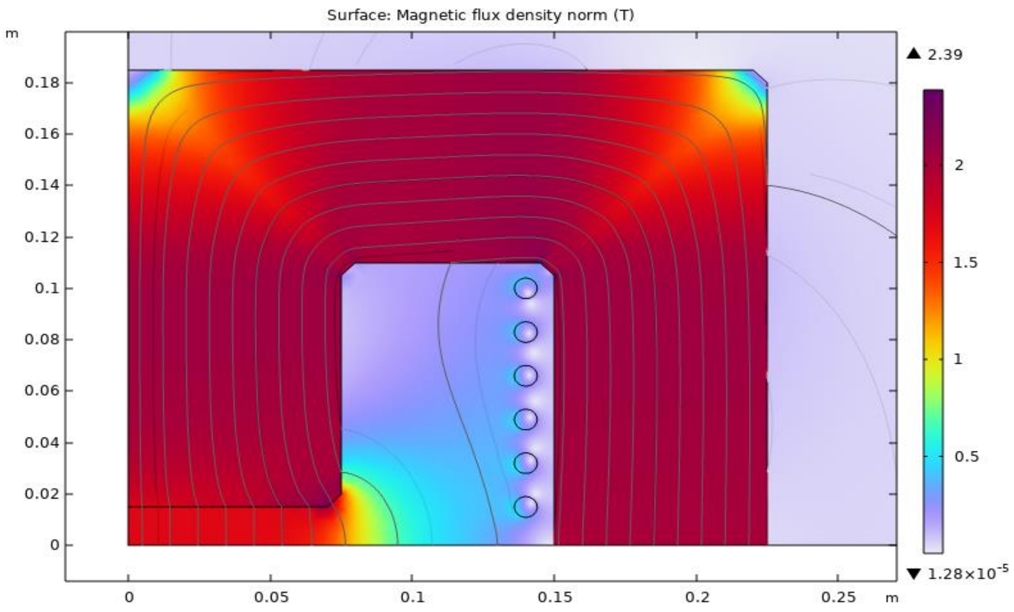


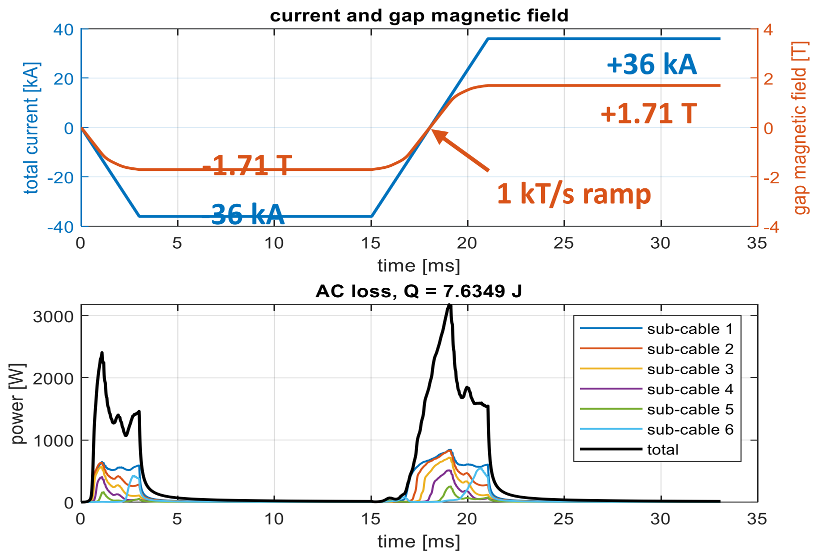
Test magnet unipolar & bipolar B-field wave-forms

Magnet power parameters and loss estimate:
I_{Magnet}: 3 kA (50 % of I_C), t_{Ramp} = 2.6 10^{-3} s.
dB/dt gap 300 T/s, dB/dt cable space 16 T/s.
LHe coolant: 5.5 K, 0.28 MPa, 2.5 g/s.
Power loss, Q, determined using change of helium enthalpy:
For ΔT_{He} < 0.003 K: Q_{CABLE} < 0.06 W/m *)

**) H. Piekarz, B. Claypool, S. Hays, M. Kufer, V. Shiltsev, MT-27 (2022)*

*HTS conductor hysteresis loss simulation for Muon RCS magnet *)*





Upgraded cable/core arrangement:

Magnet gap: 30 mm x 100 mm
Conductor: 6 sub-cables per ¼ magnet
Sub-cable: 12 x 2 mm HTS tapes
Total HTS tapes/magnet: 288
Cold pipe conduit: 9 mm OD, 0.5 mm wall

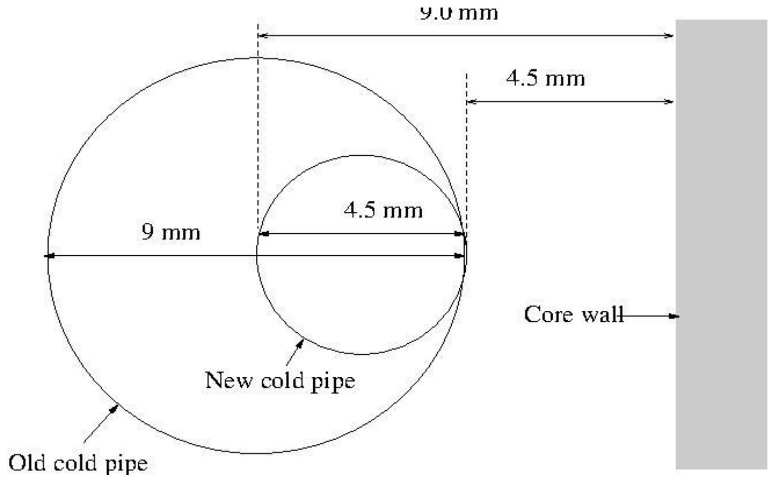
B_{max} : 1.7 T, <B_{Cable}> : 0.19 T
t_{rise} : 1.6 10^{-3} s, t_{pulse} = 6 10^{-3} s
<dB/dt>$_{Cable}$ = 119 T/s
Q_{cable} = 30 J/m-pulse
Q_{cable} = 5 kW/m-pulse
DF @ 5 Hz = 5Hz x 3 10^{-3} s = 0.015
Q_{cable} = 75 W/m-cycle
$Q_{\textit{ELEC-CYCLE}}$ = 5.3 kW/m @ 15 K

**) S. Otten, A. Cario, H. ten Kate, Univ. of Twente*

Upgraded Muon RCS magnet cable design & position

BASIC PARAMETRS OF HTS RCS MAGNET

Baseline - 1 m magnet		FNAL Test	UT/CERN	FNAL
HTS		YBCO	YBCO	YBCO
Cross-section	[mm^2]	0.25	0.20	0.20
Number of HTS tapes		12	144	144
Length	[m]	6.6	13.2	13.2
Volume	[m^3]	22.5 10^{-7}	270 10^{-7}	270 10^{-7}
Mass	[g]	20.5	246	246
Cryogenic pipe		316LN	316LN	316LN
Diameter x wall	[mm x mm]	9 x 0.5	9 x 0.5	4.5 x 0.1
Length	[m]	6	12	12
Volume	[m^3]	73 10^{-6}	73 10^{-6}	14.6 10^{-6}
Mass	[g]	569	1138	228
Copper tape		CDA102	CDA102	CDA102
Cross-section	[mm^2]	1.25	1.25	1.25
Length	[m]	18	36	36
Volume	[m^3]	15 10^{-5}	30 10^{-5}	30 10^{-5}
Mass	[g]	107	214	214
Total cable				
Volume	[m^3]	88 10^{-6}	400 10^{-6}	342 10^{-6}
Mass	[g]	676	1598	688



Based on field simulations*) we tentatively project that B-field through cable space can be reduced by ½ with cryo-pipe size reduced by ½ and placed much closer to the core, as indicated in figure above. Such arrangement will likely reduce hysteresis losses by factor 4. In the new cable design HTS tapes are wound in 2 layers at an opposite angle to minimize self-field coupling.

**) F. Boattini et al., MC Magnet Working Group, 2/15/24*
S. Otten et al., MC Magnet Working Group, 3/13/24

Projected HTS conductor hysteresis loss & cryogenic power

CABLE PARAMETERS		FNAL TEST	UT/CERN	FNAL RCS I	FNAL RCS II
He temperature	[K]	5.5	**15**	**15**	**5.5**
He pressure	[MPa]	0.28	2.0	2.0	0.28
He specific gravity	[kg/m3]	~ 68	~ 68	~ 68	~ 68
He inventory	[L/m]	0.95	1.9	1.9	0.95
Magnet gap field	[T]	0.4	1.7	1.7	1.7
Ramp rate	[T/s]	300	5000	5000	5000
Cable field	[% gap]	4	12	6	6
Cable ramp rate	[T/s]	12	120	60	60
Pulse frequency	[Hz]	10	5	5	5
Cable hysteresis loss/cycle	[W/m]	< 0.053	302	75	15
Cold pipe eddy loss/cycle	[W/m]	< 0.007	0.06	0.015	0.003
Cable loss/cycle	**[W/m]**	**< 0.060**	**302**	**75**	**15**
He flow rate	[g/s-m]	2.5	13.5	3.375	0.675
COP factor	[%]	-	5	5	1.9
Minimum cryogenic power	[kW/m]	-	6	1.5	0.79
Cryogenic plant power *)	**[MW]**	**-**	**48**	**12**	**3.1**

*) Accelerator ring 2000 m, Cryogenic plant efficiency 25 %

Thermal response of HTS conductor in normal operation & quench

HEAT EXCHANGE PARAMETERS	UT/CERN RCS	FNAL RCS
Normal operations, ΔT_{RISE} 1 K		
HTS tapes -> copper shield Contact surface area [m^2] Thermal conductivity [kW/m-K] Transverse thermal diffusivity [K/s]	 28.3×10^{-3} 20 $5\ 10^5$	 $14.2\ 10^{-3}$ 10 10^6
Copper shield <-> cold pipe/helium Contact surface area [m^2] Thermal conductivity [W/m-K] Transverse thermal diffusivity [K/s] Return time to normal operation [s]	 28.3×10^{-3} 22.6 1.4 0.7	 $14.2\ 10^{-3}$ 56.5 7 0.14
Quench, ΔT_{RISE} 10 K		
Copper shield <-> cold pipe/helium Transverse thermal diffusivity [K/s] Minimal return time to normal operation [s]	 14 0.2	 70 0.04

Summary & Conclusions

- Upgraded HTS cable design/placement is an encouraging indication for possible further minimization of power loss.
- Operation with supercritical helium of 5.5K, 0.28 MPa is best option for minimization of cryogenic power loss.
- Lack of modeling of hysteresis loss in HTS conductor below 15 K is an impediment to a reliable power loss prediction.
- A power test of a 1.8 T, dB/dt 5000 T/s short-sample magnet is needed to conclusively prove viability of HTS RCS magnet.