Ultra-Low-\textit{q} Discharges  
in REPUTE-1  

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Abstract  

The characteristics of ultra-low-	extit{q} discharges ($0 < q_a < 1$) have been studied in REPUTE-1. Results from magnetic probe measurements and parameter scans for the discharges are described. It is found that a \textit{q} profile with $dq/ dr < 0$ is formed in the setting-up phase and a high density plasma with the order of $n_e \sim 10^{20}$ m$^{-3}$ is obtained during the discharge duration of about 15 msec for low toroidal fields ($< 2$ kG).  

1. Introduction  

The REPUTE-1 (Reversed Field Pinch University of Tokyo Experiment No. 1) became operational in July 1984. Since then, plasma experiments have been carried on in parallel with the installation of power supplies, diagnostic tools and data acquisition system. So far, the experiments have focussed on plasma optimization and an extension of the operating region. In addition to the RFP discharge, the ultra-low-	extit{q} (ULQ) discharge which is characterized by a range of $0 < q_a < 1$ ($q_a$ is defined as $q_a = aB_c / RB_a$, where $a$ is the minor radius at the limiter) has been also explored as a new operational area.  

An attempt to achieve the ultra-low-	extit{q} regime in a tokamak discharge originates from an economical reason, that is, the realization of Ohmically ignited tokamak reactor. The beta value, which is defined by the ratio of plasma pressure to magnetic pressure, gives us an important criterion for the economical performance of magnetic confinement devices. One of the methods to attain the higher beta value is to reduce the $q_a$ value. So far this trial has been generally carried out, and realized in a range of $1 < q_a < 2$ (so-called “very-low-\textit{q} regime”) in T6$^1$, T11$^2$, and DIVA$^3$, all of which had a conducting shell closed to the plasma. And D-III$^4$ realized discharges with $q_a < 2$ under the condition of $q_\phi / 2$ ($q_\phi$ is the MHD safety factor).  

On the other hand, historically, the toroidal discharge with $0 < q_a < 1$ is traced back to the so-called “stabilized pinch” configuration with $q_a < 1$ ($B_\phi < B_\theta$) which was experimentally implemented in the late 1950s as reported in ZETA, but the results turned out to be unsatisfactory$^5$. It is now believed that the results were due to the failure to satisfy the requirement of ideal MHD stability theory.
because of the violence of the Suydam criterion in the vicinity of a minimum in magnetic pitch. After stabilized pinches, the followed fusion research bifurcated to other two possible means of tokamak and reversed field pinch approaches, both of which have been succeeding since over.

The research objective of tokamak operation in REPUTE-1 is to establish and study the ULQ regime by means of the techniques which are originally used for a fast setting-up of the plasma current in RFP operation. Operation in a range of \(0 < q_a < 1\) is called an ultra-low-\(q\) regime here. In tokamak operation, systematic scans of plasma parameters have been performed in a range of the plasma current from 30-100 kA. We will report the realization of the ULQ configuration with \(1/2 < q_a < 1\) under the condition of low values of the mean magnetic Reynolds number \(S (= 10^2 \sim 10^3)\). No attempt to investigate such an ULQ configuration has yet been reported. Machine status and diagnostics are presented in Section 2, and the results of ULQ experiments in Section 3, 4 and 5. Conclusion and discussion are presented in Section 6.

2. Machine status and diagnostics

REPUTE-1 is a large reversed field pinch machine which has the major radius, \(R\), of 82 cm and the minor radius, \(a\), of 20 cm at the limiter. The bellows liner with a thickness of 1 mm and the inner minor radius of 22 cm is made of Inconel 625 and closely surrounded by the thin conducting shell (SUS 316) with a thickness of 5 mm and the inner minor radius of 24 cm. The time constant of the shell for the vertical field penetration is about 1 msec. The plasma is isolated from the liner by 127 pieces of point limiters made of Inconel 625. The 54 diagnostic ports are symmetrically mounted on the torus. A peculiarity in the engineering aspects of the apparatus is the thin shell construction which is designed to be not for plasma equilibrium over a current duration but for plasma stabilization, particularly during a setting-up phase.

The plasma position for equilibrium has been preliminarily controlled by pre-programed vertical fields. Power crowbars on the poloidal and toroidal field circuits are used. Filling gas pressure is controlled by the open duration of the valves. The ion-core allows a flux swing of 1.6 V-s. The start banks in the OH primary circuit are used to generate the initial current pulse superimposed on the running plasma current which is maintained by the PFN circuit. The filling pressure is verified to be proportional to the open duration, so that the values of the filling pressure are extracted from the open duration of the valves. An electron gun with the accelerator power supply of 1 kV and 1 A is normally used for preionization.

Magnetic loops for measurements of toroidal current \(I_p\), loop voltage \(V_{loop}\) are located at the outside surface of the liner. The plasma current is measured by a Rogowski loop, which is compensated for currents induced in the liner. Magnetic fluctuations are measured by magnetic pick-up coils located just outside the liner. The internal distributions of \(B_\theta\) and \(B_\phi\) in the plasma are measured by means of the eight-channel magnetic probes inserted in the plasma, which are described in detail later.
Ultra-Low-q Discharges in REPUTE-1

Electron density measurements are made by a single chord CO$_2$-laser interferometry on axis. The electron conductivity temperature on axis is calculated using the Spitzer's formula from the measured plasma resistivity, since Thomson scattering measurements are in preparation at present. The plasma resistance $R_p$ is simply defined by the ratio of loop voltage to the plasma current. The value of $Z_{eff}$ is assumed to be unity.

3. Experimental conditions

Since originally designed for RFP operation, the REPUTE-1 has two kinds of toroidal field systems. The one generates the bias toroidal field with $B_\phi \leq 2.5$ kG and the flat top duration of about 5 msec, the other the main reversed toroidal field with $|B_\phi| \leq 1$ kG and the duration long enough. Taking into account the engineering reason mentioned above, the ULQ experiment has been carried out in two ways of the bias toroidal field for the range of $1$ kG $< B_\phi < 2$ kG and the main toroidal field for the range of $|B_\phi| < 1$ kG. Ohmic heating system in REPUTE-1 has four options of the electrical connections with the nominal current risetimes of 0.5, 1, 2, and 4 msec, in which 0.5 and 1 msec risetimes are used. Experiment is carried out with hydrogen gas.

To produce stable discharges in the ULQ regime, it has been necessary to optimize the discharges particularly by adjusting the vertical field system, gas puffing system and the crowbar timing of the Ohmic heating system. Figure 1 shows the plasma current at the flat portion $I_p$ as a function of the toroidal field over a range of 0.5 kG to 2 kG associated with the $q_a$ values of $1/2$ and 1. The different points denote discharges with using the bias field (open circles) and the main field (closed circles) (these notations are used throughout). Most of discharges are found to be placed between $q_a = 1/2$ and 1.

Figure 2 shows a typical time evolution of the line-averaged electron density $\bar{n}_e$ measured by a CO$_2$ laser.
The plasma parameters for this discharge are: $I_p = 40 \text{kA}$, $B_\phi = 1.15 \text{kG}$, $q_a = 0.7$ and $V_{\text{loop}} = 100 \text{V}$. As seen in this figure, the density pump-out observed in the ULQ discharge tends to be moderated as compared to RFPs, so that the density can be kept at relatively high value.

Figure 3 shows the dependence of the plasma resistance $R_p$ on the plasma current $I_p$ over a range of $3 < p_o < 10 \text{ mtorr}$ where $p_o$ denotes the filling gas pressure. The results of the plots are found to be fitted by an approximately single curve of $R_p \propto 1/ I_p$ for the discharges, which indicates that the loop voltage in approximately constant ($\sim 120 \text{ V}$) independent of $I_p$. Evaluated conductivity temperatures are typically less than 10 eV. Gloss energy confinement time, based on the loop resistance and Ohmic input power, is about 50 $\mu$s. Power balance for a series of discharges obtained is dominated by radiation losses from the plasma.

Our experimental remarks lie in the physical properties, in particular, MHD behavior of an ULQ plasma with high $\beta$, rather than obtaining high temperatures.

4. Discharge characteristics

The internal distributions of the toroidal and poloidal magnetic fields were measured by means of the insertable magnetic probes described bellow. The magnetic probes used in this experiment consist
Ultra-Low-q Discharges in REPUTE-1

of eight coils made of PTFE (polytetrafluoroethylene) wire 0.3 mm in diameter wound on a PTFE rod 5 mm in diameter every 2.5 cm. All the coils have rectangular cross-sections with 6 mm long and 5 mm wide, and are arranged in the direction to measure magnetic fields perpendicular to the axis of the rod. Both of $B_\theta$ and $B_\phi$ can be measured with two shots by rotating the probe around the axis. This coil array is surrounded by a SUS protective jacket with a 10 mm outer diameter and 0.5 mm thick, and inserted from the horizontal port. In this measurement, the reproducibility of two discharges with the same operational conditions was assumed in order to get a set of the magnetic distributions, so that the attention was devoted to the qualitative characteristics of the internal magnetic configuration for discharges in the ULQ regime.

In Fig. 4 (a) a typical ULQ discharge is illustrated with time evolutions of the plasma current $I_p$, the loop voltage $V_{loop}$ and the toroidal field $B_\phi$. As shown in this figure, the initial current peak is remarkably observed before a stable sustained ULQ configuration is established. The current ramping rate for this discharge is about 120 MA/s. The results from measurements of the eight-channel magnetic coils show that a transition of the radial $q$ profile from a quasi-relaxed state to a paramagnetic ULQ equilibrium occurs during the setting-up phase. In Fig. 4 (b) shown are the toroidal current density $J$ and $q$ profiles calculated from the magnetic field profiles measured at $t = t_1$, $t_2$ and $t_3$ in Fig. 4 (a).

![Fig. 4 (a) Time evolutions of the plasma current $I_p$, the loop voltage $V_{loop}$ and the toroidal field $B_\phi$ for a typical ULQ discharge.](image)

![Fig. 4 (b) Radial profiles of the toroidal and poloidal fields, $B_\theta$ and $B_\phi$, the toroidal current density, $J$, and the safety factor, $q$, at $t = t_1$, $t_2$ and $t_3$.](image)
In these figures, the \( q \) profile is calculated from the magnetic profiles of \( B_\theta \) and \( B_\phi \), each of which is fitted by a quadratic curve of \( r \), and the \( J \) profile is calculated assuming the relation of \( J = j_0 \left\{ 1 - \left( r/a \right)^2 \right\} ^\alpha \) where \( j_0 \) and \( \alpha \) are determined so that the fitted \( B_\phi \) is consistent with the \( B_\theta \) calculated from the \( J \) profile. As seen in Fig. 4, when the current comes up to the peak, the field profiles are close to Bessel-function distributions and the radial \( q \) profile is almost flat with a small negative gradient within the plasma. After the peak, the \( q_a \) value immediately increases with the current decay and a stable ULQ configuration is formed. The formation of the ULQ configuration and the onset of the current sustainment are seen at \( t = t_2 \). At this time the \( q \) value in the plasma is placed between 1 and 1/2 and the radial gradient of the \( q \) profile is still kept negative. This \( q \) profile is deformed in time towards a concave shape with \( dq(r)/dr > 0 \) and peaked current density profile such as a tokamak-like profile appears as a result of resistive field diffusion as seen in the profiles at \( t = t_3 \). In this case the current termination may be caused by MHD instabilities induced by the tokamak-like \( q \) profile. This approach to the ULQ state from the quasi-relaxed state produced by the fast current rise techniques may play an important role on the setting-up of the stable ULQ configuration.

The MHD safety factor for a circular plasma cross-section centered by position control, defined as \( q_\phi = d(\text{toroidal flux})/d(\text{poloidal flux}) \) at the minor radius, is taken to be

\[
q_\phi = q_a \left[ 1 + \left( \frac{a}{R} \right)^2 \left\{ 1 + \frac{1}{2} \left( \beta_\theta + \frac{l_i}{2} \right)^2 \right\} \right]
\]

where \( l_i \) denotes the internal inductance per unit length of the plasma, taking into account the lowest order toroidal correction to the cylindrical aperture safety factor \( q_a = aB_\phi / RB_\theta \). For example, the ratio of \( q_\phi / q_a \) becomes 1.08 when \( l_i = 1/2 \) for a flat current profile and \( \beta_\theta = 0.5 \). The observed current distribution tends to be almost flat and the \( \beta_\theta \) values are relatively low for most of the ULQ discharges, so that the discrepancy between \( q_\phi \) and \( q_a \) is estimated to be within about 10%.

Figure 5 shows the fluctuation signals of the poloidal magnetic field \( dB_\theta / dt \) measured by the pick-up coil located at the outside surface of the liner and the plasma current including the induced liner current \( dI / dt \), associated with the waveforms of \( I_p, V_{\text{loop}} \) and \( q_a \) for an ULQ discharge with \( B_\phi = 1 \text{ kG} \). In this discharge, the level of \( \delta B_\theta / B_\theta \) is less than about 3% at the coil location and the oscillations appear to be marginally stable.

The fluctuation level for the ULQ discharge tends to be sensitive to the filling gas pressure \( p_o \) which can control the density behavior in some degree. The ULQ discharges make a distinctive feature of the observation of marginally stable magnetic fluctuations with the level \( \delta B_\theta / B_\theta < 3 \% \) under a broad condition of \( p_o \geq 5 \text{ mtorr} \). On the other hand, in a range of the lower filling pressure, the fluctuation level turned out to be enhanced often exceeding more than 10%, associated with the marked density pump-out. Here we focus attention on the former case to investigate the stable ULQ configuration.

The observed frequencies have a broad band spectrum typically in the range from 1 kHz to 40 kHz.
The dominant frequency component with some coherence in oscillations obtained is with the order of the electron diamagnetic drift frequency ($1 \text{ kHz} \sim 10 \text{ kHz}$), so that the observed fluctuation may result from Mirnov oscillations. The poloidal mode number $m$ has been on some occasions clearly identified to be unity, but the broad band structure of the fluctuation, which might be caused by toroidal or non linear effects, has most often made the modes difficult to identify.

5. Preliminary estimates of the operational region

Systematic scans of the ULQ discharges have been done, so that a data base has been assembled from about 100 ULQ discharges over the following parameter space; $I_p = 30-100 \text{ kA}$, $p_0 = 3-10 \text{ mtorr}$
and $B_\phi = 0.5-2 \text{kG}$. The operational range of the ULQ discharges for different tokamak experiments is shown by Hugill-diagram in Fig. 6, where the abscissa $\bar{\eta}_e R / B_\phi$ represents the numerical factor scaling called the Murakami parameter and the ordinate is $1/q_a$. It is obviously found that the ULQ regime in REPUTE-1 has been extremely exceptional as compared with Ohmic heating experiments in TEXTOR$^6$ and DITE$^7$ and Ohmic heating experiments in D-III with titanium gettering$^8$ in a range of $q_a > 2$. However, very-low-$q$ experiments ($1 < q_a < 2$) in DIVA$^3$ are placed on an intermediate region between REPUTE-1 and other tokamaks.

The values of the Murakami parameter obtained in REPUTE-1 are extremely large as seen in Fig. 6. A high density limit line as $1/q_a \propto \bar{\eta}_e R / B_\phi$ appears to exist in the operating regime of REPUTE-1 similar to those of tokamaks. In REPUTE-1 a series of the discharges near the density limit tends to be characterized by the disruption-free termination (“soft landing”) and some quiescence of magnetic fluctuations on the magnetic coils. No clear MHD activity has been observed when the discharge crosses the Kruskal-Shafranov limit.

The Murakami density limit is theoretically expounded on the basis of the statement that the density limit is dominated by the radiative power balance. Perkins and Hulse$^9$ deduced a theoretical upper limit for the density in an Ohmically heated tokamak discharge from the simple criterion that the Ohmic heating power deposited in the current-carrying channel must exceed the power radiated within the channel by impurity ions. On the other hand, Ashby and Hughes$^{10}$ adopted the statement that the Ohmic heating power deposited in the current-carrying channel must exceed the power radiated by the plasma periphery.

The basic aspect of the radiative power balance can be suitable for all steady-state plasmas even though the discharge does not overcome the radiation barrier. Moreover, the dependence of $B_\phi / R$ on the density limit is also universal because such a relationship is related to the basic equation for a cylindrical geometry; $j_o = (2 / \mu_0) (B_\phi / q_o R)$, where $j_o$ and $q_o$ denote the current density and safety factor $q_o$.
factor at the plasma center. Therefore, the relationship of \( 1/q_a \propto \bar{n}_e R/B_\phi \) for the limiting density which is also seen in the ULQ regime on the Hugill-diagram is consistent with the original statement. An essential difference between the ULQ regime and other tokamaks lie in the numerical factor scaling \( q_a \bar{n}_e R/B_\phi \) corresponding to the density limit line for those regimes. The factor depends on the physical features within the plasma as the current distribution, impurity transport process, ionization and recombination processes. So the exceptional operating region in the ULQ experiment might result from the different physical processes in the radiative cooling due to not overcoming the radiation barrier.

Approximate estimates of volume-averaged toroidal beta value \( \beta_\phi \) have been made on each discharge. The method used is to evaluate the value using the following expression; \( \beta_\phi = (\text{plasma pressure})/(\text{magnetic pressure of the toroidal field}) \). The plasma pressure is derived from the measured \( T_e \) and \( n_e \) values at \( t=2.5 \) msec after the discharge start assuming that the radial profiles of the density and temperature are parabolic and \( T_i = T_e \) (including the ions since the equipartition time is estimated to be faster than the energy confinement time).

The so-called “toroidal beta limit” is represented by the following expression;

\[
\beta_\phi [\%] \leq C_0 \times \frac{I_p}{a B_\phi} \text{ [MA/mT]},
\]

where \( C_0 \) is a numerical constant depending on the plasma shaping and the assumed instabilities. Recent tokamak experiments have demonstrated that the critical \( C_0 \) value of 3.5 is effective for a circular cross-section of a plasma column. The results from the ULQ operation are shown with the critical beta \( \beta_c \) with \( C_0=3.5 \) in Fig. 7, where the abscissa is \( I_p/a B_\phi \) and the ordinate is the volume-averaged toroidal beta value \( \beta_\phi \). As the abscissa \( I_p/a B_\phi \) is equivalent to the value of \( (2\pi a/\mu_o R)/q_a \), Fig. 7 implies that there exists an optimum \( q_a \) value for the attainable \( \beta_\phi \) value. It is found from this figure that a similar criterion for the critical \( \beta_\phi \) value appears in the ULQ regime. The discharges plotted near the \( \beta_c \) limit correspond to the ones near the density limit in Fig. 6, hence the \( \beta_\phi \) limit may be closely related to the density limit in this case.
Figure 8 shows a spectrum of the $\beta_\phi$ and $\beta_\theta$ values associated with $q_a = 1/2$ and the limit of $\beta_\phi \beta_\theta \leq (C_0/20)^2$ derived from the above $\beta_\phi$ limit criterion, where the constant $C_0$ of 3.5 is used. It is found that the measured poloidal beta values are relatively small.

Fig. 8 Spectrum of $\beta_\phi$ and $\beta_\theta$ shown with the $q_a$ value of 1/2 and the critical beta $\beta_c$.

6. Conclusion and discussion

The ULQ experiment with a fast current rise has been carried out and produced the stable and reproducible plasmas. The results of parameter scans have provided useful information on the operating region and the discharge properties for understanding the ULQ regime. The following conclusions are summarized:

1) Stable discharges with the fluctuation level of $\delta B_\theta / B_\theta < 3\%$ are obtained in a range of $1/2 < q_a < 1$ when the filling gas pressure $p_0 \geq 5$ mtorr, where $S$ is of the order of $10^2$.

2) The results of the $q$ profile measurements suggest that the formation of a paramagnetic profile with $dq/dr < 0$ during the setting-up phase may play an important role in the establishment of the ULQ regime.

3) Experiment does not overcome the radiation barrier.

4) High density plasmas with the order of $n_e \sim 10^{20}$ m$^{-3}$ are obtained for low toroidal field less than 2 kG, associated with the values of extremely large Murakami parameter.

5) Preliminary estimates of the beta value, based on the conductivity temperature, show that the critical toroidal beta values obtained are consistent with the present empirical toroidal beta limit.
Ultra-Low-q Discharges in REPUTE-1

The ULQ regime is different from the conventional stabilized pinch from the point of view of the safety factor. The main difference between the ULQ and stabilized pinch configurations is that the former aims at the region of $1/2 < q_a < 1$ in contrast with the latter with $q_a < 1$ or $q_a = 1$ for typical values of $0.1-0.2$. And note that the $q_a$ value of the pinch is roughly estimated by $q_a^{-1} \sim (\text{aspect ratio}) \times (\text{pinch parameter})$. In fact the lower $q_a$ value, there are the more close resonant surfaces in the outer plasma edge regions, where the resulting resistive MHD instabilities can lead to island formation and overlapping which can give rise to enhanced particle diffusion through the stochastic magnetic field lines. In our experiment, too, stable discharges have not been realized in the region of $q_a < 1$. On the other hand, differing from the tokamak, the ULQ configuration is set up under the condition of low values of $S$ number ($\approx 100$) which is realized by the fast current rise and relatively high filling gas pressure, similar to RFP setting-up. Dissipation effects in low $S$ region could prevent the growth of MHD modes during the setting-up. The density pump-out in the ULQ discharge is not so furious as in the RFP discharge under some condition, so that, during the sustainment phase, $S$ is temporarily kept between $10^2$ and $10^3$ and such dissipation effects could suppress the plasma instabilities as well as during the setting-up phase.

The Suydam criterion is most crucial for the ULQ configuration on ideal MHD stability because the radial profile of the magnetic pitch can exhibit a minimum in the outer region of the plasma column. If the criterion is violated, the resulting instability is a localized flute or interchange mode. However, in general, such localized Suydam modes have not been observed in experiment. This is interpreted as being due to dissipative effects which may cause some damping of the mode spectrum. Furthermore in early linear pinch experiment, it was found that the plasma pressure distribution continuously re-adjusts itself, so that the Suydam criterion is always marginally satisfied \(^5\). In fact, the radial profile of the current density in the ULQ is observed to be relatively flat and extend closely to the wall. Hence it might be possible for the location of the pitch minimum to be shifted to the plasma edge or the outer region that can be a full dissipative region. That may be why there were no significant fluctuations observed in this ULQ experiment under the low $S$ condition.

In early stabilized pinch experiments, the life time of the magnetic field configuration was found to be limited by the time scale of the resistive interdiffusion of the magnetic fields. But, in our experiment, the time scale of the transit from the ULQ configuration to the tokamak-like one is observed to be longer than the resistive skin time across the minor radius $\tau_R (= \mu_0 a^2/\eta$, typically 0.5 ms) as seen in Fig. 4. As a possible interpretation of the phenomenon, impurity effects could be quoted. It is well known that the main effect of the impurities present in the plasma is the forming of the plasma current distribution through the electrical resistivity, and the impurities cause radiation losses and the production of cold electrons. In REPUTE-1 experiment, the ULQ discharge has not burned out the light impurities like oxygen and carbon, both of which have a peak radiative power at $T_e \approx 20$ and $\sim 6$ eV, respectively. Accordingly, the current distribution will presumably tend to be kept radially flat
owing to the radiative cooling in the central region of the plasma. Therefore our results indicate that, under our conditions, a temporal change of the current distribution during the sustainment phase is likely to be dominated by the radiative cooling due to the impurities, rather than by the magnetic field interdiffusion.

As the radiation barrier is overcome and $S$ is increased exceeding the order of $10^4$, the localized Suydam modes may deteriorate the confinement properties, in particular, in the plasma edge regions. At that time, in order to remove the pitch minimum within the plasma, one can intend to control a local shear in the vicinity of the plasma edge by means of adding the reverse helical transform with high shear. This kind of method has been applied to HLQT$^{14}$ and OHTET$^{15}$. What may be most attractive is to realize and investigate the ULQ configuration with higher values of $S$ by burning through the radiation barrier.

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REFERENCES