May 15, 1962 P. H. ROSE 3,034,846

OPTICAL ALIGNMENT OF CHARGED PARTICLE ACCELERATORS

Filed Nov. 13, 1959

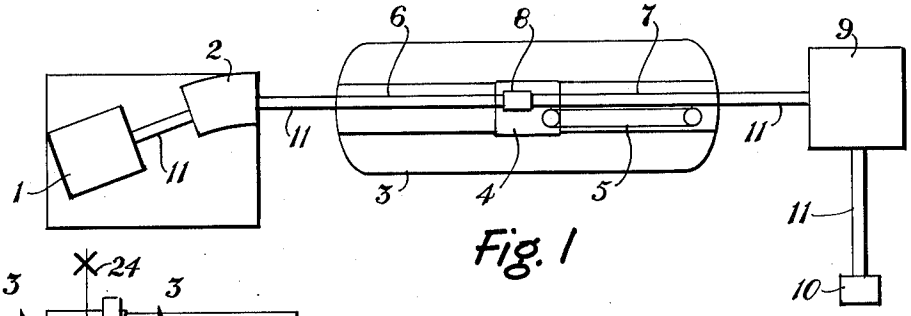


Fig. 1

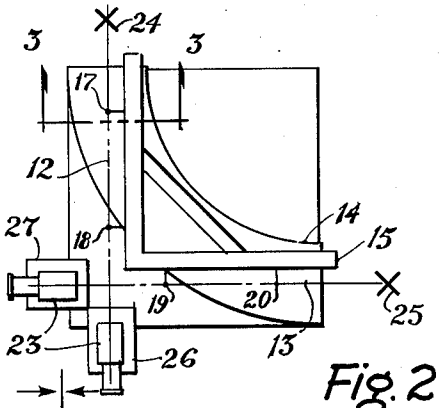


Fig. 2

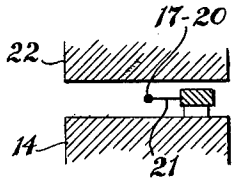


Fig. 3

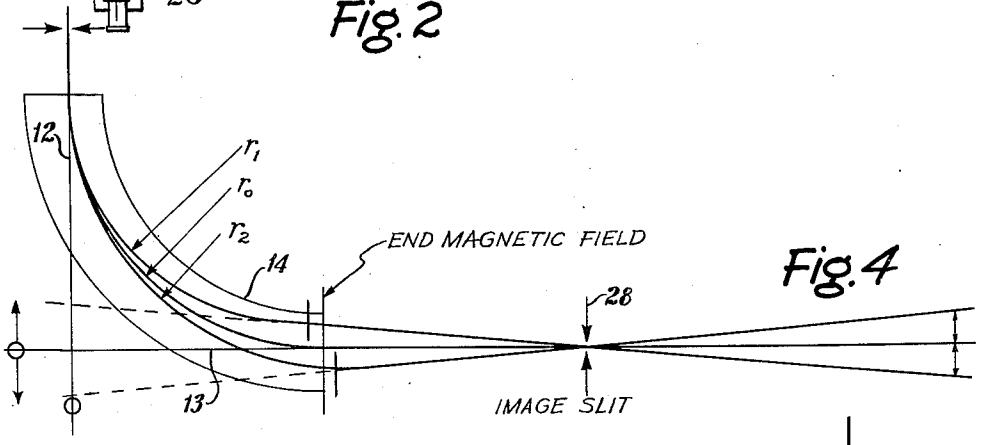


Fig. 4

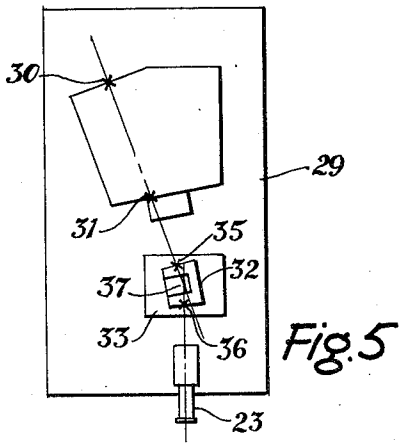


Fig. 5

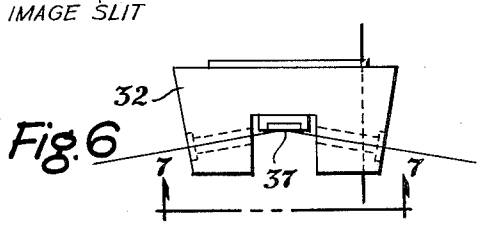


Fig. 6

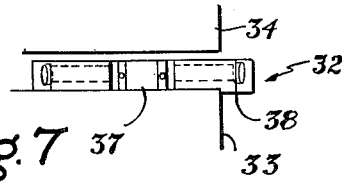


Fig. 7

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3,034,846 OPTICAL ALIGNMENT OF CHARGED PARTICLE ACCELERATORS

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This invention relates to charged particle accelerators and in particular to accelerators adapted to accelerate charged particles in a rectilinear path. The invention is particularly useful in devices such as tandem accelerators wherein the rectilinear path of the acceleration is of extended length so that problems of alignment are severe. The invention will therefore be described with particular refrence to such a tandem accelerator, although it is not limited thereto. The invention is also useful for example in aligning a relatively low voltage accelerator with the analyzing magnet associated therewith.

The invention may best be understood from the following detailed description thereof having reference to the accompanying drawings in which:

FIG. 1 is a diagram illustrating the principal components of a tandem accelerator;

FIG. 2 is a diagrammatic view of the 90° analyzing magnet of the apparatus of FIG. 2 illustrating apparatus for aligning the rest of the tandem accelerator with respect to such analyzing magnet;

FIG. 3 is a sectional view along the line 3—3 of FIG. 2;

FIG. 4 is a diagram illustrating the trajectory of charged particles through the 90° analyzing magnet shown in FIGS. 2 and 3;

FIG. 5 is a view of the anlyzing magnet associated with the negative ion source;

FIG. 6 is a top view of the jig associated with the apparatus of FIG. 5 in the alignment of the same, and

FIG. 7 is a view along the line 7—7 of FIG. 6.

Referring to the drawings and first to FIG. 1 thereof, therein are shown the principal parts of a tandem accelerator. In such an accelerator negative ions are produced by an ion source assembly 1. The negative ion beam is then directed through a 20° injection analyzer magnet 2 which eliminates all charged particles from the beam except those negative ions which it is desired to accelerate. After being analyzed, the negative ion beam is then injected into the principal part of the accelerator, which is enclosed within a tank 3 containing insulating gas under pressure. Within the tank 3 a central terminal 4 is raised to high electrical potential by conveying charge thereto on an endless travelling insulating belt 5, and charged particles are directed through the length of the tank 3 within evacuated acceleration tubes 6, 7. Within the high voltage terminal 4 there is a charge exchange chamber 8 into which gas is admitted in an appropriate manner. Alternatively, a metal foil may be used in place of the charge exchange chamber 8. The negative ions which enter the first acceleration tube 6 are accelerated to the high voltage terminal 4 by virtue of the positive charge thereon. In travelling through the high voltage terminal 4, these negative ions traverse the charge exchange chamber 8 and the gas removes negative charge in the form of excess electrons from the negative ions thus converting them into positive ions. As a result, when the beam emerges from the high voltage terminal 4, it is again accelerated by the positive charge on the high voltage terminal 4 and issues from the second acceleration tube 7 with an energy in mev. equal to the voltage of the high voltage terminal 4 in megavolts multiplied by the number of electronic charges on the charged particles. The beam which emerges contains not only the desired positive ions but also other extraneous charged particles such as the

half energy beam from the charge exchange terminal, heavy ions from charge exchange processes in the acceleration tubes, etc. There is a certain amount of gas in the acceleration tubes, including such gases as oxygen and also carbon which are ionized by the charged particle beam travelling therethrough or by electrons which are released from the various surfaces inside the tubes by the high potentials. As a result of this ionization, charged particles are accelerated to the high energy end of the accelerator. These charged particles are unfocused but they are intense enough to be a nuisance unless the beam is analyzed. Consequently a 90° analyzing magnet 9 is provided to analyze the emergent positive ion beam. Although no particular angle of deflection is necessary to analyze the beam, some magnet is needed to analyze the beam, and for convenience one uses a 90° analyzing magnet, since this diminishes the overall length of the machine in that one can build experimental apparatus to the side of the principal area. This is particularly desirable since a tandem accelerator is a very lengthy piece of apparatus. However, there is no optical reason for selecting the angle of 90°.

After passing through the 90° analyzing magnet 9, the charged particle beam is directed into some suitable beam utilization system 10. For example, the beam may be directed against various targets for the purpose of measuring various nuclear reactions.

It will be apparent from the foregoing description that there are numerous problems of alignment in connection with the apparatus shown in FIG. 1. since charged particles must travel a very great distance as a compact beam. Thus, for example, the principal components shown in FIG. 1, namely, the ion source assembly 1, the 20° injection analyzer 2, the tandem tank 3, the 90° analyzing magnet 9, and the beam utilization system 10, together with all connecting tubes 11, must be aligned with each other. Moreover, internal alignment is also required. For example, within the tank 3, the acceleration tubes 6, 7 must be lined up with each other, and with the charge exchange chamber 8.

My invention comprehends a line of sight method for aligning a tandem accelerator such as that shown in FIG. 1. Consideration of possible techniques for aligning the tandem showed that a line of sight method offered the most advantages. In this initial discussion, alignment problems are discussed on the assumption that some combinations of telescopes, axicons, or series pin holes can be used to define the line of sight. Exactly how this can be done is described in detail hereinafter.

The mechanical tolerance aimed at in a 5 megavolt tandem is $\pm 1/32''$ over the whole length of about 100 ft. Tests show that this tolerance is the best that can reasonably be specified. An upper limit is set by the size of the aperture in the charge-exchange chamber 8 which is 0.125" diameter. A tolerance not enforcing a direct line of sight through the machine is, therefore, not acceptable—that is, a tolerance of $\pm 1/16''$ would be marginal. Where it is possible, the component parts of the tandem will be aligned more accurately than specified by the overall tolerance.

For any method of alignment to be successful, the mechanical tolerances on the various parts of the system shown in FIG. 1 must be maintained to as close limits as is practicable. Attention to this can reduce the final alignment to a series of small adjustments, taking a comparatively short time.

The first step taken in devising an alignment scheme for the tandem is to divide the plumbing into sections each of which could be aligned individually and moved independently of the others. These sections are shown in FIG. 1. The various components may be lined up using removable pin hole apertures, or by an equivalent arrange-

ment, at selected points along the accelerator tubing. The criteria adopted in making the division into parts, were that each part could be accurately made and aligned in itself, and when adjusted posses adequate mechanical strength to enable it to be moved as a unit.

The setting up procedure is first, a general lining up of all of the parts on the floor of the site, so that they are in the mid range of their adjustment. It is to be expected that this need only be done once. Having achieved a satisfactory rough setting, the frame of reference for the accurate alignment must be set.

The part that has been chosen as the reference is the 90° analyzing magnet **9** and the vacuum tubing that goes with it. Although the tandem tank **3** itself at first sight would seem a better datum, there are two reasons for the choice made. Firstly, the experimentalist will set his apparatus up by the line of the analyzing magnet **9**. Secondly, tandem internal alignment is most likely of all the structures to change with time. The analyzing magnet **9** can certainly be expected to be very stable in this respect.

It is expedient to mention here that the machine could be lined up dynamically by tracking the beam from the source **1** to the beam utilization system **10**. To do this without lining up the machine carefully by other means first is to court trouble. A large range of component position would allow the beam to pass through the tandem accelerator, but the chance of an energy independent solution by these means is a small one. By starting off with an accurate mechanical alignment small adjustments should be sufficient to bring the beam on to the straight line defined by the mechanical adjustments. If this is done, the beam position can be almost independent of energy changes.

The part of the vacuum system associated with the analyzing magnet **9** is one of the longest in the machine and, because it incorporates the analyzing magnet **9**, must be a very stable unit mechanically. This sub-assembly must be aligned with reference to the magnet median plane. It is, therefore, important that the pole faces of the magnet be truly parallel, identical in size and made from uniform material.

The vacuum chamber passing between the magnet pole faces is to be designed so that the axis of the beam-entrance trajectory and the axis of the beam-exit trajectory are in the median plane of the magnet and can be defined by removable plates with pinholes in them, or by a telescope.

It is possible to think of a number of schemes for defining the median plane of the magnet. One plan is outlined below.

The magnet gap will be held accurately parallel by spacers. It is, therefore, feasible to engrave a fine center line on a number of glass spacers which can be moved about in the magnet gap. From the back of the magnet yoke, two adjustable telescope mountings can be built. These mountings can then be adjusted to be roughly at right angles, the exact angle is not important, and the axis of the telescope lined up with the center lines scribed on the glass spacers. The mountings can be made so that only one telescope is required to define both directions.

The telescope can be used again in the later steps in the processes of aligning the tandem. Thus the datum of reference is the median plane of the magnet and it can be assumed that mechanical measurements give the median plane of the magnet. A necessary condition is that the magnet should be designed symmetrically about the mid-horizontal plane. It is important that the axis of the telescope—once this axis has been adjusted to the median plane of the analyzing magnet—henceforward is the reference axis for the rest of the system. The mountings for the telescope must be designed so that they can also hold a pinhole light source.

This source must be on the axis of the telescope—i.e., on a line passing through the median plane. This light source can then be used for the alignment of the whole accelerator. This source could be replaced by a reflecting or preferably transmitting axicon. It is important that the telescope or the axicon be the fixed element that determines the axis of the system, otherwise the angle as well as the position of the device at the various stations has to be adjusted. That is an aperture defines a small region in space, but the position of the image formed by a telescope is not known unless the direction of the axis of the telescope is also known.

Let us consider the alignment procedure on the assumption that the magnet and the various large components of the accelerator are in their correct position—that is, within the range of their built-in adjustments.

Step one is to scribe lines on the magnet pole face. Lines are normally scribed as close to 90° as is possible. The telescope is then aligned to the two directions defined by these scribed lines. Individual targets have been used to define these directions, although properly speaking, an A frame of the type recommended should be employed to obtain a better degree of accuracy. There is some evidence that the method of employing individual targets is not quite good enough for the tandem accelerators. The slits are then moved into the lines established and zeroed in position. Here it must be pointed out that a basic assumption is made. It is that the scribed lines are tangents to the orbit of the protons entering and leaving the magnet. In general, this will not be true and some correction must be made. The correction is only important on the exit side of the magnet because if the alignment procedure is followed through the whole machine the beam will, in fact, be tangent to the entrance but not tangent to the scribed line at the exit of the analyzing magnet. The beam may go 70 ft. before striking a target beyond the image slits of the analyzing magnet so that if the beam has an error of $\frac{1}{200}$ rdn., then the displacement of the beam 70 ft. beyond the analyzing magnet will be about a third of an inch.

Referring now to FIGS. 2 and 3, the first step is to scribe lines **12**, **13** on the lower pole face **14** of the magnet independently of any other arrangement. The lines are scribed to form a 90° angle so as to come as near to the calculated orbit as possible.

Independently of scribing these lines, an A frame **15** is manufactured so as to define a right angle. In manufacture and assembly of the A frame, the A frame is placed on a flat table (not shown) which should be, of course, as flat as possible; the A frame is supported on pads **16** which average out the flatness of the table and, in the actual apparatus, also average out the flatness of the pole face **14**. Then targets which may comprise for example small steel balls **17**, **18**, **19**, **20** supported on suitable rods **21** are added at the proper height from the pole face **14** by using an appropriate jig (not shown). The right height is important and must be such that all these targets **17**–**20** are in the median plane between the magnet pole faces **14**, **22**. In this way, one can be sure that the beam will go out of the magnet in the right "plane," and this is the one thing one must be certain of.

Having manufactured the A frame, the first step in actual alignment is to put the A frame **15** on the lower magnet pole face **14** on its pads **16** with the targets **17**, **18** and **19**, **20** lined up over the scribed lines **12** and **13** respectively. The second step is to align a telescope **23** to the first two targets **17**, **18** sighting along the first line **12**, and the third step is to put an appropriate target comprising a piece of glass or quartz **24** with cross hairs along this line of sight, as shown in FIG. 2. The fourth step is to align the telescope **23** to the second pair of targets **19**, **20**, and the fifth step is to put another cross hair target **25** along this line of sight, as shown in FIG. 2.

The telescope **23** is alternately mounted on each of two mounts **26**, **27** whose position is fixed relative to the 90° analyzing magnet **9**. The position of each cross hair target **24**, **25** is also fixed relative to the 90° analyzing

magnet **9**, so that once the cross hair targets **24**, **25** have been placed in position, the A frame **15** may be removed and alignment may then be made through use of the cross hair targets **24**, **25** and the telescope **23** alone. It may be necessary to make a small correction by moving one **27** of the telescope mounts sideways in addition to the above mentioned steps, but this additional correction may not be necessary in applications where such refinements are not necessary. For example, with one machine the deviation is .050" in ten feet so that where the beam utilization system **10** is at only ten feet from the 90° analyzing magnet **9**, it may not be necessary to make the correction. However, the deviation can be quite large in 70 feet and some installations having beam-extension trajectories of this length have had trouble in lining up the extension, so that the additional correction is worth worrying about. The cause of the deviation and the nature of the correction may best be understood with reference to FIG. 4.

Referring now to the diagram of FIG. 4, therein is shown the lower pole face **14**, and the scribed lines **12**, **13** which define the calculated orbit. The calculated orbit is that which the charged particles will follow under ideal conditions. Such an orbit will be circular and the radius of curvature of the path is designated by r_0. This orbit emerges from the edges of the magnet tangent to the scribed lines.

The angular deflection θ produced by the passage of the charged particles through the magnetic field is given by the following formula, wherein e, V and m are the charge energy and mass respectively, of the charged particle, H is the magnetic field strength, and s is the path length.

$$\theta=\sqrt{\frac{e}{2Vm}}\int Hds=K_1\int Hds$$

As a result, the angular deflection is determined by the path integral in the magnetic field. The magnetic field H may vary on the orbit or may be constant; if it is constant the orbit is a circle. If the particle enters the magnetic field in the x-direction, the position of particle in the x-direction upon leaving the magnetic field is then:

$$X=\int[\cos\ (K_1\int H(S)ds)]ds$$

Consequently we know that even if the path integral in the magnetic field is a constant, the beam could still come out at a different position in the x direction, even though it must come out at the right angle. It must come out at the right angle because of the above equation giving the angular deflection θ, but the beam could still come out at a different position because of the second equation giving the x position. It can be shown that the latter is a negligible effect, so that the only remaining effect is the fact that the path integral in the magnetic field is not quite what we think it will be, and it is not even a very good approximation.

The magnet is designed to have a certain pole length L which approximates the true length rather than the physical length. It is usually computed as being the estimated physical length plus one-half the magnet gap g. Since this estimated pole length L is only an approximation, in practice the beam is off by a displacement e. If the displacement is off on the high energy side, the actual radius of curvature r_1 is less than the predicted one r_0. If the displacement is off on the low energy side, the actual radius of curvature r_2 is greater than the predicted one r_0. The deviation e is constant for all energies.

Referring again to the diagram of FIG. 4, the beam has to pass through the slits **28**, because of the stabilization circuit (not shown) which causes the beam energy to assume that value for which the beam does pass through the slits, but it may pass through at an angle to the scribed line **13**. In order to compensate for this error and get the true line of sight, the telescope **23** which is used to align the machine is displaced slightly, for example, it may be displaced .030". As a result, the actual angle of deflection is not strictly 90°, but this does not introduce any errors.

Initially, the optical method by itself is not enough to align the machine, and one needs to have recourse to the actual beam of charged particles for correction of small errors. However, once the telescope mounts **26**, **27** and cross-hair targets **24**, **25** have been set up in a fixed position relative to the magnet **9**, it is possible then always to align the machine with respect to the magnet **9** by the telescope **23** alone. One can then set, for example, this 90° analyzing magnet **9** up against any machine and any beam. As noted, the alignment is energy independent. Suppose, for example, the beam is adjusted for 6 mev., using a magnet having 4,000 gausses. At 8 mev. one would adjust the magnet to be the square root of

$$\frac{8}{6}\times 4000\text{ gausses}$$

Then the stabilization circuit would force the beam through the slits by making minor corrections in the energy of the beam.

As noted, the error e is energy independent and is introduced because our calculated pole length is not the actual pole length. This is because we assume a one-half-gap wide fringing field. It is also due to the fact that one cannot measure the length of the orbit accurately enough. It should be noted that this deviation e is introduced by the properties of the magnet and not by any aberration, for there is no beam deformity introduced by these properties of the magnet.

Referring now to FIGS. 5, 6 and 7, the alignment of the ion source assembly **1**, the injector analyzer magnet **2** and the telescope **23** with respect to the frame **29** on which they are all supported proceeds in much the same fashion as that employed in connection with the 90° analyzing magnet **9** of FIGS. 2 and 3. The ion source assembly **1** is affixed to the frame **29** and no adjustments to this are possible since it is not movable. The ion source assembly **1** is equipped with two targets **30**, **31**, each comprising quartz or glass with suitable cross hairs. The injector analyzer magnet **2** is movable and the alignment is accomplished by using a jig **32**, shown in FIGS. 6 and 7. The injector analyzer magnet **2** is shown as a 20° analyzing magnet and therefore the edges of pole-faces **33**, **34** are not normal to the beam path but are at an angle of 5° to that normal, or ¼ of the angle of the analyzing magnet.

The jig **32** is devised as shown so that it is adapted to be mounted upon the lower pole face **33**. The jig **32** is equipped with two targets **35**, **36** having cross hairs and a mirror **37** having an aluminized front surface. The mirror **37** is set at 85° parallel to the ridge **38** of the jig **32**, which ridge **38** insures that the location of the targets **35**, **36** is symmetrical with respect to the center line of the magnet **2**. The surface of the mirror **37** is at the intersection of the line of sight entering the magnet **2** and that leaving the magnet **2** and has to be true. The jig **32** rests on the lower pole face **33** of the magnet **2** as shown so that the angle between the entering line of sight and the outgoing line of sight is 20° and so that the targets **35**, **36** lie in the median plane of the magnet **2**.

In order to align the machine the jig **32** is placed on the magnet **2** as shown, and the telescope **23** is mounted in the position shown. One looks through the telescope **23** towards the magnet and brings all the targets **30**, **31**, **35**, **36** into line and on the center line or axis of the telescope **23**; one aligns the four targets **30**, **31**, **35**, **36** thus by trial and error, by adjusting the position of the magnet **2**.

As noted, the device in FIG. 5 shown is aligned internally on its own frame **29**. No scribbed lines are necessary as in the case of the 90° magnet; instead, the

jig 32 takes their place. In using the jig one is content to depend on machine tolerances: For example, one relies on the outer angle of the ridge 38 of the jig 32 being a right angle, one relies on all surfaces being even and true, and all measured distances being good to the accuracy asked for.

As in the case of the A-frame technique, the jig technique applies to all magnets. Any magnet can be aligned to a beam by the jig technique, and essentially this is equivalent to the A-frame technique hereinbefore described with reference to the 90° analyzing magnet. In effect, one has replaced the non-removable permanent target 24, 25 on the 90° magnet by those 35, 36 on the jig which are removable. Although in the case of the jig technique the telescope mount is on the frame and not on the magnet, in both cases the telescope mounts have to be fixed relative to the magnet in order that one may be able to replace the original line of sight. In the case of the jig, only one telescope mount is necessary because of the mirror. The mirror is not convenient in the 90° setup because the viewer would have to be at the beam axis. The question of whether to use two telescope mounts or one telescope mount and a mirror is merely a matter of convenience.

Having thus described the principles of the invention together with several illustrative embodiments thereof, it is to be understood that although specific terms are employed they are used in a generic and descriptive sense, and not for the purposes of limitation the scope of the invention being set forth in the following claims.

I claim:

1. The method of aligning components of a charged-particle accelerator which method comprises directing a beam of charged particles through one component of said charged-particle accelerator, optically ascertaining a beam-entrance point and a beam-exit point with respect to said component, establishing two reference points fixed with respect to said component and aligned with the rectilinear beam trajectory defined by said beam-entrance point and said beam-exit point, establishing an optical line of sight along said two reference points, and optically aligning other components of said charged-particle accelerator with respect to said optical line of sight, whereby said other components are aligned with respect to said rectilinear beam trajectory.

2. The method of aligning components of a charged-particle accelerator with respect to a beam-deflecting magnet which method comprises optically ascertaining a beam-entrance point and a beam-exit point with respect to said magnet, establishing a first pair of reference points fixed with respect to said magnet and aligned with the calculated beam-entrance trajectory, establishing a second pair of reference points fixed with respect to said magnet and aligned with the calculated beam-exit trajectory, directing a beam of charged particles between the pole faces of said magnet along said beam-entrance trajectory, and adjusting said second pair of reference points to alignment with the observed beam-exit trajectory, whereby said beam-deflecting magnet may be optically aligned for any charged particle beam.

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