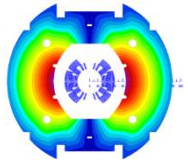
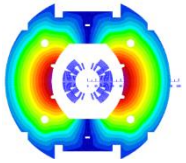


MBHSP Series 11T Dipole Magnetic Measurements

J. DiMarco

22Sep2015

CERN-FNAL Collaboration Meeting on DS 11T Dipole
FNAL, Sep. 21-23, 2015



Definitions

The magnetic field in the magnet aperture is expressed as a series expansion in terms of harmonic coefficients

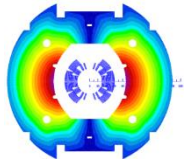
$$B_y + iB_x = B_1 10^{-4} \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1}$$

With the normalized field coefficients defined as

$$b_n = \frac{B_n}{B_2} * 10000, \qquad a_n = \frac{A_n}{A_2} * 10000$$

The B_n, A_n field coefficients are given in Tesla at the magnet reference radius $R_{ref} = 17mm$ (MBHSP aperture is 60mm)

The z-axis is defined with its zero at the center of the magnet and pointing towards the lead end (right-hand coordinate system).



MBHSP Magnetic Design

11 T central field at nominal LHC current of 11.85 kA at 1.9 K.

Design has low-order geometrical field harmonics below 10−4 level at operating current.

25 mm-thick, 11-mm-wide stainless steel core used to reduce inter-strand eddy currents in the cable.

The 0.7-mm Nb3Sn RRP-150/169 strand has ~35 μm sub-element size in order to reduce persistent current effects

Printed Circuit Board (PCB) probes – 1Hz rotation rate

MBHSP01

- 2-Layer, 14 turns/layer/track PCB with outer trace at 12mm radius (other spec. as below)

MBHSP02-04

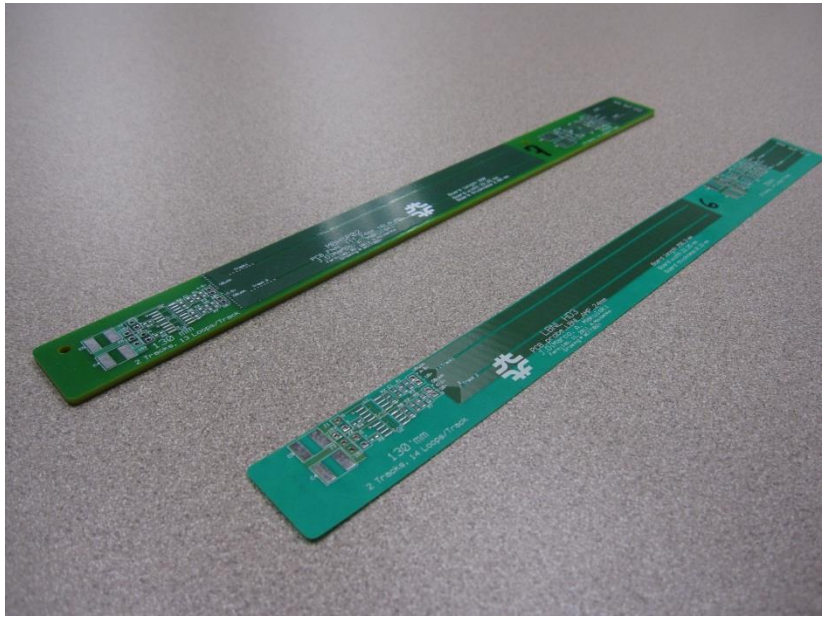
UnBucked (UB) and DipoleBucked (DB) windings

- 16-Layer, 13 turns/layer/track with outer trace at 14mm radius

Probe has two different length circuits

- 130mm (close to twist pitch)
- 26mm (1/5) for fine structure measurements
- PCB sampled simultaneously with 16 bit ADC with DSP processor

Note: Probe radius limited by warm bore tube size

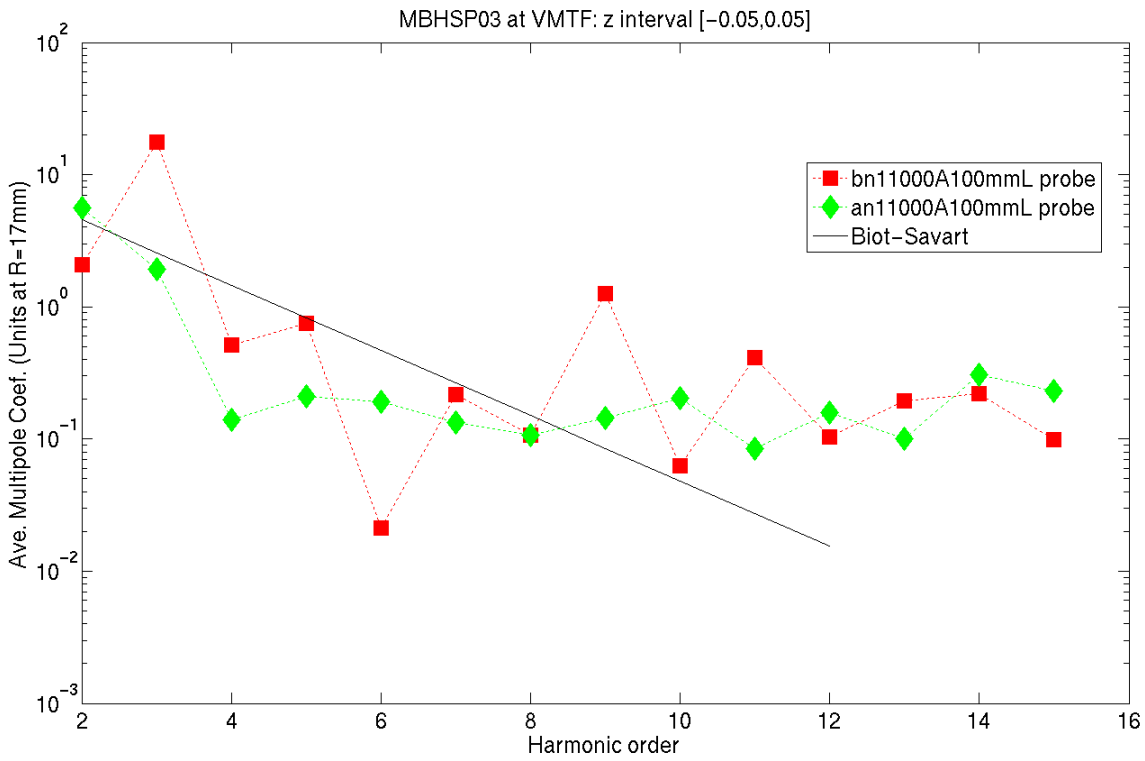


3D-printed support structure ('ABSplus' thermoplastic) with carbon-fiber rods

Probe resolution

Harmonics compared to expected fall-off from Biot-Savart

Follows expected slope out to n=8.
Resolution ~0.2 units at reference radius



Centering correction:

MBHSP01: not applied - higher harmonics close to resolution, and large dynamic effects during ramp

MBHSP02-03: applied - b2/a2 hysteresis minimization

MBHSP04: not applied - higher harmonics close to resolution, and effects from absence of collars

Measurements List:

Before Cooldown:

- Warm Zscan +/-10A – geometric harmonics w/o thermal effects

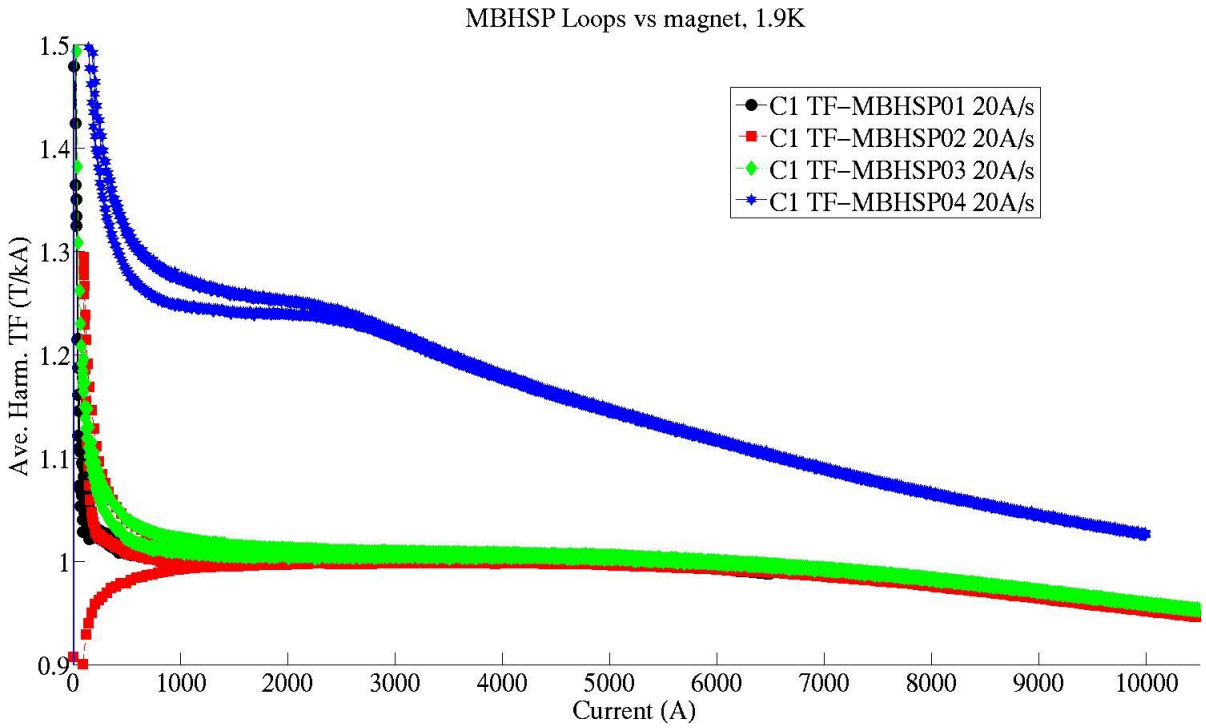
1.9K after quenching:

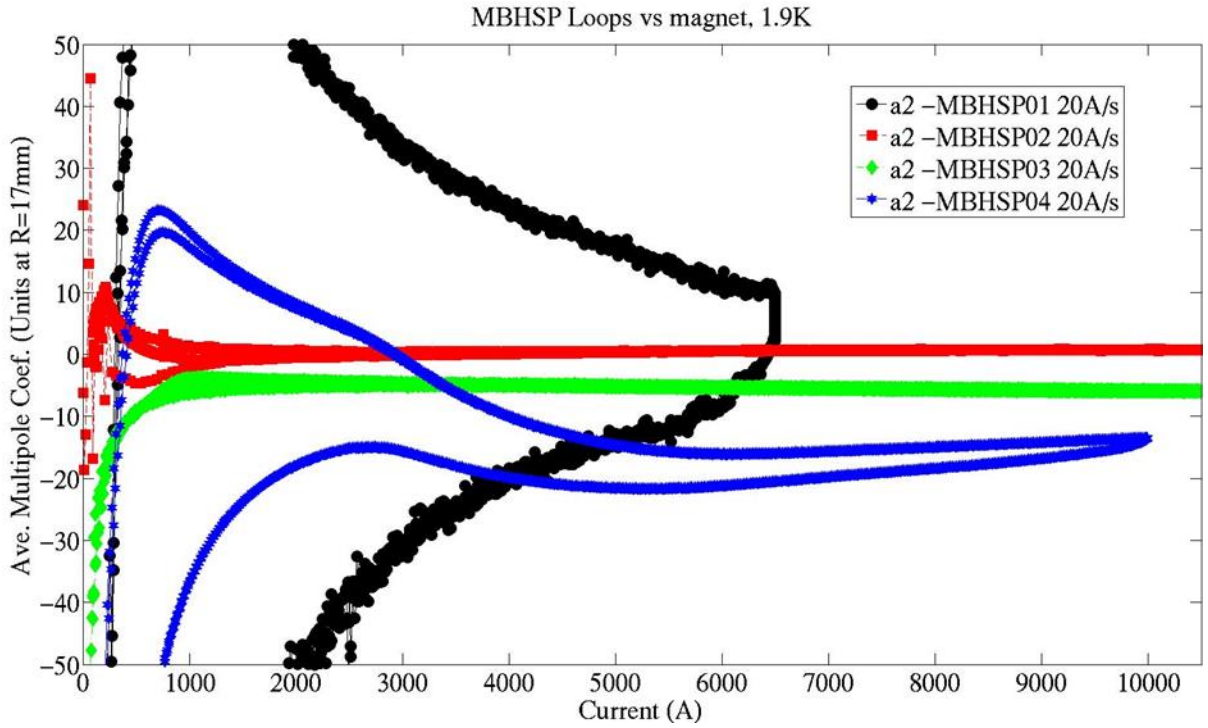
- Zscan near maximum current flattop - examine axial uniformity/features
- Loops at 10/20/40/80A/s to max. current – check ramp rate dependence/dynamic effects
- Loadline (stairstep) measurement to max. current – characterize persistent current vs dynamic effects
- Accel. cycle with 30 min. dwell at 760A – simulated accelerator injection cycle/decay and snapback

After Warm-up:

- Warm Zscan +/-10A – geometric harmonics w/o thermal effects after test cycle

MBHSP Magnets at 20A/s

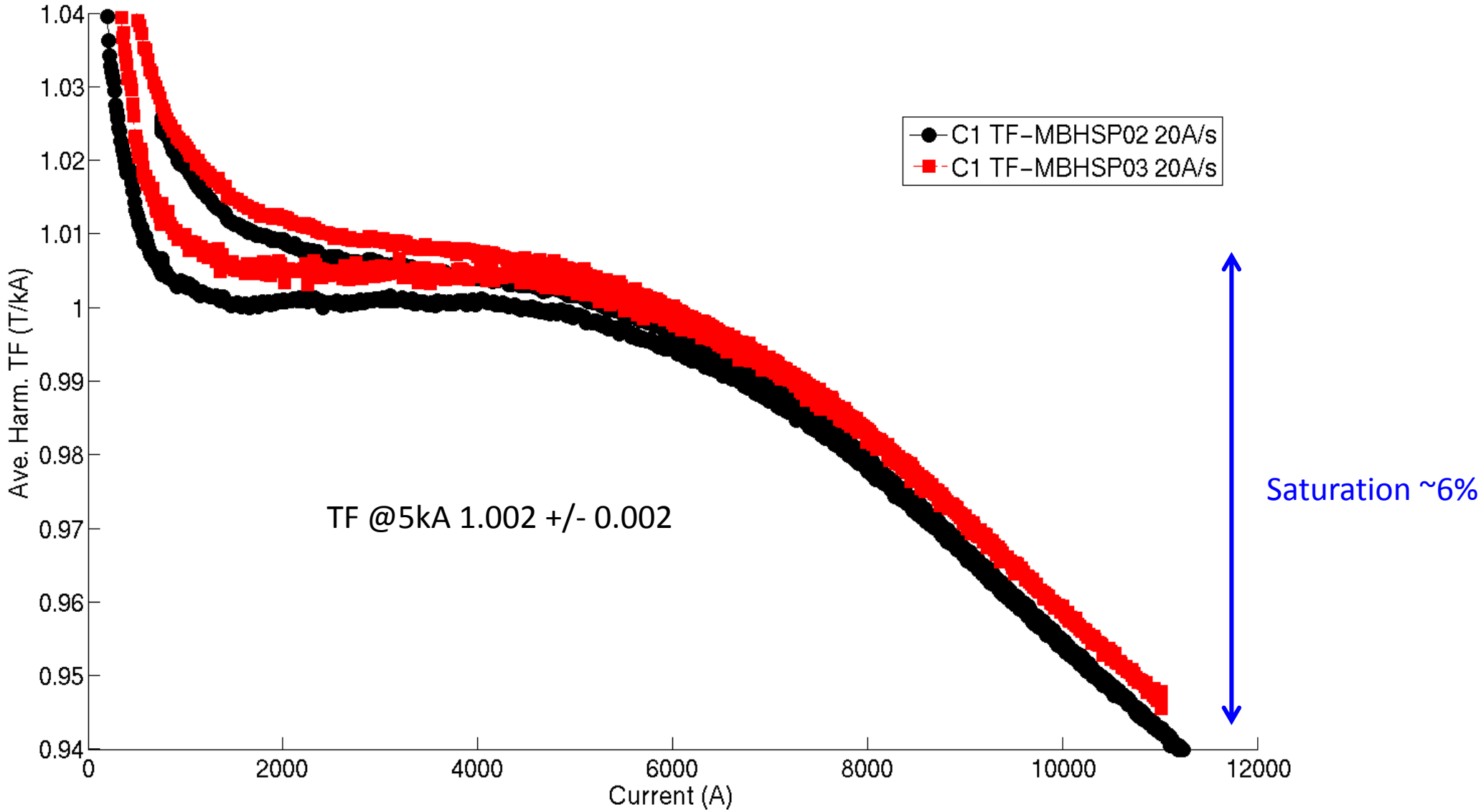




MBHSP01 has no SS core in the cable
MBHSP04 TF has no collars

➔ Will focus on MBHSP02 and MBHSP03 as representative magnets

Transfer Function



Harmonics Tables at 3kA, 1.9K
(average of upramp/downramp Stairstep data with
s.d. from axial data in the interval [-0.15, 0.15])

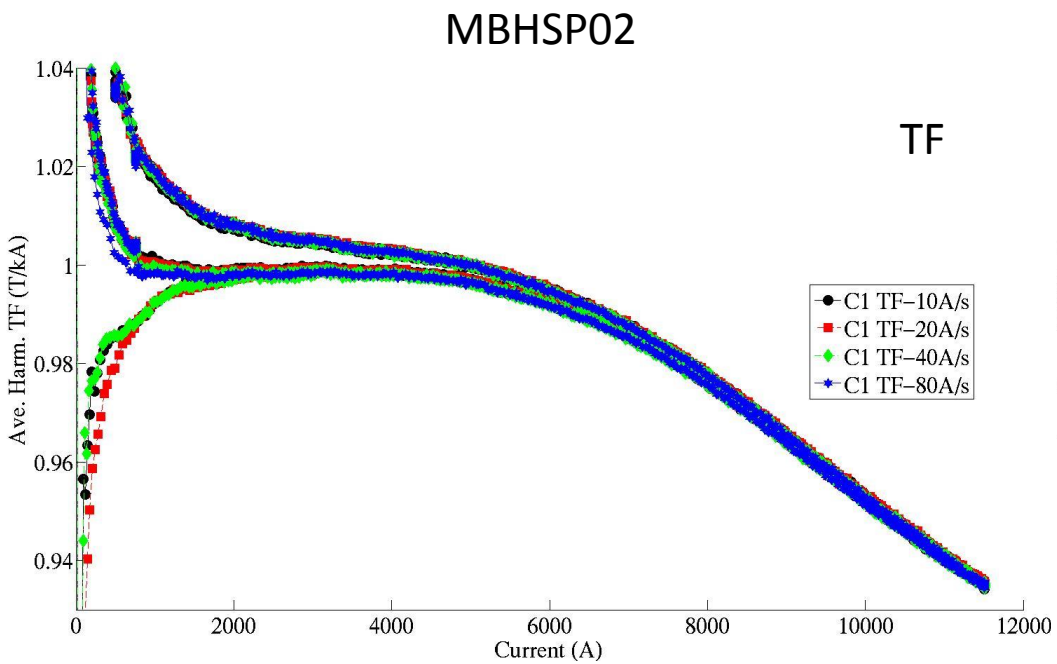
MBHSP02

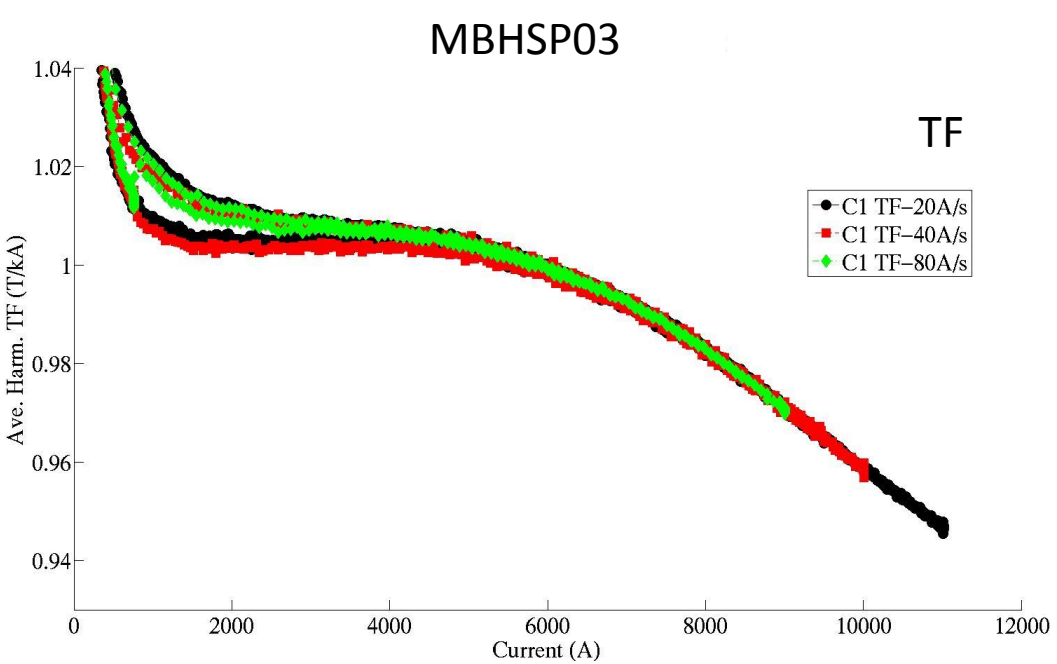
n	bn	s.d.	an	s.d.
2	-5.0	2.55	0.1	1.04
3	9.0	1.07	-1.2	0.65
4	-0.2	0.40	0.2	0.53
5	1.1	0.51	0.1	0.33
6	-0.3	0.30	0.0	0.13
7	-0.1	0.14	0.0	0.05
8	0.1	0.04	0.2	0.09
9	1.0	0.04	0.2	0.10

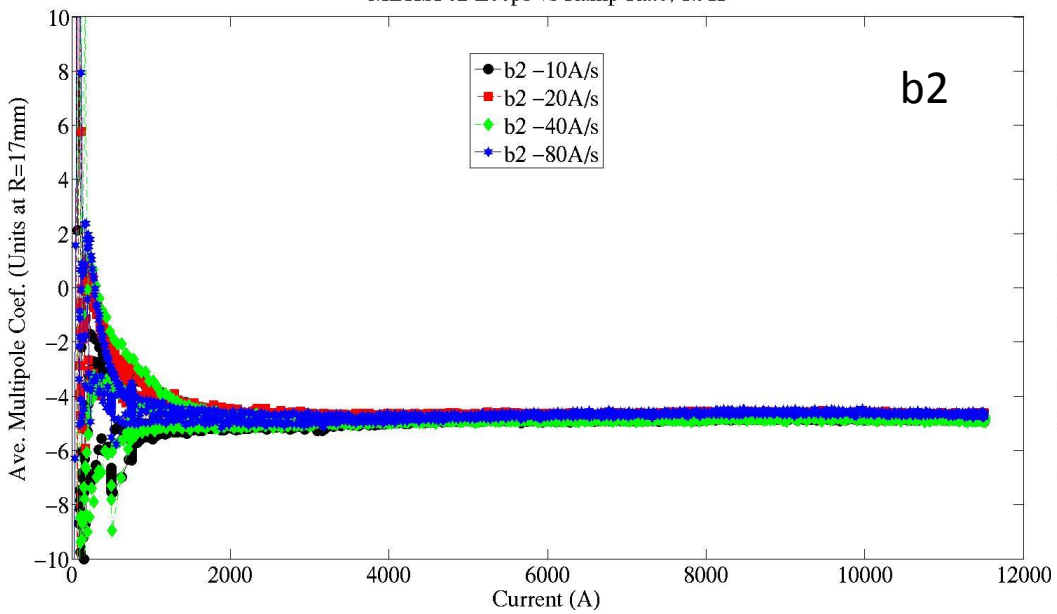
MBHSP03

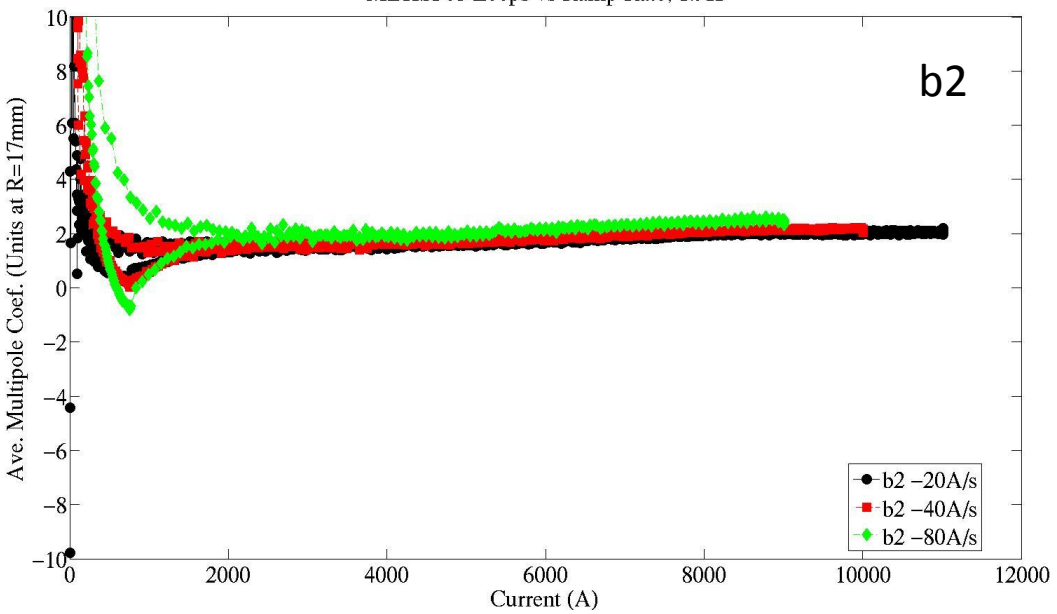
n	ave_bn	std_bn	ave_an	std_an
2	1.4	1.80	-4.6	0.39
3	16.1	2.74	2.0	1.09
4	0.1	0.18	-0.1	0.21
5	0.8	1.12	-0.1	0.57
6	-0.2	0.06	-0.3	0.05
7	0.3	0.26	0.0	0.20
8	0.0	0.07	0.1	0.06
9	1.3	0.07	0.2	0.29

Measurements vs Ramp Rate



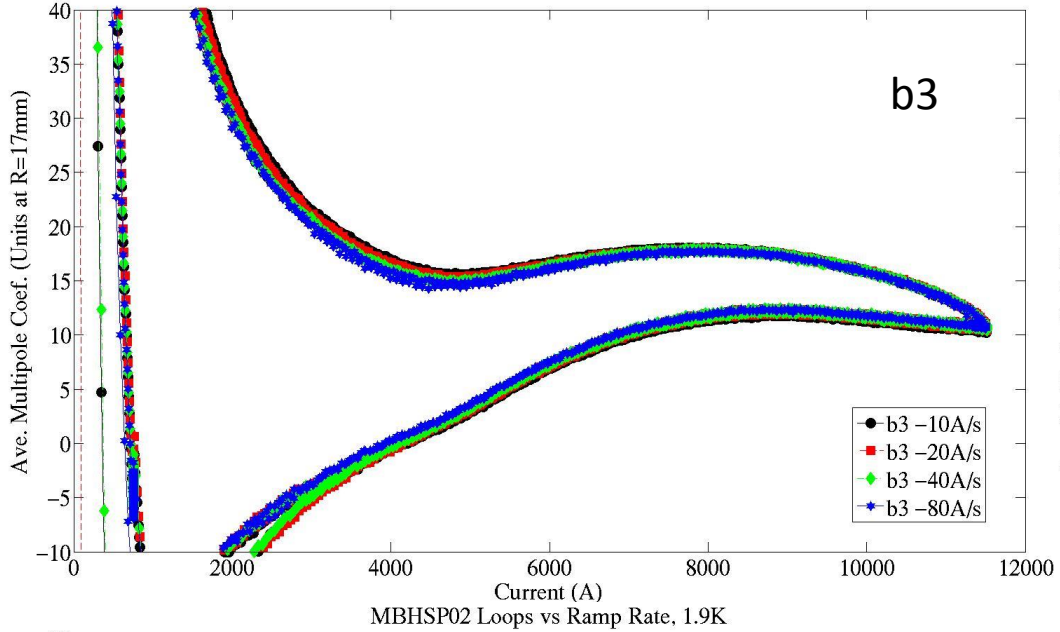




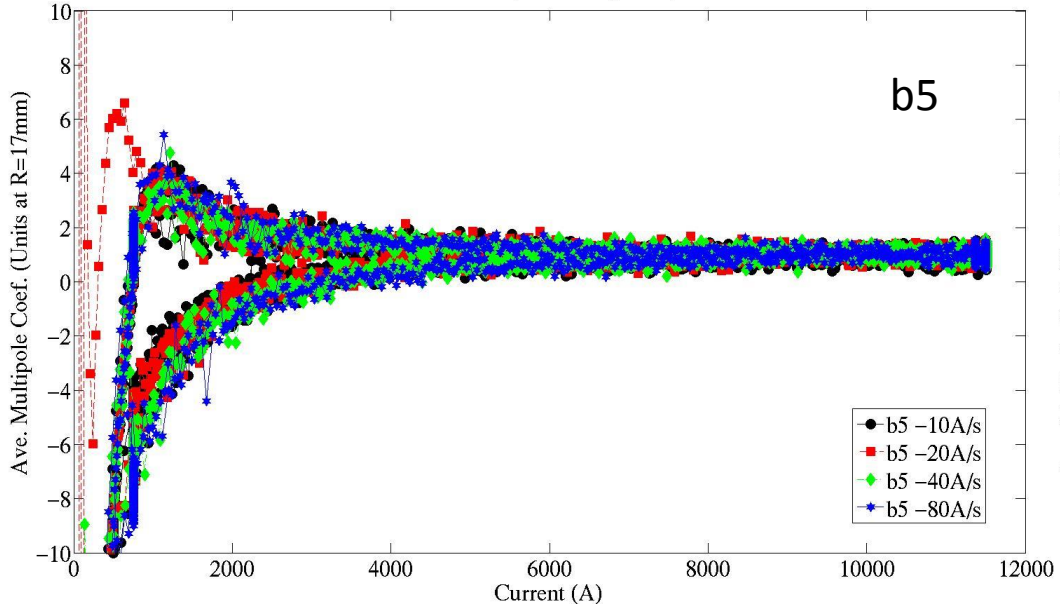


Measurements vs Ramp Rate

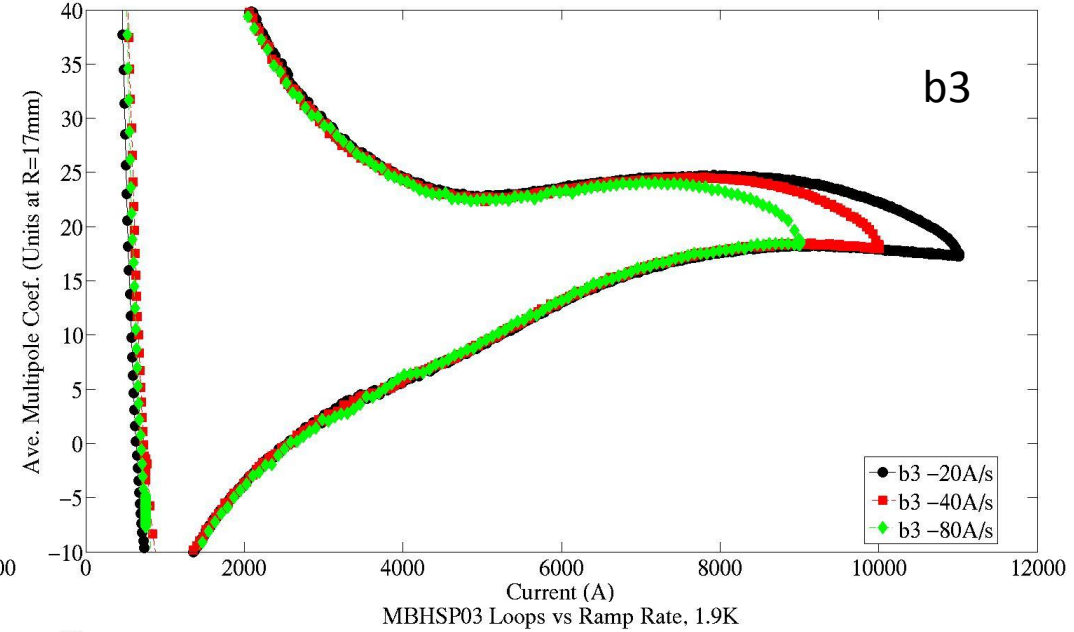
MBHSP02



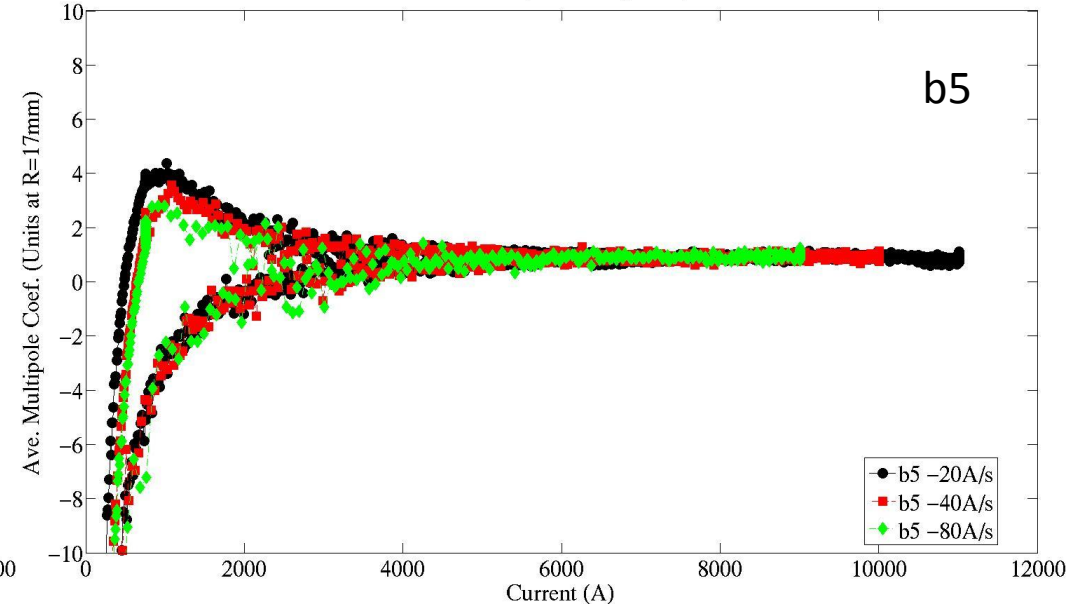
MBHSP02 Loops vs Ramp Rate, 1.9K



MBHSP03

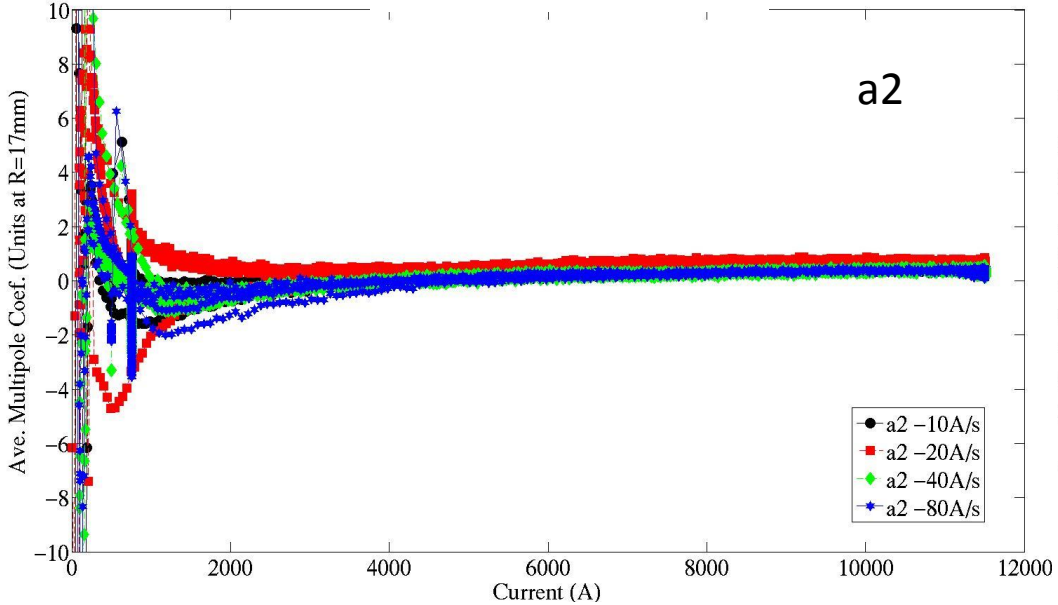


MBHSP03 Loops vs Ramp Rate, 1.9K

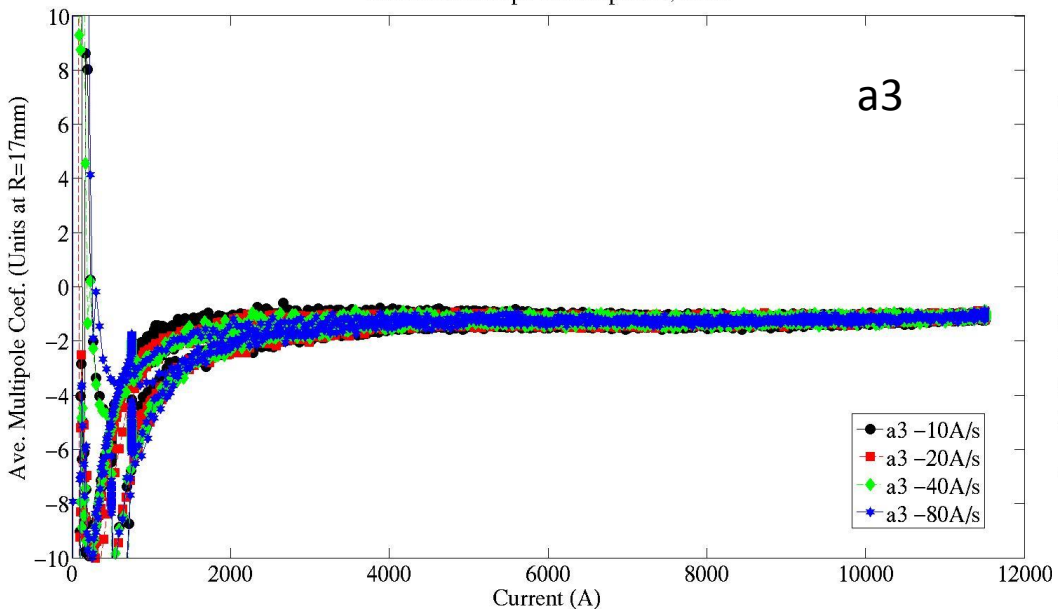


Measurements vs Ramp Rate

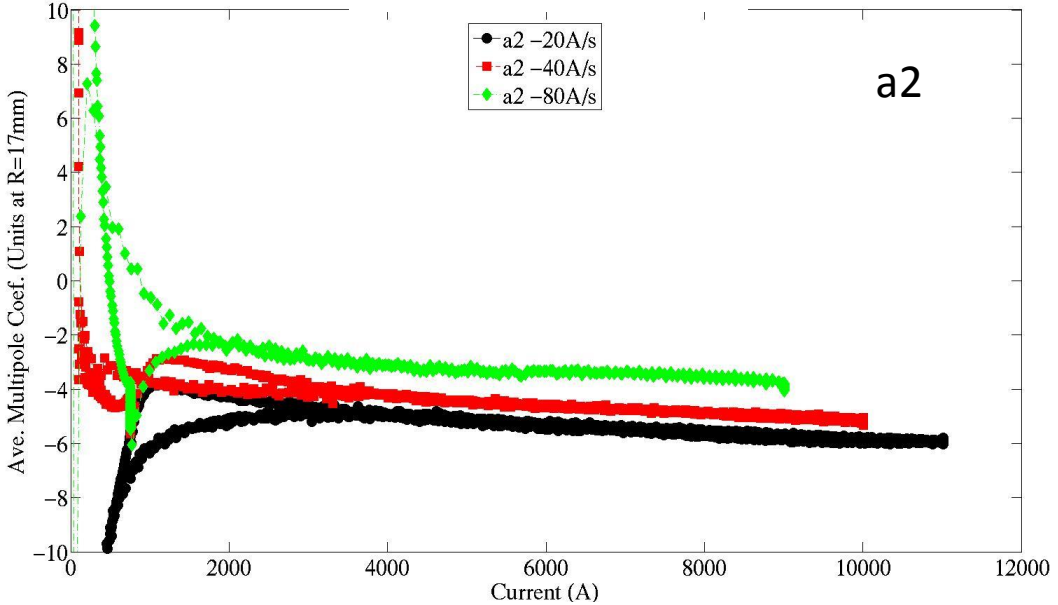
MBHSP02



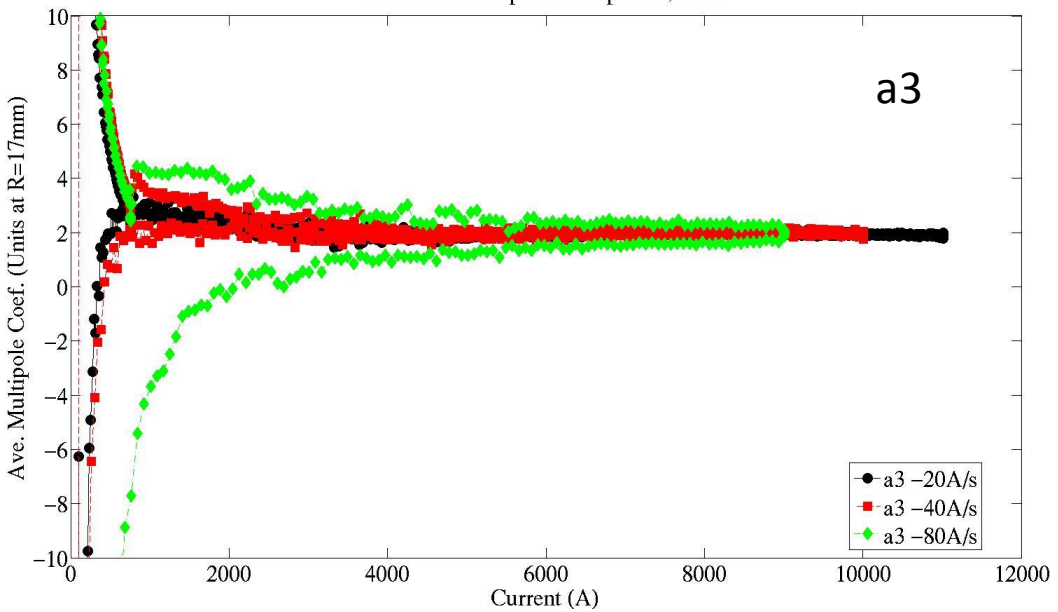
MBHSP02 Loops vs Ramp Rate, 1.9K



MBHSP03



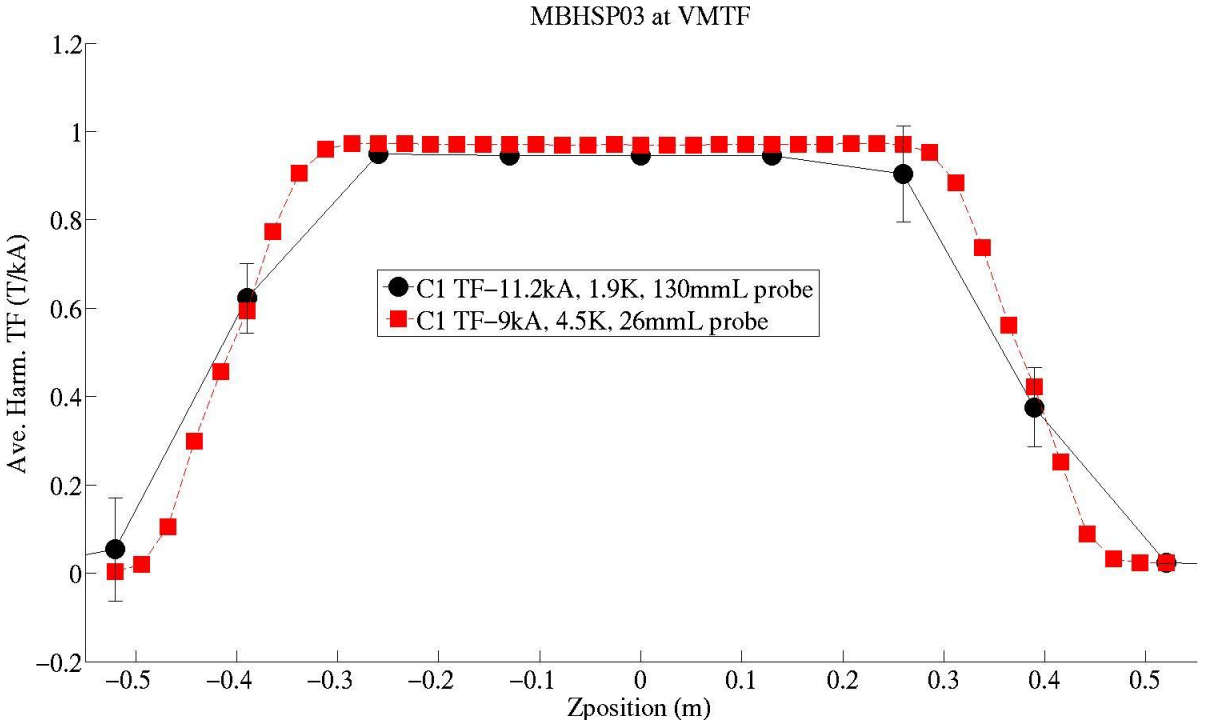
MBHSP03 Loops vs Ramp Rate, 1.9K



Measurements vs Ramp Rate

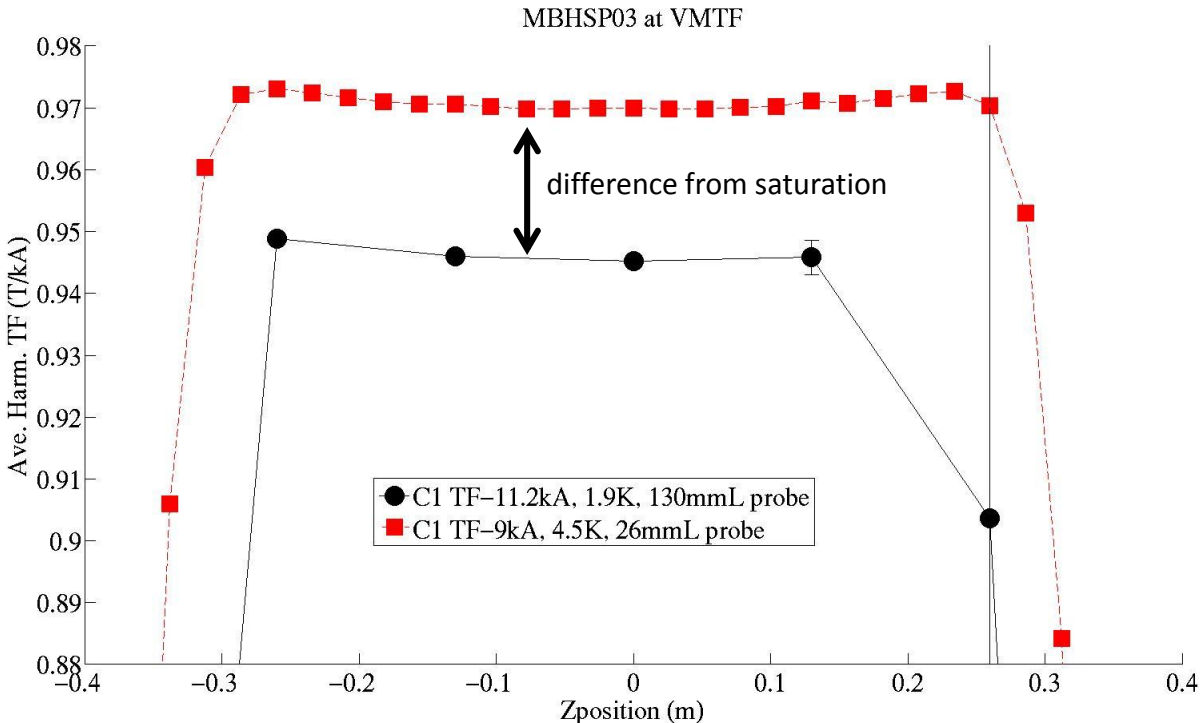
Measurements show very little change in hysteresis width as a function of ramp rate.
Largest changes at 5kA (in units) are:

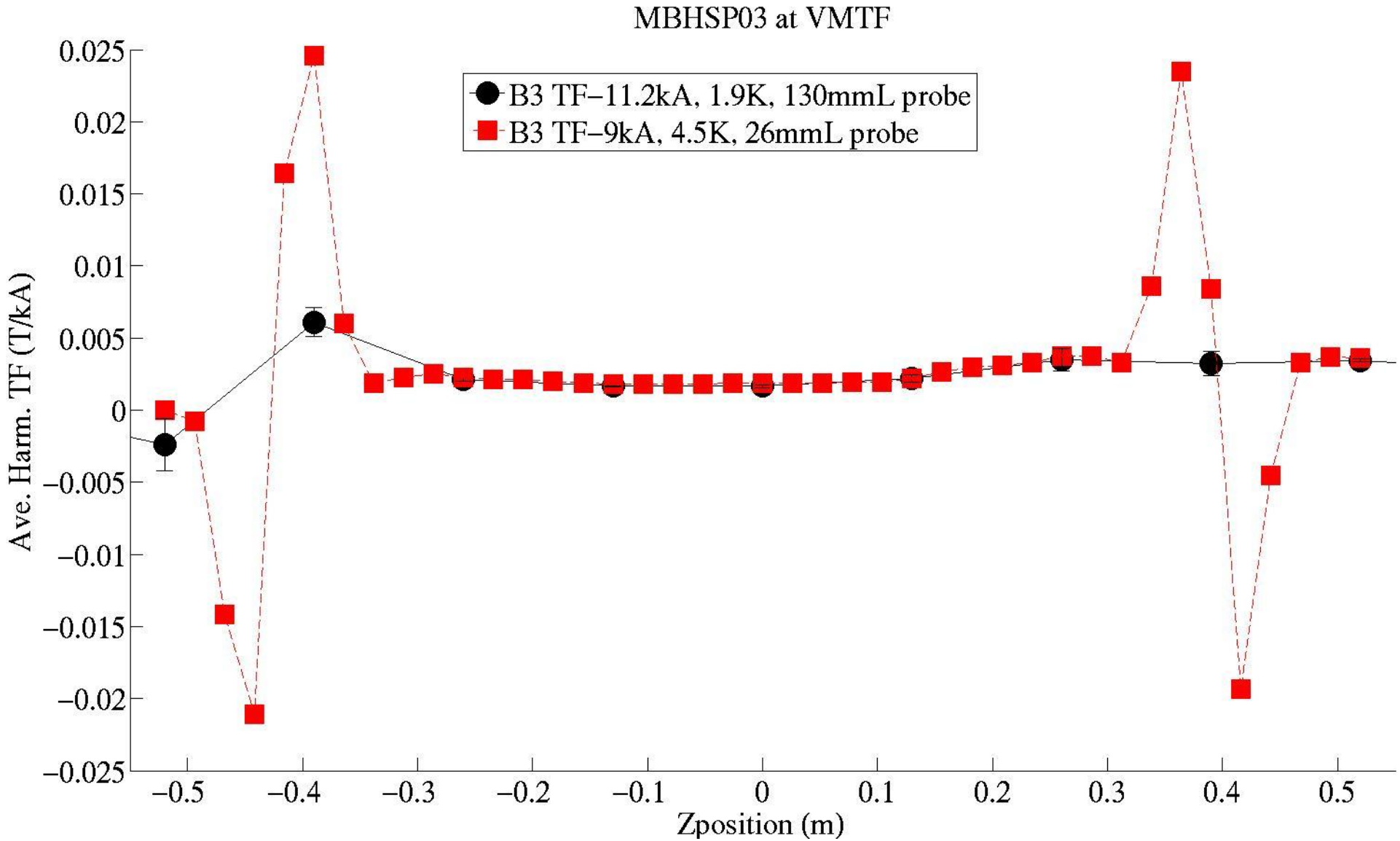
		10-20	20-40	40-80
MBHSP02_b3		0.3	0.3	0.3
MBHSP03_a3			0	1.3
MBHSP03_TF			0	-20

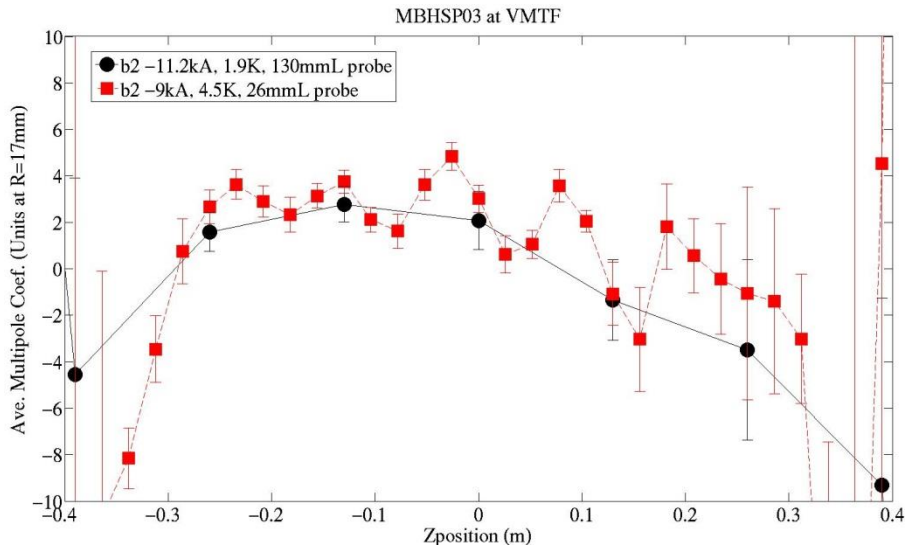


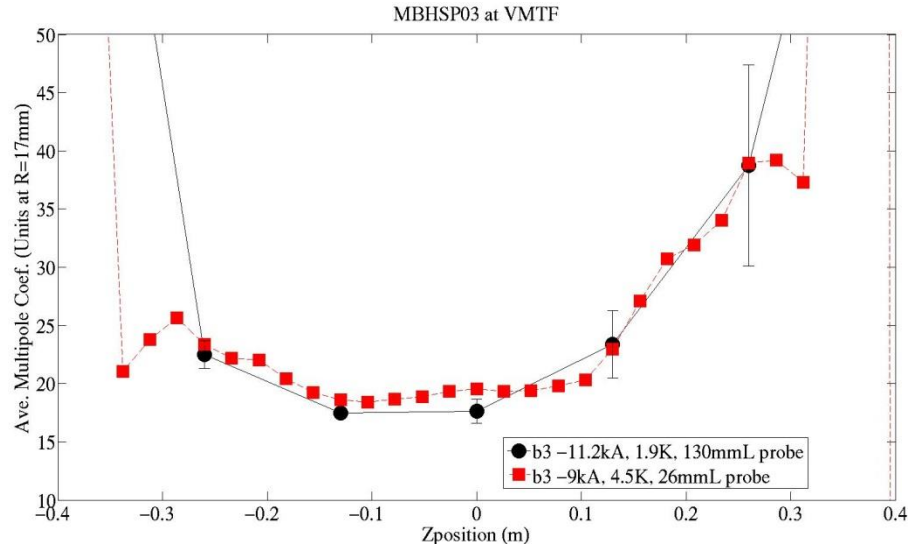
Typical Axial profile measurements (from MBHSP03)

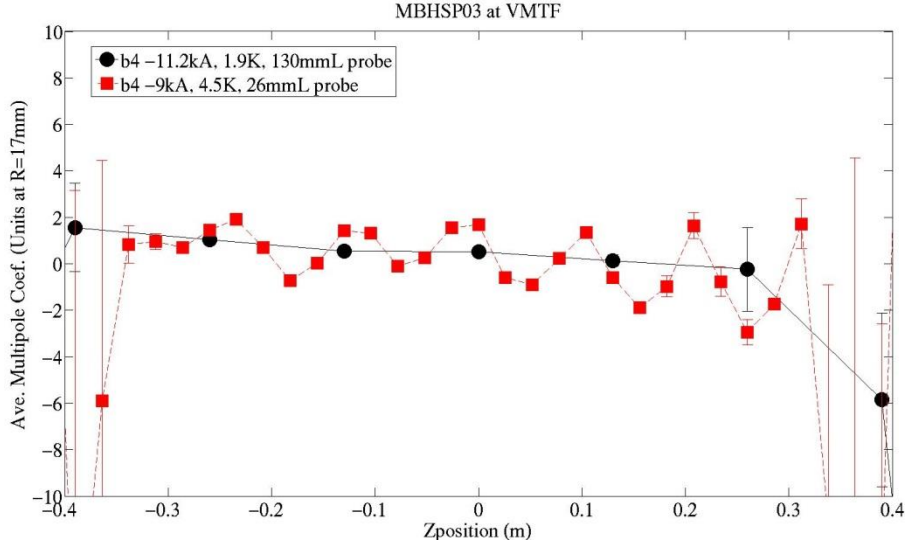
zoom of straight section

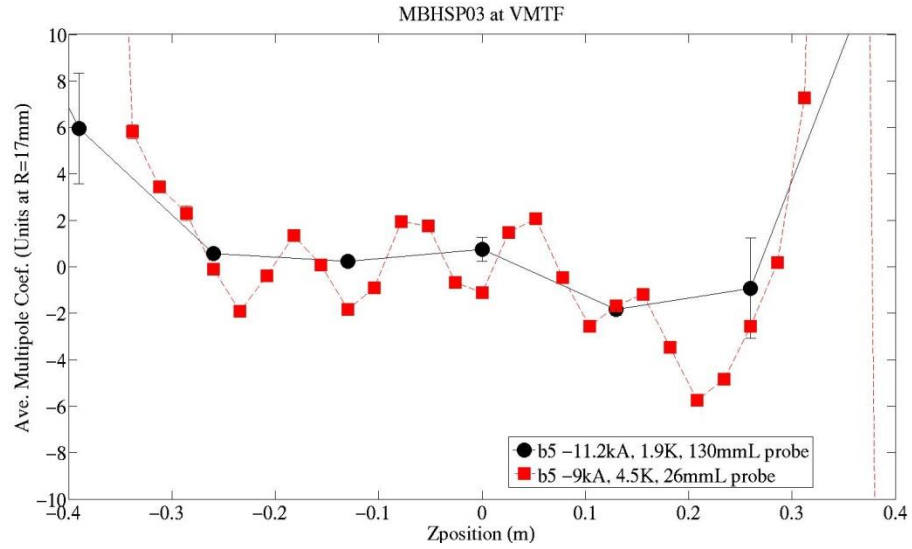


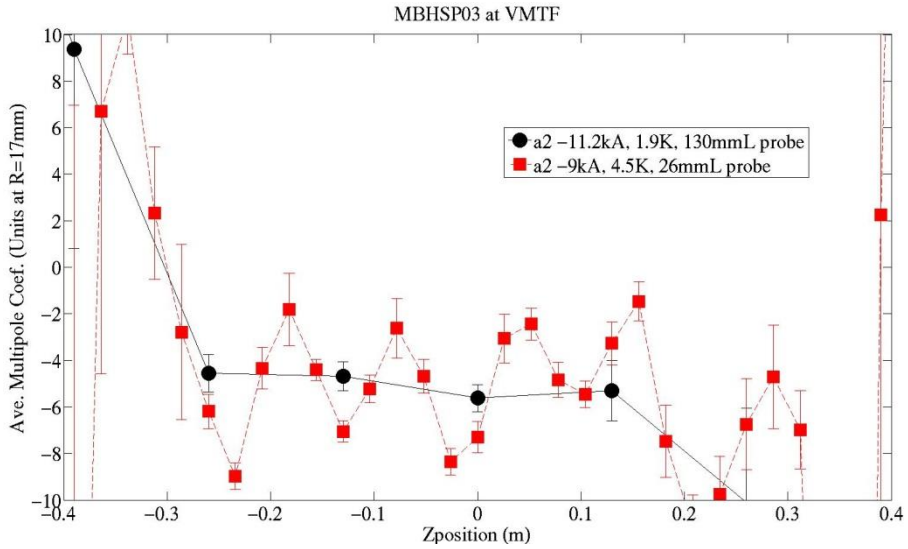

MBHSP03 at VMTF
B3 TF−11.2kA, 1.9K, 130mmL probe
B3 TF−9kA, 4.5K, 26mmL probe
Ave. Harm. TF (T/kA)
Zposition (m)
0.025
0.02
0.015
0.01
0.005
0
−0.005
−0.01
−0.015
−0.02
−0.025
−0.5
−0.4
−0.3
−0.2
−0.1
0
0.1
0.2
0.3
0.4
0.5

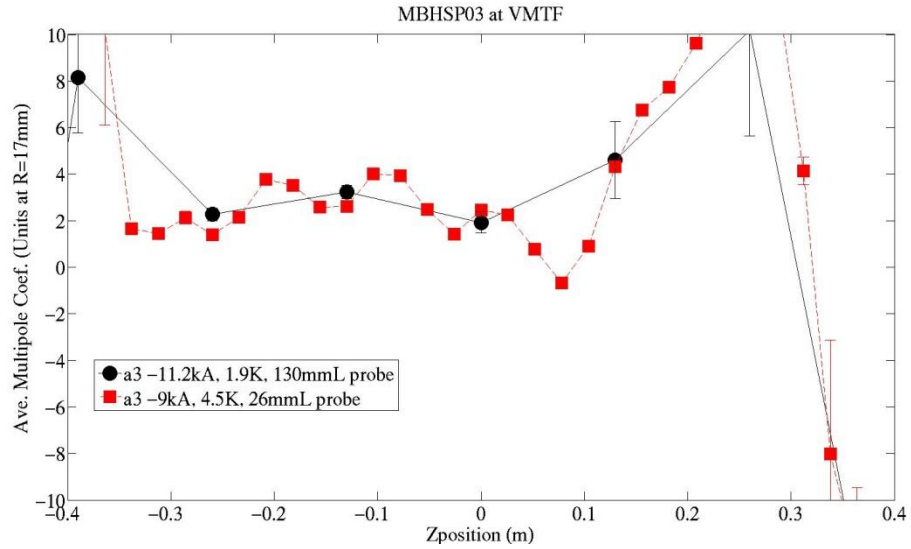

MBHSP03 at VMTF
b2 −11.2kA, 1.9K, 130mmL probe
b2 −9kA, 4.5K, 26mmL probe
Ave. Multipole Coef. (Units at R=17mm)
Zposition (m)

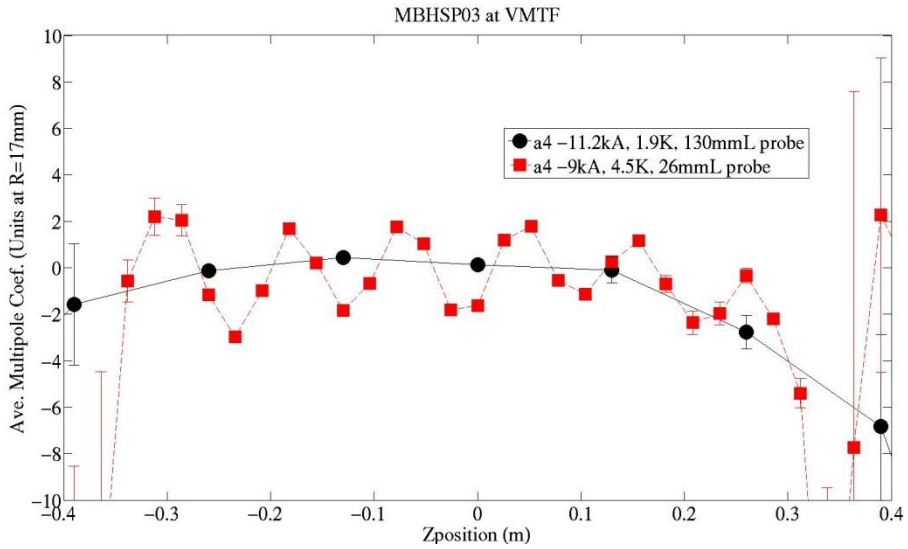

MBHSP03 at VMTF
b3 −11.2kA, 1.9K, 130mmL probe
b3 −9kA, 4.5K, 26mmL probe
Ave. Multipole Coef. (Units at R=17mm)
Zposition (m)

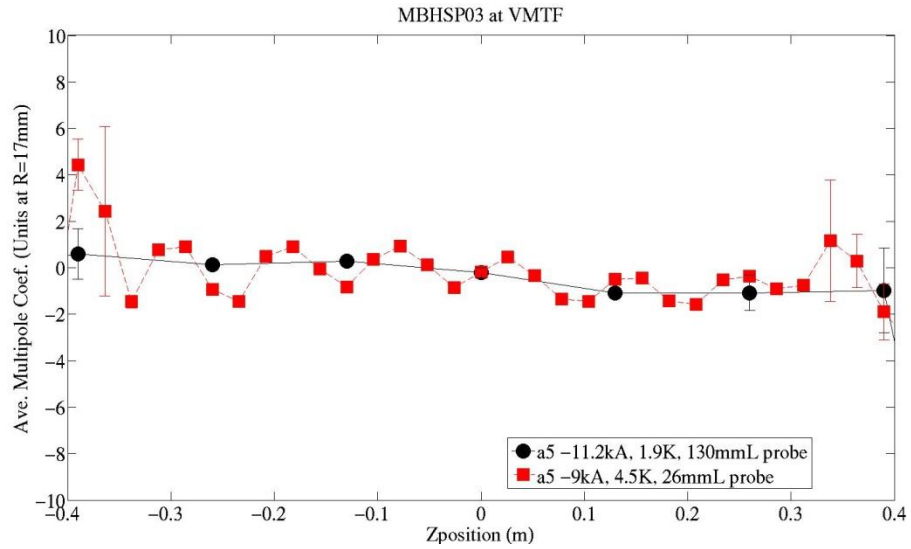

MBHSP03 at VMTF
b4 −11.2kA, 1.9K, 130mmL probe
b4 −9kA, 4.5K, 26mmL probe
Ave. Multipole Coef. (Units at R=17mm)
Zposition (m)


MBHSP03 at VMTF
b5 −11.2kA, 1.9K, 130mmL probe
b5 −9kA, 4.5K, 26mmL probe
Ave. Multipole Coef. (Units at R=17mm)
Zposition (m)

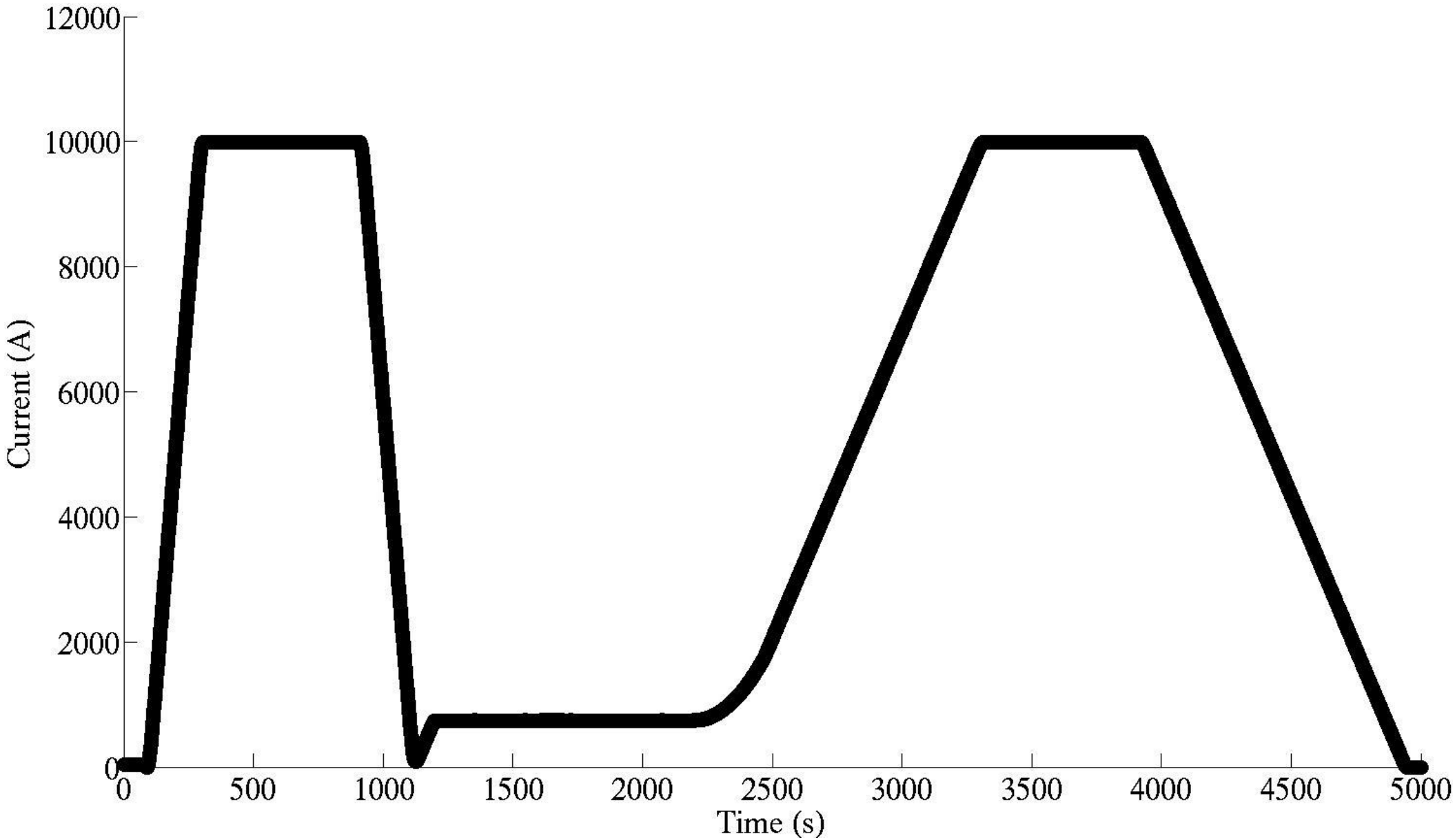

MBHSP03 at VMTF
Ave. Multipole Coef. (Units at R=17mm)
Zposition (m)
a2 −11.2kA, 1.9K, 130mmL probe
a2 −9kA, 4.5K, 26mmL probe


MBHSP03 at VMTF
Ave. Multipole Coef. (Units at R=17mm)
Zposition (m)
a3 −11.2kA, 1.9K, 130mmL probe
a3 −9kA, 4.5K, 26mmL probe

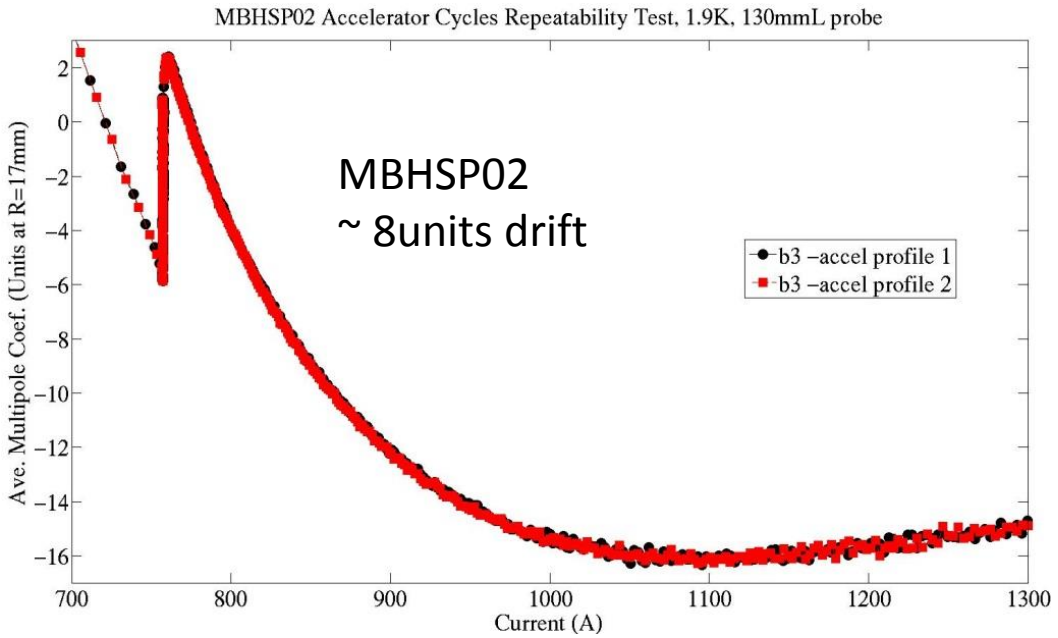

MBHSP03 at VMTF
Ave. Multipole Coef. (Units at R=17mm)
Zposition (m)
a4 −11.2kA, 1.9K, 130mmL probe
a4 −9kA, 4.5K, 26mmL probe

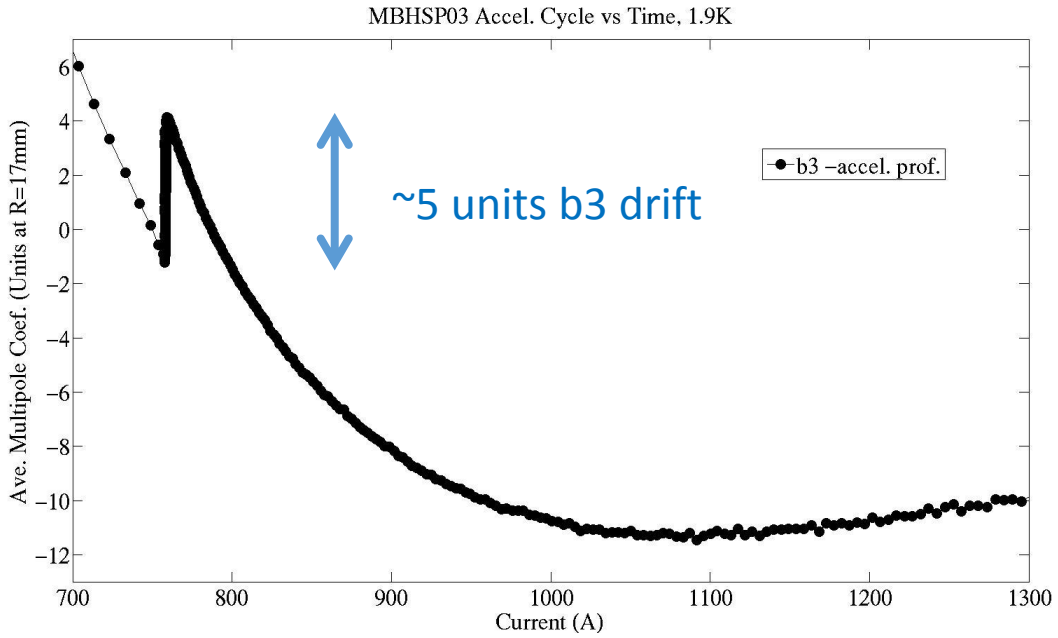

MBHSP03 at VMTF
Ave. Multipole Coef. (Units at R=17mm)
Zposition (m)
a5 −11.2kA, 1.9K, 130mmL probe
a5 −9kA, 4.5K, 26mmL probe

Sample Decay and snapback at injection (760A)– Accelerator Cycle (MBHSP04)

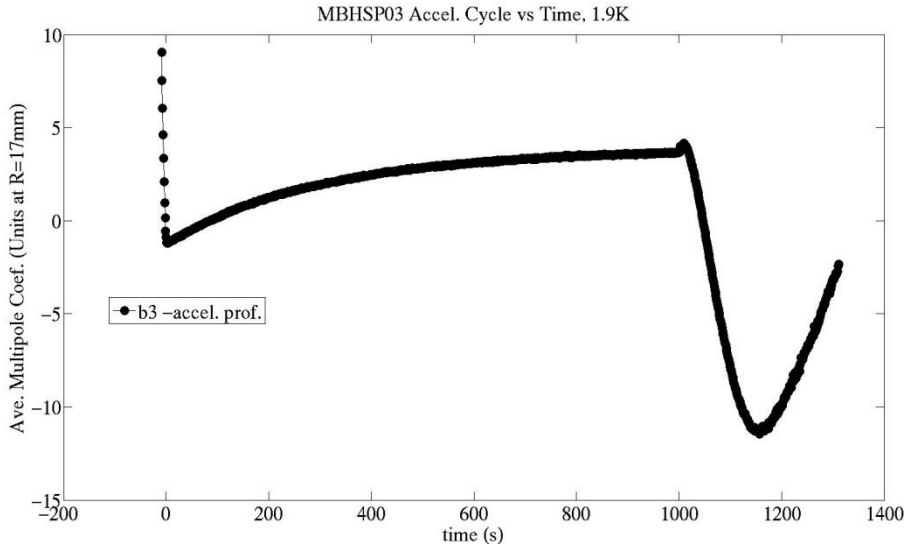


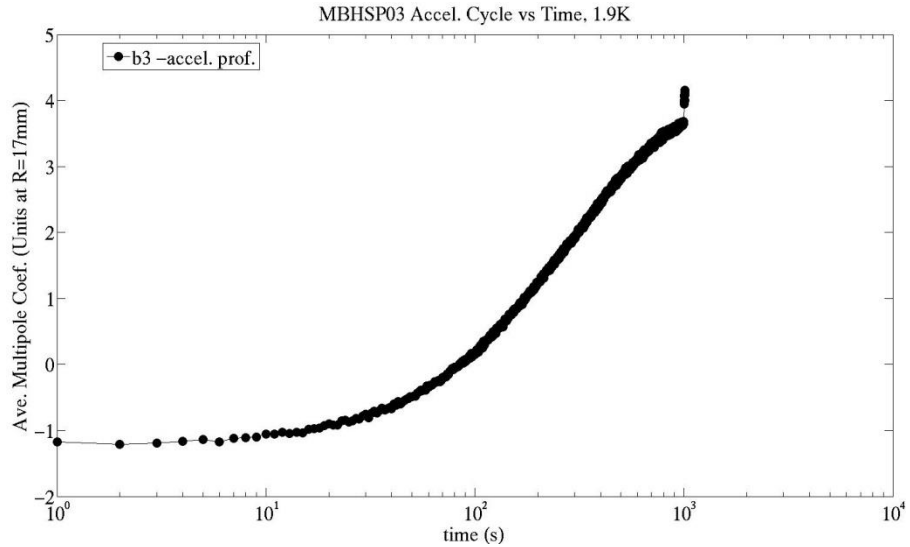
Decay and snapback at injection (760A)– Accelerator Cycle

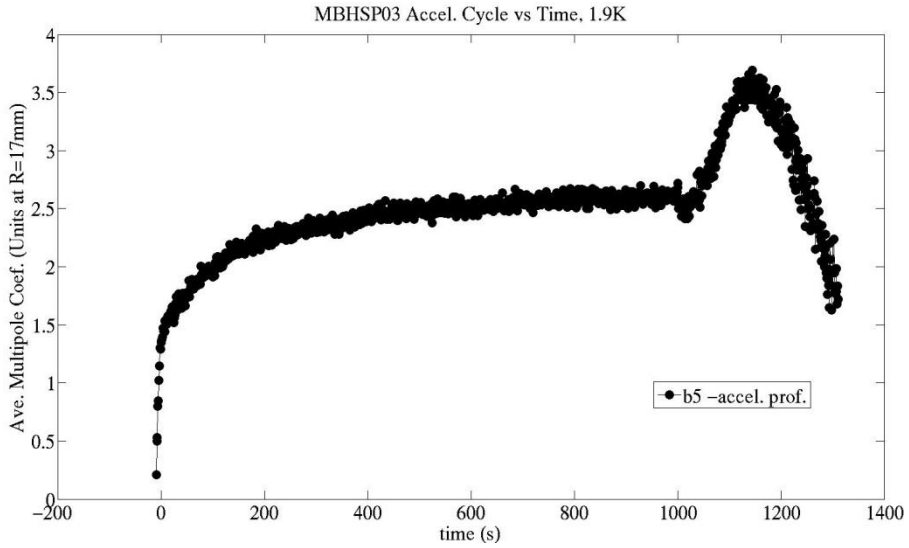


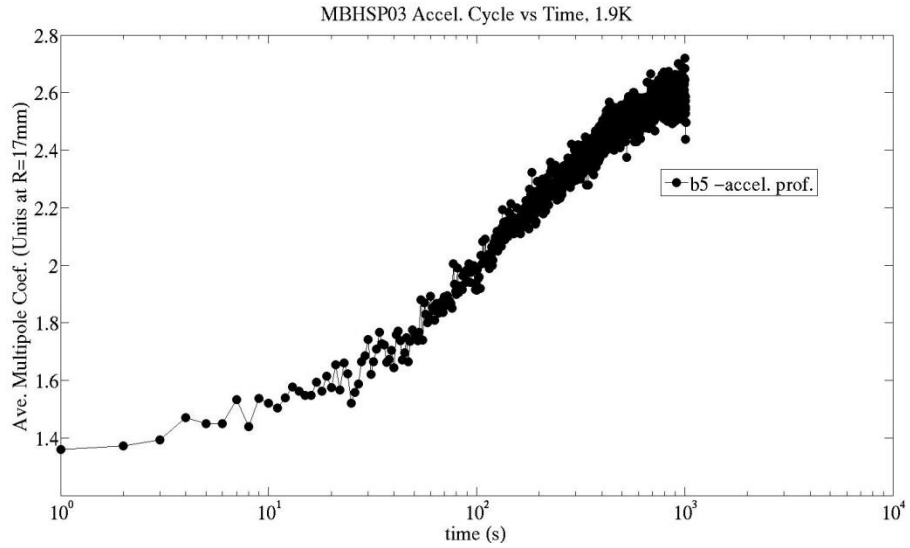


MBHSP03 harmonics at injection vs. Time

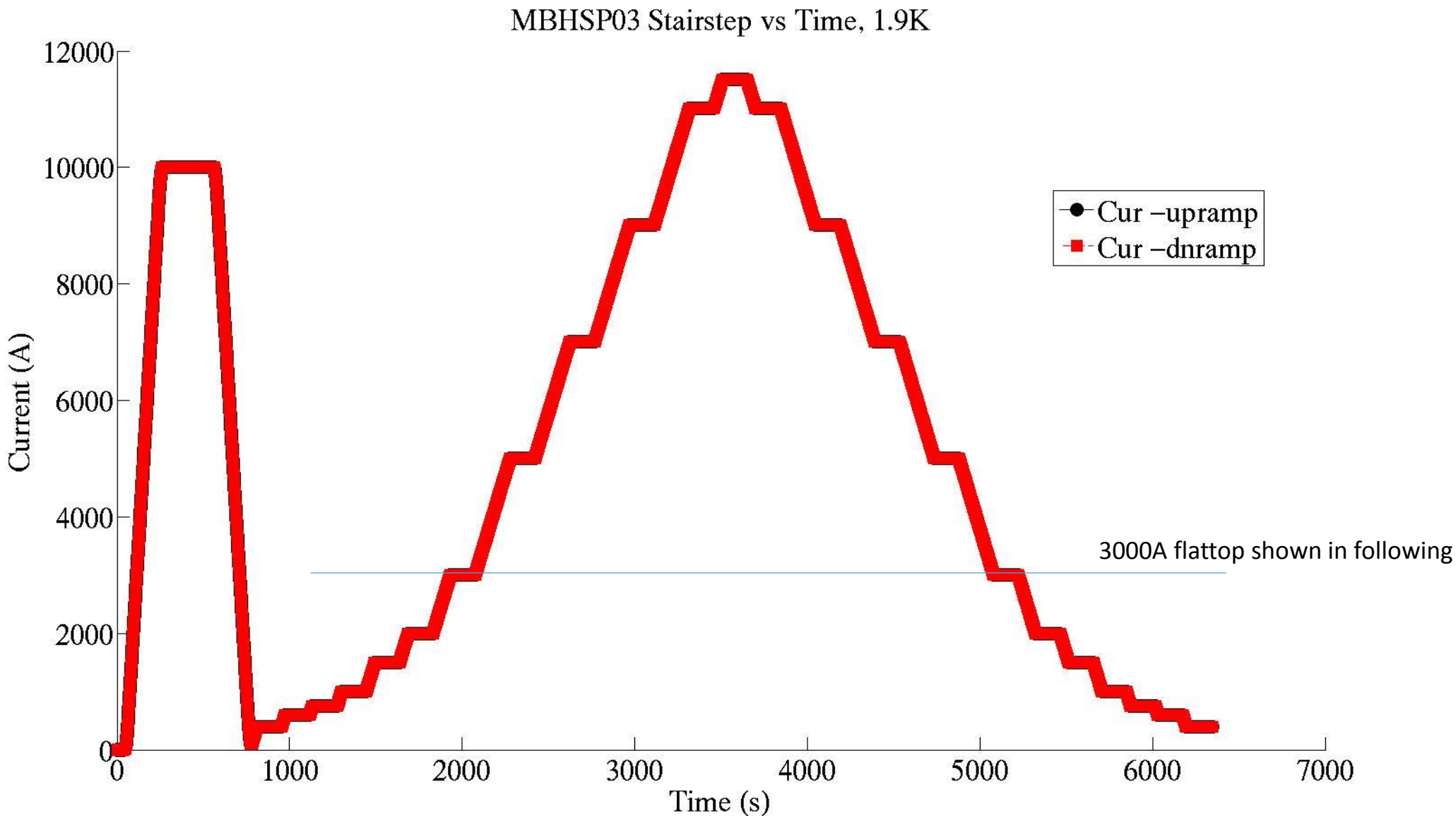






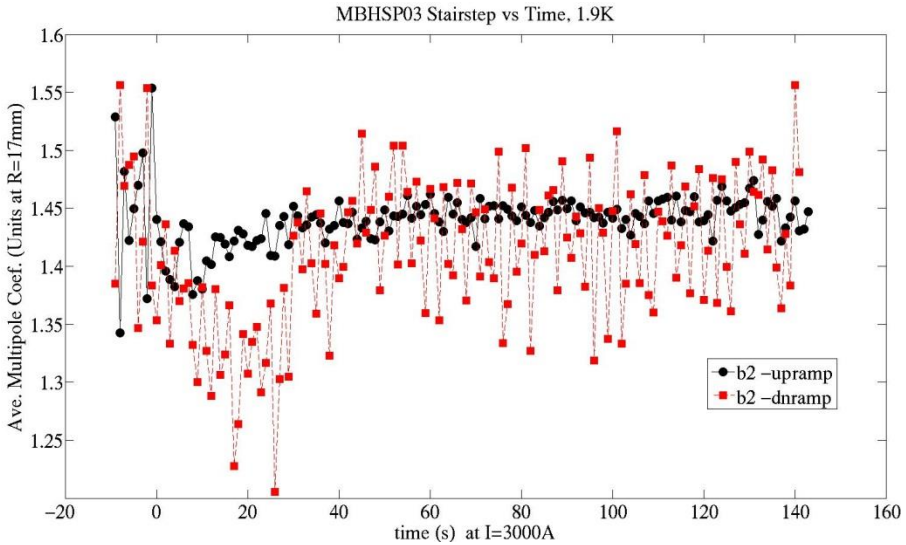


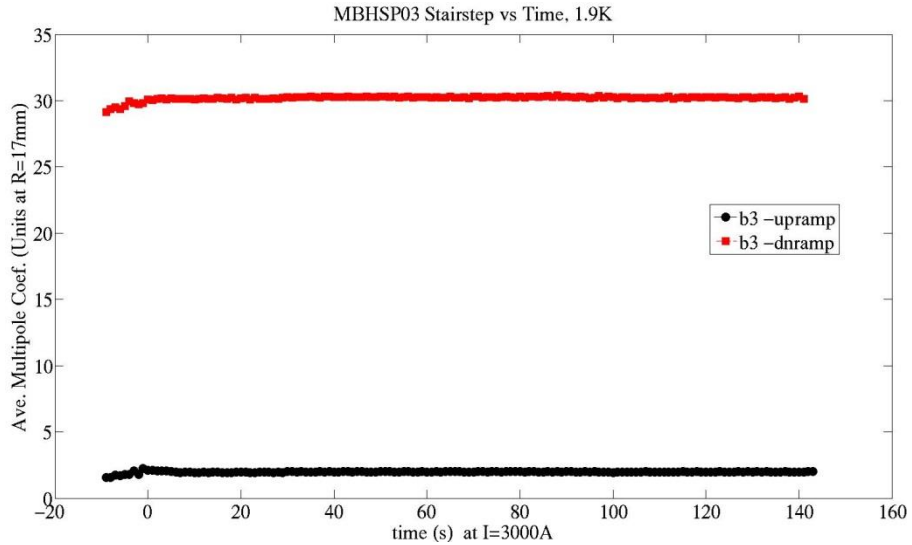
Stairstep at various currents

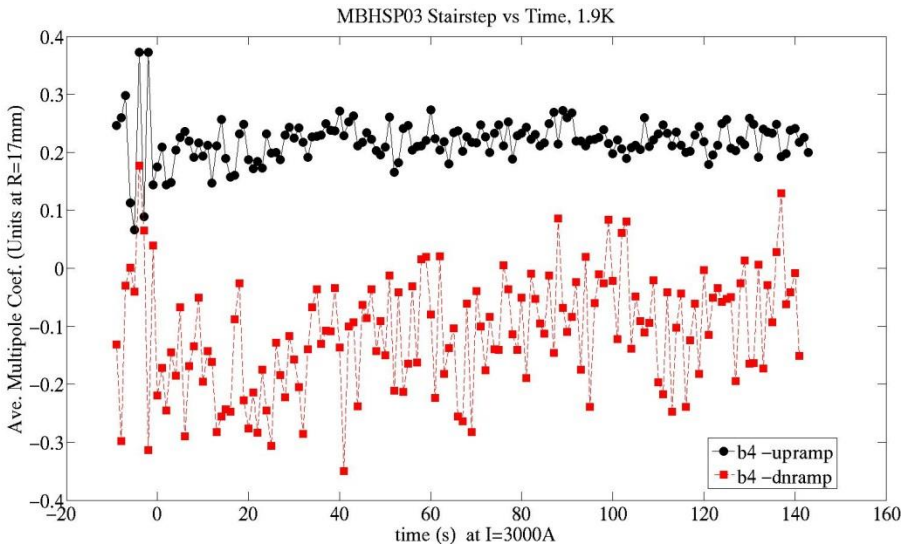


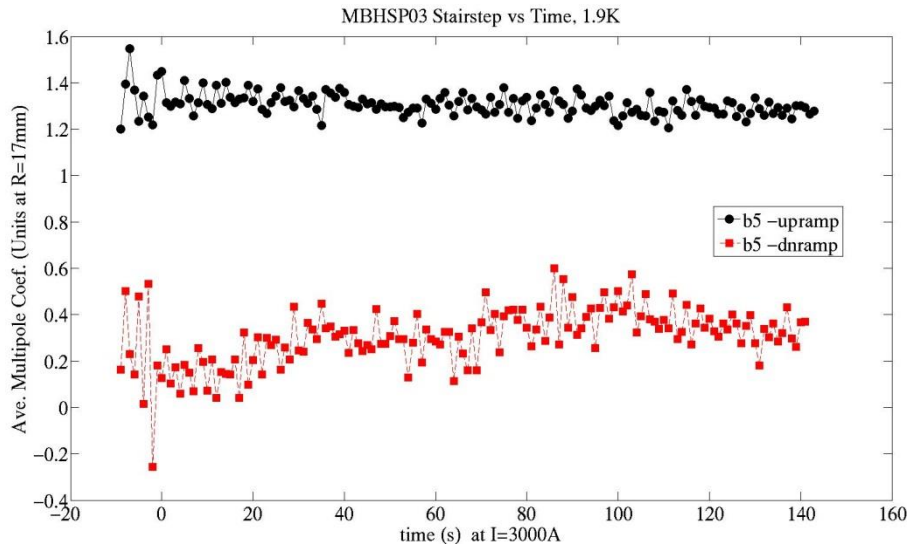
3000A flattop shown in following

Stairstep Meas at 3kA - bn

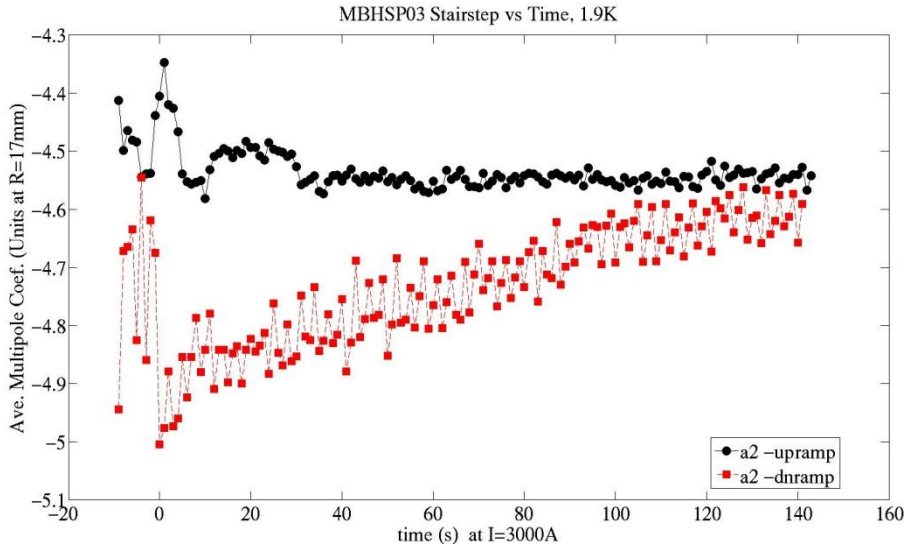


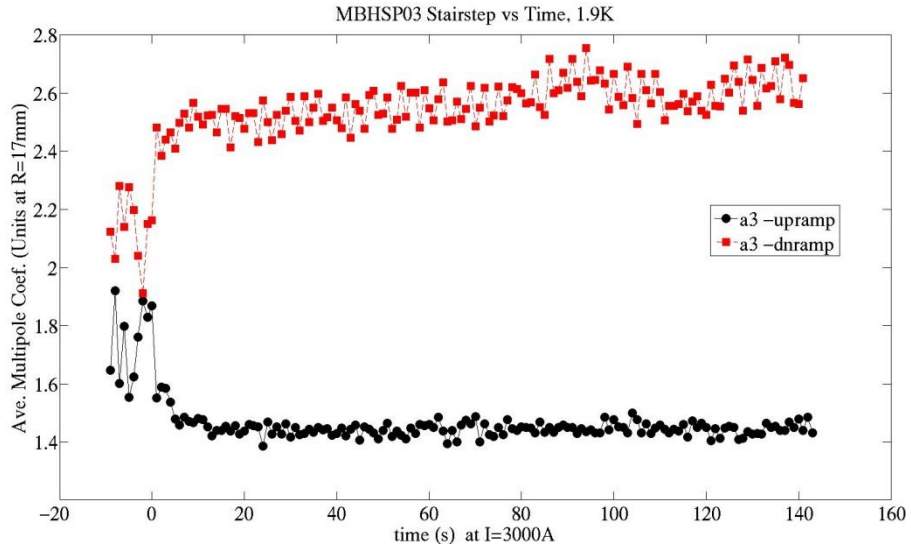


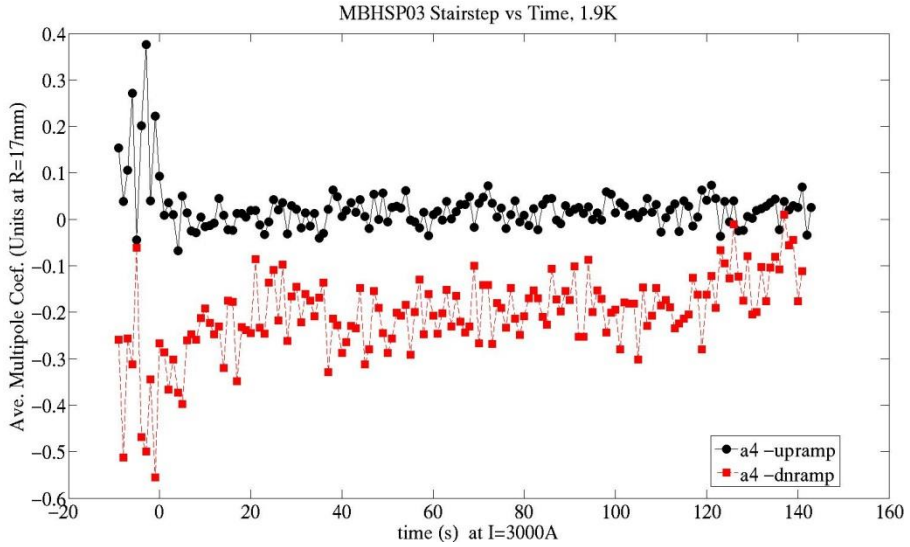


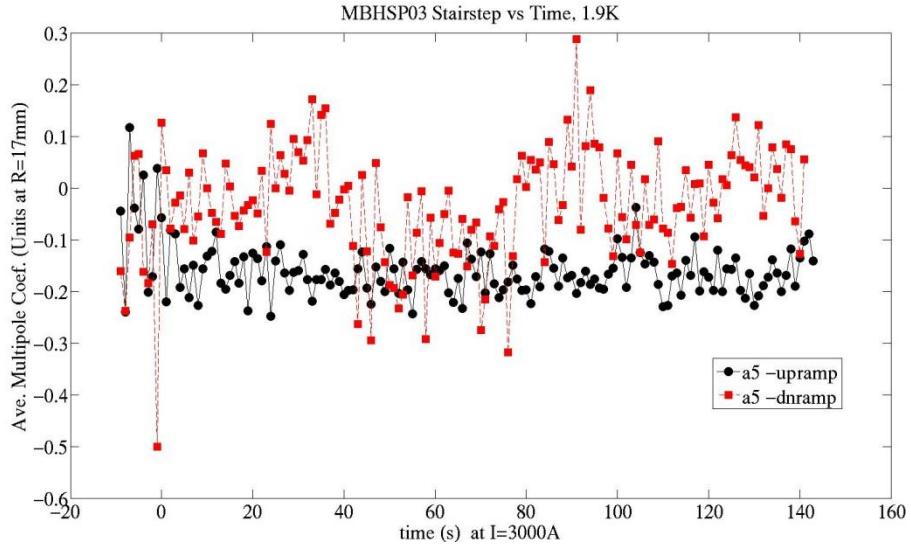


Stairstep Meas at 3kA – an









Stairstep Meas Up/Down averages

MBHSP02

Cur	TF(T/kA)	bn2	bn3	bn4	bn5	an2	an3	an4	an5
760	1.012	3.603	50.382	-0.265	-0.341	6.936	-2.126	-0.355	0.166
1000	1.008	-0.146	28.875	0.228	1.197	4.108	-1.697	0.336	-0.035
1500	1.004	-2.24	16.479	0.176	1.389	2.238	-1.506	0.49	-0.105
3000	1.003	-3.501	8.878	0.136	1.018	1.012	-1.112	0.437	0.046
5000	1	-3.338	9.183	0.151	0.978	1.4	-1.001	0.53	0.114
7000	0.988	-2.528	13.699	0.166	0.894	1.931	-1.035	0.457	0.172
9000	0.967	-2.341	14.469	0.184	0.942	2.084	-1.017	0.464	0.199

MBHSP03

Cur	TF(T/kA)	bn2	bn3	bn4	bn5	an2	an3	an4	an5
760	1.019	0.851	57.275	-1.28	-0.681	-6.169	4.185	-1.351	0.083
1000	1.015	0.832	36.484	-0.76	0.733	-4.967	3.219	-0.932	-0.015
1500	1.01	1.147	23.747	-0.281	1.015	-4.397	2.556	-0.342	0.031
3000	1.007	1.425	16.084	0.054	0.806	-4.633	2.002	-0.092	-0.097
5000	1.004	1.558	15.95	0.244	0.893	-4.816	1.846	0.032	-0.145
7000	0.993	1.731	20.149	0.3	0.865	-5.097	1.931	0.104	-0.156
9000	0.972	1.901	21.145	0.345	0.908	-5.371	1.931	0.12	-0.164

Stairstep Meas Up/Down Hystersis Width

MBHSP02

Cur	TF(T/kA)	bn2	bn3	bn4	bn5	an2	an3	an4	an5
760	0.03	16.136	103.295	-0.766	-4.613	13.101	-0.257	-2.438	0.215
1000	0.023	14.738	91.024	-1.308	-5.819	11.571	-0.971	-2.271	0.457
1500	0.016	10.181	60.789	-0.839	-3.816	8.07	-0.927	-1.446	0.324
3000	0.007	4.489	26.644	-0.13	-1.031	3.411	-0.441	-0.446	0.211
5000	0.004	2.171	13.155	0.018	-0.205	1.825	-0.269	-0.122	0.049
7000	0.003	1.253	8.178	0.096	0.039	1.43	-0.187	-0.014	0.022
9000	0.002	0.803	5.621	0.096	0.092	1.157	-0.123	0.045	0.02

MBHSP03

Cur	TF(T/kA)	bn2	bn3	bn4	bn5	an2	an3	an4	an5
760	0.022	0.56	113.444	-1.093	-5.958	-0.697	3.682	0.778	-0.041
1000	0.019	0.443	96.281	-0.932	-5.865	-1.373	3.094	0.006	-0.175
1500	0.015	0.383	63.819	-0.702	-3.854	-0.848	2.193	-0.02	0.077
3000	0.007	-0.029	28.218	-0.331	-1.003	-0.196	1.069	-0.229	0.127
5000	0.004	0	14.168	-0.178	-0.274	0.221	0.471	-0.19	0.016
7000	0.003	-0.002	8.819	-0.122	0.013	0.177	0.293	-0.208	-0.029
9000	0.002	-0.006	6.064	-0.086	0.08	0.081	0.183	-0.153	-0.029

Warm/Cold Correlation