Conf-9209187--3

Electron Ripple Injection Concept for Transport Control

PPPL-CFP--2757

DE93 002103

Paper presented for IAEA Technical Committee Meeting
on Tokamak Plasma Biasing
8-10 September 1992, Montréal, Canada

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Recent experiments in many devices have provided firm evidence that the edge radial electric field profile differs between L- and H-modes, and that these fields can greatly modify transport in tokamak plasmas. A non-intrusive method for inducing radial electric field based on electron ripple injection is being developed by the CDX-U group. This technique utilizes a pair of special coils to create a local magnetic field ripple to trap the electrons at the edge of the plasma. The trapped electrons then drift into the plasma due to the ∇B drift. An ECH power is applied to accelerate electrons to sufficient perpendicular energy to penetrate into the plasma. Application of ECH power to the trapped electrons should provide the desired 20 A of electron current with electrons of a few keV of energy and $v_\perp/v_\parallel \gg 1$. A controlled experiment to investigate the physics of ECH aided ripple injection has been designed on CDX-U. With the set of ripple coils designed for CDX-U, a ripple fraction of δ $(= \Delta B/B_{av}) \sim 5$ % is attainable. At this ripple fraction, electrons are trapped if $v_\perp/v_\parallel \geq (2\delta)^{-1/2} \approx 3$. A resonant cavity box was fabricated for efficient heating of the trapped electrons. It is also capable of measuring the effect of the field ripple in conjunction with trapped electrons. Some preliminary results are given.

1. INTRODUCTION

The discovery of the H-mode was made in ASDEX [1] a decade ago. Since then, many devices have reproduced this improved confinement regime by various different methods [2–12]. One of the most important characteristics of this mode is that the global energy confinement time is two or three times longer than in conventional L-mode plasmas. The global particle confinement time in H-mode is also significantly increased. The common features of this mode are an abrupt reduction of H_α emission, which indicates a reduction of gas recycling, steeper density and temperature profile at the plasma edge, suggesting better particle confinement, appearance of edge localized modes, and formation of a velocity shear layer at the edge. Many devices have shown that the radial electric field at the edge which generates poloidal rotation of plasma plays a crucial role in the L- to H-mode transition.

In this context, it is desirable to understand what exactly triggers the H-mode, and thereby develop more efficient ways to achieve the improved confinement in large scale future devices. CCT [2] and other experiments [3, 4] produced an H-mode plasma by an externally-injected radial current from a biased electrode inserted into the plasma. They observed poloidal rotation at the plasma edge (the electric field layer), and an increase in the energy and particle confinement times. In order to apply this same technique to high density and temperature plasmas, one must consider the methods which are compatible and extendable to such plasmas. The electron ripple injection (ERI) method [13] has some advantages in that the physics is relatively simple, it is non-intrusive, easily controllable, and therefore perhaps easier to apply to larger size fusion devices.

2. BASIC IDEA OF ELECTRON RIPPLE INJECTION

The electron ripple injection concept is designed to produce a radial electric field at the plasma edge by injecting electrons into the plasma interior. The electrons which have much larger perpendicular energy than parallel energy will be trapped in a small local magnetic field ripple region provided by local poloidal field bending magnets. These trapped electrons will move radially inward into the plasma by the ∇B drift. Since the direction of the ∇B drift depends upon the toroidal field direction, the electron injector should be placed either at the top or bottom of the machine in order for the the ∇B drift direction to be toward the plasma center. The ripple-trapped electrons will eventually be detrapped due to collisions between the particles and due to the decrease of the field ripple mirror ratio away from the coils. Once the local radial electric field is set up, **E**×**B** poloidal rotation can also help trapped electrons to move out of the ripple region. As an example, if the ripple fraction, δ (= $(B_{max} - B_{min})/(B_{max} + B_{min})$) is 1 %, then the trapping condition would be

$$\frac{v_\perp}{v_\parallel} \geq \left(\frac{2\delta}{1-\delta}\right)^{-1/2} \sim 7.$$

Therefore it is important to have electrons which have predominantly large perpendicular energy.

On the other hand, the ripple fraction should be kept minimum to prevent plasma perturbation. According to the experimental results on DIII-D [5], the thickness of the electric field layer during H-mode transition appears to be 1-3 cm. This suggests that the radial penetration distance of injected electrons which is determined by the ripple fraction need be at least of this order.

In order to provide a desired amount of the local field ripple, a pair of rectangular-shaped ripple coils has been fabricated and installed on the top flange of CDX-U. Fig. 1 depicts some of the CDX-U TF coils and a set of ripple coils located at R = 35 cm, Z = 42 cm to provide the local magnetic field perturbation. In addition, electron cyclotron waves will be used to increase the population of electrons with energies of a few keV and $v_\perp / v_\parallel \gg 1$ for more efficient trapping. A resonant cavity for cyclotron heating of electrons in CDX-U is drawn in Fig. 2. Fig. 3 shows a top view of ripple coils and ECR wave inlet. The radial distance which electrons can penetrate can be adjusted by controlling the injected electron energy and the ripple strength.

3. RIPPLE COILS AND ECH SYSTEM

In order to verify this concept, a set of ripple coils and ECH system are being developed on CDX-U. For ripple coil design, numerical work has been done to calculate the desired magnetic field ripple fraction ($=\Delta B/B_{av}$). In the code, the current sources are a pair of ripple coils as well as 16 toroidal field coils (rectangular shape), and 3 pairs of vertical field coils (circular) in CDX-U. A set of points along a magnetic field line was calculated using field line equation ($dx/B_x = dy/B_y = dz/B_z = ds/B$) and the Biot-Savart law. Since the thickness of the TF coils and VF coils is small compared to their length or radius (less than $\sim 1/20$) those coils were assumed to be line or ring filaments for simplicity. Plasma current was also included and assumed to be a ring filament. Ripple coils, however, were considered to have a finite thickness ($\sim$ 2.5 cm).

According to the calculation, a ripple fraction of δ ($= \Delta B/B$) $\sim$ 5 %, in which electrons of $v_\perp/v_\parallel \geq 3$ will be trapped, is attainable with an appropriate current in each coil.

Fig. 4 (a) and (b) shows field line loci and the field strength in the presence of toroidal field (I_{TF} = 128 kA – turn ; B_0 = 0.73 kG at R = 35 cm) with ripple current (I_{rip} = 2.2 kA – turn). As shown in the figure, field lines bulge out radially, experience some excursions in Z-direction, and there is a local dip in field strength around the coils. In the absence of the ripple coils field lines remain at constant major radius.

Fig. 5 was obtained when I_{TF} = 128 kA-turn , I_p = - 10 kA, I_{VF} = 2 kA-turn, and I_{rip} = 2.2 kA-turn. Field line moves radially outward as toroidal angle increases, and this is because of poloidal field generated by the plasma current. The direction of the radial movement would be opposite if the plasma current direction is reversed. The radial excursion of field lines near the ripple coils are also depicted in the figure. Fig. 5(b) suggests that the local ripple is noticeably large (5.35%) around the ripple coils even in the presence of the plasma current.

Based on the numerical calculation, the coil dimensions, and current were determined. Since the maximum ripple fraction occurs at R $\approx$ 35 cm, the ECR wave inlet was placed in the middle of two ripple coils at this radius (Fig. 3). 5 kW of 2.45 GHz power is available from the ECR wave source.

4. BASIC EXPERIMENT FOR RIPPLE TRAPPING

To verify the effect of magnetic field ripple on charged particles as well as the ∇B drift of these particles, a basic experiment is being done. Fig. 6 depicts a schematic of ECH resonant cavity box which is placed at the top of the CDX-U machine enclosing the ripple region. The shape of the box is cubic and it is made of 0.3 mm copper sheets. There are 14 Cu electrically-floated strips on each side of two inner walls aligned to be in the toroidal direction so that they can collect charged particles generated by the rf breakdown. 2.45 GHz microwave inlet is placed at the top of the box and rf is coupled to the box through a three-stub tuner. The box is now acting as a high-Q resonant cavity. For an absorption of the wave to electrons, an electron cyclotron resonance layer was controlled to be located at the center of the cavity box by an appropriate toroidal magnetic field strength.

Fig. 7 shows a preliminary result of this basic experiment. Strips are numbered from the top of the box. Open circles were obtained without an external field ripple and closed circles were with the ripple. In this case, the direction of the ∇B drift of electrons is downward and that of ions is upward. When the toroidal field is in an opposite direction, the direction of the particle drift is also opposite as expected (triangular points). As shown in the figure, an externally applied field ripple enhances the charge separation of particles.

5. SUMMARY

In order to generate a radial electron current which is believed to be important for improving plasma confinement, some basic research is being done in CDX-U.

An electron ripple injector has been designed and tested as a non-intrusive source of radial electric field. A pair of ripple coils were also designed and fabricated to provide a magnetic field ripple of $\sim 5\%$ so as to trap edge plasma electrons. An electron cyclotron resonance wave (2.45 GHz) will be used to create trapped electrons with predominantly perpendicular velocities. The trapped electrons will drift inward due to the ∇B drift and will be eventually detrapped by collisions and by the reduction of ripple mirror ratio. Their penetration into the plasma would charge it negatively, producing an inward radial electric field in a few cm from the last closed flux surface.

To understand the behavior of charged particles in an externally-provided ripple field, a basic experiment is being done. According to some preliminary results, the dependency of the ∇B drift on the toroidal field direction was verified and the enhancement of the particle drift due to the field ripple was confirmed.

6. FUTURE PLAN

If the prototype ripple injector is proved to be successful on CDX-U, the ripple injection experiment will also be done in the CCT tokamak at UCLA with the same goal. In order to provide the trapped electrons with a relatively large perpendicular energy, ECH will also be used as in CDX-U. The design of the resonant cavity and the estimated heating power will be based on CDX-U experiment.

7. ACKNOWLEDGEMENT

The authors wish to thank Dr. D.S. Darrow for useful discussions and Dr. C.B. Forest for the ECH source. This work was supported by the United States Department of Energy under Contracts No. DE-AC02-76-CH0-3073.

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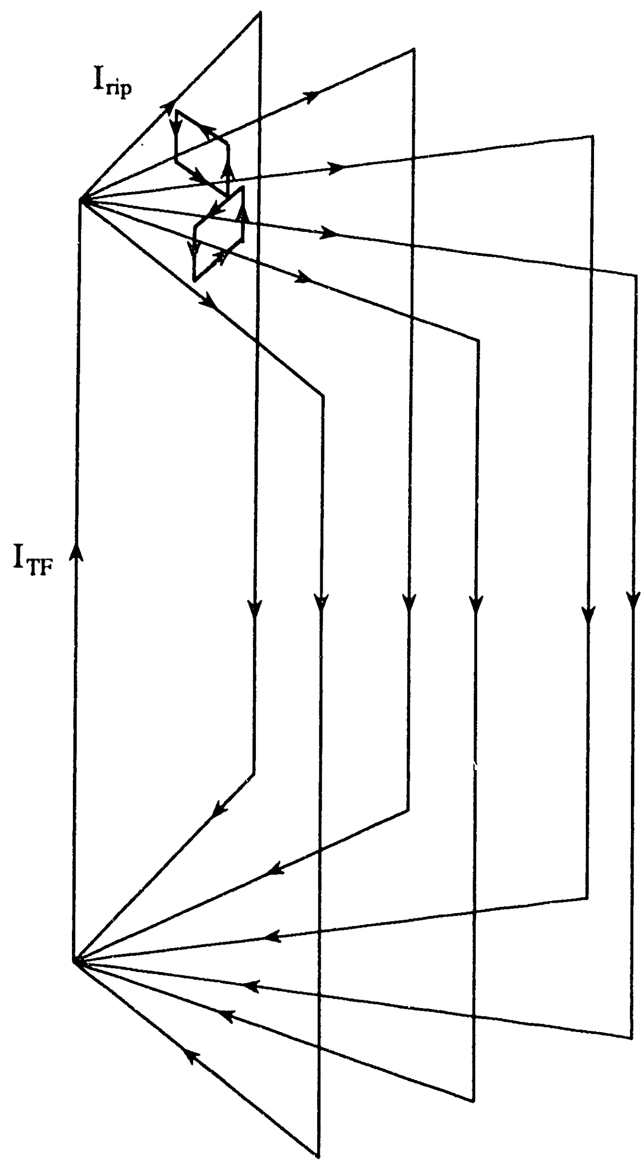

Figure 1: TF coils and a couple of ripple coils.

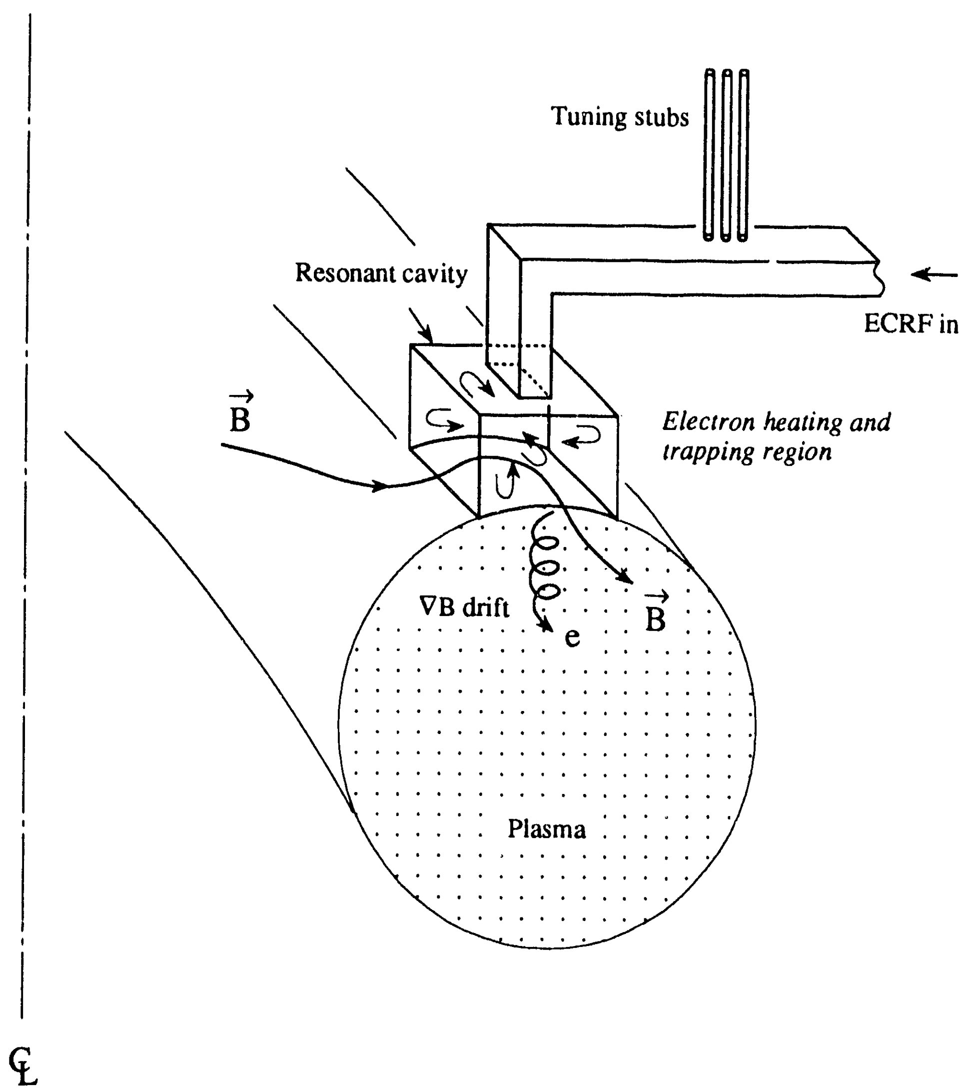

Figure 2: Resonant cavity for electron cyclotron heating of trapped electrons.

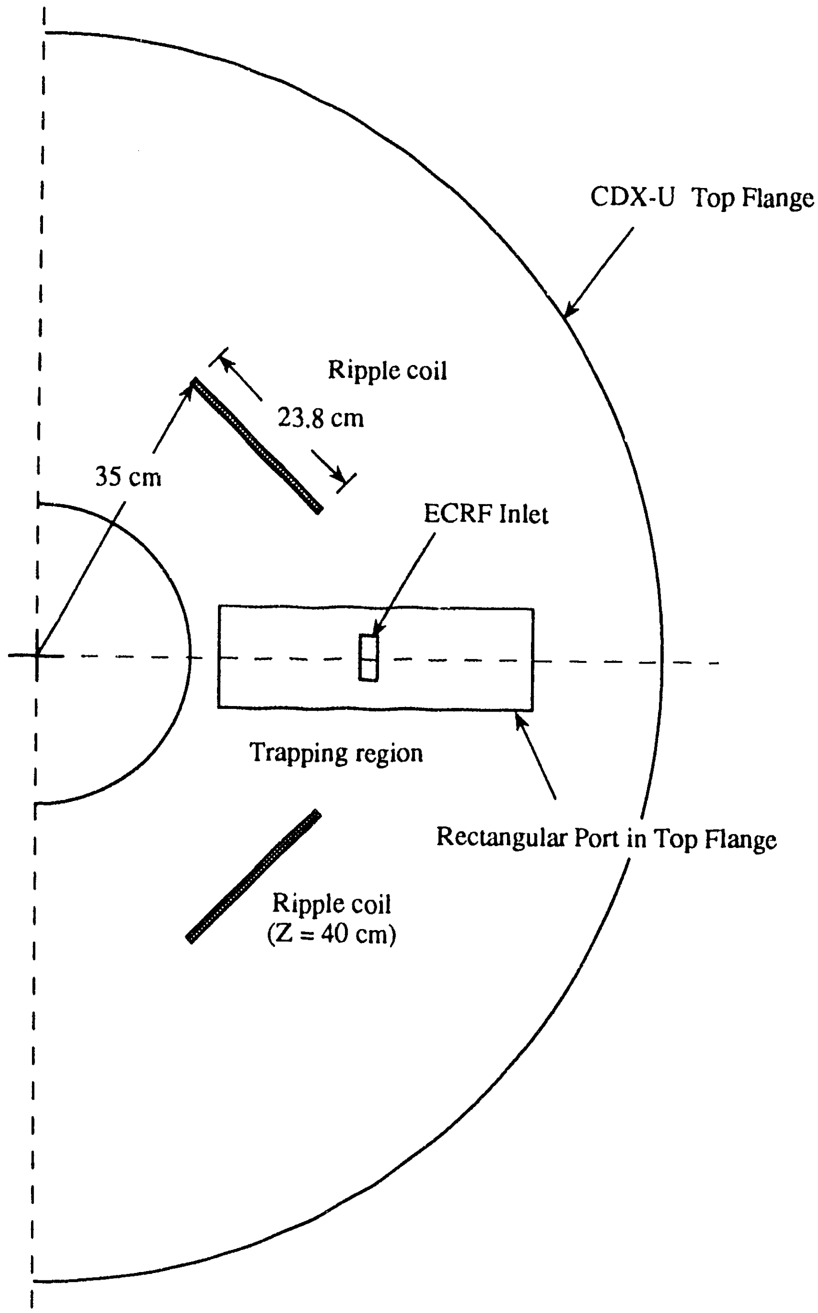

Figure 3: Top view of ripple coils and ECR wave inlet.

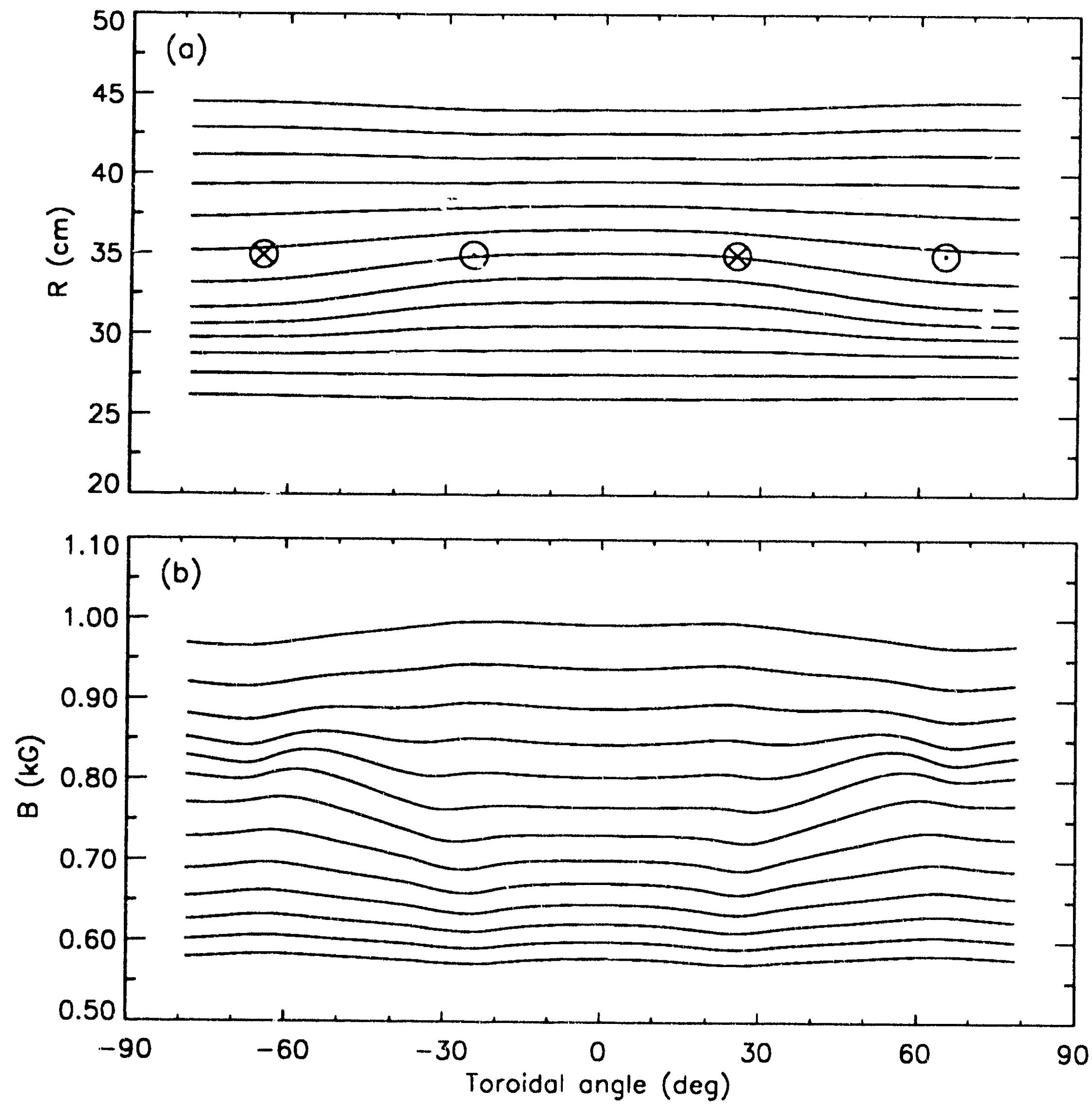

Figure 4: Calculation of magnetic field ripple with $I_{TF} = 128$ kA − turn, and $I_{rip} = 2.2$ kA. (a) Radial excursion of magnetic field lines, (b) magnetic field strength of each field line as a function of toroidal angle. Figures show that field lines are bent around ripple coils and there are local dips in magnetic field. Ripple coils are located at R = 35 cm and Z = 42 cm.

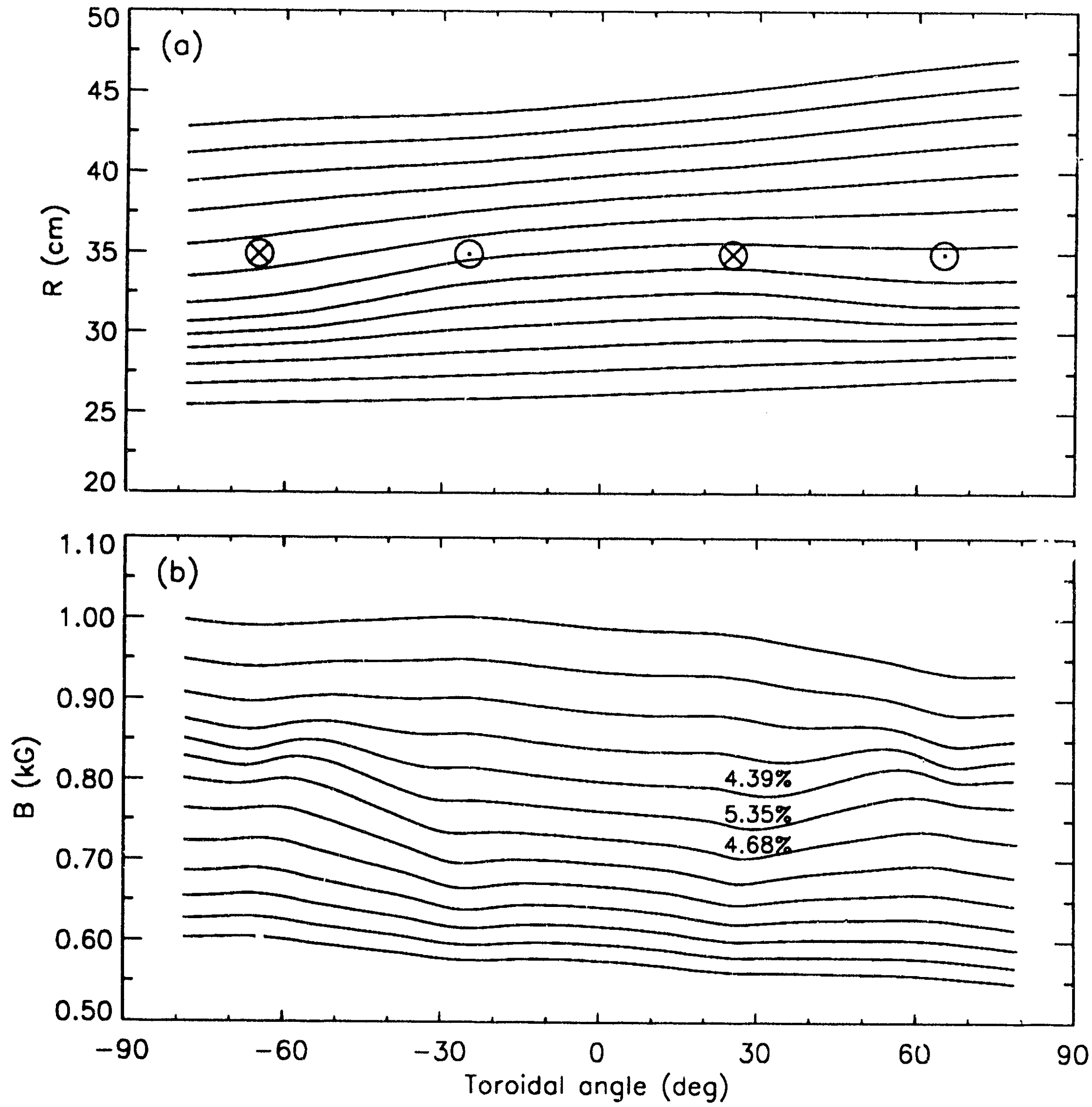

Figure 5: Calculation of magnetic field ripple in the presence of poloidal field. In calculation, I_{TF}=128 kA-turn, I_p=-10 kA, I_{VF}=2 kA. The maximum field ripple occurs at the eighth line from the outside and is 5.35%.

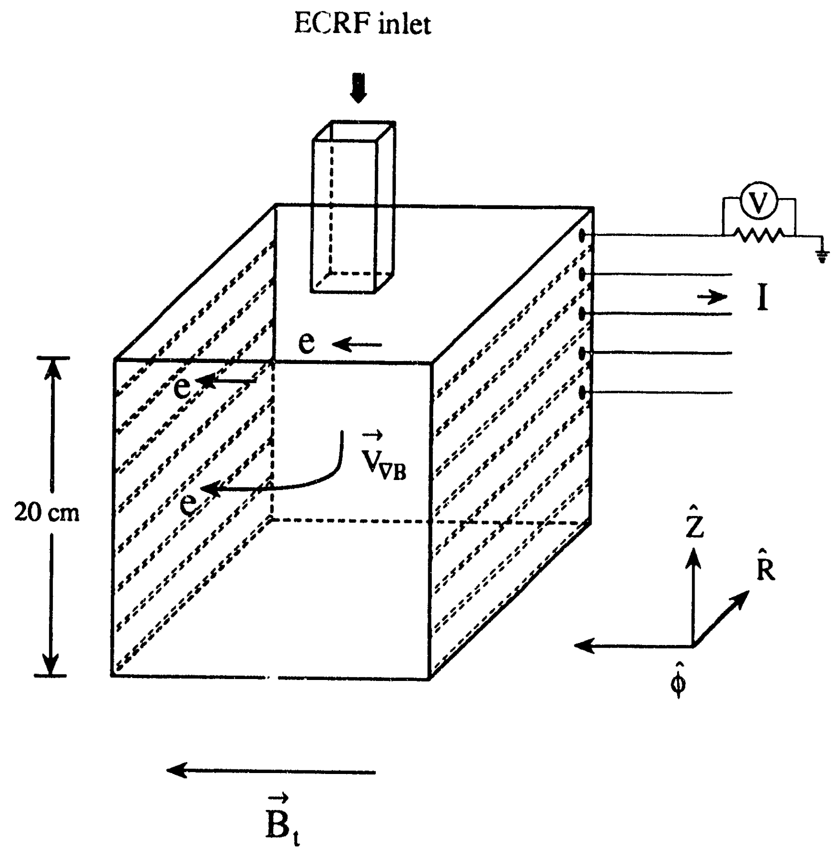

Figure 6: Schematic of ECH resonant cavity for basic experiment of ripple trapping.

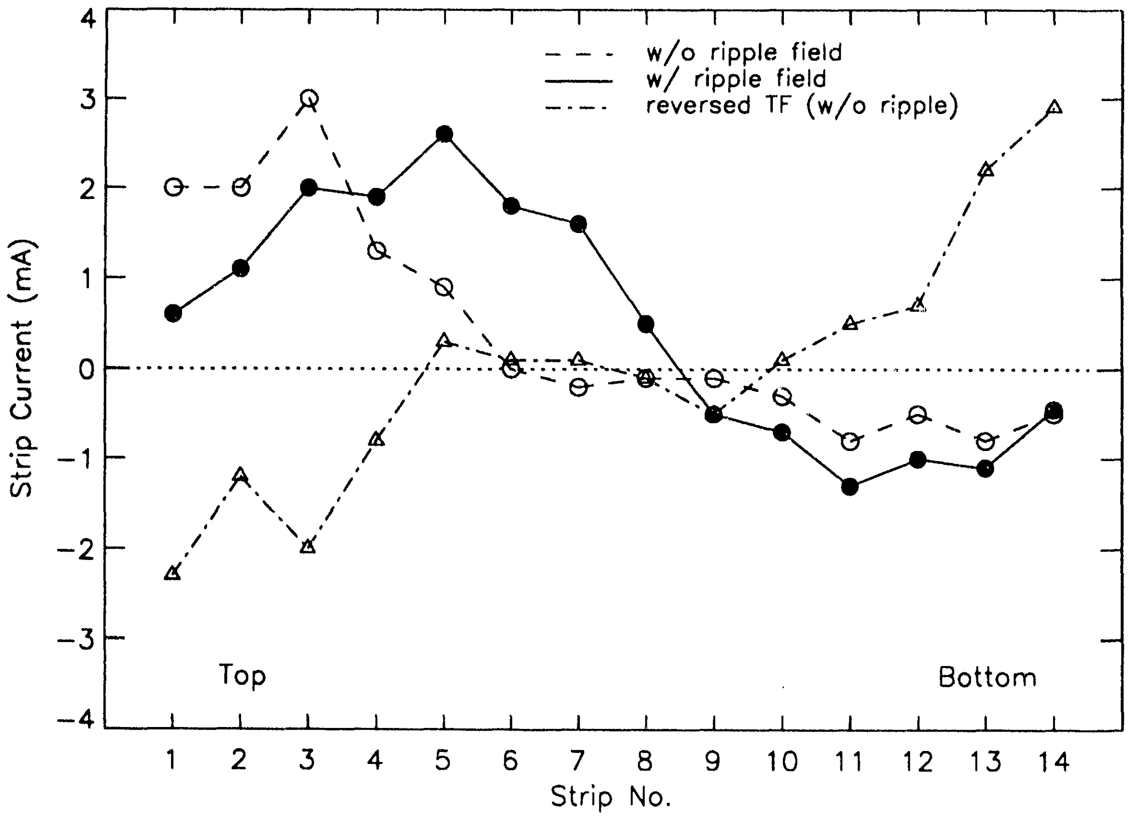

Figure 7: Current profile in vertical direction due to ∇B drift. Strip 1 is the uppermost one in the cavity box. Application of external field ripple enhances charge separation. With a reversed toroidal magnetic field, the direction of ∇B drift is opposite.

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