Calorimetric Measurements of YBCO Superconductor and Metallic Cables at High dB/dt in a Cryogenic Stator Machine Environment

Integrity ★ Service ★ Excellence

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CO-AUTHORS, ACKNOWLEDGEMENTS

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  - E.W. Collings

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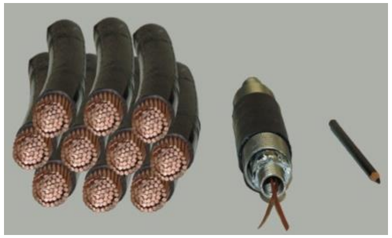
Overview

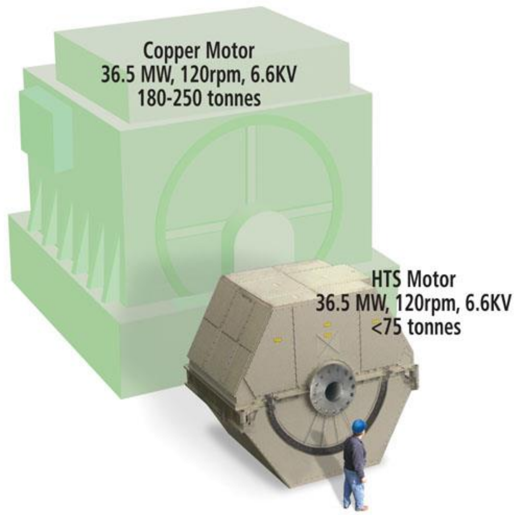
- The U.S. Air Force Research Laboratory (AFRL) facility for the measurement of AC loss in superconductors at high B*dB/dt
- The test device has a spinning rotor consisting of permanent magnets arranged in a Halbach array; which exposes samples in a stator position with a peak radial field of 0.57 T, and with high rotation speeds up to 3600 rpm achieves a radial dB/dt is 543 T/s and tangential dB/dt is 249 T/s.
- Loss is measured by calorimetry at 77.2K using nitrogen boil-off from a double wall calorimeter feeding a gas flow meter, and the system was calibrated using power from a known resistor.
- This work describes the use of this test facility to measure and compare AC losses of a variety of YBCO coated conductors and cable styles.
- Conductors of YBCO are provided by several manufacturers with different architectures including filamented, varying width, and stabilizers

AC Loss Critical for Components of Interest to the AF

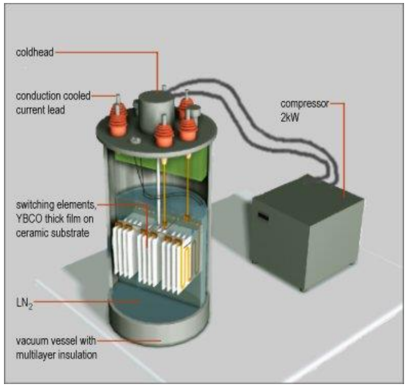
Power Transmission



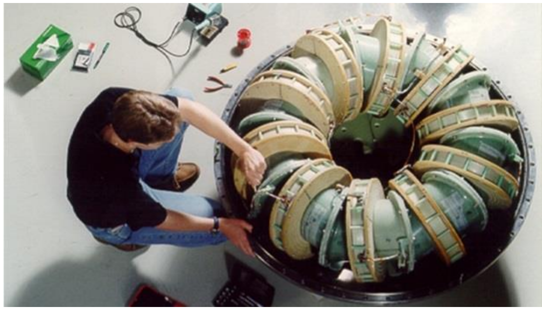
Generators/Motors



Fault Current Limiters



(SMES) Energy Storage

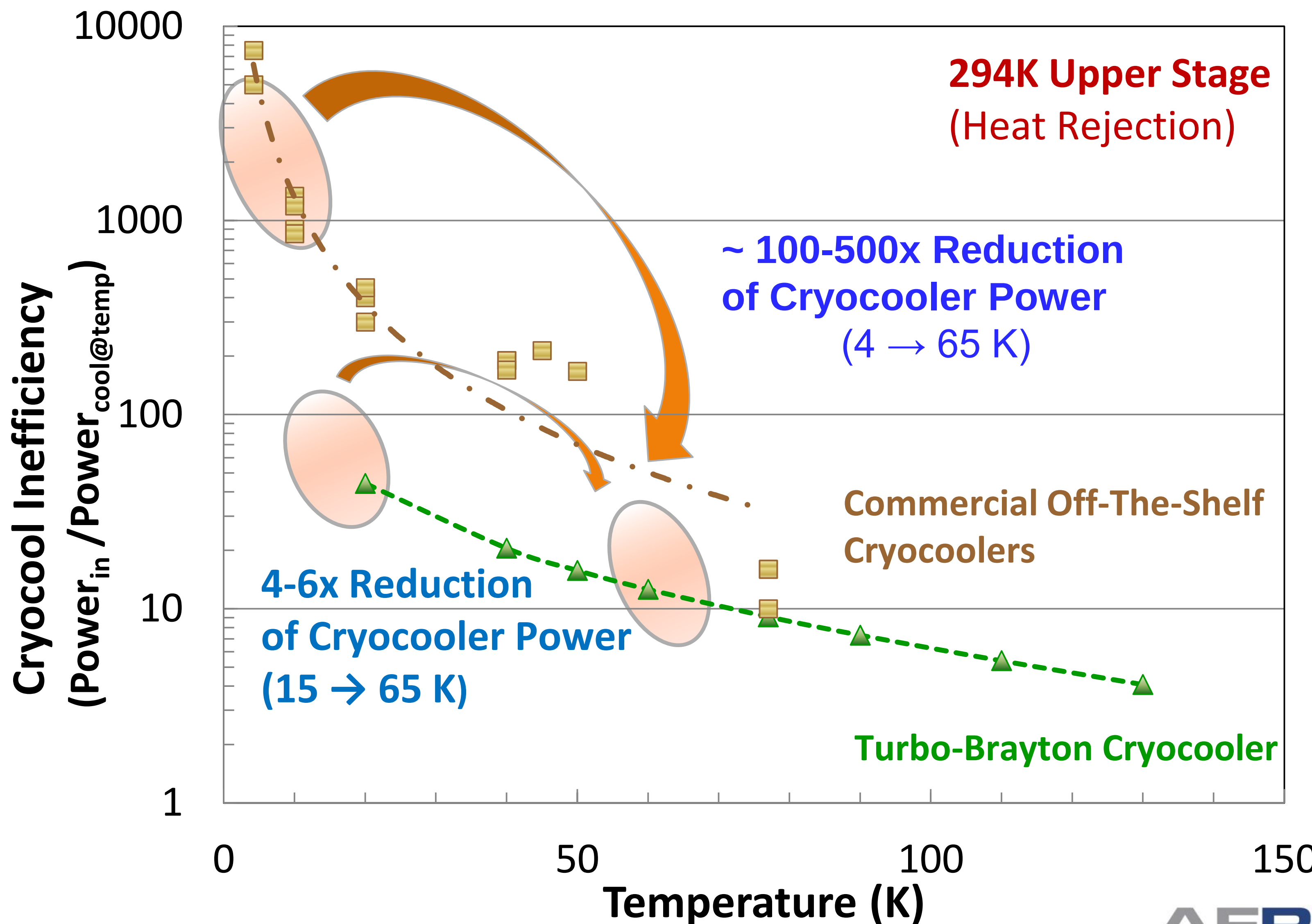


Transformers

http://www.conectus.org

http://blog.explore-house.eu/en/2012/08/16/hydrogen-storage-in-the-future/

Cryocooler Efficiencies



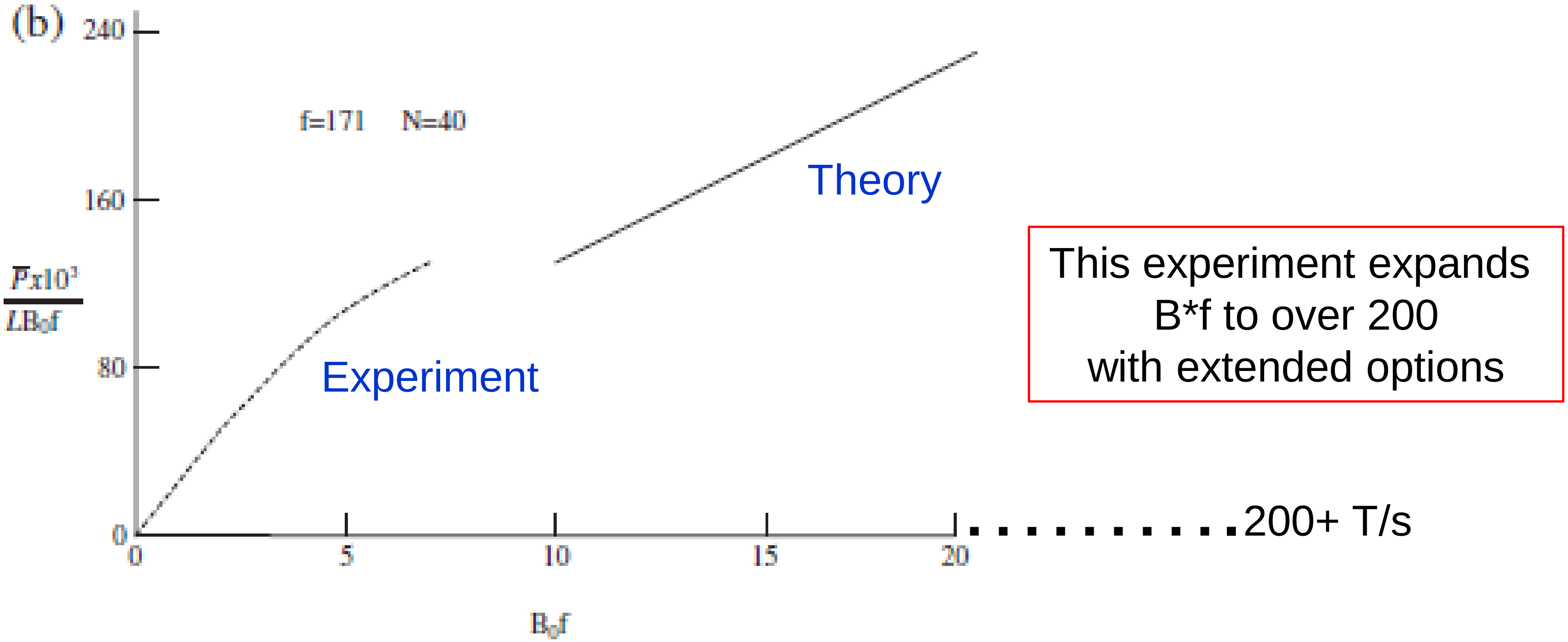
Need for high *B* and d*B*/dt Testing

- **Windings in a motor/generator see high *dB/dt* like no other superconducting machine (e.g., 400 Hz and 0.5-1 T)**
- Extrapolate to high *dB/dt* in principle, need actual tests to make predictions reliable
- Easy to imagine a magnet which can reach these values of *B* and *dB/dt,* but
  - Such a magnet would need to be SC to reach the needed fields without Fe
  - The losses would require a SC of the kind we wish to develop
  - Would require high voltage (10s of kV).

Alternative: Move sample and field relative to each other

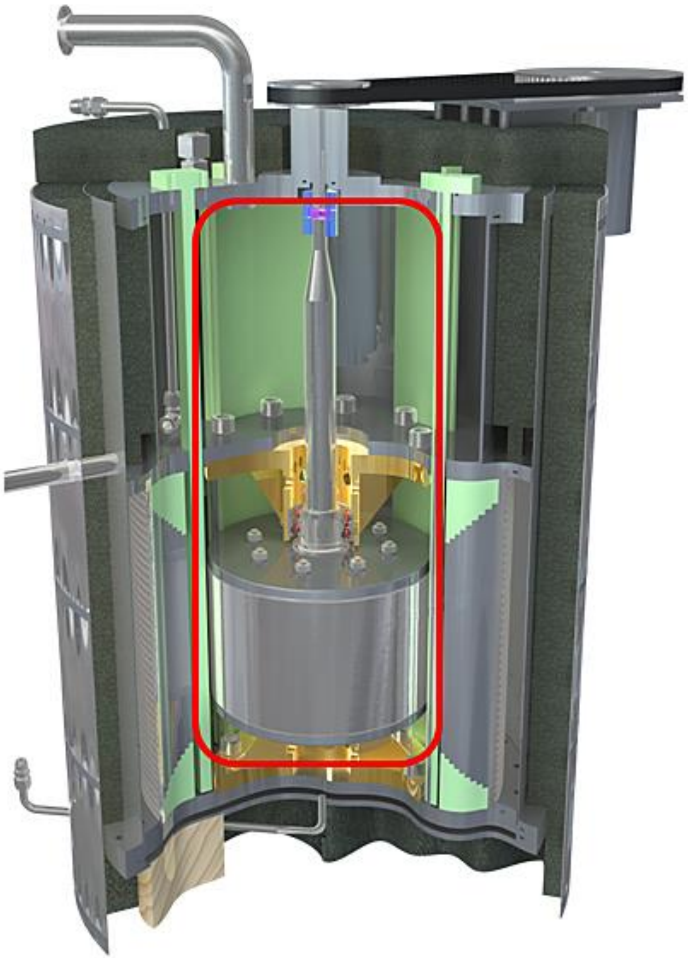
Effectively - a motor simulator- "mock" motor/generator!

SMC AC Loss Device – Investigate New Physics at High *B*f* ?



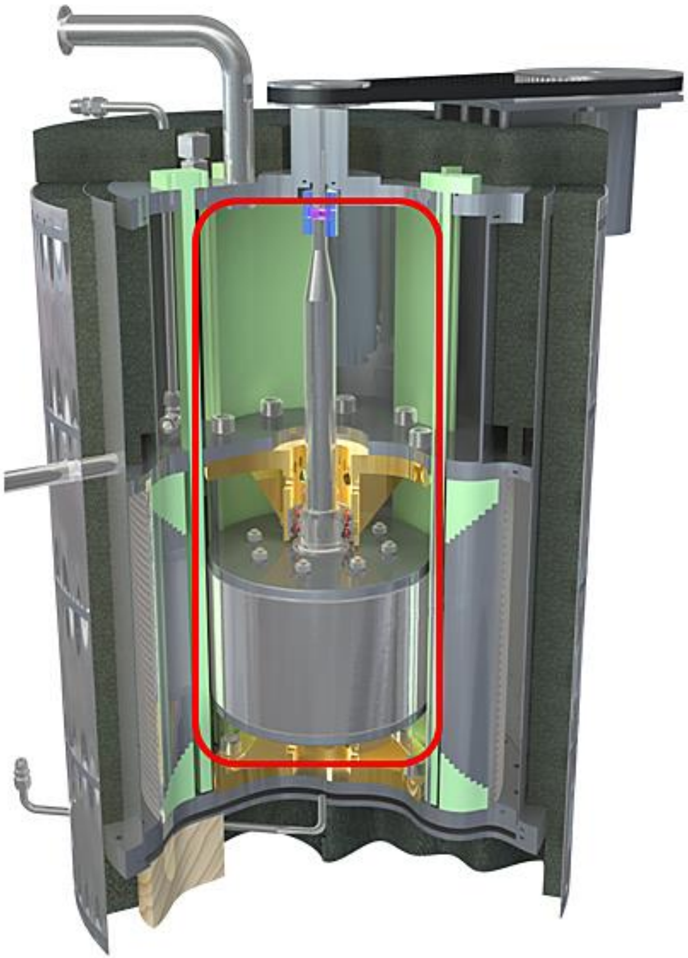
Reduced loss expression plotted against reduced magnetic field for frequency of 171 Hz for (a) … (b) 40-filament sample. Dashed lines are approximate copies of weak field measurements published by Levin *et al*, and solid lines calculated from strong field results given here. From Carr et al, Supercond. Sci Technol. **20,** 168 (2007).

Phase 2-External Magnetic Field
Stator Environment



8 Pole Permanent Magnet Rotor
Provides 0.62 Tesla
0 Hz to 400 Hz

Spin-around-magnet (SAM) AC Loss Test Device -
Time-Varying Magnetic Field in a Stator Environment



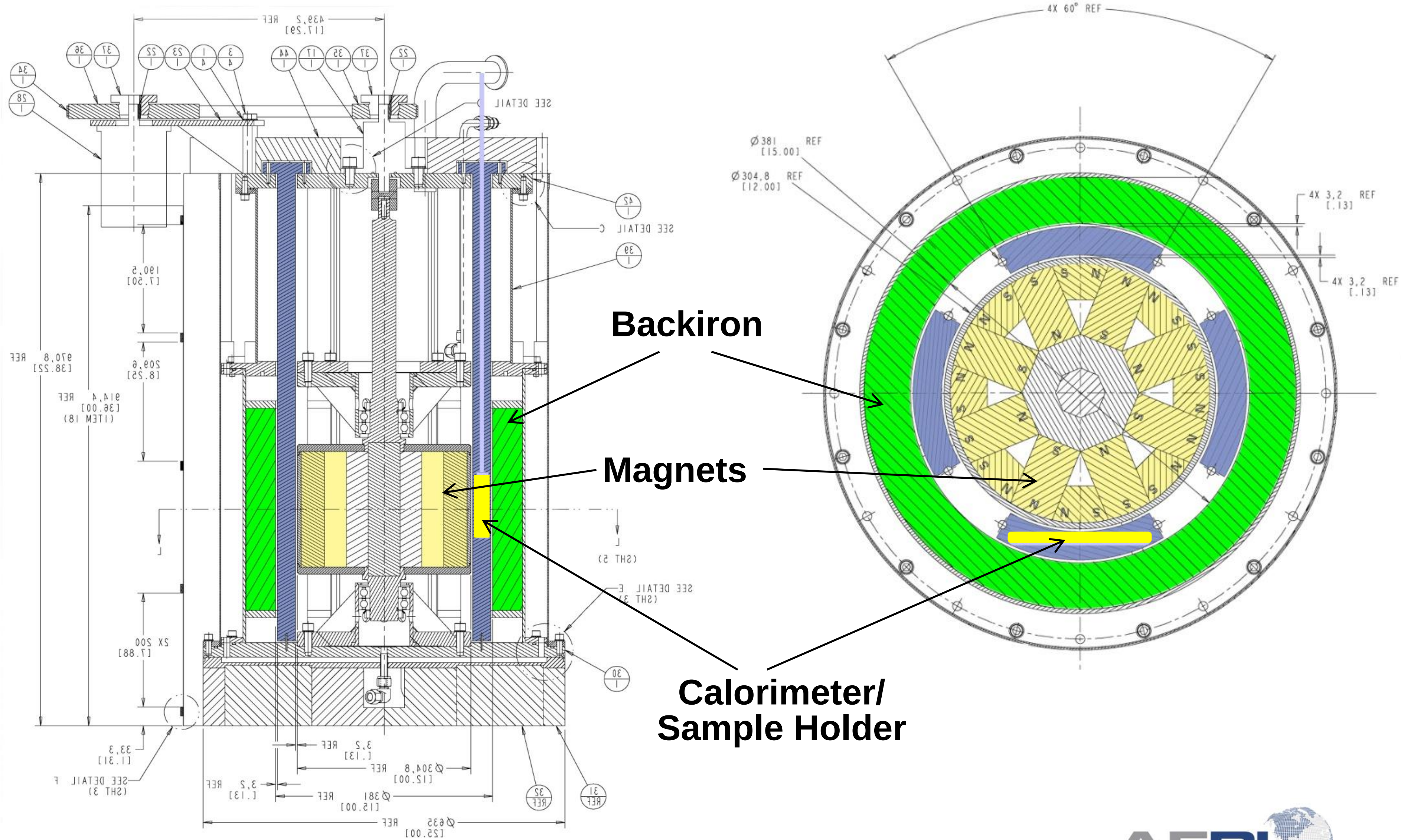
8 Pole Permanent Magnet Rotor
Provides 0.62 Tesla
0 Hz to 400 Hz

World-unique AC Loss Test Device

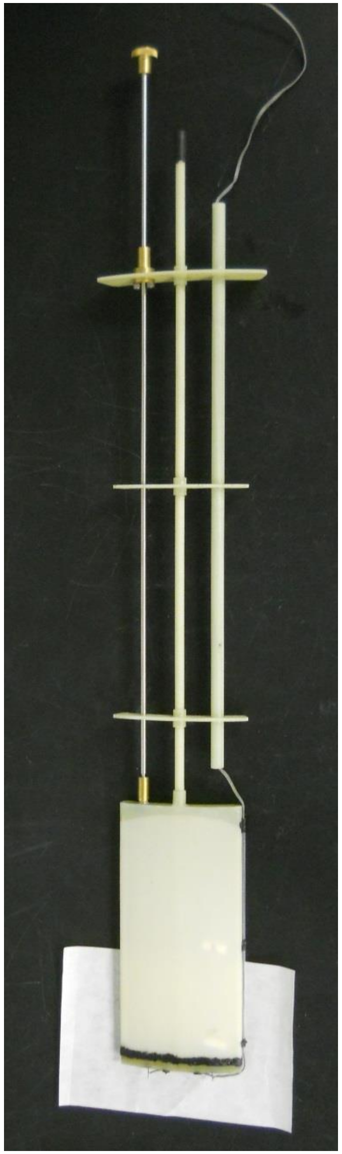
- 8-pole Hallbach Array of NdFeB Magnets
- B-field = 0.62 T
- **Frequency = 0 to 400 HZ (required for AF)**
- **Sweep Rate B*f = 240 T/s**
  (~ 15x higher than standard world-wide)
- Calorimetry Measurement – very precise
- **77K with liquid N_2**
- **4.2 K with liquid He !**
- **20 K with liquid Hydrogen (?)**
- Tapes, Cables, Coils – small or large
- AC loss in real stator environment, complex
  B and *I* varying in time and space

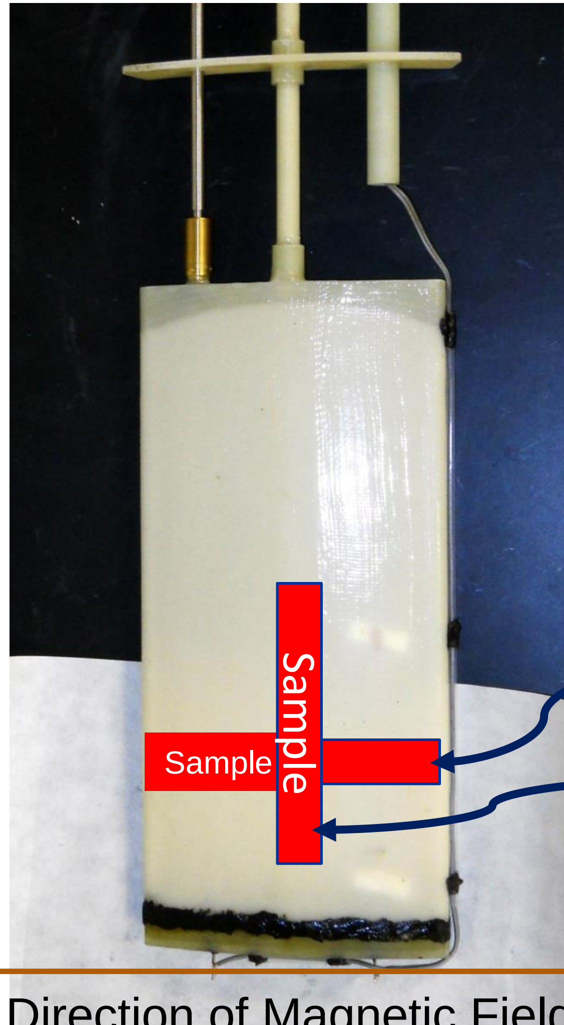
J. Murphy, et al., IEEE Trans. Appl. Supercond. **23(3)**, 4701505 (Jun 2013)

Machine Cross Sections



Sample Holder/Calorimeter





Sealed Sample holder

LN_2 Filled via remote operated valve on top

Sample inserted through bottom port which is sealed with a plug

Contains resistors for heating

All fiberglass except valve and resistance heater

Sample orientation:

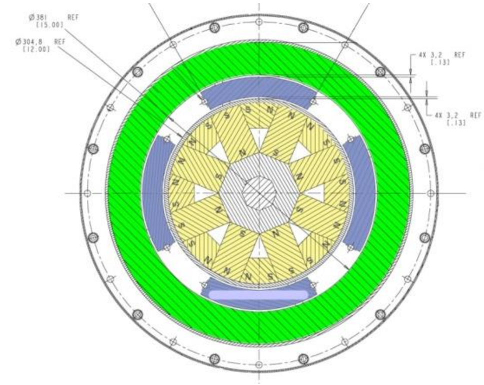
Horizontal is parallel to the magnet motion

Vertical is perpendicular to the magnet motion

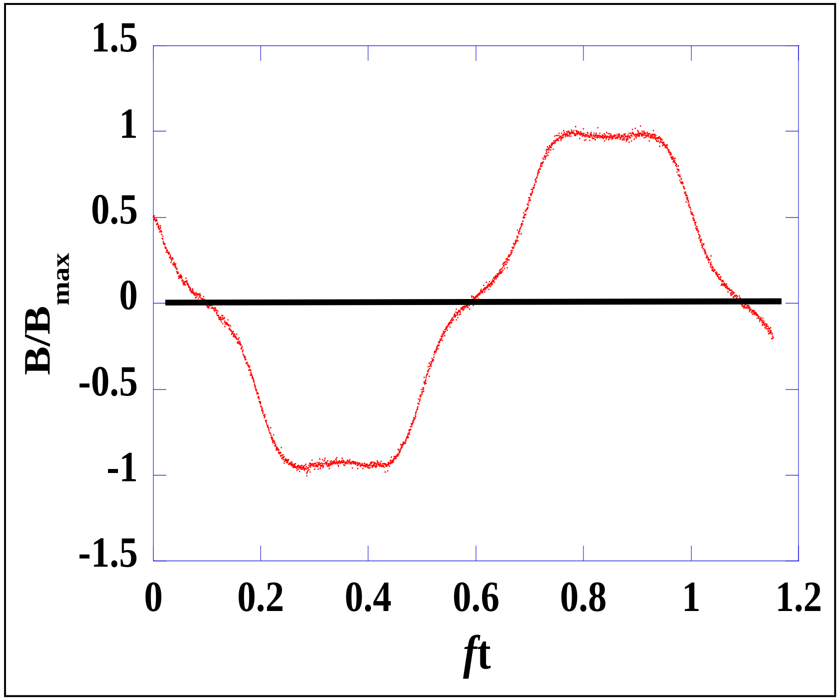
Direction of Magnetic Field Motion Relative to Sample Holder

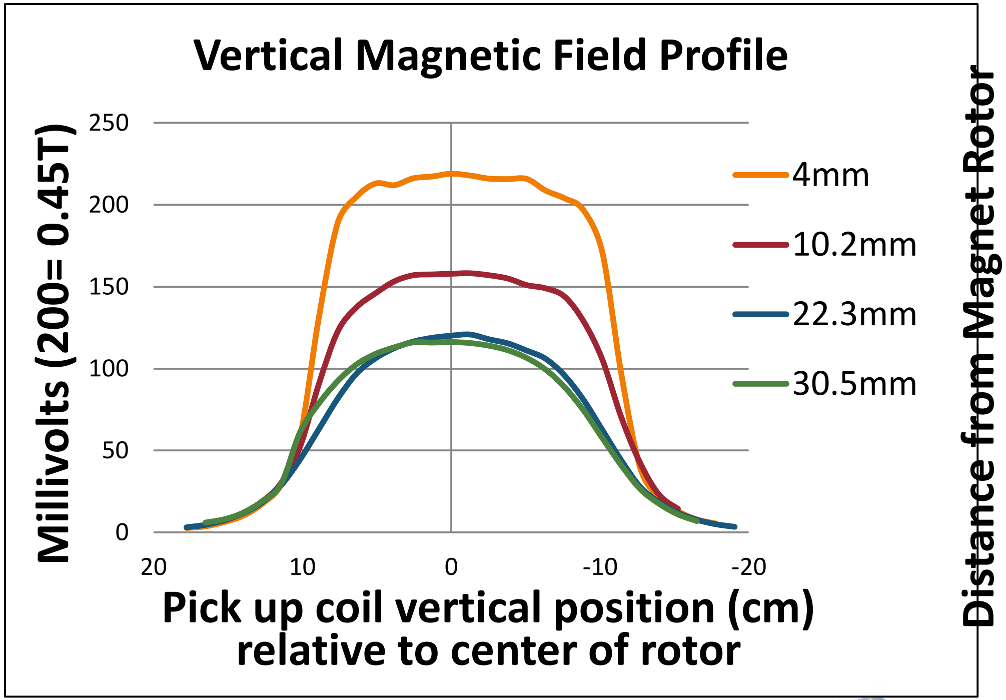
SAM Machine (dB/dt) Calibration and Properties

- In the 0.35 Tesla plane (~ 10 mm from rotor)
- At 900 RPM (60Hz) sweep rate is 12.25 T/Sec
- At 6000 RPM (400Hz) sweep rate is 140 T/Sec

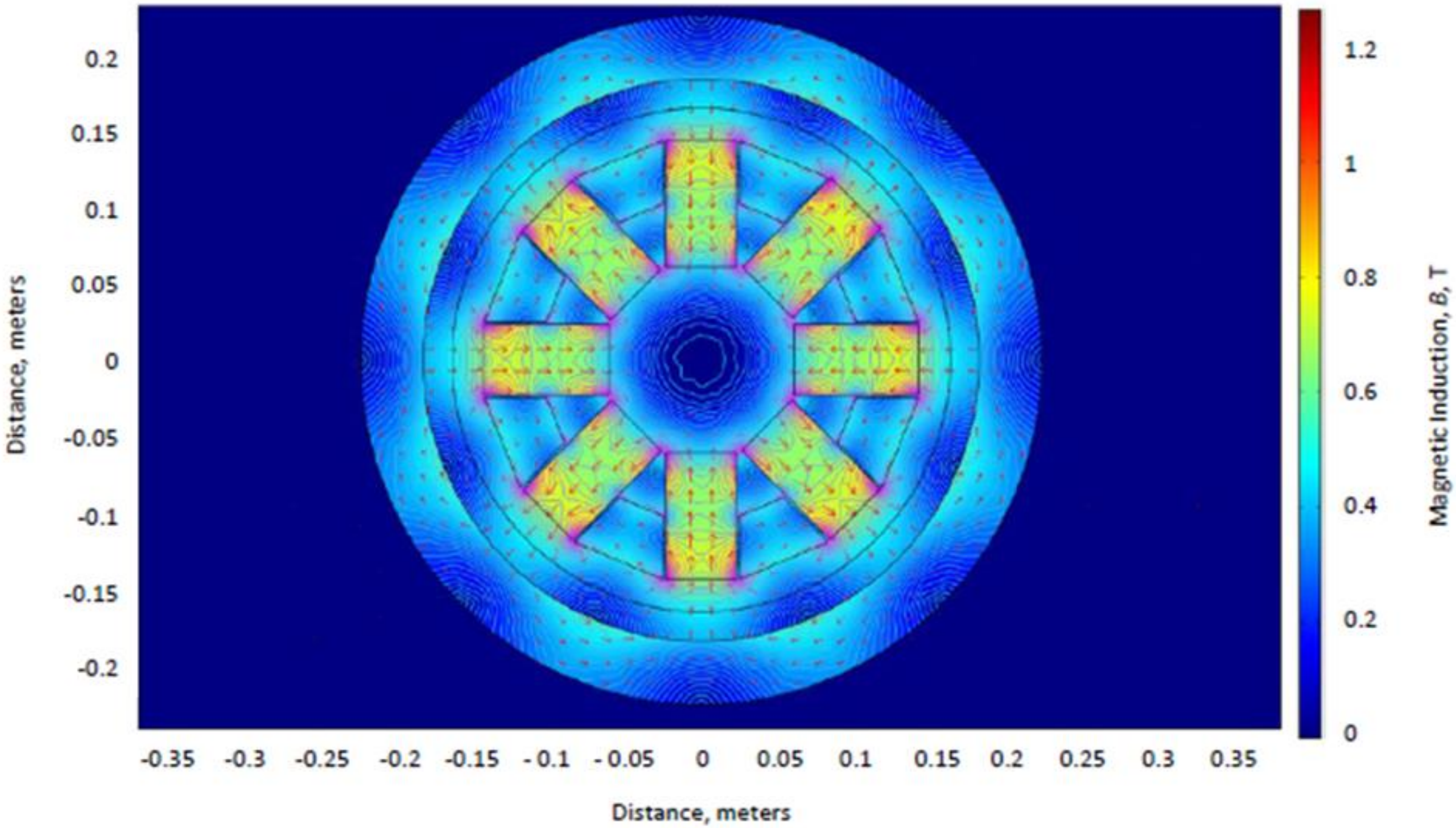


(dB/dt) at one location





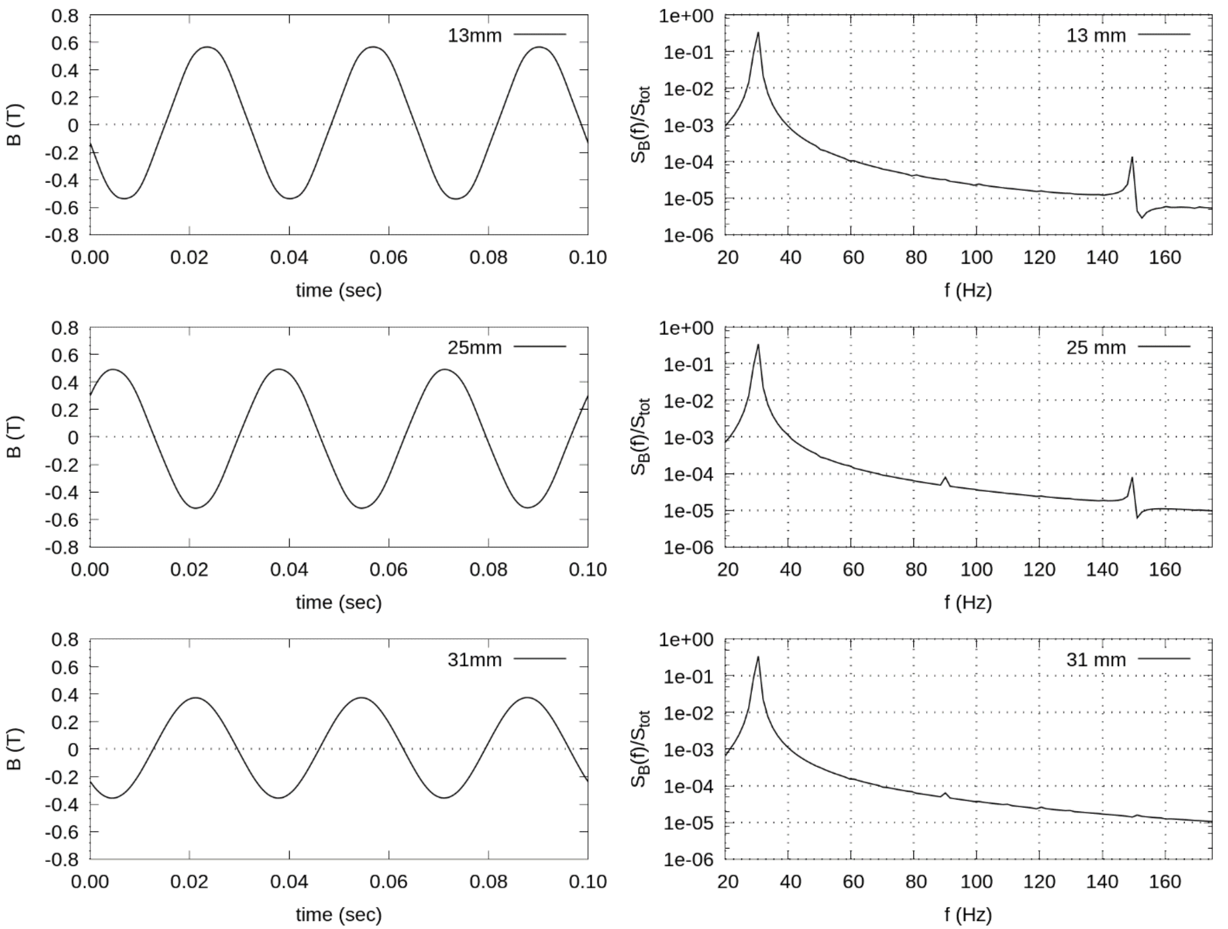
Contour and color map of |*B*| (in T) together with *B* vectors



Finite Element calculations show both radial and tangential moving fields
Actual mapped fields correspond with the calculations

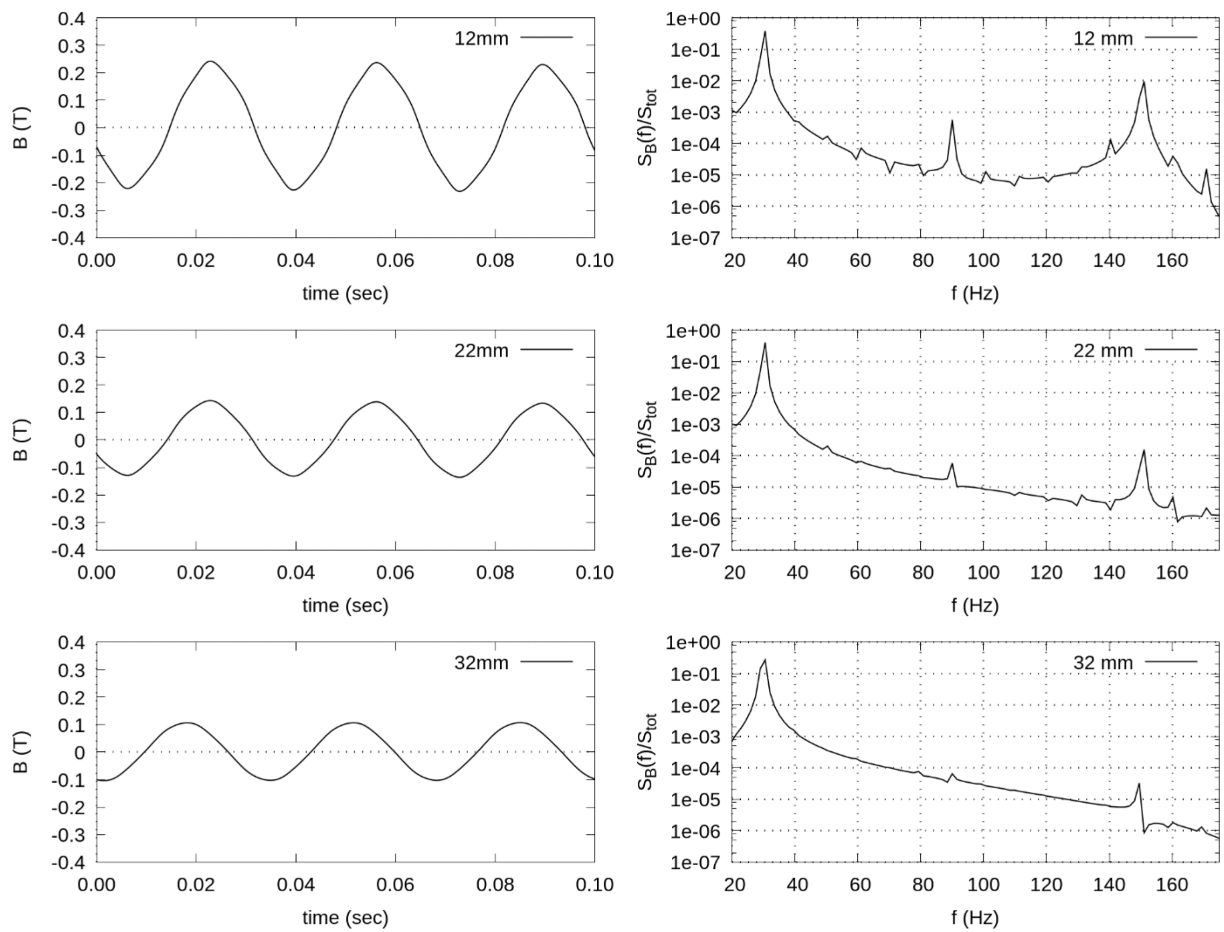
Radial Fields in SMC

- Radial *B* at three different radial distances within the gap
- The peak radial field (0.566 T) drops slightly with increasing R
- Shown at right are the fft
- The signal is very similar to a pure sine wave, with small harmonics at 3 and 5 times the fundamental

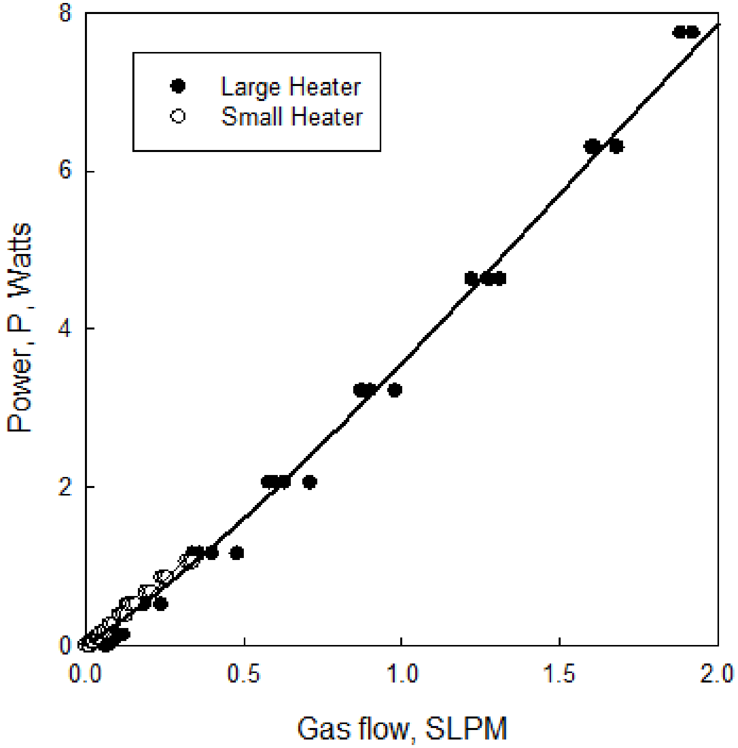


Tangential Fields in SMC

- Tangential *B* at three different radial distances within the gap
- The peak tangential field (0.242 T) drops with increasing R
- Shown at right are the fft
- The signal is still primarily a sine wave, but with greater deviations than for the radial case

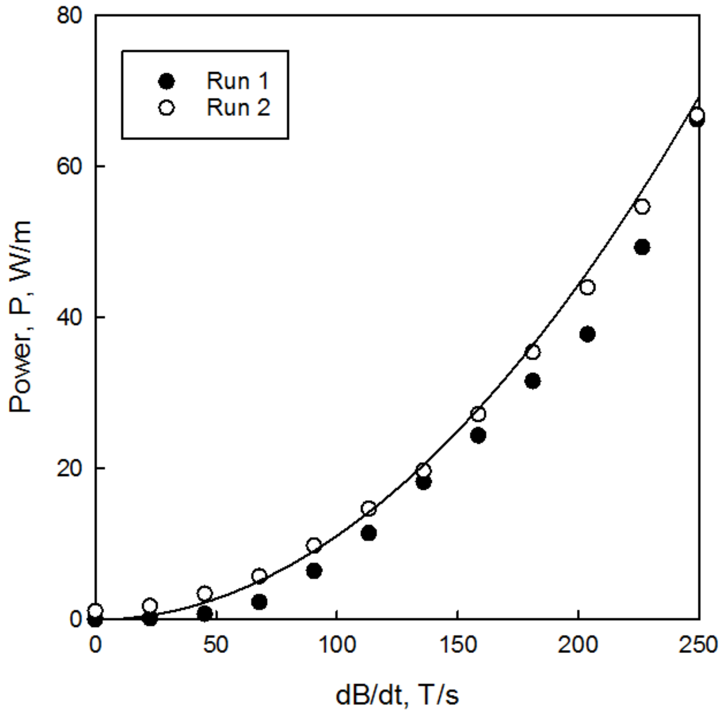


Calibration with Heater and Cu sample

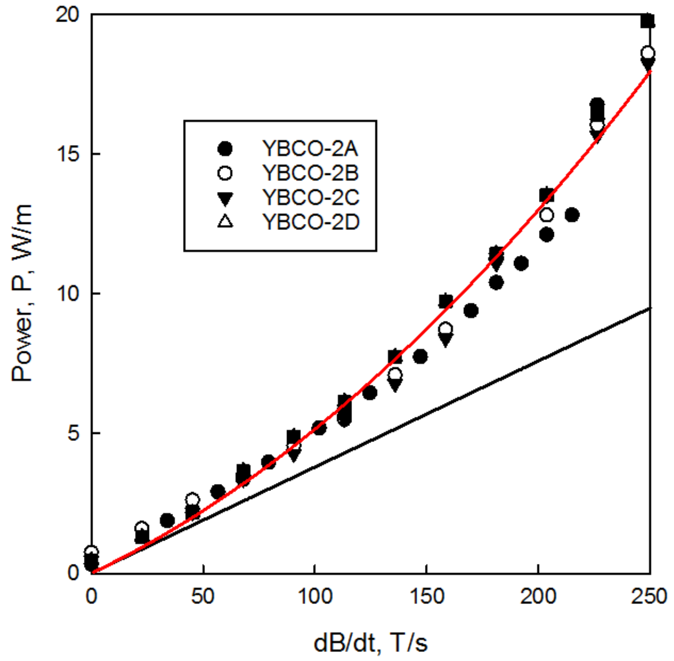


Calibration of calorimeter. $P(\mathrm{W}) = -0.0096 + 2.7581{*}GF + 1.0575{*}GF^2 - 0.2346{*}GF^3$

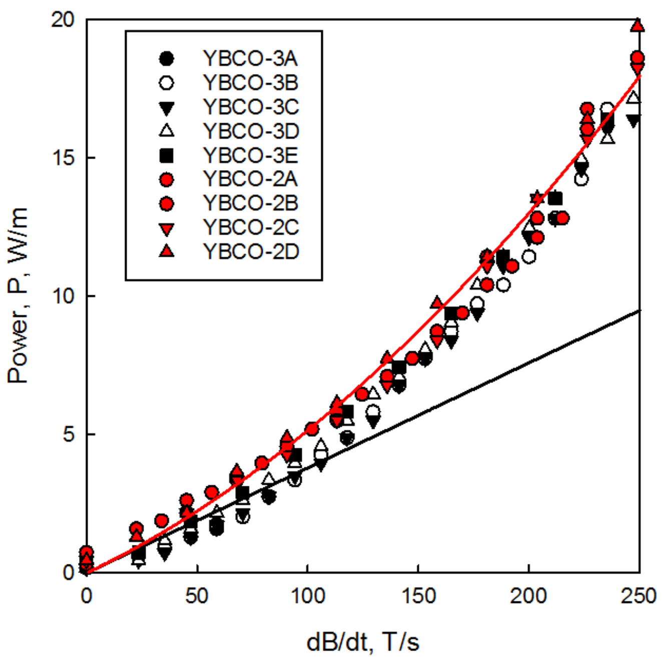
Power loss (P) vs dB/dt for the Cu strip Sample. Fit assumes RR = 7.37



AC loss of 10 cm length YBCO tape, hysteretic and eddy current

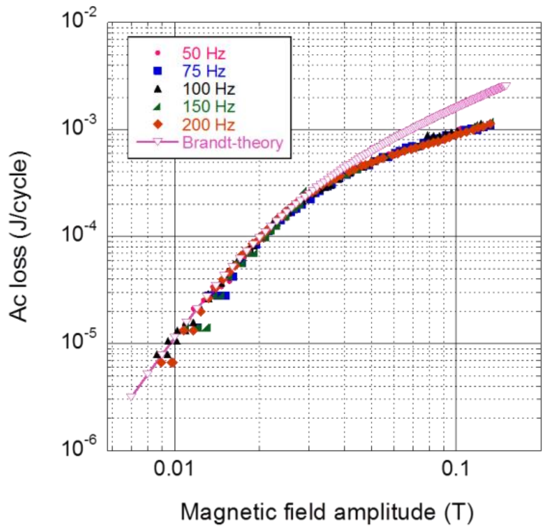


- Power Loss (*P*) vs *dB/dt* for sample YBCO tape 2
- Black line is fit for Brandt equation with I_c = 38 A, and red line includes eddy current contribution for RR (77 K) = 4.0



- Power Loss (*P*) vs *dB/dt* for YBCO tape samples 2 and 3
- Black line is fit for Brandt equation with I_c = 38 A, and red line includes eddy current contribution for RR (77 K) = 4.0

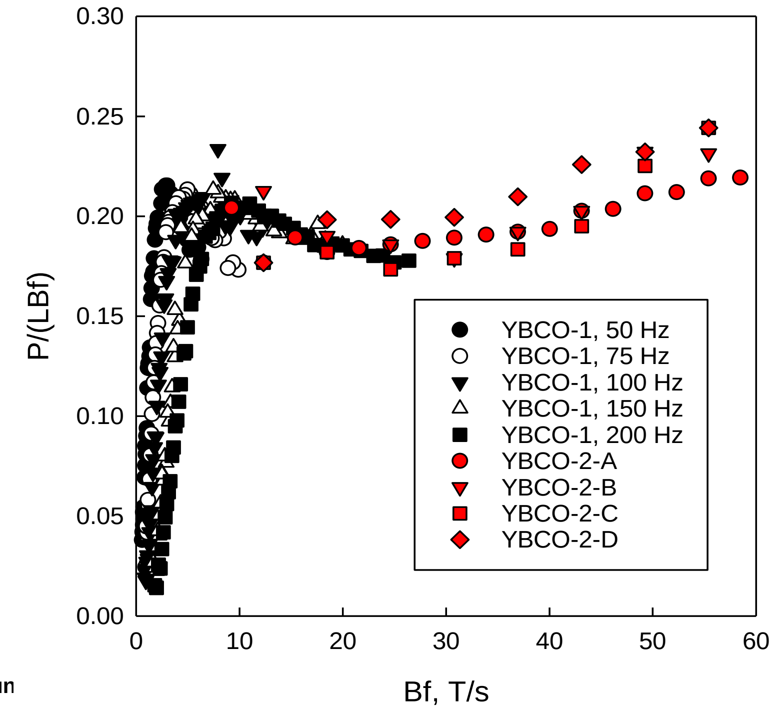
Loss measured of ***single tape*** in SMC compared to standard Inductance Measurement



- Solenoidal susceptibility rig measurements compared with Brandt theory (pink open triangles) (I_c = 128 A).

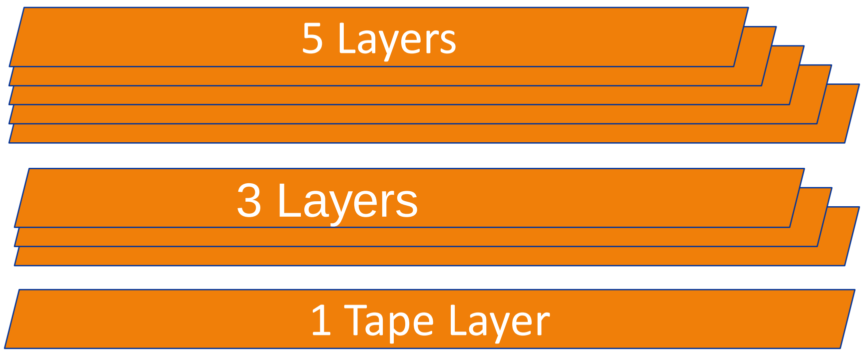
- In higher fields (> 0.05 T) the experimental data deviate from the theory (which uses I_c independent of magnetic field) apparently due to $I_c(B)$ dependence

- Power loss (per unit length) normalized by *B*f* vs *B*f* for SMC (shown in red) (YBCO-2) and solenoidal susceptibility rig (shown in black, for YBCO-1)



Two new Measurement Series– CORC and Carpet stacks

Carpet Stack cables



4 mm wide Superpower YBCO coated conductor
5 layers
3 layers
1 layer
Secured with narrow strips of Kapton tape

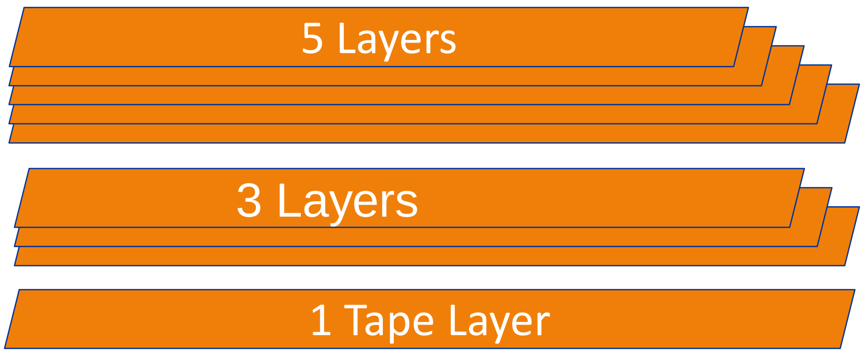
Conductor on Round Core (CORC) cable sample from Danko

- 3.13 mm OD SS304 former
- 4.76 mm overall cable OD
- 4 mm wide Sunpower YBCO coated conductor
- 2 layers with 3 tapes each, outer layer is twisted opposite of the inner layer
- 34 mm pitch with 1 mm spacing

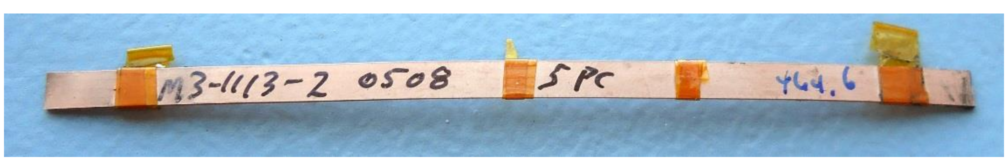
M Majoros, M D Sumption, E W Collings and D C van der Laan, *Supercond. Sci. Technol.* 27

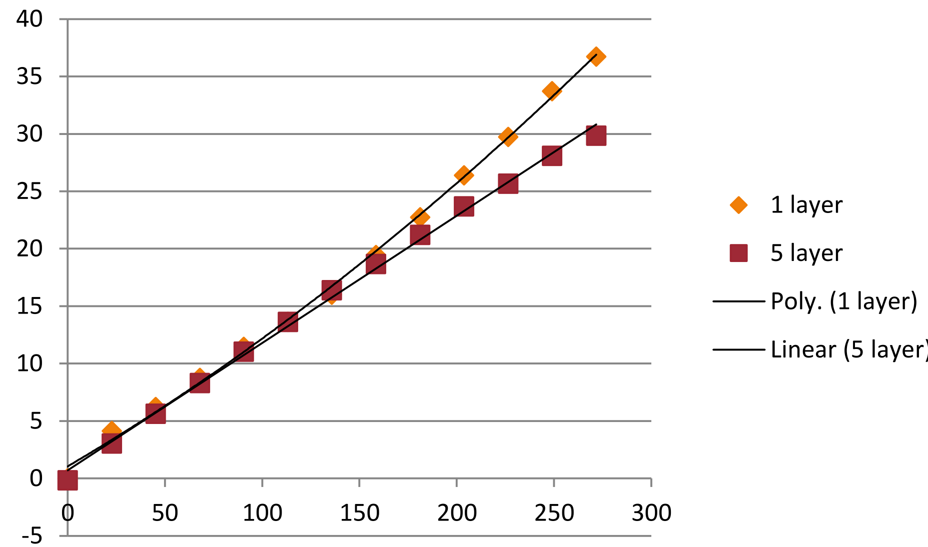
Influence of stacking on loss?

Carpet Stack cables with Un-Filamented tapes



4 mm wide Sunpower YBCO coated conductor
5 layers
3 layers
1 layer
Secured with narrow strips of Kapton tape

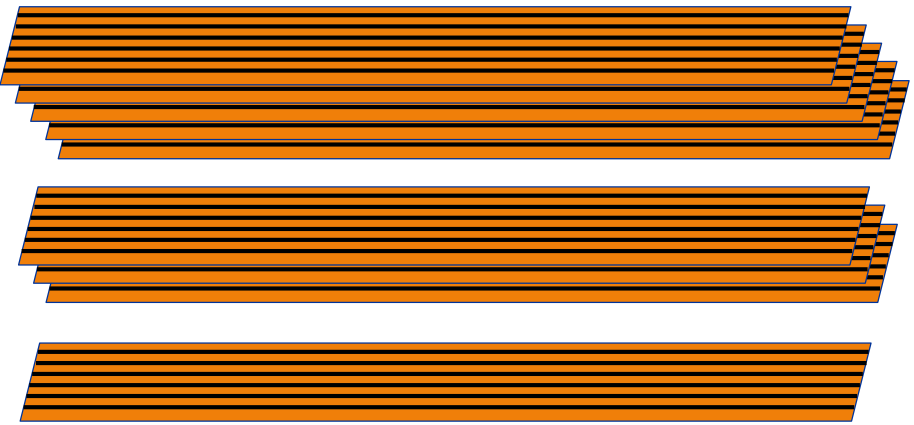




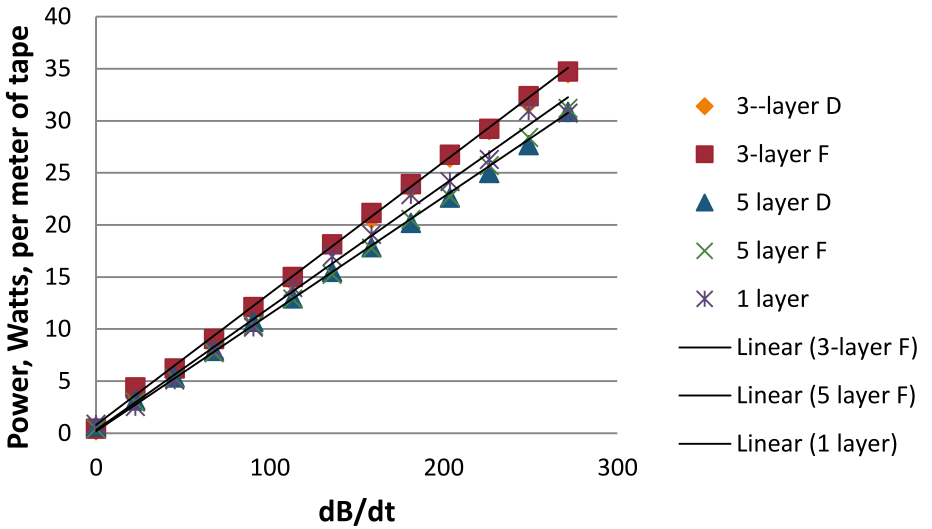
- Samples were unstriated
- L = 10 cm, untwisted
- Ic = 127 A 77 K, SF
- Loss is shown as power per meter of tape
- Here higher loss is seen for single stack, possible influence of demagnetization on loss

Loss in striated and Cu EP Tapes

Carpet Stack cables with Filamented tapes



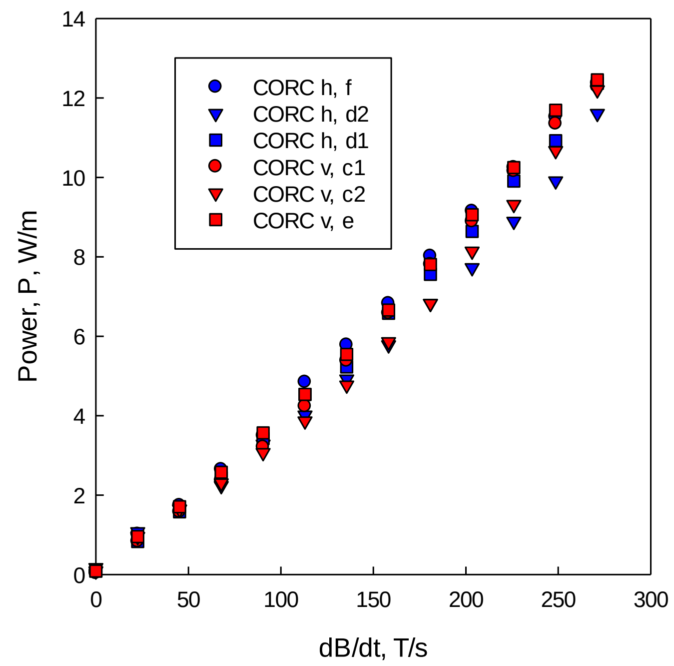
4 mm wide YBCO coated conductors
Filamented and provided by Sunpower



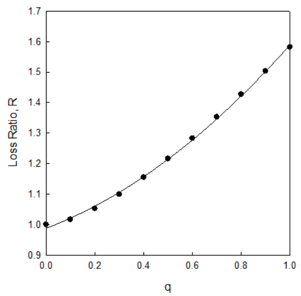
- Samples were striated
- L = 10 cm, untwisted
- Loss is shown as power per meter of tape
- Here no modification of loss with stacking of tapes is seen

CORC AC Loss Measurements

- Two layer CORC sample
- SS304 (3.13 mm OD) former
- Cable OD of 4.76
- Superpower Coated conductor
- 4 mm wide and 0.09 mm thick.
- Two layers, each with three tapes, with a 1 mm gap between the tapes.
- Twist pitch = 34 mm, outer layer twisted in an opposite sense to the inner layer.
- Measured Vertically and Horizontally



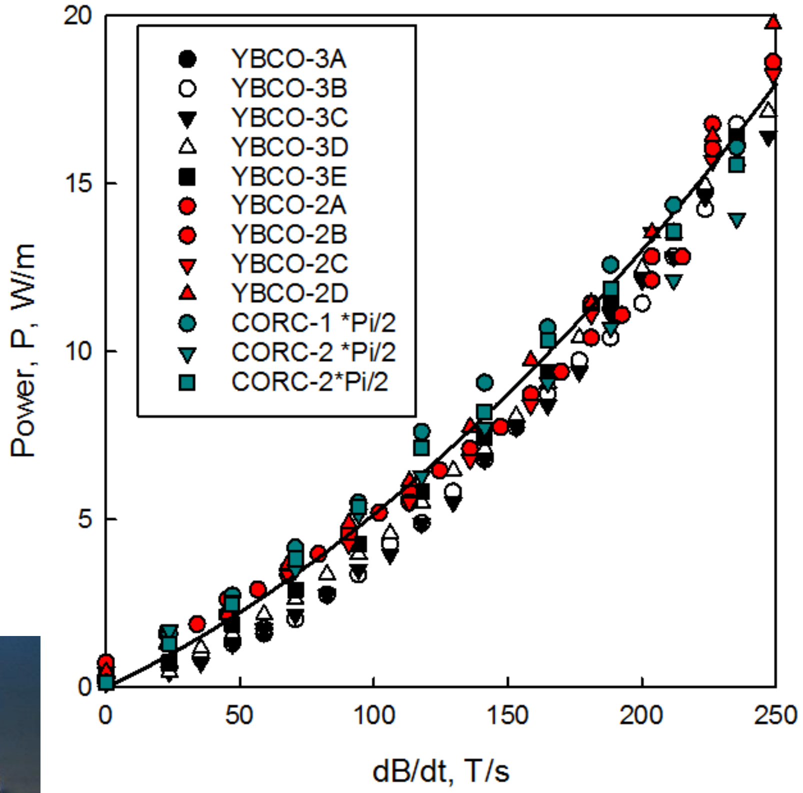
$$H_A = \vec{x}H_{x,max}\cos(\omega t) + \vec{y}H_{y,max}\sin(\omega t)$$



CORC compared to Tape it was wound with

- CORC cable loss per unit meter of tape multiplied by the factor $\pi/2$, as compared to tape loss per unit meter of tape. CORC cable was oriented horizontally.

- Simplistic integration of the field perpendicular to the tape appears to describe the loss for the tapes in the CORC !



Samples

Roebel Cable, IRL, NZ

TABLE I
PARAMETERS OF THE ROEBEL CABLE

Quantity	
Cable width (mm)	13
Cable thickness (mm)	1.5
Cable twist pitch (cm)	30
Cable length (cm)	30
Number of tapes in the cable	15
Tape width (mm)	5
Cable I_c (77.3K,self-field) (A)	1537.5

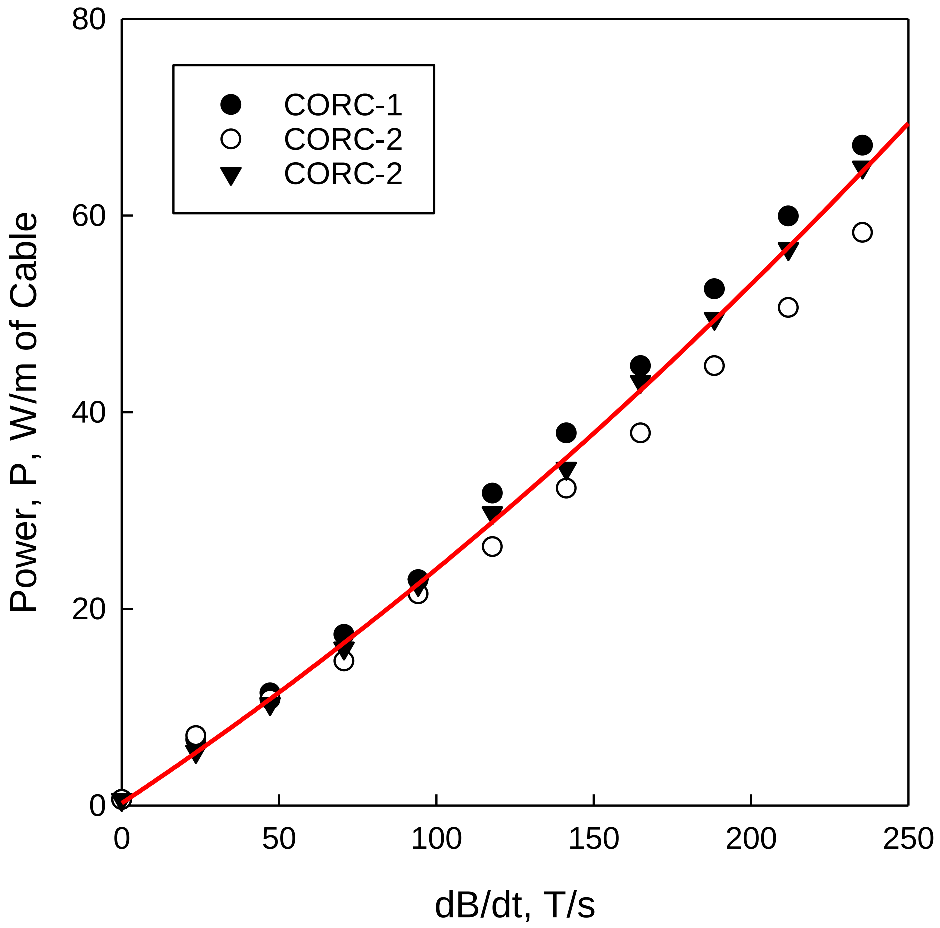
CORC Cable

Sample	Tapes	I_c (A)	ID (mm)	OD (mm)	Length (cm)	Striations
R1	2 x 3 = 6	608	4.96	6.17	11.7	none
S1	2 x 3 = 6	349	4.95	6.07	12.2	5
R2	3 x 3 = 9	904	4.93	6.37	11.7	none
S2	3 x 3 = 9	535	4.94	6.38	11.8	5
R3	4 x 3 = 12	1228	5.02	6.85	11.7	none
S3	4 x 3 = 12	750	4.97	6.78	11.9	5

CORC Cable with layers and striations

CORC Loss per meter of Cable

- 4 mm wide tape
- Cable: 2 layers, 3 tapes per layter, 1 mm gap
- Lp = 34 mm, outer layer twisted in an opposite sense to the inner layer.
- Each meter of cable has 6.552 m of strand



Loss in Roebel Cable

The cable was from IRL

TABLE I
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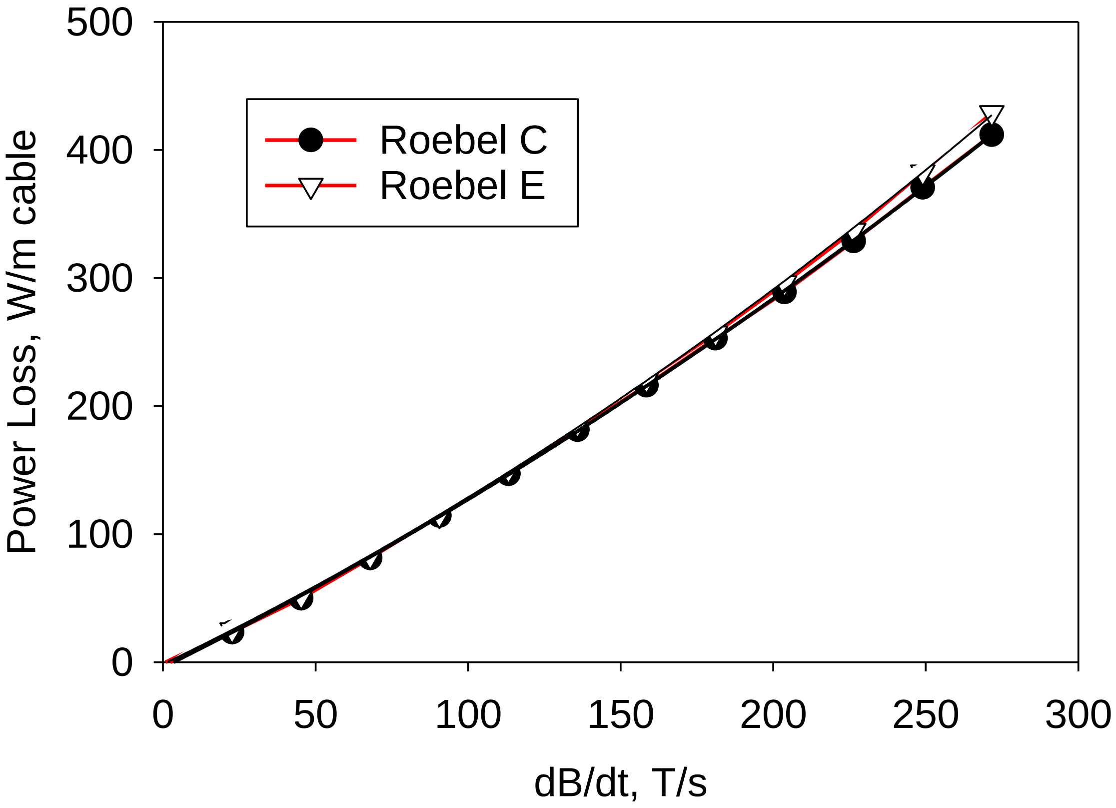
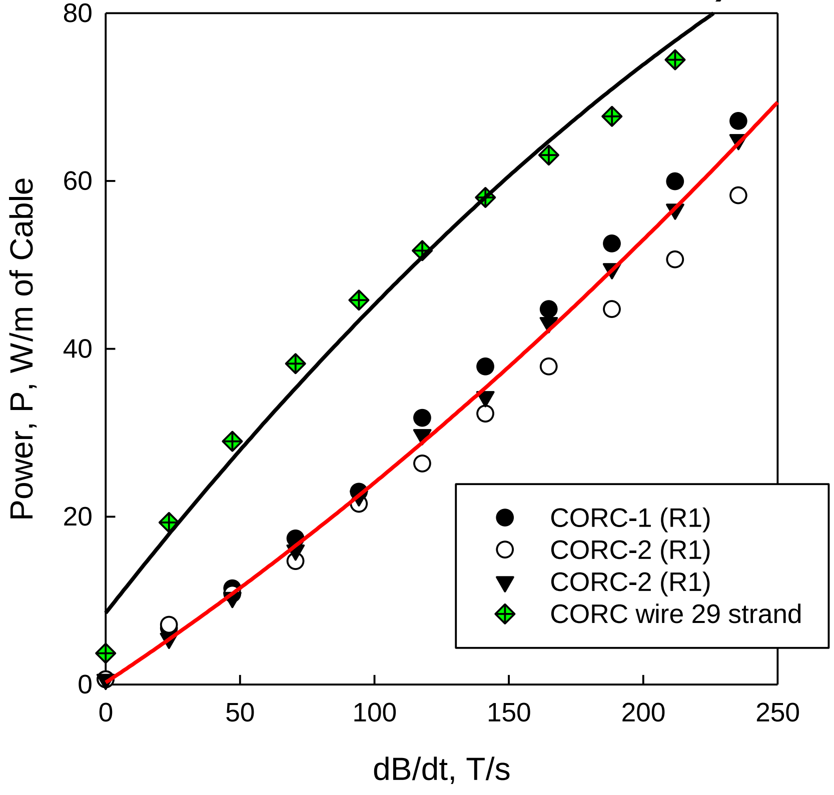
Cable length (cm)	30
Number of tapes in the cable	15
Tape width (mm)	5
Cable I_c (77.3K,self-field) (A)	1537.5

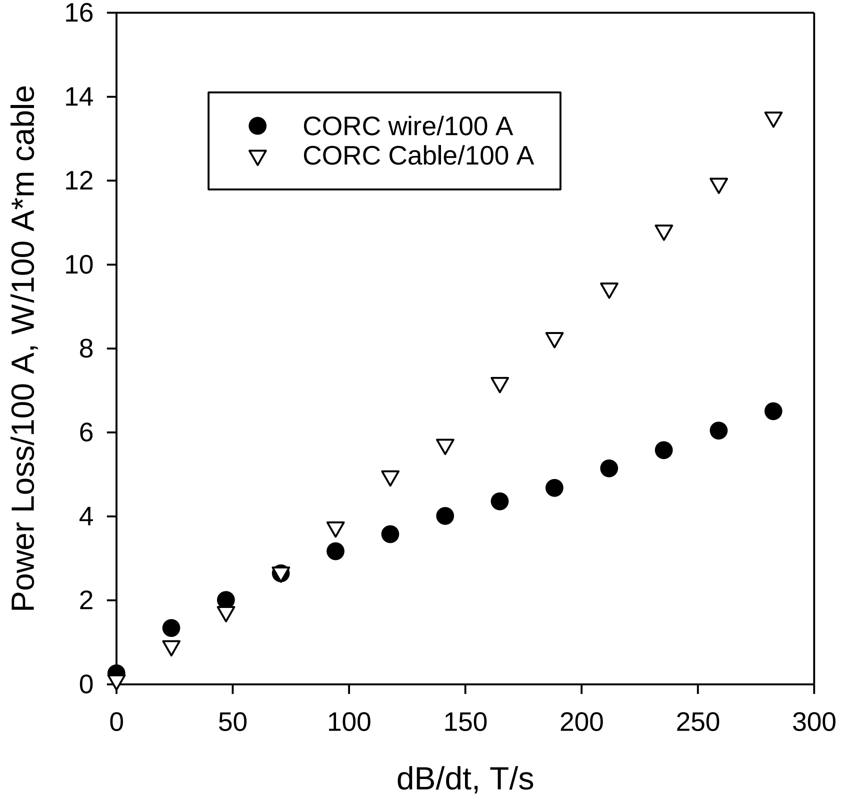
Losses per meter Cable
At 77 K, Ic per tape = 100 A, SF



CORC Wire Loss

- New CORC Wire is available which promises lower loss and higher flexibility for making very high amperage cable
- We measured this wire; OD 3.65 mm, 29 strands





Loss Measurements of 4 filament Al Hyperconductor wire

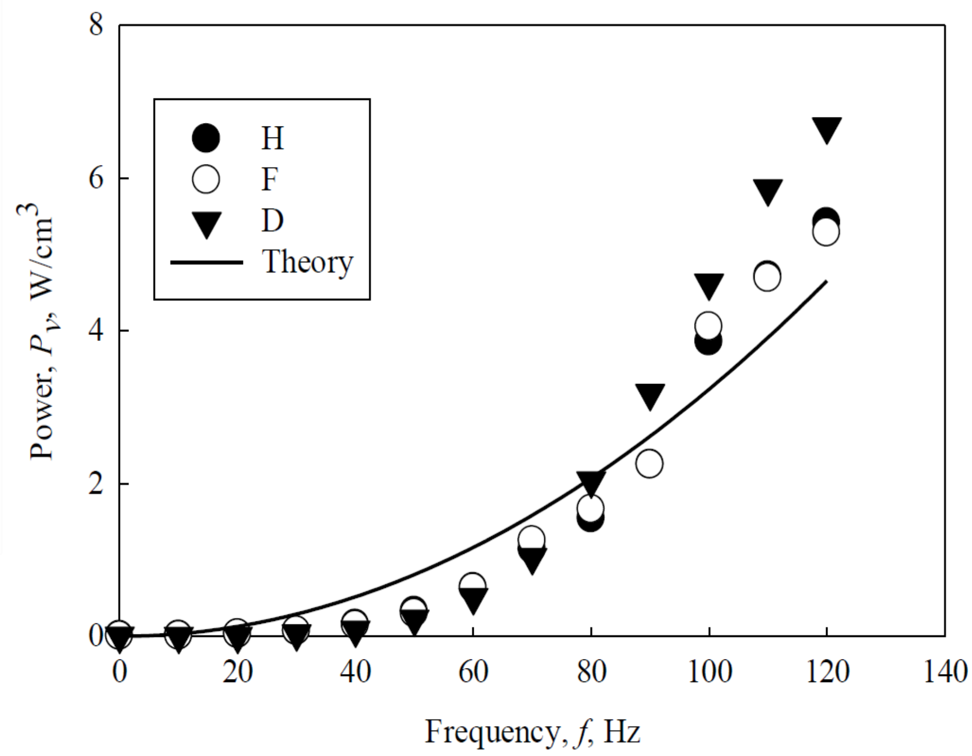
$$P_{tot} = \begin{cases} P_{e,matrix}\{d_s,\rho_m\} + P_{e,fil}\{d_f,\rho_{fil}\} + P_{coup}\{L_p,\rho_m\} & if\ L < L_c \\ \approx \frac{1}{2\rho_m}\left[fL_pB_m\right]^2 & \\ P_e\{d_s,\rho_{fil}\} = \frac{\pi^2}{4\rho_{fil}}[(\mu_0 H_0)d_s f]^2 & if\ L > L_c \end{cases}$$

Where

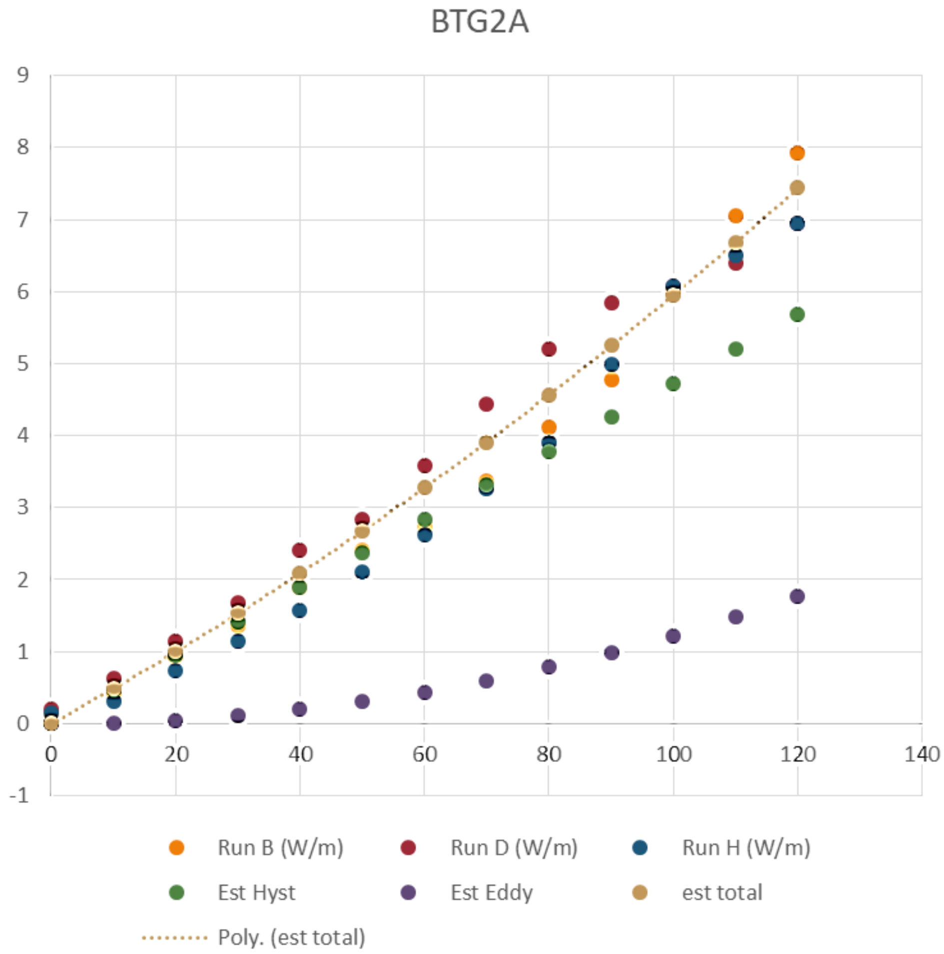
$$L_c = \pi d\sqrt{\left({\rho_m}/{\rho_{fil}}\right)}$$

We can generate a frequency limit expression for hyperconductors

$$f = \sqrt{2}\frac{J_{cc}\rho_m}{L_pB} = \sqrt{2}\frac{J_{cu,RT}\rho_m}{L_pB}\sqrt{\frac{\rho_{Cu,RT}}{\rho_{fil}}}$$



Recent Results on BNL Samples (exfoliated filament Cables)



Conclusions

- **A new, High field, High ramp rate AC loss device operational <u>which can reach 480 T/s!</u>**
- **AC loss calibrations performed using (i) Standard resistor, (ii) Cu strip of known RR**
- **Explore high d*B*/dt characteristics of cables made of YBCO coated conductors**
- **Samples: striated tapes, CORC cables, Roebel cables, CORC Wires, Al Hyperconductors, Exfoliated filament samples, ….**
- **Comparison to theory and analysis**