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RAPID-CYCLING HTS MAGNET FOR MUON ACCELERATION

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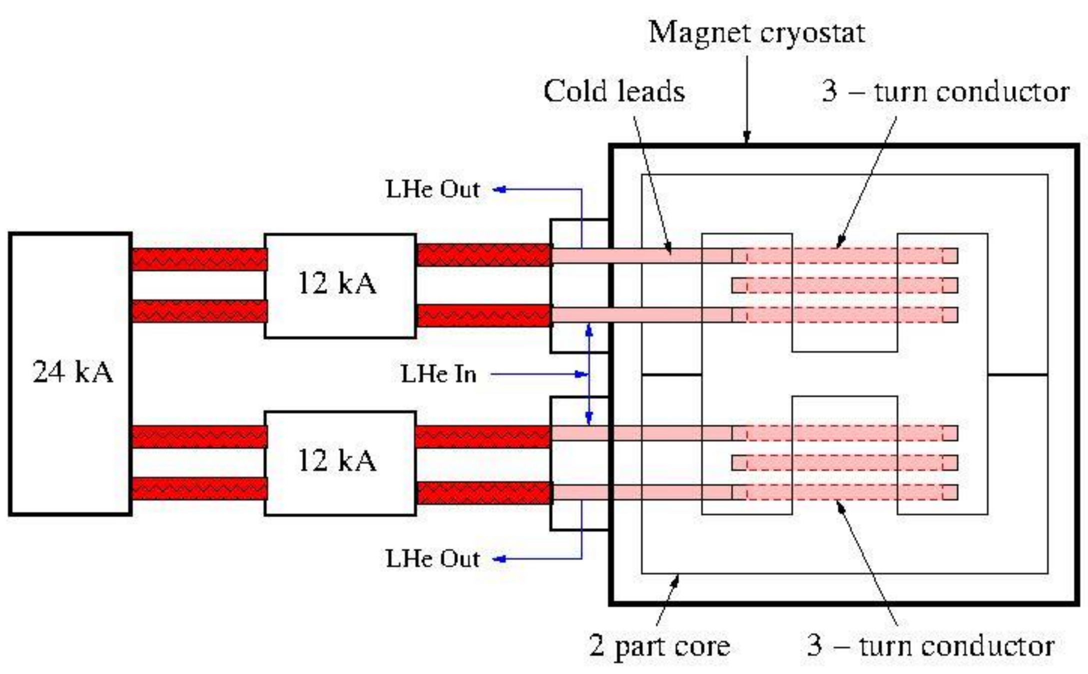
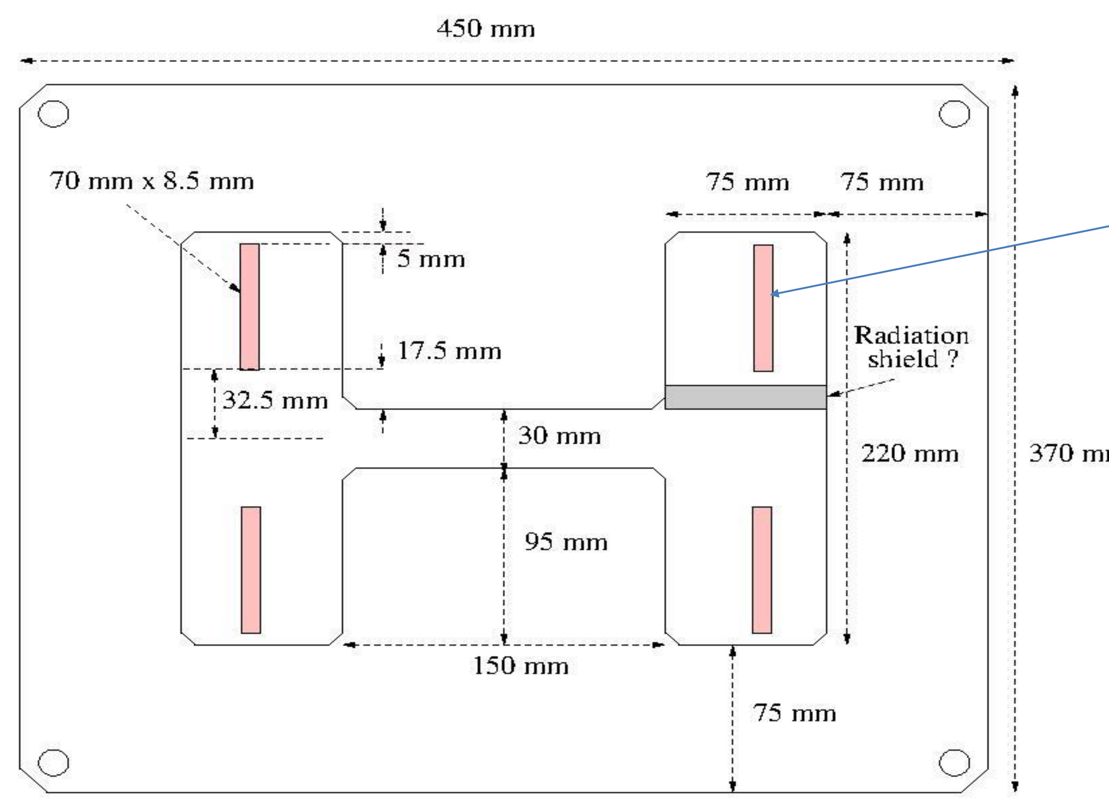
A very wide range of operational temperatures of the HTS (YBCO) superconductor makes it suitable for the construction of rapid-cycling magnets required for the muon acceleration. The measured [3] very low power loss of the 0.4 T magnet operating at 300 T/s suggested a realistic possibility of the HTS-based accelerator magnet with much higher magnetic field and ramp rate. The magnet core and the HTS cable designs for the 2 T field in the 30 mm beam gap are presented. The simulation of the HTS cable hysteresis power loss for the 1000 T/s ramp rate is discussed in terms of the operational temperatures and required cryogenic power.

RAPID-CYCLING HTS MAGNET CONCEPT



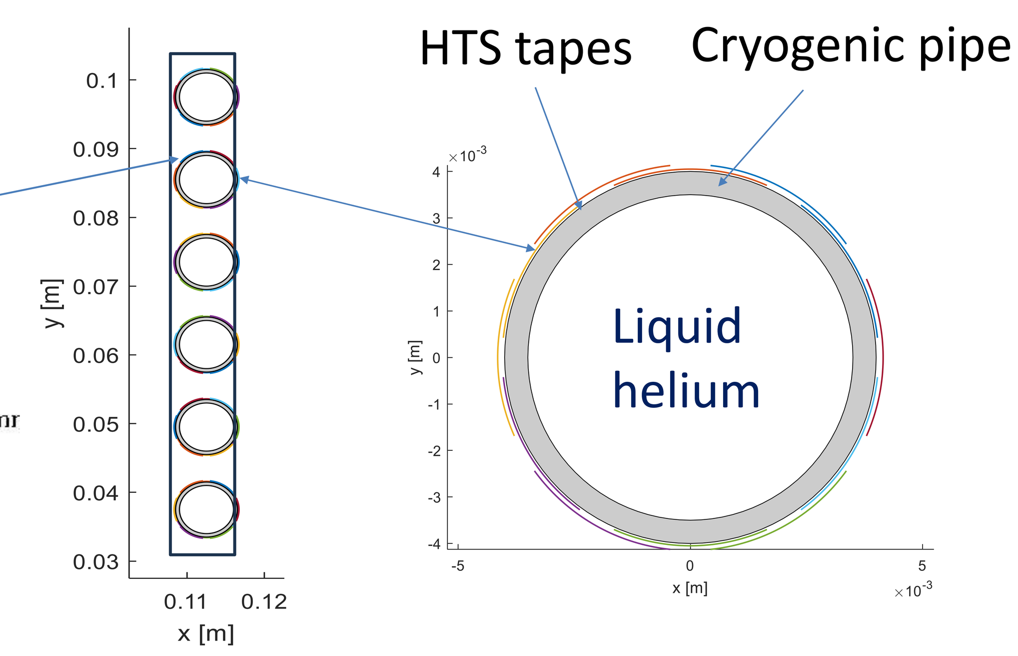
- Magnet core placed inside the cryostat
- No vacuum beam pipe
- Two 3-turn coils, each powered by 12 kA supply
- HTS conductor cooled with supercritical helium
- Current leads cold ends with spliced HTS tapes cooled through heat conduction from the conductor coil
- Magnet core LCW cooling provided to interior of cryostat

HTS MAGNET DESIGN



- Core: 0.45 m (H) x 0.370 m (V)
- Beam gap: 150 mm (H) x 30 mm (V)
- Core laminations: Fe3%Si (0.1 mm)
- 2 T field generated by 2 x 36 kA current
- Core saturation: 2 T, B-field linear: +/- 1.7 T
- Ramp rate: 1000 T/s
- Repetition rate: 5 Hz

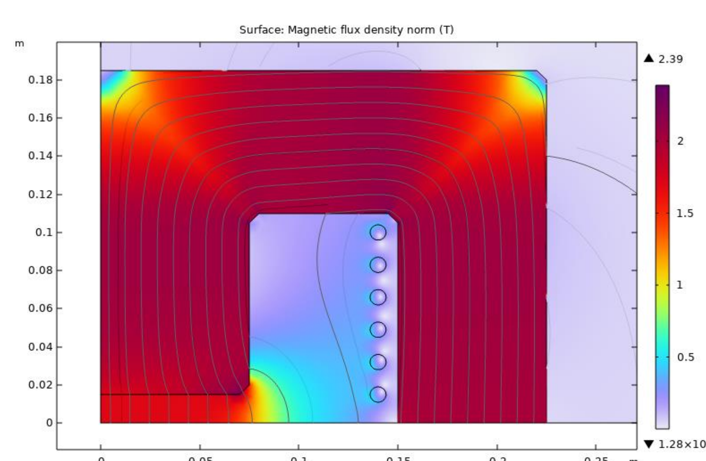
HTS CABLE DESIGN



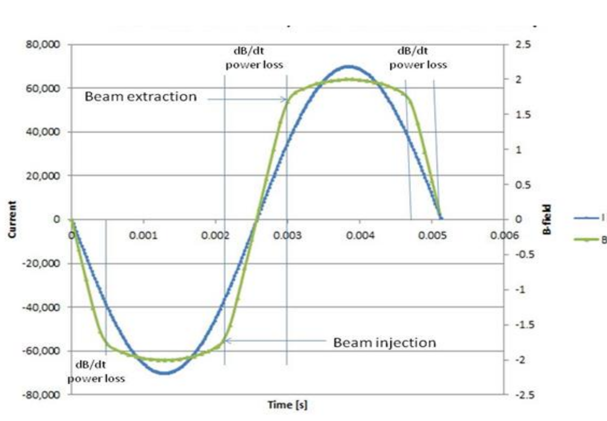
- Six sub-cables form magnet cable.
- Sub-cable consists of 12 2-mm REBCO tapes wrapped at 10 cm pitch over SS cryogenic pipe (8 mm x 0.5 mm).
- Current per sub-cable 6 kA.
- Cable current 36 kA.
- Magnet energizing current 72 kA.
- Liquid helium: 5.5 K @ 0.28 MPa, volume 2 L / m

SIMULATION OF HTS CABLE HYSTERESIS LOSS AT 2T_1000 T/S_15 K

B-field simulation of magnet core



Magnet core simulation in COMSOL. HTS sub-cables position optimized for minimum perpendicular B-field.



Sine-wave current wave-form & B-field response. Core saturates at about 2 T. Current to B-field linear in +/- 1.7 T .

Hysteresis loss of twisted HTS tapes in B_{PERP}

$$Q_{hyst} = B_{max} \, x \, N \, x \, I_c \, x \, \frac{w}{\pi \cos(\alpha)} \quad [1]$$

I_c = critical current per tape

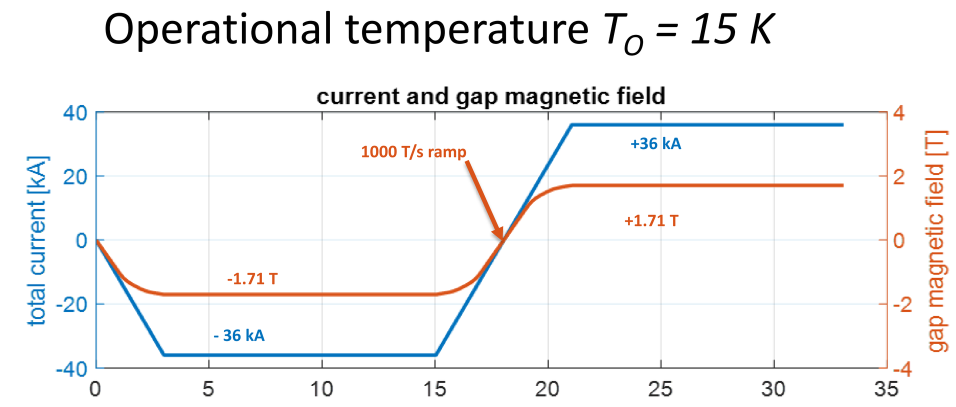
$N \, x \, I_c$ = critical current per sub-cable

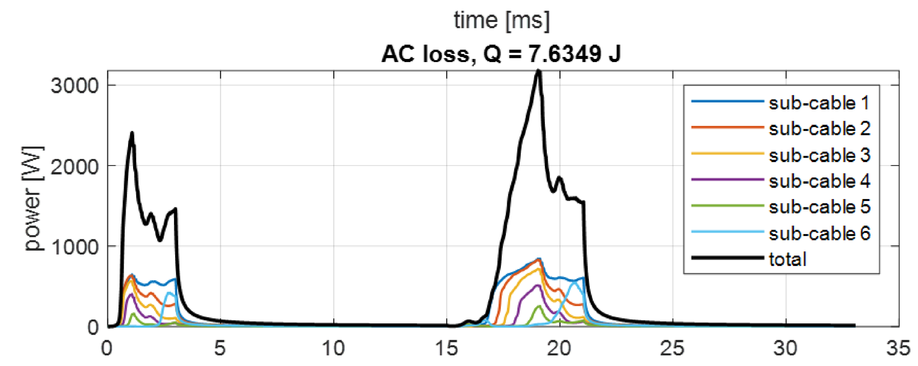
α = tape lay angle (0° = straight tape)

$\frac{w}{\pi \cos(\alpha)}$ = effective tape width & length

Operational current $I_O = 0.5 \, I_C$

Operational temperature $T_O = 15 \, K$





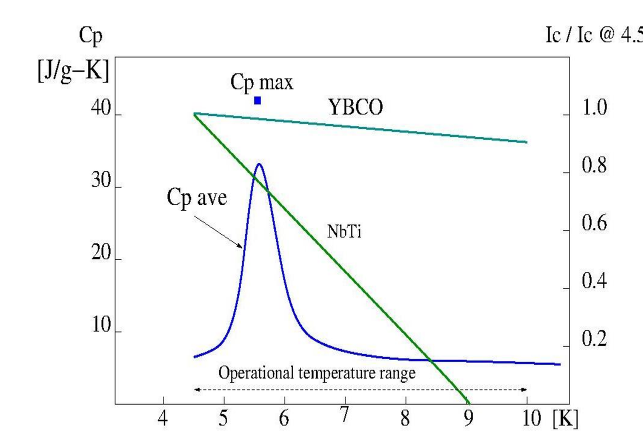
Hysteresis loss (¼ magnet) @ 2 T_1 kT/s_15 K = 7.8 J/m. Sine-wave current represented by step function. Colors show hysteresis loss of individual sub-cables.

[1] Numerical calculation, see also Solovyov et al., https://doi.org/10.1088/1361-6668/acb08e

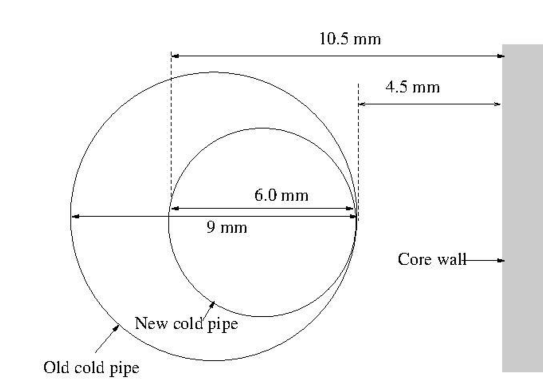
PROJECTION OF HTS CABLE HYSTERESIS LOSS AT 5.5 K

Scaling hysteresis loss from 15 K to 5.5 K

- *Effect of He specific heat*
  C_P (5.5 K) ~ 6 x C_P (15 K)
  Q_{hyst} (5.5 K) ~ 0.17 Q_{hyst} (15 K)
- *Effect of operational temperature [2]*
  Operational $T_{max} = T_O + 5$ K
  N_{HTS} (10 K) ~ 0.67 N_{HTS} (20 K)
  [2] C. Senatore et al., https://arxiv.org/1512.01930



- *Effect of B-field exposure*
  $D_{cryo\text{-}pipe}$ (5.5 K) = 0.67 $D_{cryo\text{-}pipe}$ (15 K)
  <B> @ D = 6 mm => ~ ½ <B> @ D = 9 mm
  Q_{hyst} (0.5 B) ~ 0.5 Q_{hyst} (B)



- Q_{hyst} (5.5 K) = 0.056 Q_{hyst} (15 K)

Projected hysteresis loss at 5.5 K for full magnet:

Q_{hyst} (5.5 K) = 4 x 7.8 J/m x 0.056 = 1.75 J/m

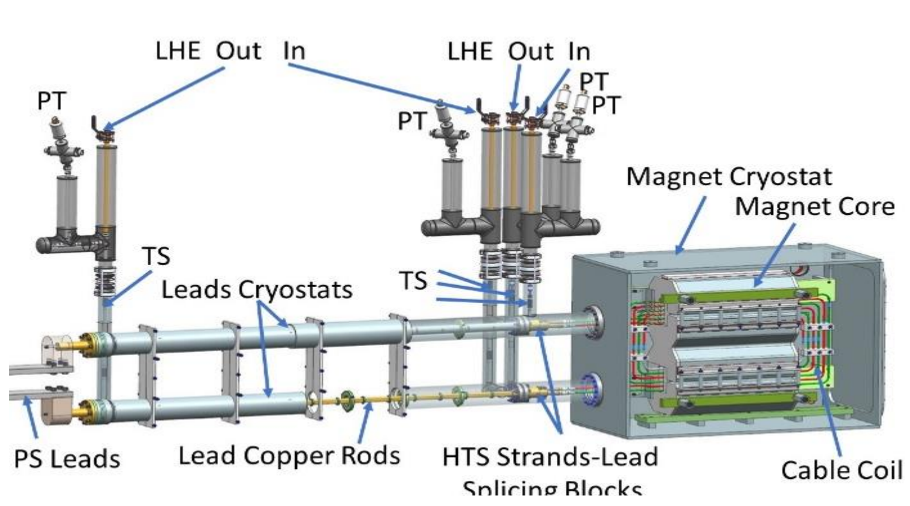
PROJECTED CRYOGENIC POWER @ 2T_1 KT/S_5 Hz_5.5 K

COP (300 K -> 5.5 K): 1.9 %, Cryo-plant efficiency: 20 %

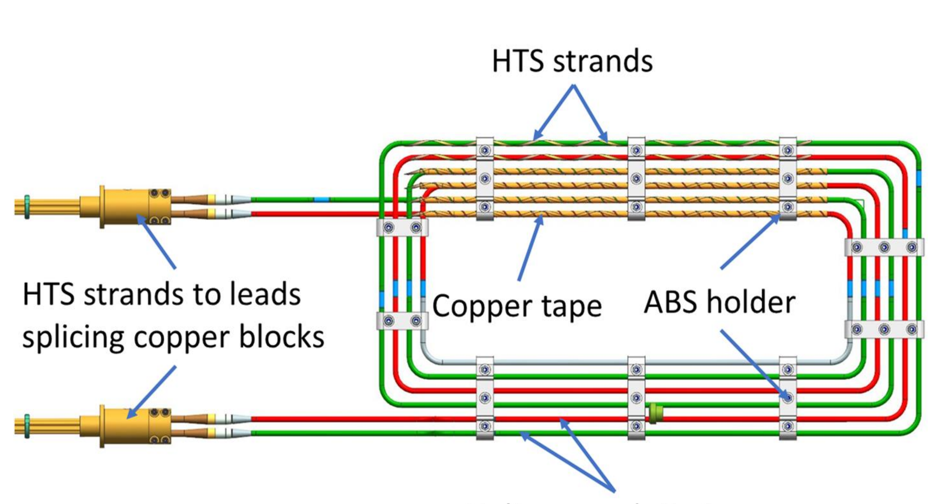
P_{CRYO} = 1.75 J/m x 0.019^{-1} x 0.20^{-1} x 5 s^{-1} = 2.3 kW/m

FNAL Booster: P_{LCW} (Cu, 0.7 T, 30 T/s, 15 s^{-1}) = 8.6 kW/m

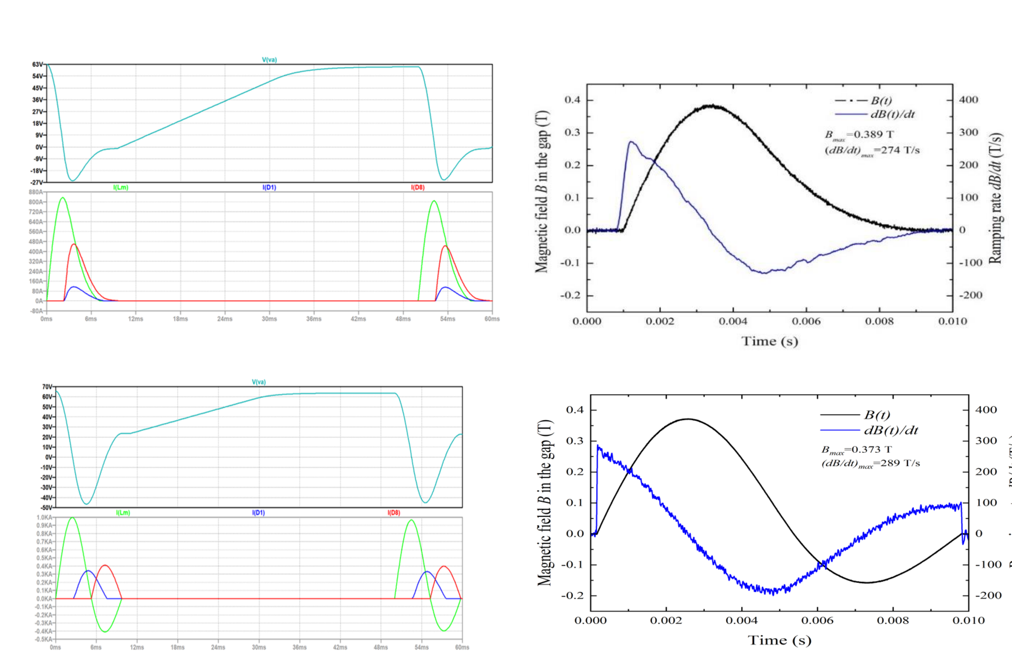
RAPID-CYCLING HTS MAGNET POWER TEST AT 0.4 T_300 T/S_10 Hz_5.5 K [3]



1 – Magnet, 2- Current leads, 3- Power supply, 4 – Control electronics, 5- Liquid Helium lines

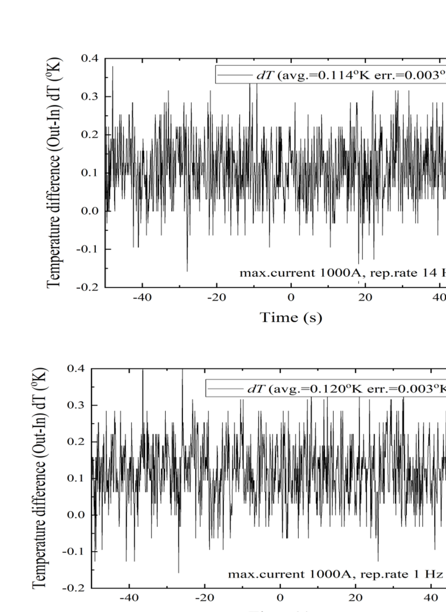


- ❑ Cable split to 2 parallel sub-cables, each 0.5 kA.
- ❑ Two sub-cables (1 kA) make 3 turns.
- ❑ YBCO tapes (2.5 mm x 0.1 mm) wrapped at 10 cm pitch over helium conduit pipe.
- ❑ Cu tape wrapped over YBCO tapes @ 5 cm pitch.
- ❑ ABS holders/spacers hold cable structure and secure position within magnet core cable space.
- ❑ MLI (40 layers) wrapped over cable assembly.
- ❑ LHe: 5.5 K, 0.28 MPa, 2.5 g/s.



Unipolar & bipolar energizing current & magnetic field generated by discharge capacitor bank: 960 μF @ 80 V.

*[3] Henryk Piekarz, Brad Claypool, Steve Hays, Matt Kufer, Vladimir Shiltsev, «Record High Ramping Rates in HTS Based Supercond. Accelerator Magnet», MT 27, IEEE Transation on Applied Superconductivity, **32** (2022) 6, 4100404*



HTS cable temp. rise @ 300 T/s. Top @ 1Hz, Bottom @ 10 Hz. ΔT (10 Hz – 1 Hz) < +/- 0.003 K.

Q_{cable} < 0.06 W/m