500
6-16-82
MLE

(1)

UC-20 F,G

UNIVERSITY OF WISCONSIN • MADISON, WISCONSIN

PLASMA PHYSICS

I-3814

dr. 627

HIGH-BETA MULTIPOLES*

Stewart C. Prager

AS02-76ET53051

MASTER

DOE/ET/53051-37

May 1982

---

*Presented at Symposium on "New Trends in Unconventional Approaches to Magnetic Fusion," Stockholm, Sweden, June, 1982.

DISCLAIMER

NOTICE

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS Price codes
Printed copy: A03
Microfiche copy: A01

DOE/ET/53051--37

DE82 015672

HIGH-BETA MULTIPOLES*

Stewart C. Prager

University of Wisconsin
Madison, Wisconsin 53706, U.S.A.

ABSTRACT

Multipoles are being employed as devices to study fusion issues and plasma phenomena at high values of beta (plasma pressure/magnetic pressure) in a controlled manner. Due to their large volume, low magnetic field (low synchrotron radiation) region, they are also under consideration as potential steady state 'advanced fuel' (low neutron yield) reactors. Present experiments are investigating neoclassical ('bootstrap' and 'Pfirsch-Schlüter') currents and plasma stability at extremely high beta.

---

*Presented at Symposium on "New Trends in Unconventional Approaches to Magnetic Fusion," Stockholm, Sweden, June, 1982.

1. Introduction

Multipoles were conceived about twenty years ago as devices for basic confinement research. There has been a resurgence of interest in multipoles for two reasons. Firstly recent experiments have extended plasma parameters to allow investigation of critical fusion issues in extremely high beta plasmas. Secondly, the low magnetic field of multipoles may present the low synchrotron radiation environment amenable to the burning of 'advanced' fuels which have low neutron yield but high ignition temperature.

In this paper we will concentrate on experimental information obtained in the high beta studies that affects both mainline and other alternate concepts, as well as the feasibility of multipoles as advanced fuel reactors. Detailed results have been obtained on the equilibrium and stability of high beta plasmas. Specifically, initial results have identified the well known 'bootstrap' current, that has long been predicted to flow in high beta toroidal equilibria. Plasmas have been created with sufficiently high values of beta that the observed stability cannot be explained by magnetohydrodynamics and requires a kinetic theory of ballooning instabilities. The information obtained in multipoles on these two paramount topics (bootstrap currents and ballooning modes) is indeed transferable to other devices, as described in detail below.

In section 2 we briefly review the multipole concept. The special features that enable multipoles to explore critical high beta issues in an extremely cost-effective manner are described in section 3A, including considerations involved in generalizing the results to other devices. Section 3B outlines the properties that suggest use of the device as an advanced fuel reactor. Sections 4 and 5 describe the experimental results obtained to date in these little-explored high beta regimes. Section 4 contains the initial observations of the neoclassical currents (including both bootstrap and Pfirsch-Schlüter components) and a detailed experimental account of the plasma diamagnetism (i.e., the perpendicular currents). Discussion of the experimental results from a stability point of view, including comparison with a kinetic theory of ballooning instabilities, is contained in section 5. Section 6 contains a summary of results and future plans.

2. The Toroidal Multipole Concept

In a toroidal multipole[1] the purely poloidal magnetic field is created by internal conductors, all of which carry current in the same direction to create a magnetic field null at the center. The magnetic field pattern of an octupole, the version with four current-carrying rings, is displayed in Fig. 1. There are two classes of field lines--'private' field lines which encircle a single ring, and 'common' field lines which encircle all four rings. The line (or surface) which separates the two classes is called the separatrix.

The plasma pressure profile which yields stability is one that peaks on the separatrix. In this case the private flux regions contain absolute good curvature with respect to stability. On the common flux surfaces, the region midway between the rings contains local good curvature whereas the region near the ring (between a ring and the wall) contains local bad curvature. The result is that the common flux region is a region of average good curvature (out to a critical flux surface near the the wall). The magnetic well in a multipole is very deep resulting in a simple and effective minimum-average-B system.

In most multipole devices a toroidal magnetic field capability has existed as an optional feature. If the toroidal field is not overpoweringly strong it will cause the field line to become helical while maintaining the average good curvature provided by the poloidal multipole field. Addition of the toroidal field permits both study of the resulting magnetic shear and exploitation of its potentially stabilizing influence.

3. The Uses of Multipoles

The use of multipoles is twofold--for general fusion plasma physics studies and as a possible advanced fuel reactor. In the former category, we will in this paper dwell on high beta plasma studies, although a wealth of other information has flowed from the devices. Since the assessment of its feasability as an advanced fuel reactor is in a formative and unfolding stage, and quite speculative, we will make no attempt to treat this topic in a careful way but will concentrate on the broader relevance of the multipole high beta results.

Only two high beta multipole devices are presently in operation, the Wisconsin Levitated Toroidal Octupole[2,3] and the U.C.L.A. Dodecapole Surmac.[4] Both devices have performed stability studies, with the Octupole also investigating the equilibrium currents. Transport implications of multipole research, excluding high beta results, has been previously summarized[5] (including results from the long-operated General Atomic d.c. Octopole).

3A. Multipoles for High Beta Studies

1. For Bootstrap Current Studies

Although the importance of the bootstrap current has been popularized for well over a decade,[6,7] the existence of the current has hitherto only been demonstrated theoretically. To our knowledge, the current, which should arise in toroidal systems (tokamaks, stellarators, spheromaks, etc.), has never been identified in these devices. Multipoles, based upon their device features and, more importantly, upon initial observations of the current in the Octupole, provide a unique opportunity to identify and obtain a thorough understanding of bootstrap currents and their ramifications. The current is of great importance for three reasons--it provides the possibility of driving a steady state tokamak, it creates the danger of a current-driven instability due to its enhancement of the rotational transform, and it plays an integral part in the general theory of neoclassical transport.

The special capability of a multipole to attack decisively these important questions, at modest cost, is due to the machine features listed in Table I. There is no ohmic current present to mask the bootstrap current. High beta plasmas have already been attained so that the current should be relatively large. Probe diagnostic techniques have been developed and already employed to measure the full three-dimensional spatial structure of the perpendicular currents. Thus the neoclassical currents are identifiable, as has already been established experimentally. Moreover, in a multipole the field transform and plasma collisionality may be varied over a wide range; e.g., from the Pfirsch-Schlüter, collisional regime to deep within the collisionless, banana regime where the bootstrap current dominates. The variation of these two parameters, upon which the bootstrap current should sensitively depend, is necessary for a thorough identification and experimental characterization of the currents. Finally, in the past, multipole plasmas have been observed in which particle transport is not fluctuation-induced. Thus, the theoretical fear that fluctuations may prevent the bootstrap current, may not preclude its identification in a multipole.

Identification of bootstrap currents in a multipole is signicant mainly to the extent that the results are applicable to other devices. The theory of neoclassical currents, when cast in magnetic flux coordinates, is virtually identical in a multipole (with toroidal field) and a tokamak; i.e., the equations are exactly the same, although the coefficients vary. Thus, the Octupole results are directly applicable to other axisymmetric toroids with helical field lines with little qualification and to stellarators with some care.

2. For High Beta Stability Studies

The beta value in a multipole, as in all minimum-average-B systems, is expected to be limited by the onset of the MHD ballooning instability,[8] the amplitude of which maximizes in the local bad curvature region. Although other high beta stability phenomena may be significant, the experiments have dwelt on searches for the ballooning mode because it is likely to be the macroscopic instability of greatest importance.

We believe the difficulty of transfer of information to other machines, while certainly not ignorable, is small in view of the scarcity of experimental knowledge of high beta plasmas. We address the issue of transferability with the aid of the rather complete list of features that describe a multipole, shown in table II. Originally invented with an uncomplicated attainment of average good curvature as a central design feature, the multipole is, in a sense, a prototypical minimum-average-B device, ideally suited to the study of curvature driven modes such as the ballooning instability.

When operated with poloidal field only, the magnetic field is shearless. This constitutes a considerable simplification in ballooning-mode theory. However, the addition of a toroidal field, which is presently available, introduces helicity and shear to the field lines for study of such features. Under usual operation, there is no driven ohmic current, thereby simplifying the experimental separation of pressure-driven modes (e.g. ballooning) from current-driven instabilities. However, multipoles are presently capable of generating ohmic current, in either the poloidal or toroidal direction, if investigation of current effects.(for example, on high beta fluctuation spectra) is desirable. Thus, the ability to operate as an axisymmetric, shearless, current-free, high-beta toroidal device, makes the multipole an excellent testbed for rudimentary ballooning-mode theory, common to nearly all devices. Moreover, various special features, such as shear, can be added.

Two other features of a multipole that are innocuous are the existence of the field null and the deep wells (relative to tokamaks) resulting in a large fraction (~80%) of trapped particles. Both of these features may be eliminated through the addition of a toroidal magnetic field. However, the field null is inconsequential in that it occupies a region in flux space which is of negligible extent and in which the ballooning-mode amplitude approaches zero. The depth of the wells is also not particularly significant since the trapped-particle fraction is not a critical parameter in ballooning-mode theory. In addition, there is no obvious machine feature that would cause the velocity distribution to acquire special features, relative to tokamaks for example, such as anisotropies, etc.

These remarks are meant to illustrate that the multipole high beta results are not device specific. For example, the FLR stabilization, a possible cause for the observed stability of past experiments, is a process applicable to other devices. The FLR theory we have employed is virtually identical to that used in the tokamak community. However, these statements should clearly not be misconstrued to imply that all stability features of other devices can be simulated in multipoles.

3B. Multipoles As Advanced Fuel Reactors

There are mainly two attractive aspects of a multipole reactor. The primary feature is that the large volume, low magnetic field region reduces synchrotron radiation losses, suggesting the possibility of utilizing proton-based fuel cycles that have low neutron yield.[9] This would minimize the induced radioactivity of the wall and other neutron bombardment problems and approximate a truly 'clean' fusion reactor. Secondly, the reactor would operate steady-state.

The feasibilility of a multipole reactor depends on three issues--the precise value of the synchrotron radiation losses, the precise value of the fusion cross-sections and the difficulty of the ring design. Although the magnetic field is small over a large part of the machine, a high field edge region exists and may significantly enhance the synchrotron losses. A detailed calculation of the losses, including realistic geometric factors is required to evaluate the net result. Similarly, a reliable estimate of the fusion power gain is needed, including realistic cross-sections, velocity space effects etc. If the energetics of the reactor prove favorable, the ring design must be addressed. Since superconducting rings will be required they will have to be shielded from neutron bombardment. The difficulty of this depends on the value of the neutron flux, which, though small relative to a DT reactor, is not ignorable. A realistic evaluation of the neutron flux requires a comprehensive calculation including the large number of branching reactions in addition to the primary proton-based fusion reaction. Unfortunately, little of this required information exists in the published literature. A summary of the status of these concerns is given in reference 10. A recent unpublished report[11] indicates that the energetics (i.e. synchrotron losses versus fusion power gains) may make breakeven only marginally attainable. This subject is still in an evolutionary stage.

4. High Beta Equilibrium Current Studies

4A. Parallel ('Bootstrap' and 'Pfirsch-Schluter') Current Results

Experimental identification of the bootstrap current is presently underway in the Wisconsin Levitated Octupole (Fig. 2), the initial results of which are reported here. A flux plot of the poloidal magnetic field contained within the 1.4 meter major radius toroid is shown in Fig. 3. The plasma, created by cross-field injection from a coaxial Marshall gun, requires about .4 msec to adopt an axisymmetric pressure profile which thereafter decays with about a 2 msec time constant. For these studies it is necessary that the magnetic field be helical and thus a toroidal magnetic field of .3 kG is applied.

In addition to interferometric, charge exchange and spectroscopic diagnostics, two proven probe techniques are employed to permit measurement of the full 3-dimensional structure of the plasma currents. Firstly, by taking the difference between signals to appropriately placed coils, 1 cm. apart, one can evaluate the magnetic field gradients and thereby the plasma current. It has been verified that the probes do not perturb the currents they are seeking to measure. In general, probes are less perturbing in large octupole plasmas which are free of ohmic currents and runaway electrons. Secondly, we have measured the ion current with a two-sided Langmuir probe that consists of two plane faces, insulated from each other, oriented with the planes perpendicular to the current to be measured. The difference between the ion saturation current to each plane yields the ion current.

These initial measurements have been performed in a plasma with a collisionality that is at the border between the banana and plateau regimes with the electron-ion mean free path, λ_{ei}, about equal to the connection length between mirroring points, L_{conn}. For this plasma, $\beta=2\%$, $\lambda_{ei}=1$m, $B_p=.86$kG, $n=10^{13}$ cm^{-3} and $T_e=T_i=20$eV. All local quantities, such as beta, are evaluated on the separatrix between the outer ring and the wall, as shown in Fig. 3.

The spatial structure of the neoclassical currents, in all collisionality regimes, is partially mandated by the requirement of current continuity. That is, since a perpendicular diamagnetic current exists ($\underline{j}_{\perp}=(\nabla p\times\underline{B})/B^2$) current continuity ($\nabla\cdot\underline{j}=0$) requires the presence of a parallel current of the form

$$J_{\parallel} = -\frac{B_T}{B_P}\frac{\nabla p}{B} + BK(\psi)$$

where K(ψ) is a constant of integration, constant on a magnetic surface. In the collisional regime K is determined by a simple Ohm's law, resulting in a parallel current, the so-called Pfirsch-Schlüter current, that changes direction along a field line. In the collisionless, trapped particle regime K is evaluated by a kinetic calculation,[7] resulting in a unidirectional current, the bootstrap current. Experimental measurement of these currents is thereby equivalent to an experimental determination of K.

The parallel ion current has been measured at two points along a field line and on two different magnetic surfaces in the common flux region. Figure 4 shows the results for a surface slightly outside the separatrix. The agreement with the kinetic theory, solved for the Levitated Octupole device, is quite good. Similar results, shown in Fig. 5 are obtained on a magnetic surface further outside. Roughly, the offset of the curve represents the unidirectional bootstrap current and the variation of the current along a field line represents the Pfirsch-Schlüter component that flows to ensure current continuity.

These results clearly are initial observations, and a thorough documentation of the currents is proceeding through more complete spatial data, variation of the collisionality over all regimes, and detection of the total current.

4B. Perpendicular (Diamagnetic) Current Results

For several years the plasma diamagnetism has been measured as part of the Octupole high beta stability studies (with $B_T=0$) in order to independently determine the beta value and to ascertain the extent to which the plasma equilibrium properties are well-described by MHD. For most of the plasmas studied, including those employed for the neoclassical current studies, the plasma perpendicular current is indeed equal, in magnitude and radial profile, to the MHD value, i.e., $\underline{J}=\nabla p\times\underline{B}/B^2$. Interestingly, for some cases described below the perpendicular current is much less than the MHD value, probably due to the influence of ion gyroviscosity.

The toroidal diamagnetic current density radial profile, measured between a ring and the wall is shown in Fig. 6 for a $\beta=2\%$ plasma in a purely poloidal octupole magnetic field. It agrees well with the MHD expectation. The current reverses direction across the separatrix, as does ∇p.

In some plasmas which have been studied at extremely high values of beta (i.e., $\beta=40\%$) the measured diamagnetic current is smaller than the MHD value by as much as a factor of 7. Inspection of the two-fluid equations with the full ion pressure tensor implicates ion gyroviscosity as a probable cause[3]. This is illustrated in Fig. 7 which shows the fractional change in the field due to the plasma current, $\Delta B/B$, normalized to beta, plotted versus $\omega_{ci}\tau_{ii}$. $\omega_{ci}\tau_{ii}$ is a rough measure of the gyroviscosity where ω_{ci} is the ion cyclotron frequency and τ_{ii} is the ion-ion collision time. As $\omega_{ci}\tau_{ii}$ becomes large the viscous influence becomes small. Indeed, empirically as $\omega_{ci}\tau_{ii}$ varies from 1 to 100 the experimental diamagnetism approaches the ideal MHD value.

5. High Beta Stability Results

In both the Wisconsin Levitated Octupole and the U.C.L.A. Dodecapole (Fig. 8) extremely high beta plasmas have been created and studied. In all cases the plasma is observed to be stable with respect to an MHD-like ballooning mode in that (1) the plasma decays slowly commpared to an MHD growth time (decay time ~500 Alfvén transit times) with no apparent degradation in confinement and (2) no fluctuations, that can be attributed to the high values of beta, occur in magnetic field, density or temperature to within an accuracy of (in the Octupole) $\Delta B/B < .1\%$, $\Delta n/n < 5\%$ and $\Delta T/T < 5\%$.

In the Dodecapole, plasmas with $\beta \simeq 8\%$ have been attained with $n = 3 \times 10^{13}$ cm^{-3}, $T_e = 35$ eV, and $T_i = 500$ eV. These plasmas have two ion gyroradii within a pressure gradient scale length (i.e., $\rho_i/L_p = .5$ where ρ_i is the thermal ion gyroradius and $L_p = p/\nabla p$) and are collisionless (i.e., $\lambda_{ei} = 2L_{conn}$). The plasma is injected from a Marshall gun and decays in energy in $<$ 100 μsec.

In the Octupole, plasmas created by simultaneous injection from three Marshall guns, have been studied with beta values between 11% and 44%. Whereas the plasma equilibrium (i.e., the diamagnetic current) at $\beta = 11\%$ is well-described by MHD, at $\beta = 44\%$ the diamagnetism deviates from the MHD prediction probably due to gyroviscosity, as discussed above. Thus, for the purpose at hand we will consider this case as pathological (although interesting) and hereafter concentrate on the $\beta \simeq 11\%$ case. $\beta \simeq 11\%$ is obtained with $n = 5.7 \times 10^{13}$, $T_e = T_i = 18$eV., $B = .86$kG, five ion gyroradii within a pressure gradient scale length ($\rho_i = .5$cm.), $\lambda_{ei} = 20$cm, $L_{conn} = 50$cm and an energy decay time of 350 μsec. The temperature is lower than the Dodecapole case, despite similar plasma guns, because the large machine size requires several hundred microseconds to be axisymmetrically filled with plasma. Thus experiments commence at about .4 msec, at which time the hot ion population (~300 eV) has been depleted by charge exchange.

The experimental results have been compared with both the MHD and kinetic theory of ballooning instabilities. The MHD theory for a dodecapole predicts that the plasma should become unstable at about $\beta \simeq 7\%$.[12] Thus the experimental value is slightly above the MHD beta limit. The MHD equations have also been solved explicitly for the Levitated Octupole device[2] including all realistic geometric factors. The MHD beta limit for the Octupole is 4.3%, a factor of 2.5 less than the experimental value. Thus the experimental plasmas do not satisfy the approximations inherent in the MHD theory.

To attempt to explain the observed stability, a detailed kinetic theory has been formulated and solved explicitly for the Octupole device.[13] The linearized Vlasov equation is employed to treat electromagnetic modes and solved through an expansion in powers of the ion gyroradius. Zeroth and first order velocity moments then yield a closed set of equations of quasineutrality and motion. Solution is obatained for the beta limit and the 3-dimensional structure of the mode (Fig. 9).

Calculation to zero order in gyroradius yields the 'Kruskal-Oberman' energy principle which includes particle trapping and free streaming effects. These effects negligibly influence the beta limit. The powerful finite ion gyroradius ('FLR') effects are obtained from the first order equations and are displayed in Fig. 10. The strongest FLR stabilization mechanism is related to the manifestation of the ballooning mode as an oscillatory ion drift wave at $\omega = \omega^*_i$, a well-known FLR effect.

The experimental $\beta = 11\%$ Octupole case, with 5 $\rho_i = L_p$, is displayed in Fig. 10 and is seen, to within experimental accuracy, to be marginally stable. Thus, there are two possible causes for the observed stability - FLR stabilization or collisional effects. For example, although the equilibrium of these plasmas is observed to agree with MHD with negligible viscous influence, it is possible that gyroviscosity may play a role in the stability equations. Since the $\beta = 8\%$ Dodecapole case is collisionless, only marginally unstable according to MHD, and has 2 $\rho_i = L_p$, it is either stabilized by FLR effects or barely within the MHD limit.

For the $\beta \simeq 40\%$ Octupole case, with parameters which place it clearly outside the scope of the collisionless kinetic theory, we can conjecture as to a likely cause for the stability. The ballooning mode is driven by the pressure gradient only in the sense that ∇p creates a diamagnetic current. That is, the linearized energy principle[14] shows that the mode grows through a decrease in the magnetic energy of the plasma $(B^2/2\mu_0)$ represented by the $(\underline{J}_0 \times \underline{B}_1) \cdot \underline{\xi}$ term in the energy integral. Thus, even though ∇p is large at $\beta \simeq 40\%$, the diamagnetic current is too small (section 4B) to drive the mode. Of course a self-consistent treatment is required which includes gyroviscosity in both the equilibrium and stability equations.

A simple physical picture of the instability is obtained through Fig. 11 which displays a plasma with bad field curvature with equilibrium field gradient ∇B_0 and diamagnetic current $\underline{J}_0$. A displacement $\underline{\xi}$, as shown, transports plasma to a weaker field region presenting a field perturbation $\underline{B}_1$ to the transported plasma. The $\underline{J}_0 \times \underline{B}_1$ force then reinforces the motion. The equilibrium pressure gradient plays no role in the instability dynamics. Its only contribution is to support the diamagnetic current in the equilibrium. We note also that the similar dependence of the ballooning and interchange modes on field curvature is for different reasons. For ballooning, curvature determines the sign of $\underline{B}_1$ whereas for interchange (where $\underline{B}_1=0$) it determines whether a flux tube volume will increase or decrease upon perturbation.

The variety of cases obtained is summarized in Fig. 12 which displays the beta value, normalized to the MHD ballooning limit, versus ion gyroradius, normalized to L_p, and collisionality (λ_{ei}, normalized to the connection lenth between mirroring points). A quantity which is not displayed is the ion gyroviscosity which, for example, is negigible for the Dodecapole plasma. For comparison we also display the results from the high beta studies on the ISX-B tokamak.[15]

6. Summary

Present multipole experiments are concentrating on examining high beta phenomena relevant to many different confinement devices in a manner such that the information can be generalized. The multipole enables high beta plasmas to be created and studied in a particularly controlled manner. Initial observation of the neoclassical currents (including bootstrap and Pfirsch-Schlüter components) indicates that a valuable opportunity is at hand for a thorough documentation of the currents which are of well-known importance for steady-state tokamaks, stellarators and other toroidal systems. Upcoming work on the Octupole will examine the currents in all collisionality regimes, its role as an integral part of neoclassical transport theory (i.e.,its relationship to the observed particle diffusion), and its effect on plasma fluctuations (and vice versa).

Investigation of the equilibrium diamagnetism and stability characteristics indicates the strength of non-MHD effects. Surprisingly high values of beta are obtainable without ballooning instability. Application of several megawatts of ion cyclotron resonance heating to the Octupole[16] will permit the high beta parameter space to be expanded so as to test the proposed explanations for the observed stability (e.g., finite gyroradius or collisional effects).

ACKNOWLEDGEMENTS

The high beta Octupole experiments described above are the result of a joint effort. The major collaborators are J.D. Callen, R.N. Dexter, and J.C. Sprott who have greatly influenced the work, A.G. Kellman who is responsible for most of the stability data, M.C. Zarnstorff who is responsible for the neoclassical current observations and M.W. Phillips who has developed the MHD and kinetic ballooning mode theory for the Octupole.

This work was supported by U.S.D.O.E.

References

[1] T. Ohkawa and D.W. Kerst, Nuovo Cimento 22, 784 (1961).

[2] S.C. Prager, J.H. Halle, M.W. Phillips, R.S. Post, and J.C. Twichell, Nucl. Fusion 20, 635 (1980).

[3] J.H. Halle, A.G. Kellman, R.S. Post, S.C. Prager, E.J. Strait, and M.C. Zarnstorff, Phys. Rev. Lett., 46, 1394 (1981).

[4] R.W. Schumaker, M. Fukao, A.Y. Wong, R.G. Suchannek, K.L. Lane, and K. Yatsu, Phys. Rev. Lett., 46, 1391 (1981).

[5] G.A. Navratil and R.S. Post, Comments on Plasma Physics and Controlled Fusion, 5, No. 20 (1979) 29.

[6] R.J. Bickerton, J.W. Connor, and J.B. Taylor, Nat. Phys. Sci. (229), 110 (1971).

[7] F.L. Hinton and R.D. Hazeltine, Rev. Mod. Phys. 42, 239 (1976).

[8] See for example, J.W. Connor, R.J. Hastie, and J.B. Taylor, Phys. Rev. Lett., <u>40</u>, 396 (1978).

[9] R.W. Conn, D. Arnush, J. Dawson, D.W. Kerst, and V. Vanek, in Fusion Reactor Design Concepts (International Atomic Energy Agency, Vienna 1978), 721.

[10] F.F. Chen, University of California at Los Angeles Report PPG-553, March, 1981.

[11] T. Samec, Proceedings of Workshop on Advance Fuel Fusion Reactors, La Jolla, California, 1981.

[12] D.A. D'Ippolito, E.A. Adler, and Y.C. Lee, Phys. Fluids, 20 (1989) 635.

[13] M.W. Phillips, Ph.D. Thesis, University of Wisconsin, 1981.

[14] I.B. Bernstein, E.A. Frieman, M.D. Kruskal, and R.M. Kulsrud, Proc. Roy. Soc., Ser. A244, 17 (1958).

[15] M. Murakami, et al. in Plasma Physics and Controlled Nuclear Fusion Research 1980 (Proc. Eighth Int'l. Conf., Brussels) Vol. 1, IAEA, Vienna (1981) 377.

[16] R.N. Dexter, C.M. Fortgang, S.C. Prager, J.C. Sprott, E.J. Strait, and J.C. Twichell, Proceedings of The Third Varenna-Grenoble International Conference on Heating in Toroidal Plasmas (1982).

STUDY OF BOOTSTRAP CURRENTS

OCTUPOLE ADVANTAGES

1. NO OHMIC CURRENT
2. HIGH BETA PLASMAS
3. CAN MEASURE 3-D CURRENT PROFILE
4. CAN VARY COLLISIONALITY AND FIELD TRANSFORM
5. FLUCTUATIONS MAY NOT DOMINATE TRANSPORT

Table I. Multipole advantages for neoclassical (bootstrap and Pfirsch-Schlüter) current studies.

MULTIPOLE FEATURES

1. "PROTOTYPICAL" MIN-AV-B DEVICE	GOOD TEST OF BALLOONING-MODE THEORY
2. SHEAR OPTIONAL	
3. OHMIC CURRENTS OPTIONAL	
4. AXISYMMETRIC	
5. FIELD NULL OPTIONAL	
6. DEEP WELLS	

Table II. Multipole features relevant for ballooning mode studies.

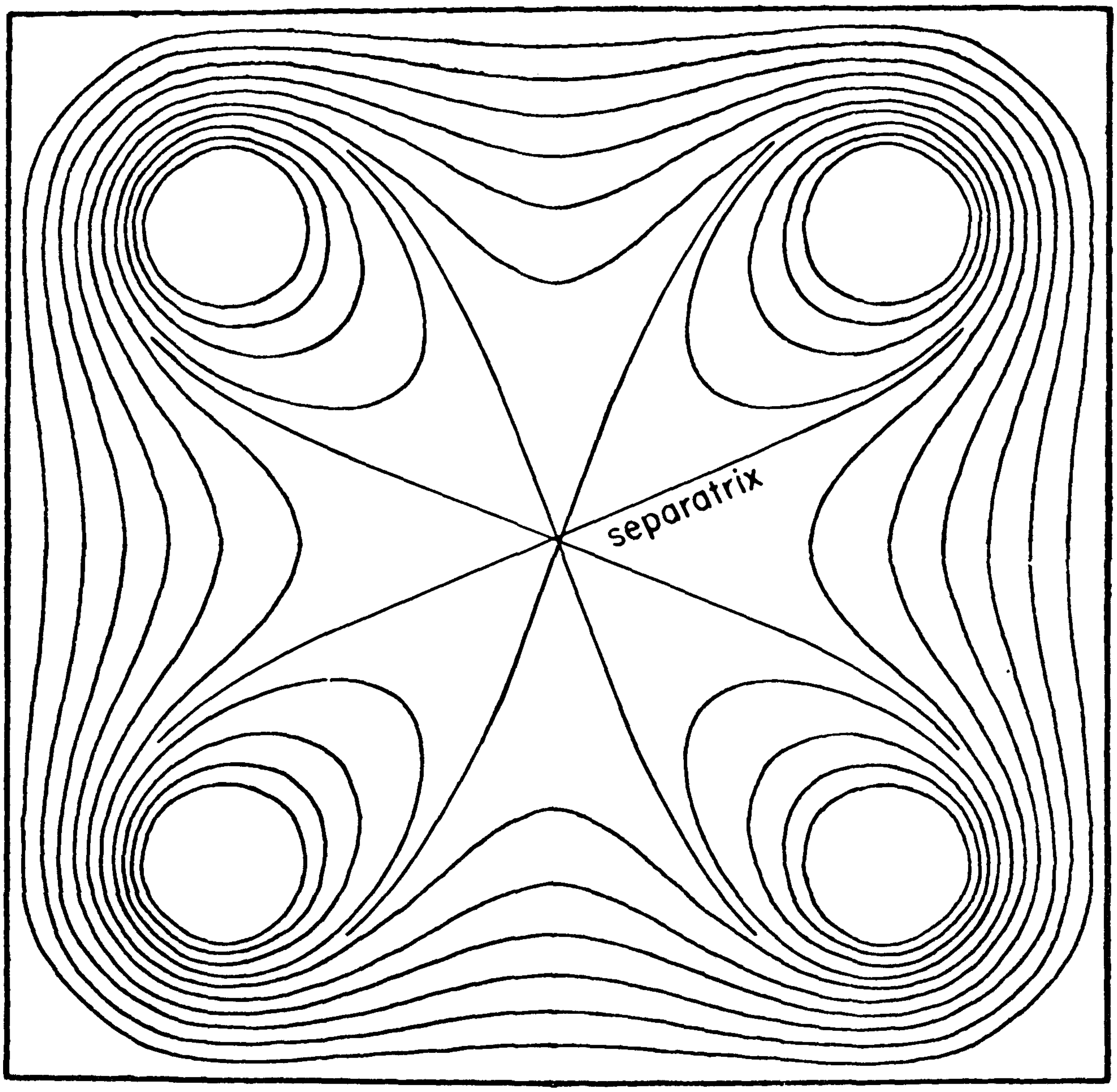

Fig. 1. Magnetic field line plot of a multipole with four rings (an octupole) indicating the separatrix which separates the private and common flux regions.

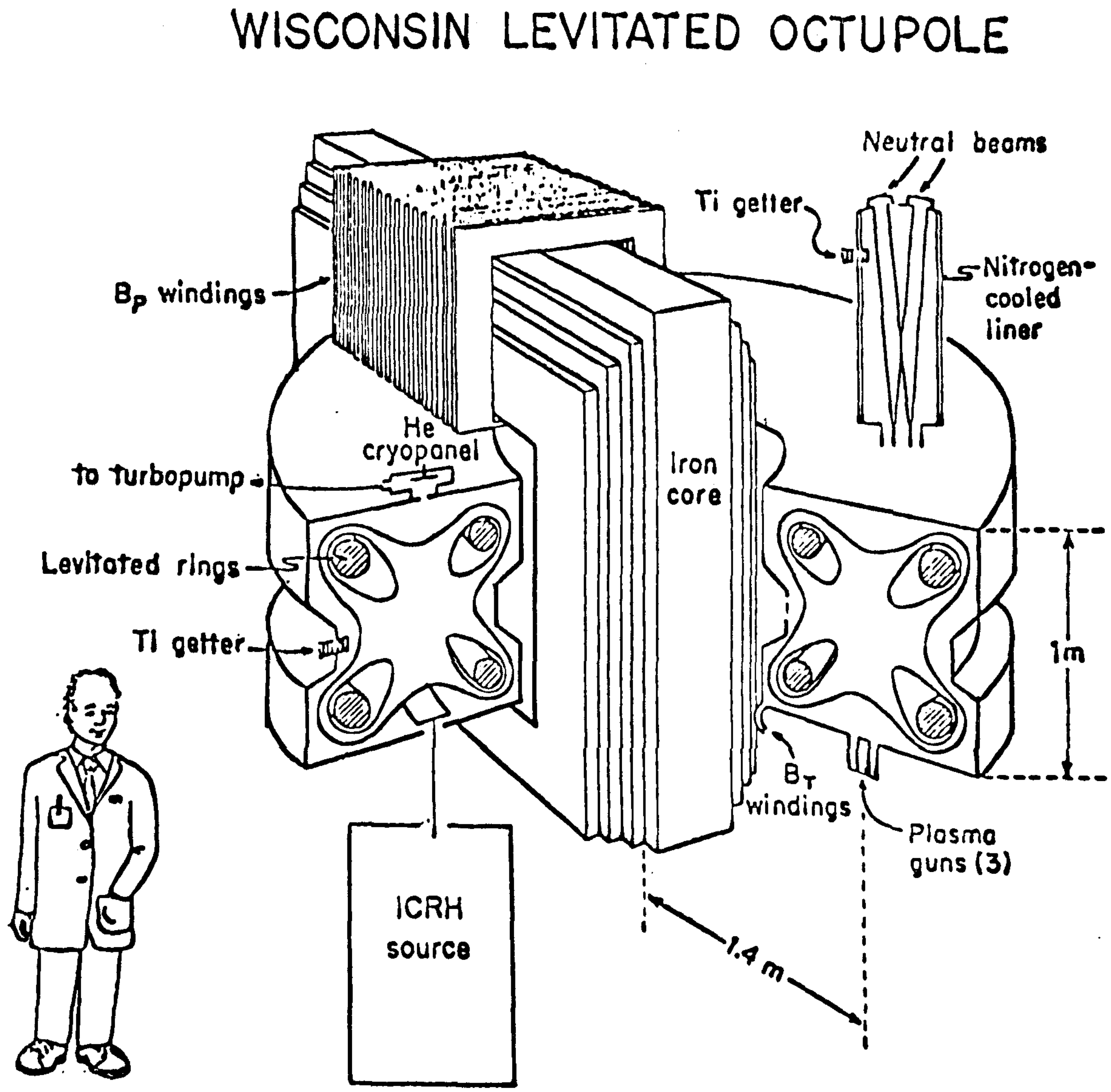

Fig. 2. Wisconsin Levitated Octupole. A total ring current of 1 Megamp is induced by a 50 ton iron core transformer. The rings (total weight of 2 tons) are levitated for 30 msec during the plasma lifetime.

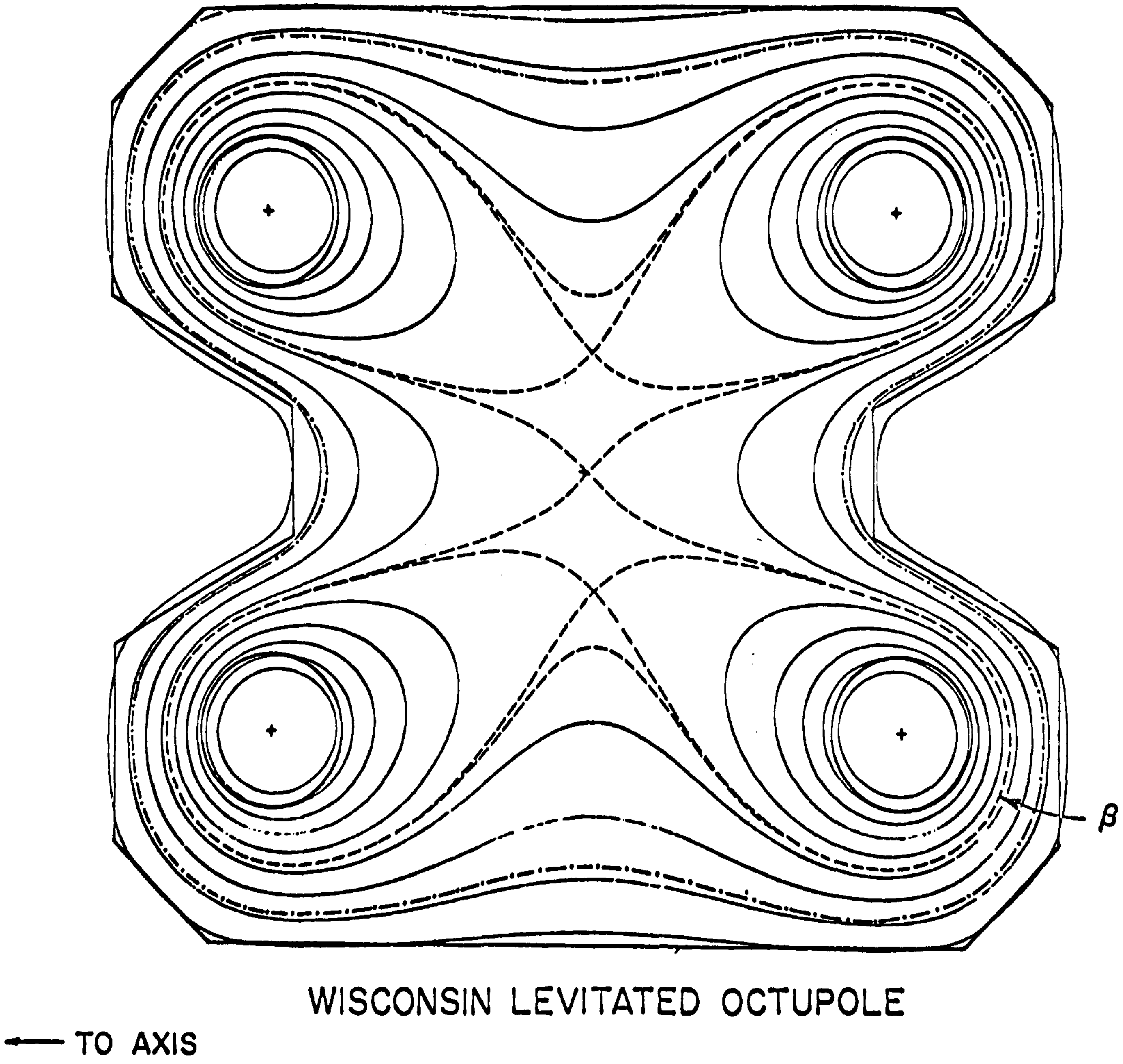

Fig. 3. Poloidal magnetic flux plot of the Wisconsin Levitated Toroidal Octupole indicating the region where β is evaluated. Major radius is 1.4 meters.

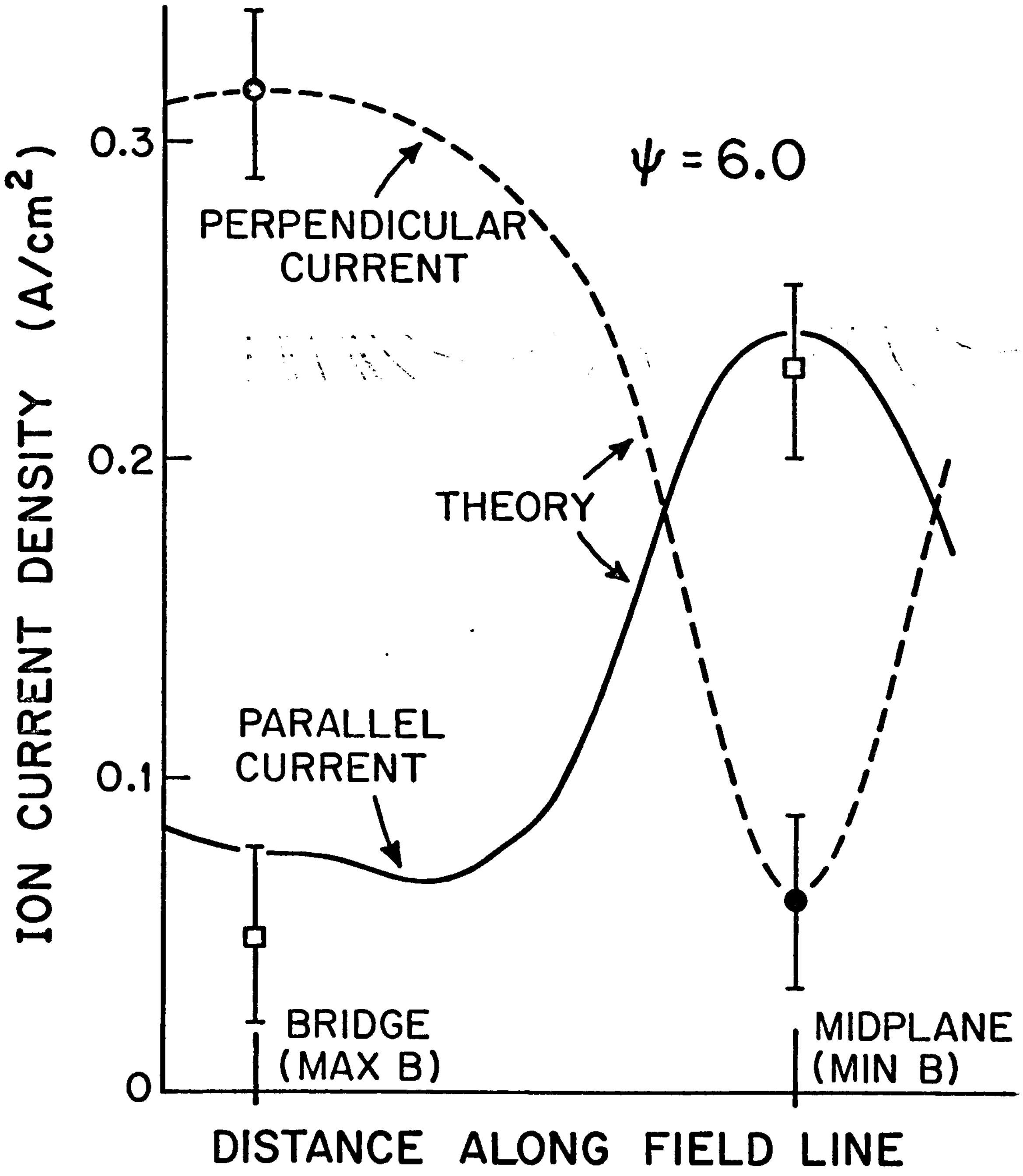

Fig. 4. Ion perpendicular and parallel (neoclassical) currents measured at two points along a magnetic field line on a surface outside the separatrix. Shown also are initial results of a theoretical calculation for the currents in the Levitated Octupole.

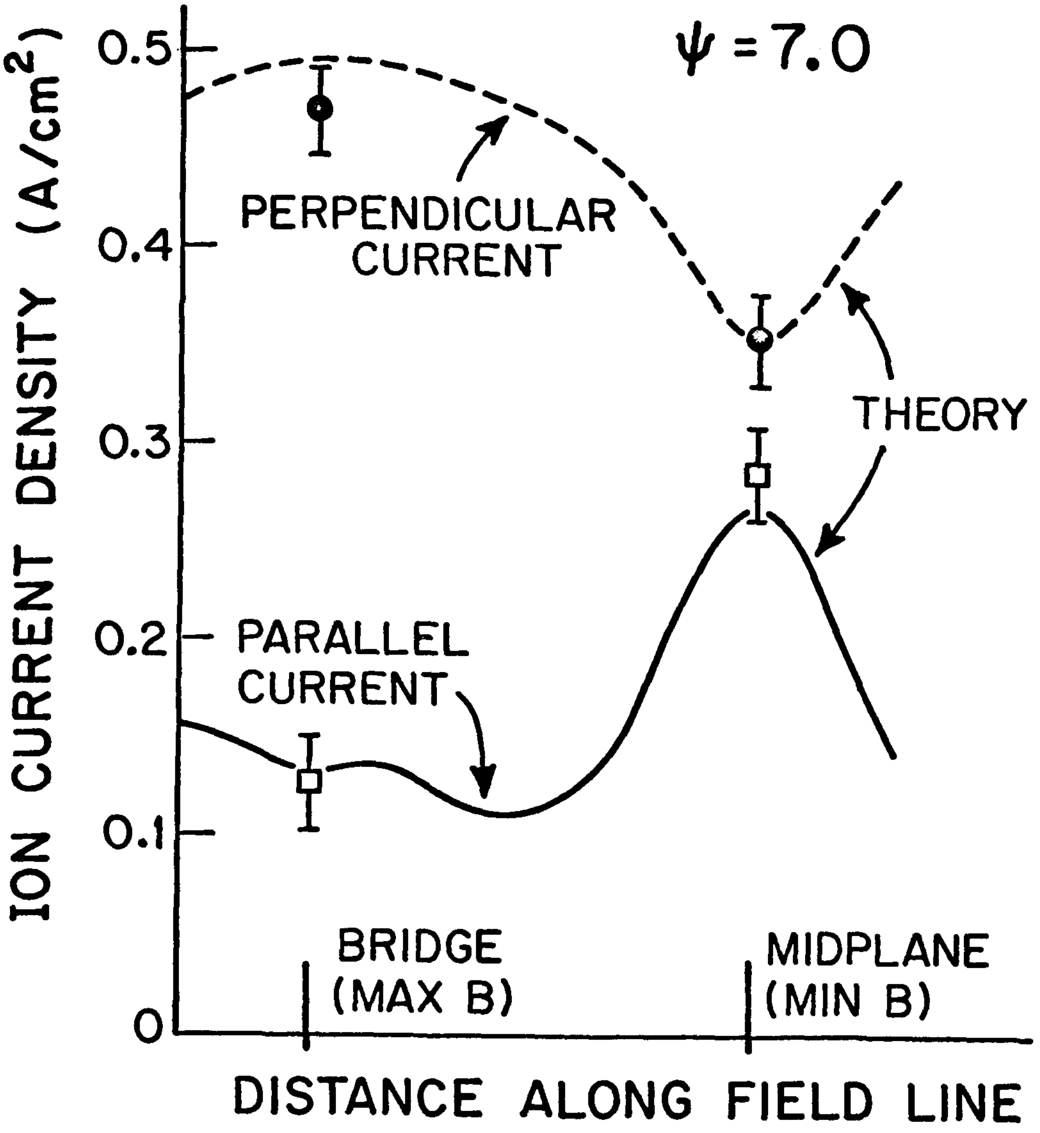

Fig. 5. Ion perpendicular and parallel currents on a magnetic surface ~1 cm outside the surface displayed in Fig. 4.

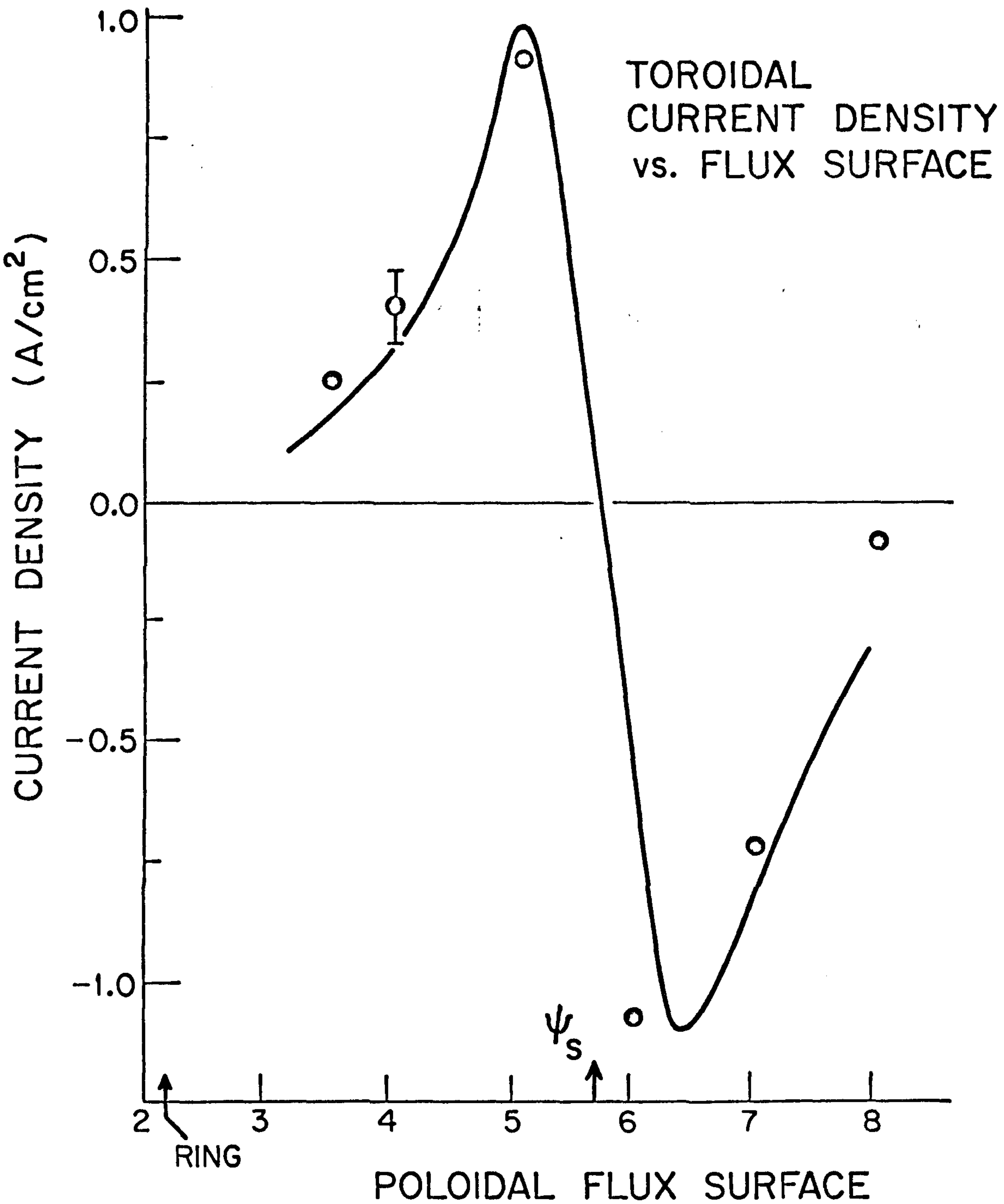

Fig. 6. Radial profile of the measured toroidal diamagnetic current density in the region between the outer octupole ring and wall. The horizontal scale is in units of the poloidal flux function ψ (which is roughly linear with distance). Full scale ≃8 cm. For this case, $B_T=0$.

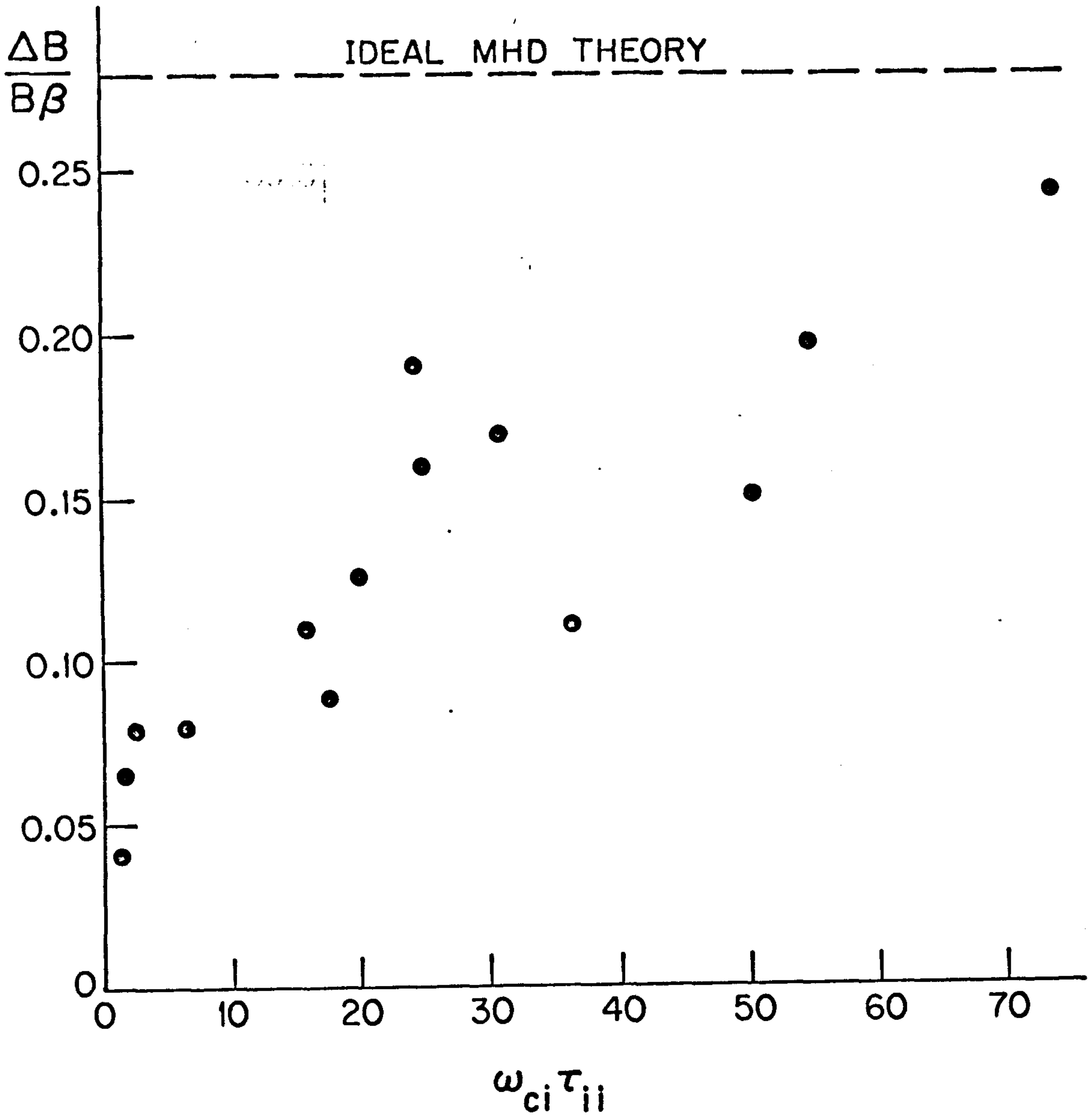

Fig. 7. Experimentally measured fractional change in the magnetic field $\Delta B/B$, normalized to beta, plotted versus $\omega_{ci}\tau_{ii}$ where ω_{ci} is the ion cyclotron frequency and τ_{ii} is the ion-ion collision time. $\omega_{ci}\tau_{ii}$ is a rough measure of the ion gyroviscosity. As $\omega_{ci}\tau_{ii}$ gets large, the viscous influence vanishes and the experimental diamagnetism approaches the MHD prediction.

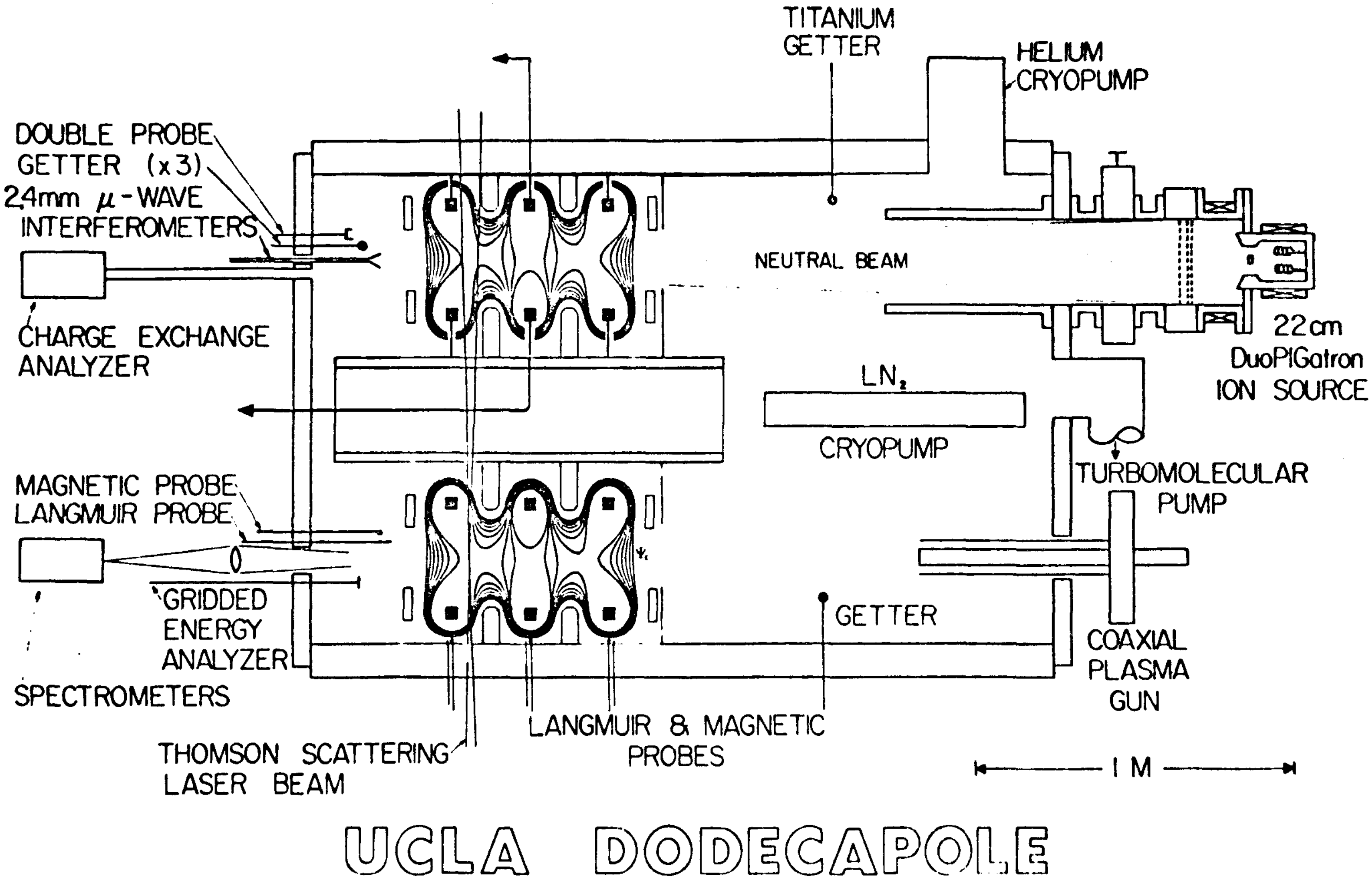

Fig. 8. The Dodecapole device (Surmac) at the University of California at Los Angeles. Major radius = .45 m, total ring current = 1.13 mA.

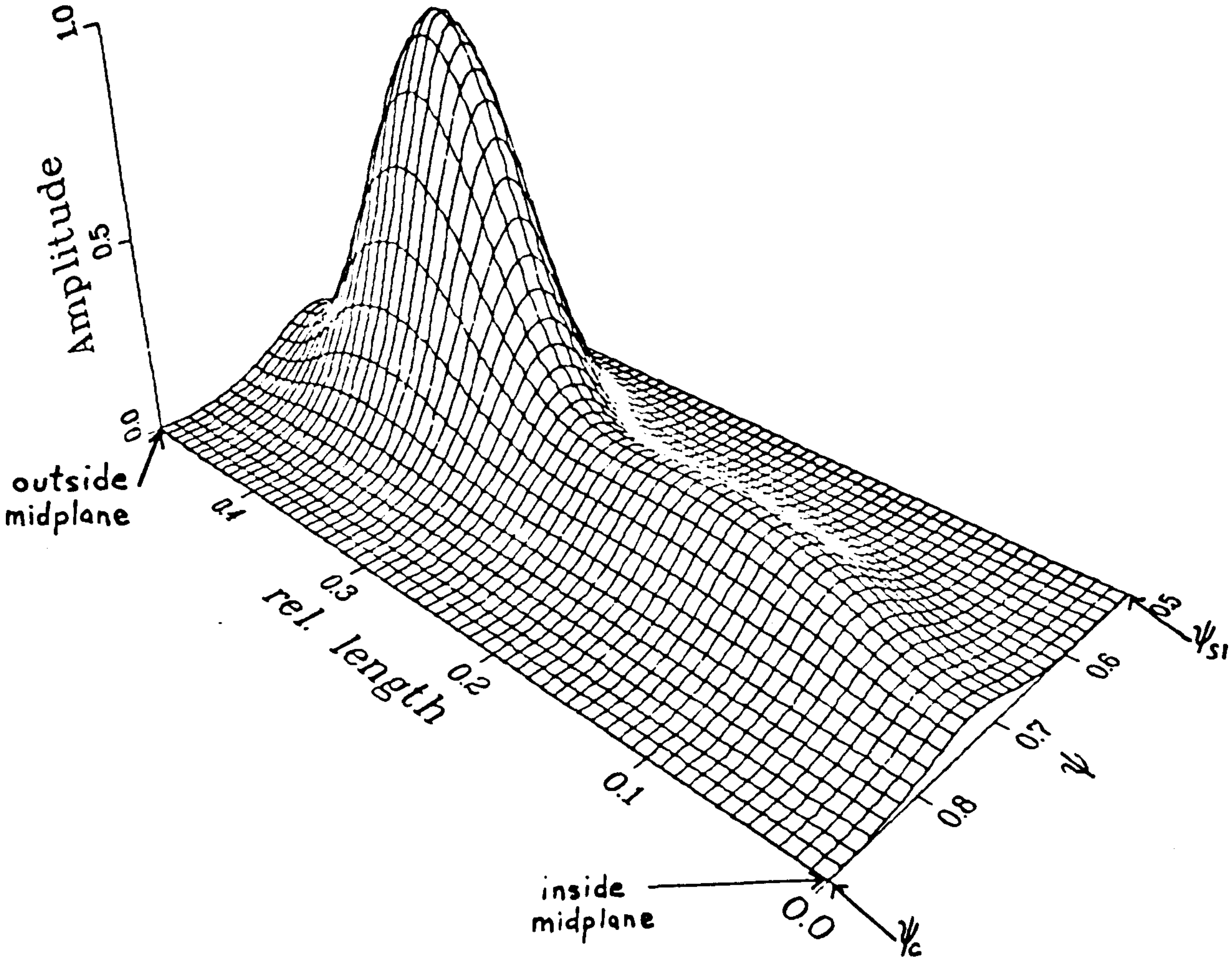

Fig. 9. Two-dimensional spatial structure of the ballooning mode amplitude (in the Octupole) plotted versus the radial flux coordinate ψ, and the distance along a field line. The mode peaks in the local bad curvature region, but is nonzero in the good curvature midplane (so as to minimize energy expenditure in field line bending).

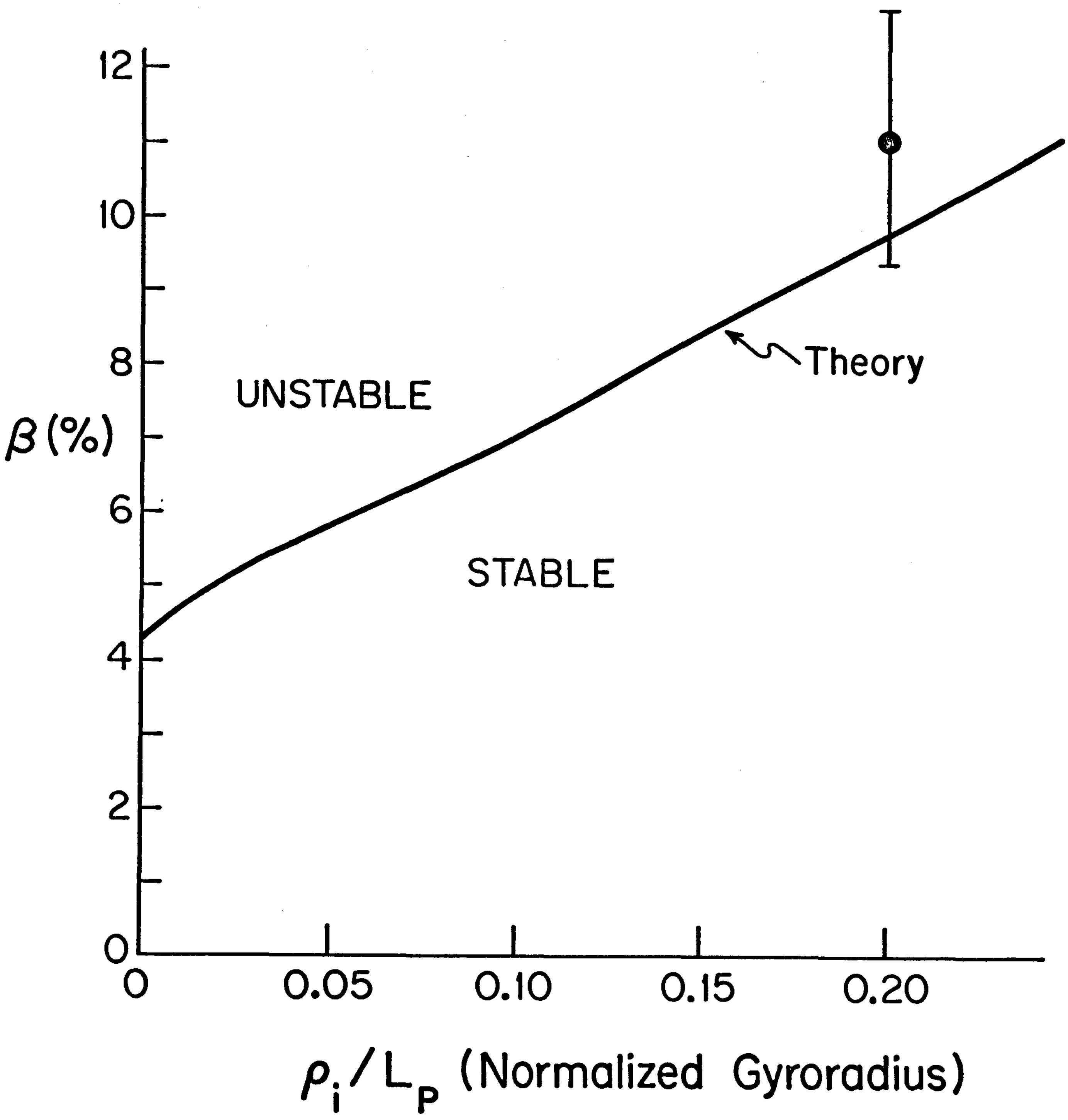

Fig. 10. Dependence of theoretical ballooning instability beta limit on thermal ion gyroradius, ρ_i, according to a detailed collisionless kinetic theory solved for the Levitated Octupole device. ρ_i is normalized to the pressure gradient scale length $L_p = |P/\nabla P|$. Shown is the $\beta = 11\%$ experimental case.

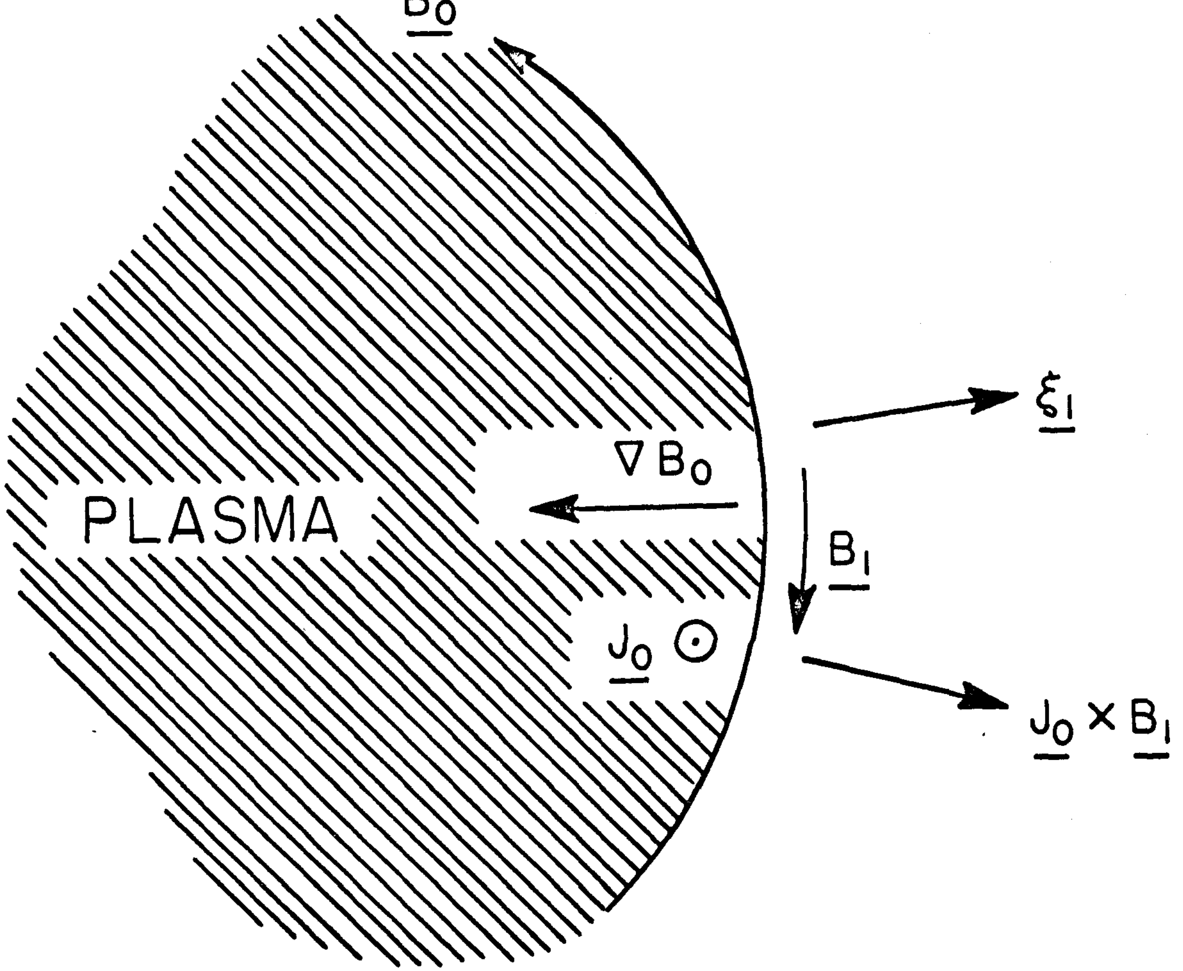

Fig. 11. Physical picture of the ballooning instability indicating equilibrium quantities $\underline{B}_0$, $\underline{J}_0$ (diamagnetic current) and B_0 and perturbed quantities $\underline{\xi}_1$ (displacement), B_1 and $\underline{J}_0 \times \underline{B}_1$ (force).

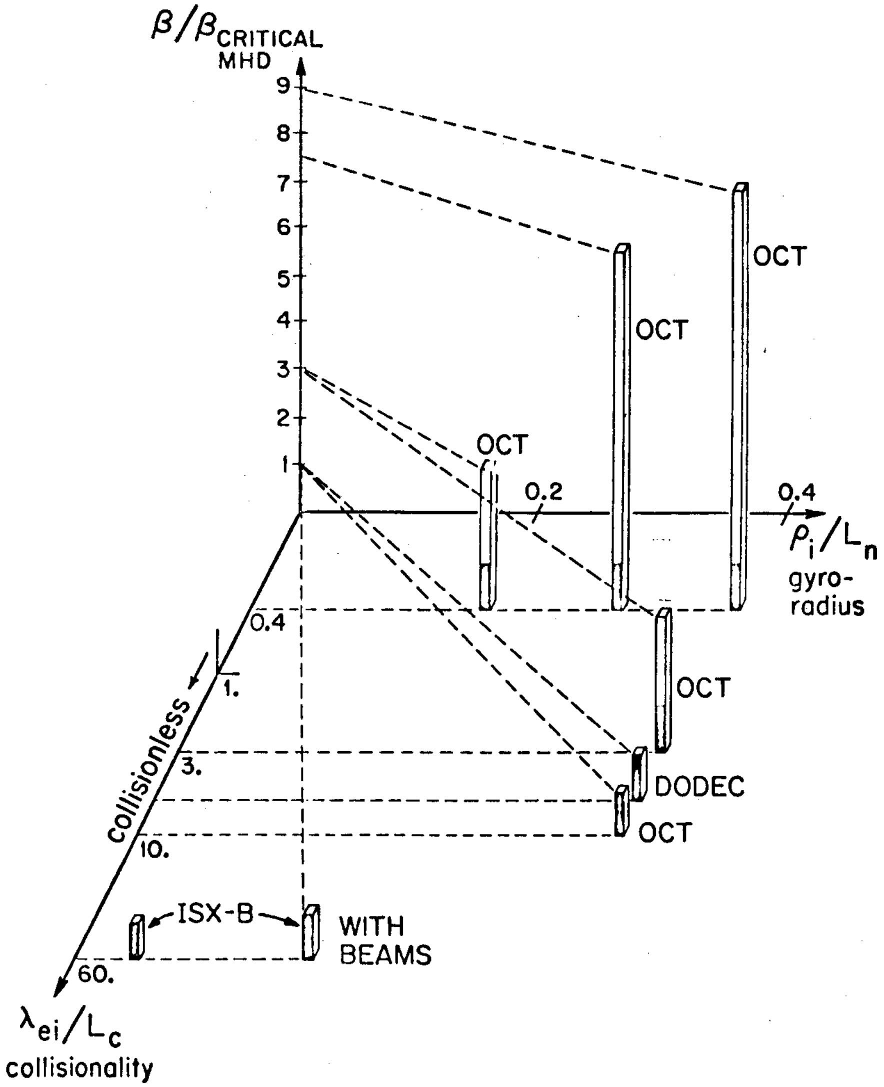

Fig. 12. Plot of several of the attained experimental high beta (Octupole and Dodecapole) illustrating the value of beta, the thermal ion gyroradius ρ_i, and the electron-ion mean-free-path λ_{ei}. β is normalized to the MHD ballooning limit, ρ_i is normalized to the pressure-gradient-scale-length and λ_{ei} is normalized to the connection length between mirroring points. A parameter not shown, is ion gyroviscosity, which is negligible for the UCLA case. For comparison is shown the ISX-B tokamak high beta data points where the case on the right is horizontally placed to include gyroradii of the neutral beam generated fast ions.

EXTERNAL DISTRIBUTION IN ADDITION TO UC-20

DO NOT MICROFILM THIS PAGE

F.C. Rock, Brigham Young University
R.W. Conn, University of California, Los Angeles
J.W. Flowers, University of Florida
H.S. Robertson, University of Miami
T. Dolan, University of Missouri-Rolla
D.T. Blackfield, MIT
R. Smith, Naval Research Laboratory
F.W. Perkins, PPPL
E.G. Harris, University of Tennessee
M. Kristiansen, Texas Technical University
Plasma Research Laboratory, Australian National University
P.E. Vandenplas, Association Euratom-Etat Belge, Belgium
P. Sananaka, Institute de Fisica-Unicamp, Brazil
A.M. Dupas, C.E.N.G., Dph-PFG-SIG, France
M.A. Loyau, Centre d'Etudes Nucleaires, France
G. VonGierke, Max-Planck-Institut Für Plasma Physic, Germany
R. Toschi, Associazione Euratom-Cnen Sulla Fusion, Cento Gas Ionizzati, Italy
K. Takayma, IPP Nagoya University, Japan
K. Uo, Kyoto University, Japan
Chi-shis Li, Chinese Academy of Science, Anhui, Peoples Republic of China
Miao-sun Chen, Chinese Academy of Science, Anhui, Peoples Republic of China
Cheng-chung Yang, Chinese Academy of Science, Lanchow, Peoples Republic of China
Mei-ling Yeh, Chinese Academy of Science, Lanchow, Peoples Republic of China
Kuei-wu Wang, Chinese Academy of Science, Loshan County, Peoples Republic of China
Chun-hsien Chen, Chinese Academy of Science, Peking, Peoples Republic of China
Yi-chung Cho, Chinese Academy of Science, Peking, Peoples Republic of China
Hsiao-wu Cheng, Chinese Academy of Science, Shanghai, Peoples Republic of China
Wei-chung Chang, Chinese Academy of Science, Shanghai, Peoples Republic of China
Fu-chia Yang, Futan University, Peoples Republic of China
M.H. Hellberg, University of Natal, Durban, South Africa
B. Lehnert, Royal Institute of Technology, Sweden
E.S. Weibel, CRPP, Ecole Polytechnique Federale de Lausanne, Switzerland
A. Gibson, Culham Laboratory, UK
R.S. Pease, Culham Laboratory, UK
D.R. Sweetman, Culham Laboratory, UK
J.B. Taylor, Culham, Laboratory, UK

6 for Chicago Operations Office
10 for individuals in Washington Offices

INTERNAL DISTRIBUTION IN ADDITION TO UC-20

100 for local group and file