BNL-102221-2014-TECH
RHIC/AP/113;BNL-102221-2013-IR

RHIC Magnet Transfer Functions

F. Pilat

October 1996

Collider Accelerator Department
Brookhaven National Laboratory

U.S. Department of Energy
USDOE Office of Science (SC)

DISCLAIMER

RHIC Magnet Transfer Functions

Fulvia Pilat

1. Introduction

This note describes the extraction, processing and management of the Magnet Transfer Function data for the RHIC control system. Its ultimate goal is to establish a correlation between magnet strength and current for every RHIC magnet in preparation for the sextant test and later, RHIC commissioning. This note complements an earlier one [1] which dealt with the ATR Transfer Functions, to which the reader is referred for basic definitions and background. The Magnet Transfer Function (MTF) is defined in this context as:

BL/I	[Tm/A]	for a dipole
GL/I	[T/A]	for a quadrupole

where B and G are the magnetic field and gradient, respectively in Tesla and Tesla/m, L the magnet length in m and I the current in amps. The Transfer Function, ideally a constant, is in reality a function of current because of saturation, and, in the case of superconducting magnets, also because of magnetization and other effects.

2. Fields

The measured field of a magnet can be represented in the following way [2][3]:

$$(LB_y) + i(LB_x) = LB(R_{ref})\left[10^{-4}\sum_{n=0}^{Nmax}(b_n^M + ia_n^M)\frac{(x+iy)^n}{R_{ref}^n}\right]$$

where $b_n{}^M$ and $a_n{}^M$ are the *measured multipole coefficients* and $LB(R_{\mathrm{ref}})$ is the *integrated field* at the reference radius (R_{ref}). The **Integral Transfer Function** (*ITF*) is defined by the relation: $ITF \times I = LB(R_{ref})$ where, for the RHIC data, I is the current expressed in kiloAmps (*kA*) and the integrated field *LB* is measured in Tesla*meter (*Tm*). Measured Integral Transfer Function data are the source of our MTF data, as will be described in more details in the next section.
There are many types of magnets in RHIC. It has been decided to extract and maintain MTF data for **types** of magnets, i.e. to assign the same MTF to magnets that are physically the same. The same decision was taken for AtR Magnet Transfer Functions. It seems

a reasonable thing to do because, firstly, not all the magnet has been individually measured, secondly, MTF data are mainly used for magnet control purposes where differences between individual magnets can be neglected. Should we need a higher degree of precision, for instance in the triplet quadrupoles, individual measured MTF data can be easily retrieved.
Table 1 reminds of the naming convention adopted for RHIC magnet and defines **FieldName** as being the name identifying a type of magnet field.

Table 1: Naming Convention for RHIC magnets.

Name	Description	Examples	
LatticeName	magnet name used in lattice files	d	qda4
SiteWideName	unique name used across systems	yo5-dh10	yo4-qd9
SlotSiteWideName	SiteWideName of magnet slot	yo5-d10	yo4-cqs9
SerialName	magnet serial name	DRG101	QRG324
DeviceName	identifies magnet type	dh	qd
FieldName	identifies group of magnet fields	DRG	QRG

Table 2 below summarizes all the magnet field data for RHIC with the exception of the DX magnet, still in the development phase, and for which no complete data are available at this time.
Fields are listed by FieldName, the second column describes the type of field, Magnet Count specifies how many magnets of that type are necessary for RHIC (Blue and Yellow Ring) while Measured Magnet Count reports how many have been effectively measured. The last column describes the functionality of the magnet in the lattice.
For most of the magnets there is a one to one correspondence between magnet and field. However, most of the correctors are "packages" of 4 fields of different multipolarity layered on top of each other. The Arc corrector packages are CRB, CRC, CRF, each containing a dipole winding, a quadrupole, an octupole and a decapole winding, while CRD and CRE contain only a dipole corrector. The Triplet corrector packages are CRI, CRJ, CRK, CRL and CRM: the multipole fields contained are also described in Table 2.

3. Data sources

The main source for Magnet Transfer Function (MTF) are Integral Transfer Function (ITF) measurements from the Magnet Groups.
The majority of magnet data has been already processed and analyzed by the code **magstat** [4]. As one of its options, the code produces an SDS file (**FieldModel.sds**) where individual measured data (ITF, multipoles, field angles, etc.) are associated to every measured magnet, together with data averaged over all measured magnet of the same type. For instance, for every current, arc dipole DRG110 will have a pointer to his own set of measurements and a pointer to the same quantities averaged over all the measured DRG dipoles. For all the correctors, all measured currents have been stored in FieldModel.sds. In these cases, the average ITF from FieldModel.sds have been used as a source of MTF without further manipulations.

Table 2: Summary of RHIC magnet data.

Field Name	Leading multipole	Ref Radius [cm]	Magnet Count	Measured Magnet Count	Magnet functionality
DRG	b0	2.5	264	42	Arc dipole
DR8	b0	2.5	24	3	Insertion D8 dipole
D96	b0	2.5	48	3	Insertion short dipole
D5I	b0	2.5	12	0	Insertion short dipole
D5O	b0	2.5	12	0	Insertion short dipole
DRZ	b0	2.5	24	4	Insertion D0 dipole for beam separation
QRG	b1	2.5	372	92	Arc and Insertion Q5, Q6, Q8, Q9 quadrupoles
QR4	b1	2.5	24	3	Insertion quadrupole
QR7	b1	2.5	24	3	Insertion quadrupole
QRT	b1	2.5	72	18	Insertion trim quadrupole, next to Q4, Q5, Q6
QRI	b1	4.0	24	3	Q1 Triplet quadrupole
QRJ	b1	4.0	24	4	Q2 Triplet quadrupole
QRK	b1	4.0	24	5	Q3 Triplet quadrupole
SRE	b2	2.5	288	48	Sextupole in the Arcs and at the Q9 quadrupoles
CB1	b0	2.5	96	19	horizontal dipole corrector layer [th](CRB)
CB2	b1	2.5	96	19	quadrupole corrector layer [gamma-T quad qgt](CRB)
CB4	b3	2.5	96	19	octupole corrector layer [oct] (CRB)
CB5	b4	2.5	96	19	decapole corrector layer [dec] (CRB)
CC1	a0	2.5	132	22	vertical dipole corrector layer [tv] (CRC)
CC2	a1	2.5	132	22	skew quadrupole corrector layer [qs] (CRC)
CC4	b3	2.5	132	22	octupole corrector layer [oct] (CRC)
CC5	b4	2.5	132	22	decapole corrector layer [dec] (CRC)
CD1	b0	2.5	78	17	horizontal dipole corrector [th] (CRD)
CE1	b0	2.5	78	17	vertical dipole corrector [tv] (CRE)
CF1	b0	2.5	36	5	horizontal dipole corrector layer [th] (CRF)
CF2	a1	2.5	36	5	skew quadrupole corrector layer [qs] (CRF)
CF4	b3	2.5	36	5	octupole corrector layer [oct] (CRF)
CF5	b4	2.5	36	5	decapole corrector layer [dec] (CRF)
CI1	b0	4.0	12	2	QD1 triplet horizontal dipole corrector layer (CRI)

Table 2: Summary of RHIC magnet data.

Field Name	Leading multipole	Ref Radius [cm]	Magnet Count	Measured Magnet Count	Magnet functionality
CI4	b3	4.0	12	2	QD1 triplet octupole corrector layer (CRI)
CI5	b4	4.0	12	2	QD1 triplet decapole corrector layer (CRI)
CI6	b5	4.0	12	2	QD1 triplet dodecapole corrector layer (CRI)
CJ1	a0	4.0	12	2	QF1 triplet vertical dipole corrector layer (CRJ)
CJ4	b3	4.0	12	2	QF1 triplet octupole corrector layer (CRJ)
CJ5	b4	4.0	12	2	QF1 triplet decapole corrector layer (CRJ)
CJ6	b5	4.0	12	2	QF1 triplet dodecapole corrector layer (CRJ)
CK2	a1	4.0	24	2	QF2/QD2 triplet skew quadrupole corrector layer (CRK)
CK4	a3	4.0	24	2	QF2/QD2 triplet skew octupole corrector layer (CRK)
CK3	a2	4.0	24	2	QF2/QD2 triplet skew sextupole corrector layer (CRK)
CK6	a5	4.0	24	2	QF2/QD2 triplet skew dodecapole corrector layer (CRK)
CL1	b0	4.0	12	2	QF3 triplet horizontal dipole corrector layer (CRL)
CL4	b3	4.0	12	2	QF3 triplet octupole corrector layer (CRL)
CL3	b2	4.0	12	2	QF3 triplet sextupole corrector layer (CRL)
CL6	b5	4.0	12	2	QF3 triplet dodecapole corrector layer (CRL)
CM1	a0	4.0	12	2	QD3 triplet vertical dipole corrector layer (CRM)
CM4	b3	4.0	12	2	QD3 triplet octupole corrector layer (CRM)
CM3	b2	4.0	12	2	QD3 triplet sextupole corrector layer (CRM)
CM6	b5	4.0	12	2	QD3 triplet dodecapole corrector layer (CRM)

For the main magnets, however, only a set of selected currents (typically injection, transition and storage) are stored in FieldModel.sds, so in this case ITF data for all measured currents have been processed and provided directly from the Magnet Group [5].

4. Data processing

A code (**rhictf**) has been written to collect and process transfer function data for RHIC. It reads ITF data from FieldModel.sds for the corrector magnets and reads and processes ITF data from Magnet Group files for the "main" magnets (DRG, DR8, D96, QRG, QR4, QR7, QRI, QRJ, QRK, DRZ). D5I and D5O dipoles have no measured data, so simulation data for the fields are used[6]. The code calculates averages and produces plot files as well as a file used to load the appropriate database table (magnet_field) with average ITF data for all FieldName's.
For all magnets, only measured data for the **UP ramp** in the hysteresis cycle are taken, as was done for the AtR data.
The magnet_field table is discussed in Section 5 and plots for all magnet types in Section 6.

Only one remark about the **correctors.** As it can be seen in the relevant ITF plots, the ITF is not a constant, because of *saturation effects* (large values of current) and *magnetization effects* (small currents), although the effect is small. Theoretically, however, for zero current, magnetization would make ITF diverge negatively in the "up" part of the hysteresis cycle and diverge positively in the "down" part. The correctors, on the contrary of the main magnets, may cross zero current frequently during operations, so it would be impossible to predict with high accuracy the response. We decided then to use a *constant transfer function* for the correctors. The program fits the transfer function data to a constant, after discarding current values larger that a "saturation" threshold or smaller than a "magnetization" threshold (the thresholds are different for different corrector types).

5. The magnet_field table

Average ITF data for every magnet type (FieldName) are loaded into the **magnet_field table** in the **r96gddb** database, which is the repository of data used in the RHIC sextant test. The structure of the table is the following:

Table 3:

Column name	Description
FieldName	name identifying type of magnet
I	current [Amps]
Transfunc	Integral Transfer Function [Tm/kA]
RefRadius	Reference Radius [m]
UpDown	flag [1 if data on the UP ramp, -1 if on the DOWN ramp, 0 if simulation]
ord	multipolarity index [0 for dipole, 1 for quadrupole, 2 for sextupole, etc.]
NormSkew	flag [1 for normal field, -1 for skew field]
b0 ---> b5	measured multipoles [normal]
a0 ---> a5	measured multipole [skew]

The magnet_field table collects the information necessary to reconstruct the field expansion for every magnet type. Only multipole up to order five are retained in the table, in analogy with what has been done for the AtR data.
The **magnet_field** table in **atr_gddb**, which holds analogous field information for the AtR line magnet fields, has been redesigned and reloaded to look exactly like the one in r96gddb.

6. Transfer Functions

Plots of Integral Transfer Function data for every type of RHIC magnet (FieldName) are attached to this note. Corrector fields with the same multipolarity (and same reference radius) are plotted together.

7. Connection to the magnet manager

The main purpose of collecting magnet transfer function data is operational, so the data have to be made available to the **magnet manager**, the high level code which controls and monitors power supplies. A program, dbsort [7] has been written to interface database information to the AtR magnet manager. That code has been modified into **dbsort2**, which combines data from both the *atr_gddb* and *r96gddb* databases. Dbsort2 reads and processes several database tables that contain power supply and magnet information, such as configuration data, wireup, location, calibration, etc. Among the other things dbsort2 reads the magnet_field table in both databases, combines and processes the data and feeds them to the magnet manager.
The ITF data in the magnet_field table get converted to MTF data by the following relation:

$$MTF\left[\frac{T}{Am^{n-1}}\right] = \frac{10^{-3}}{R^{n}_{ref}[m]} ITF\left[\frac{Tm}{kA}\right]$$

where n is the order of the field (n=0 for dipoles, n=1 for quadrupoles, n=2 for sextupoles, etc.). The actual conversion coefficients for every magnet type are maintained in another database table (*fieldfudge table*).
The magnet manager reads the data processed by dbsort2 and takes care of the interpolation between current points and of the correlation between currents and magnet strengths, defined as $\rho/L = \alpha$ for dipoles, $kL = 1/f$ for quadrupoles, etc.

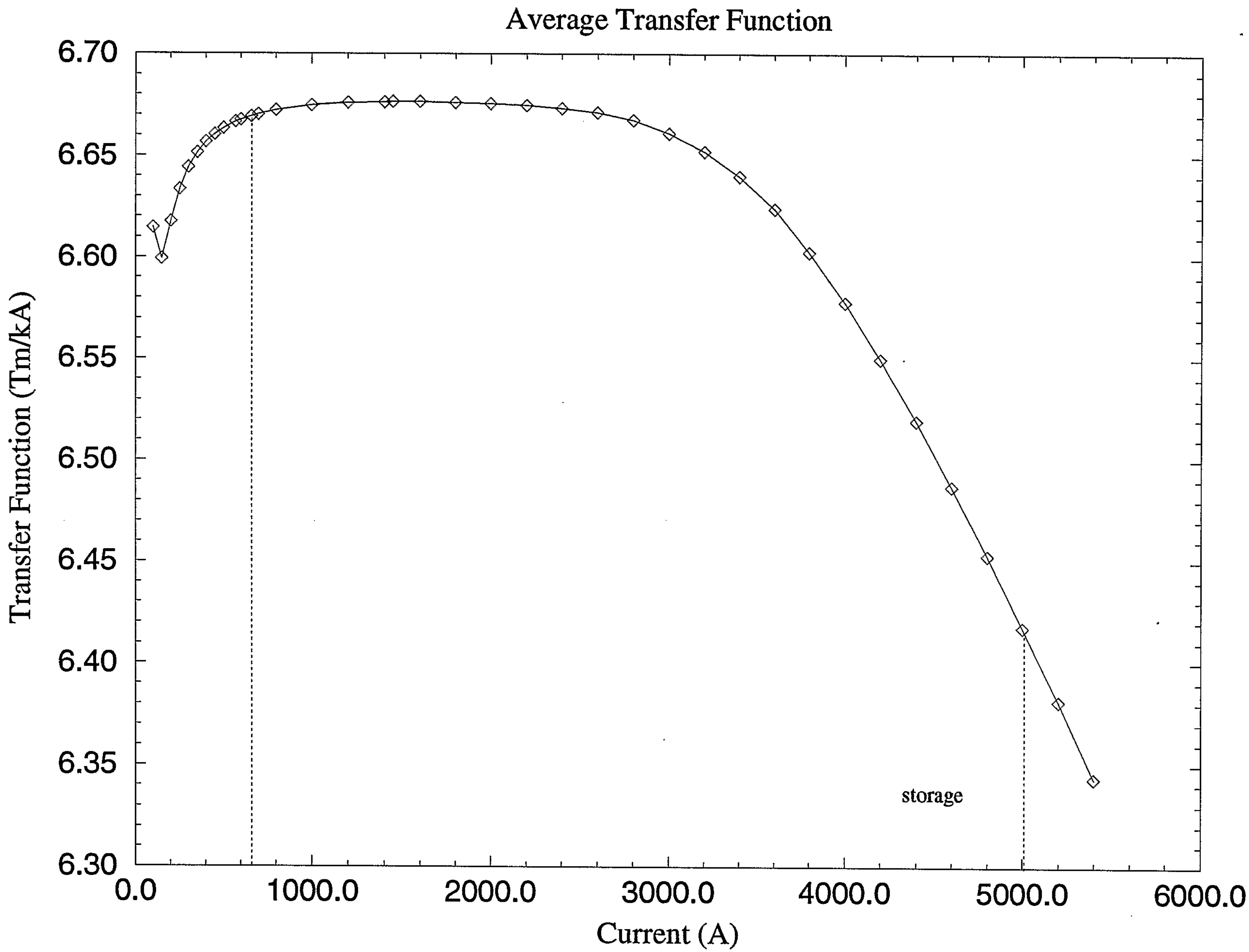
Acknowledgments

I would like to thank A.Jain and R.Gupta for providing integral transfer function data and J.Kewisch, W.MacKay, and G.Trahern for discussions and help.

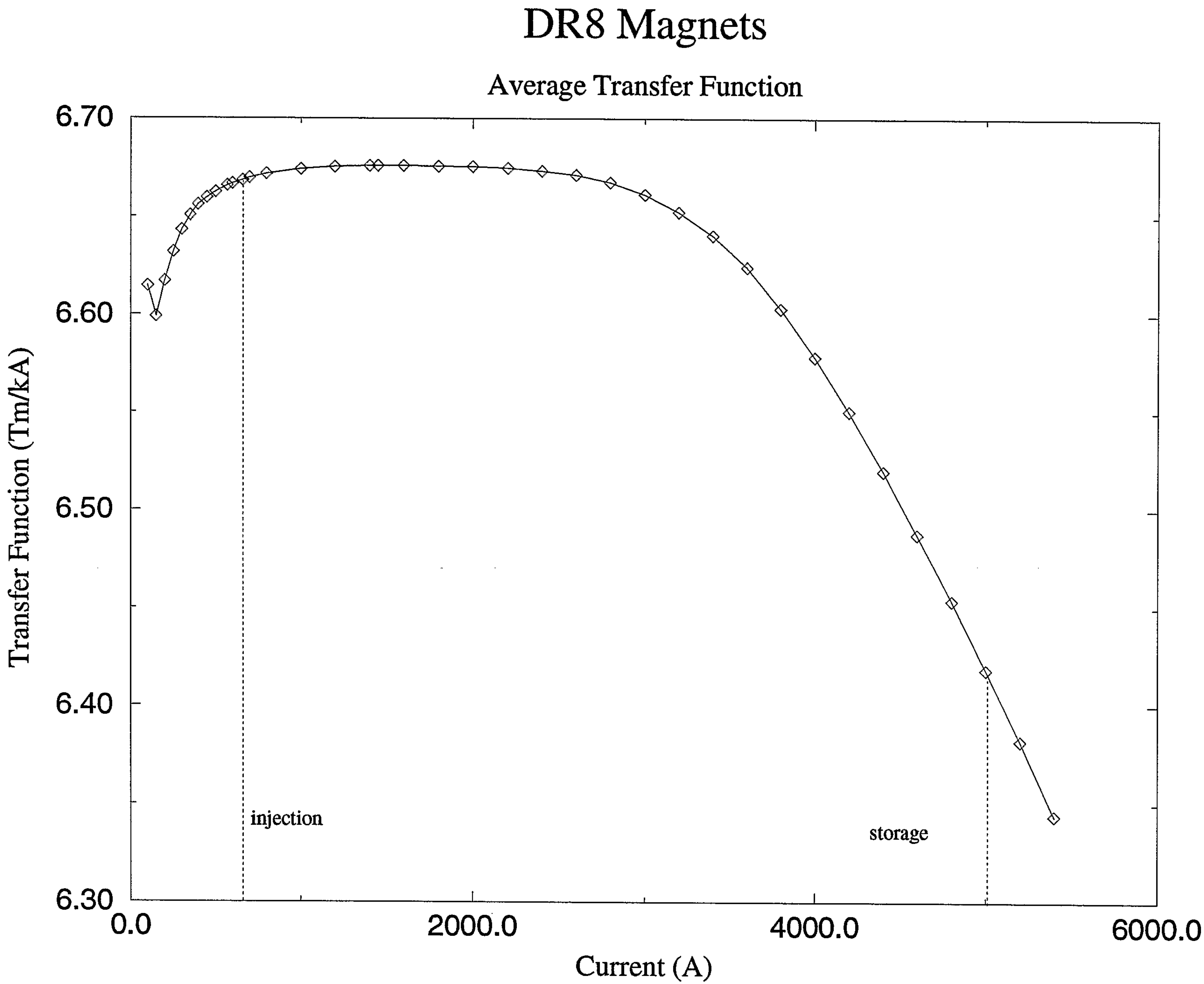
References

[1] F.Pilat, *"ATR Magnet Transfer Functions"*, RHIC/AP/73
[2] G.Trahern, F.Pilat, *"Comparing and Defining Magnetic Multipoles: I. MAD and Teapot and II. RHIC Measurements and Teapot"*, RHIC/AP/99
[3] A.Jain, D.Trbojevic, F.Dell, S.Peggs, P.Wanderer, J.Wei, *"RHIC Magnetic Measurements: Definitions and Conventions"*, RHIC/AP/95
[4] J.Wei, R.Gupta, A.Jain, S.Peggs, G.Trahern, D.Trbojevic, P.Wanderer, *"Field Quality Evaluation of the Superconducting Magnets of the Relativistic heavy Ion Collider"*, Proceedings PAC 95
[5] A.Jain, *Private Communication*
[6] R.Gupta, *Private Communication*
[7] J.Kewish, *Private Communication*

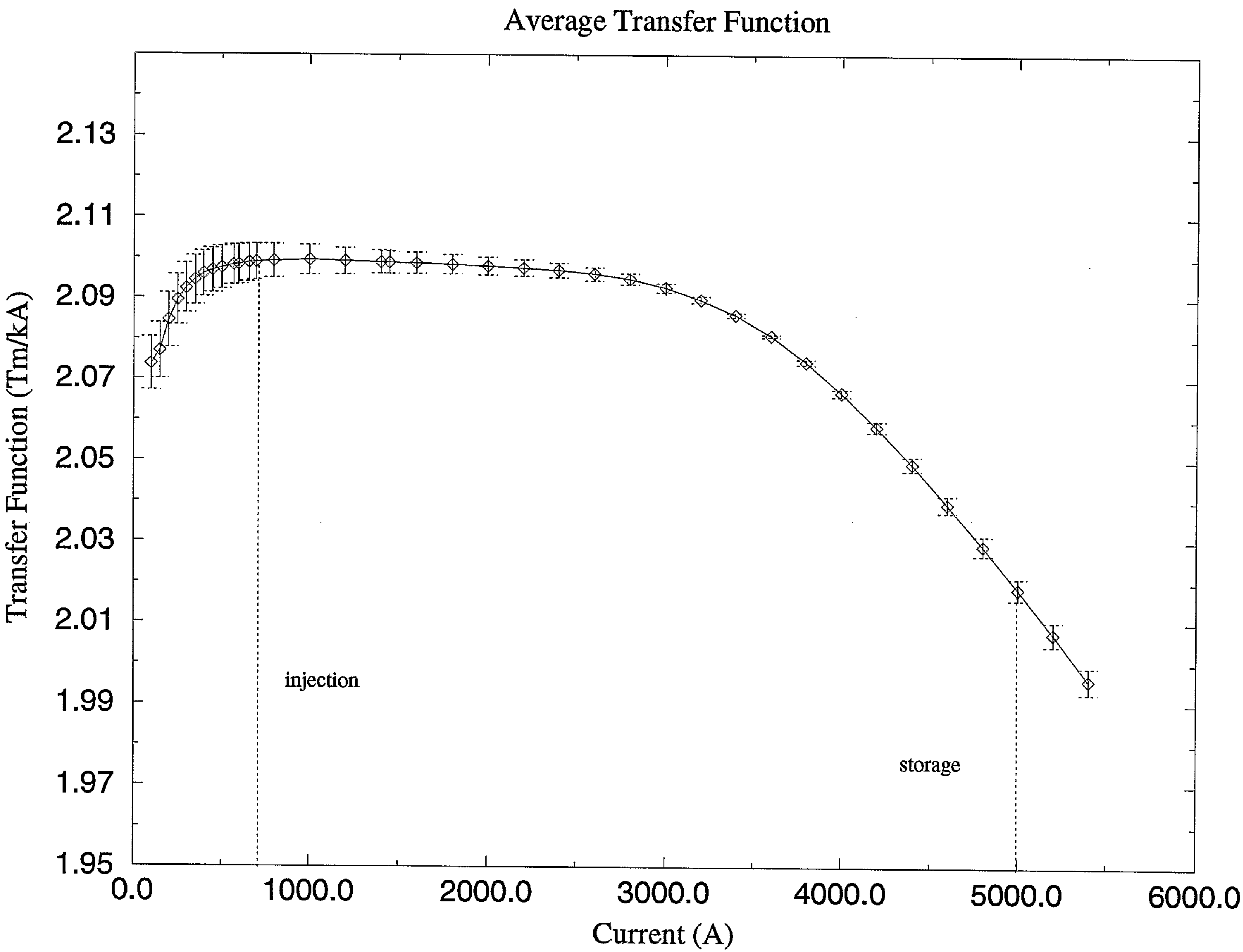
DRG Magnets

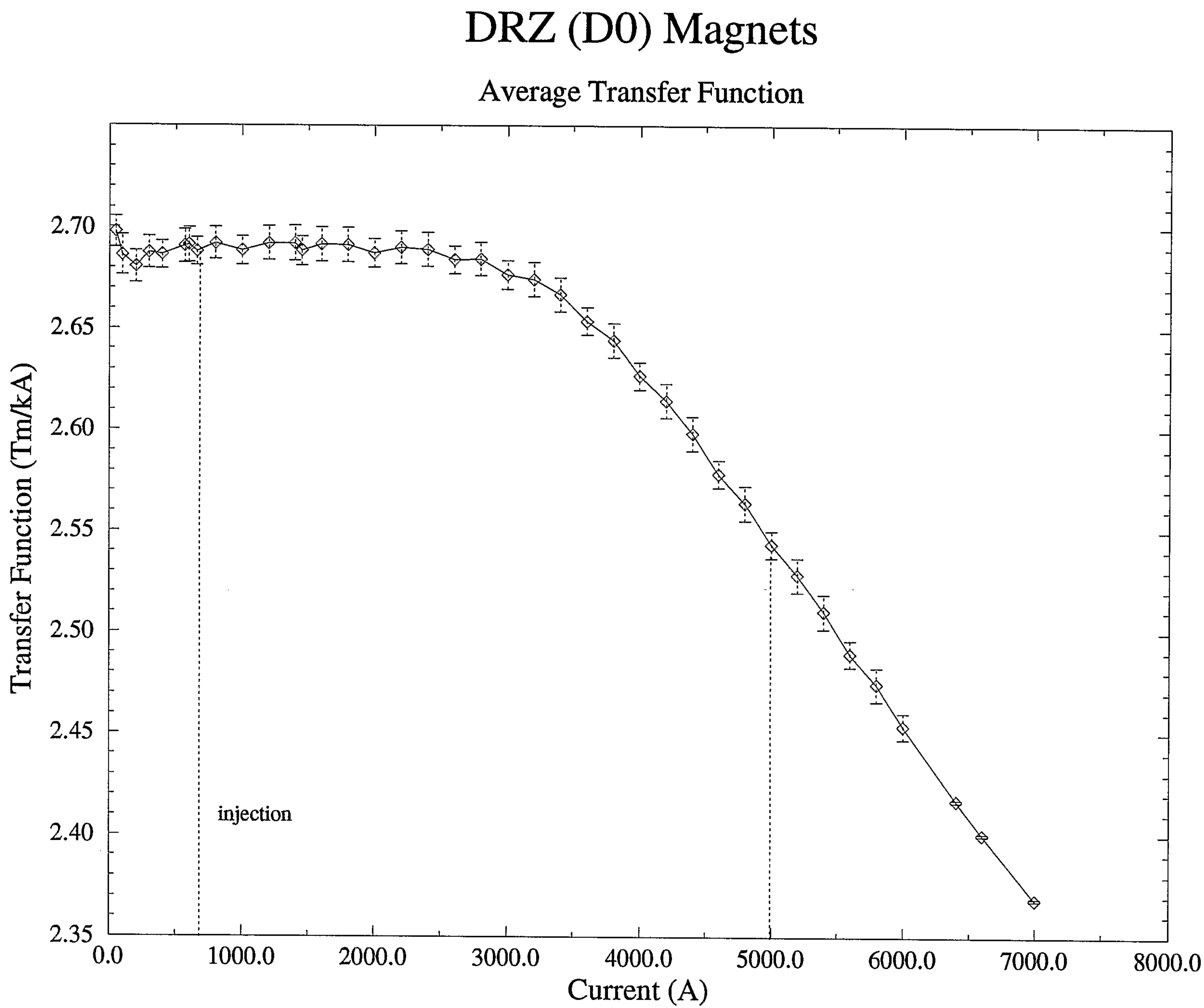


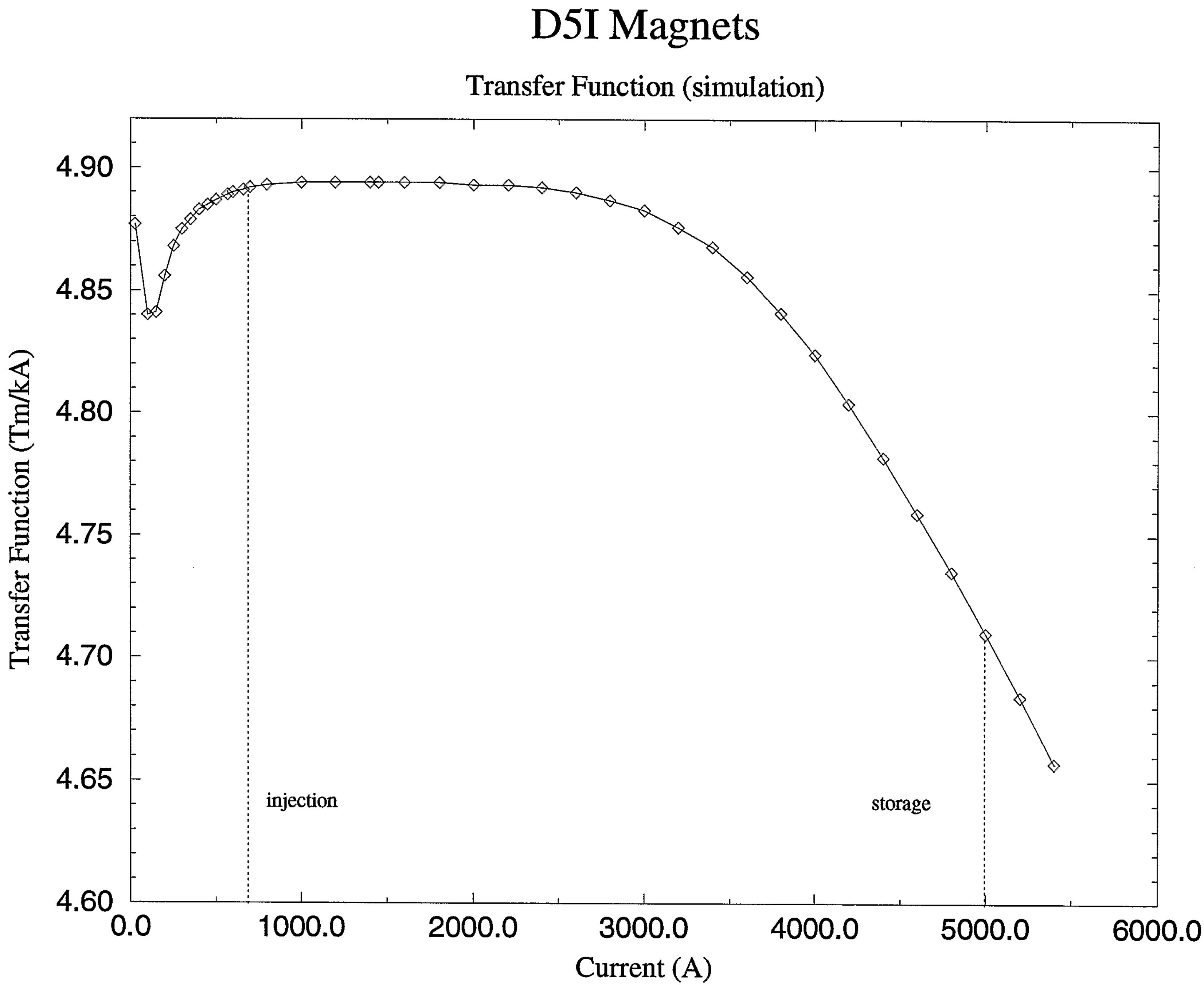
Average Transfer Function
Transfer Function (Tm/kA)
Current (A)
6.70
6.65
6.60
6.55
6.50
6.45
6.40
6.35
6.30
0.0
1000.0
2000.0
3000.0
4000.0
5000.0
6000.0
storage


DR8 Magnets
Average Transfer Function
6.70
6.60
6.50
6.40
6.30
Transfer Function (Tm/kA)
injection
storage
0.0
2000.0
4000.0
6000.0
Current (A)

D96 Magnets

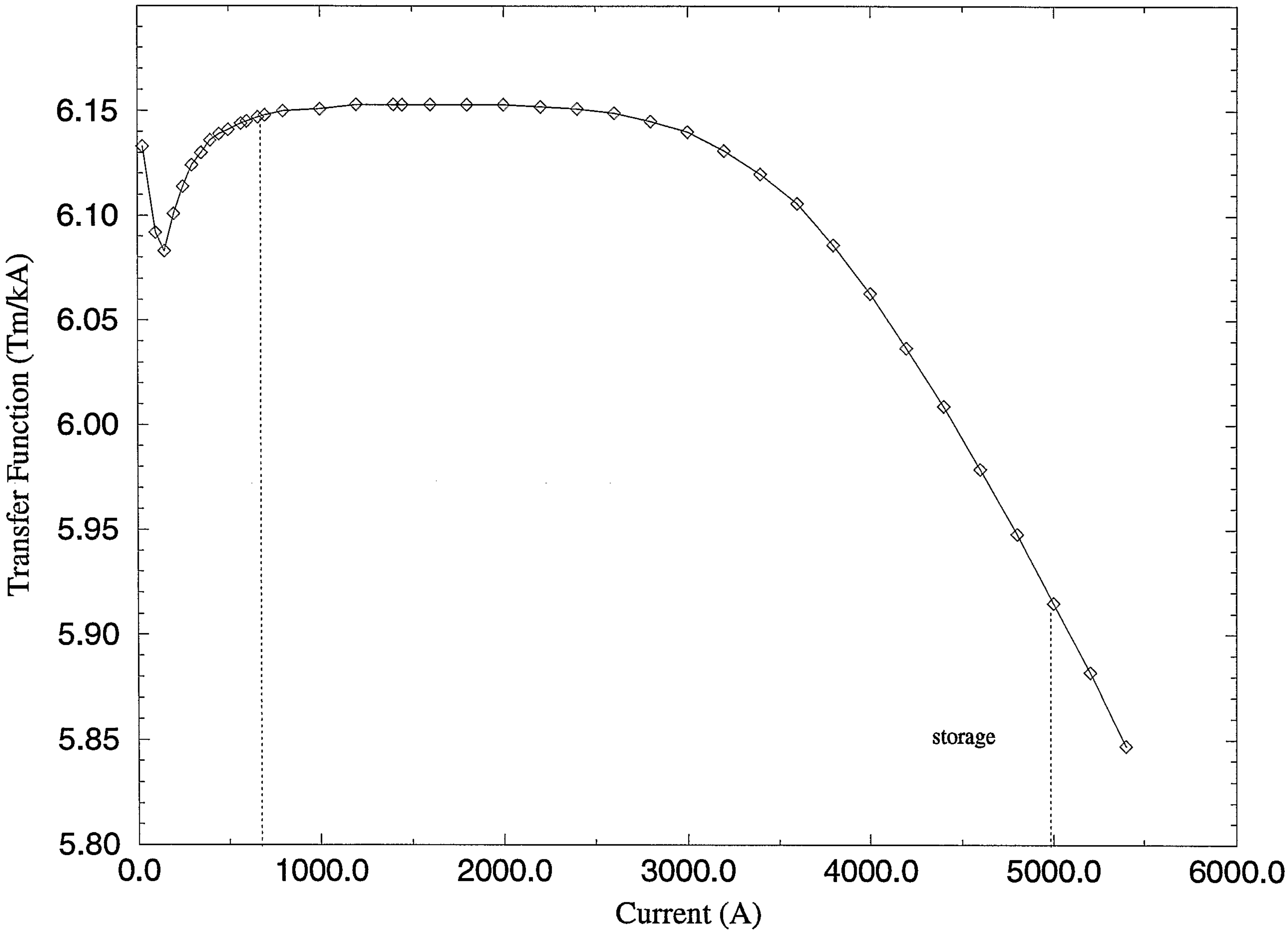

Average Transfer Function
Transfer Function (Tm/kA)
Current (A)
injection
storage
2.13
2.11
2.09
2.07
2.05
2.03
2.01
1.99
1.97
1.95
0.0
1000.0
2000.0
3000.0
4000.0
5000.0
6000.0

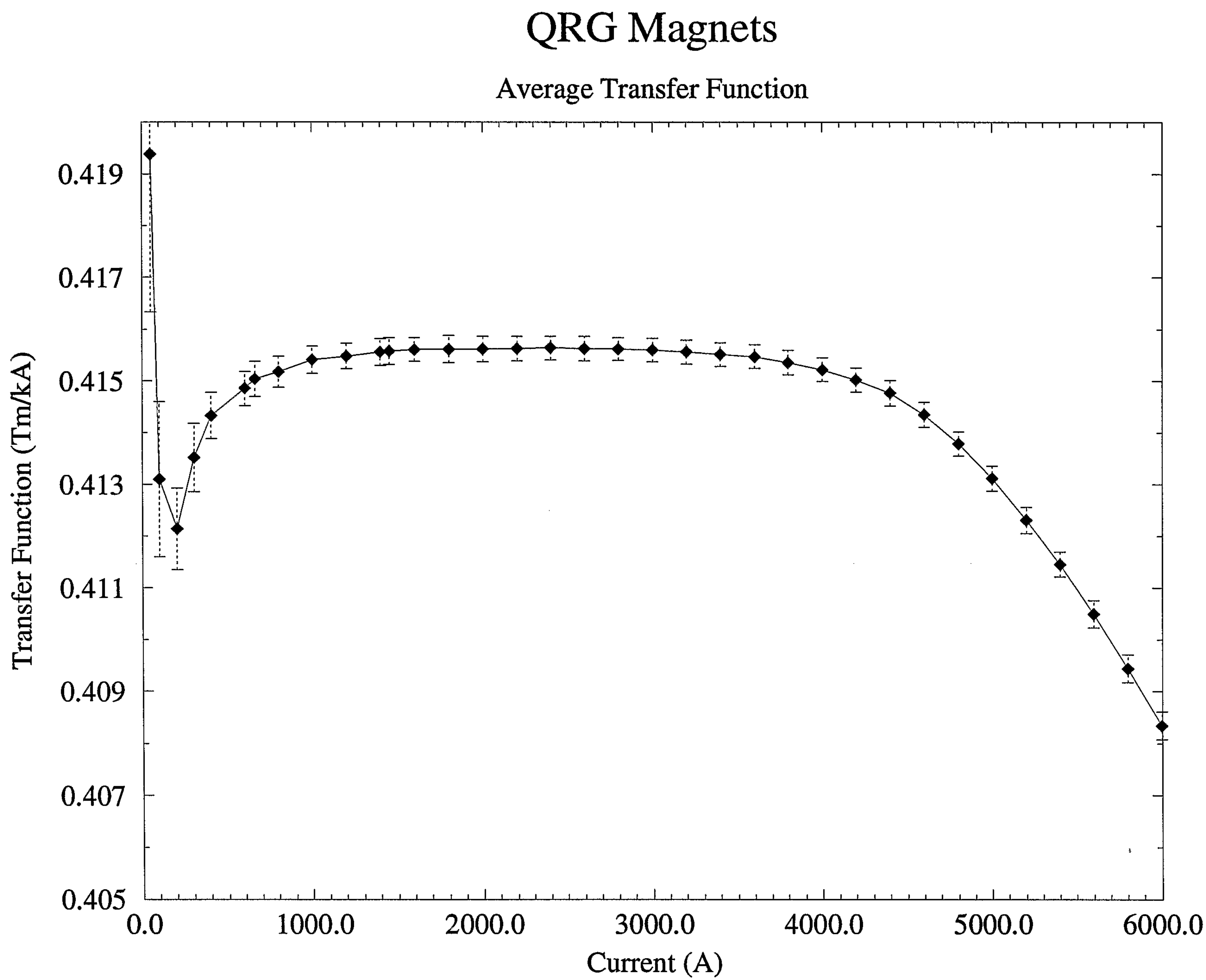

DRZ (D0) Magnets
Average Transfer Function
Transfer Function (Tm/kA)
Current (A)
injection
2.70
2.65
2.60
2.55
2.50
2.45
2.40
2.35
0.0
1000.0
2000.0
3000.0
4000.0
5000.0
6000.0
7000.0
8000.0


D5I Magnets
Transfer Function (simulation)
Transfer Function (Tm/kA)
4.90
4.85
4.80
4.75
4.70
4.65
4.60
0.0
1000.0
2000.0
3000.0
4000.0
5000.0
6000.0
Current (A)
injection
storage

D5O Magnets

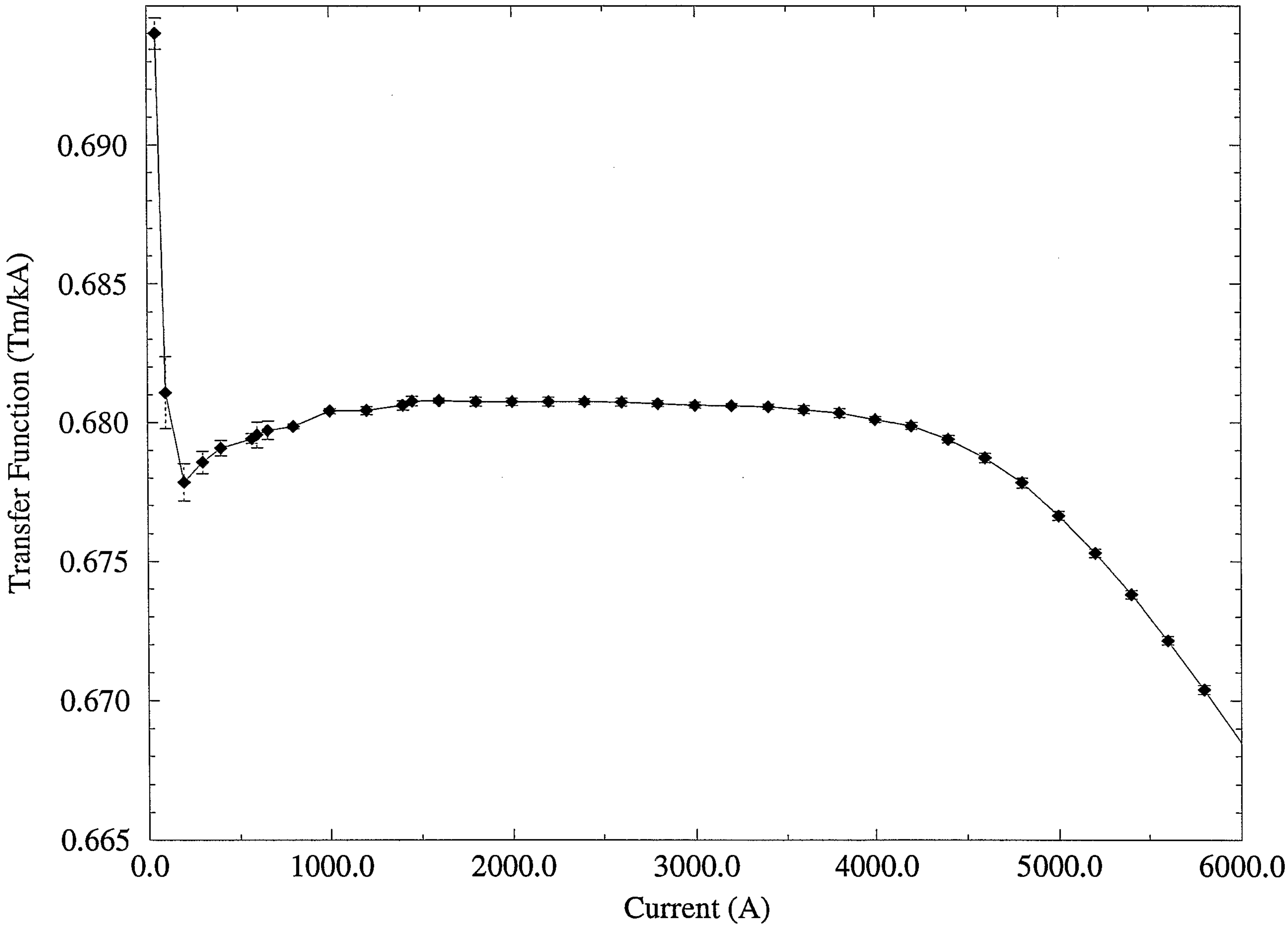
Transfer Function (simulation)

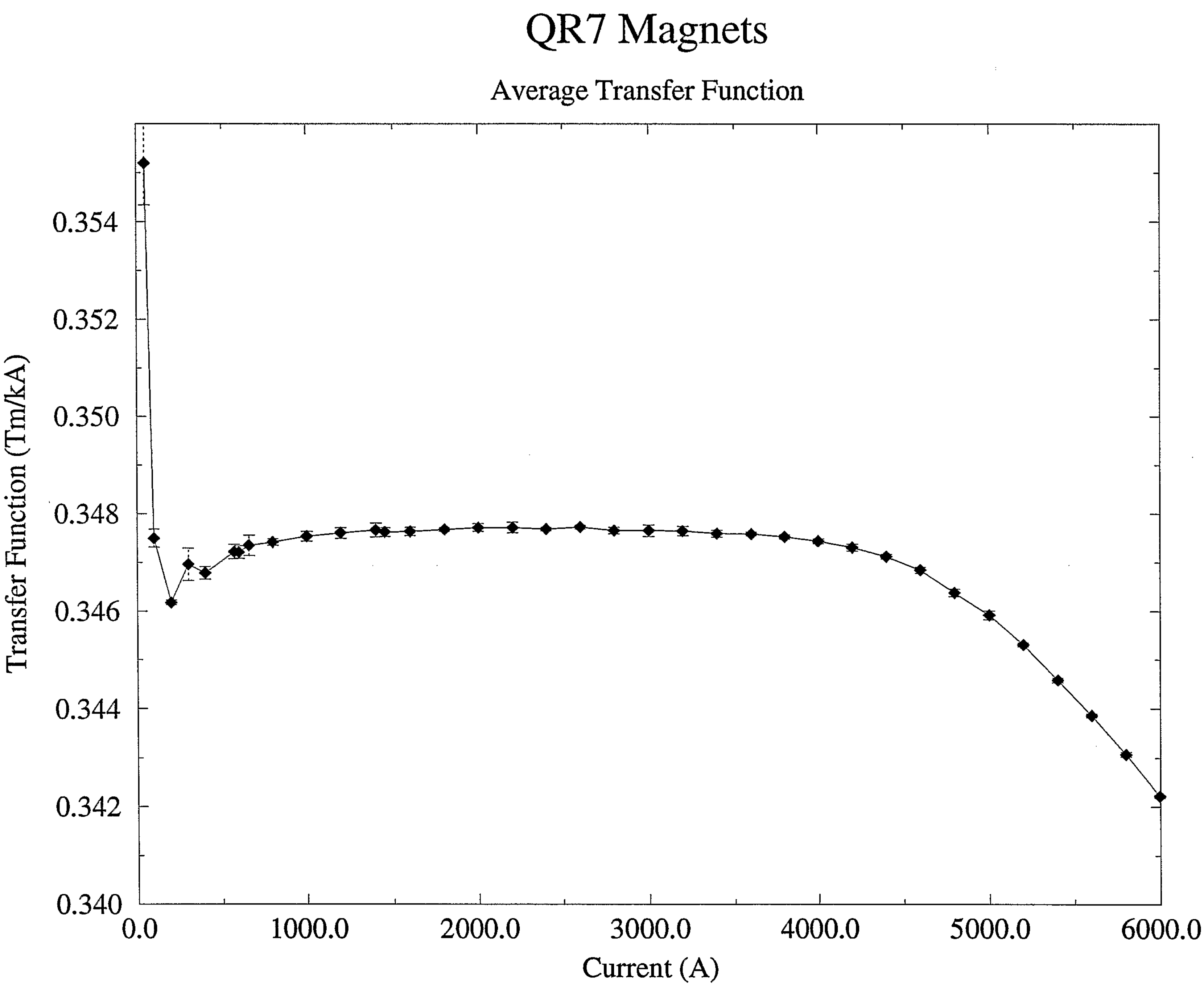


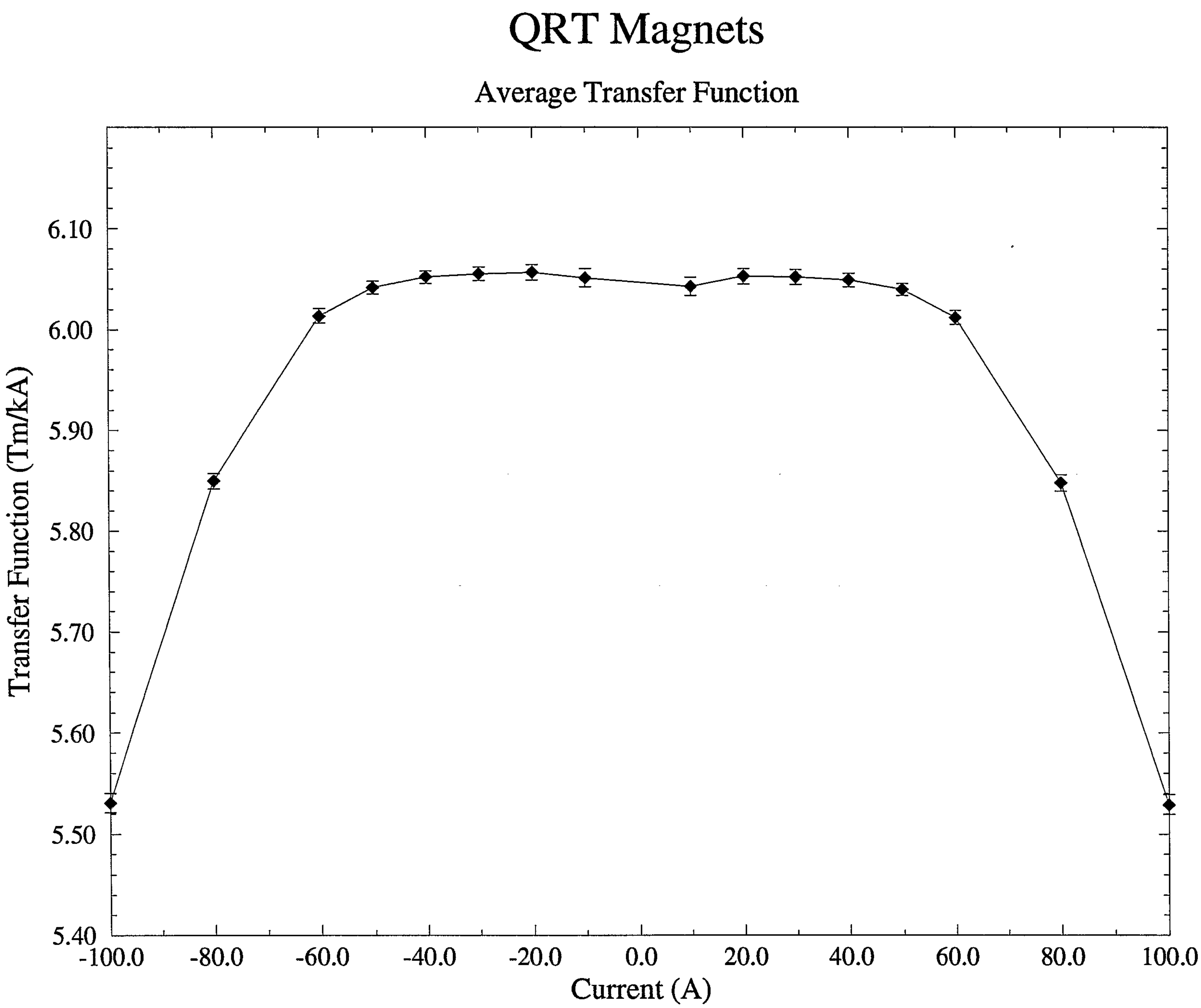

QRG Magnets
Average Transfer Function
Transfer Function (Tm/kA)
0.419
0.417
0.415
0.413
0.411
0.409
0.407
0.405
0.0
1000.0
2000.0
3000.0
4000.0
5000.0
6000.0
Current (A)

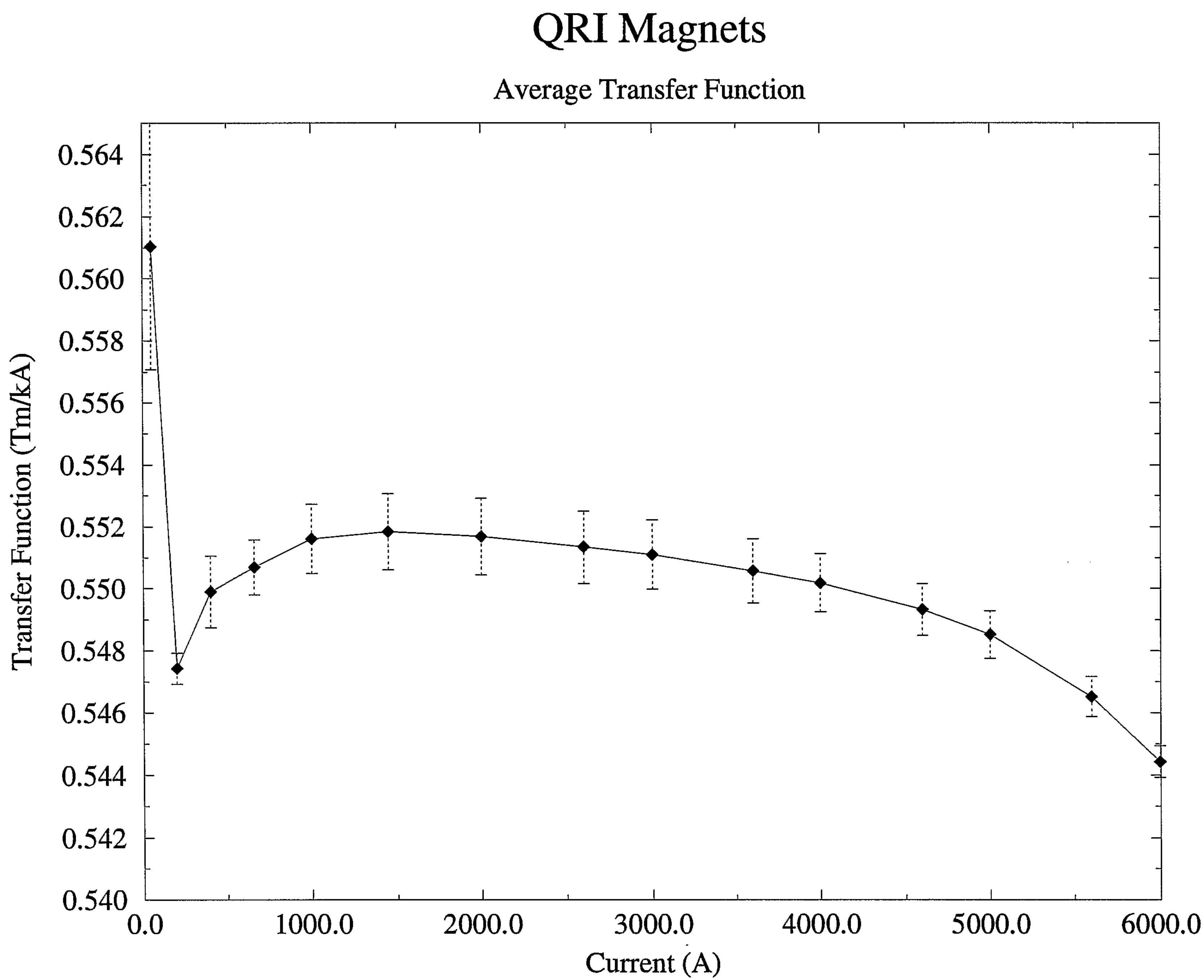
QR4 Magnets

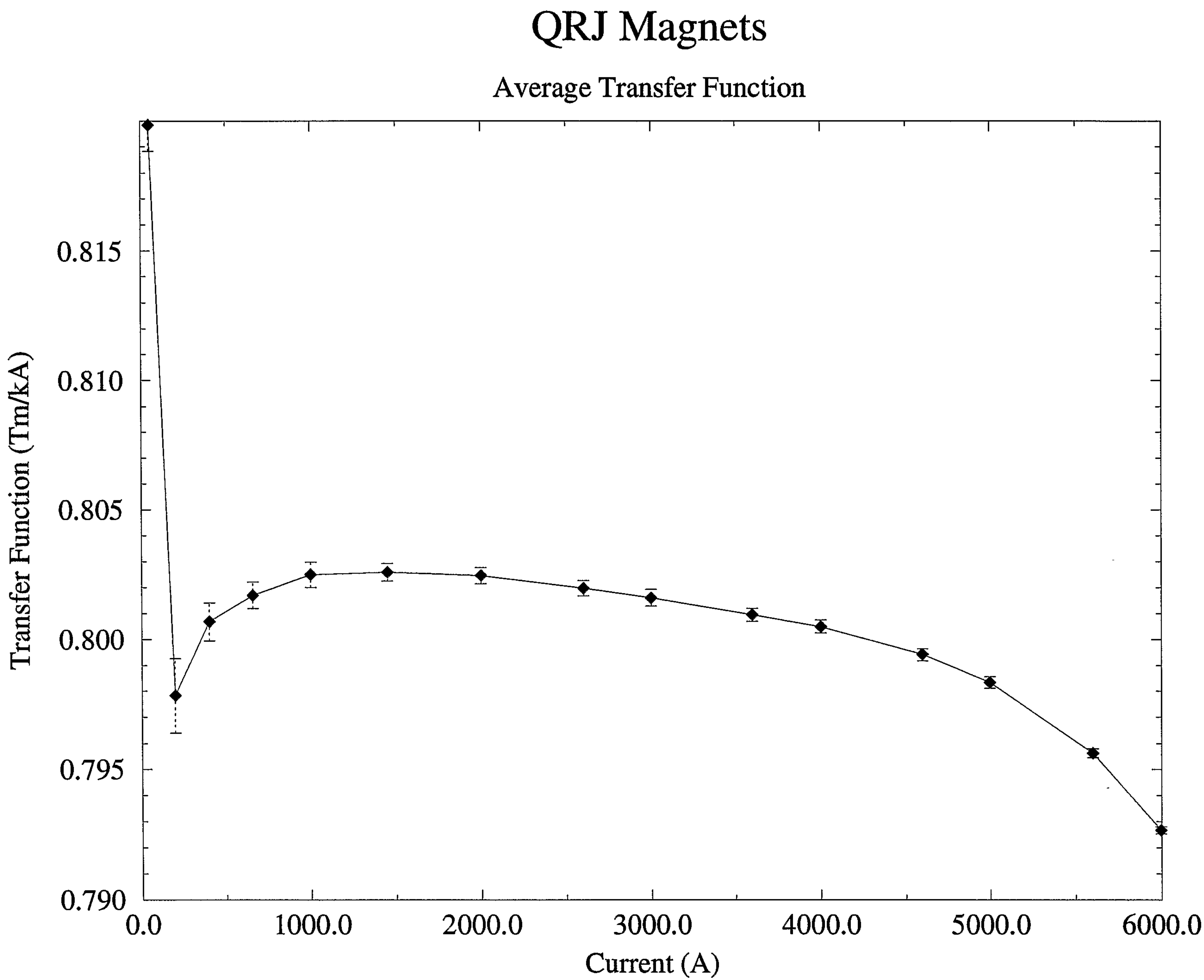
Average Transfer Function



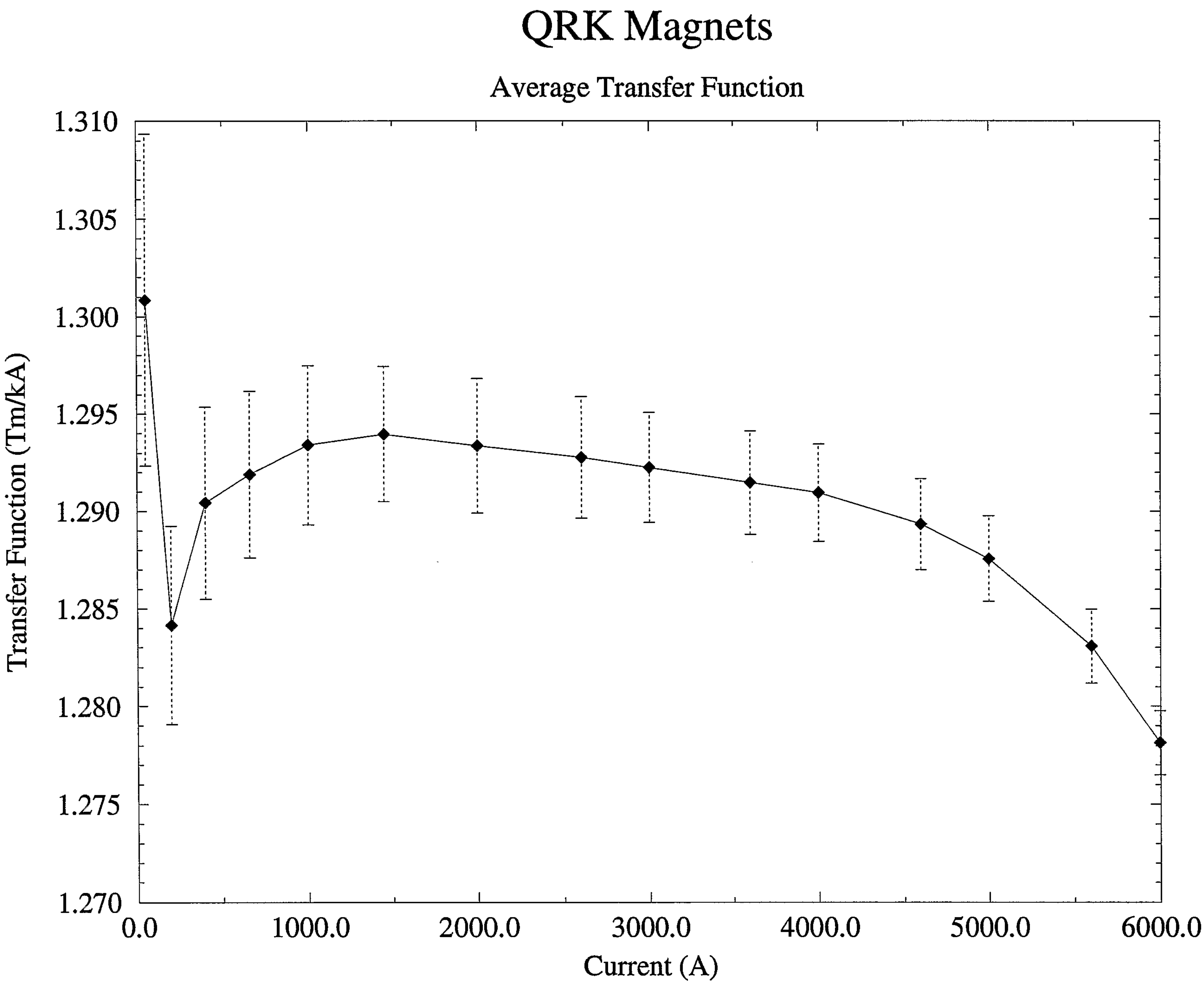

QR7 Magnets
Average Transfer Function
Transfer Function (Tm/kA)
0.354
0.352
0.350
0.348
0.346
0.344
0.342
0.340
0.0
1000.0
2000.0
3000.0
4000.0
5000.0
6000.0
Current (A)


QRT Magnets
Average Transfer Function
Transfer Function (Tm/kA)
6.10
6.00
5.90
5.80
5.70
5.60
5.50
5.40
-100.0
-80.0
-60.0
-40.0
-20.0
0.0
20.0
40.0
60.0
80.0
100.0
Current (A)

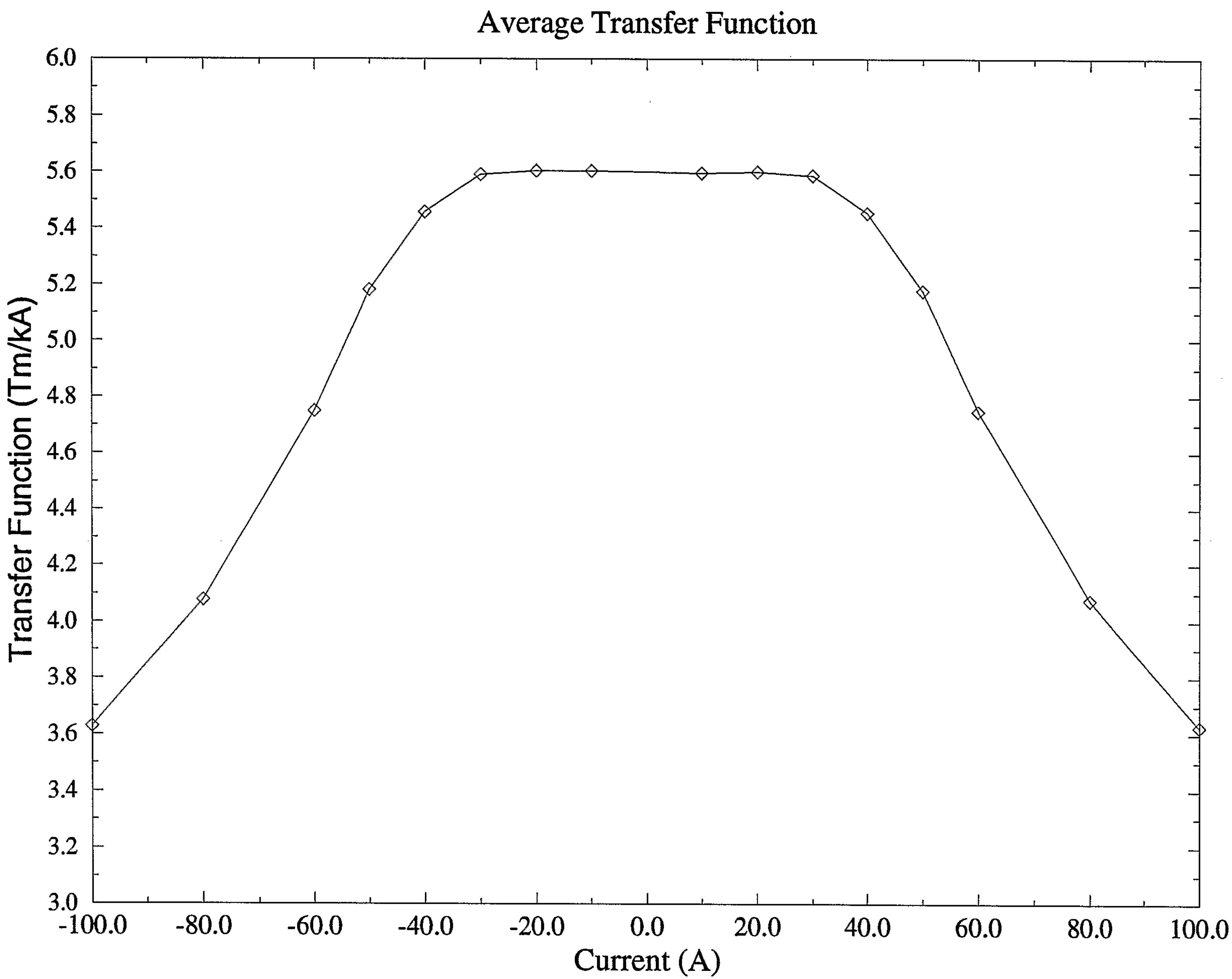

QRI Magnets
Average Transfer Function
Transfer Function (Tm/kA)
0.564
0.562
0.560
0.558
0.556
0.554
0.552
0.550
0.548
0.546
0.544
0.542
0.540
0.0
1000.0
2000.0
3000.0
4000.0
5000.0
6000.0
Current (A)

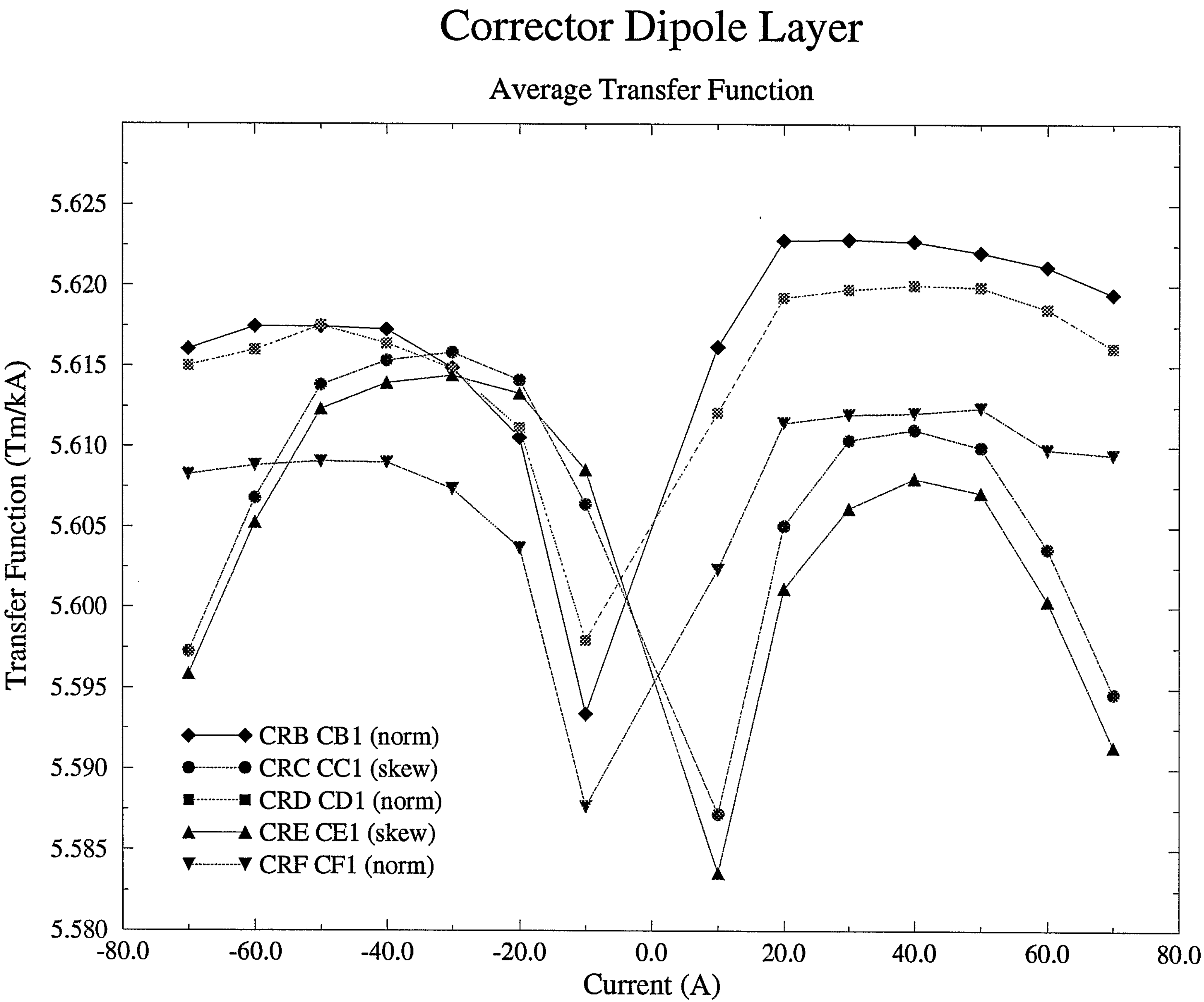


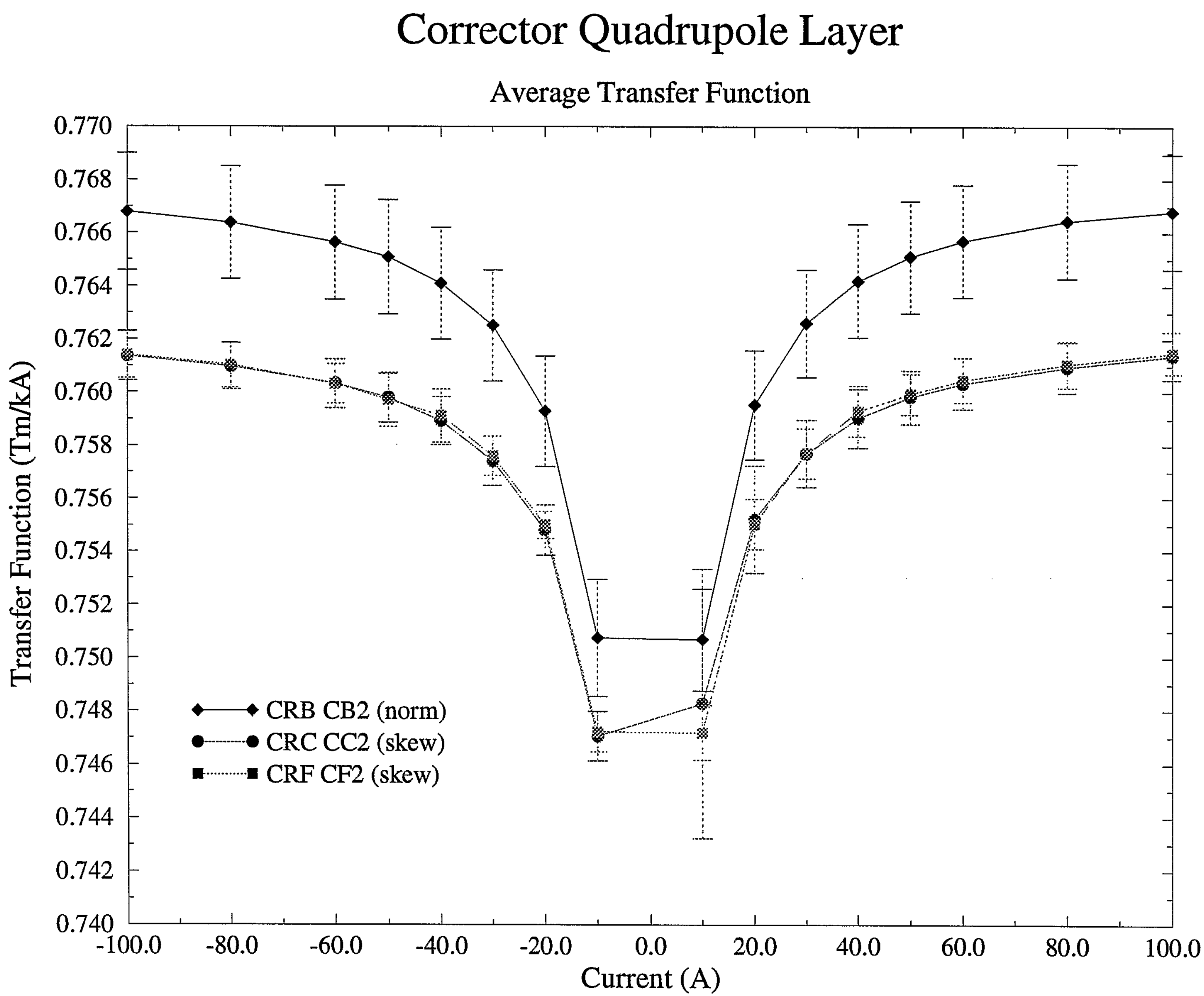
QRJ Magnets
Average Transfer Function
Transfer Function (Tm/kA)
0.815
0.810
0.805
0.800
0.795
0.790
0.0
1000.0
2000.0
3000.0
4000.0
5000.0
6000.0
Current (A)


QRK Magnets
Average Transfer Function
Transfer Function (Tm/kA)
Current (A)
1.310
1.305
1.300
1.295
1.290
1.285
1.280
1.275
1.270
0.0
1000.0
2000.0
3000.0
4000.0
5000.0
6000.0

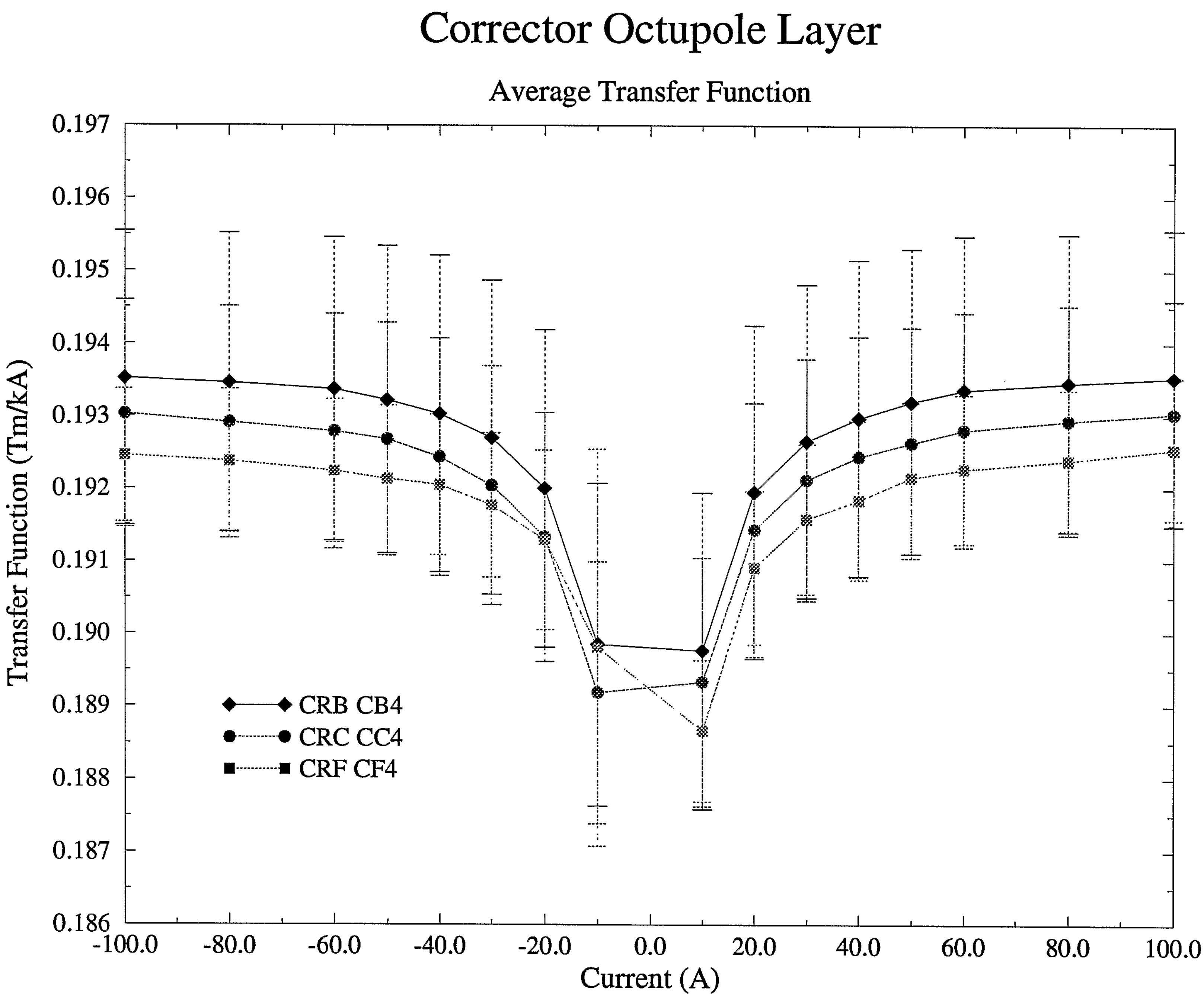
SRE Magnets


Average Transfer Function
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
Transfer Function (Tm/kA)
-100.0
-80.0
-60.0
-40.0
-20.0
0.0
20.0
40.0
60.0
80.0
100.0
Current (A)

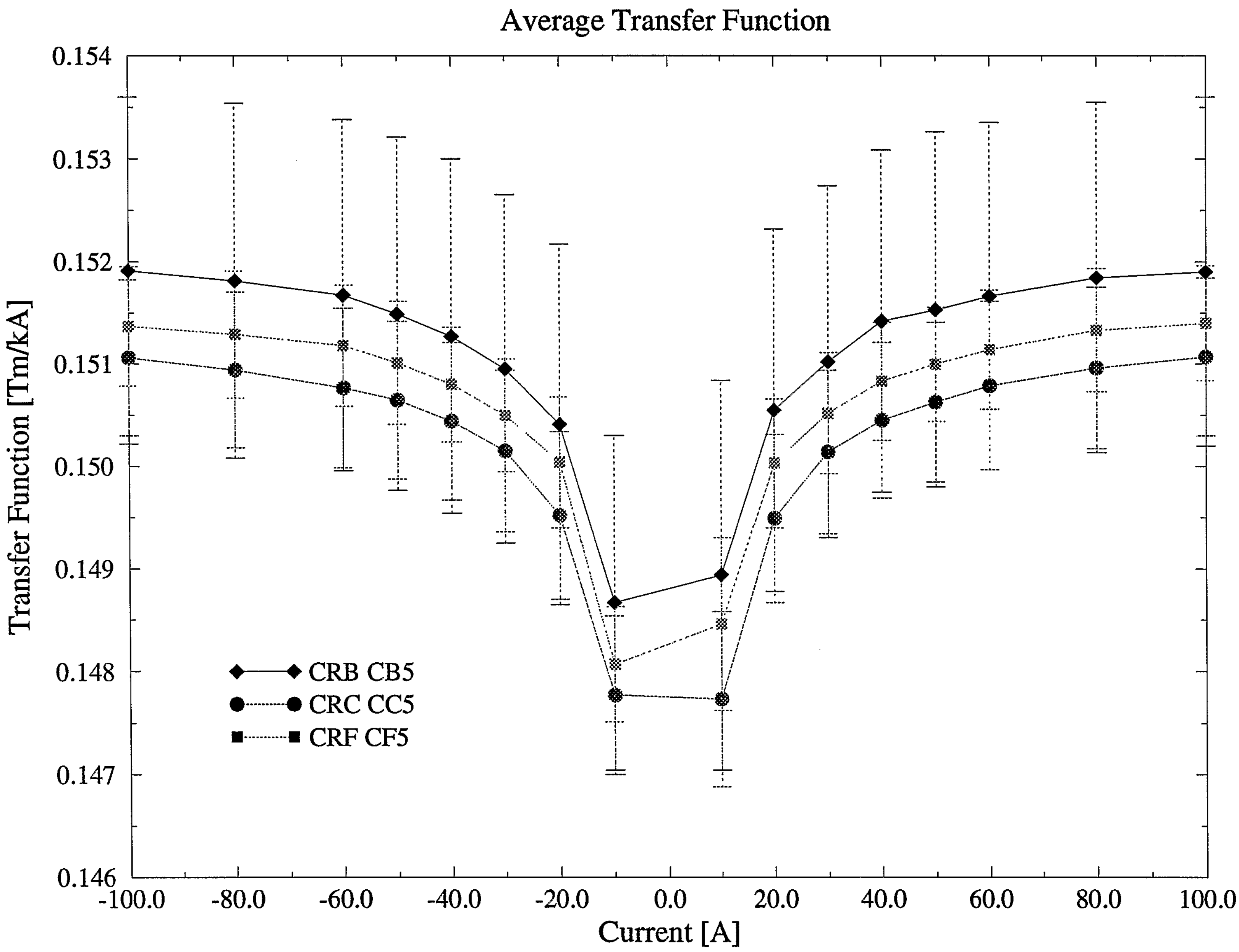

Corrector Dipole Layer
Average Transfer Function
Transfer Function (Tm/kA)
Current (A)
5.625
5.620
5.615
5.610
5.605
5.600
5.595
5.590
5.585
5.580
-80.0
-60.0
-40.0
-20.0
0.0
20.0
40.0
60.0
80.0
CRB CB1 (norm)
CRC CC1 (skew)
CRD CD1 (norm)
CRE CE1 (skew)
CRF CF1 (norm)

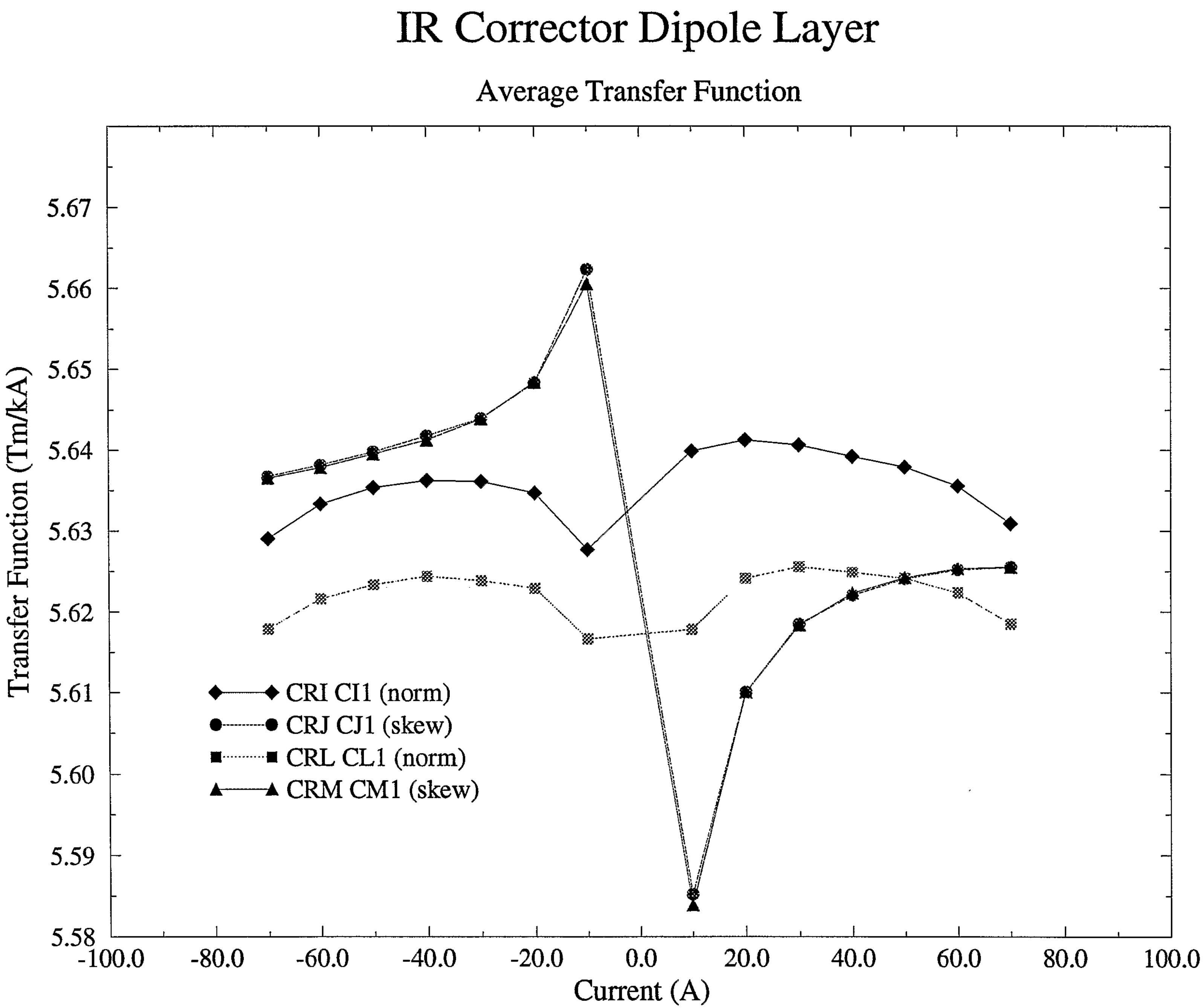


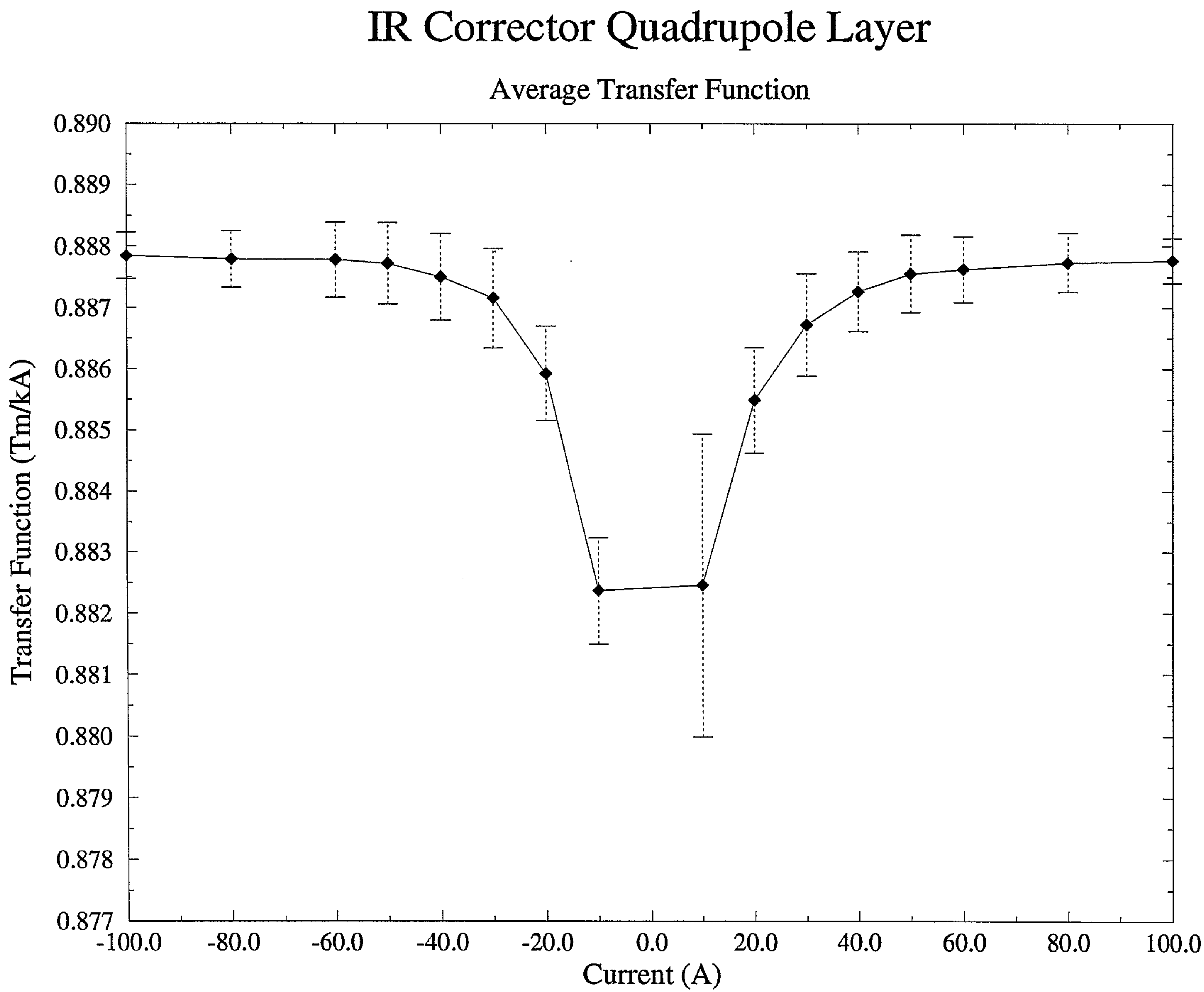
Corrector Quadrupole Layer
Average Transfer Function
Transfer Function (Tm/kA)
0.770
0.768
0.766
0.764
0.762
0.760
0.758
0.756
0.754
0.752
0.750
0.748
0.746
0.744
0.742
0.740
-100.0
-80.0
-60.0
-40.0
-20.0
0.0
20.0
40.0
60.0
80.0
100.0
Current (A)
CRB CB2 (norm)
CRC CC2 (skew)
CRF CF2 (skew)

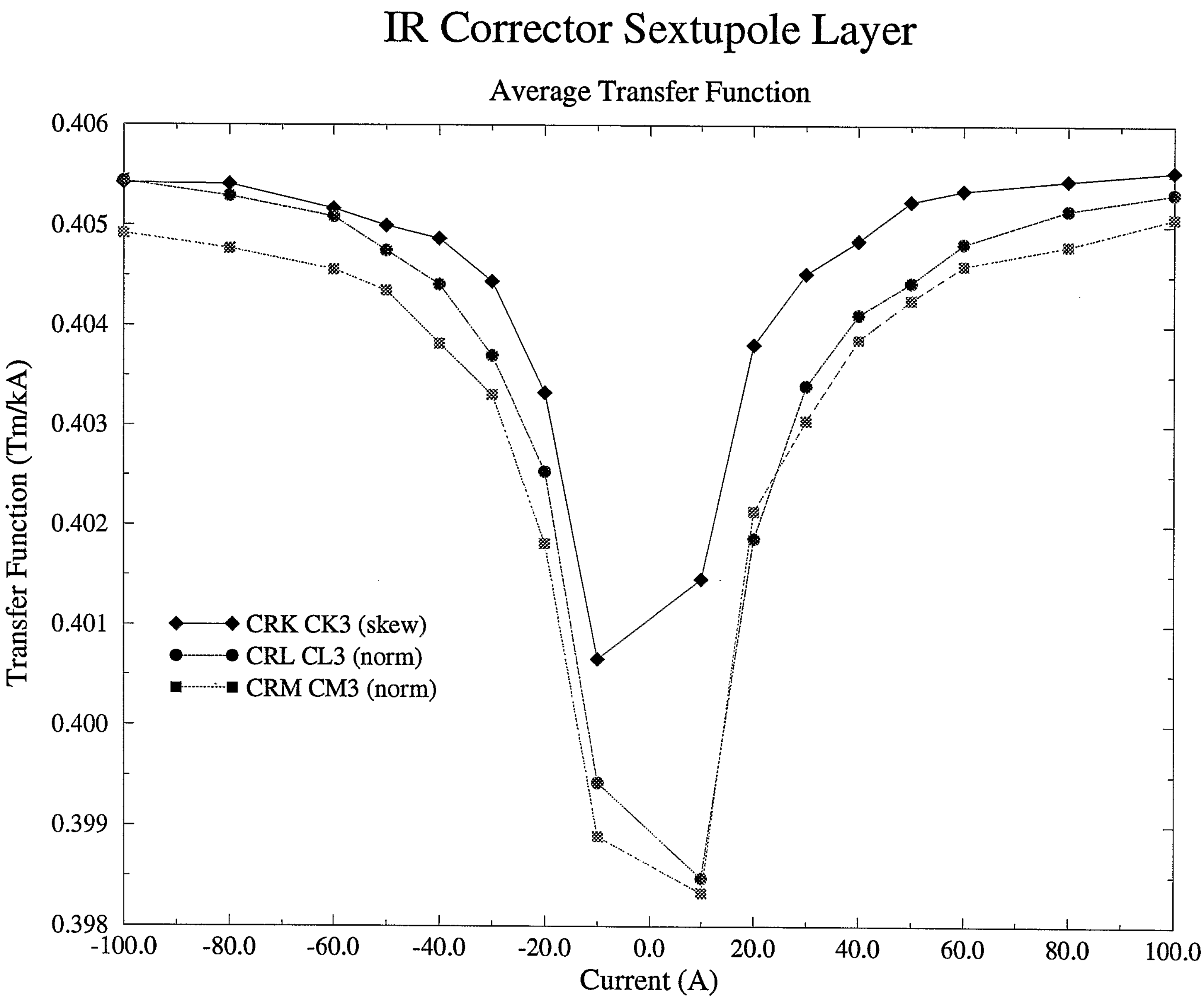

Corrector Octupole Layer
Average Transfer Function
Transfer Function (Tm/kA)
0.197
0.196
0.195
0.194
0.193
0.192
0.191
0.190
0.189
0.188
0.187
0.186
-100.0
-80.0
-60.0
-40.0
-20.0
0.0
20.0
40.0
60.0
80.0
100.0
Current (A)
CRB CB4
CRC CC4
CRF CF4

Corrector Decapole Layer

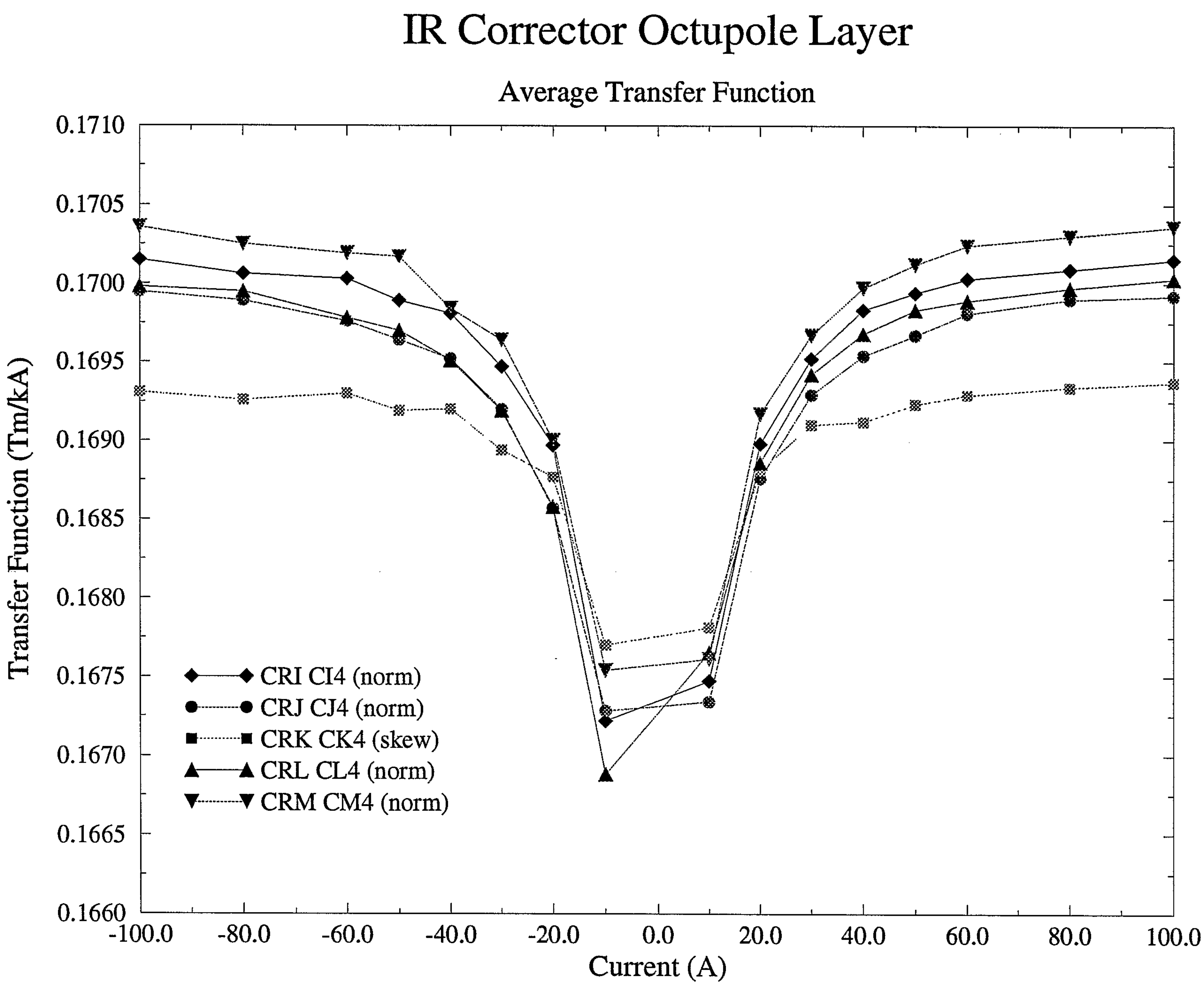



IR Corrector Dipole Layer
Average Transfer Function
Transfer Function (Tm/kA)
5.67
5.66
5.65
5.64
5.63
5.62
5.61
5.60
5.59
5.58
-100.0
-80.0
-60.0
-40.0
-20.0
0.0
20.0
40.0
60.0
80.0
100.0
Current (A)
CRI CI1 (norm)
CRJ CJ1 (skew)
CRL CL1 (norm)
CRM CM1 (skew)

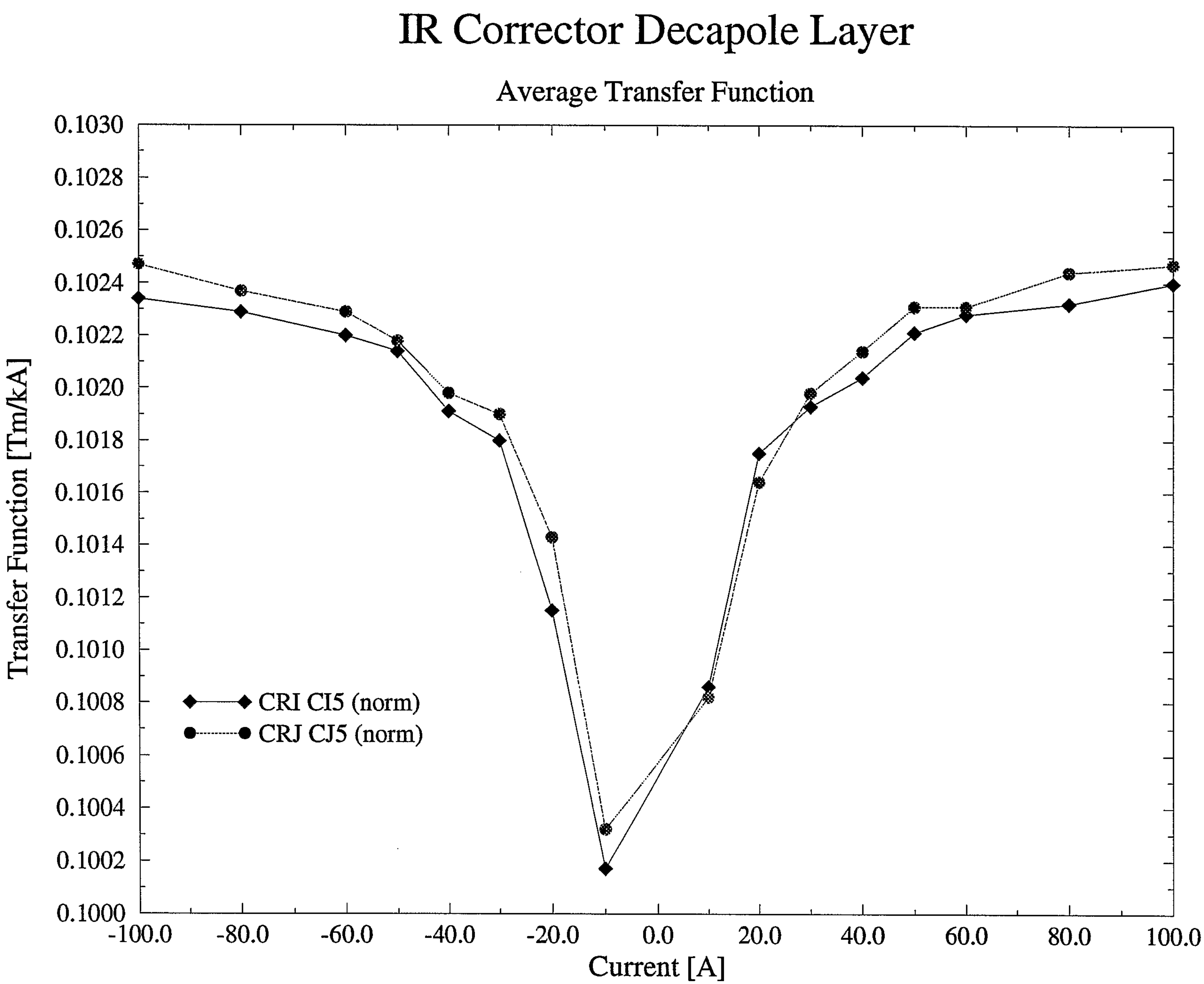

IR Corrector Quadrupole Layer
Average Transfer Function
Transfer Function (Tm/kA)
0.890
0.889
0.888
0.887
0.886
0.885
0.884
0.883
0.882
0.881
0.880
0.879
0.878
0.877
-100.0
-80.0
-60.0
-40.0
-20.0
0.0
20.0
40.0
60.0
80.0
100.0
Current (A)

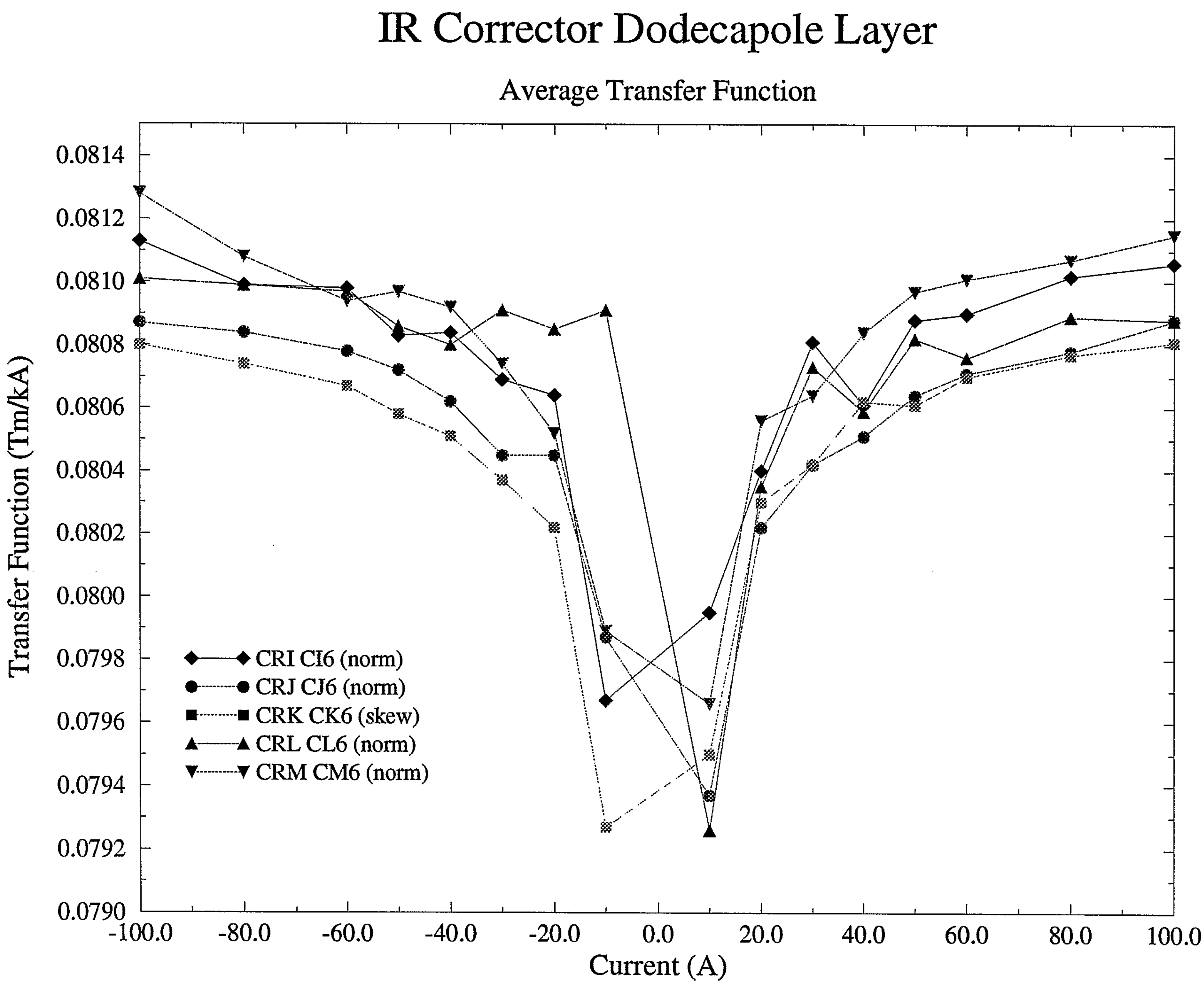


IR Corrector Sextupole Layer
Average Transfer Function
Transfer Function (Tm/kA)
0.406
0.405
0.404
0.403
0.402
0.401
0.400
0.399
0.398
-100.0
-80.0
-60.0
-40.0
-20.0
0.0
20.0
40.0
60.0
80.0
100.0
Current (A)
CRK CK3 (skew)
CRL CL3 (norm)
CRM CM3 (norm)



IR Corrector Octupole Layer
Average Transfer Function
Transfer Function (Tm/kA)
Current (A)
0.1710
0.1705
0.1700
0.1695
0.1690
0.1685
0.1680
0.1675
0.1670
0.1665
0.1660
-100.0
-80.0
-60.0
-40.0
-20.0
0.0
20.0
40.0
60.0
80.0
100.0
CRI CI4 (norm)
CRJ CJ4 (norm)
CRK CK4 (skew)
CRL CL4 (norm)
CRM CM4 (norm)


IR Corrector Decapole Layer
Average Transfer Function
Transfer Function [Tm/kA]
Current [A]
CRI CI5 (norm)
CRJ CJ5 (norm)
0.1030
0.1028
0.1026
0.1024
0.1022
0.1020
0.1018
0.1016
0.1014
0.1012
0.1010
0.1008
0.1006
0.1004
0.1002
0.1000
-100.0
-80.0
-60.0
-40.0
-20.0
0.0
20.0
40.0
60.0
80.0
100.0


IR Corrector Dodecapole Layer
Average Transfer Function
Transfer Function (Tm/kA)
0.0814
0.0812
0.0810
0.0808
0.0806
0.0804
0.0802
0.0800
0.0798
0.0796
0.0794
0.0792
0.0790
-100.0
-80.0
-60.0
-40.0
-20.0
0.0
20.0
40.0
60.0
80.0
100.0
Current (A)
CRI CI6 (norm)
CRJ CJ6 (norm)
CRK CK6 (skew)
CRL CL6 (norm)
CRM CM6 (norm)