A Critical Omission in the Critical State Model

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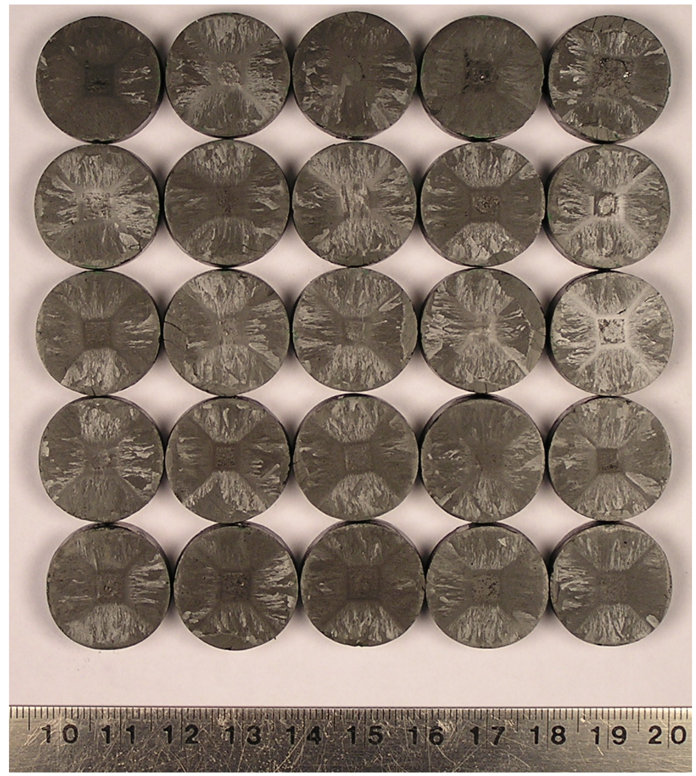

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- Trapped field magnets (TFMs), composed of bulk HTS, are able to retain fields much higher than permanent ferromagnets. For applications, quality measures generally improve as B or B^2. Therefore, there is broad interest in applications of TFMs.
- However, TFMs present added application challenges. They must be cooled below T_C and, if warmed, they must be reactivated.
- For FC activation, the critical state model (CSM) predicts $B_A = B_{T,max}$. However, the field must be kept on for ~ seconds. This results in large energy requirements, detrimental to many applications.
- For ZFC activation, the Critical State Model (CSM) predicts $B_A \geq 2 B_{T,max}$. However, ZFC does not require long cooling time, and a short pulse can be used, greatly reducing energy needs.
- As a result, pulsed-ZFC is stronlgy preferred.
- However, a problem remains: it is difficult to achieve $B_A \geq 2 B_{T,max}$ for high field TFMs.

- E.g., activation/re-activation is a limiting design factor in TFM motors. One optimized design used ~1/3 of the rotor space for activation coils. This caused a 33% loss of the expected power.
- An additional problem is that a pulsed-ZFC activation <u>heats the TFM</u>. This lowers J_C and trapped field maximum, $B_{T,max}$.
- Various world groups have spent decades trying to overcome TFM heating by high fields, in an attempt to obtain full activation.
- E.g., some have developed a 10 pulse, varying-amplitude, varying-temperature sequence in order to approach 80% of full activation.

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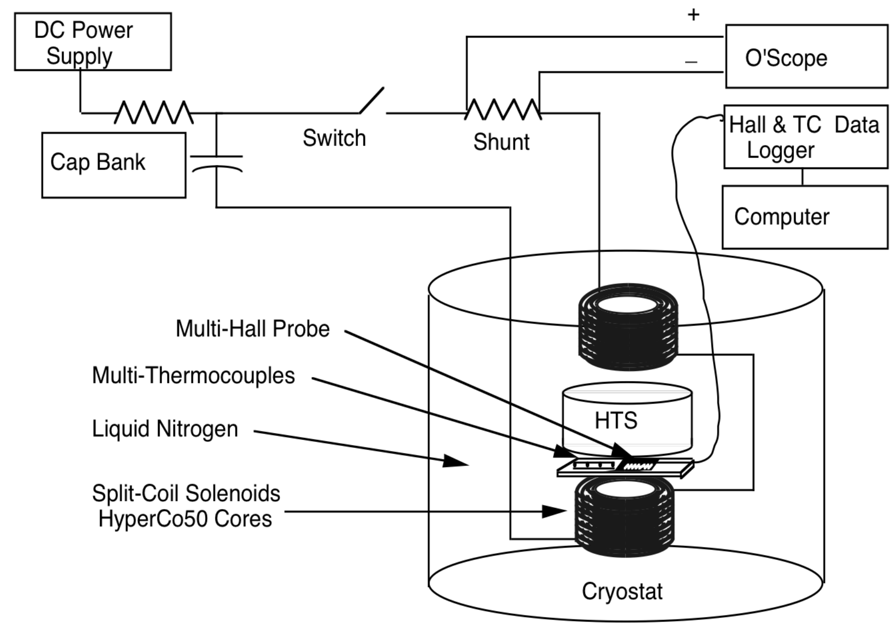
- We have performed a series of experiments at 77 K to study details of the pulsed-activation process of TFMs.
- In an earlier experiment, on high J_C TFMs, we found a factor of 2 reduction in the required field for pulsed-ZFC activation; i.e., from $B_A \geq 2\ B_{T,max}$ to $B_A \approx B_{T,max}$.

- A follow-up experiment is reported here, using TFMs with a wide range of J_C to explore for regularities of the anomalous behavior, and perhaps insight into the physics.
- As in the previous experiment, the activation field diameter is smaller than the 20 mm TFM.
- The magnet coils have Hiperco-50 cores, to obtain higher applied fields.

★ Finite element calculations, <u>based on CSM</u>, indicate <u>no activation anomalies are expected due to this geometry</u>.

- The field is approximately flat for $0 \le r \le 6$ mm, and decreases linearly to zero at the TFM periphery.



Schematic of Experiment

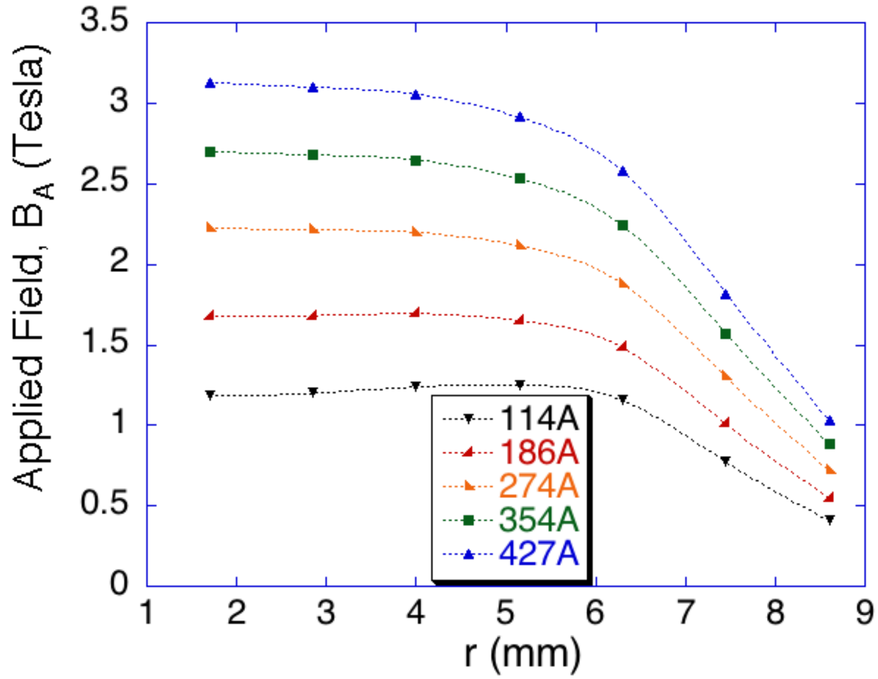
- Between the TFM and the bottom coil there is a 1.4 mm gap, into which 7 Hall probes are placed. These are placed 1.15 mm apart, spanning $1.7 < r < 8.6$ mm of the 10 mm TFM radius.

- A current pulse from capacitive discharge is used. This has a rise time of ~2 ms, and is ~30 ms long.

- For the coils used, 500 A provides $B_A \approx 3.3$ T.

- We will use the symbol $\mathbf{B_A}$ to represent the maximum of the applied field.

- The TFMs used were melt-textured, single grains of YBCO, 20 mm diameter X 8 mm long.



Applied Field, B (r,I)

- They contained pinning centers (PCs) with one of two extreme geometries: (1) Broken columnar PCs, (2) “point” PCs.

- The spectrum of J_C values used in the new experiment was $5{,}000 \leq J_C \leq 50{,}000$ A/cm^2.

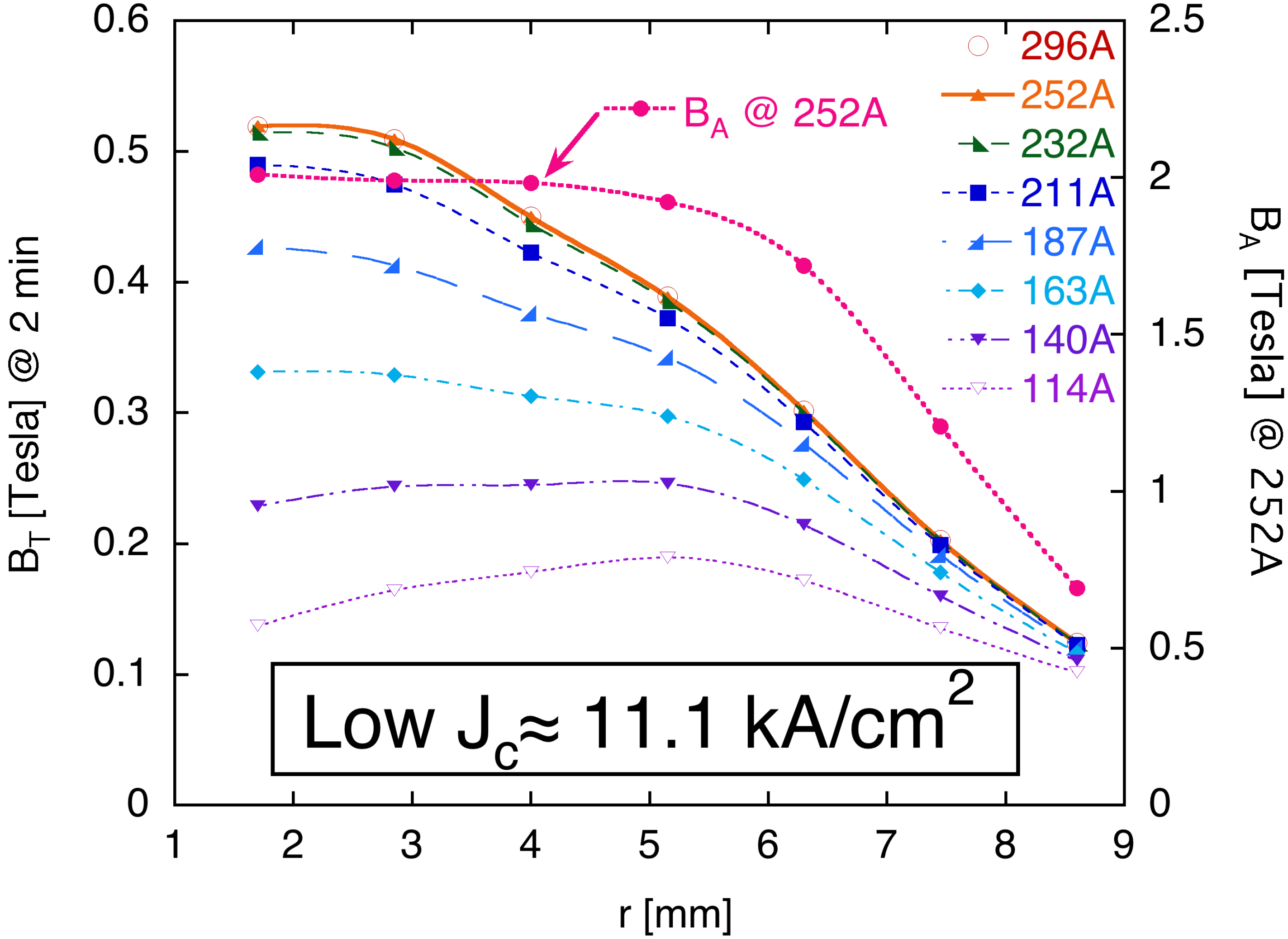
- The earlier experiment showing <u>anomalous</u> results was performed on high J_C (~50,000 A/cm^2) samples.

- Previous to that, a similar experiment, performed on low J_C samples (~10,000 A/cm^2) showed <u>good agreement</u> with CSM.

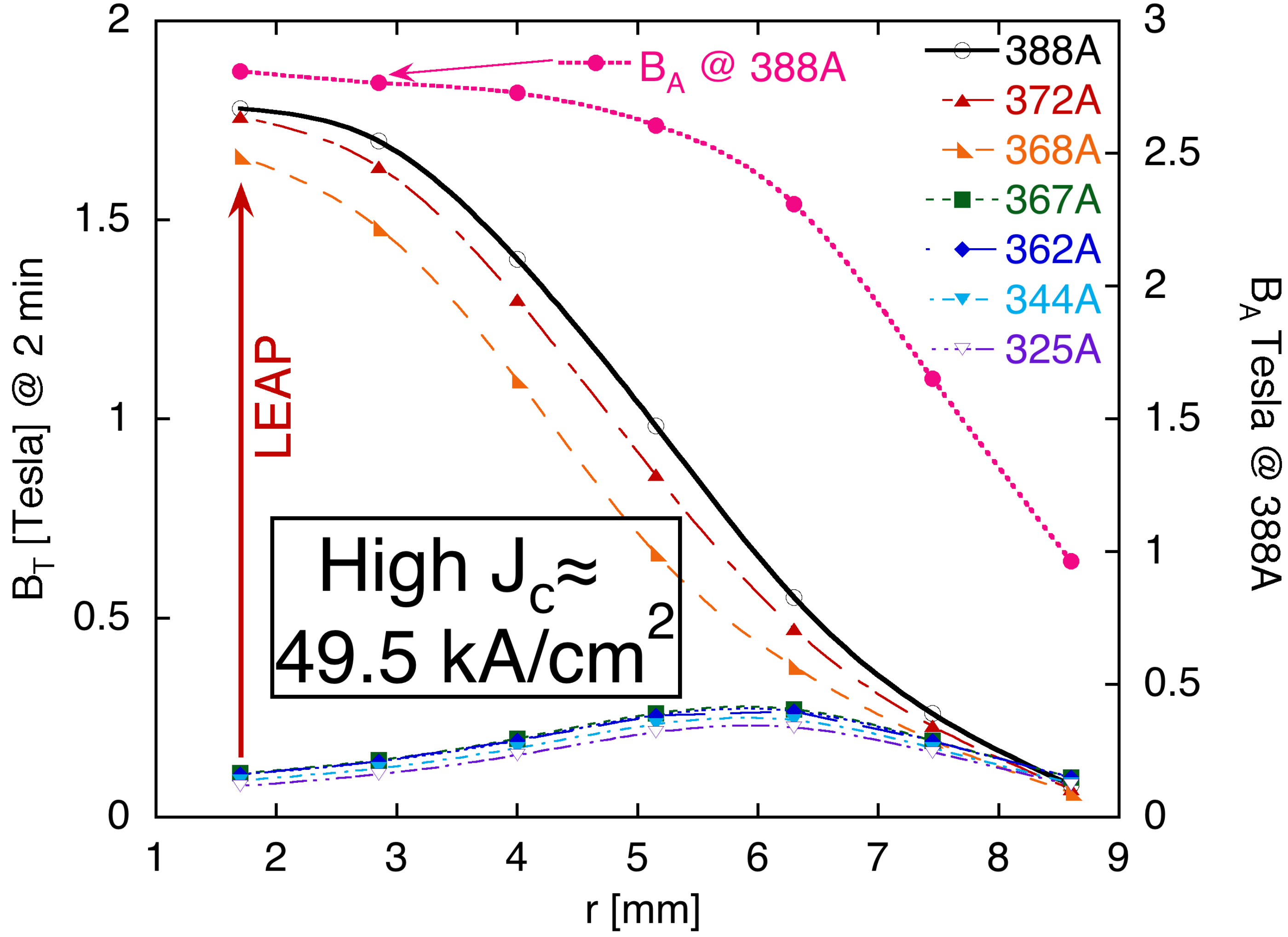
- We first consider data on trapped field, taken 2 minutes after the 30 ms activating pulse.

- We compare the samples of both low and high J_C to the critical state model (CSM).

- CSM requires a smooth rise in trapped field vs. B_A. This condition is satisfied for the low J_C sample.



- The high J_C sample exhibits an anomalous <u>giant field leap (GFL)</u> in $B_{T,max}$.



- Next we note that CSM requires $B_A \geq 2 \times B_{T,max}$ in order to fully activate a TFM to its maximum achievable $B_{T,max}$.
- The low J_C samples require $B_A \approx 4.1 \times B_{T,max}$ for full activation, thus satisfying this requirement of CSM. ($B_A \geq 2\ B_{T,max}$).
- The high J_C sample is activated to its maximum achievable trapped field when $B_A \approx 1.6 \times B_{T,max}$, <u>a clear violation of CSM</u>.
- **This violation is very encouraging for applications**.

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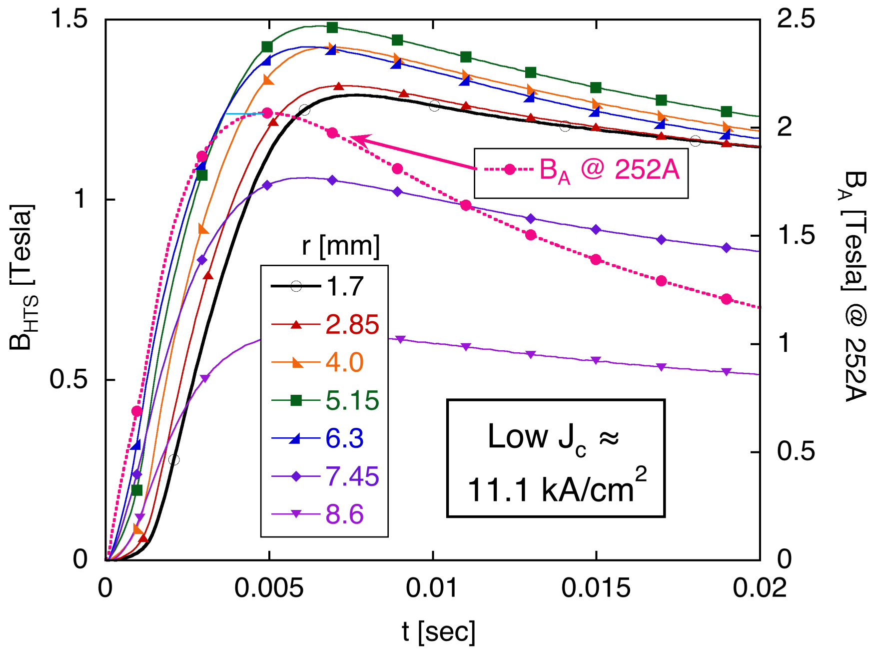
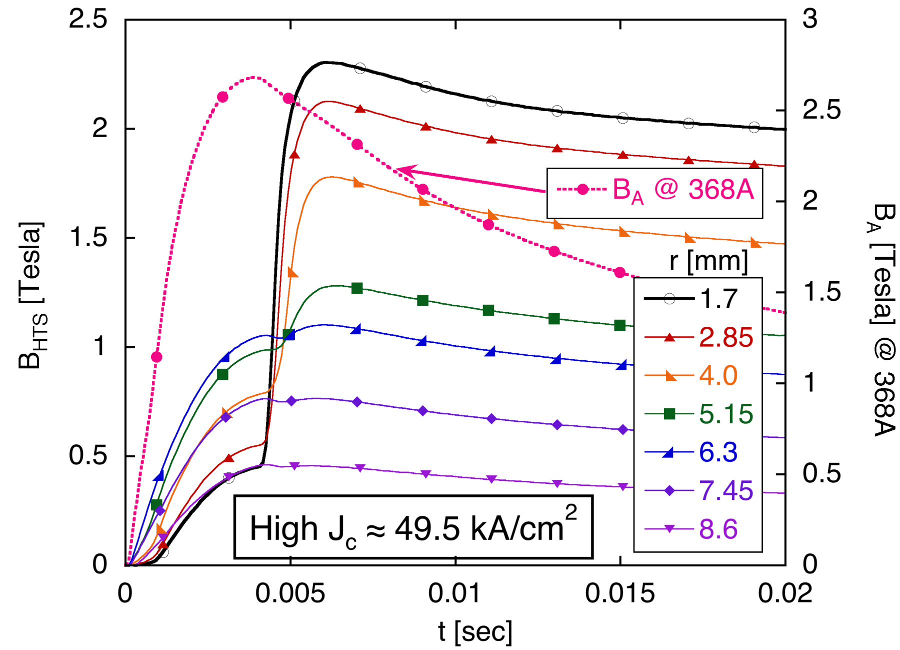
- In order to probe GFL more deeply, a study of the time evolution of the HTS field was developed.
- Data were taken every 100 micro-seconds at various values of the pulse height, B_A, of the activating field.
- We denote by $\mathbf{B_{HTS}}$ the field which has penetrated the HTS <u>during</u> activation.





- As B_A is increased, CSM requires B_{HTS} to increase most rapidly at large r, and more slowly as $r \rightarrow 0$.
- The low J_C sample behaves in accord with CSM.
- The high J_C sample behaves in accord with CSM, until (1) the pulse is at its peak value, and (2) $B_A \geq B_{T,max}$. Then, in ~500 μs, the situation rapidly reverses, in contradiction to CSM.

Critical State Model (CSM) Compared to Experiment

- The high J_C samples violate CSM in the following ways:
  - Prior to GFL the values of trapped field, $B_T(r)$, are suppressed relative to CSM by a factor of ~6.
  - After GFL, B_T is enhanced. I.e., full activation is achieved at $B_A = B_{T,max}$. CSM requires $B_A \geq 2\, B_{T,max}$.
  - CSM requires smooth increase of HTS field vs. B_A. Instead, B_T leaps when the induced $\vec{E} = 0$, $B_A \approx B_{T,max}$.
  - High J_C and low J_C samples behave differently. CSM makes no J_C distinction.
  - CSM has B_T rise at same rate as B_A. Instead, B_T leap occurs very fast (~500 μs). This is 4x faster than B_A.

The New Experiment

- We planned several experiments to look for regularities in the GFL phenomenon. The first was to study GFL vs. J_C.
- We produced samples with a variety of J_C using refined Y211, nuclear recoil, and nuclear fission to make PCs.
- Trapped field was <u>separately</u> measured for each sample by <u>field cooling</u> (FC) in a magnet with $R_{mag} > R_{TFM\ radius}$.
- $B_{T,max}$ of each sample was measured on an x,y scanner using a Hall probe.
- From these measurements, J_C was calculated.

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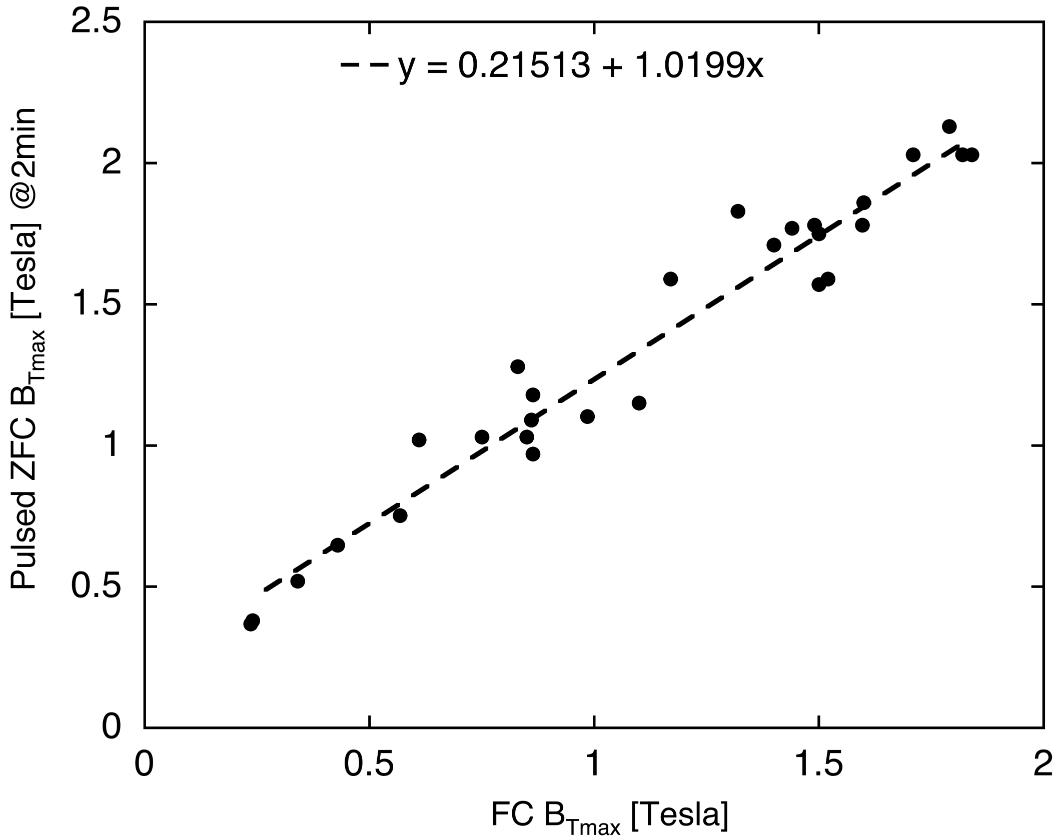
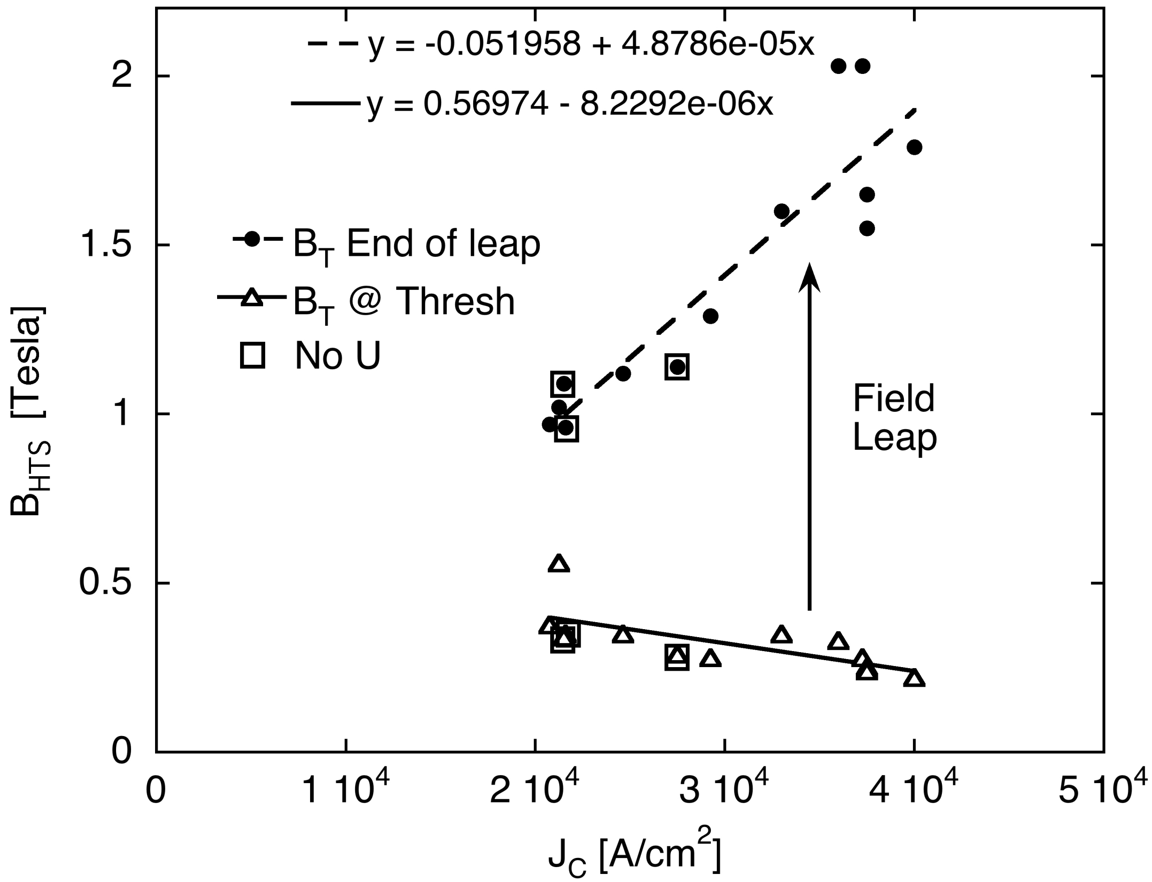
- We did several experiments to check that the equipment was properly functioning.

- E.g., the measured FC values of $B_{T,max}$ were compared to the pulsed-ZFC measurements of $B_{T,max}$.
- Good agreement with a linear relationship was found. Extrapolation to zero reflects the effect of the Hiperco-50 core.



- We next used data on trapped field at t = 2 min. to measure where the leap started (= B_{Thresh}) and where the leap ended, (= $B_{End\text{-}o\text{-}leap}$).



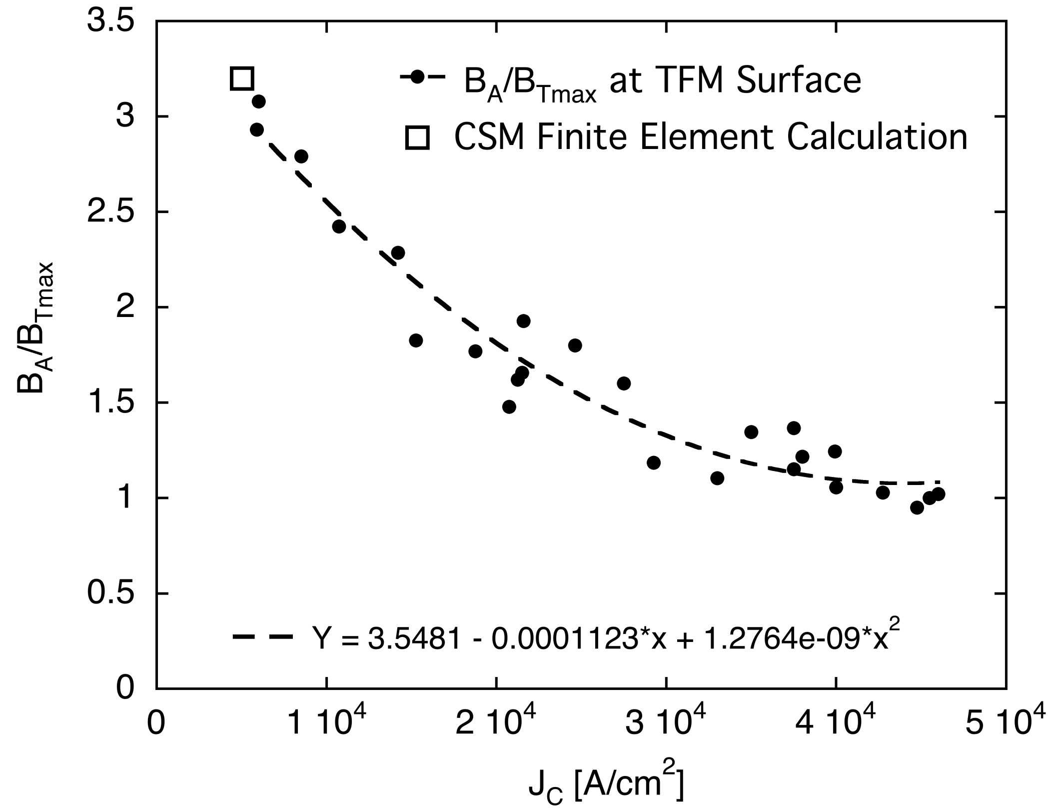
- Without recourse to any theory we see:
  - The threshold is a decreasing function of J_C.
  - The end-of-leap is an increasing function of J_C.
  - The leap phenomenon increases with J_C.
  - The magnitude of the leap grows to ~2 T at J_C ~50,000 A/cm^2.
  - Both point PCs and columnar PCs show the same general GFL behavior.
  - Therefore, at least to first order, <u>GFL is independent of pinning center geometry</u>.

- We next considered the data on $B_A/B_{T,max}$, corrected to the TFM surface.

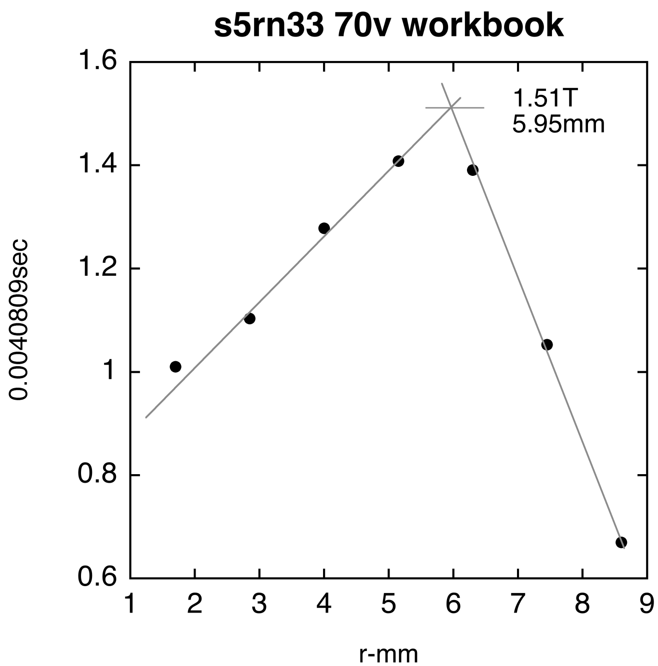
- Note that for low J_C samples, $B_A/B_{T,max} \approx 3.2$, a result in agreement with CSM.

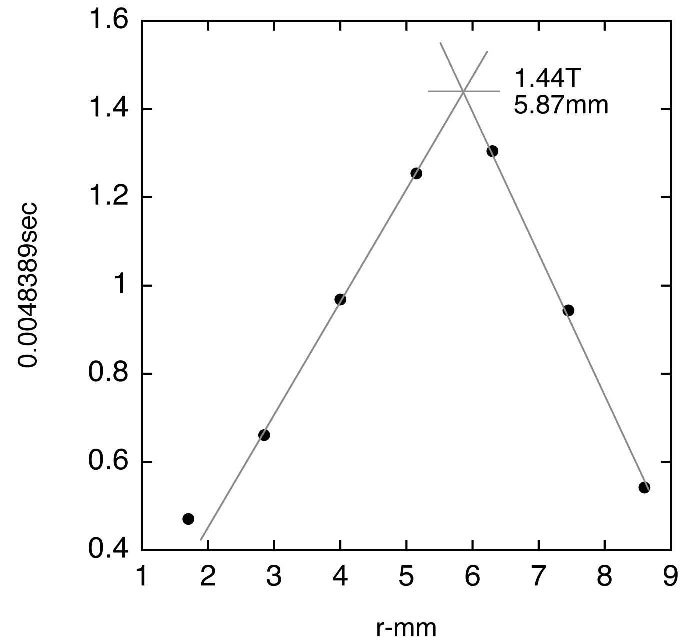
- Note that for high J_C samples, $B_A/B_{T,max} \approx 1.0 \pm 10\%$, a result incompatible with CSM.

★ The special point at 5000 A/cm^2 is a finite element calculation based on CSM.



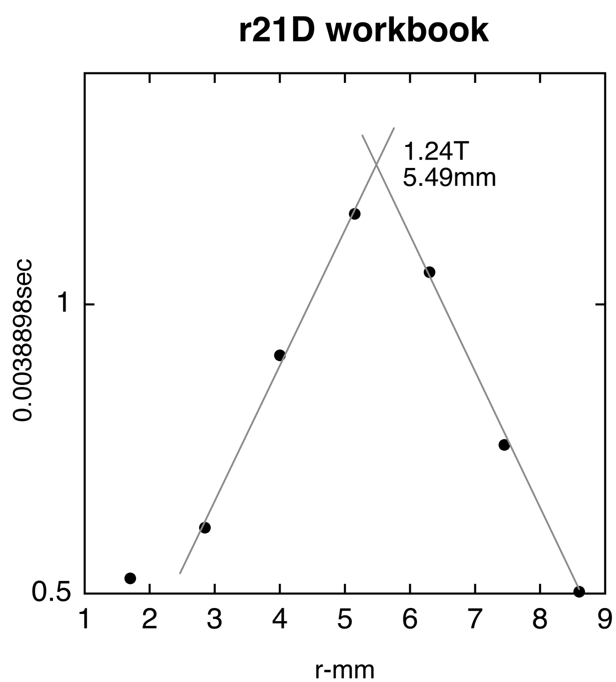
- What is the physics causing GFL?
- We **speculated** with the first GFL observation, that the very large Lorentz force, $F_L \propto J_C \times B_{HTS}$ may be moving the fluxoids away from the locations required for optimum diamagnetic shielding.
- In this new experiment we can measure B_{HTS} just prior to the leap (= B_{Thresh}), and calculate J_C x B_{thresh} $\propto F_{L,Thresh}$.
- We use the time dependent data to find B_{Thresh} so that we do not have to correct for unknown creep rate.
- We have data on seven points in r, just prior to GFL. We fit 6 of these with 2 straight lines in order to find the peak value of B_{Thresh}.
- Typical fits are shown in the next slide.
- We use the measured FC value of $B_{T,max}$ to represent J_C.



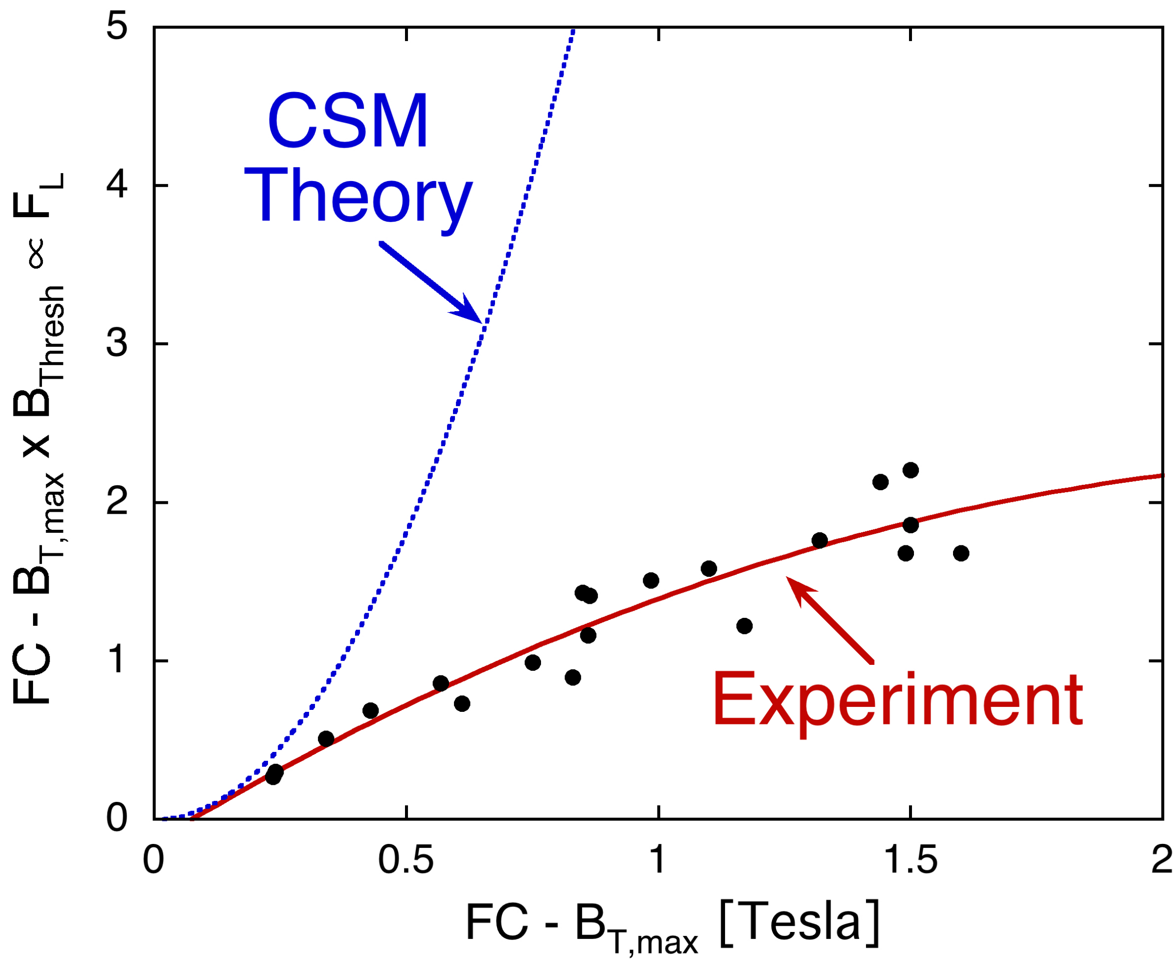


- Examples of determinations of B_{thresh} for samples with J_C:
  - (a) 14.1 kA/cm^2, PCs = Y211
  - (b) 36.6 kA/cm^2, PCs = n-recoil
  - (c) 41.2 kA/cm^2, PCs = U/n

- Falling line on right is caused by decreasing values of $B_A(r)$.



- Using the fitted values of B_{Thresh} and the FC measurements of $B_{T,max}$ as a measure of J_C, we obtain values of $B_{Thresh} \times B_{T,max,FC} \propto B_{Thresh} \times J_C \propto F_{L,thresh}$ (the Lorentz force when the leap occurs).



Our Opinions About the Physics of GFL

- We consider the most revealing behavior of the experimental results to be the suppression of B_{HTS} prior to the leap.
- But what is it that limits the increase of penetrated field?
- We postulate that rapid flux leakage causes the limitation.
- We postulate that when $\vec{E} \rightarrow 0$ (i.e., at the peak of the B_A pulse) the Lorentz force frees fluxoids from their shielding location.
- (Clearly, however, F_L may be a cause or a consequence.)
- The postulated fluxoid movement is similar to creep, but is much faster. We describe it as a **"fluxoid cascade."**
- The flux loss limits pre-leap B_T to anomalously low values.
- If F_L is indeed causal, we cannot say whether F_L or its derivative is the cause because sample geometry is constant.

- In particular, note that current reverses at B_{Thresh}, and therefore F_L reverses by 180°.
- Thus, at B_{Thresh}, $\Delta F = 2\ F_L$. This discontinuity in F_L occurs at the peak value of B_{HTS} (= B_{Thresh}).
- We favor the large stress due to ΔF_L as the cause of the fluxoid cascade.
- While the activating field is still on, the fluxoids lost in the cascade are (partially) replaced by fluxoids introduced by B_A.
- If only free fluxoids were involved we would expect a rapid increase in $B_{T,max}$ when the pulse begins to decrease, and $\vec{E}$ reverses sign.
- However, from our postulates, we do not see a reason that the GFL is delayed until $B_A = B_{T,max}$.
- Hence, at this point, our explanation is incomplete.

<u>Closing Comments</u>

- CSM was <u>*said*</u> to postulate:
  - Electric field causes maximum J to flow.
  - Ampere's Law is valid.
  - We believe that a third postulate was implied: <u>fluxoids remain in place when $\vec{E} = 0$.</u>
  - We are not alone in noting that CSM requires fluxoid stability.
  - In 1962, when C.P. Bean was developing CSM, P.W. Anderson was investigating "creep" [the decrease of B_T with time].
  - The Anderson model of creep postulates that thermally activated fluxoids escape from their pinning potential. The fluxoids then move off "guided by F_L."
  - Anderson, in his seminal paper on flux creep noted, "<u>We have obviously predicted that there is no precise critical state</u>."

- Thus, while CSM is a remarkably useful theoretical aid, we must view it as a very convenient fiction. <u>It has been a useful approximation, because the creep correction is so small.</u>
- Based upon our experiments to date, we postulate that $B_T(r)$ is suppressed by a fluxoid cascade caused by increasing F_L.
- GFL occurs uniquely at $B_A \approx B_{T,max}$, and $\vec{E} \approx 0$. When it does occur, the free fluxoids in the cascade permit it to happen quickly.
- However, a field leap would then be expected whenever the induced $\vec{E}$ field switches direction, <u>independent of B_A</u>.
- Instead, the leap only occurs when B_A is large enough to fully activate the TFM.
- Therefore our present model is, at best, incomplete.
- Our experiments continue in the hope of resolving this and other very significant anomalies.