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Technical Note

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AGS Tune Quad Production Measurements

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AGS TUNE QUAD PRODUCTION MEASUREMENTS

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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 the 30 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:

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

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

In a quadrupole the only allowed terms are B_1 and B_3 , etc. Those magnets installed as skew quads are rotated 45 degrees in effect interchanging A_1 and B_1 .

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.

$$B_1 * L_{eff} = q_0 + q_1 * I + q_2 * I^2 + q_3 * I^3 + q_4 * I^4 + q_5 * I^5 + q_6 * I^6$$

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 $B_1 * L_{eff} / I$ at 500 and at 800 Amperes for the 22 measured magnets. It shows that at 500 Amperes the average for the measured magnets is:

$$B_1 * L_{eff} / I = 0.001\,735 \pm 0.000\,003 \text{ T/A}$$

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, B_5 , 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

Figure 2

$B1 \cdot L_{eff} / I$ vs I
QNU018

Figure 3

B. STANDARD MEASUREMENT REPORT

ANALYSIS of FIELD SHAPE MEASUREMENTS

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=====
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
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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
				A1/B1	B0/B1	A0/B1
				radians	m	m
	I	B1*L _{eff} /I	B1*L _{eff} /I			
	AMPS	T/A	T/A			
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

CORE

LAMINATION LENGTH
TOLERANCE SPECIFIED
TOLERANCE MEASURED
STRUCTURAL LENGTH
COIL LENGTH
OVERALL LENGTH
APERTURE SHAPE
RADIUS AT POLE TIP
TOLERANCE SPECIFIED
TOLERANCE MEASURED
POLE WIDTH
CORE HEIGHT
CORE WIDTH

INCHES MILLIMETERS

13	330.2
0.003	0.076
#N/A	#N/A
14.5	368.3
15.625	396.9
17.5	444.5
ROUND	
3.25	82.55
0.003	0.076
0.002	0.051
5.142	130.6
23.15	588.0
23.15	588.0

REF

a
a

a
a
a

a

a
a
a

LAMINATIONS

MATERIAL
COATING
COATING THICKNESS
OVERALL THICKNESS
APPROX LAMS PER BLOCK
QUADRANT BLOCK WEIGHT
TOLERANCE SPECIFIED
TOLERANCE MEASURED

ARMCO M-36	
AISI TYPE - C5	
0.0002	0.005
0.025	0.6
520	
276.5	125.4
#N/A	#N/A
#N/A	#N/A

POUNDS, KG
POUNDS, KG
POUNDS, KG

a
a
a
a

a
a
a

VACUUM PIPE

HEIGHT - OUTSIDE
WIDTH - OUTSIDE
WALL THICKNESS
TOLERANCE SPECIFIED
TOLERANCE MEASURED
HALF HEIGHT - INSIDE
HALF WIDTH - INSIDE
MATERIAL
RESISTIVITY
TOLERANCE SPECIFIED
TOLERANCE MEASURED

6	152.4
6	152.4
0.063	1.6
0.003	0.1
#N/A	#N/A
2.937	74.6
2.937	74.6
SS 304	
78	
#N/A	
#N/A	

MICRO-OHM CM
MICRO-OHM CM

b
b
b
b

b
b
b

MAIN COIL

COIL

	INCHES	MILLIMETERS	REF
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 I _{max}	20	DEGREES F	a

CURRENT

I _{max} (PS LIMIT)	800	AMPERES	c
COIL CURRENT DENSITY @ I _{max}	2721	4.22	AMPERES/AREA
CONDUCTOR CURRENT DENSITY @ I _{max}	4468	6.93	AMPERES/AREA
DC POWER @ I _{max}	5	kWATTS	
STORED ENERGY @ I _{max}	0.5	kJOULES	

TUNE TRIM COIL

COIL

TURNS PER POLE
 POLES PER MAGNET
 RESISTANCE PER MAGNET
 INDUCTANCE PER MAGNET - DC

INCHES	MILLIMETERS
12	
4	
208	
1.5	

MILLIOHMS
 MILLIHENRY

REF
a

CONDUCTOR

MATERIAL
 SHAPE
 DIAMETER
 AREA
 LENGTH PER POLE
 LENGTH PER MAGNET

#10 COPPER WIRE - ETP	
ROUND	
0.101	2.57
0.008155	5.3
624	15850
2496	63398

a
 a
 a
 a

INSULATION

MATERIAL
 THICKNESS
 GROUND TEST
 IMPULSE TEST

kVOLTS
 kVOLTS

a
 a
 c
 c

CURRENT

I_{max} (PS LIMIT)
 CURRENT DENSITY @ I_{max}
 DC POWER @ I_{max}
 STORED ENERGY @ I_{max}

10	
1226	1.9
20.80	
0.1	

AMPERES
 AMPERES/AREA
 WATTS
 JOULES

c

MAGNETIC PROPERTIES OF THE MAIN COIL

RANDOM ERRORS

B1*Leff/I rms

0.000003

T/A

REF
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

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