Estimation of the runaway electron current during the flattop phase in COMPASS

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Introduction

Prevention and mitigation of the runaway electron (RE) beam is a topic in urgent need of investigation, because RE beam poses a serious threat for safe operation of tokamaks [1], as it can cause severe damage of the plasma facing components. Combination of numerical simulations and measurements provided on compact sized tokamaks as COMPASS (ITER-like shape, $R_0 = 0.56$ m, $a = 0.23$ m, $B_T = 1.15$ T and $I_p \leq 400$ kA) [2] can help to better understand the RE beam formation, evolution and termination. Non-disruptive COMPASS discharges with a special request on $I_p$ waveform with drops were selected for testing possibility of estimation of a fraction of plasma current carried by RE in the plasma current flattop phase. A method estimating runaway current in non-disruptive part of plasma discharge will be a useful tool for a deeper insight into the not fully understood of RE physics.

RE scenario at COMPASS and description of RE current estimation

Approximately twenty non-disruptive discharges made during three dedicated campaigns focused on the RE studies at the COMPASS tokamak were used in this study. Different initial setting of plasma parameters (elongation scan: $\kappa = 1–1.4$, plasma current scan: $I_p = 130–180$ kA, density scan: $n_e = 1–3 \times 10^{19}$ m$^{-3}$ and stable toroidal magnetic field $B_T = 1.15$ T) was used. The High Resolution Thomson scattering system [3] was set to burst mode (two laser pulses with 1 ms delay - see vertical cyan lines in Fig. 1). Initial requests for plasma parameters strongly affected the MHD activity. Influence of the MHD activity on RE losses and a detailed description
of RE related diagnostics at COMPASS are presented in [4]. Plasma current ($I_p$) drops during $I_p$ flattop phase were requested for all discharges used in this study. An example of $I_p$ and $U_{loop}$ drops is given in the top panel in Fig. 1, by blue and green solid line, respectively.

The purpose of preprogrammed $I_p$ variations was based on an assumption that $I_p$ consists of two distinct parts: Ohmic ($I_Ω$) that reacts to sudden loop voltage changes and a part which doesn’t. This part is composed by a RE fraction ($I_{RE}$) and a Bootstrap fraction ($I_{Boo}$).

Similar approach was presented in 0-D model for $I_{RE}$ calculation after disruption [5] without a bootstrap current.

We have derived $I_{RE}$ from following equations:

$$I_{nΩ} = I_p - I_Ω = I_p - \frac{U_{loop} - L_p \frac{dI}{dt}}{R}$$  \hspace{1cm} (1)

$$I_{nΩ} = I_{RE} + I_{Boo}$$  \hspace{1cm} (2)

where $L_p = \mu_0 R_0 l_i/2$ is plasma inductance with $l_i$ - self-inductance, $R_0$ - the major radius and $R$ - the plasma resistance.

We calculate $I_{RE}$ within a short time interval, where we suppose that $I_{RE}$ remains constant, due to its negligible resistance, neglected RE radiation losses and small RE radial diffusion. The time evolution of the RE population can be determined as: $\frac{\partial n_{RE}}{\partial t} = (\frac{\partial n_{RE}}{\partial t})^{Dreicer} + (\frac{\partial n_{RE}}{\partial t})^{avanche} + (\frac{\partial n_{RE}}{\partial t})^{hot-tail}$. Hot-tail mechanism can be omitted due to the absence of a rapid temperature drop during the $I_p$ flattop phase. The length of the time interval used for $I_{RE}$ estimation is determined by following time limits: collisional time for relativistic electrons $\tau_{ee}$, characteristic avalanching time [7] $\tau_{aval}$ and acceleration time $\tau_{acc}$ [8] required to accelerate a newly generated RE to relativistic speeds and RE radial diffusion with Rochester-Rosenbluth diffusion coefficient [9] changing from $40 m^2/s$ to $120 m^2/s$ for selected discharges. The collisional time $\tau_{ee}$ is in our conditions $> 180$ ms, while avalanching time approximated by $\tau_{aval} \approx \tau_{ee} a(Z_{eff})/ \ln(\Lambda(E-1)^{-1})$ is $> 60$ ms, with $E = E_∥/E_c$ and $a(Z_{eff}) \approx$
Figure 2: Left panel: prescribed waveforms of $I_{RE}$ given as an external source to METIS simulation.
Right panel: change of time evolution of $U_{loop}$ with different external source of $I_{RE}$ in METIS. Black lines is measured $U_{loop}$ and colored lines are $U_{loop}$ from METIS.

$\sqrt{\left(3(5 + Z_{eff})/\pi\right)}$, where $Z_{eff}$ is the effective charge. The strongest limitation of the time interval, where $I_{RE}$ is supposed to be constant, is the acceleration time $\tau_{acc} \approx m_e c / e E_\parallel = \tau_{ee} E_c / E$ which corresponds to $\tau_{acc} > 4$ ms. We selected 2ms long time interval for the $I_{RE}$ calculations to avoid major changes of RE population (mainly generation) and to limit influence of unwanted signal oscillations.

For each time interval used for $I_{RE}$ estimation averaged values of signals obtained from measurement ($U_{loop}$, $I_p$) and signals from METIS simulations ($U_{loop}$, $I_p$, $L_p$, $I_{Boot}$, $R$) or their combination were used. METIS [10] is a fast integrated transport code using real data from several tokamaks as an input. In COMPASS case these are: $I_p$, LCFS geometry, line averaged density from interferometer, stored energy from diamagnetic loop.

METIS provides information about global plasma parameters such as parallel electric field ($E_\parallel$), bootstrap current, resistivity [11] and plasma equilibrium. METIS outputs can be validated against experimental observations ($U_{loop}$, $T_e$ etc.) due to their sensitivity to changes of various input parameters ($Z_{eff}$, confinement time, or external sources as $I_{RE}$ (Fig. 2). Such sensitivity is shown in Fig. 3 in case of various external $I_{RE}$ waveforms used as the METIS input and it was even higher in case of different $Z_{eff}$. For this particular case $Z_{eff} = 1.5$ was derived from METIS simulation, while the stored energy was known and other inputs were

Figure 3: External RE current used as the input for METIS simulations (green line), while $I_{Boot}$ (blue dashed line), non-ohmic current (cyan line) are METIS outputs. Estimations $I_{RE}$ and $I_{RE-metis+data}$ are calculated using only METIS data (black line and stars) and METIS with combination of measured $U_{loop}$, respectively. Stars show $I_{RE}$ derived from averaged values within 2 ms time interval. $I_{RE-err}$ is also from METIS but an additional 10% random error was added to the $U_{loop}$ signal.
fixed. Runaway current can be estimated
by the same approach. This it is not possible in our case with two ($Z_{\text{eff}}$ and $I_{\text{RE}}$) or more unknown inputs. Estimation of $I_{\text{RE}}$ calculated only from METIS (black line and stars) and from combination with measured $U_{\text{loop}}$ (magenta line and stars) are in Fig. 3. Difference between these lines are given by unmatched $U_{\text{loop}}$ values from METIS and measurements. This is confirmed by the red line (Fig. 3) calculated from $U_{\text{loop}}$ given by METIS with an additional 10% random error added to the $U_{\text{loop}}$ signal. The method was most sensitive during fast variation of $U_{\text{loop}}$ and $I_p$ therefore the effect of the current diffusion, radial RE diffusion and loss processes will be included in the future.

**Results and Conclusions**

The tested method is based on simple assumption that runaway current can be estimated as a remaining component of the measured plasma current after subtraction of Ohmic and Bootstrap currents. Hypothesis was examined by the fast transport code METIS (providing information about $Z_{\text{eff}}$, $I_{\text{Boot}}$ and $E_{||}$ and current density profiles) and by the combination of METIS simulations and measurements. The method was very sensitive to $U_{\text{loop}}$ oscillations and fast dynamic changes, therefore an inclusion of a radial current diffusion and loss processes is necessary in the future.

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**References**