Physically based modelling of EC pre-ionization and assisted breakdown under ITER-like constaints

P. Ch. Papagiannis[1], G. E. Anastassiou [1], K. Hizanidis[1], Abhay K. Ram[2]

[1] *School of Electrical and Computer Engineering, National Technical University of Athens, Athens 15780, Greece*

[2] *Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

1. Introduction

To reduce energy demand on the central solenoid during start-up phase in ITER, Radio Frequency (RF) power in the electron cyclotron (EC) frequency range will be used for ionizing the neutral gas [1]. When ECRH power is used for pre-ionization, the Townsend theory for avalanche ionization of gases that models breakdown phase in pure inductive start-up [2] cannot incorporate rigorously the beam parameters such as power, width, polarization and launching inclination. Usually they are deduced through experiments [3] or 0D codes [2], ensuring that the next start-up phase (burn-through) is successful. A model has been developed in order to simulate the energization of an ensemble of magnetically confined seed electrons, interacting with a spatially localized Gaussian RF beam, in the presence of a background electrostatic potential.

2. Model-Methodology

Seed electrons inside the region illuminated by the EC-beam interact nonlinearly with the spatially localized RF-field [4]. Away from the EC-field they can move along the magnetic field lines and around the vessel, close to the magnetic null point. In the presence of loop voltage they can generally experience acceleration. Both these processes can give energy to the electrons and thus increase the possibility of impact ionizations with the molecules or atoms of the neutral gas [5]. If the two electrons produced after the ionization can gain, before the next impact, sufficient energy to further ionize other molecules/atoms then an avalanche process will eventually start and the electron density will grow exponentially. In our model we try to couple these processes in order to observe this exponential growth.

For the process of electron-RF wave interaction we derive the equations of motion of electrons interacting with the spatially localized electric field in the presence of a uniform, constant magnetic field, and integrate them numerically. These equations are derived using the Hamiltonian formalism, with the fields in the Lorentz gauge. One can use the Coulomb gauge [4] bear-

ing in mind that it is exact in the case of plane waves but an approximation in the case of localized fields. Although the contribution of scalar potential can be calculated to be small we choose to keep the scalar field contribution in the electron dynamics taking into consideration that the energization process may involve multiple interactions of the electrons with the beam. The normalized Hamiltonian is given by $h = (\chi, \psi, \zeta, U_\chi, U_\psi, U_\zeta, \tau) = \sqrt{1+|\mathbf{U}+\mathbf{a}+\mathbf{a}_0|^2} - \phi - \phi_L$. The Hamiltonian h is normalized to $m_e c^2$, $\mathbf{U}$ are the canonical momenta normalized to $m_e c$, $\mathbf{a}/\mathbf{a}_0$ are the RF/ B-field vector potential normalized to $e/m_e c$, ϕ / ϕ_L are the RF/ Inductive electric potential normalized to $m_e c^2/e$. Time τ is normalized to to $1/\omega_{\text{ce}}$, and space coordinates (χ, ψ, ζ) are normalized to c/ω_{ce} . In the case where an X-mode is launched we have

$$\mathbf{a} = Re\left\{\hat{\mathbf{y}}\alpha \exp\left((-(\chi^2+\psi^2)/2\hat{w}^2\right)\exp\left(i\nu(\zeta-\tau)\right)\right\}, \mathbf{a_0} = \hat{\mathbf{y}}(\chi\cos(\theta)+\zeta\sin(\theta)) \quad (1)$$

$$\phi = Re\left\{i\alpha\frac{\psi}{\nu\hat{w}^2}\exp\left((-(\chi^2+\psi^2)/2\hat{w}^2\right)\exp\left(i\nu(\zeta-\tau)\right)\right\}, \phi_L = \varepsilon_L(\zeta\cos(\theta)-\chi\sin(\theta)) \quad (2)$$

where $\nu = \omega/\omega_{ce}$, and two small parameters $\alpha = eE_0/m_e c\omega_{ce}$, $\varepsilon_L = eE_{loop}/m_e c\omega_{ce}$, the normalized gaussian beam amplitude and toroidal electric field respectively. $E_0 = \sqrt{2\eta P_0/\pi w^2}$ the RF amplitude related to EC beam power P_0 and its beam width w.

Away from the RF-beam the equations of motion for the electrons are rather simplified. There are four constants of motion from which we can calculate the electrons momenta and position analytically and define their state in the case of re-entry from either side in the region of interaction with the localized beam.

Additionally we can monitor the possibility of impact ionization events by calculating for each electron the accumulated value of the integral (3) along the path of the electron (following the gyration along the magnetic field line)

$$y(s_0, s) = n_{neutral}\int_{s_0}^{s}\sigma(\gamma)\,ds' \quad (3)$$

where $\sigma(\gamma)$ is the cross-section of the collision at the normalized energy γ. Collision cross-sections are evaluated based on NIST data basis [6] as well as the reference [7]. If $y(s_0, s) = 1$ then $|s - s_0| = \lambda$, where λ is the mean free path. At the impact ionization process, part of the incident electron energy equal to the ionization potential is subtracted and the rest is shared between the so called primary (ε_p) and secondary (ε_s) electron products emitted from the atom. Sharing is controlled by a random variable ξ distributed uniformly between 0 and 1 and is given by $\varepsilon_p = \xi\left(\gamma_i - 1 - W^2/m_e c^2\right)$, $\varepsilon_s = (1-\xi)\left(\gamma_i - 1 - W^2/m_e c^2\right)$, where W is the ionization potential and $\gamma_i - 1$ the normalized incident energy .The scattering angles θ and ϕ used to calculate the resulting momenta of the products, are randomly chosen between $[0, \theta_{max}]$ and $[0, 2\pi]$ respectively. The scattering cone is bounded between $\theta_{max} = 0$ at backscattering ($\xi = 0$) and $\theta_{max} = \pi/2$ when all the energy goes to one product ($\xi = 1$) .

3. Discussion-results

As a first attempt we try to identify the contribution of the RF-field in the collisionless heating stage of the breakdown, where seed electrons gain on average energy before the collisions with the neutrals (deuterium) come into play. Beginning with an average electron ensemble energy already developed by the E_{loop} action then RF-field is launced. As shown in Fig.1 (a) if EC acts on its own it gives almost immediately on average an energy boost to the initial ensemble of seed electrons and contributes continuously to the electron energization. Loop voltage on its own contributes to a slower growing slope of the averaged electron energy. EC as an assisting tool along with the loop voltage can increase the energization rate several times which in turn can lead to an ionization ratio greater at the breakdown time. Increasing the inclination of the beam or its width decreases on average the energization rate Fig.1 (c),(d) while the initial distribution of energies does not play a significant role in the rate of energy growth at this stage Fig.1 (b).

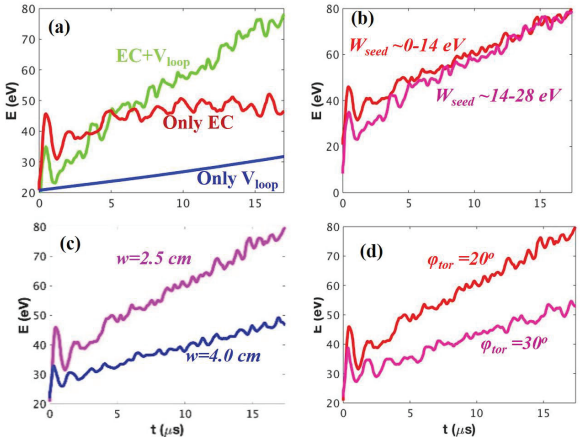

Figure 1: *Electron energization (average energy) in the collisionless heating regime of avalanche phase. Configuration related to [8].* $B = 1.475T$, $E_{loop} = 0.7V/m$, $p = 1mPa$, $f = 82.58GHz$, $P_{EC} = 500kW$, *TCV aspect ratio*

As a pre-ionization source, EC-beam can act on its own long enough to energize the seed electrons and initiate an avalanche. It has been highlighted recently in an experimental investigation [9], that studying separately the ECRH and the loop voltage contributions, is important to understand their effect in the different stages of start-up. We perform a simplified scenario using the configuration of the case above (Fig.1) but with dissociated hydrogen as the neutral gas [1]. The energization process is initiated with just a few (32) electrons, randomly distributed in terms of their initial momenta and their initial position inside the region illuminated by the beam. Their energies is taken to be at the range of 0.03eV to 1eV. The loop voltage is switched off and for simplicity we consider only impact ionization collisions. Elastic collisions of course play an important role, but for the time being they can be considered as a mechanism of random redistribution of the electron momenta. Finally we use as an effective loss mechanism the fact that if an electron travels a distance equal of the connection length (about 250m in this particular case) it is removed from the simulation process.

In Fig.2 we observe that for an initial period, the number of electrons remains very small until an abrupt multiplication of the electron population occurs, indicating that the avalanche has started. Changing the prefill pressure of the neutral gas, the power of the EC-beam, or the direction of the beam, changes the avalanche initiation time and affects the rate of growth of electron population, which follows a power law at this early phase of the developing avalanche process.

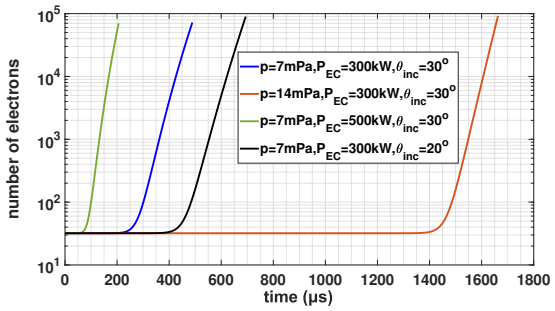

Figure 2: *Electron population growth in log-scale as a function of time*

The present work extends the theoretical approach presented in [4] where a threshold amplitude value of the Gaussian electric field is linked to the maximum electron energy gain for single electron-RF beam interaction in the case of 1D geometry. We model the whole energization process taking into account the possibility of multiple interactions of the initial ensemble of seed electrons as well as the evolving electron population generated from impact ionization collisions. At the same time we can estimate the temporal evolution of the electron energization and the avalanche growth. In the present work we focus firstly on the accelerated electron energization in the EC-assisted breakdown and secondly on the case where the EC-field can on its own initiate an avalanche.

Acknowledgement: This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

References

[1] P.C. de Vries and Y. Gribo, Nucl. Fusion, **59**, 096043 (2019)

[2] B. Lloyd etal., Plasma Phys. Control. Fusion, **38**, 1627 (1996)

[3] J. Stober etal., Nucl. Fusion, **51**, 083031 (2011)

[4] D. Farina, Nucl. Fusion, **58**, 06601 (2018)

[5] G.L. Jackson etal., Nucl. Fusion, **47**, 257 (2007)

[6] https://physics.nist.gov/PhysRefData/Ionization/intro.html

[7] Y.K. Kim et al., Phys. Rev. A, **50**, 3954 (1994)

[8] D. Ricci, et al. Proc. of the 45th EPS Conf. on Plasma Physics, P4.1074 (2018)

[9] J. Sinha et al Nucl. Fusion **62** 06601 (2022)