

EXPLORATION OF LOW-ASPECT-RATIO TOKAMAK REGIMES IN CDX-U

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ABSTRACT - In the low-aspect-ratio tokamak regime, a lower $q(a)$ regime (i.e. $q(a) \leq 5$, $A = R/a \approx 1.5$) has been explored in CDX-U. Using a relatively low toroidal magnetic field, plasma discharges with $I_p \leq 53$ kA, and $q(a) \geq 4$ [$q_{\text{cy}}(a) \geq 1$] have been obtained. Low $q(a)$, ohmic plasmas in CDX-U show stronger MHD activity as the edge safety factor is reduced. Those MHD modes appear to reduce the current ramp-up rate and, at present, limit the access to even lower $q(a)$ regimes.

1. Introduction

The low-aspect-ratio tokamak (LART) configuration offers interesting possibilities for a cost-effective, high-performance (high stable beta in the first stability boundary) plasma regime which lends itself naturally to a compact volumetric neutron source as well as a high beta advanced fuel reactor [1]. The recent results from START have been encouraging [2]. Non-inductive current drive results using internally generated bootstrap currents and helicity injection current drive in a low-aspect-ratio configuration have previously been reported [3]. To extend the parameter range of the low-aspect-ratio tokamak regime, a new class of 1 MA level devices is being considered (e.g., NSTX [4]). The CDX-U tokamak at Princeton [3] with the recent installation of an ohmic solenoid can be used to proto-type LARTs such as NSTX. In a typical LART design, due to the limited ohmic heating coil capability, an efficient tokamak start-up assist would be particularly important for saving valuable ohmic volt-

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seconds. Among various LART regimes, it is particularly important to explore a lower $q(a)$ regime [i.e. $q(a) \leq 5$] since the MHD [5] and kinetic mode stabilities [6] are expected to change with $q(a)$ and $A = R/a$.

In this paper, we report the recent LART experimental investigations in two important areas; I. tokamak start-up assist experiments in CDX-U using ECH to minimize the volt-second consumption as well as the induced wall eddy currents, and II. investigation of lower $q(a)$ regime ($q(a) \leq 5$ for $A \approx 1.5$) in CDX-U.

2. Experimental Set-up

CDX-U is a low-aspect-ratio tokamak facility with $R \approx 35$ cm and $A \geq 1.4$ with $I_{tf} \leq 240$ kA (steady-state). Presently, an OH power supply with 30 mV-s capability (OH solenoid capability is 150 mV-s) is operational on CDX-U. Four pairs of PF coils are used to control the plasma shape and position. Two 2.45 GHz, 4 kW sources provide initial plasma break-down for the start-up. The device cross-sectional view is shown in Fig. 1. Inner wall containing TF and OH coils, is made of 4 in. O.D. Inconel tube with 1/8 in. thickness wall. Top and bottom vessel walls are 5/8 in. thick stainless steel. The outer wall is made of 1.5 in. thick Aluminum with a toroidal break. A low base pressure, $P \leq 1-2 \times 10^{-7}$ Torr is maintained with the combination of cryo-pumping and Ti gettering. The experiment was conducted with hydrogen and helium. Diagnostics include a 2-D scanning microwave interferometer, a poloidal array of magnetic pick-up coils, and a 2-D scannable magnetic probe.

3. Low-Aspect-Ratio Tokamak Start-up and Volt-second Consumption

A toroidally continuous vacuum vessel is very advantageous, especially in the low-aspect-ratio tokamak design, except for presence of significant wall eddy currents. Since the CDX-U vacuum vessel has toroidally continuous wall components, OH start-up techniques in the presence of significant wall eddy currents can be prototyped. With ECH, it was possible to initiate low-aspect-ratio tokamak plasmas with a wide range of toroidal field coil current [$I_{tf} = 70$

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kA - 160 kA with R(ECH) = 16 cm - 36 cm]. Plasma initiation was also possible with an almost arbitrarily low loop voltage of $V_{loop} \leq 1V$, though we typically operated with a peak voltage of $V_{loop} \approx 1 - 5 V$, depending on the desired current ramp-up rate. Plasma current generating efficiency of 1.7 kA / mV-s was obtained up to $I_p = 53$ kA. Figure 2(a) shows the maximum plasma current obtained thus far in CDX-U ohmic discharges as a function of volt-second expenditure for various discharges. This measure of ohmic heating efficiency can be seen to improve slightly with increasing I_p , suggesting an increasing average temperature with I_p . The maximum current ramp-up rate attained thus far is 10 kA / ms. An Ejima coefficient [7] of 0.4 was routinely obtained. The observed efficiency and the ramp-up rate only dropped by 10% when I_{tf} was reduced by a factor of 2.3 (from $I_{tf} = 160$ kA to 70 kA).

4. Lower q(a) Discharge Characteristics

Taking advantage of the relative insensitivity of I_p to the toroidal magnetic field, it was possible to attain $q(a) \leq 5$ tokamak discharges with various toroidal magnetic fields. Maximum plasma current obtained thus far in CDX-U ohmic plasmas, as a function of toroidal field, is shown in Fig. 2(b). Maximum plasma currents at given toroidal magnetic fields might be limited to $q(a) \geq 4$ ($q_{cyl} \geq 1$) and $q(0) \approx 1$. Typical plasma parameters for these low q(a), low-aspect-ratio plasmas were: $R = 0.34$ m, $a = 0.22$ m, the line integrated density $n_e L \approx (4.5 - 10) \times 10^{17} \text{ m}^{-2}$, and estimated $T_{e,av} \leq 100$ eV from neoclassical resistivity with $Z_{eff} = 2$. These parameters indicate that the plasma is already in the low collisionality regime with $\nu^* \approx 0.1 - 0.3$, where trapped particle effects become important. Maintenance of a 5-10 ms flat-top discharge at $I_p \approx 20$ kA, with an average loop voltage ≈ 1 V also indicates that the plasma has entered a relatively hot, collisionless regime. We typically observe an increase in the central plasma density and density gradient with the toroidal magnetic field, suggesting an improvement of plasma confinement.

As the q(a) is decreased, however, we observed abrupt plasma terminations more often. Most terminations of high q(a) plasmas could be avoided by reducing plasma-limiter interactions with proper plasma position control. On the other hand, low q(a) plasmas still show abrupt terminations frequently. Also, a

significant enhancement of $m=1-2/n=1$ internal MHD modes in the 10-15 kHz range, as shown in Fig. 3(a), was observed with lower $q(a)$. Those modes appear to reduce the current ramp-up rate and, at present, limit the access to even lower $q(a)$ regimes. The radial structure of these modes shows a dip in the $\delta B_Z/B_Z$ signal but not in the $\delta B_R/B_Z$ signal as shown in Fig. 3(b), which suggests the possible existence of large magnetic islands at the low field side. As the central safety factor, $q(0)$ goes down to less than one, these islands can couple with $m=1/n=1$ sawteeth and terminate plasma abruptly. The $q(0)$ of maximum plasma current discharges for various toroidal magnetic fields were estimated to be near one, which supports the above conjecture. More detailed studies on these modes are undergoing. Possible stabilization schemes such as DC-helicity injection (current profile flattening) are under study.

The behavior of MHD and kinetic fluctuation activities (using various probes and a tangential CO₂ phase-contrast-imaging system) and related confinement studies as a function of the plasma aspect-ratio, $q(a)$, and plasma collisionality are presently under study.

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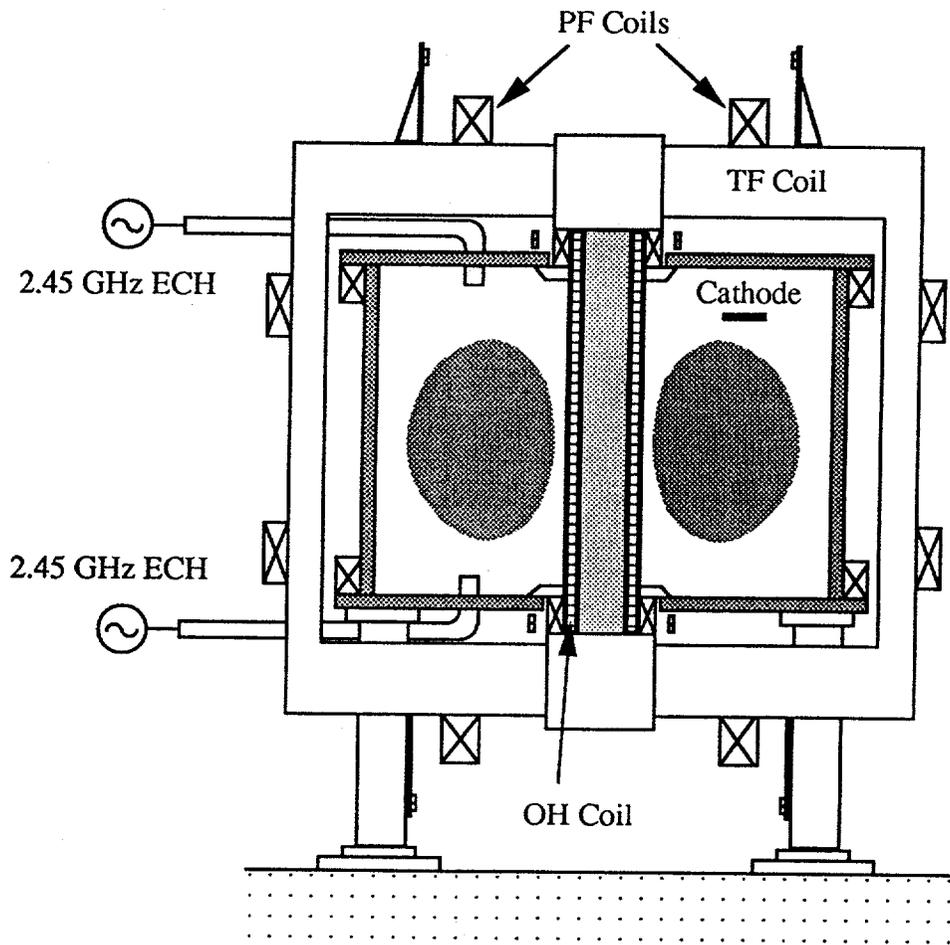
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FIGURES

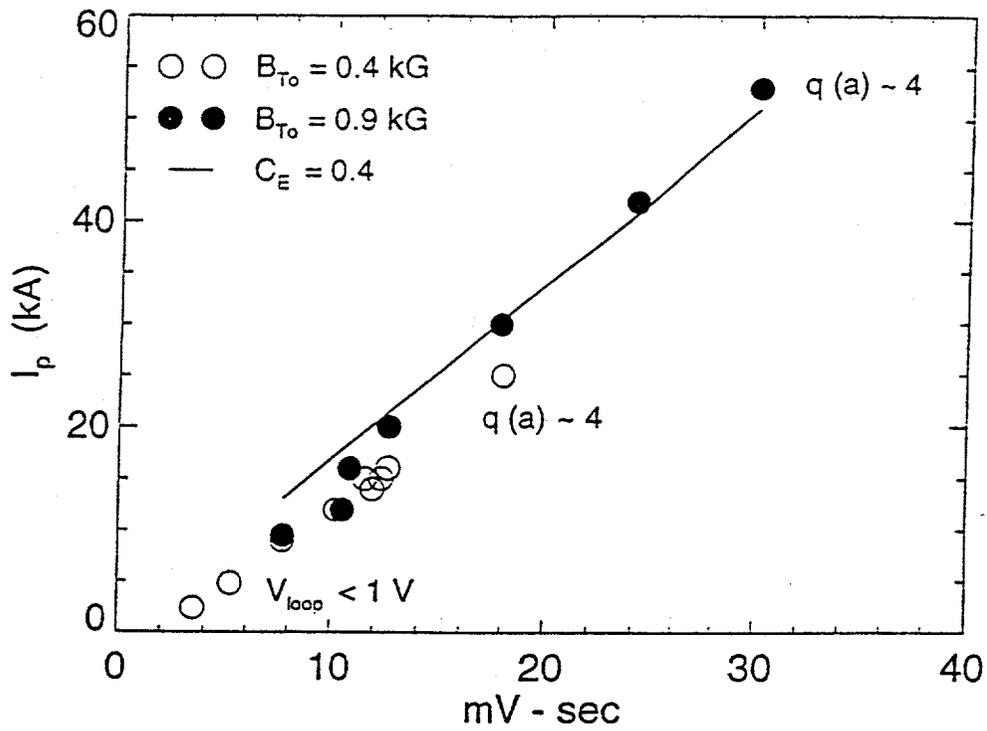
Fig.1. Schematic of CDX-U device.

Fig. 2. Ohmic efficiency during CDX-U start-up. (a) I_p vs. Volt-sec. (b) I_p vs. B_{tf} .

Fig. 3. MHD fluctuations. (a) Poloidal magnetic fluctuation amplitude dependence on q_{cyl} . The discharge of $q_{cyl} \approx 1$ is equivalent to that of $q(a) \approx 4$. (b) Radial and vertical magnetic fluctuation variations with major radius at the midplane.



(a)



(b)

