

2013年3月4日  
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# 衝撃波中の粒子加速

大澤幸治

名古屋大学大学院理学研究科  
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プラズマ研究所(1977) → プラズマ科学センター(1989) →  
物理学科(1995)

最初は1-2年ごとに新課題に取り組んだ

**Vlasov code**: Nonlinear self-modulation of ion-acoustic waves

**Magnetostatic code**: Plasma paramagnetism

**Monte Carlo code**: Plasma confinement in RF-plugged cusp field

**Electromagnetic code**: Stability of bumpy torus with hot electron rings

1984年から「**衝撃波と粒子加速**」の研究を開始



2012年12月にまとめの論文

Ultrarelativistic particle acceleration in collisionless shock waves

# Ultrarelativistic Particle Acceleration in Collisionless Shock Waves

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## Abstract

This paper describes the theory and particle simulations of ultrarelativistic particle acceleration caused by shock waves in a collisionless magnetized plasma.

Since knowledge of field strengths and structures is necessary for the analysis of particle motions, theories of magnetosonic waves are reviewed first: (1) linear and nonlinear magnetosonic waves in a single-ion-species plasma, (2) those in a two-ion-species plasma, (3) those in an electron-positron-ion (EPI) plasma, and (4) the electric field parallel to the magnetic field,  $E_{\parallel}$ . The first topic contains a general introduction to the magnetosonic wave. The second and third topics are concerned with three-component plasmas, in which the magnetosonic wave is split into two modes; the plasma behavior can thus be considerably different from that in a single-ion-species plasma. The fourth topic is the parallel electric field  $E_{\parallel}$  in a nonlinear magnetosonic wave. It is shown that  $E_{\parallel}$  can be strong even in low frequency, magnetohydrodynamic phenomena.

Next, nonstochastic particle acceleration in intense electric and magnetic fields formed in a shock wave is studied with theory and with fully kinetic, fully relativistic, electromagnetic, particle simulations. The subjects include (1) electron trapping and acceleration, (2) energization of thermal and relativistic ions, (3) heavy-ion acceleration and resultant damping of nonlinear pulses in a multi-ion-species plasma, and (4) positron acceleration due to  $E_{\parallel}$  in the shock transition region in an EPI plasma. In addition to these processes near a shock front, (5) the evolution of large-amplitude Alfvén waves generated behind a shock front and acceleration of electrons in the Alfvén

wave region are examined.

Simulations demonstrate particle acceleration caused by these nonlinear magnetohydrodynamic waves to ultrarelativistic energies much higher than those of solar energetic particles. The acceleration theory based on the investigation of nonlinear waves quantitatively accounts for these simulation results.

*Keywords:*

particle acceleration, collisionless shock wave, KdV equation, single-ion-species plasma, multi-ion-species plasma, electron-positron-ion plasma

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## Contents

<b>1</b>	<b>Introduction</b>	<b>6</b>
1.1	Cosmic rays . . . . .	6
1.1.1	Sources and energies of cosmic rays . . . . .	7
1.1.2	Extremely high energy cosmic rays . . . . .	8
1.2	Acceleration models . . . . .	9
1.2.1	Stochastic acceleration models . . . . .	9
1.2.2	Nonstochastic acceleration due to shock waves . . . . .	9
1.3	Structure of this paper . . . . .	10
<b>2</b>	<b>Structure of nonlinear magnetosonic waves in a single-ion-species plasma</b>	<b>12</b>
2.1	Linear magnetosonic and Alfvén waves . . . . .	12
2.1.1	One-fluid MHD theory . . . . .	12
2.1.2	Two-fluid theory . . . . .	14
2.1.3	Long-wavelength magnetosonic wave . . . . .	18
2.2	Finite-amplitude stationary waves . . . . .	19
2.2.1	Basic properties . . . . .	19
2.2.2	Electric potential . . . . .	20
2.2.3	Charge neutrality and pulse width in a strong magnetic field . . . . .	20
2.3	KdV equation for small-amplitude waves . . . . .	21
2.4	Shock waves . . . . .	23
2.4.1	Field profiles . . . . .	23
2.4.2	Quantities in the wave frame . . . . .	24

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2.4.3	Field strengths in a large-amplitude shock wave . . . . .	25	6.2	Theoretical analysis: Mechanism of electron acceleration . . . . .	71
<b>3</b>	<b>Waves in a multi-ion-species plasma</b>	<b>28</b>	6.2.1	Trajectories of passing and reflected electrons . . . . .	71
3.1	Perpendicular waves in a two-ion-species plasma . . . . .	28	6.2.2	Energy gain from potential $\phi$ and constant electric field $E_{y0}$ . . . . .	72
3.1.1	Linear dispersion relation . . . . .	28	6.2.3	Small relative velocity between reflected electrons and shock wave . . . . .	73
3.1.2	KdV equation for the low-frequency mode . . . . .	31	6.3	Reflection and parallel pseudo potential . . . . .	76
3.1.3	KdV equation for the high-frequency mode . . . . .	32	6.3.1	Nonrelativistic description . . . . .	76
3.1.4	Three-fluid simulation . . . . .	32	6.3.2	Relativistic description . . . . .	78
3.2	Oblique waves in a two-ion-species plasma . . . . .	34	6.3.3	Nonstationarity and deep trapping . . . . .	79
3.2.1	Oblique low-frequency mode . . . . .	35	<b>7</b>	<b>Ion acceleration</b>	<b>82</b>
3.2.2	Oblique high-frequency mode . . . . .	36	7.1	Physical considerations and numerical calculations on one and multiple reflections . . . . .	84
<b>4</b>	<b>Waves in an EPI plasma</b>	<b>40</b>	7.1.1	Conditions for reflection . . . . .	84
4.1	Waves in a pure electron-positron plasma . . . . .	40	7.1.2	One reflection . . . . .	85
4.2	Perpendicular waves in an EPI plasma . . . . .	42	7.1.3	Multiple reflections . . . . .	86
4.2.1	Linear dispersion relation of perpendicular waves . . . . .	42	7.1.4	Demonstration with particle simulations . . . . .	87
4.2.2	Effects of the displacement current . . . . .	46	7.2	Incessant acceleration of fast ions . . . . .	89
4.2.3	Nonlinear perpendicular low-frequency mode . . . . .	47	7.2.1	Energy absorption from a perpendicular shock wave . . . . .	89
4.2.4	Nonlinear perpendicular high-frequency mode . . . . .	49	7.2.2	Energy absorption from an oblique shock wave . . . . .	90
4.2.5	Nonlinear coupling of high- and low-frequency modes in an EPI plasma . . . . .	49	7.2.3	Relativistic incessant acceleration . . . . .	92
4.3	Oblique waves in an EPI plasma . . . . .	51	<b>8</b>	<b>Heavy-ion acceleration</b>	<b>96</b>
<b>5</b>	<b>Parallel electric field</b>	<b>55</b>	8.1	Simulation of heavy-ion acceleration . . . . .	97
5.1	Parallel pseudo potential $F$ . . . . .	55	8.2	Theory of heavy-ion acceleration . . . . .	99
5.2	Parallel electric field and parallel pseudo potential in nonlinear magnetosonic waves . . . . .	56	8.2.1	Acceleration due to a shock wave . . . . .	99
5.2.1	Perturbation theory for $E_{\parallel}$ and $F$ in an electron-ion plasma . . . . .	56	8.2.2	Acceleration due to a small-amplitude pulse . . . . .	101
5.2.2	Simulations for $F$ in small-amplitude pulses . . . . .	59	8.3	Damping of small-amplitude pulses in a multi-ion-species plasma	102
5.2.3	Parallel pseudo potential in shock waves . . . . .	60	<b>9</b>	<b>Positron acceleration</b>	<b>107</b>
5.2.4	Theory and simulations for $E_{\parallel}$ and $F$ in an EPI plasma	61	9.1	Theory of ultrarelativistic positron acceleration . . . . .	108
<b>6</b>	<b>Trapping and ultrarelativistic acceleration of electrons</b>	<b>64</b>	9.1.1	Acceleration nearly parallel to the magnetic field . . . . .	109
6.1	Particle simulation of shock waves . . . . .	65	9.1.2	Surfatron and generalized theory . . . . .	111
6.1.1	Simulation method . . . . .	65	9.1.3	Perturbed motions . . . . .	112
6.1.2	Simulation results: Creation of ultrarelativistic electrons in the main pulse . . . . .	68	9.2	Simulations of ultrarelativistic acceleration of positrons . . . . .	113
			9.2.1	Demonstration and analysis of acceleration . . . . .	113
			9.2.2	Dependence on plasma parameters . . . . .	118

<b>10 Wave evolution and particle acceleration behind a shock front</b>	<b>119</b>
10.1 Electron acceleration due to a compressive pulse . . . . .	120
10.1.1 Theoretical considerations . . . . .	121
10.1.2 Observed particle motions . . . . .	125
10.2 Acceleration around a moving magnetic neutral sheet . . . . .	127
10.3 Alfvén waves and particle acceleration behind a shock front . . . . .	130
10.3.1 Motions of bulk particles . . . . .	130
10.3.2 Evolution of waves and phase spaces . . . . .	132
10.3.3 Electron acceleration due to Alfvén waves . . . . .	137
<b>Appendix A Finite-amplitude, stationary, relativistic, perpendicular wave</b>	<b>144</b>
<b>Appendix B KdV Equation in a warm, single-ion-species plasma</b>	<b>149</b>
<b>Appendix C Derivation of KdV Equation for the high-frequency mode</b>	<b>155</b>
<b>Appendix D Highest energy of trapped electrons</b>	<b>159</b>
<b>Appendix E Equivalence of Eqs. (245) and (257)</b>	<b>162</b>
<b>Appendix F Conditions for ion reflection</b>	<b>163</b>
Appendix F.1 Motions in the upstream and transition regions . . . . .	163
Appendix F.2 First reflection in the transition region . . . . .	165
Appendix F.3 Second reflection . . . . .	166
Appendix F.4 Multiple reflections with small relative velocity . . . . .	168
<b>Appendix G Jumps in energy and parallel momentum</b>	<b>168</b>
Appendix G.1 Magnitude of an energy jump . . . . .	169
Appendix G.2 Increase in parallel momentum . . . . .	170
<b>Appendix H Wave energy density of the high-frequency mode</b>	<b>173</b>
<b>Appendix I Perturbed motions of positrons and ions</b>	<b>175</b>
Appendix I.1 Perturbations of positron motion . . . . .	175
Appendix I.2 Perturbations of ion motion . . . . .	180

<b>Appendix J Electron motions inside and outside a compressive pulse</b>	<b>181</b>
Appendix J.1 Elliptic orbits in the momentum space . . . . .	182
Appendix J.2 Sign of $a_1^2$ . . . . .	183
Appendix J.3 Sign of $\Delta P(t_0)$ . . . . .	183

## 1. Introduction

Cosmic rays have been investigated for nearly a century and are still attracting increasing attention from plasma, particle, and astrophysics communities [1]-[14]. Their acceleration mechanism, however, remains unresolved. Unlike the studies of plasma-based accelerators initiated by John Dawson *et al.* in the late 1970's [15, 16], in which detailed comparisons between the experiments, theories, and simulations are possible, it is quite difficult to directly observe the acceleration processes of cosmic rays produced in the distance, although we have a huge amount of experimental data, such as time variations of x-ray and gamma-ray emission associated with solar flares [3].

Because of the rapid increase in the power of computers, however, we can now perform simulations that solve large-scale plasma behavior and individual relativistic particle motions in a self-consistent manner. Their precise information about particle motions and electromagnetic fields would enable us to create new theories for particle acceleration and to test existing theories. With use of relativistic particle simulations, indeed, several distinct nonstochastic particle acceleration mechanisms caused by shock waves in a magnetized collisionless plasma have been found and analyzed in the past few decades [17]-[35]. Furthermore, to account for the field structures that lead to energization of particles, nonlinear wave theory has been developed [36]-[44]: A coherent theory for nonlinear waves and particle acceleration mechanisms has thus been constructed. This paper reviews these studies.

Before looking at detailed theories, however, we briefly describe in this section some fundamental properties of cosmic rays for the readers who are not familiar with them and then outline the structure of this paper.

### 1.1. Cosmic rays

The origin of the research of cosmic rays may date far back to 1912, when Hess revealed with balloon flight experiments that radiation causing ionization in the atmosphere comes mainly from the sky, not from the ground [45].

# Ultrarelativistic Particle Acceleration in Collisionless Shock Waves

## 1 Introduction

### Wave

- 2 Structure of nonlinear magnetosonic waves in a **single-ion-species** plasma
- 3 Waves in a **multi-ion-species** plasma
- 4 Waves in an **EPI** plasma
- 5 **Parallel** electric field

### Acceleration

- 6 Trapping and ultrarelativistic acceleration of **electrons**
- 7 **Ion** acceleration
- 8 **Heavy-ion** acceleration
- 9 **Positron** acceleration
- 10 Wave evolution and particle acceleration **behind a shock front**

Appendices A --- J

# 特徴

大振幅波の中に形成される強力な電磁場によって引き起こされる  
nonstochasticな粒子加速を探求  
(Fermi加速や乱流のようなstochasticなモデルではない)

粒子加速と大振幅波を並行して研究  
第一原理から

超相対論的加速 ( $\gamma > 100$ ) を粒子シミュレーションで実証

(太陽高エネルギー電子の $\gamma \sim 100$ 、陽子 $\gamma < 10$ )

## 注: 様々なエネルギー

地球大気	0.03 eV
太陽表面	0.6 eV
太陽コロナ	100 eV
太陽の中心部	1.5 keV
核融合プラズマ	10 keV
太陽宇宙線陽子	1~10 GeV
電子	数十MeV ( $\gamma \sim 100$ )



# Observations of high-energy particles

Cosmic Rays  $\sim 10^{20}$  eV

Phys. Rev. Lett. **100**, 101101 (2008)

EHECR: GZK cutoff, Anisotropic arrival directions

SN1006, Crab Nebula  $\sim 10^{14}$  eV (electrons)

Nature **378**, 255 (1995) , ApJ **539**, 317 (2000)

Supernova Remnant RS J1713.7-3946  $\sim 10^{12}$  eV (protons)

PASJ **55**, L61 (2003), Nature **432**, 75 (2004)

Solar Energetic Particles

$10^9 \sim 10^{10}$  eV (protons),  $10^7 \sim 10^8$  eV (electrons)

< a few seconds

ApJ **318**, 913 (1987)

Elemental Composition of cosmic rays  
similar to that of the universe

ApJ. Suppl. **57**, 173 (1985)

# 無衝突衝撃波とは

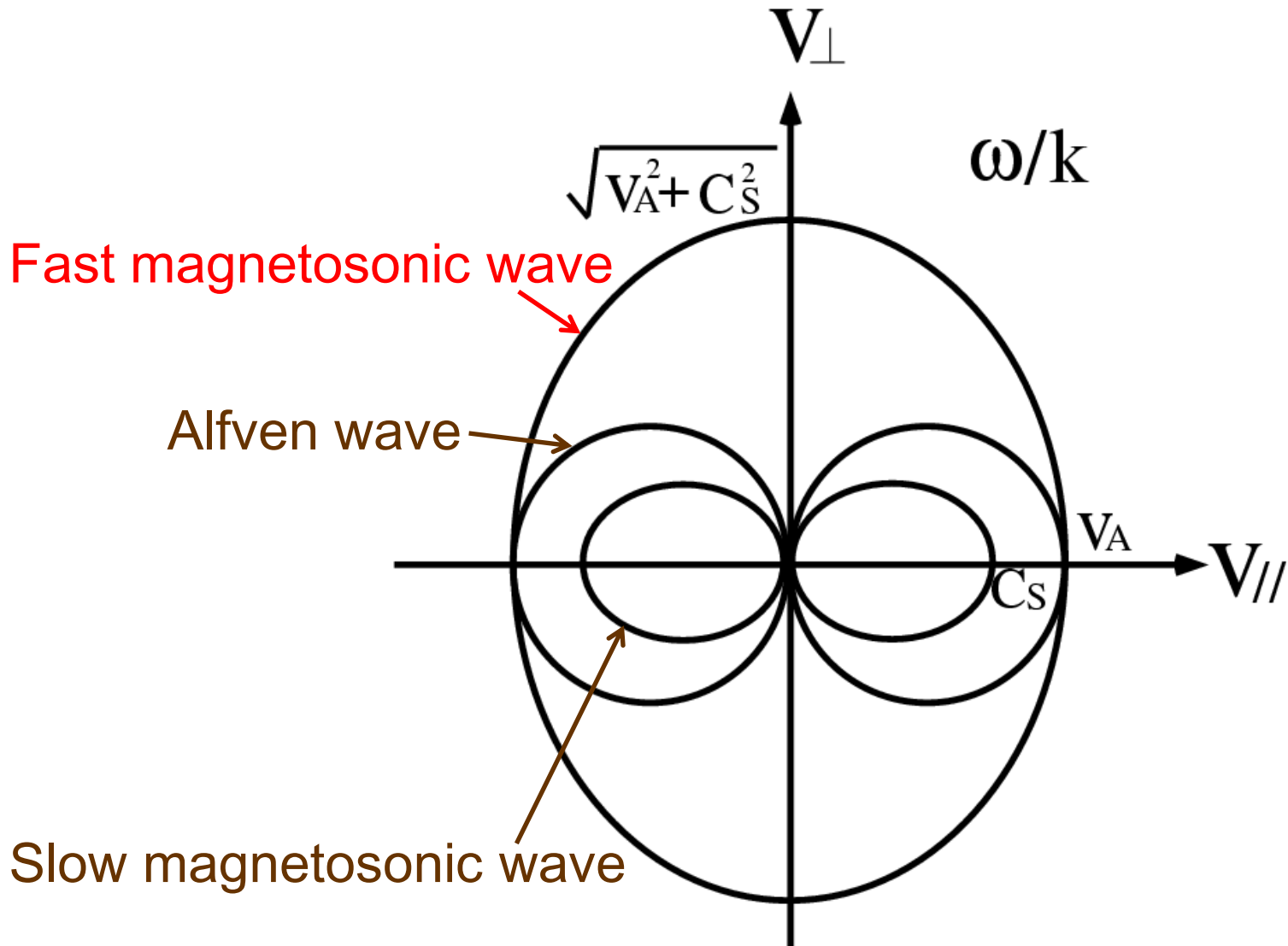
二体衝突の非常に少ない**高温プラズマ**における衝撃波  
例：バウショック、超新星爆発による星間空間の衝撃波

無衝突でなぜ衝撃波ができるか？

Morawetz    **イオン反射**で衝撃波の構造  
多数の著者    **不安定性**が乱流をつくり、散逸を生じる  
                  →プラズマ加熱



# Three waves in one-fluid MHD



# Nonlinear magnetosonic waves in a single-ion-species plasma

Small-amplitude waves propagate as solitary waves  
or wavetrains governed by the **KdV** Equation

Large-amplitude waves evolve into **shock waves**

$$\frac{B_{lzm}}{B_{lz0}} = 1 + \gamma_{sh}^2 \left[ \left( 1 + \frac{2v_{sh}^2}{v_A^2 \sin^2 \theta} \right)^{1/2} - 1 \right],$$

$$\frac{e\phi_{lm}}{m_i v_A^2} = \left( \sin^2 \theta + \frac{\sin \theta \cos \theta}{\gamma_{sh} (1 + \gamma_{sh}^2 \tan^2 \theta)^{1/2}} \right) \left[ \left( 1 + \frac{2v_{sh}^2}{v_A^2 \sin^2 \theta} \right)^{1/2} - 1 \right].$$

KdV equation

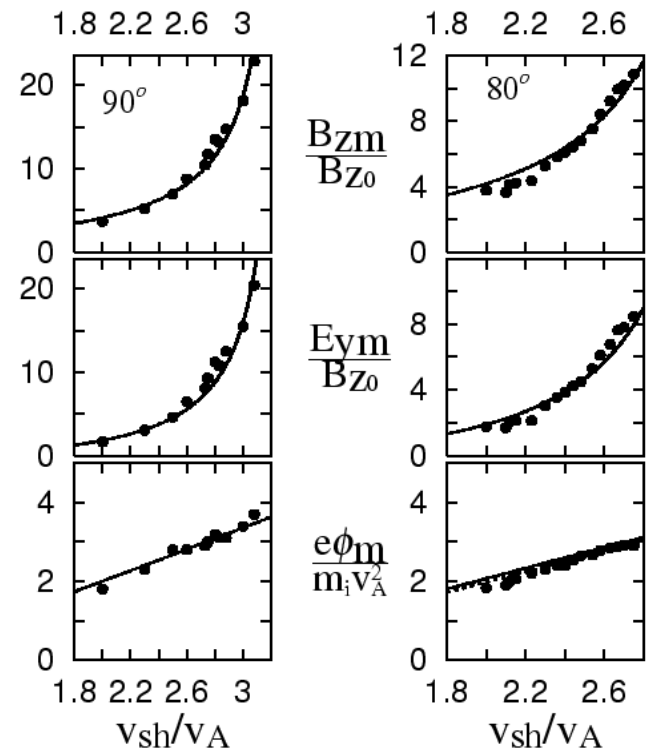
Finite-amplitude, stationary, perpendicular wave

Shock wave

field strengths

Nakazawa & Ohsawa, J. Phys. Soc. Jpn. **66**, 2044 (1997)

Miyahara, Kawashima, & Ohsawa, Phys. Plasmas **10**, 98 (2003)



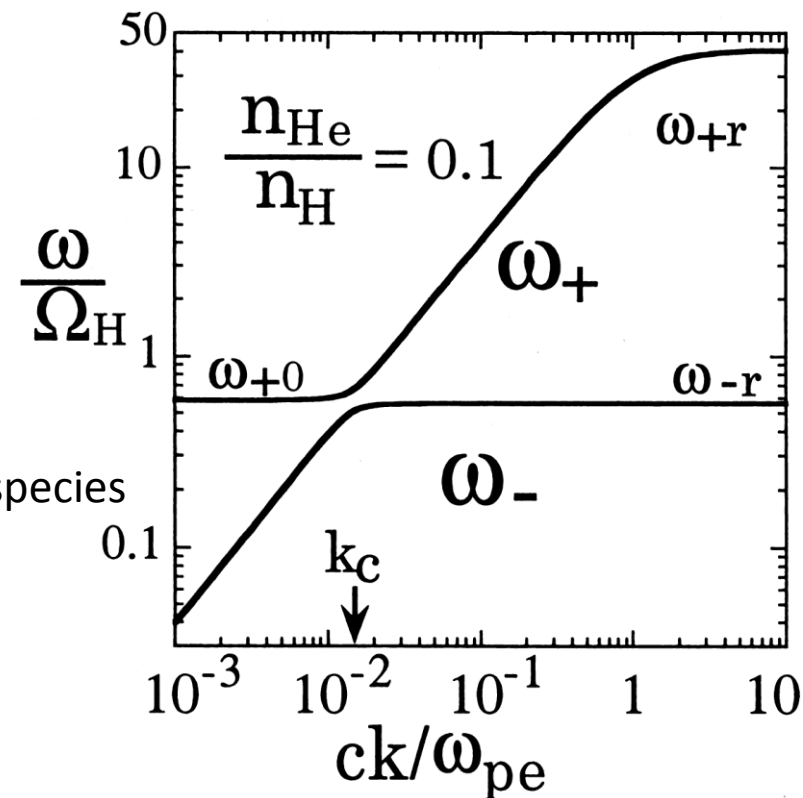
# Multi-ion-species plasma

In a two-ion-species plasma, the magnetosonic wave is split into **two modes**: High- and low-frequency modes

Although the high-frequency mode has a finite cutoff frequency, we have derived the **KdV equation for each mode**

The pulse width of the high-frequency mode,  $\sim c/\omega_{pe}$ , is much shorter than that of the low-frequency mode,  $\sim c/\omega_{pi}$

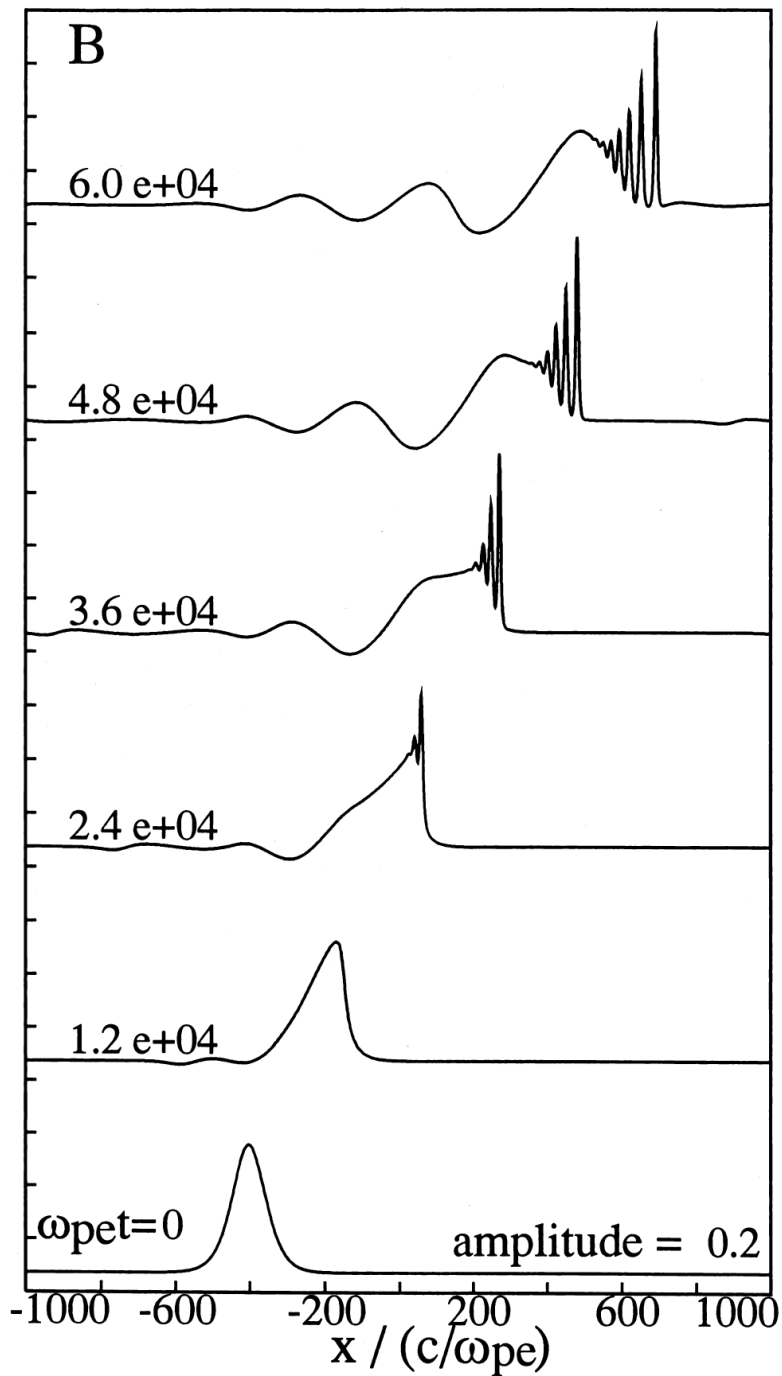
Even a perpendicular pulse is **damped** in a multi-ion-species plasma due to the heavy-ion acceleration



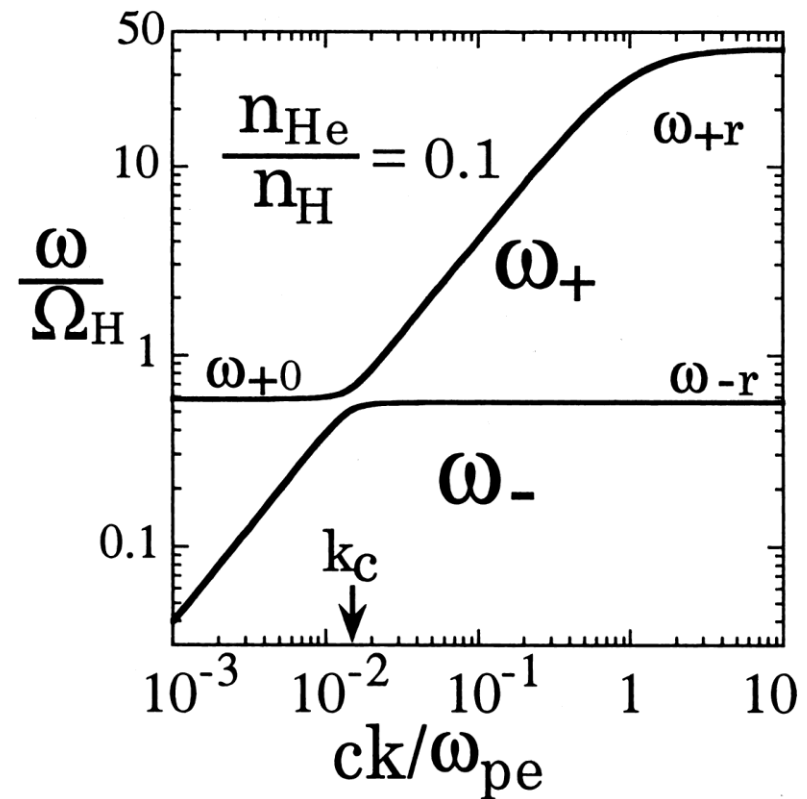
Toida, Ohsawa, & T. Jyounouchi, Phys. Plasmas **2**, 3329 (1995)

Dogen, Toida, & Y. Ohsawa, Phys. Plasmas **5**, 1298 (1998)

Irie & Ohsawa, Phys. Plasmas **10**, 1253 (2003)



High-frequency-mode solitons are generated from a low-frequency-mode pulse



Toida, Ohsawa, & Jyounouchi,  
Phys. Plasmas **2**, 3329 (1995)

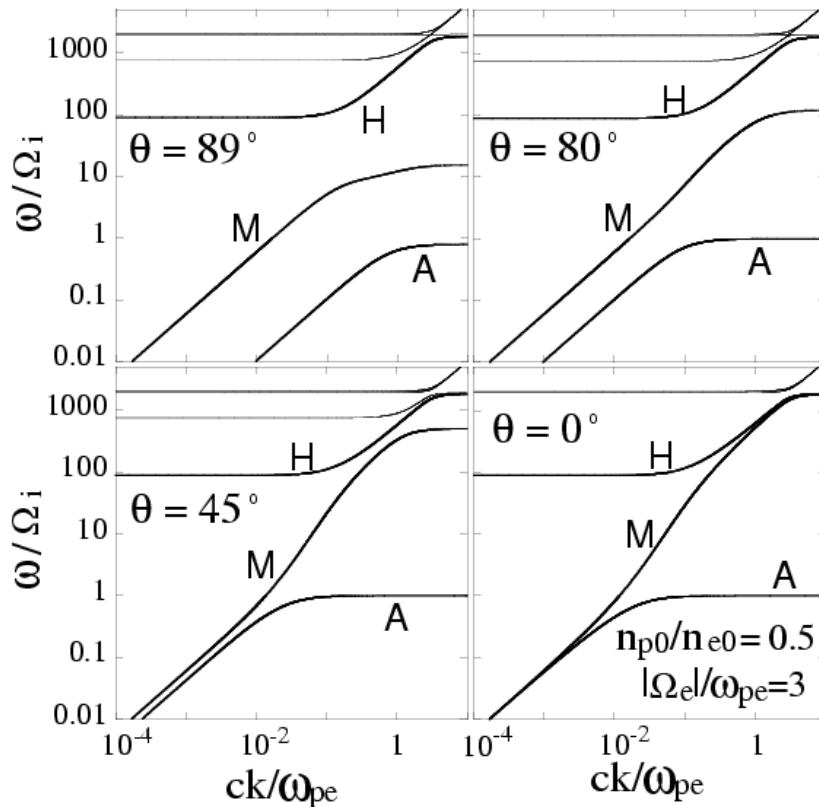
# Electron-positron-ion (EPI) plasma

The theory for two-ion-species plasmas has been extended to EPI plasmas

Linear dispersion relations are obtained

Nonlinear evolution equations for two magnetosonic modes (M & H) are derived

Their field structures are analyzed



The electric potential decreases with increasing positron density:  
 $\phi = 0$  in a pure electron-positron plasma

Hasegawa, Irie, Usami, & Y. Ohsawa,  
Phys. Plasmas **9**, 2549 (2002)

Hasegawa & Ohsawa, J. Phys. Soc. Jpn.  
**73**, 1764 (2004)

# Parallel Electric field

In the Ideal MHD,

$$\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c} = 0$$

$$E_{\parallel} \equiv \frac{\mathbf{E} \cdot \mathbf{B}}{B} = 0$$

$$F = -\int E_{\parallel} ds = 0$$

Parallel pseudo potential

It was thought that  $E_{\parallel}$  was weak in MHD phenomena

However, some simulations show that  $F \gg T$



# $F$ becomes large in shock waves

$E_{||}$  can cause strong particle acceleration

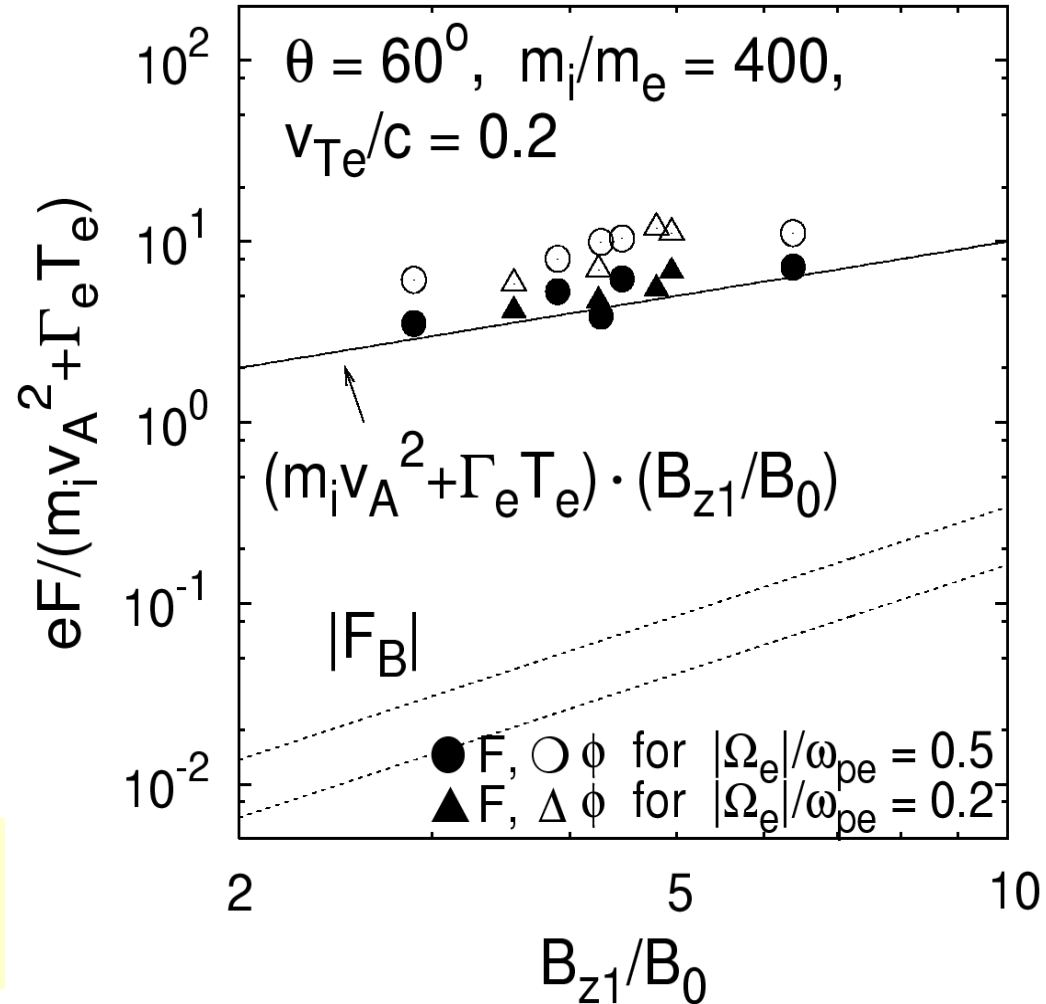
Small-amplitude pulses  $\varepsilon \ll 1$

$$eF_T \sim \varepsilon \Gamma_e T_e \quad \text{warm}$$

$$eF_B \sim \varepsilon^2 m_i v_A^2 \quad \text{cold}$$

Shock waves  $\varepsilon \sim 1$

$$eF \sim \varepsilon (m_i v_A^2 + \Gamma_e T_e)$$



Takahashi & Ohsawa, Phys. Plasmas **14**, 112305 (2007): **electron-ion plasma**

Takahashi, Sato, & Ohsawa, Phys. Plasmas **15**, 082309 (2008) : **EPI plasma**

# Simulations of particle acceleration

## Stochastic models

Fermi acceleration model (1949)

No evidence has been shown by particle simulations

Turbulence due to instabilities

Many simulations have been performed:

For instance, Dieckmann *et al.*, Instabilities,  $v \sim 20 v_{Te}$   
Astron. Astrophys. **356**, 377 (2000)

## Non-stochastic model

Acceleration caused by strong electric and magnetic fields formed in shock waves

Several different acceleration mechanisms to **ultrarelativistic energies**,  $\gamma > 100$ , have been **demonstrated** with particle simulations

# Theory and particle simulations have shown **ultrarelativistic particle acceleration in collisionless shock waves**

## 1. **protons**

Phys. Fluids **28**, 2130 (1985), Phys. Plasmas **9**, 1069 (2002)

## 2. **heavy ions**

Solar Phys. **171**, 161 (1997), Phys. Plasmas **2**, 3329 (1995); **5**, 1298 (1998)

## 3. **electrons**

Phys. Plasmas **6**, 3076 (1999); **9**, 979 (2002)

Phys. Plasmas **12**, 052308 (2005); **13**, 063110 (2006); **18**, 092307 (2011)

## 4. **positrons**

Phys. Plasmas **10**, 3455 (2003); **12**, 082306 (2005); **19**, 022302 (2012)

# Relativistic, electromagnetic particle simulation

$$\frac{d\mathbf{p}_j}{dt} = q_j \mathbf{E}(\mathbf{x}_j) + \frac{q_j}{c} \mathbf{v}_j \times \mathbf{B}_j(\mathbf{x}_j)$$

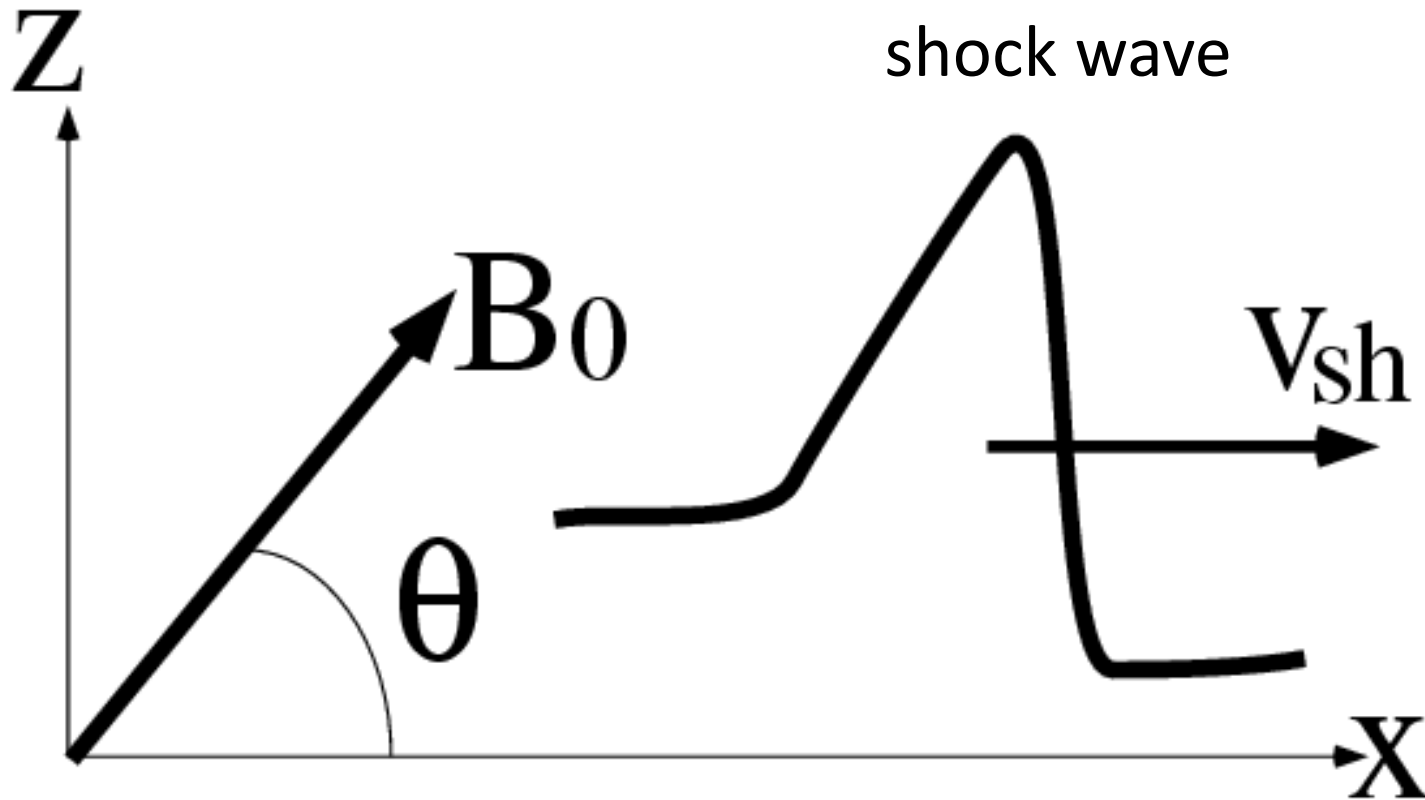
$$j = 1, 2, 3, \dots, N$$

$$\frac{1}{c} \frac{\partial \mathbf{E}}{\partial t} = \nabla \times \mathbf{B} - \frac{4\pi}{c} \mathbf{J}$$

$$\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

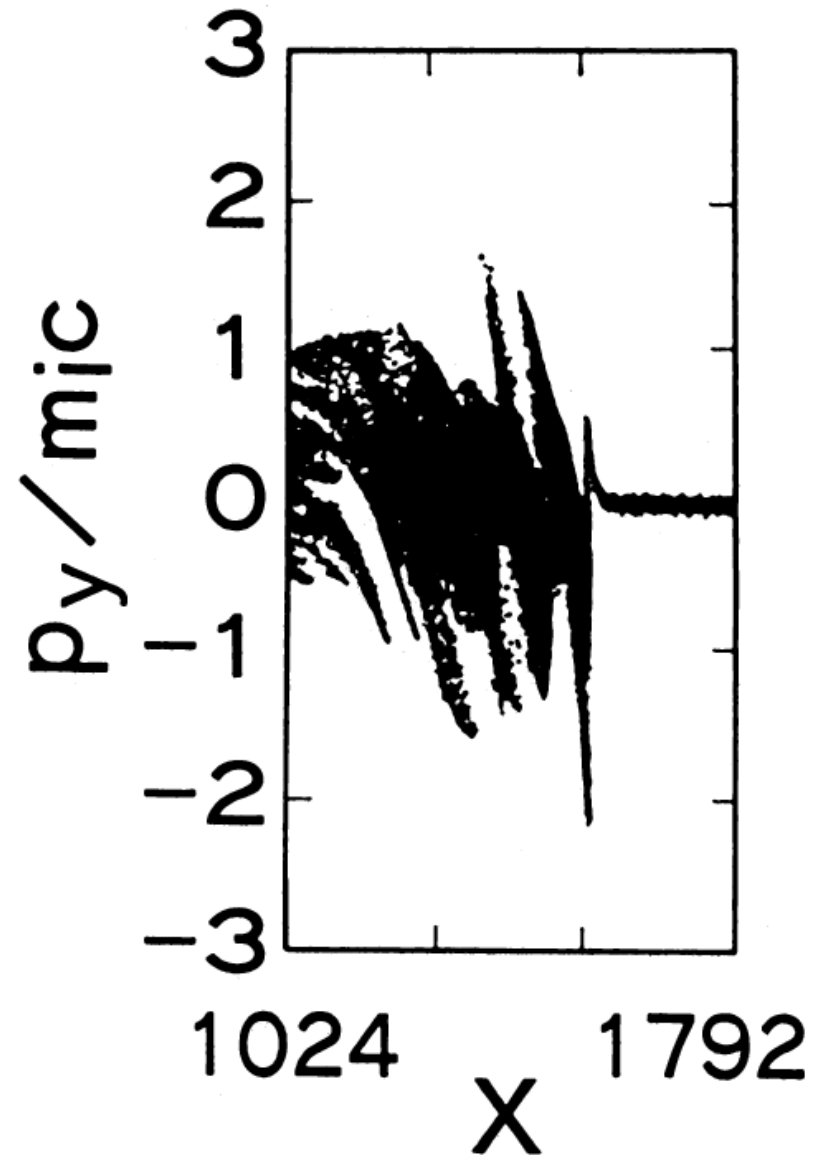
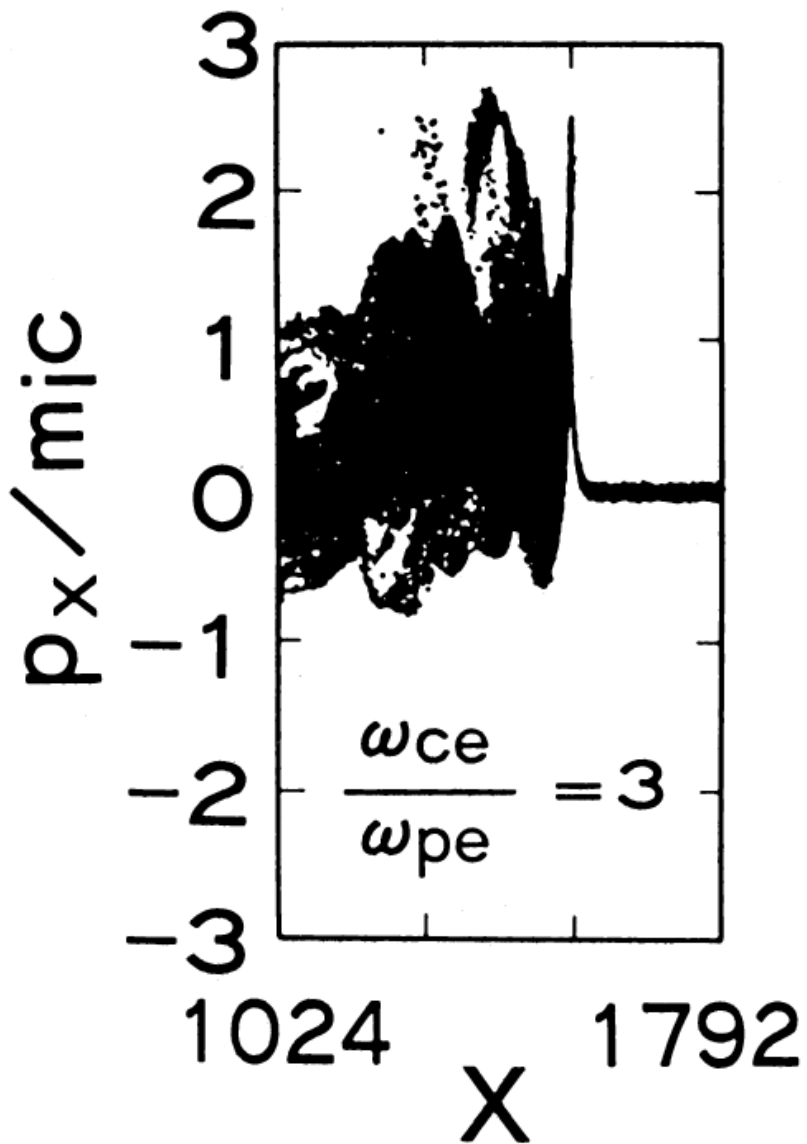
$$\nabla \cdot \mathbf{E} = 4\pi\rho, \quad \nabla \cdot \mathbf{B} = 0$$

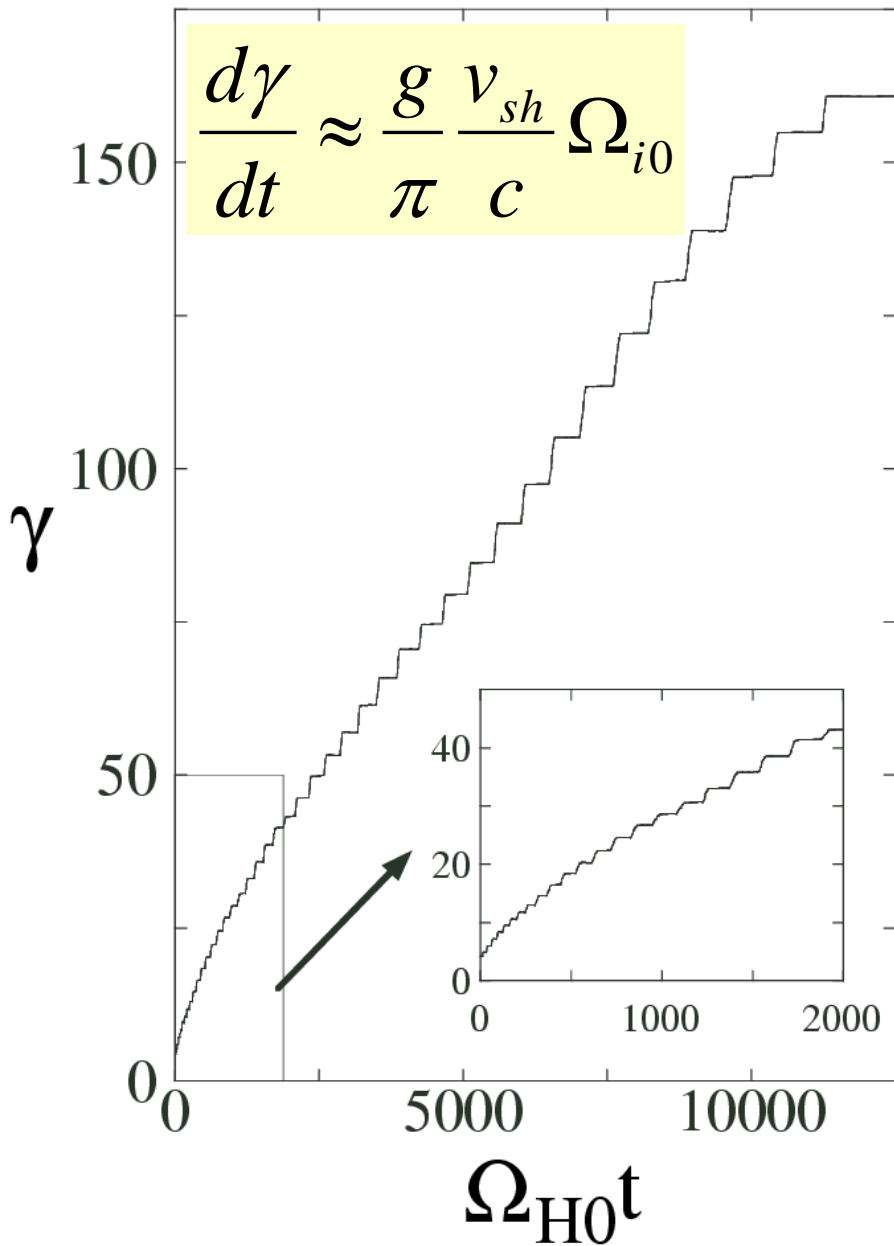
# Geometry and Simulation Code



**One dimensional (three velocities), Fully kinetic, Relativistic, Electromagnetic, Particle code**

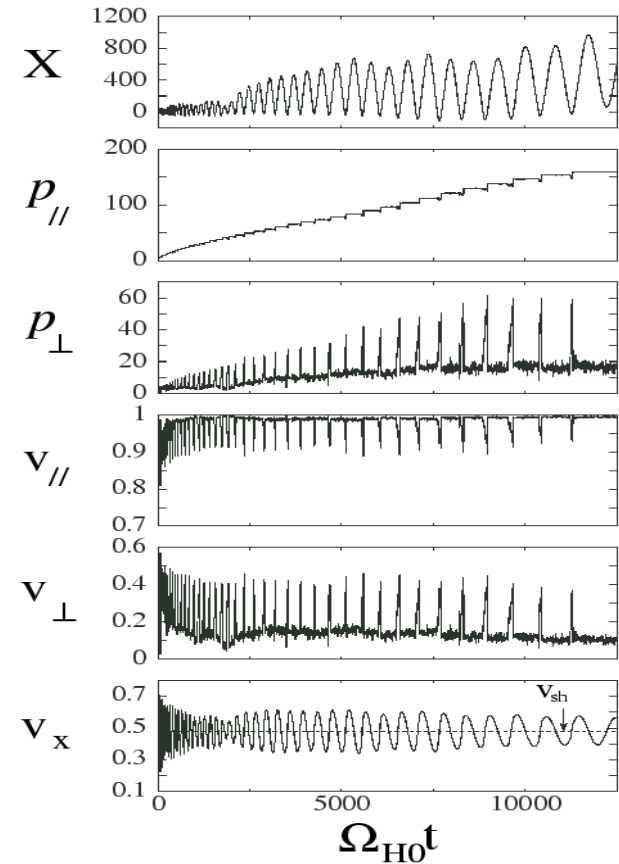
# Relativistic ions are promptly produced in a shock wave

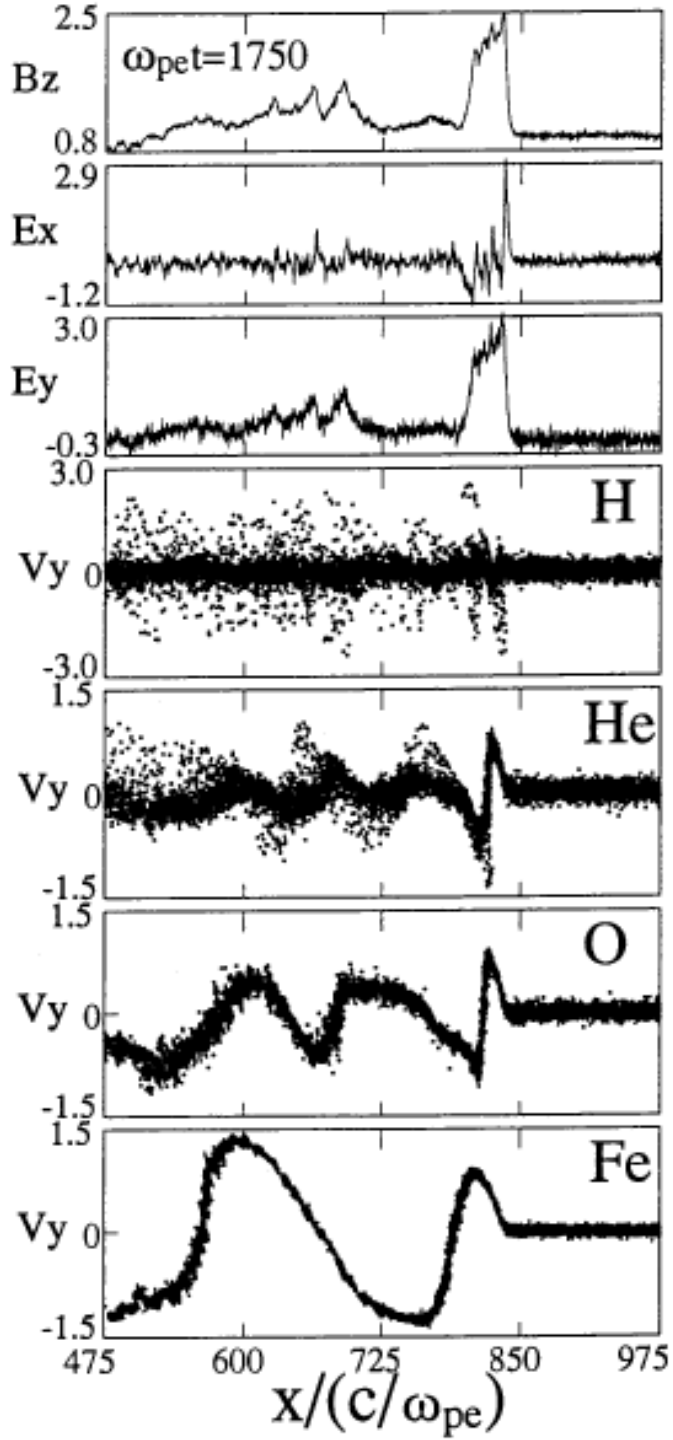




**Relativistic ions** can stay near the shock front for long periods of time, if  $v_{sh} \sim c \cos \theta$

Their energies rise **stepwise** to **ultrarelativistic energies**



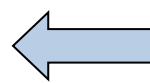


**All the heavy ions that enter a shock wave are accelerated**

Their maximum speeds are independent of particle species

$$v \approx \frac{B_m - B_0}{B_m + B_0} v_{sh}$$

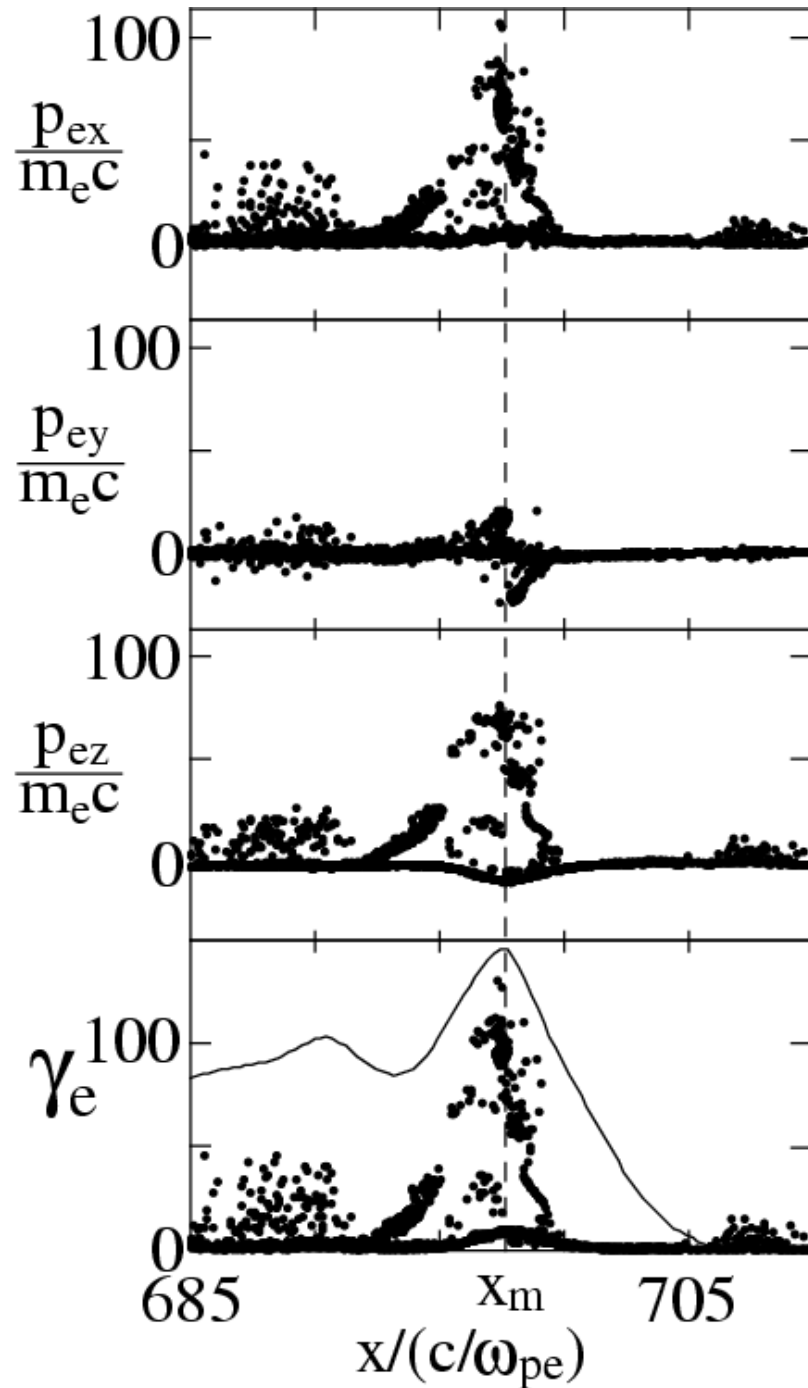
Energetic heavy ions thus have an elemental composition similar to that of the background plasma



major H ions and minor heavy ions

$\theta=90$





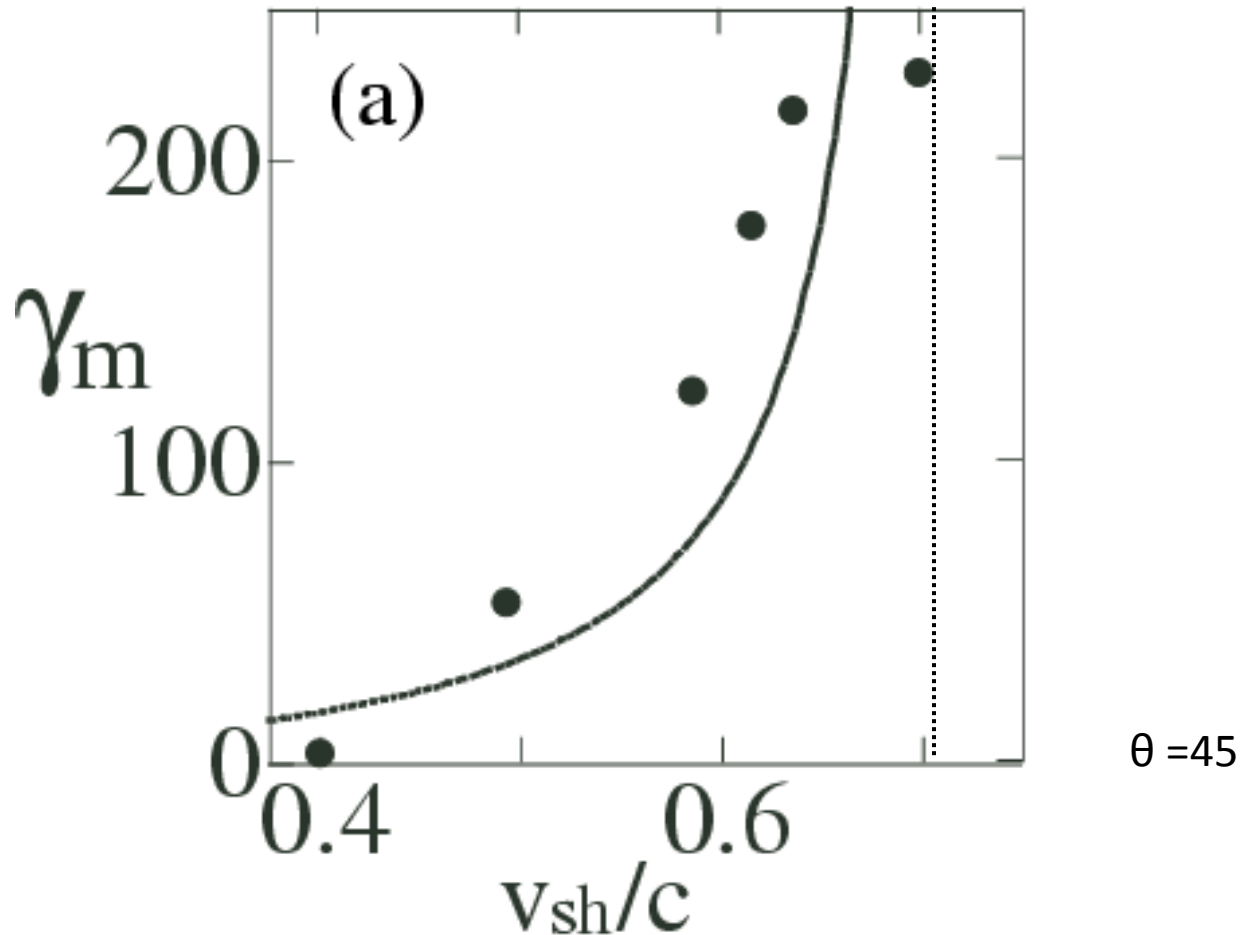
## Oblique shock waves can accelerate electrons to **ultrarelativistic energies**

Some electrons are reflected and then trapped in a shock wave

Bessho & Ohsawa, Phys. Plasmas **6**, 3076 (1999);  
**9**, 979 (2002)  
 Zindo *et al.*, Phys. Plasmas **12**, 052321 (2005)

$$|\Omega_e| / \omega_{pe} = 3, \quad \theta = 45^\circ, \quad v_{sh} = 2.2v_A$$

# Maximum $\gamma$ vs shock speed $v_{sh}$



$$mc^2(\gamma - \gamma_0) = \frac{e\phi}{1 - (v_{sh} B_{z0} / cB_{x0})}$$

Strong particle acceleration has **not** been observed  
in shock waves in an **electron-positron** plasma;

for instance, Langdon, Arons, Max, PRL **61**, 779 (1988)

However, in an **electron-positron-ion (EPI)** plasma,  
intense  $E_{||}$  persistently accelerates positrons

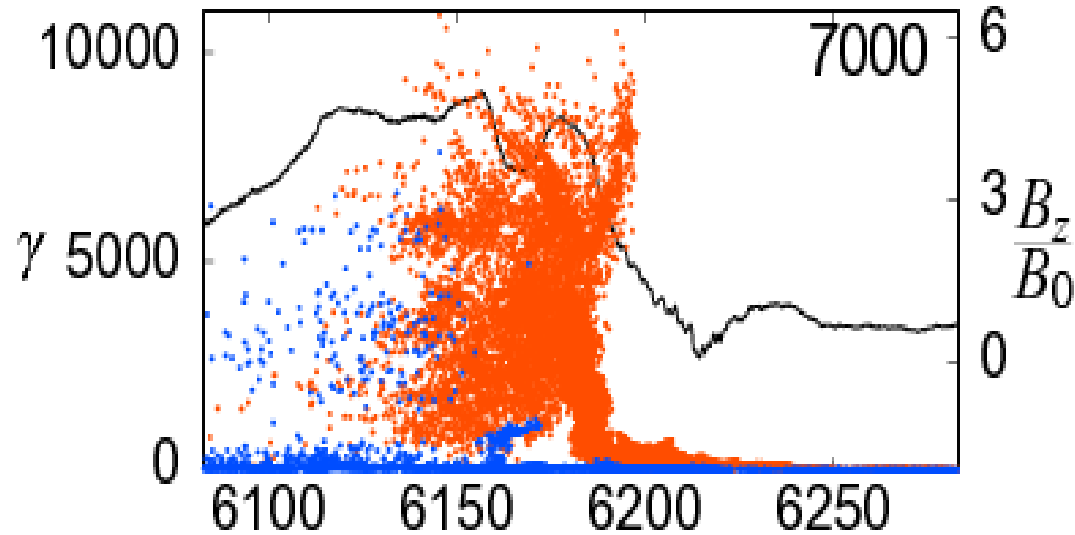
Hasegawa, Usami, & Ohsawa, Phys. Plasmas **10**, 3455 (2003);

Hasegawa, Kato, & Ohsawa, *ibid.* **12**, 082306 (2005)

$E_{||} = 0$  in an electron-positron plasma, while  
 $E_{||}$  can be **strong** in an **EPI** plasma

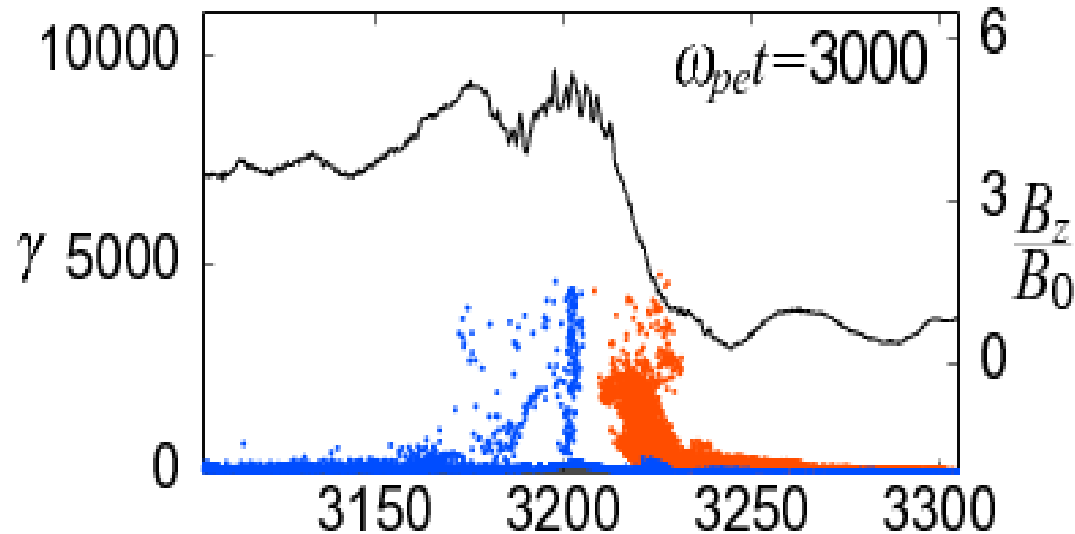
Takahashi & Ohsawa, Phys. Plasmas **14**, 112305 (2007); Takahashi, Sato, & Ohsawa, *ibid.* **15**, 082309 (2008)

# Positron acceleration to $\gamma \sim 10^4$ in an EPI plasma



The acceleration has **not** been **saturated** until the end of the run

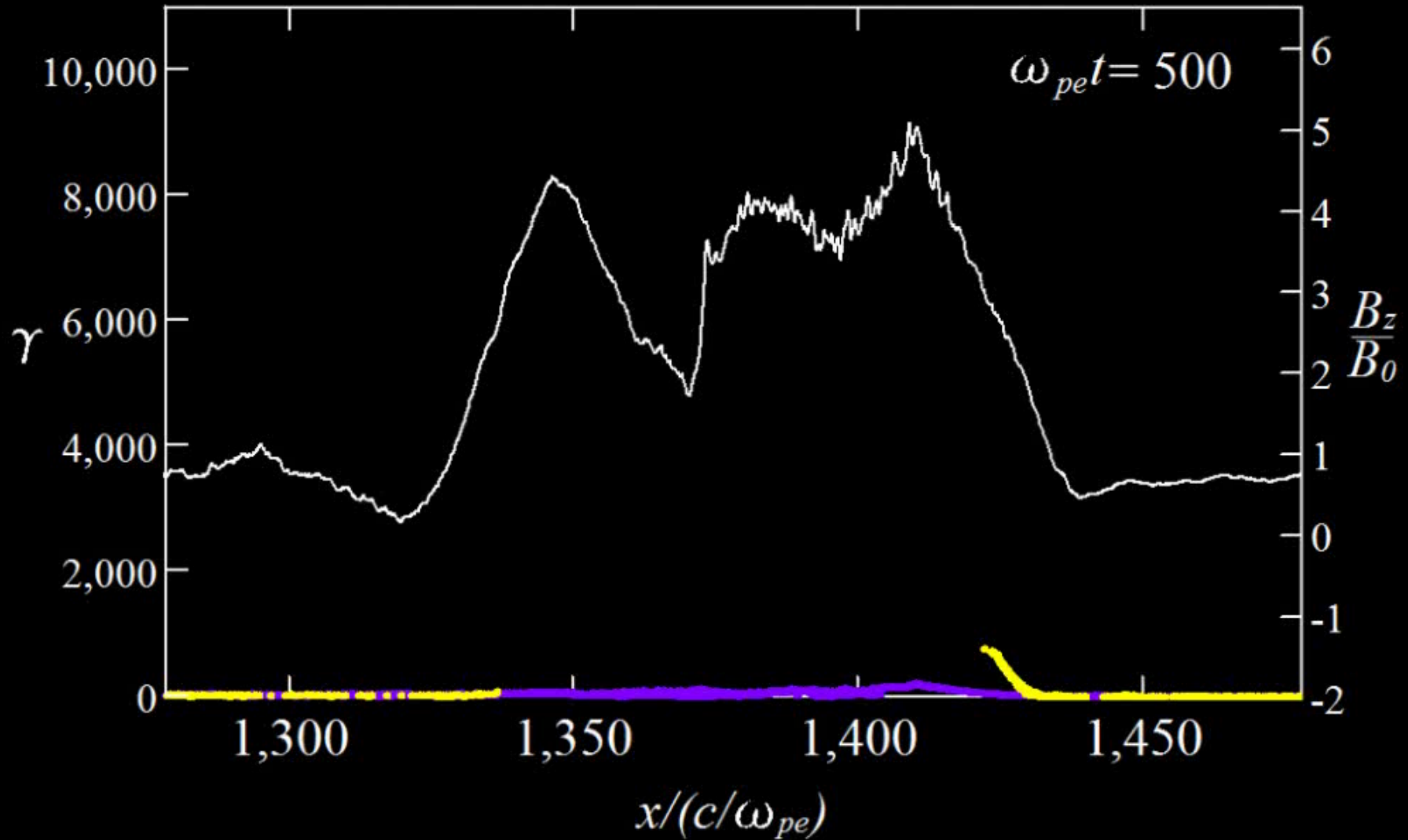
$\gamma$  will **continue to rise** in a longer simulation



$$\frac{1}{\Omega_p} \frac{d\gamma}{dt} = \frac{c \cos \theta}{v_{sh}} \frac{(\mathbf{E} \cdot \mathbf{B})}{(\mathbf{B} \cdot \mathbf{B}_0)}$$

$m_i/m_e = 1836$      $x/(c/\omega_{pe})$     • positrons  
 • electrons

# Acceleration of **positrons** and **electrons** to $\gamma \sim 10^4$



# Wave evolution and particle acceleration behind a shock front

Strong disturbances produce shock waves and, behind their fronts, large-amplitude **Alfven waves**

Three types of **ultrarelativistic electron acceleration** are found in the Alfven waves

Sato, Miyahara, & Ohsawa, Phys. Plasmas **12**, 052308 (2005)

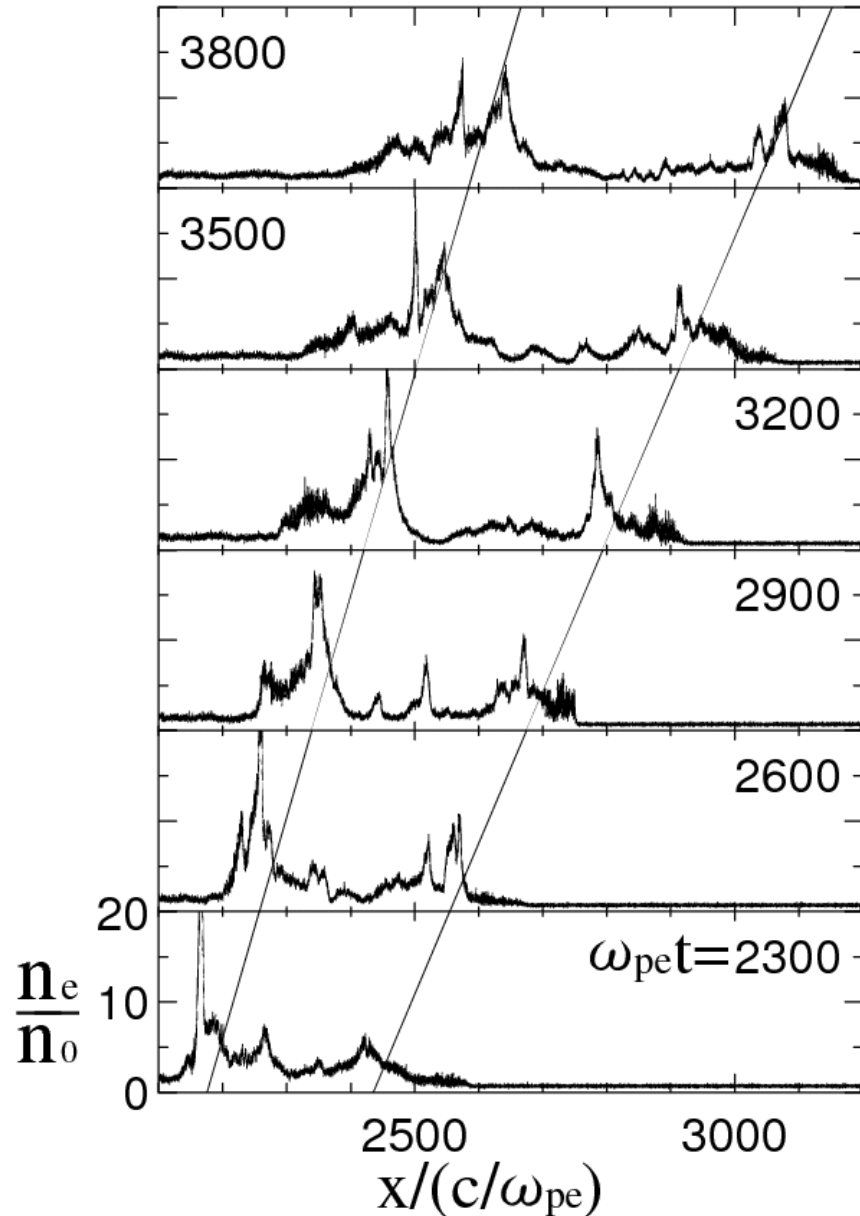
Sato & Ohsawa, Phys. Plasmas **13**, 063110 (2006)

Yamauchi & Ohsawa, Phys. Plasmas **14**, 053110 (2007)

Takeyama, Nakayama, & Ohsawa, Phys. Plasmas **18**, 092307 (2011)

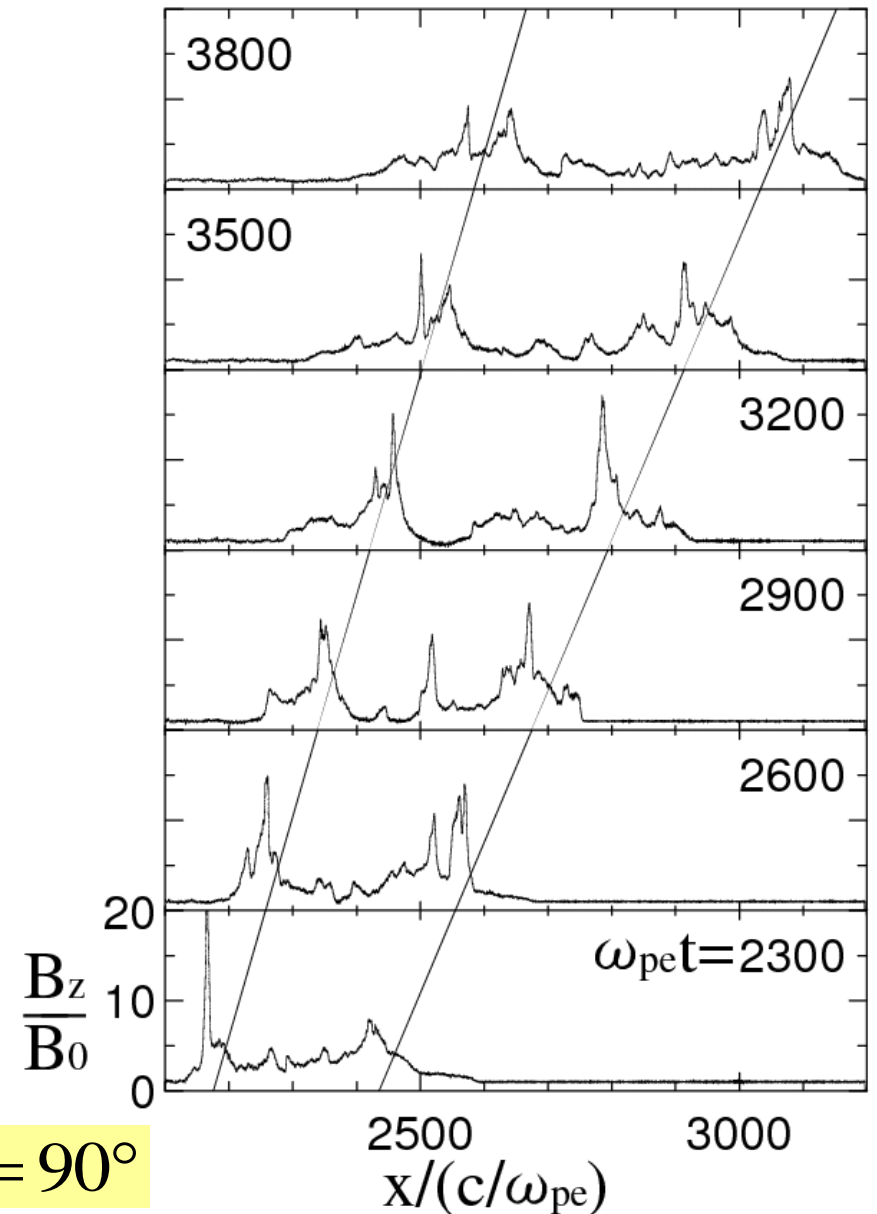
# Strong disturbance produces two shock waves

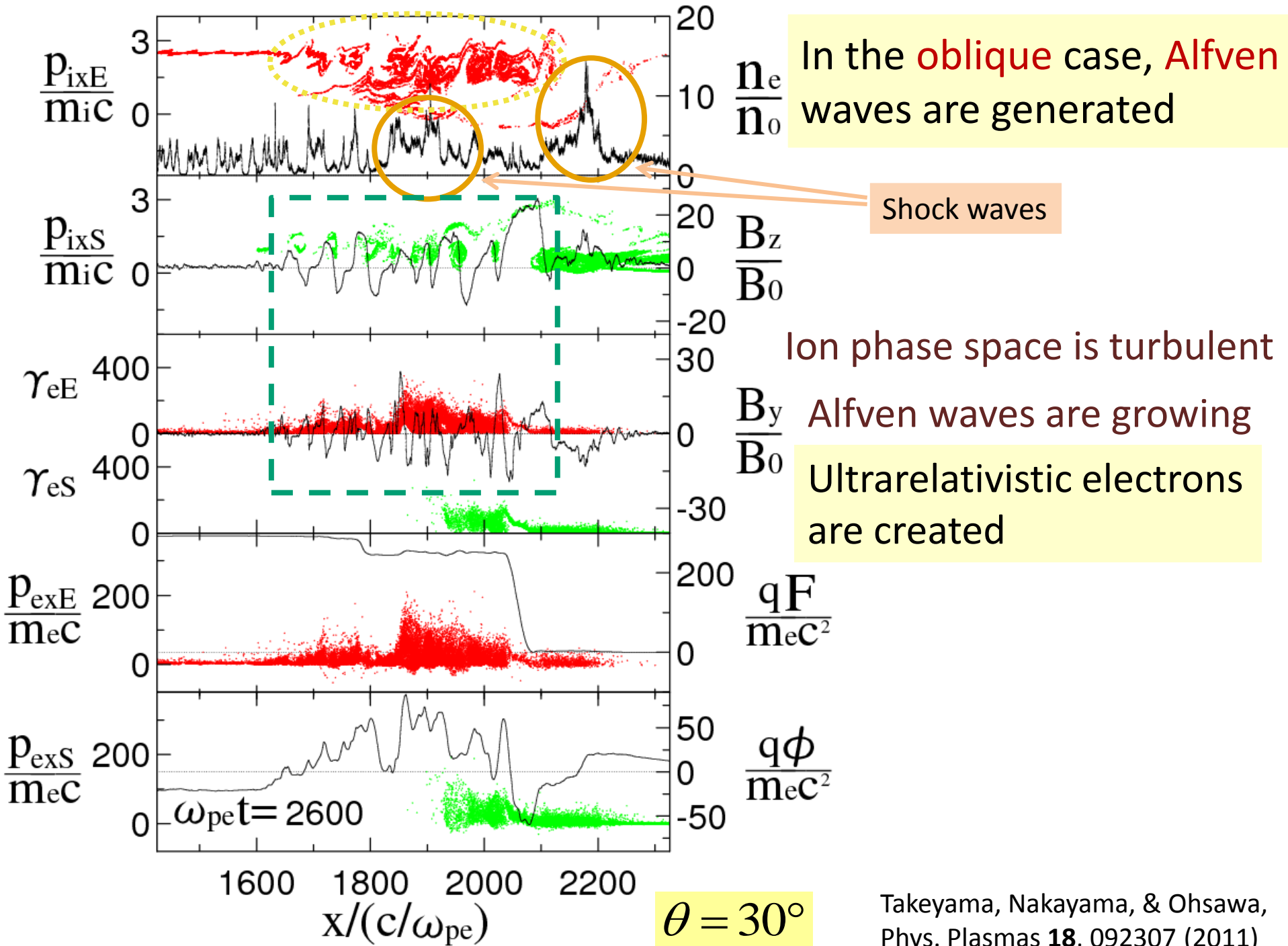
backward forward



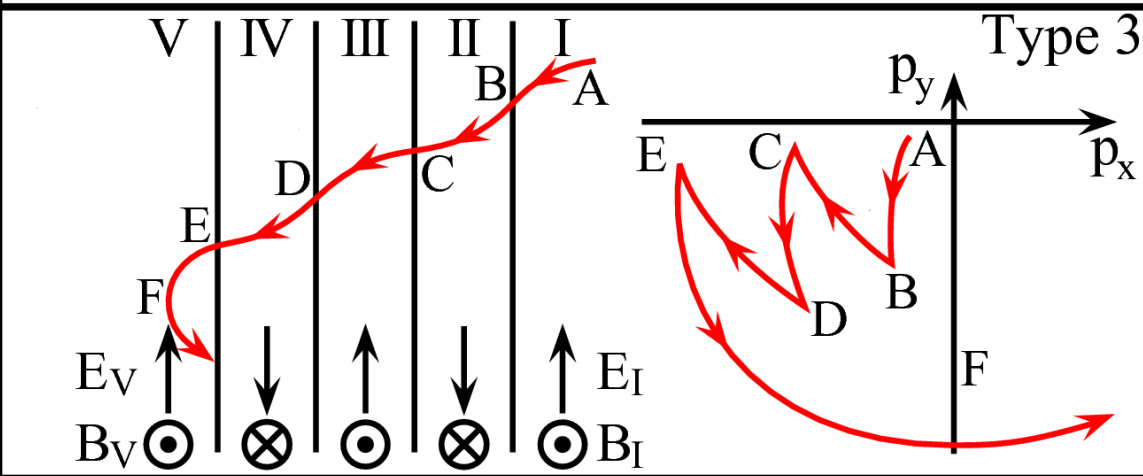
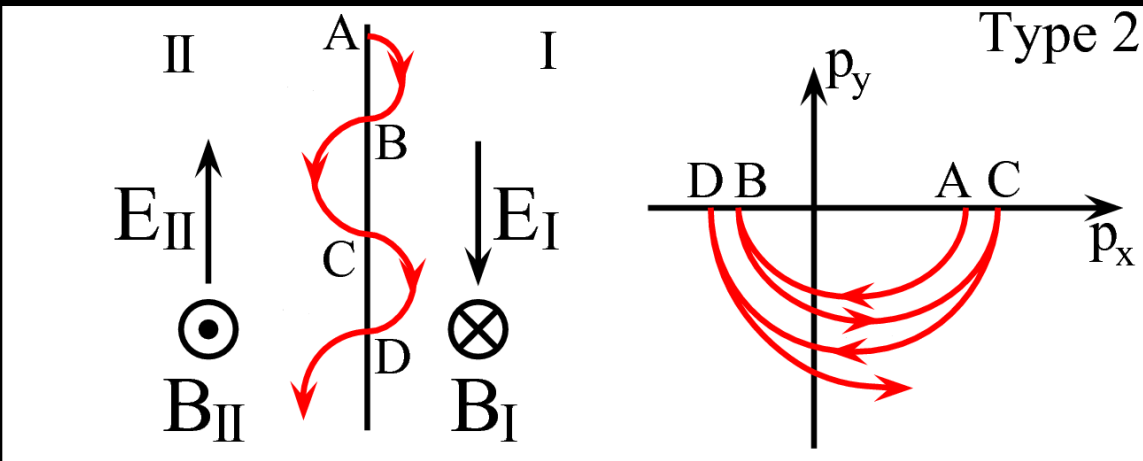
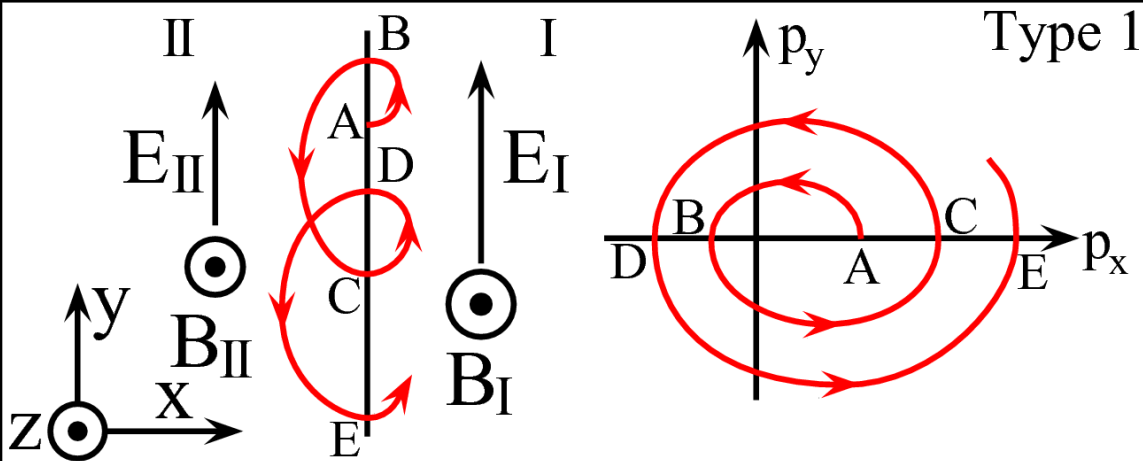
$\theta = 90^\circ$

backward forward





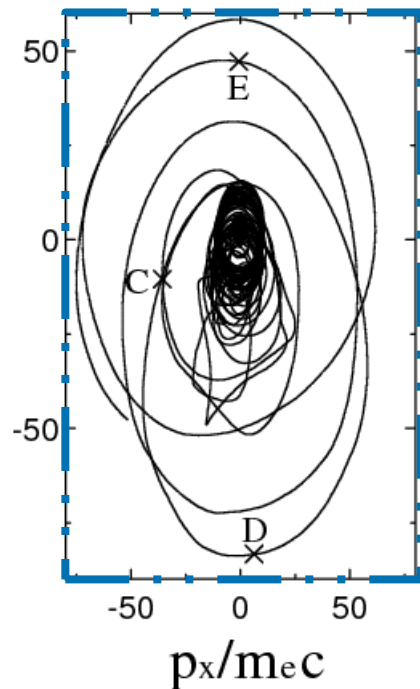
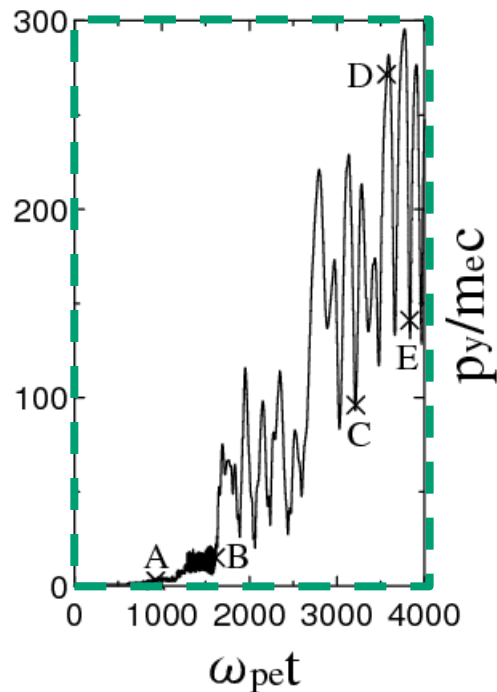
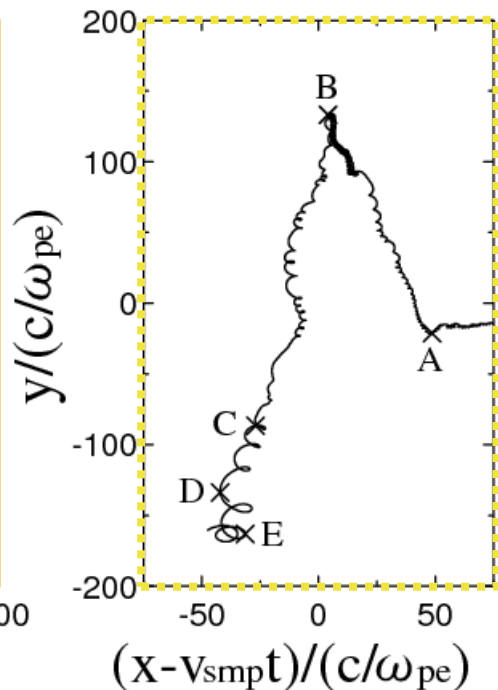
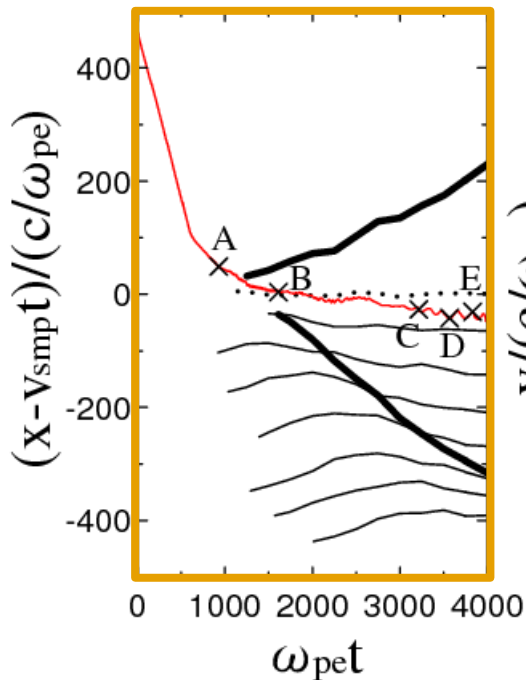




Three types of acceleration are found in the Alfvén wave region

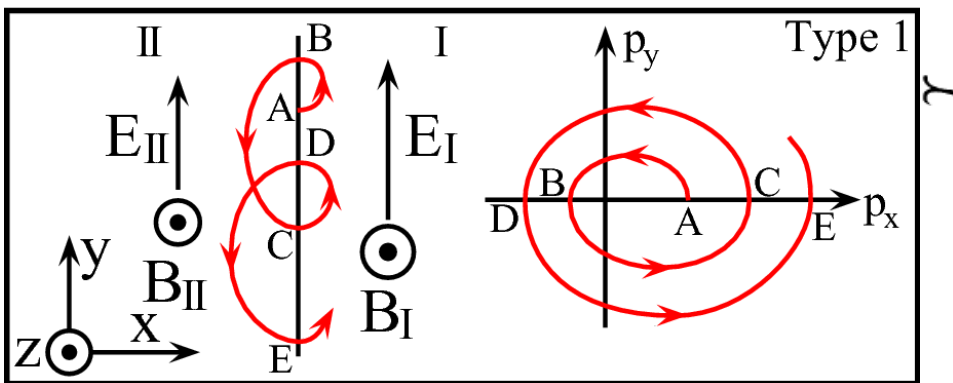
$$\gamma_C \sim \frac{1 + E_{II}/B_{II}}{1 - E_{II}/B_{II}} \gamma_B,$$

# Acceleration of electron gyrating along the strong-magnetic-field pulse

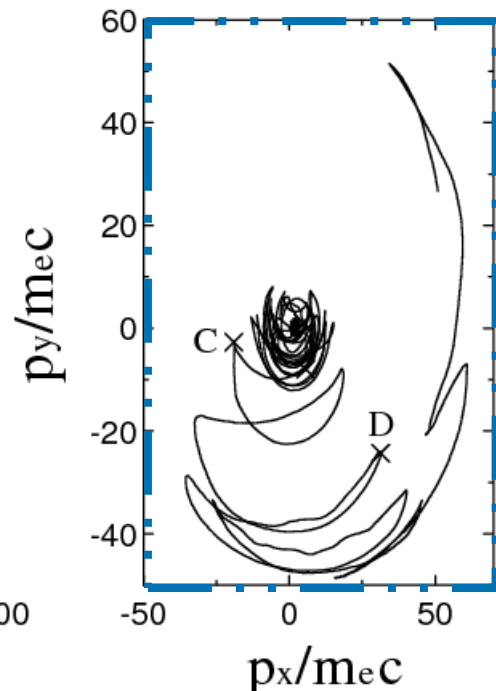
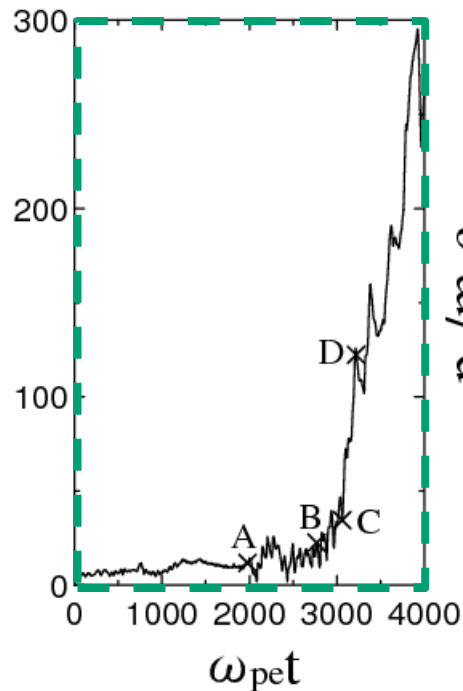
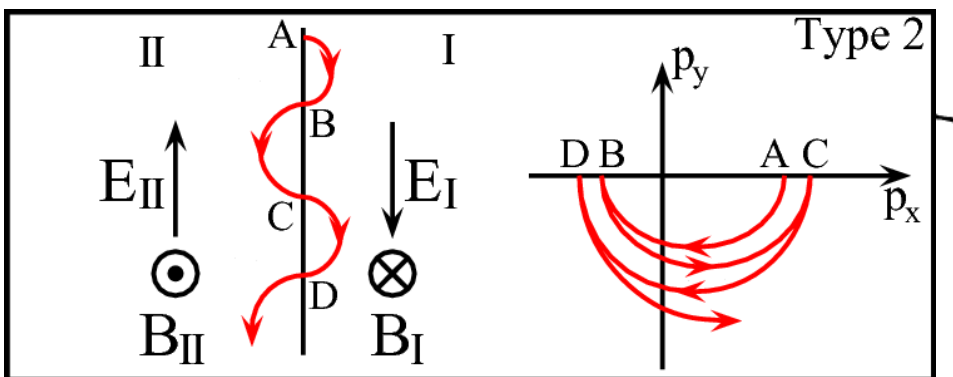
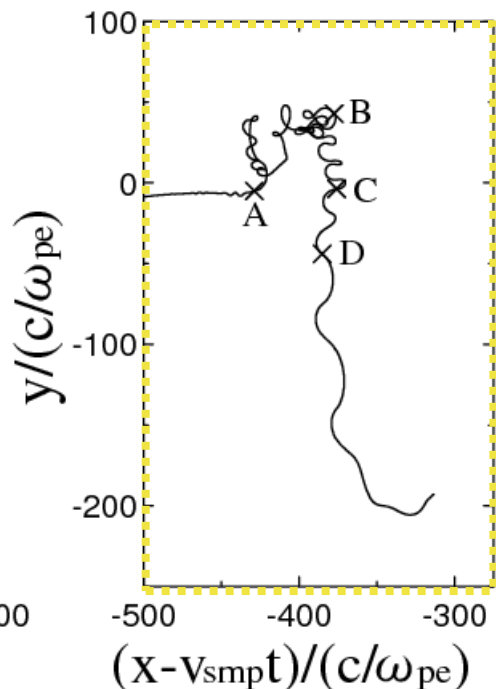
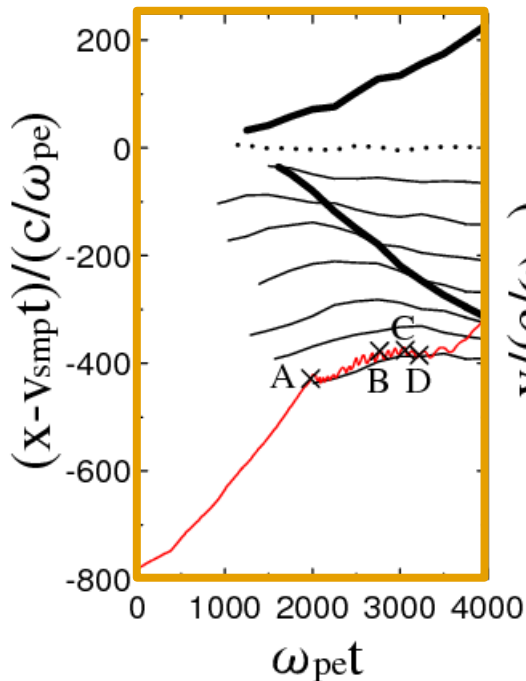


Gyration in the configuration space

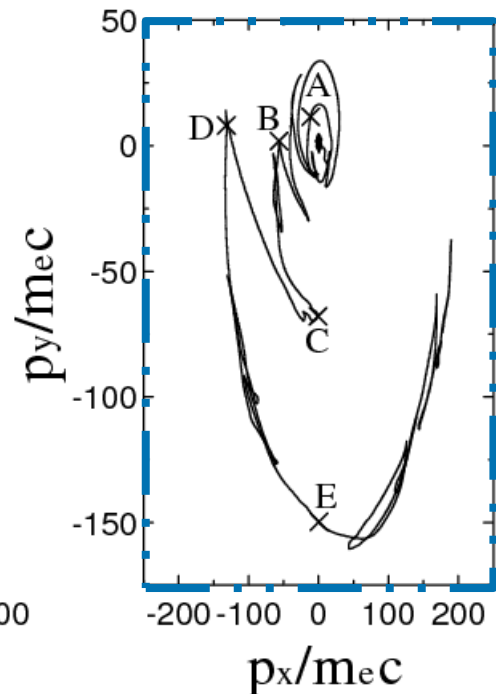
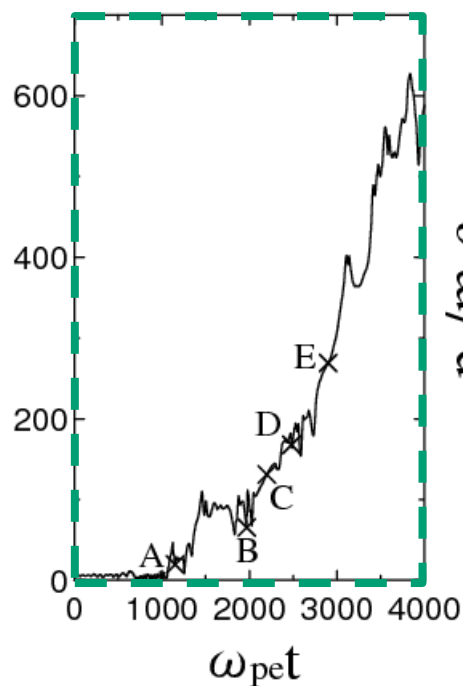
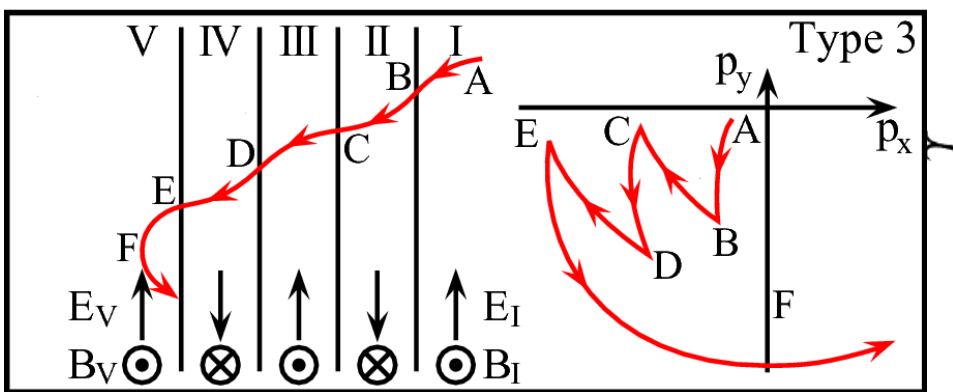
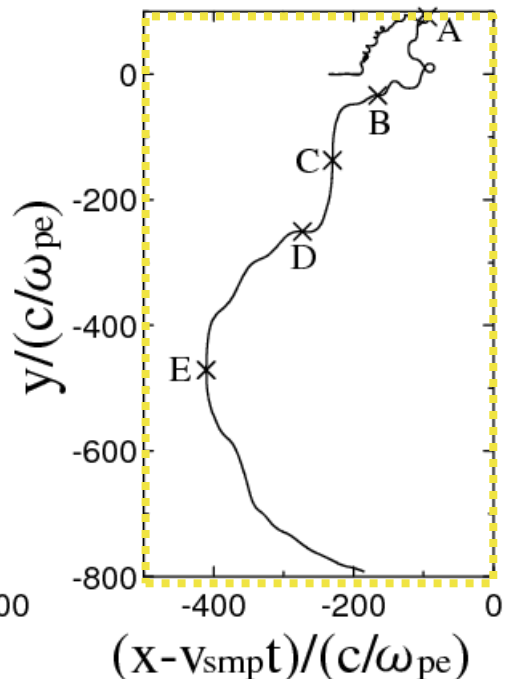
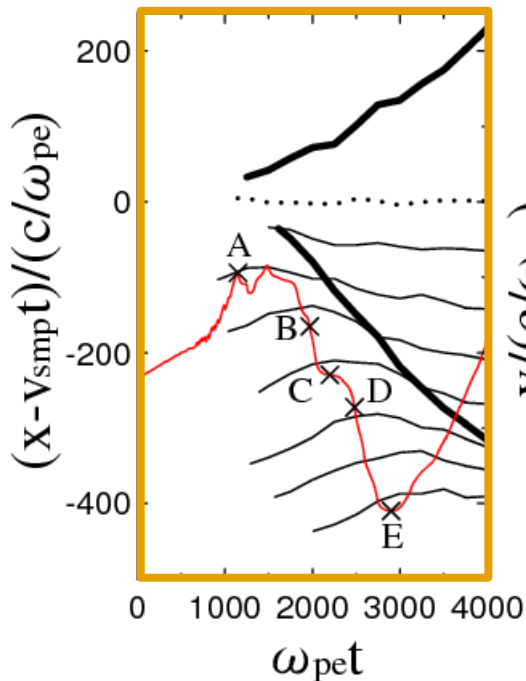
Ellipse in the momentum space



# Acceleration of electron meandering along a moving neutral sheet



# Acceleration of electron traversing the alternating magnetic field region

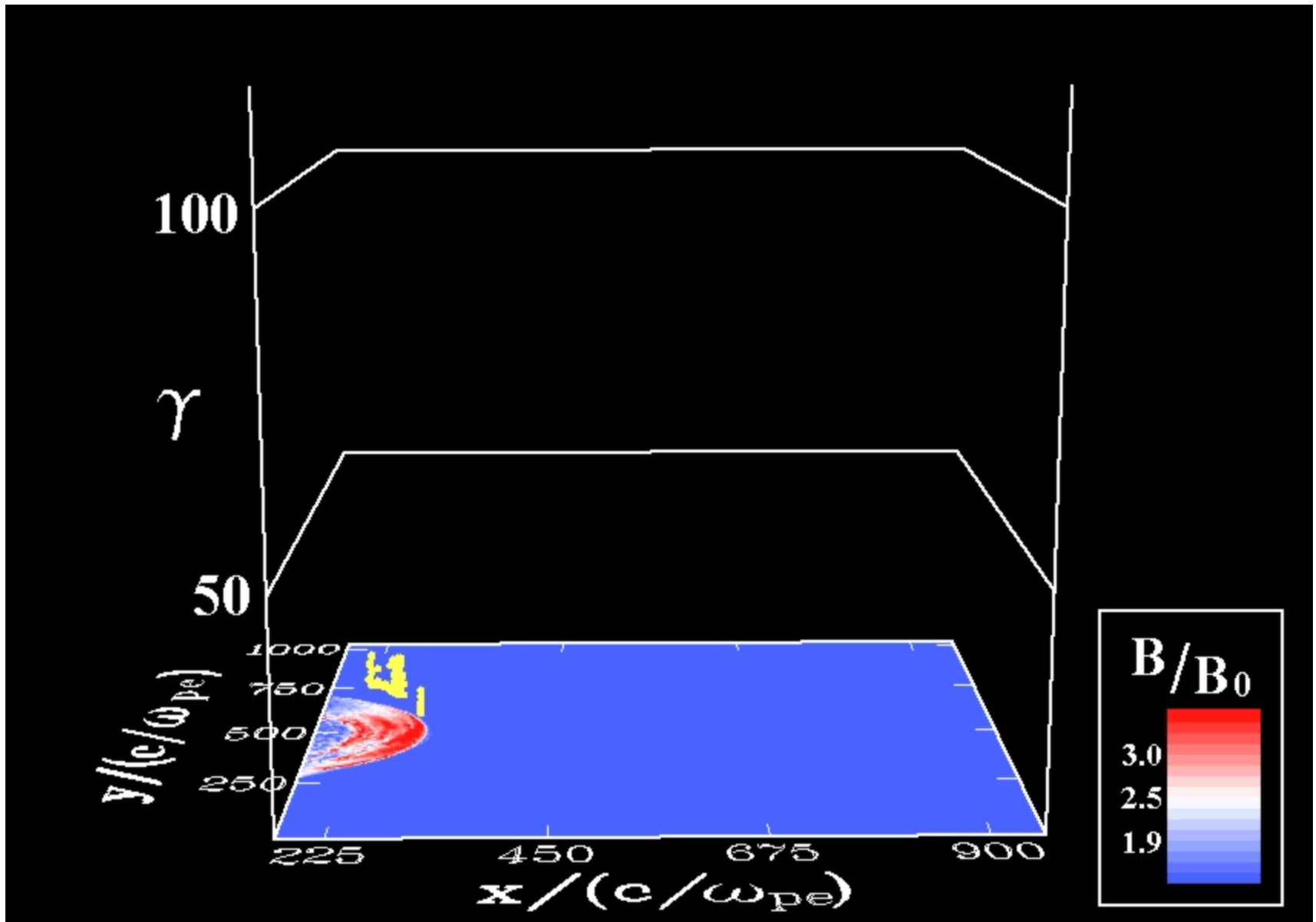


# まとめ

「衝撃波中の粒子加速」を30年間研究しました

永い間のご支援、有難うございます

Multi-dimensional codes are being developed by Toida *et al.*



Toida, Ueno & Ohsawa, J. Phys. Soc. Jpn. **77**, 084501 (2008)