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Sheath Broadening in Imploding Z-pinches due to Large-bandwidth Rayleigh-Taylor Instability

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The magnetic Rayleigh-Taylor (RT) instability has been predicted[1] and observed[2] to cause break-up of the plasma sheath in imploding z-pinches. In this work we show that, for the type of density profile encountered in strongly-radiating pinches, instability at very short wavelengths grows to the non-linear stage and seeds progressively longer wavelengths. The result is a self-similar broadening of the sheath as found for mix layers in fluid RT unstable systems[3].

An imploding sheath that remains at low pressure ($P < B^2/8\pi$) due to radiative cooling tends toward a density profile with a sharp edge[1], i.e., $\rho \to 0$ approximately linearly on a spatial scale c_s^2/g (ρ =density, c_s = sound speed, g = acceleration). This behavior has been confirmed in 1D radiation-MHD simulations of pinches driven by the SATURN accelerator at Sandia National Laboratory[4]. Differing initial profiles are rapidly brought to this form by JxB -driven advection. Recent linear theory has shown that these profiles are unstable to a surface mode that is not stabilized by resistivity[2]. The surface modes can therefore become unstable at short wavelengths, $\lambda = 2\pi/k \ll$ magnetic skin depth, with growth rate $\gamma=(kg)^{1/2}$. At very short wavelengths (typically < 10 μm) the mode may be stabilized by viscosity or finite larmor orbit effects. Modes with λ = 10 μm will exponentiate of order 100 times during the implosion, indicating strong nonlinearity should develop.

We have done 2D MHD simulations to study the nonlinear development of the modes, starting with a sheath in hydrodynamic equilibrium with uniform, steady acceleration and resistive equilibrium (uniform current density). The curvature of the sheath is neglected for simplicity. The linear growth of short wavelength surface modes is observed with growth rate independent of resistivity, in agreement with the analytic theory. The non-linear development is analogous to fluid RT behavior[3]. Short wavelength modes saturate when the amplitude is a fraction of the wavelength, and drive longer wavelength modes. These, in turn, drive even longer wavelengths until the scale is of order the size of the simulation. The characteristic perturbation scale and depth of the "mix layer" where plasma and accelerating magnetic field become intermixed is roughly proportional to gt^2. Variation of the resistivity over 2 orders of magnitude about the typical value for SATURN imploding pinches had small effect on the scaling. The implications for scaling of pinch x-ray output will be discussed.

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