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FÜR PLASMAPHYSIK

Electrostatic waves and electron holes in PIC simulations of the Earth's bow shock.

PLASMA ASTRO

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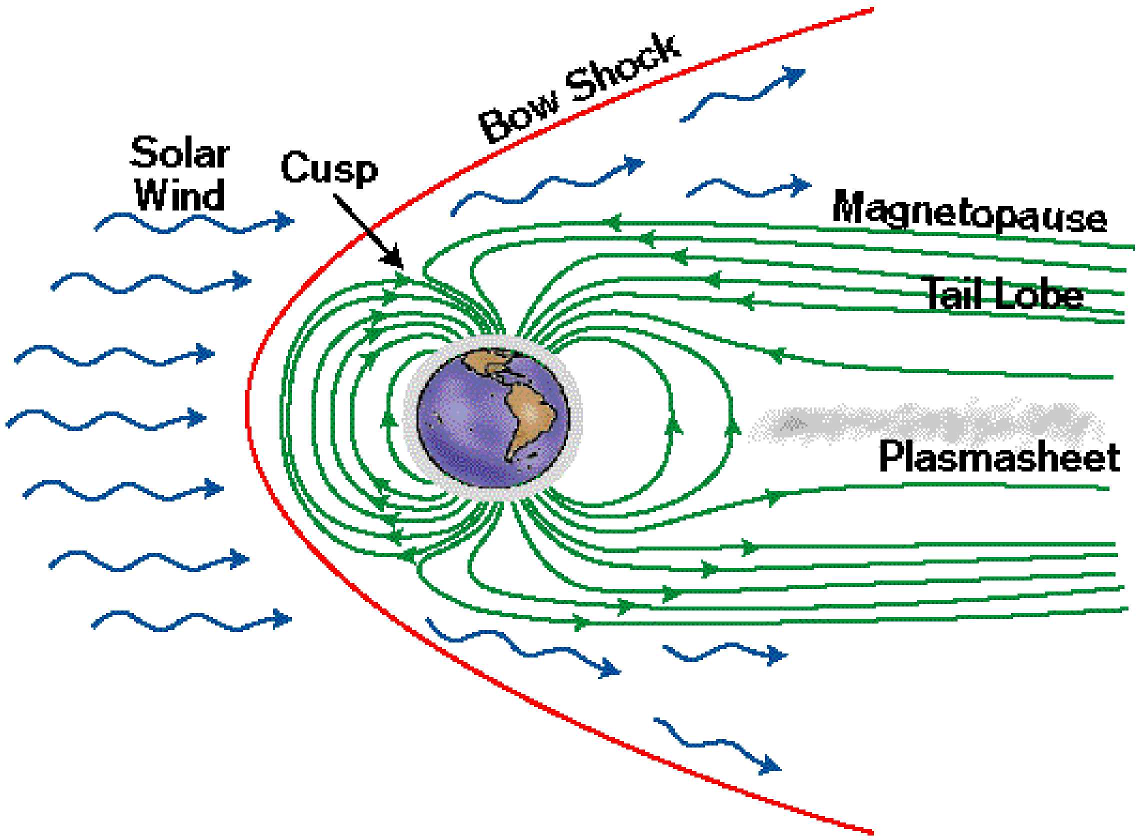
The Earth's Bow Shock

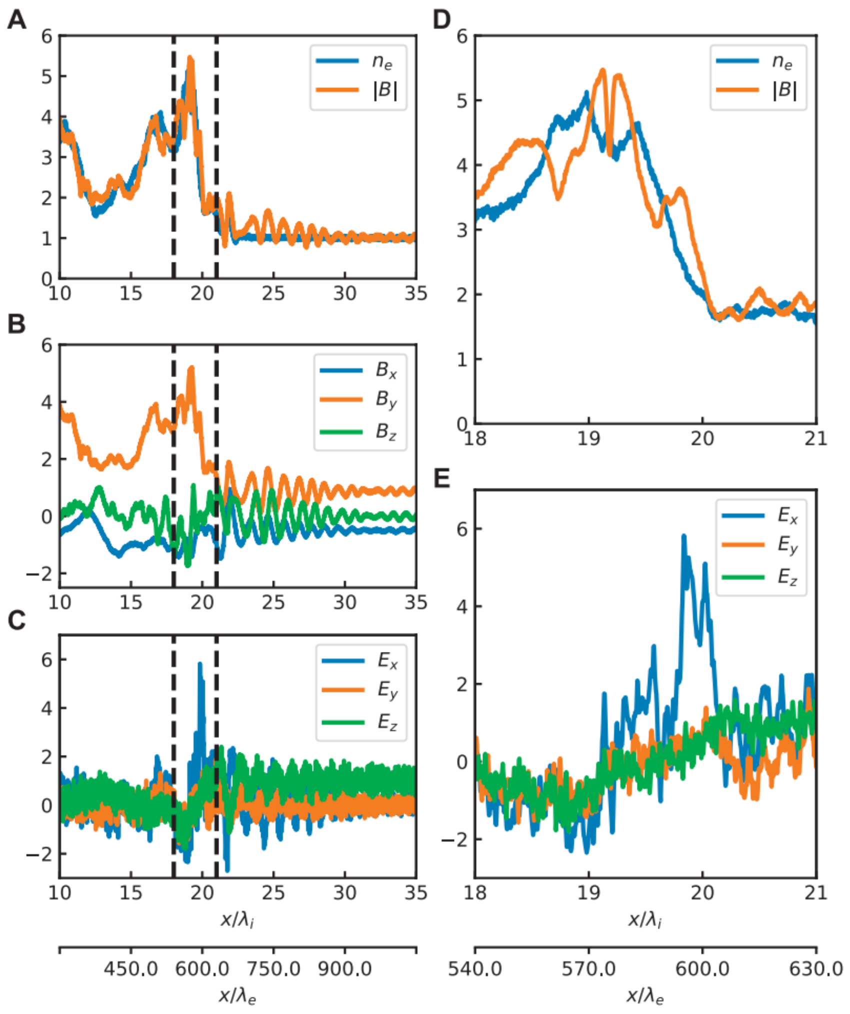
- Nonrelativistic shocks: $v_{sh} \ll c$
- Sonic Mach number: $M_S = v_{sh}/c_s \approx 2\text{-}10$
- Alfvén Mach number: $M_A = v_{sh}/v_A \approx 2\text{-}10$



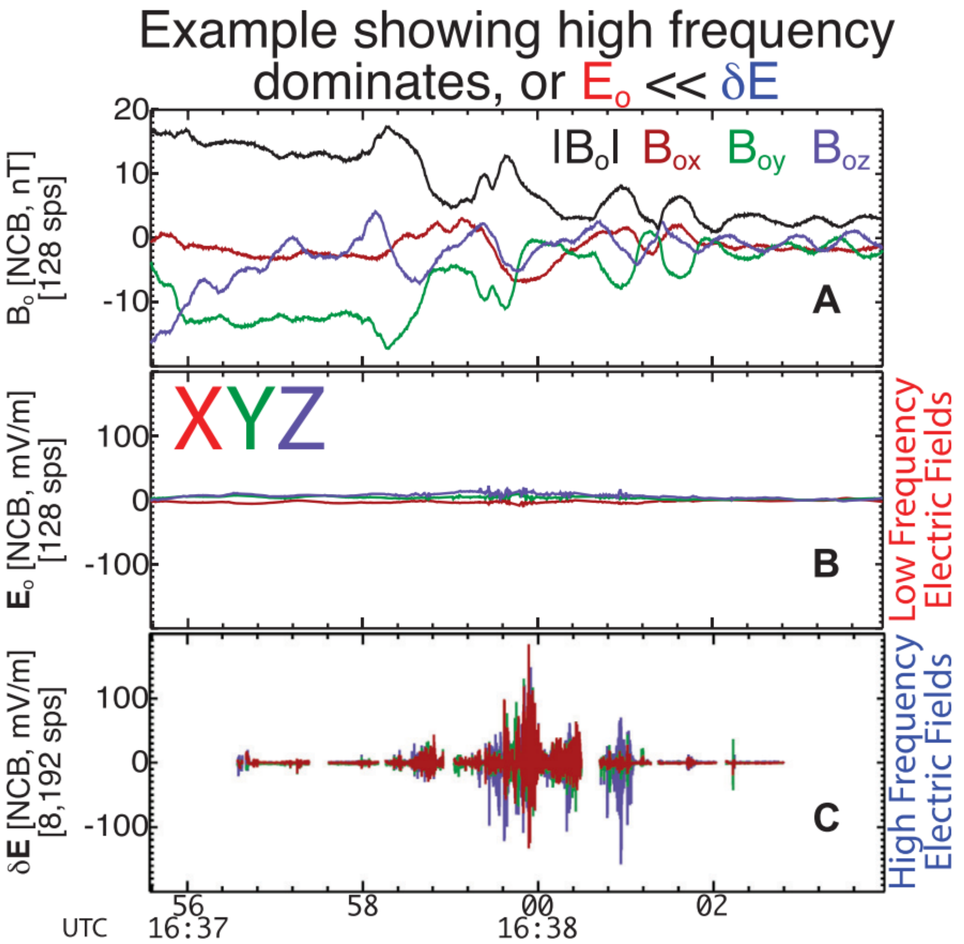
PIC simulations vs in-situ measurement: electrostatic waves

(Wilson et al. 2021)

PIC simulations



In-situ



Electrostatic waves at/near collisionless shocks (in-situ)

(Wilson et al. 2021)

Wave Name	Polarization or waveform	Frequency[α] and/or Appearance	Scale Length[β]	Free energy source or wave source
LHW	linear $\perp$ to $\mathbf{B}_o$ or oblique to $\mathbf{B}_o$	$f_{sc} \sim$ 5–40 Hz $f_{sc} \lesssim f_{lh}$ symmetric modulated sine waves[ρ]	$k\lambda_e \lesssim 1$	currents[κ], density gradients[λ], Electron heat flux[σ], or MTSI[θ]
IAW	linear $\parallel$ to $\mathbf{B}_o$	$f_{sc} \sim 10^2$–10^4 Hz $f_{rest} \lesssim f_{pi}$ symmetric[η] modulated sine waves	$\lambda \gtrsim 2\pi\lambda_{De}$	currents[δ], gyrating/reflected ions[ζ], or electron heat flux[ξ]
ECDI	elliptical or "Tear-drop"- shaped oblique to $\mathbf{B}_o$	$f_{sc} \sim 10^2$–10^4 Hz $f_{rest} \sim$ mix[ε] asymmetric[η] modulated sine waves	$k\lambda_e \lesssim 1$ and $k\lambda_{De} \lesssim 1$	relative drift between incident electrons and reflected ions[δ]
ESW	bipolar pulse $\parallel$ to $\mathbf{B}_o$ else unipolar	$f_{sc}^{-1} \sim$ few 10 s of ms isolated or trains of pulses	$\lambda \gtrsim \lambda_{De}$	electron beams[δ] or nonlinear wave decay[δ]
LW[ψ]	linear $\parallel$ to $\mathbf{B}_o$ or elliptical	$f_{sc} \sim$ 10–60 kHz symmetric modulated	$k\lambda_e \lesssim 1^{\mu}$	electron beams[χ] and/or nonlinear wave decay[ν]

Properties of IAW and ESW: $\delta E/E_0 > 50$

$$\lambda_{ESW} \approx 10\lambda_D \approx 0.05\lambda_{se}$$

Electrostatic waves at/near collisionless shocks (PIC simulations)

- **Buneman waves** at the shock foot of quasi-perpendicular high (Shimada & Hoshino, 2000; Hoshino & Shimada, 2002; Amano & Hoshino, 2007, 2009; Bohdan et al., 2017, 2019a, 2019b) and low (Umeda et al., 2009) Mach number shocks.
- **Electron Bernstein mode** (Muschietti & Lembege, 2006; Yu et al., 2022) can be excited in moderate Mach number perpendicular shocks.
- **Ion-acoustic waves** can be driven by the drift motion of preheated incoming ions relative to the decelerated electrons at the shock foot of high Mach number perpendicular shocks (Kato & Takabe, 2010b, 2010a).
- **Electron-acoustic waves** can be observed both in the shock foot as a result of the MTSI (Matsukiyo & Scholer, 2006) or in the electron foreshock of obliques shocks (Bohdan et al., 2022; Morris et al., 2022).
- **Electrostatic Langmuir waves** can be generated via the electron bump-on-tail instability at the foreshock region of oblique high-beta shocks (Kobzar et al., 2021)

Properties of electrostatic waves:

$$\delta E/E_0 \approx 1$$

$$\lambda_{EW} \approx \lambda_{se}$$

PIC simulations vs in-situ measurement

PIC simulations

$\delta E/E_0 \approx 1$

$\lambda_{EW} \approx \lambda_{se}$

In-situ

$\delta E/E_0 > 50$

$\lambda_{ESW} \approx 10\lambda_D \approx 0.05\lambda_{se}$

PIC simulations vs in-situ measurement

PIC simulations

$\delta E/E_0 \approx 1$

$\lambda_{EW} \approx \lambda_{se}$

In-situ

$\delta E/E_0 > 50$

$\lambda_{ESW} \approx 10\lambda_D \approx 0.05\lambda_{se}$

Simple explanation

Very often $\lambda \propto v_{sh}$ (two-stream instability)

Also $\delta E \propto v_{sh}$(available energy). $E_0 = B_0 v_{sh} \propto v_{sh}^2$ (assuming constant M_A) , therefore $\delta E/E_0 \propto v_{sh}^{-1}$

$v_{sim} = 0.2c$

$\lambda_{EW} \approx \lambda_{se}$

$\delta E/E_0 \approx 1$

$v_{real} = 0.002c \approx 600\ km/s$

$\lambda_{ESW} \approx 0.01\lambda_{se}$

$\delta E/E_0 \approx 100$

PIC simulations vs in-situ measurement

PIC simulations

$\delta E/E_0 \approx 1$

$\lambda_{EW} \approx \lambda_{se}$

In-situ

$\delta E/E_0 > 50$

$\lambda_{ESW} \approx 10\lambda_D \approx 0.05\lambda_{se}$

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$\lambda_{ESW} \approx 0.01\lambda_{se}$

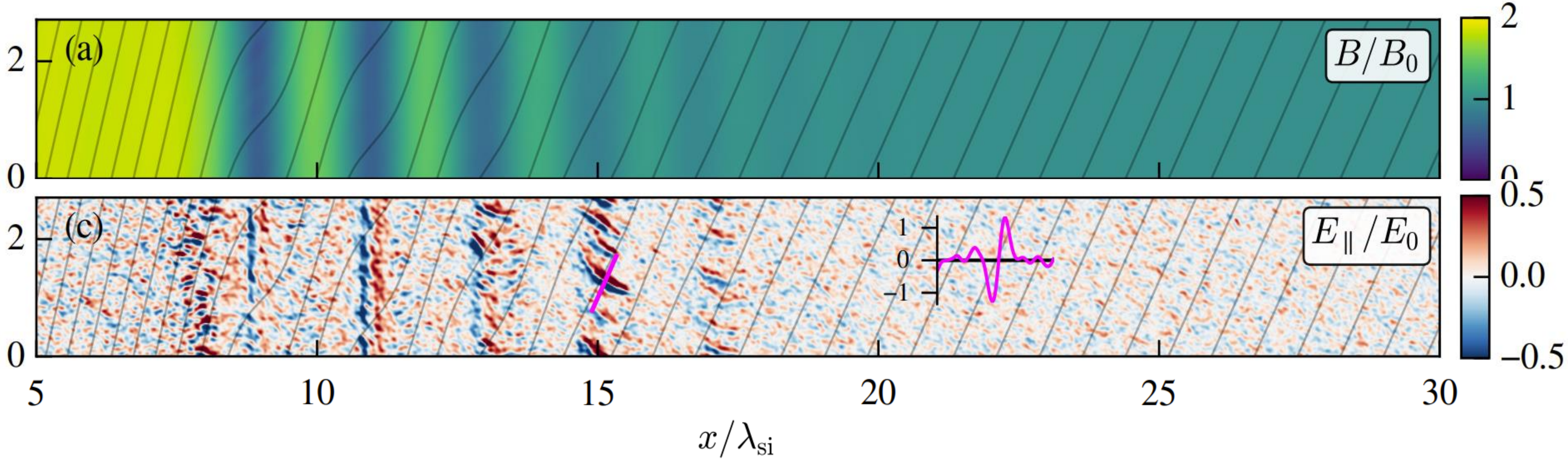
$\delta E/E_0 \approx 100$

Does it work?

Shock simulations

$M_A = 1.8, M_s = 4, \Theta_{Bn} = 65^o$

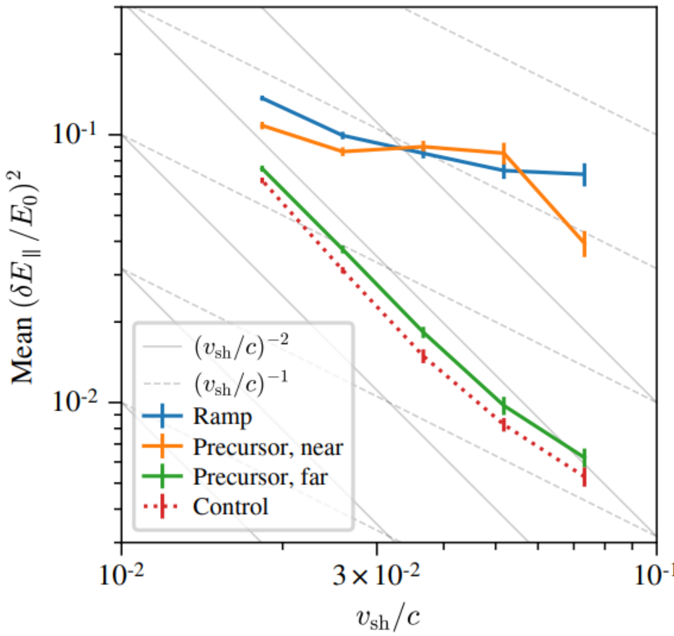
Run	m_i/m_e	$v_{sh}/c^{\dagger}$	v_0/c	Width (d_i)	Δx (d_e)	ω_{pe}/Ω_e
A	200	0.0733	0.0338	2.90	0.143	1.76
B	200	0.0518	0.0238	2.71	0.100	2.49
C	200	0.0366	0.0168	2.90	0.071	3.52
D	200	0.0259	0.0119	2.71	0.050	4.99
E	200	0.0183	0.0084	2.90	0.036	7.05



Wave parameters scaling

Electrostatic wave power

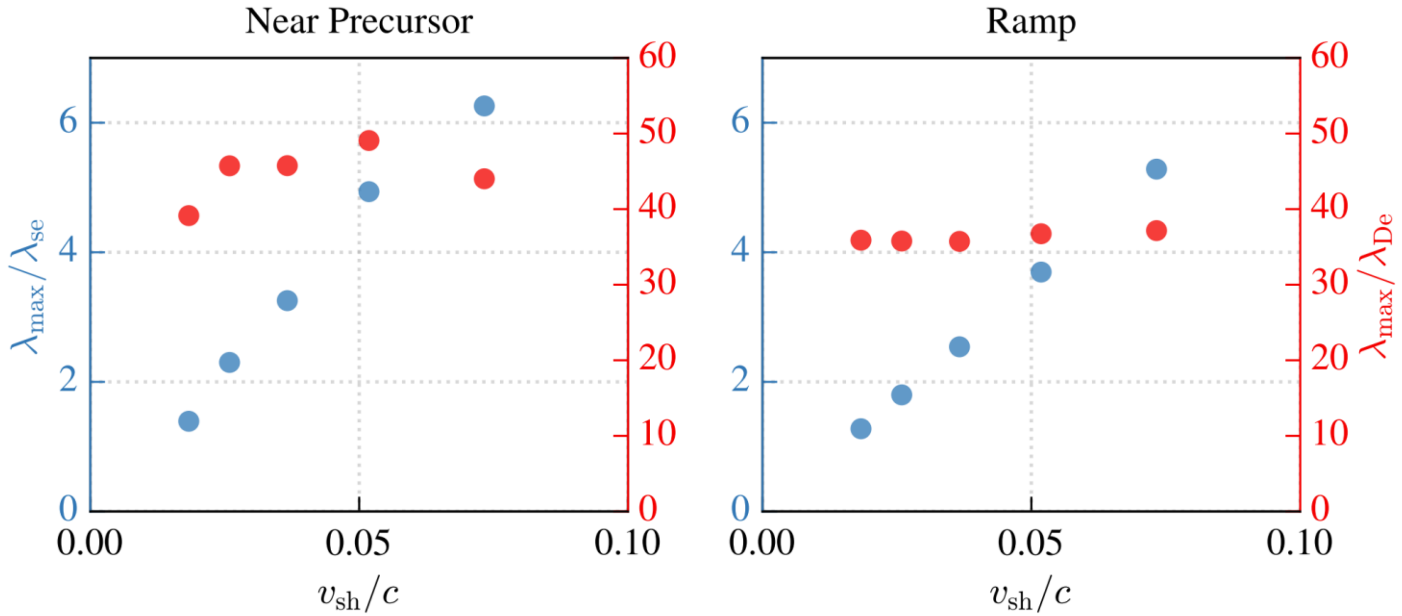
$\delta E/E_0 \propto v_{sh}^{-0.5}$



Wavelength

$\lambda_{EW}/\lambda_{se} \propto v_{sh}$

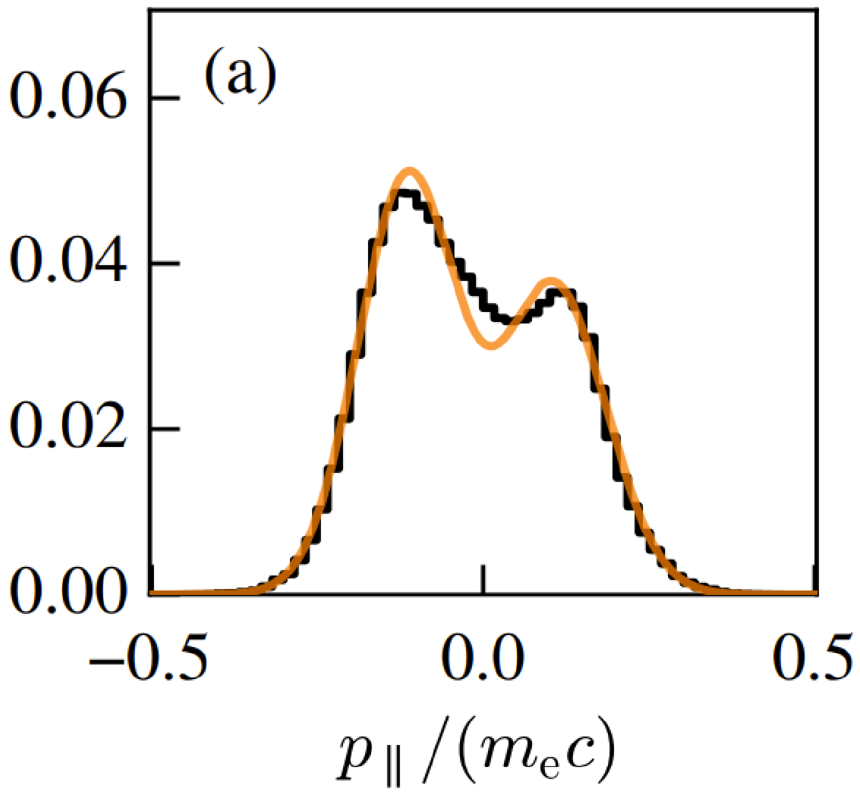
$\lambda_{EW}/\lambda_{D} \propto v_{sh}^{0}$



Linear dispersion analysis

Two-stream electrostatic instability

Electron distribution at the shock ramp (run B)



Parameters of the electron distribution

Run	$\frac{n_1}{n_2}$	$\frac{v_{dr}}{v_{sh}}$	$\frac{v_{dr}}{v_{th,1}}$	$\frac{v_{dr}}{v_{th,2}}$	v_{sh}/c
A	1.52	4.14	2.79	2.78	0.0733
B	1.36	4.15	2.88	2.75	0.0518
C	1.33	4.16	2.96	2.61	0.0366
D	1.28	4.19	2.99	2.45	0.0259
E	1.26	4.28	3.02	2.40	0.0183
S*	1.35	4.19	2.93	2.59	0.0010

*S – synthetic run, $v_{sh} \approx 312\ km/s$

Linear dispersion analysis (LDA)

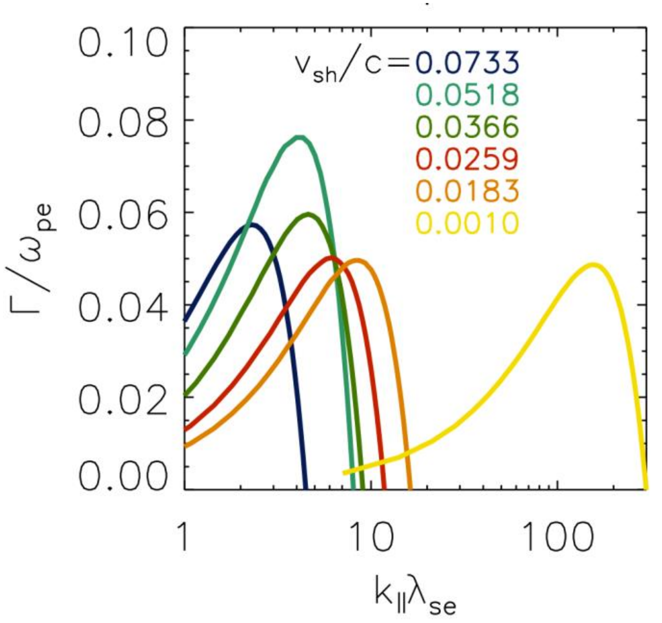
Electron-acoustic waves

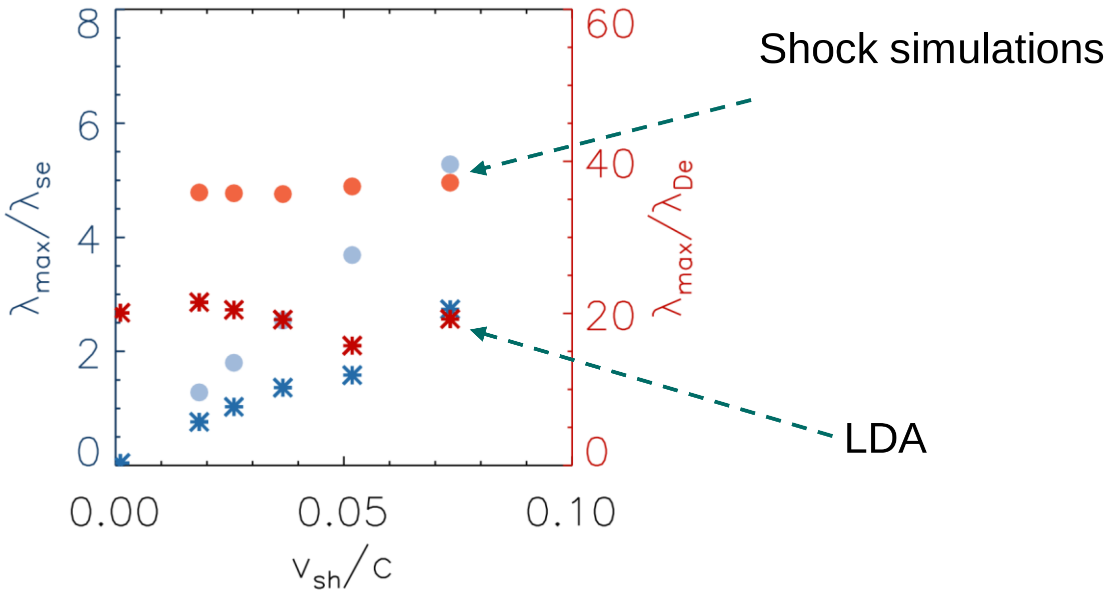
Electrostatic waves are identified as electron-acoustic waves driven by two counterstreaming hot electron beams.

$$\lambda_{LDA}/\lambda_{se} \propto v_{sh}$$

$$\lambda_{LDA}/\lambda_{D} \propto v_{sh}^0$$

But $\lambda_{ES,sh}/\lambda_{LDA} \approx 2$



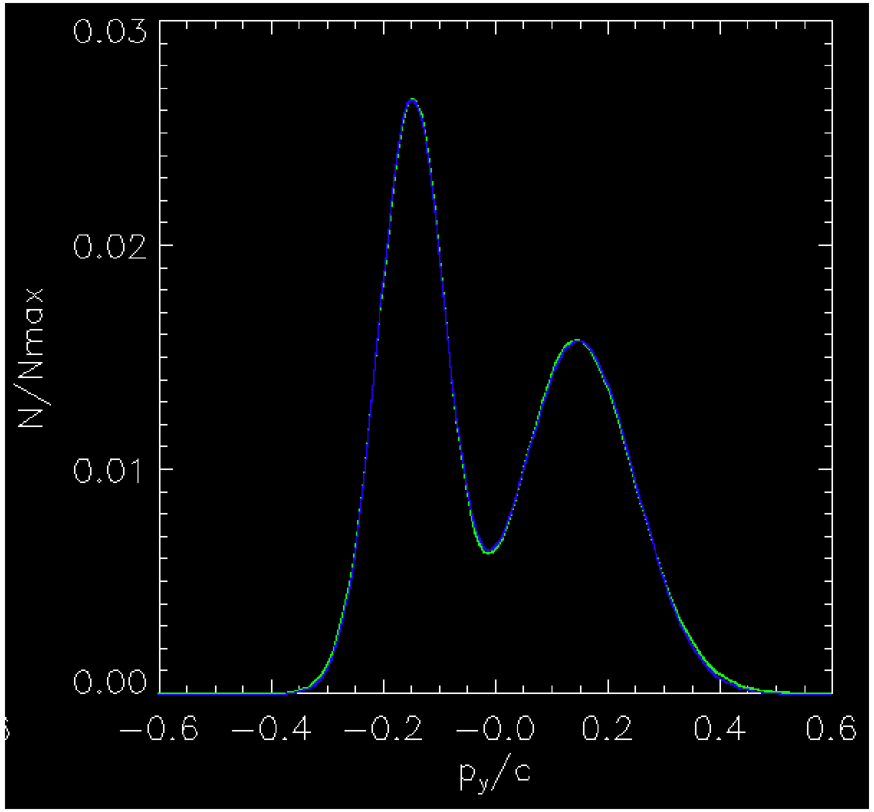


Periodic-boundary-condition simulations

Setup

$$v_1 = \frac{v_{dr}}{2} \qquad v_2 = -\frac{v_{dr}}{2}$$

$$v_{th,1} = \frac{v_{dr}}{3} \qquad v_{th,2} = \frac{v_{dr}}{5}$$



Scanned parameters

$v_{dr} \approx (0.08 - 0.3)c$

$\frac{m_i}{m_e} = 200 - 1836$

$N_{ppc} = 40 - 2560$

Ion content

Reference PBCS

$v_{dr} = 4v_{sh,\, run\ A}$

$n_1 = n_2$

$N_{ppc} = 2560$

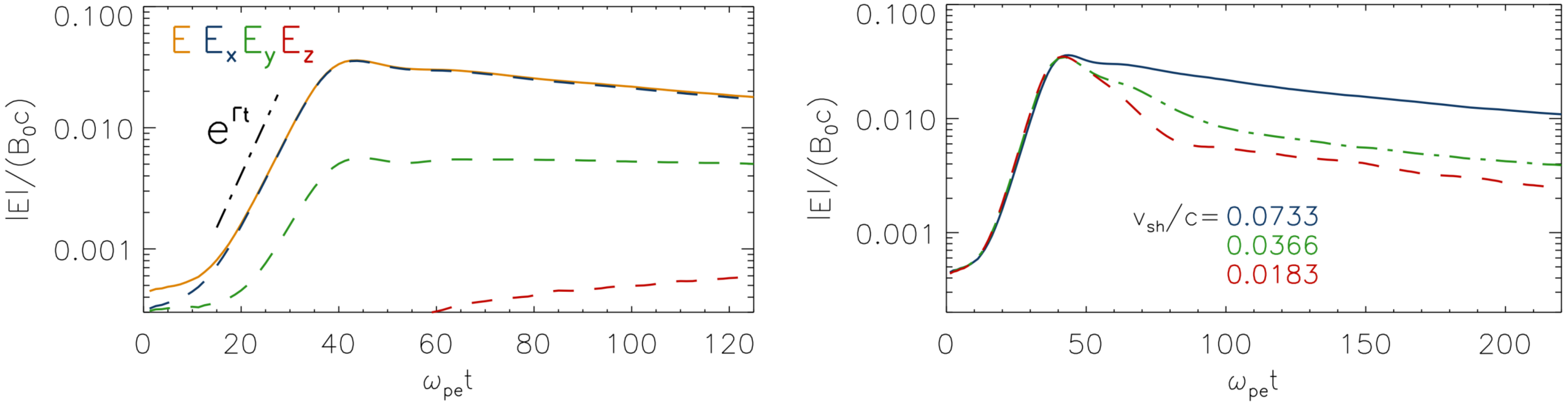
$v_{th,1} = \frac{v_{dr}}{3}$

$v_{th,2} = \frac{v_{dr}}{5}$

Periodic-boundary-condition simulations

Results

- Good match between PBCS and linear dispersion analysis (Γ/ω_{pe} ≈ 0.185, the prediction is 0.2)
- Max($\delta E/(B_0 c)$) does not depend on v_{sh}, therefore $\boldsymbol{\delta E/E_0 \propto v_{sh}^{-1}}$
- At $\omega_{pe}t > 50$, $\boldsymbol{\delta E/(B_0 c) \propto v_{sh}^{-1}}$, therefore $\boldsymbol{\delta E/E_0 \propto v_{sh}^{0}}$

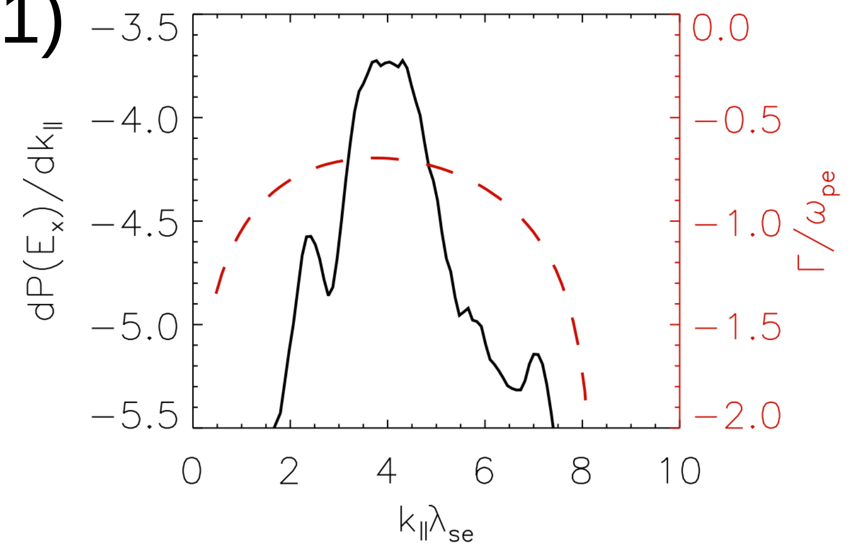


Periodic-boundary-condition simulations

Results

1) The wavelength is consistent with predictions and $\lambda_{ES}/\lambda_{se} \propto v_{sh}$
2) The wavelength $\lambda_{ES}/\lambda_{se}$ is decreasing with time
3) Structure becomes closer to solitary waves at later stages of EAW development

1)



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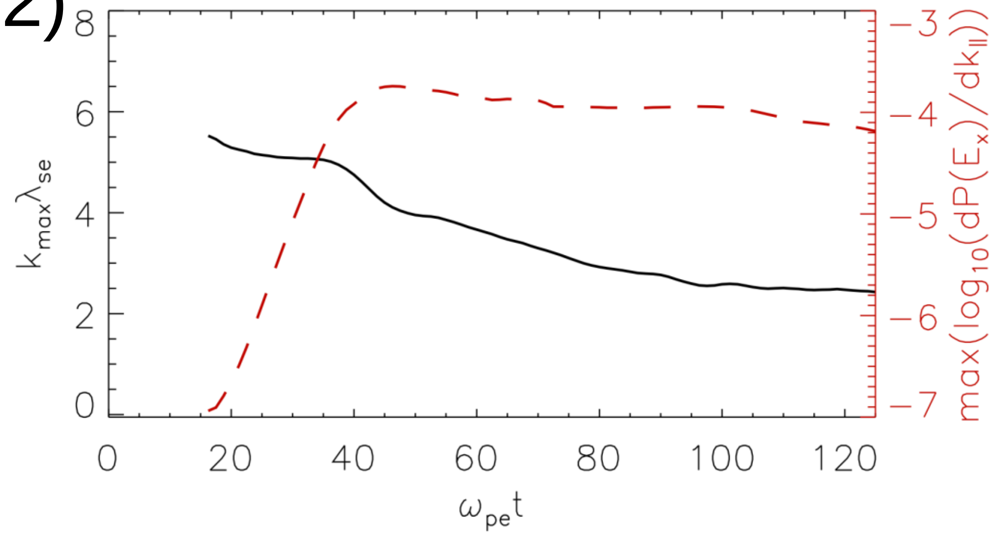

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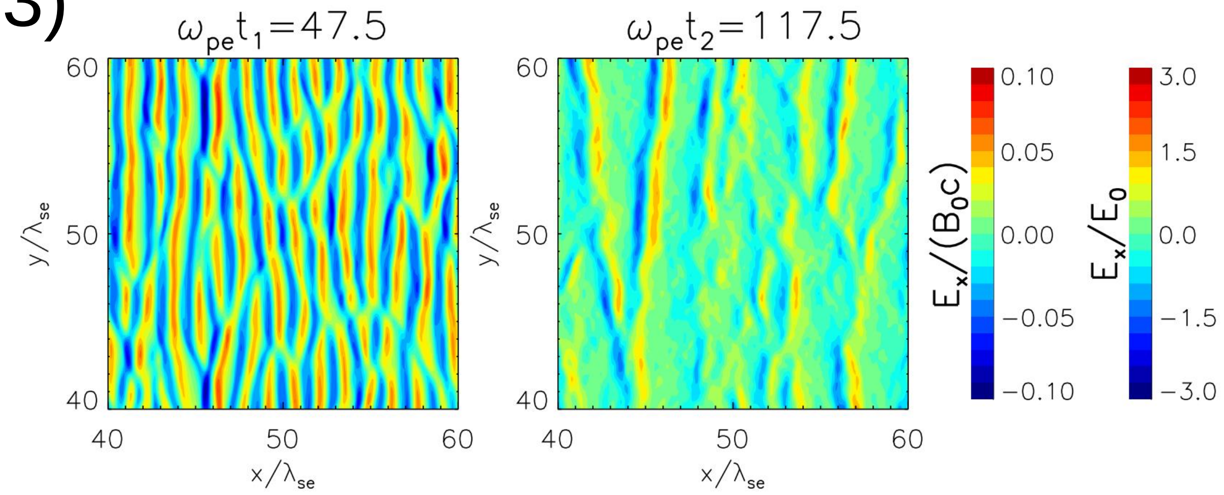

Conclusions

- Driving conditions for EAWs are independent on the shock velocity.

- The amplitude scales as $\delta E/E_0 \propto v_{sh}^{-0.5}$ or $\delta E/E_0 \propto v_{sh}^{-1}$,
  therefore $\boldsymbol{\delta E/E_0}$ in real shocks could be larger than **100**.

- The wavelength scales as $\lambda_{ESW}/\lambda_D \propto v_{sh}^{0}$, therefore $\boldsymbol{\lambda_{ESW} \approx 40\,\lambda_D \approx 300m}$.

arXiv > physics > arXiv:2408.01699

Physics > Space Physics

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Electrostatic Waves and Electron Holes in Simulations of Low-Mach Quasi-Perpendicular Shocks

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Thank you

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