BROOKHAVEN NATIONAL LABORATORY

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Title: Iron Shims to Correct the Measured Harmonics in 130 mm Aperture RHIC Insertion Quadrupoles

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Iron Shims to Correct the Measured Harmonics in 130 mm aperture RHIC Insertion Quadrupoles

Ramesh Gupta

The requirements on the field harmonics in 130 mm RHIC insertion quadrupoles are too tight to guarantee them from a normal tolerances used in manufacturing parts for constructing magnets. In this note, we discuss a possible way of correcting a part of the field harmonics after the measurements. This can be done by attaching some extra iron shims to the yoke around the pole. This scheme appears to be a practical method which can be easily adopted in the 130 mm aperture quadrupoles because of the special shape of the iron and spacer used in these magnets and because of a gap between the iron and spacer near the pole.

The cross section of the 130 mm quadrupole is shown in figure 1. We have put circle on the area of interest. There are eight such locations. They have been marked and each has been assigned a number for future reference. In figure 2, we have shown one of such section of the quadrupole in more detail, indicating the attached shim for which the calculations are done. The size of the shim used in the computer model is 1 mm wide and 9 mm high. However, the shape is not a rectangular one. This is a sort of parallelogram with two smaller sides of it being the circular arcs instead of straight lines. The radius of these two arc is 87 and 92 mm respectively and the length of these two sides is 7.4 and 6.6 mm respectively. The 4 mm is the horizontal width (dx). The vertical height (dy) is 9.3 mm on one side and 8.3 mm on the other side. Since the assembled shims will take a shape of a parallelogram, as shown in figure 2, only the smaller sides are useful for shims. Moreover, it may be pointed out that some more height and thickness of the shim has to be lost in the assembly.

To adopt this scheme, the following procedure is envisioned at present. The harmonics will be measured. The amount of shims to be used in the eight locations would be computed as to best minimize the measured harmonics. The eight shims could, in general, have eight different dimensions. The shims would be put in some sort of packages which would then be inserted at the proper locations in the magnet. The harmonics would be measured again to verify the results. Since the high current values of the harmonics are more important from beam dynamics considerations, the correction would be computed for the maximum design current of 5 kA.

In table 1 and table 2, we have listed the values of harmonics caused by 1 mm thick and 9 mm high shim used in the location 1 through 8. The nominal value of shim would be ~1.8 mm with ±1.8 mm variation in it. Therefore a 1 mm shim in reality would mean 2.8 mm magnetic shim and a -1 mm shim in reality would mean 0.8 magnetic shim in the magnet. The last four rows of this table have special meanings. The row with ++ (- -) indicates the shim locations for giving a positive (negative) contribution to the harmonic in the given column. The row with ** gives the maximum correction obtainable with eight ±1 mm shims — the sign is chosen to generate the maximum value of the harmonic in the given column. Finally the last row, indicated by ××, when one harmonic is changed by the shims, some other harmonics would change too! For example, when +1 mm shims are placed in locations 1,2,5,6 and -1 mm in locations 3,4,7,8 to generate a_3 harmonic, the unavoidable consequence of that would be an additional a_7 harmonic. Therefore, if a_7 was zero to begin with, it will have a non-zero value in the quadrupole after the shims are placed to kill a_3.

In the previous paragraph, we carried our discussion for one harmonic at a time. In reality all harmonics would be present in the magnet. Therefore, one can not easily calculate the values of shims from table 1 and table 2 to eliminate several harmonics at a time. The values of shims in eight locations must be computed to minimize all or some harmonics in a desired way. A computer program "SHIMCAL" has been written to carry out this minimization. It is based on the CERN library routines (MINIUIT, etc.), which minimizes a pre-defined error function. While running this program, the user would input the measured values of harmonics and the output of the program would be the optimized values of eight shims to obtain the lowest values of these harmonics (unless the target –an optional input parameter– is to optimize for non-zero values of certain harmonics). All harmonics would assume a weight of 1.0, unless a different weight is specified (optional parameter) for certain harmonics. A harmonic would not be optimized either if it is not included in the above input or if a zero weight is given to it. For each shim, the user must specify the initial increment in the size (step) and the minimum and the maximum values of the shim. If the step size is zero for a shim, then that particular shim would not be changed during the optimization process.

Following the rules discussed in this paragraph, the eight shims can completely eliminate eight harmonics provided that the adequate space is available to put the optimized values of shims in the magnet. The rule No. 1 is that the harmonics to be made zero should be 4 $a_n's$ and 4 $b_n's$. It may be pointed out that $a_n's$ and $b_n's$ are optimized in a orthogonal sense; which means that when the $a_n's$ are changed by shims the $b_n's$ would not change and vice-versa. The rule No. 2 is that of 4 $a_n's$ and 4 $b_n's$, 2 must be odd harmonics (e.g. a_3) and 2 must be even (e.g. a_4). Finally the Rule No. 3 is that for any odd harmonic n=k, the harmonic n=k+4 can not be independently changed simultaneously (i.e. a_3 and a_7 can not be changed independently but a_2 and a_6 can be). However, once the correction for any two even harmonics (normal or skew) is set by the computed values of eight shims, the change in all other even harmonics (normal or skew) is completely determined.

The restrictions discussed in the above paragraph, though may appear to be limiting what can be done with the shims in reducing desired harmonics in the magnet, in reality one can still choose the desired to be minimized. For example, one can independently make a_2, a_3, a_4, a_5 and b_2, b_3, b_4, b_5 zero, which is a most desirable scenario with all things considered. As mentioned above, an unavoidable consequence of this would be that the other harmonics would become non-zero if they were zero before the shims were placed. Since the program minimizes an error function based on all harmonics, not just eight discussed above, one can guide the minimization process in the desired direction using (trying) different weights for different harmonics based on beam dynamics considerations. In principle, in the error function to be minimized one can also include, for example, tune shift caused by various harmonics so that the shims are optimized for minimizing the tune shift due to these harmonics together with minimizing the values of the selected harmonics.

Shims in 130 mm aperture Quadrupoles

Table 1: Skew Harmonics due to 1mm × 9mm shim at various locations as per the POISSON computations at 5000 amperes.

#	θ	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9
1	32	2.749	1.046	-0.502	-0.921	-0.661	-0.316	-0.095	0.005	0.025	0.02
2	58	1.910	-1.046	-1.960	-0.921	0.086	0.316	0.156	0.005	-0.038	-0.02
3	122	1.910	1.046	-1.960	0.921	0.086	-0.316	0.156	-0.005	-0.038	0.02
4	148	2.749	-1.046	-0.502	0.921	-0.661	0.316	-0.095	-0.005	0.025	-0.02
5	212	-2.749	1.046	0.502	-0.921	0.661	-0.316	0.095	0.005	-0.025	0.02
6	238	-1.910	-1.046	1.960	-0.921	-0.086	0.316	-0.156	0.005	0.038	-0.02
7	302	-1.910	1.046	1.960	0.921	-0.086	-0.316	-0.156	-0.005	0.038	0.02
8	328	-2.749	-1.046	0.502	0.921	0.661	0.316	0.095	-0.005	-0.025	-0.02
++	++	1234	1357	5678	3478	2358	2468	2358	1256	1467	1357
- -	- -	5678	2468	1234	1256	1467	1357	1467	3478	2358	2468
**	**	18.64	8.37	9.85	7.37	2.99	2.52	1.0	0.04	0.25	0.16
××	××		$a_1a_5a_9$		a_3a_7		$a_1a_5a_9$		a_3a_7		$a_1a_5a_9$

Table 2: Normal Harmonics due to 1mm × 9mm shim at various locations as per the POISSON computations at 5000 amperes.

#	θ	b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8	b_9
1	32	1.910	1.0^+	1.960	0.795	0.086	-0.152	-0.156	-0.090	-0.038	-0.01
2	58	2.749	1.0^+	0.502	-0.795	-0.661	-0.152	0.095	0.090	0.025	-0.01
3	122	-2.749	1.0^+	-0.502	-0.795	0.661	-0.152	-0.095	0.090	-0.025	-0.01
4	148	-1.910	1.0^+	-1.960	0.795	-0.086	-0.152	0.156	-0.090	0.038	-0.01
5	212	-1.910	1.0^+	-1.960	0.795	-0.086	-0.152	0.156	-0.090	0.038	-0.01
6	238	-2.749	1.0^+	-0.502	-0.795	0.661	-0.152	-0.095	0.090	-0.025	-0.01
7	302	2.749	1.0^+	0.502	-0.795	-0.661	-0.152	0.095	0.090	0.025	-0.01
8	328	1.910	1.0^+	1.960	0.795	0.086	-0.152	-0.156	-0.090	-0.038	-0.01
++	++	1278	All	1278	1458	1368	None	2457	2367	2457	None
- -	- -	3456	None	3456	2367	2457	All	1368	1458	1368	All
**	**	18.64	22.5	9.85	6.36	2.99	1.22	1.0	0.72	0.25	0.08
××	××		$b_1b_5b_9$		b_3b_7		$b_1b_5b_9$		b_3b_7		$b_1b_5b_9$

$^+$ b_1 does not change since it is normalized to 1 part in 10,000. Actual increase, over the gradient without shim, is 2.81 part in 10,000.

++ Shim locations giving a positive contribution to this harmonic.

- - Shim locations giving a negative contribution to this harmonic.

** Maximum correction possible using all shims with +1 and/or -1 mm thickness at the most favorable locations for this particular harmonic.

×× Indicates that these harmonics are coupled. When one is changed by shim, the other would change too.

SHIM LOCATIONS

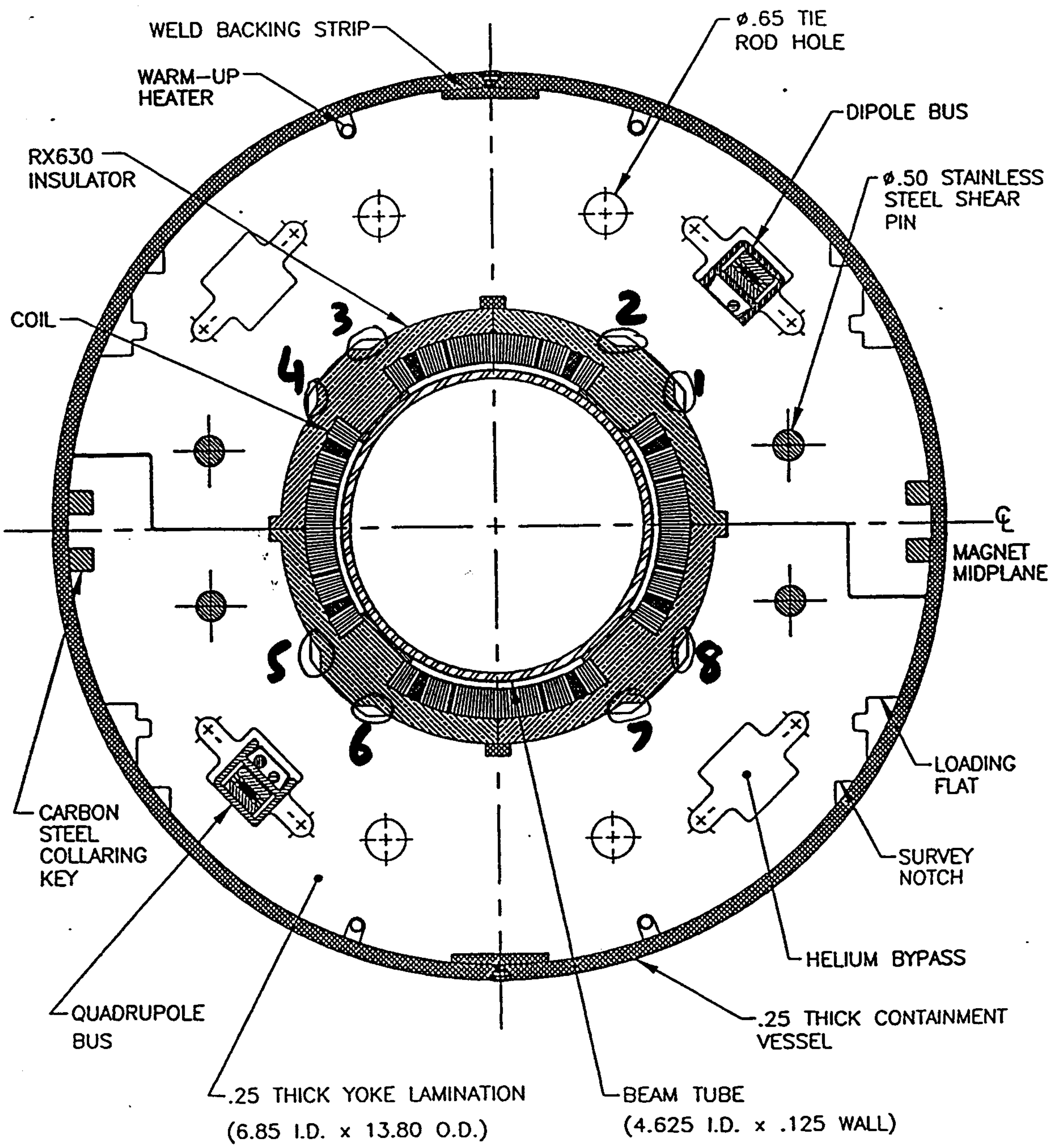

Figure 1: Cross section of 130 mm aperture RHIC insertion quadrupoles with the locations for placing shims marked on it.

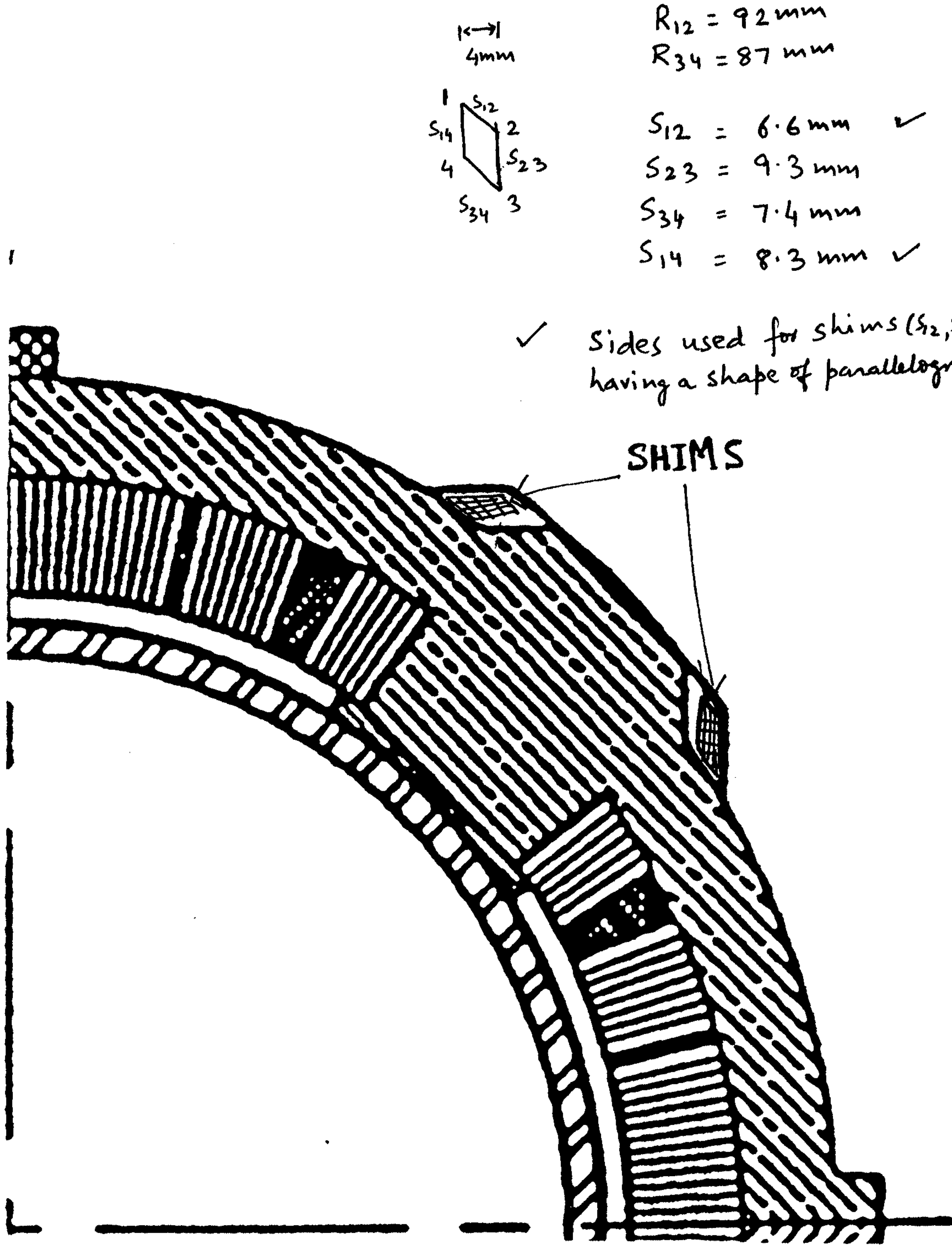

Figure 2: Details of the location where the shims are placed in the quadrupole.