

BOLOMETRY AND RADIATED POWER ON TORE SUPRA

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Introduction : On Tore Supra, as on many other tokamaks, extensive studies are made to try to exploit the very attractive potential of edge radiation to spread out the output power and to avoid excessive heat load on plasma facing components. In such experiments, including Ergodic Divertor (ED) or limiter experiments, intrinsic or extrinsic impurities, it is important both to assess the radiating efficiency of each scenario and to be able to perform in each case a proper power balance, to carry out an accurate and reliable radiated power estimate. Under some special circumstances it can be difficult, to establish this key parameter, Prad, by the only means of bolometers. In these cases an analysis based on the coherency of various measurements, as infrared thermography, which allows an indirect derivation of the total conducted power Pcond, or calorimetric data which provide a global thermal energy balance can be very helpful to validate the total radiated power estimate with respect to the other terms of the global power balance: $P_{in} = P_{rad} + P_{cond} + P_{loss} - dW/dt$. The preliminary results of these studies are: i) evidences of the presence of an artefact on some bolometer signals during ICRH in H minority scheme (HMIN), usually used in highly radiating experiments, ii) the existence of a toroidal peaking factor of the plasma emissivity with ED, which reveals the influence of the three dimensional structure of the plasma edge on the radiation pattern, iii) the non negligible impact, on the global power balance, of Ploss the power lost by fast ions trapped in the toroidal magnetic field ripple, the so called ion ripple losses and iv) a better estimate of the sensitivity of the calorimetric diagnostic which allows one to analyse even ohmic discharges. More than the absolute results themselves, some of which are still affected by large error bars, it is the method employed to validate the total radiated power estimate which will be reported in this paper.

Bolometer and ripple losses : In order to improve the confidence of the Prad estimate and to address the problem of the toroidal symmetry assumption, which usually underlies this estimate, TORE SUPRA has been equipped with three bolometer systems providing three full plasma profiles, at different toroidal and poloidal locations, from which one can derive three independent Prad estimates. It has been already reported [1] that, usually, the three estimates are close enough to point out the existence of a symmetry of measurements from ports to ports, except in the noticeable case of ICRH-HMIN scheme and mainly in Deuterium plasmas compared to Helium experiments. The main difference of this particular heating scheme, compared with others, is the existence of a fast ions tail. Recently, it has been shown that the difference between the larger estimate provided by the vertical top port bolometer system and the much lower estimate provided by the horizontal one, has to be attributed to an artefact which enhances the vertical top bolometer signals rather than to a low toroidal number asymmetry [4].

It has been demonstrated by installing a bolometer system on a bottom port (at the same toroidal location as a top one) that the artefact originates from the vertical drift of fast ions (upwards in TORE SUPRA) trapped in the toroidal magnetic field ripple. Normally, the well defined trajectories of trapped ions [2] do not intercept the bolometer sensor itself. The different behaviour of deuterium and helium experiments have pointed out the role of the neutral gas pressure inside the port, which can be significantly higher in deuterium than in helium due to the recycling properties of both gases. Thus it is believed that a small part of these fast ions can transfer their energy during the vertical drift to the bolometers (located at the top of a vertical port) by means of charge exchange reactions. The required gas pressure needed inside ports, to explain this phenomenon is of the order 10^{-5} Pa

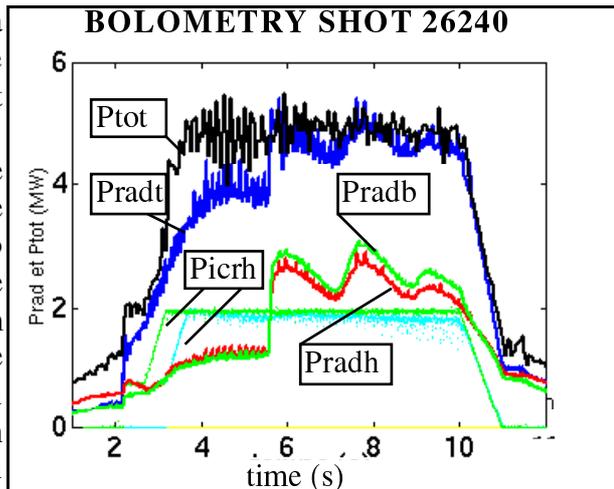


FIG.1 the three independent estimates of Prad vs time, Pradh coming from horizontal, Pradt from top and Pradb from bottom bolometers, displayed with the total input power Ptot and the heating power Picrh1&2 delivered by two antennae. At t=6s a controlled neon injection is used to increase the radiated power in this ED shot

Radiated power and calorimetry of the outer first wall : Tore Supra, designed to produce long and energetic pulses, is the first tokamak where all first wall components, except viewing ports, are actively cooled by a pressurised water loop (T~150°C P=33bars).

Each cooled element is equipped with a calorimetric sensor. The inner and outer first walls (IFW and OFW) protect the plasma vacuum chamber, which is one of the walls of the cryostat, containing the superconducting toroidal coils, against heating from plasma radiation. While the IFW (on the HFS) can be used as a toroidal limiter the OFW (on the LFS) is always away from limiting objects (10cm min radially). This actively cooled OFW, only heated by radiation, acts as a giant uncollimated bolometer with a cooling time constant of the order of 5s. The analysis performed on energetic shots ($E_{in}>60$ MJ, $P_{in}\sim 5$ MW, ICRH-HMIN+LHCD, limited on the IFW), shows that the radiated energy ERADh estimates from the horizontal bolometer system is proportional to the thermal energy EOFW exhausted from the OFW: $ERADh=f_{exp}*EOFW$.

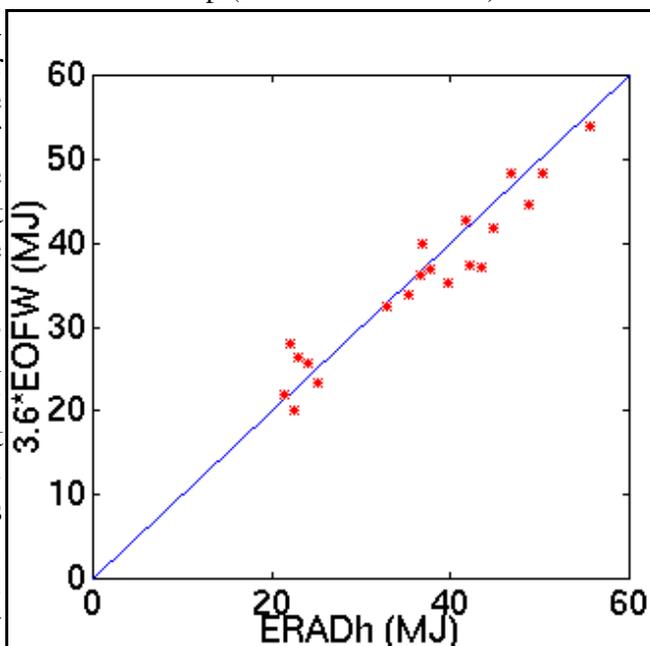


FIG.2 Correlation between the radiated energy estimates from horizontal bolometer system ERADh and the Energy exhausted from the OFW showing that $ERADh\sim 3.6*EOFW$

Experimentally $f_{exp}=3.6$ (Fig.2). The analysis shows that f_{exp} is the product of three terms which either can be calculated or measured : $f_{exp}=f_{cal}=f_{cov}*f_{coll}*f_{enh}$. Where f_{cov} is the coverage factor corresponding to the effective irradiated area with respect to the total area of the OFW: $f_{cov}\sim 2.15$. f_{coll} is the efficiency of the photon collection of the OFW. It is calculated

from the OFW geometry and from tomographic reconstructions of plasma emissivity for plasmas having similar radiating pattern than those used in Fig.2. In this case f_{coll} is found of the order of 1.4. The factor f_{enh} represents the weak over estimate of $Pradh$ for this type of experiments, where the outboard pumped limiter installed in an adjacent port of the bolometric one, is placed at 1cm of the last closed magnetic surface to play the role of a guard limiter for RF antennae. This analysis confirm, with an uncertainty lower than 20%, the estimate of $Pradh$ in these experiments ICHR-HMIN in IFW limiter configuration.

Global power balance and toroidal peaking factor (ftp) in ED experiments :One of the main issues for the physical program of TS is to study the specific properties of the ED [3]. The ED is composed of six meanderlike magnetic coils equally spaced in the toroidal direction on the low field side of the machine. These coils of poloidal and toroidal extension 120° and 10° respectively, create an alternated radial magnetic perturbation. With this device the plasma-wall interaction is mainly focused on the neutraliser plates installed between the current bars of the coils. The ED coils are installed away from the viewing ports, such that the plasma-

wall interaction region cannot be seen by bolometers. Thus, if a toroidal structure of the 6th order appears in the toroidal distribution of radiation, it is possible that $Prad$ be underestimated. This trend seems to be pointed out by the global power balance analysis:

$P_{balance} = O(\epsilon) = P_{in} - Prad - P_{cond} - P_{loss} + dW/dt$, where the estimates of the various terms are obtained with a multifactor fit procedure, based on the time behaviour coherency of the various signals [4]. $Prad$ is taken as $Prad = ftp * Pradh$. P_{cond} is estimate from thermographic measurements on a given neutraliser plate. This analysis shows that ftp varies from 1.5 to 1 with the radiation rate and radiating impurities. The peaking factor decreases when high Z impurities are used and when plasma approaches detachment (Fig3).

With this $Prad$ estimate the radiating efficiency of ED experiments does not seem to exceed a factor of 2 with respect to the Matthews law [6]. The best values being obtained with intrinsic impurities at high density. This analysis gives, in addition to the estimate of the toroidal peaking factor, due to the discrete plasma-wall interaction, also an insight into the missing power, P_{loss} , mainly attributed to the ripple losses and possibly to the accuracy of the RF power estimate. The figures obtained, significantly higher than expected, $P_{loss} \sim 0.2-0.3 * P_{icrh}$ agree well with the unexplained deficit of the global calorimetric balance usually observed on TS discharges. This last result and the agreement found between ERADh and EOFW have led to revisit the calorimetric data (see below).

Due to the importance of the accuracy of ftp on the determination of the radiating efficiency of the ED some independent methods, based on calorimetric measurements of internal components, are being developed to constrain as much as possible this parameter. The simplest, among others, is to consider that for ED experiments the IFW, as the OFW, receives only radiated power and then to study it in the same way. Thus one get directly: $ftp * ERADh = f_{coll} * EIFW$, $f_{cov} = f_{enh} = 1$, The tomographic analysis gives for ED shot a collection efficiency for the IFW of the order of $f_{coll} \sim 5.2$. With this analysis, preliminary results, gives also a toroidal peaking factor ftp in the range of 1 to 1.5 [5].

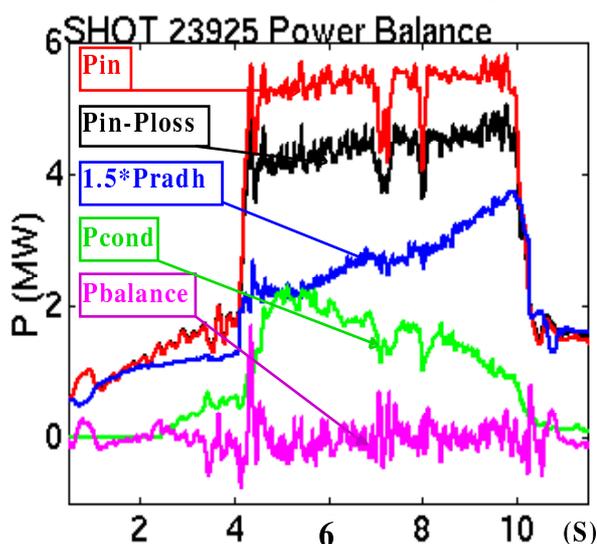
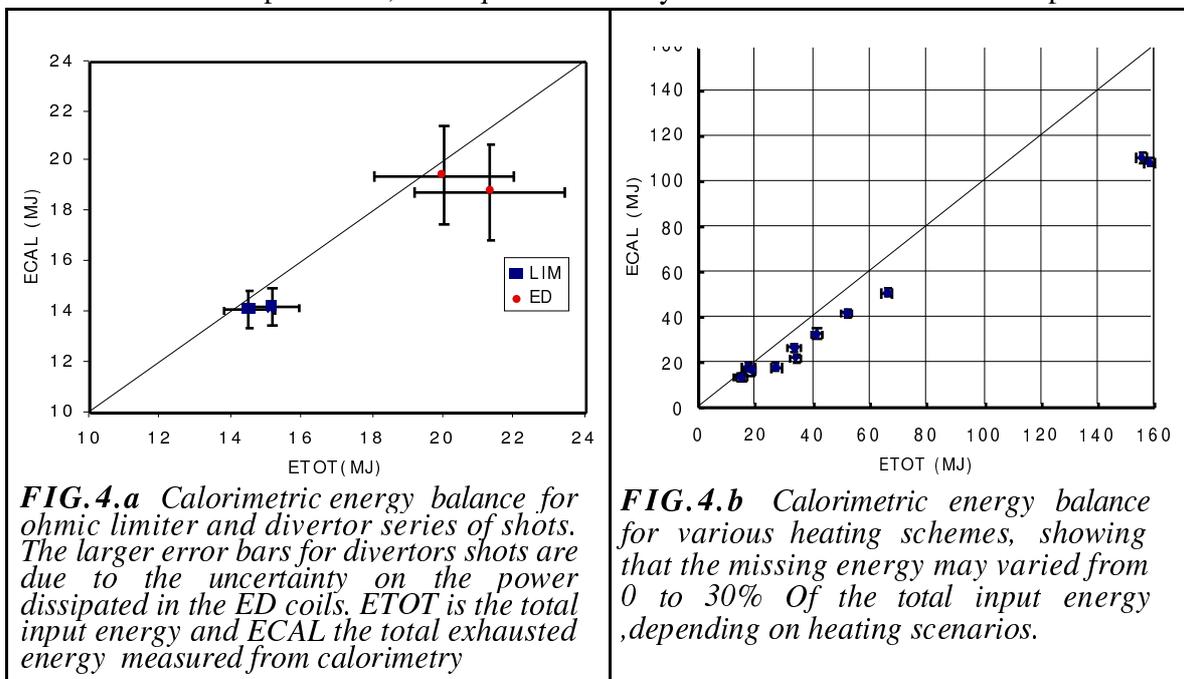


FIG.3 Global power balance, ED shot 23925, showing the complementarity between P_{cond} and $1.5 * Pradh$ and the amplitude of P_{loss} .

$Prad = Pradh$ for $t > 10s$ plasma detached

Calorimetry and global energy balance: On Tore Supra the calorimetric balance has always been a serious problem which has put in question the quality of the calorimetric measurements: at high energy, i.e. with auxiliary heating power, meaning RF power only on TS, it shows a large deficit ($\sim 0.3 \cdot E_{in}$, Fig.4b) and at low energy ($E_{in} < 40$ MJ) an unfavourable signal to noise ratio prevents the analysis of the global energy balance on the basis of individual shots. In the light of the above mentioned results, if one has to attribute the calorimetric deficit to the ripple losses and other RF losses, it is of first importance to demonstrate that for ohmic shots, for which the input energy ($E_{in} \sim 15$ MJ) is believed to be known with an accuracy of 10%, the energy balance effectively cancels. A statistical analysis has shown that the noise on calorimetric data can be significantly reduced using coherent summing methods. This, applied at series of ohmic shots, has shown that the effective sensitivity of the calorimetry is of the order of 1-2 MJ. The energy recovering rate for ohmic shot is found to be in the range of 0.9 ± 0.1 , with a special difficulty for ED experiments where the electrical power dissipated in the ED coils, not measured, has to be calculated (Fig.4a). This recovering rate which is within the uncertainty of the ohmic power estimate, seems to validate the calorimetric balance and open the way to an accurate analysis of Ploss and of these various components : ripple and RF losses and also to a check of the accuracy of the auxiliary heating power. However further additional analysis, to be made on dedicated experiments, are required to finally conclude on the calorimetric problem.



Conclusions: This set of preliminary results shows the interest of global power and energy balance analysis to improve the accuracy of the independent estimates of the various terms and especially Prad. It also shows the various points on which effort have still to be made: 1) an improvement of the signal to noise ratio of the calorimetry, 2) a calorimetric measurement of ripple losses, 3) a measurement of the electrical power dissipated inside ED coils and 4) a check of the calibration factor of RF power sources. With these new methods and measurements it will be, may be, possible to obtain accurate power and energy balances. It is possible that future results, if they confirm the already observed trend, will have a non negligible influence on the whole TS performance estimates.

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