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Bruker Strand: I_C vs. ε_B Results - Update

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25.06.2024

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Overview

1. Summary of results from first set of measurements
2. Results for barrels re-measured last week
3. Next steps

Summary of measurements performed

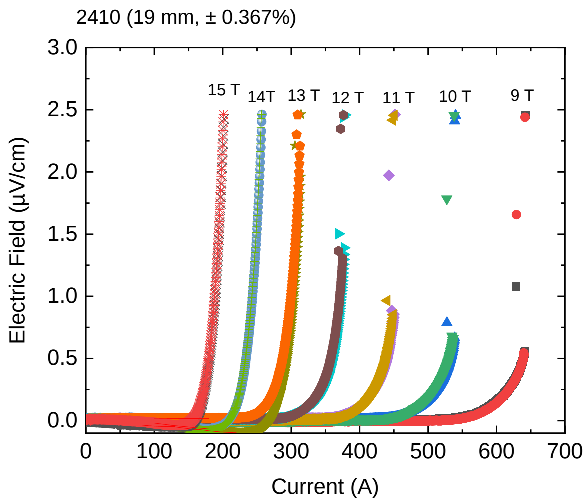
- Bruker high-J_C strands from EDIPO billet H0049-4.
- 2 strands per heat treatment radius or bending strain.
- $T = 4.2$ K
- $9\ \mathrm{T} \leq B \leq 15\ \mathrm{T}$
- $16\ \mathrm{mm} \leq R_{\mathrm{HT,o}} \leq 19\ \mathrm{mm}$
- $0\% \leq |\varepsilon_B| \leq 0.367\%$
- V tap separation 49 cm

Measurement ID	Heat Treatment Barrel Outer Radius $R_{\mathrm{HT,o}}$ / Bending Strain
2403	16 mm / 0% **(no transfer)**
2404	16 mm / 0% **(no transfer)**
2405	17 mm / ±0.137%
2406	17 mm / ±0.137%
2407	18 mm / ±0.258%
2408	18 mm / ±0.258%
2409	19 mm / ±0.367%
2410	19 mm / ±0.367%

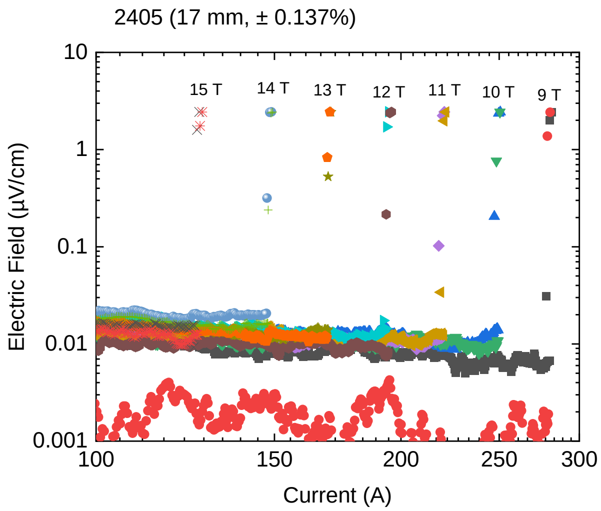
$R_{\mathrm{HT,o}}$ is the outer radius of the heat treatment barrel. See the last slide for a detailed calculation for the bending strain values.

$E - I$ traces

Typically, the baselines are flat or have linear components which are subtracted in the analysis.



Some of the strands **(e.g., 2405, bottom plot)** have no smooth transition around the 0.1 $\mu V cm^{-1}$ criterion and/or the I_C is lower than expected -> possibly damaged



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Which strand $E-I$ datasets can we fit using the power law?

Measurement ID	Heat Treatment Barrel Outer Radius $R_{\mathrm{HT,o}}$ / Bending Strain	Are the data ok to analyse?
2403	16 mm / 0% **(no transfer)**	X (resistive sample)
2404	16 mm / 0% **(no transfer)**	X (low I_C, sudden transition)
2405	17 mm / ±0.137%	X (low I_C, sudden transition)
2406	17 mm / ±0.137%	✓
2407	18 mm / ±0.258%	✓ (but not 9 T, 10 T)
2408	18 mm / ±0.258%	✓
2409	19 mm / ±0.367%	✓
2410	19 mm / ±0.367%	✓

New results

Barrels **2403-2405** (2x 0%, 1x 0.137%) were remeasured on Thursday and Friday last week.

Good news: we were able to get good $E-I$ data from the 0% barrels. The extracted I_C and n agree with the values from the Bruker datasheet.

Bad news: still getting bad data from the 0.137% barrel, and we were not able to identify what caused the problem the first time for the 0% barrels.

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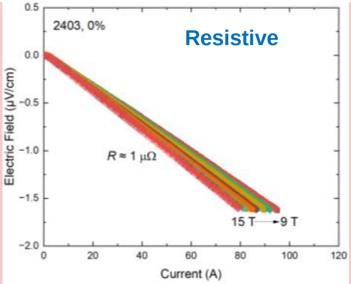
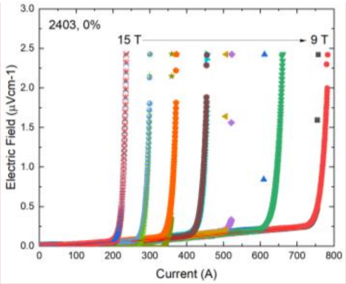
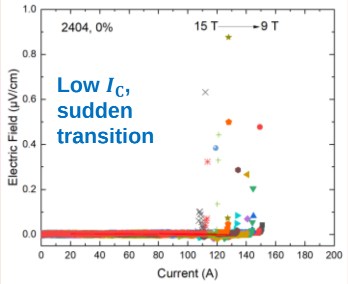
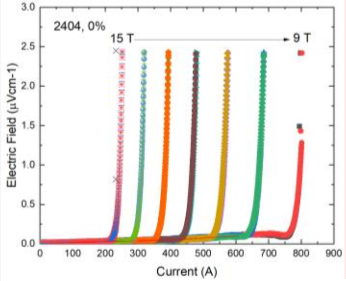
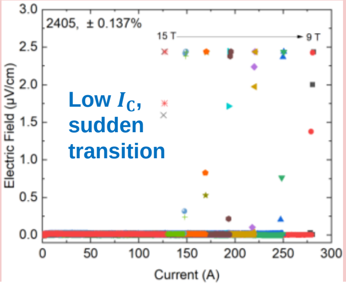
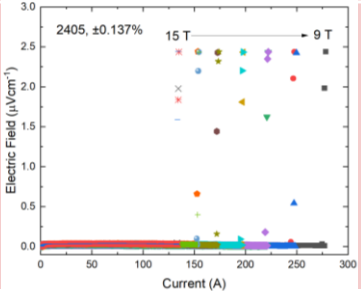
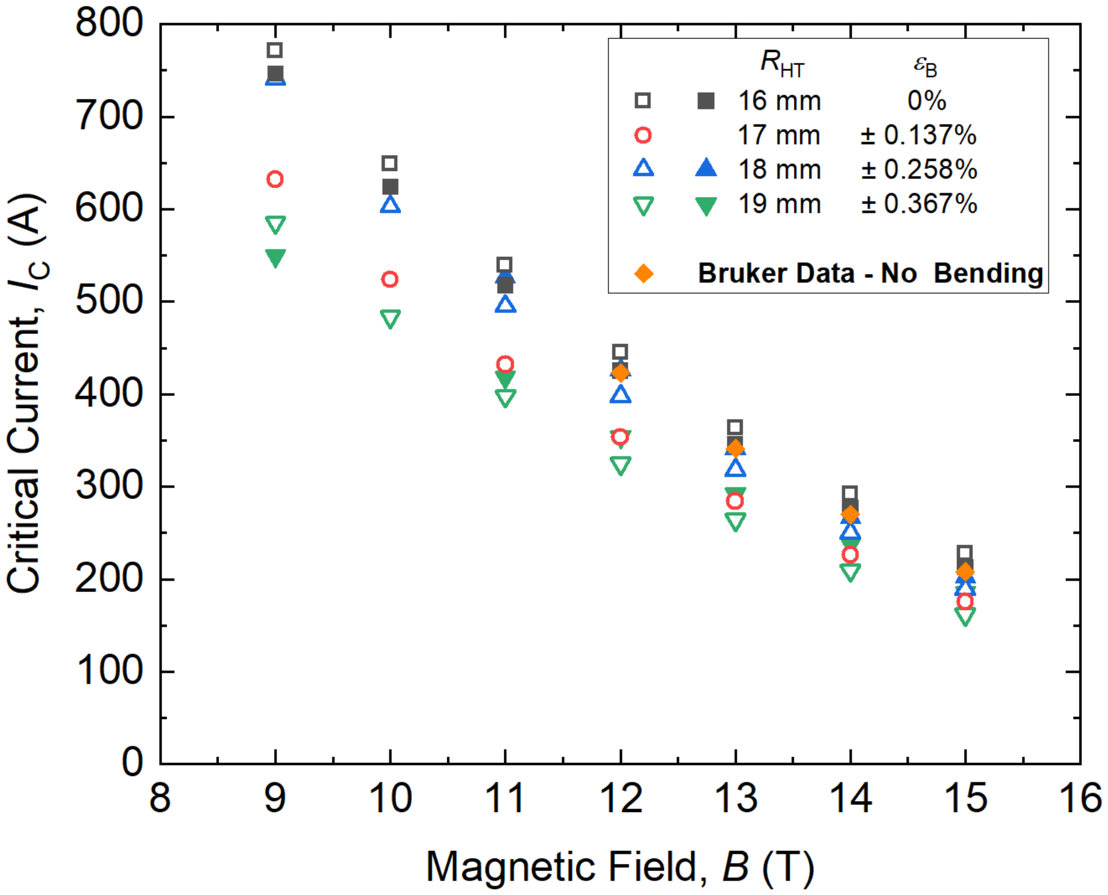
Comparison

Barrel ID and strain	First Measurement	Second Measurement
2403, 0%		
2404, 0%		
2405, ±0.137%		

Setup problem not present

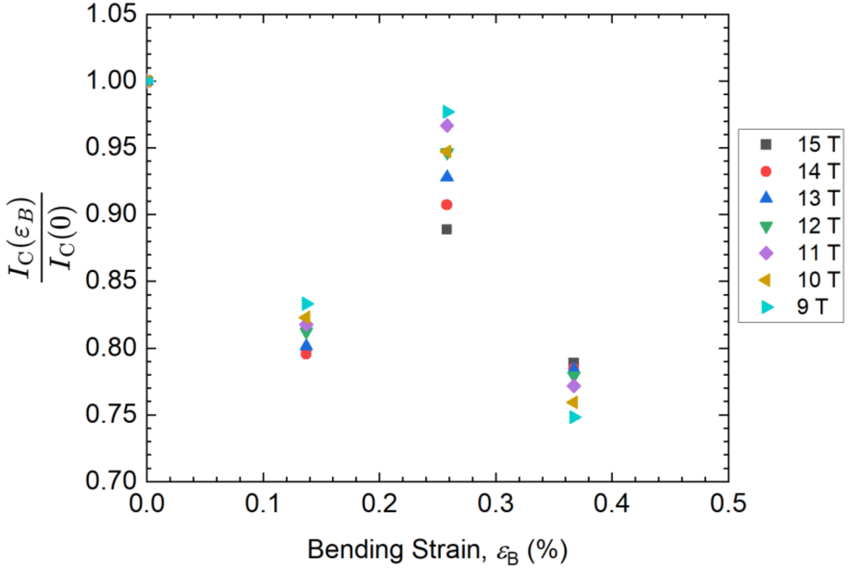
Still transitioning early at the exact same currents, to within ~1%

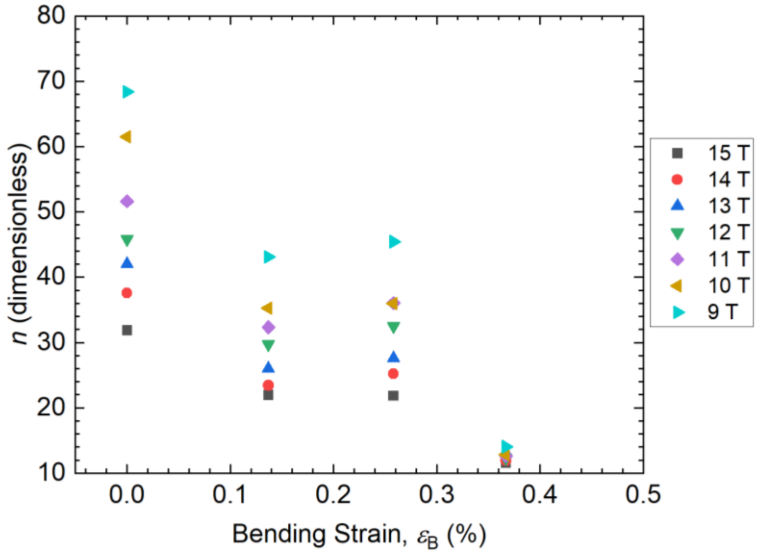
New $I_C(B)$



Critical Current, I_C (A)
Magnetic Field, B (T)
R_{HT}
ε_B
16 mm 0%
17 mm ± 0.137%
18 mm ± 0.258%
19 mm ± 0.367%
Bruker Data - No Bending

New $I_C(\varepsilon_B)$ and $n(\varepsilon_B)$





Next steps

We plan to react and measure more strands at the same bending strains and additional strains

This time, the strands will be reacted on smooth cylinders.

The heat treatment began last week and it will finish in approximately 2 weeks.

ASC starts in ~10 weeks.

Option	Bending strain	Smooth cylinder outer radius required	Quantity
1	0%	Use normal ITER barrels	4
2	0.12%	16 mm	2
3	0.25%	17 mm	2
4	0.30%	17.5 mm	2
5	0.36%	18 mm	2
6	0.41%	18.5 mm	2

New strain (rows 4 and 6 highlighted)

Priority is option 4 then option 6

Summary

I_C measurements have been performed on 8 strands (4 bending strains, 2 per strain).

7/8 strands are now producing data that can be analysed fully.

The n-value data suggest that irreversible degradation has occurred by $\varepsilon_B = \pm 0.367\%$

The next set of strands is due out of the furnace in ~2 weeks.

Measurement ID	Heat Treatment Radius / Bending Strain	Are the data ok to analyse?
2403	16 mm / 0% (no transfer)	✓
2404	16 mm / 0% (no transfer)	✓
2405	17 mm / ±0.137%	X
2406	17 mm / ±0.137%	✓
2407	18 mm / ±0.258%	✓
2408	18 mm / ±0.258%	✓
2409	19 mm / ±0.367%	✓
2410	19 mm / ±0.367%	✓

New $I_C(B)$ – fitting

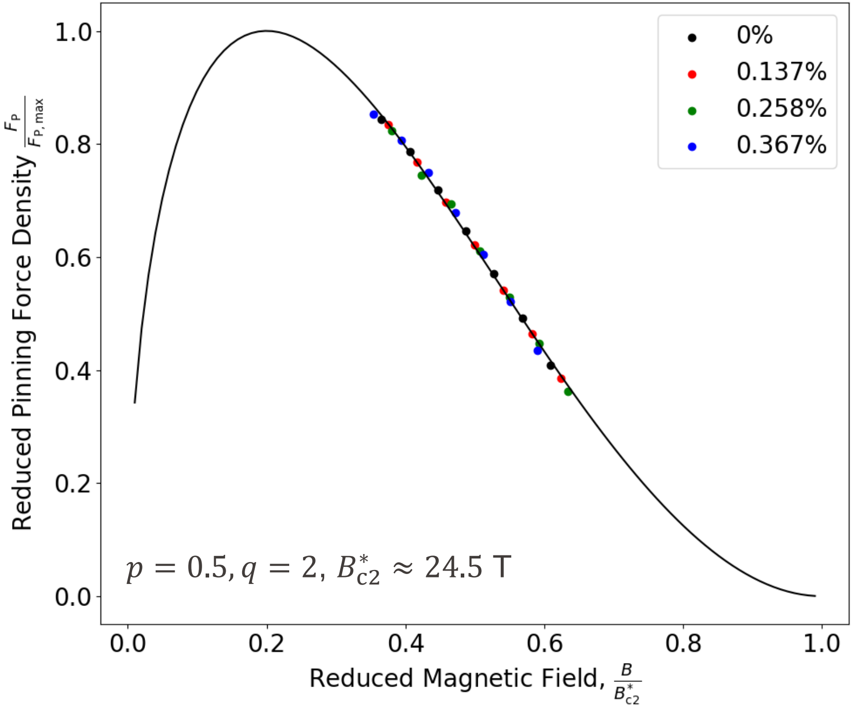
$$J_C \times B = F_P = C\left(\frac{B}{B_{c2}^*}\right)^{p-1}\left(1-\frac{B}{B_{c2}^*}\right)^{q} = F_{p,max}\left(\frac{p}{p+q}\right)^{-p}\left(1-\frac{p}{p+q}\right)^{-q}\left(\frac{B}{B_{c2}^*}\right)^{p-1}\left(1-\frac{B}{B_{c2}^*}\right)^{q}$$

Strategy for first fit attempt:

- p and q as ε_B –independent fit parameters
- B_{c2}^* and $F_{p,max}$ as ε_B -dependent fit parameters, no functional form assumed for either parameter for now

Observation

- There is a fairly wide range of parameter values that leads to good fits at the moment.



New n vs. I_C

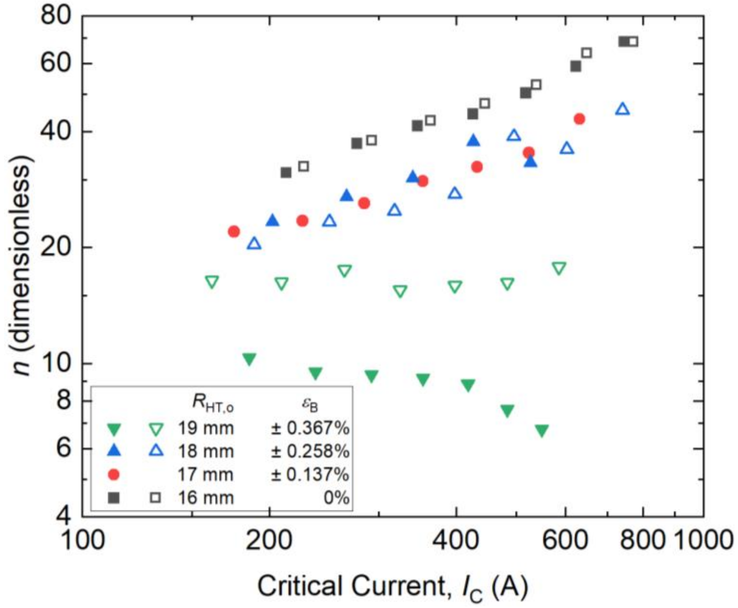
The data for $\varepsilon_B \leq 0.258\%$ are well-fitted by [1]

$$n = 1 + r_n I_C^{S_n}$$

where r_n and S_n are constants. r_n is strain dependent but S_n is not, similar to literature results for axial strain measurements.

Very low and even negative values of S_n for $\varepsilon_B = 0.367\%$ suggest significant **extrinsic behaviour** (current shunting)

More data points needed.



[1] e.g., https://iopscience.iop.org/article/10.1088/0953-2048/18/12/012, https://iopscience.iop.org/article/10.1088/0953-2048/25/5/054008

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E vs. I fitting

The data were fitted using the power law:

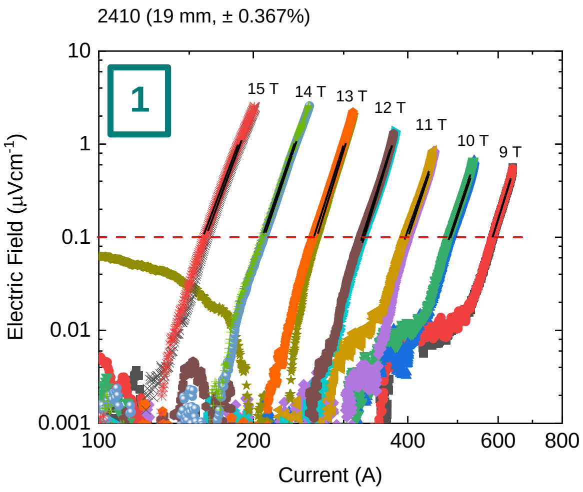
$$\frac{E}{E_C} = \left(\frac{I}{I_C}\right)^n$$

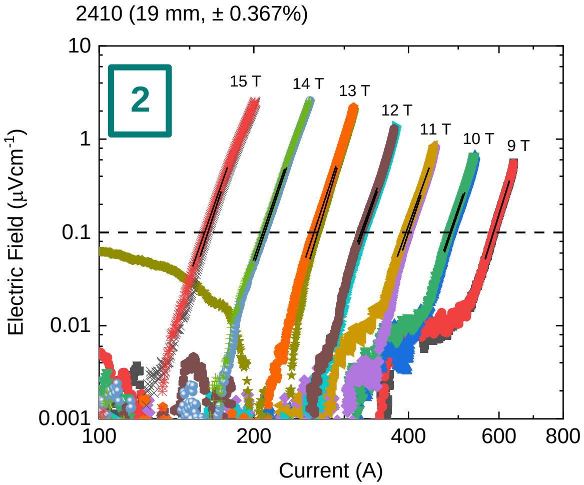
I_C was extracted at 0.1 μVcm^{-1}.

The fitting was performed twice:

1. Over roughly $0.1\ \mu\text{Vcm}^{-1} \leq E \leq 1\ \mu\text{Vcm}^{-1}$
2. Over roughly $0.05\ \mu\text{Vcm}^{-1} \leq E \leq 0.5\ \mu\text{Vcm}^{-1}$

The fit around 0.1 μVcm^{-1} is perhaps very slightly better with method 2, and data could not be collected up to 1 μVcm^{-1} in some measurements.
-> only results from method 2 are presented from now on, but the same conclusions for $I_C(B, \varepsilon_B)$ and $n(B, \varepsilon_B)$ can be reached using either method.





Appendix: Bending Strain Calculation & Uncertainty

$$\varepsilon_{\mathrm{B}} = \pm\frac{t}{2}\left(\frac{1}{R_{\mathrm{m,n}}} - \frac{1}{R_{\mathrm{HT,n}}}\right)$$

$R_{\mathrm{HT,n}}$ and $R_{\mathrm{m,n}}$ are the neutral axes of the strands on the heat treatment barrels and measurement barrels, respectively. t is the strand or (more accurately) the filamentary zone thickness.

After heat treatment, the strands are transferred to 'ITER barrels' with an outer radius of 16.00 mm and a 'groove radius' of 15.10 mm, i.e., the groove is ~0.90 mm deep. These values have been measured in the SPC-SG workshop using calipers. The diameter of each strand is 0.697 mm. For now I have assumed

$$R_{\mathrm{m,n}} = 15.10\ \mathrm{mm} + \frac{0.697}{2}\ \mathrm{mm} = 15.45\ \mathrm{mm},$$

but it is not clear whether the strand touches the bottom of the groove.

There is a similar uncertainty for the heat treatment radii. The measured strands were heat treated on the barrels with grooves. For now I only have the outer radii $\boldsymbol{R}_{\mathbf{HT,o}}$**'s** of the heat treatment barrels (16 mm, 17 mm, 18 mm, 19 mm). Assuming a 0.9 mm groove depth and the strand touches the bottom of the groove,

$$R_{\mathrm{HT,n}} = \boldsymbol{R}_{\mathbf{HT,o}} - 0.90\ \mathrm{mm} + \frac{0.697}{2}\ \mathrm{mm}.$$

There is also uncertainty around the correct t-value to use in the equation. For now I have assumed 0.697 mm because we do not know the filamentary zone diameter. Putting all this together:

$$\varepsilon_{\mathrm{B}}\left(R_{\mathrm{HT,o}}\right) = \pm\frac{0.697\ \mathrm{mm}}{2}\left(\frac{1}{15.45\ \mathrm{mm}} - \frac{1}{\boldsymbol{R}_{\mathbf{HT,o}} - 0.90\ \mathrm{mm} + \frac{0.697}{2}\ \mathrm{mm}}\right)$$

If the filamentary zone radius was around 0.55 mm, then by using 0.697 mm we would be overestimating the bending strain by ~27%.