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Nov 21, 1994 EXPECTED_D8.TABLE3_E

Table 3(e)

Expected values of INTEGRAL harmonics in 80 mm aperture Arc dipoles
at 30 A (WARM Measurements) at 25 mm reference radius:

[<bn> = mean, d(bn) = uncertainty in mean, sig(bn) = sigma for bn]

n	<bn>	d(bn)	sig(bn)	<an>	d(an)	sig(an)
1	0.	0.4	0.8	0.0	1	1.3
2	4	4	2.3	-1.1	0.1	.5
3	0.	0.2	.3	0	0.3	1.0
4	0.5	1	.6	0.2	.06	.2
5	0	.03	.1	0.0	0.1	.26
6	0.3	.2	.1	-0.1	.03	.1
7	0	.03	.1	0	.03	.1
8	0.3	.1	.1	0	.03	.1
9	0.0	.03	.1	0	.03	.1
10	-.5	0.1	.1	0	.03	.1

Expected values of INTEGRAL harmonics at 660 A (injection)
(same as above except for the following harmonics)

2	0	4.	2.3
4	0	1.	0.6
6	0	.2	0.2

Expected values of INTEGRAL harmonics at 1450 Amp (Transition)
(same as above except for the following harmonics)

2	1.7	4.	2.3
4	0.2	1.	0.6
6	0.1	.2	0.2

Expected values of INTEGRAL harmonics at 5000 Amp (Maximum)
(same as above except for the following harmonics)

1				-2.	.5	1.3
2	0.	4	2.3			
4	0.4	1	0.6			
6	1.3	.1	0.2			

Expected values of body harmonics in 80 mm aperture Arc dipoles
at 30 A (WARM) at 25 mm reference radius:

[<bn> = mean, d(bn) = uncertainty in mean, sig(bn) = sigma for bn]

n	<bn>	d(bn)	sig(bn)	<an>	d(an)	sig(an)
1	0.	0.4	0.8	0.0	1	1.3
2	1.4	4	2.3	0.0	0.4	.5
3	0.	0.2	.3	0	0.3	1.0
4	0.5	1	.6	0	.06	.2

5	0	.03	.1	0	0.1	.26
6	0.2	.2	.1	0	.03	.1
7	0	.03	.1	0	.03	.1
8	0.3	.1	.1	0	.03	.1
9	0.0	.03	.1	0	.03	.1
10	-.5	0.	.1	0	.03	.1

Expected values of body harmonics at 660 A (INJECTION)
(same as above except for the following harmonics)

2	-2.5	4.	2.3
4	0.0	1.	0.6
6	-0.1	.2	0.2

Expected values of body harmonics at 1450 AMP (TRANSITION)
(same as above except for the following harmonics)

2	-0.8	4.	2.3
4	0.0	1.	0.6
6	0.0	.2	0.2

Expected values of body harmonics at 5000 Amp (MAXIMUM)
(same as above except for the following harmonics)

1				-2.5	.5	1.3
2	-2.8	4	2.3			
4	0.5	1	0.6			
6	1.2	.2	0.2			

Expected values of harmonics in LEAD END at 600 and 1450Amp (Unit-m)

n	<Bn>	d(Bn)	sig(Bn)	<An>	d(An)	sig(An)
1	-2	2	1	2	4	1.
2	17	2	2	-10.	1	1
3	0.3	.2	.2	0	1	1.
4	1	.5	.2	2	.5	.3
5	0	.2	.2	0	1	.2
6	1	.5	.1	-0.9	.2	.2
7	0	.1	.1	0	.1	.1
8	-.2	.2	.1	0.3	.1	.1
9	-.2	.2	.2	0	.1	.1
10	.1	.1	.1	-0.1	.1	.1

Expected values of harmonics in LEAD END at 5000 Amp (Unit-m)

n	<Bn>	d(Bn)	sig(Bn)
2	21	2	2

Expected values of harmonics in RETURN END at 660 & 1450 Amp (Unit-m)

n	<Bn>	d(Bn)	sig(Bn)	<An>	d(An)	sig(An)
1	1.4	1	1.	3	.5	1.
2	-3.	1	1.	-.8	.5	1.
3	0.3	.1	.1	.2	.3	.5
4	.8	.5	.2	.2	.1	.1

5	0.	.1	.1	.2	.1	.2
6	0.	.1	.1	.1	.05	.1
7	0.	.1	.1	0	.05	.1
8	-.2	.1	.1	.1	.05	.1
9	-.2	.1	.1	0	.05	.1
10	-.1	.1	.1	0	.05	.1

Expected values of harmonics in RETURN END at 5000 Amp (Unit-m)
(same as above except)

n	<Bn>	d(Bn)	sig(Bn)
2	-1.	4.	1.

Notes:

0. X in 1st/2nd column of the following lines means that this argument is either not valid any more or not relevant any more. These lines are left here for historical reasons. Similarly, a question mark in the 1st/2nd column of a line would mean that it is under review.

1. This table derives the harmonics from the following three sources:
   (a) The measured harmonics in the short and long magnets built so far. (This is from the table prepared by Gerry Morgan).
   (b) The actual variations in the harmonics in the HERA production run. (HERA magnets have the same coil i.d. as the RHIC magnets but had two layer coil and a collar between the coil and the yoke).
   (c) The measured harmonics in recently built and tested short magnets
X DRS009 and DRS010 based on the cross section 9B84A (DREK). In the
X long magnets DRE011 and DRE012, only the warm measurements are
X available.

2. The above table is primarily based on item 1(a); a change in any value will be justified or explained. The main reason for the changes are (i) No more than the two magnets used in 1(a) were built the same way and (ii) except for the two short and two long magnets, the design used in the previous magnets was not the same as the one to be used in the production magnets.

X 3. The table 3.0 (made for Accelerator Physicists) will have only
X two columns. The 2nd column will be absorbed in the 1st. In most cases
X the magnitude of the second column would be added to the magnitude
X of the first column of this table to make the first column of the
X new table 1.0. The exception will be the systematic allowed harmonics
X at 660 A where the value will not exceed its 1450 A value, if d(bn) >
X |bn(660A)-bn(1450A)|. This general exception is given because of the
X way coil will be iterated.

X 4. An item in () means that it is either inserted after the 6/2/93
X meeting or needs further examination. This number would be
X the same in table 2(b) if it was merely inserted and different
X if I have put my best guess. If item is still in () in table
X 2(b), that means that the item is being currently examined.

5. Most non-allowed systematic come from Gerry's table, except that many terms were made zero when they within sigma/SQRT(N). I have
X put them as 0$ in the above table. Since Gerry's table was based
on N=11 magnets, the statistical error in <bn> due to sig(bn) is

[1./SQRT(11)]*sig(bn) = 0.3 * sig(bn).

6. The sigma in Gerry's table was examined against the sigma in HERA magnets made in production environment. It was found that the sigma in b3, b4, a2 and a3 were smaller than by a factor of 2 in HERA magnets. It is not clear whether it is real or is due to a limitation in statistics discussed in item (2). These <bn>/<an> in Gerry's table are replaced by HERA numbers. These new sigma are still much smaller than the numbers put in the contract with Grumman. Moreover, in the case of sig(b4), Gerry himself recommended using a value of 0.6 which has been used in the above table.

7. The target in iterating coil cross section after 30 magnets will be to make allowed harmonics zero at 1450 Amp. It is assumed that the spacer, yoke and any other tooling, etc. will not change in between. This means that any systematic value of allowed harmonics due to these parts can be empirically removed. Any systematic values of allowed harmonics will come from the following three sources:
   (a) Actual error in the design of the coil cross section
   (b) The reliability to which the coil cross-section can be iterated
   (c) The error in harmonics due to a systematic error in wedges, etc. (In this exercise it is assumed that the errors in the parts are within the specifications so that the parts pass inspection).

8. Attempt is made here to obtain the most likely case numbers without any safety factors. <b2n> represent the design value of harmonics at a given current. d(b2n) represent a more likely estimate of the errors in the iterated cross section. It is noted that a higher error is possible by the allowed errors in the mechanical specification of the parts (wedges) used in the magnets.

9. Non-zero values of <b6>, <b8> and <b10> at 1450 A in the above table represent the limitation in cross section optimization under the given constraints. Moreover, in obtaining these values, we have examined both 4 mil and 6 mil midplane gap options.

10. The following is the expected relative change in field harmonics from their 1450 A value. At 660 A the contribution is due to persistent current and at 5000 A primarily due to iron saturation. It may be noted that we have used the new location of hole and stainless steel key in estimating these numbers and in many cases the peak change is in between around 4500 Amp (e.g. Db6 is 1.1 at 4500 A)

	Db2	Db4	Db6
660 A	-3.5	-0.2	-0.15
5000 A	+1	-0.4	+0.8

11. Estimated d(b2) = +/- 4.0
    Sources (actually used are shown in []) :
    b2 due iteration error = [2.3] unit
    b2 due to +1 mil error in three wedges = -1, 0.8, [1.6]

12. Estimate of d(b4) = +/- 1.0
    Sources (actually used are shown in []) :
    b4 due iteration error = [-.6] unit
    b4 due to +1 mil error in three wedges = -0.14, [0.46], 0.03

NOTE : If the possible change in the midplane gap option is invoked then the Estimate of d(b4) would be +/- 0.5 unit with a guaranteed value of +/- 0.7 unit.

13. Estimate of d(b6) = +/- 0.1
Sources (actually used are shown in []) :
b6 due iteration error = [.1] unit
b6 due to +1 mil error in three wedges = 0.06, 0.03 ,-0.08

14. Estimate of d(b8) = +/- 0.1
Sources (actually used are shown in []) :
b8 due iteration error = [-.15] unit
b8 due to +1 mil error in three wedges = all ~ [+/-]0.05

X 15. The RETURN END harmonics are from the measurements in magnets
X DRS009 and DRS010. For the LEAD END, these measurements do not
X make much sense because of the way the lead was placed in these
X magnets. Pat is extracting useful information out of those
X measurements and will use his calculations to predict those
X harmonics. He is also checking the allowed systematic harmonics
X in the return end.

16. The computed value of a1 saturation of -2.5 unit is added in the table for the asymmetric cryostat effect at 5000 A.

X 17. The end harmonics are included in this table. These come by
X comparing calculations and measurements in DRS009 and DRS010.
X These numbers are basically from Pat Thompson and Animesh Jain
X with some "cleaning out of the data" by your friendly editor.

X 18. sig(b2) is increased from 2.3 to 2.5 as per Gerry Morgan's request.
X This is a small increase and therefore is not hotly debated by all
X members of "constitutional bench".

19. No sig(bn) and sig(an) was assigned to many higher order harmonics in table 3(b). In this table all those harmonics are assigned a small non-zero value of 0.1.

20. In table 3(b), many <an> and <bn> were zero (0$) within statistical errors (which is 0.3 * sigma for 11 magnets). In this table, that problem is dealt by assigning a value of 0.3 * sig(bn), etc. for d(bn) and d(an).

21. Many sigma numbers which were zero or very small within uncertainty are given a fixed value of 0.1.

22. All other "-" in table 3(b) are replaced by 0.0. This is specially true for d(bn).

23. This table should be directly readable by computer in ASCII format after removing comments, etc.

Oct 13, 1993

24. The iron cross section in Grumman built magnets will have a new position of saturation suppressor hole (theta=35.5 instead of theta=33 degree; radius is still 7.5 cm). This and the change in the material of the key from iron to stainless steel causes a very small change in saturation induced harmonics. The change in b2 saturation is ~1unit and in b4 1/4 unit. b6 saturation

got reduced by ~0.3; however, it does not change the expected values since the measured b6 saturation in the long dipoles was about 0.3 unit higher than the predicted.

25. Long magnets DRE011 and DRE012 are showing a large <a1> in the lead end. For this reason we have doubled the d<A1>. When <A1> and d<A1> are added they give the measured value of <A1> in these magnets.

26. The value of <A3> in the following magnets in unit-m are :

    DRS009 = .34
    DRS010 = .55
    DRE011 = .85
    DRE012 =1.33

    One can probably change <A3> to 0.7 and d<A3> to 0.5.

27. The end harmonics show a clear saturation in <B2> and <B4>. We have included only <B2> in our table since the change in <B4> is within d<B4>. The measured <B2> and <B4> saturation in the lead end is 4 and -0.35 unit-meter and in the return end is 2.8 and 0.15 unit-meter in the magnets DRE011 and DRE012.

28. DRE011 and DRE012 show a large <a1> (= 1.3 unit) in the body. This uncertainty is absorbed thru a value of d<a1> = 1.0. The previous value was zero.

29. The sign of <B4> in the lead end is changed from -1 unit-meter to +1 unit-meter to reflect the measured sign of this term in the magnets. <A2> is increased from -8.5 unit to -10 unit to reflect a higher measured value of this term in the lead end in DRE011/12.

30. The measurements are used instead of estimates for the harmonics in return end. The measurements are primarily from the magnets DRE011 and DRE012. However, we have also checked against the measurements in the short magnets DRS009 and DRS010 for any large differences.

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DATE : NOV 17, 1994 ----- SIGNIFICANT EXPANSION IN THE TABLES
(and may be minor revision)

31. Now the tables are expanded to include (a) the warm measurements and (b) the integral harmonics.

32. The target cross section is that the integral b2 at 5000 Amp (and also at 660 Amp, since the net change in b2 z-scan is almost zero between 660 A and 5000 A) and b4 at injection are zero. All other harmonics are computed relative to that.

33. The integral harmonics are computed by adding the end harmonics to the body harmonics.

34. ACCELERATOR PHYSICIST AND OTHERS, PLEASE NOTE THAT THE ABOVE HARMONICS ARE FOR Z-SCAN. THERE IS A DIFFERENCE BETWEEN b2 (Z-SCAN) AND b2 (UP RAMP).

    The difference in other harmonics is negligible.

35. When there is no geometrical reason for non-allowed harmonics to

be present, the expected mean is zero. In earlier versions, the mean had non-zero value which was supposed to reflect the uncertainty. Now this has been put in the d(bn) column, which is consistent with the table for the 13 cm quadrupoles, for example.