Sept. 20, 1960 J. S. COOK ET AL 2,953,707

ELECTRON BEAM FOCUSING SYSTEM

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FIG. 1

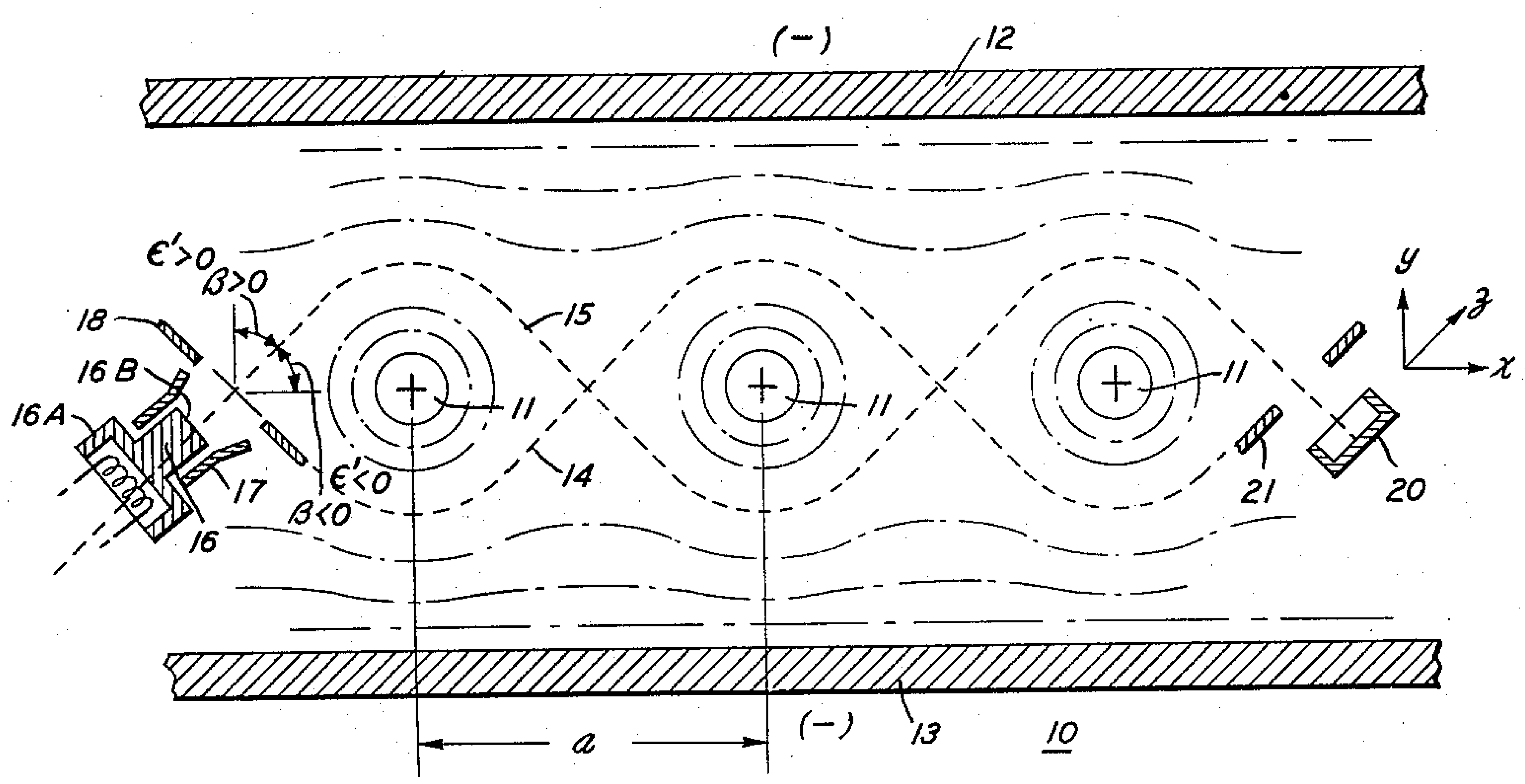

FIG. 3

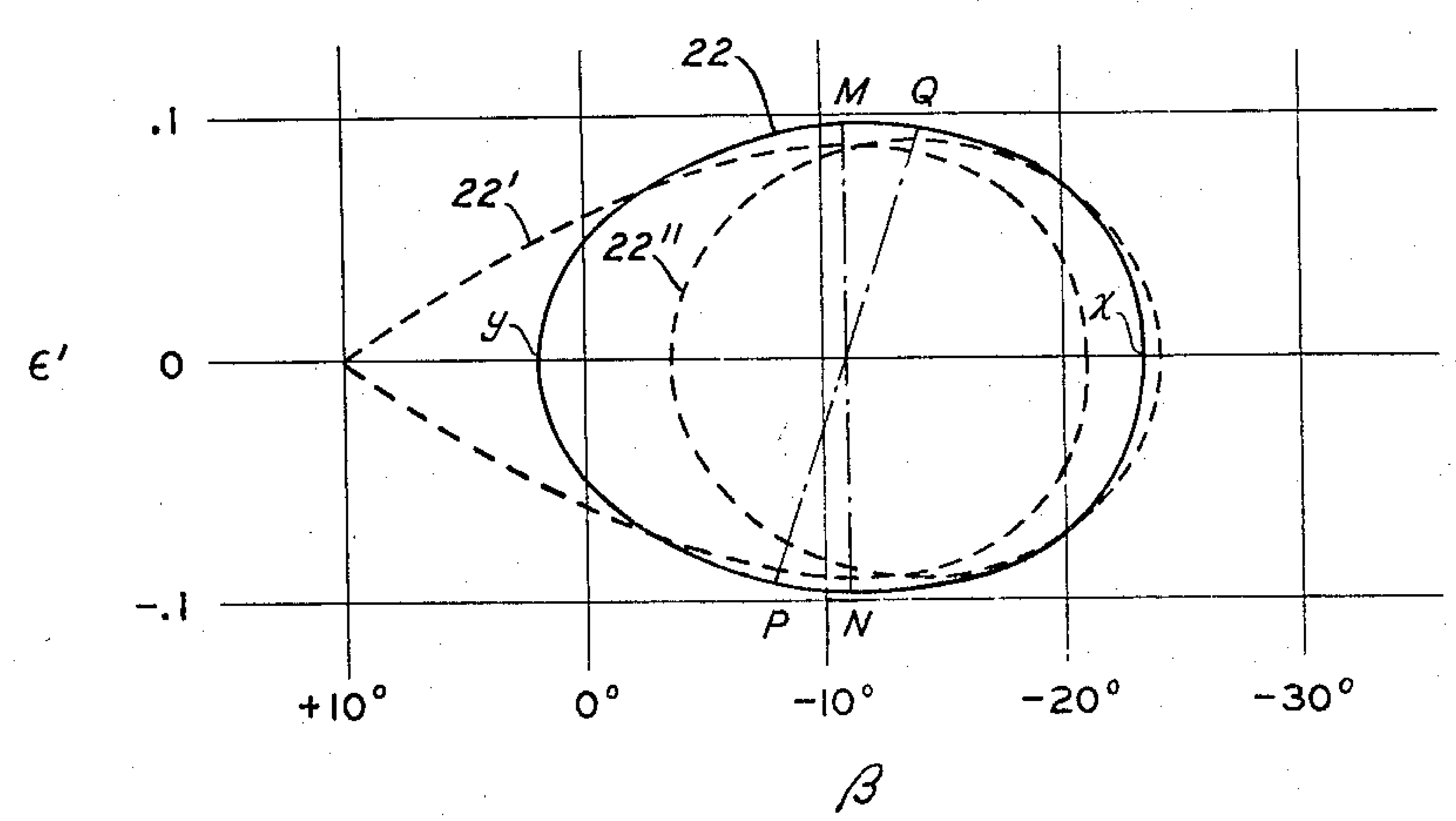

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FIG. 2A

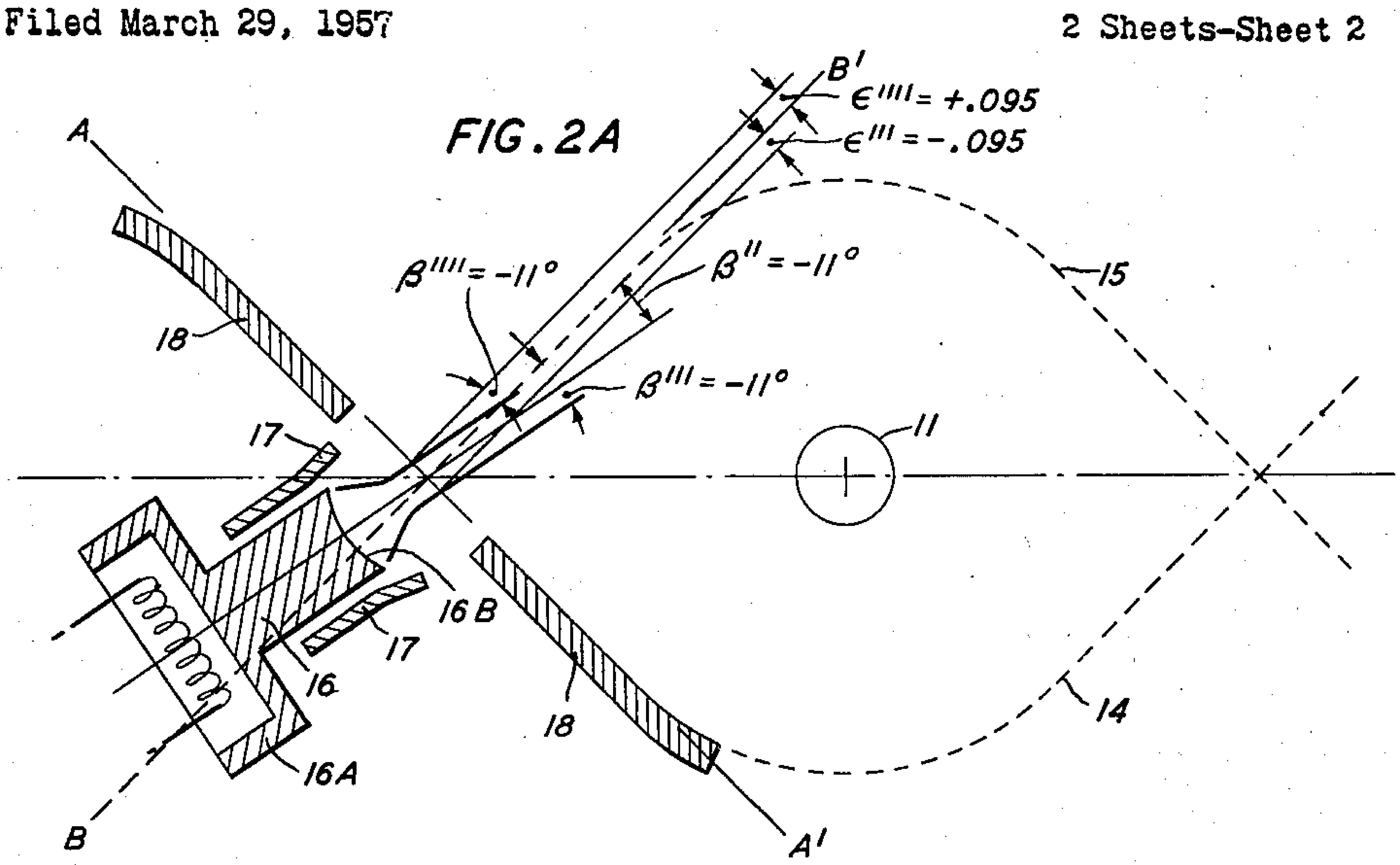


FIG. 2B

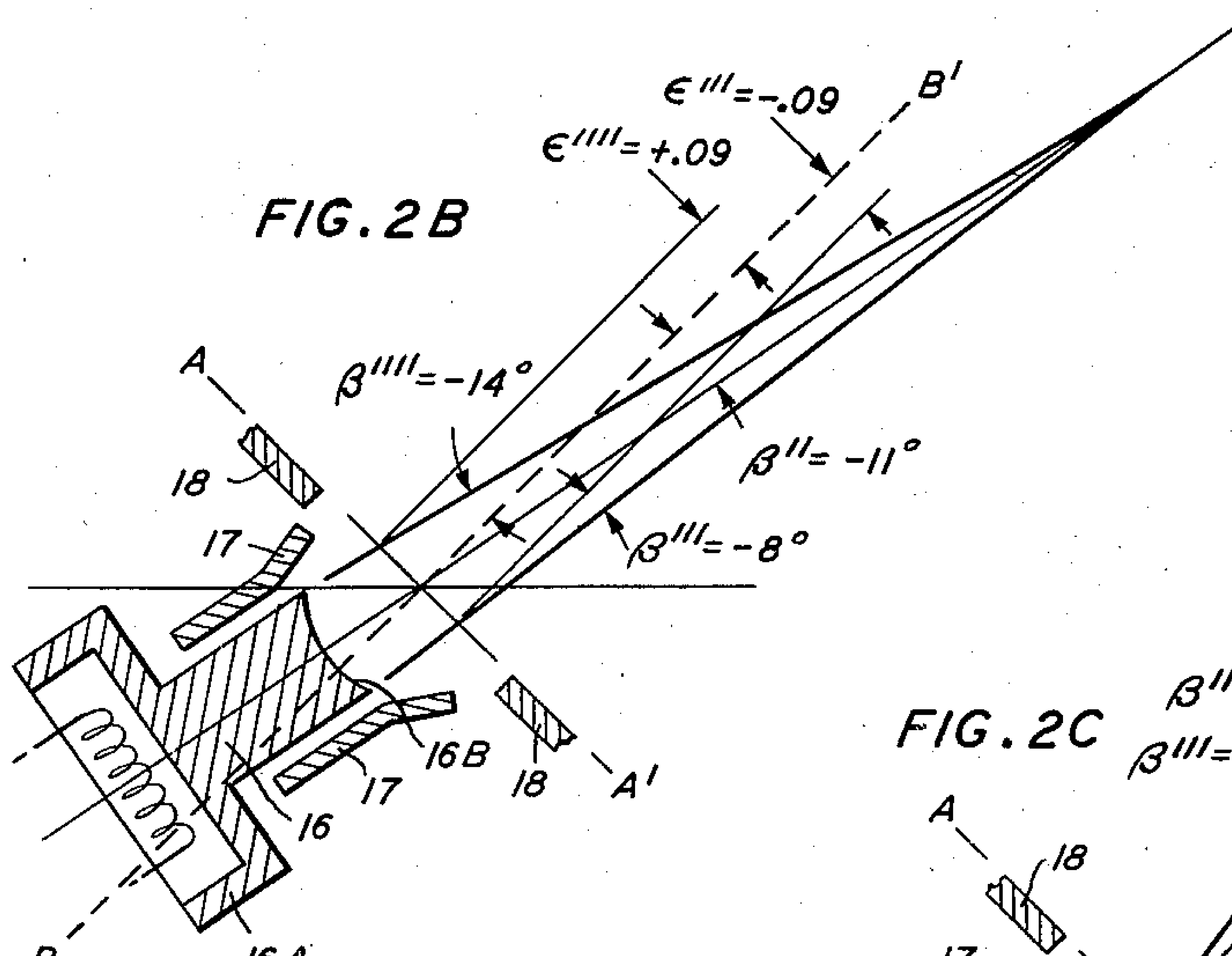
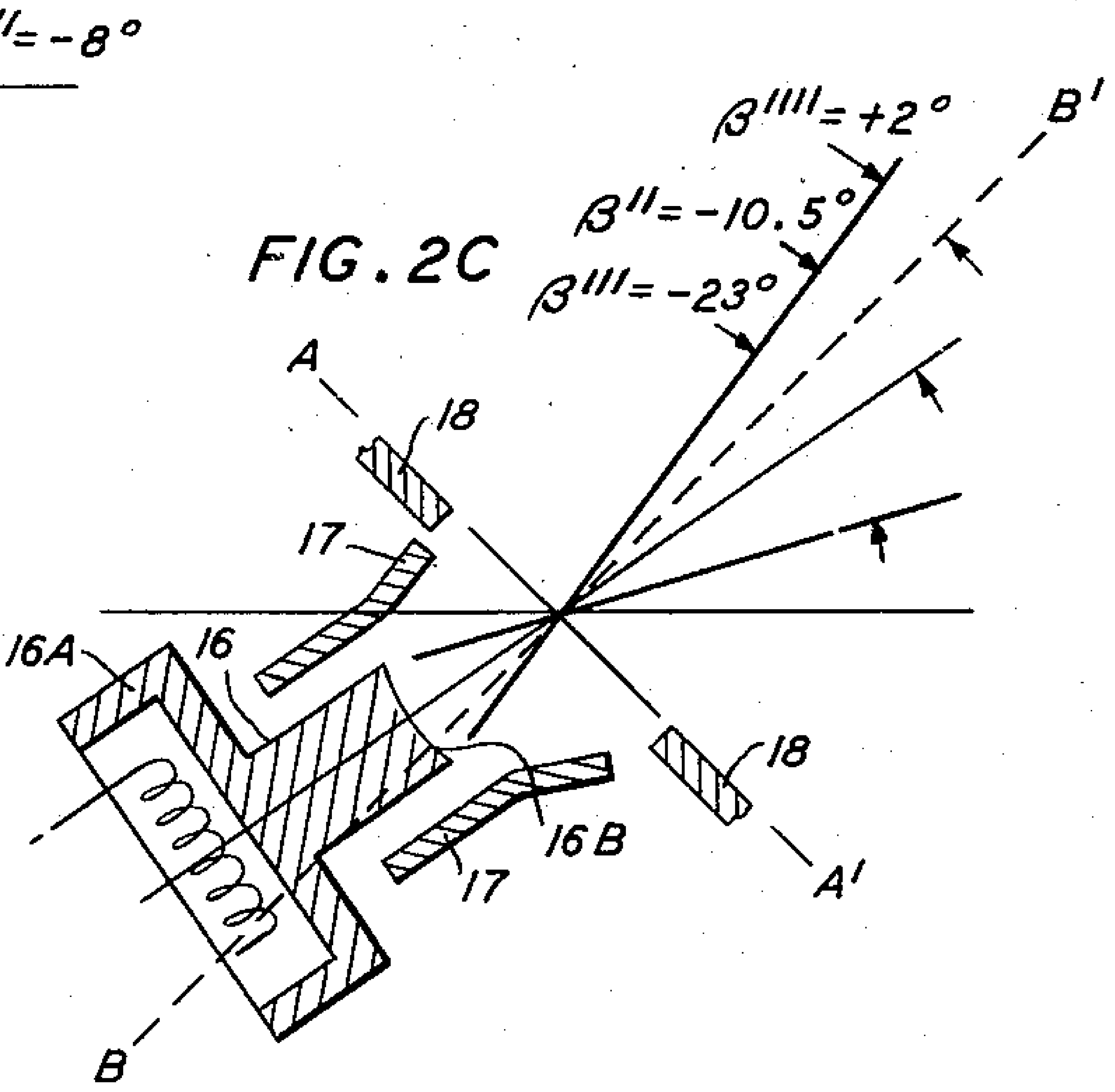


FIG. 2C



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United States Patent Office

2,953,707

Patented Sept. 20, 1960

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ELECTRON BEAM FOCUSING SYSTEM

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Filed Mar. 29, 1957, Ser. No. 649,559

10 Claims. (Cl. 315—3)

This invention relates to an electron beam system and, more particularly, to an electron gun structure for use in electron beam systems which employ electrostatic focusing fields of the kind described in copending application Serial No. 514,423, filed June 10, 1955, by R. Kompfner and W. H. Yocom, now United States Patent 2,857,548, issued October 21, 1958.

The present application is a continuation-in-part of United States application Serial No. 560,546, now abandoned, which was filed on January 23, 1956, by the present applicants.

In the aforementioned patent of R. Kompfner and W. H. Yocom, there is disclosed an electron beam system in which a focusing electrode system is used to establish an electrostatic field having a pair of single equipotential surfaces which are characterized by the fact that electrons injected on either of such surfaces with a correct velocity will flow along or in the vicinity of such surface. In an illustrative form of an electron beam system of this kind, a linear array of elements, each of which is maintained at a positive potential with respect to the electron source, comprises the focusing electrode system which sets up a pair of singular equipotential surfaces. Each of these surfaces winds sinuously between the successive elements of the array, the two surfaces being mirror images with the plane of the linear array as the reflection plane. In particular, it is set forth that a correct velocity which the electron beam should have when injected on one such surface for flow therealong may be achieved by associating with the electron source an accelerating anode which is maintained at the potential of the singular equipotential surfaces. In the use of an electron beam system of this kind, it is found relatively difficult to inject by usual expedients an electron beam of appreciable current onto one of the singular equipotential surfaces with the correct velocity. In particular, it is found that conventional beam injection arrangements result, at the region of injection of the electrostatic field, in a distortion of the field pattern set up by the focusing electrode system optimum for focusing of this kind. This, in turn, results in the loss of focusing efficiency. In a copending application of J. S. Cook, R. Kompfner and W. H. Yocom, Serial No. 514,421, filed June 10, 1955, now United States Patent 2,939,034, issued May 31, 1960, there is shown an improved electron beam system of the kind described in which the injection of an electron beam with a correct velocity is facilitated and field distortion is minimized by localizing the injection to a crossover region of the two singular equipotential surfaces. Such a system as therein disclosed provides, in general, improved performance as a result of the minimization of field distortion.

We have found that, in addition to smooth injection of the beam, there are certain optimum entrance conditions for providing a stable beam in such a focusing system, which hereinafter shall be idenitfied as a "slalom" focusing system. In particular, it has been found that for certain predetermined conditions of entrance velocity and field, there are certain maximum limits to the beam dimensions, especially the beam thickness, which, if exceeded, result in beam instability and a deterioration of the focusing effect. It has also been found that where the velocity distribution across the beam thickness is small, maximum beam perveance is given by the expression

$$p=\frac{I_0}{V_0^{3/2}}\simeq 25\times 10^{-6}\frac{TW}{a^2} \qquad (1)$$

where:

I_0 is the total current in amperes,
V_0 is the beam potential,
T is the beam thickness,
W is the beam width, and
a is the spacing of elements in the linear array.

From Equation 1 it can be seen that perveance is directly proportional to beam thickness, hence, in general, for a given system, it is desirable to operate at maximum beam thickness. Our analysis has further indicated that if the electron beam is injected into the focusing system at certain specified angles to the equipotential surface which defines the path of flow and with certain displacements from the equipotential surface crossover region of the upper and lower portions of the beam, maximum beam thickness for a stable beam can be achieved.

Accordingly, a specific object of the present invention is to improve an electron beam system of the kind described, by injecting the electron beam into the focusing system at the proper angle and position to give maximum beam dimensions which, in general, means maximum stable beam current, thereby greatly enhancing the efficiency of operation of the system.

The invention will be better understood from the following more detailed description taken in conjunction with the accompanying drawings, in which:

Fig. 1 is a schematic elevation view of a typical slalom focusing system;

Fig. 2A is a schematic view of an electron gun arrangement embodying the principles of the invention;

Fig. 2B is a schematic view of another gun arrangement embodying the principles of the invention;

Fig. 2C is a schematic view of still another gun arrangement embodying the principles of the invention; and

Fig. 3 is a graph showing the stability characteristics of an electron beam in the focusing system of Fig. 1.

Turning now to Fig. 1 in which an electron beam system **10** is schematically depicted, a plurality of conductive elements **11**, which typically are wires extending transversely normal to the plane of the drawing, are aligned to form a linear array which extends longitudinally in the direction of desired flow with successive wires spaced a distance a apart. On opposite sides, conductive members **12** and **13** serve as conductive boundaries. As pointed out in the aforementioned patent of R. Kompfner and W. H. Yocom, when the conductive elements **11** are maintained at a positive potential with respect to the conductive members **12**, **13**, as is shown schematically, this electrode system will establish in the interspace between conductive members an electrostatic field which is characterized by a pair of singular equipotential surfaces which intersect the plane of the drawing, as shown by the broken lines **14** and **15**. Each of such equipotential surfaces winds sinuously past successive elements, the two surfaces being mirror images of one another about the plane of the linear array and crossing over one another along a parallel succession of center lines. As pointed out in the aforementioned patents, it has been found that there will flow in proximity to such a surface an electron beam which is injected close to the surface with a correct velocity in the direction of the surface. A correct velocity may be, for example, one of a magnitude corresponding to the speed imparted to an electron in being accelerated from an electron source by an electric field of strength corresponding to the difference in potential of the singular equipotential surface and the electron source. The potential of the singular equipotential surface, and hence the velocity of the beam, can be adjusted to a desired value by a proper choice of the potentials at which the elements of the focusing electrode system are operated.

The electron beam is injected by an electron gun comprising a cathode **16**, a beam focusing electrode **17** and an accelerating anode **18**, as schematically shown in Fig. 1. Since the electron gun advantageously is to provide a strip beam which extends normal to the plane of the drawing, the various gun elements also extend normal to the plane of the drawing. It is to be understood, however, that the features of the present invention are not restricted to strip electron beams solely. The cathode **16** is of conventional design and includes a heater compartment **16A** in which extends a heating coil and has a portion **16B** of its surface which is electron emissive. The electrons emitted from the electron emissive portion are formed into an electron beam by the beam forming electrode **17**. As shown in Fig. 1 and as will be explained more fully hereinafter, the cathode **16** and beam forming electrode **17** are designed advantageusly to converge the electrons emitted from the cathode into a narrow well defined beam. Accelerating anode **18** cooperates with electrode **17** in forming the electrons into a beam and additionally serves to accelerate the electron in the beam to a desired velocity. In a typical example, the cathode is maintained at a potential slightly positive with respect to the beam forming electrode **17** but considerably negative with respect to accelerating anode **18**. As pointed out in the aforementioned patent of Cook, Kompfner and Yocom, the surface of the accelerating anode **18** which is more approximate to the focusing electrode system made up of elements **11**, **12** and **13**, is shaped to coincide substantially with one surface, in this example surface **14**, of the two singular equipotential surfaces associated with such focusing system, to insure smooth injection of the beam into the field.

At the downstream end of the array of elements the electron beam is collected by a target electrode **20** schematically depicted in Fig. 1, which is maintained at a suitably positive potential with respect to the electron source. For instance, the target electrode may be maintained at the potential of the elements **11** of the array. Target electrode **20** is preferably positioned behind an isolating electrode **21** to minimize the effect of the target electrode on the field pattern of the focusing system, as pointed out in the aforementioned patent of Cook, Kompfner and Yocom.

Recent investigation and mathematical analysis of the behavior of an electron beam in a slalom focusing system has revealed that there are certain optimum conditions of entrance of the beam into the focusing region which should be observed if maximum stability of the beam is to be realized. In Fig. 3 there is shown a graph which depicts the stability characteristics of the beam in a slalom focusing system of the type shown in Fig. 1. The ordinate of the graph represents displacement from the crossover of the two equipotential surfaces of the point where an electron in the beam crosses one of the equipotential surfaces as it is introduced into the focusing field. The ordinate is graduated in dimensionless units ϵ', where ϵ' is equal to

$$\frac{\epsilon_0}{a}$$

ϵ_0 being the displacement from the equipotential surface in the vicinity of which the beam travels, measured at right angles to that surface at the crossover point, and a is the wire spacing. In Fig. 2A, which is an enlarged view of the gun arrangement of Fig. 1, it can be seen that the displacement from the intersection of the equipotential surfaces **14** and **15** of the point where the center line of the electron beam emitted from cathode **16** crosses the equipotential line **14** is given by $\epsilon'=0$. The abscissa of the graph of Fig. 3 is calibrated in terms of the angle β. The angle β is defined as the angle formed between the direction of one of the equipotential surfaces at the point of intersection and the line along which an electron in the beam crosses the other of said equipotential surfaces. Thus, in Fig. 2A, the angle β'' is the angle between the line BB′ and the center line of the beam emitted from cathode **16** at the point where the center line crosses equipotential line **14**. Line BB′ in turn is tangent to equipotential surface **15** and passes through the point of intersection of surfaces **14** and **15**.

It is to be understood that because of the experimental difficulties in measuring the various quantities involved accurately and the complexity of the analytical computations, the specific limits disclosed are merely illustrative of the order of the magnitudes involved. Moreover it is believed that from the discussion included herein the general principles involved will become obvious to one skilled in the art who will be able therefrom to construct arrangements in accordance with such general principles without departing from the spirit and scope of the invention. For example, a change in electron velocity will result in a slight change in the limits of the stable region. In Fig. 3 there is shown a first stable region defined by the line **22** which represents a system where the diameter of a wire in the array is approximately one-fifth the spacing between wires in the array and where there is a particular value of the parameter δ where

$$\delta=\frac{v-v_0}{v_0} \qquad (2)$$

where v is the velocity at the crossover region and v_0 is the velocity an electron must have in order to follow exactly along the equipotential path. The stable regions defined by the lines **22′** and **22″** in Fig. 3 are the regions for, respectively, a slightly smaller and a slightly larger value of δ than that for line **22**. It can be seen that changing parameters results in a slight change in the position and shape of the curve defining the stable region, which changes are matters of degree only. Changing the wire diameter will likewise cause a change in the position and shape of the curves. For example, decreasing the wire diameter increases somewhat the maximum possible stable beam thickness and also increases the absolute value of the optimum δ. Such changes in wire diameter are confined to somewhat narrow limits because of practical considerations such as excessive heating of wires that are too small, and interception of electrons by wires that are too large.

From an examination of the graph of Fig. 3 it can be seen that maximum beam current for a converging type beam as shown in Fig. 2A can be achieved by a proper positioning of the gun structure so that electrons in the beam will enter the focusing region at the optimum angles and displacement from the point of crossover of the equipotential surfaces. Inasmuch as the closed area within the line **22** of Fig. 3 represents the region of approximately 100 percent beam stability, that is, the region wherein substantially all of the electrons in the beam reach the collector, maximum beam thickness will be represented by the straight line in the graph of Fig. 3 which is totally enclosed by the curved line **22** and which subtends the greatest range of ϵ'. Such a line for a parallel beam is represented in Fig. 3 by the line MN, which has an angle of $\beta\cong-11°$ and which intersects line **22** at two points, where $\epsilon'\cong+.095$ and $\epsilon'\cong-.095$. The center of line MN is at $\epsilon'=0$. The information thus derived from line MN of Fig. 3 is utilized in the gun structure of Fig. 2A, as follows. All of the electrons in the beam emitted by cathode **16** cross the equipotential surface **14** at an angle of $\beta=-11°$.

The uppermost electrons in the beam as viewed in Fig. 2A cross the equipotential 14 at a displacement of $\epsilon''''=+.095$ and the lowermost electrons in the beam as viewed in Fig. 2A cross equipotential surface 14 at a displacement of $\epsilon'''=-.095$. The centerline of the beam crosses surface 14 at $\epsilon''=0$. If the conditions indicated by line MN are met, maximum stable beam thickness in a parallel flow type beam is realized.

The analysis of Fig. 3 has thus far dealt with maximum stable beam thickness in a beam which was made to enter the focusing region as a parallel flow beam. Under certain conditions it may be desirable to introduce the beam into the focusing field when it is converging or even diverging so long as the stability conditions are met. In Fig. 2B there is shown schematically the gun portion of a focusing system such as is depicted in Fig. 1 which is properly positioned relative to the crossover of equipotential surfaces 14 and 15 so as to produce maximum stable beam current for a converging type beam. For the sake of simplicity only the gun portion of the focusing system has been shown as in Fig. 2A. In addition the various angles and displacements bear the same designations in order to avoid confusion.

It can be seen from Fig. 3 that when the convergence angle, that is, the total included angle of the converging beam, is known, the curve 22 defines the maximum beam thickness, as given by ϵ, at the place where the beam crosses the equipotential line. For a total included convergence angle of 6°, maximum beam thickness is represented by the line PQ. It can be seen that line PQ intersects the line 22 at two points which are defined on the graph as $\beta\cong-14°$, $\epsilon'\cong+.09$ and $\beta\cong-8°$, $\epsilon'\cong-.09$. In addition the midpoint of line PQ which corresponds to the centerline of the beam is located at $\beta\cong-11°$ and $\epsilon'=0$. Referring now to Fig. 2B, the beam as defined by line PQ in Fig. 3 will be formed if the electrons on the upper outermost edge of the beam as viewed in Fig. 2B cross the equipotential surface 14 at an angle $\beta''''=-14°$ and at a displacement $\epsilon''''=+.09$. Electrons in the lower outermost edge of the beam as viewed in Fig. 2B cross equipotential 14 at an angle $\beta'''=-8°$ and $\epsilon'''=-.09$. In addition, the centerline of the beam crosses equipotential 14 at an angle $\beta''=-11°$ and $\epsilon''=0$. All of the electrons which are introduced into the focusing region in accordance with the conditions indicated by the line PQ of Fig. 3 should arrive at collecting electrode 20, thereby achieving maximum stable beam thickness at the point of injection for a beam of this given convergence.

In the case where a diverging beam is desired, the curve 22 gives an indication of the maximum permissible beam thickness at the point of injection for a given total included angle of divergence in the same manner as for a converging beam. It can be seen in Fig. 3 that the maximum divergence or convergence angle permissible with the curve 22 is approximately 25° as represented by the line XY. In such a case, the beam thickness, as given by ϵ, is zero. The line XY intersects the line 22 at $\beta\cong-23°$ and $\beta\cong+2°$. The center of the line XY occurs at $\beta\cong-10.5°$. The information thus obtained is utilized in the gun arrangement of Fig. 2C as follows: In order to achieve a diverging beam at the point of intersection of the beam with the equipotential surface 14, various types of electron guns may be utilized. The gun arrangement of Fig. 2C is a schematic representation of one such arrangement wherein a sharply converging beam having a focus at approximately the point of intersection with surface 14 is used. It is to be understood that the gun arrangement so shown in Fig. 2C is for purposes of illustration only and various other suitable arrangements well known to those skilled in the art can be utilized. The beam emitted by the cathode 16 in Fig. 2C is made to converge and to cross the equipotential surface 14 at a displacement $\epsilon'=0$. The angle at which the uppermost electrons in the beam as viewed in Fig. 2C leave the equipotential surface after crossing it is $\beta''''=+2°$, and the angle at which the lowermost electrons in the beam as viewed in Fig. 2C leave the equipotential surface after crossing it is $\beta'''\cong-23°$. The centerline of the beam crosses surface 14 at an angle $\beta=-10.5°$. In practice, of course, the beam will have a finite thickness at the point of introduction into the focusing system, which will cause the line XY to acquire a finite thickness corresponding to the beam thickness, thereby lessening slightly the maximum permissible beam convergence.

The foregoing examples were taken for a given set of velocity conditions, that is, for a given value of δ. As was pointed out in the foregoing, changes in the value of the parameter δ will result in slight changes in position and shape of the area defining the stable region, as shown by the lines 22' and 22''. In addition, changes in various others of the operating parameters may cause similar changes in the area defining the stable region. Such changes, however, are changes in degree only and the principles underlying the invention as discussed for achieving maximum stable beam dimensions remain applicable.

It is to be understood that the specific arrangements herein described are merely illustrative of the principles of the invention, and various other embodiments may be devised without departing from the spirit and scope of the invention. In particular, various other types of electron gun structures may be used to produce a beam of the desired type. Such other gun structures must, however, in order to achieve maximum stable beam dimensions, be positioned in accordance with the teachings of the present invention. Additionally, the principles of the invention are applicable to other types of electrostatic focusing, such as, for example, a focusing arrangement of the type shown and described in the copending United States application Serial No. 534,090, filed September 13, 1955, by C. F. Quate.

What is claimed is:

1. In an electron beam system, a focusing electrode system comprising a plurality of spaced conductive elements forming a longitudinally extending array and a pair of members on opposite sides of the array for establishing a pair of periodically crossing singular equipotential surfaces in the region between said members, and means comprising a source of electrons for introducing an electron beam into the region between said members across one of said equipotential surfaces at an angle to the direction of the other of said equipotential surfaces at the crossover point, the axis of said beam being directed into the region between one of said conductive elements and one of said singular equipotential surfaces, said beam having a correct velocity for flow along said array in the vicinity of said one equipotential surface.

2. In an electron beam system, the combination as claimed in claim 1 wherein at least one of said pair of members is of electrically conducting material.

3. In an electron beam system, a focusing electrode system comprising a plurality of spaced conductive elements forming a longitudinally extending array and a pair of members on opposite sides of the array for establishing a pair of periodically crossing singular equipotential surfaces in the region between said members, and means comprising a source of electrons for introducing an electron beam into the region between said members, the axis of said beam directed into the region between one of said equipotential surfaces and one of said conductive elements in a direction at an acute angle to one of said surfaces and at an angle to the other of said surfaces, said beam having a correct velocity for flow along said array in the vicinity of said one equipotential surface.

4. In an electron beam system, a focusing electrode system comprising a plurality of spaced conductive elements forming a longitudinally extending array and a pair of conductive plates on opposite sides of the array for establishing a pair of periodically crossing singular

equipotential surfaces in the region between said plates, and means comprising a source of electrons for introducing an electron beam into the region between said equipotential surfaces and one of said conductive elements across one of said equipotential surfaces at a correct velocity for flow along said array in the vicinity of one of said equipotential surfaces, the direction of the electrons in the beam as they cross said equipotential surface being substantially the same for all the electrons and forming an acute angle with the other of said equipotential surfaces, the axis of said beam being directed into the region between said one equipotential surface and one of said conductive elements.

5. In an electron beam system the combination of claim 4 characterized in that the upper and lower surfaces of said beam are displaced equal distances from the crossover point of said equipotential surfaces, and the acute angle is less than twenty-three degrees.

6. In an electron beam system, a focusing electrode system comprising a plurality of spaced conductive elements forming a longitudinally extending array and a pair of conductive plates on opposite sides of the array for establishing a pair of periodically crossing singular equipotential surfaces in the region between said plates and means comprising a source of electrons for introducing an electron beam into the region between said equipotential surfaces and one of said conductive elements across one of said equipotential surfaces at a correct velocity for flow along said array in the vicinity of one of said equipotential surfaces, the direction of the electrons in the uppermost portion of the beam as they cross said equipotential surface being at a first acute angle to the other of said surfaces, the direction of the electrons in the lowermost portion of the beam as they cross said equipotential surface being at a second acute angle to the other of said surfaces, and the centerline of the beam crossing said equipotential surface at a third acute angle to the other of said surfaces, said centerline being directed into the region between said one equipotential surface and one of said conductive elements.

7. In an electron beam system, a focusing electrode system comprising a plurality of spaced conductive elements forming a longitudinally extending array and a pair of conductive plates on opposite sides of the array for establishing a pair of periodically crossing singular equipotential surfaces in the region between said plates and means comprising a source of electrons for introducing an electron beam into the region between said equipotential surfaces and one of said conductive elements across one of said equipotential surfaces at a correct velocity for flow along said array in the vicinity of one of said equipotential surfaces, the direction of the electrons in the uppermost portion of the beam as they cross said equipotential surface being at a first acute angle to the other of said surfaces, the direction of the electrons in the lowermost portion of the beam as they cross said equipotential surface being at a second acute angle to the other of said surfaces, and the centerline of the beam crossing said equipotential surface at a third acute angle to the other of said surfaces, said first acute angle being of lesser magnitude than the second acute angle, and the third acute angle being of greater magnitude than said first acute angle and of lesser magnitude than the second acute angle.

8. In an electron beam system, a focusing electrode system comprising a plurality of spaced conductive elements forming a longitudinally extending array and a pair of conductive plates on opposite sides of the array for establishing a pair of periodically crossing singular equipotential surfaces in the region between said plates and means comprising a source of electrons for introducing an electron beam into the region between said equipotential surfaces and one of said conductive elements across one of said equipotential surfaces at a correct velocity for flow along said array in the vicinity of one of said equipotential surfaces, the direction of the electrons in the uppermost portion of the beam as they cross said equipotential surface being at a first acute angle to the other of said surfaces, the direction of the electrons in the lowermost portion of the beam as they cross said equipotential surface being at a second acute angle to the other of said surfaces, and the centerline of the beam crossing said equipotential surface at a third acute angle to the other of said surfaces, said first acute angle being less than twenty-one degrees less than said second angle in magnitude.

9. In an electron beam system, a focusing electrode system comprising a plurality of spaced conductive elements forming a longitudinally extending array and a pair of conductive plates on opposite sides of the array for establishing a pair of periodically crossing singular equipotential surfaces in the region between said plates and means comprising a source of electrons for introducing an electron beam into the region between said equipotential surfaces and one of said conductive elements across one of said equipotential surfaces at a correct velocity for flow along said array in the vicinity of one of said equipotential surfaces, the direction of the electrons in the uppermost portion of the beam as they cross said equipotential surface being at a first acute angle to the other of said surfaces, the direction of the electrons in the lowermost portion of the beam as they cross said equipotential surface being at a second acute angle to the other of said surfaces, and the centerline of the beam crossing said equipotential surface at a third acute angle to the other of said surfaces, said first acute angle being of greater magnitude than said second acute angle and said third acute angle being of lesser magnitude than said first acute angle and of greater magnitude than said second acute angle.

10. In an electron beam system, a focusing electrode system comprising a plurality of spaced conductive elements forming a longitudinally extending array and a pair of conductive plates on opposite sides of the array for establishing a pair of periodically crossing singular equipotential surfaces in the region between said plates and means comprising a source of electrons for introducing an electron beam into the region between said equipotential surfaces and one of said conductive elements across one of said equipotential surfaces at a correct velocity for flow along said array in the vicinity of one of said equipotential surfaces, the direction of the electrons in the uppermost portion of the beam as they cross said equipotential surface being at a first acute angle to the other of said surfaces, the direction of the electrons in the lowermost portion of the beam as they cross said equipotential surface being at a second acute angle to the other of said surfaces, and the centerline of the beam crossing said equipotential surface at a third acute angle to the other of said surfaces, said first acute angle being approximately six degrees greater than said second acute angle in magnitude.

References Cited in the file of this patent

UNITED STATES PATENTS

2,059,863	Hansell	Nov. 3, 1936
2,153,190	Hollmann	Apr. 4, 1939
2,296,355	Levin	Sept. 22, 1942
2,638,561	Sziklai	May 12, 1953
2,680,823	Dohler et al.	June 8, 1954
2,687,491	Lee	Aug. 24, 1954
2,790,106	Labin	Apr. 23, 1957
2,807,739	Berterottiere et al.	Sept. 24, 1957
2,849,650	Quate et al.	Aug. 26, 1958
2,857,548	Kompfner et al.	Oct. 21, 1958

FOREIGN PATENTS

853,009	Germany	Oct. 20, 1952