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: κ = 1–1.4, plasma current scan: I_p = 130–180 kA, density scan: $n_e = 1\text{–}3 \cdot 10^{19}$ 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_{Boot}). Similar approach was presented in 0-D model for I_{RE} calculation after disruption [5] without a bootstrap current.

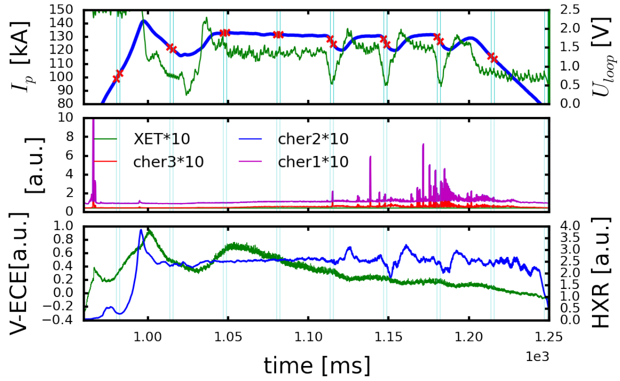

Figure 1: *Top panel: I_p - blue line, U_{loop} - green line, red crosses and vertical cyan lines show times when Thomson scattering system measured. Middle panel: signals from three channels from Cherenkov probe sensitive to energies $>$ 58*keV*, $>$ 145*keV *and* $>$ 211*keV *and signal (XET) from shielded blinded photomultiplier that demonstrates low noise due to the X-ray radiation. Bottom panel: HXR signal (blue line) from NaI(Tl) detector sensitive to energies $>$ 50*keV *and signal from vertical ECE radiometer (76.5–90* GHz*) - green line.*

We have derived I_{RE} from following equations:

$$I_{n\Omega} = I_p - I_\Omega = I_p - \frac{U_{loop} - L_p dI/dt}{R} \quad (1)$$

$$I_{n\Omega} = I_{RE} + I_{Boot} \quad (2)$$

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: $\partial n_{RE}/\partial t = (\partial n_{RE}/\partial t)^{Dreicer} + (\partial n_{RE}/\partial t)^{avalanche} + \cancel{(\partial n_{RE}/\partial t)}^{hot-tail}$. 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 τ_{ee}, characteristic avalanching time [7] τ_{aval} and acceleration time τ_{acc} [8] required to accelerate a newly generated RE to relativistic speeds and RE radial diffusion with Rechester-Rosenbluth diffusion coefficient [9] changing from 40m^2/s to 120m^2/s for selected discharges. The collisional time $\tau_{ee} = 4\pi\varepsilon_0^2 m_e^2 c^3/n_e e^4 \ln\Lambda$ 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 $E = E_\parallel/E_c$ and $a(Z_{eff}) \approx$

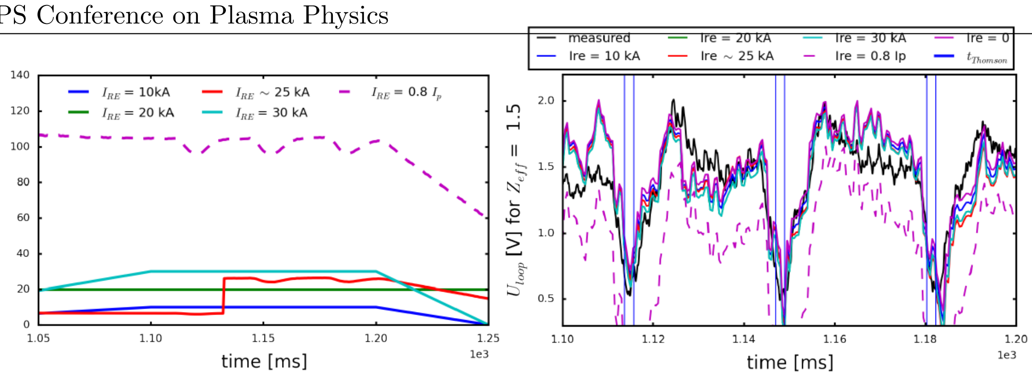

Figure 2: *Left panel: prescribed waveforms of I_{RE} given as an external source to METIS simulation. Right panel: change of time evolution of U_{loop} with different external source of I_{RE} in METIS. Black lines is measured U_{loop} and colored lines are U_{loop} from METIS.*

$\sqrt{(3(5+Z_{eff})/\pi)}$, 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 $\tau_{acc} \approx m_e c/eE_{\|} = \tau_{ee} E_c/E$ 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 ($E_{||}$), 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

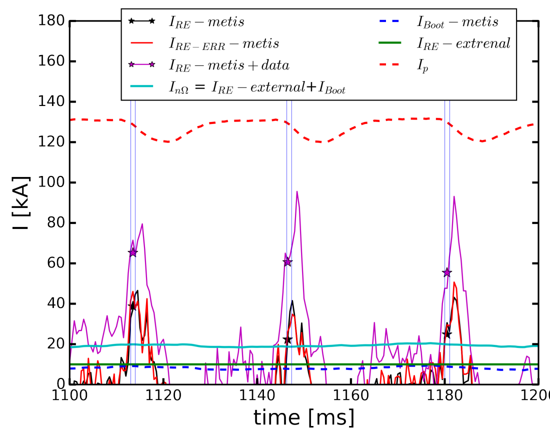

Figure 3: *External RE current used as the input for METIS simulations (green line), while I_{Boot} (blue dashed line), non-ohmic current (cyan line) are METIS outputs. Estimations I_{RE} and $I_{RE-metis+data}$ are calculated using only METIS data (black line and stars) and METIS with combination of 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_{eff} and I_{RE}) or more unknown inputs. Estimation of I_{RE} calculated only from METIS (black line and stars) and from combination with measured U_{loop} (magenta line and stars) are in Fig. 3. Difference between these lines are given by unmatched U_{loop} values from METIS and measurements. This is confirmed by the red line (Fig. 3) calculated from U_{loop} given by METIS with an additional 10% random error added to the U_{loop} signal. The method was most sensitive during fast variation of U_{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_{eff}, I_{Boot} and $E_{||}$ and current density profiles) and by the combination of METIS simulations and measurements. The method was very sensitive to U_{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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