

## Power Balance in RFX

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In this paper the power balance of the plasma of the Reversed Field Pinch (RFP) experiment RFX ( $R=2m$ ,  $a=0.457m$ ) [1, 2], at toroidal current  $I_{\phi} \sim 500kA$  and in the range of density  $2 \cdot 10^{19} < n_e < 5 \cdot 10^{19} m^{-3}$ , is analysed comparing the input power with the losses, including the effect of magnetic field line distortions due to plasma perturbations.

### MEASUREMENTS AND EXPERIMENTAL CONDITIONS

The profiles of the plasma quantities are measured by different diagnostics: the electron density profile is reconstructed by a eight chord interferometer, combined with the data of Langmuir probes at the edge, showing a flat profile with a steep gradient at the edge [3]. The radiated power is measured by a eight chord bolometer and combining with the spectroscopic measurements of impurity influx [4] the total power lost by radiation and the profile of effective charge  $Z_{eff}$  are obtained. The inner wall is monitored by 4 CCD cameras viewing through 4 equatorial ports [4]. The charge exchange losses are measured by a system of two Neutral Particle Analysers [5]. Langmuir and calorimeter probes are used to measure the energy and particle fluxes at the edge [6]. The magnetic field profiles inside the plasma are reconstructed from the externally measured magnetic quantities applying an analytical model for the  $\mu$  profile  $\mu = \mu(0)[1 - (r/a)^{\alpha}]$  where  $\mu = \mu_0 J \cdot B/B^2$ . The electron and ion temperature are measured respectively by a triple SiLi detector and by NPA diagnostics and by Doppler broadening of C and O lines [2].  $T_i$  and  $T_e$  are comparable and can be approximated [4] by the analytical expression  $T(r) = [T(0) - T(a)][1 - (r/a)^{\alpha}] + T(a)$  with  $\alpha=3$  at  $I_{\phi} = 500kA$  and the edge temperature  $T_e(a) \sim 20eV$  being measured by Langmuir probes. Fig.1 shows the waveforms of toroidal current, applied loop voltage  $V_{\phi}$ , average toroidal magnetic field and toroidal field at the wall for a 520kA discharge well centered and with reduced errors at the gaps. In the same figure the electron density  $n_e$ , the temperature  $T_e$ , the energy confinement time  $\tau_E$  and the poloidal beta  $\beta_{\theta}$  are also reported. It is seen that  $\beta_{\theta} \sim 8\%$  and  $\tau_E \sim 1ms$ , whereas for such discharge  $Z_{eff}$  is estimated to be 2.

### POWER INPUT

From the external electromagnetic measurements the Poynting vector has been calculated. Separating the magnetic energy stored in the plasma, the dissipated power is then obtained as

$$\int \bar{E} \cdot \bar{J} dv = I_{\phi} V_{\phi} - I_{\theta} V_{\theta} - \frac{dW_m}{dt}$$

where  $W_m$  is the magnetic energy and  $V_{\phi} I_{\phi} - V_{\theta} I_{\theta}$  is the input power  $P_{in}$  ( $V_{\theta}$  is the poloidal voltage at the plasma surface and  $I_{\theta}$  is the toroidal winding current). In fig.1 the waveforms of  $P_{in}$  and dissipated power  $P_{diss}$  are presented, showing that  $P_{diss} \sim 20MW$  at  $I_{\phi} = 500kA$ , corresponding to an applied loop voltage  $V_{\phi} \sim 40V$ . This value of  $V_{\phi}$  has been related to the global sustainment of the configuration, the

so-called dynamo. This process is expected to result in some enhancement of the loop voltage because of the transfer of magnetic energy from the poloidal to the toroidal magnetic field component [2]. The loop voltage required to sustain the configuration is then given by the helicity balance according to which the loop voltage is  $V_k = \phi^{-1} \int \bar{E} \cdot \bar{B} dv$  [7] where  $\phi$  is the toroidal flux and  $E = \eta_{SP} J$  with the Spitzer resistivity  $\eta_{SP}$  obtained from the profiles of electron temperature and  $Z_{eff}$ . Equating  $V_k$  to the experimental  $V_\phi$  an equivalent on axis resistivity  $\eta_k(0)$  can be computed so that a  $Z^k$  can be defined as  $Z^k = \eta_k(0) / \eta_{SP} Z = 1(0)$ , where  $\eta_{SP} Z = 1(0)$  is the on axis Spitzer resistivity with  $Z_{eff} = 1$ . In this case  $Z^k = 3$ , which is higher than  $Z_{eff} = 2$  from impurities, showing that a residual anomaly up to 30% of  $V_\phi$  could be related to other causes.

#### POWER LOSSES

In stationary conditions the input power must equal the power lost by radiation, charge exchange and transport. In RFX, Carbon and Oxygen are the dominant impurities accounting for most of the radiated power [4]. The power lost by radiation is almost constant in time and the total  $P_{rad}$  during the current sustainment is  $15\% \pm 5\%$  of  $P_{diss}$ , depending on the radiation profile at the edge [4]. In fig. 1 the waveform of  $P_{rad}$  is presented, showing no increase in time and thus confirming that the impurity content does not change during the discharge. For the same discharge the power lost by charge exchange  $P_{CX}$  has been estimated to be 5% of  $P_{diss}$ . The power lost by transport  $P_{transp}$  can be estimated locally by the edge probes, measuring the parallel energy flux  $q_{||}$  incident on an insertable limiter and its decay length in the shadow of the limiter itself, and then deriving the perpendicular energy flux  $q_{\perp}$  according to  $q_{||} / \lambda_q = q_{\perp} / L$  where  $L$  is the collection length of the limiter. In fig. 2,  $q_{||}$  measured by insertable probes in discharges with  $I_\phi \sim 520$  kA and  $n_e \sim 4 \cdot 10^{19} m^{-3}$  is shown. The values measured on the electron drift side are about 3 times larger than on the ion drift side. The energy flux decay length  $\lambda_q$  on the shadow of the limiters is  $\lambda_q = 2 \pm 0.2$  mm on both sides. When the probes, mounted on a limiter, are inserted into the plasma, the collection length of the limiter  $L$  can be taken  $L = \pi a \sim 1.5$  m, since the magnetic field is mainly poloidal at the edge of a RFP. Thus from the average value  $q_{||} \sim 200 \pm 20$  MW/m<sup>2</sup> the perpendicular flux is derived to be  $q_{\perp} \sim 0.28 \pm 0.06$  MW/m<sup>2</sup> corresponding to  $P_{transp} \sim 50\% \pm 10\%$  of  $P_{diss}$ . This estimate can be affected by the fact that the data refer to one poloidal location. However the energy flux expected from particle global balance is consistent with this estimate. The energy flux at the edge exhibits an asymmetry 3 between the electron and the ion drift side, so that it has been estimated that about 50% of  $P_{transp}$  is lost by suprathermal electrons [2]. Equating all the losses to  $P_{diss}$ , a residual 30% of  $P_{diss}$  is left to other losses.

It is observed that all the discharges are affected by locked modes [9] which are located preferably at the two vertical gaps. According to the magnetic measurements [9] the surface of the first wall invested can be estimated to be  $\leq 1/40$  of the total surface  $S_{tot}$  in agreement with the simultaneous observation made by the CCD cameras [4]. The effect of these modes, and in general of any misalignment of the magnetic field lines, is an enhancement of the power losses. A simple estimate of the power lost to the wall can be obtained for a locked mode as  $P_{lock} = S q_{||} / b/B$  where  $S$  is the surface intercepted by the field lines,  $b/B$  is the radial magnetic perturbation amplitude  $b$  normalized to the average field  $B$ , and  $q_{||}$  is the energy flux parallel to the magnetic field lines. Using the maximum amplitude  $b/B \sim 2\%$  [9] of the perturbation when the modes are locked far from the gaps and taking an average  $q_{||} \sim 200$  MW/m<sup>2</sup> as measured by edge probes when invested by locked mode [10], the fraction of power intercepted by the wall results  $P_{lock} \sim 2$  MW/m<sup>2</sup>, i.e.  $P_{lock} / P_{diss} \sim 10\%$  which could account for part of the missing fraction of power in the balance. It is worth noting that the temperature on the surface  $S$  rises by  $\Delta T_w$ , which is proportional to  $q_{||} / \sqrt{\Delta t}$  where  $\Delta t$  is the duration of the RFP phase of the discharge. With the parameter of the graphite tiles of RFX this increase is found to be  $\sim 600^\circ C$ , i.e. below the threshold for enhanced processes of impurity release. The temperature measured by CCD cameras confirms this estimate [4].

The maximum  $\Delta T_w$ , the reduced area invested by the locking and the efficient screening of the edge [8] are consistent with the fact that no increase of the impurity content is observed during the discharge, so that the assumption of stationary conditions is proved also for the impurity content and then  $Z_{eff}$ .

#### DENSITY DEPENDENCE OF LOSS PROCESSES

The loss processes have been investigated varying the density. Fig.3 shows the average values of  $P_{diss}$ ,  $P_{CX}$  and  $P_{rad}$  as a function of the density for fixed current  $I_0=520kA \pm 40kA$ . Increasing the density, the  $P_{diss}$  and  $P_{rad}$  increase whereas  $P_{CX}$  slightly decreases. In fig. 4 is shown  $\beta_0$ , taken as twice the electron value, whose optimum value ( $\beta_0 \approx 8\%$ ) is obtained at higher density. Fig. 4 shows also the power left to transport and other losses including the power lost by locked modes obtained subtracting  $P_{CX}$  and  $P_{rad}$  from  $P_{diss}$ . It is about 85% of the total dissipated power at low density, decreasing to 75% at high  $n_e$ . Comparing  $V^k$  with  $V_\phi$ ,  $Z^k$  is found to be 3 almost independent from  $n_e$ . This behaviour seems to suggest that the contribution to the power balance from locking and field errors at the gaps and misalignment of field lines at the edge in general is independent from  $n_e$  and can account for up to 30% of  $P_{diss}$ .

#### SUMMARY AND CONCLUSIONS

The analysis of the power balance of RFX discharges shows that:

- The radiated power is about 15% of the dissipated power at low density rising up to 25% at high density regimes, constant during the sustainment phase.
- The power lost by charge exchange is 3-5%, slightly decreasing with the density.
- The power lost by transport is  $\sim 50\%$  of  $P_{diss}$ ; the fraction of this power lost by suprathermal electrons is about 50%, decreasing with the density.
- About 10%, depending on the amplitude of the perturbation, is lost directly to the wall by effect of a magnetic disturbance produced by locked modes far from the gaps.

These features must be interpreted noting that the largest energy confinement time and the highest beta are obtained at high density, whereas the higher temperature and the lower loop voltage are obtained at lower density. In conclusion the present confinement is reduced by the occurrence of disturbances related to locked modes, field errors and in general misalignment of the magnetic field lines, which can result in losses up to 30% of the dissipated power. This estimate is fairly in agreement with the maximum anomaly of the loop voltage which according to present results is up to 30%, this estimate being dependent on the temperature profile. Improving the magnetic field configuration at the edge could then result in a comparable enhancement of the confinement parameters.

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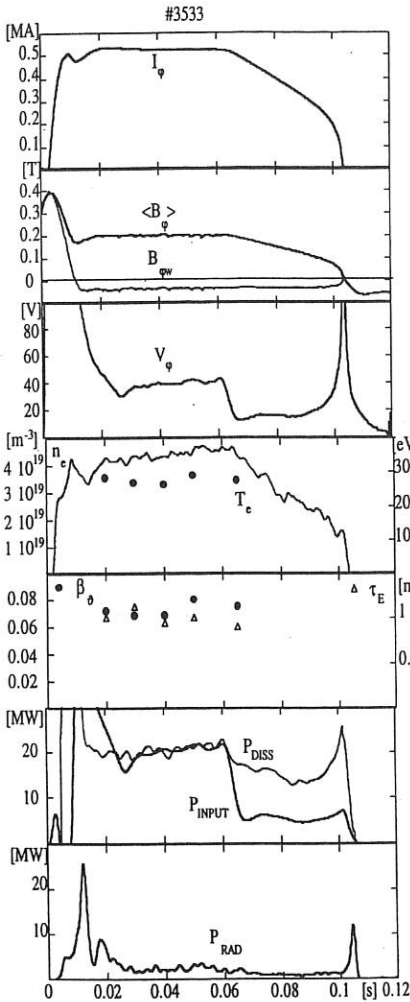


Fig.1

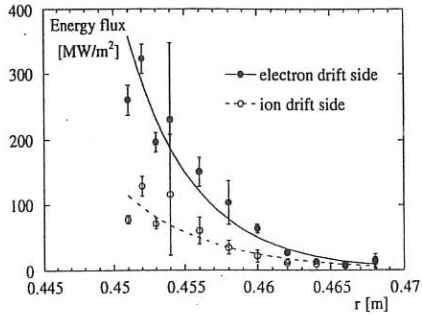


Fig.2

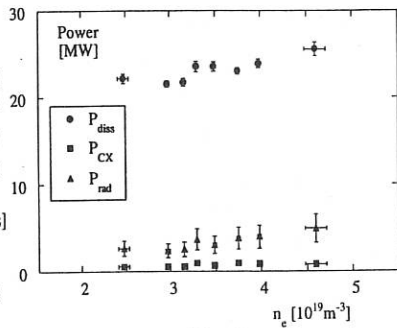


Fig.3

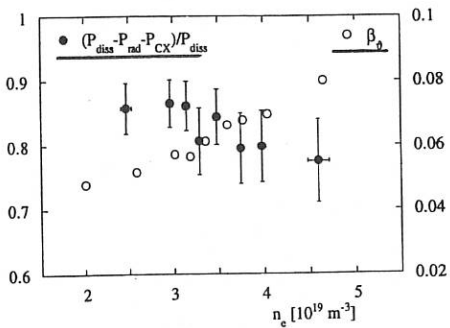


Fig.4