Evaluating energy fluxes during COMPASS disruptions

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Introduction A novel method to accurately estimate the integral plasma thermal losses during tokamak disruptions is applied to the analysis of COMPASS experiments. The method relies solely on magnetic diagnostics measurements and is based on the hypothesis of axisymmetry and evolution of the plasma through MHD equilibrium states, which is robust if the inertia to the plasma motion is rather due to eddy currents surrounding the plasma than due to the plasma mass itself. On the other hand, there is no specific hypothesis on the halo currents, whose effect on the energy balance is estimated by the means of generalized Shafranov identities. Our study confirms that the magnetic energy conversion depends on the current quench duration as compared to the typical resistive time of the vacuum vessel. The method is compared with a different estimation method based on the direct integration of conducted and radiated heat fluxes obtained respectively by processed IR camera and AXUV pinhole signals, highlighting the difficulties of using these diagnostics during fast transients. The methodology presented can be used on other machines for a more accurate evaluation of the efficiency of disruption mitigation systems. Further, the method is suitable for a real-time implementation, in view of physics-based monitoring systems of tokamak experiments.

Magnetic Method We are interested in the thermal losses from a control volume V which comprises the plasma. In particular we consider a control volume whose boundary is well diagnosed via a set of Mirnov Coils and Flux Loops, which we define as *Diagnostic Surface* in the following. The estimation method proposed here is based on the approximate energy balance equation [1]:

$$\Delta Q = -\Delta U - \Delta W_{mag,pol} - \int_{t_0}^{t_1} \Phi_{S,pol} \mathrm{d}t \tag{1}$$

The plasma losses ΔQ are either due to consumption of thermal ΔU or poloidal magnetic energy $\Delta W_{mag,pol}$ within the control volume V or due to poloidal magnetic energy entering the control volume for conversion, which is represented via the time integral of the flux of the corresponding component of the Poynting vector $\Phi_{S,pol} = \int_{\partial V} E_{tor} \times H_{pol} \cdot \hat{n}\, \mathrm{d}S$. Equation (1) is based on the hypothesis of negligible plasma mass, hence kinetic energy, and negligible poloidal plasma currents, such that the toroidal magnetic energy does not enter the energy conversion picture.

The Poynting integral $\Phi_{S,pol}$ can be approximated, discretizing the integral with a weighted sum over a finite set of locations where the poloidal magnetic field tangent to the Diagnostic Surface and the poloidal flux are known. By hypothesis of axisymmetry, this approximation can be pursued efficiently using poloidal Mirnov coils and full flux loops readings. The saturation of flux loops, which may occur during disruptions, can be checked and corrected using the radial Mirnov coil diagnostics available at COMPASS. Similarly, the variations of poloidal magnetic energy and thermal energy, can be efficiently estimated using Shafranov integral identities [7]:

$$\int_{+\partial \mathrm{V}} \left[\left(p + \frac{B_{pol}^2}{2\mu_0} + \frac{B_{\varphi}^2 - B_{\varphi,0}^2}{2\mu_0} \right) (\boldsymbol{r} \cdot \hat{\boldsymbol{n}}) - \frac{\boldsymbol{B}_{\mathrm{pol}} \cdot \mathbf{r}}{\mu_0} B_n \right] \mathrm{dS} = 2U + W_{mag,pol} + W_{dia} \tag{2}$$

$$R_0 \int_{+\partial \mathrm{V}} \left[\left(p + \frac{B_{pol}^2}{2\mu_0} + \frac{B_{\varphi}^2 - B_{\varphi,0}^2}{2\mu_0} \right) n_R - \frac{B_R B_n}{\mu_0} \right] \mathrm{dS} = \frac{2}{3} U + W_{mag,pol} - W_{dia} \tag{3}$$

Here $B_{\varphi,0}$ is the toroidal magnetic field due to external currents. In equation (3) the assumption of large aspect ratio is made. The surface integrals at the L.H.S. of equations (2)-(3) are discretized and estimate using the available Mirnov Coil diagnostics. The diamagnetic energy at the R.H.S. is defined as the toroidal magnetic energy in the control volume excluding the contribution from the self-interaction of external currents, mainly due to TF coils. This can be approximated quite well with the interaction energy between plasma poloidal currents and external toroidal magnetic field, which allows to use the diamagnetic flux loop for estimation:

$$W_{dia} = \int_V \frac{B_{\varphi}^2 - B_{\varphi,0}^2}{2\mu_0} dV \simeq \mathrm{I}_0 \Phi_{tor,pl} \tag{4}$$

Given the surface integrals and the diamagnetic energy, equations (2)-(3) can be inverted to get the poloidal magnetic energy $W_{mag,pol}$ and the thermal energy U within the control volume. Finally equation (1) can be used to get the overall thermal losses. Details on the actual implementation of the method and simulation benchmarks for its validation will be published separately.

Direct method The energy lost during the disruption is in part radiated and in part conducted as heat flux to the Plasma Facing Components (PFCs). In COMPASS, AXUV pinhole cameras can be used as bolometers to estimate the radiated energy in the UV spectrum. Furthermore an IR camera is available which measures the heat flux density into the divertor region. Hence, considering downward Vertical Displacement Events (VDEs) and assuming the conduction heat fluxes are negligible outside the divertor region, we can benchmark the losses obtained via the magnetic method against the sum of radiated and conducted power estimated by the camera diagnostics. Although it is less justified for these signals, we assume axial symmetry also for the AXUV pinhole and IR cameras, which are instead installed in a specific toroidal location. In particular we consider here shots where the IR camera signals are already pre-processed so that heat flux densities are available in the COMPASS database.

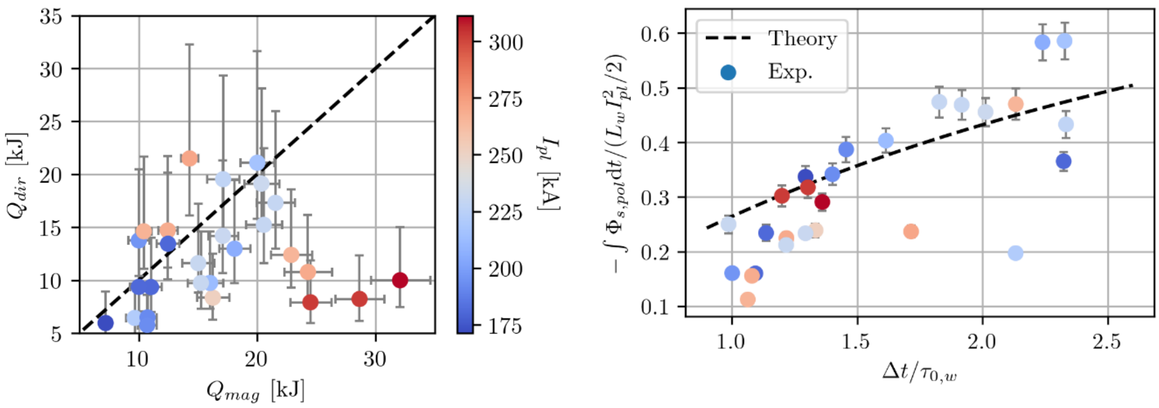

Figure 1. (a) Parity plot for benchmark of the *direct* and *magnetic* methods of estimation of losses. (b) Benchmark of magnetic energy influx with simplified circular high-aspect-ratio model.

Discussion The two methods, based on a completely different technology, provide estimates for the overall losses which are of the same order of magnitude and can be considered compatible, as illustrated in Figure 1a. The error bars illustrated for the direct method are taken to be +50% / -25% of the estimated losses, which is based on the assumption that the heat flux can vary along the toroidal angle sinusoidally with an amplitude that is 1/3 of the toroidally averaged signal (*i.e.* $P(\varphi) = P_0\,[1\ + 1/3 \cos\varphi]$) and that we do not know in advance at which toroidal location φ we are effectively taking the measurement.

Toroidal asymmetries of magnetic fields, which are determined by the overall current distribution, are expected to be much lower than asymmetries of diffusion quantities, such as the local electric current or heat flux densities. Hence, we consider as the main source of error for the magnetic method eventual errors in the Mirnov coils and full flux loops measurements. We consider the same variation for all magnetic signals simultaneously, either of the +5 % or of the -5%, rather than considering a proper statistical distribution of errors to propagate. We expect this to yield a conservative uncertainty estimation. The error introduced by the large aspect ratio assumption and by the surface integrals discretization will be discussed separately and preliminary results indicate these error sources should not be significant for COMPASS.

In Figure 1b, the poloidal magnetic energy influx during the disruption is compared to a simplified theoretical model which assumes circular plasma and wall cross-section, besides the classical large aspect ratio approximation. The analytical model solves equations (61)-(66) of Reference [1], assuming a linear ramp Current Quench and $L_w = L_{fw,ext}$, leading to:

$$\frac{\int_{t_0}^{t_1} \Phi_{S_{\mathrm{pol}}} \mathrm{d}t}{\frac{1}{2} L_w I_{pl,0}^2} = \frac{2}{\left(\Delta t/\tau_{0,w}\right)^2}\left[1 - \frac{\Delta t}{\tau_{0,w}} + \frac{1}{2}\left(\frac{\Delta t}{\tau_{0,w}}\right)^2 - \exp\left(-\frac{\Delta t}{\tau_{0,w}}\right)\right] \tag{5}$$

For COMPASS-like parameters ($R_w = 56$ cm, $b_w = 30$ cm, $d_w = 4 \pm 1$ mm, $\sigma_w = 0.787$ MS/m) we have $L_w = 49.5\,\mu$H, and $\tau_{0,w} = 0.84 \pm 0.21$ ms. Figure 1b confirms that the longer the disruption time and the larger is the fraction of poloidal magnetic energy originally outside the vessel which penetrates inside and gets converted to heat within the plasma.

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