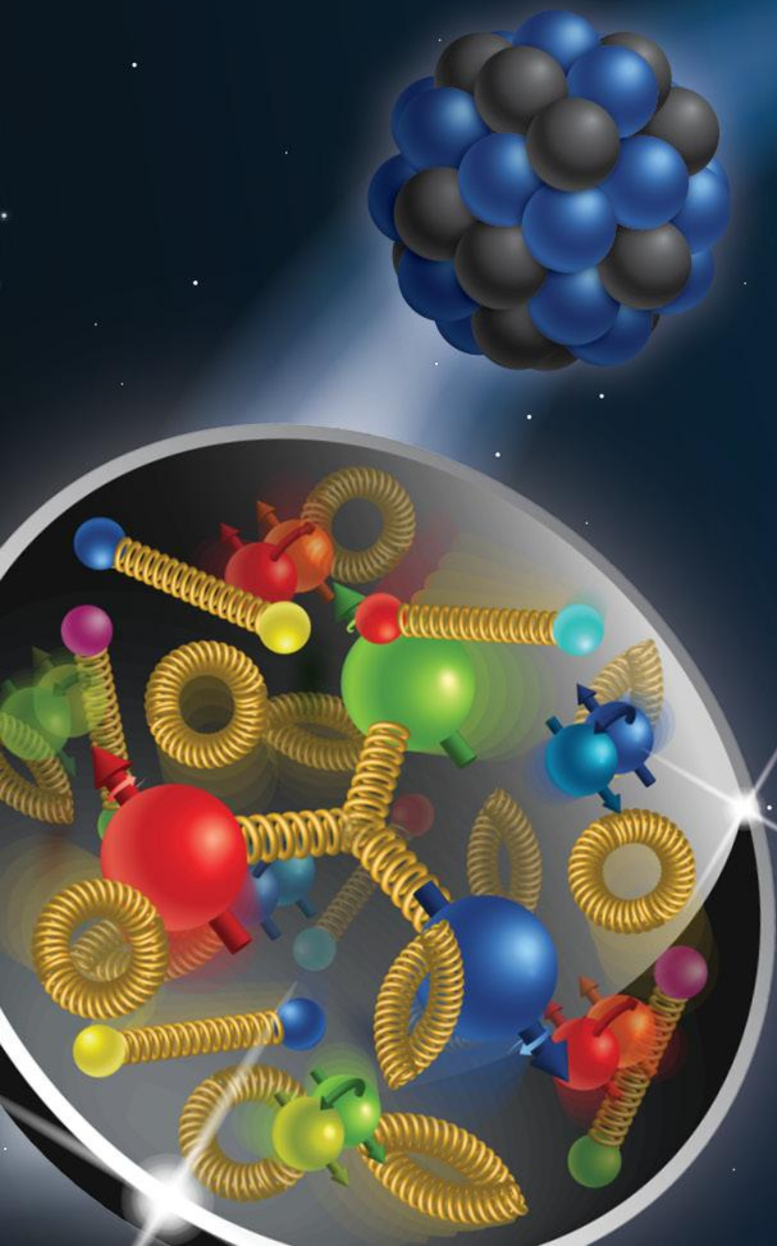


Evaluation of RHIC Magnets for EIC

100 mm Insertion Dipole
80 mm Arc Quadrupole

Ramesh Gupta
Superconducting Magnet Division
April 7, 2021

Electron Ion Collider – eRHIC

BROOKHAVEN NATIONAL LABORATORY
U.S. DEPARTMENT OF ENERGY | Office of Science

Background and Strategy

- EIC design requires RHIC magnets to operate at higher fields. The plan, furthermore, is to operate them at higher temperatures as well.
- Even though, most RHIC magnets were designed with a heathy margin, doing both (higher field & higher temperature) raises concern.
- RHIC magnet calculations were performed on VAX computers using codes that were developed extensively at BNL. VAXes don't exist now.
- Two prong approach for performing new analysis, as needed:
  a) Make models on the software that are available now – e.g., ROXIE
  b) Invest modest resources to transport VAX codes to PC/LINUX, so that the variety of design and analysis tools that were developed at BNL earlier can be used again (including input files) to evaluate performance of RHIC magnets in EIC operating conditions (MoU with Steve Kahn). This contribution will help EIC project in general.

Initial progress is usually slow as we try to find old drawings and old files

Evaluation of (a) 100 mm Insertion Dipoles and (b) 80 mm Arc Quadrupoles for EIC
(to operate at higher field and higher temperature)

Questions to be addressed:

Can RHIC (250 GeV) magnets operate safely for EIC (275 GeV)?

What are the field margins and temperature margins?

(We addressed these questions last year for the RHIC 80 mm arc dipoles with the help of ROXIE models which already existed)

- **This MoU covers other RHIC magnets that will be used in EIC**

This presentation summarizes the new ROXIE models & analysis for:

- **Insertion dipoles with 100 mm coil id**
- **Arc quadrupoles with 80 mm coil id**

Superconducting Cables used in RHIC 80 mm & 100 mm Magnets

Specifications

Table 2-2 . 30-Strand Cable Requirements

Requirement	Value
DIMENSIONAL AND MECHANICAL	
Number of Wires in Cable	30
Cable Mid-Thickness	(0.04590±0.00025 in.) 1.166±0.006 mm
Cable Width	(0.383±0.001 in.) 9.73±0.03 mm
Cable Keystone Angle	1.2±0.1 deg
Cable Lay Direction	Left
Cable Lay Pitch	(2.9±0.2 in.) 74±5 mm
Wire Twist Pitch in Cable	(1.9±0.2 twists/in.) 0.75±0.08 twists/cm
ELECTRICAL	
Cable Minimum Critical Current at 5.0 T, 4.2 K	7524 A
Cable Maximum R (295 K)	0.00268 Ω/m
Cable Minimum RRR	38

Delivered

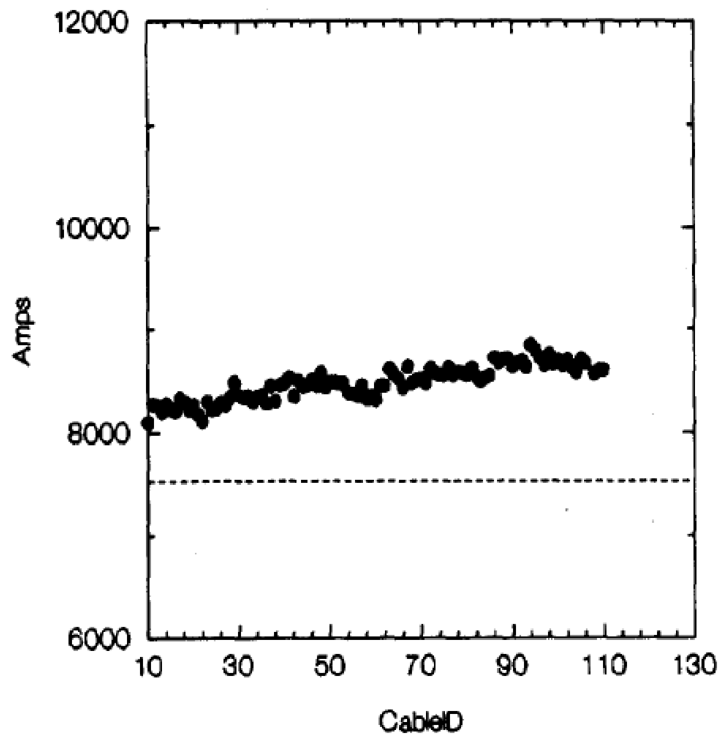


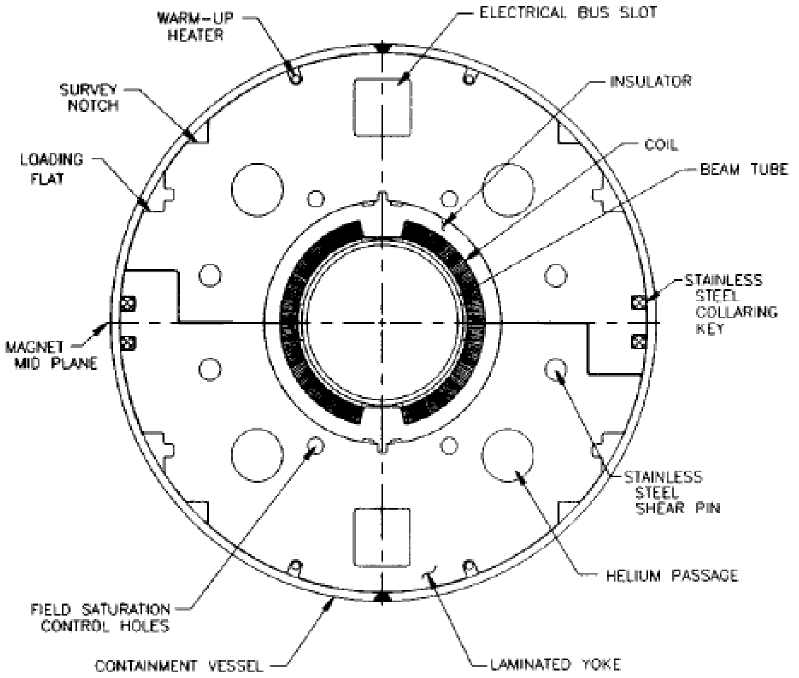
Figure 6. Cable short sample I_c (5T, 4.2 K) results. The mean value is 8475 A, std. dev. = ±163 A (1.9%). The dashed line is the specification minimum.

Cable used (8475 A on average) was ~10% better than specified (7524 A)

- **Useful help for EIC**

RHIC 100 mm dipole

Coil ID	100 mm
Coil OD	120 mm
Number of turns per pole	40
Magnetic length	3.6 m
Iron inner diameter	139.4 mm
Iron outer diameter	310 mm
Shell thickness	6.35 mm
Operating temperature	4.6 K
Design current	5.0 kA
Design field	3.5 T
Quench current	7.4 kA



RHIC 100 mm dipole design

- The design of RHIC 100 mm insertion dipole is like the RHIC 80 mm dipoles.
- 100 mm dipole has a bit higher transfer function and lower peak field (both good), giving a bit higher quench field (however, only a few percent) at about the same quench current.
- However, 100 mm insertion dipoles did not go through a large numbers of iterations as the 80 mm arc dipoles did. In fact, the first prototype became the spare and rest went into machine.

Measured Quench Performance of 100 mm Dipoles

Measurements show that RHIC 100 mm dipoles have sufficient "*mechanical*" margin for EIC operation at 275 GeV (even though they required several quenches)

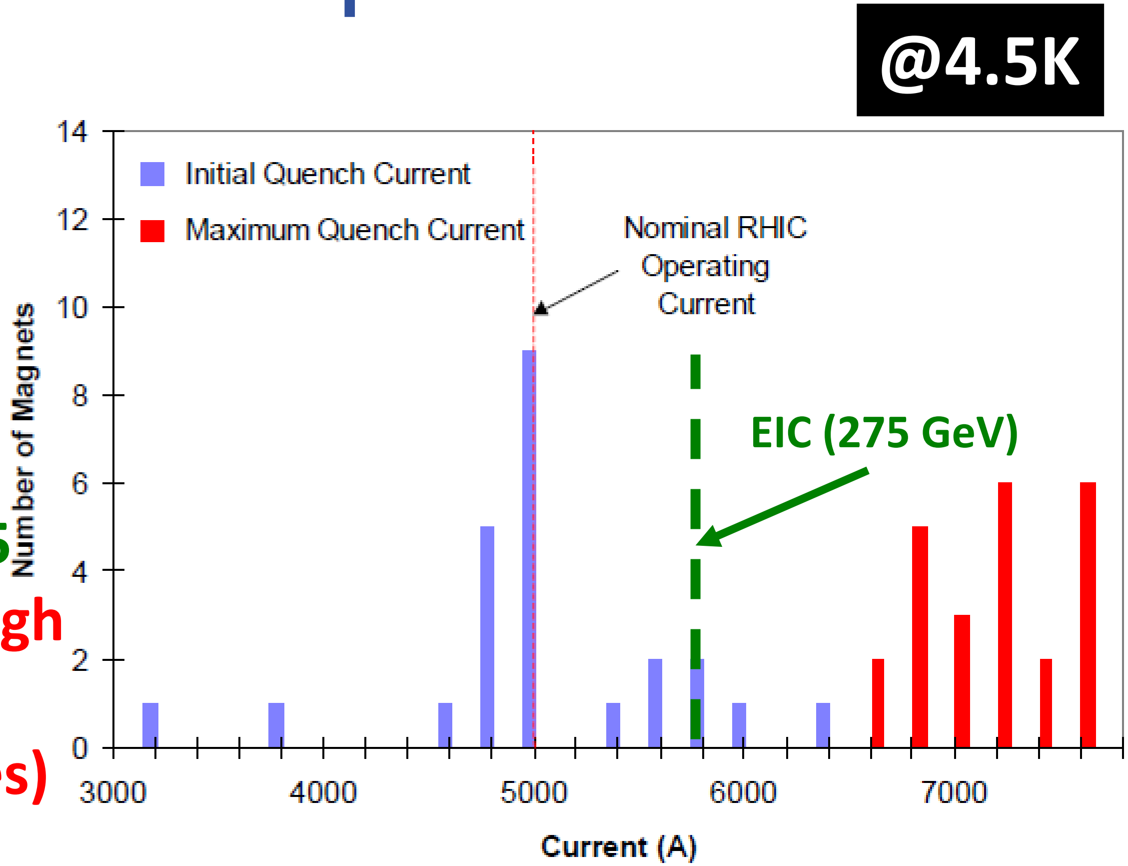
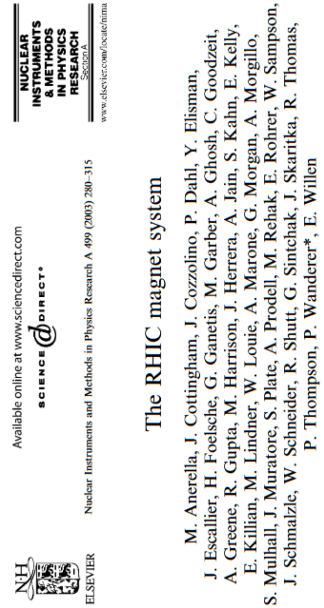


Figure 42 Quench performance of 24 large aperture (100 mm) dipoles, tested at 4.5 K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The RHIC magnet system

M. Anerella, J. Cottingham, J. Cozzolino, P. Dahl, Y. Elisman, J. Escallier, H. Foelsche, G. Ganetis, M. Garber, A. Ghosh, C. Goodzeit, A. Greene, R. Gupta, M. Harrison, J. Herrera, A. Jain, S. Kahn, E. Kelly, E. Killian, M. Lindner, W. Louie, A. Marone, G. Morgan, A. Morgillo, S. Mulhall, J. Muratore, S. Plate, A. Prodell, M. Rehak, E. Rohrer, W. Sampson, J. Schmalzle, W. Schneider, R. Shutt, G. Sintchak, J. Skaritka, R. Thomas, P. Thompson, P. Wanderer*, E. Willen

Brookhaven National Laboratory, Upton, NY 11973, USA

Comparison of 80 mm Vs 100 mm Dipoles

Measurements show that RHIC 100 mm dipoles have sufficient "*mechanical*" margin for EIC operation at 275 GeV (even though they required several quenches)

100 mm

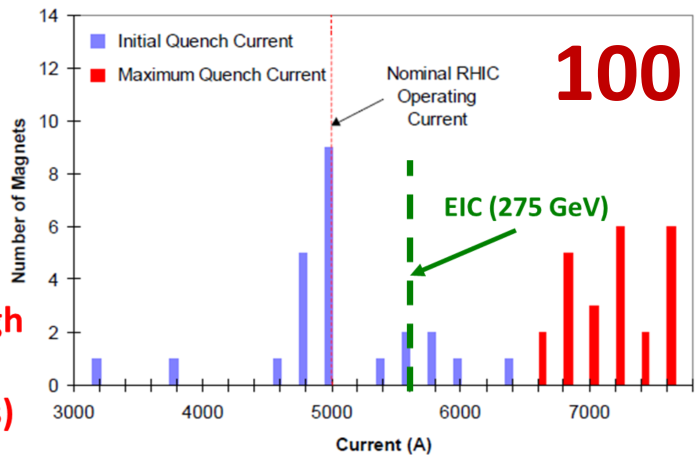
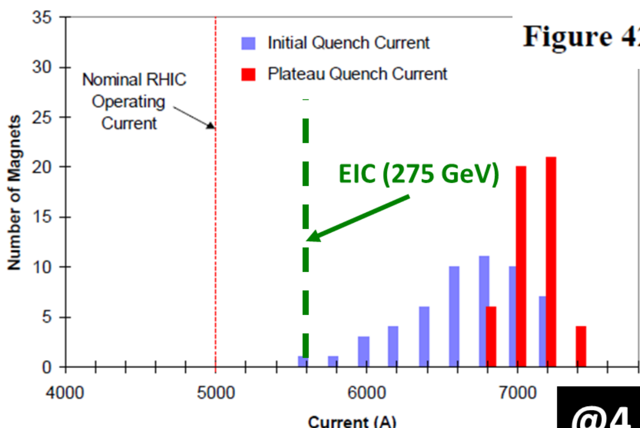


Figure 42 Quench performance of 24 large aperture (100 mm) dipoles, tested at 4.5 K

80 mm



@4.5K

Figure 3 Quench performance of 51 arc dipoles, tested at 4.5 K. The average plateau quench current of these 51 magnets was 7101 A; the field at this average quench current is 4.52 T.

Field & Field Quality in RHIC 100 mm dipoles

I(A) & B(T) measured; peak fields computed

DRZ102	body	Bpk/Bo	
RHIC 100 mm Dipole		1.129	
I(A)	Bo(T)	Bpk(T)	TF(T/kA)
51.08	0.04	0.04	0.749
201.11	0.15	0.17	0.744
401.22	0.30	0.34	0.745
661.69	0.49	0.56	0.746
1001.60	0.75	0.84	0.746
1451.25	1.08	1.22	0.746
2001.11	1.49	1.69	0.746
2600.96	1.94	2.19	0.745
3000.74	2.23	2.52	0.743
3600.41	2.65	2.99	0.736
4000.38	2.91	3.29	0.728
4600.12	3.28	3.71	0.714
5000.08	3.52	3.97	0.703
5599.99	3.85	4.35	0.687
5999.93	4.06	4.59	0.677
6399.87	4.27	4.82	0.668
6599.91	4.38	4.94	0.663
6999.58	4.58	5.17	0.654

(desired: low integral harmonics at 5 kA)

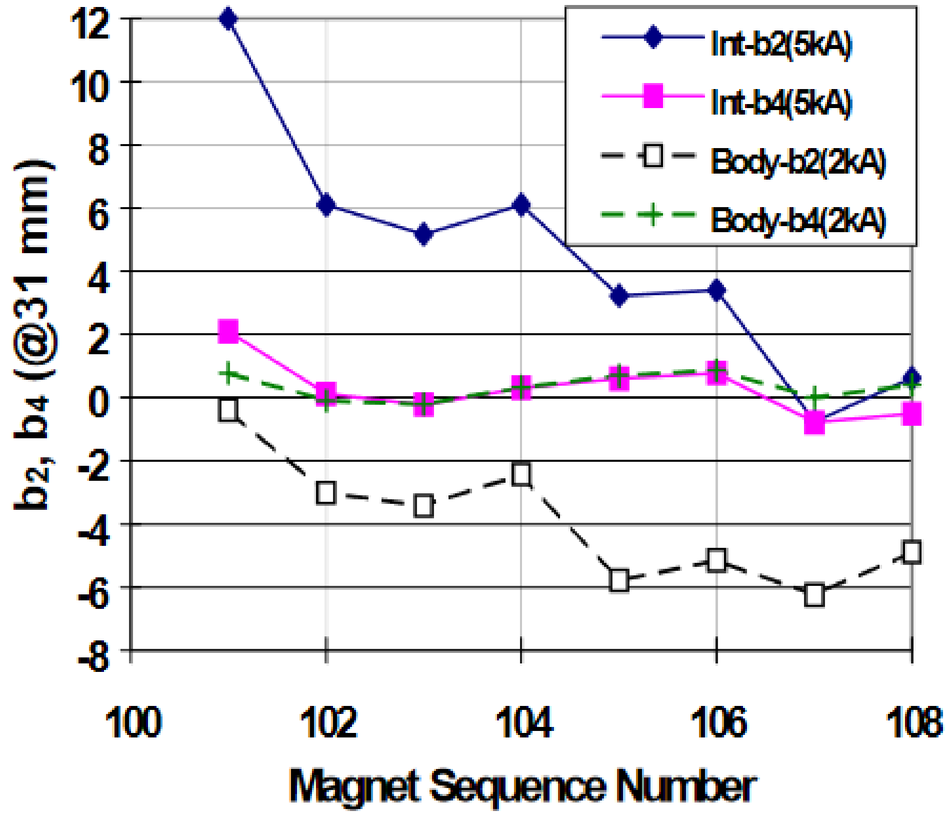


Figure 3. Plot showing b_2 and b_4 by magnet.

Field quality optimization through the production.
No prototype (1st time). Designed stabilized 105-125

Average Field errors ~10^{-4} (up to 80% of the coil radius)

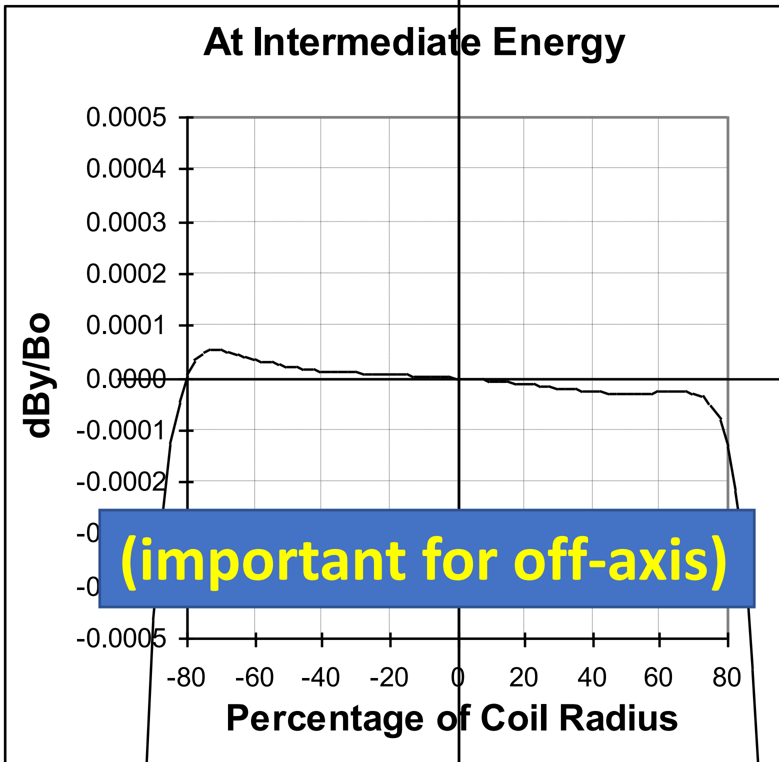
Note:
80% of coil radius, not just 2/3.

At 80%, you are close to inner radius of beam tube. This means that almost entire physical aperture has become a good field aperture.

Geometric Field Errors on the X-axis of RHIC DRZ magnets (108-125)

Coil X-section was not changed between 1st prototype and final production magnet

A Flexible & Experimental Design Approach Allowed Right Pre-stress & Right Harmonics



(important for off-axis)

Estimated Integral Mean in Final Set
(Warm-cold correlation used in estimating)
Harmonics at 3kA (mostly geometric)
Reference radius is 31 mm (Coil 50 mm)

b1	-0.28	a1	-0.03
b2	-0.26	a2	-3.36
b3	-0.07	a3	0.03
b4	0.15	a4	0.48
b5	0.00	a5	0.04
b6	0.32	a6	-0.24
b7	0.00	a7	0.01
b8	-0.08	a8	0.05
b9	0.00	a9	0.00
b10	-0.12	a10	-0.02
b11	0.03	a11	-0.01
b12	0.16	a12	0.06
b13	-0.03	a13	0.03
b14	-0.10	a14	0.02

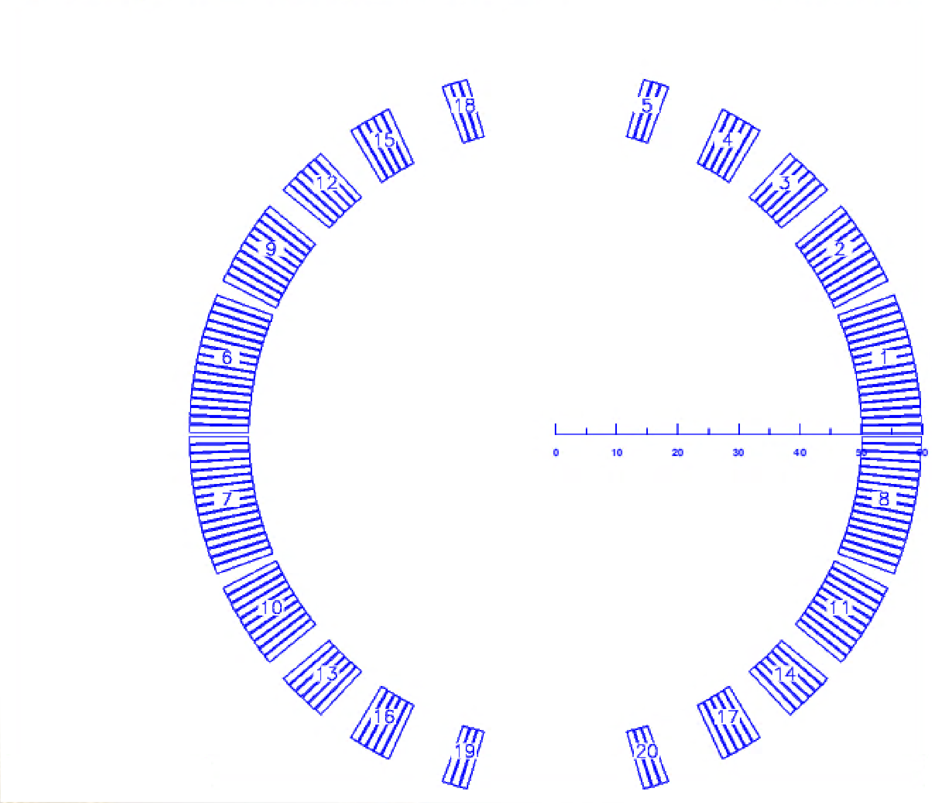
Raw Data Provided by Animesh Jain at BNL

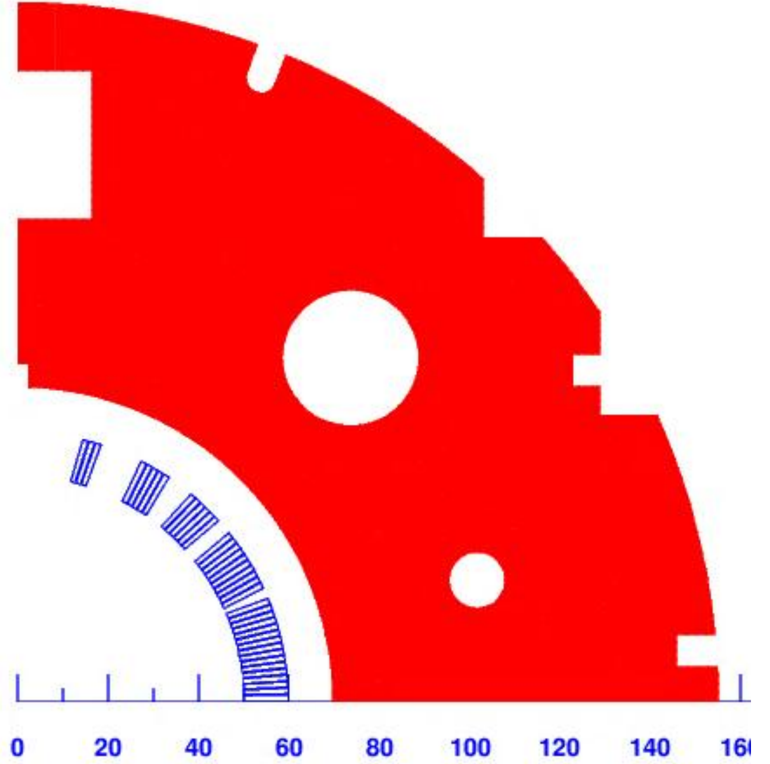
Field errors are 10^{-4} to 80% of the aperture at midplane.
(Extrapolation used in going from 34 mm to 40 mm; reliability decreases)

New Modelling and Analysis with ROXIE for evaluating the use of RHIC Magnets in EIC

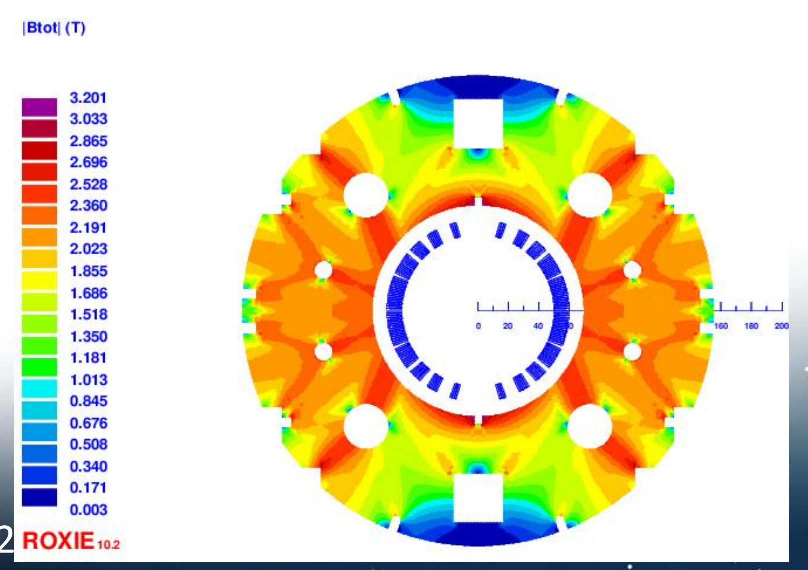
ROXIE Model of RHIC 100 mm dipole

rhic 10 cm dipole for EIC 250 GeV: 3.87 T, 5.0 K, 4.5 kA 21/03/19 09:57





rhic 10 cm dipole for EIC 250 GeV: 3.87 T, 5.0 K, 4.5 kA 21/03/19 09:57



Model Calculations for RHIC 100 mm Insertion Dipole at RHIC Design Field (250 GeV@3.5 T)

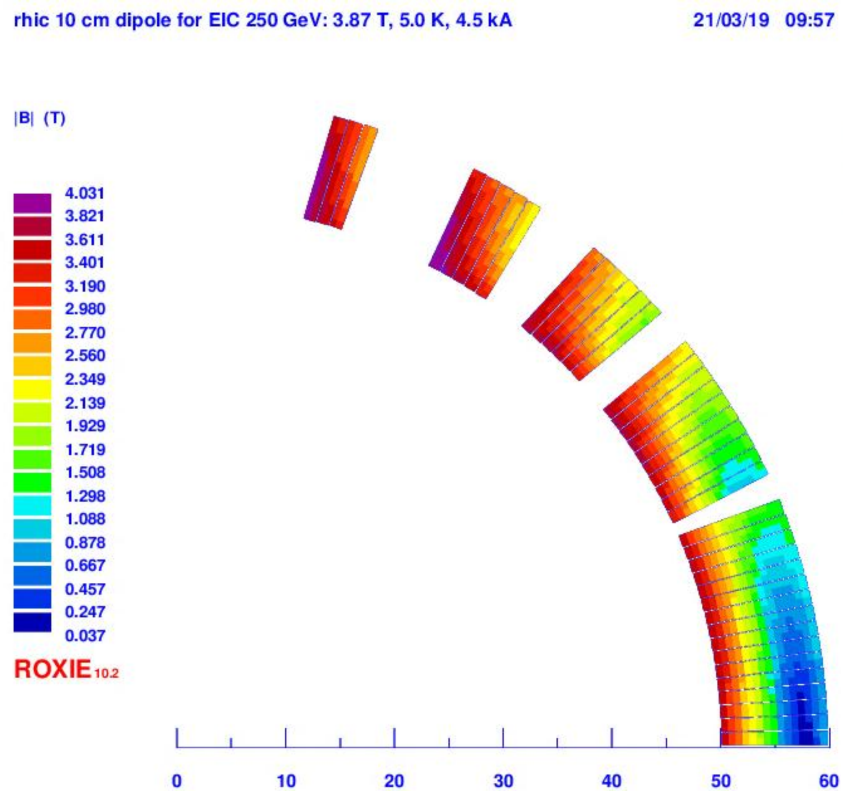
Summary of the ROXIE Model

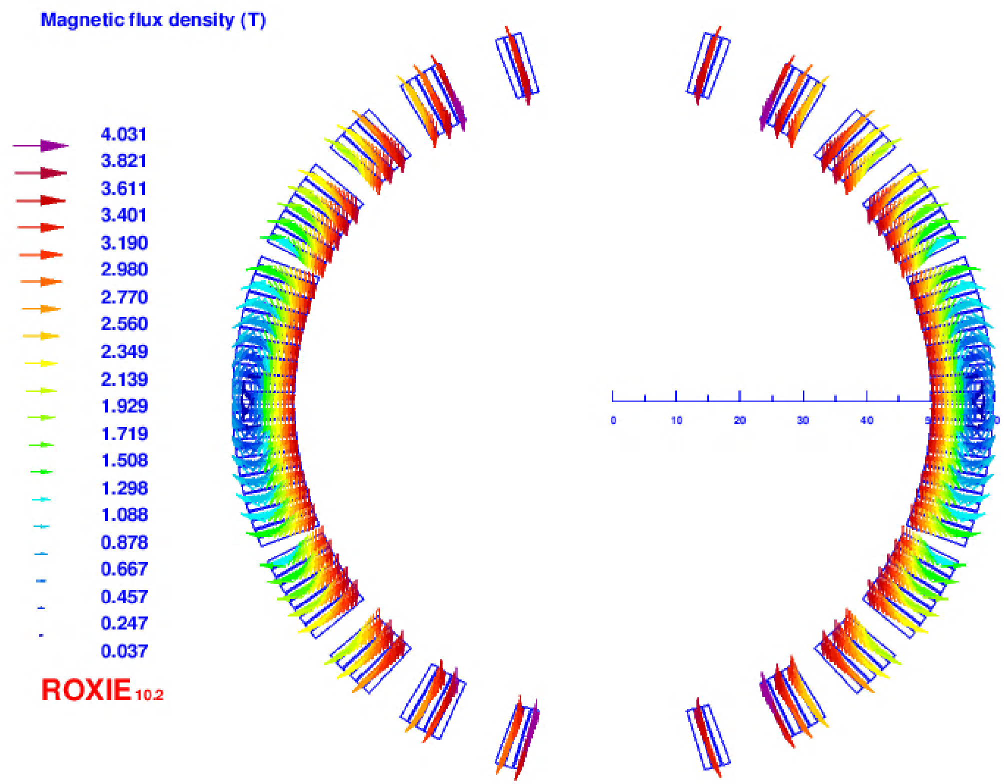
MAIN FIELD (T):3.5

PEAK FIELD IN CONDUCTOR (T): 4.01
CURRENT IN CONDUCTOR (A): 5000
PERCENTAGE ON THE LOAD LINE :75.39
QUENCHFIELD (T): 5.32
TEMPERATURE MARGIN TO QUENCH(K):1.16
PERCENTAGE OF SHORT SAMPLE CURRENT: 60.3

Field in conductor at RHIC design field

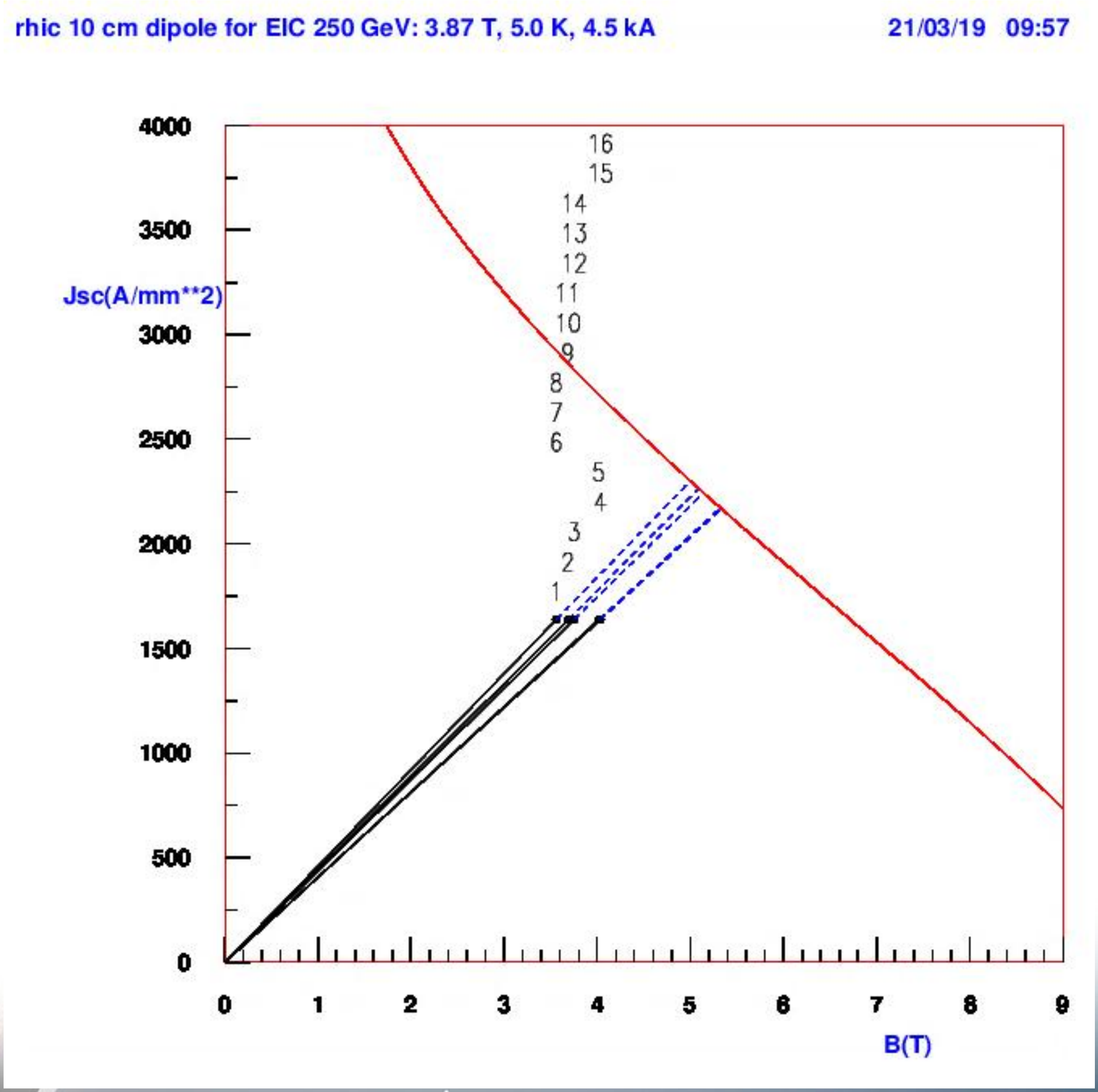
@B_o = 3.5 T   Peak Field = 4 T



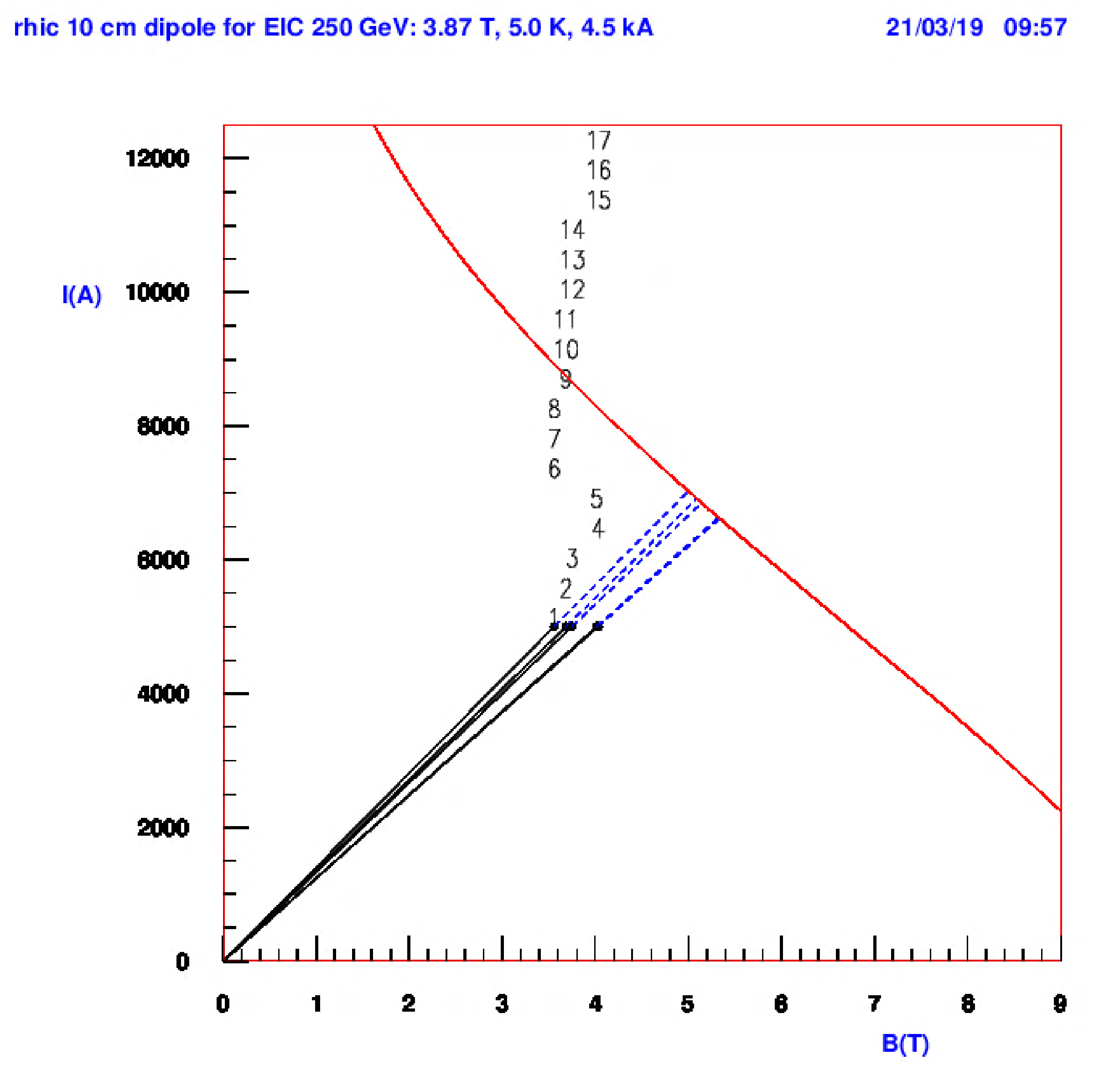


Computed Quench Margin in $J_{sc}(A/mm^2)$

@B_o=3.5 T
I = 5.0 kA
T = 4.5 K

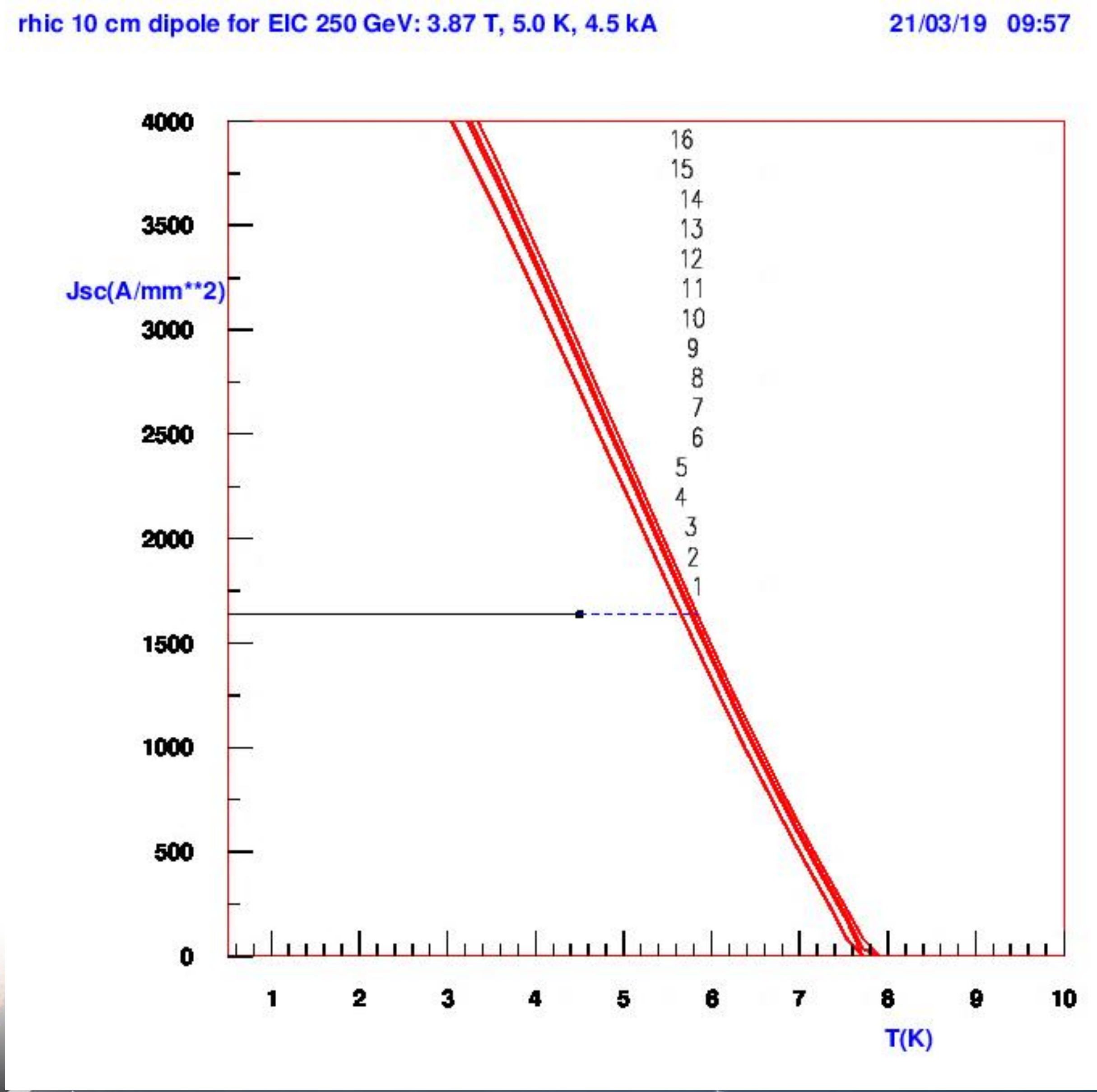


Computed Quench Margin in I(A)



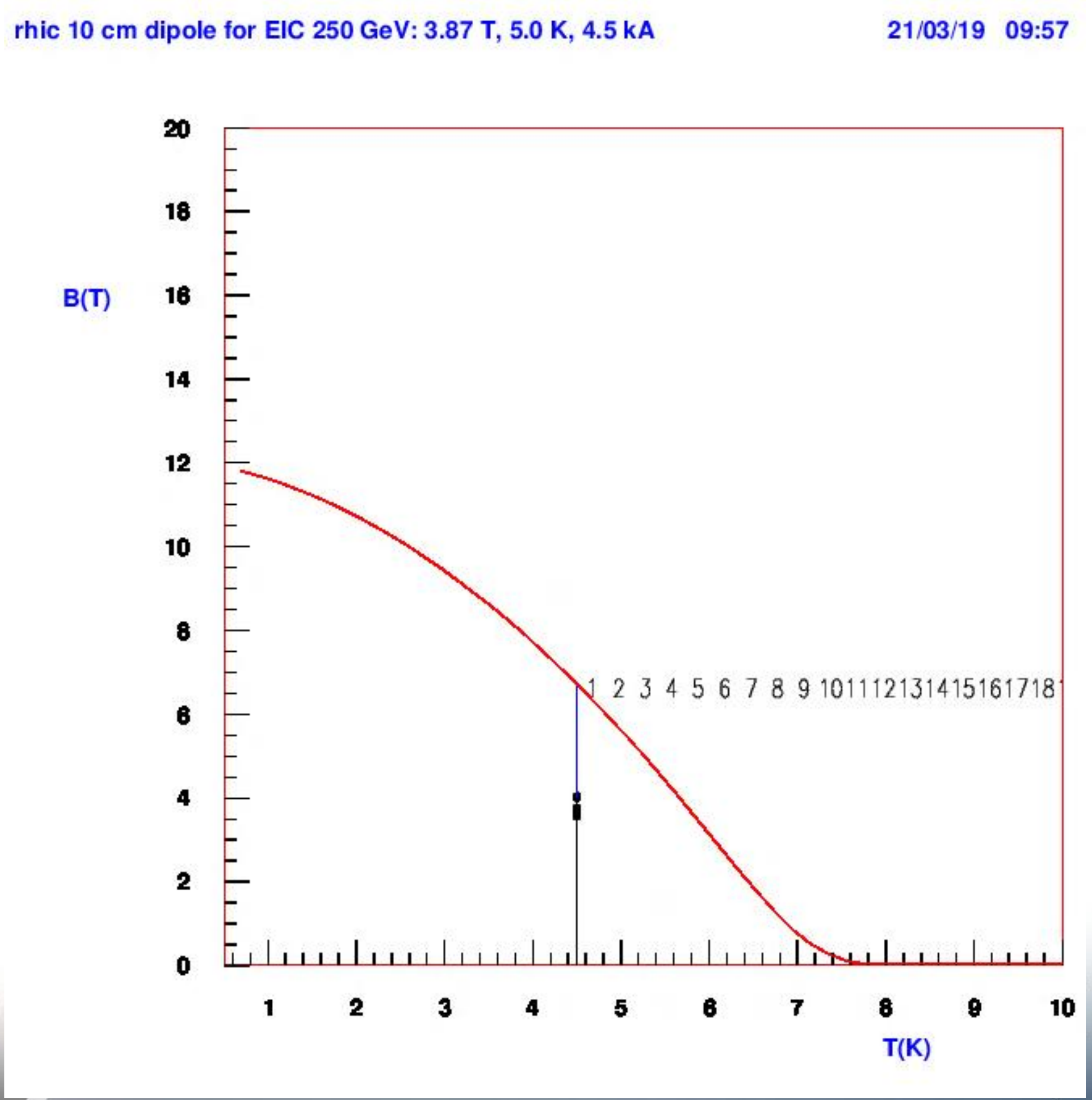
@B_o=3.5 T
I = 5.0 kA
T = 4.5 K

Computed Quench Temperature Margin



@B_o=3.5 T
I = 5.0 kA
T = 4.5 K

Computed Quench Field Margin



@B_o=3.5 T
I = 5.0 kA
T = 4.5 K

Model Calculations for 100 mm Dipole at EIC Design Field (275 GeV@3.87 T)

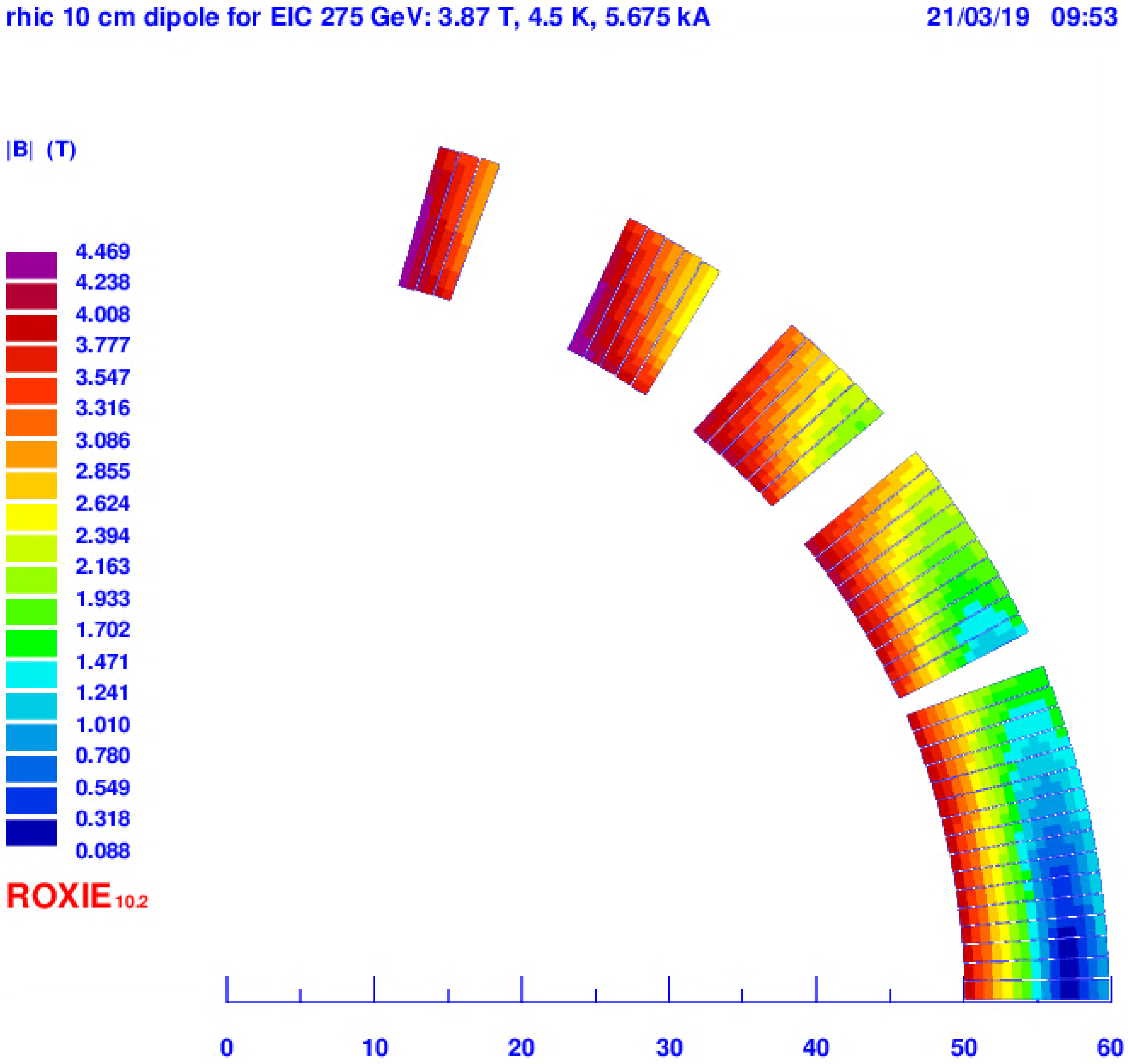
Temperature: 4.5 K

Summary of Calculations for 275 GeV @4.5 K

MAIN FIELD (T)	-3.870249
BLOCK NUMBER	20
PEAK FIELD IN CONDUCTOR 160 (T)	4.4517
CURRENT IN CONDUCTOR 160 (A)	5675.0000
LOWEST FIELD IN CONDUCTOR 158 (T)	2.9332
SUPERCONDUCTOR CURRENT DENSITY (A/MM2)	1858.4451
COPPER CURRENT DENSITY (A/MM2)	829.6630
PERCENTAGE ON THE LOAD LINE	84.6013
QUENCHFIELD (T)	5.2620
TEMPERATURE MARGIN TO QUENCH (K)	0.7386
PERCENTAGE OF SHORT SAMPLE CURRENT	73.5645

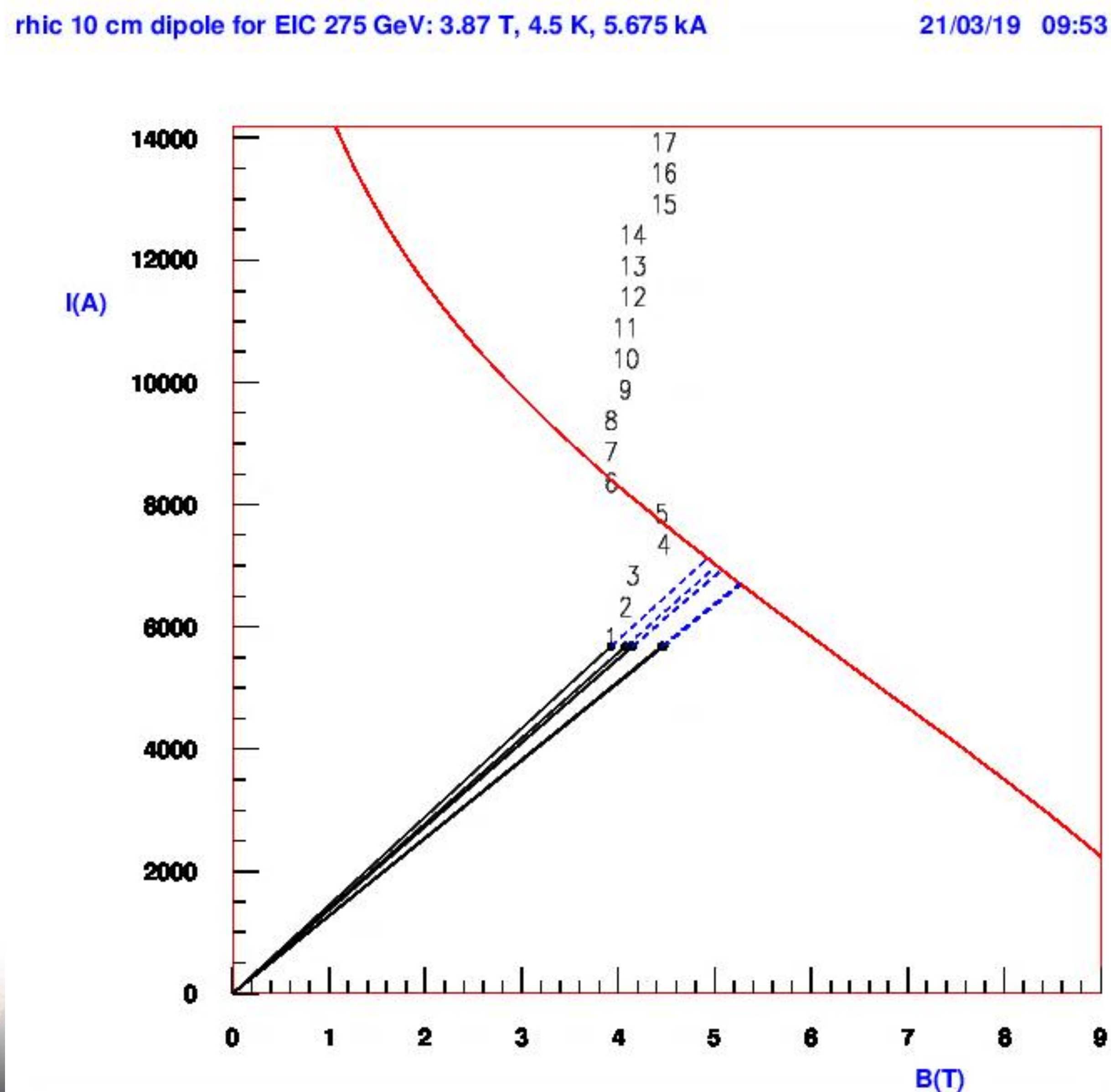
Field in conductor at EIC design field

100 mm dipole
@B_o=3.87 T
I = 5.675 kA
T = 4.5 K



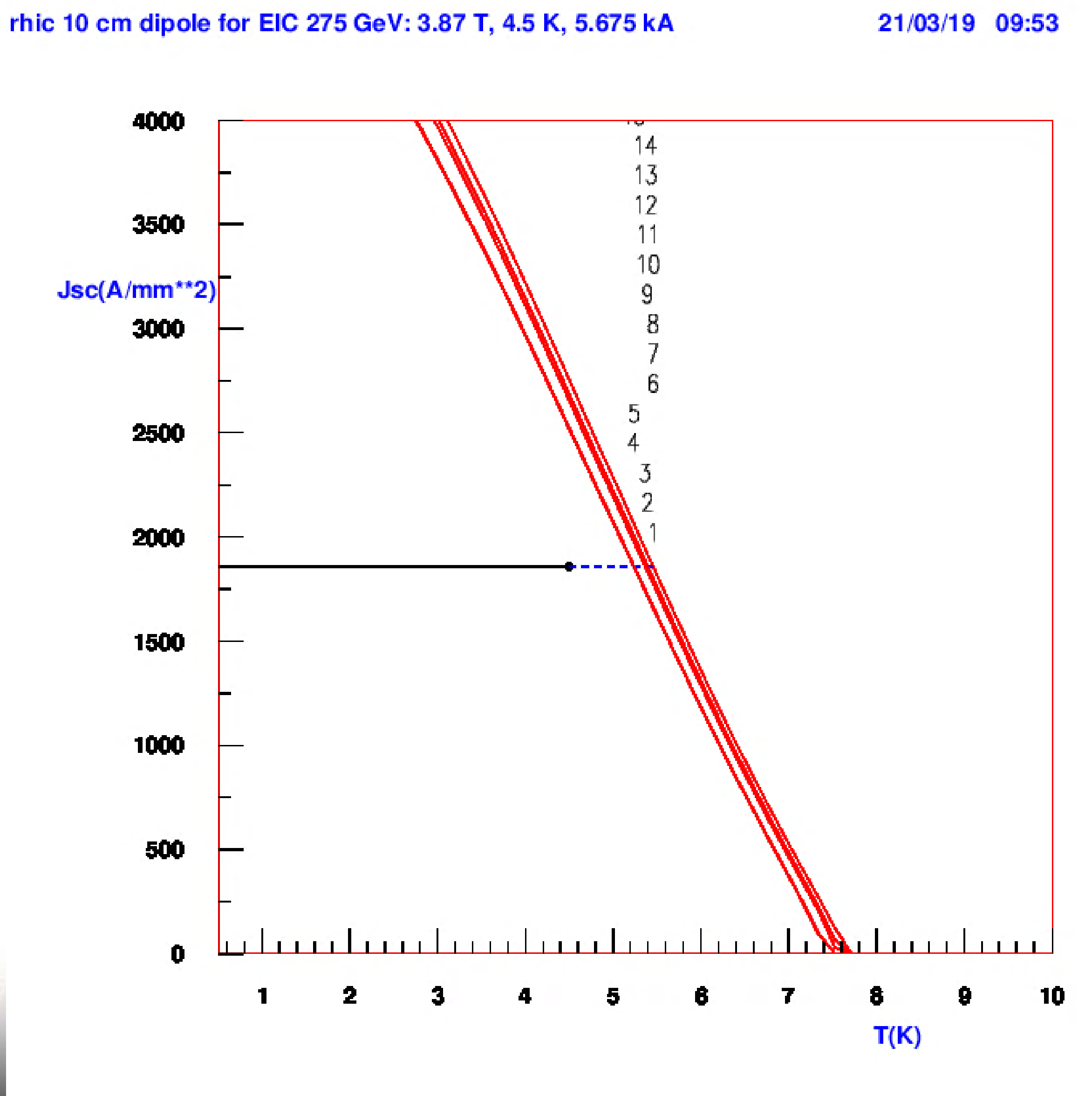
Computed Quench Margin

100 mm dipole
@B_o=3.87 T
I = 5.675 kA
T = 4.5 K



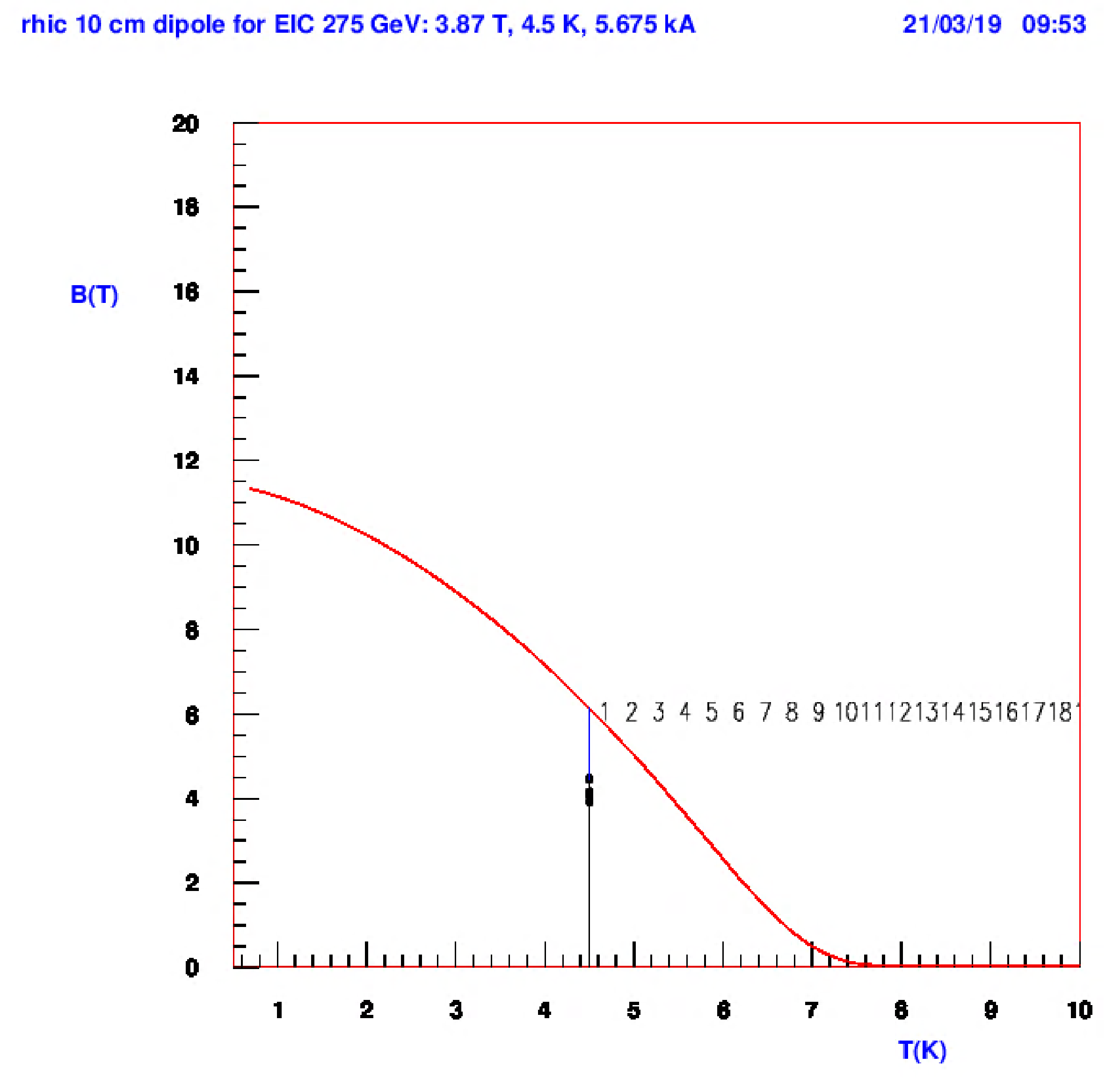
Computed Quench Temperature Margin

100 mm dipole
@B_o=3.87 T
I = 5.675 kA
T = 4.5 K



Computed Quench Field Margin

100 mm dipole
@B_o=3.87 T
I = 5.675 kA
T = 4.5 K



Model Calculations for 100mm Insertion Dipole at EIC Design Field (275 GeV@3.87 T)

Temperature: 5 K

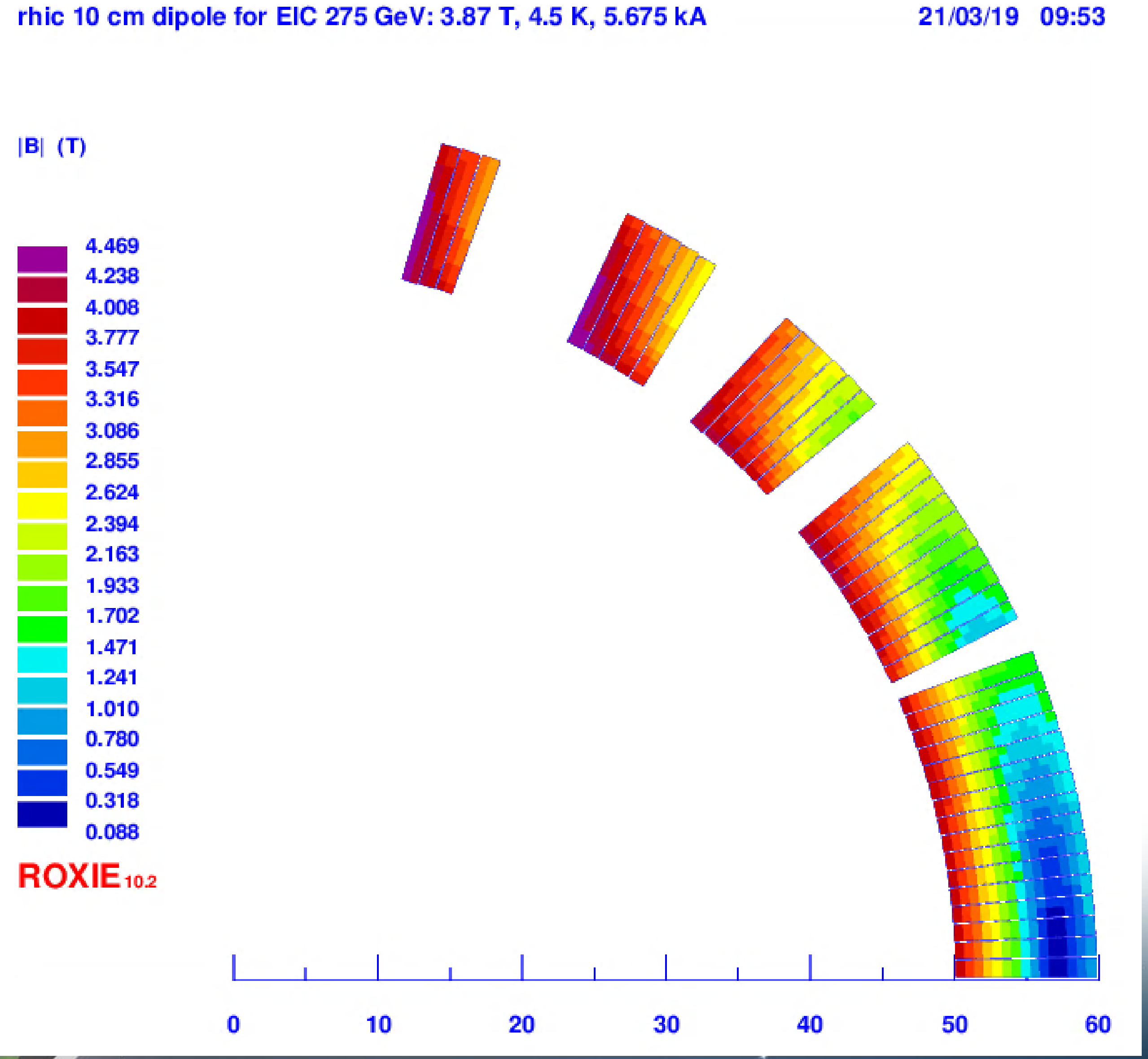
Summary of Calculations for 275 GeV @5 K

MAIN FIELD (T)	-3.870249
BLOCK NUMBER	20
PEAK FIELD IN CONDUCTOR 160 (T)	4.4517
CURRENT IN CONDUCTOR 160 (A)	5675.0000
LOWEST FIELD IN CONDUCTOR 158 (T)	2.9332
SUPERCONDUCTOR CURRENT DENSITY (A/MM2)	1858.4451
COPPER CURRENT DENSITY (A/MM2)	829.6630
PERCENTAGE ON THE LOAD LINE	94.3118
QUENCHFIELD (T)	4.7202
TEMPERATURE MARGIN TO QUENCH (K)	0.2386
PERCENTAGE OF SHORT SAMPLE CURRENT	89.6123

Field in conductor at EIC design field

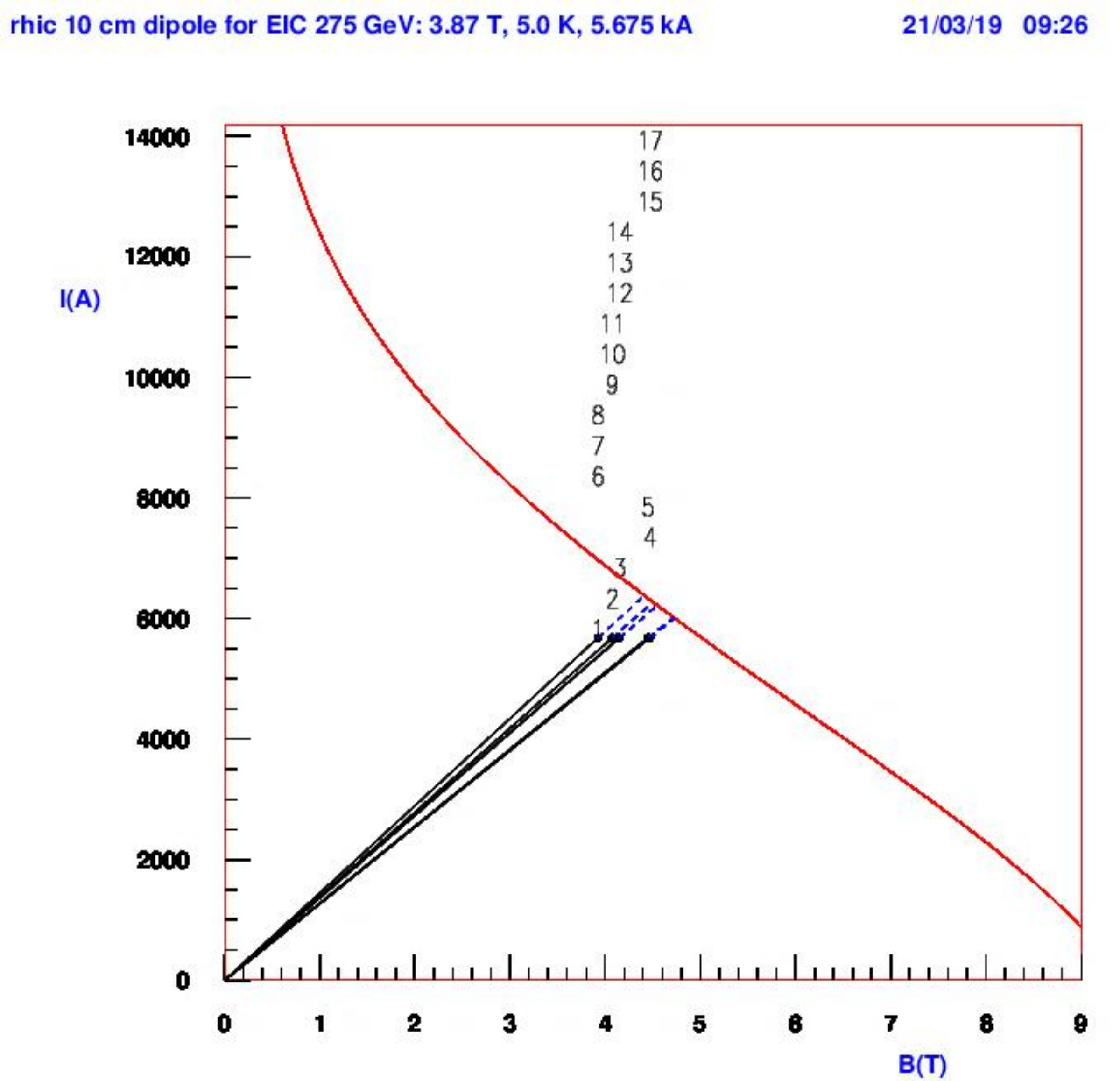
B_o = 3.87 T

B_{pk} = 4.46 T



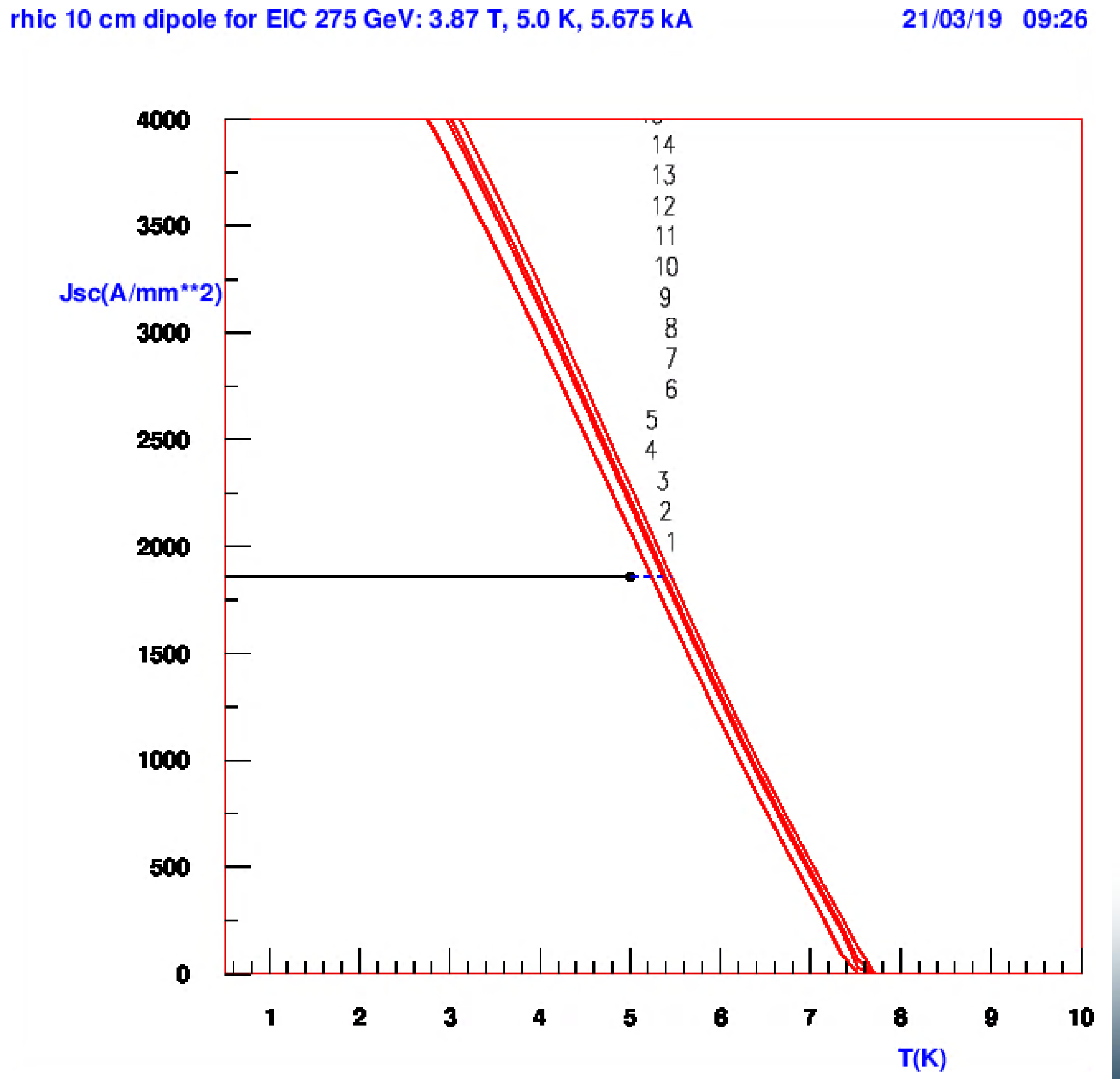
Computed Quench Margin

100 mm dipole
@B_o=3.87 T
I = 5.675 kA
T = 5.0 K



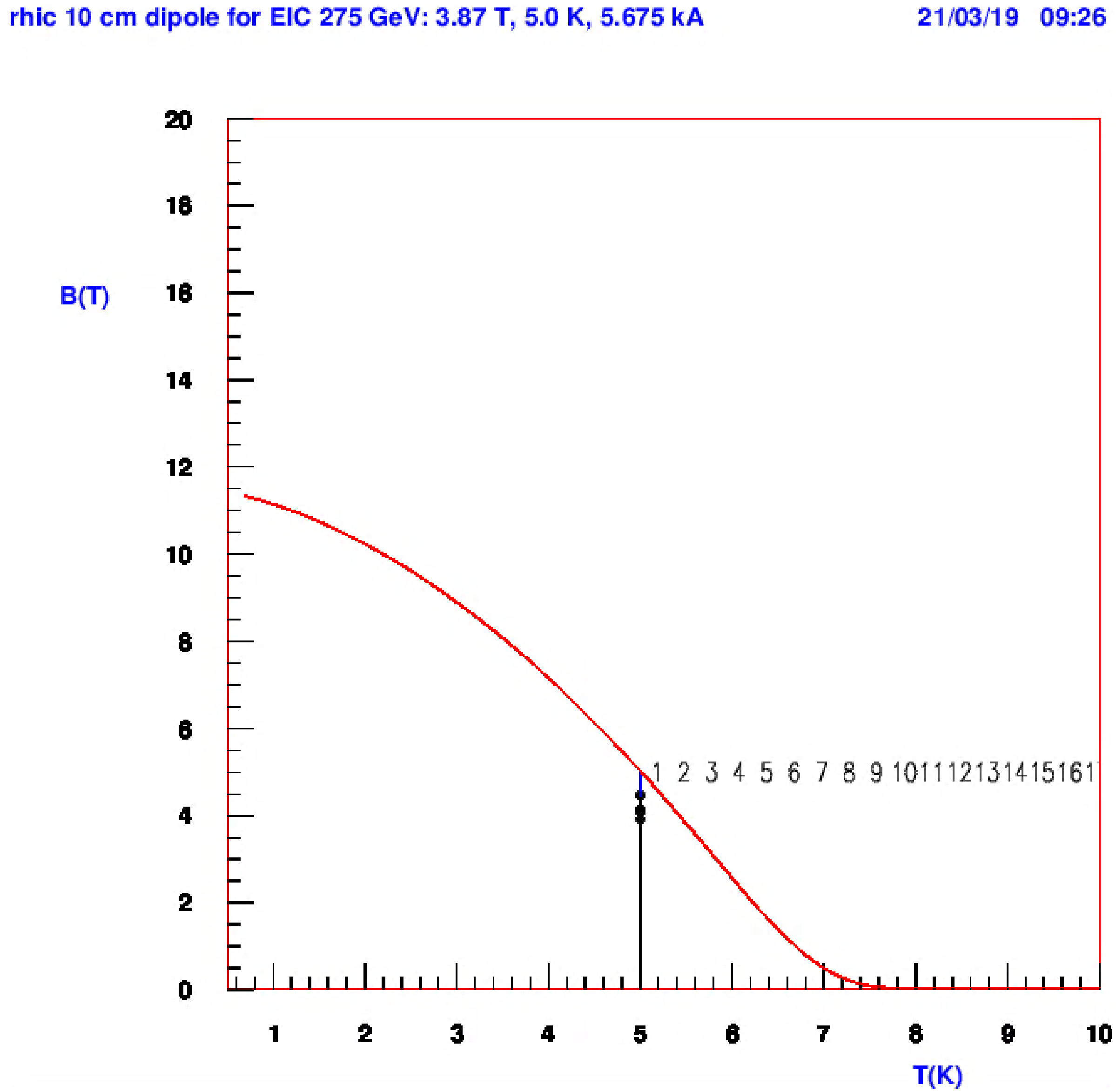
Computed Quench Temperature Margin

100 mm dipole
@B$_o$=3.87 T
I = 5.675 kA
T = 5.0 K



Computed Quench Field Margin

100 mm dipole
@B_o=3.87 T
I = 5.675 kA
T = 5.0 K



Evaluation of
RHIC 80 mm Arc Quadrupoles
for EIC
(higher gradient, higher temperature)

RHIC 80 mm ARC Quaderupole
(performance computed, field quality measured)

“B” Series RHIC Arc Quadrupoles*
(PAC 1993)

P. Thompson, M. Anerella, G. Ganetis, M. Garber, A. Ghosh
A. Greene, R. Gupta, A. Jain, S.A. Kahn, G. Morgan, A. Morgillo
J. Muratore, A. Prodell, M. Rehak, W. Sampson, P. Wanderer, E. Willen

RHIC Project
Brookhaven National Laboratory, Upton, NY 11973

The RHIC magnet system

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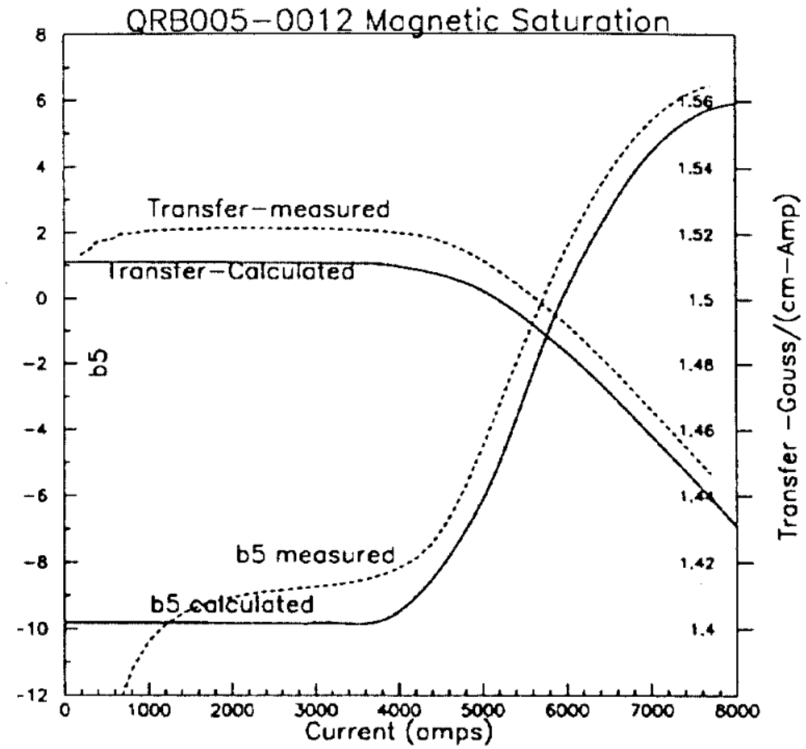
P. Thompson, P. Wanderer*, E. Willen

Brookhaven National Laboratory, Upton, NY 11973, USA

Table 8 Selected parameters of the arc quadrupole magnet.

Parameter	Value
Gradient @ top energy (T/m)	71
Current @ top energy (A)	4720
Gradient @ quench (T/m)	107
Magnetic length (m)	1.11
Cold mass length (m)	1.305
Inductance (mH)	2
Stored energy (kJ)	20

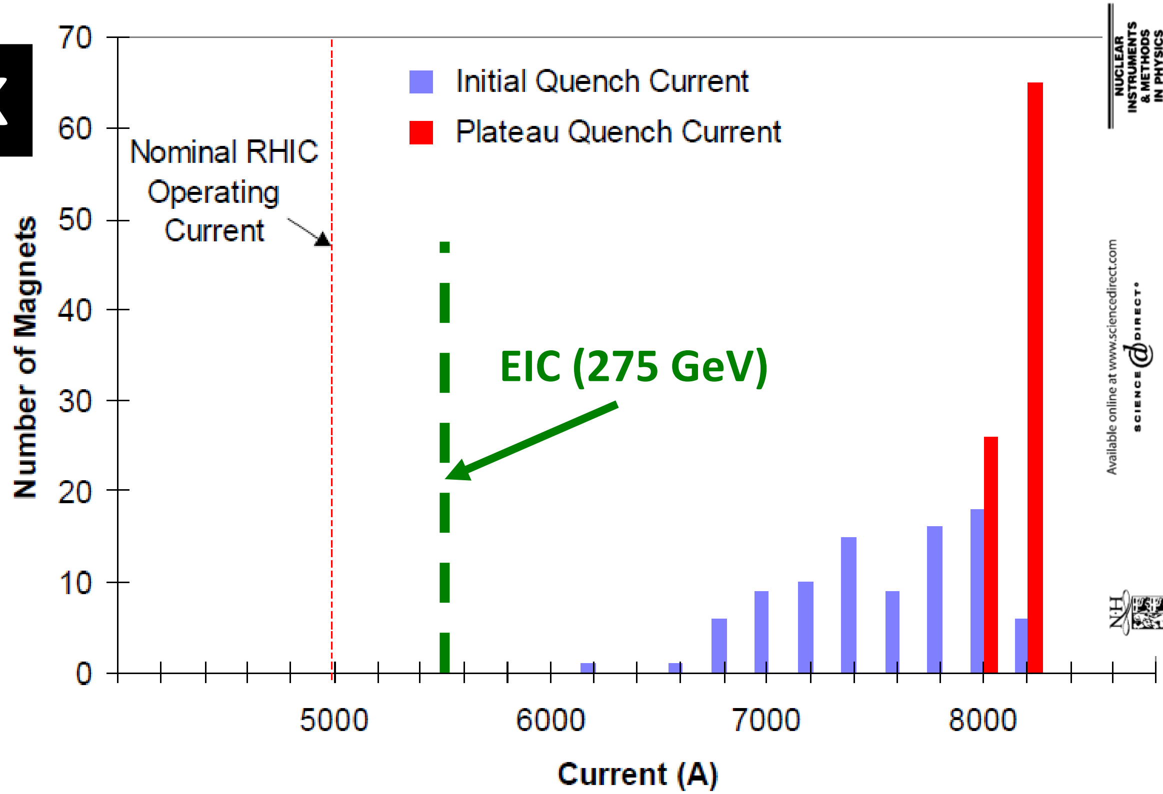


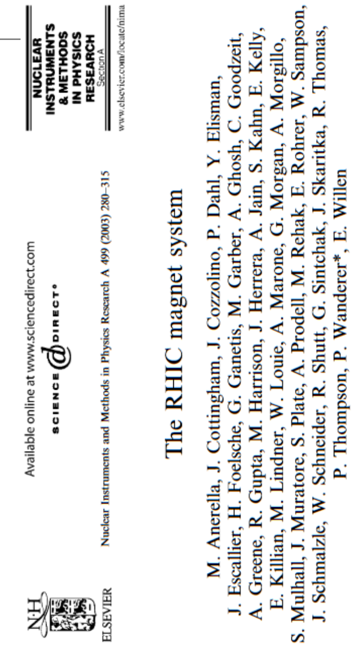
RHIC: 250GeV, 71 T/m @~4.7kA
EIC: 275 GeV, 78.1 T/m @~5.2 kA

Quench Performance of RHIC 80 mm Quadrupoles (measured in 91 magnets)

@4.5K

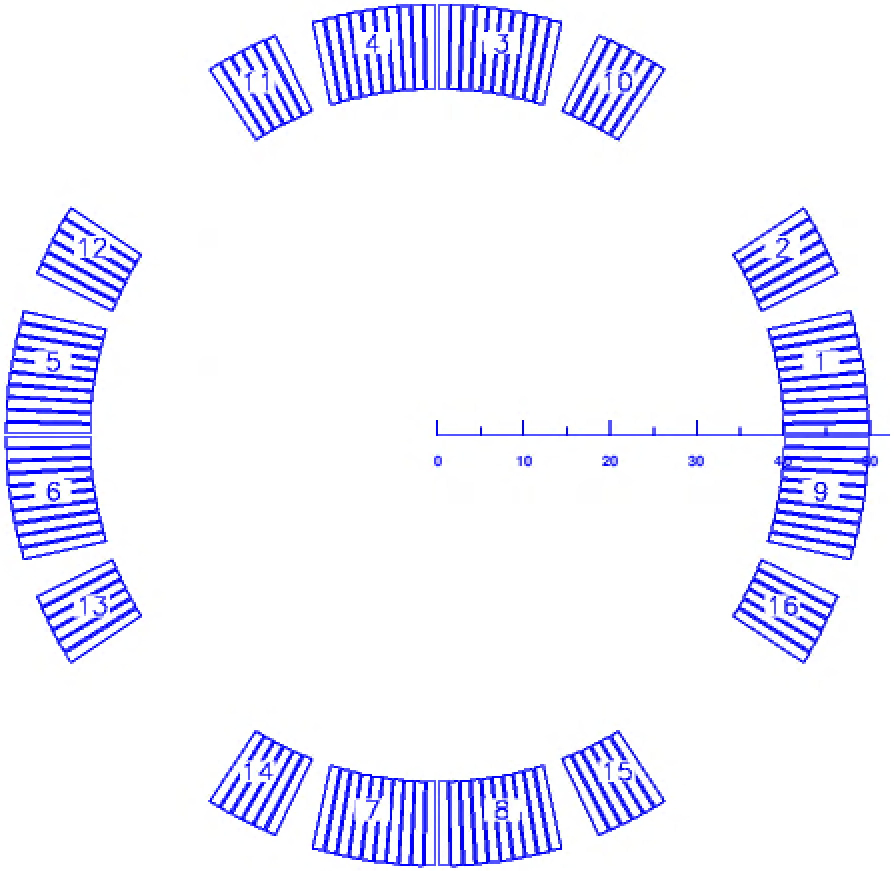
RHIC 80 mm arc quadrupoles <u>have a large quench and</u> "*<u>mechanical</u>*" margin for EIC 275 GeV operation

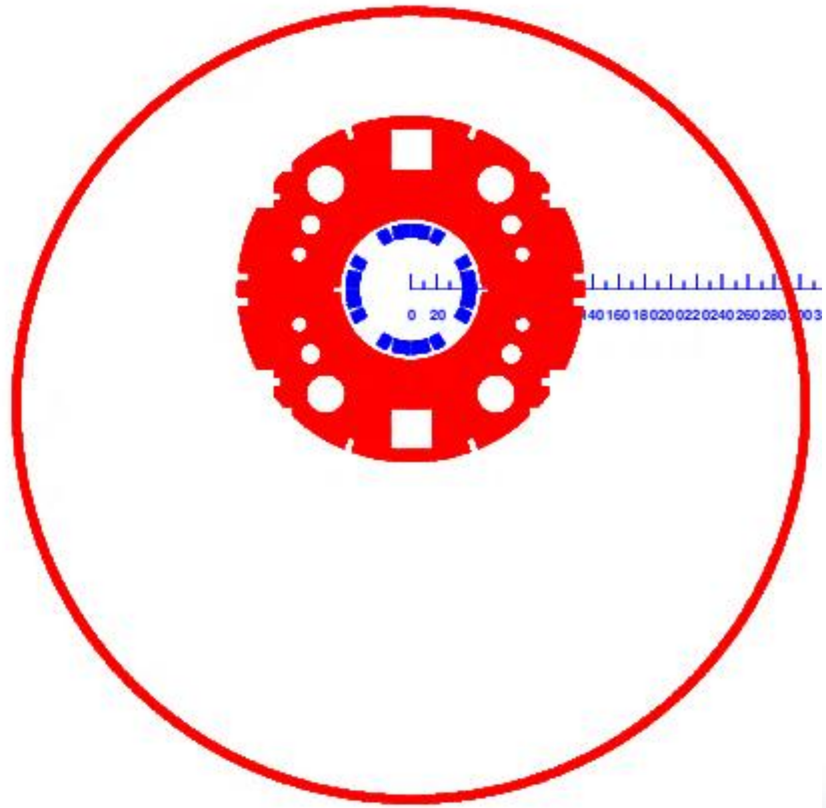




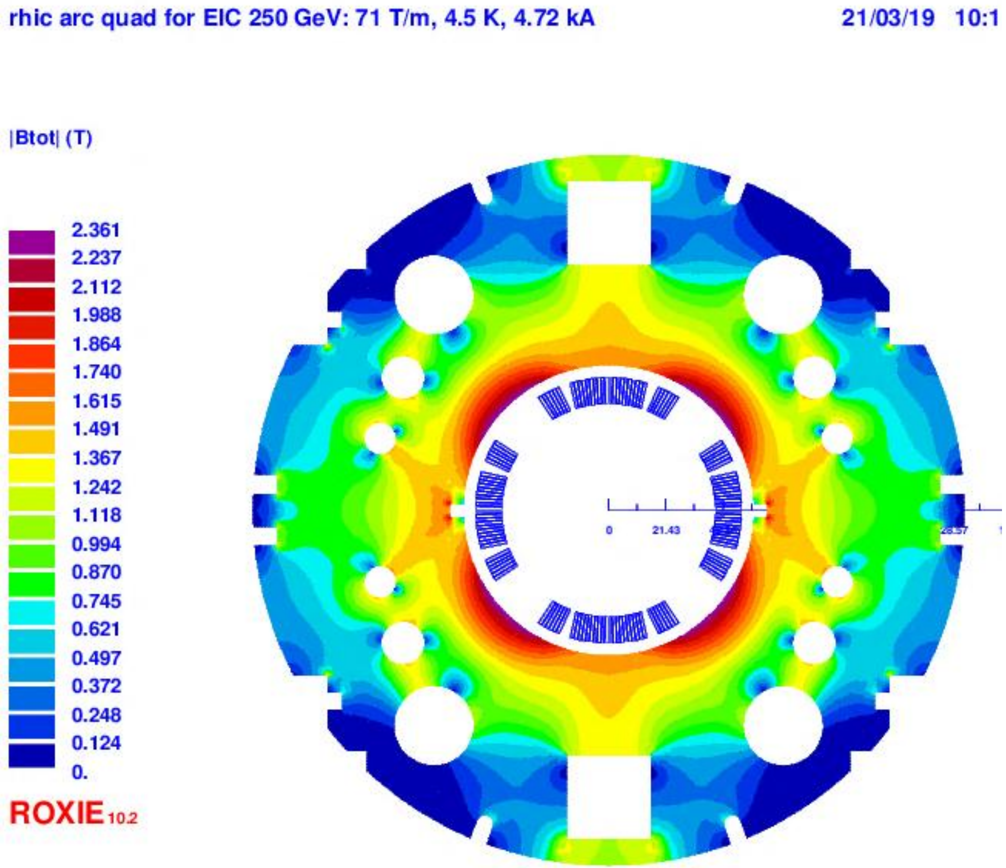
Higher performance than the design due to a better cable and good design and construction

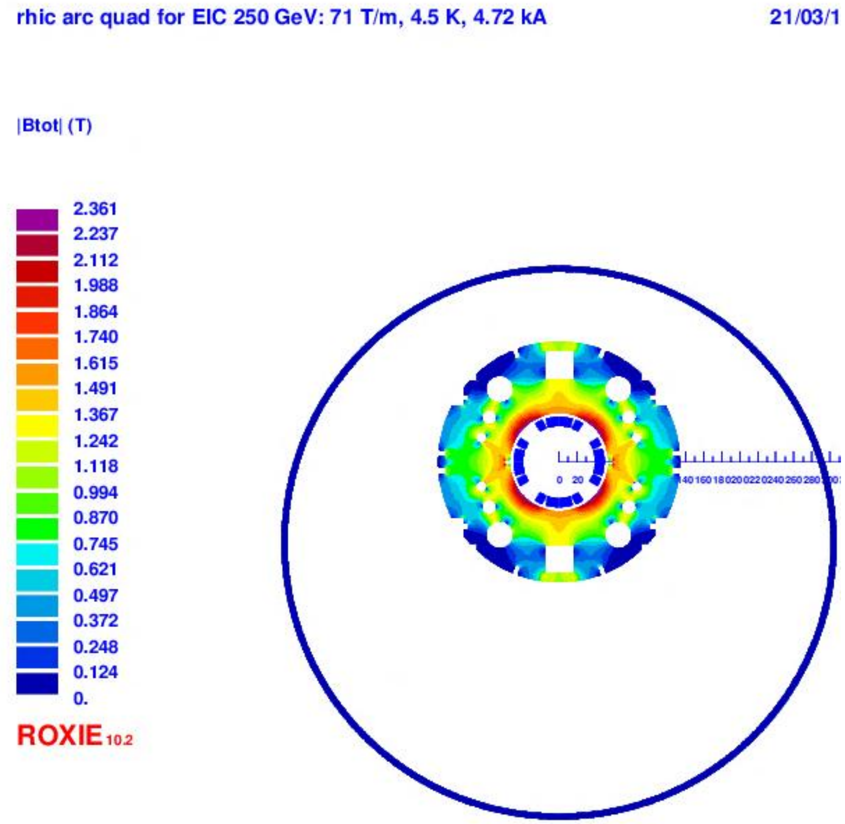
ROXIE Model of RHIC 80 mm Quad (1)





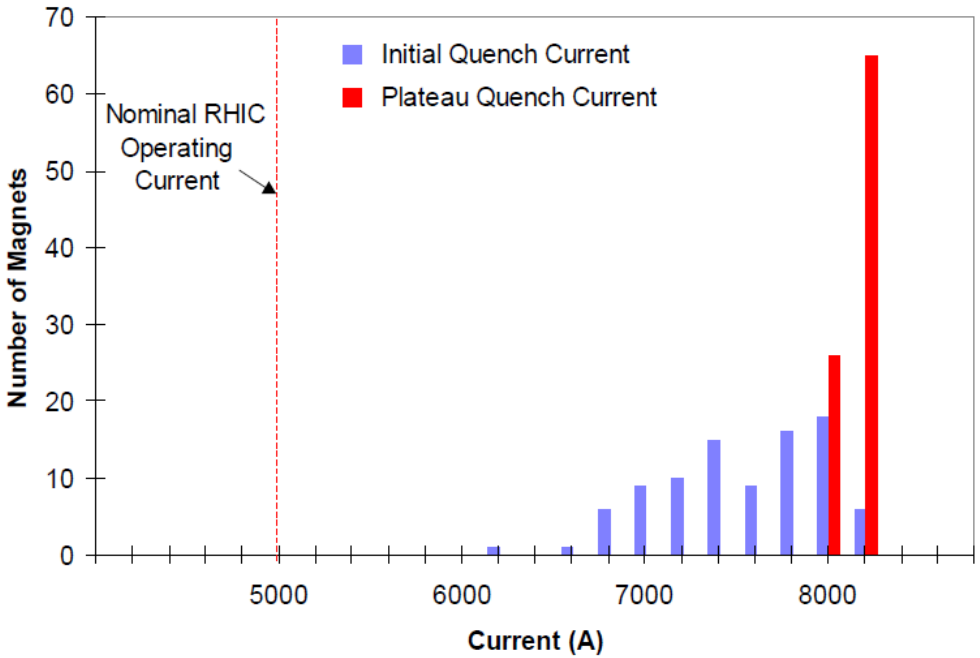
ROXIE Model of RHIC 80 mm Quad (2)

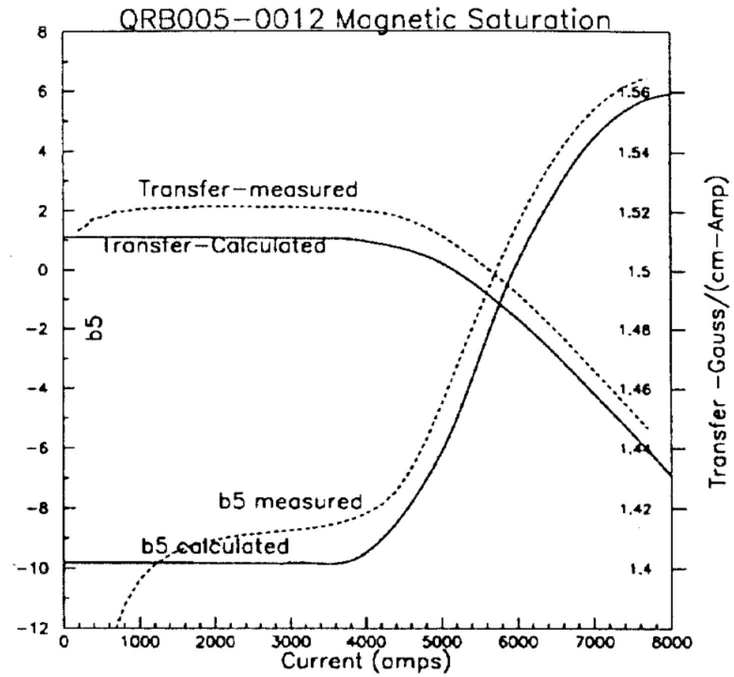




Computed quench field and temperatures margins for RHIC 80 mm quadrupoles

RHIC 80 mm ARC Quaderupole



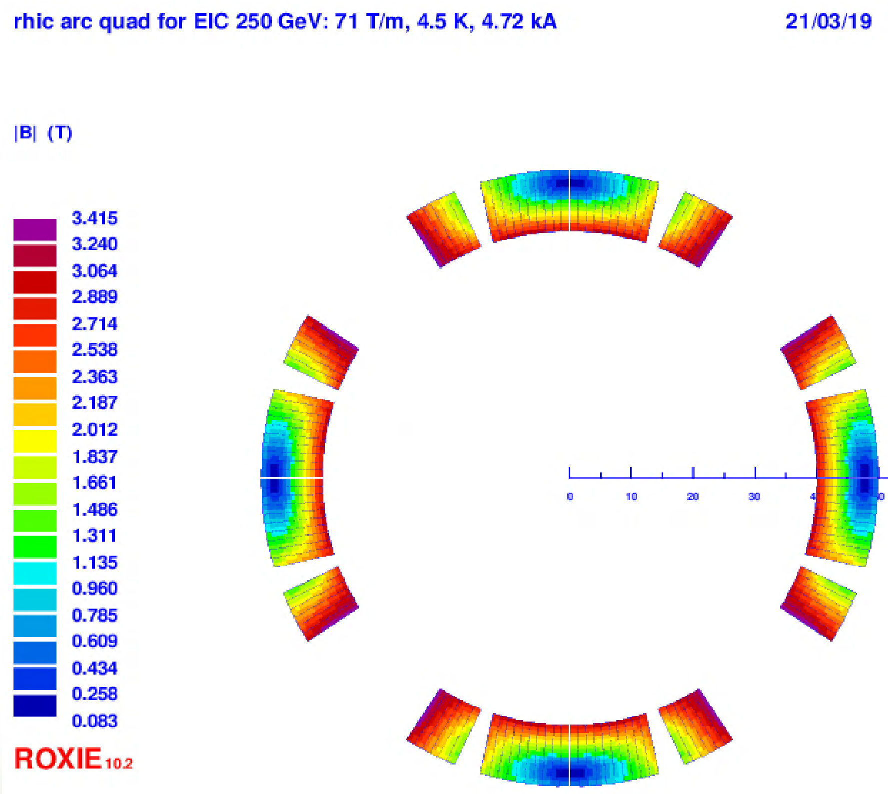


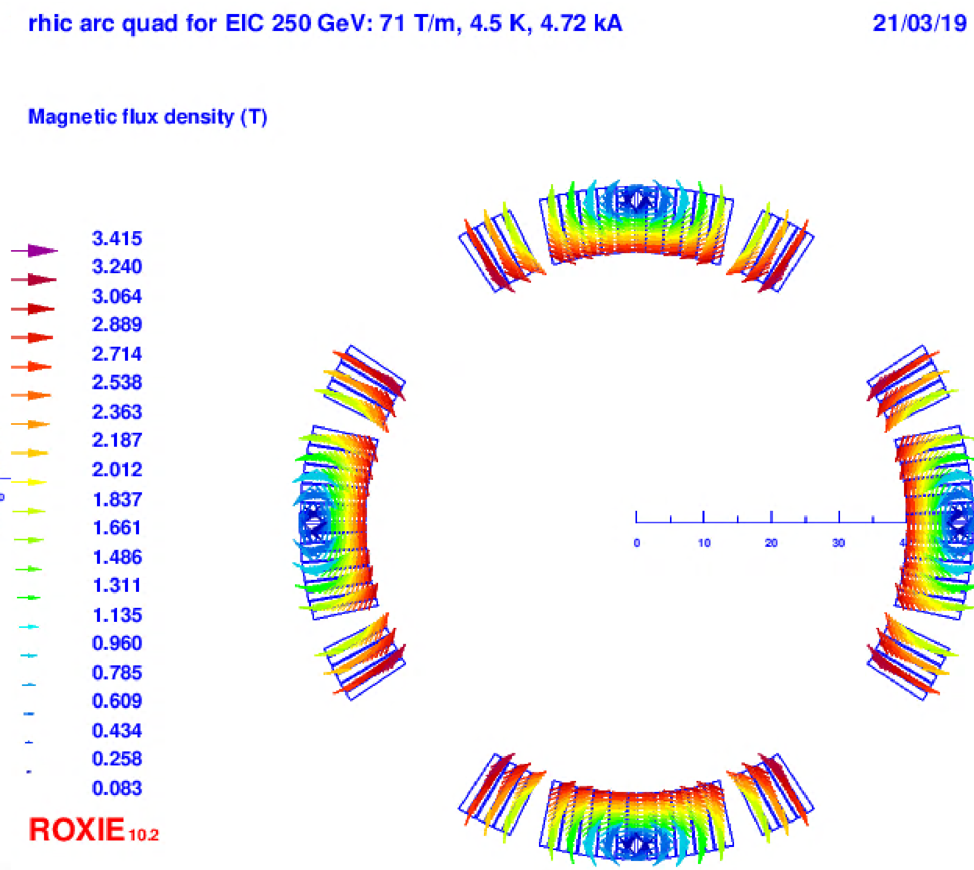
An oversight realized this morning:

- **Program assumes a linear transfer function in quench field calculations**
- **Since there is a significant change in transfer function due to iron saturation between the design field to quench field (thanks to a very large margin and a significant contribution from iron), some of the calculations may be off**
- **The calculation will be performed again which will minimize this extrapolation**
- **As such the 80 mm quad is of the least concern because of the most margin ...**

Field in conductor at RHIC design gradient

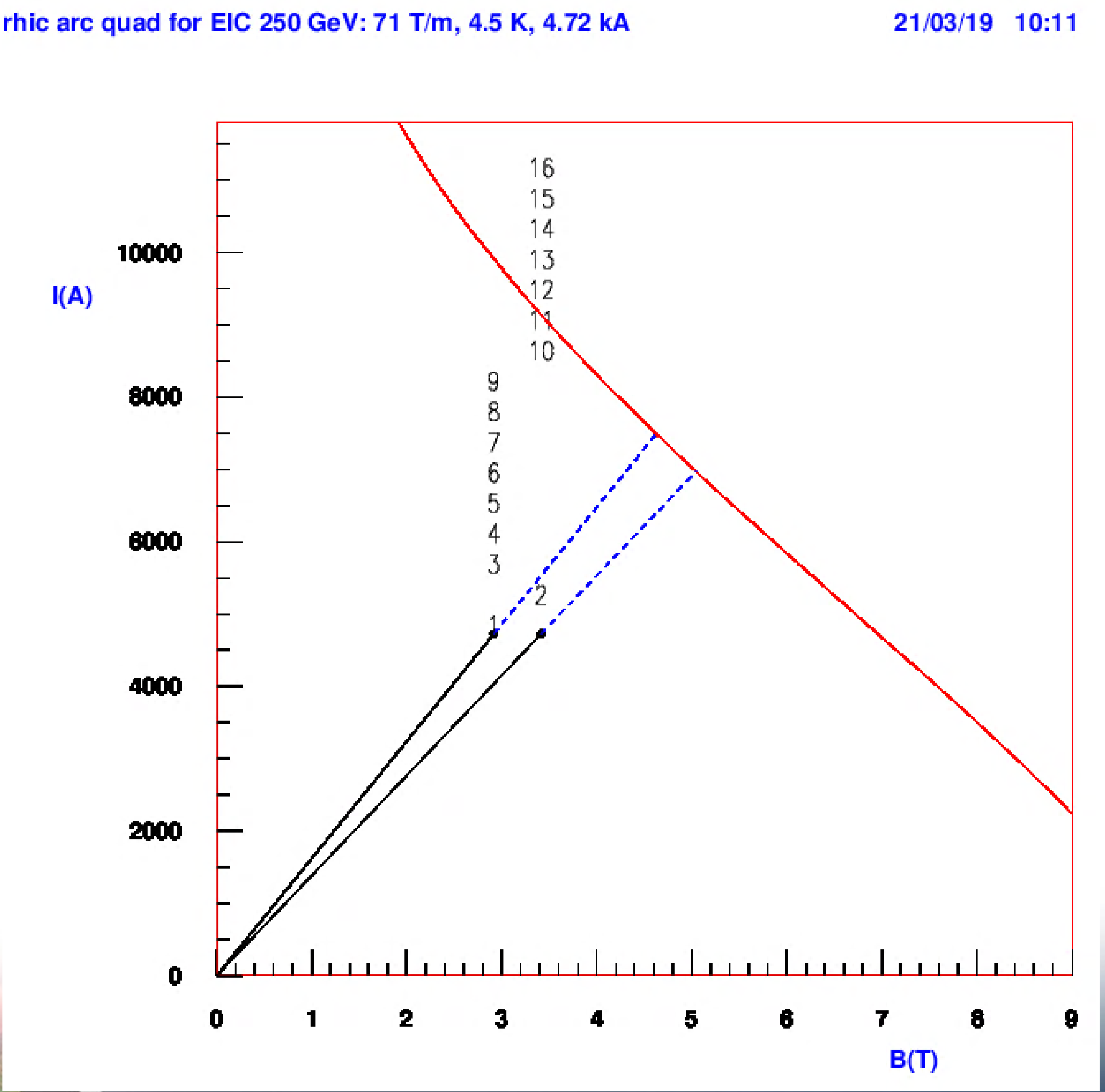
@Gradient = 71 T/m   Peak Field = 3.4 T





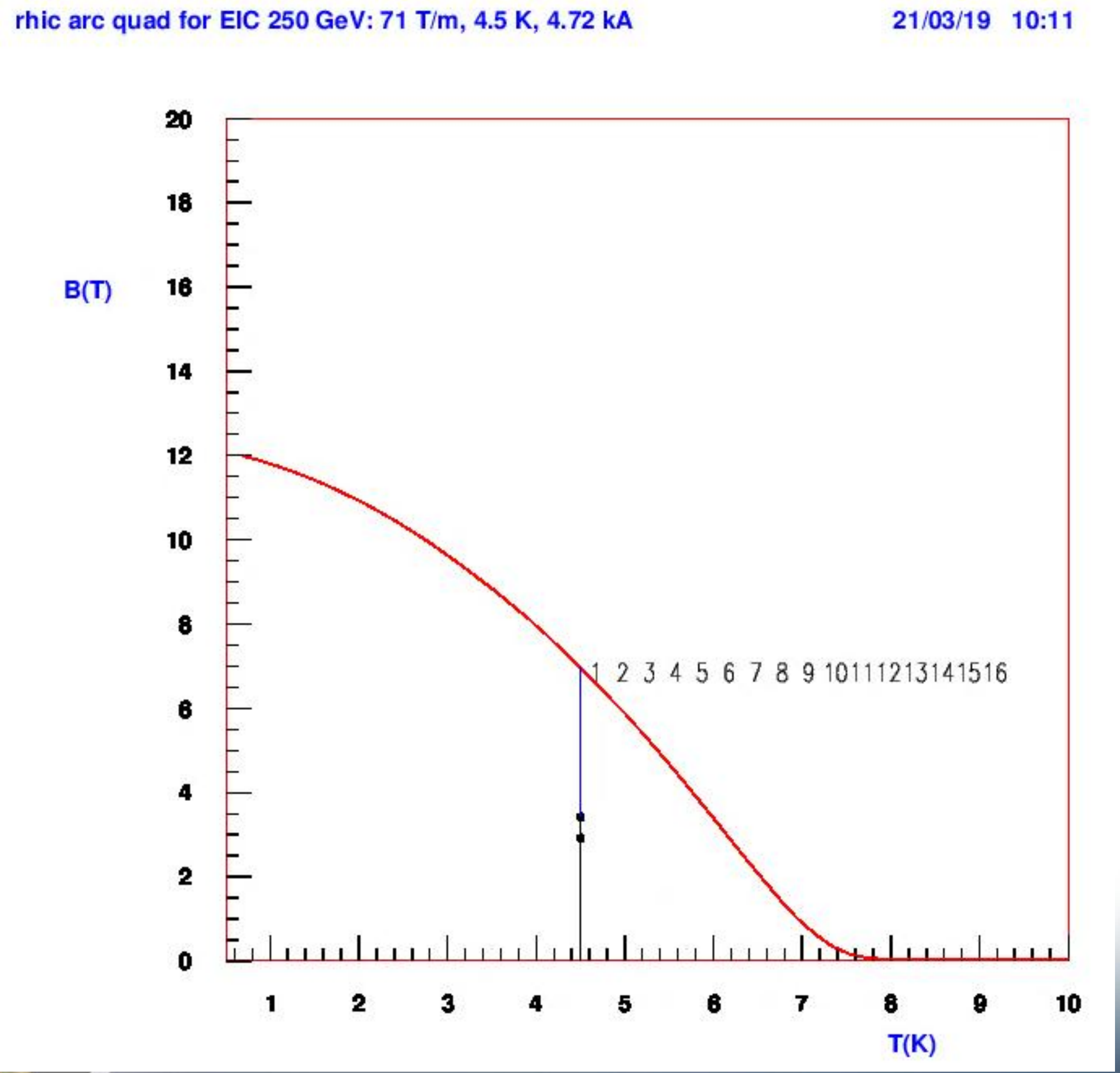
Computed Quench Margin

Gradient
= 71 T/m
I = 4.72 kA
T = 4.5 K



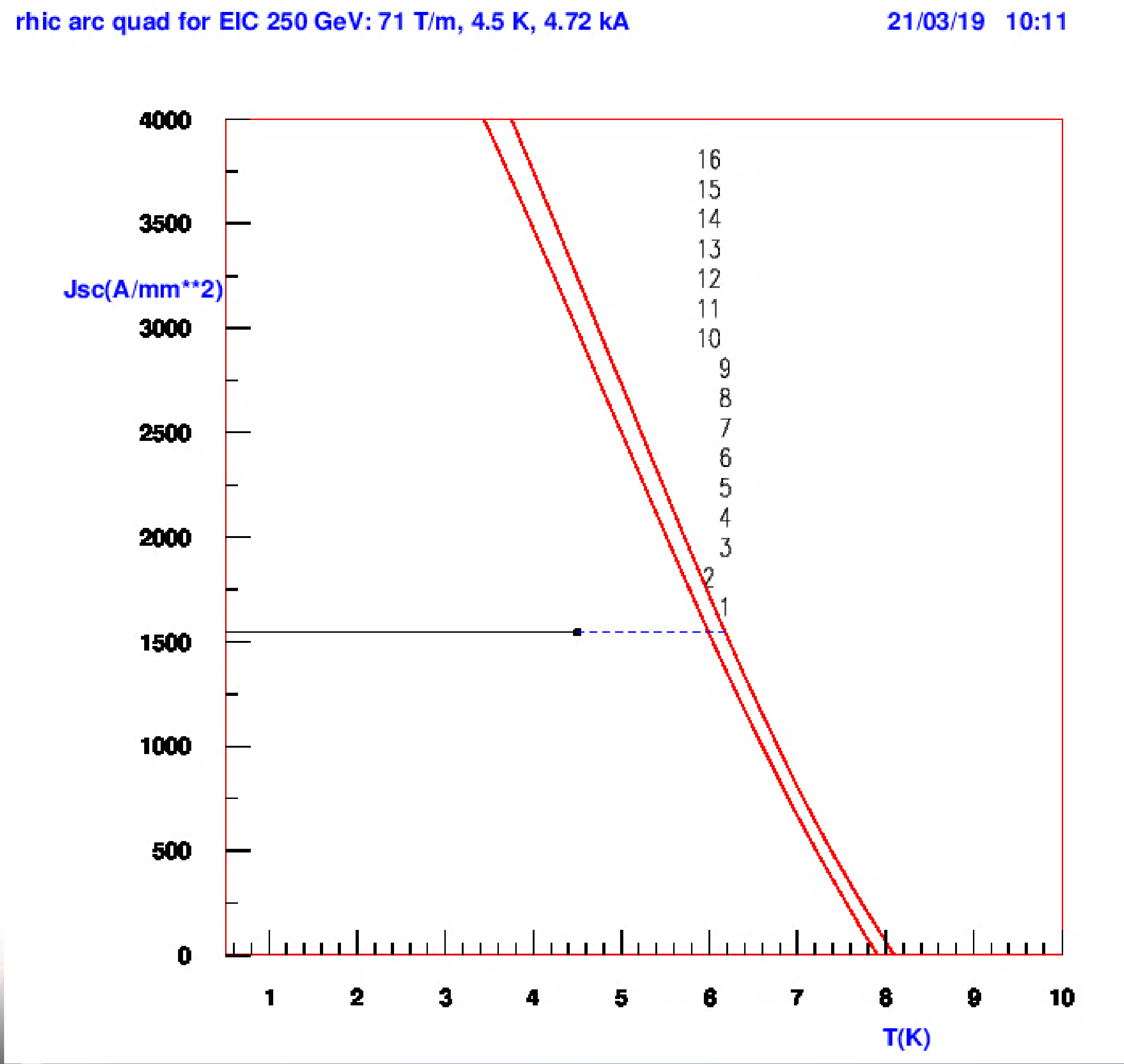
Computed Quench Field Margin

Gradient
= 71 T/m
I = 4.72 kA
T = 4.5 K



Computed Quench Temperature Margin

Gradient = 71 T/m
I = 4.72 kA
T = 4.5 K



Summary of Calculations for 250 GeV @4.5 K

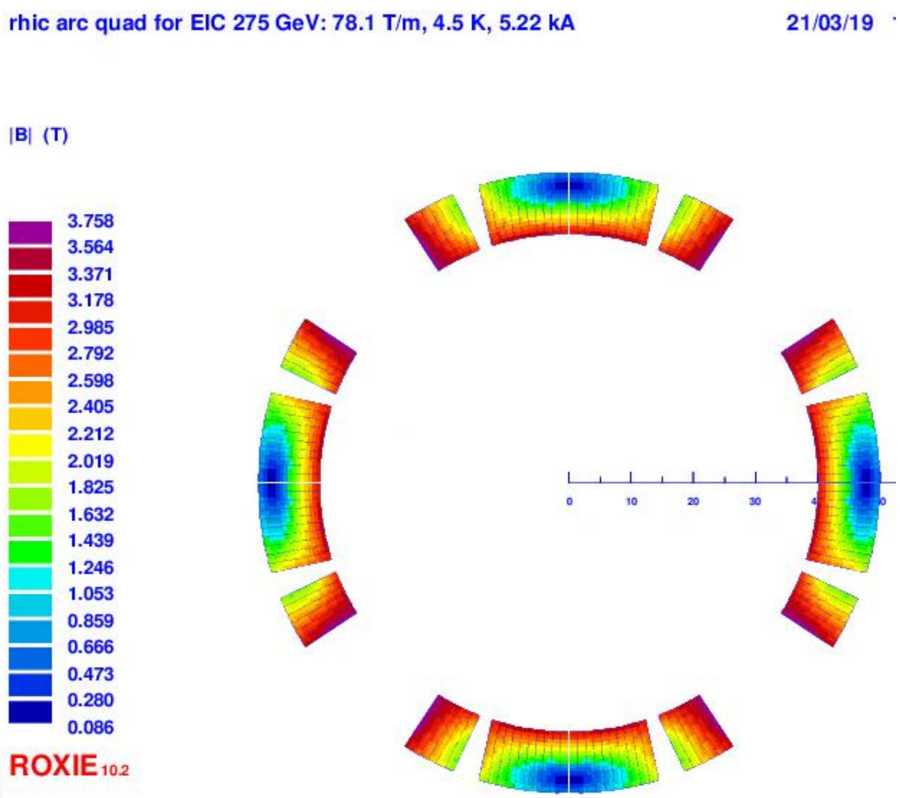
MAGNET STRENGTH (T/(m^(n-1))	-71.0053
BLOCK NUMBER	2
PEAK FIELD IN CONDUCTOR 16 (T)	3.4144
CURRENT IN CONDUCTOR 16 (A)	4720.0000
LOWEST FIELD IN CONDUCTOR 11 (T)	1.4256
SUPERCONDUCTOR CURRENT DENSITY (A/MM2)	1545.7023
COPPER CURRENT DENSITY (A/MM2)	690.0457
PERCENTAGE ON THE LOAD LINE	67.6929
QUENCHFIELD (T)	5.0440
TEMPERATURE MARGIN TO QUENCH (K)	1.4906
PERCENTAGE OF SHORT SAMPLE CURRENT	51.6622

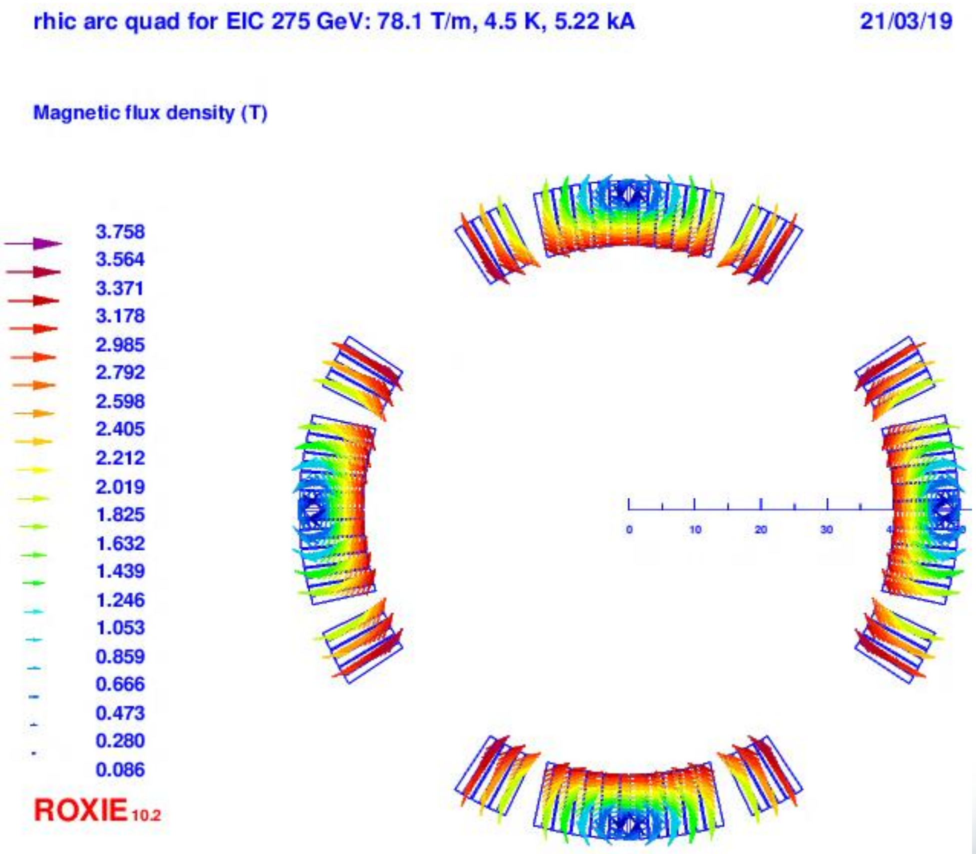
Model Calculations at EIC Design Field (275 GeV@3.81 T)

Temperature: 4.5 K

Field in conductor at RHIC design gradient

@Gradient = 78.1 T/m   Peak Field = 3.4 T



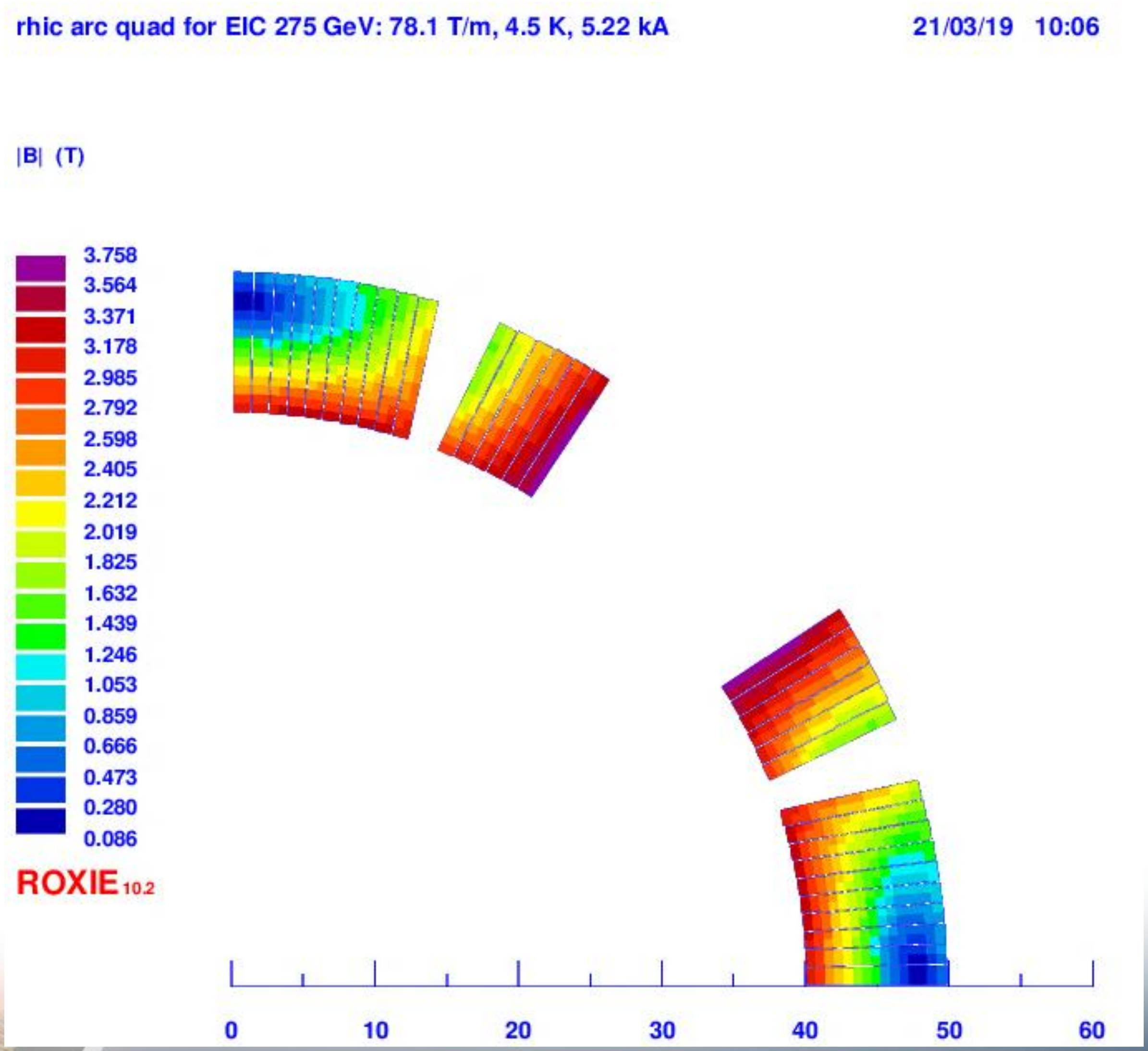


Summary of Calculations for 275 GeV @4.5 K

MAGNET STRENGTH (T/(m^(n-1))	-78.1545
BLOCK NUMBER	2
PEAK FIELD IN CONDUCTOR 16 (T)	3.7571
CURRENT IN CONDUCTOR 16 (A)	5220.0000
LOWEST FIELD IN CONDUCTOR 11 (T)	1.5822
SUPERCONDUCTOR CURRENT DENSITY (A/MM2)	1709.4420
COPPER CURRENT DENSITY (A/MM2)	763.1437
PERCENTAGE ON THE LOAD LINE	74.6873
QUENCHFIELD (T)	5.0305
TEMPERATURE MARGIN TO QUENCH (K)	1.1821
PERCENTAGE OF SHORT SAMPLE CURRENT	60.3899

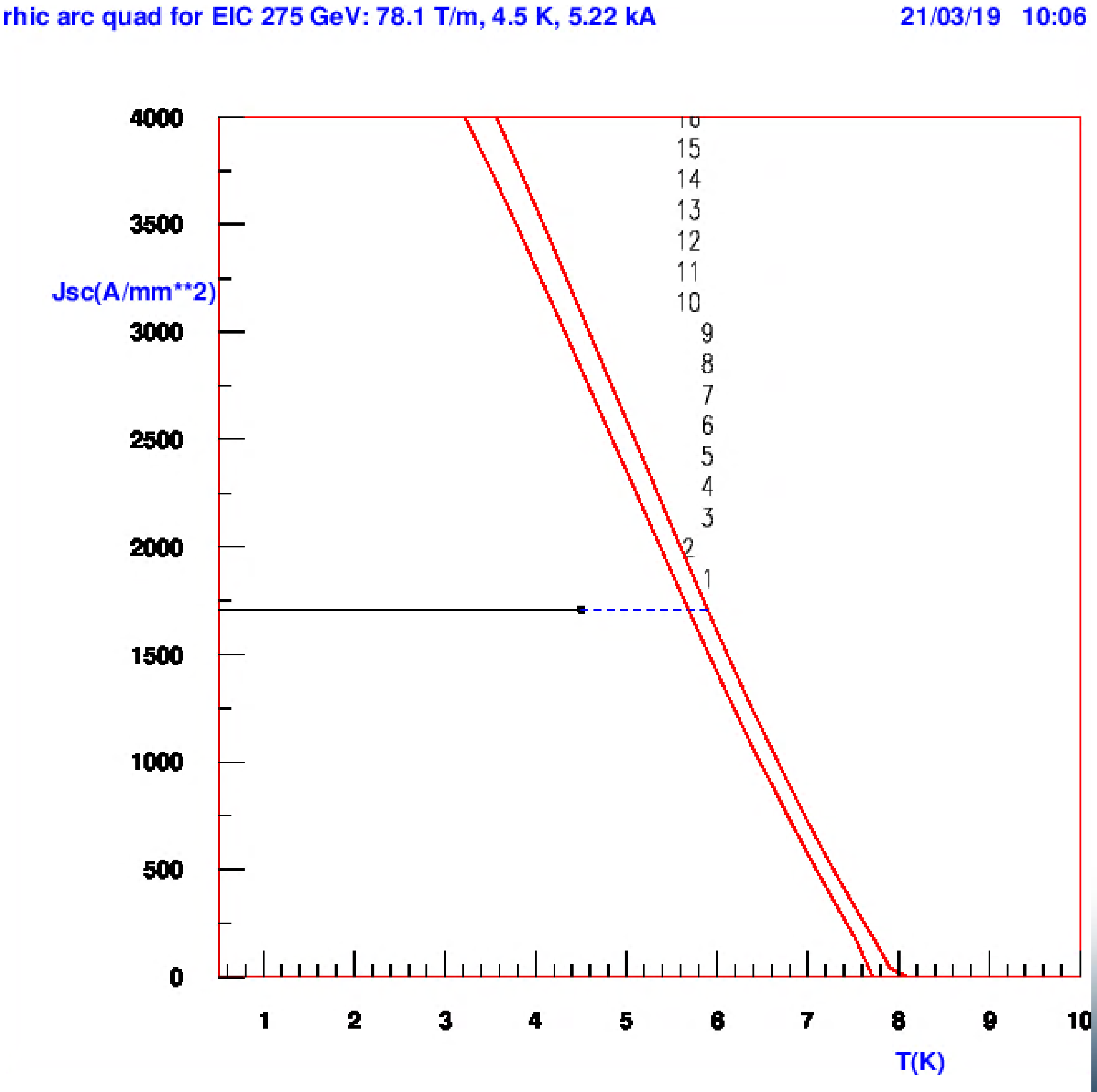
Field in conductor at EIC design field

Gradient
= 78.1 T/m
I = 5.2 kA
T = 5 K



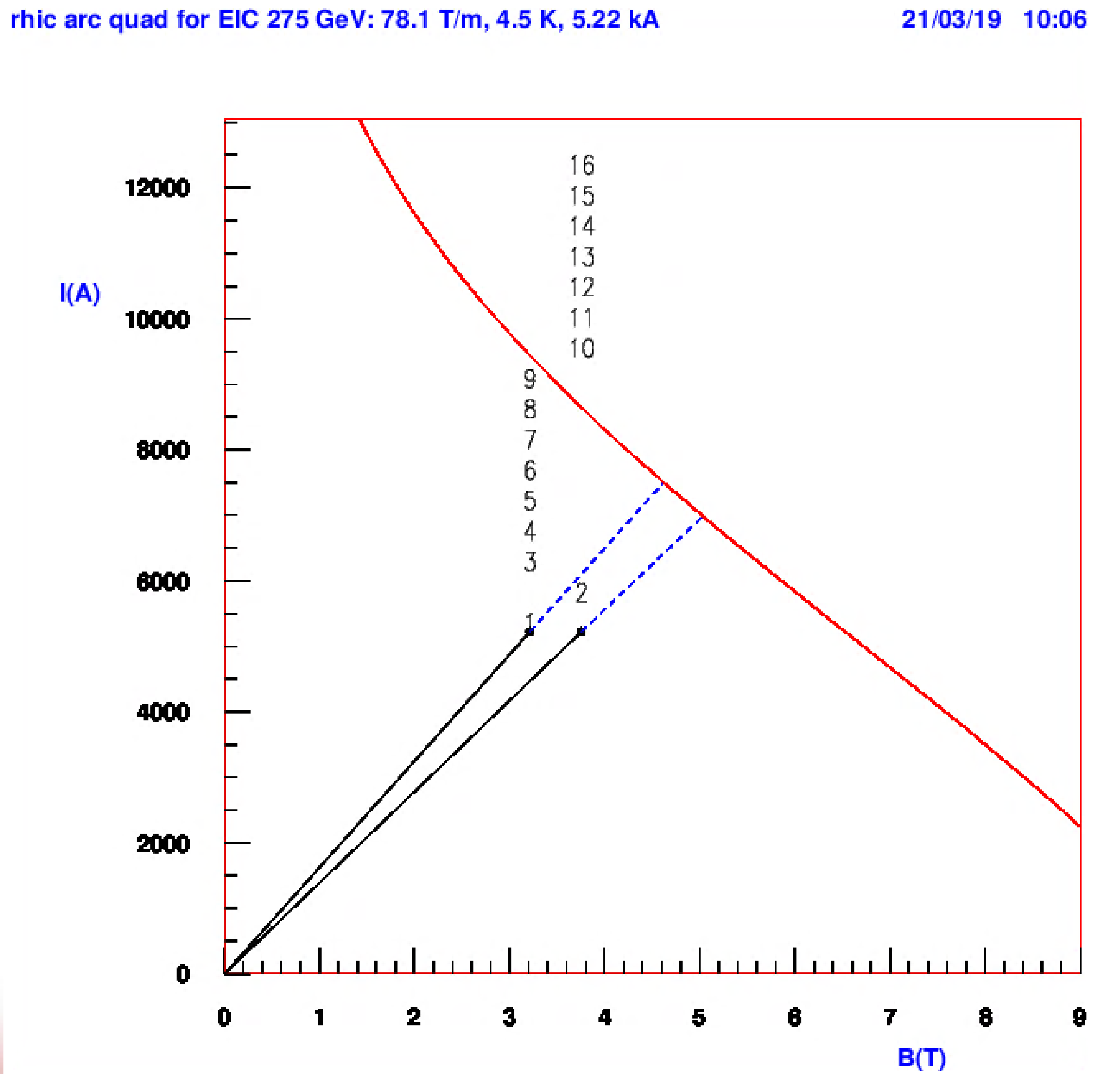
Computed Temperature Margin

Gradient
= 78.1 T/m
I = 5.2 kA
T = 4.5 K



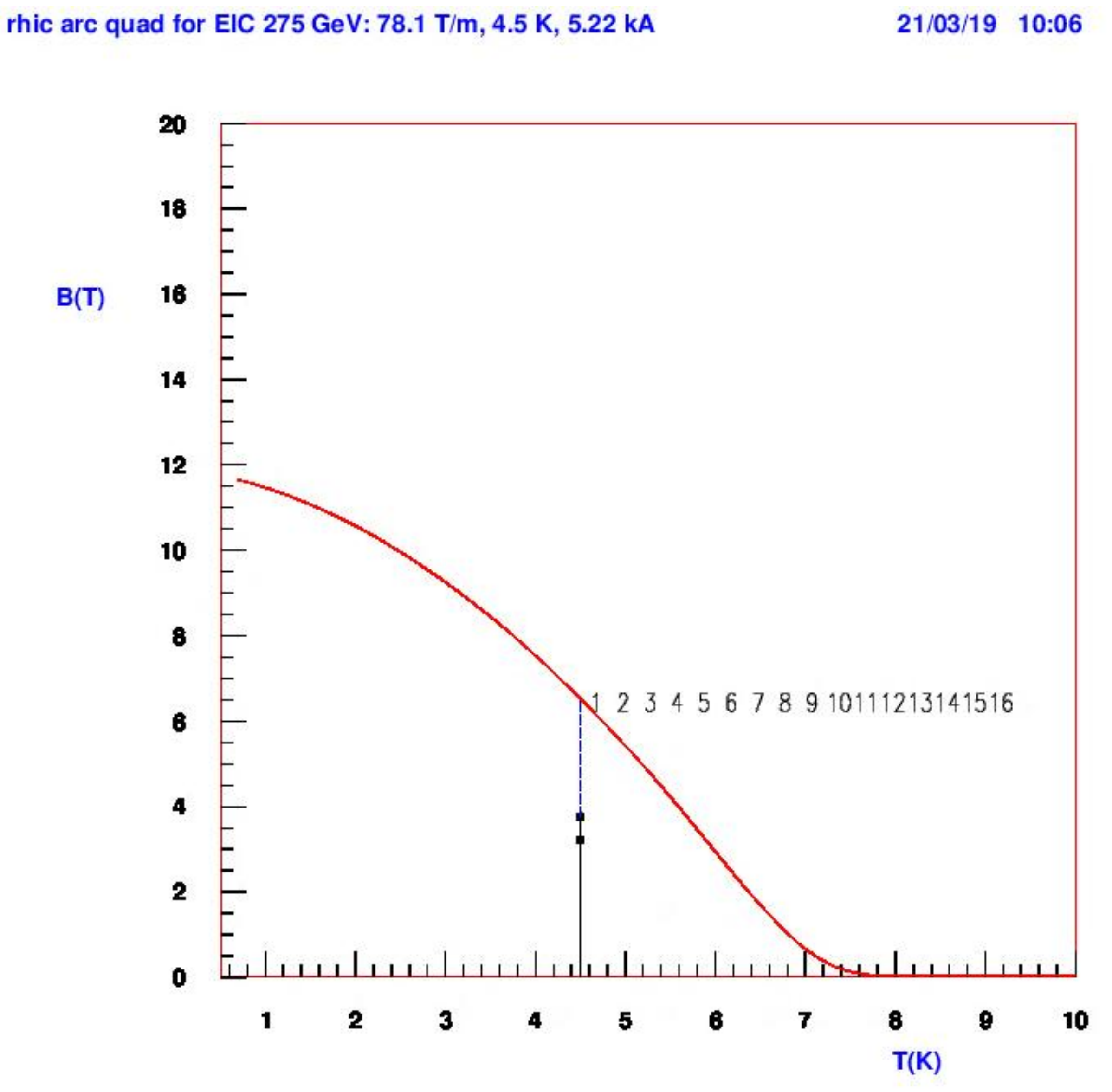
Computed Quench Margin

Gradient
= 78.1 T/m
I = 5.2 kA
T = 4.5 K



Computed Quench Field Margin

Gradient
= 78.1 T/m
I = 5.2 kA
T = 4.5 K



Model Calculations at EIC Design Field (275 GeV@3.81 T)

Temperature: 5 K

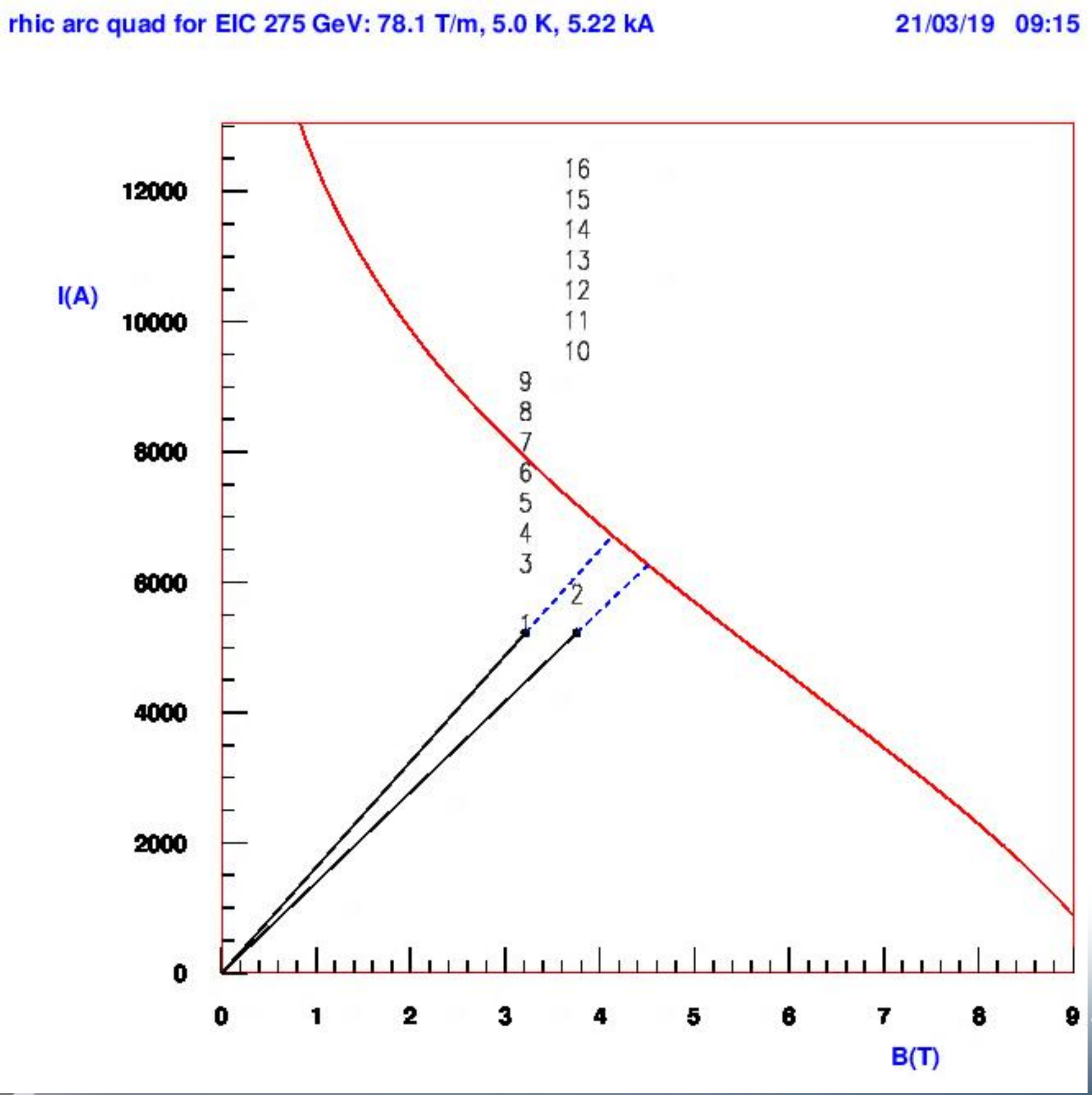
Summary of Calculations for 275 GeV @5 K

MAIN FIELD (T)	-3.841283

BLOCK NUMBER	2
PEAK FIELD IN CONDUCTOR 16 (T)	3.7571
CURRENT IN CONDUCTOR 16 (A)	5220.0000
LOWEST FIELD IN CONDUCTOR 11 (T)	1.5822
SUPERCONDUCTOR CURRENT DENSITY (A/MM2)	1709.4420
COPPER CURRENT DENSITY (A/MM2)	763.1437
PERCENTAGE ON THE LOAD LINE	83.3229
QUENCHFIELD (T)	4.5091
TEMPERATURE MARGIN TO QUENCH (K)	0.6821
PERCENTAGE OF SHORT SAMPLE CURRENT	72.6244

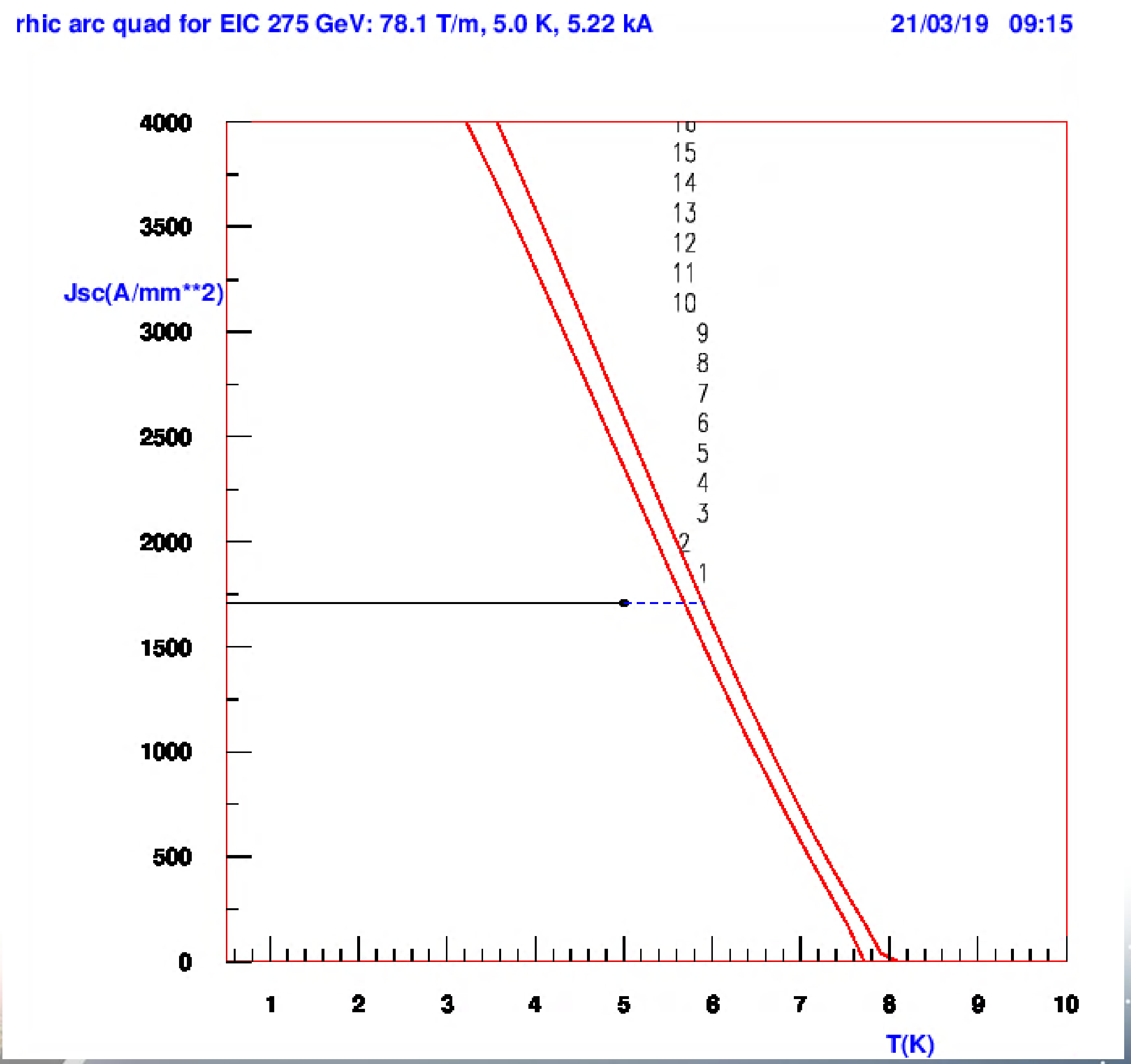
Computed Quench Margin

Gradient
= 78.1 T/m
I = 5.2 kA
T = 5 K



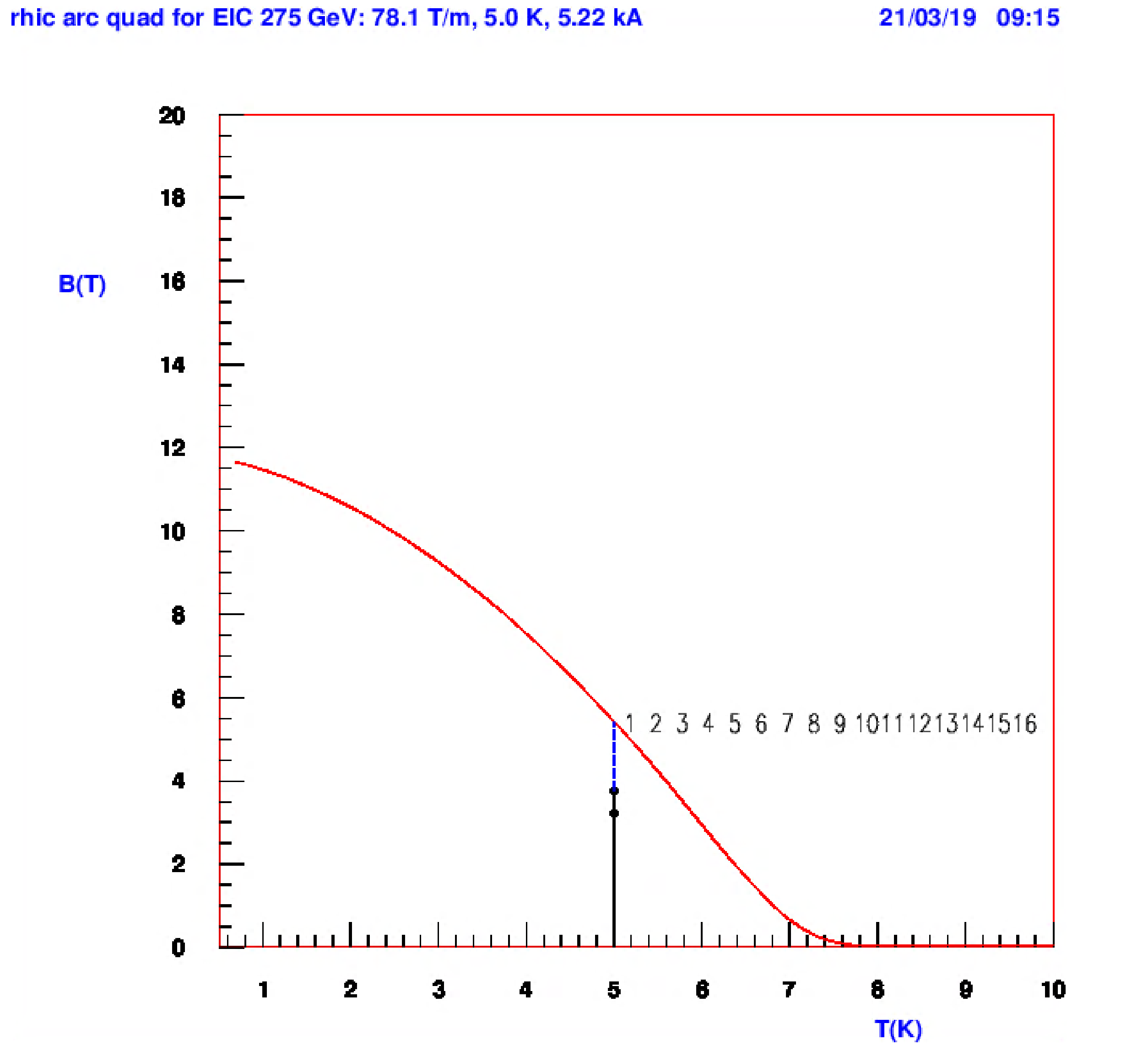
Computed Temperature Margin

Gradient
= 78.1 T/m
I = 5.2 kA
T = 5 K



Computed Quench Field Margin

Gradient
= 78.1 T/m
I = 5.2 kA
T = 5 K



Summary

- Initial evaluation of RHIC 100 mm insertion dipoles and RHIC 80 mm arc quadrupoles made for operating them with more demanding parameters as need for EIC design.
- In addition to higher fields (or field gradients), the impact of higher temperature on superconducting coils is of significant interest. This impact has been evaluated.
- Arc quadrupole are the most reliable magnets with the highest margin in any cable magnets.
- Situation is worse for insertion region magnets where the margins are lower, and performance is not so robust due to limited R&D performed during the RHIC magnet program.