# United States Patent [19]

**Seliger et al.**

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## [54] STIGMATIC, CROSSED-FIELD VELOCITY FILTER


[75] Inventors: **Robert L. Seliger**, Agoura; **Robert G. Wilson**, Canoga Park, both of Calif.

[73] Assignee: **Hughes Aircraft Company**, Culver City, Calif.



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[52] **U.S. Cl.** .....**250/49.5 T**, 250/41.9 ME, 313/79, 328/230

[51] **Int. Cl.**.....**H01j 37/26**, H01j 29/76

[58] **Field of Search** ...148/1.5; 250/41.9 ME, 49.5 T; 313/79; 328/230



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*Primary Examiner*—Leland A. Sebastian

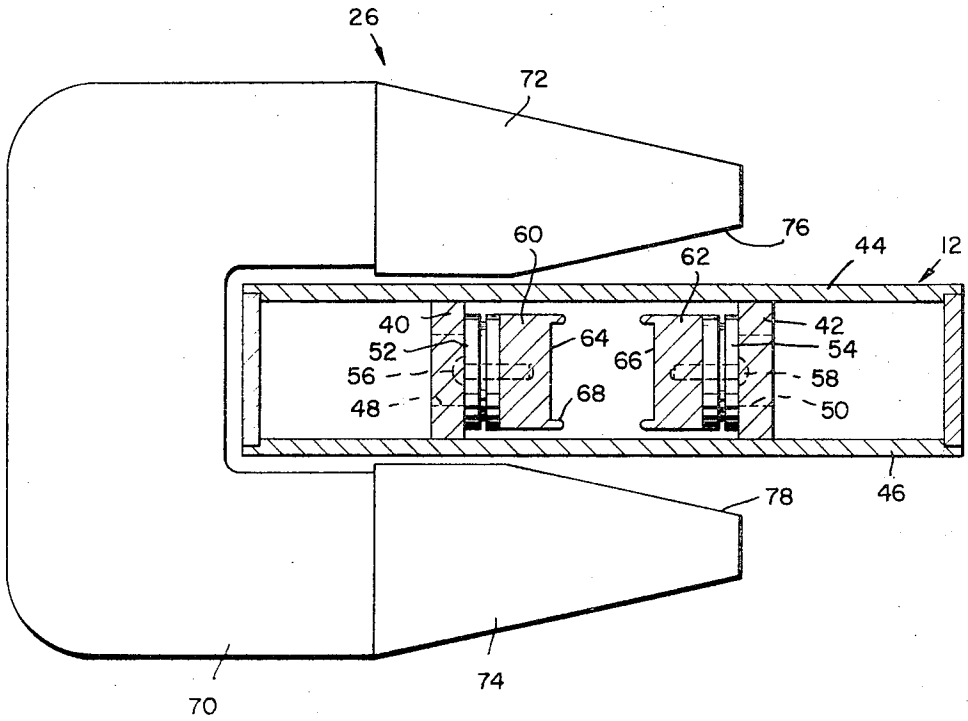
*Attorney*—W. H. MacAllister, Jr. and Allen A. Dicke, Jr.



[57] **ABSTRACT**

A stigmatic, crossed-field velocity filter for nondeflection purification of an ion beam employs shaped electrodes to increase the uniformity of the electric field and employs shaped magnetic pole pieces to produce a nonuniform magnetic field for stigmatic passage of the selected ion species through the filter.


**13 Claims, 3 Drawing Figures**



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3,723,733



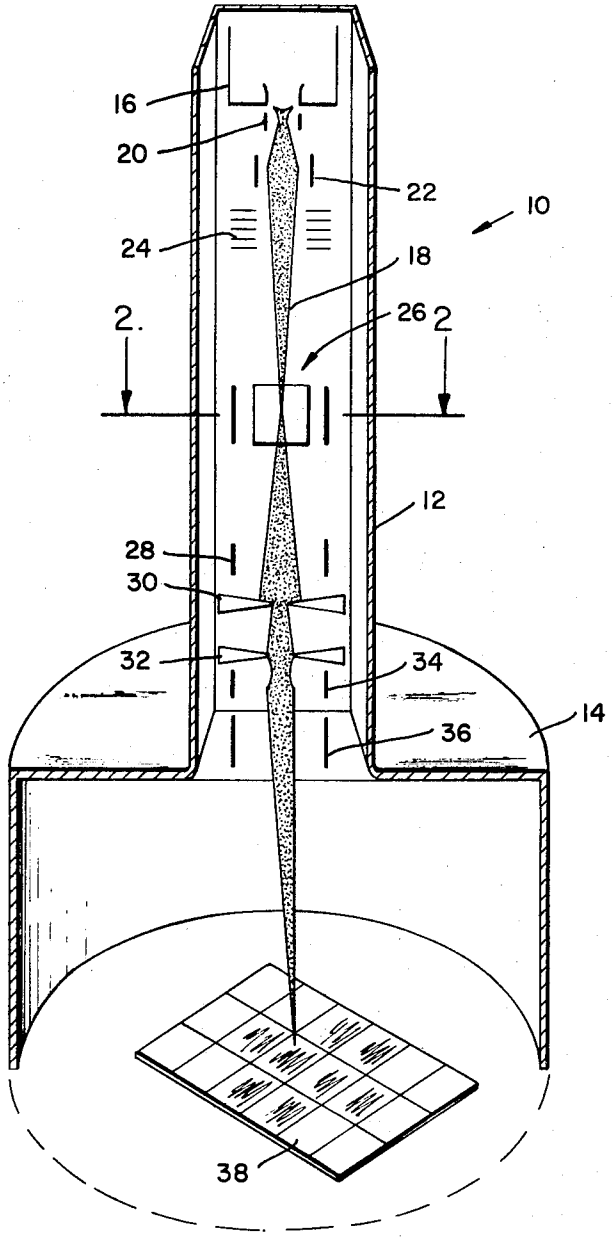
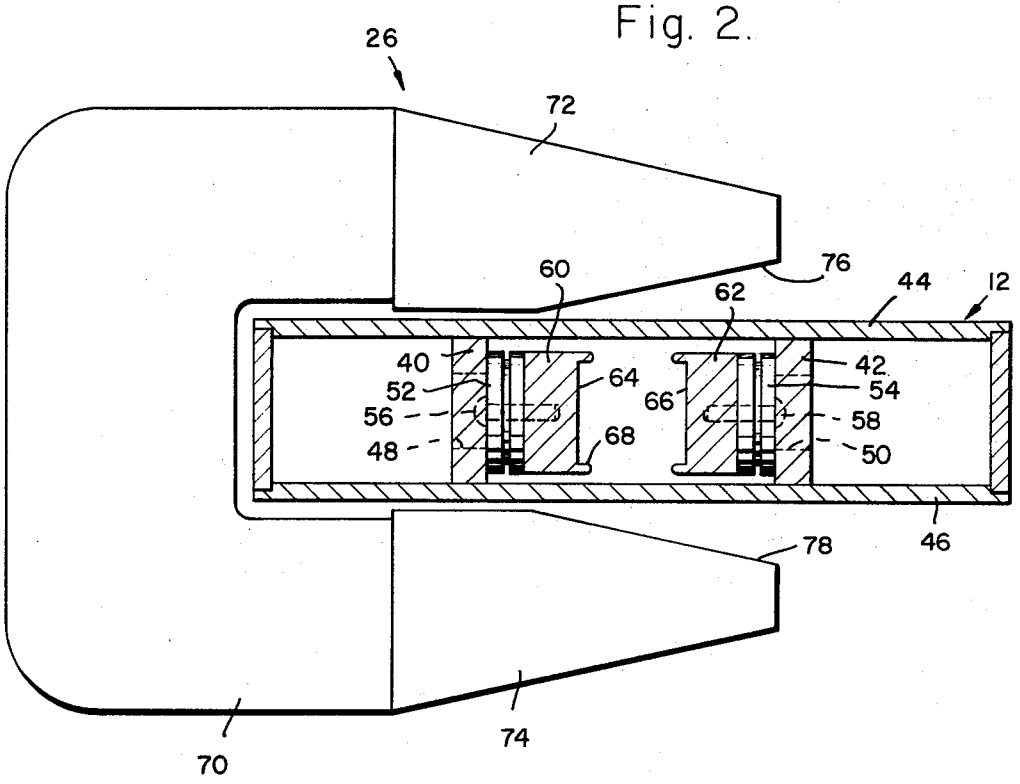



Fig. 1.

Robert L. Seliger,
Robert G. Wilson,
INVENTORS,
BY.

ALLEN A. DICKE, Jr.,
AGENT.

Fig. 2.



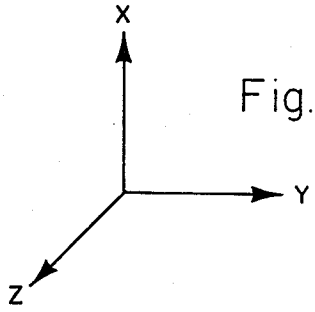




Fig. 3.

# STIGMATIC, CROSSED-FIELD VELOCITY FILTER

## BACKGROUND

This invention is directed to a stigmatic, crossed-field velocity filter for purifying ion beams by the removal of undesired ion species.

The purpose of the ExB velocity filter is to provide separation of one species of particle out of a beam consisting of a mixture of charged particles (ions) with different axial velocities, $v$. Since the velocity $v$ for a particle is related to its charge $e$, mass $m$, and potential V by $v=(2e/m)\,V$, the velocity differences between particles to be separated may be caused by differences in charge to mass ratio $e/m$, potential V, or both. By suitable adjustment of the separator's electric and magnetic field strengths E and B, deflection forces which cancel are set up inside the device for the particles with axial velocity equal to E/B. These values are selected to pass the desired particles. Such particles emerge undeflected from the separator, whereas the undesired particles with velocities other than E/B are deflected from their initial direction of travel and thus become dispersed in space. Along with the spatial dispersion, the forces inside ExB separators also have a focusing effect on the beam of desired particles. In past separator designs, this focusing is not axisymmetric and astigmatism is introduced into the undeflected beam. Typically, an entering beam with circular cross section gives rise to an emerging undeflected beam with an alliptical shape. In one prior art separator, stigmatic operation is supposedly achieved by shaping the electric field by suitably adjusting the potentials on a number of guard rings or electrostatic shims, but in practice, these adjustments are only for adjusting the grading of the electric field, so cannot result in stigmatic results. Further, such adjustments become very tedious empirical exercises which must be performed for every new beam potential V and particle mass.

Some of the prior art is described in a paper entitled "The Colutron, A Zero Deflection Isotope Separator," L. Wohlin, Nuc. Instr. and Methods 27, 55 (1964). The advantages of an ExB type separator over a sector magnet separator and astigmatic operation are described in this paper. A more recent paper, "Mass-Separated Ion Source," R. G. Wilson and D. M. Jamba, Nucl. Instr. and Methods 85, 1 (1970), discusses the advantages of the ExB velocity filters. The standard and Colutron ExB velocity filters are improved upon by the stigmatic separator of this invention.

Ion beam purification or separation has also been accomplished in the prior art by means of a sector magnet which serves as a momentum analyzer. The incoming ion beam is acted upon by a magnetic field from the sector magnet, with the resultant beam curvature. Particles having different momentum curve on different paths, so that the selected species issues from a particular path. However, the focal properties of the ion source and lens system combined with the magnet lead to an astigmatic image.

## SUMMARY

In order to aid in the understanding of this invention, it can be stated in essentially summary form that it is directed to a stigmatic, crossed-field velocity filter. The electric field in the filter is made uniform in the proximity of the beam by shaping of the electrostatic electrodes. The magnetic field is made nonuniform so that ions of the selected species which are in different potentials of the electric field are permitted to pass stigmatically through the filter.



Accordingly, it is an object of this invention to provide a stigmatic, crossed-field velocity filter. It is a further object to provide such a filter which has proper control of its field so that ions of the selected species stigmatically pass through the filter. It is a further object to provide a crossed-field velocity filter wherein the electrodes are shaped to provide a substantially uniform electric field through the beam space, even in the presence of the walls of the vacuum enclosure provided for beam passage and the proximity of the magnet poles.

It is another object to provide magnetic field grading means for providing a shaped and graded magnetic field of such nature to provide for stigmatic passage of selected ions through the filter. It is yet another object to provide a stigmatic crossed-field velocity filter which does not require adjustments beyond the general electric field adjustments to permit stigmatic passage of a beam of selected ions. It is a further object to provide a stigmatic crossed-field velocity filter which is of economic construction, easy to use, and of low maintenance. It is still another object to provide a stigmatic, crossed-field velocity filter which is effected in a minimum way by sputtering, and which does not decrease the reliability of the vacuum system.

Other objects and advantages of this invention will become apparent from a study of the following portion of the specification, the claims, and the attached drawings.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a vertical section through an ion implantation system which employs the stigmatic, crossed-field velocity filter of this invention.

FIG. 2 is an enlarged section taken generally along the line 2—2 of FIG. 1.

FIG. 3 shows the coordinates of the structure of FIG. 2.

## DESCRIPTION

An ion implantation system is generally indicated at **10** in FIG. 1. The system **10** is housed in tube **12** and target chamber **14**, which are secured together and are vacuum-tight. They are suitably pumped to provide a proper low pressure for ion beam technology. The upper end of tube **12** contains ion source **16**. Any ion source can be used. An electron bombardment ion source is illustrated, and such may receive its electrons from a spark gap or hot wire, depending upon the implanted species and other considerations.

Alternatively, ion source **16** can be of any other convenient type, such as a contact ionization source, radio frequency ionization source, plasmatron, etc. Ion beam **18** is emitted from the source. It is comprised of ions of a selected species, but may also contain energetic neutrals and ions of other species, which result from components of a compound fuel, impurities in the fuel or impurities resulting from the ionization process. Beam **18** is extracted from ion source **16** by extractor electrode **20**. Focusing of the beam is by first lens **22** which, acting with adjacent components, provides ini-

tial focusing. Acceleration of the beam is accomplished by acceleration column **24**. This is conveniently a constant gradient column of conventional design.

Next along the beam path is positioned crossed-field velocity filter **26**, which is shown in more detail in the enlarged section of FIG. **2**. After leaving the crossed-field velocity filter **26**, the beam **18** now has only the selected ion species therein. As a particular example of use of a purified beam, it passes successively through lens **28** and limiting aperture **30**. For finer definition, a second limiting aperture **32** can be positioned after aperture **30**. Next along the beam path is positioned final focusing lens **34**, and then electrostatic deflection system **36**. Target **38**, to be treated with the electron beam **18**, is positioned in target chamber **14**. The filter of this invention is also useful for beams treated and employed in other ways.

All of the electrically-activated and controlled devices along the column **12** and the target are connected to suitable source of voltage so that they are regulated to be at the desired potential.

Referring to FIG. **2**, a section through the ion implantation system at the crossed-field velocity filter is shown therein. Tube **12** can be formed in any convenient way, providing it serves as a beam passage. Holding a vacuum is required, and thus the tube must be closed. It may be extruded, or may be formed of welded flatstock, as shown. In FIG. **2**, the tube **12** is made of **4** pieces of stainless steel flatstock welded at the corners to provide vacuum integrity.

Crosspieces **40** and **42** are secured inside the tube and extend laterally thereacross between the tube sidewalls **44** and **46**, and are secured, as by welding. Crosspieces **40** and **42** preferably have a length along the tube at least equal to the length of the electrodes in the velocity filter.

Crosspieces **40** and **42**, respectively, have holes **48** and **50** therein. Ceramic insulators **52** and **54** are respectively secured over the holes, for example by being brazed to the metal crosspieces. Screws **56** and **58** pass through ceramic insulators **52** and **54** and have their heads spaced away from the crosspieces by virtue of the holes in the crosspieces. Screws **56** and **58** are respectively threadedly engaged in electrodes **60** and **62**. Conventional vacuum leadthroughs are provided in tube **12** to electrically connect to electrodes **60** and **62** so that they can have a potential difference applied to cause an electric field between the electrodes. The faces of the electrodes are shaped to provide a uniform electric field in the presence of the tube sidewalls **44** and **46** and in the presence of a magnetic field. With different dimensions and criteria of these parameters, and with different electrode spacings, the particular electrode faces will be different.

The particular dimensions given below were determined in an analog, electrolytic tank. They are valid for scaling in both the increasing and decreasing size, as long as everything related is scaled in the same manner. For the particular example for an interelectrode voltage of 5.6 kilovolts and a magnetic field strength of 1,500 Gauss, the spacing between tube sidewalls **44** and **46** would be about 1.700 inches. Spacing between the electrode faces **64** and **66** would be 1.100 inches. The noses **68** which extend toward the opposite electrodes from the edge of the faces would extend upward about 0.100 inch and be 0.0625 inch thick. Each nose has a circular section. The overall electrode width in the direction between tube sidewalls is about 0.800 inch. The distance between the noses results in a flat front of the electrode face between noses of about 0.675 inch. This electrode face configuration is of uniform cross section along the beam axis and provides a substantially uniform electric field in the area between the noses. These dimensions can be scaled up or down with the system to provide the uniform electric field.

Magnet **70** has pole pieces **72** and **74** which embrace the tube **12** to direct the magnetic flux into the interelectrode zone to provide magnetic flux therein. Pole pieces **72** and **74**, respectively, have faces **76** and **78** which are shaped to provide an appropriate magnetic field in the interelectrode space. In the present case, the shaping comprises providing planar faces which diverge from each other at a total included angle of 0.9°, for the particular embodiment described. This angle is determined in accordance with the concept described below and is a function of the particular dimensions of a particular system. Thus, the angle may be different under other circumstances. The functional requirement of this angle is defined below.

Under perfect focusing conditions for an ideal lens, an entering ray is bent in proportion to its distance from the lens axis. In terms of the equations of motion for ions, this means that the electric and magnetic fields must provide a transverse restoring force which is linear in the off-axis directions. Astigmatism occurs, when the restoring force is not axisymmetric. FIG. **3** illustrates the axes of the structure of FIG. **2**, with Z-axis perpendicular to the paper. These notations are used for discussion of the various directions.

A uniform magnetic field can be achieved in practice by having the pole pieces wider than the channel. A uniform electric field is more difficult to achieve, however, because of the proximity of the zero potential magnetic pole pieces and the vacuum channel walls to the electrodes, as described above. However, the uniform electric field can be accomplished by shaping the electrodes, as described, or by having the channel diameter large, compared to the beam diameter. Presuming there are uniform fields in the interelectrode space, there is focusing in the Y-axis, but no focusing in the X-axis. Consider a round beam passing along the Z-axis through the separator. As the ions move along the Z-axis, those to the right in a positive Y-axis direction are at a higher potential, due to the potential gradient between the electrodes. Those ions experience a larger magnetic force $-B(v + \Delta v)$ than electric force $-E(Bv)$. The resultant force drives the ions to the right of the Z-axis back toward the Z-axis. On the other hand, ions lying to the left of the Z-axis move at a reduced velocity and are deflected toward the Z-axis by the larger electric force. The net effect is a focusing in the Y-direction. The variation in the magnetic force from $B(v - \Delta v)$ to $B(v + \Delta v)$ across the beam can be compensated for by having the magnetic field vary in the Y-direction. The Y-axis focusing can be eliminated completely by tilting the pole pieces.

When the pole pieces are radii from the cyclotron radius $r = mv/eB$, the variation in the magnetic field strength is such that there is no focusing in the Y-

direction. HOwever, this magnetic field gradient causes a linear restoring force on the ions which produces X-direction focusing. The amount of focusing in the X-direction caused by this tilting of the pole pieces so that they are radii from the cyclotron radius is equal to the previous amount of Y-direction focusing.

It is discovered that a sloping of the pole piece faces **76** and **78** so that they converge at a point which is twice the cyclotron radius produces a condition in which there is equal focusing in the X and Y-directions. Thus, the point at which the planes of the faces **74** and **78** intersect is a distance back from the interelectrode space equal to $2r$ where:

$2r = 2mv/eB$

$= 4V/E$, where:

$r$ — cyclotron radius

$V$ — ion beam voltage

$E$ — interelectrode potential

$m$ — ion mass

$v$ — ion velocity

$e$ — ion charge

$B$ — magnetic field strength.

If the velocity filter is fabricated with the angles of the faces of the pole pieces in fixed configuration, during separator operation, the ratio of 2V/E must be kept equal to $r$, in order to have no astigmatism in the beam. To maintain stigmatic operation over a range of beam voltage V, the fields E and B must be varied according to the relationship $E = 2V/r$ and $B = E/\sqrt{2e/mV}$. to provide stigmatic separation of ions of different masses, at a fixed beam voltage V, the electric must must remain fixed ($E = 2V/r$) and the magnetic field must be varied to satisfy $B = E/\sqrt{2e/mV}$. For high energy beams ($V \geq 100$ kV), the velocities of the ions are generally high enough that sufficiently large magnetic forces ($Bv$) for separation are achieved at moderate magnetic field strengths ($B \approx 1 - 10$ kG). The corresponding electric fields required for balance are more difficult to achieve. In the case of a 100 kV boron ($m = 11$) beam, a magnetic field strength of 6,000 G requires an electric field of 7.9 kV/cm. For a typical electrode spacing of 3 cm, voltages of about 12 kV must be held off by the vacuum feedthroughs and 24 kV by the gap between the electrodes and the pole pieces. In general, the maximum attainable electric field strength $E_{max}$ is therefore the limiting feature for an ExB separator.

Thus, with a magnetic field which varies through the interelectrode space to produce a magnetic field gradient from one electrode to another, equal focusing in the X and Y-directions is accomplished. Providing the magnet would otherwise produce a uniform magnetic field, having magnet pole faces which slope toward each other such that the planes thereof intersect at twice the cyclotron radius produces this desired effect, in conjunction with a uniform electric field.

This invention having been described with respect to its preferred embodiment, it is clear that it is susceptible to numerous modifications and embodiments, including scaling, within the ability of those skilled in the art and without the exercise of the inventive faculty. Accordingly, the scope of this invention is defined by the scope of the following claims.

What is claimed is:

**1**. A crossed-field filter for purification of a charged particle beam comprising:

a tube having an axis defining the position of a charged particle beam therethrough;

first and second electrodes positioned to form a substantially uniform electric field adjacent said axis;

a magnet for producing a magnetic field which is graded in strength between said first and second electrodes so that charged particle deflection is axisymmetric as a charged particle beam passes along said axis.

**2**. The filter of claim **1** wherein said electrodes are shaped to provide a substantially uniform field adjacent said axis.

**3**. The filter of claim **2** wherein said electrodes have a uniform cross section of at least a portion thereof which faces said axis.

**4**. The filter of claim **3** wherein each of said electrodes has a substantially planar face and a protuberant nose adjacent each edge of said face.

**5**. The filter of claim **4** wherein said nose terminates in a substantially hemicircular section.

**6**. The filter of claim **1** wherein said magnetic field is produced by shaped magnetic pole faces on poles which are connected to said magnet.

**7**. The filter of claim **6** wherein said magnetic pole faces are each substantially planar, with said planes being convergent.

**8**. The filter of claim **7** wherein said planes converge to define a line which is substantially parallel to said axis.

**9**. The filter of claim **7** wherein said planes converge at a distance from axis equal to substantially twice the cyclotron radius of charged particles in said beam.

**10**. The filter of claim **9** wherein said electrodes are shaped to provide a substantially uniform field adjacent said axis.

**11**. The filter of claim **10** wherein said electrodes have a uniform cross section of at least a portion thereof which faces said axis.

**12**. The filter of claim **11** wherein each of said electrodes has a substantially planar face and a protuberant nose adjacent each edge of said face.

**13**. The filter of claim **12** wherein said nose terminates in a substantially hemicircular section.

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