

TOWARDS A GLOBAL POWER BALANCE IN TORE SUPRA

R. Reichle, J.C. Vallet, M. Chantant, V. Basiuk, A. Grosman and D. Guilhem

CEA-Cadarache, Assoc. EURATOM-CEA, 13108 St. Paul-lès-Durance, France

A global power balance is a necessary consistency test in tokamaks. The general problem is incomplete spatial coverage of the local power loss measurements. Tore Supra has a large range of such measurements, but it has also some specific problems due to its toroidally inhomogeneous in vessel structure and its high magnetic field ripple. The discharges selected are highly radiative ergodic divertor¹ discharges with ion cyclotron resonance heating (ICRH) since these are important for ITER and for the evaluation of the ergodic divertor. A recent investigation regarding the radiation efficiency of this divertor [3] suffered from uncertainties regarding the total radiation and the 'ripple losses', which is the power lost directly due to particles trapped in the magnetic field ripple. Progress based on new analysis methods and measurements is presented here.

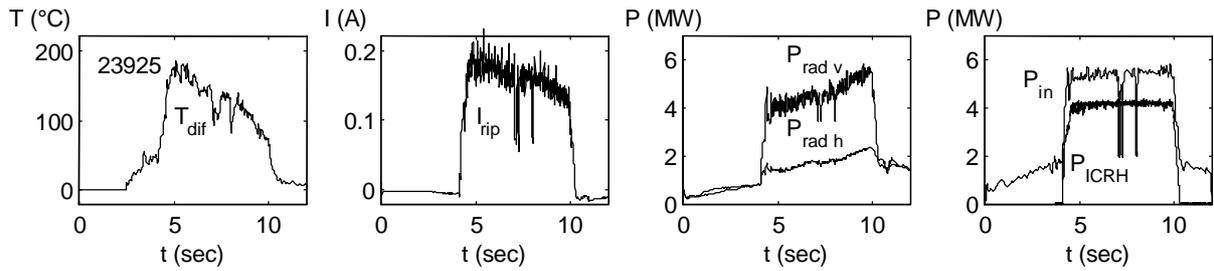


Fig. 1: Raw measurements: T_{dif} , I_{rip} , P_{radh} , P_{radv} , and for comparison P_{ICRH} and P_{in} .

Fig. 1 shows a typical set of primary measurements used to determine the three power loss channels considered here together with the additional heating power P_{ICRH} . The relative evolution of the conducted power P_{dep} , is determined by an infrared temperature measurement² on the front end of one neutraliser of the ergodic divertor. The deposition profile has its maximum there and in principle the deposited power is proportional to the temperature rise T_{dif} unless the divertor current is changed [5], which was not the case here. Slight deposition profile changes during the discharge along the length of the neutraliser do not compromise the validity of the measurement at the hot front end. The relative evolution of the ripple losses P_{rip} is measured with a segmented collector probe in one upper port. The measured value is the accumulated charge extracted in the form of a current I_{rip} of the ionic ripple loss particles [6]. There is presently no energy or power information. The total radiated power is estimated with three bolometer arrays [7], each assuming toroidally uniform radiation. Initially the two vertical bolometer arrays were both installed in upper ports. Both

¹ For details on the ergodic divertor experiments in general see [1,2].

² For some details on the IR measurement techniques see [4].

measured about the same value P_{radv} (Fig. 1) which was during ICRH significantly higher than the horizontal value P_{radh} . Recently one vertical array has been displaced to the lower vertical port opposite to the other vertical bolometer. The new vertical measurement seems to be now in good agreement with the horizontal measurement. A few thermally isolated pyrolytic graphite platelets are embedded in the protection structure of one of the divertor coils to measure the local radiation distribution in front of the divertor coils. They are recessed to receive only radiation and neutrals but no ionic fluxes. The low conductivity direction of the graphite is perpendicular to the surface receiving the heat flux. The temperature rise of these 'passive bolometers' is measured by the infrared cameras. Tore Supra has a calorimetry system which measures the energy deposited on the actively cooled elements covering most of the vessel directly seen by the plasma. Only about 60% of the injected energy is recovered [8]. For this investigation it is significant to note, firstly that the energy deposited onto the divertor and its structures is measured separately and secondly that the ripple loss protection tiles are not actively cooled.

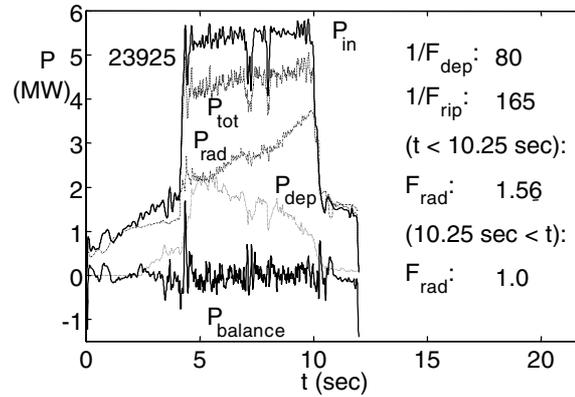


Fig. 2: Typical result of power balance analysis using Equation (1).

For the analysis a few working hypothesis are made. Firstly, the upper vertical bolometer is strongly affected by ripple loss particles which undergo in front of the detectors charge exchange collisions and are scattered directly with high energy into the detectors. Therefore the upper vertical bolometer measurements are either ignored (Eq. (1)) or compensated using the ripple loss measurement (Eq. (2)). Secondly, due to the discrete structure of the divertor coils it is expected [9], that in discharges where the plasma is attached, these bolometers under-estimate the global radiation since they are toroidally halfway between two of the 6 divertor coils. Completely detached, the radiation distribution may be toroidally uniform.

$$P_{in} = F_{rad} \cdot P_{radh} + F_{dep} \cdot T_{dif} + F_{rip} \cdot I_{rip} + dW/dt \quad (1)$$

$$P_{in} = F_{rad} \cdot (0.33 \cdot P_{radh} + 0.67 \cdot (P_{radv} - I_{rip}/C)) + F_{dep} \cdot T_{dif} + F_{rip} \cdot I_{rip} + dW/dt \quad (2)$$

P_{in} is the input power, W is diamagnetic energy. The coefficients F_{rad} , F_{dep} , F_{rip} are deduced by least square fits to these equations either simultaneously (Eq. 2) or by assuming a fixed value

for F_{dep} (Eq. (1)). Typical results from using Eq. (1) are shown in Fig. 2. In this case the plasma detaches at 10.25 sec. At this point F_{rad} is set to 1.0. The trace P_{balance} is the difference between the right and the left term of Eq. (1). A relatively high F_{rad} is found while the plasma is attached implying at least 2 times more radiation in front of the divertor coils than at the bolometer position. Since the ripple losses are immediate and do not contribute to the plasma heating the total power is defined as $P_{\text{tot}}=P_{\text{in}}-P_{\text{rip}}$. Fig. 3 illustrates the correction of P_{radv} .

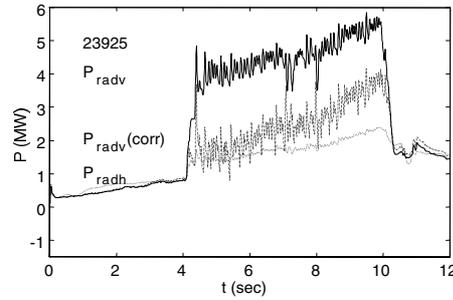


Fig. 3: Correction of upper vertical bolometer signal.

In the case chosen (Fig. 3), the depth of 3 dips in the ripple signal (see Fig. 1) is used to determine the ripple effect on the vertical bolometers. One finds that the horizontal and the vertical estimates coincide at the beginning of the additional heating phase. This is used as criterion to determine C for other discharges. Eq. (2) yields about the same absolute powers as Eq. (1) (see Table 1) but requires less enhancement in front of the divertor coils since the corrected vertical values contribute in the same sense. Extending the fit beyond detachment until 11.5 sec results in drastic changes of the values and a larger deviation of P_{balance} from zero.

Table 1: Results of power balance analysis

Discharge	23925	23925	23925	23925	23925	23918...23961
Equation	1	1	1	2	2	2
Fit interval (sec)	3.5...10.25	3.5...10.25	3.5...10.25	3.5...9.5	3.5...11.5	during attachment
$1/F_{\text{dep}}$	80(fix)	90(fix)	100(fix)	71.7	83.7	82.9
F_{rad}	1.56	1.56	1.56	1.13	0.89	1.16
$1/F_{\text{rip}}$	165	140	125	145	86	105
C	-	-	-	78	78	73.4
P_{balance} (average) (MW)	0.26	0.26	0.26	0.26	0.28	0.30
P_{tot} (max) (MW)	4.7	4.6	4.4	4.6	4.0	
P_{rad} (max) (MW)	3.8	3.8	3.8	3.8	3.0	
P_{dep} (max) (MW)	2.1	1.9	1.75	2.2	2.1	
P_{rip} (average)(MW)	0.9	1.05	1.2	1.0	1.9	
$f_{\text{Prip/PICRH}}$ (%)	21	25	28	23	45	
$f_{\text{Prad/Ptot}}$ (max) (%)	81	83	87	83	75	

From the calorimetry one can also deduce F_{dep} . With the assumption of a toroidally uniform radiation distribution one finds for the discharges here a value of 100. Local radiation enhancement in front of the limiters, which is according to the fit results more likely, will reduce this value such that the fit result of about 80 together with a local enhancement in front of the divertor coils of about a factor 2 seem the most likely. The passive bolometers seem to indicate that such an enhancement may be present since in detached discharges, the temperature rise of the passive bolometers in the middle of a divertor module is smaller than in attached discharges with the same radiation. A detailed heat flux analysis of the influence of the environment is necessary to arrive at a definitive statement here.

Support for the hypothesis that charge exchange particles stemming from ripple loss ions enhance the upper vertical bolometer signal is found when calculating (cross section data [10]). the mean energy of these neutrals (350 keV) and the neutral density required in the port to produce the reaction rate necessary (10^{18}m^{-3}) by using the enhancement of the bolometer and the total ripple loss (1 MW). The ripple loss and the particle energy are somewhat higher than earlier measurements [6], but plausible, since here the losses had not been carefully minimised and part of the ions missed the detector. Further confirmation can be derived from the observation that the bolometers indicate a pronounced maximum of these losses on the outboard side of the port, and also from a characteristic difference of He and D₂ discharges.

In summary it can be stated that both working hypotheses are most likely correct. The deficit of the calorimetry could stem largely from the ripple losses deposited on inertially cooled protection plates. Regarding the absolute value of the local radiation enhancement in front of the divertor coils more detailed measurements and analysis are necessary.

References

- [1] Ghendrih Ph., Grosman A., Capes H.: Plasma Phys. Control. Fusion **38** (1996) 1653-1724
- [2] Equipe Tore Supra (*presented by Ph. Ghendrih*): Plasma Phys. Control. Fusion **39** (1997) B207-B222
- [3] Monier-Garbet P., et al.: *Contrib. 13th Int. Conf. Plasma Surf. Int.* San Diego USA-CA 18 -23 May, 1998
- [4] Guilhem D., et al.: *Contrib. 13th Int. Conf. Plasma Surf. Int.* San Diego USA-CA 18 -23 May, 1998
- [5] Grosman A., Ghendrih Ph., Meslin B., Guilhem D.: JNM 241-243(1997) 532-537
- [6] Basiuk, et al.: Nucl. Fus. **35** (12), (1995) 1593-1596
- [7] Vallet J.C., et al.: *Contr. 24th EPS*, 9-13 June 1997, Berchtesgaden, Germany
- [8] Surle F., Mayaux G., Cordier J.J.: *Contr.19th SOFT*, 1996, Lisbon, Spain
- [9] Bush C.E.: Rev. Sci. Instr. **57** (8), (1986), 2078-2080
- [10] Barnett C.F.: Atomic Data for Fusion, Vol. **1**, ORNL-6086/V1 1990