April 7, 1964 G. R. LAMBERTSON 3,128,405

EXTRACTOR FOR HIGH ENERGY CHARGED PARTICLES

Filed July 31, 1962 2 Sheets-Sheet 1

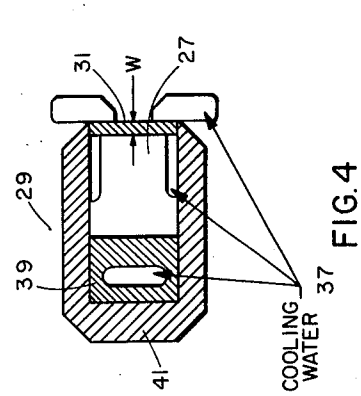



FIG. 4

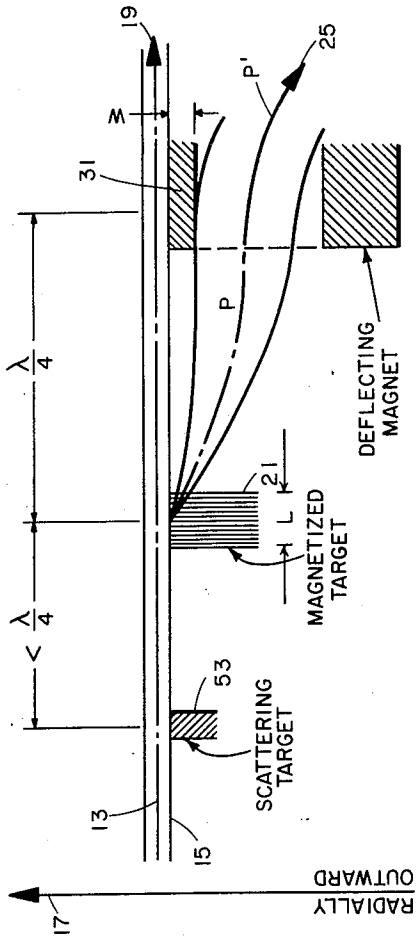



FIG. 1

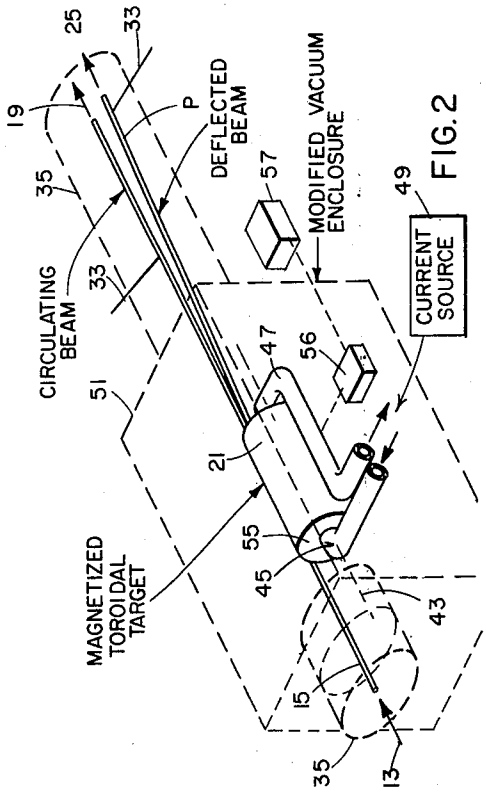



FIG. 2

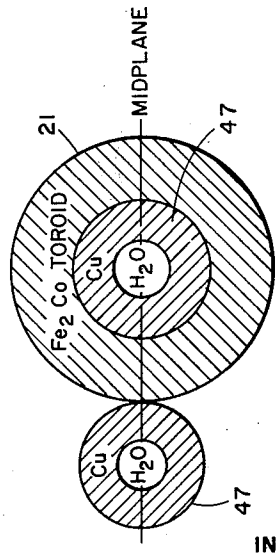



FIG. 3

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EXTRACTOR FOR HIGH ENERGY CHARGED PARTICLES

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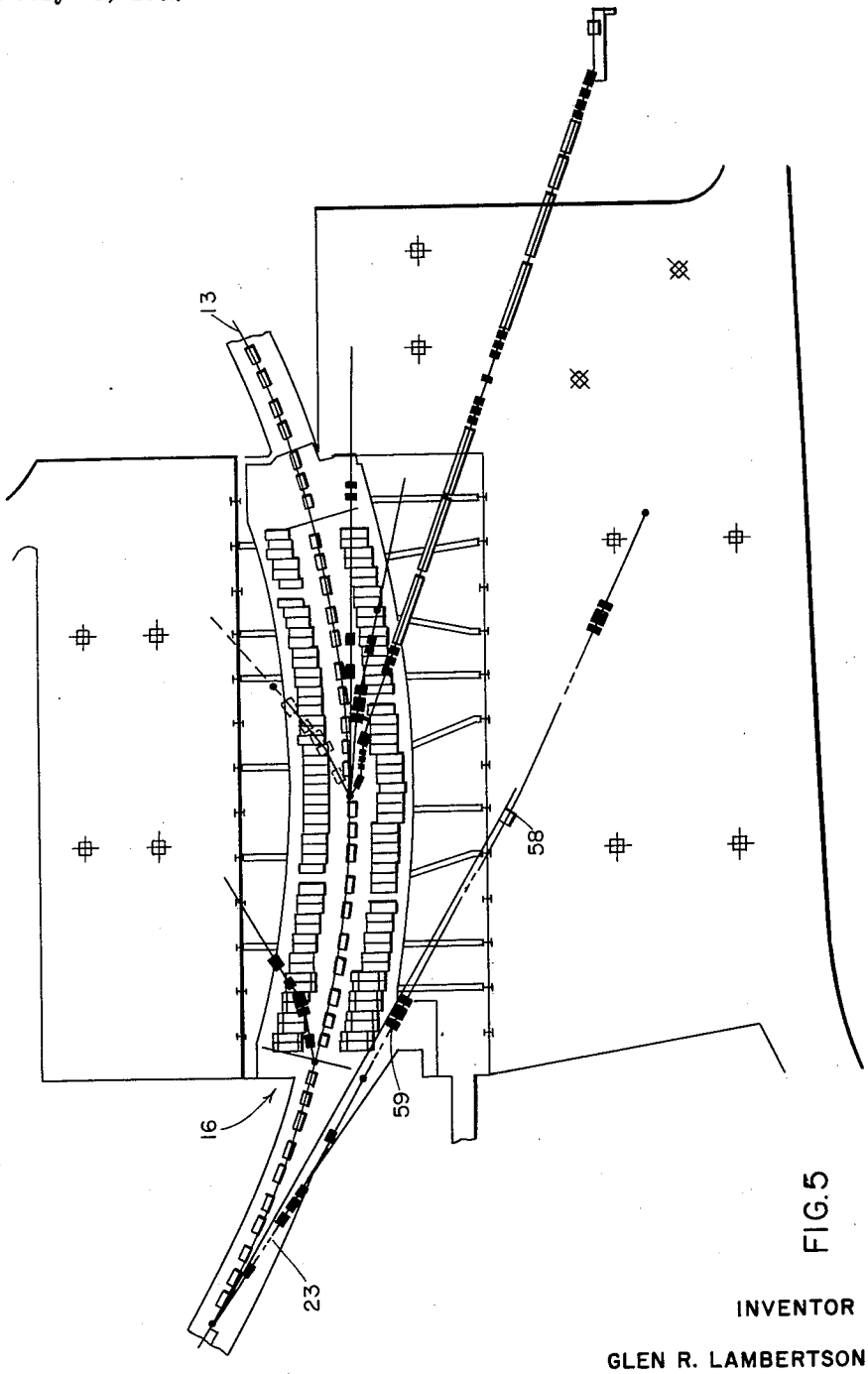



FIG.5

INVENTOR

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3,128,405

# EXTRACTOR FOR HIGH ENERGY CHARGED PARTICLES

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7 Claims. (Cl. 313—62)

This invention relates to a method and apparatus for accomplishing the extraction of particles from a beam of high energy charged particles and more particularly to a method and apparatus for separating small numbers of particles from a beam of high energy charged particles to achieve low counting rates in experiments using the extracted particles.

In high energy physics, it has been desirable to separate particles from a beam of high energy charged particles having energies on the order of several billion electron volts. Various proposals have been made and used to accomplish such separation including those arrangements shown in application Serial Numbers 16,902, filed March 22, 1960, now Patent No. 3,016,458, issued January 9, 1962; 41,708, filed July 8, 1960, now Patent No. 3,093,733, issued June 11, 1963; and 70,877, filed November 18, 1960, now Patent No. 3,056,023, issued September 25, 1962. While these arrangements have been useful and can accomplish the desired extraction, they have required the manufacture and assembly of expensive or complicated electronic guides around the beam and have been bulky or otherwise hard to handle or control. Furthermore, it has been difficult, if not impossible, to use these devices for the separation of small numbers of particles at an angle to the beam to achieve low counting rates in experiments using the extracted particles or to use these devices for extraction of particles from a beam circulating along an axis in an endless evacuated tube such as provided in a synchrotron. A synchrotron is an accelerator having an annular particle-confining magnet array which is energized in synchronization with a radio-frequency acceleration means.

By this invention there is provided method and apparatus for the separation of high energy particles produced by accelerating devices operating in the multiple bev. range, such as the Brookhaven National Laboratory Alternating Gradient Synchrotron, referred to hereinafter as the Brookhaven AGS. The method and construction involved in this invention utilize standard and well-known techniques and apparatus and are highly flexible for a wide range of applications, beam energies, counting rates and particle equilibrium axes including straight and endless particle equilibrium axes. More particularly, this invention contemplates the use of a magnetized ferromagnetic target to deflect particles from the beam. In one embodiment, the magnetized ferromagnetic target is located inside an evacuated chamber in which the beam is travelling along an equilibrium axis and the beam is moved relatively slowly into the target so that one or more high energy particles pass through the target and are deflected at an angle to the beam axis by the magnetic induction in the target. With the proper selection of target lengths through which the impacted particles pass and magnetic induction, as described in more detail hereinafter, it is possible by this invention to obtain the desired extraction.



It is, thus, a first object of this invention to provide a method and apparatus for the extraction of particles from a beam of high energy particles.

It is a further object of this invention to provide a magnetized ferromagnetic targeting system in which the extraction of particles from a beam of high energy particles takes place.

It is still a further object of this invention to provide the extraction of more particles from a high energy particle beam by magnetic deflection than by coulomb scattering.

Still another object of this invention is provision for handling of high energy charged particles produced in impacting a beam of high energy particles against a magnetized ferromagnetic target.

The above and further objects and novel features of this invention will appear more fully from the following detailed description when the same is read in connection with the accompanying drawings. It is to be expressly understood, however, that the drawings are not intended as a definition of the invention but are for the purpose of illustration only.

In the drawings where like parts are marked alike:

FIG. 1 is a diagrammatic illustration of the principles involved in this invention;

FIG. 2 is a partial isometric view of the magnetized target of FIG. 1;

FIG. 3 is a partial cross section of the magnetized target of FIG. 2;

FIG. 4 is a partial cross section of the septum magnet of FIG. 1;

FIG. 5 is a partial top view of a high energy beam source for the apparatus of FIG. 2, and particle handling apparatus for use therewith.

It is known that beams of high energy particles can be piped over long distances or around an endless orbit along an axis provided in an evacuated tube. An alternating gradient synchrotron beam source for a beam of protons travelling at close to the speed of light is shown and discussed in, "The Brookhaven Alternating Gradient Synchrotron" by John P. Blewett, which was printed in the 1960 International Convention Record. FIG. 5 of that paper illustrates the tubular vacuum chamber enclosing the beam to reduce scattering from air molecules. Focusing of a beam in this tube is based on the strong focusing or alternating gradient system which confines the beam along an equilibrium axis or orbit in the tube so that the beam does not hit the sides of the tube as it oscillates with a predetermined small betatron oscillation along this axis. In the Brookhaven 33 bev. proton AGS the wave length of this oscillation is 300 feet and the betatron frequency is 1–3 megacycles per second from injection to full beam energy where the beam diameter is about .25 inch on the average. The beam position and diameter are determined with conventional probes.

As is well known, the protons in this AGS are injected at relatively low energy into an endless evacuated tube between confining and focusing magnets and the injected particles are accelerated by radiofrequency accelerating stations between other confining and focusing magnets in synchronization with a rising field in these magnets. This invention hereinafter described utilizes a beam source of this type supplying high energy particles into which a magnetized ferromagnetic target is impacted to magnetically deflect said particles at an angle to the beam equilibrium

axis or orbit for their removal from the beam and the tube.

In order to explain how the method and apparatus of this invention accomplish the function of extracting particles from a beam of high energy charged particles, reference is made to FIG. 1 wherein is illustrated an equilibrium axis **13** along which a beam **15** of high energy particles pass in bunches (as in an AGS **16** partially shown in FIG. 5). Orientation of the figure is shown by arrow **17**, which is disposed radially outwardly from a point (not shown) corresponding to the center of the beam orbit **13** in a synchrotron. The direction of the beam travel is represented by arrow **19**. Particles in the beam **15**, in passing through magnetized target **21**, increase the betatron amplitude (distance from equilibrium axis **13**) by both coulomb scattering and magnetic deflection. These amplitudes are given by:

(1)

$$\text{Magnetic deflection amplitude}=a_m=\frac{R}{\nu}\frac{3\times10^{-4}}{p}BL$$

(2)

$$\text{R.M.S. coulomb scattering amplitude}=a_s=\frac{R}{\nu}\frac{15}{p\ \text{v./c.}}L/L_r$$

where

$R$=orbit radius (cm.)
$\nu$=beatron frequency
$p$=particle momentum (M.e.v./c.)
$B$=magnetic induction (gauss)
$L$=thickness of target (cm.)
$L_r$=radiation length of target material (cm.)

The orbit displacement caused by energy loss in synchrotrons with large betatron frequencies $\nu$ (such as in the Brookhaven AGS) is small and may be neglected. Clearly, as the target thickness L (the length of the target through which the beam particles pass) increases, the magnetic deflection ($a_m$) will exceed the scattering ($a_s$) and may be used to inject the beam particles into an extraction channel (such as channel **23** in FIG. 5).

The target length at which scattering and magnetic deflection are equal is found from Equations 1 and 2 to be:

(3) $$L\ \text{min.}=\frac{25\times10^8}{B^2L_r}$$

and is independent of the details of the synchrotron. If the target material is a high magnetic saturation material such as an iron-cobalt alloy including the alloy sold under the trademark by the Allegheny Ludlum Steel Coporation, Permendur or Hyperco an induction of 20,000 gauss is readily allowed with low stray fields. Approximate properties of these alloys are:

Density,

$$p=8\ \text{g./cm.}^3$$
$$L_r=15\ \text{g./m.}^2$$

Collision,

$$\text{Length}$$
$$L_c=100\ \text{g./m.}^2$$

For such materials, L min. is 3.3 cm. at $B$=20,000 gauss.

Advantageously, target **21** forms a longitudinally extending toroid as shown in FIG. 2 with a uniform cylindrical cross section and flat ends normal to its axis **43**. This axis **43** is parallel to the beam axis **13**. Annulus **45** of target **21** accommodates a hollow copper conductor **47** attached to a suitable direct current electrical power supply **49** and a suitable cooling water source (not shown) which circulates water in conductor **47** to cool target **21**. These current and water supply means pass through the sides of modified vacuum enclosure **51** in a vacuum-tight manner and this enclosure **51** connects with tube **35** to enclose target **21** and insure the proper high vacuum in tube **35**, which surrounds beam **15**. Energization of conductor **47** is conventional, and magnetizes target **21** to extract particles from beam **15** when impacted against the target **21**.



Advantageously the outside of beam **15** is moved slowly into the outside of one end of target **21** so that particles from beam **15** pass through substantially the entire length L of the target **21** and come out the opposite end **21** at an angle to the beam axis **13**. To move the beam inward, the beam acceleration is decreased while the confining magnets remain energized so that the beam loses energy and spirals slowly inwardly in tube **35** and into the target **21**. As is well known, the same system for controlling the increase in the radiofrequency accelerating power can be used to decrease and stop this power. With a one millisecond spillout (or an energy increase during a longer spillout), a normal spiral-in separation per turn of a few thousandths of an inch together with careful alignment of the target will provide complete traversals of particles through the target. For long 0.1 sec. constant energy beams, a standard scattering target **53** placed somewhat less than a quarter of a betatron wave length upstream from target **21**, deflects particles from beam **15** below the outer edge of the exposed side **55** of target **21** and into that side **55** for traversal of the target **21**. It is also possible, as is known, to suddenly force target **21** (and target **53**, if desired, simultaneously) into the outside of beam **15** to extract particles therefrom. To this end piston **56** suddenly forces target **21** into beam **15** by means of pressurized fluid from a source **57** which has a conventional solenoid valve and timer control for actuating the piston during each synchrotron cycle.

Stray fields outside the magentized target **21** at 20,000 gauss are only up to about 40 gauss. This causes very small perturbation of the circulating beam **15**. It is also possible to increase the magnetism thereof by at least 10% and to compensate for stray fields with field sources on the sides of target **21**.

Referring further to FIG. 1, arrow **25** indicates the path $p$ of particles which when beam **15** strikes target **21** are deflected magnetically. The extraction may be directly into an extraction channel **23** or into the aperture **27** of bending magnet **29** which has a thin septum **31** of width $w$. To miss this septum, the magnetic deflection is such that:

(4) $$a_m \geqq w+a_s+a_\beta$$

where $a_\beta$ is the betatron amplitude as determined with regard to axis **13**, for example, by conventional charged particle probes **33** in the side of evacuated tube **35** in which the beam **15** travels along axis **13** as shown in FIG. 2. In a practical arrangement, values for an extractor target **21** in a 30 bev. AGS, including values of R and $\nu$, and values of L, $a_s$, and $a_m$, for a septum **31** of width $w$ of 1 millimeter are:

| | |
|---|---|
| R($10^4$ cm.) | 1.285 |
| $\nu$ | 8.25 |
| $R/\nu$=(cm.) | 1,560 |
| $a_\beta$(cm.) | 0.32 |
| L(cm.) | 5.8 |
| $a_m$(cm.) | 1.75 |
| $a_s$(cm.) | 1.32 |

The thin septum **31** of 1 millimeter thickness is advantageous in the deflecting magnet **29** as shown in FIG. 4. This magnet has cooling water channels **37** around conducting septum **31**, and in copper magnet winding **39**. Currents in septum **31** include pulsed current densities up to 10,000 amp./cm.$^2$, giving a field of 1260 gauss over a useful gap of 0.5 cm.

The particles which are extracted from beam **15** by target **21** and passed through bending magnet **29** into a suitable extraction channel such as the channel **23** shown in FIG. 5 may be further handled by suitable bending magnets **58** and focusing magnets **59** as are well known. For example, suitable focusing magnets **58** include

conventional quadrupole magnets and suitable bending magnets including H type magnets. The use of such magnets **58** and **59** are well known as shown, for example, in the referenced application, Serial Number 70,877, and the article by E. D. Courant in vol. 31, No. 2, pp. 193–6, February 1960, of the "Review of Scientific Instruments."

In summary of the operation of this invention the particles in a high energy beam **15** impact into side **55** of target **21**. The beam may be moved slowly into the target **21** or the target moved rapidly into the beam in time with the bunches of particles in beam **15** as determined with probes **33**. This can be done carefully to pass the beam particles completely through the length L of target **21**. The target **21** is magnetized to magnetically deflect the impacting particles from the beam at an angle to the beam axis **13**. By the described sizing and magnetization, the magnetic deflection of these particles exceeds that caused by scattering. The particles deflected by target **21** may be one or more particles and these are ejected to clear septum **31** at bending magnet **29**, which is located one quarter of a betatron wave length downstream from target **21**. This magnet **29** deflects the particles at a further angle to the axis of beam **15** along path P'. From there the particles pass into extraction channel **23** which directs the extracted particles at further targets for experiments where long counting periods are desired. It is understood from the above, however, that target **21** may be used for direct extraction into a channel **23** where as sharp an angle to the beam axis **13** is not required. As described, in the case of magnetic deflection, the deflection angle is greater than the deflection angle from a standard non-magnetized scattering target.

In another embodiment where long (0.1 sec.) constant energy beams **15** are used, scattering target **53** is used to impact particles from beam **15** into side **55** of target **21**. In this embodiment target **53** is less than one quarter of a betatron wave length upstream from magnetized target **21**.

This invention provides a simple trouble-free particle extractor for extracting particles from a high energy charged particle beam and finds utility for the extraction of particles from endless beams in synchrotrons. This invention additionally has the advantage of improved overall beam extraction, performance at sharper angles than was possible heretofore, and also provides single particle extraction of particles from a beam in experiments where low counting rates are desired. Also, the extracted beam of particles extracted from a high energy beam by extractor **21** will occupy a phase space area only about five times that of the circulating beam which is a useful feature for experimental purposes.

I claim:

1. Particle extracting apparatus for use with a beam of high energy charged particles travelling in an evacuated chamber along an axis, comprising an evacuated chamber and a magnetized target in said chamber, said target being impacted relatively against said beam whereby said beam particles are deflected from said beam by the magnetic induction in said target.

2. Particle extracting apparatus for use with a beam of high energy charged particles, travelling in an evacuated chamber along an axis, comprising an evacuated chamber for said beam, a magnetized target in said chamber, and means for impacting said target relatively slowly against said beam whereby coulomb scattering and magnetic deflection of said beam particles is produced by said target in said target, said magnetically deflected particles exceeding in number the particles extracted by coulomb scattering.

3. Particle extracting apparatus for use with a beam of high energy charged particles travelling in an evacuated chamber along an axis, comprising an evacuated chamber for said beam, a longitudinally extending cylindrical target in said chamber having its axis parallel to said beam axis, means for impacting the outside of said beam relatively against one end of said target to produce coulomb scattering of said beam particles from said beam, and means for inducing in said target a high magnetic field which deflects particles from said beam at an angle exceeding that produced by coulomb scattering.

4. Particle extracting apparatus for use with a beam of high energy charged particles travelling along an axis, comprising an evacuated chamber having a first axis therein along which said beam travels, a longitudinally extending cylindrical target in said chamber having a second axis parallel to said first axis, means for moving said target relatively toward said beam axis for impacting the outside of said beam against said target to produce coulomb scattering of particles from said beam, and means for inducing in said target a high magnetic field which magnetically deflects particles from said beam, said target length parallel to said first axis being greater than $L_{min}$ in centimeters in the formula:

$$L_{min}=\frac{25\times 10^8}{B^2 L_r}$$

where

$B$=the magnetic induction in gausses in the target and,

$L_r$=the radiation length of the target material in centimeters.

5. Particle extracting apparatus for use with a beam of high energy charged particles travelling in an evacuated chamber along an axis, comprising an evacuated chamber having a first axis along which said beam travels, a longitudinally extending cylindrical target in said chamber having a second axis parallel with said first axis and opposite ends normal thereto, means for moving said target relative to said beam so that particles from the outside of said beam can be impacted relatively against one end of said target, means for inducing in said target a high magnetic field which magnetically deflects particles from the outside of said beam at an angle to said first axis, and a magnetic septum magnet for receiving said magnetically deflected particles in its aperture and deflecting them at a further angle to said first axis whereby high energy charged particles can be extracted from said beam.

6. Particle extracting apparatus for use with a beam of high energy charged particles travelling in an evacuated chamber along an axis, comprising a longitudinally extending evacuated chamber having a first axis along which said beam is adapted to travel in one direction, a longitudinally extending cylindrical first target in said chamber having a second axis parallel with said first axis and opposite ends normal thereto, a scattering second target upstream from said first target, means for moving said second target relative to said first axis for the impacting and scattering of particles in said second target from the outside of said beam, means for inducing in said first target a high magnetic field so as to receive particles scattered from said second target and deflect them magnetically at an angle to said first axis, and a deflecting septum magnet for receiving said magnetically deflected particles in its aperture and deflecting them at a further angle to said first axis.

7. Particle extracting apparatus for use with a beam of highly energized charged particles travelling in an evacuated chamber along an axis, comprising a longitudinally extending evacuated chamber having a first axis along which said beam is adapted to travel in one direction with a betatron oscillation wave length around said first axis, a longitudinally extending cylindrical first target in said chamber having a second axis parallel with said first axis and opposite ends normal thereto, a scattering second target upstream from said first target, means for

moving said second target relative to said first axis for impacting and coulomb scattering of particles in said second target from the outside of said beam, means for inducing in said first target a high magnetic field so as to receive scattered particles from said second target and deflect them magnetically at an angle to said first axis, and a septum magnet for receiving and deflecting magnetically deflected particles from said first target at a further angle to said first axis, the distance separating said first



and second targets being less than one quarter the betatron wave length, the distance separating said magnetized target from said septum magnet being substantially equal to one quarter betatron wave length.

**References Cited** in the file of this patent

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