United States Patent [19]
Furth et al.

BEST AVAILABLE COPY

[11] **3,886,402**
[45] **May 27, 1975**

[54] **MAGNETIC PUMPING IN SPATIALLY INHOMOGENEOUS MAGNETIC FIELDS**

[75] Inventors: **Harold P. Furth; Robert A. Ellis, Jr.,** both of Princeton, N.J.

[73] Assignee: **The United States of America as represented by the United States Energy Research and Development Administration,** Washington, D.C.

[22] Filed: **May 7, 1974**

[21] Appl. No.: **467,685**

[52] **U.S. Cl.** **315/111.7;** 176/3; 313/231.3; 315/111.4
[51] **Int. Cl.** **G21b 13/04**
[58] **Field of Search** 176/3; 315/111.2, 111.4, 315/111.7, 112; 313/231.3, 231.5

[56] **References Cited**

UNITED STATES PATENTS

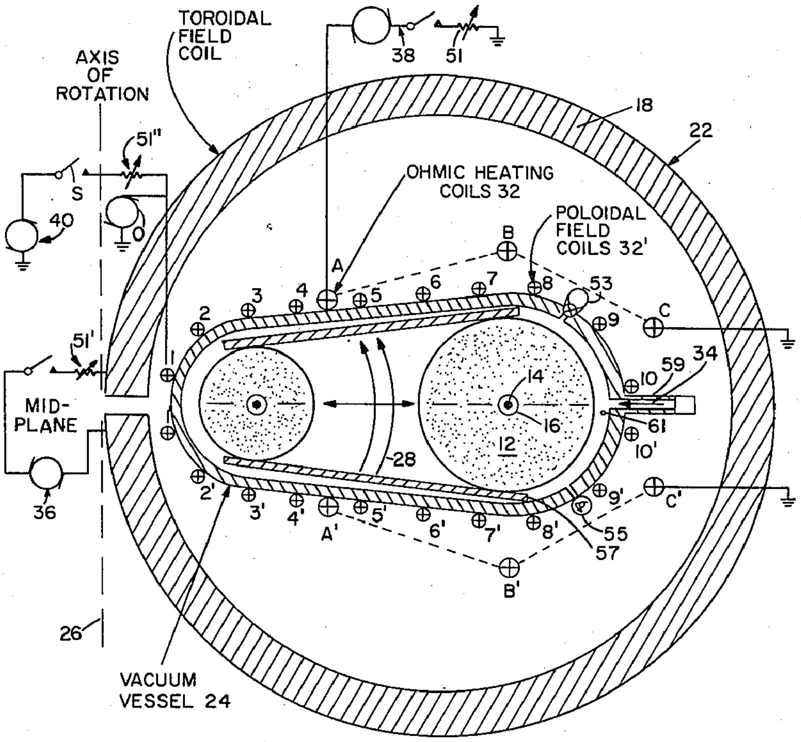
3,445,722 5/1969 Scott et al. 315/111.4
3,614,525 10/1971 Uleski 315/111.4
3,674,634 7/1972 Watson .... 315/111.7 X
3,702,163 11/1972 Furth et al. 176/3

Primary Examiner—James W. Lawrence
Assistant Examiner—E. R. La Roche
Attorney, Agent, or Firm—Dean E. Carlson; C. Daniel Cornish

[57] **ABSTRACT**

Method for fast radial toroidal plasma column acceleration in an average ion-ion collision time or less back and forth in the plane of the closed containment means of the ATC described in U.S. Pat. No. 3,702,163, irreversibly to heat the plasma column. In accordance with this invention, current is flowed through the toroidal and poloidal coil means of the ATC and these coils are distributed to provide an unbalanced biasing force on the toroidal, current carrying, plasma column by means of a shaped magnetic field having an unstable region between spaced apart stable regions. By modulating the shaped field the plasma column is pushed back and forth between the two stable regions. In another embodiment, the plasma current is modulated to the same end.

9 Claims, 8 Drawing Figures

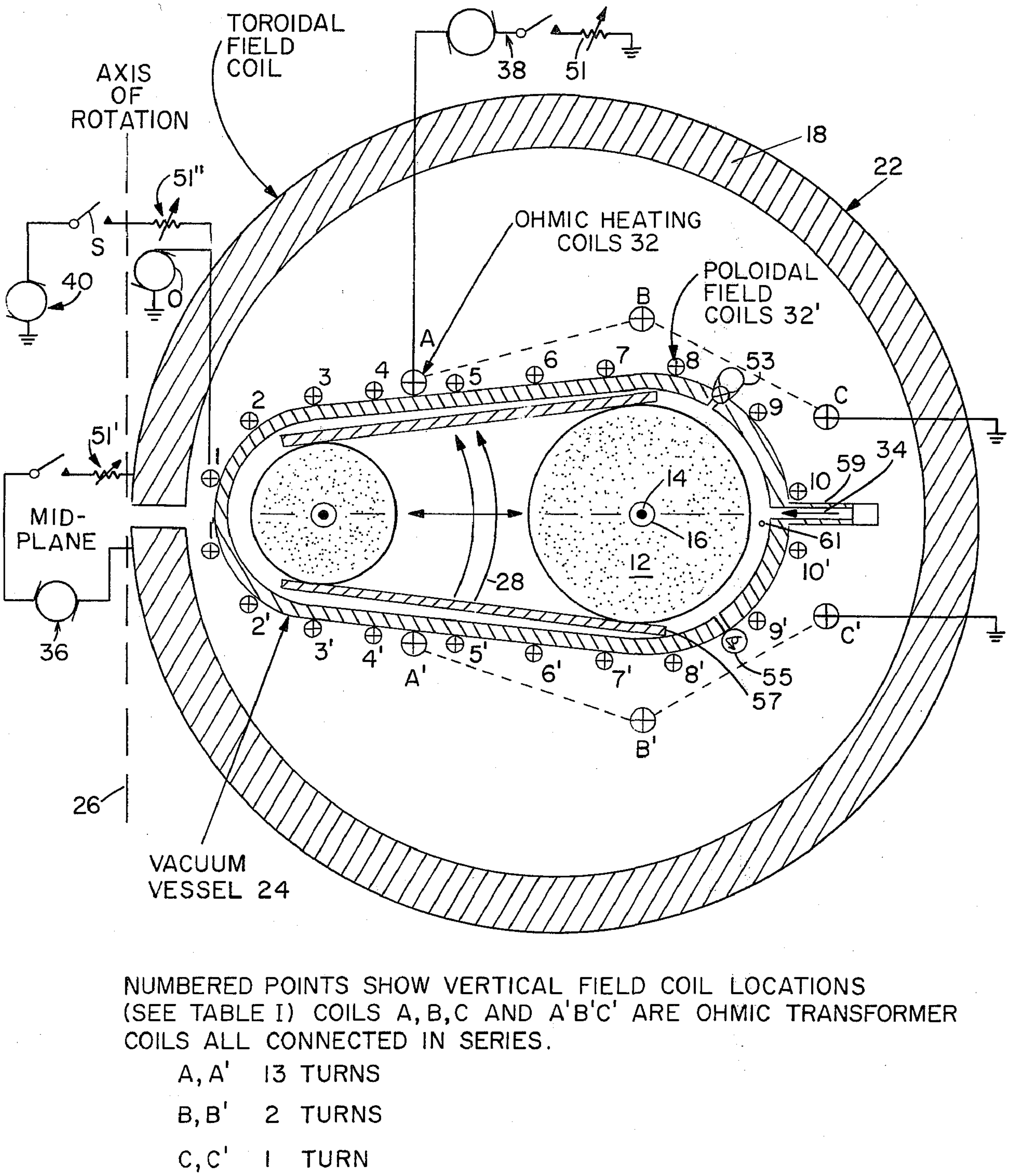


NUMBERED POINTS SHOW VERTICAL FIELD COIL LOCATIONS (SEE TABLE I) COILS A, B, C AND A'B'C' ARE OHMIC TRANSFORMER COILS ALL CONNECTED IN SERIES.

A, A' 13 TURNS

B, B' 2 TURNS

C, C' 1 TURN



NUMBERED POINTS SHOW VERTICAL FIELD COIL LOCATIONS (SEE TABLE I) COILS A, B, C AND A'B'C' ARE OHMIC TRANSFORMER COILS ALL CONNECTED IN SERIES.

A, A'	13 TURNS
B, B'	2 TURNS
C, C'	1 TURN

Fig. 1

ARRANGEMENT OF COILS
THE COIL LOCATIONS ARE REPRESENTED BY HEAVY DOTS WITH NUMBERS. SEE TABLE I FOR CURRENTS IN EACH COIL AND PRECISE LOCATIONS.

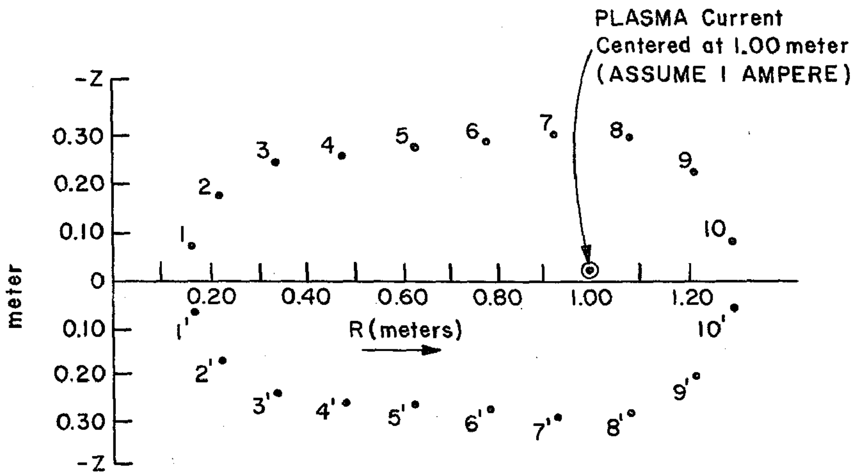


Fig. 2

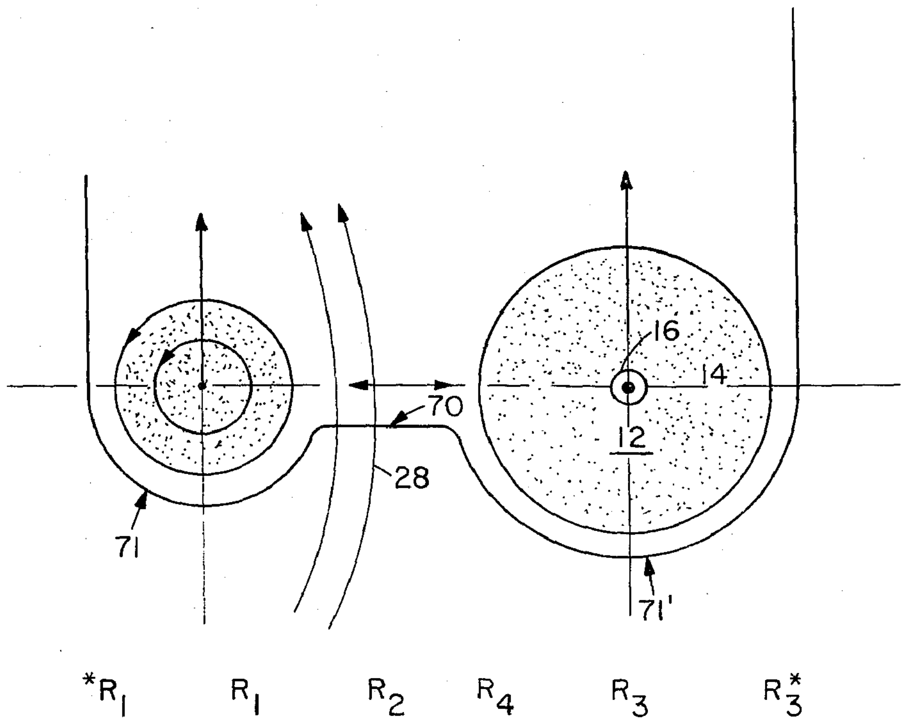


Fig. 3

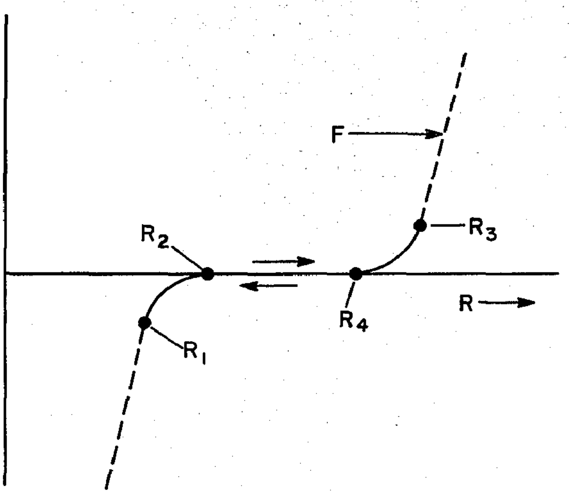


Fig. 4

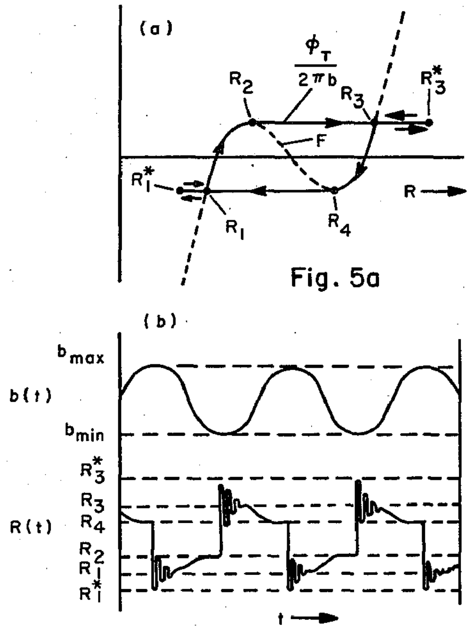


Fig. 5a

Fig. 5b

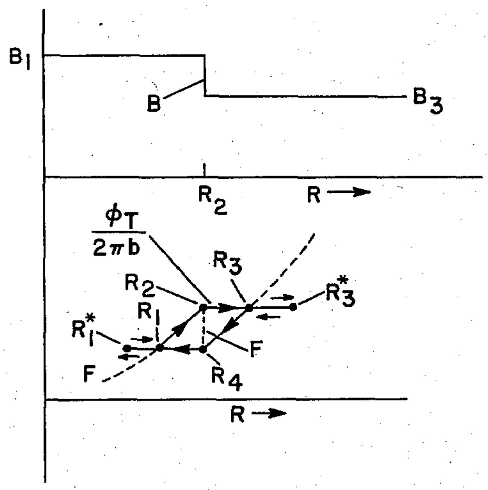


Fig. 6

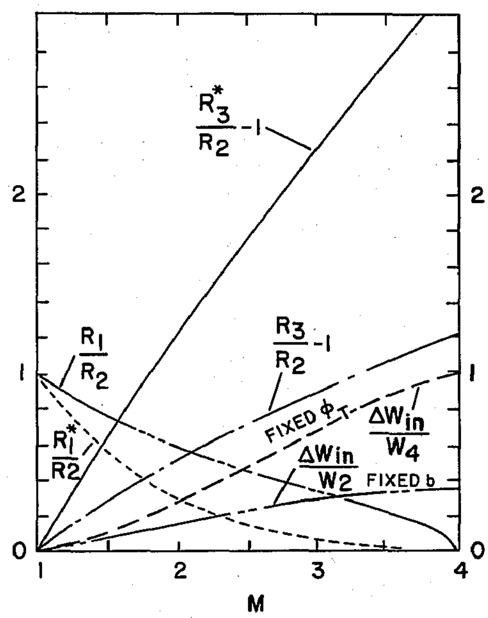


Fig. 7

MAGNETIC PUMPING IN SPATIALLY INHOMOGENEOUS MAGNETIC FIELDS

This invention was made in the course of, or under a contract with the United States Atomic Energy Commission.

BACKGROUND OF THE INVENTION

In the field of controlled thermonuclear fusion, a need exists for heating a toroidal plasma column. Heretofore, there were basically two different ways in which radial compression was helpful in raising the plasma temperature. The first way involved the slow, one-way, single compression in five average ion-ion collision time periods t_i or more in the Adiabatic Toroidal Compressor (ATC) at Princeton University Plasma Physics Lab. (PPL), as described in U.S. Pat. No. 3,702,163, but this did not provide irreversible heating. The second way, described in Nuclear Fusion 12, 215 (1972), required radio-frequency injection into the plasma column, but it was difficult or impossible with this system as a practical matter to inject the radio-frequency electromagnetic energy required through the closed toroidal containment means containing the toroidal plasma column, or into the center of the plasma column itself.

SUMMARY OF THE INVENTION

It has now been discovered, in accordance with this invention, that the toroidal plasma column can be radially compressed and expanded respectively in an average ion-ion collision time period t_i or less, and that this cycle can be repeated over and over again in a time period t_E less than the plasma relaxation time period by shaping the magnetic field in an ATC and modulating either the field or the plasma current. For purposes of this invention, it will be understood that the average ion-ion collision time period and the plasma relaxation time period are so well known in the art that they can be determined by one skilled in the art with conventional instruments. For example, Thompson scattering of laser light, heavy ion beam probes, Langmuir probes, and the rf diagnostics of U.S. Pat. No. 3,265,967 can be used to determine the density and temperature of the plasma, which determines the average ion-ion collision time, and the plasma relaxation time is simply the total plasma energy W divided by the power P required to maintain that energy. A typical average ion-ion collision time in the PPL ATC is 100 microseconds at a particle number density of 10^{13} ions/cc and a temperature of 200 ev, and a typical relaxation time is 3000 microseconds. Thus, it will be understood that this invention provides the desired irreversible heating by modifying the inhomogeneous magnetic fields existing in the PPL ATC.

The method involved in this invention, contemplates the use of the existing series wound toroidal and poloidal field coil means in the PPL ATC to produce a toroidal confining field and curved vertical magnetic field lines forming a magnetic field gradient in an equilibrium for centering the plasma column in a closed containment means. By suitably distributing the poloidal coil means and flowing current therethrough, the magnetic field is shaped to form spaced apart regions of stability having an instability region therebetween. This can be done, for example, by adding poloidal coil windings and flowing currents therethrough to provide the desired field shape forming the instability region in between the two spaced apart stable regions. By the simple step of modulating the current in the poloidal coil means, the plasma column is pushed back and forth in an average ion-ion collision time alternately periodically to displace the column in a cycle that produces inward compressions and outward expansions of the major and minor radii of the plasma column within the plasma relaxation time. The total effect of this cycle is simply and effectively to heat the plasma irreversibly without injecting rf through the containment means or into the plasma column. Also, complicated and expensive fast, high voltage switching is avoided.

In one embodiment, this invention provides in the method of heating a toroidally extending current carrying plasma column in a system of first and second poloidal and separate toroidal coil means distributed so as to produce magnetic field shapes having spaced apart regions of stability within a closed toroidal containment means for establishing the plasma column in first and second positions spaced from the inside wall of the containment means, the plasma column being stabilized along a transverse axis parallel to the axis of rotation of the containment means, radial axes extending from the axis of rotation in the plane of the toroidal containment means, and an endless equilibrium axis at the center of the plasma column co-axially with the plasma current, the improvement comprising the step of flowing current through the poloidal coil means to produce a magnetic instability region in the middle region between the spaced apart stability regions so that the magnetic field shape in the middle region is adapted to provide an unbalanced biasing force on the plasma column along the radial axes for displacing the plasma column radially from one of the regions of stability to the other in an average ion-ion collision time or less. By modulating the current flowing through the poloidal coil means the biasing force acts in the regions of stability in the spaces in the closed containment means on either side of the instability region initially to displace the plasma column radially into the instability of the middle region along the radial axes in the direction of the axis of rotation so as to cause the plasma column to be displaced radially inwardly to the second position and compressed thereby within an average ion-ion collision time period t_i or less to increase the temperature of the plasma column, and alternately periodically to be returned to the aforesaid first position successively to compress and expand the plasma column in a cycle that irreversibly heats the plasma column in accordance with the number of the cycles, the same being within the plasma relaxation time period t_E, as determined from the initial temperature and density of the plasma column by the total energy of the plasma current carrying plasma column, and the power for maintaining that total energy by flowing currents through the toroidal and poloidal coil means.

It is an object of this invention, therefore, to provide an improved system for irreversibly heating a toroidal plasma column by fast radial compression and expansion in an unstable region between two spaced apart stable regions.

The above and further novel features and objects of this invention will appear more fully from the following detailed description of one embodiment when read in connection wwith the accompanying drawings, and the novel features will be particularly pointed out in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

In the figures, where like elements are referenced alike:

FIG. 1 is a partial cross-section of the ATC of U.S Pat. No. 3,702,163 showing the modification thereof in accordance with this invention;

FIG. 2 is a graphic illustration of the actual location of poloidal field coils of the apparatus of FIG. 1 so that the coils produce an unstable region with very strongly curved vertical magnetic field gradient in accordanace with this invention. The coil locations are represented by heavy dots with numbers (see Tables I and II for currents in each coil and precise locations);

FIG. 3 is a partial schematic view of the plasma column of FIG. 1 with the strongly curved vertical magnetic field gradient and opposite stable regions in accordance with this invention.

FIG. 4 is a graphic illustration of the marginally stable compression cycle for the apparatus of FIG. 1 following the equilibrium rule $F=\phi_T/2\pi b$;

FIG. 5*a* is a graphic illustration of the partly unstable compression cycle of this invention for the apparatus of FIG. 1 following the equilibrium rule $F=\phi_T/2\pi b$ from R_1 to R_2 and R_3 to R_4. Passage from R_2 to R_3 and R_4 to R_1 is dynamic, with fixed $\phi_T/2\pi b$; over-shoot is damped by subsequent high frequency oscillation; FIG. 5*b* is a graphic illustration of the time-dependence illustrated in FIG. 5*a* for a B_T driven cycle;

FIG. 6 is an idealized magnetic field configuration for the partly unstable compression cycle of FIG. 5*a*;

FIG. 7 is a graphic illustration of the compression cycle of FIG. 6 as a function of $M=B_1/B_3$. Higher fractional energy input is achieved for B_T—driven cycle (fixed ϕ_T).

PREFERRED EMBODIMENT OF THE INVENTION

Referring to FIG. 1, it is known that a toroidally extending, current carrying plasma column can be centered in a toroidal containment means by suitably distributing toroidal and poloidal fields around the plasma column to confine the same. To this end, suitably flowing current through the poloidal field means provides magnetic field lines for forming spaced apart stable regions in the containment means.

One apparatus for producing stable regions, is the ATC of U.S. Pat. No. 3,702,163, which is described in detail in Princeton U. Plasma Physics Lab. Rpt. MATT-847. This ATC establishes a toroidal plasma column **12** having along an endless equilibrium axis **14** a continuously variable plasma current **16** that is successively received and transported in successive stages by a system of continuously variable current toroidal magnetic confining coils **18** that are arranged seriatim around the axis **14** in a tokamak tokopressor **22** of the type having a vacuum discharge tube **24**, wherein there is produced at intervals adiabatic toroidal compression and heating of the toroidal plasma column in both its major and minor radii. The containment means formed by the discharge tube **24** transports the toroidal plasma column as it is compressed toward the axis **26**, which is the axis of rotation of the tube **24** and the plasma column **12**, in locations of curved vertical magnetic field **28** that are produced by continuously variable current poloidal field coils **32** and **32'** for accelerating and centing the plasma column in tube **24**. As illustrated in FIGS. 2*a*, 2*b* and 2*c* of the above-mentioned ATC patent, the curved vertical magnetic field lines are referred to in the art as producing an equilibrium field and this field has a gradient for producing an equilibrium field for centering the toroidal plasma column **12** in the discharge tube **24** in first and second stable regions along a transverse axis parallel to the axis of rotation at first and second locations spaced from the inside wall of the containment means.

It will be understood that the ATC **22** provides a toroidal containment means in the form of a specially-shaped elongated vacuum discharge tube **24**, a system of continuously variable current poloidal field coils **32**, and **32'**, as understood in more detail hereinafter, means for injecting a neutral beam **34**, and sources **36**, 38 and **40** for energizing the coils **18, 32** and **32'**. A specially programmed continuously variable equilibrium is established during a continuously variable ohmic-heating phase having a first control **51**. A periodic compression phase is provided by a continuously variable current toroidal magnetic field control means **51'**. Continuously variable amplitude and gradient control means **51''** distributes the desired current flow for the curved vertical magnetic field **28** that pushes the plasma into the desired region of stronger toroidal magnetic field. Continuously variable control means for decreasing the major radius R, and toroidal flux conservation for forcing the minor radius to shrink according to $a \rightarrow R^{1/2}$, all are as understood in the art, and are described in the cited publications. For example, it will be understood that continuously variable current control is provided by conventional means, and while variable resistors are shown, other means, such as generators, thyratrons and capacitor banks may be used. Also source **53** injects gas, such as D or DT gas, into vacuum vessel discharge tube **24**, pumps **55**, such as ion evaporator pumps, remove unwanted gas, rail limiters **57** limit the outside of the plasma column, ports **59** are provided for diagnostics, as well as neutral beam injection **34**, and an ionization breakdown loop **61** provides initial ionization. An initial *rf* ionization loop **61** is conventional, as are the ATC inhomogeneous magnetic fields.

It has now been discovered in accordance with this invention that coils **32** and **32'**, as shown in FIGS. 1 and 2 and Tables I and II, can be distributed and current can be flowed therethrough and/or added to form an unstable region **70** between two spaced apart stable regions **71** and **71'** having non-curved vertical field lines, as shown in FIG. 3, so that there is a middle region that supplies a strong, radial, unbalanced biasing force for accelerating the plasma column **12** from one stable region to the other in an average ion-ion collision time period t_i or less. Then, by merely modulating the current flow in the poloidal field coil means **32'**, the unbalanced biasing force comes into play to push the toroidal plasma column back and forth into the unstable region in a cycle within a plasma relaxation time period t_E with vertical field lines curving concavely toward the axis of rotation **26**. In accordance with this invention, therefore, the modulation cyclically increases and then decreases the current in coils **32'** by conventional means of having a conventional sinusoidally varying timer to cause the plasma column **12** to undergo alternative expansions and contractions. Accordingly, the plasma column continuously periodically re-enters the unstable region **70**, undergoes a dynamic instantaneous contraction in its major and minor radii within an ion collision time, undergoes a damped oscillation around the center of the inner stable region 71, reenters the unstable region 70, undergoes a dynamic instantaneous expansion in its major and minor radii within an ion collision time, and undergoes a damped oscillation around the center of the outer stable region 71' to complete a cycle within the plasma relaxation time. The cycle can be continuously repeated periodically by pushing the plasma column into the described unstable region periodically to begin the described cycle periodically anew within the relaxation time.

It will be understood in the art from the above that this invention is a modification of the heretofore known ATC, in which the toroidal, plasma current carrying tokamak plasma is cyclically compressed and expanded by being reciprocated and oscillated in major and minor radii in order to heat it irreversibly, whereby high frequency compression pumping of the plasma is accomplished with low-frequency applied power without in any way whatsoever requiring the penetration of the toroidal discharge tube with a high frequency driving field, and/or without in any way requiring complicated and expensive fast rise-time, high voltage switching. Thus, while the apparatus of this invention is similar to the heretofore known ATC, an unstable region of very strongly curved vertical magnetic field 28 is provided between two stable regions and modulation is added thereto to achieve the desired acceleration between the stable regions within an average ion collision time of 100 microseconds or less. By modulating the shaped field or plasma current with a time constant of less than 3000 microseconds, the plasma column is accelerated back and forth in a cycle that is at least as short as the plasma relaxation time period. This will be understood from FIG. 4, which illustrates a middle region that is marginally unstable. On the other hand the middle region can be made fully unstable as illustrated in FIG. 5*a*. In one embodiment the vertical field coils are located as enumerated in Tables I, and II, the coils A, B, C and A' B' C' being distributed and energized as ohmic transformer coils that are all connected in series to source 38 by switches having suitable continuously variable control means 51 for producing slowly varying currents, as shown in FIG. 5*b*. Thus, magnetic pumping by major-radius reciprocation of a toroidal plasma is made practical by introducing a major-field radius range within which the vertical-field gradient is sufficiently great so that major-radius perturbations are actually unstable, in which case high-frequency pumping effects are created with moderate-to-low-frequency applied power to change the vertical field 28 or the plasma current 16.

As shown in FIG. 1 a suitable continuously variable control means 51' flows current from source 36 into the toroidal field coils 18 and the current from a like source 38 and control 51 supplies the poloidal field coils 32 which comprise ohmic heating air core transformer coils 32 that are all connected in series. However, the number of windings in coils 32 varies. For example, coils A and A' have 13 turns, coils B and B' have 2 turns, and coils C and C' have 1 turn. Meanwhile, a suitable control 51'' and a switch S, such as a conventional electronic thyratron and crow-bar mechanical switches connected to a source 40, such as suitable generators, batteries, and/or capacitor banks of the desired sizes, energize the coils 32' with the required continuously variable currents. The ATC switching means can be used, but other systems, comprising the switching system disclosed in copending application Ser. No. 231,324, filed Mar. 2, 1972, the continuation filed thereon, or a co-pending Bonanos application (Ser. No. 416,902, filed Nov. 14, 1973); can alternately be used. By simply closing switch S' the desired modulation is added when desired from a suitable square wave source 0. A suitable storage system for such a modulation source 0 for controlled thermonuclear reactors, is disclosed in U.S. Pat. No. 3,177,408.

In connection with the use of the described ATC in accordance with one embodiment of this invention, source 53 supplies gaseous fuel to tube 24 while pump 55 maintains a vacuum of 10^{-6} to 10^{-10} torr therein. Rail limiters 57 limit the outside diameter of the plasma column 12. Ports 59 are used for diagnostics and injection of neutral beams 34.

In the operation of the embodiment of FIG. 1, where FIG. 2 shows the location of the desired coils of FIG. 1, and FIG. 3 shows the vertical field lines produced during the described cycle, the vacuum chamber in tube 24 includes a range between zero curvature vertical field lines over which the vertical field 28, referred to as $\delta B_V/\delta R$, is sufficiently negative so that the plasma can arbitrarily be pushed into a region of instability, where B_V=vertical magnetic field strength, and R=the major radius of the plasma column 12. Then the region of instability is bounded by inner and outer stable regions having zero curvature vertical field lines 28, as shown in FIG. 3. This contrasts with the situation where the range is arbitrarily close to instability. Then B_V (or the plasma current amplitude I) is modulated to oscillate the plasma column major radius in the mid-plane of tube 24, and the marginally stable range of R is bounded by inner and outer ranges of R that have positively stable values of $\delta B_V/\delta R$, as illustrated in FIG. 4, the illustrated scheme calling for modulation of B_V or of the amplitude I of the plasma current 16 with coils 32.

Referring again to the above-mentioned operating range of R that is made unstable against radial displacement and where the inner and an outer stable regions are shown in FIG. 3 in accordance with this invention, the cyclical variation of B_V or I at any frequency whatsoever will cause the plasma column 12 to undergo rapid alternative expansions and contractions, as illustrated in FIG. 5*b*, when the plasma column 12 of FIG. 1 is pushed into the unstable region.

Here the vertical field has the separable form $B_V=b(t)\ B\ (R)$, where the time variation $b(t)$ is externally controlled and b and B are the vertical and toroidal field strengths in gauss, as understood from FIGS. 1 and 4 and Table III and IV. Where ϕ_T represents the additional externally controlled vertical transformer flux, which links the discharge plasma current 16 but which does not appear within the discharge region of FIG. 1, then for an externally fixed, positive, added, vertical transformer flux ϕ_T, and a vertical field strength b in gauss, the condition for stability against perturbation in R (the major radius of the toroidal plasma column 12) is

$$\frac{dF}{dR} > \text{ or } \frac{d(BR^{3/2})}{dR} > 0 .$$

When the plasma enters a region where the strength B decreases more steeply then $R^{-3/2}$, the plasma column

12 begins to accelerate rapidly in the direction of its initial velocity.

The maximum attainable radial velocity is a fraction of the plasma sound speed, and for typical tokamak parameters, the plasma transit time across the unstable region is thus readily made comparable to, or even shorter than, the ion-ion collision time. This is because the tokamak ion mean free path is typically much larger than R: a plasma moving at sound speed, i.e., roughly ion speed, can therefore go through a displacement of the order R in a time very short compared to that for ion scattering. Also, the plasma column **12** only contains about 10^{-2} gram of plasma, so that a small vertical magnetic field of a few gauss can rapidly move this small amount of plasma in the plasma column **12** a large distance.

There is a considerable practical advantage in going beyond a marginally stable central region, as illustrated in FIG. **4,** into the unstable region **70** of FIG. **5***a*. A typical cycle then proceeds as follows: The plasma is first expanded slowly (as compared with sound speed) from a plasma column major radius R, to R_2, under the control of the vertical field. This is accomplished in increasing $\phi_T/2\pi b$, either by varying $b(t)$ in time, or with fixed $b(t)$ by the described plasma current manipulation. At the plasma column major radius R_2, the plasma encounters a local maximum of F, where $F=\phi_T/2\pi b$, which corresponds in time to the plasma excursion into the described inner and outer stable regions of FIG. **5***a*. This causes the desired plasma oscillation in accordance with this invention.

A further description is provided in Princeton Plasma Physics Laboratory Report MATT-948.

FIGS. **6** and **7** illustrate examples of an idealized magnetic field configuration for the compression cycle of FIG. **5,** and FIG. **7** shows the compression cycle of FIG. **6.** These cycles are discussed in more detail in "Plasma Physics", August 1973, Vol. 15, pp 719–728.

This invention is an improvement of the method and apparatus described in U.S. Pat. No. 3,702,163, and provides irreversible plasma heating by modifying existing apparatus. To this end, this invention has the advantage of providing and selectively changing the curved vertical magnetic field gradient and the plasma current in an ATC. The result is that this invention provides for irreversibly heating the plasma without requiring penetration of the vacuum vessel discharge tube by high frequency fields and without requiring complicated and expensive technical changes in the existing ATC, which would require fast high voltage switching without the unstable region of this invention. This unstable region, which is undesirable in the existing ATC, is achieved simply and inexpensively by distributing the currents in the existing equilibrium and ohmic heating windings so as to provide the windings and currents of FIGS. **1** and **2** and Tables I–III. The average ion-ion collision time is well known in the art, since it increases with plasma temperature, as understood from "Controlled Thermonuclear Reactions" by Glasstone and Lovberg, 1960. The relaxation time t_E=W/P, where W=the total energy contained in the plasma, and P=the power required to maintain the total energy W.

EXAMPLE I

In one example, the ATC of U.S. Pat. No. 3,702,163 is modified by the use of coils **32** and **32'**, as shown in FIGS. **1** and **2** and Tables I and II, and the current in these coils is selectively increased and decreased by standard modulation techniques and means. An initial 10^{-2} grams of confined DT plasma is at a density of 10^{13} ions/cc^3, and an average temperature of 200 ev, and has a predetermined diffusion time related to an average ion-ion collision time of about 100 microseconds. Therefore, the compression and expansion times are each at least as fast as 100 microseconds, and can be much faster, with the location and currents shown in Tables I and II providing the required magnetic unstable region for instantaneously accelerating the plasma column selectively inwardly and outwardly within a relaxation time of about 3000 microseconds. Thus, in this example the total cycle time is about 3000 microseconds or less.

EXAMPLE II

The instantaneous acceleration of Example I within an ion—ion collision time was actually accomplished in the ATC at Princeton U. using therein the conventional published energy confinement times, total energies contained, and power for maintaining the contained energy, as described and/or understood from the cited publications, and MATT-994; 15th Annual Phys. Mtg. of the Am. Phys. Soc., Oct.–Nov. 1973; MATT-834; MATT-841; MATT-765; MATT-847; MATT-948; The Phys. of Fluids, Oct. 1970, Vol. 13, No. 10, p. 2593 et seq; MATT-1, Supplement III; The 1974 Wash. Mtg., Am. Phys. Soc., 22–25, April 1974; MATT-1024; and MATT-1016, which in FIGS. **1–10** shows the actual device, simplified diagrams of the ohmic heating and compression power supplies, the ATC magnetic field configuration, etc. The compression and expansion are selectively produced by either changing the shaped field or the plasma heating current.

EXAMPLE III

The steps of Examples I and II are repeated whereby a marginally stable curved vertical field gradient is established in the ATC, as illustrated in FIG. **4,** to produce the described magnetic and instantaneous inward and outward acceleration within an average ion collision time. The vertical field is modulated an infinitely small amount above and below the equilibrium value in the stable regions by up to only a few percent (5%) of this equilibrium value to produce the desired acceleration and irreversible heating of the plasma.

EXAMPLE IV

The steps of Example III are repeated using the curved verticle magnetic field gradient for achieving the unstable region illustrated in FIGS. **5***a* and **5***b*. This field gradient is then modulated for pushing the plasma column into the unstable region.

EXAMPLE V

The steps of Example IV are repeated using an increased vertical magnetic field gradient for increasing the bounce frequency of damped oscillations around the center of the inner and outer stable regions, as shown in FIG. **5***b*.

EXAMPLE VI

The steps of Example I are repeated using a fast compression and expansion time respectively for each one-half cycle that is faster than the average ion-ion collision time. Since the plasma temperature is higher than in Example I, this provides a longer (slower) average ion-ion collision time.

EXAMPLE VII

The steps of Example I are repeated in the closed vacuum tight PPL ATC containment means of U.S. Pat. No. 3,702,163 using an initial plasma current of ~200 *k*A in 10^{-2} grams of DT plasma in a volume of 10^5 cm^3 at a plasma particle number density of $3 \cdot 10^{13}$ ions-cm^3 at an electron temperature $T_e \sim 1$ *ke*V, an ion temperature of ~0.5 *ke*V, and an average ion—ion collision time t_i determined by the plasma temperature and density, i.e. 100 microseconds. The total plasma relaxation time t_E, and the energy and the power required for maintaining this total energy are so well understood from the above cited MATT reports, "The Physics of Fully Ionized Fluids" by Lyman Spitzer and "Controlled Thermonuclear Reactions" by Glasstone and Lovberg, 1960, that they are well within the skill of the art without experimentation. The plasma density, confinement time, energy, etc., are determined with conventional lasers by Thompson scattering, heavy-ion beam probes, Langmuir probes, *rf* diagnostics, e.g. as described in U.S. Pat. No. 3,265,967.

EXAMPLE VIII

The steps of example VII are repeated, except that instead of modulating the shaped magnetic field by modulating the current to the vertical magnetic field coil means, the shaped field is held constant and the plasma current is modulated. To this end, the current is modulated in the ohmic heating coils by moving the modulation source from the vertical magnetic field coil to the ohmic heating coil means.

TABLE I

	Location of Coils A, A', B, B', C, C' in cm R	Z	
A	57.8 cm	25.5	13 turns
A'	57.8	−25.5	13
B	103.5	40.9	2
B'	103.5	−40.9	2
C	135.5	21.2	1
C'	135.5	−21.2	1

The toroidal field should have 10–30 million amp turns.

TABLE II

Location of the soloidal coils of FIG. 1 and specification of currents.

Assume +1 ampere in plasma centered at Radius of 1 meter. (The currents all scale proportionally to the plasma current, i.e. if the plasma current is A times larger, then all the coil currents will be A times larger, then all the coil currents will be A times larger).

Coil No.	R (metere)	Z (metere)	Ampere Turns
1	0.16	0.065	−0.1559
1'	0.16	−0.065	−0.1559
2	0.22	0.175	−0.1719
2'	0.22	−0.175	−0.1719
3	0.335	0.24	−0.1389
3'	0.335	−0.24	−0.1389
4	0.475	0.26	−0.0158
4'	0.475	−0.26	−0.0158
5	0.625	0.27	−0.1233
5'	0.625	−0.27	−0.1233
6	0.78	0.28	−0.0097
6'	0.78	−0.28	−0.0097
7	0.92	0.295	−0.0426
7'	0.92	−0.295	−0.0426
8	1.08	0.29	−0.0180
8'	1.08	−0.29	−0.0180
9	1.215	0.215	−0.0445
9'	1.215	−0.215	−0.0445
10	1.29	0.067	−0.0243
10'	1.29	−0.067	−0.0243

TABLE III

Values of the parameter *n* for several values of R

$$\text{where } |n| = \frac{R}{B_V} \cdot \frac{dB_V}{dR}$$

R (meters)	*n*
0.3	0.994
0.4	0.979
0.5	1.086
0.6	1.840
0.7	2.244
0.8	1.680
0.9	1.253
1.0	0.899
1.1	1.017

When $|M| > 1.5$ there is radial instability, and when $|n| < 1.5$ there is radial stability.

There is a region of radial instability from 0.6–0.8 m.

TABLE IV

Symbol	Definition
(from above and/or MATT-948)	
dF/dR	
R	major radius of plasma column 12 as shown in FIG. 3
R_1	major radius of plasma column 12 as shown in FIG. 3
R_2	major radius of plasma column 12 as shown in FIG. 3
R_3	major radius of plasma column 12 as shown in FIG. 3
R_4	major radius of plasma column 12 as shown in FIG. 3
B	toroidal magnetic field strength in gauss
C_1	constant in expression $B(R) = C_1R^{-3/2}$
ψ	magnetic flux - distributions of the magnetic surface that surround and confine the plasma
F	force on plasma ring times a constant
b(t)	function of time describing field B = b(t)B(R)

TABLE IV-Continued

Symbol	Definition
$f(t)$	
I	magnitude of plasma current 16 in ab amps
ΔR	change in plasma major radius R
L'	approximate value of $\frac{dL}{dR}$
L	self-inductance of ATC tokamak
$\phi_T/2\pi b$	expression for F above
$\frac{d(BR^{3/2})}{dR}$	condition for stability
$B_{\iota} = b(t)\,B(R)$	vertical field acting on plasma ring
$b(t)$	(externally controlled) time variation of the curved vertical
$I(R)$	radial variation of plasma column 12
$B(R)$	radial variation of magnetic field
$\psi = \int_0^R dR'R'\beta(R')$	measure of the flux associated with B_{ι}
ϕ_T	represents an additional externally controlled vertical "transformer" flux, which links the discharge but does not appear within the discharge region
B_{ι}	curved vertical magnetic field
$L = 2\pi RL'$	simplified model of tokamak (ATC) self-inductance with constant L'
β	ratio of plasma pressure to magnetic field pressure
(1) $\frac{dF}{dR} > 0$ or (2) $\frac{d(BR^{3/2})}{dR} >$	condition for stability against perturbation in R
(3) $\frac{RIL'}{b} = 2R^2B = 2R\frac{d\psi}{dR}$, (4) $\frac{\phi_T}{2\pi b} = F = 2R\frac{d\psi}{dR} - \psi$	(Eq's used in Princeton Plasma Physics Report MATT 948)
	current into the plane of the paper
	current out of the plane of the paper
$\lvert n \rvert$	$\left(\frac{R}{B_{\iota}}\frac{dB}{dR}\right)$
$\lvert M \rvert$	field ratio in idealized compression cycle

What is claimed is:

1. Apparatus for heating a toroidally extending plasma column in an ATC having poloidal and toroidal coil means and toroidal containment means, comprising:

a. means for producing a magnetic field having spaced apart regions of stability and an unstable region therebetween for providing unbalanced biasing forces on the plasma column along the radial axes of the containment means for alternately, periodically and oppositely displacing the plasma column radially back and forth between the regions of stability in the plane of the containment means within a time period t_i of an average ion-ion collision time; and

b. means for modulating said poloidal coil means.

2. In the method of heating a toroidally extending current carrying plasma column in the ATC in a system of first and second current carrying poloidal and first toroidal coil means distributed so as to produce vertical curved magnetic field lines and magnetic field shapes having equilibrium regions of stability within a closed toroidal containment means for establishing the plasma column in first and second positions spaced from the inside wall of the containment means, the plasma column being stabilized along a transverse axis parallel to the axis of rotation of the containment means, radial axes extending from said axis of rotation in the plane of the toroidal containment means, and an endless equilibrium axis extending in the plasma column coaxially with the plasma current, the improvement, comprising the steps of:

a. flowing current through the poloidal coil means and distributing the same to produce a magnetic field shape forming spaced apart stability regions having an instability region in the middle region between the spaced apart regions of stability so that said magnetic field shape in said middle region is adapted to provide an unbalanced magnetic biasing force on the plasma column along said radial axes for displacing the plasma column radially from one of said regions of stability to the other in an average ion—ion collision time or less; and

b. pushing the plasma column back and forth by modulating said current flowing through said poloidal coil means alternately periodically to change the direction of the biasing force in the regions of stability in the spaces in the closed containment means on either side of the instability region so that the plasma column is initially displaced radially into the middle region along said radial axes in the direction of said axis of rotation so as to cause said plasma column to be displaced radially inwardly to said second position and compressed thereby within an average ion-ion collision time period t_i or less to increase the temperature of said plasma column, and for returning the plasma column to the aforesaid first position in a cycle successively to compress and expand the plasma column in a cycle that irreversibly heats the plasma column in accordance with the number of the cycles that are produced within the plasma relaxation time period t_E from the initial temperature and density of the plasma current carrying plasma column defined by the total energy of the plasma column divided by the power for maintaining that total energy by the flowing of the currents through the toroidal and poloidal coil means.

3. The method of claim **2** in which said modulation is applied to the current carrying poloidal coil means for producing a modulation in the plasma current to produce said biasing force.

4. The method of claim **2** in which the modulation is within a relaxation time t_E of up to about 3000 microseconds in said ATC, and said average ion-ion collision time is up to about 100 microseconds in 10^{-2} grams of DT plasma having a density of at least 10^{13} ions/cm^3 at a temperature of at least 200 eV.

5. The method of claim **2** wherein the initial field shape provides in the plane of the toroidal containment means first and second regions of stability, and sandwiched therebetween a middle-region of marginal instability toward radial plasma column displacement; and

wherein said magnetic field shape is changed in the middle region to be fully unstable toward the radial displacement of the plasma column in an average ion—ion collision time t_i or less; and

wherein said flowing current is periodically alternately increased and decreased to push the plasma column into the fully unstable middle-region so as alternately to produce said compression and expansion respectively within an average ion—ion collision time t_i or less for producing the irreversible heating of the plasma column without fast high voltage switching means for increasing the currents in the toroidal coil means or for increasing the aspect ratio of said containment means to produce said first biasing force.

6. The method of claim **5** wherein current is flowed through the poloidal coil means to produce in the middle region a magnetic field gradient and field lines that curve convexly toward the axis of rotation of the containment means, said convex curving of the field lines in said middle region increasing in opposite directions in the plane of the containment means from a zero curve respectively in said regions of stability.

7. The method of claim **6** in which the current flow in the poloidal coil means is modulated up to only 5% to produce said biasing force at a frequency of up to only every 3000 microseconds for one complete cycle in 10^{-2} grams of plasma at a density of at least 10^{13} ions/cm^3.

8. The method of claim **7** wherein said current flowing step, comprises:

flowing said current in series in said first poloidal field coil means, adjacent coils having different numbers of windings so as to produce the magnetic field shapes for a period of time to cause the unbalanced magnetic biasing force on the plasma column along the radial axes in the direction of the axis of rotation to cause the plasma column to be displaced radially inwardly from the first to the second position and compressed thereby irreversibly to increase the temperature of the plasma column within an average ion—ion collision time or less.

9. The method of claim **8** in which the modulating step, comprises:

alternately periodically increasing and decreasing the aforesaid current so as to alter the aforesaid magnetic field shapes for a period of time cyclically to bias the plasma column between the aforesaid first and second positions successively to compress and expand the plasma column in a cycle that irreversibly heats the plasma column in accordance with the intensity of said plasma current and the relaxation time period t_E of the plasma column as determined by the initial temperature and density of the plasma column, the total energy of the plasma column, and the power for maintaining that total energy.

* * * * *