Validation of state-of-the-art runaway electron generation models in simulations of ASDEX Upgrade disruptions

O. Linder[1], E. Fable[1], F. Jenko[1], G. Papp[1], G. Pautasso[1],
the ASDEX Upgrade Team[†] and the EUROfusion MST1 Team[‡]

[1] *Max-Planck-Institut für Plasmaphysik, 85748 Garching, Germany*
[†] *See author list of H. Meyer et al. Nucl. Fusion* ***59****, 112014 (2019)*
[‡] *See author list of B. Labit et al. Nucl. Fusion* ***59****, 086020 (2019)*

Introduction Plasma disruptions in high-current fusion devices may cause conversion of a substantial fraction of the Ohmic current to runaway electrons (REs) with relativistic energies [1]. Upon RE deconfinement, severe localized melting of wall material can occur [2]. For the successful operation of high-current devices, such a scenario must be avoided. In ITER, massive material injection is to be used to suppress RE formation [1]. The efficacy of this scheme is being investigated experimentally in present day fusion devices (e.g. at ASDEX Upgrade (AUG) [3]), complemented by theoretical and computational studies [4, 5]. In this work, RE formation following massive gas injection (MGI) in AUG is investigated with a toolkit based on the coupled transport codes `ASTRA-STRAHL` [6, 7] in self-consistent simulations of the background plasma, material injected and REs [8, 9]. In this context, the importance of applying state-of-the-art RE generation models [10, 11] and of material propagation is emphasized.

Model description In `ASTRA-STRAHL`, the evolution of plasma quantities Y along the radial coordinate ρ is described by the transport equation $\partial_t Y = V'^{-1}\partial_\rho\left(V' g\left[D\partial_\rho Y - vY\right]\right) + \sum_j S_j$ in the presence of diffusion D, convection v and sources S_j (g describes geometric factors and $V' \equiv \partial_\rho V$ with plasma volume V). Here, the poloidal magnetic flux Ψ, the electron and ion temperatures T_e and T_i, as well as the impurity densities $n_{i,k}$ of impurity i with charge state k are evolved. Quasineutrality determines the electron density n_e. For the temperature evolution, Ohmic heating, impurity radiation and electron-to-ion heat transfer are considered. Impurity densities are evaluated inside `STRAHL`, taking into account neoclassical transport through `NEOART` [12] and electron-impact atomic processes with rate coefficients from ADAS [13]. Material is deposited outside the confined plasma and propagates inwards with thermal velocity. Upon reaching the $q = 2$ surface at time $t_{q=2}$, $(2,1)$ MHD modes are excited [14], resulting in breakup of the magnetic surfaces and enhanced radial transport. The impact on heat and impurity ions is mimicked by prescribing additional transport coefficients $X(t) = X^{\max}\exp(-\left[t - t_{q=2}\right]/\tau)$ for $t \geq t_{q=2}$ inside the $q = 2$ surface [8, 9]. During the disruption following, RE generation is calculated due to the Dreicer [11, 15], hot-tail [16] and avalanche [10, 17] mechanisms. Assuming parallel RE propagation at the speed of light, the RE current density impacts the evolution of Ψ.

Simulating AUG #33108 The toolkit `ASTRA-STRAHL` is applied for self-consistent simulations of argon (Ar) MGI in AUG discharge #33108; a low density ($\langle n_e \rangle = 2.8 \times 10^{19}$ m^{-3}), high temperature ($T_e(0) = 9.3$ keV) experiment with a predisruption current of 763 kA. Key plasma quantities such as plasma current I_p and line integrated electron density $\bar{n}_e$ (see figure 1(a,b)) are calculated well in agreement with experimental observations under application of state-of-the-art RE generation models [8, 9]. The slow increase of the line averaged electron density during the pre-thermal quench, as well as the rapid rise during the thermal quench (TQ) are described in agreement with measurements. As observed across several simulations, an accurate description of $\bar{n}_e(t)$ is required to achieve a plasma current decay rate as measured experimentally. For this purpose, additional impurity transport with coefficients $D_{\mathrm{imp}}^{\mathrm{max}} = 100$ m^2 s^{-1} and $v_{\mathrm{imp}}^{\mathrm{max}} = -1000$ m s^{-1} is applied on a time scale of $\tau = 1.0$ ms at $t_{q=2}$. The plasma stored energy is dissipated through impurity radiation. Onset and duration of the subsequent TQ are captured adequately by this approach (see figure 1(c)). In the cold plasma, strong electric fields are induced, resulting in significant Ohmic heating, thus maintaining high levels of impurity radiation and preventing noticeable ion recombination. Simultaneously, significant avalanche multiplication amplifies a small RE seed in the order of a few kA. The RE seed is generated by both the hot-tail and the Dreicer mechanisms, each contributing a similar population. Until the end of the current quench (CQ), a RE current of 330 kA is generated by avalanching. Thus, strength and composition of the RE seed are of minor importance for the formation of a post-CQ RE beam, as observed in further simulations varying these parameters. Note, that the postdisruption RE current calculated exceeds experimental observations, likely due to the absence of RE loss mechanisms in the simulations. In conclusion, first-time self-consistent transport simulations with `ASTRA-STRAHL` successfully describe MGI and RE formation in Ar induced disruptions [8].

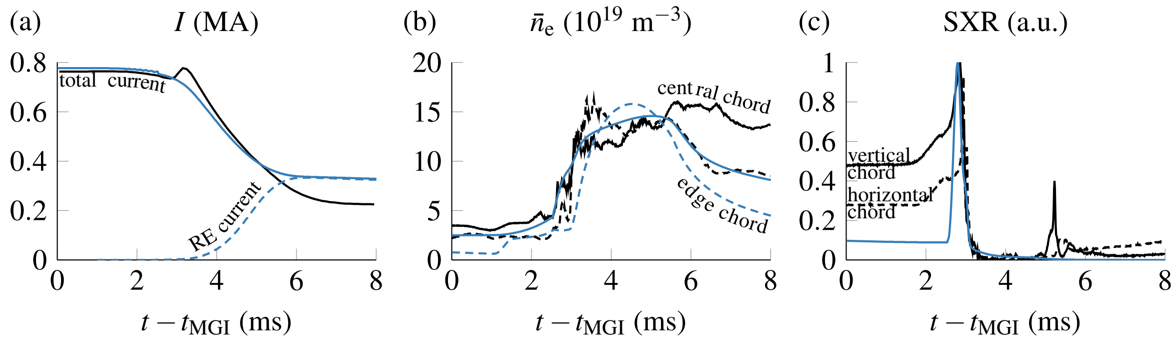

Figure 1: Self-consistent simulations of AUG discharge #33108 with `ASTRA-STRAHL` showing the temporal evolution of plasma quantities calculated (blue) after the onset of MGI at t_{MGI} compared to experimental measurements (black), being (a) the total plasma current I_p (solid) and RE current I_{RE} (dashed), (b) the line-averaged electron density $\bar{n}_e$ along the central (solid) and edge (dashed) vertical chords and (c) the central soft x-ray signal (SXR) along the vertical (solid) and horizontal (dashed) central chords as a proxy for the occurrence of the thermal quench.

Validation of state-of-the-art RE generation models

Commonly used formulae describing RE generation due to the Dreicer [15] and avalanche [17] mechanisms were initially developed for fully ionized plasmas. Yet, following high-Z MGI, impurities injected are likely ionized only partially, thus increasing electron-ion friction. The impact of these effects on RE generation is taken into account in state-of-the-art models [10, 11] (used in the simulations presented above). To assess the importance of these effects, self-consistent simulations of Ar MGI are performed with ASTRA-STRAHL, utilizing either state-of-the-art or classical RE generation models (hot-tail REs are neglected) [8]. In both cases, the post-disruption RE current is of similar magnitude (see figure 2), yet differs in the composition of RE populations. Neglecting increased impurity friction, a significantly increased Dreicer RE seed of 84 kA is calculated to be generated until the end of the TQ. Simultaneously, avalanche multiplication in the absence of high-Z effects is strongly reduced, as seen by the slower increase of the RE current during the CQ. The decay of the total plasma current is slowed-down in the presence of increased levels of RE current, resulting in decreased Ohmic heating and less radiative dissipation. From hard x-ray measurements in AUG #33108, a noticeable population of highly energetic REs is present only in a late stage of the CQ, in contrast to calculations using the classical RE formulae. In conclusion, despite obtaining similar post-CQ RE currents using either set of models, simulations using the classical formulae are inconsistent with experimental observations, thus highlighting the importance of interactions between partially ionized impurities and REs.

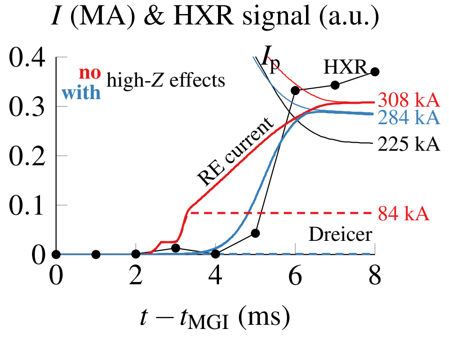

Figure 2: ASTRA-STRAHL simulations of the RE current evolution in AUG #33108 using classical formulae (red) or state-of-the-art models (blue) to describe RE generation by the Dreicer and avalanche mechanisms. The measured hard x-ray (HXR) signal is shown for comparison.

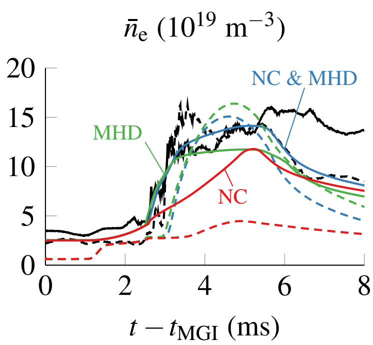

Figure 3: ASTRA-STRAHL simulations of the evolution of $\bar{n}_e$ assuming impurity transport due to neoclassical (NC) and MHD effects (blue), only NC (red) and only MHD (green).

Impurity transport The increase of the line-averaged electron density during the TQ can be explained in ASTRA-STRAHL simulations only under the assumption of rapid redistribution of impurities as a result of broken flux surfaces (referred to as *MHD effects* in figure 3). In simulations considering impurity ion transport only due to neoclassical effects, the inward propagation of material is driven by the neutral gas, resulting in a significantly slower increase of the line-averaged electron density. Consequently, no sudden loss of the plasma stored energy is observed; being stretched over several ms instead. Simulations neglecting the effect of rapid redistribution are in clear contrast to experimental measurements, highlighting the importance of these effects in AUG disruptions. Simultaneously, neoclassical impurity transport should not be neglected in self-consistent simulations, as inward impurity ion transport is less effective. Under these conditions, the electron density is larger at the edge and smaller in the center than in the reference case (see figure 3). In conclusion, the propagation of impurities is well described in the 1D framework of ASTRA-STRAHL when assuming transport due to neoclassical effects and rapid redistribution, despite the 3D nature of MGI. The validity of the additional transport has to be studied in future work with non-linear MHD codes such as JOREK [18].

High temperature AUG scenarios The toolkit ASTRA-STRAHL is applied to study the impact of a variation of the predisruption on-axis electron temperature $T_e(0)$ on RE generation under the assumption of applying varying amounts of central heating [9]. For $T_e(0) < 9$ keV, the RE current I_{RE} obtained is insensitive to a variation of $T_e(0)$, in agreement with the experimentally observed dependence on $T_e(0)$ (see figure 4). Recall, the RE current calculated exceeds experimental levels likely due to the absence of RE loss mechanisms. For higher $T_e(0)$, the hot-tail generated RE seed and consequently I_{RE} increases. Yet experimentally, no RE beams are generated for $T_e(0) > 12$ keV, suggesting loss of the entire RE seed under these conditions. This behavior is observed also in recent experiments from the 2021 AUG campaign. Consequently, further work with e.g. non-linear MHD codes is required to investigate RE loss during the breakup of magnetic surfaces under these conditions.

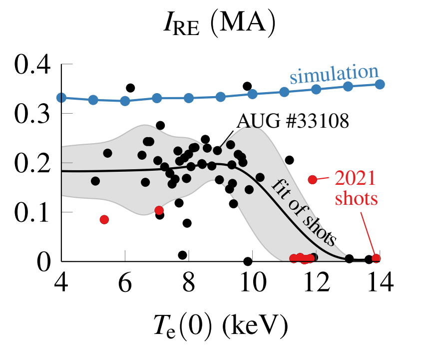

Figure 4: ASTRA-STRAHL simulations showing the impact of the predisruption electron temperature $T_e(0)$ on RE generation in AUG compared to experiments (shots from 2021 shown in red).

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