Title: Fast radio bursts as precursor radio emission from monster shocks

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Collection/Series: Magnetic Fields Around Compact Objects Workshop

Subject: Strong Gravity

Date: March 28, 2025 - 2:00 PM

URL: https://pirsa.org/25030151

Abstract:

It has been proposed recently that the breaking of MHD waves in the inner magnetosphere of strongly magnetized neutron stars can power different types of high-energy transients. We have studied the steepening and dissipation of a strongly magnetized fast magnetosonic wave propagating in a declining background magnetic field, by means of particle-in-cell simulations that encompass MHD scales. Our analysis confirms the formation of a monster shock as B^2-E^2 approaches zero, that dissipates about half of the fast magnetosonic wave energy, and reveals, for the first time, the generation of a high-frequency precursor wave at the monster shock, carrying a fraction of 0.001 of the total energy dissipated at the shock. The spectrum of the precursor wave exhibits several sharp harmonic peaks, with frequencies in the GHz band under conditions anticipated in magnetars. Such signals may appear as fast radio bursts.

Monster shocks, fast radio bursts and chaos

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In collaboration with (and all credit to) Arno Vanthieghem

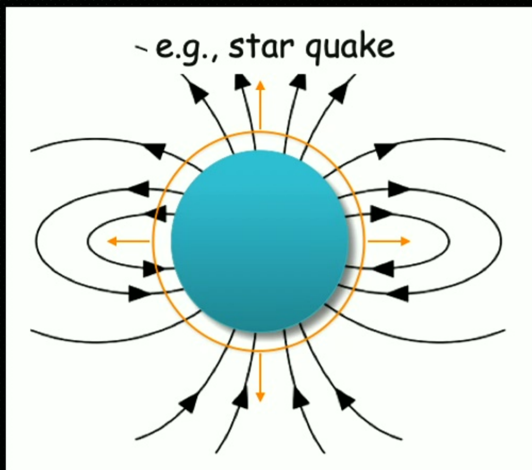
Outline

- PartI: PIC simulations of monster shocks + precursor wave
  (Vanthieghem+AL, PRL 25)

- Part II: work in progress
  - physics of magnetized shocks (solitons, chaos, thermalization)
  - shocks with strong cooling (work in progress)

Excitation of MHD waves in disturbed magnetospheres

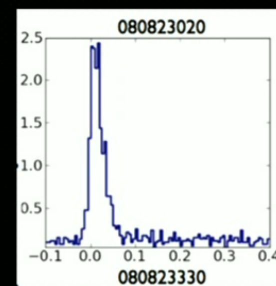
Force-free magnetosphere: $\mathbf{E}\cdot\mathbf{B}=0, \qquad \sigma=\dfrac{B_{bg}^2}{4\pi\rho c^2}\gg 1$

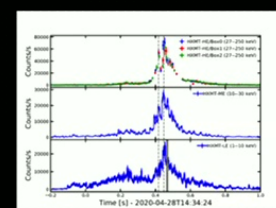


Two modes:

Alfven wave: $B_w \propto k\times B_{bg}$
move along field lines

Compressive fast: $E_w \propto k\times B_{bg}$
can propagate across field lines.

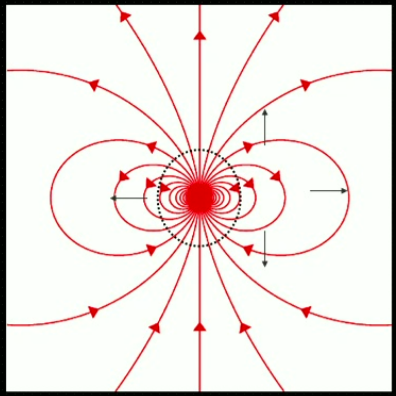


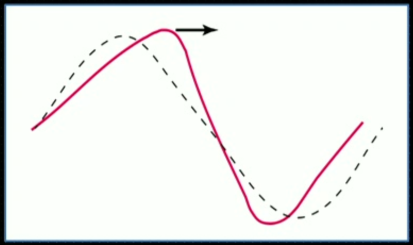


linear waves:	$B^2-E_w^2>0$
Non-linear regime:	$B^2-E_w^2\to 0$
E-zone:	$B^2-E_w^2<0$

Nonlinear propagation and steepening

FM wave propagating in a declining background field B_{bg}





- wave fields: E_w, B_w. total: $B = B_{bg} + B_w$
- propagation: $E_w / B_{bg} \propto r^n$ (In a magnetar $E_w / B_{bg} \propto r^2$)
- Starts linear ($B^2 - E_w^2 > 0$). As $B^2 - E_w^2 \to 0$ it steepens abruptly, forming a monster shock .

Note that $v = \dfrac{E \times B}{B^2} \to 1 \Rightarrow \gamma \to \infty$ as $B^2 - E^2 \to 0$. Inertia is important around wave trough!

Applications: X-flares from magnetars and precursor BNS mergers, FRBs ...

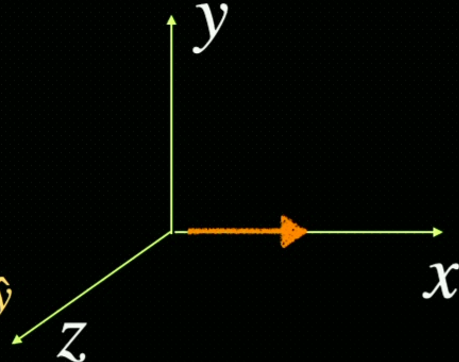
Lyubarsky, Beloborodov, Chen +, Most +, Vanthieghem +AL

1D FMS - exact solution in a cold plasma

$$\mathbf{B}_{bg} = B_{bg}(x)\hat{z}$$

$$\mathbf{B}_w = B_w(x,t)\hat{z}$$

$$\mathbf{E}_w(x,t) = E_w(x,t)\hat{y}$$



$$\lambda \equiv \frac{1}{2}\ln\left(\frac{1+v}{1-v}\right), \quad v = E/B$$ (invariant if $\partial_x B_{bg} = 0$)

$$\boxed{\partial_t\lambda + v_+\partial_x\lambda = A(\lambda)\,\partial_x B_{bg}}, \quad v_+ = \frac{v+a}{1+av}$$ (velocity of characteristic)

Cold plasma: $v_+(\lambda) = \tanh(3\lambda/2 + c), \quad \sinh^2(c) = \sigma_{bg}$

Note: $(B^2 - E^2)/B_{bg}^2 = e^{2\lambda}$

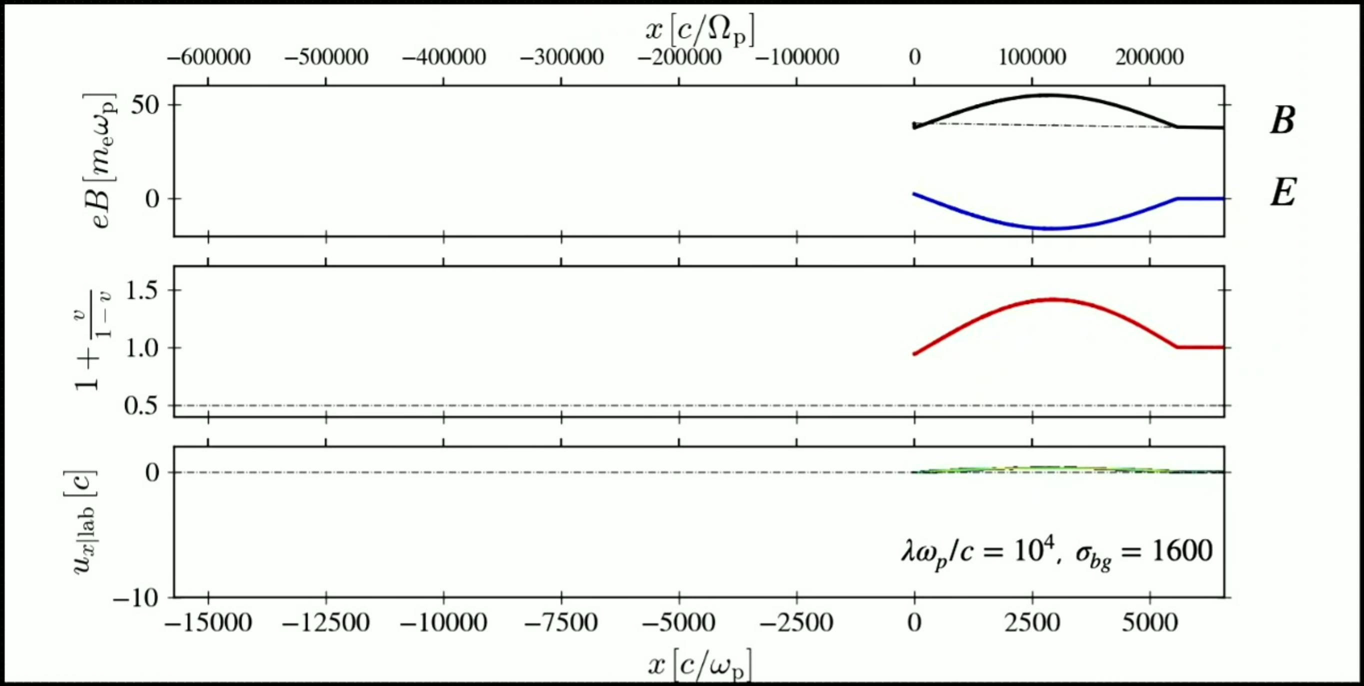
1D PIC simulations

Vanthieghem +AL 25

- Large scale separation: $\lambda_w \omega_p / c = 10^4$
- Background field profile: $\mathbf{B}_{bg} = \hat{z} B_0 (1 + x/R_0)^{-1}, \quad R_0 = 10\,\lambda_w$
- Large magnetization: $\sigma_{bg} = \sigma_0 (1 + x/R_0)^{-2}, \quad \sigma_0 = 1600$
- No cooling at present (now added but preliminary)
- 60 cells per skin depth, PPC = 50

Simulations of FMS propagation in a declining field

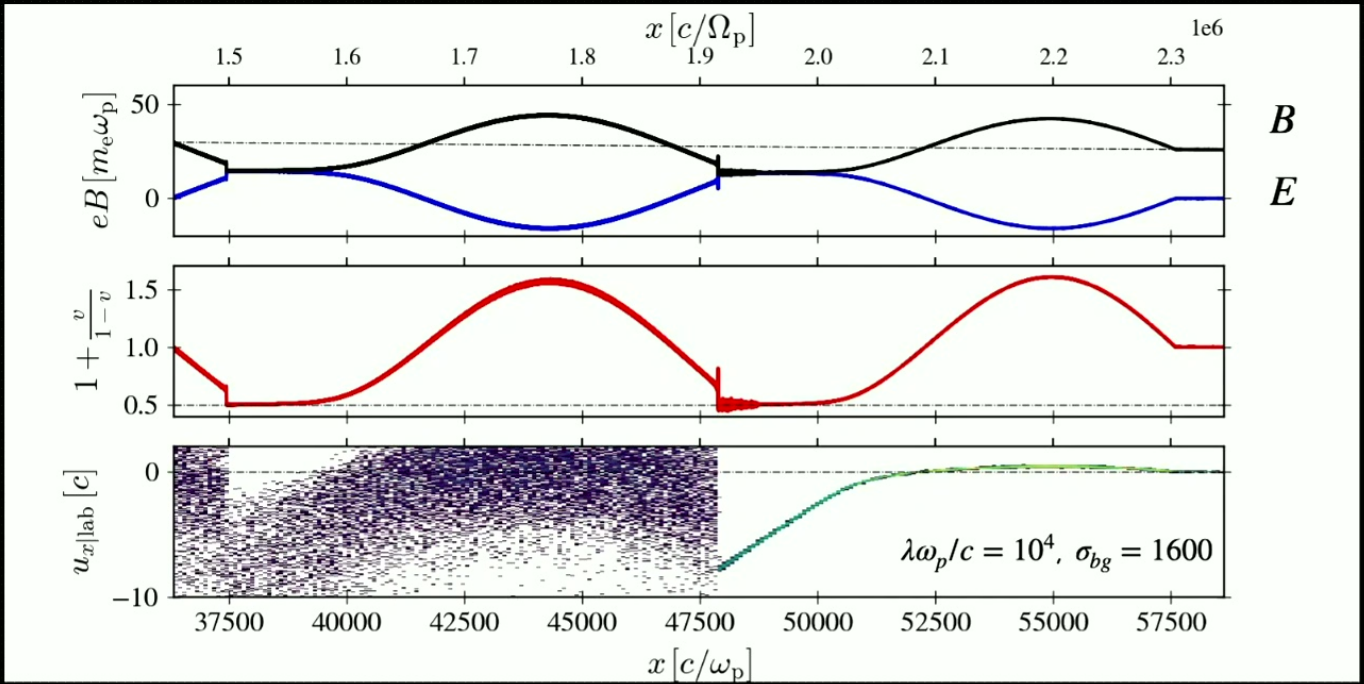
Vanthieghem +AL 25



- Plasma upstream of the shock accelerates backwards.
- Precursor wave is generated in the leading shock.
- No precursor wave is generated at trailing shock due to high T

Simulations of FMS propagation in a declining field

Vanthieghem +AL 25



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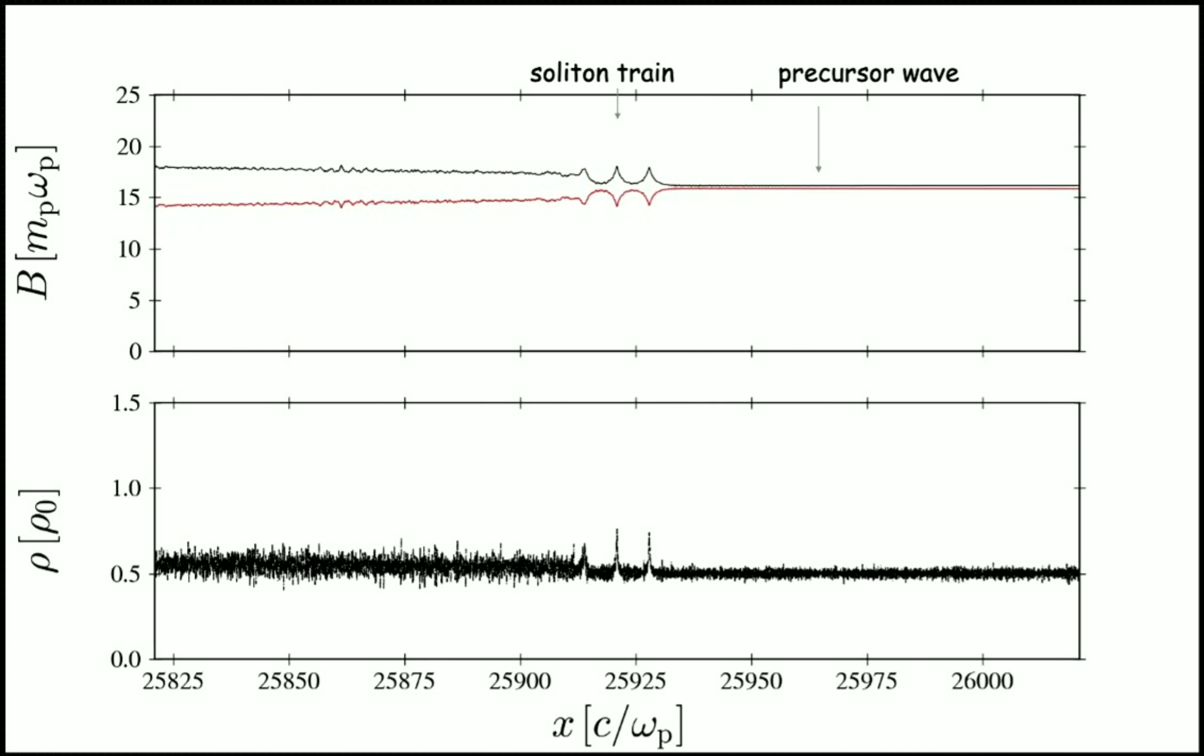
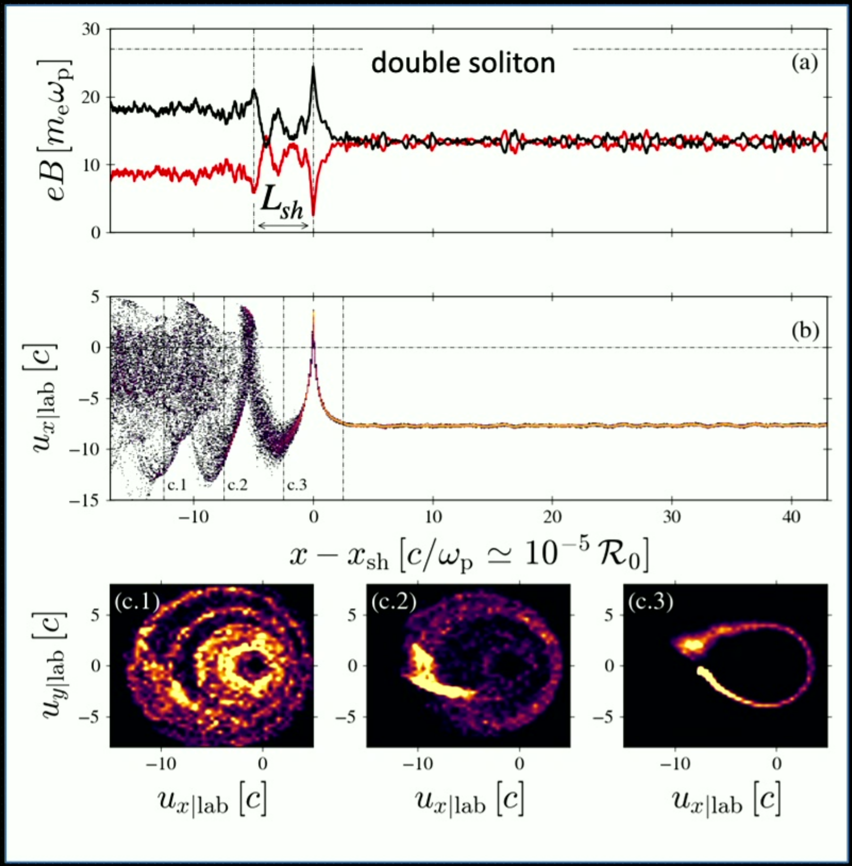
Zoon-in on shock structure



- Note initial train of magnetosonic solitons (subcritical regime).
- Precursor wave is generated once the shock strengthen.

Shock structure



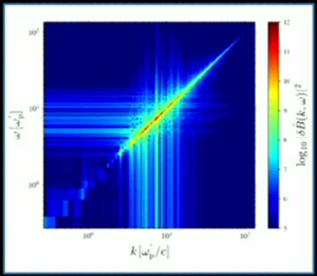
Precursor wave is generated by synchrotron maser instability

In planar shocks: Iwamoto + 17,18, Plotnikov&Sironi 19, Sirnoi + 21, Babul +21

Both X and O modes are generated. O-mode is negligible

double soliton structure operates as a resonant cavity

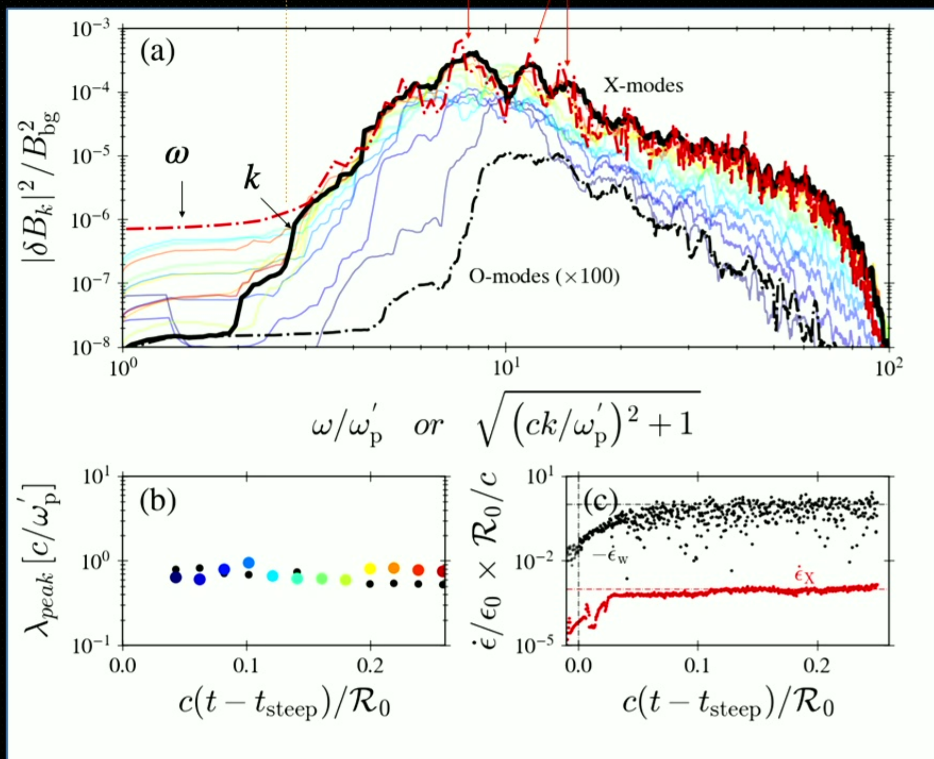
Plotnikov&Sironi 19



dispersion relation of X-mode

Spectrum and efficiency of precursor X-mode

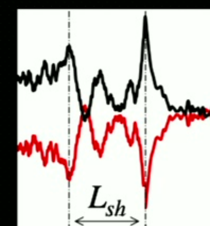
ω_{cut} ω_{peak} higher harmonics



measured in Lab (observer) frame

main peak in SF: $\lambda''_{peak} \approx L_{sh}/3$

Lab frame: $\omega_{peak} \approx 1.6\sqrt{\sigma_u}\,\omega'_p$



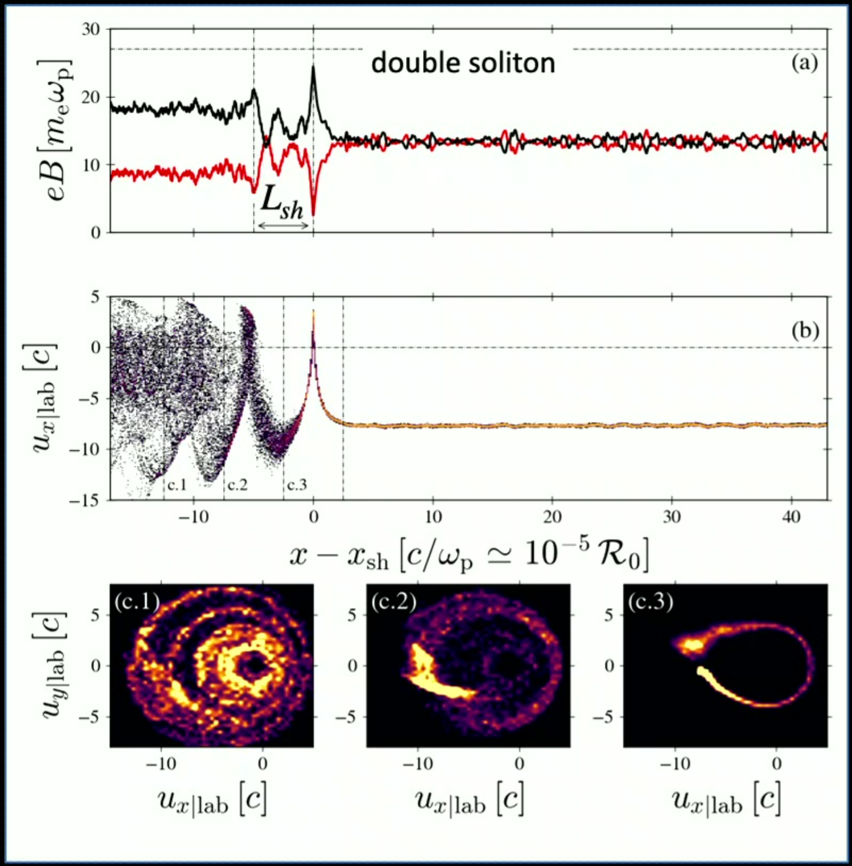
low energy cutoff: $v_g < v_{sh|Lab}$

$\Rightarrow \omega_{cut} = \omega'_p \gamma_{sh|lab}$

fraction of dissipation energy carried by the X-mode:

$\epsilon_X = 10^{-3}$

Shock structure



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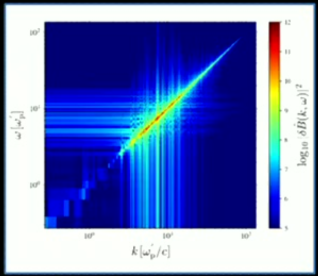
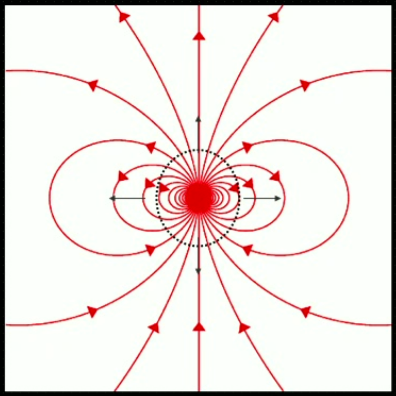


dispersion relation of X-mode

Application to FRB



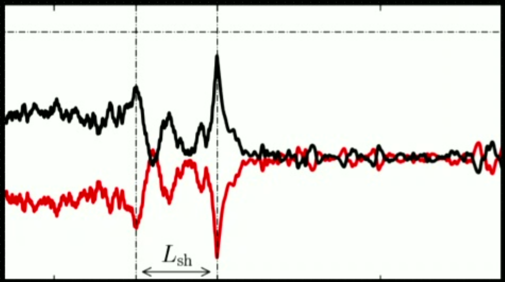
- $B_{bg} = B_{15}(R/r)^3, \quad R = 10^6\,\mathrm{cm}$
- multiplicity $\mathscr{M} = n_{bg}/n_{GJ} = 10^6\mathscr{M}_6$
- wave power: $L_w = 10^{43}L_{43}$ erg/s
- FMS wave frequency: $\nu = 10^4 \quad \mathrm{Hz}$

- shock formation radius: $r_s = 2\times10^8\,B_{15}^{1/2}L_{43}^{-1/4} \quad \mathrm{cm}$
- dissipation zone: $r_s < r_{diss} < 3r_s$ Beloborodov 23
- upstream magnetization: $\sigma_u \approx 300\,B_{15}^{1/2}L_{43}^{-1/4}$
- $\omega_p' = 10^8\,(r/r_s)^{1/2}\mathscr{M}_6\Omega^{1/2}B_{15}^{1/4}L_{43}^{-1/8} \quad \mathrm{Hz}$

$\omega_{peak} \simeq \sqrt{\sigma_u}\,\omega_p'\mathscr{M}_6 \sim 2\mathrm{GHz}$ scaled from our simulations

Can the X-mode escape ?

Part II: Work in progress



- Analytic study of magnetosonic solitons and the shock structure
- Study of emission process by the double-soliton configuration

Single fluid model for magnetosonic solitons: Kennel & Pellat 76, Alsop & Arons 88

1D Multi-fluid model: Vanthieghem & AL, PRE 25

- Steady flow ($\partial_t = 0$)
- Multi-fluid pair plasma: density n_s , velocity $(u_s^x, u_s^y, 0)$
- Fields: $\mathbf{B} = B_z \hat{z}$, $\mathbf{E} = E_y \hat{y} = E_0 \hat{y}$
- Initial conditions: upstream velocity, magnetic field and temperature (velocity spread)

$$\sum_s n_{s,u} = n_u, \quad u^x_{s,u} = u_u + \delta u_u$$

$$n_s u_s^x = n_{s,u} u_{s,u}^x,$$

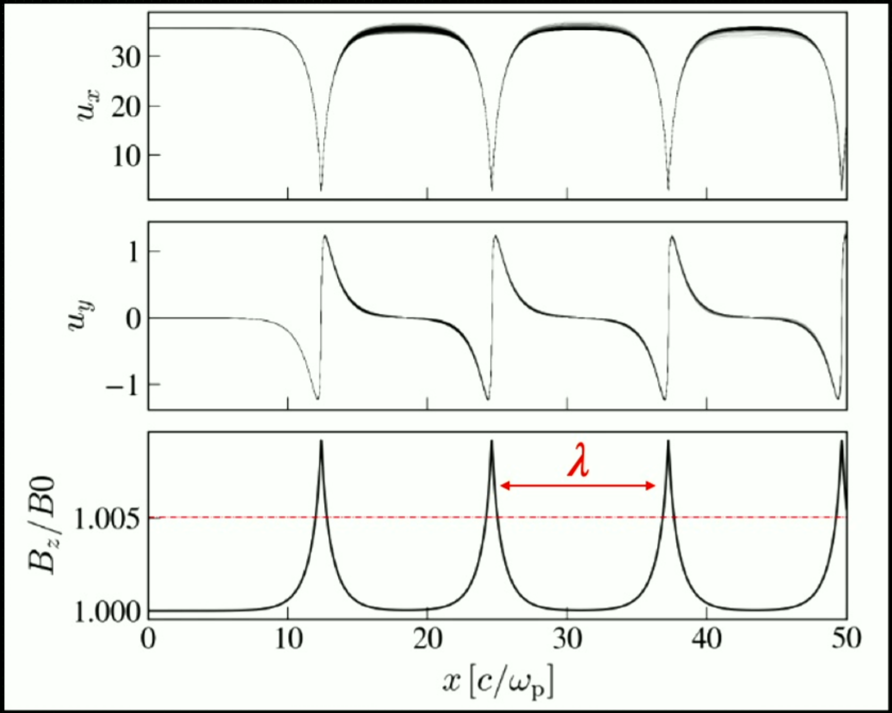
$$u_s^x \partial_x u_s^x = \frac{e}{m_e} B_z u_s^y,$$

$$u_s^x \partial_x u_s^y = \frac{e}{m_e} (\gamma_s E_y - u_s^x B_z),$$

$$\partial_x B_z = j^y = -8\pi \sum_s e n_s u_s^y$$

Periodic soliton train

nearly cold beam

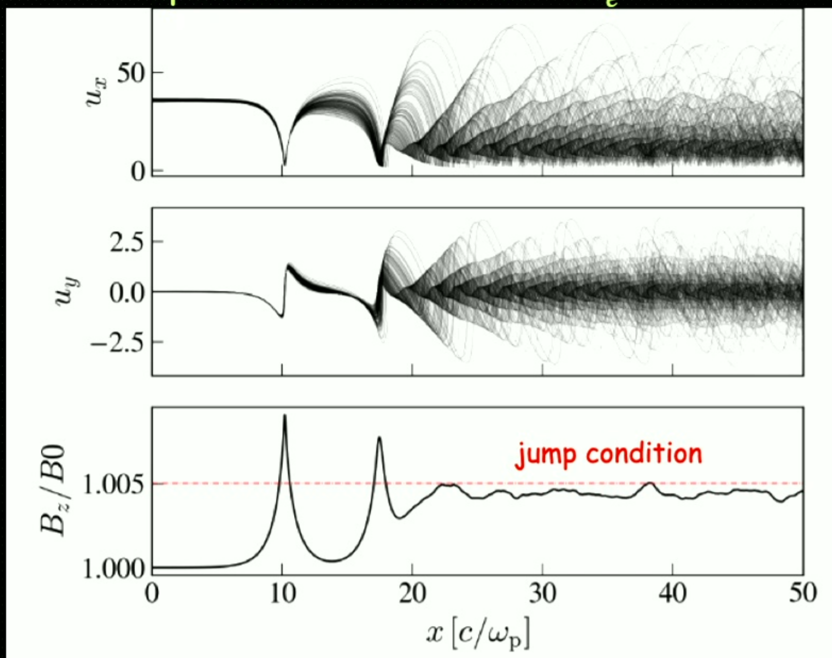


$\sigma = 100, \quad u_u = 38.8$

$$\lambda = \frac{\ln(M_A^2 + \sqrt{M_A^4 - 1})}{\sqrt{1 - M_A^{-2}}}$$

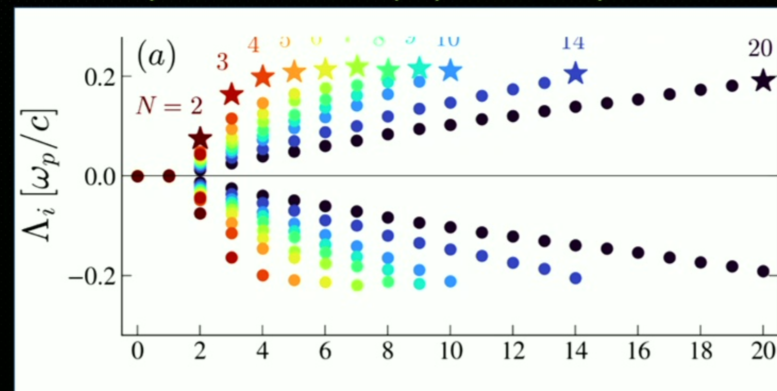
Divergence of trajectories and transition to chaos

upstream $T = 2.5 \times 10^{-5}\, m_e$

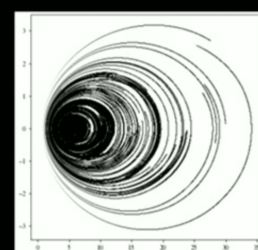


# of fluids = 200

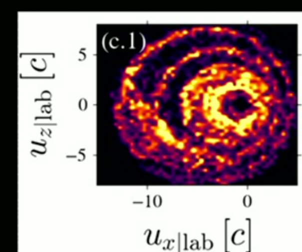
spectrum of Lyapunov exponents



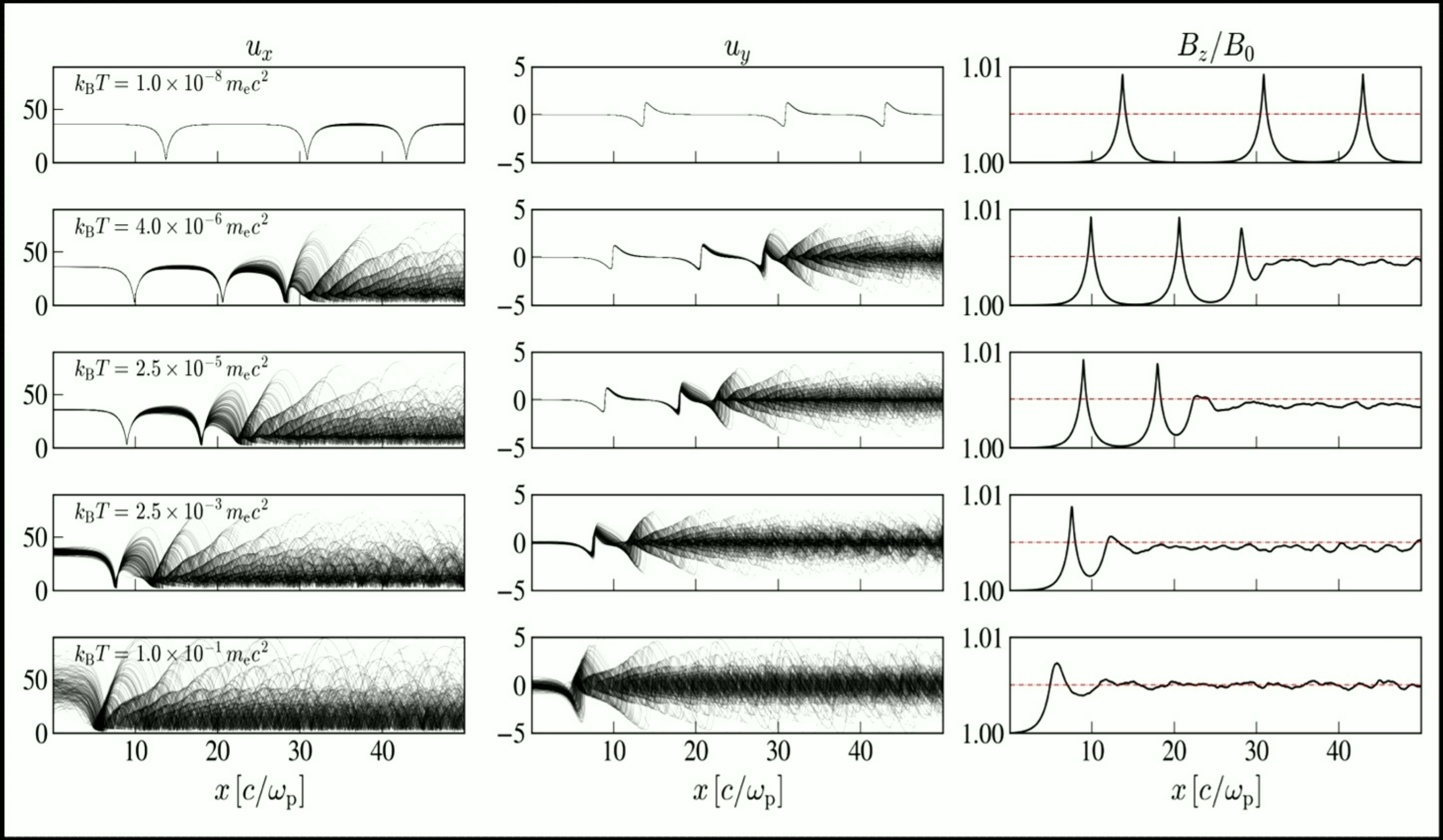
multi-fluid model



PIC simulations

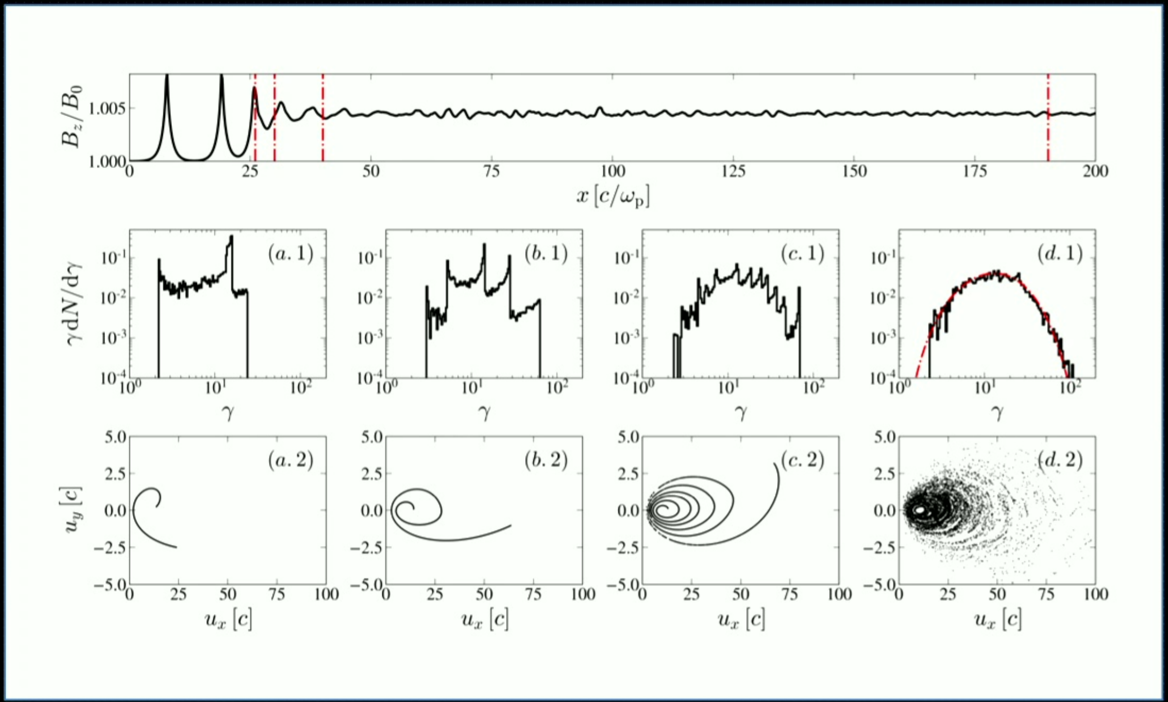


$\sigma = 100, \quad u_u = 38.8$ different T



At $T = 0.1 m_e$ solitons disperse. Maser emission shuts down (Babul+Sironi 20)

Thermalization



For the s beam:

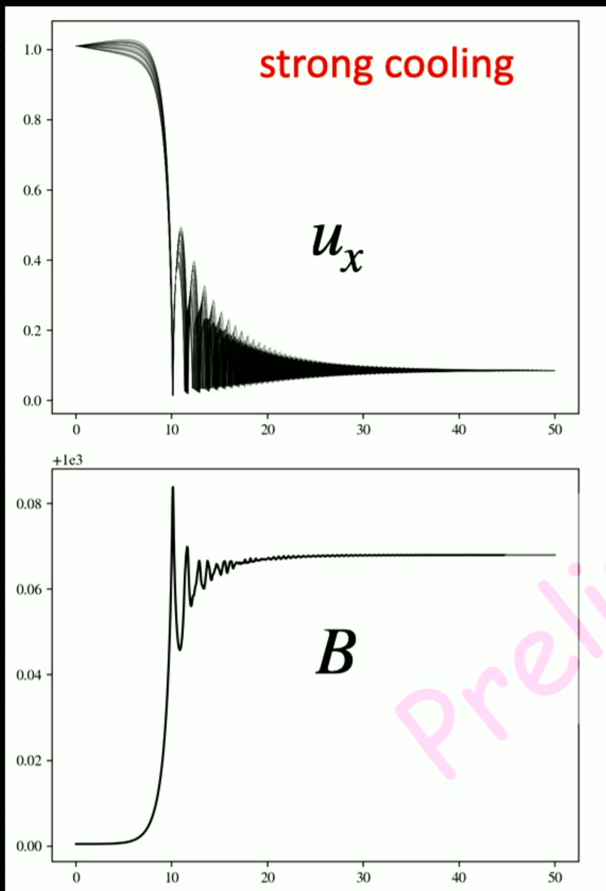
$$\partial_x \gamma_s = \frac{eE_0}{m_e}\frac{u_s^y}{u_s^x}$$

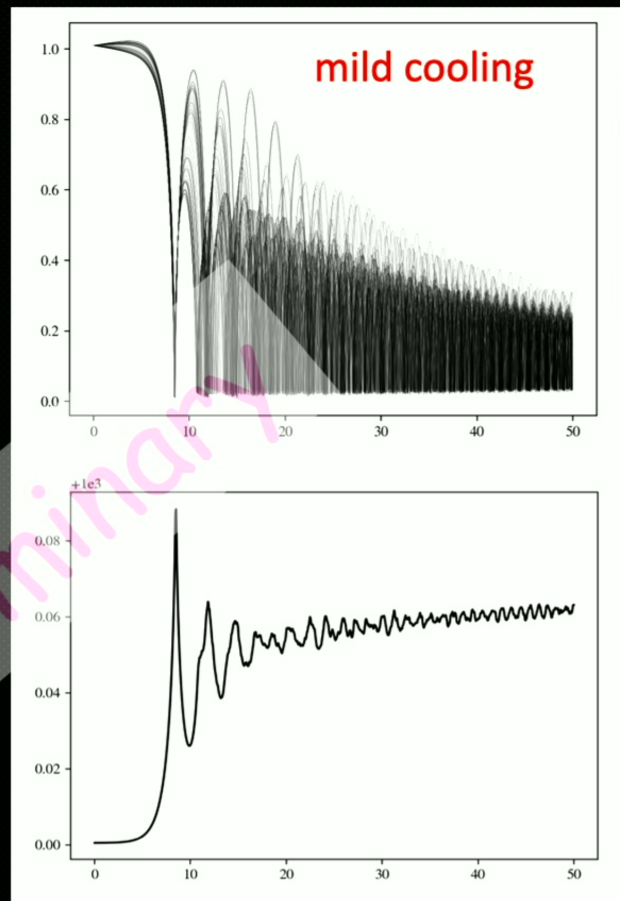
Energy gain/loss by phase shifts during scattering off B field fluctuations

Spectrum downstream approaches Maxwell-Juttner distribution regardless of initial conditions

Cooling (preliminary)

Inclusion of radiation back reaction



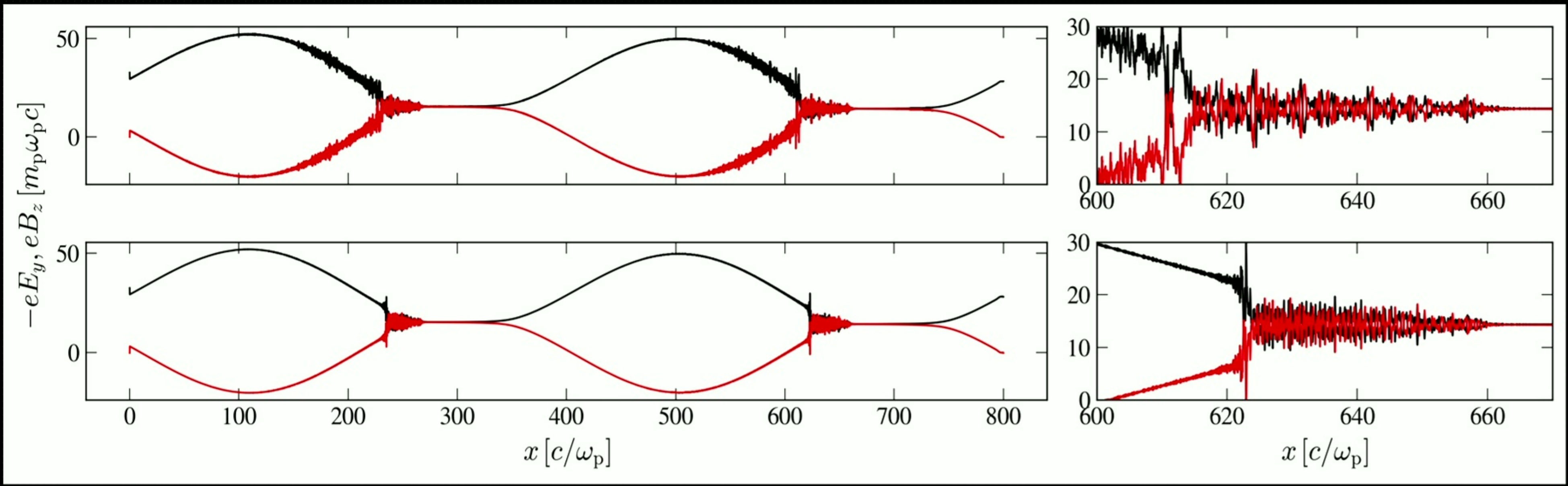


$$
\begin{aligned}
\mathbf{f} &= \frac{\sigma_T}{4\pi}(\boldsymbol{\kappa} - \gamma^2 B_\perp^2 \boldsymbol{\beta}), \\
\boldsymbol{\kappa} &= (\mathbf{E} + \boldsymbol{\beta} \times \mathbf{B}) \times \mathbf{B} + (\boldsymbol{\beta} \cdot \mathbf{E})\,\mathbf{E}, \\
B_\perp^2 &= (\mathbf{E} + \boldsymbol{\beta} \times \mathbf{B})^2 - (\boldsymbol{\beta} \cdot \mathbf{E})^2.
\end{aligned}
$$

cooling suppresses soliton amplitude, but at the same time increases coherence.

Cooling (preliminary)

Preliminary results of PIC simulations



Conclusions

- Shocks form in a FF system when $B^2 - E^2 \rightarrow 0$
- Shock structure consists of a decaying soliton train. Dictated by upstream temperature and ms Mach number
- Collective plasma instabilities play minor role in shock formation
- Precursor X-mode is generated by the synchrotron maser instability inside the shock. Spectrum reflects harmonics of the double soliton structure.
- Effect of strong cooling on the shock structure (in progress)
- Obliqueness (2D simulations are planned).
- Can the precursor wave escape ?