Plasma Confinement and Relaxation on ATRAS-RFP Experiment

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It is important in the plasma research to obtain more detailed internal magnetic field structure of the plasma. Details of confinement and relaxation process will be known from the structure of the internal magnetic field. We observed radial profile of the magnetic field on equatorial surface by a probe array inserted in plasma. This probe array is composed from sixty coils set on twenty points by 5mm to measure toroidal, Bz, poloidal, Bp, and radial, Br, components of magnetic field at each points. Generally, the measurement inserted probe in to plasma disturbs the plasma seriously, and the effects are shown in Fig.1 comparing usual discharge, A, with the disturbed one, B, by the insertion of array. Plasma current, toridal flux and duration of discharge decreases 20-30% when the probe is inserted. However, pinch parameter, Θ, and reversal parameter, F, are not affected by the presence of probe. It means

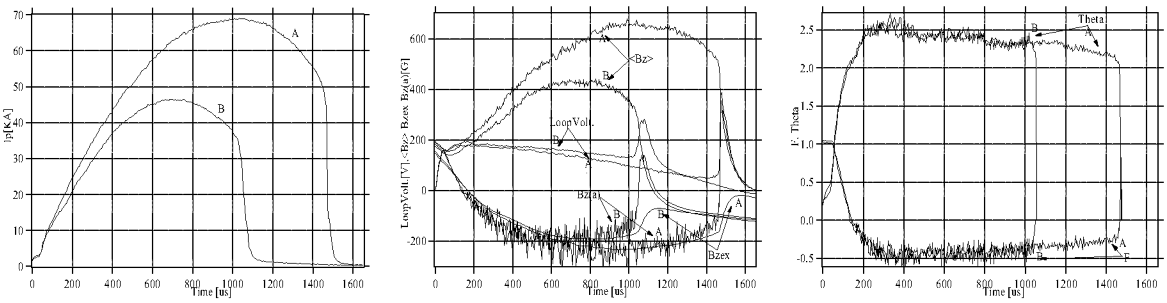

Fig.1 Typical ATRAS-RFP discharge without probe, A, and with probe, B.

that the probe does not influence magnetic field configuration on ATRAS-RFP plasma (major radius of 50cm, minor radius of 10cm). Therefore, the magnetic field distribution observed by the probe is deeply reflecting one of the usual plasma without the probe array. The distributions for each component of magnetic field at the time of maximum plasma current are shown in Fig.2. Each symbol marks are the value of the field observed by each probe and the solid lines are approximated curves for each field component by a higher-order polynomials. The time progresses for each magnetic field distribution are shown in Fig.3. The left horizontal axis shows the time progress, right horizontal axis shows the distance from center of vacuum vessel and vertical axis shows strength of the magnetic field, respectively. The maximum value of the toroidal field becomes ~ 1600 G at

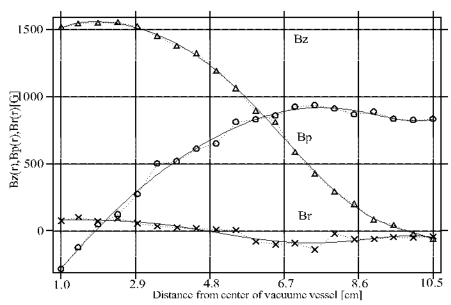

Fig.2 Approximated radial distribution of magnetic field component.

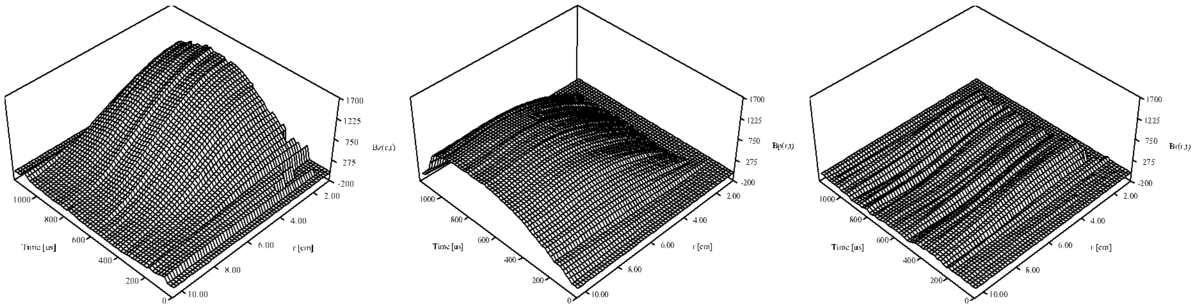

Fig.3 Time progress of each magnetic field component Bz, Bp, Br.

the center of plasma, the poloidal field becomes ~800G at the plasma surface and radial field becomes ~100G on average. We observed comparatively large radial field during discharge. As one of the reason, there is a possibility that plasma has helical deformation because of very high- Θ (2.2~2.4) operation on ATRAS-RFP. The magnetic axis appears at the position of Δ ~2cm from the center of the vacuum vessel, reversal surface also appears at the position of 0.5 ~1 cm inside from the wall as shown in Fig.4.

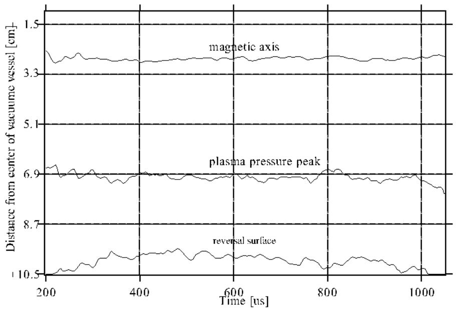

Fig.4 Time progress for the positions of magnetic axis, reversal surface and maximum pressure.

The current density and plasma pressure profiles are calculated from the magnetic field approximated by a higher-order polynomials by assuming the cylindrical symmetry of equilibrium configuration as follows,

$$\frac{dP}{dr}+\frac{B_z}{\mu_0}\frac{dB_z}{dr}+\frac{B_p}{\mu_0 r}\frac{d}{dr}rB_p=0,\ j_z=\frac{1}{\mu_0 r}\frac{\partial}{\partial r}rB_p,\ j_p=\frac{-1}{\mu_0}\frac{\partial}{\partial r}B_z .$$

The current densities and plasma pressure distributions are shown as their time progress in Fig.5. The average value of toroidal current density is <jz>~$1.3\times10^6\ A/m^2$, poloidal current

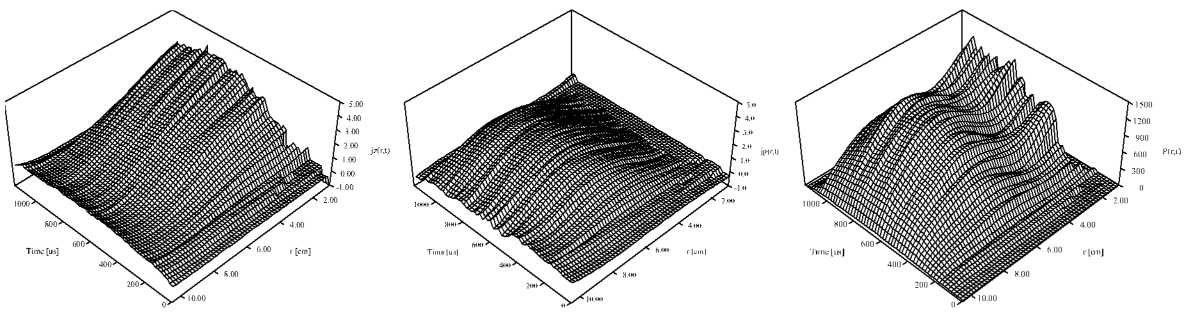

Fig.5 Profile of current density component j_z, j_p and plasma pressure P.

density is <jp>~$1.4\times10^6\ A/m^2$ and plasma pressure is <P>~$1400 N/m^2$. Plasma pressure has the maximum value at the distance of ~7cm from the magnetic axis. The distribution has the hollow shape oscillating with ~20KHz in inner region of the plasma column. Outside the layer of maximum pressure the plasma is very stable during the discharge. Beta, ß(r), and beta averaged in plasma volume, <ß>, are defined as follows,

$$\beta(r) \equiv P(r) \Big/ \frac{B_{ex}^2}{2\mu_0} \qquad B_{ex}\text{:ExternalMagneticField}$$

$$\langle \beta \rangle \equiv \frac{1/\pi a^2 \int_0^a \int_0^{2\pi} P(r) d\theta dr}{B_{ex}^2 / 2\mu_0} \qquad a\text{:PlasmaRadius}$$

and shown as their time progress in Fig.6 respectively. The profiles of magnetic pressure and

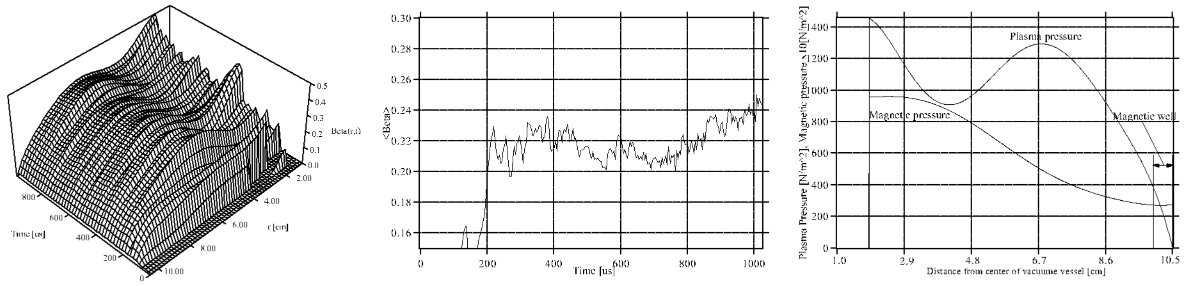

Fig.6 Time progress of radial distribution of ß(r), time progress of <ß> and magnetic well.

plasma pressure are also shown in Fig.6. ß(r) reaches a maximum value about 40%. Volume averaged beta value exceeds 20% from the early phase and sustain the value to the end of discharge. Magnetic well is generated around the reversal surface by the reverse of toroidal field. This is the characteristic of RFP and it has a good effect for the confinement as seen in Fig.6.

Here, we define two functions of radial position as follows, $\lambda_z \equiv \mu_0 j_z / B_z, \lambda_p \equiv \mu_0 j_p / B_p$. Then, radial component of equilibrium equation is written as follows, $\partial P / \partial r = j_z B_p (\lambda_p / \lambda_z - 1)$. Where, $\lambda_z = \lambda_p = const$ means Taylor's relaxation state and pressure gradient becomes to zero there. The time progress of radial distribution of λ_z, λ_p and $\mathbf{j} \cdot \mathbf{B} / B^2$ are shown in Fig.7, where negative part of λ_z are not plotted. The last term is obtained by taking the scalar product of $\mathbf{B}$ to the both side of $\mathbf{j} = \lambda \mathbf{B} / \mu_0 + (\mathbf{B} \times \nabla P) / B^2$, and it means Taylor's λ of partially relaxed state of the field. The profile of λ_z becomes flat from early phase of discharge in the inside of the reversal surface, and it becomes infinity because toroidal plasma current density is not zero at reversal surface. On the other hand λ_p profile has a peak around the r/a~0.65 in the early phase of discharge then the peak becomes widely with the

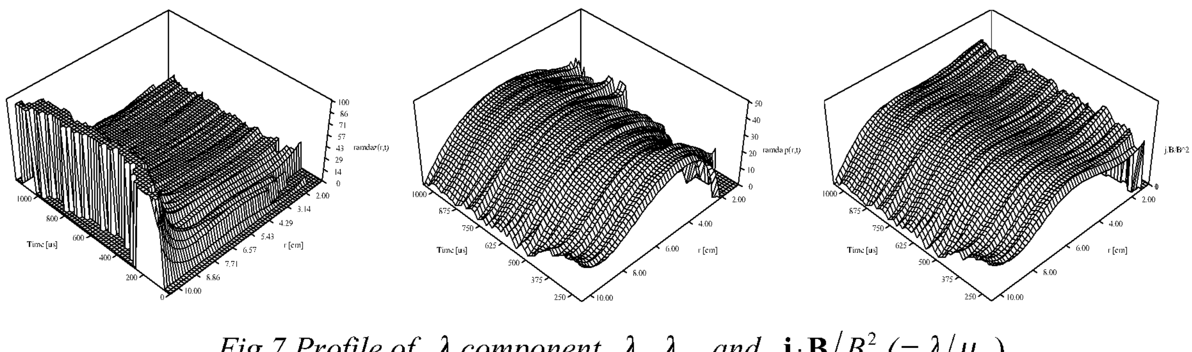

Fig.7 Profile of λ component λ_z, λ_p and $\mathbf{j} \cdot \mathbf{B} / B^2$ $(= \lambda / \mu_0)$

passage of time. In the region of $\lambda_z \sim \lambda_p$ (r/a~0.65), the values of λ_z and λ_p are almost coinciding to the value calculated from pinch parameter $\Theta \sim \lambda\, a/2$ and pressure profiles become flat. It means that plasma is relaxed state in this region. The value of $\mathbf{j}\cdot\mathbf{B}/B^2$ is almost constant in the inner region of plasma column, and it decreases monotonically toward plasma surface in the outer region of plasma column and becomes zero on plasma surface. This profile is similar to the λ profile of MBFM. The current distribution parallel and perpendicular to the magnetic field are shown in Fig.8. Almost current are parallel to the magnetic field and little perpendicular current are seen in the outer region of the plasma column. The positions of several rational surface are calculated as the position of q=n/m (n=1,2,3, m=2,3,) and shown in Fig.9 comparing with the position of maximum plasma pressure, where q is safety factor. The position for q = 3/4 and 2/3 are well coincide with the position of the maximum plasma pressure which is the outer boundary of the oscillation of plasma pressure.

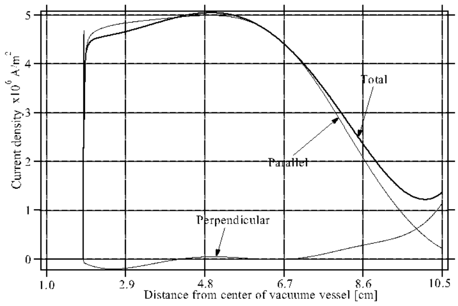

Fig.8 Profiles of total, parallel and perpendicular current densities.

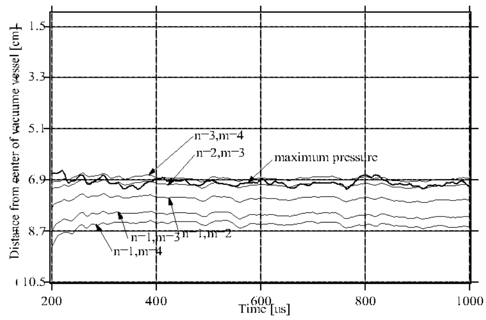

Fig.9 Positions of rational surfaces compared with the position of maximum pressure.

Conclusive Discussions

Plasma pressure is successively calculated from the magnetic field observed by using of the probe array inserted into plasma column. The beta value averaged all over plasma volume is very high (20%~25%), and this is also suggested by the large shift of magnetic axis. One of the reason is high Θ (2.2~2.4) and deep F (~-0.4) operation which produce strong shear of the magnetic field and deep magnetic well around the reversal surface of the toroidal magnetic field. In figure.8, almost current are relaxed force free current and the distribution is like as MBFM. A little perpendicular currents contributing to plasma confinement are droved in the outer region of the plasma column by loop voltage. Large negative gradient of plasma pressure appearing in the outer region of the plasma column are also explained by these operating conditions. The pressure profile is hollow inside the maximum pressure layer and oscillates with the frequency of about 20kHz. The rational surfaces around the layer of maximum pressure are searched because boundary of the oscillation is around there. The surface with q=2/3 correspond with it as the lowest m number as shown in Fig.8 and stability of this mode is under studying.