Brookhaven National Laboratory

Jefferson Lab

U.S. DEPARTMENT OF ENERGY

Report on Magnetic Design and Analysis Bi-weekly Meeting

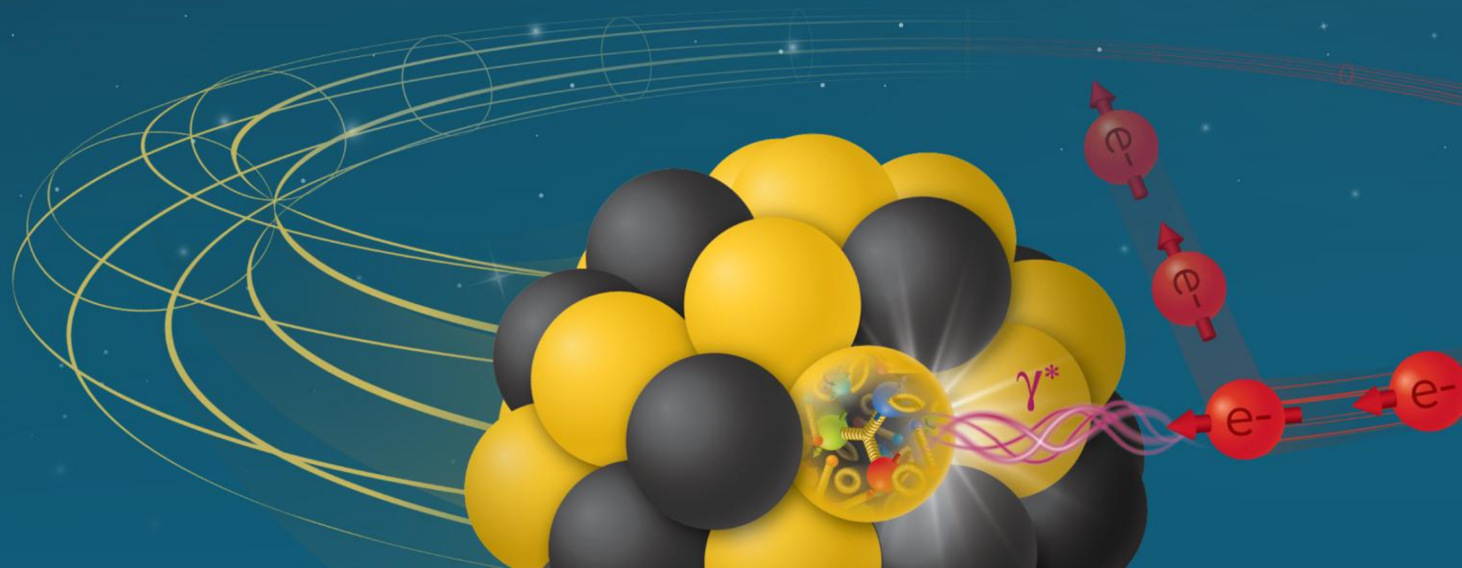
Conductor Modelling

Ramesh Gupta

EIC IR Magnet Meeting

January 20, 2026

Electron-Ion Collider



Key Goals: Obtain Conductor Information for Reliable Modeling

Part I

- **Measurement of critical current as a function of field**
  - **4.2 K available, 1.9 K discussed (OSU presentation)**
- **Apply self-field correction (in progress)**
- **Develop fitting parameters (in progress)**
  - **For margin, magnetization and quench calculations**

Part II

- **Impact of non-transposed wire 6-around-1 cable**
  - **EIC ramp rates are low for any practical impact on I_c**
  - **Not included in quench analysis (this and a few other)**
    - ✓ **these could have a significant positive impact on quench**

Self-field correction to critical current measurements (always applied in designing SSC and RHIC magnets)

Short Sample Measurements of Conductor

Measured 9/6/94, Test # 1516, T=4.22K

(routinely applied by Arup Ghosh)

$$B = \frac{\mu_0 I}{2\pi r}$$

Bself=mu0/4Pi*2I/a	
mu0	1.26E-06
a	0.0005

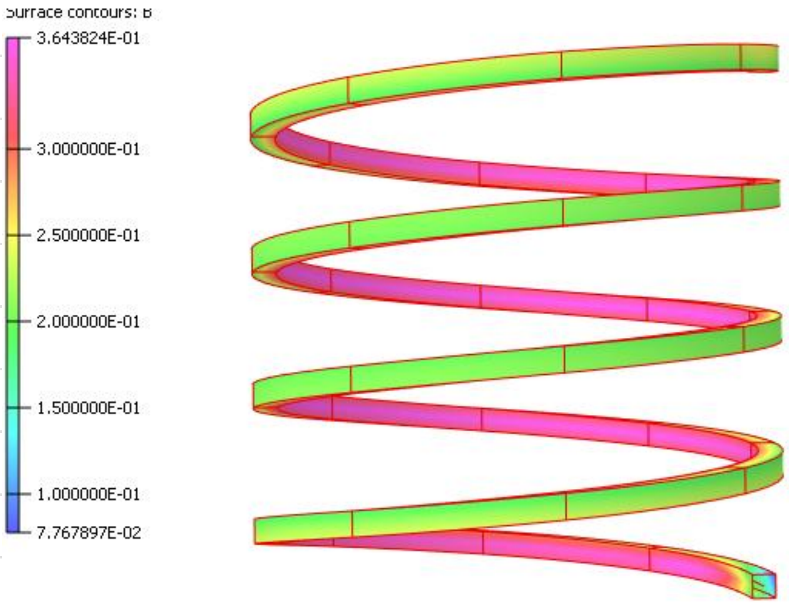
$I_{4.35}/I_{4.22}$= 0.957

1 mm diameter cable

I_c@4.22K	I_c@4.35K	B_{bkgd}	B_{self}	B_{tot}
403	386	6	0.16	6.16
509	487	5	0.20	5.20
615	589	4	0.25	4.25
675	646	3.5	0.27	3.77
755	723	3	0.30	3.30
840	804	2.5	0.34	2.84
945	904	2	0.38	2.38
1100	1053	1.5	0.44	1.94
1300	1244	1	0.52	1.52

A better method:

- **Model calculation (of test configuration)**



Field correction from the line current model >50% at 1 T

No Measurements Yet at 1.9 K

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 17, NO. 2, JUNE

Critical Current Measurements of the Main LHC Superconducting Cables

A. P. Verweij and A. K. Ghosh

Guidance from Arup Ghosh, Ron Scanlan and Amalia Ballarino: (a) 4.2K/1.9K ratio doesn't vary too much, at least when the process remains the same, (b) Can use a shift of 3T +/- 0.1T in I_c

TABLE I
MAIN CABLE AND STRAND CHARACTERISTICS

	Cable 01	Cable 02	Cable 03
Delivered no of UL	5369	5407	894
Length of a UL	450 m	740 m	660 m
Cable			
Width	15.08-15.10 mm	15.08-15.10 mm	
Thin edge	1.736±0.006 mm	1.462±0.006 mm	
Thick edge	2.064±0.006 mm	1.598±0.006 mm	
Mid thickness	1.900±0.006 mm	1.480±0.006 mm	
Number of strands	28	36	
Transposition pitch	110±5 mm	100±5 mm	
Cable Ic @ 4.222K, 7 T	>14140 A		
Cable Ic @ 4.222 K, 6 T		>13236 A	
Cable Ic @ 1.900 K, 10 T	>13750 A		
Cable Ic @ 1.900 K, 9 T		>12960 A	
Strand			
Diameter	1.0650±0.0025 mm	0.8250±0.0025 mm	
Cu/SC ratio	1.6-1.7	1.9-2.0	
Strand Ic @ 1.900 K, 10 T	>515 A		
Strand Ic @ 1.900 K, 9 T		>380 A	

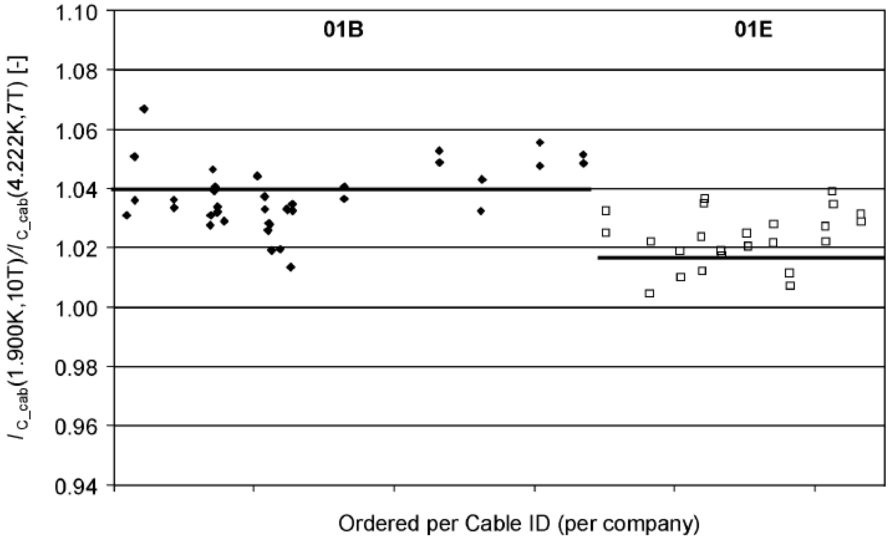
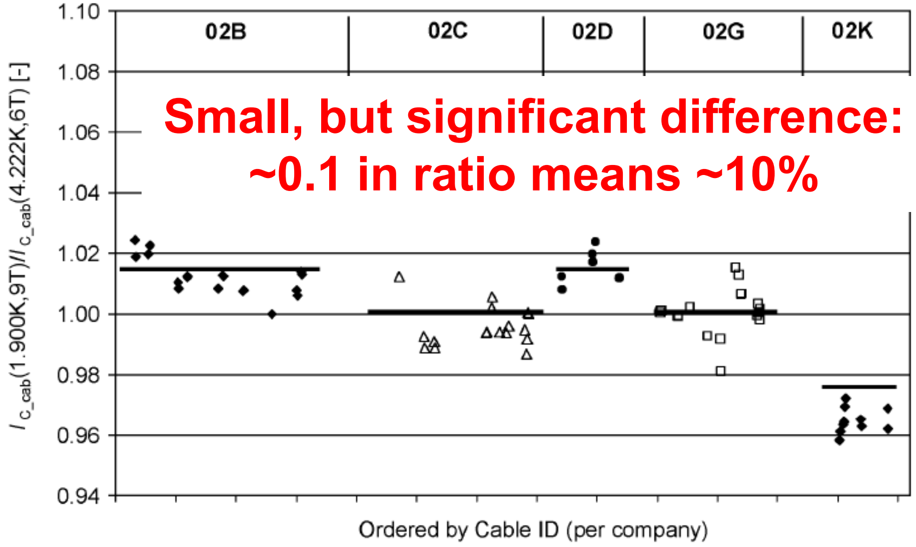


Fig. 11. Ratio between cable I_C at 1.9 K (10 T) and at 4.222 K (7 T) for the cables of type 01.



Small, but significant difference: ~0.1 in ratio means ~10%

Fig. 12. Ratio between cable I_C at 1.9 K (9 T) and at 4.222 K (6 T) for the cables of type 02. The 02B production cables at FEC is not included.

➢ **Message: Need a few (not too many) measurements at 1.9K**

Presentation from Mike Sumption (OSU)

Test facilities and capabilities at OSU for testing EIC wires and cables

Mike Sumption

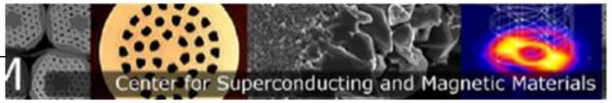
EIC Collaboration meeting

Jan 9, 2026

Targets/Needs

Our understanding is that a few important areas of need are…

- Magnetization of strands and cables (NbTi based for IR region EIC magnets) at 4.2 K and 1.9 K
- I_c and maybe quench measurements for single strand and 6 x 1 small cables at 4.2 K and 1.9 K, fields up to 6-7 T
- Interested to know if other needs exist….



Department of Materials Science and Engineering

Outline/Overview of capabilities

Presentation from Mike Sumption (OSU)

- **Magnetization measurements and devices**
  - PPMS short sample
  - PPMS helical samples
  - Hall probe system
  - Dipole magnet system
  - Note on the importance of extended samples and contact resistance in cables if ramp rate properties are important
- **Transport and quench measurements on strands and cables**
  - 15 T magnets (A and B), 2 kA capability probes, 3.8 kA current PS capacity
  - Routine 4.2 K measurements, 1.9 K capability
- **ICR measurements on cables/composites**
  - Set up to measure contact resistance in SC cables, significant experience in measurement and analysis over many years (**SSC, LHC {NbTi}**, also CORC)
  - Knowledge of intersection of magnet/conductor preparation/manufacture impact on ICR and from this magnetization/loss and current sharing (**LTS** as well as HTS)
- **Other items of possible interest**
  - High quality Electron Optics (SEM), and micro-CT (studies of conductors, cables, windings?)
  - Mechanical testing
  - Substantial size cryocooling test stand

CSMM Center for Superconducting and Magnetic Materials

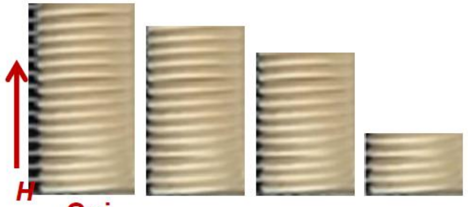
Department of Materials Science and Engineering

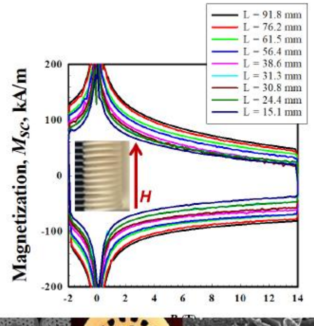
Presentation from Mike Sumption (OSU)

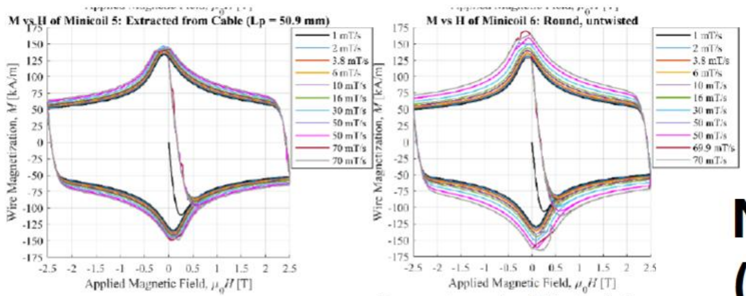
Magnetization measurements and devices I (PPMS results)

Can use short samples and also small helical coils

- ICR can affect cable magnetization in fast ramps
- Important to pay attention to pitch selected
- Important to pay attention to sample prep on ICR







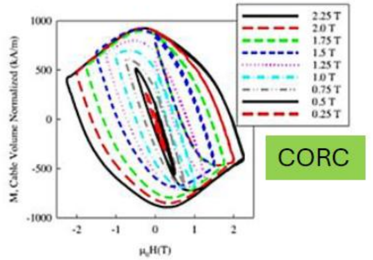
CSMM Center for Superconducting and Magnetic Materials

Department of Materials Science and Engineering

Physical Property Measurement System (PPMS)

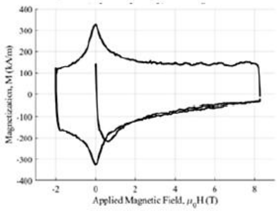
Magnetization measurements and devices III (Dipole Magnet System)

Dipole Magnet System



CORC

Fig. 3. The 4 K $M - \mu_0 H$ of CORC™ sample 160823-Berkeley 250-C with maximum field amplitude 2.25 T. Field is applied perpendicular to the cable length cables. Normalization volume is total cable volume.

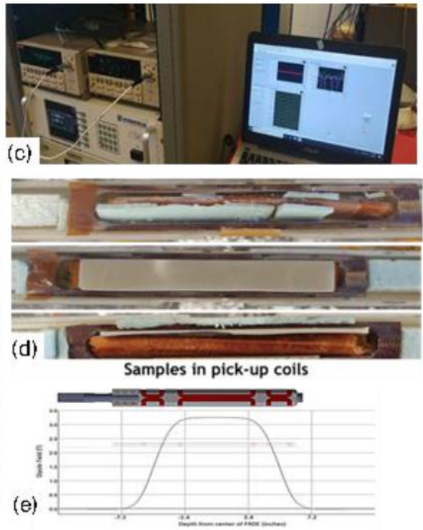


Bi:2212 Rutherford

Fig. 3. M-H loop (-2 T to 8 T). Initial Susceptibility method was used to calibrate data. Volume normalized to region of strand excluding flux.

Good for Cable studies, moderate ramp

samples up to 2 cm wide and 15 cm long



Facilities at BNL (not presented during the meeting)

BNL has been doing this for a long time (SSC, RHIC and LHC)

- **We lost many at SMD, but still have most at CFN**

https://www.bnl.gov/cfn/equipment/details.php?q=300319

Equipment Catalog

Physical Property Measurement System (PPMS)

Facility: Materials Synthesis and Characterization **Category:** Electrical Probing Full Catalog

The Quantum Design Dynacool 12T Physical Property Measurement System (PPMS)features a cryogen-free cryostat that is cooled by a He-4 compressor, with a continuous temperature range from 400K to 1.8K, under closed-loop temperature. The same cryocooling system supports a superconducting magnets that achieves a maximum magnetic field of 12 T. With an optional He-3 insert, the PPMS performs low voltage DC and low frequency AC (< 200 Hz) electrical measurements from 0.35 K to 400 K, under 0-12 T magnetic field applied by the superconducting magnet. It accepts wire bonded samples for continuous measurements as a function of temperature and magnetic field.

Contact

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Lab Phone: Not available

A New Critical Surface for RHIC NbTi

Gerry H. Morgan

In a previous report [1], the parameters for two different empirical formulations for the NbTi critical surface were fitted to data available at the time. Theoretical work by Campbell & Evetts [2] leads to a general formulation for the pinning force, (1), which, when supplemented with a formulation (2) due to Lubell [3] for the upper critical field, $B_{C2}(T)$, gives an excellent fit to recently available data [4] for the NbTi used in the RHIC arc magnets. The I_C of these data is for a resistivity of 10^{-14} ohm-m for the wire cross-section.

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

where

$$B_{C2} = B_{C0} \cdot (1 - (T/T_C)^E) \quad (2)$$

where T_C is the zero-field critical temperature.

The non-linear least-squares fitting routine used for the present work is the CERN program MINUIT. When all seven parameters, C_1, m, p, q, B_{C0}, T_C, and E are simultaneously fitted, rounded to two or 3 decimals and C_1 is refitted, the following values are obtained:

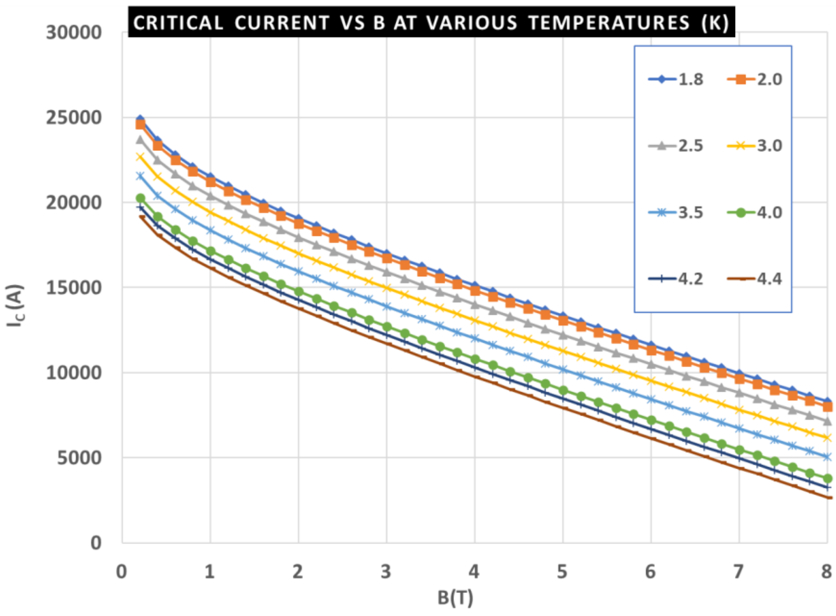
C_1	m	p	q	B_{C0}	T_C	E
106.13	1.73	0.948	1.000	14.45	8.66	1.61

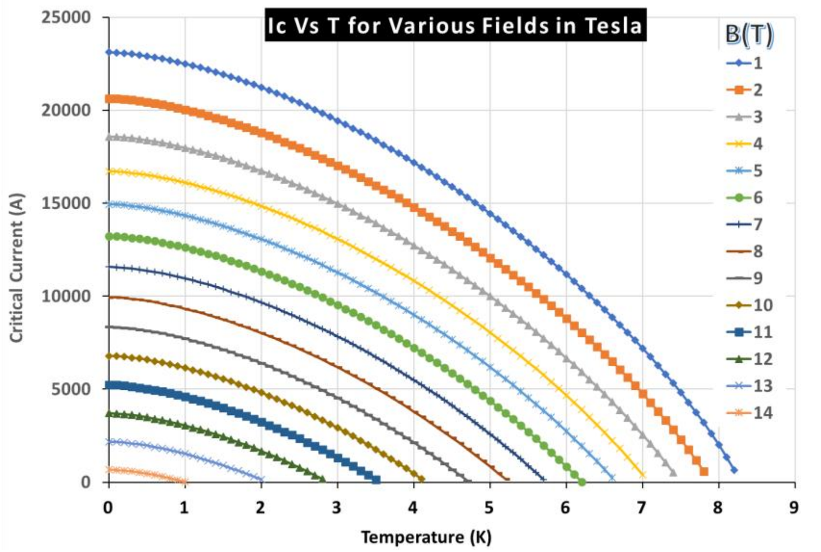
Ic(4.2K,5T), A	8475
Original calculations for RHIC Wire	
Ic(4.2K,5T),A	292.43
Scaling Factor (X)	28.981
C1 original	106.13
C1 modified	3075.78

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

C1	C1m	m	p	q	BC0	Tc	E
106.13	3075.78	1.73	0.948	1	14.45	8.66	1.61

		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
	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





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

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

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

x	J_c (A/mm²)									
1.00E-06		Bc2(T) 13.45	Bc2(T) 13.25	Bc2(T) 12.70	Bc2(T) 12.07	Bc2(T) 11.35	Bc2(T) 10.56	Bc2(T) 10.23	Bc2(T) 9.88	
		Jc	Jc	Jc	Jc	Jc	Jc	Jc	Jc	
T(K)=>	B(T)	1.8	2.0	2.5	3.0	3.5	4.0	4.2	4.4	<=T(K)
	0.2	8032	7939	7674	7366	7015	6622	6453	6276	
	0.4	7631	7540	7284	6985	6646	6264	6100	5929	
	0.6	7357	7268	7016	6722	6388	6013	5851	5683	
	0.8	7135	7047	6798	6507	6176	5805	5645	5478	
	1	6941	6854	6606	6318	5989	5620	5461	5295	
	1.2	6765	6678	6432	6145	5818	5451	5292	5127	
	1.4	6602	6515	6270	5984	5658	5292	5134	4969	
	1.6	6447	6361	6116	5831	5506	5140	4983	4818	
	1.8	6300	6214	5969	5685	5360	4995	4837	4673	
	2	6158	6072	5828	5544	5219	4854	4697	4532	
	2.2	6020	5934	5691	5407	5082	4718	4560	4396	
	2.4	5887	5801	5557	5273	4949	4584	4426	4262	
	2.6	5756	5670	5427	5142	4818	4453	4295	4131	
	2.8	5628	5542	5299	5014	4690	4325	4167	4002	
	3	5503	5417	5173	4889	4564	4198	4040	3875	
	3.2	5379	5293	5049	4765	4440	4073	3915	3749	
	3.4	5258	5172	4928	4643	4317	3950	3792	3626	
	3.6	5138	5052	4807	4522	4196	3829	3670	3503	
	3.8	5019	4933	4688	4403	4076	3708	3549	3382	
	4	4902	4816	4571	4285	3958	3589	3429	3262	
	4.2	4786	4700	4455	4168	3840	3471	3311	3143	
	4.4	4672	4585	4339	4052	3724	3354	3193	3025	
	4.6	4558	4471	4225	3937	3609	3237	3076	2908	
	4.8	4445	4358	4112	3824	3494	3122	2960	2792	
	5	4333	4246	3999	3710	3380	3007	2845.3	2676	
	5.2	4222	4135	3887	3598	3267	2893	2731	2561	
	5.4	4111	4024	3776	3486	3155	2780	2617	2447	
	5.6	4002	3914	3666	3375	3043	2667	2504	2333	
	5.8	3893	3805	3556	3265	2932	2555	2391	2220	
	6	3784	3696	3447	3155	2821	2443	2279	2108	
	6.2	3676	3588	3338	3046	2711	2332	2168	1996	
	6.4	3569	3481	3230	2937	2602	2222	2057	1884	
	6.6	3462	3374	3123	2829	2493	2111	1946	1773	
	6.8	3356	3267	3016	2721	2384	2002	1836	1662	
	7	3250	3161	2909	2614	2276	1893	1726	1552	
	7.2	3145	3056	2803	2507	2168	1784	1617	1442	
	7.4	3040	2951	2697	2401	2061	1675	1508	1332	

Ic(B,4K-5.4K) | Ic(B,1.8K-4.4K) | Bottura | Ghosh-RHIC-Wire | Sheet1 | Ic(B,T) | MDN

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 the critical surface as a function of the reduced parameters *t* and *b* is given by:

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

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

TABLE II
SUMMARY OF RESULTS FOR THE TI...
PUBLISHED JC DATA SETS (DATA SOURCE ...

source		Ref.[9]	Ref.[10]
Ti content	[%]	46.5	46.5
points	[-]	33	16
B_{c20}	[T]	14.5	14.2
T_{c0}	[K]	9.2	8.5
C_0	[T]	23.8	28.6
α	[-]	0.57	0.76
β	[-]	0.90	0.85
γ	[-]	1.90	1.76
ε_{max}	[%]	20	3.5
σ	[%]	5	1.5

Edit Cable Data [/home/gupta/roxie10.3.1/persistent-current/rhic/roxie.cadata]

File Display

Insulation

Jc-Fit

No	Name	Type	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	Comment
1	FIT1	1	3E+09	9.2	0.57	0.9	2.32	27.04	14.5	0	0	0	0	MB FILAMEN
2	TES1	1	3E+09	9.2	0.57	0.9	2.32	27.04	14.5	0	0	0	0	FILAMENT T
3	GSIFIT	1	3E+09	9.2	0.7	1.57	1	25	14.5	0	0	0	0	APPROXIMAT
4	SISFIT	1	3E+09	9.33517	0.68	0.8477	2.23234	25	14.5	0	0	0	0	Glyn MQYT5

Jc-Fit

No	Name	Type	Jcref	Tc0	alpha	beta	gamma	C0	Bc20
1	RHIC	1	3E+09	9.2	0.8	0.7	2.5	27	14.5
2	RHICRG	1	3E+09	9.2	0.89	1.1	2.09	37.7	14.4
3	RHIC2	1	3E+09	9.2	0.795	1	1.25	25	14.5
4	RHICW	1	3E+09	9.2	0.7	1.57	1	25	14.5
5	RHIC4	1	3E+09	9.2	0.7	1	1.4	25	14.5
6	RHIC3	1	3E+09	9.2	0.7	1	1.5	25	14.5
7	RHICA	1	3E+09	9.2	0.8	0.9	1.5	25	14.5

Filament

	symbol	LHC	RHIC
C1			
C2	Tc0	9.2	9.2
C3	α	0.57	0.89
C4	β	0.9	1.1
C5	γ	2.32	2.09
C6	C0	27.04	37.7
C7	Bc2o	14.5	14.4

Ye Bai to develop fitting parameters for EIC conductors

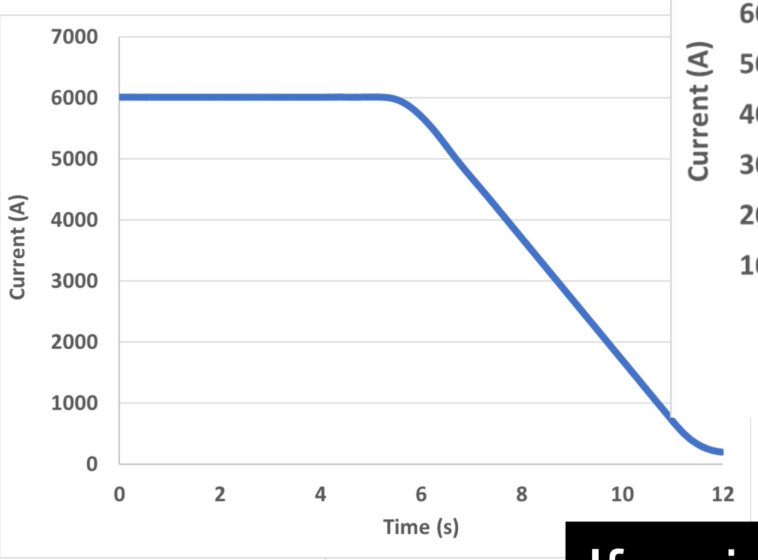
Information on Cable for Quench Analysis Models

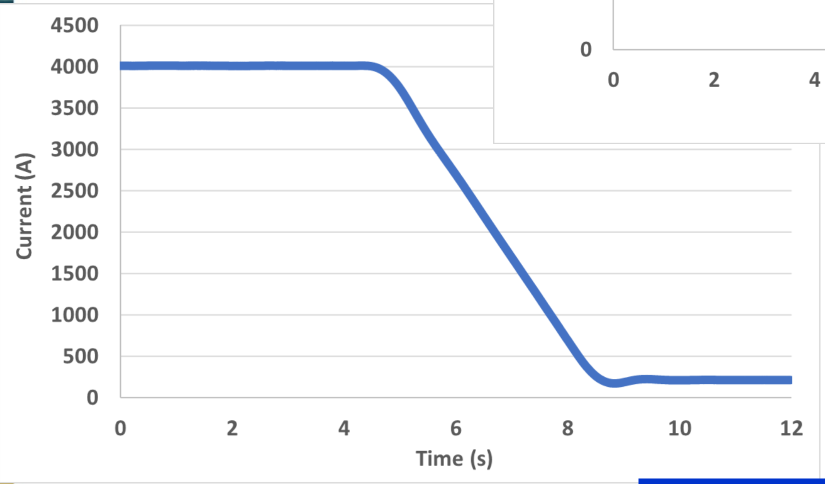
- Need $J_c(B,T)$ fit (covered in the last task)
- Need to understand if the cable goes normal sooner than assumed in the models
  - Need to know the role of central non-transposed wire in 6-around-1 cable
  - Impact of rapid change in current during the energy extraction
  - Quench back effect
  - Temperature rise due a/c looses (Emanuella's presentation?)

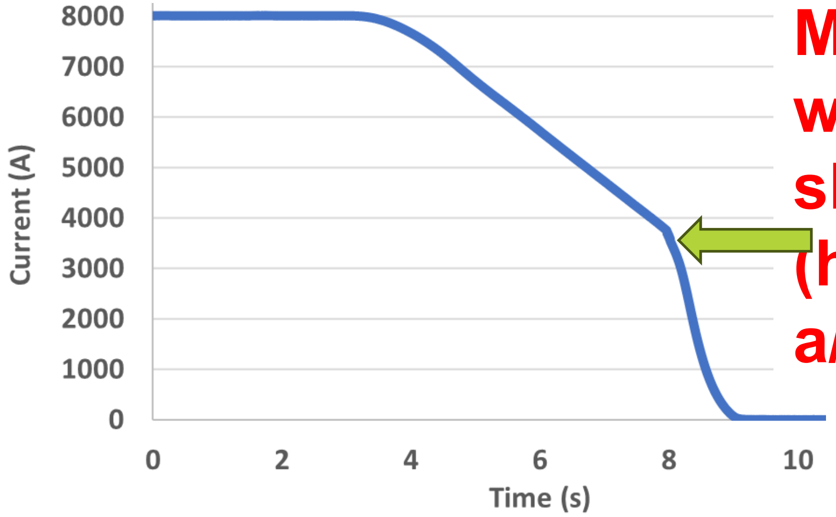
If the impact of above is large, quench model may be significantly off

Ramp Down at High Ramp Rates in Nb_3Sn Common Coil Dipole

Ramp down from different initial current





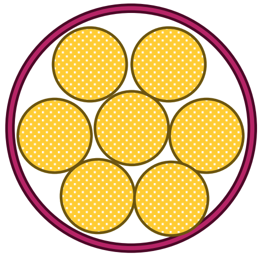


Magnet quenches well below the short sample (heating due to a/c losses?)

If a significantly larger portion of the conductor go normal than assumed in the model during energy after the quench (for whatever reason), then model may be significantly off.

Mithlesh has observed this in the previous coil tests.
We can make this part of the test plan of upcoming tests.

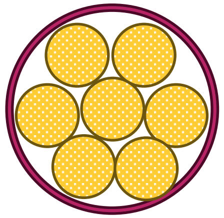
Role of the Cetral Wire in 6-around-1 Cable On Quench Protection



- Direct wind magnets operate at low current (<2 kA, most < 1 kA). This is a positive feature for current leads and for power supplies. However, the quench protection becomes challenging due to high inductance in many large aperture, high field direct wind magnets in EIC IR.
- Many are built with 6-around-1 cable, with the central wire not transposed. The transport current may not share equally between the central wire and the 6 wires around it. Impact could be large when the rate of change in current is high.
- We have seen a negative impact of it in the quench current experimentally at a ramp rate higher than 20 A/s. Models are being developed to explain this drop. However, this is not a practical concern in EIC IR magnets operate at a lower ramp rate.
- However, this could have a large positive impact on the quench protection and in quench analysis as the current falls rapidly after the power supply is shut off. The 6-around-1 cable is likely going normal much sooner than assumed in the models.
- We need to know that soon, as that is driving the magnet and quench protection system design. By not including this, we may be unnecessarily increasing the cost.

Measurements to Help Build More Complete Quench Models

- We must experimentally measure if the central wire has a significant impact in driving the cable normal sooner, as it will reduce the hot-spot temperature and will change the quench protection system design.



- A few relatively simple measurements will not only determine that but should also give necessary input for accounting them in quench analysis.
- Keep the background field at a constat value. That value will change in different runs.
- First ramp up the 6-around-1 cable at different ramp rates from 10 A/s to 1000 A/s and measure the impact on critical current. Perform this experiment at different fields.
- Second (more importantly) ramp up the cable to a set of currents (100 A to 2000 A, depending on the field). Hold and then ramp current down at different ramp rates (say 10 A/s to 1000 A/s). Perform this experiment at different background fields.
- Above experiments will tell us how important the role of non-transposed central wire (or something else) plays in quench protection. It will provide input to quench models.
- These measurements are not too expensive but could/would have major impact.

Extra Slides

Introduction and Purpose of these Meetings

- **The focus of these meetings will be on technical discussion on a specific topic or EM design of a magnet, rather than providing the status report.**
- **Expect to have a technically objective and lively (respectful) discussion.**
- **Today's meeting is for producing a common set of conductor parameters. Test results and facilities will also be presented.**
- **Future topics:**
  - ➢ **2-d and 3-d designs (approach and modelling)**
  - ➢ **Cross-talk**
  - ➢ **Assuring good field quality**
- **Above will follow by in-depth discussion on EM design of individual magnets**
- **Feedback to above and suggestions on more topics are welcome.**
- **A SharePoint site has been created (thanks Angelika) to store presentations.**

Agenda (January 9, 2026)

- Introduction to the meeting & standardizing conductor parameters
  - Ramesh Gupta
- Test facilities at FSU for testing EIC wires and cables
  - Jun Lu
- Measurements and parameterization of EIC wires
  - Ye Bei
- Test facilities at OSU for testing EIC wires and cables
  - Mike Sumption
- Parameterization for quench calculations and 6-around-1 cable
  - Emmanuele Ravaioli
- General discussion
  - All

Self-field correction

- **Outside a Long Straight Wire:** The magnitude is calculated using the formula:

$$B = \frac{\mu_0 I}{2\pi r}$$

where μ_0 is the permeability of free space ($4\pi \times 10^{-7}\ \mathrm{T \cdot m/A}$).

Simple calculations
Use r=a cable radius
(0.5 mm in the smaller 6-around-1 cable)

- **Inside the wire (r < R):** $B = \dfrac{\mu_0 I r}{2\pi R^2}$

(assuming uniform current density)

Superconducting Wire and Cable for RHIC

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Abstract—The superconducting dipole and quadrupole magnets in the RHIC accelerator ring are to be fabricated from 30-strand superconducting cable. The RHIC wire has a diameter of 0.65 mm, copper-to-superconductor ratio of 2.25, filament diameter of 6 μm and high critical current density. Primary emphasis during manufacturing has been on uniformity of materials, processes and performance. Near final results are presented on a production program which has extended over two years. Measured parameters are described which are important for design of superconducting accelerator magnets.

I. INTRODUCTION

A decade ago the principal concern of superconducting magnet design was to obtain wire with the highest possible value of the critical current density, J_c. Since then, due primarily to the work of Larbalestier and others [1], J_c values in the neighborhood of 3000 A/mm^2 have become more or less routine in production [2]. For machines like HERA and RHIC this is a comfortable level of current density and attention has turned to the equally important concern of magnet designers, uniformity of superconductor wire and cable. In two previous articles [3,4] the manufacturing objectives and procedures of the RHIC procurement program were described, and early test data were given. Now, nearly all wire and two-thirds of cables for the RHIC dipole and quadrupole magnets have been produced. In this paper we give a summary of the main performance results on this material.

A. Wire Data

The most important quantities in the RHIC wire specification [5] are the critical current at an applied field of 5 Tesla and a temperature of 4.2 K, I_c(5T, 4.2 K), the electrical resistance per meter at 295 K, R295, and the wire diameter, D. Together, these quantities determine J_c and the copper-to-superconductor ratio, C/S. Our reasons for preferring the above set of specifications have been discussed in detail elsewhere [6,7]. Another quantity, $I_c(3T)/I_c(5T)$ or "3/5 ratio" is also specified. This quantity checks on control of metallurgical processing for the Nb-Ti superconductor as raw material and in wire processing and, as a consequence, on the low field magnetization.

1) Wire diameter: Wire diameters were measured by OST during final draw using on-line laser micrometry. Figure 1 shows the data for nearly the entire production of approximately 18 million meters of wire. The variation in D settled down considerably in the second half of the production run; it appears that a variation tolerance of $\pm 5 \times 10^{-5}$ inches (1.3 μm) would be feasible in the future. Wire cleanliness and surface integrity are checked by visual and eddy current inspection.

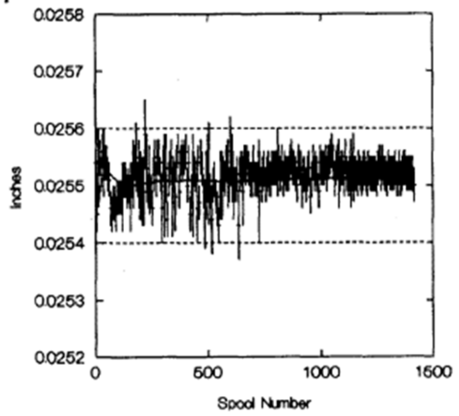

Figure 1. On-line laser diameters with two axes typically measured every meter. Average value for one-sixth of all spools, with ± 3 std. dev. vertical bars. Solid line is the running average.

2) Wire I_c(5T, 4.2 K): Figure 2 shows the critical current data. The small but steady increase in I_c during the first half of production is not attributable either to diameter variation or to variation in C/S. Instead it appears to be associated with slight decreases in interfilament spacing which resulted from changes in assembly during the earlier billet set ups. Gregory et al [8] first showed that closer packing led to greater uniformity of filament cross section and, hence, increased J_c. Ii et al [9] showed that this effect was active even for relatively small interfilament spacing decreases of order 0.1 μm. The present data were found to correspond to a decrease in interfilament spacing over the first half of production of about 0.07 μm as determined by photomicrography of the wire cross sections. The Quality Indices (n-values) from wire critical current measurements increased very slightly when interfilament spacing decreased.

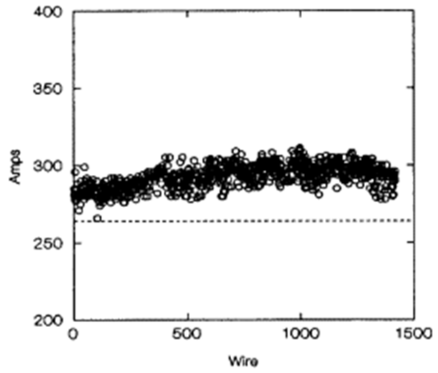

Figure 2. I_c(5T, 4.2 K). Mean value = 293 A; std. dev. = ± 7 A (2.4%). Dashed line is RHIC minimum specification limit.

3) $I_c(3T)/I_c(5T)$: Values of this quantity were determined by short sample tests at OST. These tests are also performed on approximately 15% of the wires by BNL. The I_c(5T) data generally agree within 1% (± 1.5 A) with those at OST. The distribution of 3/5 ratios has remained very uniform throughout the entire production, thereby indicating very good control of the metallurgical processing of the source alloy and wire production. The mean value and standard deviation are 1.49 and 0.01, respectively. A graph of the 3/5 distribution is shown in Ref. [4].

4. R295: Figure 3 shows the R295 distribution. The method of calculating C/S is discussed in Refs. [6,7]. It is necessary to measure the residual resistance also. The value of RRR is typically between 40 and 44; the effect of this variation on C/S is 0.02 (1%). (In final RHIC magnets RRR increases to above 200 because the copper is annealed during coil curing.) The calculated C/S distribution has a mean value of 2.20 and standard deviation of ± 0.06. This variation is largely due to billet processing. Since the electrical method of determining C/S is not practical during billet processing, the chemical method is used. The correlation of this value of C/S and the resistance of final size wire is subject to some uncertainty due to the resistance of interfilamentary copper and the resistance of barrier layers. It is necessary, therefore, to establish a correlation between billet assembly parameters and final size wire resistance.

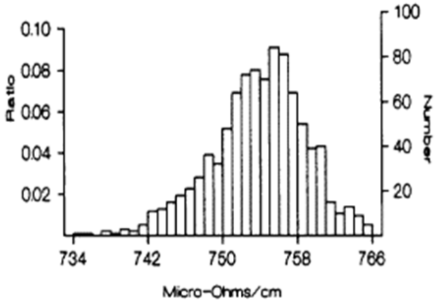

Figure 3. R295 distribution. Mean = 753; std. dev. = ± 5.

5. Piece length: The RHIC specification calls for a minimum cabling spool length of 700 m and no cold welds. These conditions have proven to be very easy in view of the long piece lengths achieved by OST [4]. Since the earlier report, the average piece length has increased to 10.9 km, with greater than 98% of all drawn lengths in excess of 2 km.

B. Cable Data

1. Mid-thickness: Uniform, stable magnet performance depends critically on uniform cable dimensions. Cable mid-thickness is especially important as it directly affects critical current degradation and coil pre-stress. Figure 4 shows results for approximately 370 km or about 70% of total production. These measurements were made at NEEW using a Cable Measuring Machine (CMM) apparatus. Periodic checks are made by a 10-stack short sample method in order to insure the accuracy of this important measurement. The results are shown in Fig. 5. For the second half of production shown in the figure, CMM measurements were made at intervals of one foot and averaged for the exact 10-stack sample length.

2. Cable width and keystone angle: Measured values of these parameters are well within specified tolerances. The mean values and standard deviations are: cable width = 0.383 $\pm$ 0.0002 inches, and keystone angle = 1.18 $\pm$ 0.02 degrees.

3. Cable critical current: Figure 6 shows the short

Standardized Ic(B,T) Curves for Magnet Designers

- All EIC IR magnet designers should use the same I_c(B,T) curve for various analysis.
- The I_c(B,T) curves are standardized with a set of fitting parameters. The type of fitting (e.g., Bottura curve) should be the same even if the exact values of the fitting parameters is different for different wires and/or cables, if and as necessary.
- The fittings should ideally be based on the measurements. However, in the absence of the measurements (e.g., they are currently not available at 1.92 K for margin calculations, and they may never become available at higher temperature for quench analysis), they should be based upon agreed set of fitting parameters.
- The basis of arriving to a set of parameters maybe debated and periodically updated (with version numbers) as the measurements become available.
- Measurements at 4.2 K and possibility of performing them at 1.9 K and also the proposed fitting parameters will be presented in the following talks.

Other Measurements

- Magnetization measurements have a significant impact on the models to compute errors due to persistent currents.
- They are already being performed in certain ways and more possible and will be discussed in next presentations.
- Measurements of cable performance (I_c Vs. B) are expensive. They should be carried out at certain stage. As such, relatively speaking, we don't expect much degradation to have significant impact on designs, particular since the keystone angles are small and operating margins are large (65%-70% on the loadline).
- Given above, I suggest not to include cable degradation in the magnetic design calculations.
- Any feedback?