PIC Simulations of Reforming Supercritical Shocks- prospects for particle acceleration

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•Kinetic physics of collisionless, supercritical shocks via full kinetic (PIC) simulations

•Simplest geometry- perpendicular, '1.5D'

• what happens at higher Mach nos- non- steady 'reforming' solutions.

•discuss generation of suprathermal particles at the shock- do not treat subsequent diffusive acceleration, Fermi etc

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Thanks to….

R. Lee (Warwick), M. E. Dieckmann (Warwick-Linkoeping-Bochum), H. Schmitz (Warwick-Bochum)

R. O. Dendy, K. McClements (UKAEA Fusion, Culham)

Astroplasma Network members…..

Results in:

Chapman et al, Space Sci. Rev., in press (2005)

Lee et al. Astrophys.J. 604:187 2004, Phys Plasmas 12, 12901,2005, Annales Geophys. 23,643,2005

Schmitz et al Ap. J. 570, 637, 2002a, 597, 327, 2002b

McClements et al PRL, 87,25502,2001

***See also the literature** on reforming shocks… Hoshino and Shimada, Lembege et al, Scholer et al ++….plus an extensive literature on stationary q-perp shocks, q- parallel shocks..*

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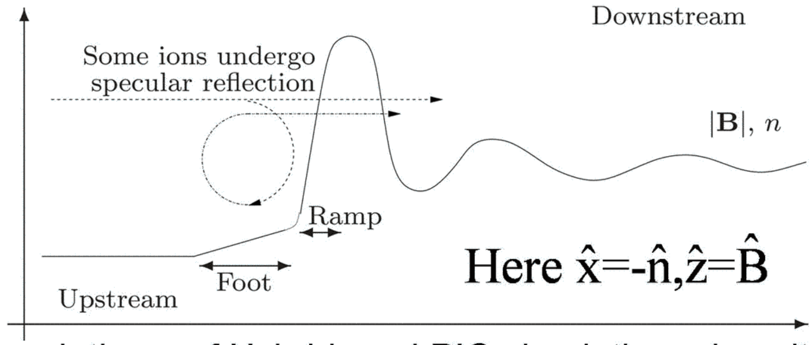
‘Standard’ quasi-perpendicular supercritical shock



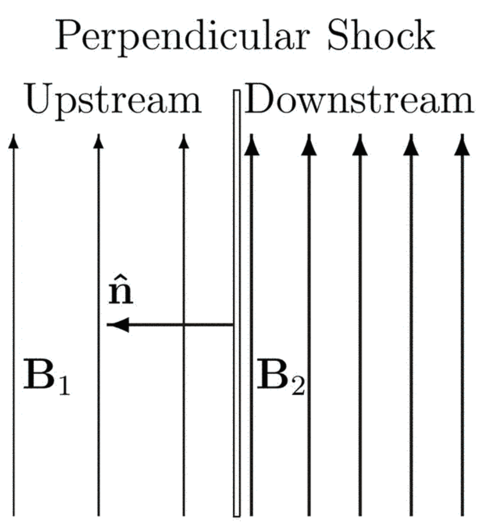
Here $\hat{x}=-\hat{n}, \hat{z}=\hat{B}$

Steady solutions, cf Hybrid, and PIC simulations, in –situ observations of planetary bow shocks -for sufficiently high β_i, sufficiently low M_A

Ions are (I) Specularly reflected to form foot, energised and transmitted- collisionless shock heating or (II) transmitted directly.

Geometry

- B-field constrains upstream ion transport
- Physical shock not exactly ⊥- but here treat this geometry as a simplifying first step (k⊥B)



Here $\hat{x}=-\hat{n}, \hat{z}=\hat{B}$

Numerical Simulation Method

- Relativistic Particle In Cell code
- Simulation box:
  - 15000 cells ~$30R_{gi}$
  - 200 particles / cell each species

$m_i / m_e = 20$, $\omega_{pe}/\omega_{ce}=20$

SNR:

bulk protons only

$M_A = 10.5$,

$\beta_i = \beta_e = 0.15$

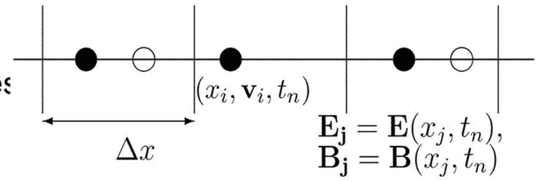
+α's up to 25%(preliminary results)

Pickup protons (if time/interest):

Bulk protons +10%pickup protons

$M_A = 8$

$\beta_i = 0.2$, $\beta_e = 0.5$



Fields on spatial grid, λ_D

1-D (x), 3-D velocities,E,B

Shock following algorithm

Particles moved via Lorentz, fields evolved by full Maxwell

All results shown in downstream rest frame

$v_A/\omega_{ce} \approx 70\Delta x$, $c/\omega_{pi} \approx 320\Delta x$ for SNR case

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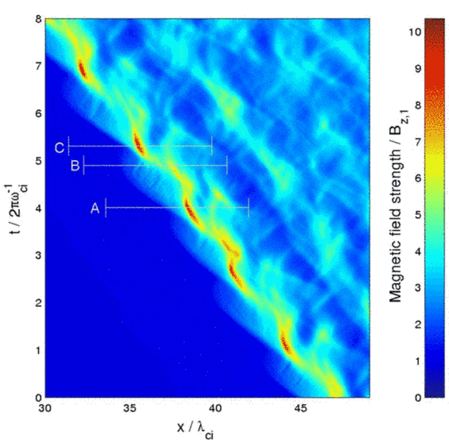
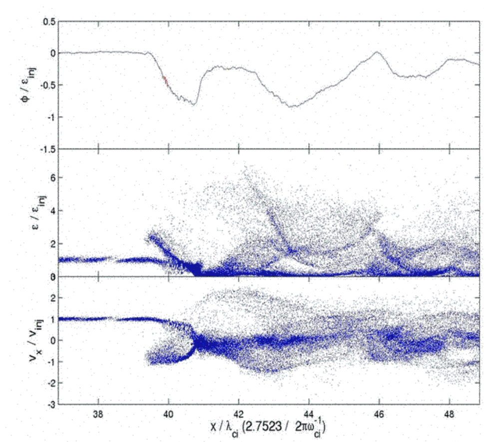
PIC simulations of 'SNR': bulk protons, electrons only

$M_A = 10.5$, $\beta_i = \beta_e = 0.15$



B field



proton phase space

Lee, Chapman, Dendy, Ap. J.,2004

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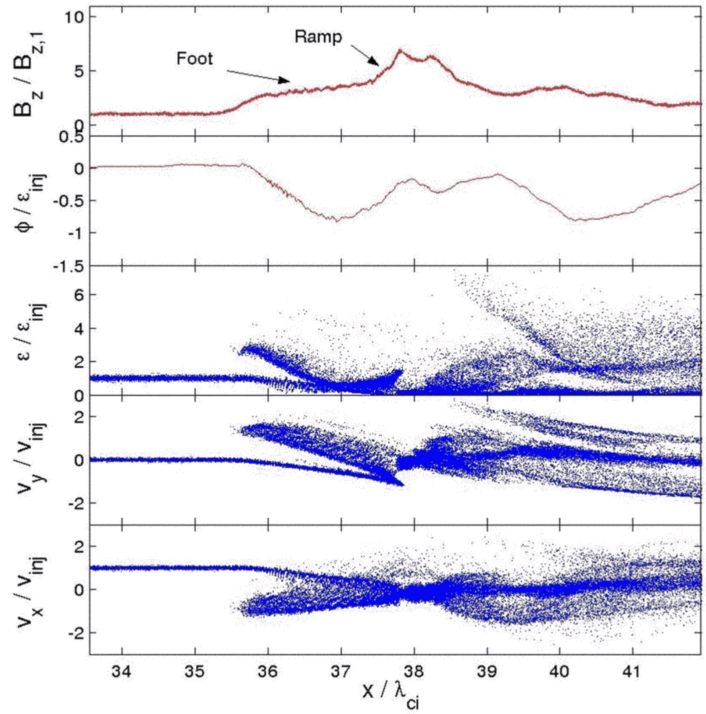
A

- Ions reflected from ramp to form foot region.

- B_z increases.
- Potential well.
- Ions energised in foot region.



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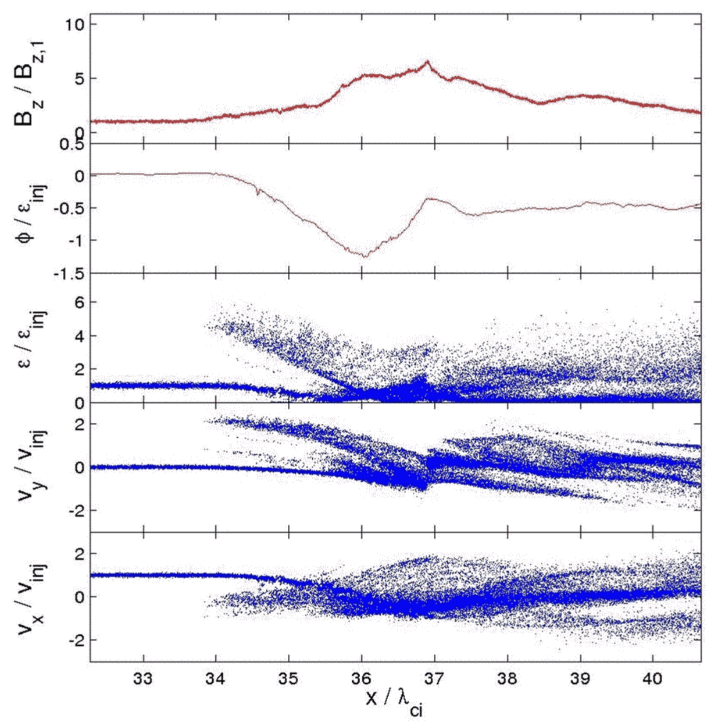
B

- Gyration brings reflected ions back to the shock front.
- Energisation finishes-move downstream.
- New ramp starts to form at upstream edge of foot.
- Potential well collapses as ions leave.



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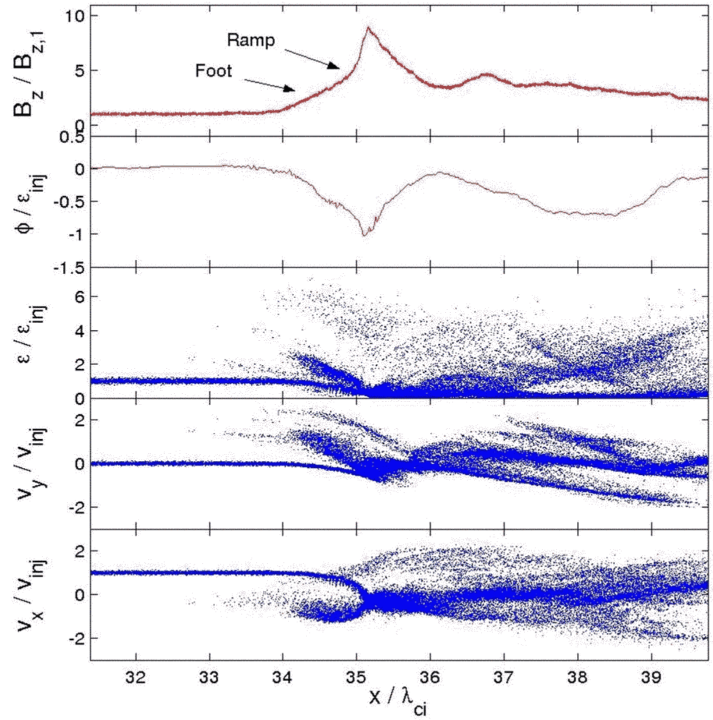
C

- New ramp now fully formed.
- Ions reflection recommenced.
- Potential well at narrowest, and deepest.



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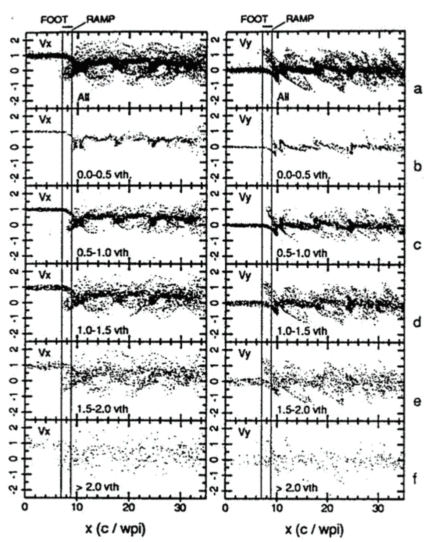
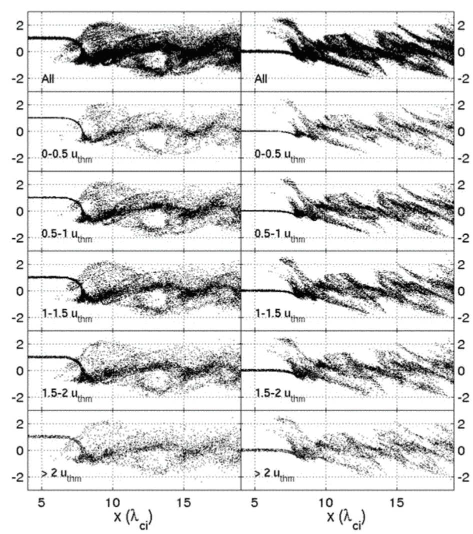
Which Ions Are Accelerated?





Stationary (hybrid)
-Burgess et al JGR'87

Reforming (PIC)
-Lee et al, PoP '05

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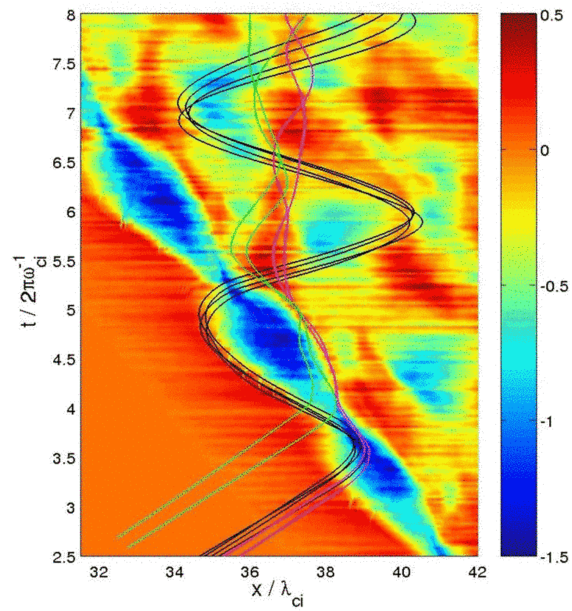
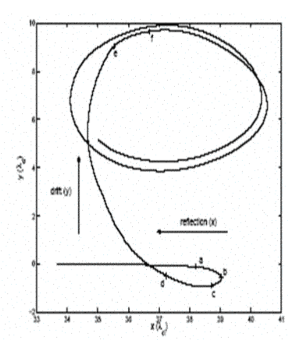
‘Bunching’ of reflected ions

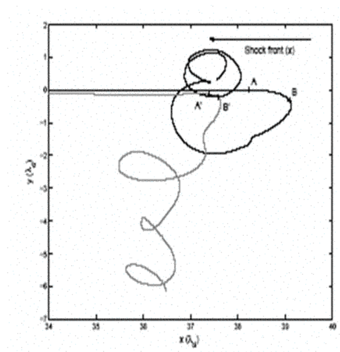
- Energised ions: Black
- Low energy ions, Before: Magenta
  After: Green
- Reflected ions coherent in phase space



Proton trajectories perpendicular to B



Shown in **downstream rest frame-** shock is moving to the left



Suprathermal proton- reflection and acceleration along shock (limited to one gyration) in the foot region

Directly transmitted protons

Relevant fields are on ion scales

Fields on ion scales:

$$m_e n_e \frac{D\mathbf{v}_e}{Dt} = -en_e(\mathbf{E} + \mathbf{v} \wedge \mathbf{B}) - \nabla P_e + ..$$

with $m_e n_e \frac{D\mathbf{v}_e}{Dt} \to 0$,

$\nabla \wedge \mathbf{B} = \mu_0 \mathrm{J}$ and $n_i \approx n_e$

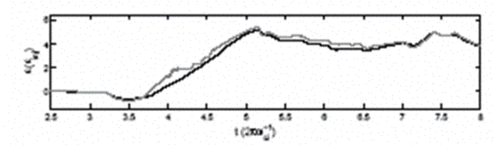
gives 'ion scale' fields:

$$\mathbf{E} \sim -\hat{x}\frac{1}{en}\frac{\partial}{\partial x}\left(\frac{B^2}{2\mu_0}\right) - \mathbf{v}_\mathrm{i} \wedge \mathrm{B}$$

compare with ion energy gain

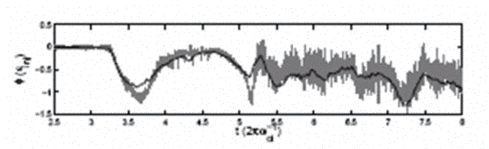
$$\varepsilon = \int \mathbf{v} \cdot \mathbf{E} dt$$

Lee et al, Phys. Plasmas 2005



$\varepsilon = \int \mathbf{v} \cdot \mathbf{E} dt$ along trajectory

for $\mathbf{E}(\mathbf{PIC}), \mathbf{E}(\textbf{ion scale})$



$\int^t \mathbf{E}(x_i(t)) \cdot \mathbf{dx}$ along trajectory $x_i(t)$

for $\mathbf{E}(\mathbf{PIC})$, $\mathbf{E}(\textbf{ion scale})$

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Scaling of ion acceleration

characteristic scales of the foot region: $T \sim \frac{1}{\omega_{ci}}, L \sim \frac{v_{inj}}{\omega_{ci}}$

and since non relativistic at injection: $\varepsilon \sim \frac{1}{2} mv^2$

now change parameters, as: $L \to L', T \to T', m \to m', v_{inj} \to v_{inj}'$

if a reforming shock still exists (same physics) then:

$$\Delta\varepsilon' = \Delta\varepsilon \frac{m' L'^2 T'^{-2}}{m L^2 T^{-2}} = \Delta\varepsilon \frac{m' v'^2_{inj}}{m v^2_{inj}}, \text{ or, with } \varepsilon_{inj} = \frac{1}{2} m v^2_{inj}, \quad \frac{\Delta\varepsilon'}{\Delta\varepsilon} = \frac{\varepsilon_{inj}'}{\varepsilon_{inj}}$$

then from our simulations 'ballpark figure' $\Delta\varepsilon \approx 6\varepsilon_{inj}$, so $\Delta\varepsilon' \approx 6\varepsilon_{inj}'$

putting in numbers (*Ellison et al*, 1999)

$M_R = 1836, v_{inj} \approx 2.5 \times 10^7 ms^{-1} (M_A \sim 100, B \sim 10^{-7} T)$

gives: $\Delta\varepsilon' \sim 16 MeV$

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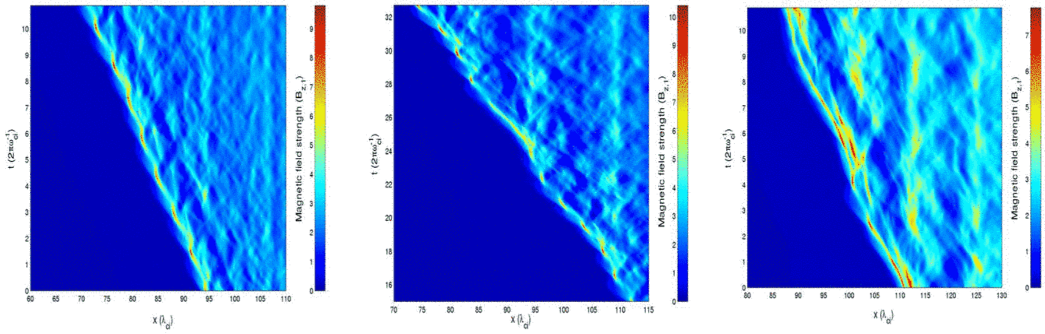
B field M_A=10.5



4% α's 10% α's 25% α's

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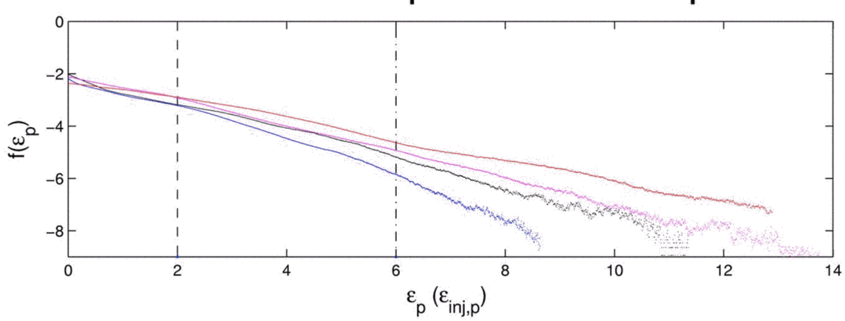
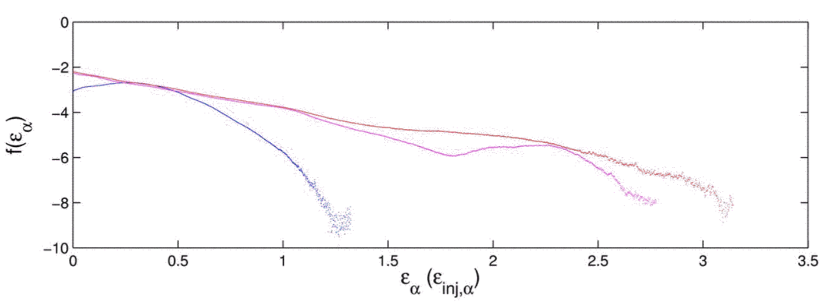
Ion acceleration in the presence of α particles



Upper plot-Protons log scale f(E) vz E M_A=10.5 and 0(black) ,4,10,25% α's
Lower plot- α's as above



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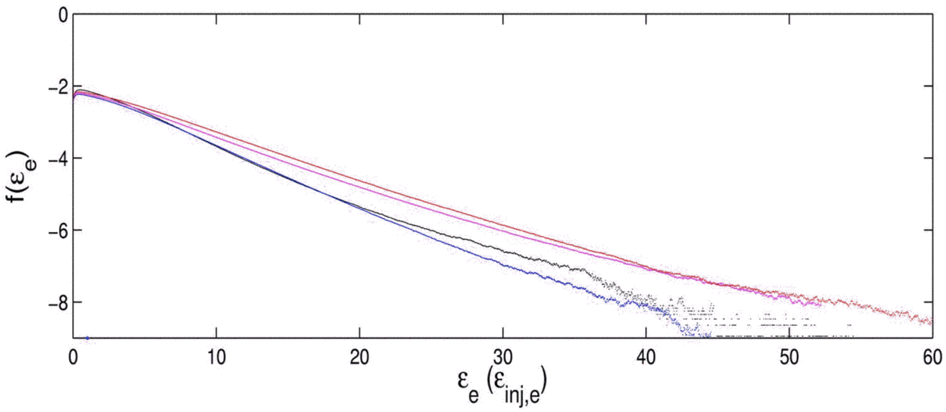
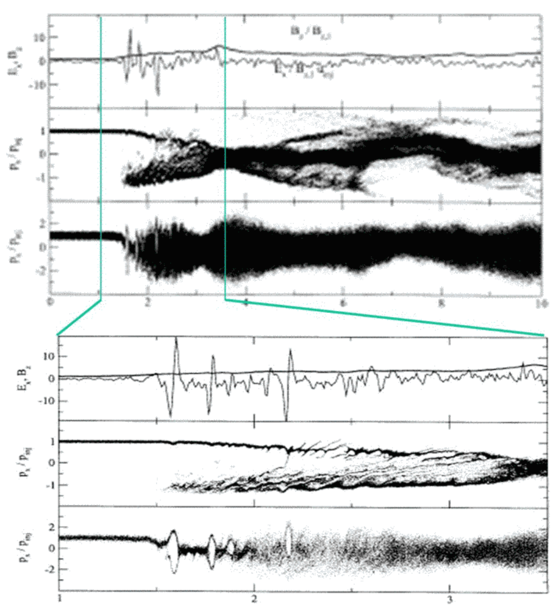
Electron acceleration in the presence of α particles



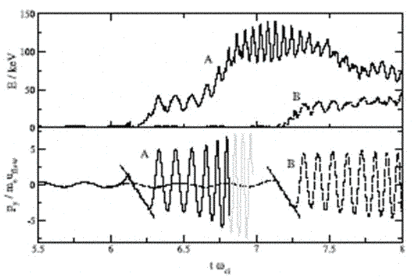
A different story to the protons…

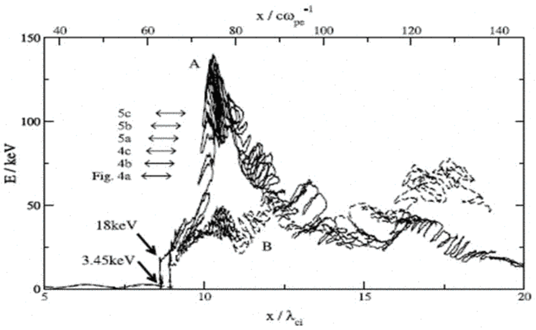
Electron acceleration?

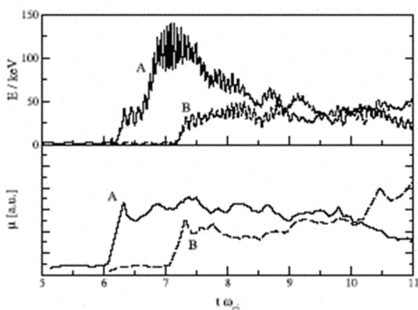


beta=0.15 ,
M_A=10.5
n.b. m_i/m_e=20

Schmitz et al Ap. J. 2002a, 2002b
McClements et al PRL,2001







y acceleration along E_y within phase space hole, then gyration

Depends on generation of phase space holes…

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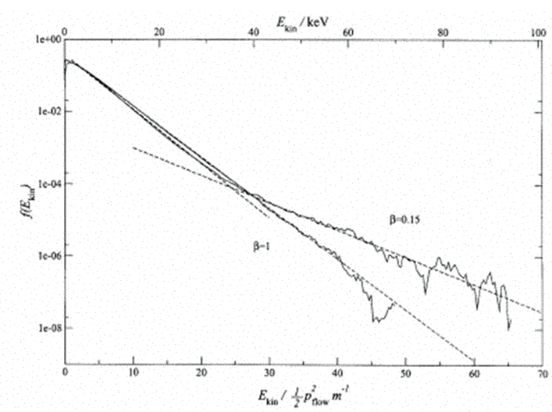
Electron f(e)



- Exponential suprathermal tail
- Increased upstream β 'switches off' phase space holes- and energization

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Conclusions

Full kinetic (PIC) simulations of reforming perpendicular shock solutions, to investigate generation of suprathermal particles

Bulk protons have 'bursty' acceleration ~6x(upstream KE), exponential f(E)

- energization scales with upstream KE, ie with m_p, U^2
- 'additional' acceleration occurs in foot region, not at shock ramp
- Energization due to fields on ion scales- unaffected by details of electron kinetics thus insensitive to mass ratio

At SNR: energization scales to ~ 16 MeV protons leaving shock front

- new dynamics at >10% α's- possible new acceleration mechanisms?

Electrons- 'surfatron' acceleration in phase space holes- if they exist

Pickup protons: Reforming shock dynamics persist in the presence of pick up proton extended foot region upstream of shock

- Pick up protons accelerated to ~few 10s of (upstream KE)- reforming shocks no longer support MRI acceleration?

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Values

- $M_A = 10.5$
- $\beta_i = \beta_e = 0.15$
- $m_i / m_e = 20$
- $\omega_{pe} / \omega_{ce} = 20$
- Simulation box:
  - 15000 cells
  - 200 particles / cell

- $B = 10^{-7}$ Tesla
- $n = 4 \times 10^7\ m^{-3}$
- $v_1 = 3.4 \times 10^7\ ms^{-1}$
- $2\pi\omega_{ci}^{-1} = 46000\Delta t$
- $r_{li} = 530\Delta x = 530\lambda_D$
- $\lambda_D = 12\ m$
- $v_A / \omega_{ce} = 186m = 73\Delta x$
- $c / \omega_{pi} = 4000m = 326\Delta x$

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