TEMPERATURE SCALINGS IN THE REPUTE-1 REVERSED FIELD PINCH PLASMA

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ABSTRACT

Statistical property of ion and electron temperatures on various plasma parameters has been investigated in REPUTE-1 reversed field pinch (RFP) plasmas. The scalings laws are expressed in terms of the plasma current, loop voltage and line averaged density. Dependence on other parameters seems to be weak. The operational range of density is wide in REPUTE-1, and it is limited by Hugill number $H^{*}\sim 1$, which is another expression of I_p/N, where I_p is the plasma current and N is the area density. Obtained scaling laws are

$$T_i \propto V_{Loop}^{\ 1.3} \times \bar{n}_e^{\ -0.3}, \quad T_e \propto I_p^{\ 0.8} \times \bar{n}_e^{\ -0.2},$$

where n_e is the line averaged electron density and V_{Loop} is the loop voltage. The electron temperature has roughly same dependence as other RFP devices. The I_p dependence of ion temperature is not found in REPUTE-1, while some RFP devices demonstrate linear dependence.

I. INTRODUCTION

RFP plasmas [1] have been studied as an alternative concept to the tokamak. Specifically, RFP may be more compact as a reactor. However, empirical scaling laws have not been established to determine the potential of RFP magnetic fusion concepts as an attractive fusion energy system. Most of the RFP devices have a thick shell to stabilize MHD instabilities. Since the REPUTE-1 device (R/a=0.82[m]/0.22[m]) [2] has a thin shell, which will be used inevitably in reactors, the obtained scaling laws provide an important database for RFP reactor concepts. Scalings in RFP have been discussed in terms of the plasma current and I_p/N. The poloidal beta of pinch plasmas is written as $\beta_p=8\pi/\mu_0(kT/I_p)(N/I_p)$ and electron temperature is roughly proportional to I_p in RFP devices. In addition, the resistivity can be represented by the product of Spitzer resistivity and anomalous enhancement factor Z^*. Thus, the confinement of RFP plasmas, which is heated by Ohmic input $I_p V_{Loop}$, can be characterized by I_p and I_p/N. The value of I_p/N is related to Hugill number, which yields density limit, and electron drift velocity. In RFP devices, edge heat flux is asymmetric (larger at electron drift side), and high energy electrons are observed. In addition, electron loss channel due to stochastic field lines is suggested. Thus, I_p/N has been used to characterize RFP plasmas. In the present paper, temperature scalings are expressed as a power law of I_p, $\overline{n_e}$ and V_{Loop}, and dependencies on each parameter are resolved. The data are distributed in the wide range of these parameters including different wall conditions (and wall history), which are thought to affect the loop voltage.

II.TEMPERATURE MEASUREMENTS

Ion temperature is measured by the following three methods. A neutral particle energy analyzer (NPA) measures the temperature of bulk ions (hydrogen). In some discharges time of flight system (TOF) is also used. A visible spectrometer is used to measure the temperatures of intrinsic impurities, such as carbon and oxygen. C^{4+}line(227.1 [nm]) is used for high current discharges (>200 [kA]) and O^{4+}(278.1 [nm]) for low current discharges. Temperatures are calculated from the Doppler broadening of their lines. Good agreement of NPA measurements with TOF method is found under the same condition of measurements. The density profile of neutrals is calculated from the measured profile of Hα emission, and a calculation of charge exchange neutral flux indicates that the ion temperature measured by the NPA represents almost the central temperature.

A Thomson scattering system measures electron temperature at up to 6 points. About a half of the minor radius is covered by this system. The scattered light is collected by a condenser lens at a horizontal port and imaged onto 6-channel fibre-optic bundle. The line-averaged electron density is measured by a CO_2 laser interferometer. The wavelength of the laser is 10.6 [μm] and the power is 2 [W]. Typical relative error of temperatures is about 10%. The central electron temperature and the line averaged density are used to calculate scaling laws, and parabolic density profile is assumed to calculate the area density.

III. OPERATIONAL REGION OF REPUTE-1 PLASMAS

The main controllable parameter in operation is the plasma current. Achieving desirable density is rather difficult, and the density appears to depend on wall conditions. In some devices, it linearly increases with the plasma current, while in REPUTE-1 they have rather weak correlation resulting in a wide operational region of plasma current and density. Figure 1 shows the operational region of the REPUTE-1. The high density boundary has I_p/N of about 3×10^{-14} [Am]. The number number of I_p/N is equivalent to the tokamak Hugill number [3]. The Hugill number H^* for RFP is written as

$$H \equiv \frac{n[10^{20}\,\mathrm{m}^{-3}]\,q_a R[\mathrm{m}]}{B_t[\mathrm{T}]} = \frac{na}{B_p(a)}$$

$$\approx 10\frac{N[10^{20}\,\mathrm{m}^{-1}]}{I_p[\mathrm{MA}]} \equiv 4H^* ,$$

where H is the standard Hugill number. The factor of 4 is called as the 'screw-up factor', which is a ratio of root mean square current density to mean toroidal current density. It is defined as

$$\left[\langle j^2\rangle / \langle j_t\rangle^2\right]^{1/2} \approx 4 .$$

The value of this factor is around 4, and it is a weak function of the magnetic configuration.

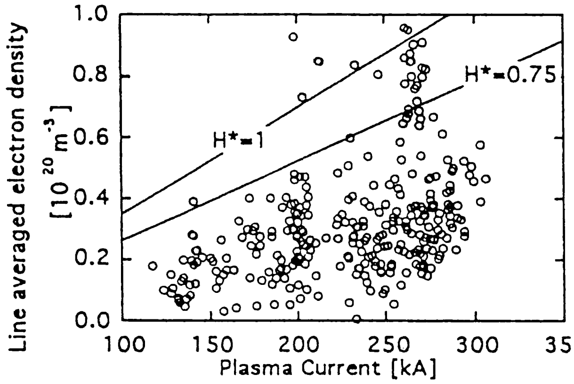

Fig.1. Operational region of the plasma current and line averaged electron density. The solid lines represent $H^*=1$ ($I_p/N=2.5\times10^{-14}$ [Am]), and $H^*=0.75$.

The standard Hugill number represents the ratio of radiation power to the Ohmic heating power assuming the latter can be described by Spitzer resistivity. In contrast to tokamaks, RFP has anomalously high resistivity and Ohmic input is quite large. Since Joule heating arising from Spitzer resistivity heats electrons and residual non-Spitzer component is believed to heat ions mainly, the same expression can be used for the density limit. As shown in Fig.1 the operation is limited at the line $H^*=1$. This limit in H^* is the same as the limits achieved in other RFP devices. Note that higher density operation is possible when objects (probe) are inserted into the plasma and when carbonization of the vacuum vessel is done. At the initial phase of a discharge the density decreases rapidly to a certain value, and it is difficult to achieve higher density in RFP plasmas which have relatively short discharge duration. This phenomenon is known as the 'density pump-out'. The fraction of the radiation power to the total input power increases as I_p/N decreases in the REPUTE-1 and other devices. These facts suggest that the radiation and/or particle fueling method impose the density limit and affect the density pump-out. In addition, the energy confinement time of tokamaks saturates when Hugill number exceeds a certain number, while in RFP the saturation is not observed.

IV. TEMPERATURE SCALINGS

Statistical property of ion and electron temperatures has been investigated. Empirical scaling laws in terms of plasma current I_p, loop voltage V_{Loop}, and line averaged electron density $\overline{n_e}$ are calculated, because the dependence on other plasma parameters is not clear. The correlations between I_p-V_{Loop} and $\overline{n_e}$-V_{Loop} are small except in the discharge series under careful control of boundary conditions including the surface of wall and error field [4,5]. In those plasmas, V_{Loop} decreases as I_p increases. The profile of the magnetic configuration is characterized by pinch (Θ) and reversal (F) parameters, where $\Theta=B_p(a)/<B_t>$ and $F=B_t(a)/<B_t>$. Since the basic property of the RFP configuration is well described by Taylor's minimum energy state, the pinch and reversal parameters have strong correlation. In the present paper, the plasmas with the following plasma parameters are used.

$120 < I_p < 300$ [kA], $140 < V_{Loop} < 240$ [V],

$-0.9 < F < -0.3$, $1.8 < \Theta < 2.6$, $\overline{n_e} < 1.2\times10^{20}$ [m^{-3}] .

Time averaged (0.2 [msec] at the flat-top phase) data were accumulated for hydrogen discharges. Since the NPA is available at low density ($\overline{n_e} < 0.5\times10^{20}$[m^{-3}]) and the Thomson scattering system is available at higher density, we have not enough data to derive those scaling laws from a single data set.

A. Anomalous Ion Heating

The ion temperature is anomalously high, and this fact can not be interpreted from classical collision between ions and electrons. Furthermore, carbon impurity C^{4+} temperature T_{CV} is higher than the bulk ion temperature

T_{NPA} in REPUTE-1 plasmas. The ratio of the impurity temperature to the bulk ion temperature increases from one to three with the increase of plasma resistance from 0.5 to 0.8 [mΩ] (Fig.2). An estimation of temperature relaxation times suggests that the carbon impurity is heated directly, and that not only anomalous heating of bulk ions but also that of impurity exists.

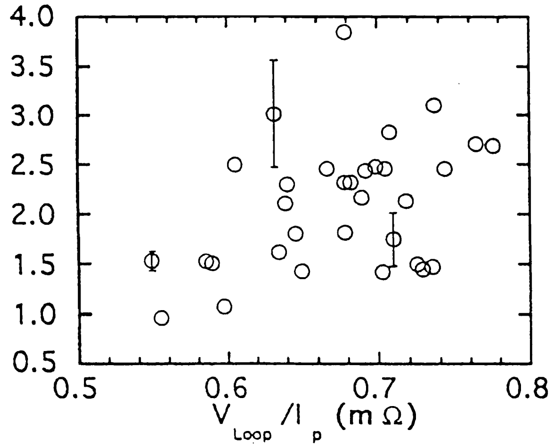

Fig.2. The ratio of carbon temperature to bulk ion temperature as a function of plasma resistance.

Anomalously high ion temperature has been observed in many RFP devices, and ions are believed to be heated through dynamo activities, which is an inevitable process to sustain RFP configurations. The ratio of ion heating power to the total input (Ohmic input) has been calculated by helicity and energy balance equations. However, the ion heating mechanism, especially that including impurity heating, is not yet fully understood. The fraction of ion heating power to the total input in REPUTE-1 plasmas is estimated to about 20% by the helicity and energy balance model. This ratio is consistent to several experimental results.

B. Ion Temperature Scaling

Since the plasma current is the most important parameter to characterize RFP plasmas, firstly, we will show the dependence with a fixed plasma current (I_p=200 [kA]) to study dependence on the other plasma parameters. The ion temperature T_{NPA} measured by the NPA increases as the loop voltage increases and as the density decreases. Figure 3 shows the bulk ion temperature as a function of line averaged density. The open circles represent the discharges with high (>165 [V]) and the closed circles represent those with low loop voltage (<165 [V]). The solid line, which is calculated by a least square method, is a guide to show the dependence on the density. The data with the higher loop voltage tend to exist above the line, and the data with lower one tend to exist below the line. Thus, the ion temperature depends on both the loop voltage and the density.

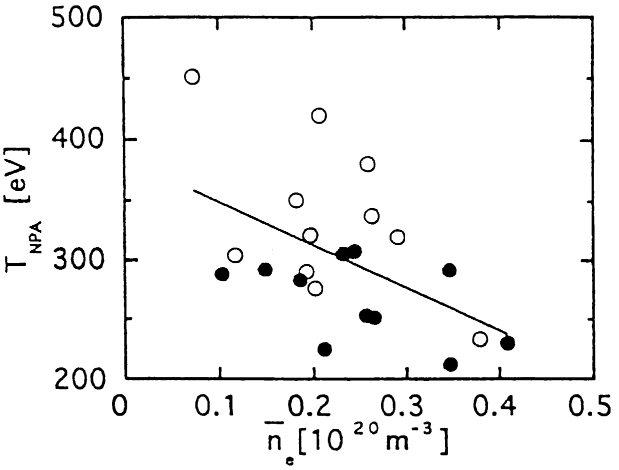

Fig.3. Ion temperature as a function of line averaged density for plasmas with Ip=200 [kA].

The power law of bulk ion temperature is calculated from the data with various plasma current (Fig.4). It is written as

$$T_{NPA} \sim 230 \times (\bar{n}_e / 0.3)^{-0.32} \times (V_{Loop} / 150)^{1.33},$$

where T_{NPA} in [eV], $\overline{n_e}$ in [10^{20}m^{-3}] and V_{Loop} in [V]. The dependence on plasma current is weak. The ion temperature is related to the loop voltage. A drastic decrease in ion temperature and a decrease in loop voltage by about 15% were observed after a carbonization of the vacuum vessel [5]. Enhancement in loop voltage and ion temperature is observed in HBTX1 and ZT-40M devices by changing boundary conditions. The scaling law obtained in HBTX1C device is written as [6]

$$T_i \sim 0.31 \times I_p[\mathrm{kA}] \times \Delta V_{Loop}[\mathrm{V}]^{0.5} \times n_i[10^{19}\mathrm{m}^{-3}]^{-0.5},$$

where ΔV_{Loop} is the non-Spitzer loop voltage. The index of ΔV_{Loop} is much smaller than that of V_{Loop} in REPUTE-1. The following describes a possible explanation of this difference. If we take into account that the ion heating power is estimated to be about 20% of the total input power and if we assume that only a part of loop voltage (ΔV_{Loop}) contribute to ion temperature in the form of power law, the temperature would show an offset power law. The index derived from a power law fitting to such an offset power law is several factors larger than that of offset power law. Due to large scatter in data and relatively narrow range in V_{Loop}, it is difficult to distinguish the difference in the REPUTE-1 plasmas. Although there are less database for ion temperature, the temperature increases with Ip in some other RFP devices. In the TPE-1RM device, the temperature linearly increases with Ip, while the density also linearly increases [7]. The fact that Ip dependence is not clear in REPUTE-1 appears contradictory to other devices. Further accumulation of ion temperature database is needed.

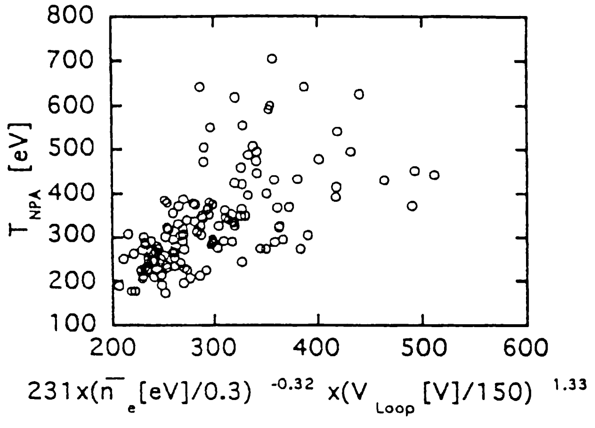

Fig.4. Ion temperature scaling.

C.Electron Temperature Scaling

In contrast to the ion temperature, the electron temperature increases as the plasma current increases, and it increases as the line averaged density decreases (Fig.5). The power law of the central electron temperature T_e is written as

$$T_e \sim 73 \times (I_p / 200)^{0.84} \times (\bar{n}_e / 0.5)^{-0.21},$$

where I_p in [kA] and $\bar{n}_e$ in [10^{20}m^{-3}]. χ^2-test shows this is the most probable power law among the combinations of I_p, $\bar{n}_e$ and V_{Loop}. The dependence on V_{Loop} is weak. In HBTX1C, the dependence is

$$I_p^{0.57 \sim 0.78} \times \bar{n}_e^{-0.63 \sim -0.55},$$

where the range of indices includes different boundary conditions [8].

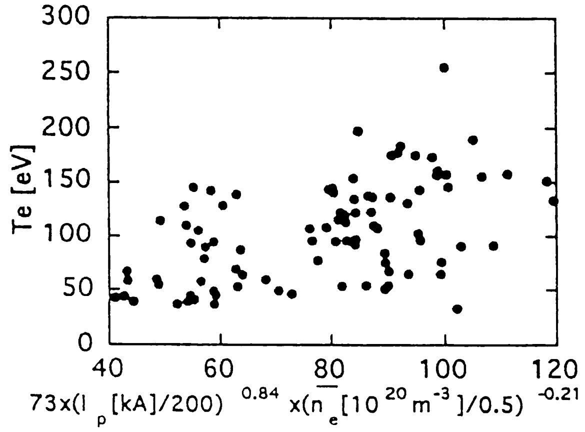

Fig.5. Electron temperature scaling.

All of the reported electron temperature scaling shows strong dependence on Ip with the index 0.5-1.2. Reported temperature seems to indicate small index of n_e as calculated in the present paper. The absolute temperature (or the coefficient of power law when we adopt a certain power law on I_p and I_p/N) is quite different between devices even though we take into account the effect of major and minor radii in power law. REPUTE-1 has a low coefficient. This is probably due to large field error at the edge and resultant electron diffusion in stochastic fields. Another parameter is required to obtain generalized scaling laws and extend it to a reactor relevant regime.

V. CONCLUSION

The temperature scalings are expressed in terms of the plasma current, loop voltage and line averaged density. Dependence on other parameters seems to be weak. The operational range of density is wide in REPUTE-1, and it is limited by Hugill number $H^* \sim 1$, which is another expression of I_p/N. The electron temperature has roughly the same dependence as other RFP devices. It increases as the plasma current and decreases as the density. The ion temperature increases as the loop voltage. This is consistent to the scenario that the anomaly in loop voltage is related to the dynamo activity and the induced fluctuations are dissipated by ions. The I_p dependence of ion temperature is not found in REPUTE-1, while some RFP devices show linear dependence.

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