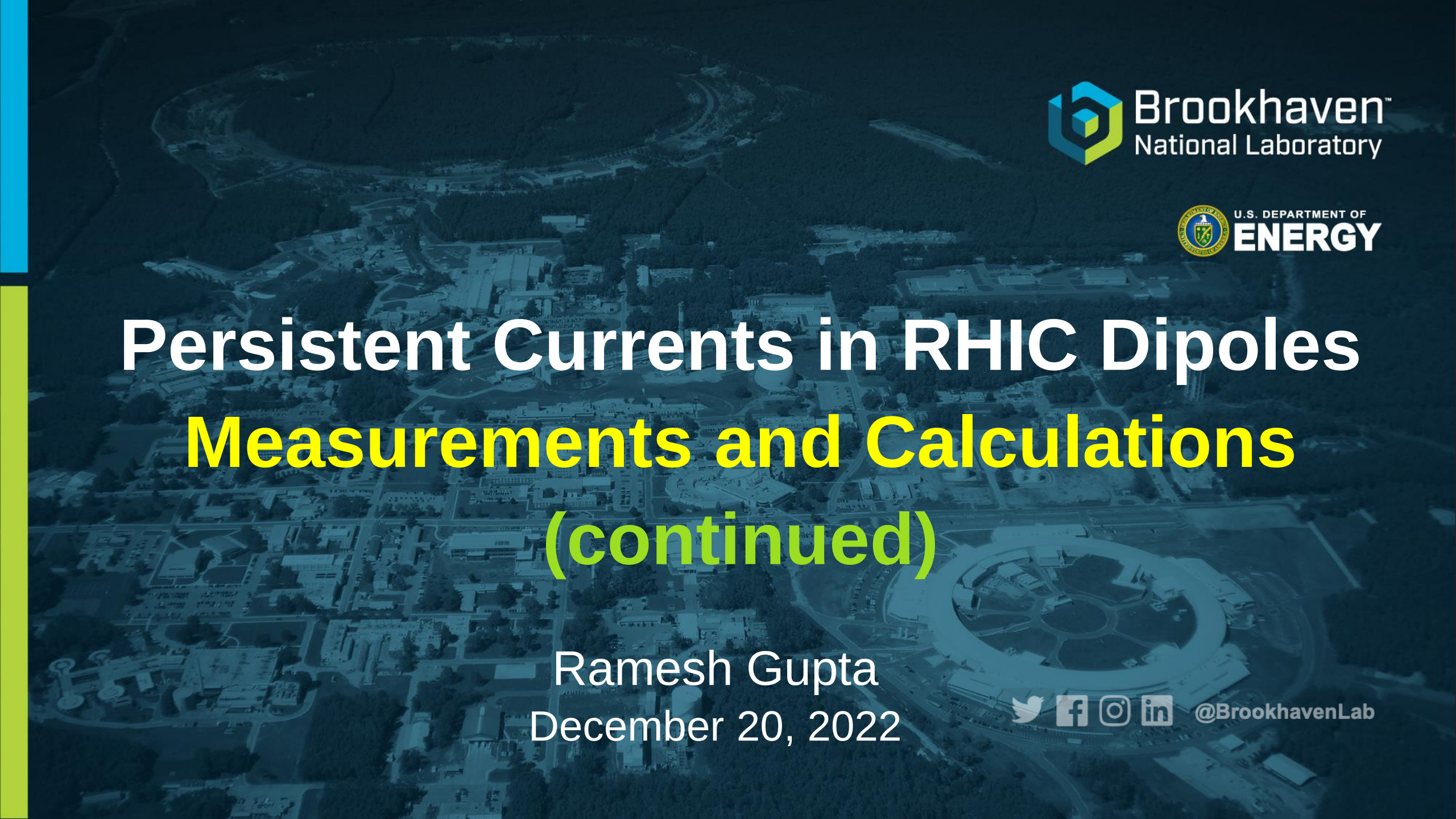


Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Persistent Currents in RHIC Dipoles

Measurements and Calculations (continued)

Ramesh Gupta

December 20, 2022

@BrookhavenLab

Introduction

- Modelling of superconductor properties for persistent current calculations
  - ➢ Morgan curves (used in RHIC/SSC designs)
  - ➢ Bottura curves (used in ROXIE)
  - ➢ Several email exchanges with Luca Bottura on converting one to another
- Impact of previous cycles on RHIC dipole (calculations and measurements)

Bottura Fitting and Morgan Fitting

A Practical Fit for the Critical Surface of NbTi

L. Bottura
CERN, LHC Division, 1211 Geneva 23, Switzerland

***Abstract*—Known expressions for the critical temperature, critical field and Pinning force in NbTi are combined into a self-consistent fit formula that provides the critical current density** strain. The function chosen here for the fit of surface as a function of the reduced parameters given by:

Author: G. Morgan

Date: January 6, 1997

No: 560-1 (RHIC-MD-261)

Task Force: Coil Geometry Analysis

Title: A New Critical Surface for RHIC NbTi

Bottura - From [1] with $B_{c2}(T) = B_{c20}(1-(T/T_{c0})^{1.7})$,

$$J_c(B,T) = \frac{J_{c,\mathrm{ref}}\, C_0 B^{\alpha-1}}{(B_{c2}(T))^{\alpha}} \left(1-\frac{B}{B_{c2}(T)}\right)^{\beta} \left(1-\left(\frac{T}{T_{c0}}\right)^{1.7}\right)^{\gamma}$$

$$F_p = C_1 \cdot B_{C2}^{m}(T) \cdot (B/B_{C2})^{p} \cdot (1 - B/B_{C2}(T))^{q}$$

$$F_p = J_C B, \qquad B_{C2} = B_{C0} \cdot (1 - (T/T_C)^{E})$$

C_1	m	p	q	B_{C0}	T_C	E
106.13	1.73	0.948	1.000	14.45	8.66	1.61

Jc = C1 . Bc2(T) ^m . B^(p-1) / Bc2 ^p . (1-B/Bc2(T))^q

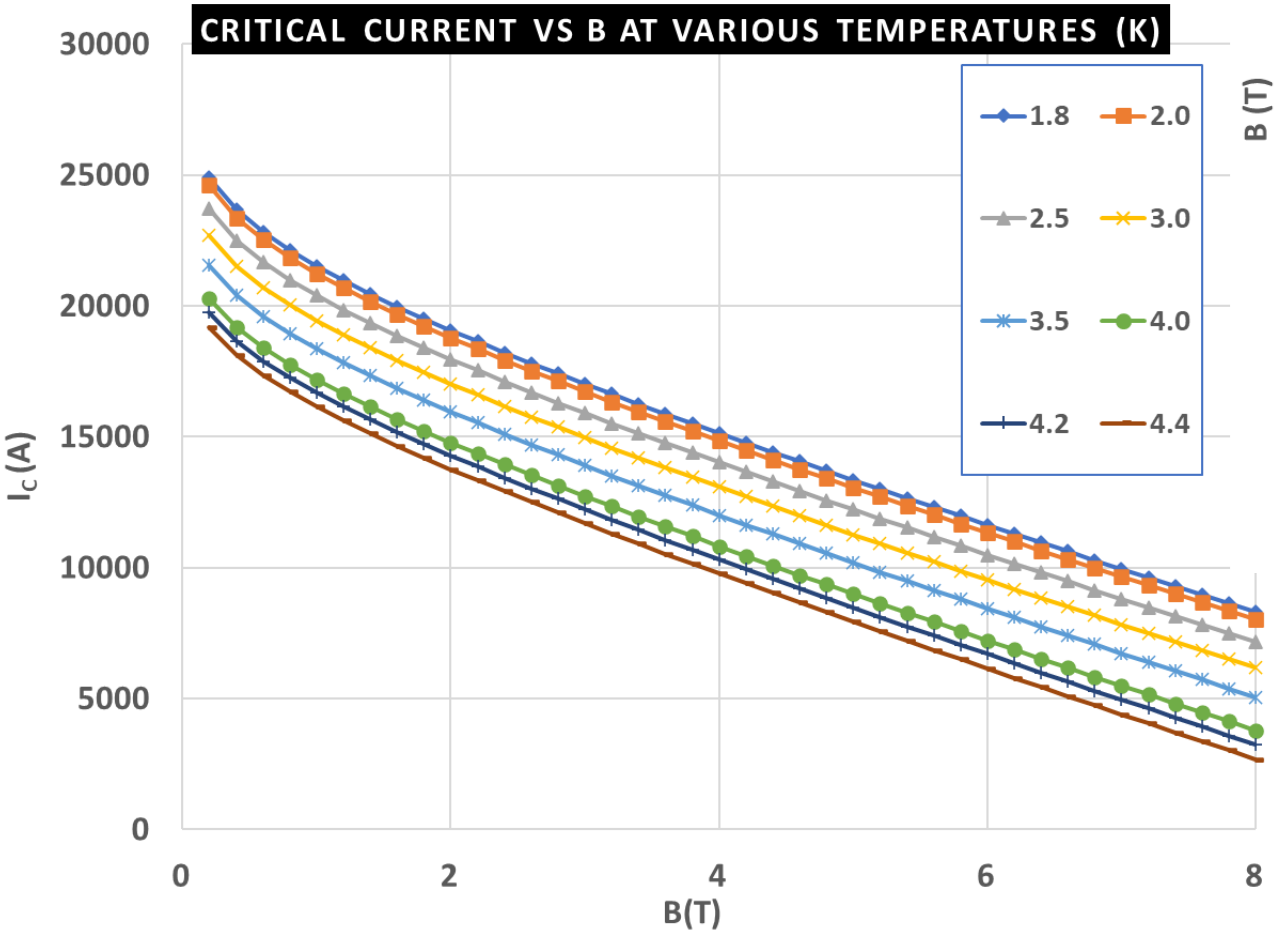
(as used in ROXIE)

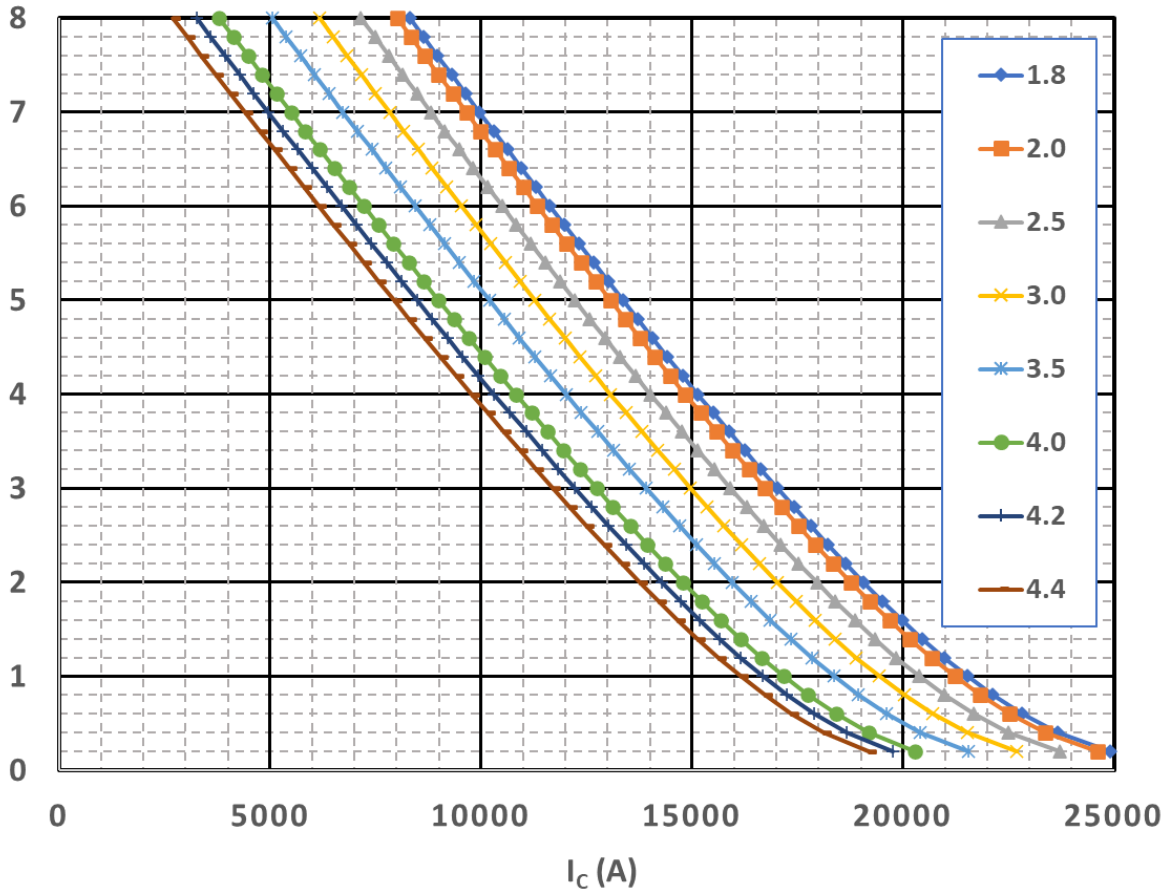
Morgan Curves

RHIC data	
Wire Diameter (in)	0.0255
Wire Diameter (mm)	0.6477
Wire Area (mm^2)	0.329487
Wire Ic (4.2K,5T), A	293
Wire Jc (4.2K,5T), A/mm^2	889.3
Cu/SC ratio	2.2
SC Area	0.102965
Wire Jsc (4.2K,5T), A/mm^2	2845.6
Number of Wires in cable	30
Cable Ic (no degradation), A	8790
Measuured Cable Ic(4.2K,5T)	8475
Degradation (%)	3.6

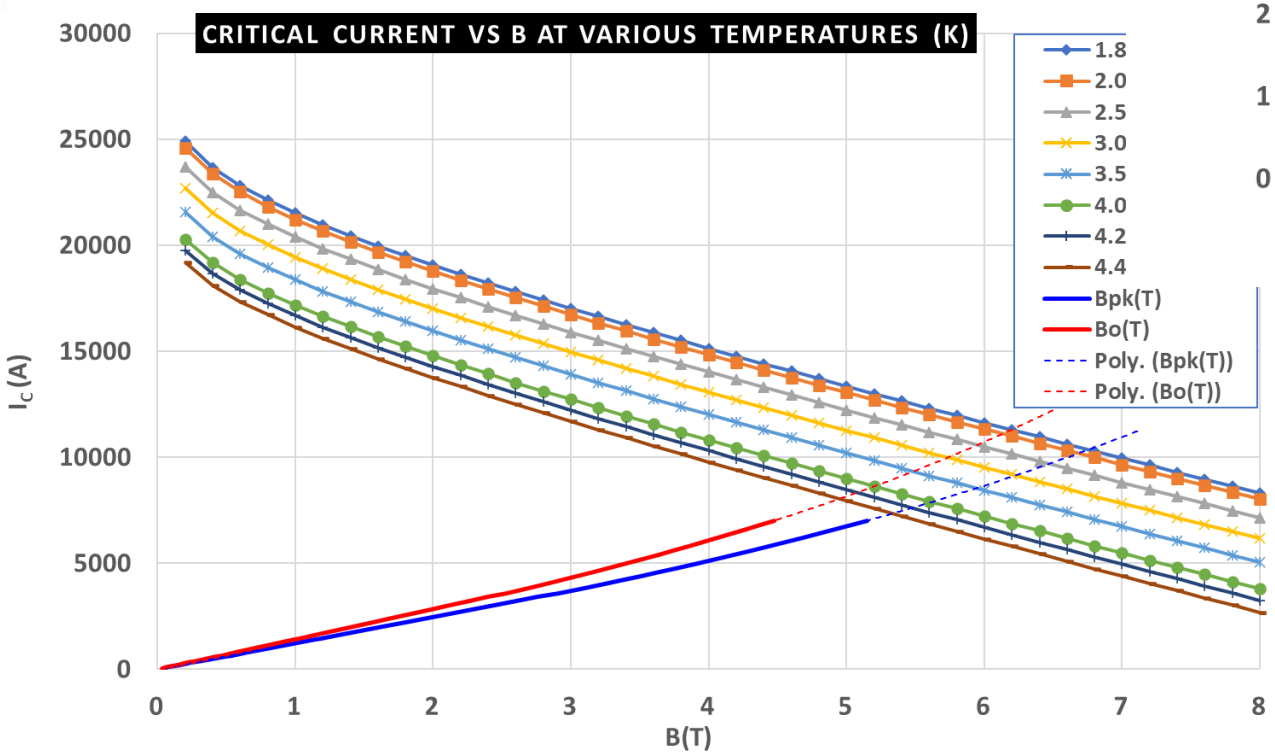
		Bc2(T)	Bc2(T)	Bc2(T)	Bc2(T)	Bc2(T)	Bc2(T)	Bc2(T)	Bc2(T)	
		13.298	13.085	12.495	11.828	11.0894	10.2834	9.94292	9.59239	
		Ic	Ic	Ic	Ic	Ic	Ic	Ic	Ic	
T(K)=>	B(T)	1.8	2.0	2.5	3.0	3.5	4.0	4.2	4.4	<=T(K)
	0.2	24918.5	24599.8	23710.6	22694.1	21553.5	20289.2	19748.5	19187.5	
	0.4	23669.3	23360.6	22499.1	21514.2	20408.6	19182.7	18658.3	18114.1	
	0.6	22816.1	22512.6	21665.5	20696.7	19608.9	18402.4	17886.1	17350.3	
	0.8	22123.3	21823	20984.9	20026.2	18949.4	17754.7	17243.4	16712.5	
	1	21518.2	21220.1	20388.1	19436.1	18366.7	17179.8	16671.6	16143.9	
	1.2	20968.5	20672	19844.3	18897.1	17832.8	16651	16145	15619.4	
	1.4	20457.2	20161.8	19337.3	18393.5	17332.7	16154.4	15649.7	15125.4	
	1.6	19974.1	19679.6	18857.3	17915.9	16857.4	15681.4	15177.6	14654.1	
	1.8	19512.8	19218.9	18398.1	17458.3	16401.4	15226.7	14723.3	14200.1	
	2	19068.6	18775.1	17955.4	17016.6	15960.6	14786.5	14283.2	13760.1	
	2.2	18638.4	18345.2	17526.2	16587.9	15532.2	14358.2	13854.7	13331.4	
	2.4	18219.9	17926.8	17108.1	16170	15114.2	13939.7	13435.9	12912.1	
	2.6	17811.3	17518.2	16699.5	15761.3	14705	13529.6	13025.3	12500.9	
	2.8	17411	17118	16299.1	15360.4	14303.4	13126.8	12621.8	12096.7	
	3	17018.2	16725	15905.7	14966.3	13908.3	12730.2	12224.5	11698.5	
	3.2	16631.8	16338.4	15518.5	14578.2	13519	12339.1	11832.5	11305.5	
	3.4	16251	15957.4	15136.8	14195.5	13134.8	11953	11445.4	10917.3	
	3.6	15875.4	15581.5	14760	13817.5	12755.2	11571.3	11062.7	10533.4	
	3.8	15504.4	15210.2	14387.6	13443.8	12379.7	11193.5	10683.8	10153.2	
	4	15137.5	14842.9	14019.2	13073.9	12008	10819.3	10308.4	9776.56	
	4.2	14774.3	14479.4	13654.5	12707.6	11639.6	10448.4	9936.23	9403.04	
	4.4	14414.6	14119.2	13293	12344.5	11274.4	10080.4	9567.02	9032.41	
	4.6	14058.1	13762.2	12934.7	11984.4	10912.1	9715.29	9200.53	8664.45	
	4.8	13704.5	13408.1	12579.2	11627.1	10552.4	9352.69	8836.56	8298.95	
	5	13353.6	13056.7	12226.2	11272.2	10195.2	8992.45	8474.91	7935.75	
	5.2	13005.2	12707.8	11875.7	10919.8	9840.26	8634.42	8115.43	7574.68	
	5.4	12659.1	12361.2	11527.5	10569.5	9487.45	8278.45	7757.98	7215.61	
	5.6	12315.2	12016.7	11181.4	10221.3	9136.65	7924.4	7402.42	6858.4	
	5.8	11973.4	11674.3	10837.3	9875.01	8787.72	7572.17	7048.65	6502.95	
	6	11633.5	11333.8	10495	9530.56	8440.55	7221.64	6696.56	6149.15	
	6.2	11295.4	10995.1	10154.5	9187.82	8095.04	6872.72	6346.06	5796.92	
	6.4	10959	10658.1	9815.66	8846.7	7751.11	6525.32	5997.05	5446.16	
	6.6	10624.3	10322.7	9478.39	8507.11	7408.67	6179.37	5649.47	5096.8	
	6.8	10291.1	9988.86	9142.62	8168.98	7067.64	5834.78	5303.23	4748.77	
	7	9959.28	9656.44	8808.25	7832.22	6727.95	5491.49	4958.28	4402.01	
	7.2	9628.9	9325.38	8475.24	7496.79	6389.54	5149.44	4614.55	4056.45	
	7.4	9299.83	8995.64	8143.5	7162.6	6052.36	4808.58	4271.99	3712.04	
	7.6	8972.03	8667.14	7813	6829.61	5716.33	4468.84	3930.55	3368.74	
	7.8	8645.42	8339.84	7483.66	6497.76	5381.42	4130.19	3590.17	3026.49	
	8	8319.97	8013.68	7155.44	6167.01	5047.57	3792.57	3250.81	2685.25	

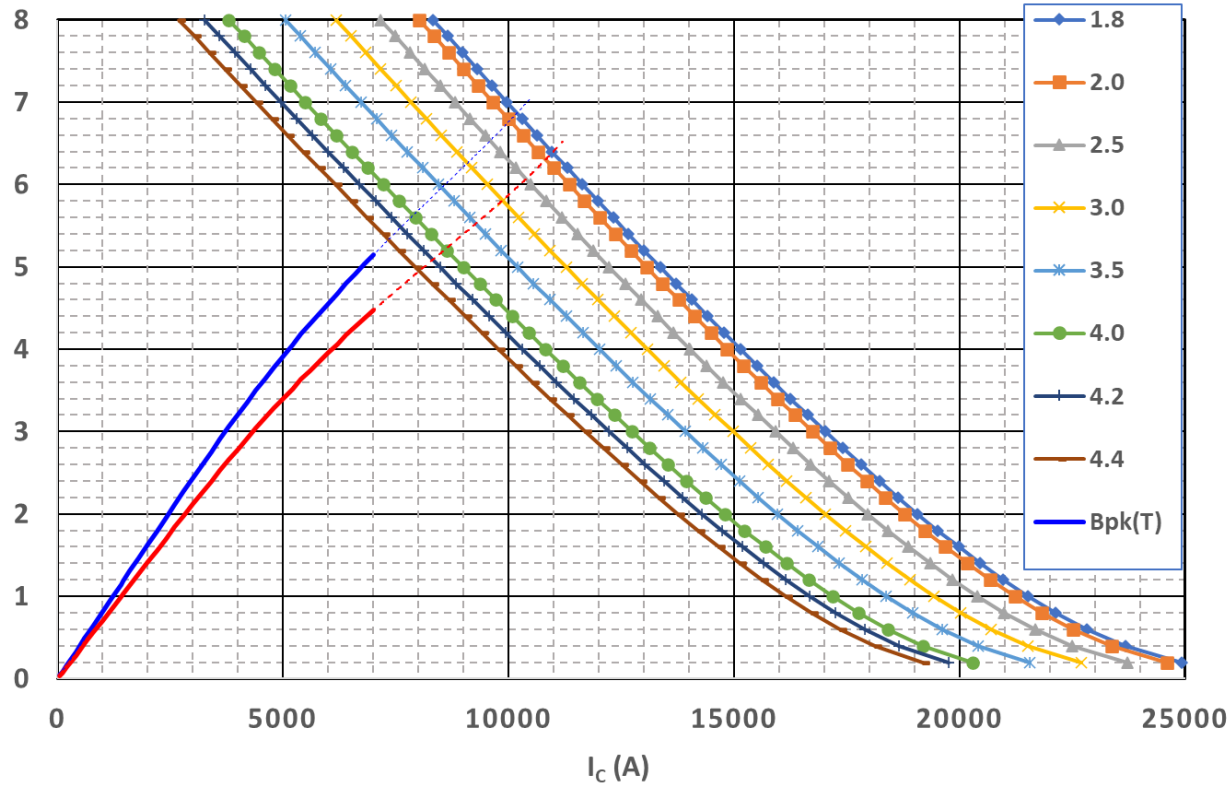
Morgan Curves





Morgan Curves as used in the design calculations





These can also be used in the persistent current calculations.

However, ROXIE doesn't have that as an option (requested to include in the next version).

Bottura Curves

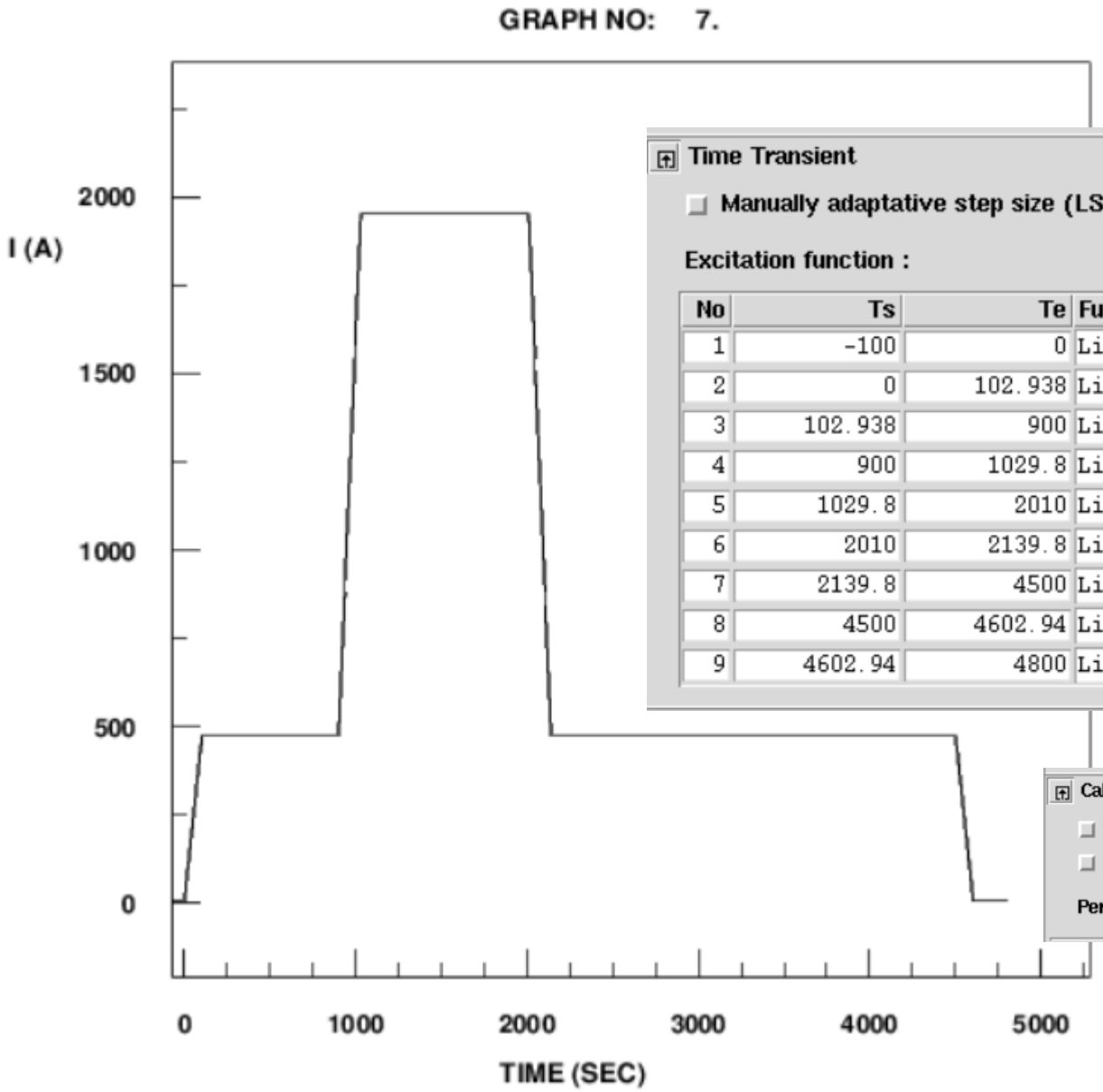
Bottura - From [1] with $B_{c2}(T) = B_{c20}(1-(T/T_{c0})^{1.7})$,

$$J_c(B,T) = \frac{J_{c,\mathrm{ref}}\, C_0 B^{\alpha-1}}{(B_{c2}(T))^{\alpha}} \left(1-\frac{B}{B_{c2}(T)}\right)^{\beta} \left(1-\left(\frac{T}{T_{c0}}\right)^{1.7}\right)^{\gamma}$$

SSC Fit

Fitting for Bottura curve				
		RHIC (paper)	RHIC (try)	LHC
Jc	C1	3.00E+09	3.00E+09	3.00E+09
Tc0	C2	9.2	8.66	9.2
α	C3	0.89	0.948	0.57
β	C4	1.1	1	0.9
γ	C5	2.09	1.73	2.32
Co	C6	37.7	33.25	27.04
Bc2o	C7	14.4	14.45	14.5

Persistent Current Cycle Used in ROXIE



Time Transient

Manually adaptative step size (LSTEP)

Excitation function :

No	Ts	Te	Function	A	B	N/a	N/a	Nsteps	Groups
1	-100	0	Linear	0.05	0.05	0	0	4	1-2
2	0	102.938	Linear	0.05	4.73	0	0	20	1-2
3	102.938	900	Linear	4.73	4.73	0	0	5	1-2
4	900	1029.8	Linear	4.73	19.52	0	0	40	1-2
5	1029.8	2010	Linear	19.52	19.52	0	0	5	1-2
6	2010	2139.8	Linear	19.52	4.73	0	0	40	1-2
7	2139.8	4500	Linear	4.73	4.73	0	0	5	1-2
8	4500	4602.94	Linear	4.73	0.05	0	0	20	1-2
9	4602.94	4800	Linear	0.05	0.05	0	0	4	1-2

Cable Eddy Currents

IFCC (magnetization model) (LIFF) ISCC (magnetization model) (LICCA) ISCC (network model) (LICC)

Mut. inductances (LICCIND) Nonlinear inner iterations (LITERNL)

Pers current (Mag. model) : Scalar model

Several options were examined to see the sensitivity on the results

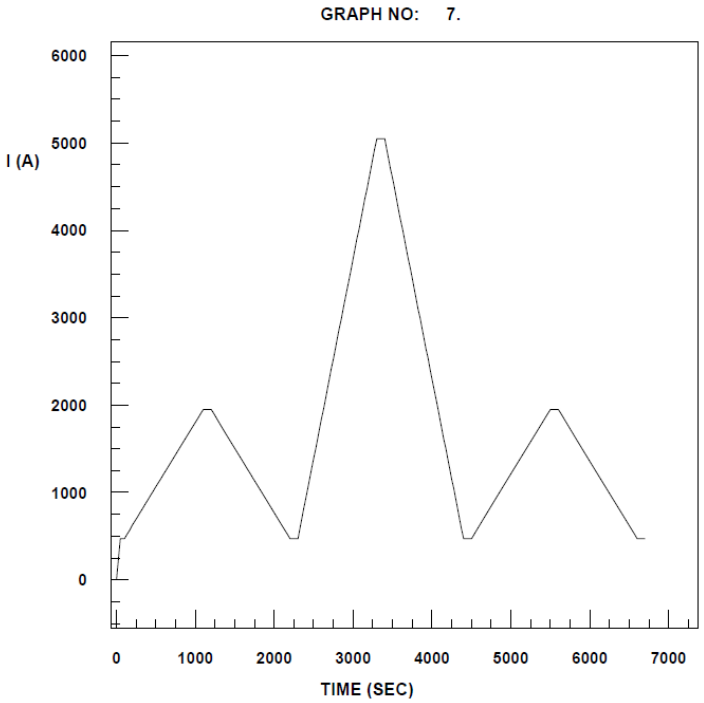
Impact of previous cycles on RHIC dipole

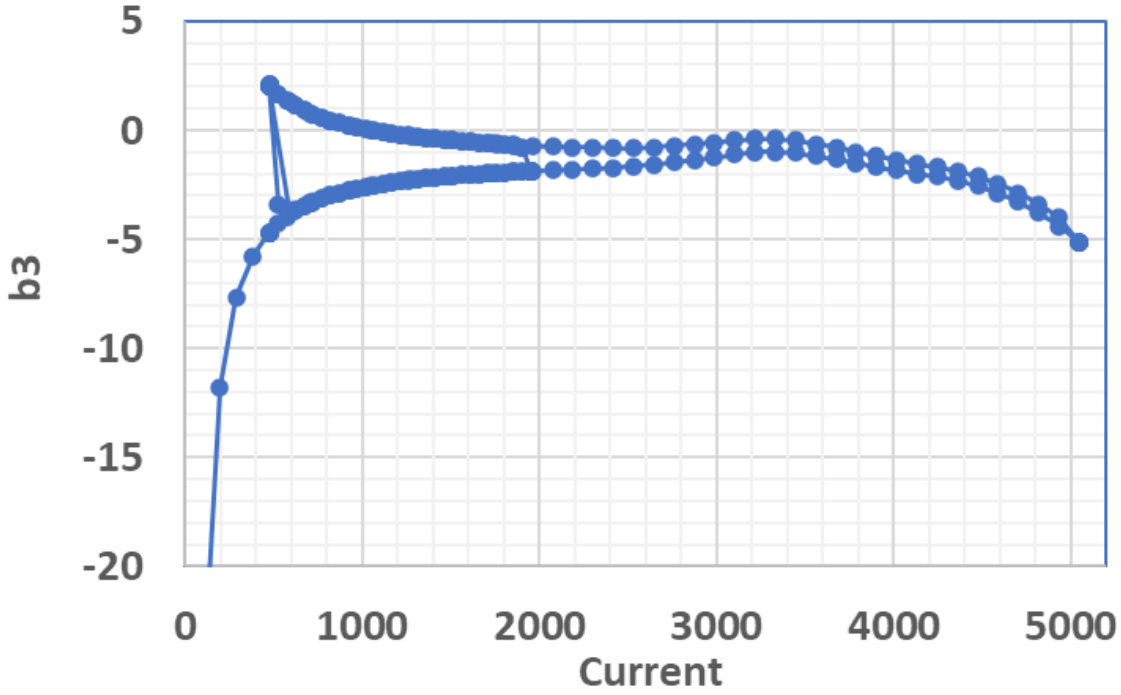
Qualitative agreement between ROXIE calculations and measurements

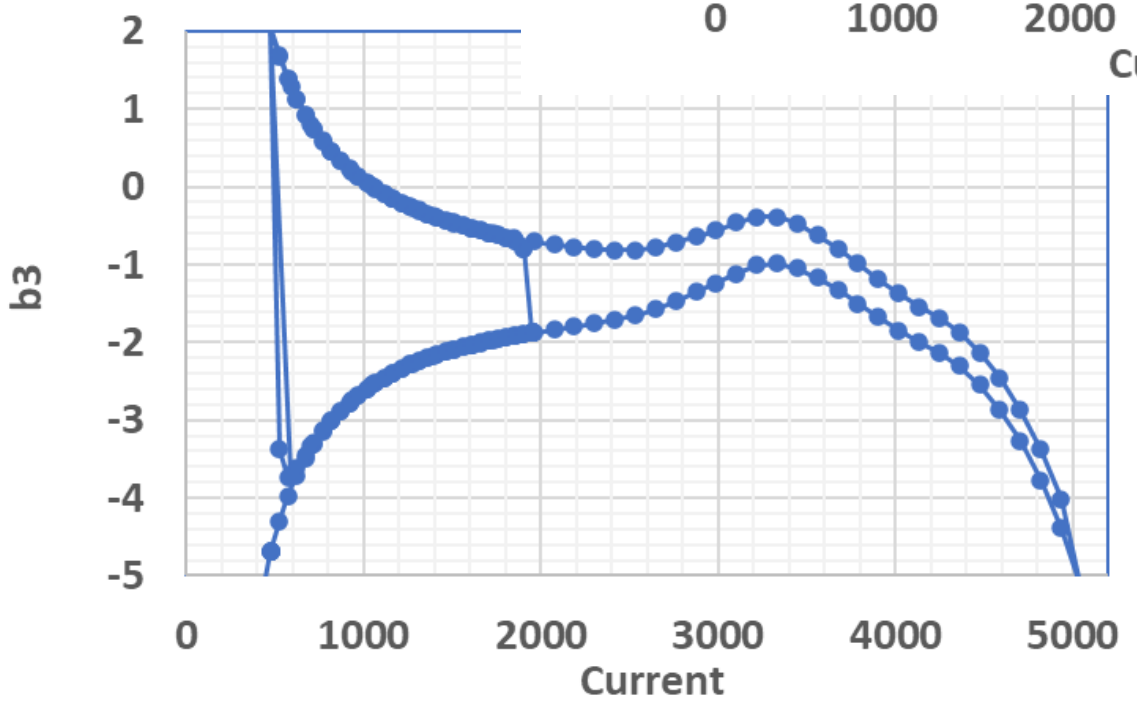
on the spread of harmonic errors between up and down ramp (not

decay or snapback yet)

ROXIE Calculations (not with the latest fi

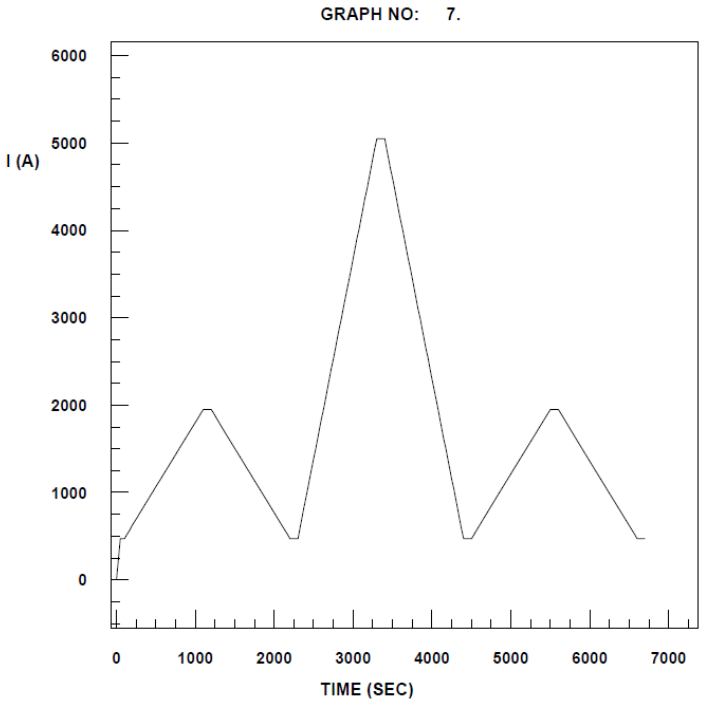


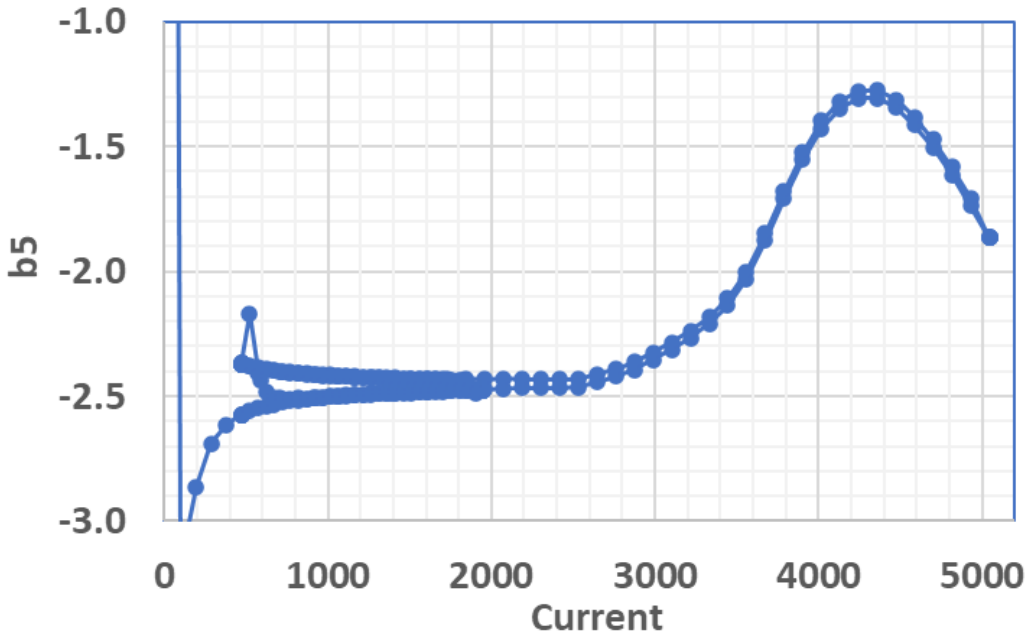


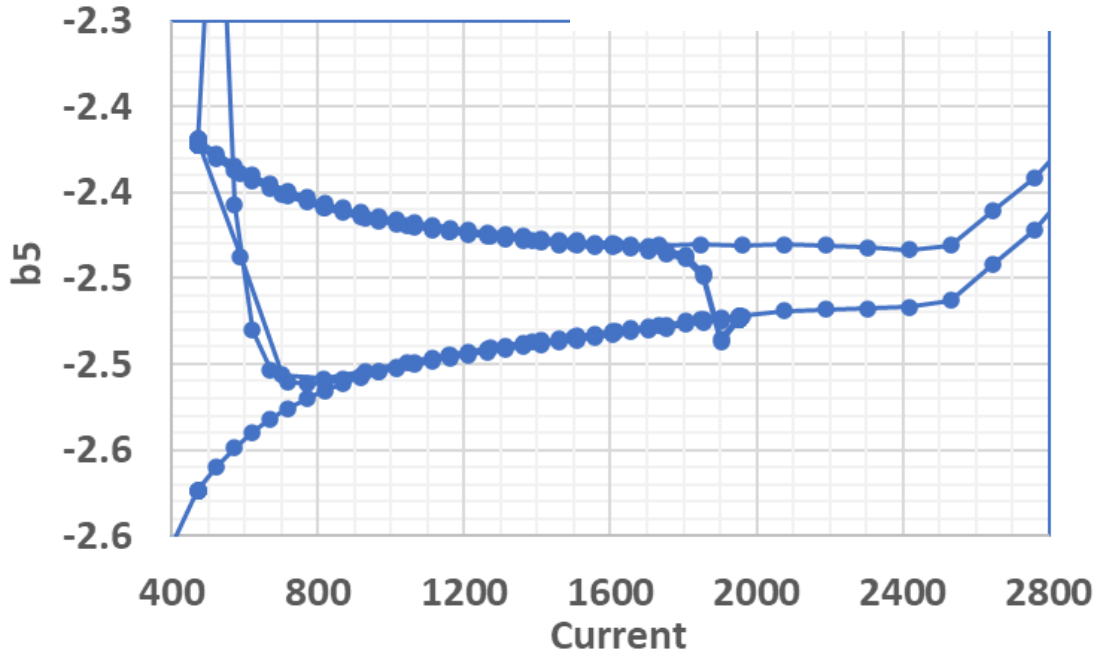


Not a large impact of cycling to a higher current

ROXIE Calculations (not with the latest fit)

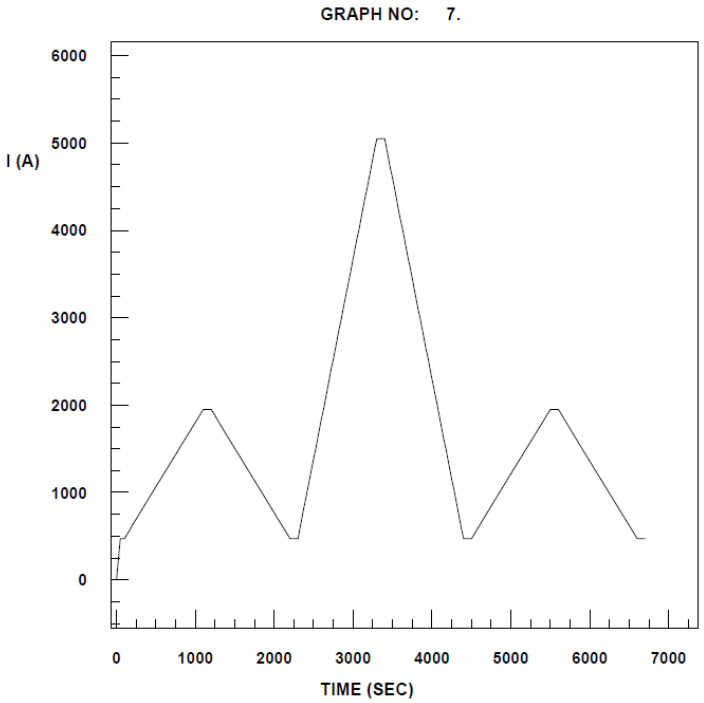


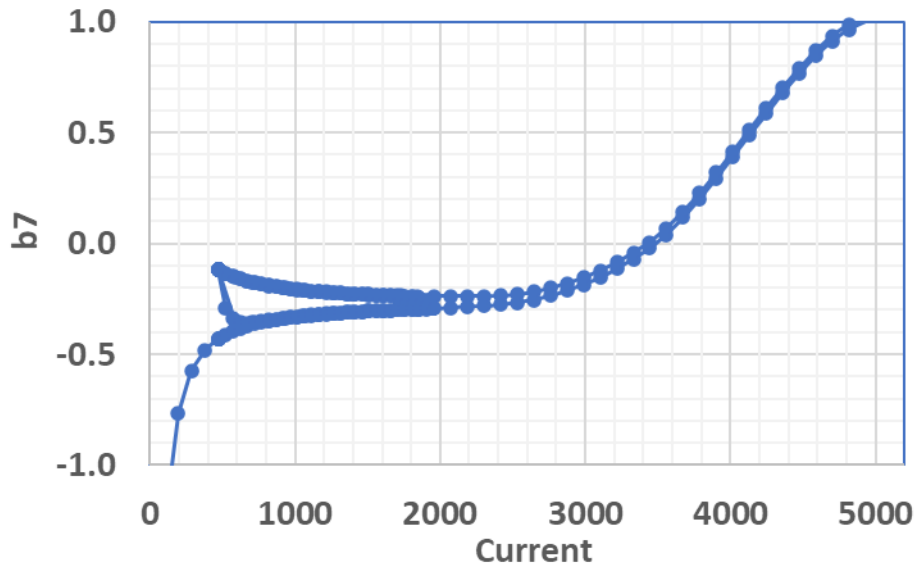


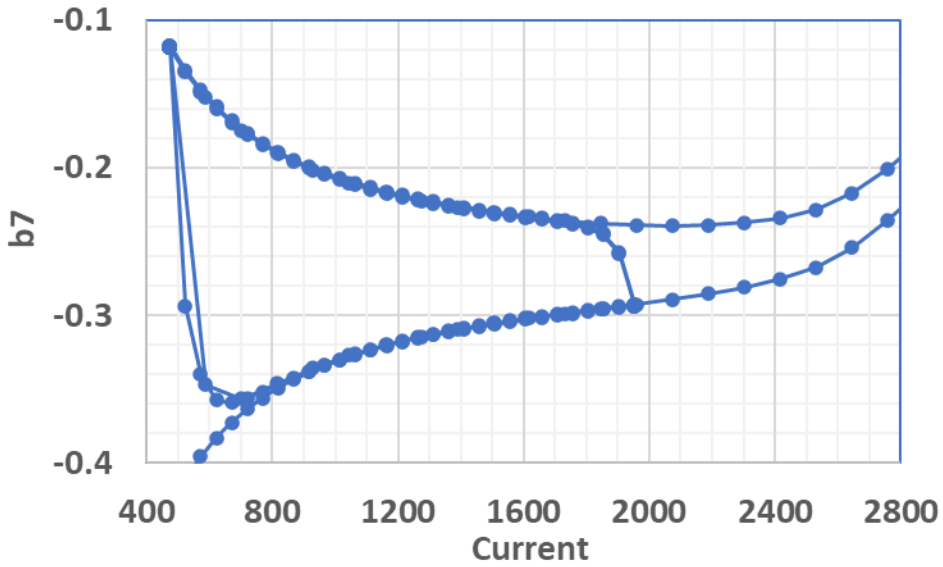


Not a large impact of cycling to a higher current

ROXIE Calculations (not with the latest fit)

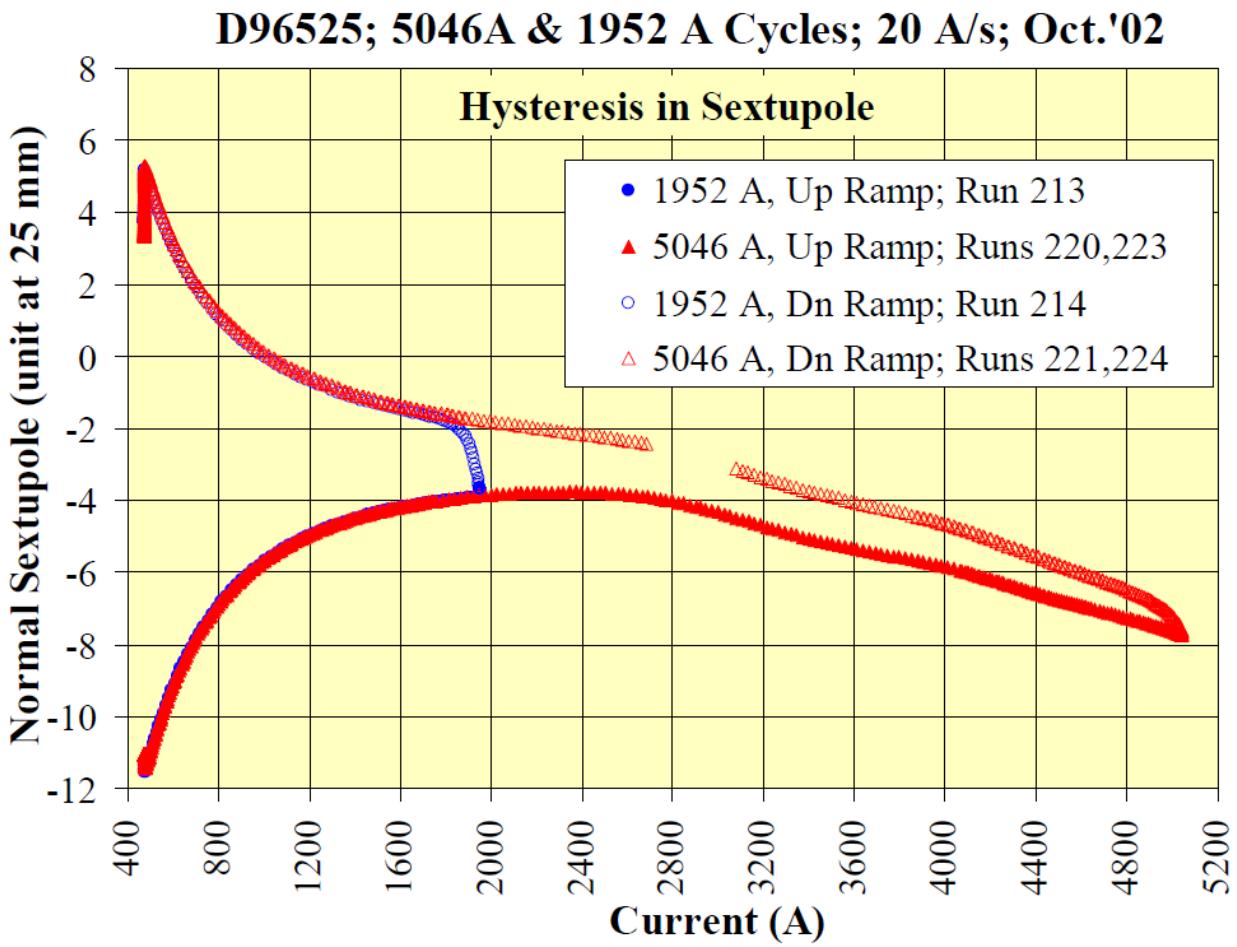


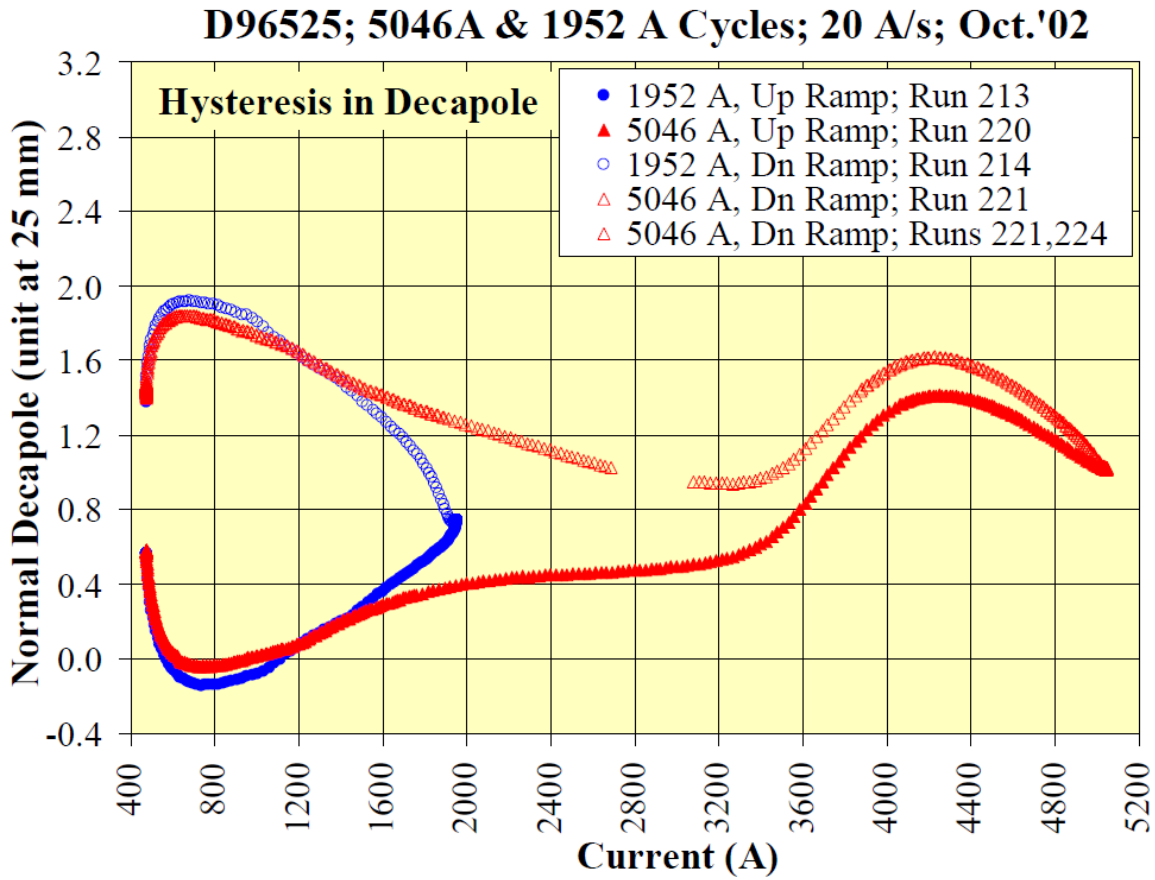




Not a large impact of cycling to a higher current

Measurements





Not a large impact of cycling to a higher current