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On the Formation of Toroidal Plasma Confinement Configurations
by Using Hot Electrons

Charles W. Hartman

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INTRODUCTION

There exist a variety of reasons (and configurations) for employing hot electrons in toroidal or mirror-toroidal hybrid confinement. In addition to in situ heating of dense plasma,¹ the hot electron diamagnetic current can be employed to shape hydromagnetically unstable field configurations, as in EBT,² or to increase the allowable β of a closed system as in Tormac.³ Alternatively, hot electron current along B, nearly dissipationless if classical, can be used to "construct" toroidal pinch-like fields as in SPIRE.⁴ In either case the tendency of hot electron plasma to be immune from usual fluid instability can play an important role.

This note discusses two possible means of producing closed, toroidal pinch-like configurations with hot electrons starting from a microwave-heated, hot electron plasma confined in open fields. The final configurations are directly related to Spheromak⁵ and Tormac.

II. Initial Plasma and Field Shape

The "preheat" phase consists of well-known ECR heating in a magnetic mirror. Two configurations employing the same ring-coils are shown in Fig. 1. Only supported rings are considered here, consequently electrons scattered onto orbits which pass around the rings are lost - only mirror confinement takes place.

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A hot electron plasma can be produced by the usual technique.⁶ Microwaves resonant with ω_{ce} within the mirror region are applied to breakdown and heat the plasma. Typically, at the end of heating, a hot electron plasma would be produced with parameters

$$n_{eh} = 10^{11} - 10^{12} \text{ cm}^{-3}, T_{eh} = 0.1-0.5 \text{ MeV}, \alpha = 0.2-0.7.$$

III. SPIRE - Like Pinch Formation

Starting with the cusp-like mirror (Fig. 1a), the formation of a hot electron pinch has been discussed earlier neglecting all contributions to current other than by hot electrons.⁴ A driving flux is introduced inside the x-point radius which induces toroidal pinch current to modify the poloidal field configuration of Fig. 1a to that shown in Fig. 2 which is qualitatively the same as that obtained in the Tokapole.⁷ Although the mechanisms of the initial current strike along the x-point are not known (possibly ion current will be responsible) it is observed experimentally that a strike does occur⁷ and leads to the fields of Fig. 2.

Subsequent buildup of current and collisionless reconnection of field lines in an anisotropic plasma has been examined from a single particle viewpoint.⁸ Guiding center trajectories are bannanas as shown in Fig. 2. As the driving flux ϕ is changed, the bannanas (A) drift perpendicular to B_p with velocity $v_D = E_t \times B_p / B_p^2$ as in Ware pinching⁹ in tokamaks. At the X (or stagnation) point the bannana undergoes a topological change to a "flutterby" orbit, Fig.

2(B), which, under further drift, fissions into two bannanas one drifting out of the region of interest, and the other (C) towards the 0-point. Further drifting (D) carries the banana into tokamak-like orbits (E) which drift towards the 0-point to go into passing orbits as shown. Passing occurs when either the reflection points merge or when the banana flattens to encompass the 0-point, depending on the particle gyroradius and the field distribution. The passing orbits are then accelerated by E_z contributing current to pinch buildup. Note the current flows in the opposite sense of the midplane ring.

A final interesting aspect of collisionless field reconnection in the context discussed here is related to the fact that except for the orbit transition to passing near the 0-point, almost all the hot electrons mirror along B. Near the stagnation point almost all electrons oscillate in v_z and j_z is a purely diamagnetic current. It would appear therefore that field reconnection would be uninhibited.

IV. Spheromak/Tormac Formation

The formation of a Spheromak/Tormac configuration begins with the Levitron-like, Min B mirror shown in Fig. 1b with, as before, a preheated, hot electron plasma. The formation process is similar to a method of generating a Spheromak suggested recently by T. Stix.¹⁰ It differs in that all the rings are supported and only mirror trapped hot

electrons are considered.*

To form an isolated, closed field region the current in the two small radius coils would be increased as shown in Fig. 3. The increase in current forces field reconnection as in the Stix concept and the change in flux within the rings tends to accelerate passing electrons and increase the toroidal current.

Forcing reconnection in the collisionless hot electron plasma has some interesting differences from the usual resistive-fluid reconnection postulated in the Stix concept. Electron guiding center orbits will likely undergo topological transitions as illustrated in Fig. 4. In addition to the orbits shown, electrons trapped against the toroidal field gradient have bannana orbits which do not intersect the midplane. These orbits will undergo the "Flutterby" transition described earlier into trapped, tokamak-like bannanas and bannanas trapped on the small major radius side of the midplane ring.

The orbits shown in Fig. 4 all make a transition to passing electrons in the pinch region and are accelerated by the flux change of the small radius rings to increase the pinch current. Note that the pinch current is in the same sense as the current of the midplane ring. If the small radius ring current is turned off the pinch would be attracted to the outer ring and the outer x-point would flatten

*Studies of current formation in a hot electron plasma with a floating ring in the levitron were conducted.¹¹ Where both passing and trapped electrons are contained. A change in the toroidal field in this case induced ~ 10 KA of hot electron current which decayed classically with a time constant of 2-5 sec.

forming a Tormac bicuspid configuration imbedded in a hot electron, mirror confined plasma.

The fact that the outer ring is supported allows consideration of plasma formation without a toroidal field with stability provided by conventional line tying with cold plasma to metal surfaces which intercept B_p on the large major radius side of the ring. For this case the electron banana orbits collapse to zero poloidal width and nearly coincide with poloidal flux surfaces. The transition in orbit topology at the x-point takes place by nonadiabatic scattering at the x-point ($B_p = 0$) and the field lines reconnect in the presence of both hot electrons and cold plasma. The resulting pinch (or field-reversed-mirror) current would be carried largely by diamagnetic current of the hot electrons which, if classical under typical conditions, could last for seconds.

Although a hot electron ring without B_t would be expected to be hydromagnetically unstable, the tendency of hot electrons is to be immune from MHD and other instabilities if, in the presence of dense cold plasma, the precessional drift frequency exceeds the ion gyrofrequency. Such a ring, if injected with energetic neutrals may have a stable pathway in parameter space to a hot-ion, FLR stabilized state.

Alternatively, if a toroidal field is necessary for stability, the potentially very long lifetime of the hot electron rings (1-10 seconds) makes it possible to turn off the toroidal field current and disconnect and remove parts of the winding, and remove the ring on a technically nondemanding timescale.

V. Summary

Several methods of producing toroidal plasma confinement configurations with and without toroidal field have been described based on poloidal field configurations formed by three, supported current rings. SPIRE, Hot Electron Tormac, Spheromak, and Field-Reversed-Mirror configurations can be formed starting with a mirror-confined, hot-electron plasma. Since the hot electron plasma energy density can be high, and the lifetime long, high current, high energy density rings can be produced with a potential lifetime of seconds. Dense plasma can be formed either by heating of cold gas by energetic electrons or by direct injection of energetic neutral atoms into a target ring.

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(a) Cusp-Like, Min $|B|$ Mirror

(b) Levitron-Like, Min $\bar{B}$ (or Min $|B|$) Mirror

Fig 1. Min B Mirror Vacuum Fields

Fig2 Cusp-Like Min|B| Mirror with Induced Current

(a) Initially, with Mirror-trapped Hot Electrons.

(b) After the current in the small radius coils is increased.

Fig 3 Spheromak/Toroid Formation

(a) Initially

(b) Transitional

(c) Bifurcated

(d) Trifurcated

Fig 4 Electron Guiding Center Orbits Evolution
as Small Radius Ring Current is Increased.