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(54) **Racetrack linear accelerators**

(57) In a recirculating linear accelerator system of the racetrack type the beam path consists of two shorter straight legs 12 and two longer straight legs 11 with four Pretzel beam-bending magnets 13 disposed one each at the corners of the beam path. The magnets may each bend the beam through 90°, as shown, or through 84°, in which case the two longer legs cross over one another (Figure 2, not shown). Two linear accelerators are disposed either as shown, or two in one leg (Figure 2). The beam is injected from a high voltage gun 20 via one of the magnets such that the axis of the injected beam lies at a tangent to the normal trajectory of a beam of similar energy in the magnet. The beam emerges by way of one of the magnets which is arranged in back-to-back double Pretzel configuration with a fifth Pretzel magnet 16.

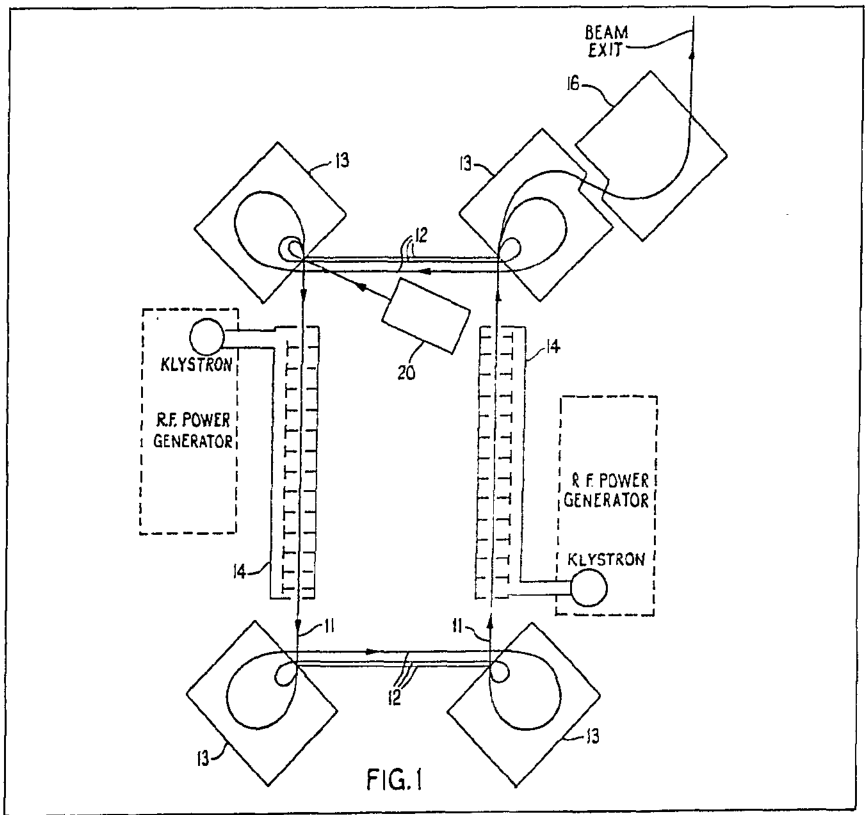

FIG. 1

The drawings originally filed were informal and the print here reproduced is taken from a later filed formal copy.

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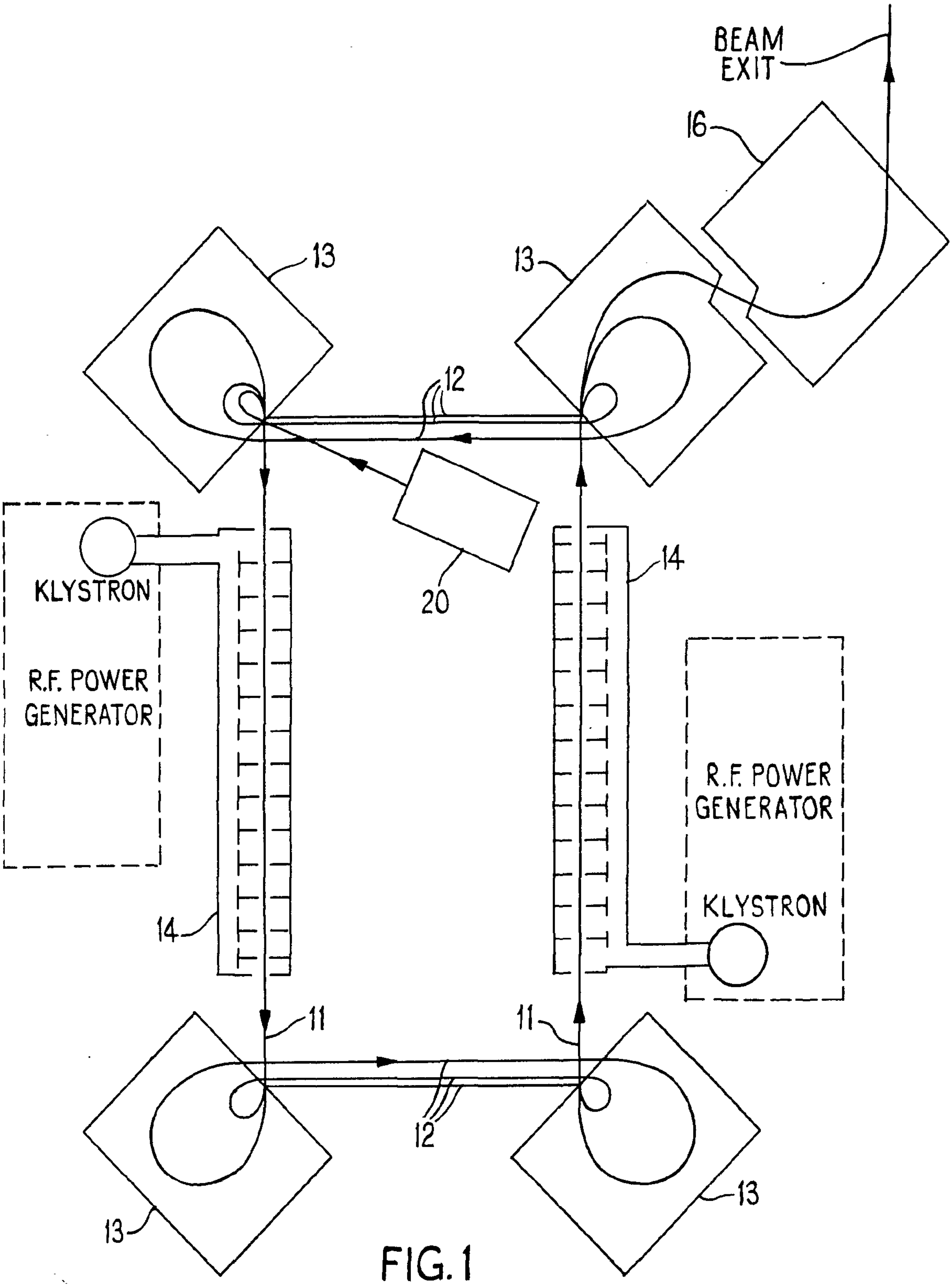
BEAM
EXIT
16
13
13
12
20
14
KLYSTRON
R.F. POWER
GENERATOR
R.F. POWER
GENERATOR
KLYSTRON
14
11
11
12
13
13

FIG. 1

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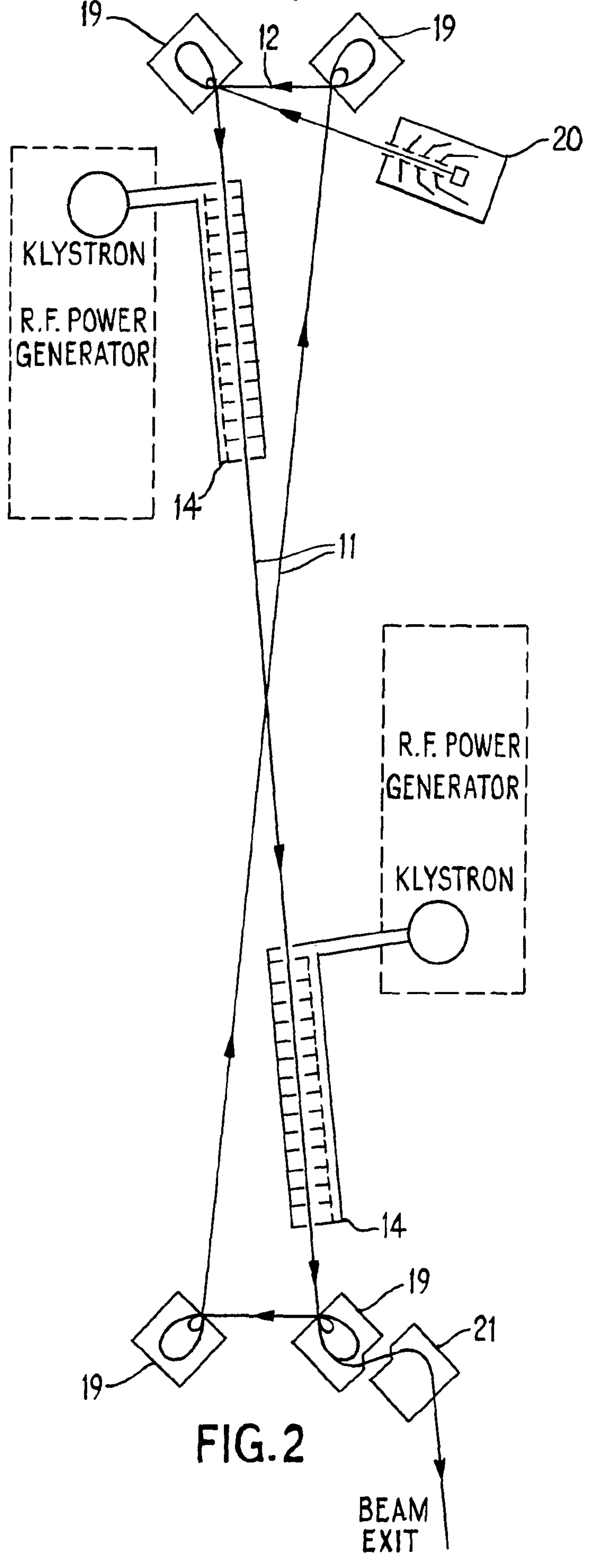

FIG.2

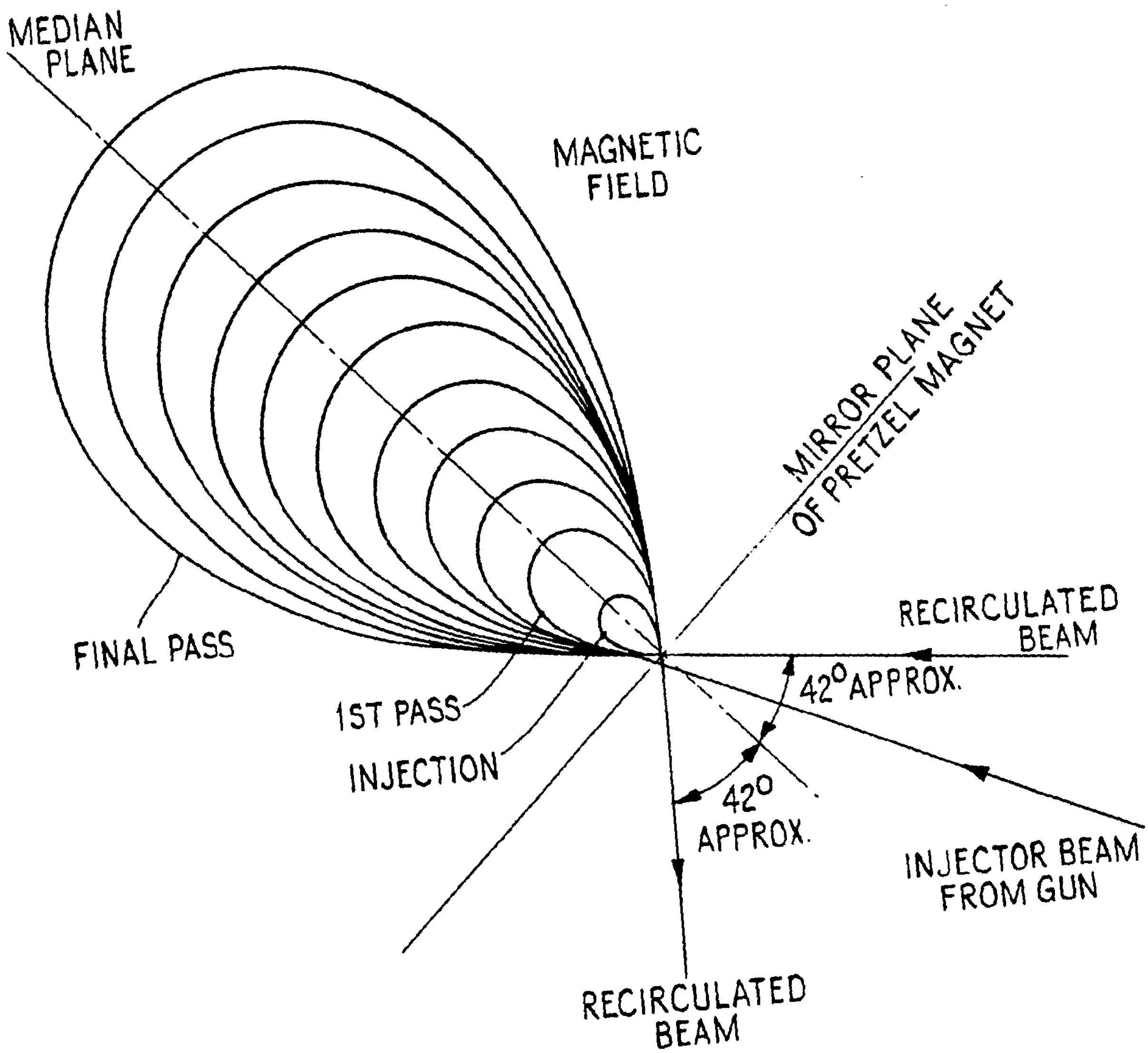
MEDIAN PLANE
MAGNETIC FIELD
MIRROR PLANE OF PRETZEL MAGNET
RECIRCULATED BEAM
42° APPROX.
FINAL PASS
1ST PASS
INJECTION
42° APPROX.
INJECTOR BEAM FROM GUN
RECIRCULATED BEAM

FIG.3

SPECIFICATION

Improvements in or relating to linear accelerators

This invention relates to linear accelerators, it being an object thereof to achieve an improved recirculating electron beam linear accelerator system.

Various kinds of recirculating linear accelerator systems are known. In the racetrack microtron the electron beam passes repeatedly in the same direction through the same accelerator, a magnetic guide field being arranged to steer the beam, on leaving the accelerator exit, in an orbit that brings it back to the accelerator entrance. In the shuttle microtron, the electron beam is caused to travel repeatedly backwards and forwards in opposite directions through the linear accelerator by reflecting magnets at opposite ends of the beam path.

According to the present invention, a recirculating linear accelerator system of the racetrack type comprises a beam path having four straight legs, with four Pretzel bending magnets disposed at the ends of the four legs so as to redirect the beam at the end of each leg into the next leg of the beam path, at least one of the beam path legs including a linear accelerator.

The Pretzel magnet is afocal and achromatic and non-dispersive or nearly so over a wide energy range. It can readily be arranged to give an effective bending angle in the region of 90° (although the beam actually turns in a loop through 270°). By employing four such magnets at the 'corners' of a racetrack made up essentially of four straights, with a linear accelerator or accelerators in one or two of the straights, a continuous beam of electrons of up to 10 milliamps can be injected and recirculated through up to ten complete circuits of the track to achieve an output energy of 5 to 40 million electron volts.

Two arrangements according to the invention are illustrated diagrammatically in the accompanying drawings, in which:–

Figure 1 is a diagram of a first embodiment of the invention,

Figure 2 is a diagram of a second embodiment, and

Figure 3 illustrates typical electron beam trajectories in the design of Pretzel used in Figure 2.

In Figure 1, the racetrack electron beam path consists of two long legs 11 and two short legs 12, with four 90° Pretzel beam-bending magnets 13 at the four 'corners' and a linear accelerator 14 in each of the two long legs. To achieve a 90° bending angle, the Pretzel design uses a magnetic gradient defined by the shape of the magnet pole where $B = G x^n$ and where $n = 0.8$.

B = magnetic flux density along the median plane between $x = o$ and x_{max}.

G = gradient of magnetic flux density.

x = distance along median plane inside the magnet from the mirror plane to the maximum excursion of the electron beam trajectory.

This configuration is known to provide achromatic bending with afocal properties but displaces the emergent beam by a small fraction of x_{max}. However, when such magnets are used in pairs as shown in Figure 1, the displacement is cancelled out and such a pair of Pretzel magnets provides achromatic bending of 180° with afocal and non-dispersive properties. The beam is injected from a high voltage gun 20 via the Pretzel preceding the accelerator (or one of them) in a manner whereby the axis of the injected beam lies at a tangent to the normal trajectory of a beam of similar energy in the Pretzel. The beam emerges by way of one of the Pretzel magnets which is arranged as a back-to-back double Pretzel beam bending electromagnet 13, 16. Alternatively, beam emergence can be achieved by the cyclotron technique.

The two linear accelerators 14 comprise standing wave coupled cell radio frequency accelerator structures each excited by a respective continuous wave 100 kW klystron amplifier 17, giving a total of 200 kW of radio frequency power. Alternatively, travelling wave accelerators can be employed.

A continuous beam of electrons is injected at 250 to 450 kV and up to 10 milliamps and circulated 5 to 20 times to give an emerging electron beam with an output energy of 5 to 40 million electron volts, the energy gain per circuit being 1 to 2 MeV. Thus, the output power of the emergent beam can be up to 100 kW. The electron transit time per circuit is 20 to 30 nanoseconds and the guide loading by the beam current up to 100 mA.

For efficient acceleration, it is essential that the bunches of electrons trapped at or near to the peak intensity of the accelerating field at radio frequency in the guide structure are phased to coincide or nearly so with the same radio frequency at each pass through the accelerator sections. It follows that the total path length of the beam at each circuit must be at or nearly at an integer multiple of the wavelength of the same radio frequency. Adjustment of the following parameters enables this phase coincidence to be obtained:–

(i) injection voltage
(ii) R.F. power and frequency
(iii) magnet excitation
(iv) dimensions of the quadrilateral beam path, the first three of which can be interactively programmed to achieve a steady state phase stability.

In Figure 2, there are again two long legs 11 and two short legs 12, but in this case 84° Pretzel magnets 19 are used and the two long legs 11 of the electron beam path cross over. The accelerators 14 are situated in the long legs on one side or the other of the cross over point. This configuration uses a special case of the Pretzel design where n is equal or very nearly equal to 0.95 and the bending angle of 84° between incident and emergent beams provides achromatic bending with afocal and non-dispersive conditions.

Figure 3 shows typical electron beam trajectories over the wide range of energies in the design of Pretzel used in Figure 2. It shows approximate separation of the trajectories which are handled by the magnet when the magnet is excited at a steady level, as well as clarifying the method of beam injection from the gun.

A system according to the invention as described above has the following benefits,

The recirculating beam accelerator system with four bending magnets at each corner provides a continuous beam of electrons at energies between 5 to 40 million electron volts and currents up to 10 mA combining to give a continuous beam power in the region of 100 kW. Such beam power can be utilised in industrial processes such as irradiation of plastics, and processes such as sterilisation of medical disposables and effluent, and processes such as chemical reactions in compounds.

The afocal, achromatic and non-dispersive properties of the Pretzel bending magnets allow the beam to pass through the same accelerator sections over the energy range of 250 KeV to 10 MeV and higher.

The interactive adjustment of the voltage of the injected beam of electrons, the excitation of the four bending magnets at the corners and the radio frequency power and frequency achieves phase stability of the bunches of the accelerated electrons with the radio frequency and allows efficient acceleration at each pass through the accelerator sections.

CLAIMS

1. A recirculating linear accelerator system of the racetrack type, comprising a beam path having four straight legs, with four Pretzel bending magnets disposed at the ends of the four legs so as to redirect the beam at the end of each leg into the next leg of the beam path, at least one of the beam path legs including a linear accelerator.

2. A system according to claim 1, comprising four 90° Pretzel beam-bending magnets, and wherein the beam path has two long parallel legs and two short parallel legs with a linear accelerator in each long leg.

3. A system according to claim 1, comprising four 84° Pretzel beam-bending magnets, and wherein the beam path has two short parallel legs, and two long legs which cross over and include linear accelerators situated on one side or the other of the cross over point.

4. A system according to claim 3, wherein each Pretzel magnet has a magnetic gradient determined by the shape of the magnet pole as defined by $B = G x^n$ where

B = magnetic flux density along the median plane between $x = o$ and x_{max}

G = gradient of magnetic flux density

x = distance along the median plane inside the magnet from the mirror plane to the maximum excursion of the electron trajectory

$n \simeq 0.95$.

5. A system according to any one of the preceding claims, wherein the beam is injected into the beam path from a high voltage gun via a Pretzel magnet preceding an accelerator in a manner whereby the axis of the injected beam lies at a tangent to the normal trajectory of a beam of similar energy in the Pretzel magnet.

6. A system according to any one of the preceding claims, wherein the beam emerges from the beam path by way of one of the Pretzel magnets which is arranged in back-to-back double Pretzel configuration with a further Pretzel magnet.

7. A system according to any one of the preceding claims, wherein each linear accelerator comprises a standing wave coupled cell radio frequency accelerator structure excited by a respective continuous wave 100 kW klystron amplifier.

8. A system according to any one of the preceding claims, wherein a continuous beam of electrons is injected at 250 to 450 kV and up to 10 milliamps and circulated 5 to 20 times to give an emerging electron beam with an output energy of 5 to 40 million electron volts.

9. A system according to any one of the preceding claims, wherein the total beam path length per circuit is at or nearly at an integer multiple of the wavelength of the radio frequency in the linear accelerator or accelerators.

10. A recirculating linear accelerator system substantially as described with reference to Figure 1 or Figure 2 of the accompanying drawings.

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