Calorimetric Measurements of AC losses in HTS tapes in a Stator Environment

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UDRI Contractor
Propulsion Directorate
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CO-AUTHORS, ACKNOWLEDGEMENTS

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AC Loss in Superconductors

- **Critical factor, sometimes considered at the end of machine design, instead of at the beginning**
- **AC Loss in Motors/Generators typically 3-4x higher than theory**

•**Q =** $Q_{Hysteresis} + Q_{Coupling} + Q_{Eddy\text{-}current} + Q_{Transport} + Q_{Interaction\ (eg.\ Dynamic)}$

For motor/generator – the loss induced by external fields (blue terms) are dominant, and can be denoted Q_{magn}

$$\mathbf{Q_{Magn}} = Q_{Hysteresis} + Q_{coupling} + Q_{Eddy\text{-}current}$$

Flux Pinning and AC Loss Studies on YBCO, Ch. 15: Second Generation Superconducting Wires for Power Applications, G. Levin & P. Barnes, p. 306, Nova Science Publishers Inc., 2007

YBCO Tape Loss

$$Q = Q_{Hysteresis} + Q_{Coupling} + Q_{Eddy\text{-}current}$$

$$Q_{h,v} = \mu_0 J_c w H_a \left[2\frac{H_c}{H_a} \ln\left(cosh\left(\frac{H_a}{H_c}\right)\right) - tanh\left(\frac{H_a}{H_c}\right)\right]$$

(Brandt / Müller)

$Q \propto \boldsymbol{w}$: minimize filament diameter to decrease Q

Heat due to AC loss must be removed, with cryocooler penalty

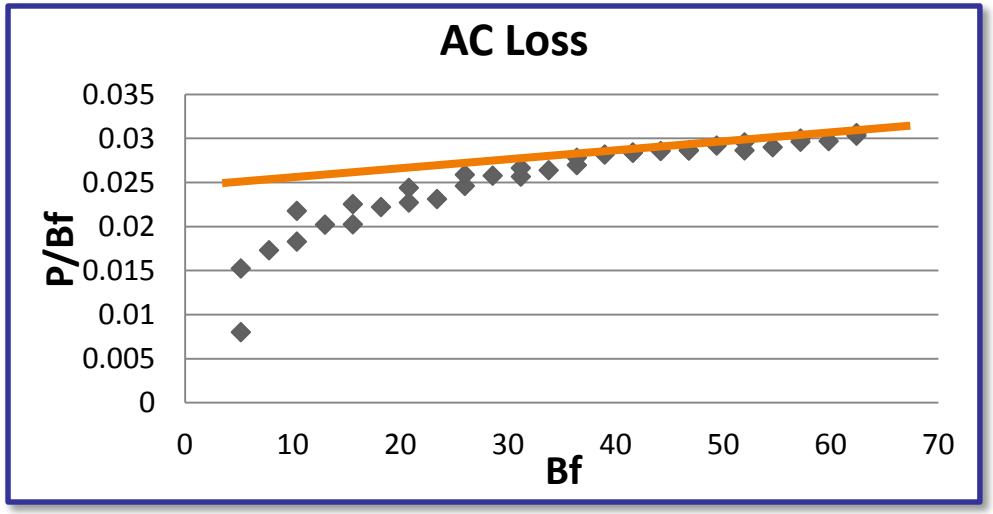
Where $Q_{h,v} \approx \mu_0 J_c w H_m$

$Q_h/L = B_a w J_c w t = B_a w I_c$

$P/L = B_a f w I_c$

Hysteretic Loss | Normal Metal Eddy Current

$$\frac{P}{L} = B_a f w I_c + \frac{\pi^2}{6\rho} w^3 t (B_a f)^2$$



Hysteresis | Eddy Loss

$$\left(\frac{P}{L}\right)\left(\frac{1}{B_a f}\right) = w I_c + \frac{\pi^2}{6\rho} w^3 t + (B_a f)^2$$

Intercept | Slope

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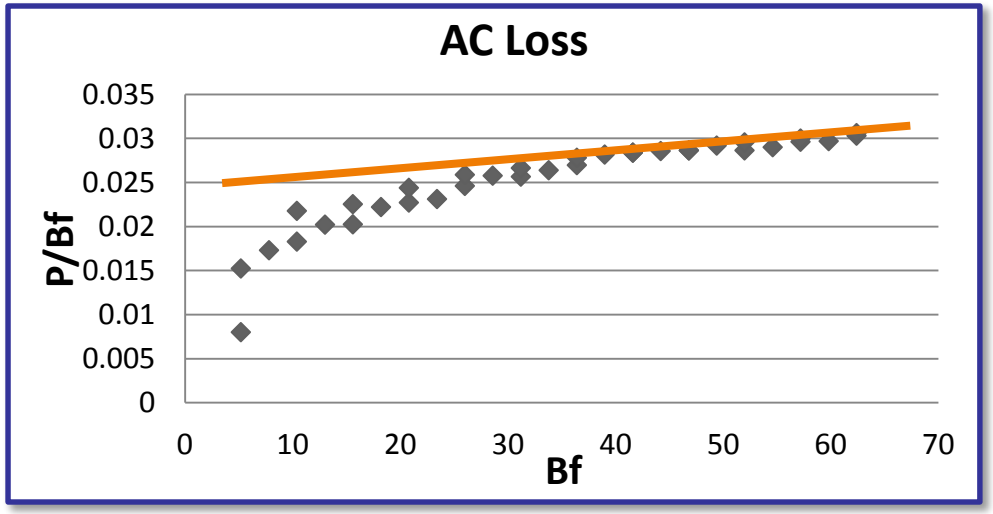

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Intercept | Slope

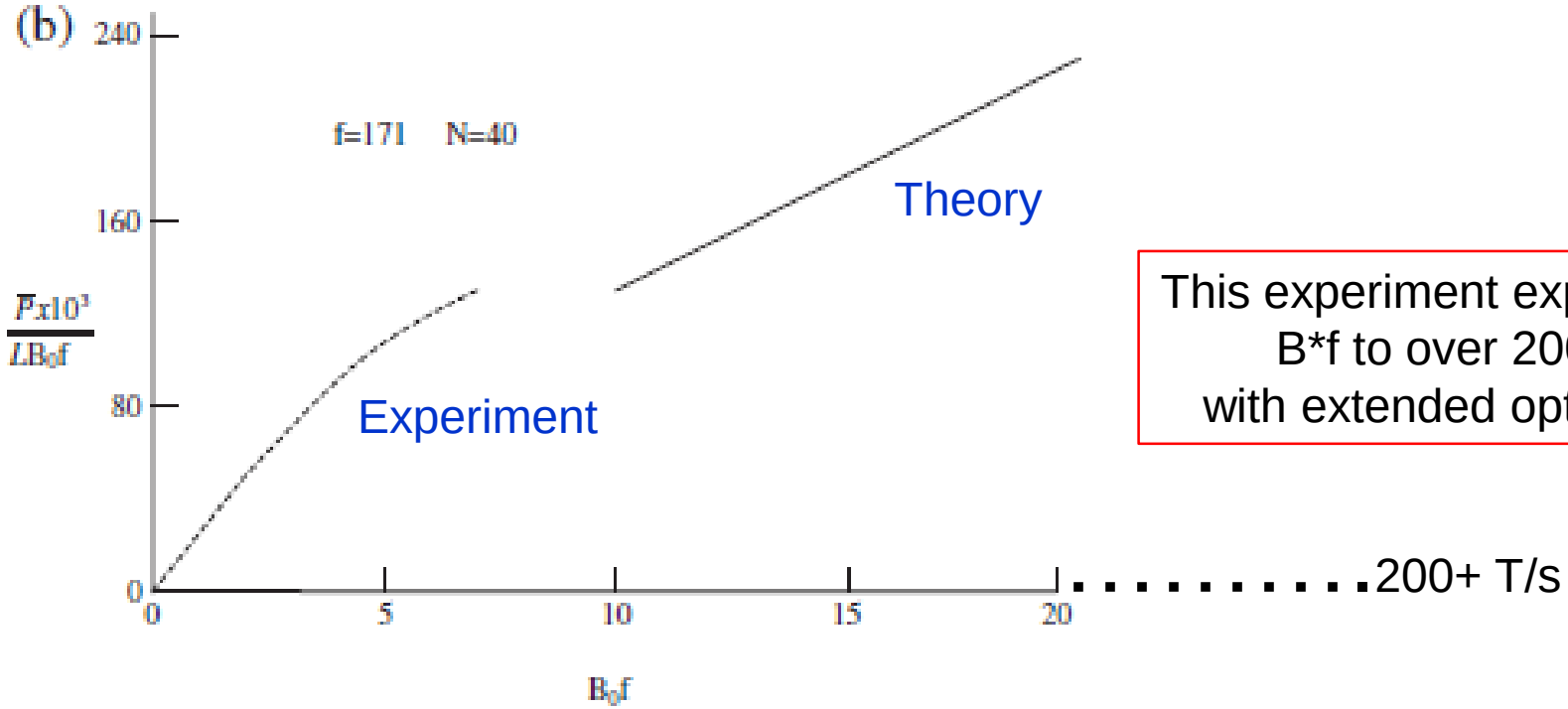
Need for high B and dB/dt Testing

- **Windings in a motor/generator see high *dB/dt* like no other superconducting machine (e.g., 500 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!

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



This experiment expands B*f to over 200 with extended options

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).

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

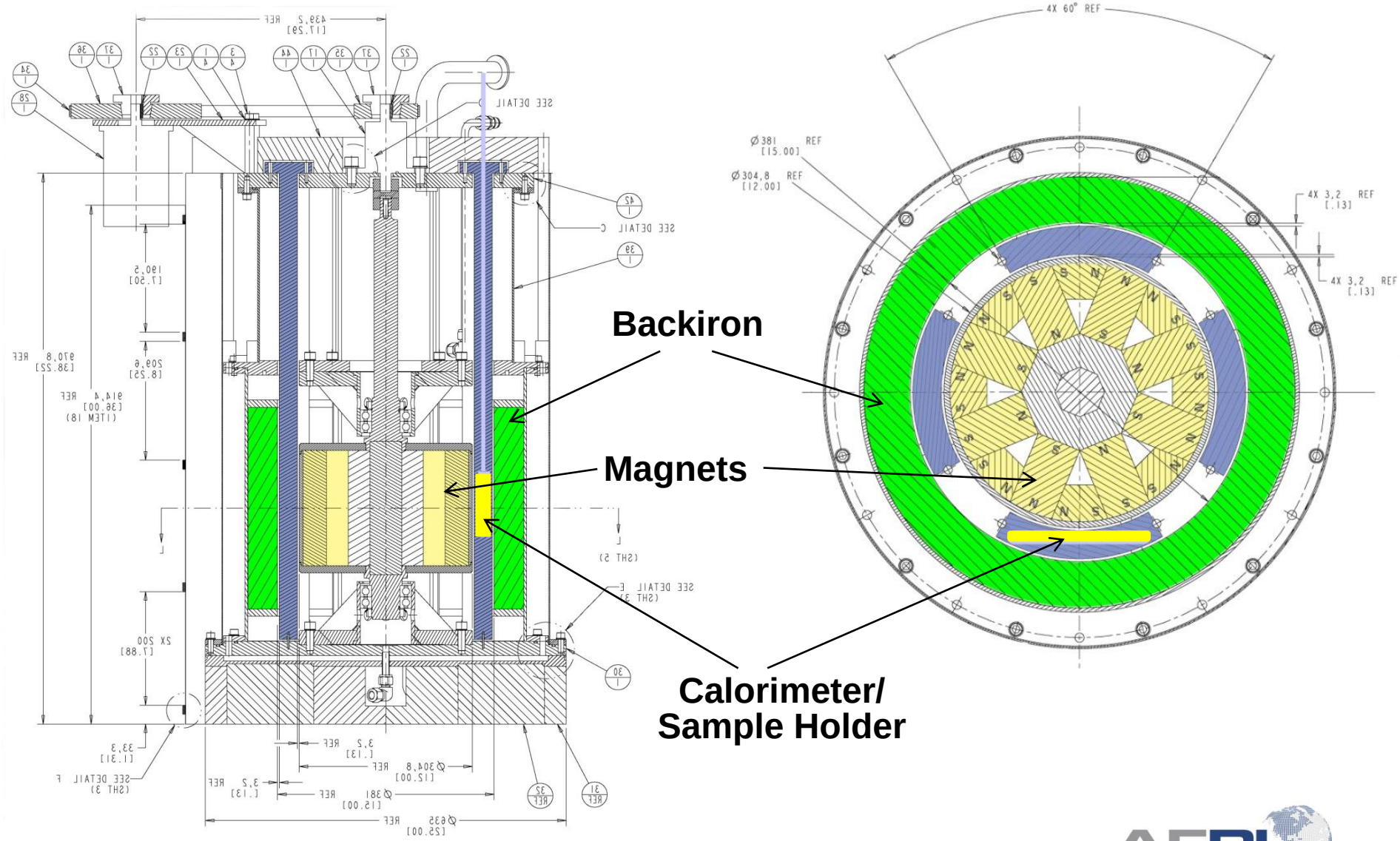
Unique AC Loss Test Device

- 8-pole Hallbach Array of NdFeB Magnets
- B-field = 0.62 T
- **Frequency = 0 to 400 HZ (required for AF)**
- **Sweep Rate B*f = 800 T/s**
  (~ 48x 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
- AC loss in real stator environment, complex *B* and *I* varying in time and space

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

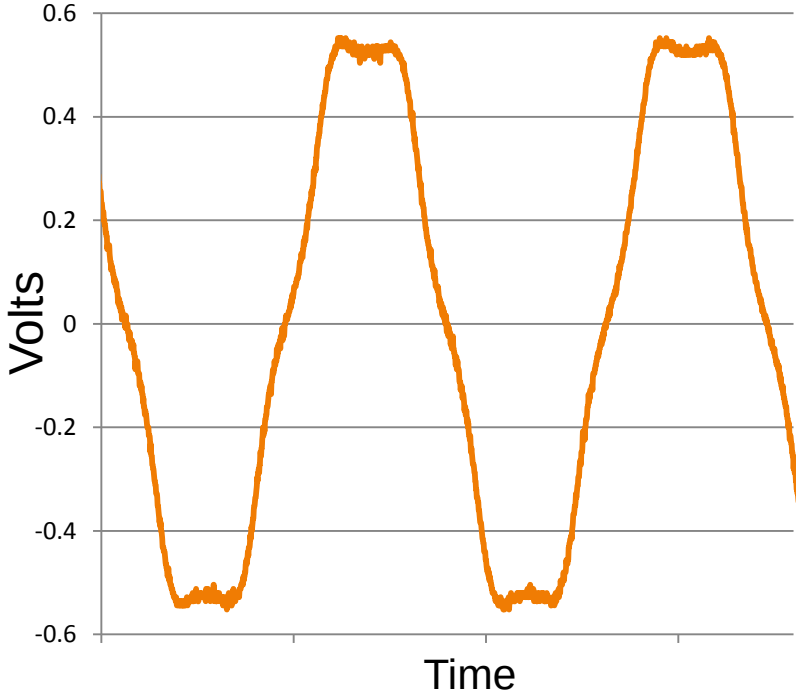
J. Murphy, et al., IEEE Trans. Appl. Supercond. **23(3)**, 4701505 (Jun 2013)

Machine Cross Sections

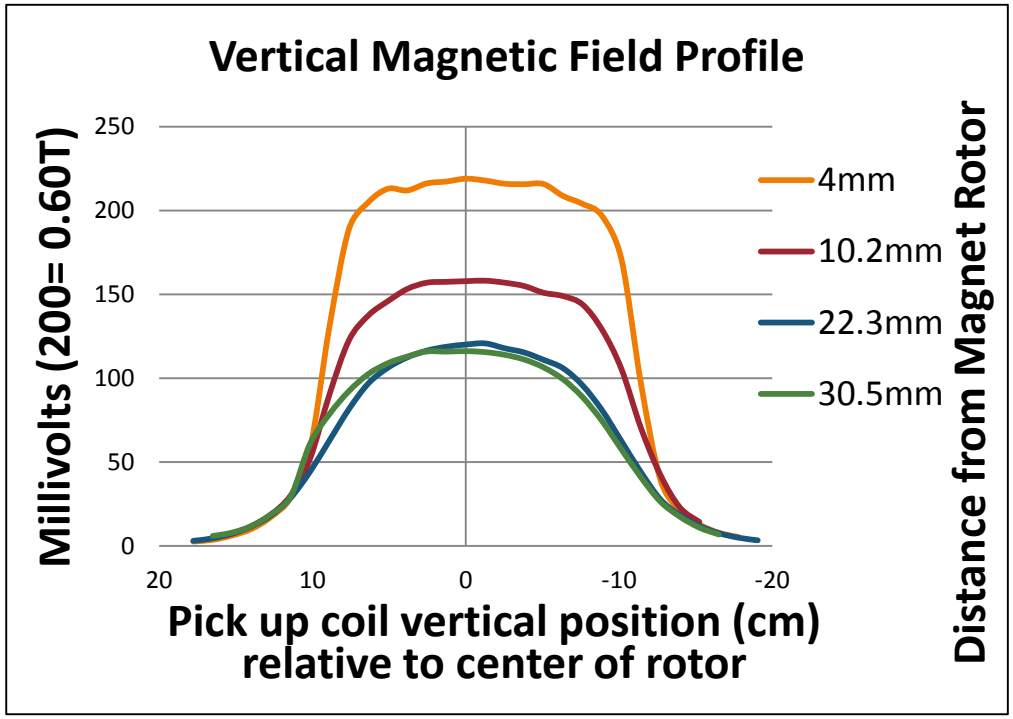


AC Field Characteristics

In the 0.5 T sample plane (~ 14 mm from rotor)
At 1800 RPM (120Hz) sweep rate is 240 T/Sec
At 6000 RPM (400Hz) sweep rate is 800 T/Sec



High field harmonics contribute to waveform shape



Calculating $\boldsymbol{Bf}$

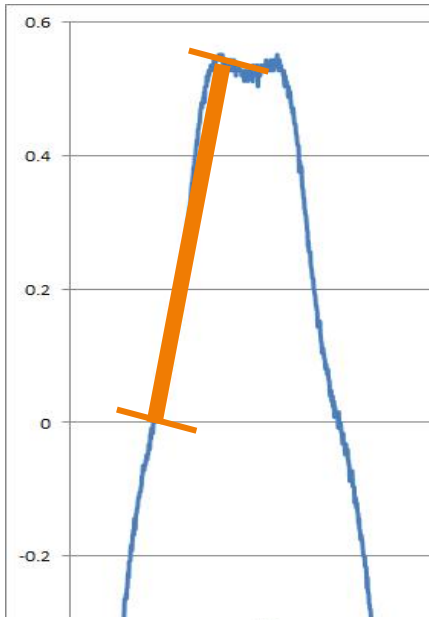
There are four N and four S poles projecting out from the rotor. Thus, there are four complete field cycles as we go one time around the rotor.

Frequency of the AC field: RPM * 1/60 * 4 = f
Assume 1800 RPM: 1800 * 1/60 * 4 = 120 Hz

Using the maximum field measured in the sample holder for the radial field in the center of the magnet space (B_{max} =0.5 T),

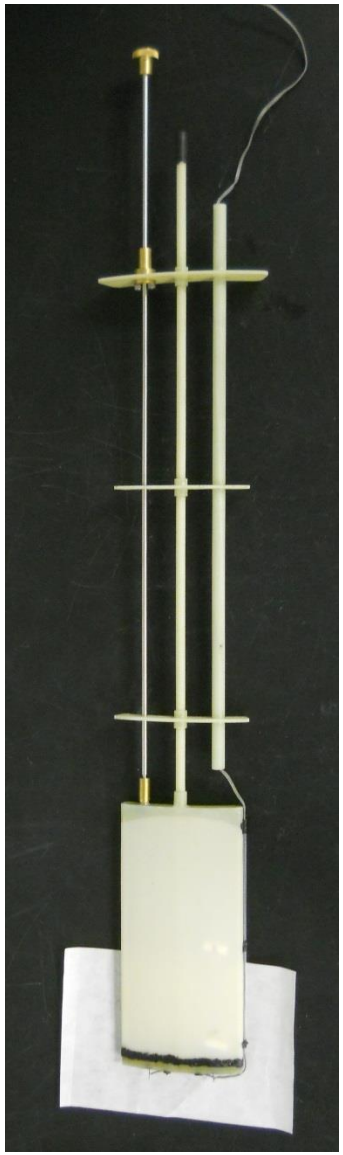
<u>0.5 T * 120 Hz = 60 T/s.</u>

But, taking only the first quarter cycle,



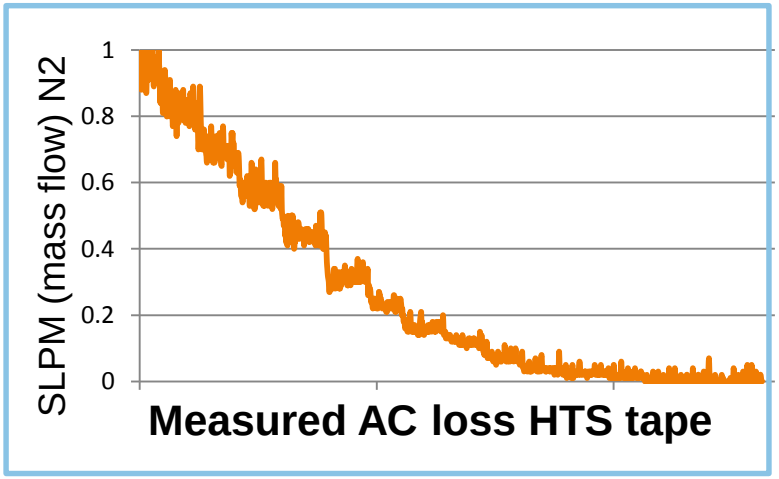
$$\frac{\Delta B}{\Delta t} = \frac{B_{max}}{\tau/4} = \frac{B_{max} f}{1/4} = 4 B_{max} f = 240\ T/s$$

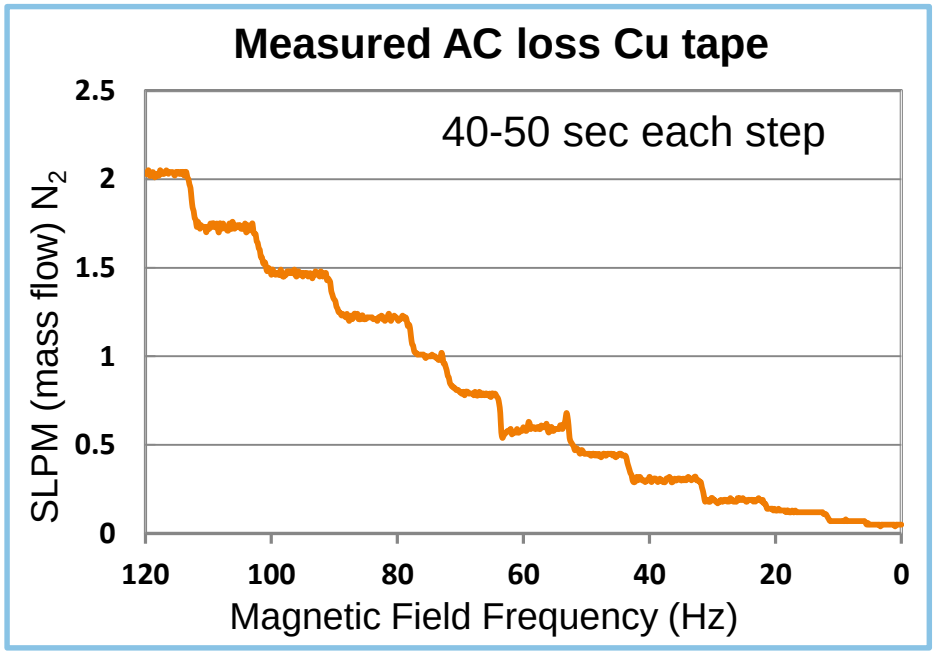
Sample Holder/Calorimeter

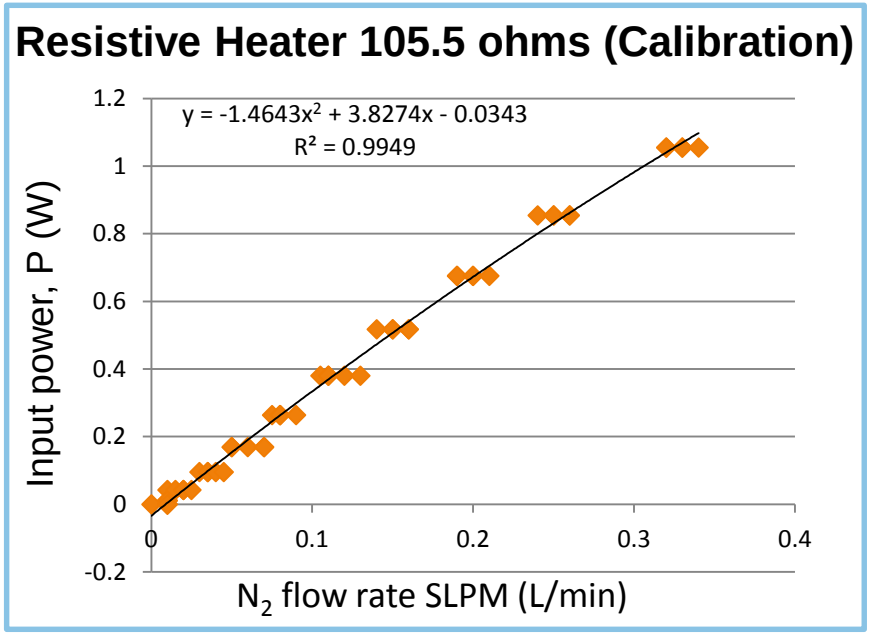


Sealed Sample holder
LN_2 Filled via remote operated valve on top
Sample inserted through bottom port which is sealed with a plug
Contains resistors for heating and to indicate LN_2 level
All fiberglass except valve and resistors

Typical AC Loss Measurements and Resistive Heater Calibration



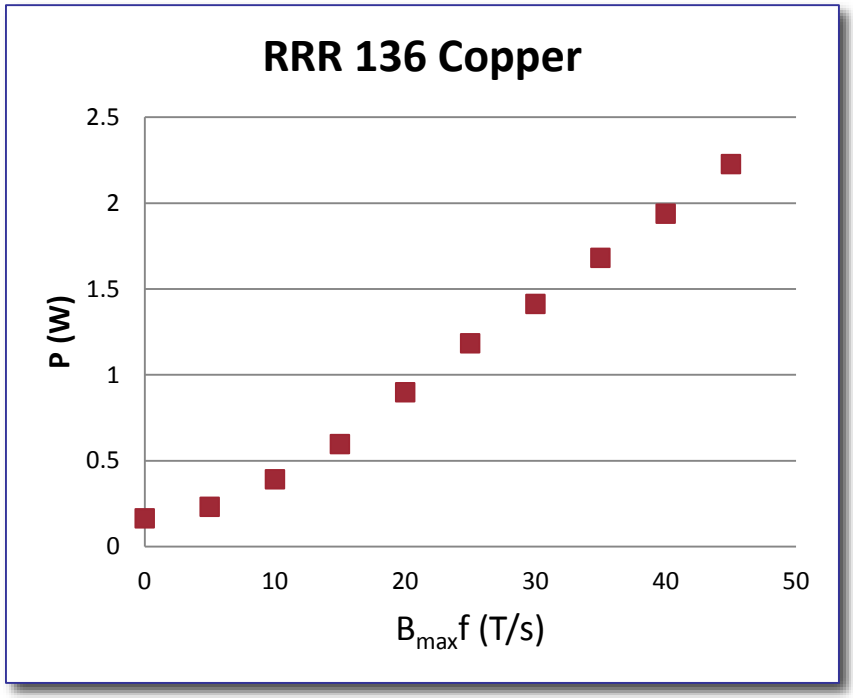


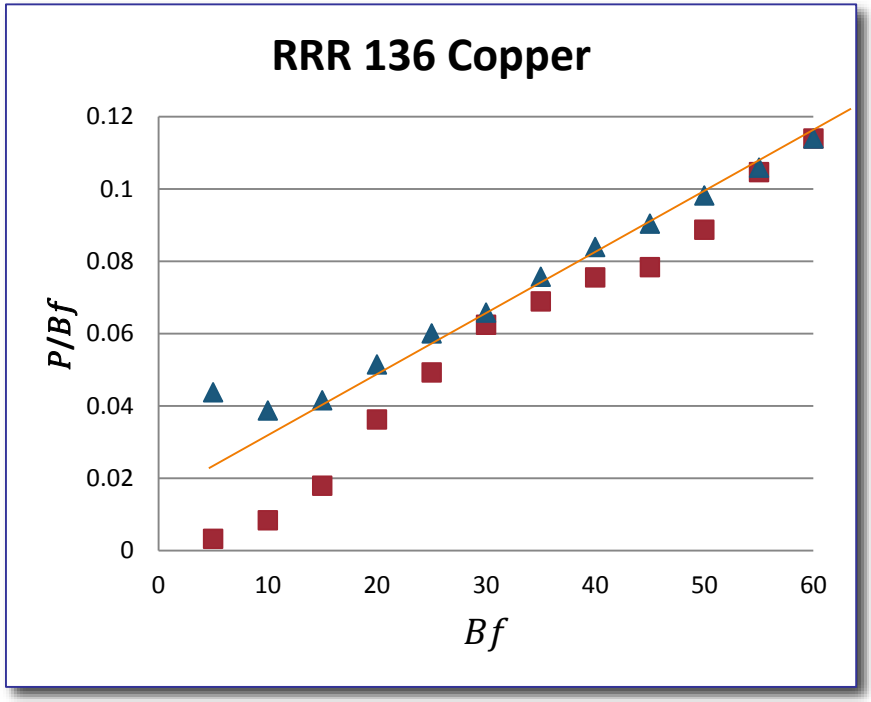


Calibration equation Power (W)=….

- Fast accurate measurement (< 15 min!)
- Small or large tapes, cables, coils
- Sample geometry sufficient for calorimetry
- Tapes are best, good mass to surface area

Eddy Currents in Copper:
Secondary Calibration

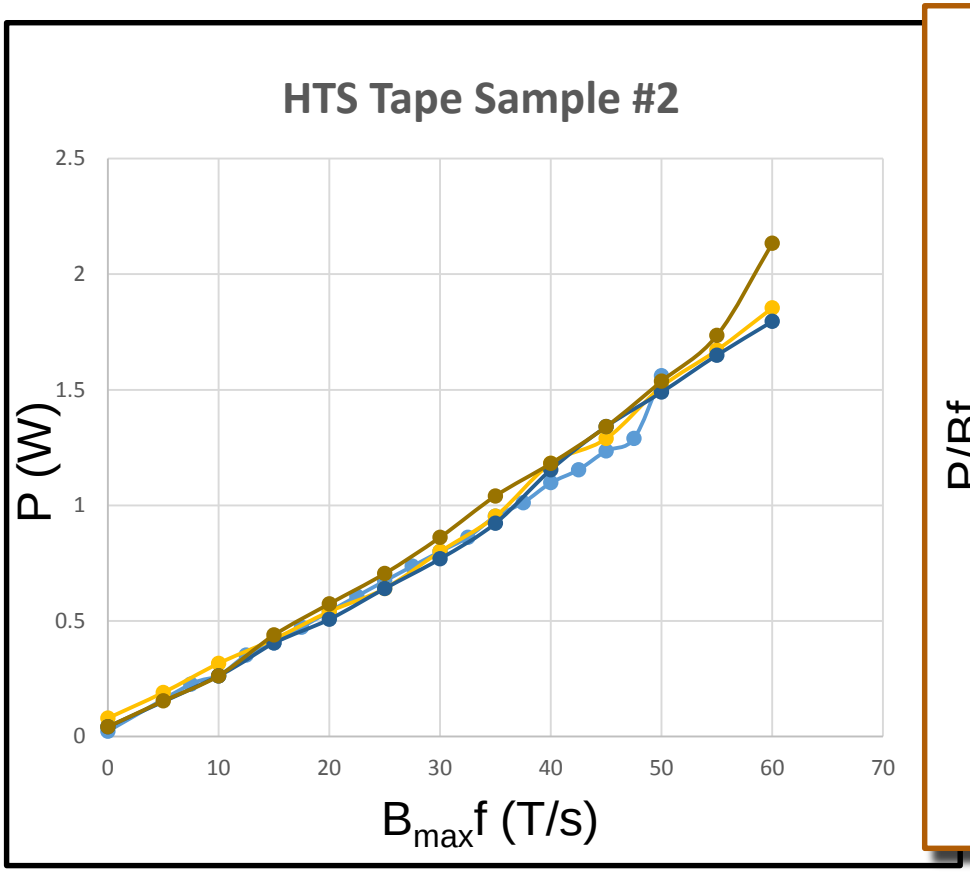


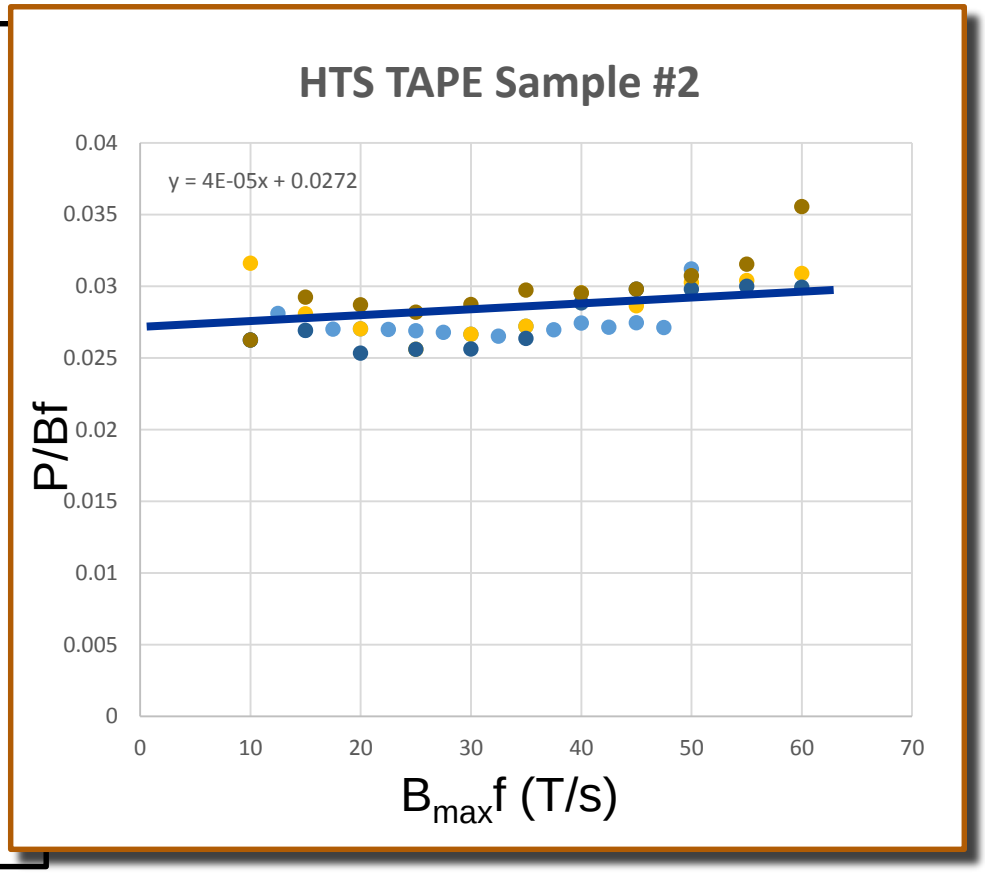


$$P_{eddy} / L = \frac{\pi^2}{6\rho_n} B_m^2 f^2 w^3 t$$

Direct resistivity measurements led to a RR = 7.355
Based on Ice point resistivity 1.553 μΩcm that gives 77K resistivity of 0.21 μΩcm.
Graph at right slope is .002 Wsec/T giving rho = 0.16 μΩcm which is 25% low, defining our error bar.

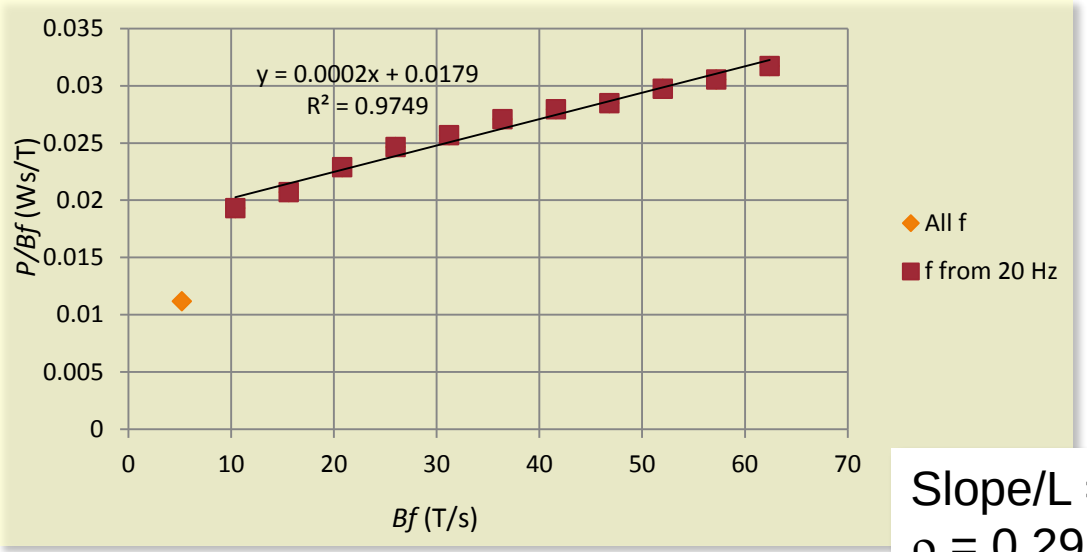
REBCO Loss Measurements





Using calibrations to determine the hysteresis (Intercept) and eddy current (Slope) losses in HTS sample

Finding the Critical Current in an HTS Sample

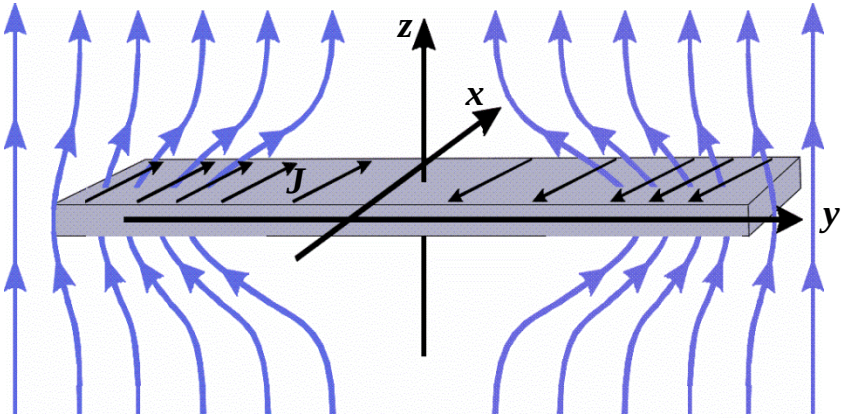


$$P_{eddy} / L = \frac{\pi^2}{6\rho_n} B_m^2 f^2 w^3 t$$

Slope/L = $\pi^2 t w^3 / 6\rho_n$
ρ = 0.29 $\mu\Omega$cm is a bit high because of "shadowing" of magnetic field

$$P = P_{hysteresis} + P_{eddy}$$
$$P = \lambda_1 I_c B f + \lambda_2 I_c (Bf)^2$$
$$\frac{P}{I_c B f} = \lambda_1 + \lambda_2 B f$$

I_c = Intercept/Lw
L = 0.1 m
w = 0.004 m
Intercept (here) = 0.0179 Ws/T
I_c = 45 A



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**
- **Measurements performed on YBCO tape. The Ic and sheath resistivity consistent with expectations**
- **Next samples: striated tapes, CORC cables, Roebel cables, and small Coils**
- **We have developed a new machine for testing HTS tapes, cables, and coils at high B-dB/dt in motor/generator-like environments**