USE OF STRONG RELATIVISTIC ELECTRON RINGS FOR THE CONFINEMENT OF THERMONUCLEAR PLASMAS

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Summary

Various schemes proposed for the confinement of thermonuclear plasmas are reviewed in which it may be possible to generate and maintain the necessary plasma-internal ring currents by strong self-focussed rings of relativistic electrons or protons. Thus, confinement advantages inherent in some of these schemes may become available for an actual fusion reactor. The results of first experiments injecting very-high current beams of relativistic electrons into a magnetic mirror trap show that such electron rings can be generated and give good indications for their stability.

Introduction

Notwithstanding the recent substantial progress achieved with Tokomak-type machines, the tailoring of magnetic field configurations capable of providing the best or at least sufficient plasma confinement times for a fusion reactor still remains one of the foremost problems in controlled thermonuclear research. Following some of the results of the extended experimental and theoretical research of the last 20 years, it now is generally accepted that field configurations in which the plasma would be confined in the vicinity of minima areas of the absolute magnetic field strength will be able to suppress at least all large-scale instabilities which often led to a rather catastrophic loss of plasma in many earlier experiments. Furthermore, it is widely accepted that this suppression may provide sufficiently good plasma confinement if the respective field lines do not leave these minimum-B areas. The required minimum-B quality can be achieved either by averaging along such closed field lines, so that $\oint(1/B)d\ell$ becomes a maximum within a set of nested field surfaces ("average minimum-B") or, better still, if the value of the magnetic field strength increases everywhere outside the confined plasma ("absolute minimum-B" with closed field lines). In both cases, such configurations necessitate the existence of ring currents within the surface of the confined plasma. In average minimum-B configurations, these currents can flow in regions not directly occupied, though fully surrounded by plasma. Thus, it is principally possible to maintain them in closed metallic hoops; however, the cooling and the support of these hoops would pose very serious and hitherto not fully solved engineering problems in an actual fusion reactor. In absolute-minimum-B geometries with closed field lines, these currents would have to flow within the region of plasma confinement itself. Furthermore, the cited stability advantages of this scheme largely are lost if the dynamic motion of these currents is not sufficiently decoupled from the motion of the plasma itself, i.e. if the plasma itself is carrying these currents. In both cases, the respective problems could be avoided if these currents were generated and maintained by rings of highly energetic charged particles, preferentially relativistic electrons.

In this paper, first various proposed schemes in which high-energy particles are used for field shaping are reviewed and analyzed. Then, results of first experiments at Cornell are described in which strong electron rings were generated by injecting electron beams from a very high current accelerator into a magnetic mirror trap. The obtained results also give good indications concerning the hydrodynamic stability of such rings.

General Considerations

The first confinement scheme ("Astron") to make use of relativistic electrons for field shaping was proposed by Christofilos in 1958[1]. As shown in Figure 1a, a cylindrical layer of relativistic electrons was to be trapped between two magnetic mirrors. The superposition of the magnetic mirror field and the field generated by the electron coil leads to a decrease of the field strength inside the electron layer. When the layer becomes sufficiently strong, the field direction at the cylinder axis reverses, and a nested system of closed magnetic field lines with absolute minimum-B character is generated within the electron layer. The electron layer was to be established by consecutive injection of a train of electron pulses.

In the well-known "Levitron"[2] and "Spherator"[3] schemes (see Figure 1b), generally an average minimum-B configuration is generated by a combination of two opposing coil systems, A and B, and an axial current C. In a later publication[4], Yoshikawa proposes and analyzes the replacement of the inner current loop by a ring of relativistic electrons. Similarly, some stability advantages possibly could be obtained in Tokomak devices if the plasma current could be carried by large-Larmor-radius relativistic electrons.

Neglecting inductive reacceleration of the electrons, in all these cases the slow-down time of the electrons by collisional drag in the fusion plasma

$$\tau_{slow} \simeq \frac{1}{n\gamma\sigma_{ms}c} \qquad (1)$$

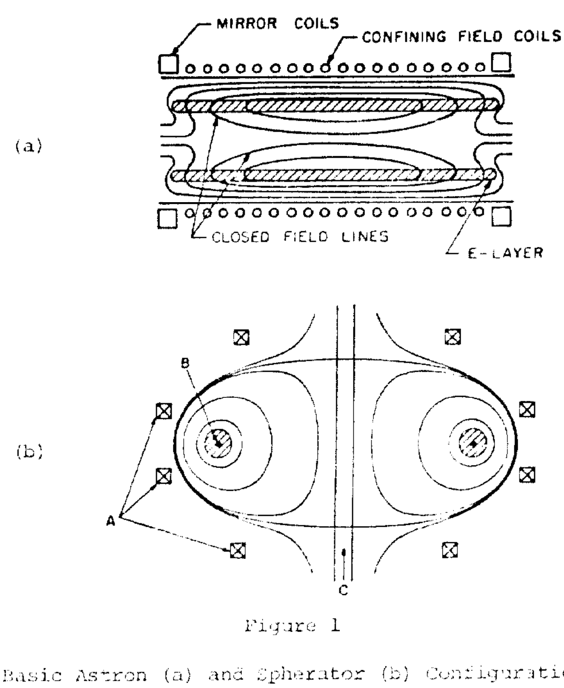

Figure 1

Basic Astron (a) and Spherator (b) Configurations (n = plasma density, γ = relativistic mass ratio, $\sigma_{ms} \approx 2(-24)/E_{MeV}^2 cm^2$, E_{MeV} beam energy in MeV)

has to be larger than the plasma confinement time required by the Lawson criterion, i.e. $n\tau_{slow} \gtrsim (n\tau)_{Lawson} \approx 10^{14} cm^{-3}$nc for a DT-reactor. According to (1), this requires

$$E_{MeV} \gtrsim 12 \text{ MeV} .$$

or we obtain

$$\frac{\tau_{slow}}{\tau_{Lawson}} \approx \frac{E_{MeV}}{12} .$$

On the other hand, the slow-down time of the electrons due to their own synchrotron radiation also has to be larger than the Lawson confinement time. Assuming that the plasma pressure nKT is equal to the energy density of the beam generated magnetic field $B^2/4$, and putting KT = 10 keV, this condition limits the electron energies to less than about 50 MeV in the original Astron scheme where the beam generated fields determine also the orbital radius of the electrons and, thus, renders this scheme somewhat marginal as actual fusion reactor.

However, this problem can be obviated in several ways: First, when stronger toroidal fields B_θ are applied, as in the Spherator Astron scheme[4], these toroidal fields help to guide the electrons along the major circumference of the machine and thus allow stronger beam generated fields than in the simple Astron.

Also, this condition possibly may be somewhat relaxed in a conceptual "Bumpy Electron Ring Torus" (see Figure 2)[5] in which a series of short electron rings is arranged along a toroidal sequence of mirror fields. In this case, the ratio of total volume available for stable plasma confinement to the volume occupied by the electron beams may be significantly increased over the same ratio available in the normal Astron scheme. Results of preliminary experiments[6] at Cornell indicate that the stability of these electron rings may not be significantly worsened by a canting of the mirror fields. The "Bumpy Torus" presently under construction in Oak Ridge[7] is similar to this scheme, though the electron radii in this case are significantly smaller than the minor machine radius.

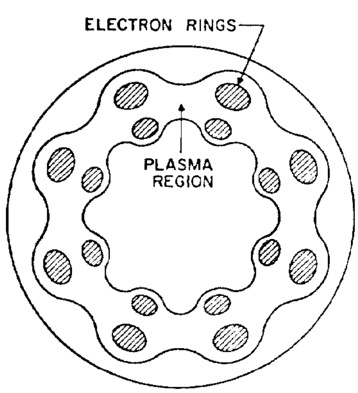

Figure 2

Bumpy Electron Coil Torus

Third, the synchrotron radiation problem could be avoided altogether if corresponding current layers could be generated by high-energy protons or other heavy particles, as first proposed by Christofilos. Such a "p-layer" could be generated either again by stacking of pulse trains of very high energy protons or, considerably easier and cheaper[5], by injection of a constant H_2^+beam of only several MeV into a performed electron ring. The H_2^+ would break up by collisions with plasma ions and release protons of 1/2 the energy which would remain in the ring and thus slowly convert it into a p-layer. A constant beam of a few amperes probably would suffice for this conversion. A subsequent compression of the entire ring would increase the proton energy to the required values. An alternate way to use heavy particle rings for confinement may be the usage of fission alpha-particles as proposed by McNally[8]. The main unknowns in either of these schemes that are to be tested experimentally are ways to generate the required rings or layers, and their stability with respect both to rather violent macroscopic instabilities and to small scale two-stream modes. The question of macroscopic stability still is undecided theoretically; comparison with known belt-pinch and similar configurations points to good stability. Experimental and theoretical evidence on possible microinstabilities is somewhat divided with experimental evidence more pointing to stability. More experimental tests of stable parameter ranges are needed.

As a first direct experimental test of his original idea, the ASTRON[1] experiment at Livermore was started by Christofilos. After the solution of considerable technological problems, now a train of up to hundred electron pulses of 5 MeV, 600 A and 300 nsec duration can be injected into a magnetic mirror trap. In most recent experiments[9] of the group, single-pulse injection led to the generation of electron layers which reducing the magnetic field on the mirror axis by up to 35%, lasting about 1 msec and, with smaller field reduction, can last up to 200 msec. Stacking of several pulses does not increase the achievable layer strength, but is capable of maintaining existing layers exhibiting up to 15% field suppression on axis.

Relativistic Electron Coil Experiment (RECE) at Cornell[6,10,11]

The RECE-program at Cornell is aimed at investigating in a mirror configuration the various problems associated with use of charged particle coils for field shaping. In contrast to the Livermore experiment, only a single high-current pulse of electron is injected into a mirror trap (see Figure 3). Presently electron beams of energies of about .5 MeV, currents of about 10 - 20 kA, and a pulse duration of 70 nsec are provided by the Cornell QWIBBLE facility. These beams are injected into a vacuum tank 45 cm in diameter and 2 m long. For space charge neutralization, a hydrogen gas pressure of several hundred micron is maintained in the tank. A magnetic field (see again Figure 3) of about 200 gauss is generated by a set of homogeneous field coils and movable mirror coils energized in series from a capacitor bank. The diagnostic instruments presently include magnetic pick-up loops at various positions along the tank axis and at the tank wall, collimated scintillator X-ray detectors directed at the trap center, a fast electronic framing camera, and time integrated optical cameras.

Figure 4 shows an early sample of the recordings of two magnetic probes (both on axis, one in the trap center, one 30 cm downstream), of the X-ray detector, and of the time-integrated camera. These recordings indicate that current layers persisting for several microseconds (presently up to 40 μsec, and strong enough to reverse the magnetic field on the tank axis) (field changes presently range up to - 190% of the

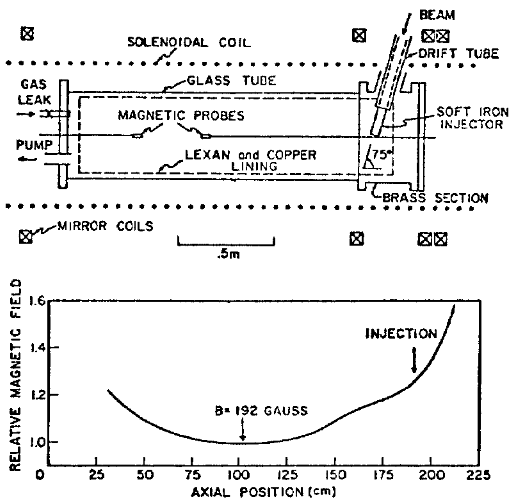

Figure 3

Experimental Arrangement and Axial Field Distribution in the RECE-Berta Experiment

original vacuum field) are generated. The X-ray detector recording which is proportional to the number of electrons hitting the tank wall indicates, after a relatively strong burst at the beginning when most of the electrons are lost, only small losses of fast electrons until the final faster decay, "dump", occurs in the magnetic probe signals when the layer strength has decayed to rather small values. Comparison measurements with two different gas fillings, one with 800 microns of hydrogen and the other with 400 micron hydrogen and 40 micron of krypton, indicate the usual long layer lifetime in the first case, but a strongly reduced life times of at most 2 μsec in the second case. Since both filling are identical in respect to the total ionization cross section of the gas and its scattering cross section for slow electrons, and differ only with respect to their total scattering cross section for relativistic electrons, this result leads to the conclusion that the observed current layers actually consist of relativistic electrons. Thus, by this method, it is possible to generate relativistic electron rings sufficiently strong to reverse the magnetic field in the trap center, i.e. to create an overall magnetic field configuration with closed field lines and absolute minimum-B characteristic.

From the same traces optimistic indications can be obtained with respect to the gross stability of these rings. The relatively slow initial decay agrees quite well with the decay to be expected from the scattering of the fast electrons from the background gas. Only the faster "dump" at the end of the pulse, reminiscent of similar occurrences in the Livermore machine, is indicative of some instability. However, it seems to occur only at a strength level of the layer which is considerably below the level of interest for fusion applications.

To test these points further, the dependence of the negative initial slopes of the magnetic probe signals on the hydrogen gas pressure in the tank were determined. Figure 5 gives some of the results. Except a small offset at small pressures, the decay constant is inversely proportional to the gas pressure as to be expected if the decay is mostly governed by the scattering of the fast electrons in the hydrogen gas.

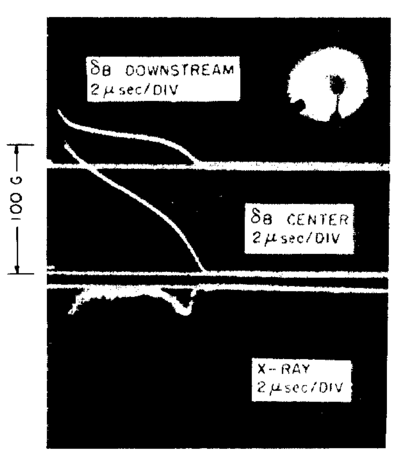

Figure 4

Sample Recordings from Optical Camera, Magnetic Probes and X-ray Detector

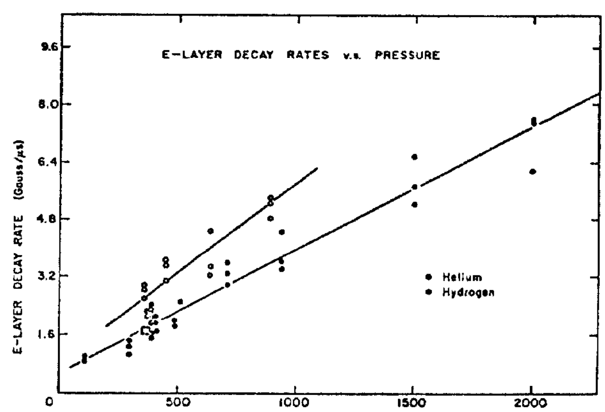

Figure 5

Dependence of Magnetic Probe Slopes on Hydrogen Pressure in Tank

The initial offset is easily explained by the relatively larger scattering cross sections of additional background gas of higher atomic number. Measured background pressures with the hydrogen supply shut off amount to several microns, which easily corresponds to the necessary equivalent of 200 micron hydrogen. Thus it appears that under the present conditions most of the initial decay of the layers is due to simple scattering which would be seriously reduced in an actual fusion reactor. Additional measurements with varying admixtures of high-Z gases support this conclusion.

The origin of the final dump was the target of some other measurements. In a number of respects, it appears to behave similar to the "precessional dump" in the Livermore experiment. In particular, the dump level decreases with decreasing radial gradient of the magnetic field strength, and it can be quenched by the application of poloidal magnetic fields generated by currents driven along the tank axis. A clear discrepancy with the Livermore results, however, exists in its dependence on the initial layer strength (see Fig. 6).

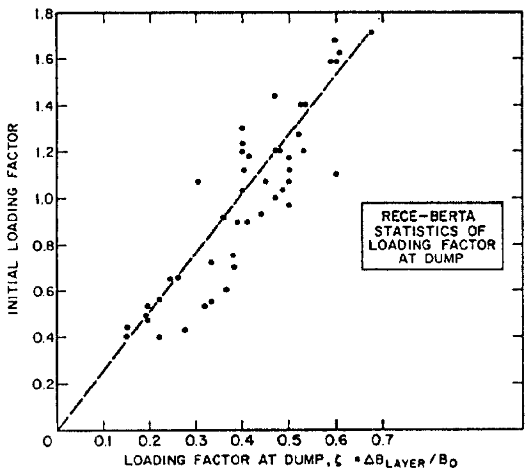

Fig. 6 Dependence of Dump Level on Initial Strength of Electron Ring

The spatial distribution of the magnetic field changes resulting from the electron coil were investigatedusing seven magnetic probes along the tank axis and three probes at the tank wall. A sample of the resulting spatial plots for various times is shown in Fig. 7. Assuming a radially thin coil with a $\cos^2 kz$ distribution of the currents, the dimensions of the coil were computed . Quite reproducibly, coil radii around 9 cm and a half-intensity length of around 15 cm, somewhat increasing during the collisional decay, were observed after the initial settling period of 1 - 2 usec.

Layer sensitivity against perturbations of the magnetic field were tested using canting of the downstream mirror by angles of up to 7 deg and asymmetries in the poloidal field of up to 10 %. In both cases, no significant change in the decay of our rings was found.

Presently, the time dependence of the energy of the fat electrons is being investigated using X-ray absorption techniques. Preliminary results indicate energy losses roughly compatible with the known collisional losses of fast electrons in gaseous hydrogen.

Conclusions

Overall, the described experiments show that strong rings of relativistic electrons trapped in a magnetic mirror can be rather stable against MHD and micro-instabilities, and against quite pronounced large-scale field perturbations. In anext step, these tests have to be extended to other parameter ranges, in particular to longer confinement times, a less collisional neutral background (i.e. smaller hydrogen pressures), and larger poloidal fields (presently up to 40 %). For this purpose a somewhat larger facility, RECE-Christa, which is presently under construction will be used. Using this facility, it may be possible to obtain also first indications concerning the plasma confinement properties of the electron rings.

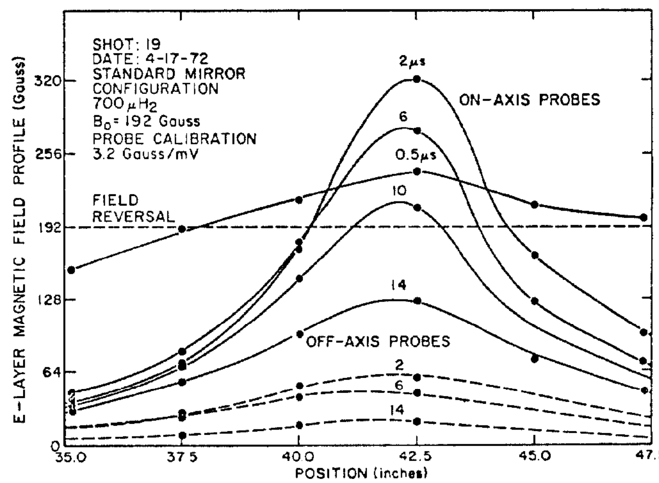

Fig. 7 Spatial Distribution of Magnetic Field Changes Generated by the Electron Coil.

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