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Particle energization inside plasmoids: numerical and analytical investigations

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In an idealized system where four magnetic islands interact in a two-dimensional periodic setting, we follow the detailed evolution of current sheets forming in between the islands, as a result of an enforced large-scale merging by magnetohydrodynamic (MHD) simulation. The large-scale island merging is triggered by a perturbation to the velocity field, which drives one pair of islands move towards each other while the other pair of islands are pushed away from one another. The "X"-point located in the midst of the four islands is locally unstable to the perturbation and collapses, producing a current sheet in between with enhanced current and mass density. Using grid-adaptive resistive magnetohydrodynamic (MHD) simulations, we establish that slow near-steady Sweet-Parker reconnection transits to a chaotic, multi-plasmoid fragmented state, when the Lundquist number exceeds about 3×10^4, well in the range of previous studies on plasmoid instability. The extreme resolution employed in the MHD study shows significant magnetic island substructures. Turbulent and chaotic flow patters are also observed inside the islands. We set forth to explore how charged particles can be accelerated in embedded mini-islands within larger (monster)-islands on the sheet. We study the motion of the particles in a MHD snapshot at a fixed instant of time by the Test-Particle Module incorporated in AMRVAC (). The planar MHD setting artificially causes the largest acceleration in the ignored third direction, but does allow for full analytic study of all aspects leading to the acceleration and the in-plane, projected trapping of particles within embedded mini-islands. The analytic result uses a decomposition of the test particle velocity in slow and fast changing components, akin to the Reynolds decomposition in turbulence studies. The analytic results allow a complete fit to representative proton test particle simulations, which after initial non-relativistic motion throughout the monster island, show the potential of acceleration within a mini-island beyond $(\sqrt{2}/2)c\approx0.7c$, at which speed the acceleration is at its highest efficiency. Acceleration to several hundreds of GeVs can happen within several tens of seconds, for upward traveling protons in counterclockwise mini-islands of sizes smaller than the proton gyroradius.