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_ϕ~500kA and in the range of density $2\cdot10^{19}<n_e<5\cdot10^{19}$ 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 μ profile $\mu=\mu(0)[1-(r/a)^\alpha]$ where $\mu=\mu_0\mathbf{J}\cdot\mathbf{B}/B^2$. 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 $T(r)=[T(0)-T(a)]\cdot[1-(r/a)^\alpha]+T(a)$ with $\alpha=3$ at $I_\phi=500$kA and the edge temperature $T_e(a)$~20eV being measured by Langmuir probes. Fig.1 shows the waveforms of toroidal current, applied loop voltage V_ϕ, 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 τ_E and the poloidal beta β_θ are also reported. It is seen that β_θ ~8% and τ_E~1ms, whereas for such discharge Z_{eff} is estimated to be 2.

POWER INPUT

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

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

where W_m is the magnetic energy and $V_\phi I_\phi - V_\theta I_\theta$ is the input power P_{in} (V_θ is the poloidal voltage at the plasma surface and I_θ is the toroidal winding current). In fig.1 the waveforms of P_{in} and dissipated power P_{diss} are presented, showing that P_{diss}~20MW at I_ϕ~500kA, corresponding to an applied loop voltage V_ϕ~40V. This value of V_ϕ 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 $V_k = \phi^{-1}\int \overline{E}\cdot\overline{B}d\mathbf{v}$ [7] where ϕ is the toroidal flux and $E=\eta_{Sp}J$ with the Spitzer resistivity η_{Sp} obtained from the profiles of electron temperature and Z_{eff}. Equating V_k to the experimental V_ϕ an equivalent on axis resistivity $\eta_k(0)$ can be computed so that a Z^k can be defined as $Z^k=\eta_k(0)/\eta_{SpZ=1}(0)$, where $\eta_{SpZ=1}(0)$ 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_ϕ 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%±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_ϕ~520kA and n_e~$4\cdot10^{19}m^{-3}$ 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 λ_q on the shadow of the limiters is λ_q=2±0.2mm 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 $L=\pi a$~1.5m, since the magnetic field is mainly poloidal at the edge of a RFP. Thus from the average value $q_{//}$~200±20MW/m^2 the perpendicular flux is derived to be $q_\perp$~0.28±0.06MW/m^2 corresponding to P_{transp}~50%±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 ≤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 misalignement 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 $P_{lock}=Sq_{//}\,b/B$ 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~2% [9] of the perturbation when the modes are locked far from the gaps and taking an average $q_{//}$~200MW/m^2 as measured by edge probes when invested by locked mode [10], the fraction of power intercepted by the wall results P_{lock}~2MW/m^2, i.e. P_{lock}/P_{diss}~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 ΔT_W, which is proportional to $q_{//}\sqrt{\Delta t}$ where Δt 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 ~600°C, i.e. below the threshold for enhanced processes of impurity release. The temperature measured by CCD cameras confirms this estimate [4].

The maximum ΔT_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_ϕ=520kA±40kA Increasing the density, the P_{diss} and P_{rad} increase whereas P_{cx} slightly decreases. In fig. 4 is shown β_θ, taken as twice the electron value,whose optimum value (β_θ~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_ϕ, 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 ~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 misalignement 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.

REFERENCES

[1] G. Malesani and G. Rostagni, *Proc. of 14th Symp. on Fusion Technology* , Avignon, 1986, Vol. I, p. 173.

[2] V. Antoni et al., Plasma Phys. and Controlled Fusion **35**, B333 (1993).

[3] P. Innocente et al.*Behaviour of profiles in RFX*, this conference.

[4] M. Valisa et al., *Radiation studies on RFX* , this conference.

[5] S. Costa et al., *The Cx Neutral Particle Analysis of the RFX Plasma* , Proc. of the 20th EPS Conf. on Controlled Fusion and Plasma Physics, Lisboa, 1993, Vol. III, p. 1215.

[6] V. Antoni et al,,*Characterisation of the RFX edge plasma* , Proc. of the 20th EPS Conf. on Controlled Fusion and Plasma Physics, Lisboa, 1993, Vol. II, p. 695.

[7] K. F. Schoenberg, R. W. Moses and R. L. Hagenson, Phys. Fluids **27**, 1671 (1984).

[8] V. Antoni et al., *Plasma wall interaction and energy fluxes in RFX*, to be published in *Journal of Nuclear Materials.*

[9] A Buffa et al., *Magnetic field configuration and locked modes in RFX* , this conference.

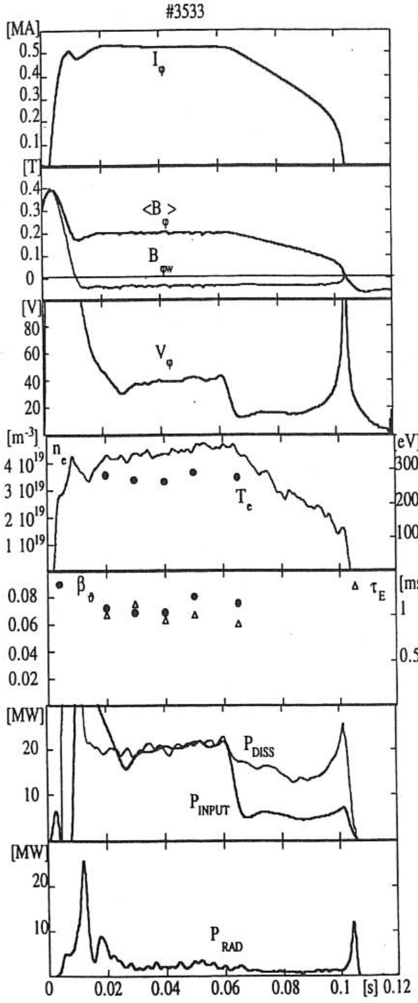

Fig.1

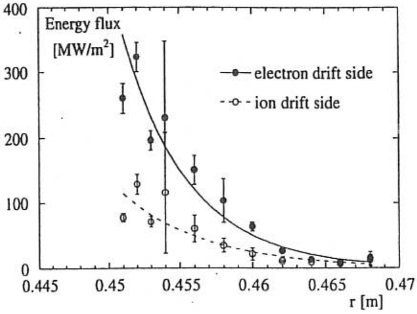

Fig.2

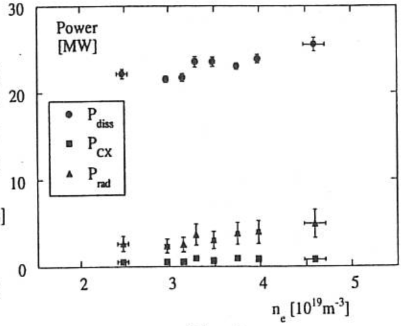

Fig.3

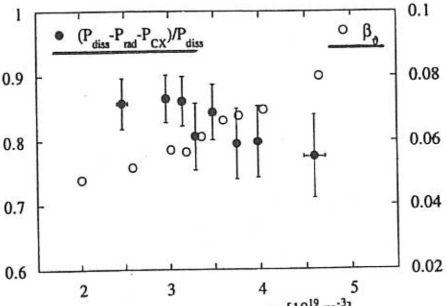

Fig.4