Maser emission from relativistic shocks and electron-ion energy equilibration

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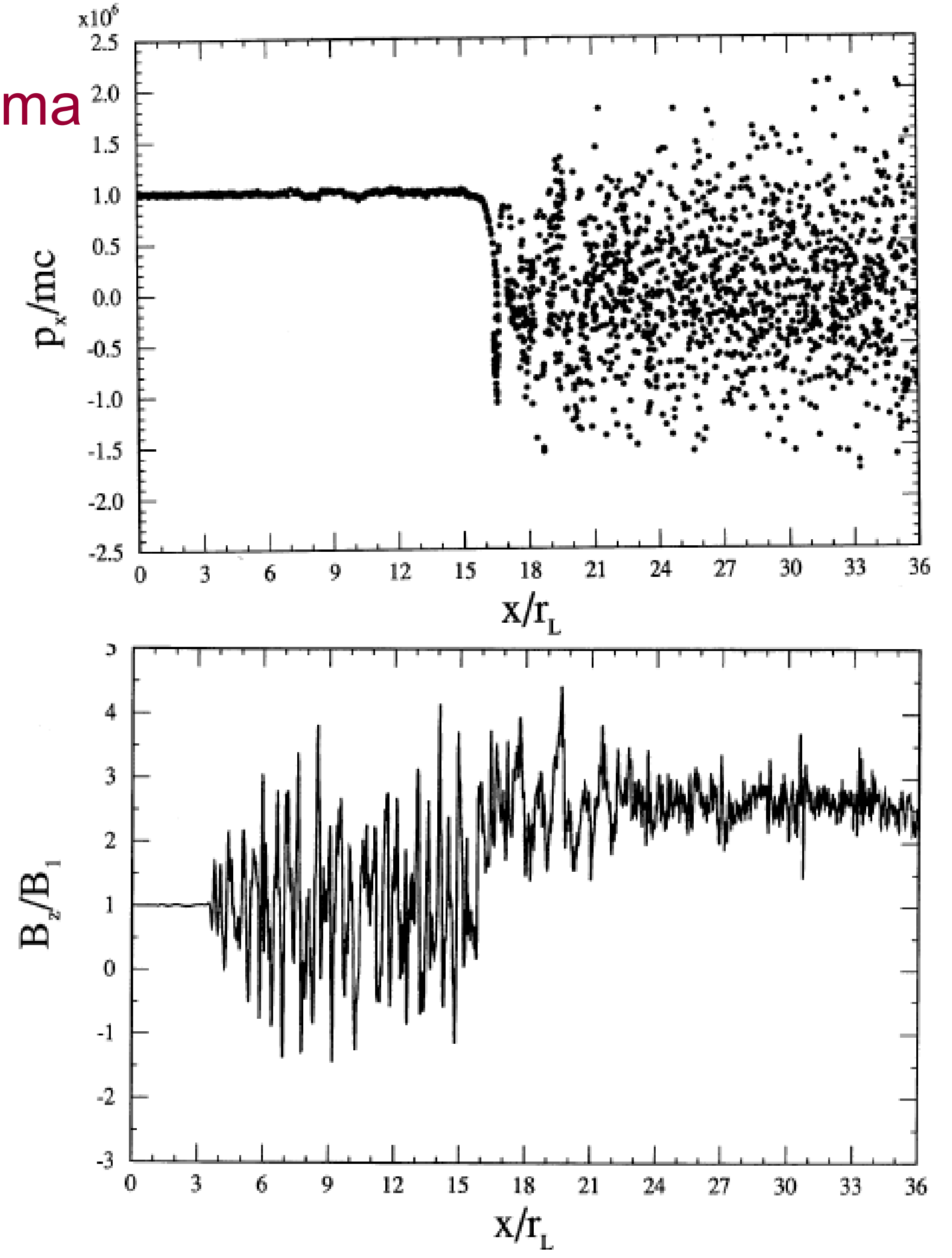
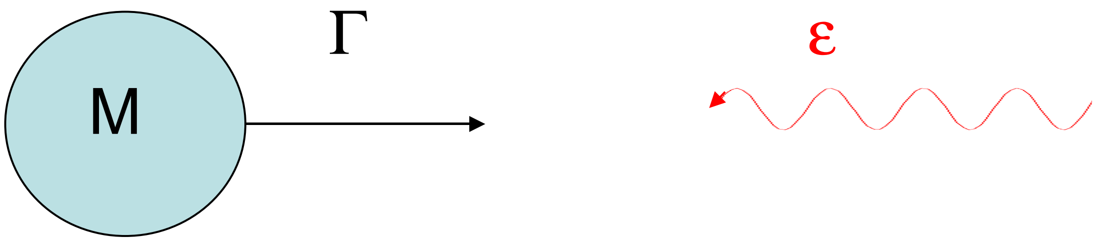
Shock in electron-positron plasma

Langdon, Arons, Max 1988;
Gallant, Hoshino, Langdon,
Arons, Max 1992





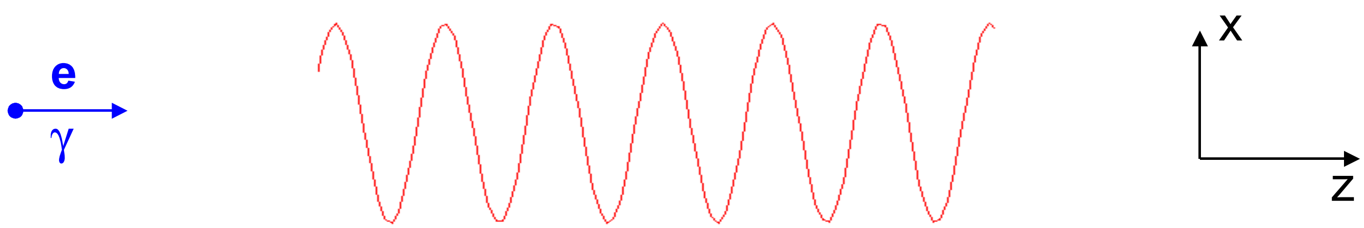
$$\varepsilon << E \equiv M\Gamma$$

$$E + \varepsilon = E_1; \qquad p - \varepsilon / c = p_1$$

$$\Gamma_1 = \frac{E}{\sqrt{M^2 c^4 + 4E\varepsilon}} = \frac{\Gamma}{\sqrt{1 + 4\Gamma^2 (\varepsilon / E)}}$$

$$T = \frac{(E_1^2 - p_1^2 c^2)^{1/2}}{M} = \sqrt{1 + 4\Gamma^2 (\varepsilon / E)}$$

Electron in a strong wave



$$A_x = \frac{E_0}{\omega}\sin\omega(t+z/c)$$

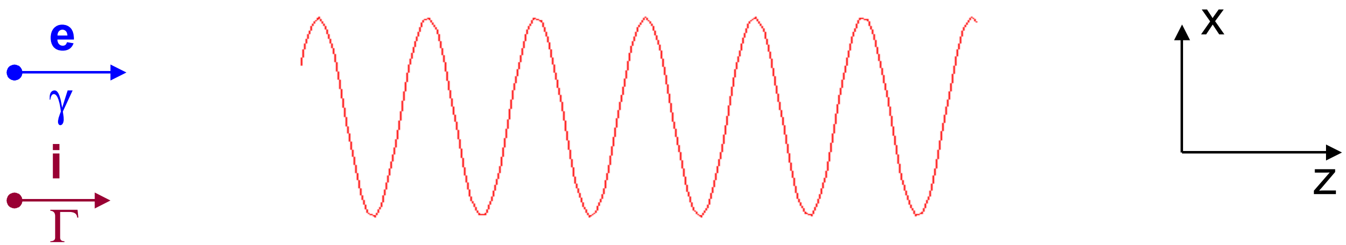
$$p_x + \frac{e}{c}A_x = const \;\Longrightarrow\; u_x = \mathrm{v}_x\gamma = a\sin\omega(t+z/c); \quad a = \frac{eE_0}{m_e c\omega}$$

$$z \to z+s; \quad t \to t - s/c \;\Longrightarrow\; u_z + \gamma = const$$

$$\gamma = \gamma_0 + \frac{a^2\sin^2\omega(z+t/c)}{2(1+\mathrm{v}_0)\gamma_0} \qquad 1 << a << \gamma_0 \;\Longrightarrow\; \gamma \approx \gamma_0$$

$$\gamma_{\mathrm{gc}} \equiv \left(1 - \langle \mathrm{v}_z/c\rangle^2\right)^{-1/2} = \frac{\sqrt{2}}{a}\gamma_0$$

Electron-ion flow in a strong wave



$$\mathbf{E}_w = E_0 \hat{\mathbf{x}} \cos \omega(t + z/c)$$

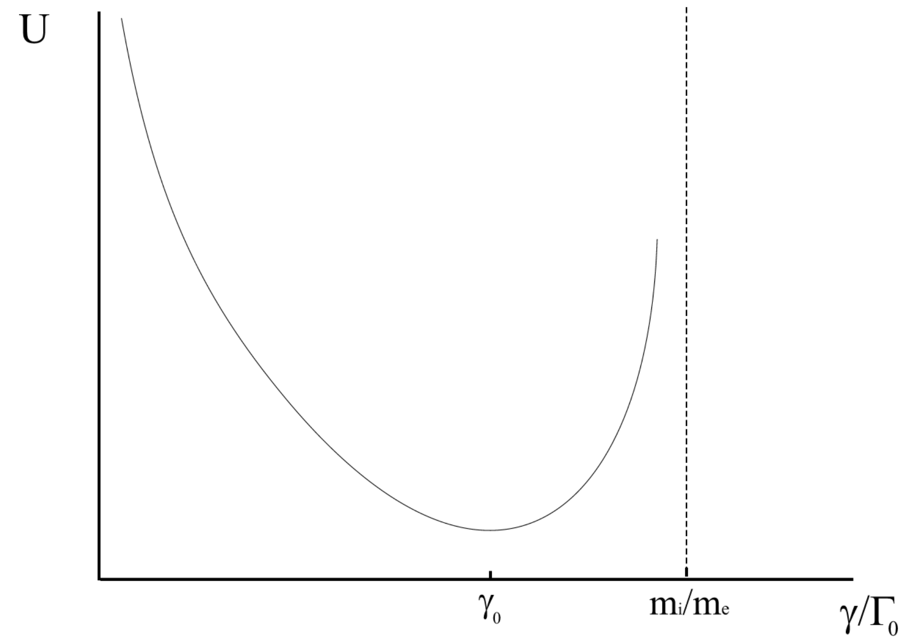
$$\mathbf{B}_w = E_0 \hat{\mathbf{y}} \cos \omega(t + z/c)$$

$$m_e \frac{d\mathbf{v}\gamma}{dt} = -e\left(\mathbf{E}_l + \mathbf{E}_w + \tfrac{1}{c}\mathbf{v}\times\mathbf{B}_w\right)$$

$$m_i \frac{d\mathbf{V}\Gamma}{dt} = e\left(\mathbf{E}_l + \mathbf{E}_w + \tfrac{1}{c}\mathbf{V}\times\mathbf{B}_w\right)$$

$$\frac{\partial E_l}{\partial t} + \frac{4\pi}{c} en(\mathrm{V}_z - \mathrm{v}_z) = 0;$$

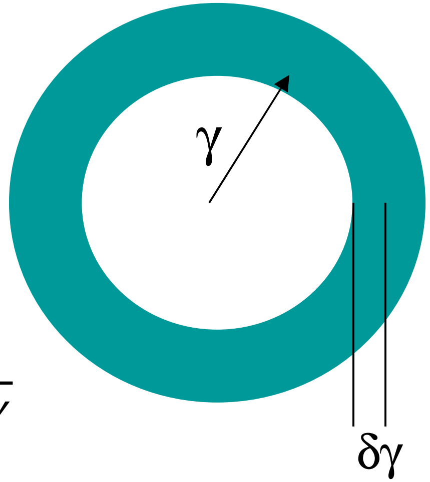
$$\frac{d^2\gamma}{dt^2} = \frac{a^2}{4\gamma^2} - \frac{2m_i^2 + a^2 m_e^2}{4(m_i\Gamma_0 - m_e\gamma)^2}$$



$$\gamma_0 = \frac{a\Gamma_0}{\sqrt{2+(am_e/m_i)^2} + am_e/m_i} = \begin{cases} \frac{a}{\sqrt{2}}\Gamma_0; & a < m_i/m_e \\ \frac{m_i}{2m_e}\Gamma_0; & a > m_i/m_e \end{cases}$$

$$\gamma_{\mathrm{gc}} = \frac{\sqrt{2}}{a}\gamma$$

Maser emission from electron ring



1) $\Omega_p << \Omega_B$ $\qquad \Omega_p = \sqrt{\frac{4\pi e^2 n}{m_e \gamma}}$ $\qquad \Omega_B = \frac{eB}{m_e c \gamma}$

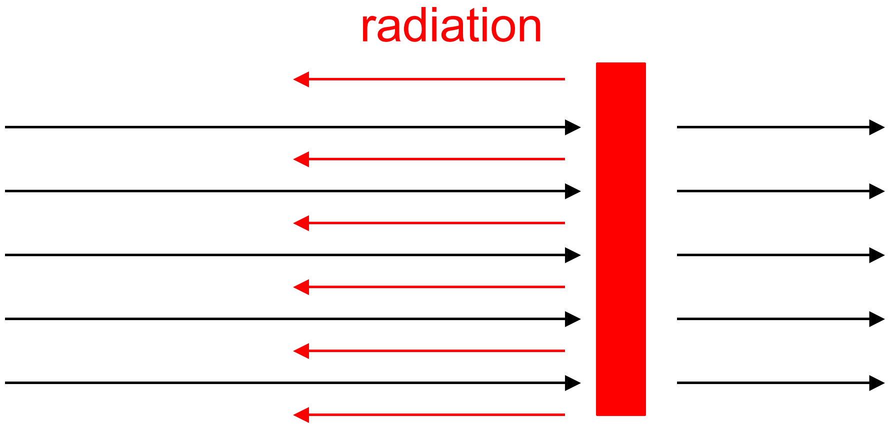
$$\sigma_e = \frac{B^2}{4\pi n m_e c^2 \gamma} = \frac{\Omega_B^2}{\Omega_p^2} >> 1$$

$$\omega = \Omega_B = \sigma_e^{1/2}\Omega_p; \qquad \kappa = 0.3\sigma_e^{-1/3}\Omega_B$$

2) $\Omega_p >> \Omega_B$ $\qquad \sigma_e << 1$

McCray 1966; Zheleznyakov 1966; …Sazonov 1970… Sagiv&Waxman 2002

$$\omega = \sigma_e^{-1/4}\Omega_p; \qquad \kappa = 0.1\sigma_e^{1/4}\Omega_B \frac{\gamma}{\delta\gamma}$$

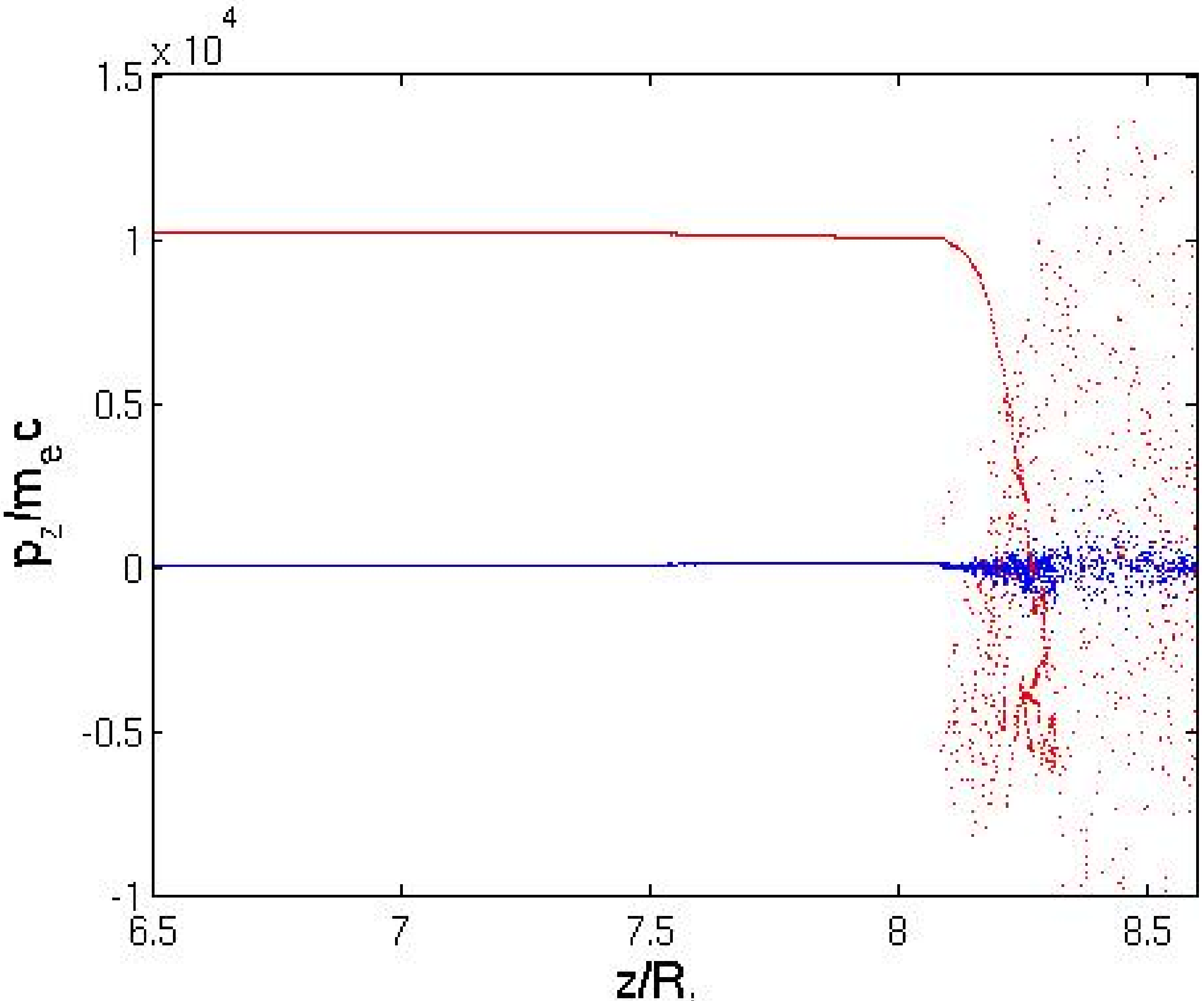


$$\xi = \frac{\text{radiation flux}}{m_e c^3 n \gamma} < 1$$

$$\omega = \zeta \Omega_p ; \qquad \zeta > 1$$

$$a = \frac{eE_0}{m_e c \omega} = \frac{\sqrt{2\xi}}{\zeta} \gamma$$

1.5D PIC simulations

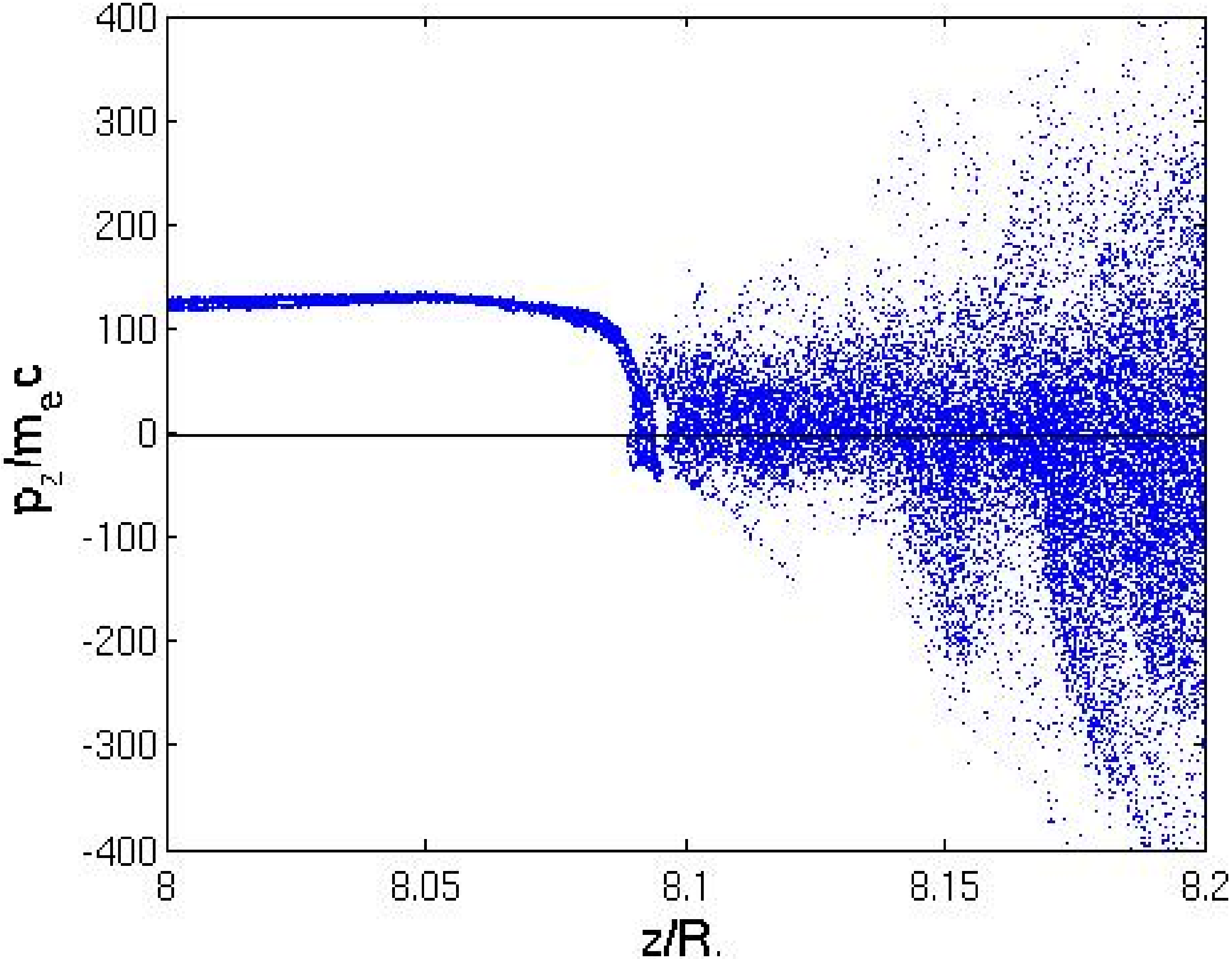


$$N = 2 \times 8 \cdot 10^5$$

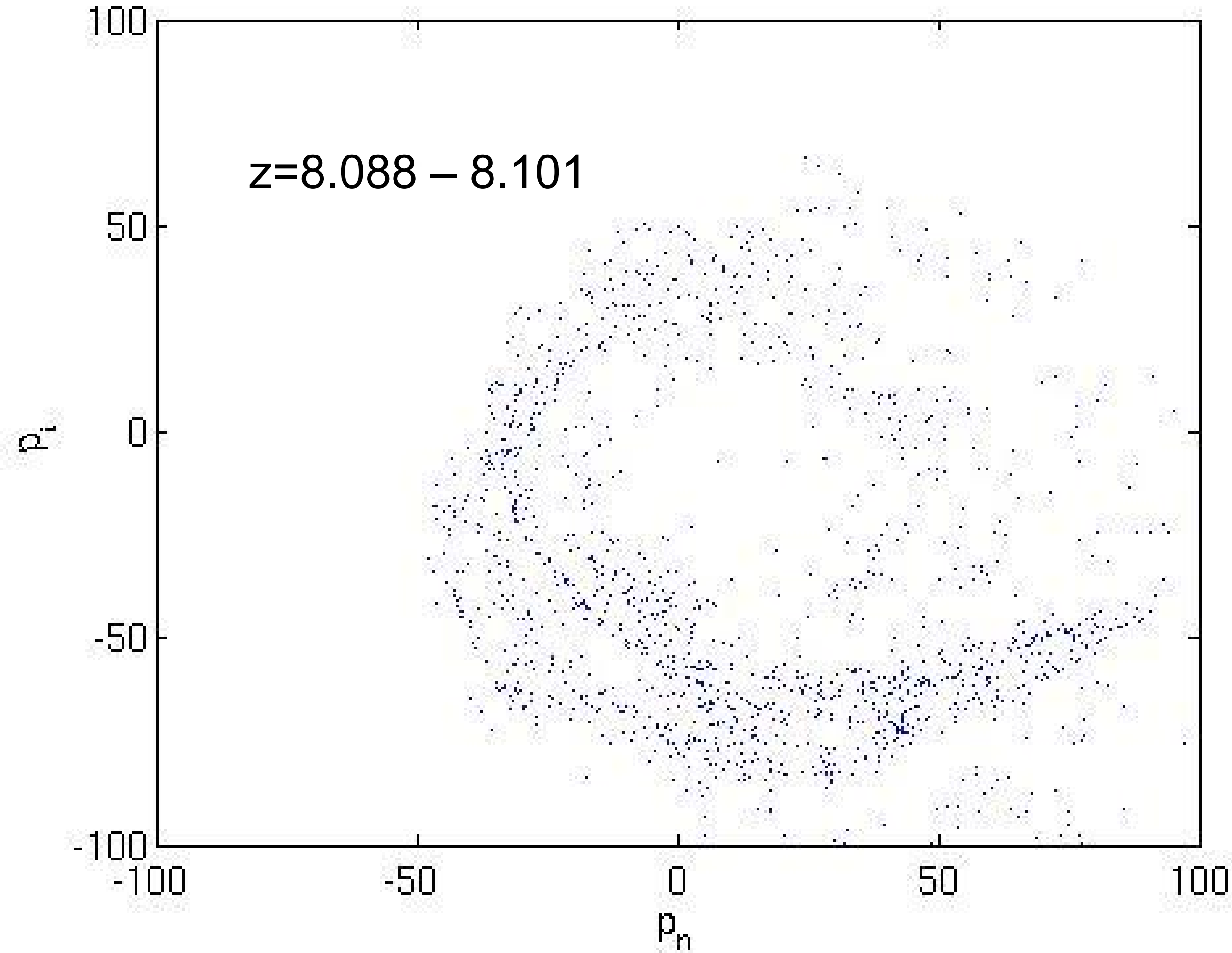
$$\gamma = 50$$

$$m_i / m_e = 200$$

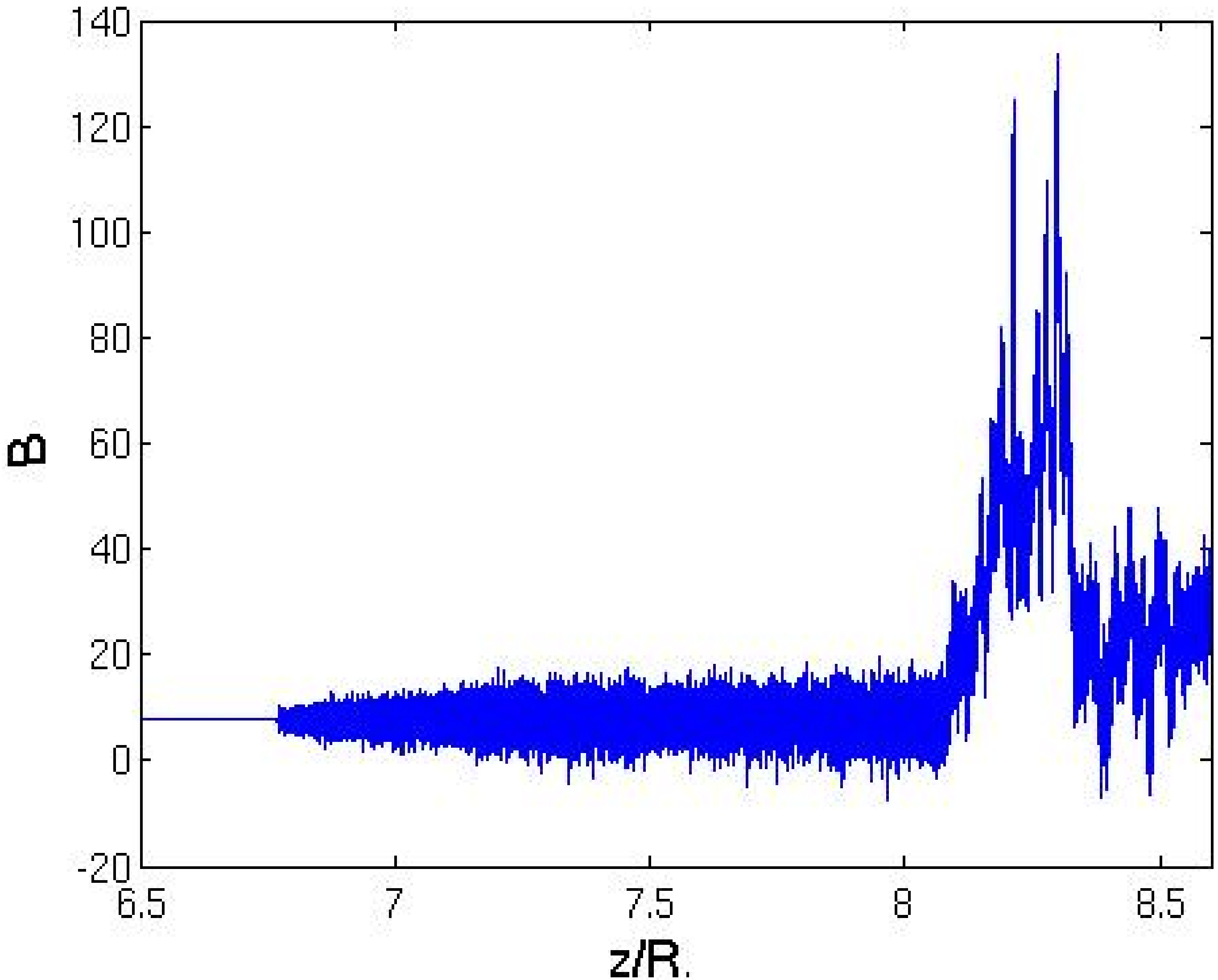
$$\sigma = 0.003$$



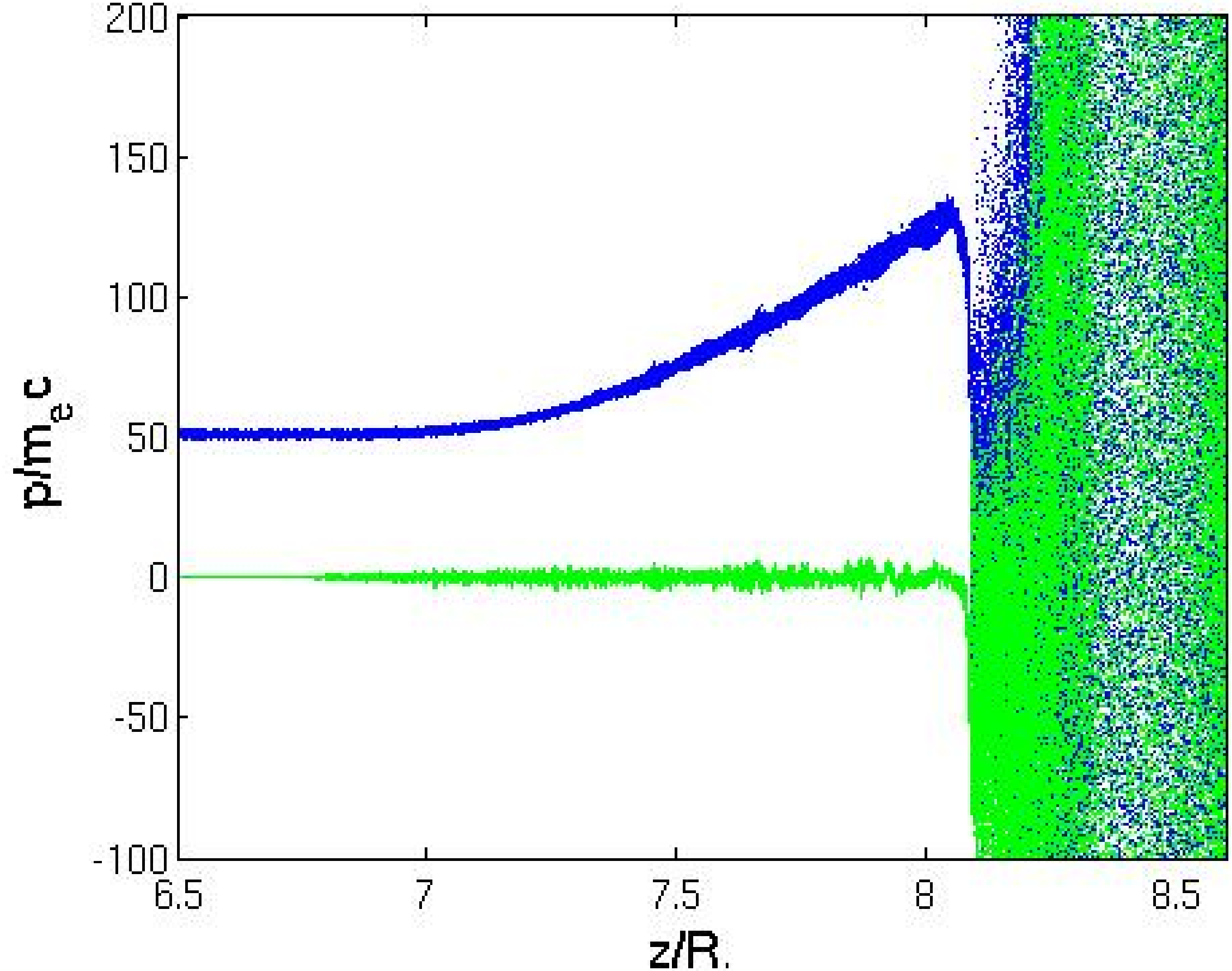
400
300
200
100
0
-100
-200
-300
-400
8
8.05
8.1
8.15
8.2
$p_z/m_e c$
z/R

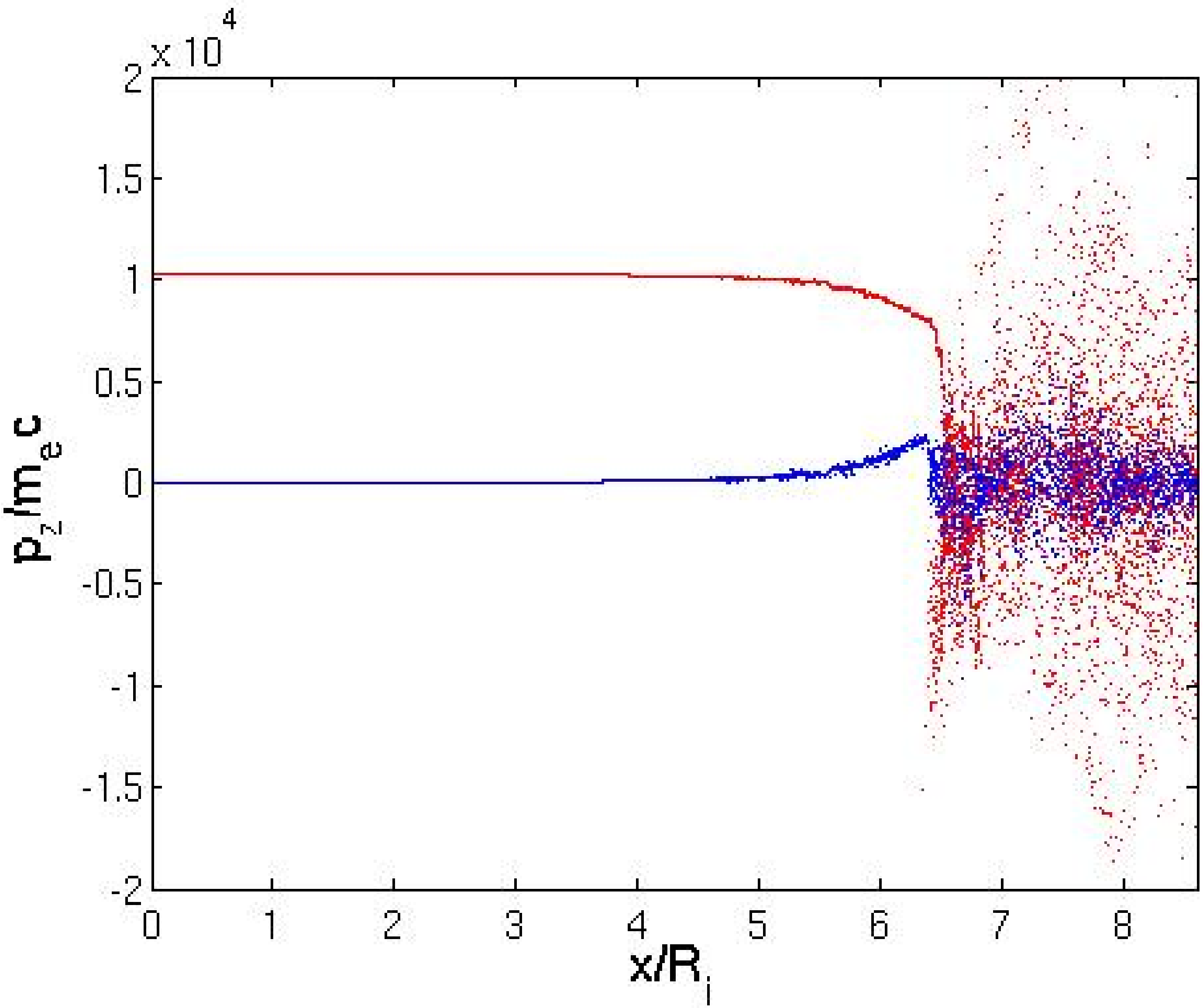


z=8.088 – 8.101
100
50
0
-50
-100
-100
-50
0
50
100
p_n
p_t

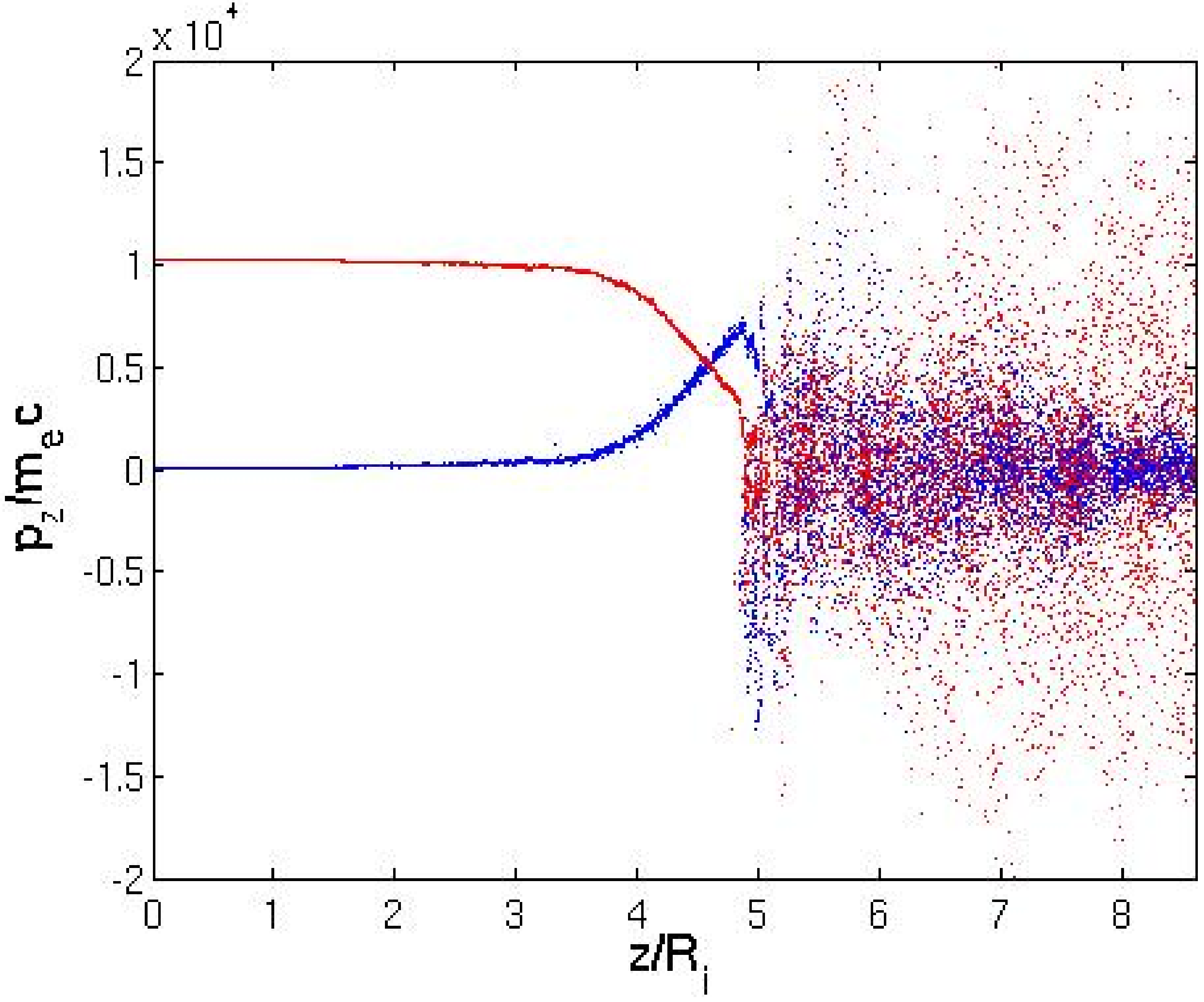


140
120
100
80
60
40
20
0
-20
B
6.5
7
7.5
8
8.5
z/R.

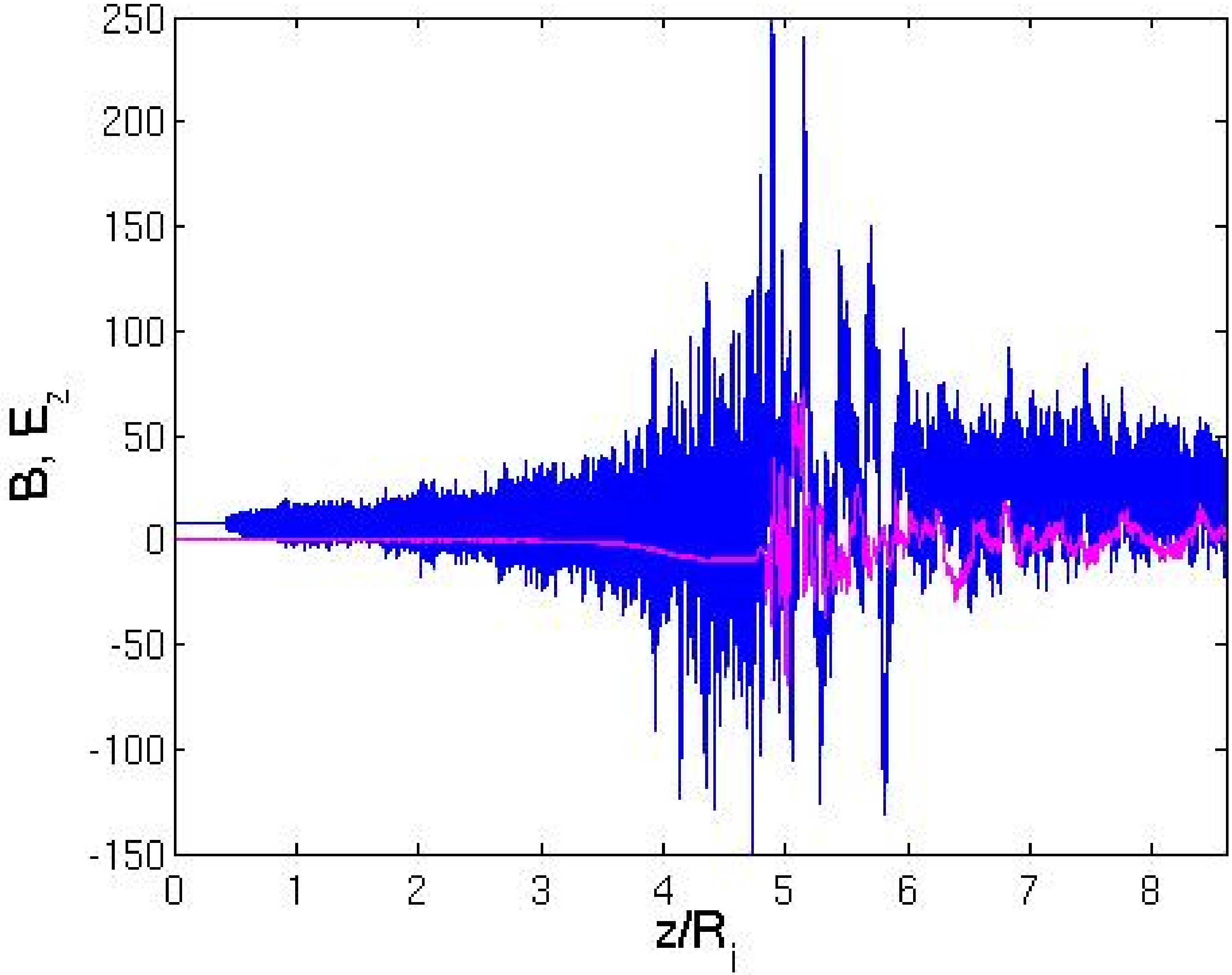

200
150
100
50
0
-50
-100
6.5
7
7.5
8
8.5
z/R.
p/m_e c



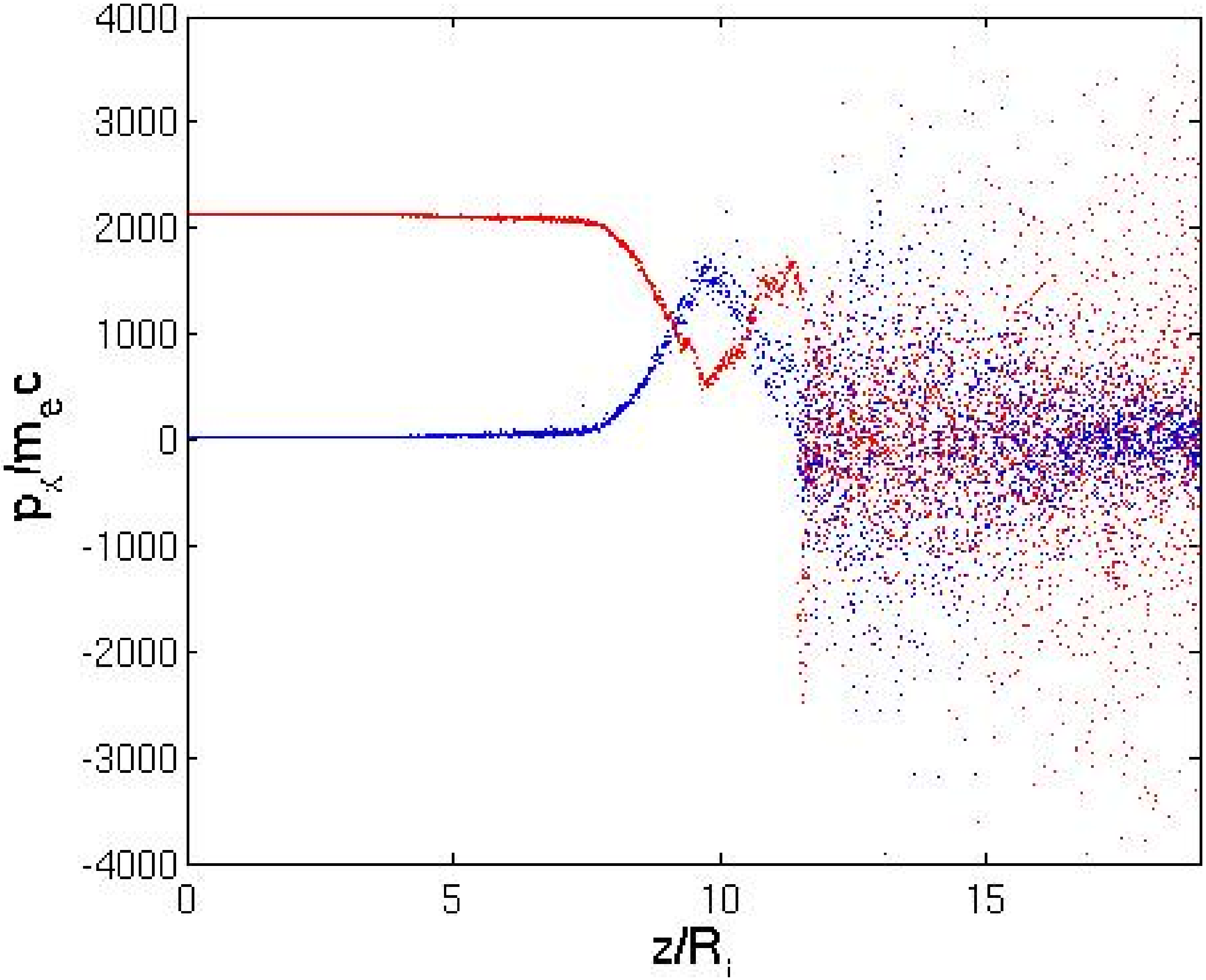
x 10^4
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
p_z/m_e c
0
1
2
3
4
5
6
7
8
x/R_i



x 10^4
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0 1 2 3 4 5 6 7 8
$p_z/m_e c$
z/R_i



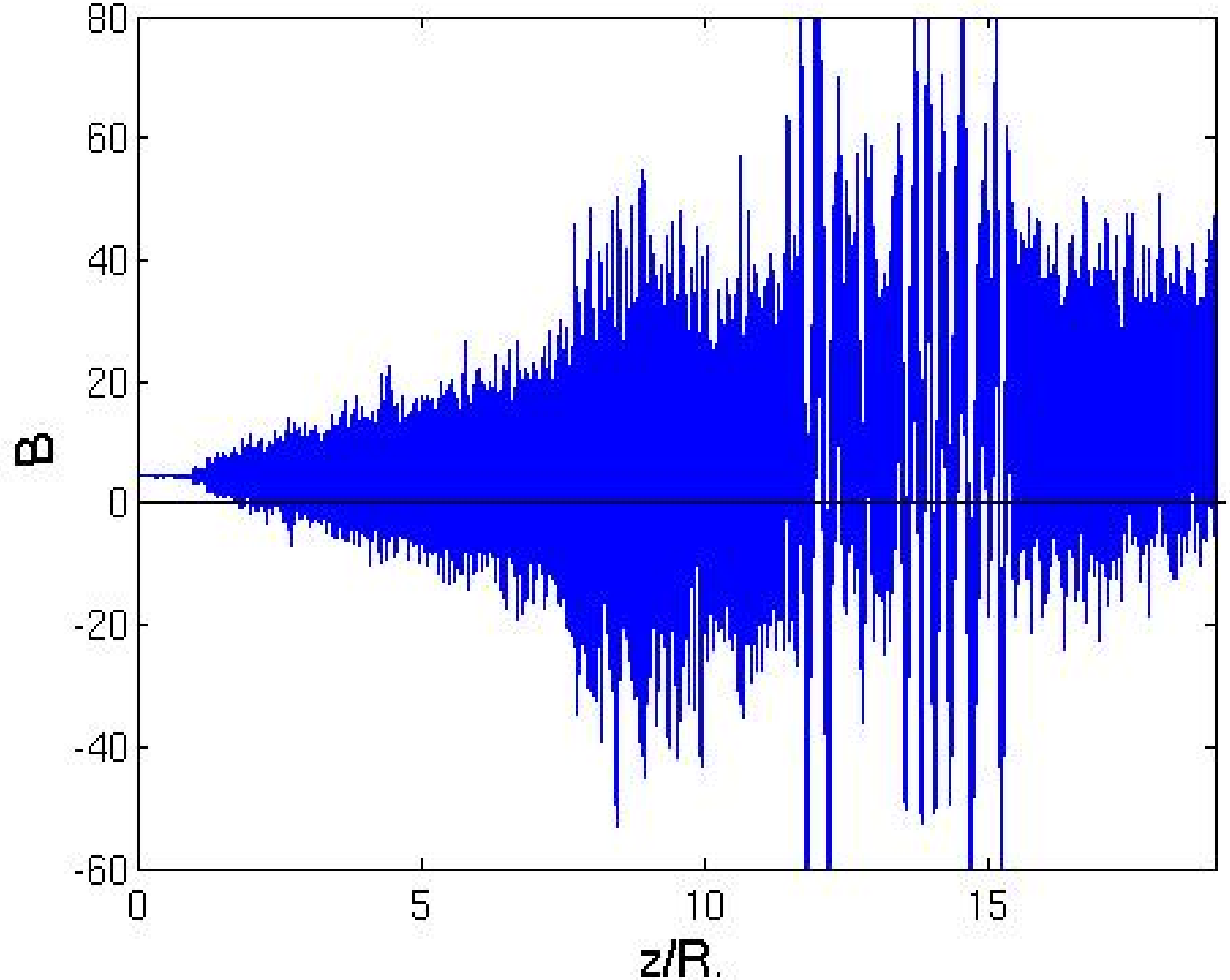
250
200
150
100
50
0
-50
-100
-150
B, E_z
0
1
2
3
4
5
6
7
8
z/R_i



$$\gamma = 20$$

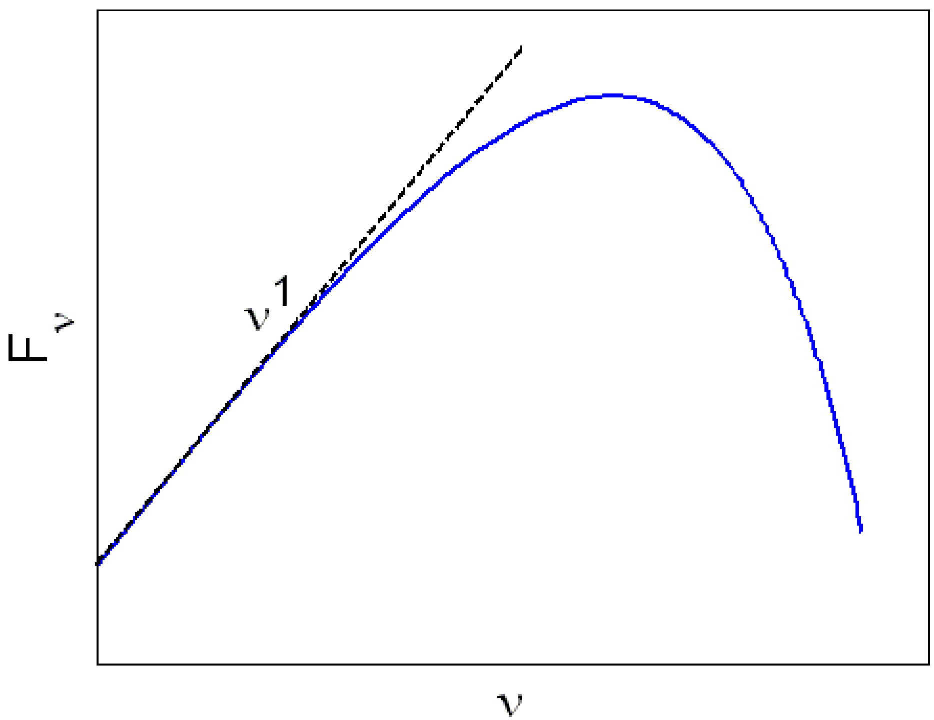
$$m_i / m_e = 100$$

$$\sigma = 0.005$$


80
60
40
20
0
-20
-40
-60
B
0
5
10
15
z/R

Nonlinear inverse Compton scattering

$$\nu \approx \frac{eE_0}{m_e c}\gamma^2; \qquad P \approx \sigma_T E_0^2 c\gamma^2$$



Conclusions

1. Relativistic shocks in weakly but non-negligibly magnetized plasmas emit strong, low-frequency electromagnetic waves

2. Upstream of the shock, these waves make electrons lag behind ions.

3. A longitudinal electric field arises; electrons are accelerated; eventually equipartition with ions is achieved

4. Energy density of the waves may exceed the energy density of the shock compressed magnetic field