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(54) NUCLEAR FUSION REACTORS

(71) I, BOGDAN C. MAGLICH of
90 Bertrand Drive, Princeton, New Jersey,
United States of America, a citizen of the
United States of America, do hereby declare
the invention, for which I pray that a patent
may be granted to me, and the method by
which it is to be performed, to be particularly
described in and by the following statement:—

This invention relates to nuclear fusion
reactors, and more particularly, but not
exclusively, to a method of and means for
deriving electrical power from nuclear fusion
produced by the self-colliding of the ions
within a mixture of accelerated ions of like
charge in a magnetic field.

In the field of nuclear energy and nuclear
power generation, it is advantageous to use
the nuclear process in which two ions (nuclei)
collide and form, as a result of their inter-
action, new ions (nuclei), the sum of whose
masses is smaller than the sum of the masses
of the two original colliding ions, the mass
difference being converted into the kinetic
energy of the new ions (nuclei).

Various means have been proposed to this
end comprising the systems described in the
review: "Controlled Fusion Research and
High Temperature Plasmas" published in
Annual Review of Nuclear Science Vol. 20
(1970), p. 509, et seq. However, these and the
other systems proposed or attempted here-
tofore are based on a plasma thermonuclear
approach; that is, they employ various means
to heat neutral or nearly neutral mixtures of
positive and negative ions (nuclei, molecules
and electrons) to a high enough kinetic
temperature so that the ions gain sufficiently
high velocities to overcome their electro-
static repulsion and thus undergo the fusion
reaction by collision. None of the hitherto
proposed devices associates self-trapping and
self-colliding features; stable self-confine-
ment for periods of seconds; automatic
multiple traversal and high kinetic tempera-
ture of the order of over a thousand million

degrees needed to produce a sufficient
number of nuclear reactions for the net
production of fusion energy; nor do they
have, because of the relatively high plasma
densities involved, the possibility for con-
version of the fusion energy into electricity in
a simple manner.

Historically, the idea of achieving nuclear
fusion in colliding beams of positively
charged ions is at least 20 years old. The
rejection of the idea is very nearly as old. The
main problem encountered has been that
Coulomb scattering removes particles from
the reacting beam so much faster than fusion
occurs that producing a net power output is
hopeless.

Recently, however, several developments
have occurred which make this old idea look
very attractive. Firstly, the concept of self-
colliding orbits was conceived in 1969 by
R. Macek and B. Maglich and published in
the paper "The Principle of Self-Colliding
Orbits and its Possible Application to π - π
and μ - μ Collisions", published in Particle
Accelerators Vol. 1, p. 121-136 (1970).
Secondly, it was realized that this concept,
originally proposed for collisions of particles
of opposite charges, makes possible mixing of
positively charged particle beams and head-on
collisions of the particles of the same charge
in spite of the fact that they precess in the
same direction. Thirdly it was realized that
this concept makes possible the construction
of a device which produces automatic return
to the reaction region of elastically scattered
particles in one revolution, i.e. instantaneously,
thus increasing the probability of self-
collision between the particles. Fourthly, it
was realized that the vertical and horizontal
focusing in such a self-colliding device is
capable of greatly reducing losses due to
elastic scattering beyond the vertical and
horizontal confinement angle, namely, that
the effect of focusing on the scattering of ions
with residual gas which was originally found

in the accelerator studies and published e.g. by Fisher in "Residual gas scattering, beam intensity and interaction rate in proton storage rings" CERN Report ISR-VAC 167-16, is also applicable to the scattering between accelerated ions in the organized mixture of ions. Fifthly, it was realised that by using deuterons and injecting them into the self-colliding device with a particular range of energies, a breeding effect can be achieved releasing significantly greater ion energy per fusion.

Finally, the first device for colliding beams of nuclei, the CERN Intersecting Storage Rings at Geneva, has provided supporting experimental information on the long-term stabilities of organised systems of colliding positively charged ions in contrast to the well-known instabilities problem with plasmas. In particular it was found empirically, that the removal of the electrons from the colliding system by the use of clearing fields and ultra-high vacuum increases the stability of the colliding beams by a factor of 10^5 (see report of K. Johnsen in Proceedings of 8th International Conference on High-Energy Accelerators - CERN - 1971).

According to the present invention there is provided a fusion reactor comprising:

- (a) means defining an evacuated volume having a central axis and a centre plane normal thereto;
- (b) means for producing a magnetic field within said volume which field decreases with the radial distance from the central axis and increases with the distance along the central axis from the centre plane; and
- (c) means for injecting ions of like charge from the periphery into the vicinity of the centre of symmetry of said magnetic field with induced vertical oscillation and with an initial rate of injection sufficient to produce fusion reactions by the collisions of the resultant orbitally precessing ions with each other.

According to the present invention there is also provided a method for controlled release of nuclear fusion power, comprising the steps of:

- (a) producing a magnetic field within an evacuated reaction volume having a central axis and a centre plane normal thereto, the strength of which field decreases with the radial distance from the central axis and increases with the distance along the central axis from the centre plane so as to induce precession of, and exert radial and axial focusing forces on, orbiting ions within said volume; and
- (b) injecting a beam of ions of like charge from the periphery into the vicinity of the centre of symmetry of said mag-

netic field with induced vertical oscillation and with an initial rate of injection sufficient to produce fusion reactions by the collisions of the resultant orbitally precessing ions with each other.

According to the present invention there is also provided a fusion reactor comprising:

- (a) means for defining an evacuated volume;
- (b) a plurality of cell means within said volume, each having a central axis and a centre plane intersecting normally at a centre of symmetry and means for producing a magnetic field therein which field decreases with the radial distance from the central axis and increases with the distance along the central axis from the centre plane; and
- (c) means for injecting ions of like charge into each of said cell means from the periphery into the vicinity of the centre of symmetry of its magnetic field with induced vertical oscillation and with an initial rate of injection sufficient to produce fusion reactions by the collisions of the resultant orbitally precessing ions with each other;
- (d) said cell means being arranged in a three-dimensional matrix with their central axes and centre planes in substantial alignment.

Embodiments of the present invention include a magnetic field which decreases with the radial distance from its central axis and increases with the distance along the central axis from its centre plane, so that injected accelerated ion beams are mixed in an organised manner in precessing orbits designed so as to make them collide head-on or nearly head-on in the central region of the device continuously and automatically; and ions that have not undergone fusion are continuously and automatically returned by the field to the collision region, thus considerably increasing the collision probability through self-multiplication of collisions by such multiple traversals which may occur on the order of 10^8 per second.

The collision probability is further increased by accelerating (rather than heating) the ions to an energy at which the reaction parameter (the product of the fusion cross-section and the relative ion velocity) is maximized. For example, in the preferred embodiment described below, deuterons are accelerated to an energy of 2.6 MeV which corresponds to a kinetic temperature of collision of over 10 thousand million degrees centigrade; at these energies, the reaction parameter for deuteron-deuteron fusion is about 10^4 times larger than at thermonuclear temperatures.

Additionally in embodiments of the present invention, the properties of the self-colliding

orbits can be exploited to inject and confine the atomic nuclei without external means, namely based purely on their "self-trapping" processes to be described below, thus differing from all other injection and confinement schemes hitherto proposed for fusion devices.

Also in embodiments of the present invention by limiting the injection energy of the deuterons to a particular range, it is possible to achieve a breeding effect such that seven times more ion energy per fusion is released as compared with other ranges of injection energy.

Finally, embodiments of the present invention may have means to maintain the density of the organized ion mixture along with a geometrical configuration of the magnetic field producing coils and the external electrical fields in such manner that the charged nuclei resulting from the fusion reactions may have their energy directly converted into electric energy by a decelerating electric potential outside the magnetic field.

An advantageous consequence is miniaturization in the field of nuclear power sources based on simple elements with sizes of the order of one-inch radius, particularly suited to economical mass production.

For the purpose of the following description the organized mixture of precessing self-colliding orbits of positively charged ions will be referred to as a *migma* (Greek word for mixture). An elemental *migma* fusion power source device disclosed herein will be referred to as a *migmacell*. A *migma fusion reactor* consists of a plurality of *migmacells*.

The invention will now be described by way of example with reference to the accompanying drawings, in which like elements have like references, and

Figures 1a and 1b are graphic diagrams of the shape of a magnetic field B_z as a function of a radius r , and the vertical distance from a center plane z , respectively, for the ion orbits shown in Figure 3a and 3b. The equations describing this field are approximately given by $B_z = B_0 [1 - k (r/R)^2 + 2k (z/R)^2]$ where the constant k is the "field index", less than 1; and B_0 the field at the center; and this field shape can be obtained in a number of ways by combining two or more pairs of coils. Figure 1c is an example of the simplest configuration of coils to achieve the field (the correction coils are not shown).

Figures 2a and 2b present the time sequence of an ion in a precessing orbit of radius a in the magnetic field shown in Figures 1a and 1b, with $R \approx 2a$ = Figure 2c shows the injection of another ion at one-half precession period, $1/2 \tau_p$. Figure 2d illustrates the orbits continued precessing in the head-on collision configuration at the center, with a multiple traversal factor of about 10^8 /sec. For simplicity of presentation, the orbits are drawn as

circles (the true shape of the orbits is shown in Figure 3a).

Figures 3a and 3b are computer drawn deuteron orbits respectively in the horizontal (3a) and vertical (3b) plane in a magnetic field with a field index $k = 0.2$. In Figure 3b the deuteron was scattered through a vertical angle of 10° at the center; its automatic return to the center is facilitated by the focusing properties of the field. Figure 3c shows the vertical oscillations vs time of the deuteron shown in Figure 3b; the small dots are equally spaced markers to correlate the various projections at equal times. Note that large values of r correspond to large values of z .

Figure 4 is a graphic diagram of ion density as a function of the radial distance from the center of the *migmacell* (solid line) and of the current density in a *migma* as a function of said radial distance (dashed line).

Figure 5 is a graphic example of the distribution of the intersecting angles of the deuteron-deuteron collisions in a *migma* orbit configuration such as shown in Figure 3a.

Figure 6 is an example of a graphic diagram of the energy distribution of ions in a *migma* in the laboratory frame of reference for the case of deuterons injected with a kinetic energy of 2.2 MeV and with an energy dispersion of 4%.

Figure 7 is a graphic diagram comparing the distributions of the kinetic energy in the rest frame of a single particle ("effective collision energy") for a *migma* (heavy line) and a plasma (dashed line) in the units of the injection energy.

Figure 8 is a graphic diagram of the deuteron-deuteron reaction parameter $\langle \sigma v \rangle$ (fusion cross section times relative velocity) averaged over a *migma* velocity distribution as a function of the injection energy; the operating points for the preferred embodiment as well as for the thermonuclear region are indicated.

Figure 9 is a graphic diagram showing the ratio of the loss rates to fusion reaction rate in a *d-d-migma* as a function of the injection energy for various loss mechanisms: (a) peripheral multiple scattering, (b) vertical multiple scattering and (c) charge transfer. The line (d) is the ratio of the charged energy release in *d-d* fusion, 0.7 W. over the injected energy 2T, minus 0.3 (the latter term following from the fact that a fraction of the injected energy is carried by the uncharged neutron). To have a net energy generation, the sum of (a), (b) and (c) must lie below (d). A vacuum of 10^{-11} torr is assumed in computing the curve (c).

Figures 10a and 10b are respective top and side schematic diagrams of a *migmacell* system for direct conversion of fusion energy into electricity.

Figure 11a is a top view of a schematic of a

part of a migma fusion reactor showing a portion of two migmacolumns, each of which may comprise 100 migmacells; Figure 11b is a side view of a schematic of part of a migma fusion reactor such as shown in Figure 11a.

Referring first to Figure 2a, the path of an ion 100 circulating in an orbit 101 off center in a magnetic field acting perpendicularly to the plane of the figure is shown. For concreteness, the large circle of radius R may be thought of as a pole tip. The ion orbit 101 has radius $a \approx 1/2 R$.

If the magnetic field is not homogeneous but decreases slightly towards the outside, that is, has the shape given in Figures 1a and 1b, the circular orbit 101 will not close, but will precess about the center of symmetry O_1 , as shown in Figures 2a and 2b. In Figure 2c it will be seen that orbit 101 reverses the particle velocity vector after half a precession period, $1/2 \tau_p$. If a second ion 200 is injected at that time with an orbit 102 as shown in Figure 2c, the two paths 101 and 102 meet head-on at the center O_1 , which facilitates a head-on collision between the ions and results in fusion, if the ions are deuterons or some other ions that can undergo a fusion reaction. The two orbits 101 and 102 continue precessing as shown in Figure 2d, about the center O_1 , maintaining their head-on collision configuration which, in turn, may result in about 10^8 multiple traversals, by the ions per second. This increases their collision probability by the same factor.

The described system of two revolving, and at the same time precessing, particle trajectories is similar to the common household dual-rotor mixer, which combines both the rotor and mixing bowl rotation. The main differences are: (1) the colliding orbits "rotate" in the same direction, which cannot be done in the cited mechanical system without rotor collision; and (2) a migma precesses typically at a rate of about 10^9 RPM, having no moving parts.

A more efficient orbit configuration is shown in Figures 3a and 3b, resulting from particles of like charge which have been continuously injected into the center of the magnetic field for one precession period or more so that the magnetic field region is filled with orbiting particles.

The shape of the magnetic field and the radius of the migma orbits are predetermined so as to produce an *automatic return* to the central zone of all particles, by virtue of horizontal and vertical focusing by the field. Any perturbation to a particle in the central zone, such as caused by scattering between migma particles, will be overcome and the particle restored to its orbit within one revolution period by these forces, regardless of the energy transfer to it (or from it) during the collisions; and regardless of its angle, provided the vertical component of the

perturbation is not above the vertical confinement angle of the device (i.e. the orbital angle with respect to the central plane above which the ion overcome the vertical focusing forces and leaves the migma). This return effect is due to the fact that, contrary to the situation in plasmas, the migma orbits are large compared to the size of the device so that the field gradient across the orbit is large too, and the net focusing forces are felt by the particles in every turn. By way of contrast it should be realized that the gyroradius of plasma orbits is very small so that it takes very many turns of the plasma ion to move from the strong field region into a region of weak field (and vice versa) thus resulting in slow restoring forces.

This return effect is illustrated in Figure 3b for a vertical scattering through $\theta_z = 10^\circ$ and a field of index $k = 0.2$.

This automatic return feature within the closed axially symmetric system makes a migmacell advantageous over the simple concept of two colliding ion beams as used in the previously mentioned CERN Intersecting Storage Rings. By comparison, a migma is the equivalent of an infinite number of colliding beams all intersecting at one point with all crossing angles confined to a single volume.

One simple shape of the magnetic field preferred for the migmacell which has the requisite precessing and focusing properties is given by the equation:

$$B_z = B_0 [1 - k (r/R)^2 + 2k (z/R)^2], \quad (1)$$

where r is the distance from the axis of the field, R measures the physical size of the field, and $k (<1)$ the field index determines both the strength of the vertical focusing and the precession rate.

An example of a simple coil configuration for producing a magnetic field such as given by equation (1) is shown in Figure 1(c). Two pairs of coils 1a and 1b, and 2a and 2b are wound co-axially about a central axis Z in the same direction so as to carry current in the same direction, over respective stainless steel tubes 3a and 3b, and 4a and 4b. The opposing coils in each pair are, equidistantly spaced from each other so as to define a central plane for the system, that is a plane perpendicular to the Z axis and half-way between the opposing surfaces of the respective pairs of coils, which is indicated by the line r in Figure 1c. The intersection of the Z axis with the central plane will be the center of symmetry of the magnetic field and a central zone of the system may be defined as a spherical volume with its center at the center of symmetry and having a radius of about 10% of the radial distance from the center of symmetry to the outer edges of the outermost coils 1a and 1b. Preferably, the opening between the outer edges of the outermost pair of coils 1a and 1b defines a radial angle β of approximately 45° with respect to the center

of symmetry.

A pair of jackets 5 and 6 for conducting cooling agents is disposed about each of these sets of coils. For clarity, these cooling jackets 5 and 6 are only shown disposed about the lower set of coils in Figure 1c, but it will be understood that the system is completely symmetrical about the central plane. The inner jacket 5 may contain circulating liquid helium to facilitate superconductivity in the surrounded coils. The outer jacket 6 may contain circulating liquid hydrogen to facilitate the removal of heat generated by stray ions from the migma which may strike and impart their energy to it.

To provide for clearing fields for low energy electrons, two pairs of metallic plates 7a, 7b and 8a, 8b are disposed within the magnetic field as shown in Figure 1c at suitable electric potentials with respect to one another with polarities as noted in the figure. The combination of the two pairs of plates makes the time average electrical field felt by a precessing ion equal to zero if the right-hand pair of plates 7a, 7b sets up an electric field opposite in sign but equal in magnitude to the left-hand pair of plates 8a, 8b. Each of the plates may be approximately semicircular in plan view.

Superconducting leads 9 and 10 to the respective cooling jackets 5 and 6 as well as the leads 11 and 12 to the clearing field plates 7a and 8a, respectively, are shown in the upper part of Figure 1c only. The stainless steel bar 110 between the leads 9 and 10 provides rigid support.

The precession period τ_p and the revolution period, τ_R , (cyclotron period) are related approximately by:

$$\tau_p \approx \frac{4}{k} \tau_R \quad (2)$$

For the preferred embodiment $k = 0.8$, $a = 2$ cm, $B_0 = 200$ Kgauss, $v = 1.5 \times 10^9$ cm (2.2 MeV deuterons), $\tau_p \approx 3 \times 10^{-8}$ sec. The preferred embodiment will be described in terms of the injection and collisions of 2.2 MeV deuteron ions producing the fusion reactions: $d + d \rightarrow \text{He}^3 + n$ and $d + d \rightarrow t + p$ and releasing about 2.6 MeV per reaction in charged energy on the average. However, all the statements are generally valid for all kinds of fusion reactions for example, $d + t \rightarrow \text{He}^4 + n$ and $d + \text{Li}^6 \rightarrow 2\text{He}^4$.

It is apparent from Figures 3a and 3b that both the radial and vertical density of particles in a migma are highly peaked in the central zone. The migma density that is, ion density, as a function of the distance from the center is shown by the solid line in Figure 4. This is one of the advantageous features of a migma. The particles are concentrated so much in the center where the particles have large relative velocities, v_{12} , that the probability of fusion reactions is greatly enhanced. Typically, 50% of the reactions occur in 2%

of the radius

Hence, a migma may be thought of as a spherical "core" on the order of 1 mm in radius, surrounded by a "cloud" of root mean square radius of about 3 cm which is relatively inert. These dimensions are given for the preferred embodiment (2.2 MeV deuterons in a central field $B_0 = 200$ Kgauss and the field index $k = 0.8$).

Because of the high density and high relative velocities at the center, most Coulomb scattering will occur there. However, since it is a property of the migma configuration that any particle leaving the center will be returned to the center, the losses due to Coulomb scattering will be reduced by orders of magnitude from those that would occur in a colliding beam system. An additional mechanism that reduces multiple scattering losses is the restoring force of the radial and axial focusing of the magnetic field described by Equation (1) and Figures 1a and 1b.

The current density distribution in a migma is also shown in Figure 4 as the dotted line. It should be noted that where the charge density is highest (at the center), the current is zero. The magnetic field due to this current is a negligible perturbation to the guiding field.

A further advantageous feature of a migma is that, while all crossing angles from 0° to 180° are allowed, the average crossing or intersecting angle is about 155° since it is very likely that two orbits will overlap somewhat so that there will be two intersections between them near the center. Thus, the near head-on collision are enhanced. This is shown in the plot of Figure 5.

The energy distribution of particles in a migma is distinctly non-Maxwellian, being very sharply peaked at the injection energy (see Figure 6). The effective energy dispersion which combined the energy and angular spread (emittance) is made sufficiently large to avoid the negative-mass and other known accelerator type instabilities.

The effective kinetic energy of the collision of an ion with injection energy T_1 as seen by another ion of the same mass at an angle α is given by $T_{12} = 2T_1 (1 - \cos \alpha)$. Since the average crossing angle is $\alpha = 155^\circ$, the average effective collision energy is about 4 times the injection energy. As a result, unlike in a plasma, 80% of the particle pairs in a migma collide at an energy greater than the injection energy. This is seen in the plot in Figure 7.

The energy distributions shown in Figures 6 and 7 are true only at the time of injection however. The multiple collisions will gradually spread the spacial extent of the migma, which, in turn, will lead to losses of fast particles and eventually "thermalize" the distribution down to Maxwellian. But, this process is comparatively slow and the fusion energy will be extracted long before this happens.

For instance, the $d-d$ relaxation time for 2.2 MeV deuterons is of the order of 10^3 seconds. In contrast, the present intention is to store and syphon off energy of the order of 1% of the total potential migmacell energy in about 1 second and to refill the migmacell in the same time, thus maintaining the non-thermal energy distribution shown in Figures 6 and 7 by virtue of this continuous regeneration.

An important advantage of the migmacell is that the particles in the preferred embodiment will be injected with energies above 2 MeV as opposed to energies of 1–10 KeV in current plasma machines. Figure 8 shows the benefit of the higher energies in larger fusion parameter $\langle dv \rangle$, where the averaging was done for migma velocity distribution.

It will be noted that two head-on colliding deuterons of 2.2 MeV correspond to about a 10 meV laboratory deuteron incident on a stationary target. In terms of kinetic "temperature" – if it has a meaning here – 10 MeV corresponds to about 10^{11} degrees.

Unlike in a plasma, the kinetic energy of the fusion products is of the same order of magnitude as the kinetic energy of the primary deuterons, thus it can be recuperated by the same technique used to extract the kinetic energy from the fusion products. The relatively low migma density allows the singly charged products to fly out of the reaction volume without interacting. Thus by disposing an array of positively charged plates outside of the reaction volume all their energy can be recovered directly as electrical energy.

Furthermore, by choosing a relatively high kinetic energy for the injected deuterons, the fusion reaction products are highly peaked along the velocity collision direction. Since the collision direction in the central zone lies in (or nearly in) the central plane, and most of the fusion reactions take place in the central zone 90% of the charged fusion products leave the zone within a radial angle of about $\pm 22.5^\circ$ about the central plane, without intersecting with the field coils.

The present fusion method is therefore "non-thermonuclear" because no attempt is made to heat the ionized deuterium gas to thermonuclear kinetic temperature, 1 to 10 KeV. The present method starts with accelerated ions about 1,000 times more energetic and in the form of beams; and fires them against each other in a special manner. The energy distribution is not allowed to become Maxwellian in a migmacell. The magnetic field which confined the migma is more a guiding field than a "pressure field", as it is required to contain particles of only one charge and having a very restricted set of momenta and positions. In contrast, the magnetic field of plasma devices must contain particles of both signs having a great variety of momenta and positions.

And finally, since it is an essential part of the device to remove the electrons from the migmacell by means of clearing fields, such as by the pairs of plates 7a, 7b, 8a, 8b shown in Figure 1(c), and keep the electron/ion ratio at the 10^{-2} level or less, the electron ion thermal equilibrium – an essential feature of plasma – is meaningless here. The consequence of the absence of the electrons is that the energy losses due to synchrotron radiation and bremsstrahlung are absent in a migma.

The maximum total number of ions, N, that can be stored in a migmacell is determined by the "Space Charge Limit". This limit is reached when the electrostatic repulsion of the migma on an ion becomes equal to the focusing restoring force. The space charge limit N is for the preferred embodiment with a magnetic field of $B_0 = 200$ Kgauss and 2.2 MeV deuterons:

$$N = 4 \times 10^{12} \text{ ions} \quad (3)$$

N is proportional to the injection energy to the $3/2$ power.

The fusion reaction rate I of a migmacell is proportional to N^2 and is approximately given by:

$$I = 1 \times 10^{25} \langle dv \rangle \text{ fusions per second.} \quad (4)$$

which for 2.2 MeV deuterons gives from the diagram in Figure 8,

$$I = 2 \times 10^{10} \text{ fusions per second.} \quad (5)$$

This gives a net charged power production in a steady state regime in which the losses are continuously replenished by new injection.

Net Power = 3 m Watt per migmacell (6)
Criticality condition for the migmacell power source

The condition for a critical power source is obtained from the requirement that the electric energy output be at least equal to the energy input, the input rate being balanced by losses. The three main loss mechanisms in a migmacell are: (a) peripheral multiple scattering, (b) vertical multiple scattering and (c) charge transfer in gas (see Figure 9). If T_1 is the deuteron injection energy, the charged power output (71% of the total power output, W) to total power input has been found to be:

$$\frac{0.71 W}{2T_1} = 0.3 \quad (7)$$

The sum of the ratio of rates of all three losses to the fusion rate must be smaller than the value of Equation (7) in order to achieve a critical power source. Referring to Figure 9, this implies that the sum of all three curves (a), (b) and (c) must be below the "criticality line" given by Equation (7). We can see that this condition is easily met for deuteron injection energies above 0.5 MeV.

Energy gain factor of migmacell power source

To determine the energy gain factor in a migmacell consider that the gross power output P_+ , and the power input in the quasi steady-state regime P_- may be expressed as:

$$P_+ = I F_e (W + 2T_1) \quad (8)$$

$$P_- = I(2 + \dots)T_1 \quad (9)$$

where I = fusion reaction rate; F_c = charged fraction of the average reaction energy W , T_1 = injection energy and λ the leak losses, which are added to reaction losses $2T_1$.

Equation (9) means that the deuterons are replenished at their loss rate – the factor 2 comes from the fact that each fusion process removes 2 deuterons from the migma.

The “energy gain factor” of the migma power source G is defined as:

$$G = \frac{P_+}{P_-} - 1 = \frac{F_c(W + 2T_1)}{(2 + \lambda)T_1} - 1 \quad (10)$$

Since for the $d-d$ reaction $F_c = 0.71$, and $W = 3.655$ MeV, the maximum gain factor ($\lambda = 0$) for injection energies of 0.5, 1 and 2.2 MeV are $G = 230\%$, 100% and 29% respectively. With leak losses of 20% ($\lambda = 0.2$), $G = 200\%$, 82% and 18% for $T_1 = 0.5$, 1 and 2.2 MeV respectively. On the other hand the absolute rate of power production is proportional to T_1^2 . Let us define as the earning factor E the product:

$$E = G T_1^2 \quad (11)$$

Taking into account that the leak losses λ also decrease with the increase of energy, it can be shown that the optimal earning factor E is obtained at the highest possible injection energy T_1 . This will be shown hereinafter to be 2.2 MeV for a breeder reactor.

The Method of Injection

The method of injection and trapping of ion beams into a migma, which will be called “self-ensnaring” will now be more fully described. It makes use of the salient property of self-colliding orbits, that is, the high central density, to trap the injected beam by interacting with itself.

There are two types of self-ensnaring: (1) the self-ensnaring of atomic ions, which will be referred to as “self-trapping” and (2) the self-ensnaring of molecular ions, referred to as “self-capturing”.

SELF-TRAPPING is based on the multiple Coulomb scattering in the central region of a migma. In a small region at a large radius of the main magnetic field, a perturbing local field is created. This local field may be in the form of a “magnetic channel”, such as described in the text “Particle Accelerators” by M. S. Livingston and J. P. Blewett, page 390 et seq. (McGraw-Hill 1962), and is created in a manner well-known in the synchrocyclotron beam extraction art. The magnetic channel will differ from 1–10% in strength from the magnitude of the main field given by Equation (1). Ions are injected into the center of symmetry of the field from the periphery through this magnetic channel. By co-ordinating, in accordance with synchrocyclotron principles, the injection angle, the shape of the magnetic channel, the magnetic field strength and ion energy, the ion may be kept inside the field for many precession periods without violating the well-known Liouville’s theorem. If the ion is injected at an

angle θ_z to the vertical plane so as to induce vertical oscillations, these combined with the precession will keep the particle from returning to the entry point for say, ν precession periods, or for the time $\nu\tau_p$. Note that this time is a metastable containment to be referred to as artificial confinement, because it does not change the density in phase space. It is suggested by orbit studies that for $\theta_z = 10^\circ$, the ion can be kept in the migma for 40 precession periods, ($\nu = 40$). During the artificial confinement the ions undergo Coulomb interaction between themselves, thus changing their density in phase space and gradually resulting in a stable confinement. This requires a very fast build-up of the central migma density – a high instantaneous current I_0 . The density will increase linearly with time while the scattering rate increases quadratically.

The instantaneous current I_0 , needed to have 50% particles escape the injection point after precessions is given by:

$$I_0 \approx \frac{10^{-19}}{\langle dv \rangle_{ms} v^2 \tau_p^2} \text{ Amps.} \quad (12)$$

where $\langle dv \rangle_{ms}$ is the product of the cross-section for deviation through an angle $\Delta\theta$ by multiple scattering averaged over the migma distribution. A Monte Carlo calculation shows for $\Delta\theta = 2.5$ mrad, that $\langle dv \rangle_{ms} \sim 10^{-9} \text{ cm}^3 \text{ sec}^{-1}$. For a field index of $k = 0.8$, $\tau_p \approx 10^{-7} \text{ sec.}$, so that with $\nu = 40$,

$$I_0 \approx 10 \text{ Amps.} \quad (13)$$

Such instantaneous currents can be obtained from pulsed ion sources (100 microsec. pulse length) within the realm of present technology.

SELF-CAPTURING is the process of injection of molecular ions which leads to dissociation collisions in the central zone in the same manner as self-trapping leads to multiple scattering. The processes are: $D_2^+ + D_2^+ \rightarrow 2D^+ + e^- + D_2^+$; $\rightarrow 3D^+ + e^- + D^0$; $\rightarrow 4D^+ + 2e^-$. Since the dissociated atoms have one-half of the injected momentum, all of them will find themselves captured.

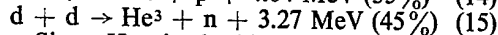
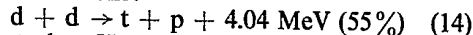
The cross-section for the sum total of the three processes is measured to be $\sigma \approx 1 \times 10^{-16} \text{ cm}^2$ at about 2.2 MeV, so that $\langle \sigma v \rangle \sim 10^{-9} \text{ cm}^3 \text{ sec}^{-1}$. This gives the same magnitude for the reaction parameter $\langle \sigma v \rangle$ as for that for multiple scattering (MS) beyond 2.5 mrad. Therefore, for self-capturing, the instantaneous current needed is also given by Equation (13).

Method of Breeding Fusion Fuel

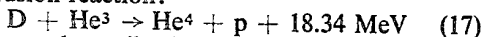
A further benefit is obtained by injecting the deuterons into the system with energies within a particular range so as to produce a “breeding” effect. This improved method wherein the injected deuteron-deuteron migma is converted into a deuteron-helium-3 migma which releases 7 times more ion energy per fusion will now be described.

A deuteron-deuteron migma yields 3

charged fusion products from the following two reactions:



5 Since He^3 is doubly charged, it will be appreciated that under certain conditions, the exit of the He^3 ions from the migma can be prevented while letting the tritons and protons fly out, to give their energy to an outside electrical system. This latter condition is achieved when the deuteron injection energy T_1 is greater than a certain value given by:
 10 $T_1^{\min} = 0.1154 W(\text{dd} \rightarrow \text{He}^3\text{n}) = 377 \text{ KeV} \quad (16)$
 15 With Equation (16) satisfied, the migma will be continuously enriched by the retained He^3 ions which, in turn, collide with the deuterons from the migma producing another fusion reaction:



20 it can be easily shown that in order to extract the energy from the reaction (17) by extracting both the doubly charged He^4 and the proton from the migmacell, another condition has to be imposed onto the injection energy T_1 . This condition is achieved when T_1 is less than a certain value given by:

$$T_1^{\max} = \frac{W(\text{dHe}^3)}{8} = 2.29 \text{ MeV.} \quad (18)$$

30 If the conditions of (16) and (18) are both fulfilled at the same time, the He^3 ions will stay inside the migma while *all* the other charged fusion products will exit. Thus, the appropriate conditions for fusion fuel breeding occur when the deuteron injection energy lies between the limits given by:

$$0.377 \text{ MeV} < T_1 < 2.29 \text{ MeV} \quad (19)$$

35 It will now be seen that based on Equation (19) we chose an injection energy $T_1 = 2.2 \text{ MeV}$ for our preferred embodiment, although the breeding will be operative for a range of T_1 within the limits in (19). With

$$T_1 = 2.2 \text{ MeV} \quad (20)$$

40 the charged fusion products exiting from the migmacell will have the following energies:

$$\text{triton (t): } T_{t1} = 2.22 \text{ MeV} \quad (21)$$

45 proton from d-d (p): $T_{p11} = 6.33 \text{ MeV} \quad (22)$
 proton from He^3 -d (p):

$$T_p = 17.97 \text{ MeV} \quad (23)$$

50 while the He^3 ions whose energy will be:

$$\text{helium-4(He}^4\text{): } T_4 = 4.49 \text{ MeV} \quad (24)$$

$$\text{helium-3(He}^3\text{): } T_3 = 1.92 \text{ MeV} \quad (25)$$

55 will be contained within the migmacell and the migma will be continuously enriched by the high-power fuel, thus increasing the power output beyond the values given by Equation (6), as well as the energy gain values computed from Equation (12).

60 Broadly speaking, then, breeding is accomplished by matching the migmacell radius R to its average magnetic field B to satisfy the following relationship:

$$\frac{R}{2} = \frac{4\sqrt{T}}{0.3 B} \quad (26)$$

65 where T_1 is the d^+ ion injection energy in KeV, given by the limits in (19) and B is in Kilo-

gauss, Equation (26) along with (19) defined the conditions for maintaining the He^3 in the migma while extracting all the other fusion products from reactions (14), (15) and (17) thus promoting breeding. 70

Direct Conversion of Fusion Energy into Electricity

A means for converting the energy of the charged products of the fusion reactions as well as for recovering the energy of the primary injected ions will now be described. It is based on the following facts: 75

1. At the high colliding energies considered, 90% of the products of fusion reactions are emitted at within 45° of the collision plane which is nearly the horizontal plane. 80

2. In the d - d reaction, 71% of the fusion energy is carried by the charged particles and 100% in the $\text{He}^3 + d$ reaction (breeder mode). 85

3. With the deuteron injection energy of 2.2 MeV, the charged fusion product ions carry the energies stated in Equations 20-25.

Although the magnetic field strength is designed to contain both the He^3 and the deuterons, some of these ions will leak out of the migmacell as the result of single and multiple elastic scattering and the space charge effects ("leak losses") at a rate of about 10% of the fusion products rate. 90

Since He^3 and He^4 are doubly charged, they can be decelerated and fully stopped by positively charged plates placed in their path at potentials of 0.96 and 2.2 MV respectively. 95

The tritons; the protons from $d + d$ fusion; the protons from $\text{He}^3 + d$ fusion; and the primary deuterons may be stopped by plates at 2.2, 6.3, 18 and 2.2 MV respectively. 100

It will be noted that nearly the same potential stops He^4 , tritons, and deuterons. This permits the use of four plates to stop the six kinds of particles listed in Equations 20-25. However, for practical reasons, it is advisable to subdivide the gaps between the plates, so as to not exceed 400 KV per gap. 105

Figures 10a and 10b are a top cross-sectional view and an elevation, respectively of the migmacell shown in Figure 1c enclosed by a plurality of cylinders of which only seven, 201-207, are shown for simplicity. The cylinders, 201-206 are thin (5 micron) aluminium foils stretched onto a copper mesh of about 98% transparency as frames for rigidity. The outermost cylinder 207 is made of about 1/2 cm thick copper. All the cylinders are embedded at their upper ends into an insulating plate 300 made of isostatically pressed high alumina ceramic, with respective high voltage connectors 301-307 for each plate. The superconducting leads 9 and 10 held by stainless steel supports 110 between them provide mechanical support for the upper and lower pairs of coils, with the open space between them defining the reaction region. 110
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The whole system is immersed in a jacket 408 through which liquid FREON (Registered Trade Mark) 310 is circulated by piping upwardly from below as a cold liquid and back down as a warm liquid at a rate such that the FREON never becomes a gas, and using known cooling techniques such, for example, as that used for the 6 MV Van der Graaf accelerator terminal at Oak Ridge National Laboratory designed by the high Voltage Engineering Corporation of Burlington, Massachusetts.

The migmacell coils 1a and 1b, as well as the leads 9 and 10 are at ground potential (the cooling) jackets 5 and 6 are not shown in Figures 10a and 10b). The cylinders 201, 202 and 206 are at positive potentials of 0.8, 2.2 and 6.3 MV respectively. Cylinders 203, 204 and 205 are at about 3.5 and 5 MV respectively. A plurality of cylinders not shown in the drawing is put between each pair of cylinders in a well-known manner to provide a gradual voltage distribution.

The outer cylinder 207 is used to stop the 18 MeV protons from the $\text{He}^3 + d$ fusion reaction by the combined action of the features: (1) a decelerating voltage in the range above 6.3 MV and up to the energy of the proton 18 MV; and (2) the stopping power of the thick plate and the liquid FREON. Therefore only a fraction of the energy of these high energy protons is expected to be converted into electricity. The remaining energy will be converted into heat and carried away by the circulating liquid FREON.

The bottom of the copper cylinder 207 is sealed to a pyrex glass cylinder 208. A set of eight tungsten pins (of which four are shown 209-212) provides support to an outside jacket 408 made of isostatically pressed high alumina ceramic. High voltage feedthroughs 400-407 are used for the respective leads.

Through this cylindrical arrangement, the 2.2 MeV deuteron beam 500, focused at the center of the migmacell by a system of quadrupole lenses 412, is injected through a tube 411 at an angle of 30° to the vertical into the lower coil of the migmacell to produce the migma and the resultant electric power output.

Migma Fusion Reactor

A migma fusion reactor may be constructed comprising a plurality of migmacells. In a preferred embodiment, one hundred migmacells are stacked in a column, called a "migmacolumn" and a matrix of one hundred by one hundred migmacolumns may be used to make the reactor.

A top view of a section of two migmacolumns in a preferred embodiment is shown in Figure 11a. The elevation view of the same is shown in Figure 11b. It is seen in Figure 11b that each migmacell is suspended by its stainless steel bar 110 sandwiched between the super-conducting leads 9 and 10.

A technical advantage to be obtained with a

migmacolumn configuration over that of a single migmacell (Figure 10a and 10b) is that the positively charged repulsive cylinders can be replaced by flat plates, comprising thin metal foils stretched over a 98% transparent copper mesh.

Referring to Figures 11a and 11b, the plates, 611, 711, 811 and 911 are placed at a potential of + 0.8 MV; plates 612, 712, 812 and 912 are at + 2.2 MV; and plates 613, 713, 813 and 913 are at + 6.3 MV. A plurality of plates not shown in the drawings is put between each pair of the above-cited plates in a well-known manner to provide a gradual voltage distribution. Plates 514, 614, 717, 814, 914 and 1014 of 1/2 cm thickness are placed at a decelerating voltage in the range from above 6.3 MV and up to the energy of the proton from the $\text{He}^3 + d$ fusion reaction, 18 MV, to stop it by the combined action described in connection with outer cylinder 207 above.

All of the plates are suspended from a plate 620 made of isostatically pressed high alumina ceramic and connected to a high voltage source through connectors 641. Plate 650 is made of the same insulating ceramic.

Plates 514, 614, 714, 814, 914 and 1014, together with plates 620 and 650 provide a jacket for circulating liquid FREON in the manner described in connection with jacket 408 above.

It will be seen from Figure 11a that while two pairs of coils are used for a single migmacell, in a migmacolumn three pairs of coils will act to provide the magnetic fields for two migmacells, so that in general, $N + 1$ pairs of coils will provide the fields for N migmacells. Therefore, for a migmacolumn of one hundred migmacells only 101 pairs of coils, 550a and 550b are required.

It should be noted that migmacolumns are not made up of a number of physically independent migmacells, but are rather a system of coupled migmacells. An advantage of this coupled configuration is that when all of the cells are filled with a migma, the end losses through the escape cone, defined by the vertical confinement angle, along the Z-axis is reduced by the number of cells in the column. This is accomplished by the following automatic mechanism.

If a deuteron enters the escape cone of one migma cell, that is starts moving, as a consequence of the multiple Coulomb scattering, through the cell coils into the next migmacell, the combined action of the sharp repulsive potential of the migma in the next cell and the Coulomb scattering therein are such that the probability is 50% for the ion to deviate away from the Z-axis and stay trapped in the new migmacell with new initial conditions, thus contributing to the fusion rate.

The filling of a migmacolumn utilizes the same 60° injection technique as the filling of a

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single migmacell except that the ion injection rate is adjusted such that only a small fraction, approximately 1% of the ions, become self-ensnared in each cell in the column. The remaining ions enter the next cell, precess in an artificial confinement mode and, if not captured into continue the following cell, following the trajectory 999.

The filling time for a migmacolumn is approximately 10^{-4} sec. The accelerated ion beam 900 is then shifted to the next migmacolumn according to the well-known technique of two-dimensional scanning developed by the High Voltage Engineering Corporation for ion implantation and for accelerating and scanning micrometeorites in the NASA Space Program. Refilling is performed periodically in intervals of the order of one second or longer as may be required by the need to replace the deuterons lost through fusion and leaks.

WHAT WE CLAIM IS:—

1. A fusion reactor comprising:

(a) means defining an evacuated volume having a central axis and a centre plane normal thereto;

(b) means for producing a magnetic field within said volume which field decreases with the radial distance from the central axis and increases with the distance along the central axis from the centre plane; and

(c) means for injecting ions of like charge from the periphery into the vicinity of the centre of symmetry of said magnetic field with induced vertical oscillation and with an initial rate of injection sufficient to produce fusion reactions by the collisions of the resultant orbitally precessing ions with each other.

2. A fusion reactor according to claim 1 wherein the means for producing the magnetic field comprises a plurality of pairs of magnetic coils, the respective coils of each pair being disposed on opposite sides of the centre plane and spaced equidistantly therefrom, and with the opening between the edges of the outermost pair of coils defining a radial angle of approximately 45° with respect to the centre of symmetry.

3. A fusion reactor according to claim 2 including a jacket enclosing said pairs of coils, for guiding a cooling medium there-around to promote super-conductivity in said coils.

4. A fusion reactor according to claim 3 including an outer housing enclosing said jacket for guiding a cooling medium there-around for heat removal.

5. A fusion reactor according to any one of the preceding claims including positively chargeable electrodes disposed about said magnetic field to produce clearing fields for the removal of electrons therefrom.

6. A power source including a fusion reactor according to any one of the preceding claims and means disposed outside of said magnetic field for producing a repulsive electrical potential such that charged nuclei, resulting from the fusion reactions, which are emitted from said magnetic field have their deceleration energy directly converted to electrical energy.

7. A method for controlled release of nuclear fusion power, comprising the steps of:

(a) producing a magnetic field within an evacuated reaction volume having a central axis and a centre plane normal thereto, the strength of which field decreases with the radial distance from the central axis and increases with the distance along the central axis from the centre plane so as to induce precession of, and exert radial and axial focusing forces on, orbiting ions within said volume; and

(b) injecting a beam of ions of like charge from the periphery into the vicinity of the centre of symmetry of said magnetic field with induced vertical oscillation and with an initial rate of injection sufficient to produce fusion reactions by the collisions of the resultant orbitally precessing ions with each other.

8. A method according to claim 7 wherein the density of the injected ions is maintained such that charged nuclei resulting from the fusion reactions are caused to be emitted from the reaction volume into a region of repulsive electrical potential whereby the deceleration energy of the nuclei is extracted as electrical energy.

9. A method according to claim 7 or claim 8 wherein electrodes are disposed about the reaction volume, and including the further step of applying positive voltages to said electrodes to produce clearing fields for removing electrons therefrom.

10. A method according to claim 7, claim 8 or claim 9 wherein the beam of injected ions is focused at the centre of symmetry of the field and the initial rate of injection is such that single and multiple Coulomb interactions between ions in the central zone of the field significant within the time of unstable confinement and therefore change the density in the "phase space" thus preventing most of the charged ions from leaving the central zone and producing a stable confinement.

11. A method according to any one of claims 7 to 10 wherein the injected ions are deuterons injected with an energy in the range from 0.377 MeV to 2.29 MeV.

12. A method according to any one of claims 7 to 10 wherein the injected ions are deuterons and the injection energy of the ions and the average strength of the magnetic

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field are selected such that after the fusion reactions the He³ ions are confined within the magnetic field and the He⁴ ions exit therefrom.

- 5 13. A fusion reactor comprising:
 (a) means for defining an evacuated volume;
 10 (b) a plurality of cell means within said volume, each having a central axis and a centre plane intersecting normally at a centre of symmetry and means for producing a magnetic field therein which field decreases with the radial distance from the central axis and increases with the distance along the central axis from the centre plane; and
 15 (c) means for injecting ions of like charge into each of said cell means from the periphery into the vicinity of the centre of symmetry of its magnetic field with induced vertical oscillation and with an initial rate of injection sufficient to produce fusion reactions by the collisions of the resultant orbitally precessing ions with each other;
 20 (d) said cell means being arranged in a three-dimensional matrix with their central axes and centre planes in

substantial alignment

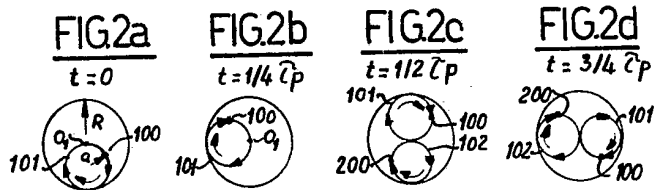
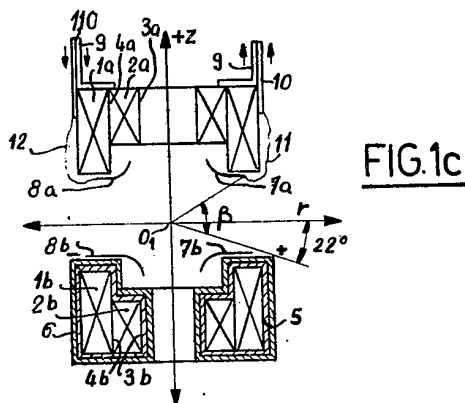
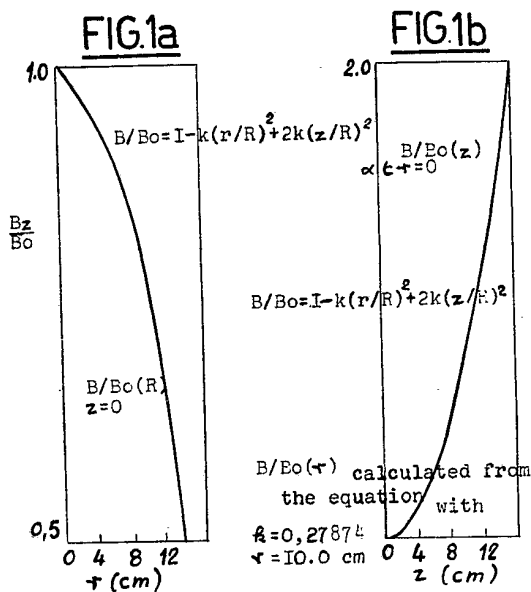
14 A fusion reactor according to claim 13 including positively chargeable electrodes disposed within said cell means to produce clearing fields for the removal of electrons therefrom. 30

15. A fusion reactor according to claim 13 or claim 14 wherein said means defining an evacuated volume comprises a jacket for guiding a cooling medium therearound. 35

16. A power source including a fusion reactor according to claim 13, claim 14 or claim 15 and means disposed within said matrix for producing a repulsive electric potential such that charged nuclei resulting from the fusion reactions which are emitted from said cell means have their deceleration energy directly converted to electrical energy. 40 45

17. A Migma Fusion Reactor substantially as described herein before and as illustrated in the accompanying drawings.

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 London WC1V 7RD.



1422545

COMPLETE SPECIFICATION

9 SHEETS

*This drawing is a reproduction of
the Original on a reduced scale*

Sheet 2

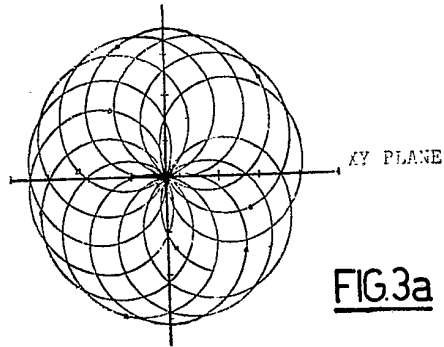


FIG.3a

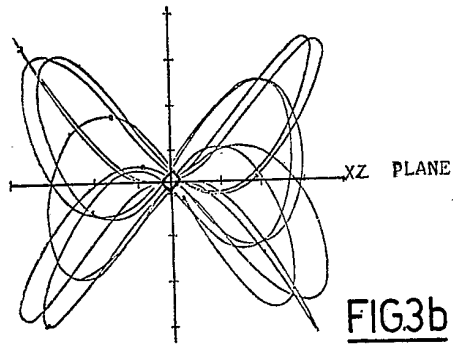


FIG3b

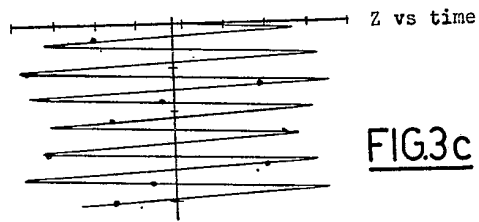
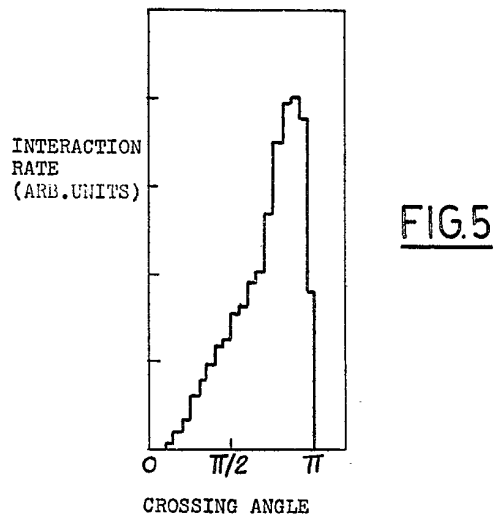
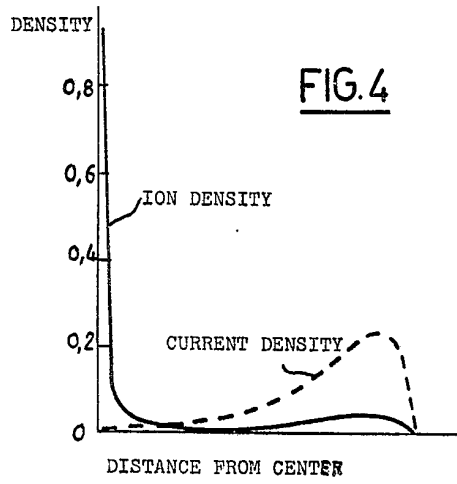


FIG3c



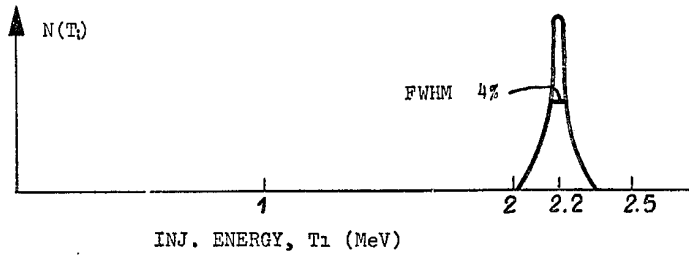


FIG.6

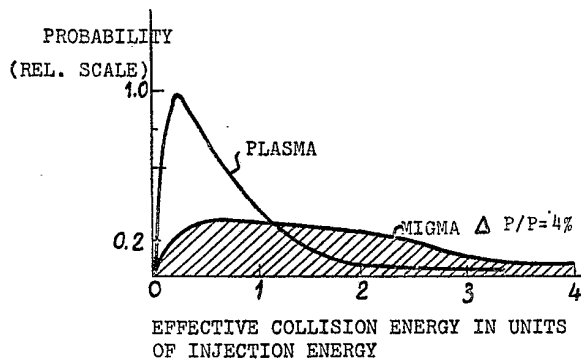


FIG7

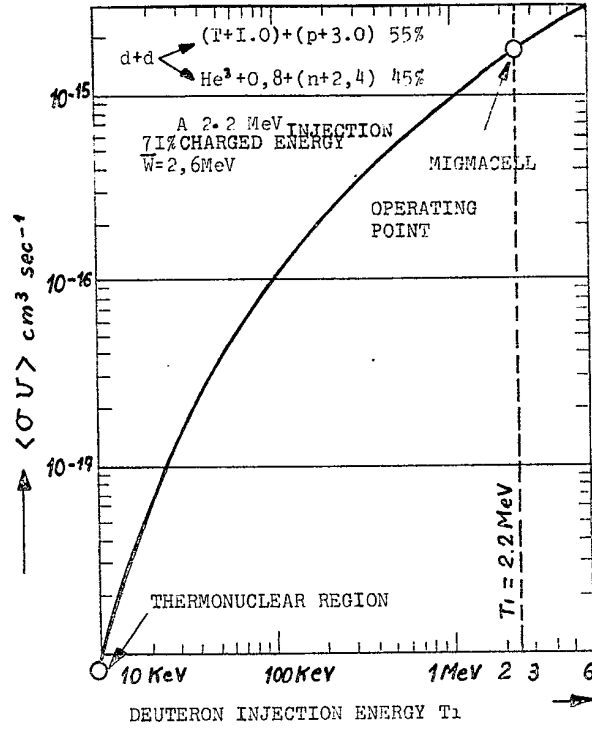


FIG.8

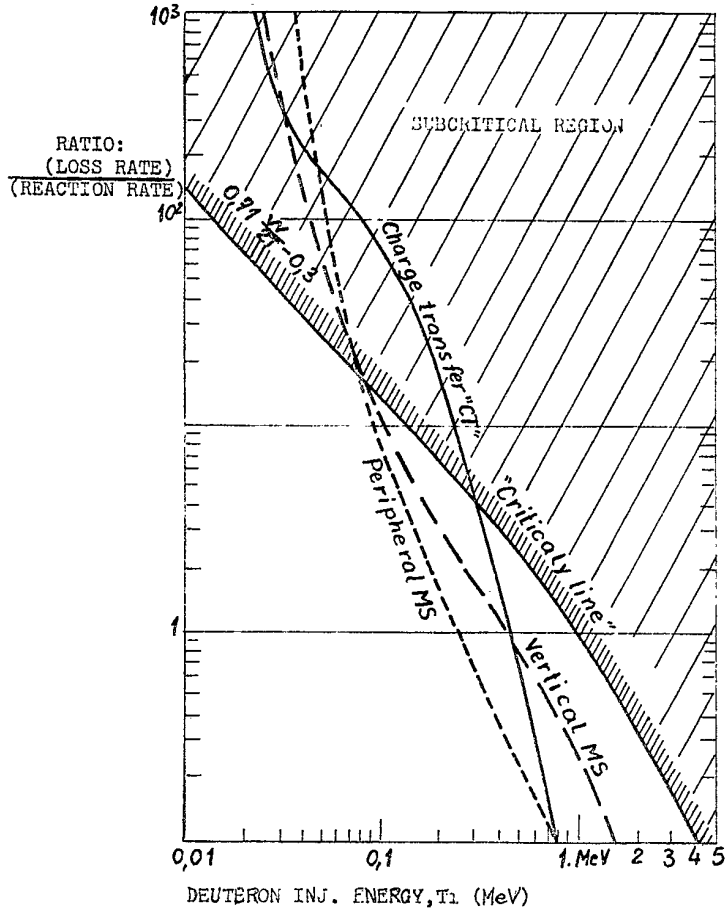


FIG 9

FIG. 10a

