Shock reformation

The non-stationarity of a quasi-perpendicular collisionless fast mode shock was studied with one dimensional PIC simulations (*Comişel et al., 2011*). The shock parameters, θ_{Bn}=81°, M_A=10, β_i=0.5, β_e=1.7, were similar to those determined for the Cluster event from January 24, 2001, analyzed by *Lobzin et al. (Geophys. Res. Lett., 2007)*. In this paper, the shock was found to be non-stationary, and reforming on the time scale of the ion gyroperiod. The argument for shock reformation was mainly based on the different magnetic field profiles observed by different spacecraft when traversing the bow shock.

The simulations were performed by using both the real ion to electron mass ratio, m_i/m_e=1836, and a reduced ratio, m_i/m_e=100. The ion beta in the simulations had the actual value of $\sim$0.6, as compared to the initial estimate of 2.0 used by *Lobzin et al.* The simulations showed the presence of waves with large and short wavelength in the foot, ramp, and overshoot of the shock, simultaneously with vortices in the ion phase space of the incoming ions — indicating the excitation of the modified two stream instability between incoming ions and electrons. These vortices triggered non-stationarity on a time scale considerably smaller than the ion gyroperiod.

Two closely spaced artificial satellites, flown from upstream to downstream (Figure 1), observed different magnetic field profiles during shock traversal. The simulated profiles are very similar the ones observed by Cluster, suggesting that the bow shock of January 24, 2001, does actually not reform, but is non-stationary. One can identify two different time scales of the non-stationarity: one time scale is much smaller than the ion gyroperiod, due to mini-cycles involving ion phase space vortices, while the other time scale is of the order of 1–2 ion gyroperiods, due to a periodically changing shock potential — which leads to enhanced reflection of the ions, and subsequent excitation of waves far upstream. The non-stationarity can also be seen in the filtered spacecraft data, suggesting that this is the reason for the difference between the magnetic field profiles measured by different Cluster spacecraft, not the large scale shock reformation.

A central goal of this study was to understand how the reflected ions control the dynamics of the shock for intermediate ion $\beta_i = 0.5$ values. In the simulation with a low ion to electron mass ratio, m_i/m_e=100, the B_z component of the magnetic field has a similar periodical steepening and flattening behavior as for the real mass ratio (Figure 2). However, unlike for the real mass ratio, there are no indications about upstream or downstream small wavelength waves, which means that the modified two stream instability (MTSI) is not excited. Nonlinear whistler precursors are also not visible. The periodical flattening and steepening of the shock ramp appears thus to occur irrespective of the excitation or not of the MTSI, and the associated non-stationarity is better described as a ”breathing” behavior of the shock, with periodical changes in the ramp steepness.

We have also determined an averaged reflected ion density upstream of the minimum E_x location, n_{ref}, shown in the left top panel of Figure 3, by counting the reflected ions within a given small distance back upstream. The left bottom panel of Figure 3 shows the variation of the minimum E_x (maximum absolute value) with time — changing with the same periodicity as the reflected ion intensity. When the shock ramp is sharp, the large electric field in the normal direction leads to a high reflection rate of solar wind protons. As these protons propagate upstream, the ion bulk velocity decreases and the magnetic field increases in the foot of the shock, which results in a flattening of the magnetic field profile and at the same time in a decrease

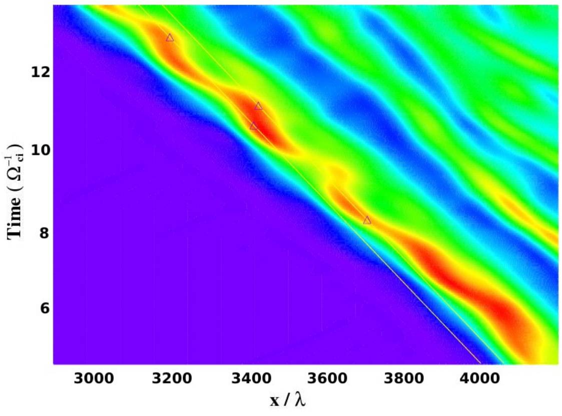

Figure 1: Color-coded magnetic field (in the simulation frame), after removing the high-frequency waves by a low-pass filter. The traces of two artificial spacecraft traversing the shock from upstream to downstream are indicated by the two white lines.

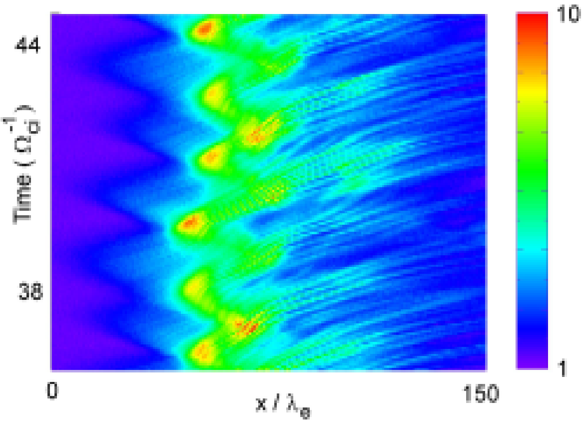

Figure 2: Color coded magnetic field B_z component in the $t - x$ plane for an ion to electron mass ratio of 100. The magnetic field is shown in a reference frame moving with the average speed of the shock.

of the normal electric field. Subsequently, the reflection rate decreases and the shock steepens again, on a time scale of the order of the ion gyroperiod.

This work is currently extended by a deeper inspection of the relationship between the reflected ions and the non-stationarity of the shock ramp. Each ion trajectory is followed from the injection in the simulation box until the particle reaches the downstream plasma region, which enables the exact counting of the reflected ions at any given time and position. The right plot of Figure 3 shows the newly obtained temporal variation of the reflected ion intensity (top) and of the maximum fluctuation in the electric field, $|\Delta E_x|$, measured in the vicinity of the shock ramp (bottom).

Shocks in the solar system (bow shocks, interplanetary traveling shocks) have Alfvén Mach numbers below about 10. However, higher Mach number shocks are of great interest for other astrophysical objects, like young supernova remnants (SNRs). We have therefore expanded our work to higher Mach numbers, for example we performed a one-dimensional PIC simulation of a shock with $M_A = 22$ (*Scholer and Comişel, 2011*). Other parameters in this case were Θ_{Bn} = 85°, $\beta_i = \beta_e$ = 0.5. The ion to electron mass ratio was close to the physical ratio, m_i/m_e = 1500, and the ratio of the electron plasma frequency to the electron gyrofrequency was $\omega_{pe}/\omega_{ge} = 20$. The simulated shock was highly non-stationary, but did not exhibit the reformation pattern reported in other simulation studies, for medium Mach number perpendicular or quasi-perpendicular shocks. The magnetic field profile flattened and steepened with a time period of about $1.5\omega_{gi}^{-1}$. Up to 60% of the incident ions were reflected at a steepened ramp during times with large electric field component in the shock normal direction. Large amplitude waves were excited in the foot by the modified two-stream instability.

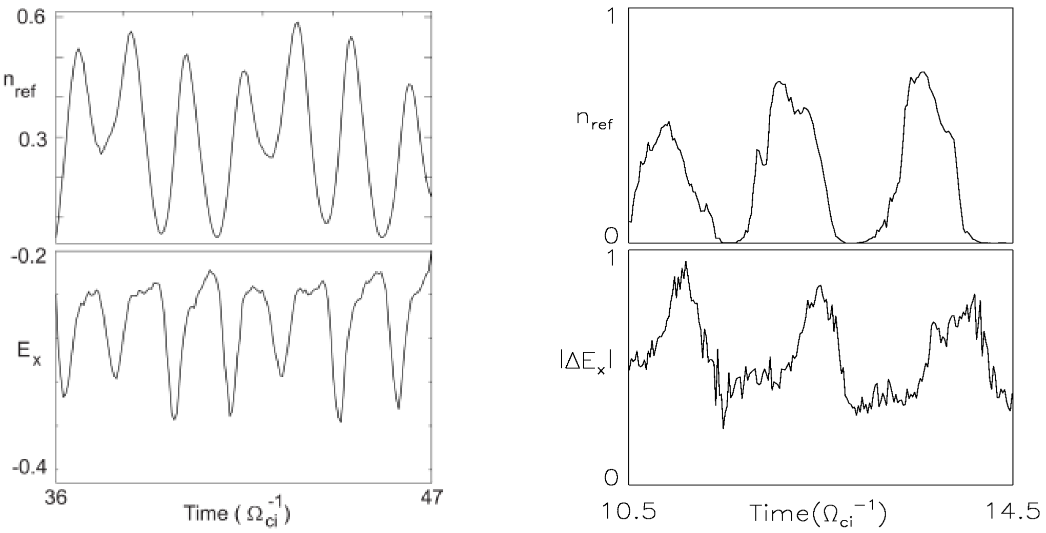

Figure 3: *Left:* Number of reflected ions (normalized to the incoming number), within a distance of $50\lambda_e$ upstream of the minimum E_x (top) and minimum E_x (bottom). *Right:* Number of reflected ions upstream of the shock ramp (top) and maximum fluctuation in the electric field (bottom).