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MULTIPOLE AND TOKAMAK RESEARCH AT THE UNIVERSITY OF WISCONSIN*

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ABSTRACT. A historical survey is given of the experimental multipole and tokamak fusion research programme carried out at the University of Wisconsin since 1962. The programme has concentrated on axisymmetric toroidal confinement through the utilization of a series of different multipole devices and of a poloidal divertor tokamak. The gross plasma stability and good confinement properties of the multipoles led to a number of experimental results not easily achievable in other toroidal devices. The paper describes the major results obtained in multipoles with and without Ohmic heating current and toroidal field, and their influence on the development of plasma theory. In the poloidal divertor tokamak, stable discharges have been found at very low values of the safety factor.

1. INTRODUCTION

Experimental axisymmetric toroidal confinement research has been pursued at the University of Wisconsin through the utilization of multipole and tokamak devices. Multipoles facilitated the controlled study of key confinement issues since in a single device one is able to vary, over a wide range, critical plasma parameters including Ohmic current level, collisionality, field transform, magnetic shear, and plasma beta. This feature, and the natural quiescence of multipole plasmas, has been exploited for over twenty years at Wisconsin through a sequence of different multipole devices culminating in the Levitated Toroidal Octupole. Important aspects of toroidal plasma equilibrium, stability, heating and transport have been studied which often could not be addressed in existing tokamaks. Toroidal confinement research using the Tokapole II poloidal divertor tokamak began in 1978, with emphasis on issues relating to the magnetic limiter topology.

2. MULTIPOLE CONTRIBUTIONS TO TOROIDAL CONFINEMENT ISSUES

Magnetic fusion energy research began at Wisconsin in 1962 when D.W. Kerst joined the Physics Department faculty. While at General Atomic, Kerst and Ohkawa had conceived of a new toroidal confinement concept, the multipole, in which minimum-average-B stabilization would be provided by current-carrying, toroidal rings immersed in the plasma [1, 2]. By 1964 toroidal octupoles were operating at Wisconsin [3] and General Atomic [4]. Previously, toroidal devices had been dominated by violent fluctuations and macroscopic instabilities which severely degraded confinement. The multipole devices provided the first toroidally confined plasmas with gross plasma stability and greatly improved confinement; indeed, the residual microscopic fluctuations were sufficiently small for the remaining transport to be dominated by other effects [5, 6]. By the mid-1960s, most major fusion laboratories throughout the world had some form of internal ring device [7].

The quiescent plasmas of these devices provided a new opportunity to study many facets of toroidal confinement. The addition of a toroidal field permitted the study of the effects of rotational transform and Ohmic currents on fluctuations, stability, and transport [8]. These low-density ($\sim 10^9$ cm^{-3}) plasmas were observed to have an anomalous resistivity resulting from the excitation of ion waves [9]. Although the earliest plasmas were produced by co-axial guns and injected from outside the magnetic field [10], electron cyclotron resonance heating was also used to provide a broader range of plasma parameters [11, 12]. It was initially assumed that confinement was determined by the flow of ions to the ring supports. There was, however, growing evidence that magnetic field errors and low-frequency, long-wavelength, convective cells were also important [13, 14, 15]. Experiments with magnetically

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TABLE I. MULTIPOLE AND TOKAMAK DEVICES AT THE UNIVERSITY OF WISCONSIN

Device	Major radius (m)	Cross-section	Dates
Small Octupole	0.43	0.36 × 0.36 m^2 square	1964–1978
DC Machine	0.23	0.46 × 0.66 m^2 rectangular	1970–1983
Levitated Octupole	1.39	1.21 × 1.1 m^2 with indentations	1970–1985
Ohmic Quadrupole	0.26	0.2 × 0.1 m^2 rectangular	1973–1976
Tokapole II	0.5	0.44 × 0.44 m^2 square	1978–
RFP (under construction)	1.5	0.32 m radius circular	1987–

guarded ring supports successfully reduced the loss of plasma to the supports but did not improve the confinement [16].

To more fully address these issues, several new internal ring devices were constructed at Wisconsin (see Table I). A small DC device with a single internal ring and a plasma produced by electron cyclotron heating was built. The device could operate in a variety of magnetic configurations and was especially suited for detailed studies of the effect of magnetic field errors on the loss of plasma to an internal ring [17, 18].

The second device was a much larger (1.4 m major radius, 8.6 m^3 volume), pulsed, toroidal octupole in which the four internal rings were transiently levitated for 20 ms [19]. It began operation in 1970, at a time when the attention of the worldwide fusion community was turning to tokamaks.

A first set of experiments examined in detail the spatial structure of non-thermal convective cells and, through scaling over a wide range of densities, temperatures and rotational transforms, established a one-to-one correspondence between these plasma vortices and anomalous transport [20–25]. The measured wavenumber spectrum of these large, ordered, electrostatic structures agreed with two-dimensional, guiding-centre theory. The measured particle diffusion coefficient agreed with calculations based on the measured electric field spectrum. Upon damping of the cells through ion collisional viscosity or magnetic shear, the diffusion decreased to classical.

A third new device was a small, inductively driven quadrupole with co-planar rings [26, 27]. It had strong Ohmic heating and anomalous resistivity, but since the field null was only quadrupolar, the magnetic flux plot was that of a multipole rather than a poloidal divertor tokamak.

Meanwhile, the original Wisconsin Octupole was being used for studies of electron cyclotron heating [28], ion cyclotron heating [29], and Ohmic heating [30]. When strong Ohmic currents were induced, the magnetic field topology became that of a four-node, poloidal divertor tokamak, and it was given the name Tokapole I.

In the late 1970s, there was a growing interest in the use of multipoles as advanced fuel (pB^{11}, pLi^6) reactors because of their good confinement properties and low magnetic fields which presumably would minimize synchrotron radiation and permit the required high temperatures [31]. Radiation damage and heating of the internal rings would be tolerable for reactions which produce few neutrons. When these ideas emerged, the Wisconsin Levitated Octupole and the Dodecapole (Surmac) [32] at the University of California-Los Angele were the only remaining multipoles. The Wisconsin Octupole was upgraded by the addition of 4 MW of ion cyclotron heating [33] in order to produce high-beta plasmas in the collisionless regime. However, the interest in advanced fuel multipoles declined under the opinion that the energy gain would be marginal.

On the other hand, the Octupole was producing plasmas with beta values as high as 44%, well in excess of the 4% ballooning mode limit predicted by single-fluid MHD [34]. Comparison with kinetic stability calculations, which included gyroradius effects and were adapted to the experimental configuration, indicated the limitations of existing theories and emphasized the importance of kinetic effects in all high-beta, magnetically confined plasmas [35].

The attainment of high plasma beta in an Ohmic-current-free plasma led to the observation [36] of the pressure-gradient-driven, parallel, neoclassical (bootstrap and Pfirsch-Schlüter) currents that had long been predicted to flow in all toroidal plasmas, but never observed. Detailed measurement was obtained of the collisionality dependence, parallel spatial structure, toroidal-magnetic-field dependence, and charge make-up of the parallel currents.

3. TOKAMAK RESEARCH

In 1978, Tokapole I was replaced by a slightly larger poloidal divertor tokamak, called Tokapole II [37]. This device was initially used to study the axisymmetric stability of square, dee, and inverse dee-shaped equilibria [38]. It has also been used for RF heating studies using electron cyclotron heating to lower the startup loop voltage [39], harmonic ion cyclotron heating up to $5\ \omega_{ci}$ [40], and shear Alfvén resonance heating [41]. The shear Alfvén resonant enhancement of the driven wave magnetic field within the plasma on the resonant magnetic surface was observed and agreed with calculations of the resonance properties for the two-dimensional Tokapole configuration [41].

An unexpected feature of the device was its ability to form stable tokamak discharges with a safety factor as low as $q = 0.4$ on axis [42], and without disruption. These unique discharges are presently under study, with particular emphasis on the influence of the magnetic divertor separatrix on tearing mode stability and magnetic island growth. Tokapole II differs from other poloidal divertor tokamaks in that it can operate without scrape-off plates; the plasma is then bounded by a true magnetic limiter (separatrix) which is not in contact with a material surface and is surrounded by closed magnetic surfaces. The role of the separatrix (magnetic limiter topology) on plasma stability at all q values ($0.4 < \overline{q} < 3$, where $\overline{q}$ is a volume-averaged q) is under study [43]. At $\overline{q} \approx 3$, the absence of material limiters eliminates the sudden current termination and plasma quench that accompanies the major disruption.

The observation of $q < 1$ tokamak discharges in Tokapole II and the availability of hardware from the Levitated Octupole (50 ton iron core, 1.6 MJ capacitor bank, etc.) provided the impetus to extend the low-q observations into the reversed-field pinch regime ($q \lesssim 0.1$) on a larger device. Plans are now under way to construct a large, circular, reversed-field pinch (called MST for 'Madison Symmetric Torus'), which will also be capable of tokamak or non-reversed-field-pinch operation. This device will be dedicated to RFP boundary condition studies and to observing the evolution of the stability, fluctuations, and confinement as q is continuously varied from the RFP regime to the tokamak regime, thereby providing a better understanding of all axisymmetric toroidal confinement concepts.

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