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BISTABLE EQUILIBRIUM OF TOKAMAK
AND ITS APPLICATION TO
MAGNETIC PUMPING

BY

H. HSUAN, AND K. BOL

MASTER

PLASMA PHYSICS
LABORATORY

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H. Hsuan and K. Bol

Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08540

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Bistable Equilibrium of Tokamak and Its
Application to Magnetic Pumping*

H. Hsuan and K. Bol
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08540

ABSTRACT

It has been experimentally demonstrated in the ATC device that, with appropriate adjustment of the external magnetic circuitry, the tokamak plasma may be stable for two different major radii. The dynamics of transition between the two equilibria involves a faster compression and expansion of the plasma, than is practical in the monostable case; this may be useful in the Artsimovich-Furth-Ellis axisymmetric magnetic pumping scheme.

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We present the results of experiments with the ATC tokamak⁽¹⁾ in which a bistable radial equilibrium was obtained, and multiple transitions from one stable region to the other were demonstrated. Here "bistable" means that a flux-conserving plasma ring is in stable radial equilibrium at either of two different major radii, but unstable in between. The transition through the unstable region was an order of magnitude faster than for a normal adiabatic compression, and had a duration comparable to the ion-ion collision time for the ATC plasma. Hence these experiments demonstrated the principle of the Furth-Ellis proposal⁽²⁾ for implementing the Artsimovich axisymmetric magnetic pumping scheme⁽³⁾; however, the practical limitations were such as to limit this nonadiabatic heating effect to a level too small ($\sim 3\%$) for definitive detection.

It has long been pointed out that a tokamak plasma can be in radial equilibrium only if the index of curvature of the vertical field is not too large. In the ATC tokamak, the ohmic heating flux is provided by a current, I_{OH} , in an air-core transformer which was designed to provide a field B_{OH} that vanishes at the normal operating radius of $R = 90$ cm, but which rises rapidly for $R < 70$ cm. The radial equilibrium of the plasma in this field alone would be strongly unstable. But by energizing the normal equilibrium field winding with a suitable current, I_{EF} , which generates a nearly uniform vertical field, B_{EF} , it is possible to create a radially unstable region in the major radius sandwiched by two stable ones. This is shown in Fig. 1a, which shows $I_{EF}(R)$ calculated for equilibrium and the corresponding plasma current, $I_p(R)$, assuming the conservation of I_{OH} and I_p linked magnetic fluxes as well as the validity of the Shafranov equilibrium equation with the proper scaling of plasma pressure and

inductance. However, eddy currents in the device, which are significant for rapid transients in current and plasma position, were neglected. The unstable region exists when the major radius becomes multi-valued for a given I_{EF} .

A point to note is that the plasma current scales more or less inversely with the major radius until the unstable region is reached. Since poloidal flux conservation inside a perfectly conducting plasma always forces the total toroidal body current of the plasma to scale inversely with the major radius, it follows that wide departure from this scaling by the total plasma current implies the induction of large surface currents. This is generally the case with unstable compression and expansions.

In our experiment, I_{OH} and I_{EF} were kept essentially constant, except that a (1-2) msec impulse was added to I_{EF} . It is seen in Fig. 1b that below a certain amplitude of the impulse, the plasma is pushed to a certain radius, and then returns to its initial position. During such a push, the plasma ring compresses to a radius determined by the compression ratio at the peak of the impulse, and then expands to about the initial major radius; the current decays slowly in the L/R time for lack of any additional supply of OH flux. However, in Fig. 1c, with an almost undetectably small increase in the amplitude of the impulse on I_{EF} , the plasma ring compresses to a much smaller radius and then stays at its new equilibrium position. The plasma current decays at a somewhat faster rate, indicating a shorter L/R time. Comparing the results of this experiment with the curves of Fig. 1a for the case $I_{OH}/I_{po} = 0.04$, which is close to the experimental value, we find

qualitative agreement between them. Quantitative agreement is not to be expected without including the image currents induced in the windings of the toroidal field coils; these constitute a nearly solid, though laminated central copper core.

We also note from Fig. 1d, which expands 1c, that the net increase in total plasma current (20%) is much less than the 2:1 increase in volume current expected for an 80/40 cm compression, thus implying the induction of a negative surface current almost as large as the original plasma current. The relative constancy of the total current for several milliseconds during which R , I_{OH} , and I_{EF} are all rather constant, in turn implies the persistence of the induced current distribution on the same time scale.

The radial position of the plasma in ATC is normally monitored by five small calibrated coils equally spaced from 40 cm to 90 cm of the major radius. The position curves in Figs. 1b and 1c were obtained by processing these signals after sampling them at a 1 kHz rate. However, a more sensitive measurement of the plasma radial motion can be conveniently made by monitoring the Hall potential between upper and lower rail limiters. In Fig. 2a, results for a normal adiabatic compression are shown, in which the plasma is compressed from 80 cm to 40 cm in major radius. For a normal compression special attention is given to make the net I_{OH} at compression almost zero, and the plasma sees a spatially uniform vertical magnetic field due to I_{EF} . It takes 2 to 3 msec for the whole compression process to be completed at a more or less uniform speed of about 2×10^4 cm/sec. Fig. 2b shows the corresponding result for an unstable compression. The first msec is about the same as

in Fig. 2a, but it is followed by a region of faster motion, most of which is transversed in less than 100 μ s. The peak amplitude of the Hall potential might have been reduced by the plasma-limiter sheath coupling efficiency, and the small size of the minor radius of the plasma also contributes to the apparent smaller peak. Nevertheless, it is obvious that the speed over most of the distance of travel is above 10^5 cm/sec, which is about an order of magnitude faster than the normal adiabatic compression.

A close observation of the last part of the compression shows that there exist oscillations of the order of 30 kHz before a final small inward drift motion continues. This oscillation also appears on a voltage loop placed at $R = 39$ cm inside the vacuum vessel. Both signals are shown in Fig. 2c. A simple interpretation of the oscillation would be that the inward motion overshoots and is restored by the steep gradient in the inhomogeneous vertical magnetic field. But despite its appeal the model is questionable, for an estimate of the frequency from machine and plasma parameters gives a frequency of about 200 kHz - an order of magnitude too high. A quadrupole mode ($m = 2$, $n = 0$ poloidal and toroidal wavenumbers) should also be excited during the compression, but would have an even higher frequency. We have not been able to resolve the discrepancy.

The fast compression, which moves the plasma ring from 60 cm to 45 cm in less than 100 μ s, which is on the order of the ion-ion collision time for ATC, suggested the possibility of an axisymmetric

magnetic pumping experiment. Such an experiment was carried out but with great technical difficulties. These difficulties mainly arise from the narrow operative ranges of I_{OH} and I_{EF} and the decay of the plasma current from lack of a separate source of ohmic heating flux.

To perform the experiment I_{EF} was amplitude modulated at about 500 Hz while I_{OH} was maintained at a level that gave an unstable equilibrium as shown in Fig. 1a. Since the cyclic motion consists of a stable compression followed by an unstable one and, then a stable expansion followed by an unstable one, the maximum operating frequency is determined mainly by the slow motions in the stable portions of the cycle. The theoretically achievable heating⁽⁴⁾ is in turn limited by the number of cycles that can be completed in an ion energy confinement time, and in ATC this was estimated to be less than 5% for the ion energy confinement time of 10 ms.

Fig. 3a shows I_{EF} , I_{OH} and the plasma current for the large excursion of the plasma position that is indicated in Fig. 3b. The controlled parameters are mainly the I_{OH} level at the start of the sequence and the amplitude and frequency of the I_{EF} perturbation. The applied signal on I_{EF} was sinusoidal and the distortions in wave shape were induced by the plasma motion and the mutual inductances among the currents. As shown in Fig. 3b, at the end of the second compression the plasma did not respond to the I_{EF} sufficiently to expand into the unstable region, so that the next compression destroyed the plasma on the inner limiter. Such difficulties were

typical in performing the experiments, but they are qualitatively understandable from the decay of I_p and the shift of unstable curves in Fig. 1a due to the change of I_{OH} and I_p . They are difficulties that stem from the device parameters of ATC rather than from the physics.

The number of cycles could be increased and the motion made more controllable by making the mutual inductance M_{EF-OH} between EF and OH circuits more negative, so that a given increase in I_{EF} would cause a larger decrease in I_{OH} ⁽⁵⁾. By making the compression more stable and the expansion less so (cf. Fig. 1a), the risk of losing the plasma on the inner limiter was thereby reduced. Fig. 4 exhibits such a case in which the fast unstable motion is absent during the compression but present during the expansion phase.

The modified, more controllable cycle retains some non-adiabatic heating effect, and so charge-exchange ion temperature measurements were made for a case in which the plasma was brought back to the original position after four cycles. However, the expected heating (~ 3) fell within the error bars of the measurements and therefore an actual demonstration of heating by axisymmetric pumping is still lacking.

In conclusion, we have demonstrated the creation of bistable equilibria with respect to major radius of a tokamak plasma, and multiple cycles of fast compression and expansion of the plasma ring during transitions between the equilibrium positions. This lays the groundwork for an axisymmetric magnetic pumping experiment.

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- ⁴The upper limit of per-cycle heating rate can be calculated from the conservations of magnetic moment and toroidal angular momentum as $.22(C-1)^2/C$ where C is the unstable compression ratio.
- ⁵This was possible because the EF and OH circuits, which are strongly coupled by the machine windings, are decoupled by an adjustable external decoupling transformer.

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Fig. 1. Bistable equilibria in major radius: (a) Computed flux conserving equilibrium for different I_{OH}/I_{P0} , where I_{P0} is the initial plasma current at compression, (b) and (c) gives two different plasma equilibria for a very small change in the perturbed I_{EF} , (d) expands (c).

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Fig. 2. Hall potential measured between upper and lower rail limiters for plasma compressions: (a) A normal adiabatic compression, (b) an unstable compression, (c) the detail oscillation at the end of an unstable compression. Approximately 350 cm/sec/volt.

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Fig. 3. Fast compression and expansion of the plasma ring: (a) I_{EF} is externally applied, I_{OH} is maintained at nearly constant level except for the induction from M_{EF-OH} , the corresponding I_p is measured, (b) the plasma motion is detected by the position loops and the speed monitored by Hall voltage ~ 350 cm/sec/volt.

Fig. 4. Multiple cycles of slow compression and fast expansion of the plasma ring; notice that M_{EF-OH} is made negative.

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