Comparative studies of CT/ST configurations with varied q-values in TS-4

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1.Introduction

Recent theoretical results suggest that compact RFPs(aspect ratio:A < 3) have higher center-q value and peripheral magnetic shear than the conventional RFPs[1], [2]. Since the most of rational surfaces are removed from the core, the compact RFPs are expected to have better stabilizing mechanism against internal kink and better confinement ability than conventional RFPs. In this study, the compact RFPs with A $= 1.23$ were produced by co-helicity merging and compared with spheromaks and STs in a single device, TS-4.

Figure 1 illustrates the basic merging processes in TS-4, co-helicity and counter-helicity mergings with two spheromaks. Before and after the merging, the following relations exist among the poloidal fluxes Ψ and the toroidal fluxes Φ before suffix(1, 2) and after suffix(3) merging;

$$\text{Poloidal flux } \Psi : \Psi_3 = max.(\Psi_1, \Psi_2) \tag{1}$$

$$\text{Toroidal flux } \Phi : \Phi_3 = \Phi_1 + \Phi_2 \tag{2}$$

The co-helicity merging of two spheromaks with the parallel toroidal field Bt produces another single spheromak, whose toroidal flux Ψ_3 is the sum of Ψ_1 and Ψ_2. On the other hand, the OH current drive increases the poloidal field. Therefore, the combination of the co-helicity merging and the OH current drive can be used as a novel current drive method that can simultaneously increase toroidal and poloidal fluxes without any assistance of the hazardous dynamo effect.

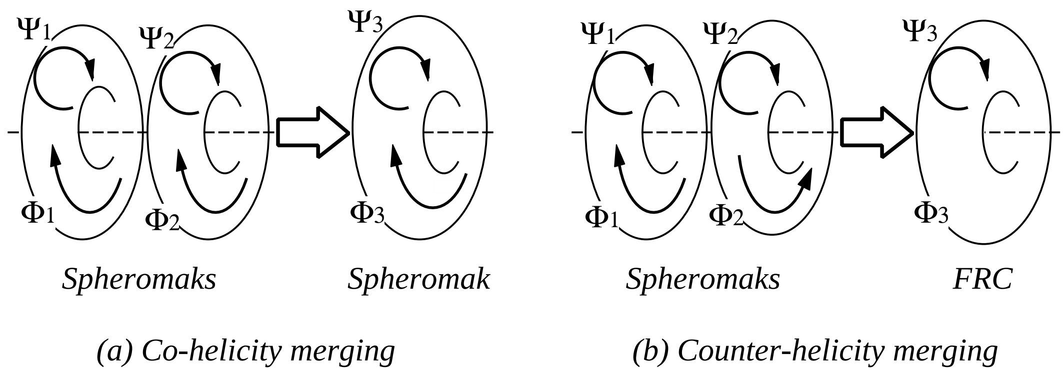


Fig. 1: Axial merging.

As shown in Fig.2, TS-4 has two sets of plasma production parts using an inductive method with flux core and separation coils located in the center portion for controlled merging/reconnection experiments. The TS-4 flux core (R=0.5m) consists of poloidal field coil (PF coil) and toroidal field coil (TF coil) to achieve inductive CT/ST formation without electrode discharge. It can produce various CT/ST configurations, including the spheromak, the ST, the FRC, and the compact RFP, by proper control of the current in the center coil assembly (the external toroidal field coil and the OH coil). At present, magnetic probe array for the reconstruction of the poloidal and toroidal flux contours is the main measurement system in TS-4. Seven parallel glass tubes, each containing 10 pick-up coils for the Bt component and 10 pick-up coils for the Bz component, are installed. And also, eight channel and three component(Bt, Bz, Br) toroidal mode probes are installed at the probe position (r,z) = (294.5mm, 77mm). The each discharge current of all capacitor banks is measured by Rogowsky coil. The TS-4 plasmas have the following parameters; q = 0-30, R = 0.45-0.55m, A = 1.2, elongation = 0.8-3.

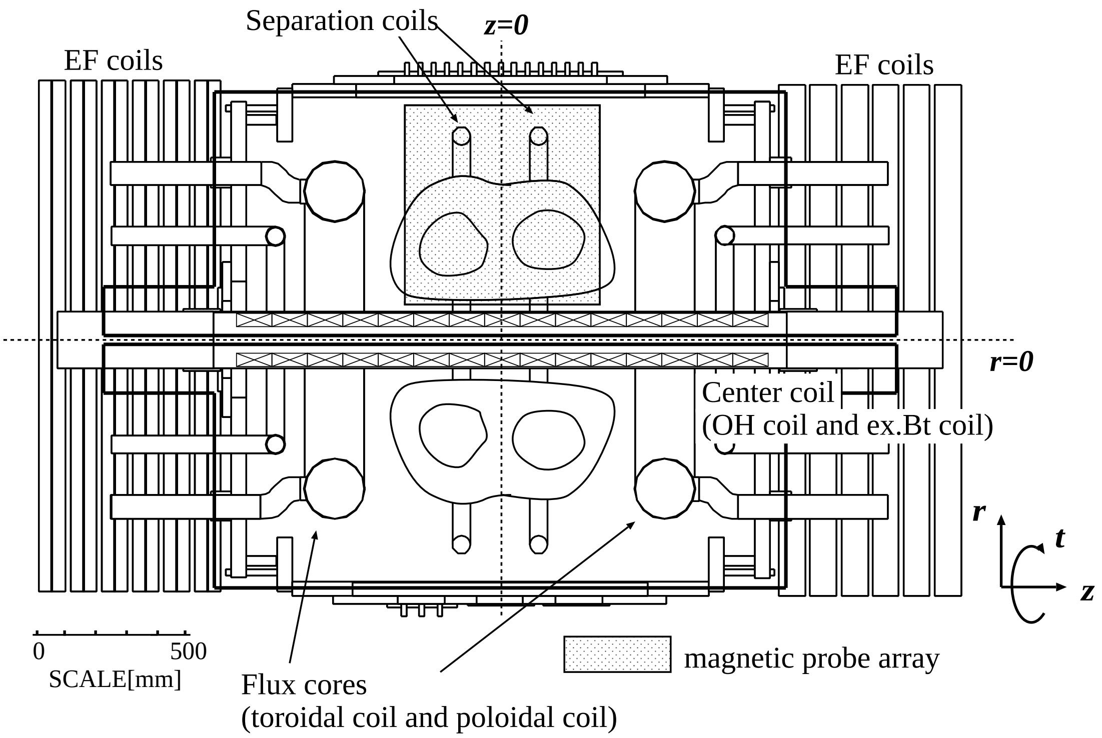


Fig. 2: TS-4 device.

2. Experimental results

Figure 3 shows plasma decay time τ of compact RFPs, spheromaks and STs produced in TS-4. It directly indicates the operation regime of all our experiments. The decay time τ of CT was observed to increase with q-value. The STs had three times larger τ than the RFPs. It is noted that the q-value scan from spheromaks through low-q STs to high-q STs revealed an abrupt drop in τ around external toroidal field current $I_{tfc} \sim 15$[kAT]. This fact indicates that q=1 surface causes the disruption of low-q ST and also that its effect peaks when q=1 surface is located around Ψ_{20}.

Figure 4 shows time evolution of poloidal fluxes Ψ during and after compact RFP merging. The figures show time evolution of (a) Ψ contours and (b) maximum of the poloidal fluxes before the merging: Ψ_1, Ψ_2 and the reconnected poloidal flux: Ψ_3. Two compact RFPs produced by flux-cores approach from right and left, and then merge. The increase in Ψ started around t = 214[μsec], during merging. And it reached to the peak around t = 230[μsec] after the merging was completed at t = 224[μsec]. The increase in Ψ during and after merging is due to the flux conversion from extra toroidal flux to Ψ (equations (1), (2)). However, the decrease in the toroidal flux was not clear; this is probably because the present 2-D probe array does not cover the peripheral area of the

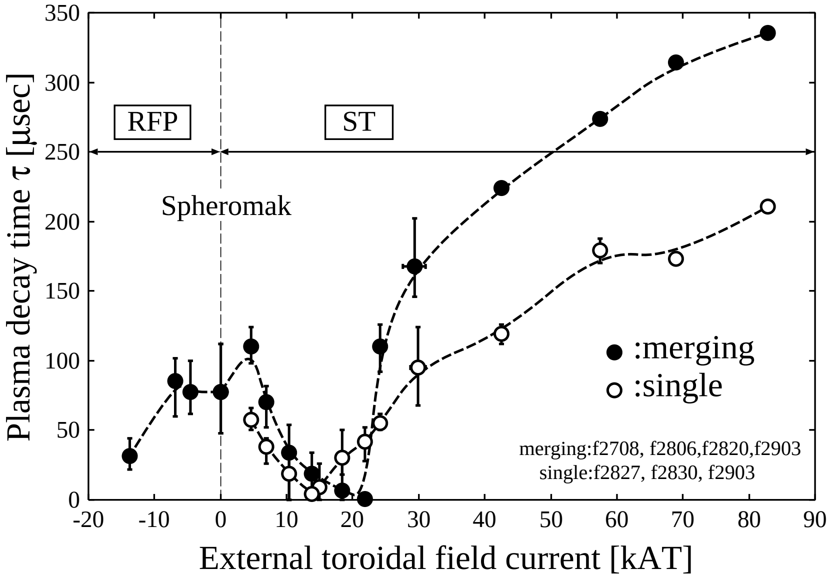
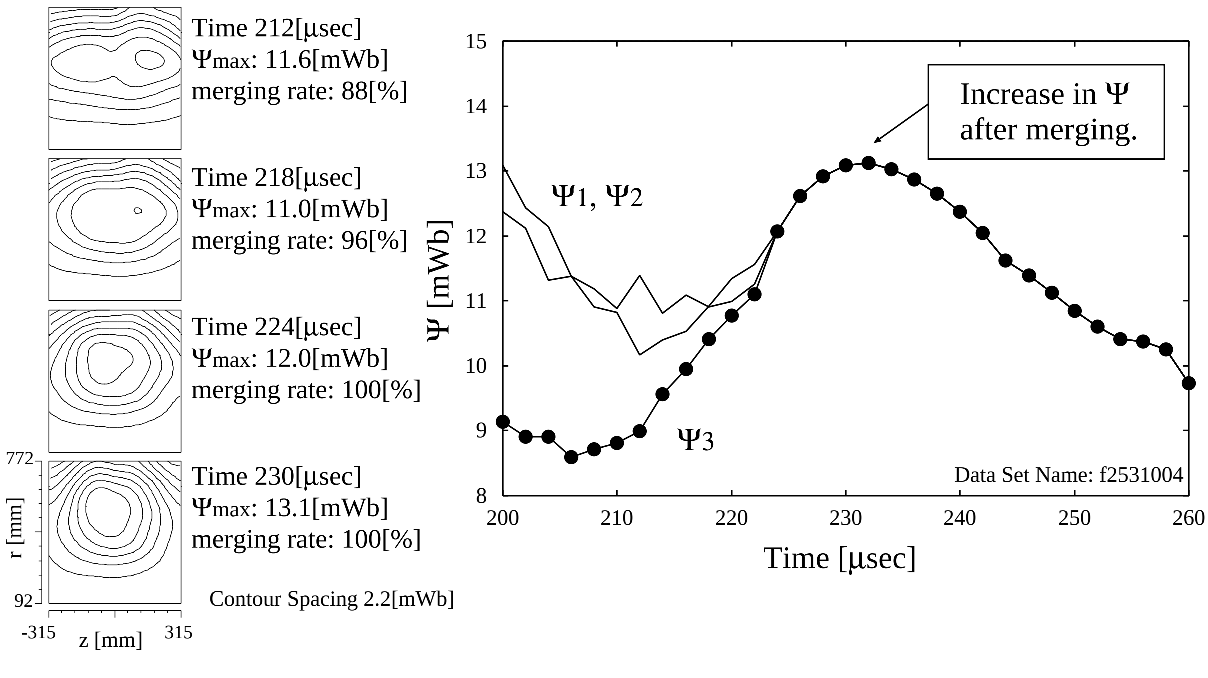
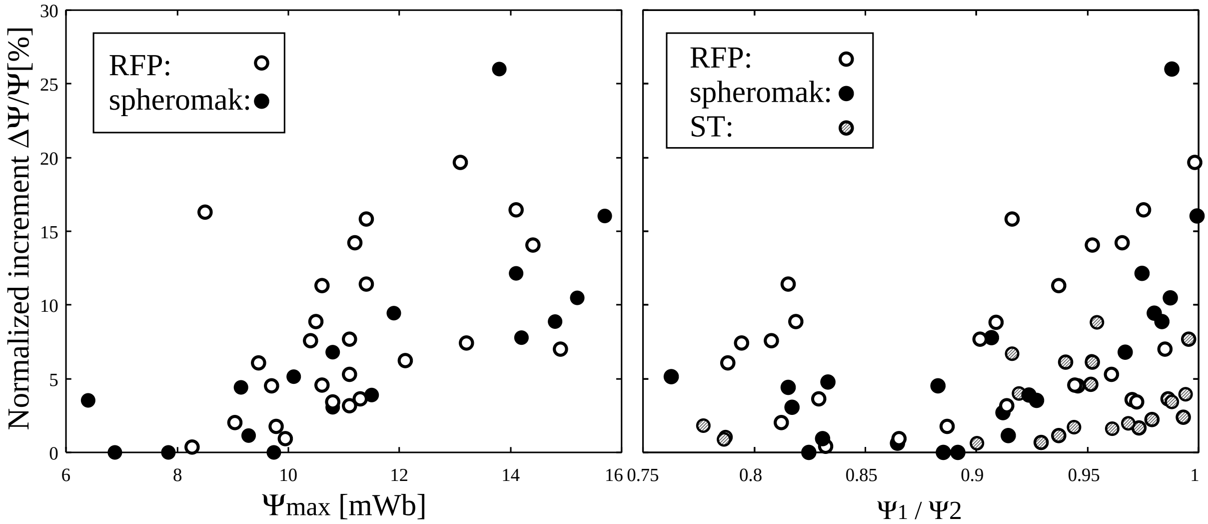


Fig. 3: Dependence of plasma decay time on I_{tfc}.



(a) Poloidal flux contours *(b) Time evolution of Ψ*

Fig. 4: (a) Poloidal flux contours of two merging RFPs and (b) time evolution of poloidal fluxes: Ψ_1 and Ψ_2 of two merging RFPs and Ψ_3 of merged RFP.



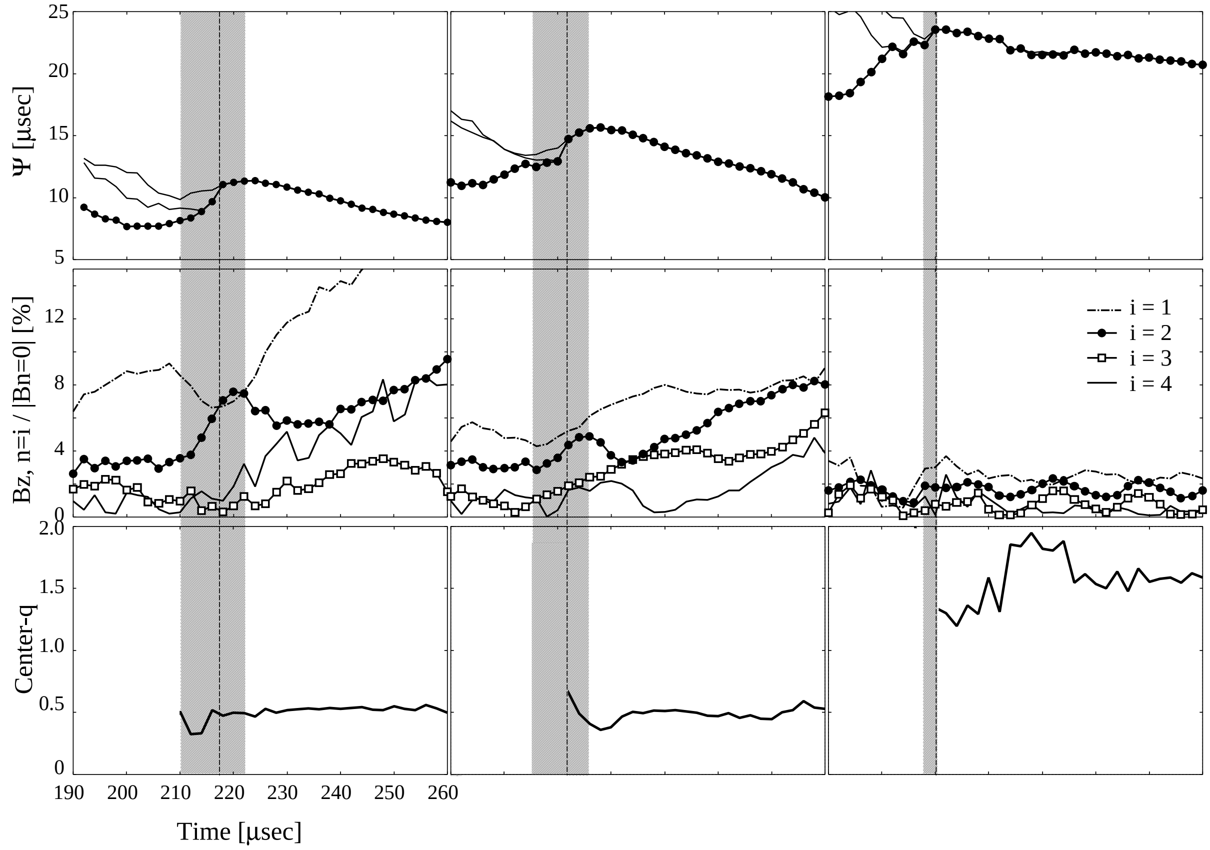
(a) Dependence on Ψmax *(b) Dependence on Ψ1 / Ψ2*

Fig. 5: Dependence of normalized increment on Ψ_{max} and Ψ_1/Ψ_2.

CTs. Figure 5 shows relations of Ψ increase rate with (a) plasma size and (b) plasma size ratio of single plasmas before merging. Ψ increase rate was defined as (the maximum of Ψ after merging: Ψ_{max} - the minimum of Ψ during merging: Ψ_{min})/Ψ_{min}. When Ψ_{max} was large enough and $\Psi_1/\Psi_2 \sim 1$, high Ψ increase rate were observed. And fig.5 (b) suggests that both RFP and spheromak mergings have higher Ψ increase rate (RFP: white circles and spheromak: black circles) than ST merging(gray circles).

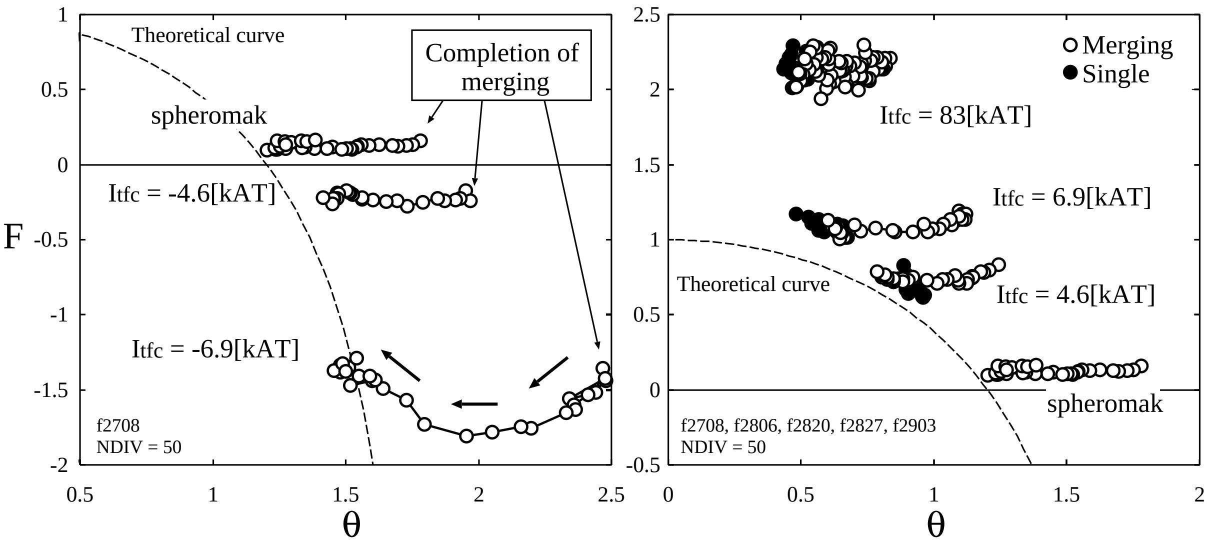
Figure 6 shows time evolution of Ψ, toroidal mode($B_{z,n=i}/|B_{n=0}|, i = 1-4$) and center-q during and after the CT/ST merging. The Ψ increased in the case of the compact RFPs and the spheromaks(fig.6 (a), (b)) and, particularly in the compact RFP case, n=2 mode were observed with the increase in the Ψ. However, the increase in the Ψ and the toroidal mode was not clear in the ST case(fig.6 (c)). And the center-q of STs increased after merging instead of the Ψ. These results indicate that the flux conversion of compact RFPs with n=2 mode of dynamo and STs have a different relaxation process.

Figure 7 shows time evolution of F-θ parameters of (a) compact RFPs, spheromak and (b) spheromak and STs in the F-θ diagrams. The F and θ values were defined as F = (average of toroidal field included in space of 2%Ψ_{max})/(average of toroidal field), θ = (average of poloidal field included in space of 2%Ψ_{max})/(average of toroidal field). The theoretical curves were obtained from a series of Grad-Shafranov solutions for the Taylor minimum energy state. In the all cases, θ was the highest right after merging and decreased to left(circle spacing: 2[μsec]). It was observed that the F-θ parameters of compact RFPs relaxed to a theoretical curve(Taylor state) finally in fig.7 (a). Ψ increases during and after merging occur in the high θ phase. The high θ is expected to have high temperature by merging effect. And next, the hollowly decrease in θ suggests the high beta compact RFPs lose most of thermal energy during the relaxation after the merging. As shown Fig.7 (b), F-θ parameters of low-q STs(I_{tfc}=4.6, 6.9[kAT], white circles) approached to theoretical curve after merging like the case of compact RFPs and at last, reached to black circles. The black circles represent time evolutions of F-θ parameters for single STs. However, F-θ parameter did not relax to theoretical curve in the case of high-q ST with I_{tfc}=83[kAT]. The high-q STs are maintained partially relaxed state, suggesting different



(a) Compact RFP(I_{tfc} =-4.6[kAT]) *(b) Spheromak* *(c) ST(I_{tfc} = 83[kAT])*

Fig. 6: Comparison of CT/ST during co-helicity merging.



(a) RFP (I_{tfc} < 0) *(b) ST (I_{tfc} > 0)*

Fig. 7: F-θ diagram.

relaxation from that of CTs and low-q STs.

Figure 8 shows poloidal current I_{pol}, poloidal lambda λ_p and q value as a function of Ψ just after the compact RFP merging (with white circles, t = 214[μsec]). And also, the curves for t = 230[μsec] (with gray circles) show these profiles around Ψ peak (the high θ state), and for t = 266[μsec] (with black circles) show these profiles with F-θ near the theoretical curve (the low θ state). At first, the compact RFPs had extra toroidal flux around magnetic axis after merging (t = 214[μsec]), causing high q value around magnetic axis. Next, the Ψ profile was changed into a peaked profile and the q value decreased (t = 230[μsec]). And finally λ_p profile relaxed into flat(Taylor state).

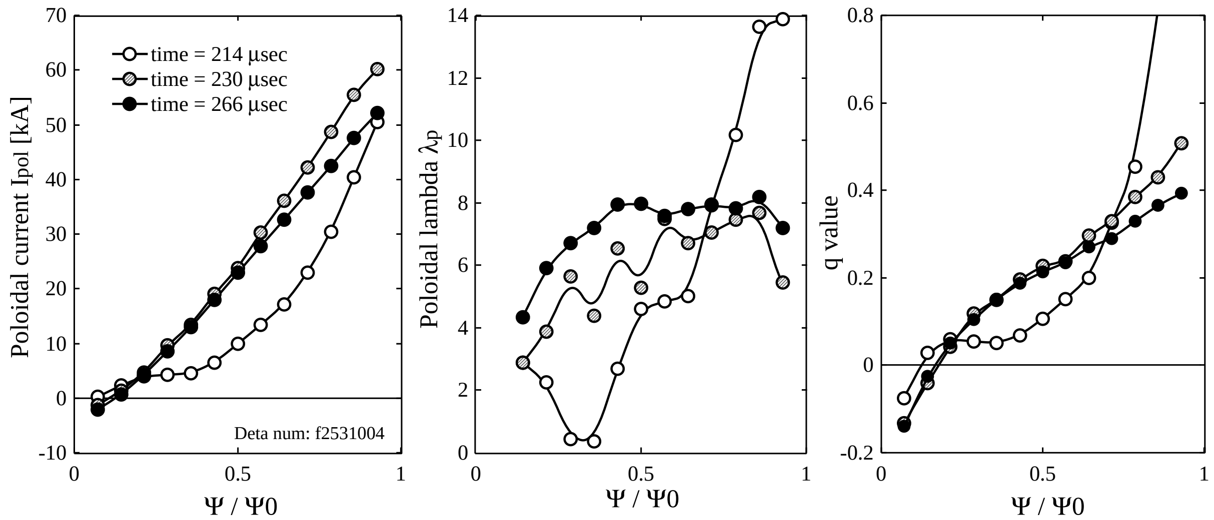


Fig. 8: Profiles of poloidal current I_{pol}, poloidal eigen value λ_p and q-value during relaxation of the compact RFP.

3. Conclusions

In summary, CT/ST, compact RFPs, spheromaks and STs were produced in TS-4. The flux conversion from Φ to Ψ was observed in both compact RFP and spheromak mergings, but it was not clear in ST merging. In the case of compact RFPs and spheromaks, the Ψ began to increase during merging and had the peak after merging. And the n=2 mode increased with the Ψ. These results indicate that the flux conversion of compact RFPs is caused by the n=2 mode and that of STs is weak possibly due to a different relaxation process. The F-θ diagram during and after merging indicated that the RFPs had two states: the high θ state and the low θ state. The high θ state is probably produced by co-helicity merging. And the Ψ increases occurred in this state. The compact RFPs produced by merging relaxed to the low θ state(Taylor state) finally. On the other hand, F-θ diagram of the low-q ST merging moved to the theoretical curve as the case of compact RFPs and at last, closed to that of a single low-q ST. This result maintains that the high θ state is produced by co-helicity merging. And the case of high-q STs, F-θ diagram did not relax to theoretical curve, suggesting that relaxation of high-q STs is considered to be different from that of CTs and low-q STs.

References

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[2] Y. Ueda, Y. Ono, Nucl. Fusion 41, 981 (2001).