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SELF-MODULATING, PARTIALLY REENTRANT CROSSED FIELD AMPLIFIER

Filed April 22, 1969

Fig. 1

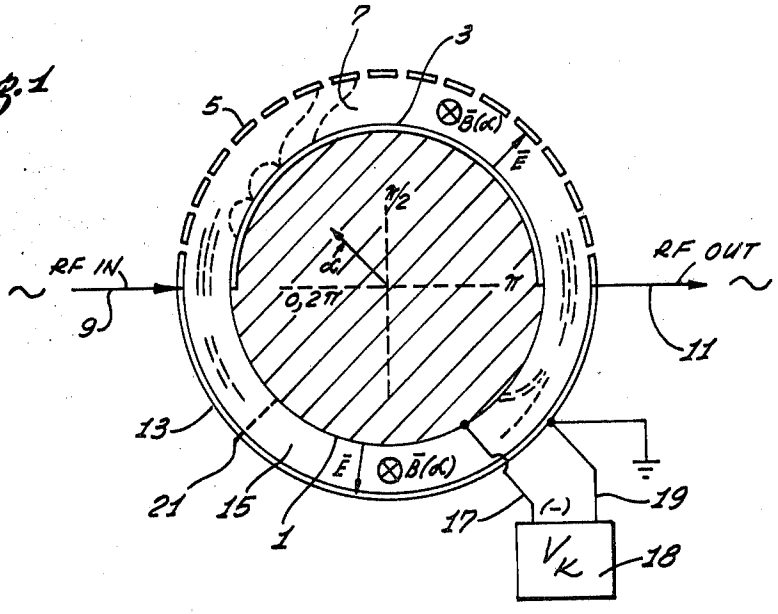


Fig. 2

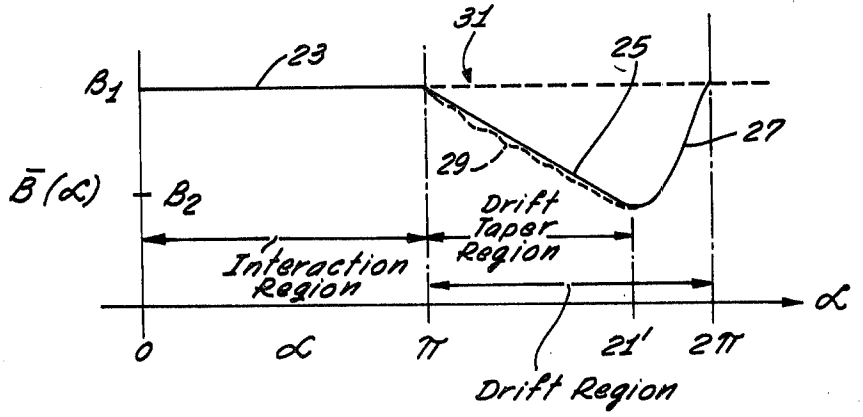
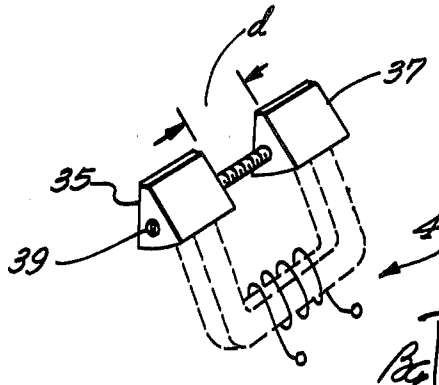


Fig. 3



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SELF-MODULATING, PARTIALLY REENTRANT CROSSED FIELD AMPLIFIER

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ABSTRACT OF THE DISCLOSURE

A cold cathode distributed emission reentrant type crossed field amplifier is provided which possesses electrical efficiencies approaching that available in the reentrant type crossed field amplifiers of the prior art but which features the simplicity of the non-reentrant type crossed field amplifier. A circular configuration is used for the tube; one in which the beginning and end of the interaction region is connected with the drift space region, so as to form a complete annular passage abou the sole and cathode. The magnetic structure produces a magnetic field at the programmed level, which may be constant, in the interaction region and in addition provides a variation in the drift space. At the entrance to the drift space the magnetic intensity decreases as a function of position along the length of the drift space from the programmed level, gradually, over a predetermined length of the drift space to a second lower predetermined intensity. Along the remaining length of the drift space the field intensity increases in level until at the end of the drift space, coincident with the beginning of the interaction region, the magnetic field intensity is again at the programmed level. The tapering of the magnetic field in the drift space region is designed so that it diverts significant amounts of those electrons that pass through the interaction region and enter the drift space region. Hence, the remaining electrons which reenter the interaction region are insufficient in quantity or energy to cause self-oscillation after the RF drive signal has been removed.

This invention relates to cross field amplifiers and, more particularly, to cold cathode, distributed emission, forward wave cross field amplifiers.

Distributed emission crossed field amplifiers have heretofore been available in either reentrant or non-reentrant beam configurations for the purposes of amplifying very high frequency pulse signals generally used in laboratories or radar systems. The non-reentrant beam configuration, familiar in the linear format such as the Dematron sold by Litton Industries of San Carlos, Calif., is of a structure which includes a length of slow wave structure spaced from and confronting a length of high secondary emission material forming a cold cathode. The space between those elements is defined as the interaction region. Side by side with the cathode and slow wave structure and spaced apart by a distance substantially the same as that of the interaction region is a sole and a collector electrode. The space formed between the latter two elements is defined as the drift space. An electric field is applied between the cathode and slow wave structure and a magnetic field is applied perpendicular or crossed to the electric field. In such a linear configuration the electrons generated due to the application of an RF drive signal to the slow wave structure forms a beam, effectively, over the surface of the cathode in the interaction region.

In such non-reentrant configuration the crossed field amplifier becomes completely self-modulating. That is, the electron beam obtained by electrons from the cold

secondary emission cathode is automatically "turned-on" by the input RF drive signal and is "extinguished" a few nanoseconds after the RF drive signal ceases.

On the other hand the reentrant beam crossed field amplifier is of a circular configuration in which the interaction region and the drift space form a continuous ring like circular passage about a cylindrical shaped sole and cathode. The slow wave structure confronts a length of cathode and both are shaped as arcs of a circle. Complementary circular arcs are formed by the space confronting the sole and collector electrodes to form an annular passage.

In present reentrant type crossed field amplifier configurations a portion of the sole is removed and a control electrode is inserted therein electrically insulated from the sole. This element is connected to a source of high voltage pulses. An RF drive signal applied to the input of the slow wave structure "turns-on" the electron beam in the same manner as the non-reentrant tube. However, in the operation of this device part of the electron beam generated in and passing through the interaction region continues out the end of the interaction region around into the drift space and therearound back into where they reenter the interaction region. When the RF signal is extinguished or removed, however, the movement of electrons through the interaction and drift space regions continues in a self-limited, self-generating condition. In short, when the drive signal is removed the tube commences oscillation and continues to oscillate unless the control or "shut-off" electrode is properly energized.

Accordingly, to operate existing reentrant tube configurations a high voltage pulse generator or modulator is connected to the control electrode which is synchronized with the RF drive signal so that when the RF drive signal is removed the modulator applies a large voltage pulse to this control electrode. That voltage appears across the drift space and, under the influence of this high voltage, the beam of electrons traveling through the drift space is diverted from its path of travel to the control electrode. Inasmuch as those electrons have been diverted and cannot then reenter the interaction region, tube oscillation stops. Thus, proper operation of present reentrant type crossed field amplifiers requires that a control electrode be included and that the electron beam be shut off at the termination of each RF drive pulse.

Because many electrons do not fully interact with the electromagnetic fields in the interaction region of the non-reentrant type cross field amplifier and continue into the drift space with some potential energy, they cannot be collected at cathode potential and their energy is dissipated at the collector. It is estimated that approximately 35% of the energy available in the electrons is not fully utilized in the interaction region and is isdissipated as wasted energy in the collector. Accordingly, in contrast to the reentrant format where electrons continue to circulate around and around through the interaction and drift space the non-reentrant format results in a lower electrical efficiency.

By contrast the reentrant type crossed field amplifier, although more efficient than the non-reentrant type, continues to oscillate unless the shut-off or control voltage is applied to an additional shut-off or control electrode. As explained, this requires both additional equipment and tube structure which makes the construction of a complete amplifier system more complex, heavy, and expensive.

Accordingly, it is an object of this invention to provide a crossed field amplifier having an efficiency approaching that of the reentrant type crossed field amplifier but which does not require the additional control or shut-off electrode required in reentrant type tubes.

It is a further object of the invention to provide a reentrant type crossed field amplifier having the self-extinguishing characteristic of the linear format non-reentrant crossed field amplifier without the use of a shut-off electrode and synchronized modulator.

Briefly, in accordance with the invention a cold cathode distributed emission reentrant type crossed field amplifier is provided in which a circular configuration is employed. The interaction region and drift space regions form an annular passage about a cylindrical core surface containing both the cathode and sole electrodes.

A magnetic field structure is provided which sets up an axial magnetic field of a substantially constant level, the level which results in optimum interaction, in the interaction region. In addition, the magnetic structure provides a field along a predetermined length of the drift space region commencing from the juncture with the interaction region that positionally decreases in intensity from the optimum intensity level applied in the interaction region to a second lower magnetic field intensity. Additionally, in the remaining portion of the drift space region the magnetic field thereafter positionally increases in level until the optimum level is again reached at the end of the drift space region and entrance of the interaction region.

The foregoing and other advantages and objects of the invention become apparent from the following detailed description taken together with the figures of the drawing in which:

FIG. 1 schematically illustrates a reentrant cross field amplifier which embodies the principles of the invention;

FIG. 2 is a graphic illustration showing the change in magnetic field intensity with angular distance in the interaction and drift space regions of the cross field amplifier of FIG. 1; and,

FIG. 3 illustrates a pole piece which is adjustable to vary the magnetic field therebetween which may be utilized in a mechanically complete assembly which incorporates the principles illustrated in FIG. 1.

The novel crossed field amplifier schematically illustrated in FIG. 1 employs a circular format in which a cylindrical core body includes a first accurate length cylindrical surface **1** that forms a sole electrode. Sole electrode **1** extends about the core axis a distance of π radians. An accurate length of a cylindrical layer of cold cathode high secondary emission material, suitably tungsten matrix, extends about the core axis, complementing the sole electrode, a length of π radians, and forms the cathode **3**. The cathode **3** and sole electrode **1** are formed on the same metallic core and thus are at a common electric potential. Spaced from and surrounding cathode **3** is a semi-circularly shaped slow wave structure **5** which also extends over a length of π radians. It is noted that in other embodiments the slow wave structure and interaction region, hereinafter discussed, can be made up to $3/2\pi$ radians in length, as may be desired. Slow wave structure **5** is of any conventional forward wave type which supports propagation of a slow electromagnetic wave. The space **7** separating slow wave structure **5** and cathode **3** is termed the interaction region. Input coupling **9** represents conventional means for coupling electromagnetic energy such as microwave energy to the input end of slow wave structure **5**. Likewise, an output coupling **11** is provided to couple microwave energy from the output end of slow wave structure **5** to suitable external equipment in which the amplified signal is used.

A metallic wall or collector electrode **13** similarly cylindrically shaped is spaced from and confronts the sole electrode surface **1**. Collector electrode **13** is joined at its ends to the input and output ends of the slow wave structure **5** and is suitably π radians in length to complement the slow wave structure. The annular space **15** formed between collector **13** and sole electrode **1** is termed the drift space. Together region **7** and drift space region **15** form a complete circular or annular space around the cylindrical surface which includes sole electrode **1** and cathode **3**.

The mechanical details of this schematic structure are known and obvious to those skilled in the art. Suitably the elements described are enclosed in a metal and ceramic housing which is evacuated of air and sealed so that both the interaction and drift space regions are essentially a high vacuum. Likewise the details of the sockets used to form the electrical input and output couplings **9** and **11** are also well known as are the sockets for applying the high voltages to the elements as hereinafter described. A coupling lead **17** is connected between sole **1** and the negative terminal of a high voltage power supply **18**. Another coupling lead **19** connects collector electrode **13** to the positive terminal of high voltage supply **18** which in turn, as is illustrated, is grounded. With the high voltage applied a radially directed electric field is formed between the cylindrical shaped center structure and the other surrounding portions of the tube, this is denoted in FIG. 1 by the symbol E adjacent the radially directed arrow. In particular, the electric field is radially directed in the interaction region between cathode **3** and slow wave structure **5** and in the drift space region between sole electrode **1** and collector electrode **13**.

Additionally, a magnetic field structure which includes conventional permanent or electromagnets and pole pieces are provided to establish a magnetic field B in both the interaction region **7** and drift space region **15**. The magnetic field is "programmed" to provide predetermined field variations in the cited regions. This magnetic field is applied perpendicular or "crossed" to the electric field and is essentially parallel to the cylindrical axis of sole electrode **1**. Conventionally this direction of the magnetic field is denoted by an arrow, the symbol $\otimes$ which is directed perpendicular to the surface of the drawing. The intensity of this magnetic field is represented by $\overline{B}(\alpha)$; the (α) represents that $\overline{B}$ is a function of angular position as hereafter explained. In the interaction region the intensities of the magnetic field and the electrical field are suitably chosen in accordance with well known design principles to permit maximum interaction between electrons emitted from cathode **3** and any RF energy applied to and propagating along the slow wave structure **5**. In the interaction region of this embodiment $\overline{B}(\alpha)$, the magnetic field intensity therein, is a substantially constant value, B_1, throughout. However, in other embodiments suitable variations in magnetic field intensity in the interaction region can be programmed to optimize, gain, bandwidth, etc.

In drift space region **15** magnetic intensity $\overline{B}(\alpha)$ is functionally dependent upon the position within that region. This positional dependence or functionality may be related to the angular distance, α, about the axis of sole **1** from the zero radian position represented in FIG. 1 or it may be represented by actual length along the drift space region which is essentially equal to $R\alpha$, where R is the average radius from the cylindrical axis to the middle of the drift space region.

Commencing from the entrance of the drift space region adjacent the end of the interaction region and proximate output coupling **11**, the magnetic field intensity $\overline{B}(\alpha)$ decreases gradually as a function of position therealong into the drift region from the optimum value B_1 provided in the interaction region to a second lower level B_2 of intensity at a second predetermined position along the drift space region. This second position in drift space region **17** is represented as **21**. From there the magnetic field intensity $\overline{B}(\alpha)$ commences increasing in intensity as a function of position from that point increasing in level until it reaches again the optimum intensity level B_1 at the entrance to the interaction region **5** adjacent input coupling **9**.

The variation in magnetic field intensity throughout the interaction and drift space region provided by the magnet structure is better understood by considering the graph of FIG. 2. The magnetic field intensity $\overline{B}(\alpha)$ is plotted

as a function of the angular position in radians (α) from the input to the interaction region, the zero, around to the end of the sole electrode at 2π radians. Ideally between zero and π radians, which coincides with the relative length of the interaction region **7** in FIG. 1, the magnetic field intensity throughout is plotted as **23**. This plot is substantially a straight line at a constant value B_1 on the ordinate. Commencing at π radians the magnetic field intensity $\overline{B}$ decreases gradually as a function of position along the drift space and is represented in the graph by the portion of the curve labeled **25**. The magnetic intensity $\overline{B}(\alpha)$ decreases from level B_1 to a second predetermined lower level B_2 in what is now termed the drift taper region. The position at which the minimum field intensity B_2 is reached is represented on the abscissa as location **21'**. This corresponds to the location **21** in the schematic illustration of FIG. 1.

Continuing from that position, the magnetic field intensity $\overline{B}(\alpha)$ increases between **21'** and 2π radians until the optimum level B_1 is again attained at the location corresponding to the zero radian or interaction region input as is represented by that portion of the plot labeled **27**.

Although the magnetic field intensity, as hereinbefore described, decreases gradually ideally it does so in a smooth manner. However, because of the necessity for using discrete pole pieces of finite dimension to obtain this field variation, as hereinafter described in this embodiment, the magnetic field intensity therealong may decrease in a series of less than linear transitions labeled in the figure as curve **29**. The net effect is believed to remain the same. For purposes of comparison, reentrant type crossed field amplifier tubes of the type heretofore available used in a magnetic structure which provided a constant magnetic field intensity of level B_1 throughout both the interaction and drift space regions. Such a result is illustrated in the drift region by the dashed line **31** which is essentially a continuation of the portion of the plot **23** characteristic of the field intensity within the interaction region.

Portions of conventional magnetic circuit structure used to obtain this field variation include suitable pole pieces and magnets schematically illustrated in FIG. 3. However, it is apparent that other available magnetic structures may be used to accomplish the same function and result as that illustrated and may be substituted. Pairs of adjustable wedge shaped pole pieces, such as **35** and **37**, are placed side by side around the interaction and drift space regions. In each pair a screw **39** connects the two pole piece segments together in a familiar track and slide arrangement with which the inner hole within segment **35** is threaded and segment **37** is relatively fixed in position. Accordingly, turning screw **39** clockwise or counterclockwise serves to move segments **35** closer together or farther apart to define the magnetic gap D. One of the segments in each pair is magnetically connected with the north and the other segment the south pole of a magnet structure **40**.

The back side of segment **35** abuts the magnet pole of magnet **40** so that the two are slidable relative to one another. In this manner the gap D may be varied to vary the intensity of the magnetic field B across the underlying portion of either the interaction or drift space where this particular pole piece pair is postoned. It is also possible in the alternative to use a plurality of individual electromagnets spaced about the interaction and drift space and to maintain a fixed gap D. In that construction the magnetic intensity is varied by varying in intensity the current through the electromagnet coil. The chief advantage of the former structure, however, is that while the magnetic arrangement **40** is illustrated connected to a single pair of segments it can be manufactured readily so that it energizes a plurality of segments and, perhaps, all pairs of pole piece segments used in either region. Those segments about the interaction region are all adjusted to provide the same intensity; whereas, those about the drift space are separate a greater amount to provide the magnetic intensity arrangement described.

The mode of operation of cold cathode distributed emission crossed field type amplifiers is well known and is amply described in the literature. The theoretical mechanism for starting operation of the amplifier is essentially the same in this as it is in both the reentrant and non-reentrant amplifier types found in the prior art. Namely, the electric and magnetic field intensities within the interaction region are sufficent in intensity to cause interacton between electrons emitted from the surface of cathode **3** and an RF or electromagnetic field traveling from the input **9** to the output **11** of slow wave structure **5**. Initially however, under the influence of the electric field E alone is insufficient to cause emission. For one reason or another it is a known physical phenomenon that electrons in a random manner move off of cathode surface **3** into interaction region **7**. Because of the electric and magnetic field intensities, such electrons travel in a cycloidal pattern and return to the cold cathode surface. Because the cathode is of high secondary emission material the returning electron in turn may knock out another electron which goes through the same motion. However, the electric and magnetic fields are such that by themselves almost none of the electrons can progress across the interaction region to slow wave structure **5**.

When an RF drive signal is coupled to the input of slow wave structure **5** via the input coupling **9**, an additional electric field is set up in the slow wave structure which adds to that all ready provided by field E. Together these fields give the electrons a greated energy and the available electrons move through a wider cycloidal pattern, however, being of increased energy when they return to the surface of the cathode **3** they knock out more than one electron due to the high secondary emission of the cathode. In a very short time a large number of electrons appear in the interaction region and form a space charge which has the same characteristic of an electron beam and which appears to move through the interaction region. The electric and magnetic fields are such that the electrons move in phase and at substantially the same speed as the propagation on slow wave structure **5**. The conversion mechanism is such that the loss of potential energy in the electron results in a net gain of energy in the RF field. With full interaction the electron loses all of its potential energy and falls into the slow wave structure. Those electrons which do not fully interact and which have some potential energy remaining pass out of the interaction region **5** and into the drift space region where they are subject to the influence of the positionally decreasing magnetic field. In the drift taper region the decreasing field causes some of these electrons to be diverted into the collector **13** while permitting the remainder to travel out of the drift space region and into the interaction region and hence reenter this region. The optimum slope of curve **25**, value of the predetermined lower field intensity, B_2, and its position along the drift space are experimentally determined for each tube since they will vary with tube dimensions, frequency, and power, etc.

Because a substantial number of electrons are turned to the interaction region and are not dissipated in the form of heat, such as occurs to those which fall into the collector **13**, the device is electrically more efficient than the non-reentrant type wherein all the electrons are collected.

When the RF drive signal is extinguished at input coupling **9**, the influence of the RF field in giving greater potential energy to electrons emitted by the cathode **3** is absent. In the prior art reentrant type crossed field amplifiers it was possible for these electrons coming from the drift region to provide sufficient energy to maintain the secondary emission mechanism. However, because the number of electrons coming through in this manner is limited by the diverting action of the magnetic field in the drift taper region and a sufficient number of the electrons

which enter the RF region are by themselves unable causing continued electron emission from the cathode and accordingly the tube ceases operation almost simultaneously with the removal of the RF drive signal.

It is to be understood that the above described arrangements are intended to be illustrative of the invention and not by way of limitation since other arrangements and equivalents suggest themselves to those skilled in the art which do not depart from the spirit and scope of my invention. Accordingly, it is to be expressly understood that the invention is to be broadly construed within the spirit and scope of the appended claims.

What I claim is:

1. A cold cathode distributed emission crossed field amplifier in which an electron beam is generated within an interaction region upon application to the amplifier input of a drive signal to be amplified, said amplifier having a reentrant interaction region wherein a passage for electrons is formed between the output end and input end of said interaction region, said passage being defined as a drift space region; the improvement comprising in combination: a sole electrode which borders said drift space region opposite and spaced from a similarly bordering collector; means providing an electric field between said sole and collector, said electric field being substantially of that same intensity as that which appears in said interaction region; magnetic field means for providing, crossed to said electric field, a magnetic field of intensity B_{ds} where B_{ds} decreases in magnitude in said drift space region from an intensity, B_i, substantially equal to that magnetic field intensity at the output of said interaction region to a lower intensity, B_{MIN}, wihin said drift space region at a predetermined distance from the input end thereof as a continuous function of position along said drift space region for diverting to said collector a portion of electron traveling from said interaction region into said drift space region to prevent reentry into said interaction region of electrons in such quantities as would cause containuance of an electron beam in said interaction region subsequent to removal of said drive signal, whereby said electron beam is extinguished upon removal of said drive signal and the amplifier does not self-oscillate.

2. The invention as defined in claim **1** wherein the magnetic field, B, within said interaction region is substantially constant and substantially equals B_i.

3. The invention as defined in claim **1** wherein said magnetic field B_{ds} increases in intensity as a function of position along said drift space region from said predetermined position to the input end of said interaction region.

4. The invention as defined in claim **2** wherein said magnetic field B_{ds} increases in intensity as a function of position along said drift space region from said predetermined position to the input end of said interaction region.

5. In a cold cathode distributed emission type crossed field amplifier in which an electron beam is generated in response to the application at an input of a signal to be amplified the combination including: a cylindrical surface having a circular cross section; said cylindrical surface including an electron emissive material, having a high coefficient of secondary emission, extending about an arcuate portion of said surface periphery to form a cold cathode; and presenting a metallic surface covering the remaining arcuate length of said cylindrical surface periphery to form a sole electrode; said sole electrode and said cathode being electrically in common; a slow wave structure spaced from and extending about said cathode and forming in the space therebetween an interaction region; a metallic wall forming a collector electrode spaced from and extending about said sole electrode to form in the space therebetween a drift space region; said slow wave structure and said collector forming with said sole electrode and cathode an annular passage about said surface periphery which comprises said interaction and drift space regions; means for establishing an electric field, E, radially between said cylindrical surface and both said surrounding slow wave structure and said collector; magnetic field means for establishing a magnetic field in a direction parallel to the axis of said surface and perpendicular to said electric field in both the interaction and drift space regions; said magnetic field means including first means for establishing a first magnetic field, B_i, in said interaction region and second means for establishing a second magnetic field, B_{ds}, in said drift space region which decreases in intensity as a continuous function of distance along said drift space region from B_i, the level of magnetic field at the output of said interaction region, to a second predetermined lower value, B_i, at a predetermined position within said drift space region and which thereafter increases as a function of position along said drift space region to a level of B_i, the magnetic field level at the input of said interaction region, for diverting into said collector a sufficient portion of electrons traveling into said drift space region from said interaction region to prevent reentry into said interaction region of such quantities of electrons as would sustain generation of an electron beam subsequent to removal of the signal to be amplified from an input means; input means for coupling input signals at one end of said slow wave structure; and output means for coupling amplified signals from the other end of said slow wave structure; whereby said crossed field amplifier supplies an output signal only during the application of a signal to the input means and such output signal ceases upon the removal of said applied signal.

6. The invention as defined in claim **5** wherein the magnetic field, B, within said interaction region is substantially constant and substantially equals B_i.

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