Some considerations on the alignment–accuracy for accelerators

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1 Introduction

For the running of an accelerator it is of great importance to have good alignment for each particular component. Each component will be clearly defined by 6 degrees of freedom. Especially important are the "radial position component" and "vertical position component" of the quadrupoles and the sextupoles, which have to be adjusted to a high accuracy. The alignment-accuracy of these degrees of freedom, for example, is 0.2 mm for the electron-machine of the HERA-accelerator /2/. This value refers to the middle of the magnet. How is this statement of accuracy to be interpretated? This question can't be answered with a single sentence. By using the example of ring-accelerators we can try to discuss the accuracy-aspects and the associated combined model of alignment.

2 Philosophy of alignment

Supposing all accelerator components are positioned on a circle as shown in Fig. 1. These would be the nominal positions of the magnets. If the actual positions of the magnets diverge from the nominal positions in a systematic manner the running of the accelerator will not be affected. What is meant by this? For the running of an accelerator it isn't necessarily essential that the magnets are positioned exactly, for example, to the centre of the accelerator. On the contrary the aim is to adjust neighbouring magnets with a high accuracy to one another. Therefore it will only be necessary to have a high accuracy in the neighbourhood. If neighbouring magnets are positioned on a smoothing curve systematic deviations between the nominal and the actual position will be unimportant. Nevertheless care must be taken so that the systematic deviations don't follow a sinusoidal function, the frequency of which is near the betatron-frequency of the accelerator or its multiples.

In fact the magnets will not be positioned on a smoothing curve exactly but they will deviate more or less as shown in Fig.2. The deviations determine the quality of the alignment /3/. Therefore it is useful for example to define the quality of alignment as follows:

$$g = \sqrt{\frac{\sum_{i=1}^{n}(a_i)^2}{n}} \qquad (1)$$

In addition it is required that each single deviation is smaller than 2g or 3g. The quality value "g" of alignment isn't a standard of adjustment. The quality value "g" contains systematic and random parts. The systematic parts represent the remaining significant deviations, while the random parts will be determined by the accuracy of the measurements (see section 3).

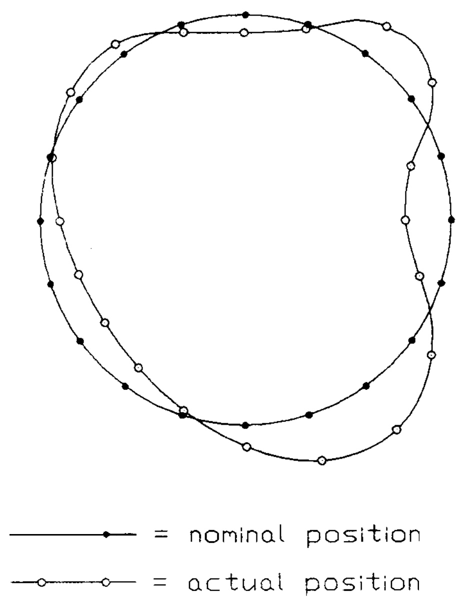

Figure 1: Philosophy of alignment

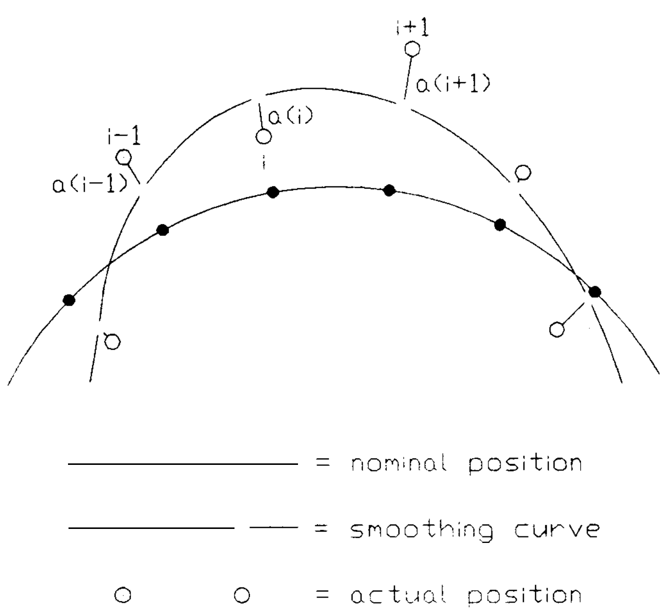

Figure 2: Detail of Fig. 1

How does an alignment of an accelerator proceed?
I confine my remarks only to the "radial position component".

Step 1: As far as possible the whole accelerator will be measured. The adjustment then shows the actual coordinates of the fiducial points on the magnets.

Step 2: The actual coordinates will be compared with the nominal values. One can then calculate the difference vector of the coordinates and determine the radial component.

Step 3: Systematic parts, which are included in the radial components, will be calculated by means of interpolating functions (polynoms, fourier series, spline functions). This will produce a "smoothing curve".

Step 4: Now the magnets will be moved only by the difference between the "radial component" and the function value of the interpolating function at this place.

This cycle will be carried out until the differences (see Step 4) are so small that the quality value "g" of the alignment and the additional condition is obtained.

3 Measuring of an accelerator and the assessment of the relative accuracy

Up to now we have supposed that the actual positions of the magnets are fixed without errors. In this section I would like to talk about the techniques to measure an accelerator and how to assess the accuracy of the "radial position component".

We start with the determination of the actual positions of the magnets. After all the magnets are fitted out with fiducial points the coordinates of these have to be determined. Being constrained by the constructional conditions two measuring techniques come into consideration. With the first technique the offset between each fiducial point and its neighbours will be measured with a stretched wire /1/ /4/. With the second technique - which we use at DESY - the directions from each fiducial point to several neighbours will be measured with a theodolite (Fig.3). By knowing the distances between the fiducial points one can calculate the coordina-

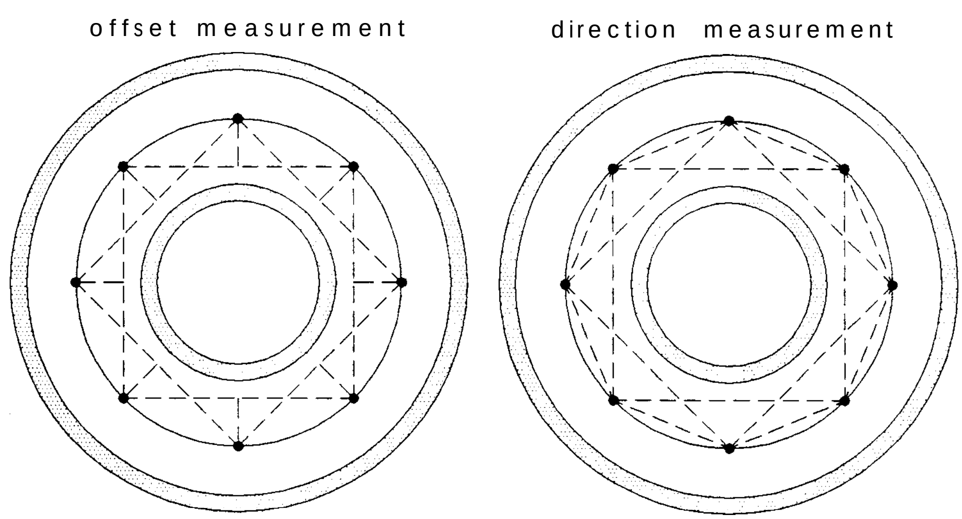

Figure 3: Measuring techniques

tes. The aim of both measuring techniques is to have a particular high accuracy for the “radial position component”. How can you find out with which accuracy or properly speaking with which relative accuracy the fiducial points are determined?

The adjustment. for each fiducial point produces error ellipses. In what way are these error ellipses suited to judge the relative accuracy ? The answer is: the error ellipses aren’t suited for this. The error ellipses refer always to the datum of the network /5/ /8/. Since the definition of the datum of accelerator networks is arbitrary the error ellipses are also arbitrary. An example will illustrate this.

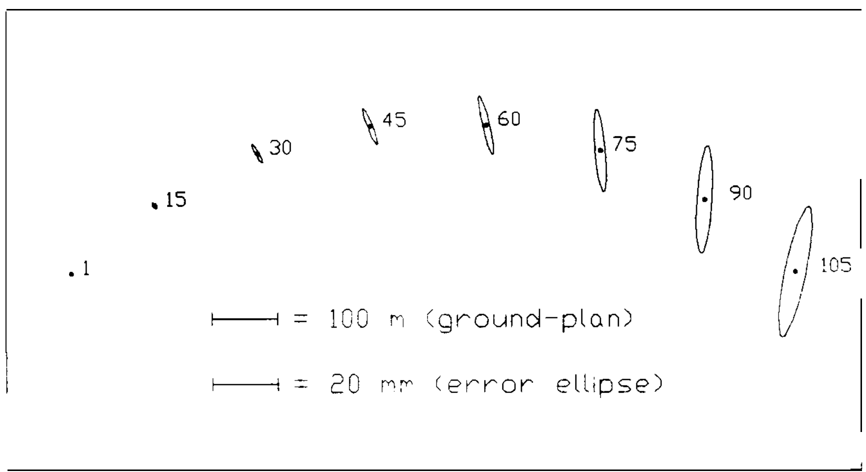

Figure 4: Error ellipses from an adjustment (datum at the beginning)

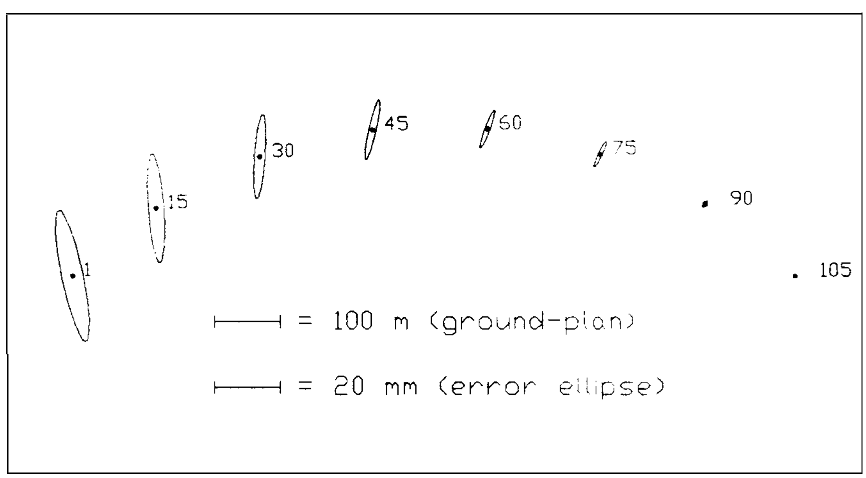

Figure 5: Error ellipses from an adjustment (datum at the end)

The Fig. 4 shows the results, if the first fiducial point and the bearing to the neighbouring point are fixed to define the datum. As you see the error ellipses are increasing with the distance from the datum point. You will have reverse conditions if the final fiducial point and the bearing of the connecting line of the last two fiducial points are fixed (see Fig.5). For a free adjustment naturally all error ellipses are more regular (Fig.6). In comparison with the previously discussed error ellipses the relative error ellipses are better qualified to describe the relative accuracy. The relative error ellipse is defined for the centre of the connecting line of two points (/8/ page 146). With only one exception relative error ellipses also refer to the datum of the network /5/. They aren't suited to describing the relative accuracy. Fig. 7 gives an example.

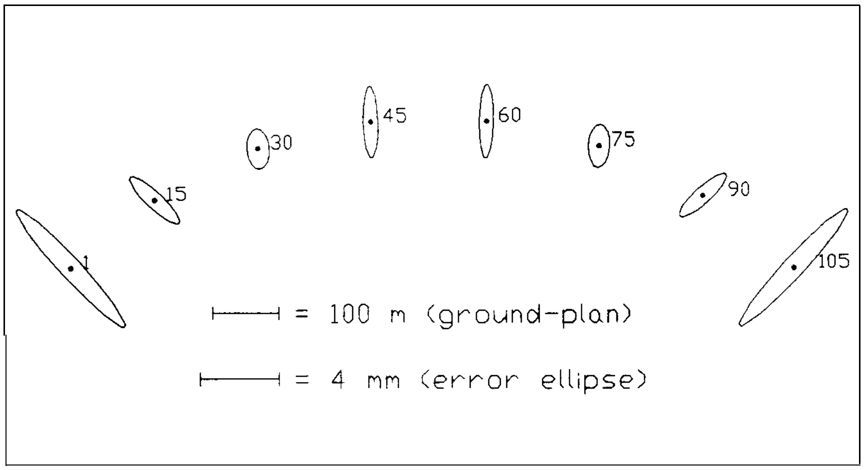

Figure 6: Error ellipses from a free network adjustment

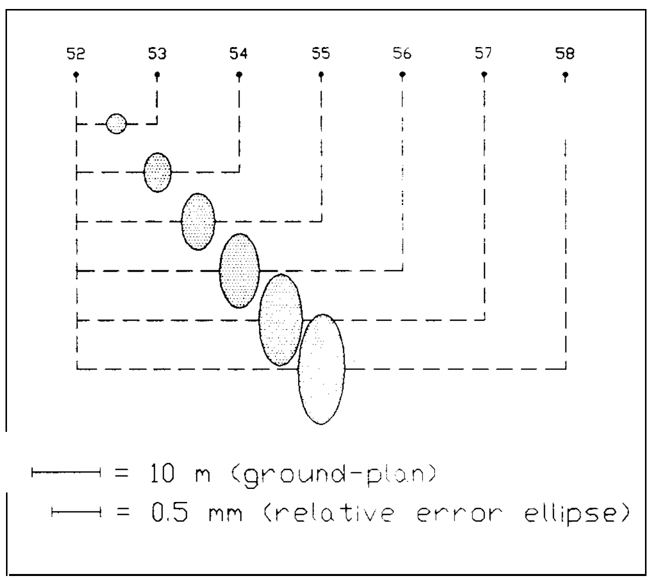

Figure 7: Relative error ellipses

How is the relative accuracy to be determined? As has been said at the beginning, the neighbouring magnets are to be aligned with a high accuracy between each other. For that reason it is useful to fit the definition of the relative accuracy to this condition. The relative accuracy of the “radial position component” of a magnet therefore can be defined for example by the standard deviation of the distance from the considered fiducial point to the connecting line of corresponding neighbouring points (see Fig. 8). These accuracy values will be calculated in the adjustment as standard deviations of the functions of the unknowns /6/. They are independent of the datum of the network and don't have the disadvantages of the error ellipses.

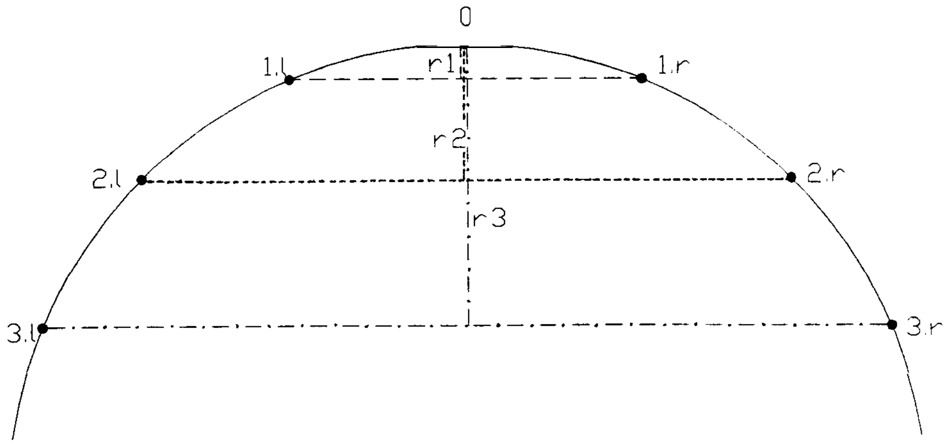

Figure 8: Definition of the relative accuracy of the "radial position component"

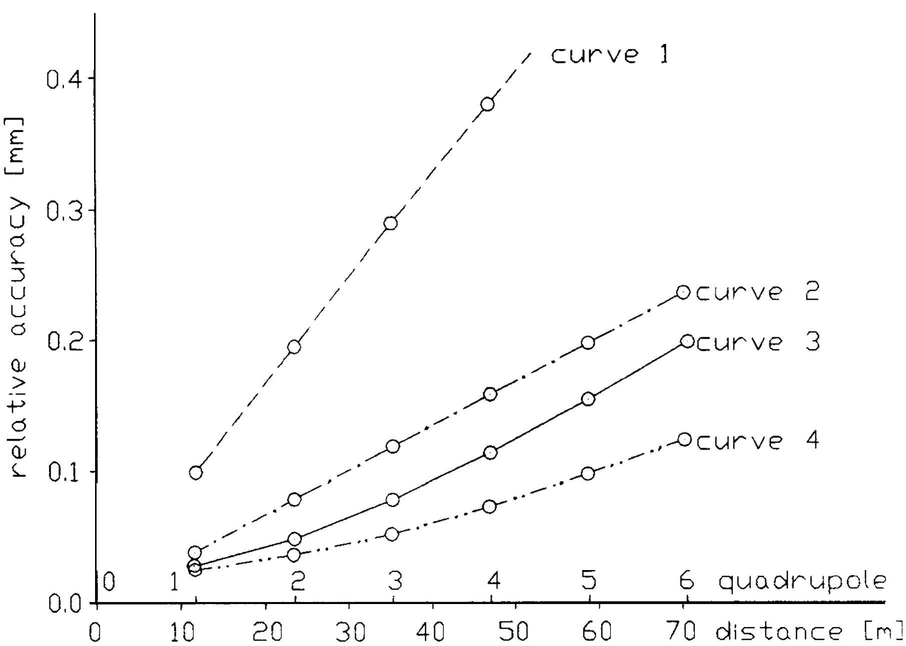

Figure 9: Comparison of different relative accuracies

In Fig. 9, for example. they are compared with the discussed accuracy values for the electron-machine of the HERA-accelerator. For the simulation calculation we proceed thus, that the directions are observed to two fiducial points forward and backward with an accuracy of 0.3 mgrades and for the adjustment. the two points at the beginning and at the end of a quadrant are defined as fixed. The distances between the fiducial points are known with an accuracy of 0.1 mm. The curve 1 shows the accuracy deduced from the relative error ellipses. The curve 2 describes the relative accuracy of the "radial position component" calculated, without adjustment, only by the error-transmission-formula

$$s_r = \frac{a \cdot b}{a + b} \cdot s_\alpha \tag{2}$$

with s_r = accuracy of the radial position
s_α = accuracy of the angle
a = distance to the left target
b = distance to the right target

The accuracy of the angle is for this example $s_\alpha = \sqrt{2}$ x 0.3mgrades. The accuracy values (see curve 2 in Fig. 9) are already essentially more favourable than the relative error ellipses. Thus the unsuitability of these error ellipses is confirmed. The curve 3 shows the standard deviations of the offsets calculated by an adjustment. As expected these values are more favourable than the values calculated by the error-transmission-formula. The differences are produced by the redundant observations in the direction measurements leading to a raising of the accuracy. These differences characterize the winning of the adjustment. The curve 3 is calculated by a data set in which two directions forward and backward are observed from every point. On the other hand if you observe three directions forward and backward the relative accuracy will be higher about a greater range (see curve 4 in Fig. 9). The adjustments were executed by the program PAN provided by the firm of GEOTEC.

4 Conclusion

The model of alignment procedure for all DESY-accelerators was explained. The aim of the measurements is to have a particular high accuracy for the radial and for the vertical position component. Error ellipses and also relative error ellipses are not suited to describing the relative accuracy. The relative accuracy of the radial position component of a magnet can be defined by the standard deviation of the offset between each fiducial point and its neighbours. This accuracy value is independent of the datum of the network.

5 References

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