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Publication Date
1975-08-01

Presented at the 3rd International
Conference on Alpha Beta Plasma,
Culham, England, September 9 - 15, 1975

LBL-3262
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August 1975

Prepared for the U. S. Energy Research and
Development Administration under Contract W-7405-ENG-48

LBL-3262

PLASMA CONTAINMENT IN A TOROIDAL BICUSP (TORMAC)[*]

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In this paper the stable containment of a fully ionized, high-β plasma in a toroidal "bicusp" (Tormac) is reported.

The concept for Tormac is not new. It represents a combination of what was thought to be the best characteristics of the H-centered pinch [1], later called the stabilized pinch [2] and cusp geometries [3]. Levine and Combes in 1954 showed that the stability of the Bennett Pinch could be improved if a toroidal magnetic field was trapped within the plasma. This configuration combined an internal region with a toroidally trapped magnetic field and an outer shear-stabilized sheath. Measurements reported by Levine [4] in 1955 showed that while this internally trapped magnetic field improved the stability of the Bennett Pinch it did not seem to eliminate all instabilities. At about this time Grad and his coworkers presented characteristics of the $\beta = 1$ cusp.

In the $\beta = 1$ cusp it was possible to obtain an absolute minimum-B at the plasma surface by proper use of magnetic field curvature [5]. Ironically, while a cusp geometry eliminated enhanced diffusion loss due to instabilities, a calculation of loss time on the basis of a nonturbulent plasma for cusps gave the same Bohm-like time constant [6] characteristic of unstable turbulent plasmas.

From the Grad cusp and the stabilized pinch the Tormac concept was devised. It combined the absolute minimum-B characteristics of the cusp geometry with the field trapping concept of the stabilized pinch.

The internally trapped magnetic field in Tormac gives a number of very desirable features. First of all, the inclusion of a magnetic field, which is without curl across the plasma boundary and within the plasma region, does not alter the absolute minimum-B characteristics of the plasma. Secondly, by trapping the magnetic field within the plasma the existence of zero magnetic field is eliminated and the motion of particles within the cusp is adiabatically interconnected [7]. Thirdly, the plasma is divided into two regions, a region of open field lines and a region of closed field lines. Finally, magnetic shear is introduced into the sheath region in order to enhance sheath stability.

Thus the cusp with an internally trapped magnetic field results, at least at first glance, in a stable geometry with mirror-trapped particles in the sheath and an interior region where particles can only escape by cross field diffusion. The time constant for Tormac is estimated to be $\tau_{ii} R_p/\delta$, where τ_{ii} is the ion-ion collision frequency, R_p the characteristic dimension of the plasma region with closed field lines, and δ the characteristic dimension of the plasma region with open field lines.

Jukes' theorem [8] states that an absolute minimum-B can not exist without open magnetic field lines. Tormac can be looked upon as a device which attempts to satisfy Jukes' theorem with a minimum percentage of open magnetic field lines.

Early experiments investigated the characteristics of the straight-line cusp [9] and its minimum-B geometry. Later, analog computations of the plasma equilibrium for the toroidal line cusp [10] were presented and experimental measurements of a low-temperature plasma in a Tormac hexapole were reported [11]. In these reports an extraordinarily long plasma time constant was noted.

Recently it was shown [12] that there is a canonical invariant associated with the toroidal line cusp $P_\psi = mR^2\psi + \frac{e}{c} RA_\psi$, where P_ψ is the toroidal component of momentum. Thus P_ψ is a function of the major toroidal radius. One implication of this result is that the loss cone for the toroidal cusp is a function of the cusp radius. This can lead to an enhanced particle loss rate. For this reason the Bicusp shown in Fig. 1 was devised. It has the advantage that both cusps terminate at the same major radius. At the same time, the Bicusp minimizes the magnetic energy and the number of open cusp lines where plasma can efflux and interact with the chamber walls. The toroidal Biscusp depends on both toroidal and poloidal magnetic fields to support the plasma pressure.

To understand the Bicusp equilibrium, a $\beta = 1$ model was calculated with the help of an electrolytic analog tank [10]. In this first model, a zero poloidal magnetic field was used at point A in the diagram. In this sharp sheath model an absolute minimum-B is insured if each magnetic field line on the plasma surface is concave away from the plasma. If we assume that point B is the worst point and that the radius of curvature of the poloidal magnetic field is of the order of twice the radius of curvature of the plasma, the Bicusp is absolute minimum-B for all aspect ratios. To this $\beta = 1$ equilibrium an arbitrary amount of curl-free toroidal magnetic field can be added to produce a correspondingly arbitrary value of beta.

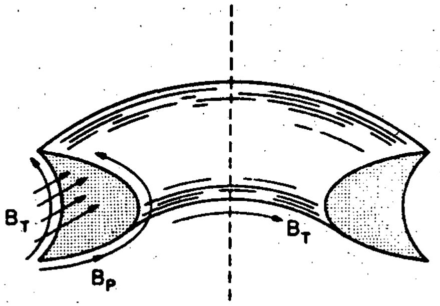

Fig. 1. Toroidal Bicusp.

To heat the plasma, "Shaker" heating is used. Shaker heating is accomplished by launching into the plasma a magneto-acoustic wave which propagates in a direction orthogonal to the internal toroidal magnetic field. The frequency of these waves should be low compared to the ion cyclotron frequency but high enough for the wavelength to be at least comparable or shorter than the minor radius of the plasma. These waves can be produced by varying the poloidal field on one side of the plasma, thus strengthening and weakening the pressure asymmetrically on the plasma.

One of the most important characteristics of the Shaker heating method is the manner in which it is coupled to the plasma. The current in the Shaker heating coil is almost parallel to the current in the main magnetic field coils which support the plasma. Thus the plasma pressure is proportional to $(I_0 + I_H)^2$, so that the plasma pressure is linear in the heater current to the first approximation. Boozer [13] has calculated the effective circuit $Q = E/\Delta E$ using a total absorption model for the magneto-acoustic wave.

A second feature of Shaker heating is that the waves launched into the plasma by the driving coil are scattered by the plasma boundary in such a way that the reflected wave no longer couples to the outside coil. This means the wave energy is trapped in the plasma.

A third characteristic of Shaker heating is that it is nonresonant with any absorption mechanism known for a plasma. This makes it possible for the energy to be absorbed uniformly throughout the plasma and not in any local region.

Fortunately, there are several nonresonant mechanisms for energy absorption in the plasma. Steepening of the strong sound waves into shock waves is one candidate. A less desirable but more likely possibility is the focusing of wave energy into regions where the amplitude is large enough to give rise to nonlinear irreversible effects.

Despite the uncertainties in understanding the Shaker method of plasma heating the simplicity of application and the effectiveness of energy transfer from capacitor to plasma make this method very attractive.

To test the Tormac Bicusp, a device has been built around a Pyrex glass chamber. This chamber is constructed from two Pyrex cylinders 30 cm high, 15 and 50 cm in radius, respectively, with flat Pyrex end plates. The chamber was assembled using epoxy.

The magnetic field design was performed with the aid of the electrolytic analog tank mentioned above. A single-turn coil was constructed using many single wires in parallel, wound at an angle so as to produce both the toroidal and poloidal magnetic fields. A 12 kJ capacitor bank is used to energize the magnetic field.

The plasma is produced from a 5 to 30 mTorr mixture of hydrogen and helium <u>in situ</u>. A 300 G magnetic field is turned on first to provide a toroidal field to be trapped within the plasma. The gas is then preionized and finally compressed and heated with the main holding magnetic field.

Both laser interferometer and time-resolved spectra are used to examine the plasma. Figure 2 is a record of the light emitted by the ionized (4686 Å) and un-ionized helium (5876 Å) as a function of position along the major axis of the torus. The light from the ionized line is observed to peak toward the center of the chamber. Laser interferometer records, not shown, would indicate the plasma is also localized radially. The un-ionized helium indicates the ionization and compression of the gas at early times. At later times a small amount of helium is seen throughout the chamber. In Fig. 3 the plasma density is obtained from the broadening of H_β in the central region is shown. It is observed to increase with the Bicusp magnetic field, indicating the plasma compression.

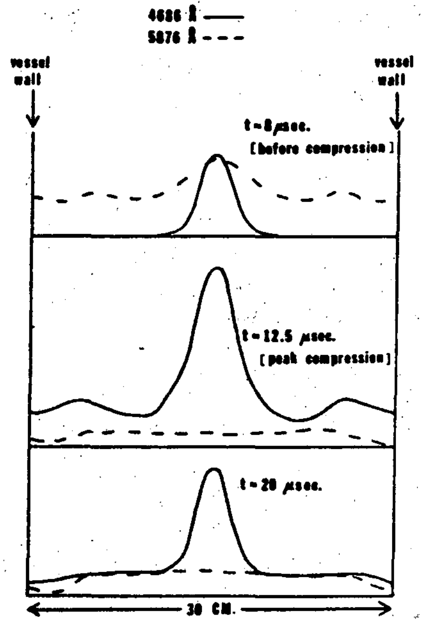

Fig. 2. Light intensity along the major axis of the torus

Figure 4 shows a plot of the electronic temperature as indicated by the intensity of the ionized helium line and the continuum radiation. It is observed to peak 12 to 15 μsec after the peak of the magnetic field and density. The timing and magnitude of of the plasma temperature are most probably the result of Shaker heating by the waves indicated on top of the magnetic field trace. The relatively high temperature of the plasma and the long time persistence of the density indicate the basic stability of the Bicusp equilibrium. The rate of plasma loss along magnetic field lines is slow because of the slow rate of recombination of the cold gas near the wall.

On the basis of data of Rose [14] for the interdiffusion of ions and gas, a time constant for plasma loss of milliseconds is indicated. On the other hand, the high conductivity of the plasma restricts cross-field diffusion to a negligible rate.

The persistence of plasma density in the Bicusp indicates the basic equilibrium and MHD stability of the system. It will remain for higher temperature experiments now in the construction phase to prove the mirror containment of particles in the sheath region.

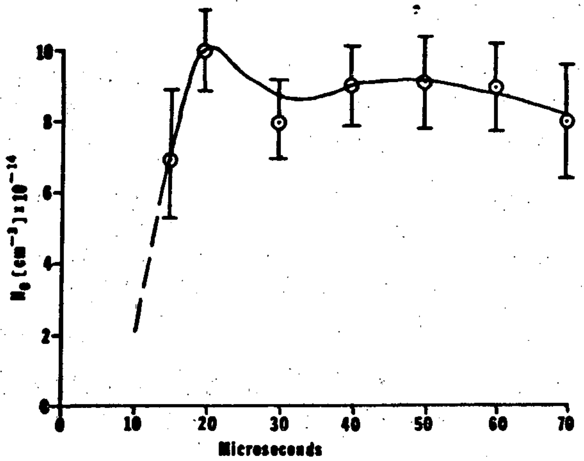

Fig. 3. Electron density in the central region of the Bicusp.

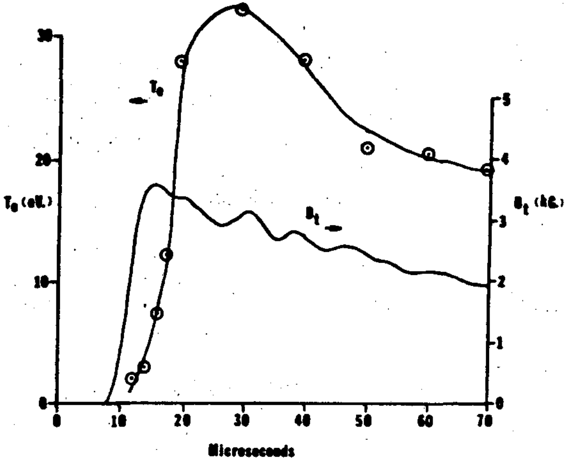

Fig. 4. Bicusp magnetic field and electron temperature in the center of the Bicusp.

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*Work supported under the joint auspices of the Electric Power Research Institube and the U. S. Energy Research and Development Administration.

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