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AGS Tune Quad Production Measurements

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Collider Accelerator Department

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Accelerator Division
Technical Note

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AGS TUNE QUAD PRODUCTION MEASUREMENTS

E. BLESER

INTRODUCTION

This note reports on the magnetic measurements made on the high field quadrupoles which were installed in the AGS in the early 1990's as the Horizontal and Vertical Tune Quads and as the Skew Quads. It consists of three parts. Part A summarizes the available measurements. It includes results on 22 of the30 quads installed. Part B is an example of a detailed report which is generated for each magnet. These reports will not be given wide circulation, but they will be stored as part of the permanent record for each magnet. Part C is a data sheet for these magnets.

A. SUMMARY OF RESULTS

This note reports on results from 22 measured quadrupoles. The magnets were measured by the AD Group and the results were reported in their TMG Series of notes as well as being made available to us on the VAX computer.

The nomenclature we shall use is as follows:

$$B_y(X) = B_0 + B_1 * X + B_2 * X^2 + B_3 * X^3 + \ldots.$$

$$B_x(X) = A_0 + A_1 * X + A_2 * X^2 + A_3 * X^3 + \ldots.$$

In a quadrupole the only allowed terms are B_1 and B_5 etc. Those magnets installed as skew quads are rotated 45 degrees in effect interchanging A1 and B1.

All the measurements are DC, and are made with a rotating coil, 36.5 inches long, which projects well outside the ends of the magnets. Therefore all our data is in the form of integrated field values, written as $B_1 * L_{eff}$ etc. Figure 1 shows a typical plot of $B_1 * L_{eff}$, the integrated gradient, versus the current, I. Figure 2 is a more interesting plot of the integrated gradient divided by I versus I. The simple linear fit shown in Figure 1 does not give a good fit to the data when it is plotted on the greatly expanded scale of Figure 2. The fit shown in Figure 2 is derived from a sixth power fit to the plot in Figure 1.

$$B1 * L_{eff} = q_0 + q_1 * I + q_2 * I^2 + q_3 * I^3 + q_4 * I^4 + q_5 * I^5 + q_6 * I^6$$

Table 1 gives the results of this fit.

TABLE 1	
q0	1.7718E-03
q1	1.7193E-3
q2	6.3848E-8
q3	-6.4030E-11
q4	-1.1111E-13
q5	2.5804E-16
q6	-1.3982E-19

The precision used here may seem excessive but something of this sort is needed to give a good fit in Figure 2, the classic form of presenting precision magnet data. In this case there is very little saturation but a very visible residual field effect. The relative measurement accuracy has been reported in previous results (Booster Technical Note 174) as one part in ten thousand. This applies to all of these quads. The absolute measurement accuracy (essentially the area of the measuring coil) must be known to compare these quads against the AGS main magnets but has not been calibrated and at present can be estimated to be accurate to one or two per cent.

Figure 3 is a plot of B1*Leff/I at 500 and at 800 Amperes for the 22 measured magnets. It shows that at 500 Amperes the average for the measured magnets is:

$$B1*L_{eff} / I = 0.001\ 735 \pm 0.000\ 003 \text{ T/A}$$

and that the saturation in each magnet is very similar from magnet to magnet. Magnet number 18 matches this average value and will be used to typify the entire collection of magnets. The first allowed term, B5, is so small that the results do not seem reportable.

B. STANDARD MEASUREMENT REPORT

The appended report has been generated and permanently stored for each magnet. It is intended to be self-explanatory.

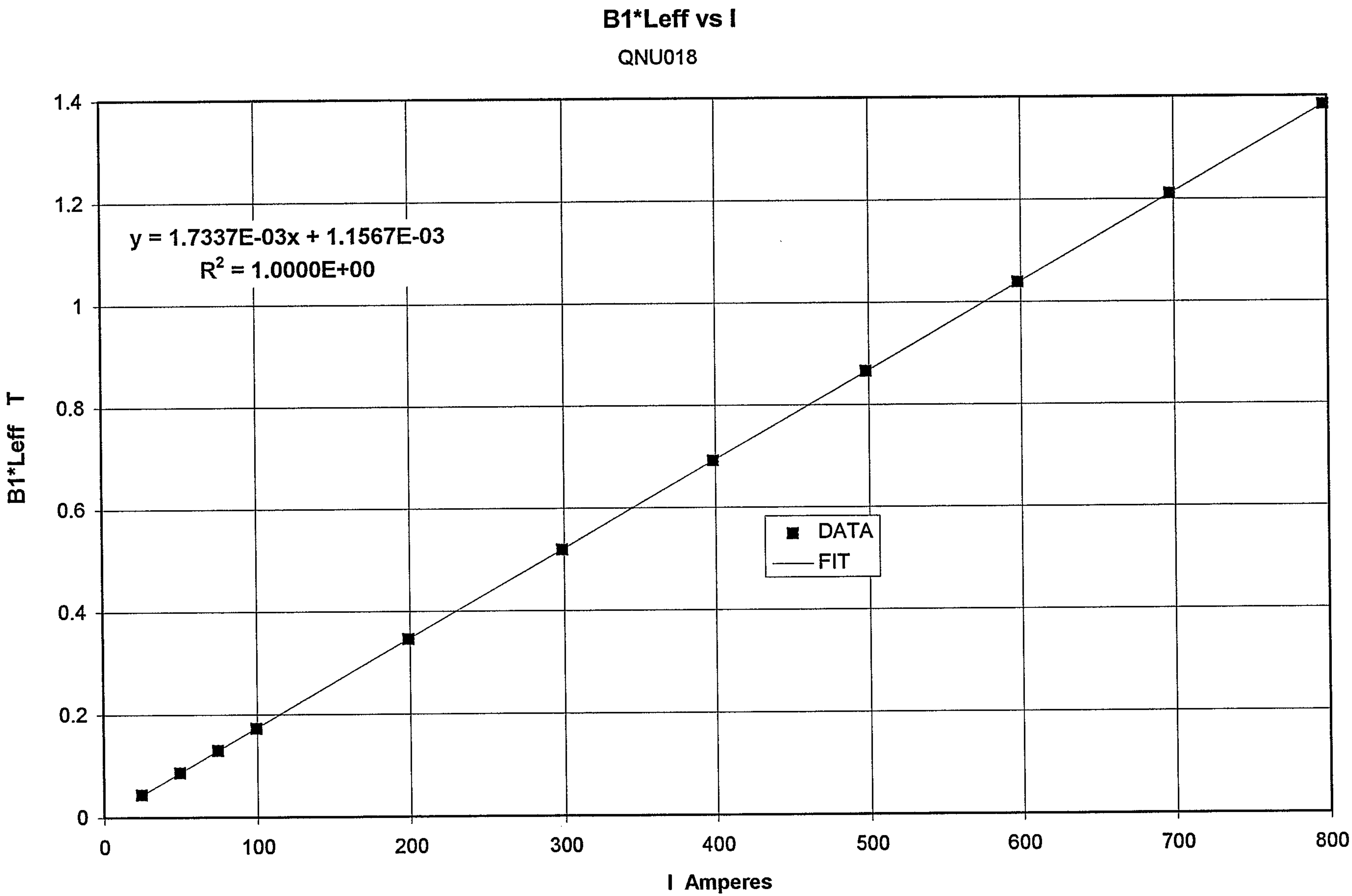
C. PARAMETER SHEET FOR THE AGS TUNE QUAD

The appended data sheet is an attempt to provide a fairly complete description of a magnet.

ACKNOWLEDGMENTS

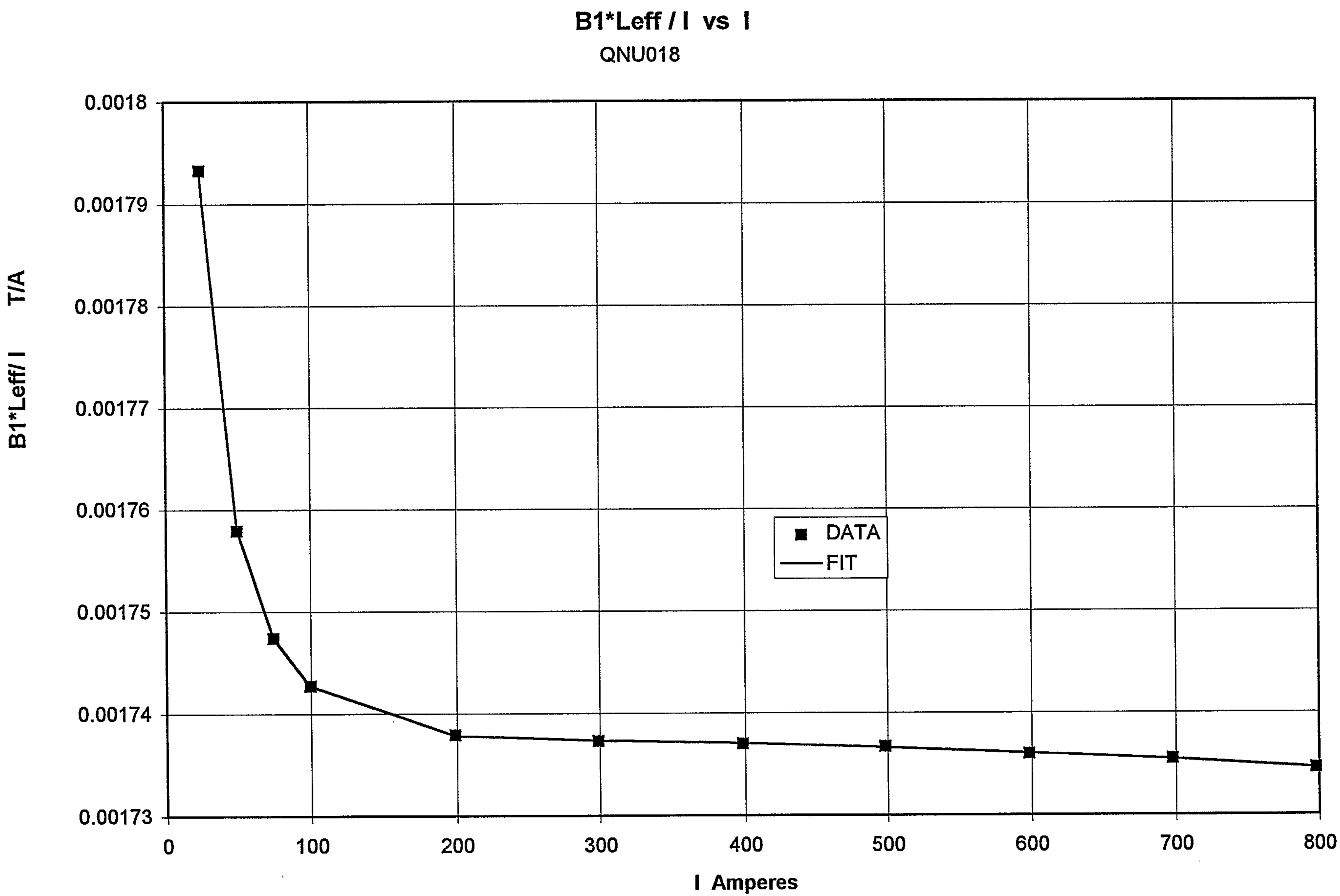
The analysis and the conclusions in this note are the responsibility of the author alone and represent his sole contribution to this effort. The measurements were carried out by the Measurements Group of the Accelerator Development Division, using a system developed over many years by many people, with a particular effort having been expended over the past several years to adapt the system to the present application.

Figure 1



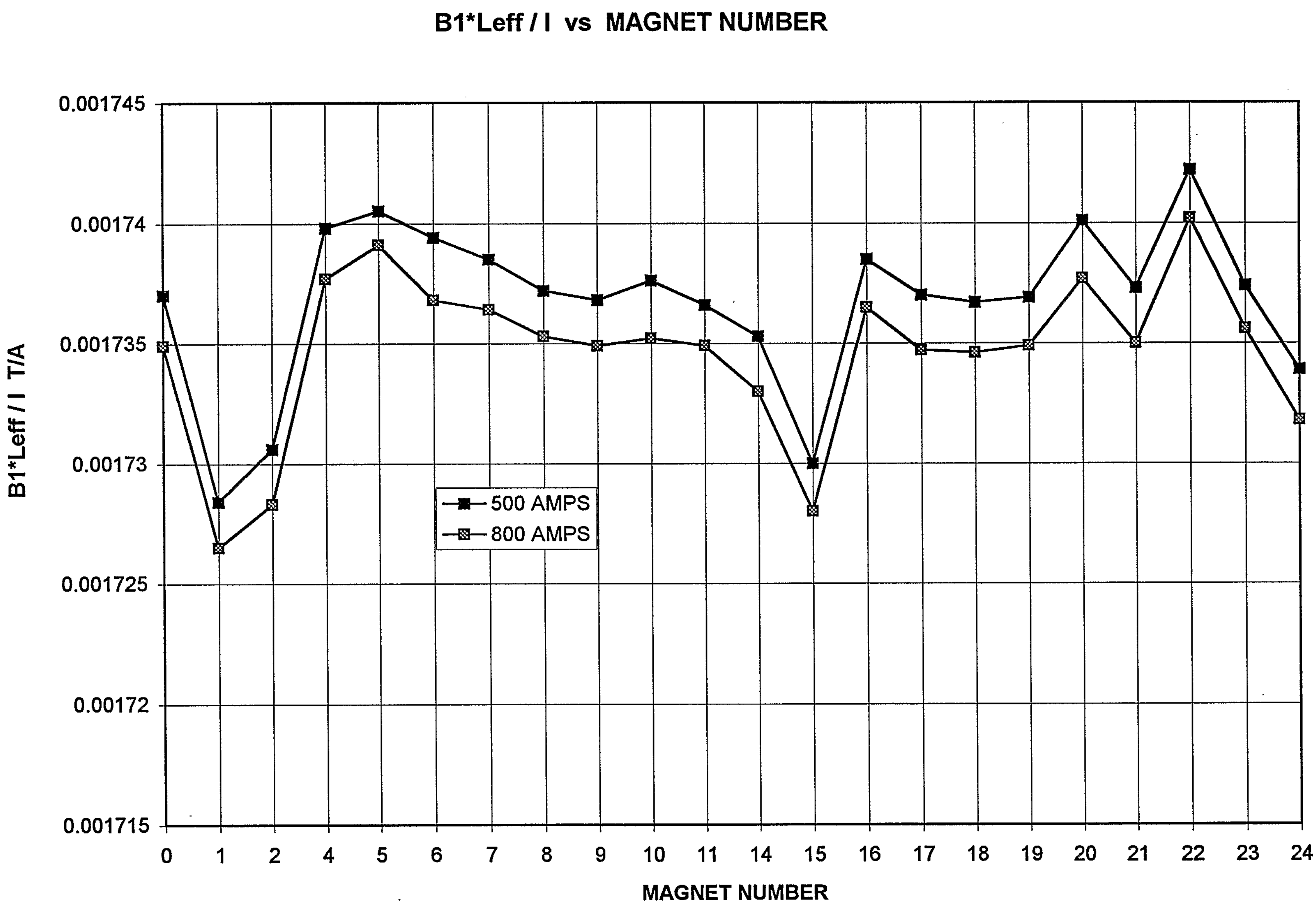
B1*Leff vs I
QNU018
y = 1.7337E-03x + 1.1567E-03
R2 = 1.0000E+00
DATA
FIT
B1*Leff T
I Amperes
0
0.2
0.4
0.6
0.8
1
1.2
1.4
0
100
200
300
400
500
600
700
800

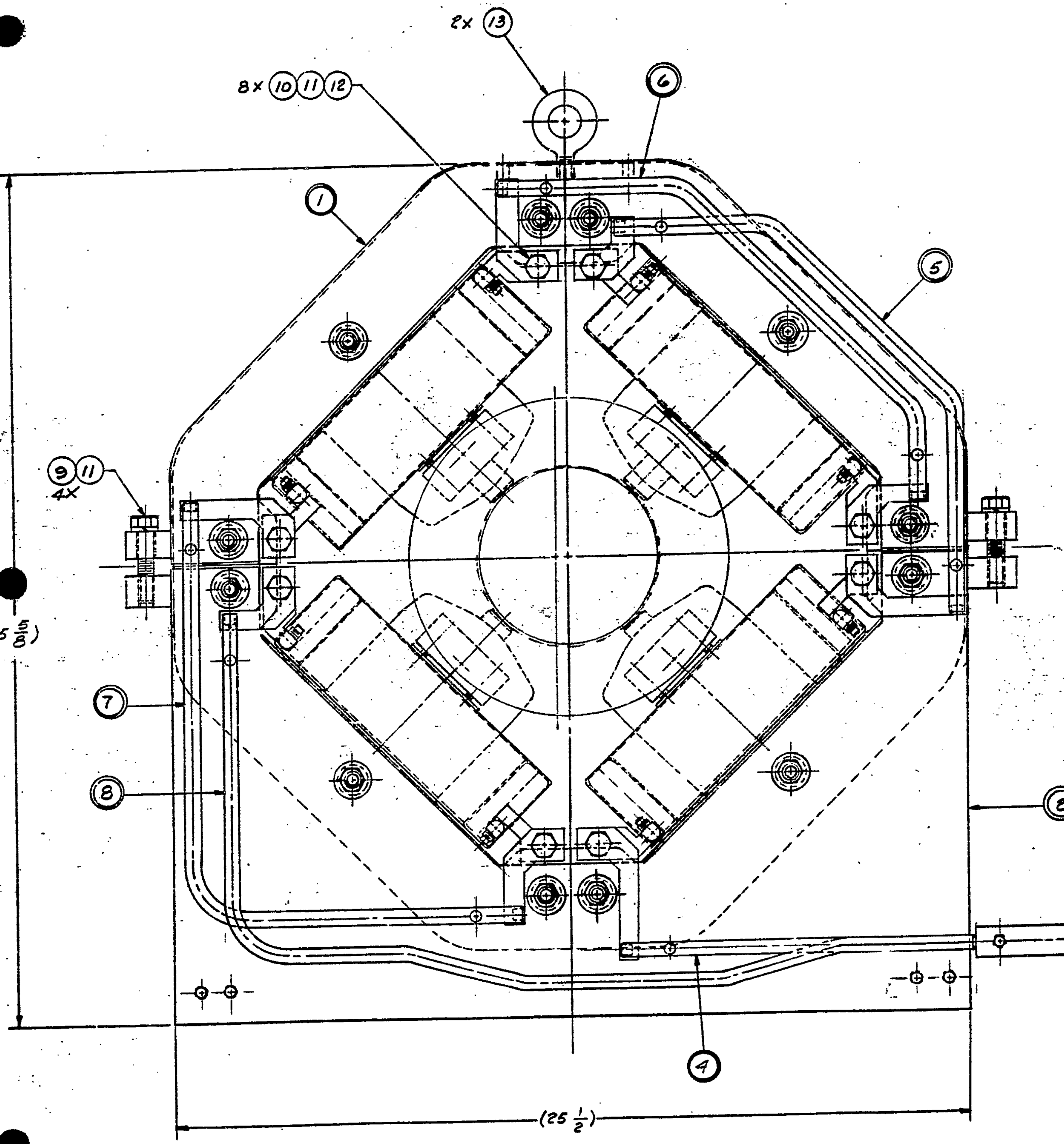
Figure 2

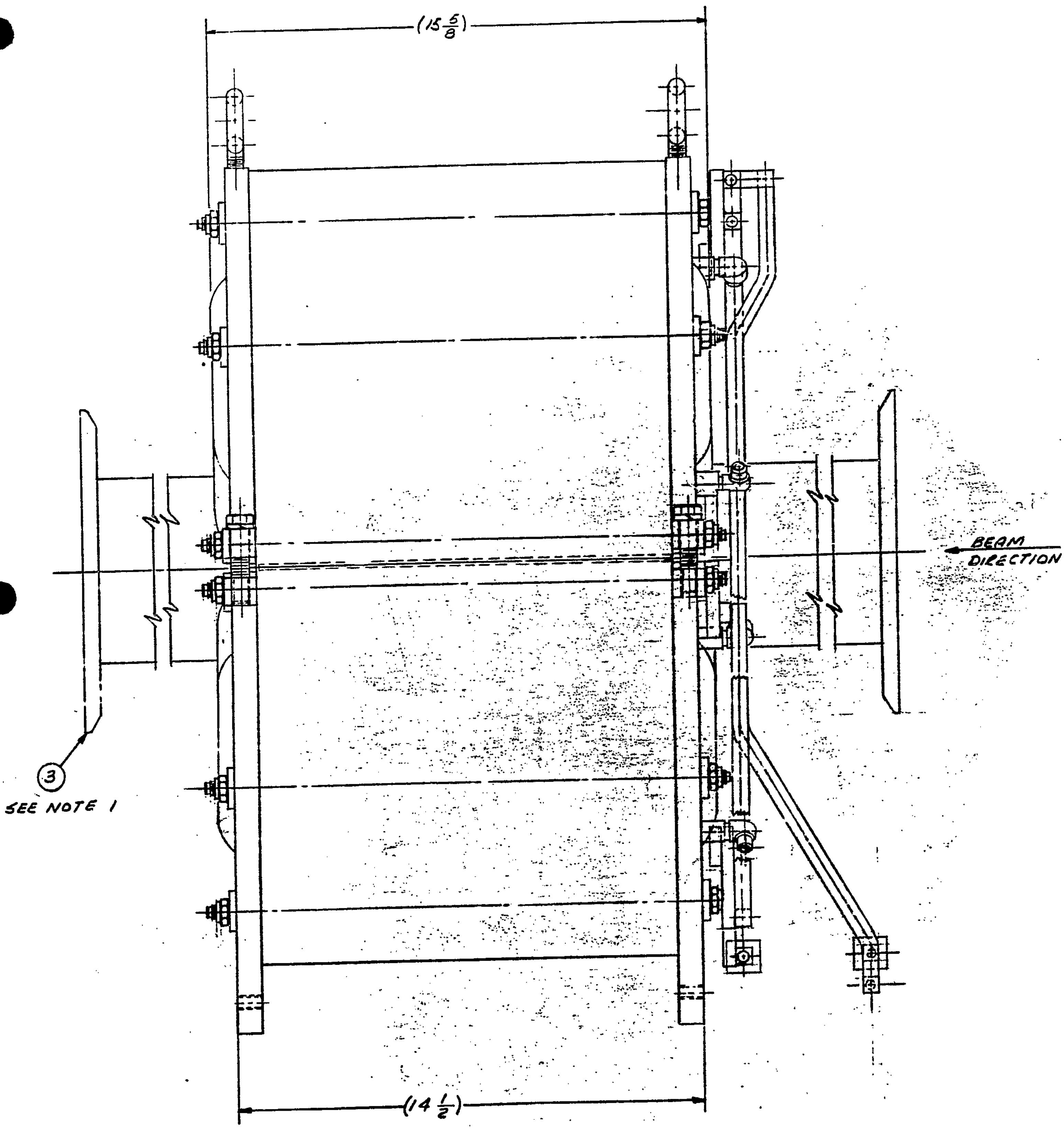


B1*Leff / I vs I
QNU018
0.0018
0.00179
0.00178
0.00177
0.00176
0.00175
0.00174
0.00173
B1*Leff/ I T/A
DATA
FIT
0
100
200
300
400
500
600
700
800
I Amperes

Figure 3


B1*Leff / I vs MAGNET NUMBER
0.001745
0.00174
0.001735
0.00173
0.001725
0.00172
0.001715
B1*Leff / I T/A
500 AMPS
800 AMPS
0 1 2 4 5 6 7 8 9 10 11 14 15 16 17 18 19 20 21 22 23 24
MAGNET NUMBER


2X (13)
8X (10)(11)(12)
(6)
(1)
(5)
(9)(11)
4X
(7)
(8)
(4)
(25 1/2)
5 5/8)


(15 5/8)
BEAM DIRECTION
3
SEE NOTE 1
(14 1/2)

B. STANDARD MEASUREMENT REPORT

ANALYSIS of FIELD SHAPE MEASUREMENTS

MAGNET TYPE	AGS TUNE QUAD
MAGNET NUMBER	QNU018
RUN NUMBER	QNU018.101 TX
DATE of MEASUREMENT	17-Mar-90
DATE of ANALYSIS	11-Feb-92

SHORT SUMMARY of MAGNET QUALITY

SUMMARY of QUADRUPOLE FIELD RESULTS

$B1*L_{eff}/I$ @ 500 Amps	1.7367E-03	T/A
$B1*L_{eff}/I$ @ 800 Amps	1.7346E-03	T/A

SATURATION EFFECT	1.00123

[$B1*L_{eff}/I$ @ 500 Amps]/[$B1*L_{eff}/I$ @ 800 Amps]

SUMMARY of HARMONIC CONTENTS

	AVG	STD DEV	UNITS
B2/B1	-1.12E-02	3.20E-04	m^{-1}
A2/B1	1.93E-03	2.90E-04	m^{-1}
B3/B1	1.09E-01	8.40E-03	m^{-2}
A3/B1	7.00E-02	1.30E-02	m^{-2}
B4/B1	-2.78E-01	9.30E-02	m^{-3}
A4/B1	-1.87E-03	1.20E-01	m^{-3}

SUMMARY of ALIGNMENT PARAMETERS

xo	2.71E-04	6.50E-06	m
yo	-1.33E-04	1.30E-06	m
Theta	-5.68E-04	3.70E-05	radians

SUMMARY of RESIDUAL FIELDS

$B0*L_{eff}$	6.75E-05		T*m
$A0*L_{eff}$	1.70E-06		T*m
$B1*L_{eff}$	1.88E-03		T
$A1*L_{eff}$	1.10E-04		T

BASIC MEASUREMENT RESULTS
=========================

	I	B1*L_{eff}	B0*L_{eff}	B2*L_{eff}	B3*L_{eff}	B4*L_{eff}
	AMPS	T	T*m	T/m	T/m^2	T/m^3
1	0.004	0.00188	6.750E-05	-9.40E-05	5.80E-04	8.30E-02
2	24.529	0.04399	7.800E-05	-7.00E-04	7.50E-03	1.70E-02
3	49.502	0.08702	8.900E-05	-1.10E-03	9.40E-03	-8.10E-02
4	74.451	0.1301	9.910E-05	-1.40E-03	1.80E-02	1.20E-01
5	99.373	0.17318	1.113E-04	-2.10E-03	1.50E-02	-4.70E-02
6	199.141	0.34609	1.588E-04	-3.70E-03	3.80E-02	-1.60E-01
7	298.774	0.51907	2.051E-04	-5.80E-03	6.00E-02	-2.00E-01
8	398.529	0.69226	2.472E-04	-7.70E-03	7.90E-02	-1.20E-01
9	498.351	0.8655	2.905E-04	-9.80E-03	9.20E-02	-1.80E-01
10	598.176	1.03842	3.413E-04	-1.20E-02	1.20E-01	-3.00E-01
11	697.751	1.21097	3.855E-04	-1.30E-02	1.30E-01	-2.50E-01
12	797.565	1.38345	4.284E-04	-1.60E-02	1.60E-01	-3.30E-01

	I	A1*L_{eff}	A0*L_{eff}	A2*L_{eff}	A3*L_{eff}	A4*L_{eff}
	AMPS	T	T*m	T/m	T/m^2	T/m^3
1	0.004	1.10E-04	1.70E-06	-1.50E-05	3.60E-03	3.50E-02
2	24.529	9.00E-05	-3.70E-06	-1.30E-04	3.60E-03	-1.50E-01
3	49.502	6.00E-05	-8.50E-06	1.20E-04	8.00E-03	-5.50E-02
4	74.451	4.00E-05	-1.54E-05	5.80E-04	1.40E-02	-9.20E-04
5	99.373	1.00E-05	-2.04E-05	4.50E-04	1.70E-02	-1.90E-02
6	199.141	-7.00E-05	-4.34E-05	6.20E-04	2.40E-02	-2.40E-02
7	298.774	-1.90E-04	-6.76E-05	8.40E-04	4.20E-02	2.50E-02
8	398.529	-3.20E-04	-9.04E-05	1.40E-03	4.80E-02	1.90E-01
9	498.351	-3.80E-04	-1.14E-04	1.50E-03	5.30E-02	-5.60E-02
10	598.176	-5.00E-04	-1.37E-04	2.00E-03	5.90E-02	-1.00E-01
11	697.751	-6.10E-04	-1.58E-04	2.50E-03	7.80E-02	1.20E-01
12	797.565	-7.60E-04	-1.84E-04	2.30E-03	8.10E-02	-1.20E-01

GRADIENT and POSITION ANALYSIS

Residual Field Subtracted

				Theta	xo	yo
	I	B1*L_{eff} /I	B1*L_{eff} /I	A1/B1	B0/B1	A0/B1
	AMPS	T/A	T/A	radians	m	m
1	0.004					
2	24.529	1.7933E-03	1.7155E-03	-3.24E-04	3.58E-04	-1.37E-04
3	49.502	1.7579E-03	1.7194E-03	-5.32E-04	3.06E-04	-1.24E-04
4	74.451	1.7474E-03	1.7218E-03	-5.03E-04	2.82E-04	-1.36E-04
5	99.373	1.7427E-03	1.7235E-03	-5.26E-04	2.82E-04	-1.31E-04
6	199.141	1.7379E-03	1.7283E-03	-5.03E-04	2.78E-04	-1.32E-04
7	298.774	1.7373E-03	1.7309E-03	-5.62E-04	2.75E-04	-1.35E-04
8	398.529	1.7370E-03	1.7323E-03	-6.04E-04	2.67E-04	-1.34E-04
9	498.351	1.7367E-03	1.7329E-03	-5.58E-04	2.64E-04	-1.34E-04
10	598.176	1.7360E-03	1.7328E-03	-5.85E-04	2.69E-04	-1.34E-04
11	697.751	1.7355E-03	1.7328E-03	-5.87E-04	2.67E-04	-1.32E-04
12	797.565	1.7346E-03	1.7322E-03	-6.24E-04	2.65E-04	-1.34E-04

AVERAGE(100 to 800 Amps) =	-5.68E-04	2.71E-04	-1.33E-04
STANDARD DEVIATION =	3.70E-05	6.50E-06	1.30E-06

HARMONIC ANALYSIS
=================

	I	B1*L_{eff} /I	B0/B1	B2/B1	B3/B1	B4/B1
	AMPS	T/A	m	m^{-1}	m^{-2}	m^{-3}
1	0.004	4.6900E-01	3.60E-02	-5.00E-02	3.12E-01	4.40E+01
2	24.529	1.7933E-03	1.77E-03	-1.59E-02	1.71E-01	3.80E-01
3	49.502	1.7579E-03	1.02E-03	-1.32E-02	1.08E-01	-9.30E-01
4	74.451	1.7474E-03	7.60E-04	-1.10E-02	1.35E-01	9.30E-01
5	99.373	1.7427E-03	6.40E-04	-1.19E-02	8.94E-02	-2.70E-01
6	199.141	1.7379E-03	4.60E-04	-1.07E-02	1.08E-01	-4.70E-01
7	298.774	1.7373E-03	4.00E-04	-1.13E-02	1.15E-01	-3.80E-01
8	398.529	1.7370E-03	3.60E-04	-1.11E-02	1.14E-01	-1.70E-01
9	498.351	1.7367E-03	3.40E-04	-1.13E-02	1.06E-01	-2.00E-01
10	598.176	1.7360E-03	3.30E-04	-1.11E-02	1.18E-01	-2.90E-01
11	697.751	1.7355E-03	3.20E-04	-1.11E-02	1.08E-01	-2.10E-01
12	797.565	1.7346E-03	3.10E-04	-1.14E-02	1.13E-01	-2.40E-01

AVERAGE(100 to 800 Amps) =	-1.12E-02	1.09E-01	-2.78E-01
STANDARD DEVIATION =	3.20E-04	8.40E-03	9.30E-02

	I	A1/B1	A0/B1	A2/B1	A3/B1	A4/B1
	AMPS	radians	m	m^{-1}	m^{-2}	m^{-3}
1	0.004	6.10E-02	0.00088	-8.25E-03	1.89E+00	1.90E+01
2	24.529	2.00E-03	-0.00009	-2.89E-03	8.20E-02	-3.40E+00
3	49.502	6.50E-04	-0.0001	1.41E-03	9.16E-02	-6.30E-01
4	74.451	2.90E-04	-0.00012	4.48E-03	1.10E-01	-7.00E-03
5	99.373	6.70E-05	-0.00012	2.58E-03	9.88E-02	-1.10E-01
6	199.141	-2.10E-04	-0.00013	1.79E-03	7.01E-02	-6.80E-02
7	298.774	-3.60E-04	-0.00013	1.62E-03	8.03E-02	4.90E-02
8	398.529	-4.60E-04	-0.00013	2.05E-03	6.86E-02	2.70E-01
9	498.351	-4.40E-04	-0.00013	1.79E-03	6.17E-02	-6.40E-02
10	598.176	-4.90E-04	-0.00013	1.92E-03	5.72E-02	-1.00E-01
11	697.751	-5.00E-04	-0.00013	2.05E-03	6.44E-02	1.00E-01
12	797.565	-5.50E-04	-0.00013	1.68E-03	5.87E-02	-8.90E-02

AVERAGE(100 to 800 Amps) =	1.93E-03	7.00E-02	-1.87E-03
STANDARD DEVIATION =	2.90E-04	1.30E-02	1.20E-01

C. PARAMETER SHEET FOR THE AGS TUNE QUAD

Issue Date: October 25, 1996

PROTOTYPE NAME	**QNU (AGS TUNE QUAD & SKEW QUAD)**
MAGNET CLASS	**QUADRUPOLE (Uses booster quad laminations)**
NUMBER OF MAGNETS	**30**

MECHANICAL

	INCHES	MILLIMETERS		REF
CORE				
LAMINATION LENGTH	13	330.2		a
TOLERANCE SPECIFIED	0.003	0.076		a
TOLERANCE MEASURED	#N/A	#N/A		
STRUCTURAL LENGTH	14.5	368.3		a
COIL LENGTH	15.625	396.9		a
OVERALL LENGTH	17.5	444.5		a
APERTURE SHAPE	ROUND			
RADIUS AT POLE TIP	3.25	82.55		a
TOLERANCE SPECIFIED	0.003	0.076		
TOLERANCE MEASURED	0.002	0.051		
POLE WIDTH	5.142	130.6		a
CORE HEIGHT	23.15	588.0		a
CORE WIDTH	23.15	588.0		a
LAMINATIONS				
MATERIAL	ARMCO M-36			a
COATING	AISI TYPE - C5			a
COATING THICKNESS	0.0002	0.005		a
OVERALL THICKNESS	0.025	0.6		a
APPROX LAMS PER BLOCK	520			
QUADRANT BLOCK WEIGHT	276.5	125.4	POUNDS, KG	a
TOLERANCE SPECIFIED	#N/A	#N/A	POUNDS, KG	a
TOLERANCE MEASURED	#N/A	#N/A	POUNDS, KG	
VACUUM PIPE				
HEIGHT - OUTSIDE	6	152.4		b
WIDTH - OUTSIDE	6	152.4		b
WALL THICKNESS	0.063	1.6		b
TOLERANCE SPECIFIED	0.003	0.1		b
TOLERANCE MEASURED	#N/A	#N/A		
HALF HEIGHT - INSIDE	2.937	74.6		
HALF WIDTH - INSIDE	2.937	74.6		
MATERIAL	SS 304			b
RESISTIVITY	78		MICRO-OHM CM	b
TOLERANCE SPECIFIED	#N/A		MICRO-OHM CM	b
TOLERANCE MEASURED	#N/A			

MAIN COIL

	INCHES	MILLIMETERS		REF
COIL				
TURNS PER POLE	12			a
POLES PER MAGNET	4			a
RESISTANCE PER MAGNET	8.4		MILLIOHMS	a
INDUCTANCE PER MAGNET - DC	1.5		MILLIHENRY	c
COIL AREA	3.5	2277		
CONDUCTOR				
MATERIAL	OFHC COPPER			a
SHAPE	SQUARE			
WIDTH	0.472	11.99		a
HEIGHT	0.472	11.99		a
COOLING HOLE DIAMETER	0.236	5.99		a
CONDUCTOR AREA	0.179	115.51		a
LENGTH PER POLE	624	15850		a
LENGTH PER MAGNET	2496	63398		a
INSULATION				
MATERIAL	EPOXY FIBERGLASS			a
THICKNESS	0.01	0.25		a
GROUND THICKNESS	0.02	0.51		a
GROUND TEST	2		kVOLTS	a
IMPULSE TEST	3		kVOLTS	a
COOLING				
CIRCUITS PER MAGNET	4			a
FLOW RATE PER MAGNET	2.5		GALLONS/MINUTE	a
INPUT PRESSURE	55		PSI	a
TEMP RISE @ RAMP to Imax	20		DEGREES F	a
CURRENT				
Imax (PS LIMIT)	800		AMPERES	c
COIL CURRENT DENSITY @ Imax	2721	4.22	AMPERES/AREA	
CONDUCTOR CURRENT DENSITY @ Imax	4468	6.93	AMPERES/AREA	
DC POWER @ Imax	5		kWATTS	
STORED ENERGY @ Imax	0.5		kJOULES	

TUNE TRIM COIL

	INCHES	MILLIMETERS		REF
COIL				
TURNS PER POLE	12			a
POLES PER MAGNET	4			
RESISTANCE PER MAGNET	208		MILLIOHMS	
INDUCTANCE PER MAGNET - DC	1.5		MILLIHENRY	c
CONDUCTOR				
MATERIAL	#10 COPPER WIRE - ETP			a
SHAPE	ROUND			a
DIAMETER	0.101	2.57		a
AREA	0.008155	5.3		
LENGTH PER POLE	624	15850		a
LENGTH PER MAGNET	2496	63398		
INSULATION				
MATERIAL				a
THICKNESS				a
GROUND TEST			kVOLTS	c
IMPULSE TEST			kVOLTS	c
CURRENT				
Imax (PS LIMIT)	10		AMPERES	c
CURRENT DENSITY @ Imax	1226	1.9	AMPERES/AREA	
DC POWER @ Imax	20.80		WATTS	
STORED ENERGY @ Imax	0.1		JOULES	

MAGNETIC PROPERTIES OF THE MAIN COIL

			REF
RANDOM ERRORS			
B1*Leff/I rms	0.000003	T/A	e
TYPICAL MEASUREMENTS			
B1*Leff @ I = 0	0.001880	T	e
B1*Leff/I			
@200 AMPS	0.001738	T/A	e
@400 AMPS	0.001737	T/A	e
@600 AMPS	0.001736	T/A	e
@800 AMPS	0.001735	T/A	e
CALCULATIONS			
B1/I	0.004426	[T/m]/A	e
Leff			
@200 AMPS	0.393	meters	e
@400 AMPS	0.392	meters	e
@600 AMPS	0.392	meters	e
@800 AMPS	0.392	meters	e
POLE TIP FIELD			
@200 AMPS	7.31E-02	T	e
@400 AMPS	1.46E-01	T	e
@600 AMPS	2.19E-01	T	e
@800 AMPS	2.92E-01	T	e

MAGNETIC PROPERTIES OF THE TUNE TRIM COIL

CALCULATIONS			
B1/I	0.004426	[T/m]/A	e
B1*Leff/I	0.001738	T/A	e

REFERENCES

a. E. RODGER, Private communication
b. H. C. HSUEH, Private communication
c. A. SOUKAS, Private communication
e. E. BLESER