Plasma Physics View of Particle Acceleration

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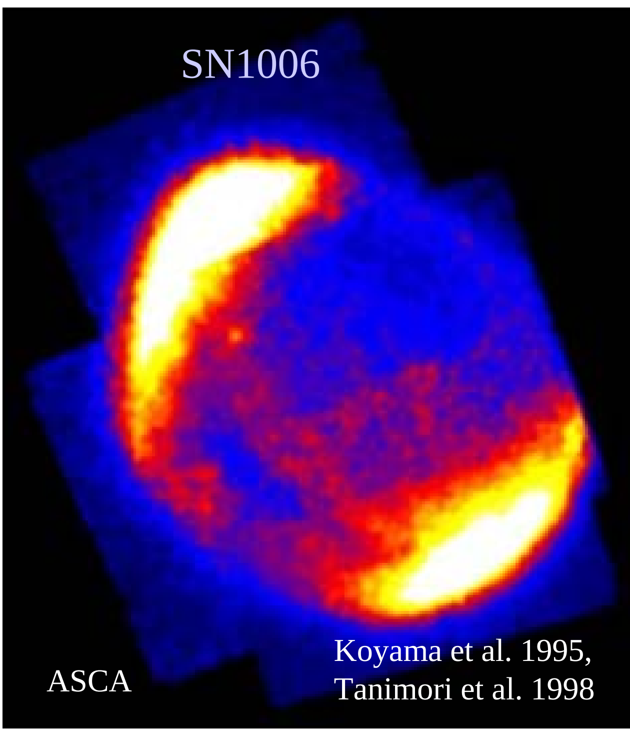
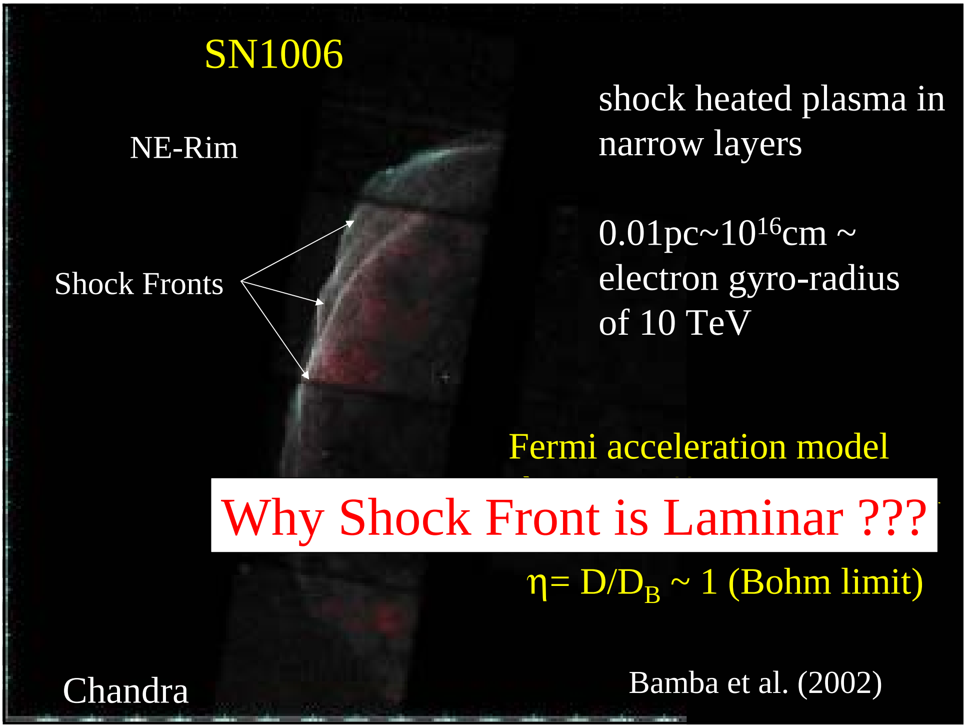


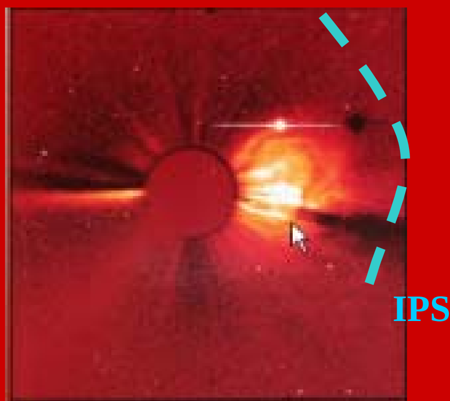
Super Nova Explosion in A.D. 1006

Bright Rim→ Shock Heated Plasma 100TeV



Interplanetary Shock: Diffusive Shock Acceleration in Heliosphere

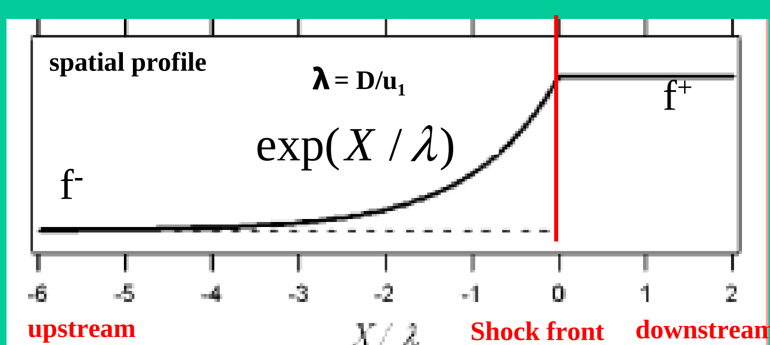
Strong Shocks --- Interplanetary Shock (IPS)
(Solar Flare-Initiated Shock)



1000 ~ 4000 km/s

Coronal Mass Ejection (CME)

Diffusive Shock Acceleration (DSA)



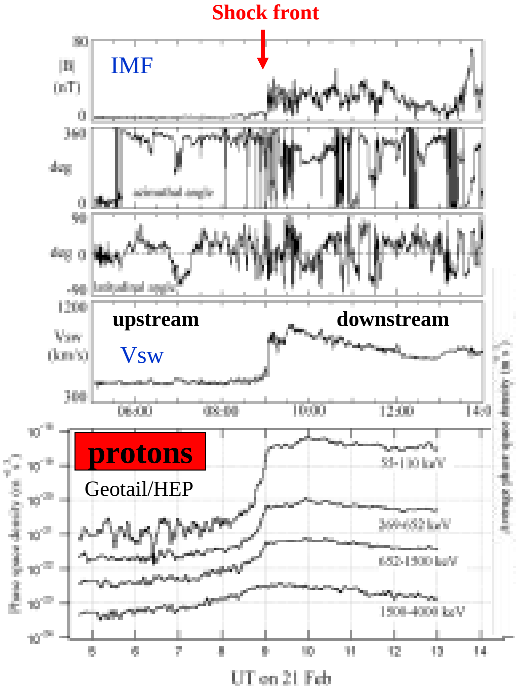
differential momentum spectrum

$N(p) \propto f(p) \cdot p^2 \propto p^{-q}$

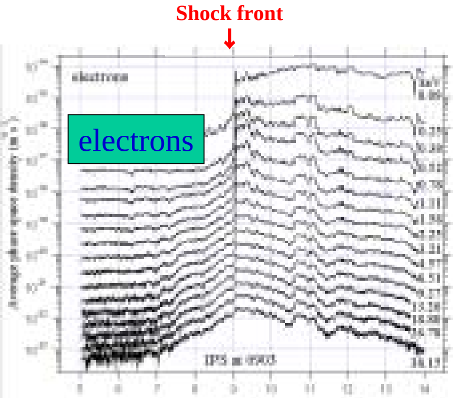
with $q=(r+2)/(r-1)$,

r: compression ratio

Nonthermal Energy Spectrum E^{-2}



Interplanetary Shock
on 1994/2/21 at 1AU



(Shimada et al. Ap. Space Sci., 2000)

Diffusion Coefficient: $D=(1/3)\ l\ w$

(l : mean free path; w :particle velocity)

"l" depends on level of turbulence

strongest limit :

Bohm limit: $l \rightarrow \rho_c$, $D_B=(1/3)\ \rho_c w$

Heliosphere : Interplanetary Shocks

$\eta=D/D_B$ with $\eta \sim 10 - 100$ for proton

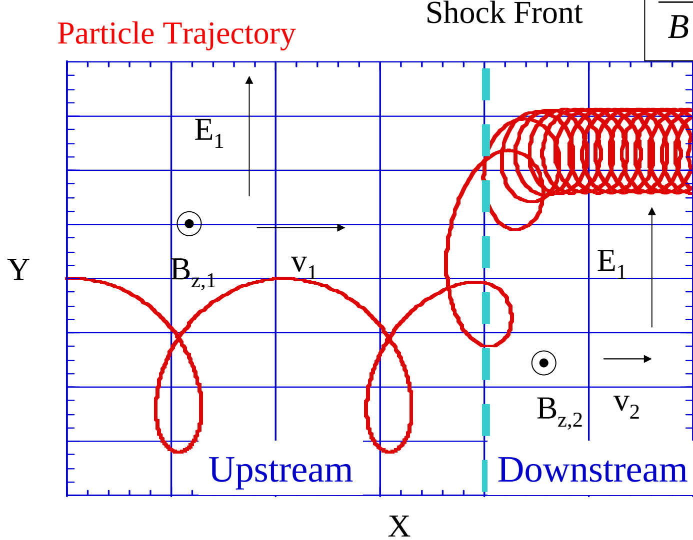
$\eta \sim 500\text{-}10000$ for electron

Other Acceleration Processes

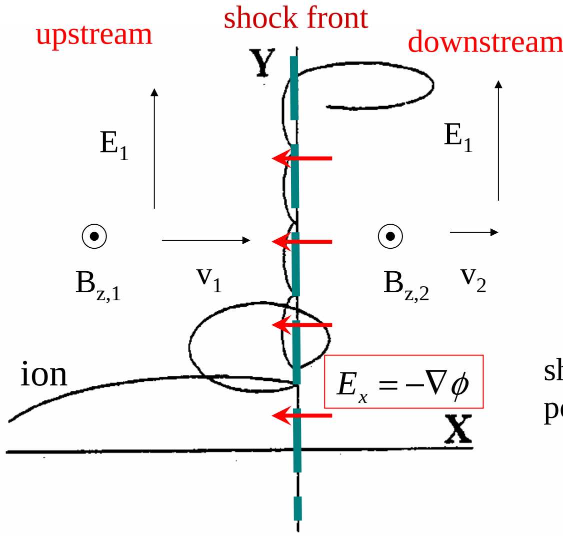
- ☐ Shock Drift Acceleration
- ☐ Shock Surfing Acceleration

Shock Drift Acceleration

$$\frac{v_\perp^2}{B} = cnst$$



Ion "Shock Surfing" Acceleration



Reflection condition

$$\frac{1}{2} m v_x^2 < e\phi \cong \frac{1}{2} m v_1^2$$

shock potential ϕ due to polarization electric field

Sagdeev (1966), Sagdeev and Shapiro (1973), Katsouleas and Dawson (1983), Lembege et al. (1983), Ohsawa (1990),…Lee et al. (1996), Zank et al. (1996),….

Energy Spectrum in Shock Surfing Acceleration

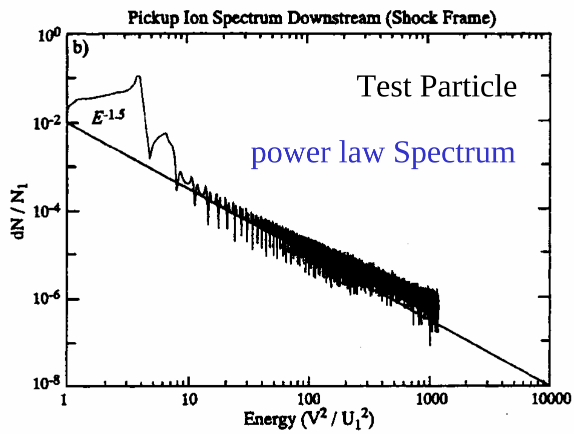


Figure 8. The transmitted PI spectrum at a perpendicular shock in the (a) fluid and (b) shock frames. An $E^{-1.5}$ power law has been plotted over the computed spectrum for the purposes of illustration. See text for further details. $V_{spec}/u_1 = 0.25$.

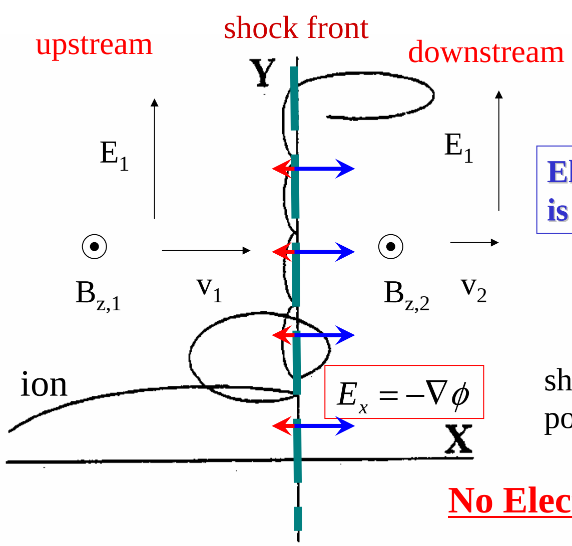
(Zank et al. JGR, 1996)

Shock Surfing Acceleration (SSA)

→ Localized Region along Shock Front
→ Fine Structure

But …
electron acceleration cannot be realized by the standard shock surfing acceleration

Ion "Shock Surfing" Acceleration



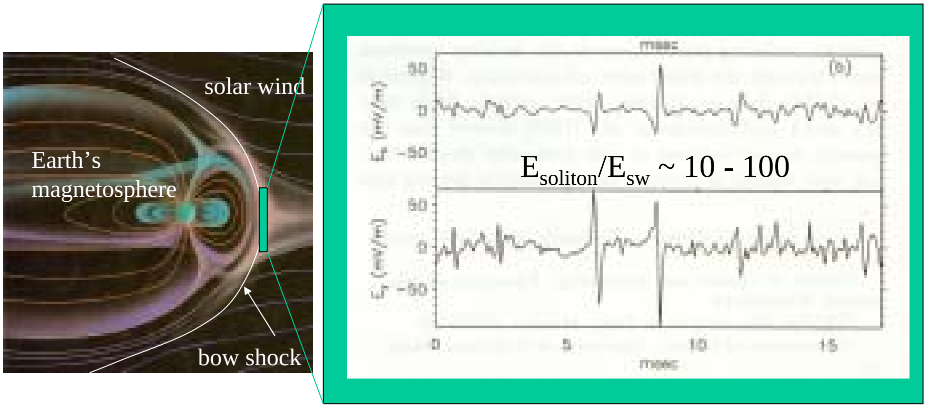
Electron Shock Surfing is possible

shock potential ϕ due to polarization electric field

No Electron Reflection !

“Solitary waves” in the Earth’s bow shock

quasi-perpendicular, $M_s \sim 9.5$



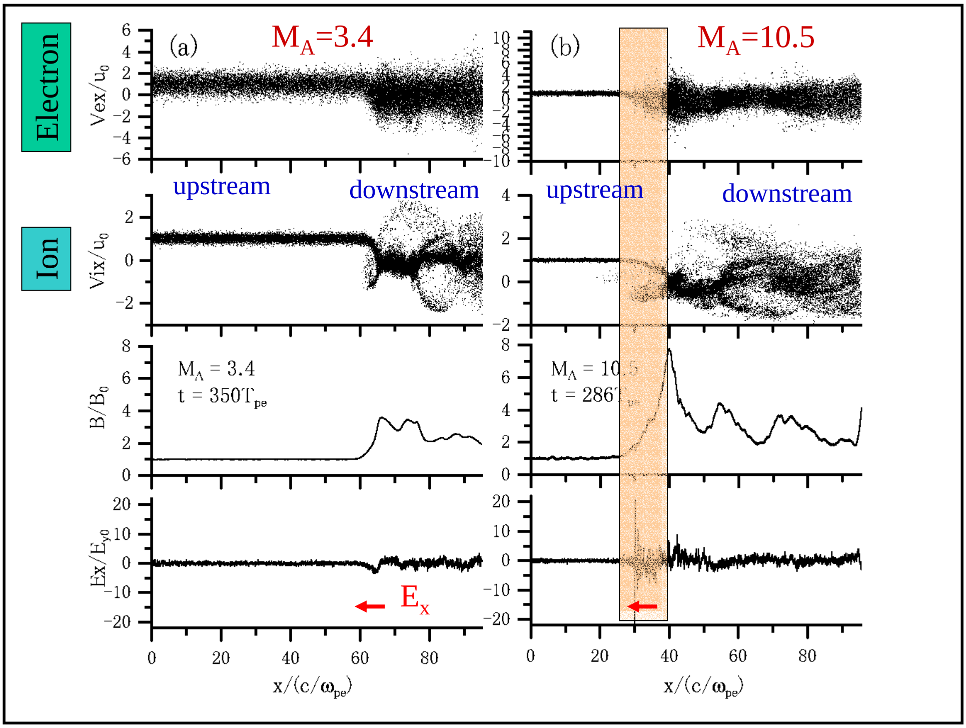
<u>Scale of Solitary wave ~ Electron gyro-radius</u>

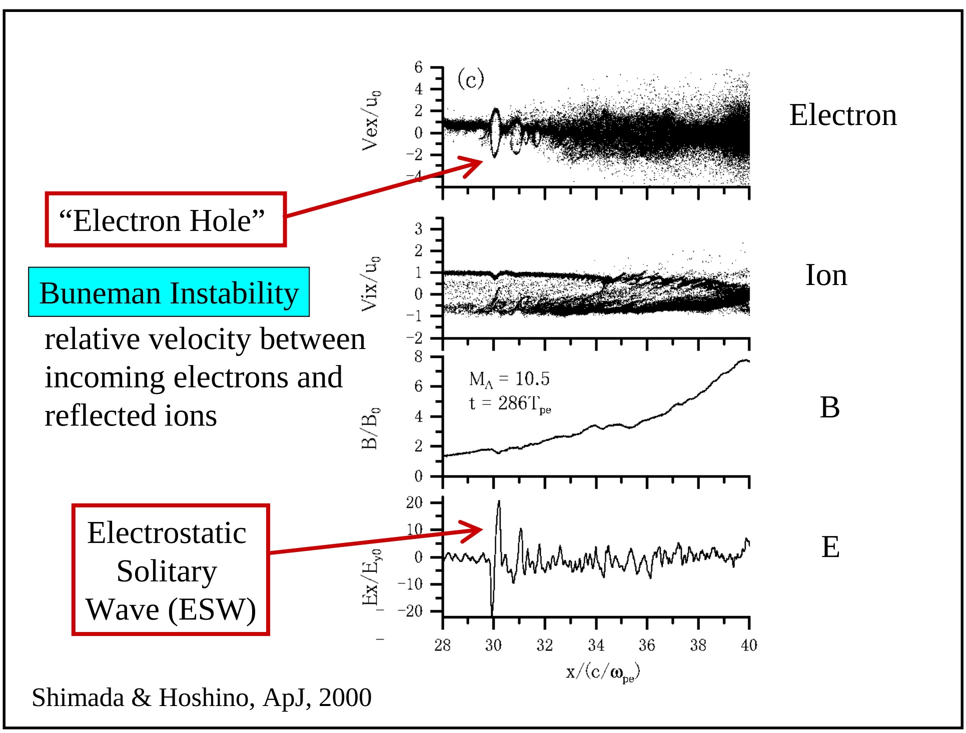
(Bale et al. GRL 1998, Matsumoto et al. ASR 1997)

<u>Plasma Particle-in-Cell Simulation</u>

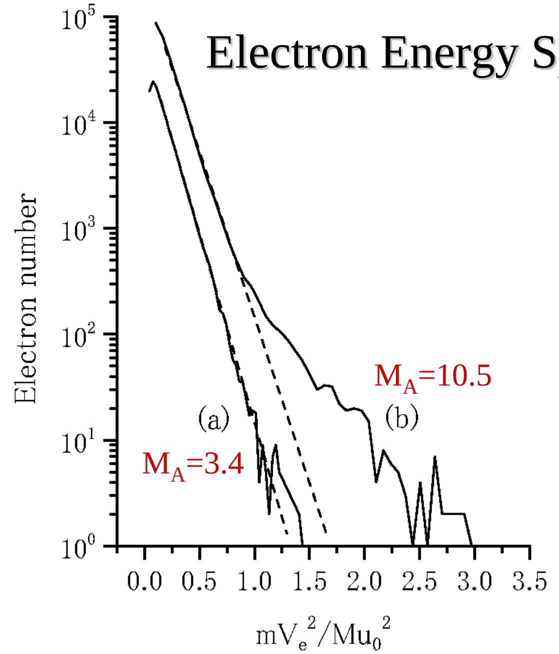
A set of Maxwell’s Equations
+ relativistic Lorentz Equation

Mach number : 3 ~ 20
$M_{ion}/M_{ele} = 20$
100 grids for electron inertia length
Simulation system size: 100 ~ 300 electron inertia

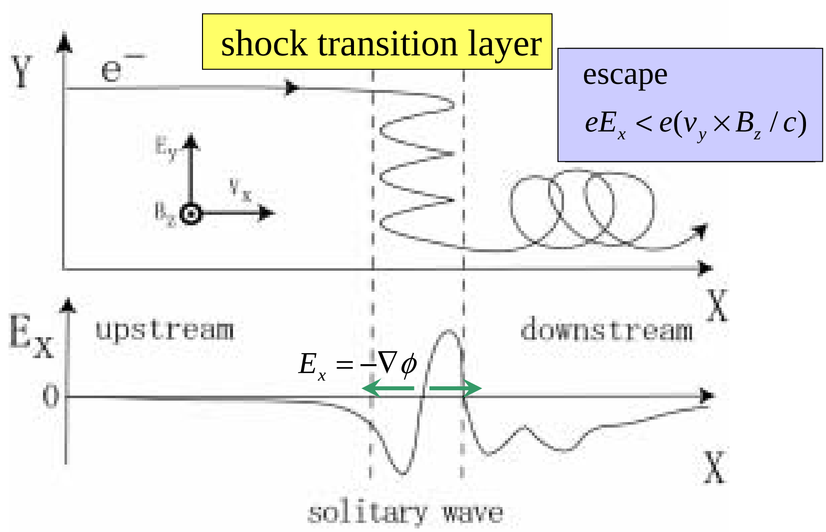

Electron
Ion
(a)
M_A=3.4
(b)
M_A=10.5
Vex/u_0
Vix/u_0
B/B_0
Ex/E_{y0}
upstream
downstream
upstream
downstream
M_A = 3.4
t = 350T_{pe}
M_A = 10.5
t = 286T_{pe}
E_x
x/(c/ω_{pe})
x/(c/ω_{pe})


(c)
Vex/u_0
Vix/u_0
B/B_0
Ex/E_{y0}
M_A = 10.5
t = 286T_{pe}
x/(c/ω_{pe})
Electron
Ion
B
E
“Electron Hole”
Buneman Instability
relative velocity between incoming electrons and reflected ions
Electrostatic Solitary Wave (ESW)
Shimada & Hoshino, ApJ, 2000

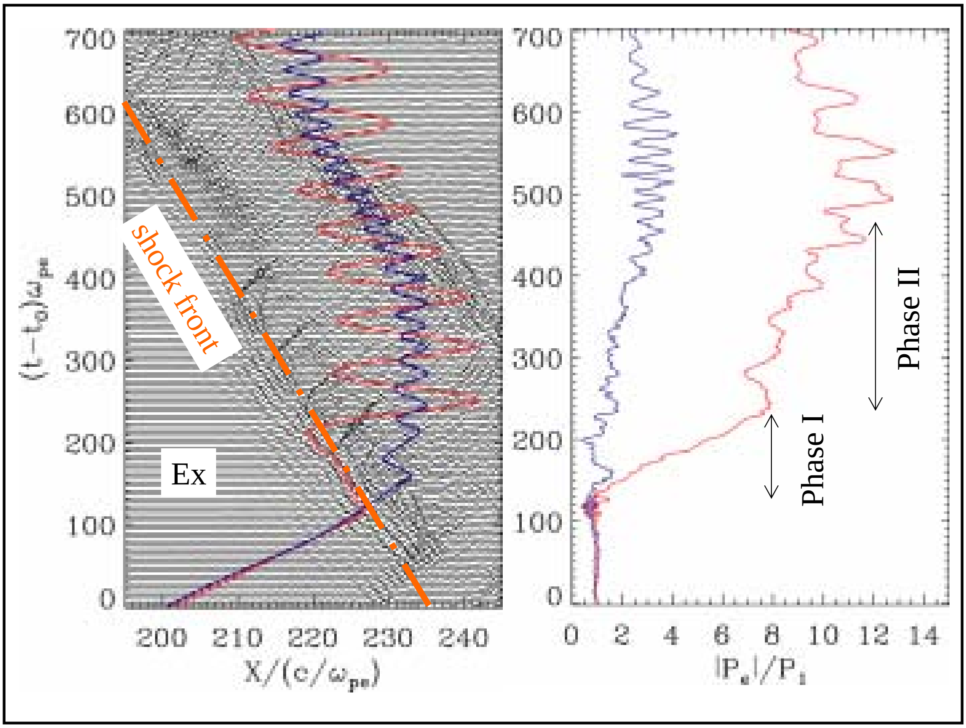
Electron Energy Spectra



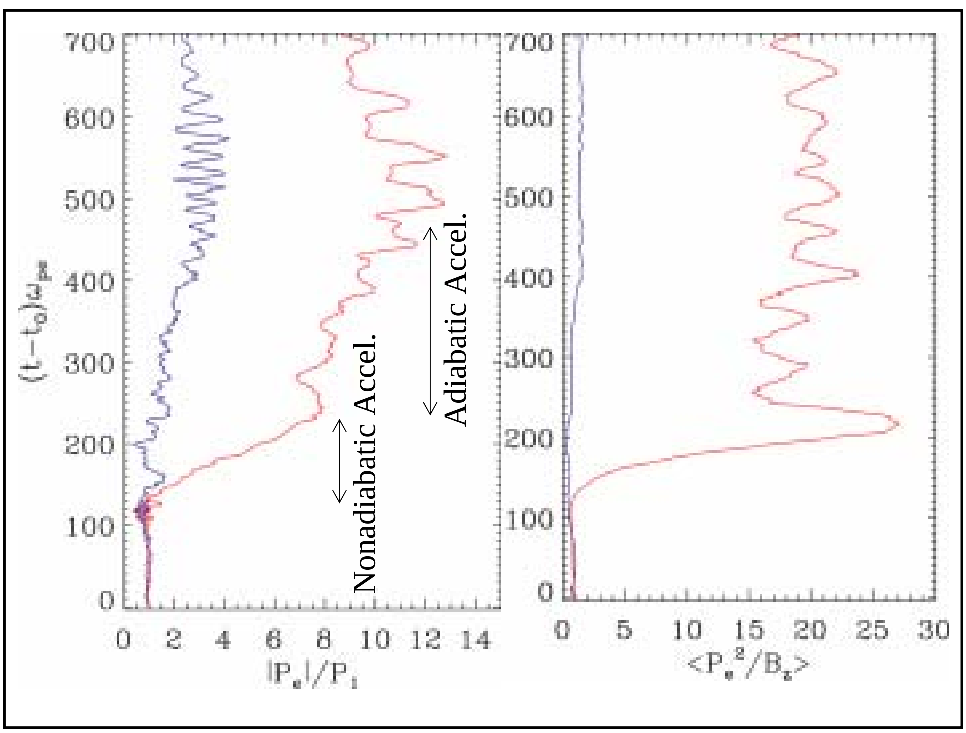
"Electron Shock Surfing" Mechanism



Hoshino & Shimada, ApJ 2002



shock front
Ex
Phase I
Phase II
(t-t0)ωpe
X/(c/ωpe)
|Pe|/Pi



Nonadiabatic Accel.
Adiabatic Accel.
(t-t0)ωpe
|Pe|/Pi
<Pe²/Bz>

Maximum Electron Energy

$$\frac{dp_x}{dt} = eE_x + e\frac{v_y \times B_z}{c}$$

$$F_E > F_B \rightarrow \text{trapped}$$
$$F_E < F_B \rightarrow \text{deptapped}$$

$$F_E \approx eE_{ESW}$$
$$F_B \approx \frac{e}{c} v_y B$$

Nonlinear Buneman Instability

$$E_{esw}^2 / 8\pi \approx \alpha m_e n V_d^2 / 2, \qquad \alpha = 1/4 \sim (m_e / m_i)^{1/3}$$

Ishihara et al, 1981; McClements et al. 2001

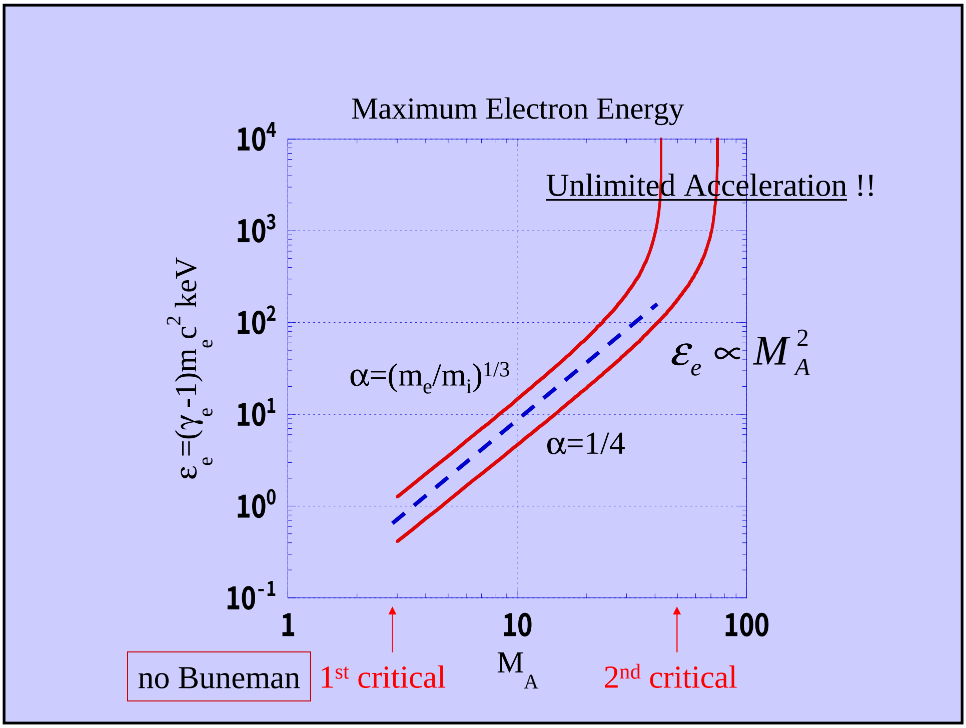
Maximum Electron Energy

$$F_E = F_B \quad \Rightarrow$$

$$v_{y,\max} \sim \begin{cases} 2cM_A\sqrt{\alpha m_e / m_i} & \text{for } 2M_A\sqrt{\alpha m_e / m_i} < 1 \\ c & \text{for } 2M_A\sqrt{\alpha m_e / m_i} > 1 \end{cases}$$

unlimited electron acceleration condition

$$M_A > (1/2)\sqrt{m_i / (m_e \alpha)} \approx 43 \sim 75$$



Summary

- "Electron" Shock Surfing Acceleration
  fine structure along shock front
- Unlimited Acceleration if M_A > several 10
- Acceleration Time Scale
  $\tau_{SSA}\,\Omega_c \sim c/v_s$ (cf. $\tau_{DSA}\,\Omega_c \sim \eta(c/v_s)^2$)

possible to explain up to knee energy