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OBSERVATIONS OF RAMPED CURRENT OPERATION IN ZT-40M

by

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ABSTRACT

A new mode of reversed-field pinch (RFP) startup has been tested in the RFP experiment ZT-40M. Instead of increasing the toroidal current almost sinusoidally to its maximum, as is normally done, the current is initially raised to ~ 70 kA in 0.8 ms and subsequently slowly ramped up to ~ 170 kA in 14 ms. The behaviors of toroidal flux, particle density, temperature, and radiated power for the ramped discharges are compared with fast current rise, flat-topped operation. The successful demonstration of ramped toroidal discharges has an important impact on future large RFP experiments since the voltage necessary to drive the toroidal current for slow (~ 10 to ~ 20 ms) startup is reduced.

I. INTRODUCTION

A new mode of RFP startup has been tested in the RFP experiment ZT-40M. Instead of increasing the toroidal current almost sinusoidally to its maximum, as is normally done, the current was initially raised to ~ 70 kA in 0.8 ms (an RFP was formed with toroidal field reversal at the wall) and subsequently slowly increased to ~ 170 kA in 14 ms. Discharges with this mode of startup are called "ramped discharges."

This report describes the main observations made on ramped discharges over two days' operation. The results should then be considered preliminary since a limited amount of ZT-40M machine time was set aside for this test.

At the start of the tests on ramped discharges, it was thought there were at least two advantages for this startup mode:

1. Since the power input to the discharge increases roughly as the square of toroidal current, a fast current rise to 70 kA would have a power input that is about five times smaller than that for a 170-kA discharge. (This will be seen later in this paper.) Substantial energy loss takes place during the nonreversed position of the startup. By forming an RFP at low current and then ramping the current up slowly in time during the reversed-field phases, the instantaneous power input is reduced, and wall damage and impurity influx may be considerably reduced.
2. The successful demonstration of ramped RFP discharges would have an important impact on the design of future large RFP experiments since the voltages necessary to drive the toroidal currents for a slow startup would be reduced.

When the "ramped discharge" mode of startup was proposed, the following two questions were raised which would have prevented successful RFP formation:

1. Since the fast ~ 70 -kA discharge would be run in the standard matched-mode operation, the toroidal flux would have to increase by a factor of 2 as the current was raised to ~ 170 kA. This additional toroidal flux is supplied by the toroidal current power supply through a "dynamo action," and there was uncertainty as to how the plasma would react having to internally generate such a large toroidal flux.
2. The gas-fill pressure for a 70-kA discharge is ~ 1.4 mtorr, considerably lower than the 2.8 mtorr ordinarily needed for a 170-kA discharge with fast startup. Would pumpout of the fill gas then starve the discharge, causing an early termination of the discharge?

In the ramped discharge test, the toroidal current of the experiment was to be raised first to ~ 70 kA with the 0.8-ms risetime capacitor bank, forming an RFP, and then the current was to be ramped up by the toroidal current power crowbar bank.

Prior to performing the experiments, we performed computer simulations¹ to determine the needed loop voltage, using the modified Bessel function model, i.e., μ cutoff at 0.7 times the minor radius. The plasma resistance was held

constant at 0.3 m Ω . The desired wave shape could be produced relatively simply, which led us to believe that the waveform would not be difficult to produce experimentally. The results of the simulation are shown in Fig. 1.

After the experiments were performed, the results could be matched using the same programs. Figures 2 and 3 show the match between the model¹ and experiment that can be obtained.

In the test of ramped discharges, the only change to a 70-kA flat-topped discharge was to increase the toroidal current power crowbar voltage from 2.8 kV to 5.3 kV. The ramped discharge was then compared with a standard fast 170-kA flat-topped discharge.

II. OBSERVATIONS

1. The toroidal current, Fig. 3a, ramped up to ~ 170 kA in ~ 15 ms at which time the protect circuits were fired to prevent saturation of the iron cores of the power crowbar transformers.

2. Starting with the toroidal flux in the 70-kA matched-mode operation, the increase in toroidal flux follows closely the toroidal current, Fig. 3b. Note the fluctuations in the increasing flux which are identical to those flux regeneration events seen during flat-topped high- θ operation and which are associated with soft x-ray sawteeth.²

3. The reverse toroidal field at the wall, Fig. 3c, deepens to -250 G close to that of a 170-kA flat-topped discharge. The increased reverse poloidal current is caused by the positive rate of change of toroidal flux in the poloidal current winding. This poloidal voltage is induced by the "dynamo" which couples poloidal flux into toroidal flux. This voltage is in a direction to add to the voltage of the toroidal field capacitor bank, resulting in increased current.

4. There is a phase shift between the toroidal flux and the toroidal current (Fig. 4a and 4b). A ramped discharge moves to higher θ and more negative F values, ~ 1.6 and ~ -0.30 , compared with the standard 170-kA discharge, ~ 1.4 and ~ -0.15 . This can be explained by the circuit arguments given above.

5. The volt-seconds/A input to form the two types of discharges is about the same at ~ 15 ms, Fig. 5a and 5b. Ramping the toroidal current requires then

about the same flux consumption to achieve the same current as a flat-topped discharge.

6. A comparison of the peak power inputs for the two startup modes, Fig. 6, shows the reduction of input power with ramped discharges, about a factor of 5 in these examples.

7. The plasma densities for the two types of discharge are shown in Fig. 7a. Following the rapid pumpout typical of a standard fast 70-kA discharge (1.4 mtorr deuterium fill pressure), the density increases as the current is ramped up and at about current maximum is ~ 1.4 higher than that for a 170-kA flat-topped discharge (initial fill 2.8 mtorr). The ratio I/N for the ramped discharge, Fig. 7b, is almost constant during the time interval 5-14 ms.

8. Plotting the electron temperature and densities for the ramped discharges (squares) on the Phase II data obtained during the dedicated scaling runs^{3,4} shows somewhat higher values for ramped discharge at the same toroidal currents (Fig. 8a and 8b). The temperatures and densities in the scaling runs are those measured at 5 ms into the discharge and are approximately constant for the duration of the flat-top discharge, whereas those for equivalent current in the ramped discharge extend out to 14 ms. Even with these uncertainties, we conclude that the ramped discharge is at least as hot and as dense as standard flat-topped discharges at equivalent currents.

9. Calculations of β_p for ramped discharges, Fig. 9 (using the same form factor, $f = 1$, flat profile of plasma energy with $T_e = T_i$), show that β is similar to, if not somewhat higher than, those for standard discharges.

10. Of particular interest is the power lost during the current ramp and the power radiated, Fig. 10. At about the same toroidal currents, ~ 150 -170 kA, the power lost by the two types of discharges is about the same since the discharges have about the same temperatures. The radiated power for the ramped discharge, however, is twice that of a flat-topped discharge. This increase is probably due to the increased density and an increase in impurity content (see below). Surprisingly, the ramped discharge is sustained at the same temperatures and densities with one-half (rather than one-quarter) of its power lost through radiation.

11. While the number of consistent ramp shots was small, several spectroscopic observations were obtained. Since the typical shot-to-shot reproducibility of spectroscopic observations is of order 20%, only a global interpretation can be presented.

The Johns Hopkins University absolutely calibrated EUV spectrometer measured the brightness of line emissions from OIV, OV, OVI, CIII, NiIII, NIV, and L_{α} . These data are compared with typical emissions obtained at equivalent current level "flat-top" shots in the same series. The only significant change found was that NiIII increased by a factor of 2-3 at 5 ms (~ 120 kA) compared with a flat-top 120-kA shot. CIII also seemed to be a little higher, but the difference could be explained by shot-to-shot variations. The oxygen and nitrogen levels appeared unchanged. These data indicate that there may be increased wall interaction in the ramp mode. Ramps of different rates may provide an insight into the degree of wall interaction.

A second observation is that of the absolutely calibrated D_{α} monitors, which, when normalized to the chord-averaged electron density, provide an estimate of the recycling time. Again at 5 ms, the recycling time was comparable to that of "flat-top" shots, with the slight increase noted being probably due to the fact that the global density inventory is increasing during ramp shots, while it is very slowly decreasing on "flat-top" shots. (The term describing the global inventory change is set to zero in these computations.)

12. A striking feature of the long, slow ramp shots is the greatly enhanced ($\sim 10X$) soft x-ray flux over "normal" shots of comparable or greater toroidal current. For the central chord surface barrier x-ray diode (SBD) raw signal, Fig. 11 compares three different types of shots, labeled by their current waveform. At late times, it is clear that the ramped shot has at least an order of magnitude higher emission level than either a flat-topped 120-kA or 170-kA discharge. Since the detector actually began to saturate at $\sim 19 \mu A$ for some of the ramped shots, one can infer as high as $23 \mu A$ of signal.

The x-ray signal can be roughly estimated to vary as $n_e n_i \exp(-E/T_e)$, where $E \approx 800$ eV. Consequently, it is instructive to normalize the x-ray signal by the electron density squared, to remove density dependence. This is done in Fig. 12, where it can be seen that the ramped shot still shows significantly higher x-ray emission. This emission is centrally peaked and not hollow. When a higher energy plastic scintillator x-ray detector signal is divided by low-energy SBD signal, the ratio actually falls for most of the ramp shot (5-15 msec) and is lower overall than the 120-kA or 170-kA flat-top shots.

One general observation has been that shots with a higher loop voltage tend to be brighter in the soft x rays. This is certainly true of the ramped shots, which have a higher (80-50 V) loop voltage than 120-kA shots (40-35 V). Since

the ramped shots start out with a very low fill pressure (1.5 mtorr), runaway electrons are suspect.

The reason for the observed enhanced soft x-ray emission (slideway electrons, increased Z_{eff} , or T_e higher by ~ 50 eV) is not clear at this time. The observed increase in electron density is by itself not adequate to account for the brighter soft x-ray emission.

13. Hard x rays, ≥ 200 keV, are observed during the second half of a ramped discharge, Fig. 13a and 13b. (No such hard x-rays are observed in flat-topped discharges.) It has been suggested (A. Jacobson, CTR-2) that the higher toroidal voltage, Fig. 13c, needed to drive the ramped discharge could accelerate runaway electrons.

14. The energy confinement times, τ_E , for the ramp shots when plotted on the data of the dedicated scaling runs⁴ are given in Fig. 14. If a nonradiative energy confinement time is defined, i.e., the energy input minus the energy lost by radiation is used in the calculation of the energy replacement time, the τ_E for the ramped discharge is about twice that for a flat-topped discharge.

These observations on the ramped discharge, although preliminary, show that the toroidal current can successfully be raised with very long time scales, ~ 15 ms. In addition, there have come out of these investigations data which will help in the understanding of some of the important aspects of RFP behavior, e.g., dynamo action, density pumpout, and energy confinement. Further work needs to be done to examine these factors in greater detail.

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Fig. 1.

Computer simulation run to determine proper settings of capacitor bank voltages for ramped discharges. B_ϕ wall refers to the toroidal field inside the liner.

(a)

(b)

(c)

Fig. 2.

Comparisons of computer simulation run with an experimental ZT-40M discharge: (a) toroidal current, (b) B_ϕ (wall), and (c) toroidal flux.

(a)

(b)

(c)

Fig. 3.

(a) Toroidal current for 60- and 170-kA, flat-topped discharges and for a ramped discharge. (b) The toroidal flux for the three discharges. (Note the discrete flux regeneration events in the ramp discharge.) (c) The toroidal field at the wall for the three discharges.

(a)

(b)

Fig. 4.
F-θ diagram: (a) for a 170-kA, 0.8-ms rise discharge and (b) for a ramped discharge.

(a)

(b)

Fig. 5.
V·s/A input for a 170-kA, 0.8-ms rise discharge. The dotted line is an extrapolation of the V·s/A with the assumption of constant resistance to 15 ms. (b) V·s/A input for a ramped discharge.

(a)

(b)

Fig. 6.
Power input as a function of time
(a) for a 170-kA fast discharge and
(b) for a ramped discharge.

(a)

(b)

Fig. 7.
(a) The plasma densities for the two
types of discharge versus time.
(b) The ratio I/N for 10 ramped dis-
charges and the shot-averaged ratio
 I/N and standard deviation of the same
discharges.

(a)

(b)

Fig. 8.
Comparisons of (a) the electron temperature and (b) the density for the two types of discharge.

Fig. 9.
Comparisons of poloidal beta/f for 180-kA, 0.8-ms rise discharges and the ramped discharge.

POWER RADIATED AND POWER LOST
170 kA FLAT-TOP x, 70 - 155 kA CURRENT RAMP o

Fig. 10.
The power lost and power radiated for 170-kA, flat-topped, and current ramped discharges. The power radiated is determined from the bolometer measurement assuming a radially uniform source.

Fig. 11.
Central chord soft x-ray signals for three types of discharge.

Fig. 12.
Normalized soft x-ray signals divided by the electron density squared for the same three types of discharge, as in Fig. 11.

(a)

(b)

(c)

Fig. 13.

The toroidal current and hard x-ray signals (a) for a 170-kA, flat-topped discharge and (b) for a ramped discharge. (c) The toroidal voltages for the two types of discharge.

(a)

(b)

Fig. 14.

The energy confinement time/ f for (a) flat-topped discharges and (b) ramped discharges. The dotted curves in each figure indicate the energy confinement times when corrected for the power loss by radiation.