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NEUTRAL BEAMLINE WITH IMPROVED ION-ENERGY RECOVERY

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NEUTRAL BEAMLINE WITH IMPROVED ION ENERGY RECOVERY

Background of the Invention

This invention relates generally to neutral beam injection systems for use in controlled nuclear fusion devices such as Tokomaks, magnetic

5   mirror systems, bumpy tori and the like, and, more particularly, this invention relates to improvements in neutral beam injectors with direct ion energy recovery.

In the field of controlled nuclear fusion, a high temperature plasma is formed of fusionable light isotope ions contained within a

10   magnetic field confinement or containment zone, in an evacuated region. Such plasma may generally comprise one or more isotopes, such as hydrogen, deuterium, tritium, helium 3, etc., which undergo fusion reactions under appropriate conditions of confinement time, density, and temperature. These conditions may be brought about or supplemented by

15   the injection of properly accelerated neutral particle beams of one or more of the appropriate species into the magnetically confined plasma. The injected particles must be neutral in order to penetrate the very strong magnetic field. These energetic neutral particles are subsequently ionized either by collision with the plasma ions or by

20   action of the magnetic confinement field (Lorentz force), and are accordingly trapped to increase the plasma temperature in the magnetic containment zone.

Since the neutral particles cannot be directly accelerated to high velocity, i.e., high kinetic energies, they are produced in an indirect manner from an ion source. It has been the practice to produce a neutral beam by accelerating either positively or negatively charged

5   ions of one or more of the above species emerging from an ion source, and by transporting them through a gas-cell neutralizer wherein they interact with background neutral atoms of the same species at a specified pressure through charge-exchange collisions. A certain portion of the energetic ions is converted into neutrals (or neutralized) as

10 they emerge from the neutralizer. The ion-to-neutral conversion efficiency depends on the species and the beam energy. The positive ion-to-neutral efficiency decreases monotonically as the energy per nucleon increases, e.g., from 60% for 40 kilo electron volts (keV) to 15% for 100 keV per nucleon.

15   As future ion sources are developed toward energies of about 100 keV per nucleon, the efficiency of producing energetic neutral hydrogen isotopes from positive ions is intolerably low.

One way to improve the neutral beam injector efficiency is to recover the energy contained in the unneutralized residual ion fraction

20 of the beam, which is otherwise wasted. In order to recover the kinetic energy of the unneutralized residual ion component of the beam emerging from the neutralizer cell in the form of usable electric energy, the beam ions must be diverted from the neutral beam passage, decelerated, and collected. The electrons present in the neutralizer

25 cell must be blocked from entering the ion collector area since they would be accelerated into it, thereby producing an energy loss which may be equal to or greater than the recovered ion energy.

In the process of developing direct energy recovery in neutral
beam injectors, various means have been devised or suggested, which may
be generally divided into two groups, depending upon the ion deflection
method used. They are either electrostatic or magnetic ion deflection
5 methods.

An electrostatic deflection system is described in a paper by
W. L. Barr et al, "Proceedings of 7th Symposium on Engineering Problems
of Fusion Research", Vol. 1, page 308, 1978. This paper discloses an
electrostatic system developed at Lawrence Livermore National
10 Laboratory, Livermore, California, in which the neutralizer cell wall
is held at ground potential, the ion beam collector is biased highly
positive up to the initial beam energy, and the electrons emerging from
the cell are repelled by a negative voltage (approximately 20 kV)
applied to a set of electrodes which closely encompass the beam. One
15 negative electrode is placed between the neutralizer cell exit and a
funnel-shaped ion collector which also encompasses the beam. The other
negative electrode is placed at the exit of the collector. The ion
collector acts to decelerate and collect the ions diverging radially
from the beam. For a successful electron blocking in this system, the
20 negative electrodes must be biased sufficiently negative to drive the
beam potential negative even on the axis in the presence of the
positive-ion space-charge and the nearby positive-ion collector. There
are inherent problems with this system which include a severe vacuum
requirement for efficient direct conversion, increased beam-line length
25 needed to collect most of the diverging and decelerating ions which
consequently reduces the neutral power transmission efficiency, and
uncertain trajectories of fractional energy ions. Low gas pressure

is critically required since the slow ions and electrons produced by
ionization and charge exchange of the background gas are likely to be
drawn to these electrodes causing excessive power loading. The sub-
sequent emission of secondary electrons from the surface of the nega-
5 tive electrodes would give rise to an additional power drain.

Other electrostatic electron-blocking and ion-collection systems
utilizing electrostatic grids are discussed by P. Raimbault in
EUR-CEA-FE-823, 1976. One specific system outlined in this reference
employs a cylindrical grid arrangement which surrounds the beam exiting
10 the neutralizer which is biased negative with respect to the neutra-
lizer to suppress the electrons. This long cylindrical suppression
grid is supposed to ease the higher negative voltage required to
penetrate into the beam and to block the electrons. However, this
scheme also suffers from direct interception of the ion beam on the
15 negative potential, cylindrical grid. Not only is the ion energy lost,
but secondary electrons ejected from the grid by the ion impingement
constitute an additional power loss. In this system, unlike the former
system, the ion source is operated at near ground potential, and the
ions are accelerated by operating the neutralizer at a high-negative
20 potential, which makes it possible to recover the energy of the ions by
deceleration to ground potential.

Further, it has been suggested in the art to employ magnetic means
for deflecting the ions from the neutral beam, and it has been further
suggested to employ magnetic suppression, or blocking, of the electrons
25 from emerging from the neutralizer tube. It has been recognized in the
art that magnetic suppression would be advantageous in that the magne-
tic field can penetrate beams that are too thick and too dense for

electrostatic supression to work. However, in the prior-art experiments employing magnetic suppression, there was no provision made to terminate the electrons, nor was there a strong enough magnetic field.

5   A U.S. Patent application of common assignee with the present invention, S.N. 164,990 filed July 1, 1980 by William L. Stirling for "Neutral Beam Line with Ion Energy Recovery Based on Magnetic Blocking of Electrons" discloses a system employing magnetic blocking of the electrons and electron collection at the neutralizer exit. The neutralizer is operated at a high-negative acceleration potential and the

10   emerging ion beam experiences a strong electric field due to the surrounding ground potential structure which is transverse to the magnetic field applied across the beam at the neutralizer exit. Any electrons present in the beam-generated plasma in the neutralizer are quickly moved out of the beam due to $\overline{E}x\overline{B}$ field drift and directed into

15   a slightly positive biased, electron collector. However, there exists a finite fraction of molecular ions (e.g., H_2^+ and H_3^+) along with the atomic ions in the extracted beam from the ion source. These molecular ions are mostly dissociated into atomic particles as they pass through the near-equilibrium gas cell, and thus these dissociated ion particles

20   have kinetic energies of fractional values (one-half or one-third) with respect to the original full acceleration energy (E) of the atomic ions accelerated through the neutralizer and cannot reach the ground-potential surfaces on which the full energy (E) ions are collected. These fractional energy ions are deflected along paths of substantially smaller

25   radius and, in a bad geometry, could impinge upon the outer walls of the neutralizer cell producing secondary electrons which cannot be suppressed from being accelerated to the surrounding ground potential surfaces.

Therefore, it will be appreciated that there is a need for improvements in neutral beamline systems with ion energy recovery based on the advantages of magnetic blocking of electrons and magnetic beam ion deflection. One particular need is to improve the handling of frac-

5 tional energy ions to prevent their interferring with the recovery of the full energy ions when the fractional energy ions cannot be recovered readily. Further, improvement is needed to prevent full energy ions from prematurely deflecting onto the gas cell wall due to the close proximity of the magnet region to the neutralizer end region.

10   Summary of the Invention

In view of the above needs, it is an object of this invention to provide an improved neutral beam injection system with unneutralized residual ion energy recovery based on magnetic blocking of electrons within the neutralizer gas cell.

15   Another object of this invention is to provide an improved neutral beam injection system as in the above object wherein the efficiency of direct energy recovery of full energy ions is enhanced.

Another object of this invention is to provide an improved neutral beam injection system as in the above objects wherein the efficiency is

20 improved by preventing fractional energy ions from interferring with the full energy ion recovery.

Another object of this invention is to provide an improved neutral beam injection system as in the above objects which may be retrofit to existing neutral beam injectors, thereby increasing their electrical

25 efficiency and high-power, long-pulse capability.

Additional objects, advantages, and features of the invention will be set forth in part in the description which follows, and will become

apparent to those skilled in the art upon examination of the following or may be learned by practice of the invention. The objects and advantages of the invention may be realized and attained by means of the

5   instrumentalities and combinations particularly pointed out in the appended claims.

To achieve the foregoing and other objects and in accordance with the purpose of the present invention, as embodied and broadly described herein, an improved neutral beam injection system is provided. Ions

10 produced in an ion source operated near the ground potential are accelerated to a desired energy by a high negative potential applied on the neutralizer tube. Ions which are not converted into neutrals experience a retarding electric field developed between the end of the neutralizer and the surrounding ground surfaces. A transverse magnetic

15 field (B) is provided in the exit region of the neutralizer. The magnetic field strength is sufficiently provided so as to block the electrons in the neutralizer from exiting by the action of the crossed fields drift and also to deflect the full energy ions and the fractional energy ions along separate paths. An electrically conductive

20 structure defines the exit region of the neutralizer for providing an electric field shielding in such a way that fractional energy ions can be magnetically reflected back into the interior of the neutralizer while the full energy ions are deflected out of the neutralizer. A ground potential, full energy ion collector surface is provided in the

25 path of the full energy ions deflected from the neutral beam path, which needs only a minimal cooling. The full energy ions are sufficiently decelerated and their charge is collected in the form of electric current which is returned to the high voltage power supply. Thus, their energy is not expended.

The structure defining the exit region of the neutralizer has a downstream opening corresponding to the paths of the neutral beam and the deflecting full energy ion beam. Around its opening is an electron collecting collar which is electrically biased slightly positive rela-
5 tive to the neutralizer tube to collect the electrons drifting from the neutralizer by an $\overline{E}x\overline{B}$ crossed fields force.

The geometry of the gas cell extension forming the electrically conductive structure defining the exit region of the neutralizer precludes any strong electric fields in the exit region where ions are
10 bent by the magnetic field. The fractional energy ions are contained within the gas cell end structure and any secondary electrons emitted as a result of impingement of the fractional energy ions upon the internal surfaces of the extension are suppressed likewise and ter- minated on the electron collector ring. The wide opening of the
15 neutralizer end structure toward the ion bending direction minimizes the wasteful loss of full energy ions bent into the neutralizer inner wall.

Brief Description of the Drawings

The accompanying drawings, which are incorporated in and form a part of the specification, illustrate the present invention and,
20 together with the description, serve to explain the principles of the invention. In the drawings:

Fig. 1 is a schematic illustration of a neutral beam generator employing direct energy recovery of positive ions based on magnetic blocking of electrons in accordance with the present invention;

25 Fig. 2 is a plot of the operating potential of the various com- ponents along the beamline shown in Fig. 1;

Fig. 3 is a perspective view of the gas neutralizer end structure made in accordance with the teachings of the present invention; and

Fig. 4 is a schematic illustration of an alternate embodiment of the neutralizer end geometry of the magnet region conceivable from the

5 teaching of this invention.

Detailed Description of the Preferred Embodiment

Referring now to Fig. 1, there is shown schematically a neutral beam system employing direct energy recovery of full energy (E) ions in accordance with the principles of the present invention. A light iso-

10 topic species positive ion source 11 is operated at essentially ground potential. The ion source may be mounted to a vacuum enclosure 13 for the beamline system by means of an electrical insulator and vacuum seal assembly 15. A plasma is generated in the source 11 containing the selected species positive ions (in the present case, hydrogen ions)

15 which is accelerated by means of a V_{accel} power supply 19. The value of the acceleration voltage V_{accel} will depend upon the beam energy requirements and the ion source capability. For the illustration here V_{accel} is 40 kV, which is typical for heating plasmas in the Princeton Large Torus or Impurity Study Experiment Tokamak.

20 The V_{accel} source 19 is connected between ground and the extraction grid 17 of the source 11 so that the grid is biased negative with respect to ground. A slight boost voltage (V_{boost}), typically less than 4 kV, is applied by means of a power source 21 connected between ground and the plasma grid 23 of the ion source. The exit grid 25 of

25 the ion source 11 is connected electrically to a gas neutralizer cell 27. The gas cell 27 and the exit grid 25 are operated slightly posi-tive relative to the extraction grid 17, typically 1 kV (V_{decel}), to

prevent electrons generated in the neutralizer cell 27 from drifting back into the ion source 11. This may be accomplished by resistively dividing the voltage from the power source 19 by means of appropriate resistors, R_1, R_2, and R_3. When the power source is pulsed on, an

5 electric current flow through these resistors, thus providing the appropriate potentials. These voltages between various electrodes are slightly modified when ions are extracted.

It will be obvious that these voltages may be provided by separate power supplies floating on the V_{accel} power source 19 to minimize the

10 power loss associated with the current drained through the resistors.

Conversion of the accelerated ions into neutrals occurs inside the neutralizer 27 at a high negative potential. The neutral beam thus produced then travels through an evacuated drift duct 29 coupled to a neutral beam utilization device such as a fusion device 31. The

15 unneutralized residual ions exiting the neutralizer experience first the magnetic bending force and then the retarding electric field developed between the neutralizer and the surroundings as illustrated in Fig. 2. Any ions arriving at the surrounding ground potential surface constitute an energy recovery, the kinetic energy of each recovered ion

20 being only eV_{boost}. However, the crux of the problem in direct energy recovery concerns the electrons produced inside the neutralizer at high negative potential since the electric field is such that it attracts electrons toward the ground potential. These electrons loosely contained by the space charge field of the ion beam itself are prevented

25 from leaking upstream toward the ion source by means of V_{decel} between grids 17 and 25. Blocking the electrons from exiting through the downstream opening of the neutralizer is the key solution for the success of energy recovery.

. To accomplish electron blocking and ion deflection, a magnetic
field is provided transverse to the beam in the exit end of the neutra-
lizer tube 27. Referring now to Fig. 3 in conjunction with Fig. 1, it
will be seen that the magnetic field (B) is provided by means of

5 electromagnetic pole pieces 33, composed of pieces 33a and 33b, or
equivalent magnetic field-producing means in juxtaposition across the
beam path in the exit end region of the neutralizer 27, as shown more
specifically in Fig. 3. The magnetic field may be varied to obtain the
proper field strength to block the exit of electrons. The magnet pole

10 pieces may be tilted at a 45° angle, as shown in Fig. 1 and Fig. 3, but
a right angle orientation of the magnets as shown in Fig. 4 is
preferred.

In accordance with the present invention, the exit region of the
gas cell 27 is modified to provide more efficient energy recovery of

15 the full energy ions. The end structure in the exit region is an
electrically conductive metal box 37 with its forward (downstream)
sides open for the passage of the neutral beam and the deflected full
energy ions. The box 37 is formed of a nonmagnetic material such as
copper. The downward extending side plates of the box structure

20 parallel to the magnetic pole pieces overlap most of the magnet pole
faces. With this geometry, both the electrons and residual ions within
the extended neutralizer end structure experience the transverse magne
tic field alone in the absence of any strong electric fields. An
electron-collecting ring 39 is fastened around the opening downstream

25 end of the box structure 37 by means of insulators (not shown) and
extends a few centimeters beyond the opening. The collector 39 is also
nonmagnetic and conforms to the open end geometry of the box 37.

The separation of the beam plasma electrons and the residual energetic ions begins at the entrance to the magnetic region in the exit structure of the neutralizer 27. Electrons tend to gyrate along the transverse magnetic flux lines, whereas ion trajectories are only

5 bent. Any electric field owing to the ions moving away or to electric field penetration through the open downstream end of the end structure 37 is approximately perpendicular to the magnetic field, producing only $\overline{E}x\overline{B}$ drifts of the electrons. Thus, electrons within the exit region eventually terminate either on the gas cell wall or at the collector

10 ring 39 which is biased slightly positive with respect to the neutralizer cell 27 for sufficient attraction of the drifting electrons. This bias is provided by connecting the collector ring 39 to a voltage divider network formed of resistors R_2 and R_3. The electron collector 39 voltage is approximately one kilovolt positive with respect to the

15 neutralizer cell 27. The full energy ions are immediately decelerated upon leaving the exit end of the neutralizer cell and their charge is collected at ground potential. It will be appreciated that the entire ground potential enclosure may be used for collecting these full energy ions and recovering their energy. The small positive (V_{boost}) poten-

20 tial from the power source 21 applied to the ion source plasma grid 23 ensures that the full energy ions deflected from the neutral beam have sufficient potential energy to reach the grounded collecting surfaces.

As pointed out above, the residual ions exiting the neutralizer cell 27 into the exit end structure 37 are not all full energy (E) ions

25 but contain fractional energy ions due to molecular ions of the gas species entering the neutralizer from the ion source. In the case of a hydrogen source, as exemplified here, molecular ions (H_2^+ and H_3^+)

extracted from the source 11 along with atomic ions (H_1^+) are dissociated
into atomic particles as they pass through the neutralizer cell 27.
These particles have energy of one-half (E/2) and one-third (E/3)
respectively, of the original acceleration energy (E) and thus cannot

5   reach the ground-potential surfaces on which the full energy ions are
collected. Therefore, these ions are deflected from the beamline about
substantially shorter radii than that of the full energy ions. This is
illustrated in Fig. 4. If these ions are allowed to enter the vacuum
region outside the neutralizer cell they tend to strike the outer wall

10 of the neutralizer releasing their energy and generating secondary
parasitic electrons. Since these electrons are born at the high nega-
tive potential, they will be accelerated to ground, detracting from the
energy recovery. Under a proper range of magnetic field strengths, the
lower-energy ions (E/2) and (E/3) are reflected into the inside walls

15 of the gas cell formed by the downward extending end structure 37.
Thus, electrons emitted from these fractional energy ions striking the
inside wall of the neutralizer cell are blocked in the same way for the
neutralizer electrons and collected by the electron collector ring 39
and do not exit with the full energy ions to degrade their energy

20 recovery. The full energy ions are deflected from the neutral beam and
leave the gas cell through the open downstream end. Another purpose of
the downward extending structure is to minimize the loss of full energy
ions on the wall caused by the magnetic bending.

The magnet pole pieces 33 need not be oriented at the approxi-

25 mately 45° angle shown in Fig. 1. As illustrated in Fig. 4 the magnet
pole pieces 33' may be oriented vertically with added advantages such
as the shorter downstream length and the simpler particle trajectories.

The dimensions of the magnet poles, the magnetic-field strength, and
the geometry of the gas cell end structure are the primary parameters
to vary in order to enhance the energy recovery for various kinetic
energy levels. The electron collector is not shown in Fig. 4, but
would be placed at the end of structure 37 as in Fig. 1. It will
be noted that the top-side of the gas cell end structure 37 is extended
for the additional purpose of intercepting negative ions that are pre-
sent in the beam as a result of charge-exchange collision processes
along the neutralizer.

10   In operation, a system electrically biased, as shown in Fig. 1 and
illustrated in Fig. 2, extracts ions from the ion source plasma genera-
tor 11 and accelerates them into the neutralizer cell 27. The residual
full energy ions whose energy is to be recovered are magnetically
deflected downward in the absence of any strong-retarding electric
15   field. The fractional energy ions, whose energies are too low to be
recovered, are controlled by the magnetic field alone and are reflected
back into the interior wall of the gas cell formed by the downward
extending portion of the end structure 37. The secondary electrons
produced by the fractional energy ions striking the inner surface of
20   the structure 37 are thus contained within the gas cell extension. The
geometry of the gas cell extension 37 maximizes the escape of the full
energy ions from the gas cell onto the ground potential recovery
surfaces. Further, its open structure assists the pumping of hydrogen
gas that streams out the gas cell exit.

25   The energy loss due to the termination of the electrons on the
collector 39 is less than one keV per electron. The recovered ions
impart only an energy corresponding to the boost voltage, which is kept
as low as possible and lies between 2% and 10% of V_{accel}. The primary

role of the boost voltage is to ensure that the full energy ions exiting the gas-cell have enough energy to reach a grounded surface rather than reflect back into the neutralizer cell. Secondary electrons generated from the ground surface upon impingement of the

5. recovered ions do not pose a problem since they are born approximately in the electric field-free region at ground potential.
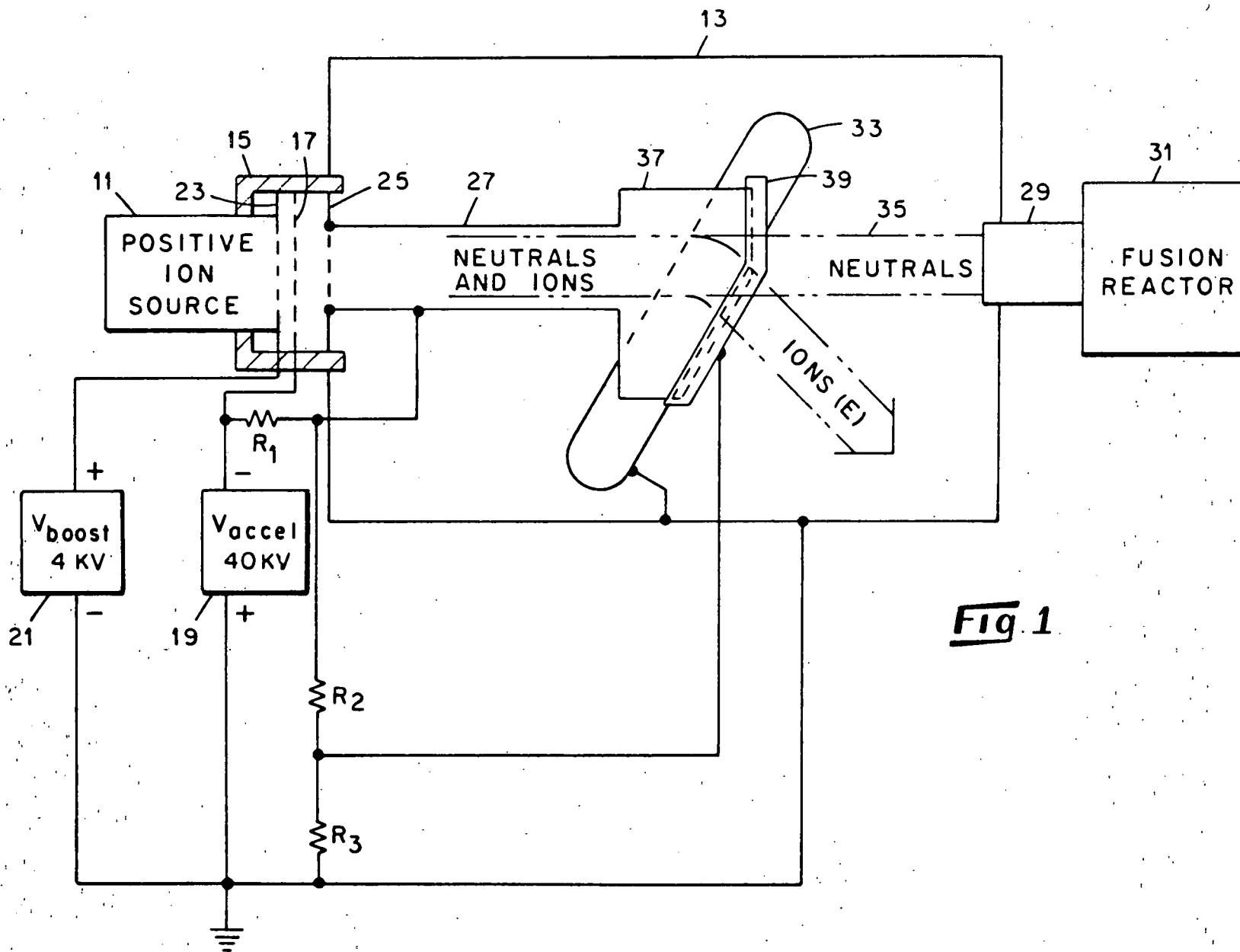
As pointed out above, various light isotopic species may be used for the source of ions to be generated depending upon the particular reactor application requirements. The full energy ions are of primary

10 interest for the purpose of energy recovery in accordance with this invention since the fractional energy ions cannot easily be recovered simultaneously. It is therefore desired to employ an ion source that can produce high atomic ion fraction in the beam. The ion source used in this example typically yields the atomic hydrogen ion species of 80

15 to 85%. In an experiment set up as shown in Fig. 1 to show the feasibility of this invention, an average full-energy ion recovery efficiency of about 80% was observed.
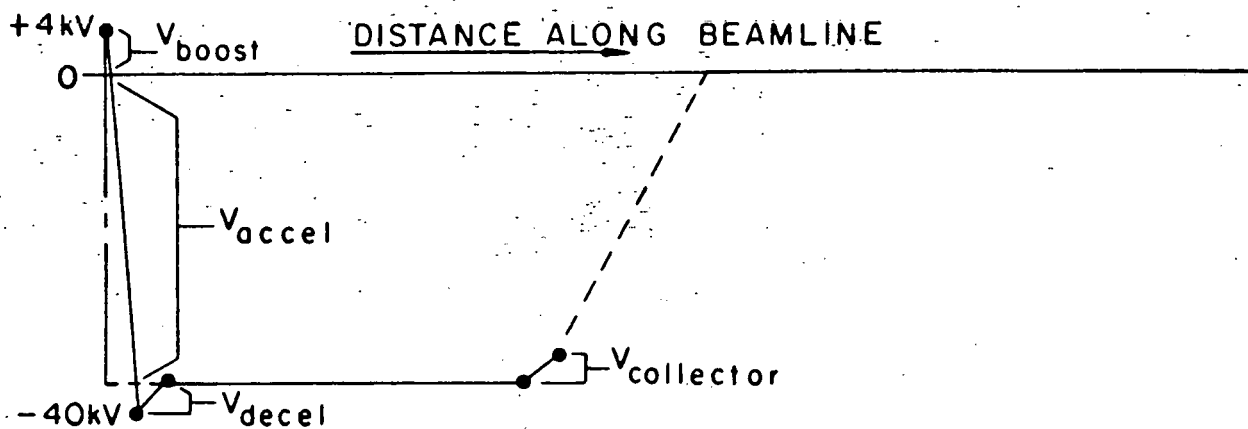
The foregoing description of a preferred embodiment of the invention has been presented for purposes of illustration and description.

20 It is not intended to be exhaustive or to limit the invention to the precise form disclosed, and obviously many modifications and variations are possible in light of the above teaching. The embodiment was chosen and described in order to best explain the principles of the invention and its practical application to thereby enable others skilled in the

25 art to best utilize the invention and various embodiments and with various modifications as are suited to the particular use contemplated. It is intended that the scope of the invention be defined by the claims appended hereto.
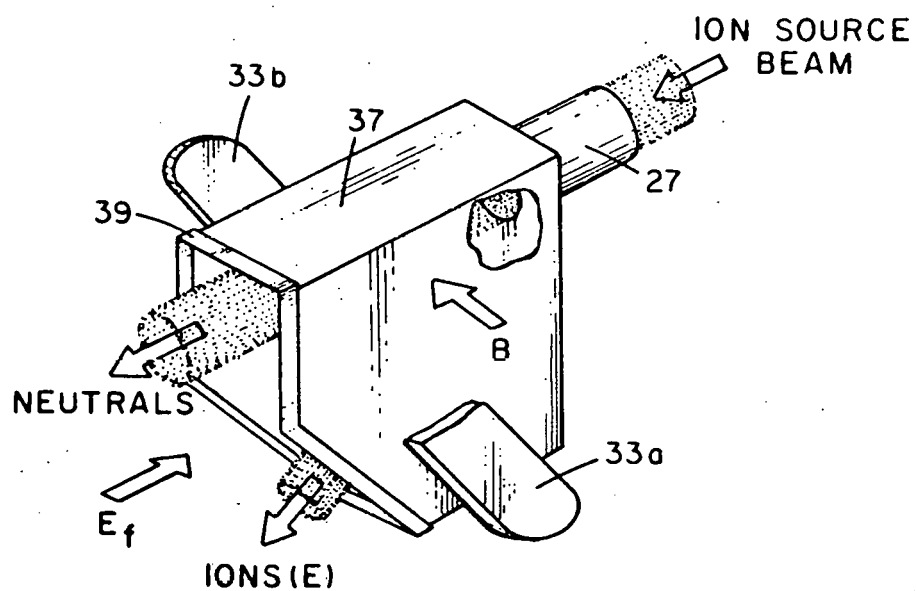
NEUTRAL BEAMLINE WITH IMPROVED ION ENERGY RECOVERY

Abstract of the Disclosure

A neutral beamline employing direct energy recovery of unneutral-
ized residual ions is provided which enhances the energy recovery of
5   the full energy ion component of the beam exiting the neutralizer cell,
and thus improves the overall neutral beamline efficiency. The
unneutralized full energy ions exiting the neutralizer are deflected
from the beam path and the electrons in the cell are blocked by a
magnetic field applied transverse to the beam direction in the neutral
izer exit region. The ions which are generated at essentially ground
potential and accelerated through the neutralizer cell by a negative
acceleration voltage are collected at ground potential. A neutralizer
cell exit end region is provided which allows the magnetic and electric
fields acting on the exiting ions to be loosely coupled. As a result,
15 the fractional energy ions exiting the cell are reflected onto and
collected at an interior wall of the neutralizer formed by the modified
end geometry, and thus do not detract from the energy recovery effi-
ciency of full energy ions exiting the cell. Electrons within the
neutralizer are prevented from exiting the neutralizer end opening by
20 the action of crossed fields drift ($\overline{E} \times \overline{B}$) and are terminated to a
collector collar around the downstream opening of the neutralizer. The
correct combination of the extended neutralizer end structure and the
magnet region is designed so as to maximize the exit of full energy
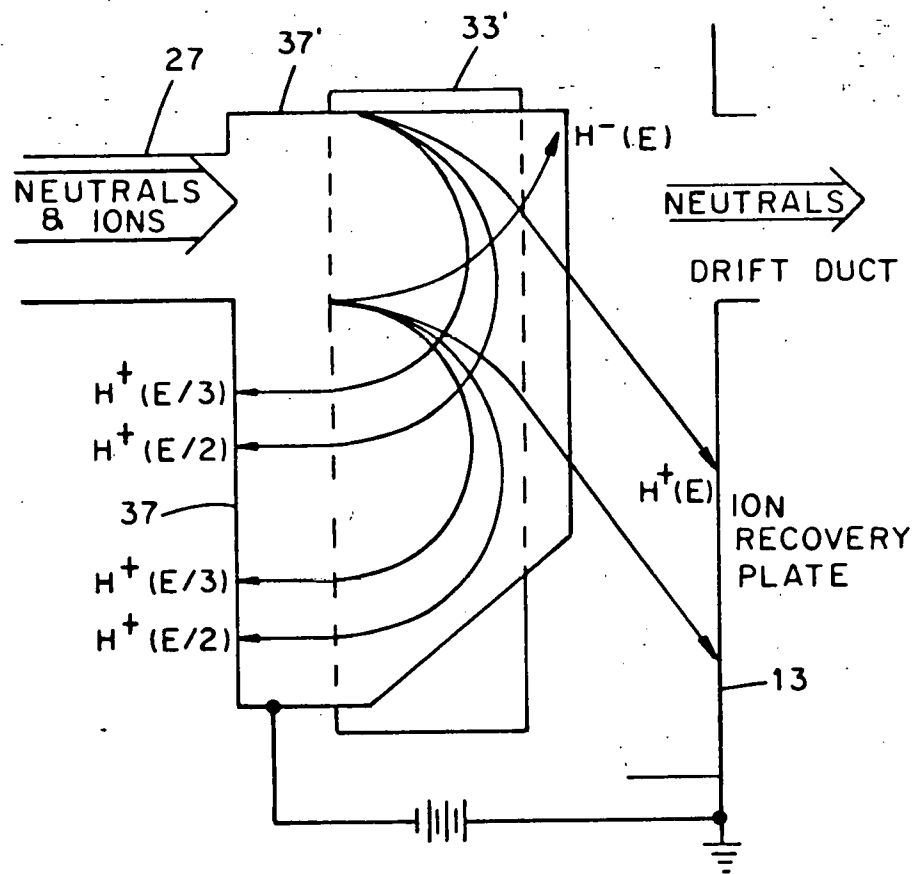ions and to contain the fractional energy ions.

POSITIVE
ION
SOURCE

NEUTRALS
AND IONS

NEUTRALS

FUSION
REACTOR

IONS (E)

V_{boost}
4 KV

V_{accel}
40KV

R_1

R_2

R_3

Fig.1

Fig. 2

Fig. 3

*Fig.*4