Time evolved current drive modelling of solenoid-free microwave start-up in tokamaks

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Start-up is the initial phase of a tokamak pulse comprising the plasma ionisation and initiation of the plasma current, I_P, which is ramped until the plasma is fully confined within closed flux surfaces (CFS). In most present-day tokamaks, start-up is achieved with a central solenoid. However, a solenoid can be used only once per pulse and fills a large amount of space in the centre column which places a limit on how compact the machine can be. This is particularly acute for spherical tokamaks like STEP, the UK's prototype power plant currently being designed. Developing solenoid-free start-up methods is therefore a high priority for tokamak power plants. Microwaves can both ionise the plasma and initiate I_P, are relatively robust to the harsh conditions of a power plant and can be used to drive current for the entire duration of the pulse. They are also routinely used for start-up in small machines and for EC-assisted solenoid driven start-up. Solenoid-free microwave start-up has been demonstrated on several machines including on MAST [1, 2] which achieved 73 kA of I_P but was limited by a gyrotron power of ~80 kW. MAST-U will extend these experiments with 10 times the power [3]. In addition to experiments, microwave start-up modelling is required to better understand the current drive (CD) mechanisms and phenomena observed in experiments to optimise these, and work towards predictive modelling for power plants. This is challenging because the CD mechanisms, magnetic field and plasma parameters are all changing in time and interacting with each other. We are developing a microwave start-up code Start-Up Modelling of Microwaves in Tokamaks (SUMMIT). SUMMIT is a time-evolved Fokker-Planck code which solves for the electron distribution function, f, including terms for the plasma sources due to ionisation, losses to the walls due to open magnetic field lines, microwave heating, collisions and induction due to the back e.m.f. from the rising I_P. At each time step, the magnetic field is calculated as the sum of the background field from the coils and the field induced by I_P. A guiding centre solver traces particle orbits originating from the resonance location of the microwave beam to calculate the loss time of the particles. A ray tracer can be used to calculate the microwave absorption. This information is used to solve for f from which I_P is calculated and used for the field in the following timestep. The simulations presented in this work are based on shots 16815, 28941 and 28954 from the MAST experiments. The microwave diffusion term is not used and instead the effects of isotropic heating are investigated. The source term is represented by a Maxwellian with a temperature of 0.01 keV scaled by a fixed ionisation rate of $1 \times 10^{22}\text{m}^{-3}$. The background temperature is not yet predictive but is estimated be ~1 keV based on experimental data and is given as an input. Collisions are assumed to be with a background Maxwellian of electrons of temperature fixed by the input and a background Maxwellian of ions fixed at 0.01 keV. For the full simulations, the plasma area is approximated by a bean shape shown in Figure 1 [4]. The CD mechanisms are investigated under these conditions.

Initially, the magnetic field lines are open, and particles are lost with both $v_\parallel < 0$ and $v_\parallel > 0$ as shown in Figures 1 and 2. For the magnetic field topology of MAST, lost particles with $v_\parallel > 0$ are travelling down and driving co-current and lost particles with $v_\parallel < 0$ are travelling up and driving counter-current. There is an asymmetry in the loss time as the region of absorption is above the midplane. This drives a current in SUMMIT as the co-current electrons take longer to be lost than the counter-current electrons. This is supported by MAST data as the vertical field at the centre column showed that initially counter-current was driven in the top half of the vessel and co-current in the bottom half. At the time, proposed explanations were differences in microwave CD or a trapped electron current. Using the guiding centre solver in SUMMIT to calculate a normalised current density using the particle trajectories, we see negative current above the absorption region and positive current below. Translating this into a magnetic field, we obtain a poloidal magnetic field shape which bends closer to the centre column above the midplane than below, remarkably like the image of the plasma in the experiments. The current density, resulting magnetic field and plasma image are shown in Figure 3.

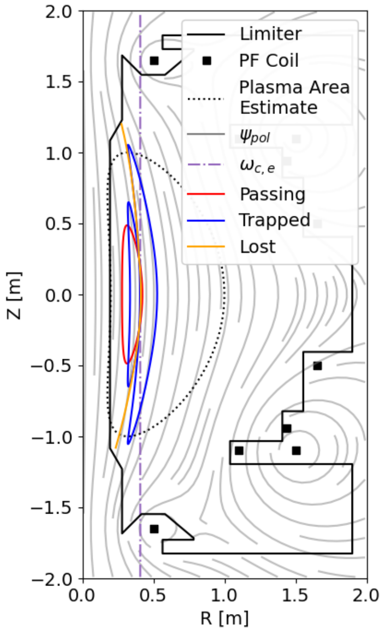

Figure 1: Poloidal cross section of MAST showing example orbit trajectories in open field lines.

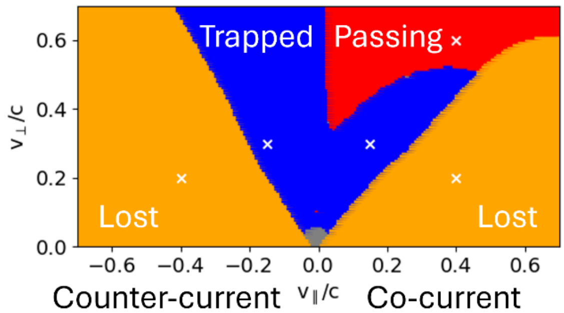

Figure 2: Orbit types in velocity space of initial velocity for particles in open field lines. Crosses represent the orbits in Figure 1.

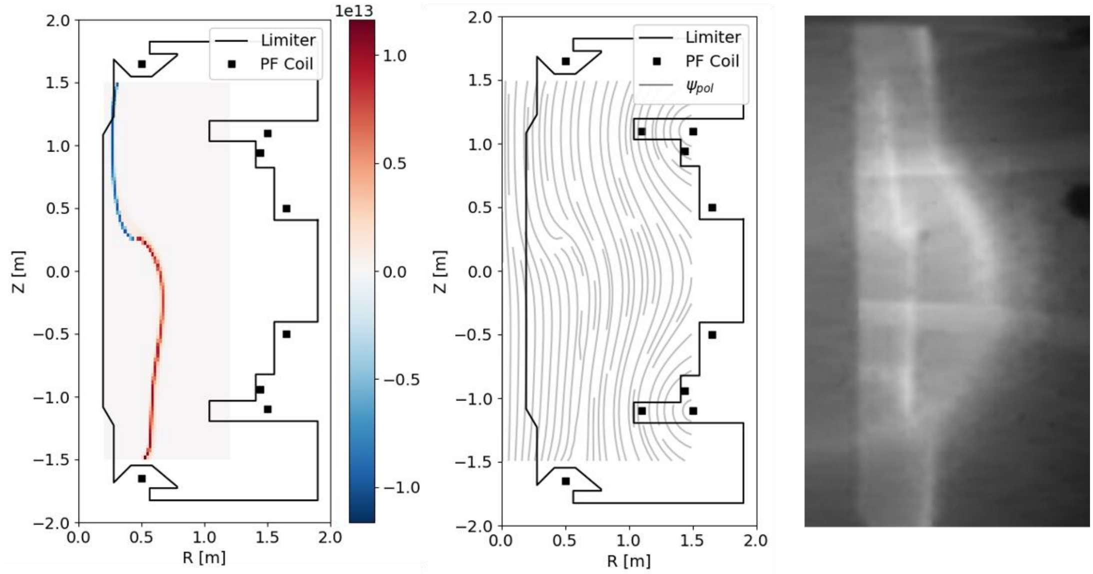

Figure 3: Left: Normalised current density profile generated from the particle velocities over their trajectories for shot 16815. Middle: Magnetic field generated from the normalised current density profile. Right: Image of the plasma in MAST shot 16815 at 42 ms.

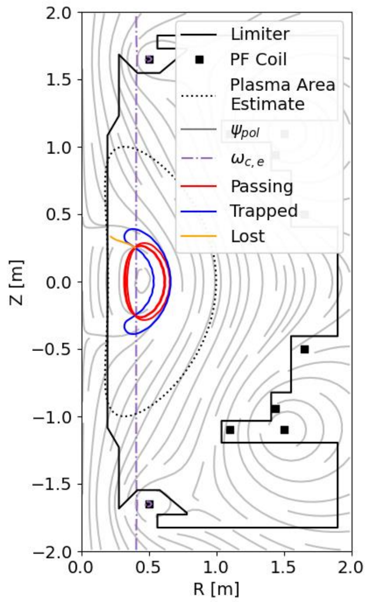

Figure 4: Poloidal cross section showing example orbit trajectories in a field with some CFS.

When CFS start to form, the co-current side of f becomes confined as shown in Figures 4 and 5. This leads to a spike in density which has been observed in both simulation and experiments. However, particles are still lost on the counter-current side of f. This drives positive current as counter-current particles are lost while co-current particles are confined. For a simulation in SUMMIT with isotropic heating, the temporal gradient of I_P saturates at a given rate. This gradient changes at distinct points corresponding to changes in the poloidal field (PF) coil currents and therefore the background vertical magnetic field strength, B_V. This shape qualitatively agrees with experiment as shown in Figure 6. The gradient of I_P has been found to be determined by a feedback loop represented in Figure 7 where decreasing the ratio of I_P/B_V leads to worse confinement, leading to more losses and therefore higher CD, which increases the ratio of I_P/B_V leading to better confinement and therefore fewer losses and less CD decreasing the ratio of I_P/B_V. This loop saturates to a particular slope of I_P for a given

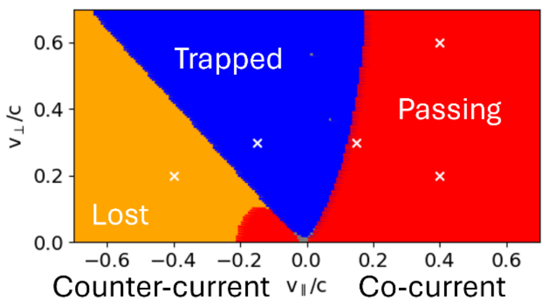

Figure 5: Orbit types in velocity space of initial velocity for particles in a field with some CFS. Crosses represent orbits in Figure 4.

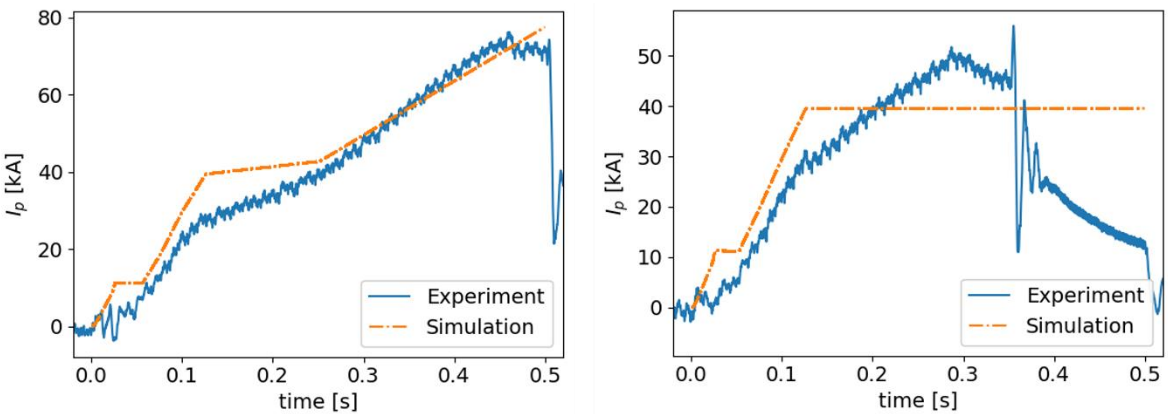

Figure 6: Left: MAST shot 28954 with ramping coils. Right: MAST shot 28941 coils constant after 125 ms. Experimental and simulated I_P. Shot 28954 shows slope of I_P changing at the same time in simulations and experiments. Shot 28941 shows I_P keeps increasing in experiment when simulation I_P stops increasing.

increase in B_V. However, it is likely not to be the only CD mechanism present, as shots which had a constant B_V still saw an increase in I_P as shown in Figure 6. This is likely to be due to asymmetric heating from the microwaves not currently included in these simulations.

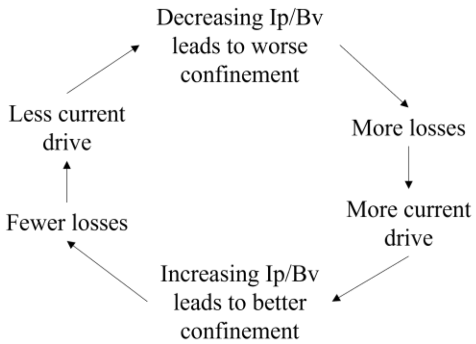

Figure 7: Feedback loop relating I_P and B_V ramp rates.

In conclusion, solenoid-free microwave start-up has been studied using the SUMMIT code which has shown that the loss particles are particularly important for CD and has had remarkable agreement with experiment. Further work will integrate the microwave CD from ray tracing as well as adding power balance and ionisation physics to calculate the temperature and ionisation rate self consistently.

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References

[1] V.F. Shevchenko *et al* 2010 *Nucl. Fusion* **50** 022004

[2] V.F. Shevchenko *et al* 2015 *EPJ Web of Conferences* **87** 02007

[3] H. Webster *et al* 2023 *EPJ Web of Conferences* **277** 04004

[4] T. Maekawa *et al* 2012 *Nucl. Fusion* **52** 083008