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Integral Suppression of Pfirsch-Schlüter Current in the Inward Shifted Stellarator Plasma in Heliotron E

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Abstract

Observation of the complete suppression of integral effect of Pfirsch-Schlüter current in Heliotron E plasmas is reported. Poloidal magnetic field was measured to control the plasma boundary position. We found that pressure-induced plasma shift, an observable characteristic of Pfirsch-Schlüter current, depends strongly on the initial position of magnetic axis. When it was moved by the vertical field inside the torus, finite-β shift became smaller. Complete suppression of finite-β shift was achieved in a deeply inward shifted configuration: 7 cm from the standard position $R_{\mathrm{axis}}=2.20$ m. Observed effect is explained by MHD equilibrium theory for planar circular axis stellarator plasma with a high magnetic hill and deep inward shift.

Keywords:

planar circular axis stellarator, Pfirsch-Schlüter current, finite beta plasma shift, magnetic hill, Heliotron E

1. Introduction

In toroidal magnetic systems, such as tokamaks and stellarators, magnetic field is inevitably inhomogeneous. When plasma is maintained in equilibrium in such a field, a dipole current appears to compensate the toroidal drift of charged particles. This pressure-induced current, flowing along the whole system, is called Pfirsch-Schlüter (PS) current. It becomes larger with increasing plasma pressure, which finally puts the upper limit for β. This limit, β_{eq}, is related with a strong shift of magnetic axis (known as Shafranov shift) produced by the vertical field of PS current [1]. Progress in operation with a finite-β plasma allowed to study it in stellarator experiments also [2,3].

In tokamaks the standard method to measure the plasma shift is based on magnetic diagnostics. It was logical to apply the same technique in stellarators. Necessary theory was developed in Ref. [4], and then method of Ref. [4] was realized [5]. At the same time we found unexpected strong dependence of the finite-β plasma column shift Δ_β on the geometry of initial vacuum configuration.

Obviously, this experimental observation was an evidence of PS current suppression in inward shifted configurations. There were theoretical indications that such suppression might be possible in conventional stellarators [6,7]. But existing theory was insufficient to

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explain our first results. The knowledge was rather limited: two numerical examples [1,6] and model analytical expression for PS current [6,7]

$$j_{PS} = \frac{2p'(\rho)}{\iota(\rho)B}\left(1 + B^2 V''(\Phi)\frac{\Delta(\rho)}{2}\right)\cos\theta, \quad (1)$$

where p is the plasma pressure, B is the magnetic field at the axis, $V''(\Phi)$ is the vacuum magnetic hill value, $\Delta(\rho)$ is the shift of a magnetic surface of minor radius ρ, and θ is the poloidal angle. This expression is good for shearless systems, but it is not justified for stellarators with large shear like Heliotron E. Till recently [8,9] these results of [1,6] were neither confirmed, nor refuted. Now it is known that proper shaping of magnetic surfaces could provide a considerable reduction of PS current in stellarators [10,11]. But it was shown for configurations evidently different from those produced in Heliotron E.

2. Experiment on Complete Integral Suppression of Pfirsch-Schlüter Current

Heliotron E device is a stellarator/torsatron toroidal device with a large shear of the vacuum rotational transform: ι_0=0.5, ι_b=2.8. The major radius is R_0=2.20 m and typical minor radius is b=0.21 m. An ℓ=2 helical coil with m=19 helical field periods can produce a toroidal magnetic field B up to 2 T at the axis. We can control the vacuum configuration by changing the total vertical field B_v produced by poloidal coils in the range $-0.2227<\beta^*<-0.15189$, where $\beta^*=B_v/B$ [12]. Then we get configurations with magnetic axis positions 2.10 m $< R_{axis} <$ 2.28 m at B=1.9 T. Figure 1 shows the poloidal cross section of vacuum magnetic surfaces of strongly inward shifted configuration with R_{axis}=2.13 m.

The experiments were performed at B=1.9 T. Currentless target deuterium plasmas were produced with the second-harmonic electron cyclotron resonance heating (ECRH) by 300 to 400 kW of rf power from 106 GHz gyrotron, without ohmic transformer. The line averaged density $\bar{n}_e$ rose to (1.5−2.0)×10^{13} cm^{-3}, then 28° and 11° co-injecting neutral beam injectors were turned on. Up to 2 MW of hydrogen neutral beam power at energy of 24−26 keV was thus injected almost perpendicularly into the torus. Deuterium gas puffing was used to raise the density further during injection to reduce shine through loss. The typical plasma parameters during the discharge were: $\bar{n}_e$=(3−7)×10^{13} cm^{-3}, T_{e0}=(400−800) eV, T_{i0}=(400−700) eV.

Finite-β plasma boundary shift Δ_β, the part of Δ due to plasma-generated magnetic field, was measured

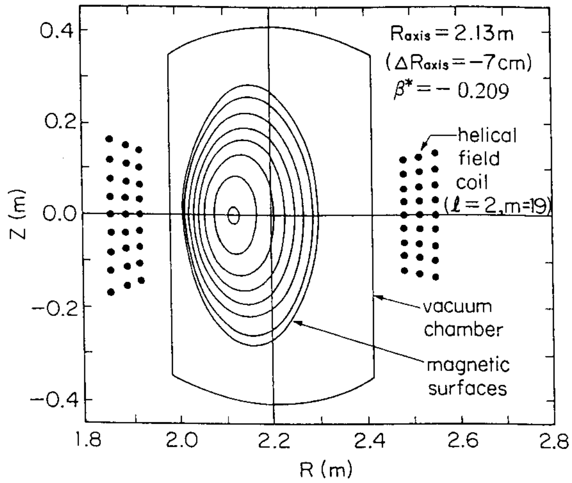

Fig. 1 Vacuum magnetic surfaces of Heliotron E configuration with inward shifted magnetic axis (R_{axis}=2.13 m, ΔR_{axis}=-7 cm), where complete suppression of Pfirsch-Schlüter current was observed. The surfaces are produced by the helical coil (l=2, m=19), main vertical coils and auxiliary vertical (AV) coils. Magnetic surfaces rotate helically along the toroidal direction.

magnetically as described in [4, 5]. We have used one pair of poloidal magnetic flux loops (ψ-loops) which are set in the equatorial plane and form a saddle loop to determine the "ribbon" averaged vertical field. One pair of cosine coils, separated by a half helical period, was also used. These two signals and the measured net toroidal current allow to derive the shift Δ_β, which was nearly proportional to the dipole moment of PS current [13]. Diamagnetic volume averaged β was used as a measure of plasma pressure.

Figure 2 shows the measured values Δ_β, β, plasma current and poloidal magnetic diagnostic signals in the discharge in strongly inward shifted configuration (R_{axis}=2.13 m, $\Delta R_{axis}=R_{axis}-R_0$=−7 cm, see Fig. 1). The diamagnetic β, as well as the stored energy, increased during neutral beam injection to 0.21% and 13 kJ. The net toroidal plasma current increased from zero to 3 kA in the direction of co-injection mainly due to the neutral beam driven current. The line averaged density increased to 7×10^{13} cm^{-3}. We observed the finite amplitude signals in the cosine coils and the ψ-loops, although Pfirsch-Schlüter current was integrally completely suppressed as indicated by almost zero plasma shift, Fig. 2(a).

On the other hand, in initially outward shifted Heliotron E configurations we could detect "normal" finite-amplitude fields due to Pfirsch-Schlüter current. The finite-β plasma shift *vs.* diamagnetic β are shown in

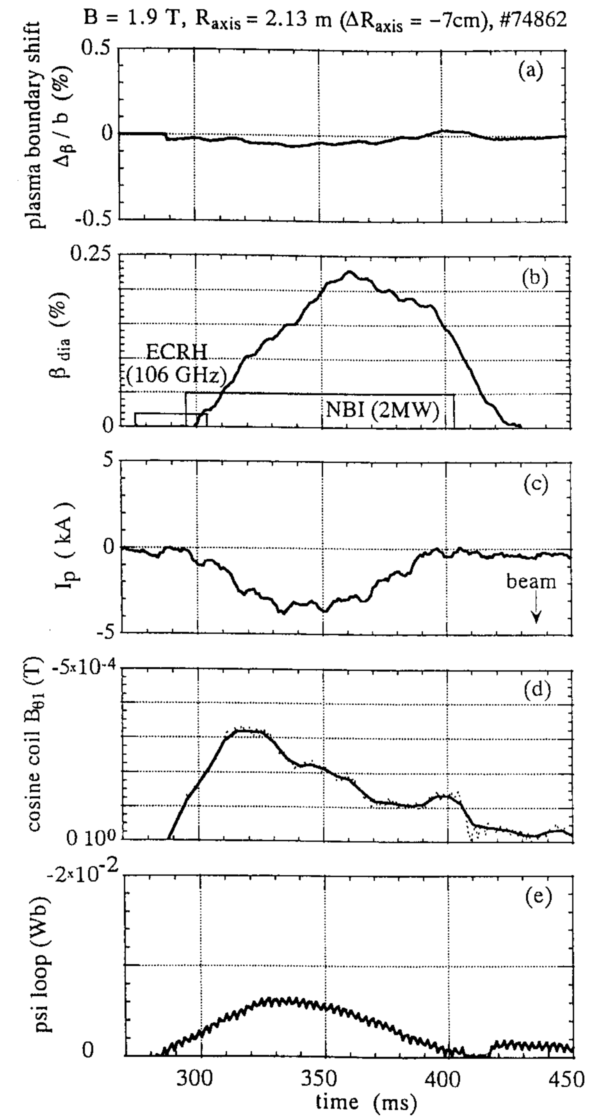

Fig. 2 The wave forms of plasma parameters of the discharge with the complete suppression of Pfirsch-Schlüter current (R_{axis}= 2.13 m): (a) finite-β plasma boundary shift, (b) volume averaged β measured by diamagnetic loop, (c) net toroidal plasma current, (d) first Fourier harmonic of the poloidal magnetic field measured by the cosine coil, (e) magnetic flux signal of ψ-loops.

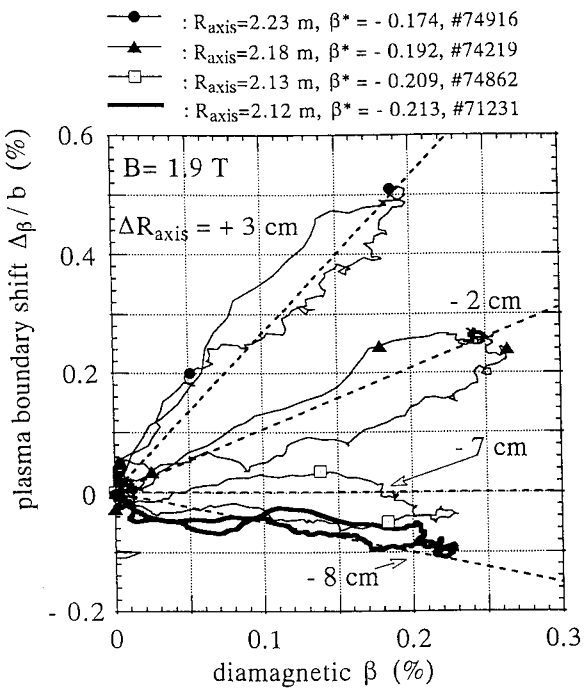

Fig. 3 Measured finite-β plasma shift at various initial positions of the magnetic axis. Each curve represents one plasma shot. Shown is dependence of Δ_β on diamagnetic β in outside shifted configuration with R_{axis}= 2.23 m, in slightly inside shifted configuration with R_{axis}= 2.18 m, in configuration with R_{axis}= 2.13 m, where almost complete compensation of Pfirsch-Schlüter current was observed, (plasma boundary was insensitive to plasma pressure), and in another deeply inward shifted configuration with R_{axis}= 2.12 m, where pressure-induced shift was "reversed". Dotted lines show average behavior of Δ_β as function of β.

Fig. 3 (ΔR_{axis}= +3 cm) in configuration with R_{axis}= 2.23 m. In this case, as in other typical regimes with a small $|\Delta R_{axis}|$, we observed relatively large "natural" outward pressure-induced plasma shift during the neutral beam heating (2 MW).

Our final goal was to verify the prediction of MHD theory [8,9] that in Heliotron E we can realize an exotic regime with overcompensation, when increasing plasma pressure moves plasma inward. And, indeed, when the magnetic axis was shifted deeply toward the major axis (R_{axis}= 2.12 m, ΔR_{axis}= −8 cm), we observed this "anomalous" behavior of plasma column during neutral beam heating, Fig. 3. Figure 3 summarizes magnetically determined finite-β plasma shift as a function of diamagnetic β in the magnetic axis scan (R_{axis} scan) experiments.

The measured equilibrium plasma shift was strongly dependent on the initial magnetic axis position R_{axis}. It is unusual for conventional stellarators, however it can be explained from the first principles of MHD equilibrium theory. In stellarators there are two sources of inhomogeneity of the magnetic field: toroidicity and helical field. Accordingly

$$j_{PS} = j_t - j_h. \tag{2}$$

In $l=2$ stellarator with a shear [8], we can control this ratio j_t/j_h, but rather strong vertical field $B_\perp$ is necessary to get substantial effect. At the same time, in a real device the acceptable range of $B_\perp$ is determined by the natural geometrical constraints: being shifted by $B_\perp$, plasma should not touch the wall. This restriction leads to the conclusion [8] that experimental efficiency of PS current reduction must be characterized by the value $\omega^0 = \iota_b mb/R$. The larger this value, the stronger suppression can be achieved by inward shifting of the vacuum magnetic axis. Heliotron E with $\omega^0=4.3$ turns out to be a unique device: in other stellarators $\omega^0=1.6$ (ATF), 1.5 (LHD), 1.3 (CHS) or smaller. Such a pronounced difference is the reason why the effect shown in Fig. 3 could not be seen in other stellarators or in calculations with a typical choice of parameters.

3. Conclusion

We have made the unique observation of the complete integral suppression of Pfirsch-Schlüter current with magnetic diagnostics in a finite-β stellarator plasma in Heliotron E and even more exotic "reversed" pressure-induced plasma shift. These effects are generally explained by MHD equilibrium theory for stellarator toroidal plasma with a strong magnetic hill and deep inward shift.

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