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NMR MEASUREMENTS OF SAVER DIPOLES AND THE HORIZONTAL CLOSED ORBIT

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I.

For superconducting dipoles, two quantities are obtained at the MTF with respect to the bend field strength. One, called "DCX", is a stretched-wire measurement and, in principle, this represents the integrated bend field $\int B \cdot d\ell$ at various excitation currents from 500A to 4,000A or beyond. The other quantity "TF" (transfer function) is an NMR measurement of the field strength in the body of dipoles at the excitation current of 2,000A. The effective length of a dipole is $\ell_{eff} \equiv (DCX/TF)$ and this should be close to the theoretical estimate* of 240.77". The stretched-wire measurement is inherently more difficult than the NMR measurement and DCX is much less reliable as the absolute measure of the field strength compared to TF. Because of the mounting evidence on the unreliable nature of DCX values, it was finally decided in January, 1982 to use TF only (instead of both TF and DCX) for the magnet acceptance. DCX values are of course still very useful in seeing the field strength as a function of the excitation current.

Recently, Ray Hanft pointed out that some values of TF obtained by the NMR measurement may have systematic errors of 0.003 kG/kA (or less) out of 10 kG/kA. The major source of the systematic error seems to be a relatively long-term drift in calibration of the shunt which is used to read the current. The introduction of the "new" 7500A system in May, 1981 further complicated the situation. He is still working on the data-salvaging project and a definitive story must come from him someday in the near future. Meanwhile, succumbing to my incessant

* Stan Snowdon, private communication.

pestering, he has reluctantly come up with a "quick-and-dirty" receipe for fixing the existing data of TF. In spite of his caveat, it is my belief that the MTF has already done the necessary work fou us and any improvement over and above the quick-and-dirty fix will not affect the saver commissioning effort substantially. This note is a somewhat circuitous attempt to explain this belief on my part.

II.

Altogether 609 dipoles have been installed in the tunnel and this is a significant fraction (79%) of the total number needed in the ring. Fig. 1 is the histogram of TF for these dipoles fixed according to the suggestion by Ray Hanft. Ten dipoles lying outside the range 9.9775 to 10.005 kG/kA are most likely measurement errors but the exclusion of them from the samples does not change the overall picture significantly. Even with this "fix", there may still be errors of the order of 0.001 for some dipoles but I believe it is safe to assume that the ring with 609 dipoles is well represented by the average value 9.9893 kG/kA and the standard deviation 0.0058 kG/kA. If one ignores all other effects such as the nonlinearity in field and the quadrupole misalignment, one finds the horizontal closed orbit to have

rms of $x_{c.o.}$ (at β_x = 100m) = 3.73mm if all 774 dipoles are installed randomly;

= 3.31mm if 609 dipoles are installed randomely in A1-A3, C, D, E and F sectors.

Compared to these, the actual arrangement in the ring yields 3.57mm indicating that the arrangement we chose was not a particularly unlucky one. The maximum excursion x_{max} in the regular cells can be estimated at a certain confidence level using, for example, a receipe in the CERN yellow handbook (CERN/MPS-SI/Int. DL/70/4, 23 April, 1970; pp 23-24) or the analytical work by Gluckstern (Particle Accelerators, 8, 1978, p. 203). With the probability of 68%, x_{max} will not exceed

8.1 mm (CERN receipe)
or 7.4 mm (Gluckstern)

when 609 dipoles are randomly installed. For our arrangement, the maximum excursion at β_x = 100m is 7.3mm, again showing that we did not goof. An interesting observation can be made by taking the raw data on TF without any "fix" and calculating the horizontal closed orbit. The average and the standard deviation then turn out to be 9.9895 kG/kA and 0.0061 kG/kA, respectively instead of 9.9893 and 0.0058 for the laundered data set. The arrangement in the tunnel would give rms of $x_{c.o.}$ = 3.57mm (no difference) and x_{max} (at β_x = 100m) = 8.2mm. The change in x_{max} from 7.3mm to 8.2mm may be regarded as a roundabout measure of the effect of data fixing. The uncertainty of this magnitude would be trivial compared to others coming from the quadrupole misalignment and maybe even one from the nonlinearity of the field.

III.

As usual, different people have different things to say on the question of quadrupole misalignment. Taking advantage of this lack of unanimity, I arbitrarily propose here that we take 10 mils (with a cutoff of ±25 mils) as the rms value of the horizontal misalignment relative to the floor marks. This includes not only the survey and installation errors but the MTF measurement and lug-setting errors as well. The standard formula tells us then that the rms value of $x_{c.o.}$ at β_x = 100m is expected to be 4.60mm. Combined with the distortion arising from the fluctuation in TF, this becomes

$$\text{rms of } x_{c.o.} = \sqrt{(4.60)^2 + (3.73)^2} = 5.92\text{mm}$$

if all 774 dipoles are installed randomly. The final closed orbit in the ring should not be far from this unless we committed a blunder in assigning the remaining dipoles in A4 and B.

The rms value of this magnitude is of course not really a serious

problem in commissioning the superconducting ring. Once a closed orbit is established, it is straightforward to eliminate the observed orbit distortion completely, as our experience in the main ring operation has amply demonstrated, provided the necessary correction strength is within the capability of the steering elements. The real concern should rather be whether we could expect to have a closed orbit at all within the given magnet aperture with a reasonable probability. If the answer is yes, the tuning to establish a circulating beam involves only four independent "knobs", one each for x, x', y and y' of the injected beam. If the answer is no, the procedure will undoubtedly be very elaborate and painful involving many more knobs for the steering elements.*
In order to obtain the information on this question, six hundred cases of error distributions have been examined and the results are shown in Fig. 2 as A-1 and B-1. They are the maximum horizontal beam excursion in the entire ring (and not just in the regular cells) expected for a certain confidence level. For example, the maximum excursion will not exceed 16mm with the probability of 80% or so. A-1 is for 609 dipoles as assigned already and the remaining 165 dipoles chosen randomly while B-1 is when all 774 dipoles are randomly installed in the ring. For TF, the fixed data are used and the quadrupole misalignments are of course random for both A-1 and B-1 with the standard deviation of 10 mils. Since the field is still assumed to be linear, results beyond ∿15mm may have to be modified to some extent. Nevertheless, it seems that we have a good chance to see a circulating beam by simply adjusting the injected beam so that the betatron oscillation is very small. Even with the quadrupole misalignments increased to 15 mils (std. dev.), the probability to have a closed orbit within ∿20mm should be ∿75%. One must of course consider the orbit distortion in the vertical direction together with the horizontal distortion. The uncertainty in the median plane ("vertical plane" for MTF) should be 1mr or less with all the known sources such as survey, installation, thermal cyclings and lug setting, and the quadrupole misalignment in the vertical direction is expected to be of the same magnitude (and <u>not</u> substantially <u>smaller</u>)

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* I understand a group of people have been working on this to find the optimum procedures.

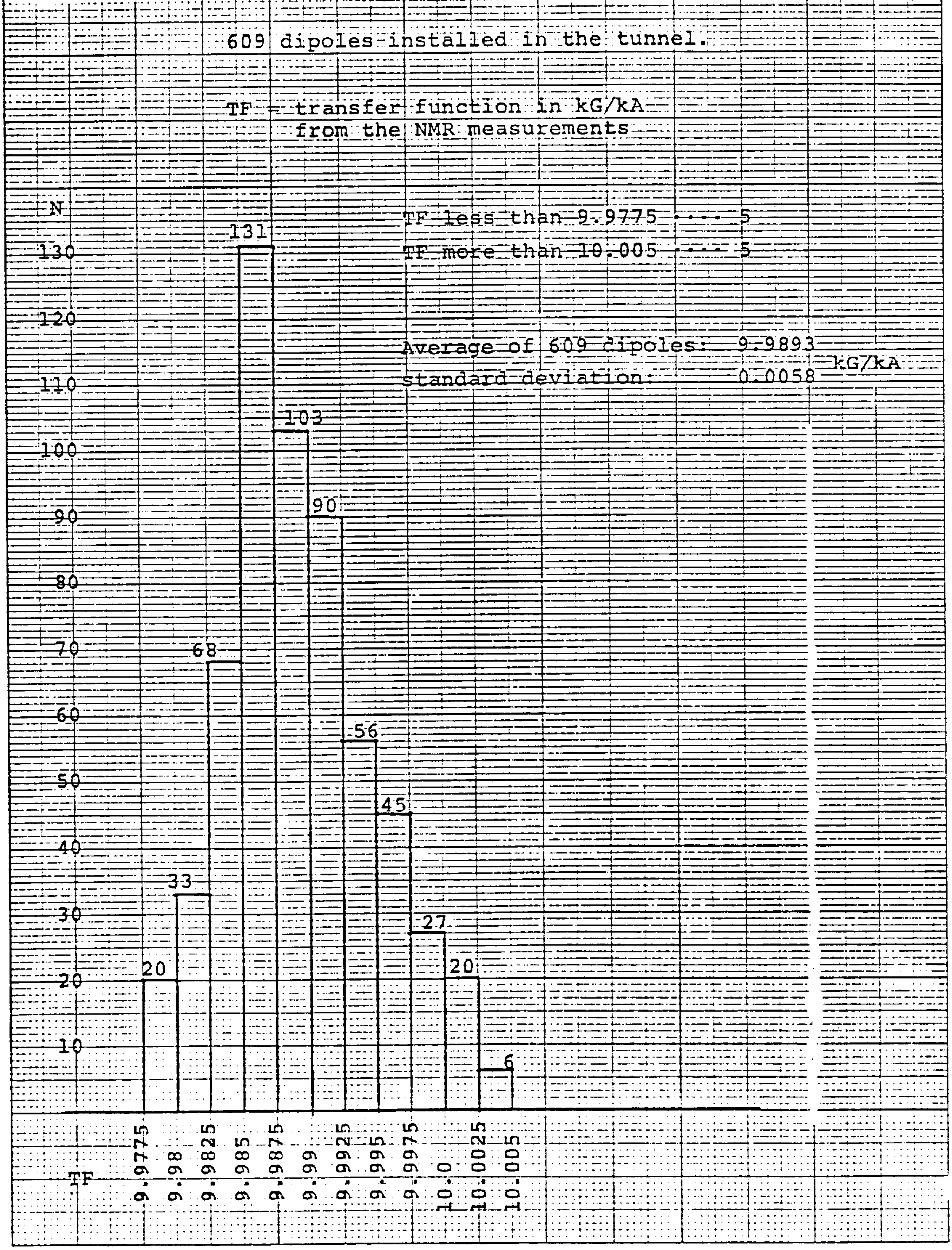
as the one in the horizontal direction. The vertical closed orbit is then statistically represented by B-1 of Fig. 2. The chance of finding a closed orbit within $\sim$15mm from the axis should still be better than fifty-fifty (which, however, is not good enough for most people).

Although the correction of closed orbit is not the main topic of this note, it is of some interest to see how much one can expect from a simple harmonic correction. For this study, total of ninety steering elements are grouped into four sets:

19th harmonic,	"cos" term	---	24
	"sin" term	---	24
20th harmonic,	"cos" term	---	22
	"sin" term	---	20

Within a given group, the polarity of each element is chosen appropriately but the strength is common to all members of the group. We then have essentially two or four independent "knobs" to twist for eliminating either the 19th harmonic contribution alone or the 19th and the 20th together. Three hundred samples of error distribution have been taken to find each of four curves (A-2, A-3, B-2 and B-3) in Fig. 2. When one is lucky and the maximum orbit distortion is small, the contribution from the 19th and the 20th harmonic components is not dominant and the improvement is insignificant. (Of course one does not need any correction under such a lucky situation.) For a very unlucky combination of errors, on the other hand, the improvement is substantial with four independent parameters (or, more realistically, eight with four more coming from the vertical correction system). For example, the maximum excursion does not exceed 10mm with a probability of 95% when both 19th and 20th harmonic components are eliminated. It is not clear to me whether one-harmonic correction, A-2 and B-2, is a substantial reduction worth considering. Neither is the observable difference between A-2 and B-2 for large probabilities understood with respect to its significance or its implication. It may even be true that finding the right combination of four (or eight) independent parameters is no less painful than twisting one- or two-hundred knobs for the commissioning of the Saver.

Fig. 1


609 dipoles installed in the tunnel.
TF = transfer function in kG/kA
from the NMR measurements
TF less than 9.9775 ---- 5
TF more than 10.005 ---- 5
Average of 609 dipoles: 9.9893
standard deviation: 0.0058
kG/kA
N
130
120
110
100
90
80
70
60
50
40
30
20
10
131
103
90
68
56
45
33
27
20
20
6
TF
9.9775
9.98
9.9825
9.985
9.9875
9.99
9.9925
9.995
9.9975
10.0
10.0025
10.005

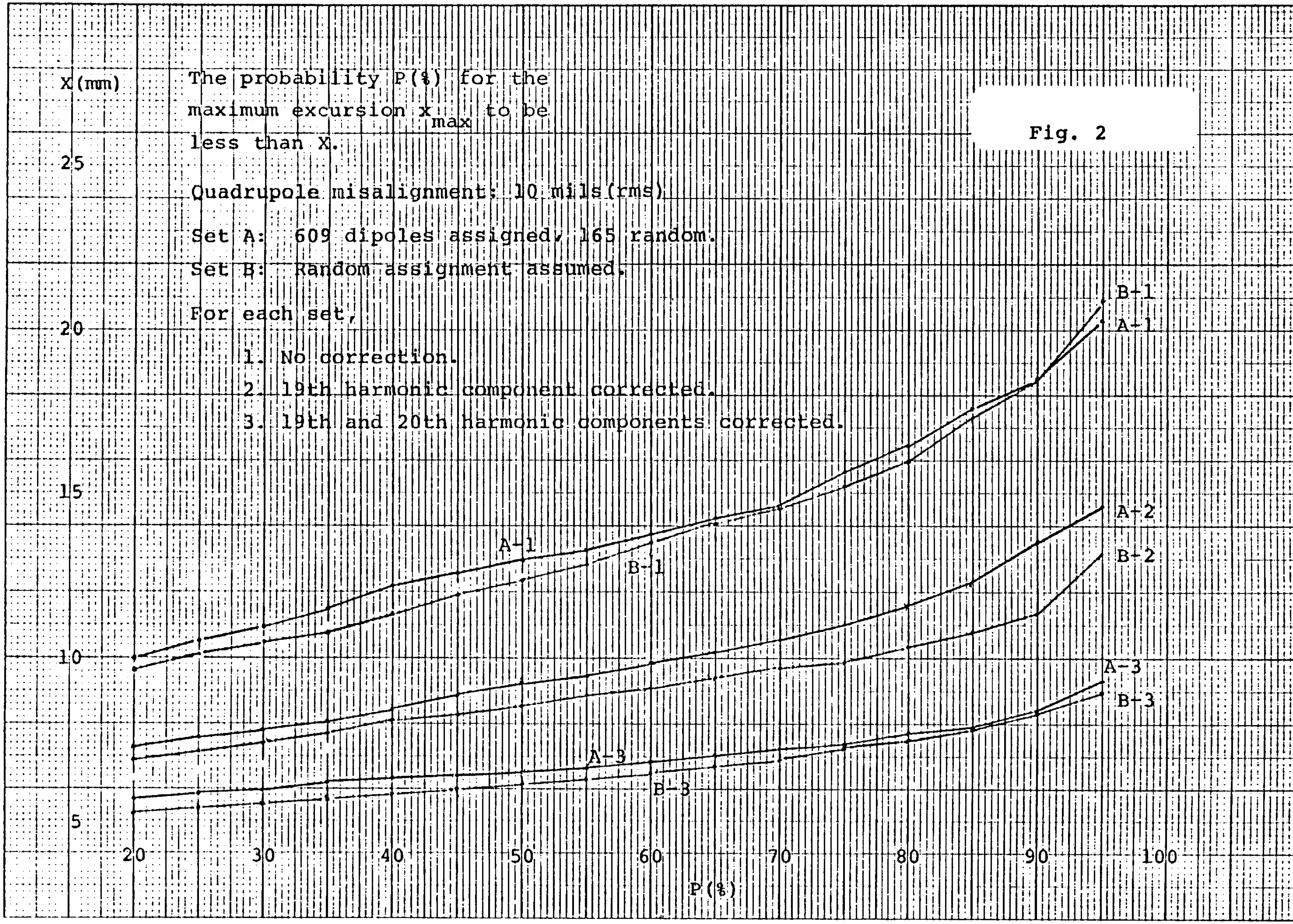

X (mm)
The probability P(%) for the maximum excursion x_{max} to be less than X.
Quadrupole misalignment: 10 mils(rms)
Set A: 609 dipoles assigned, 165 random.
Set B: Random assignment assumed.
For each set,
1. No correction.
2. 19th harmonic component corrected.
3. 19th and 20th harmonic components corrected.
25
20
15
10
5
20
30
40
50
60
70
80
90
100
P(%)
A-1
B-1
A-2
B-2
A-3
B-3

Fig. 2