Introduction to Plasma Particle Simulations

PHYS 312: Basic Plasma Physics

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Outline

Plasma Physics via Particle Simulation?

ES1: Electrostatic 1D simulation Code

Case 1: Landau Damping

Case 2: Two-Stream Instability

ES1 Demonstration

Plasma and Test particles

- electrons + ions, long-range ES force
- Debye length Ld, plasma parameter Nd >>1
  e.g., in confined fusion, Nd ~ 10^6
- test particle: collective force dominates over individual collision at length scale > Ld

$$E = E1(Collision) + E2(Collective)$$

Particle Simulation

- Collisionless: L >> Ld and Nd >>1
- KE/PE(=Nd)>>1, However, physically, so Nd ~ 10 may be satisfactory
- 1D: Nd -> $(Nd)^{1/3} = (10^6)^{1/3} = 100$
- L>>Ld: periodic models; L ~ 50 Ld
- Dawson (1950s) & Buneman (1960s) showed that a few thousand particles can simulate collective behavior in real plasma
- inevitable noise due to limited particles

ES1 for Particle simulation

- 1D electrostatic code for periodic problems
- developed by PTSG@UCB, Birdsall et al.
- particle in cell or particle-mesh
- spatial grids (~Ld), field concept
- tracking individual particles in phase space

$$\dot{\mathbf{x}}_i = \mathbf{v}_i$$

$$m_i \dot{\mathbf{v}}_i = q_i \mathbf{E}(\mathbf{x}_i)$$

$$\mathbf{E} = -\nabla \phi$$

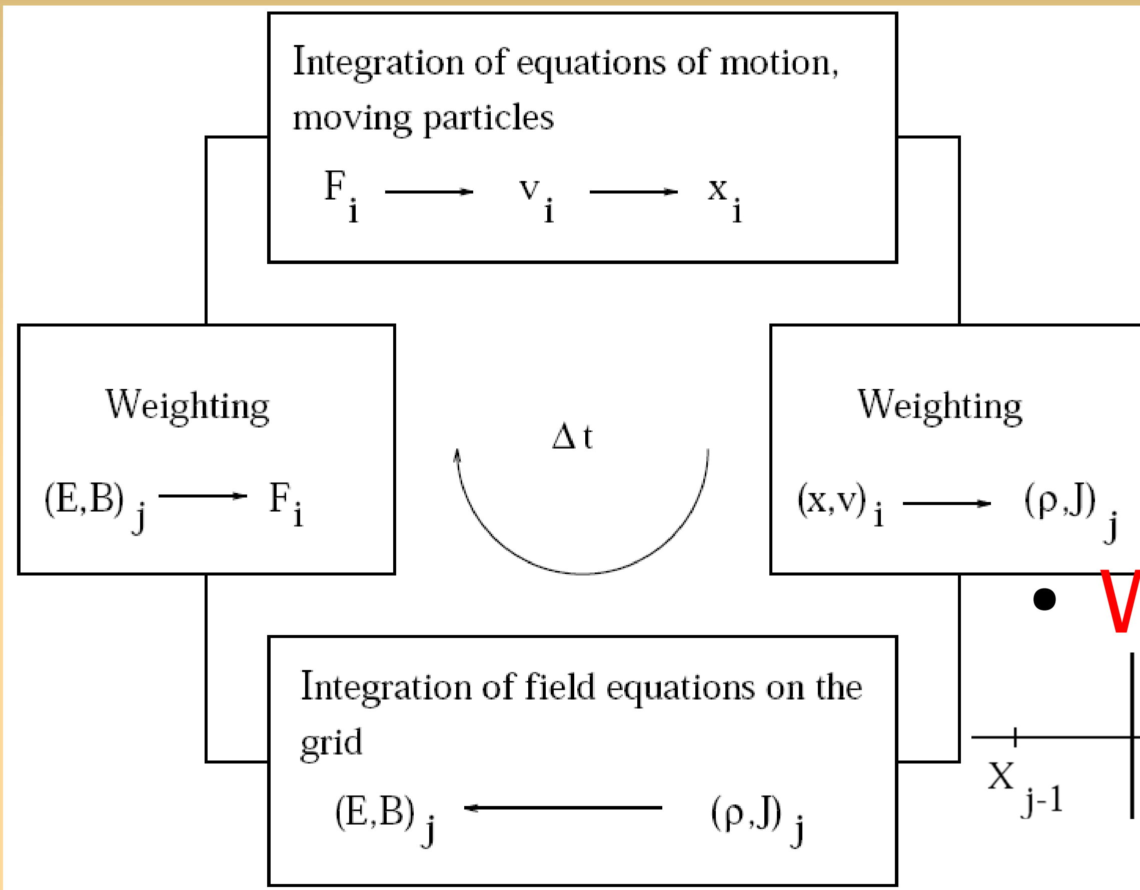
$$\nabla^2 \phi = -\frac{\rho}{\epsilon_0}$$

- particle
- field

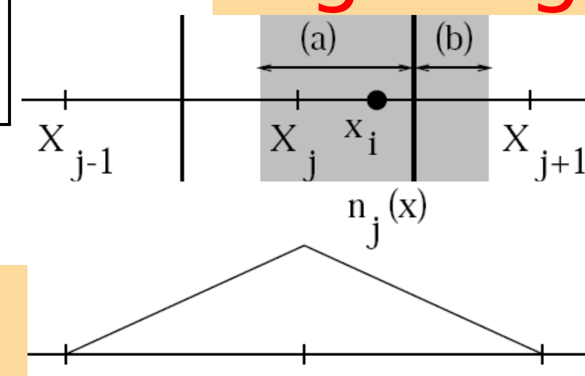
Computational Cycle

- Particles

$$\begin{aligned} v^{n+1/2} &= v^{n-1/2} + a^n \Delta t \\ x^{n+1} &= x^n + v^{n+1/2} \Delta t \end{aligned}$$



- Weighting



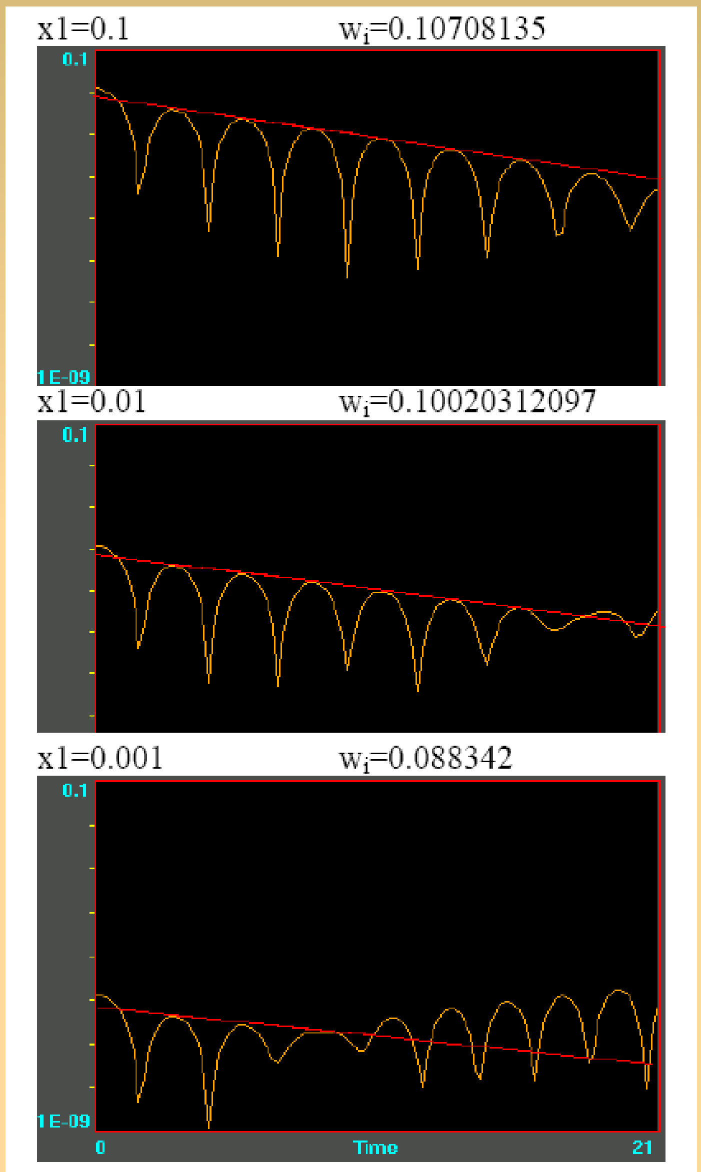
- Field

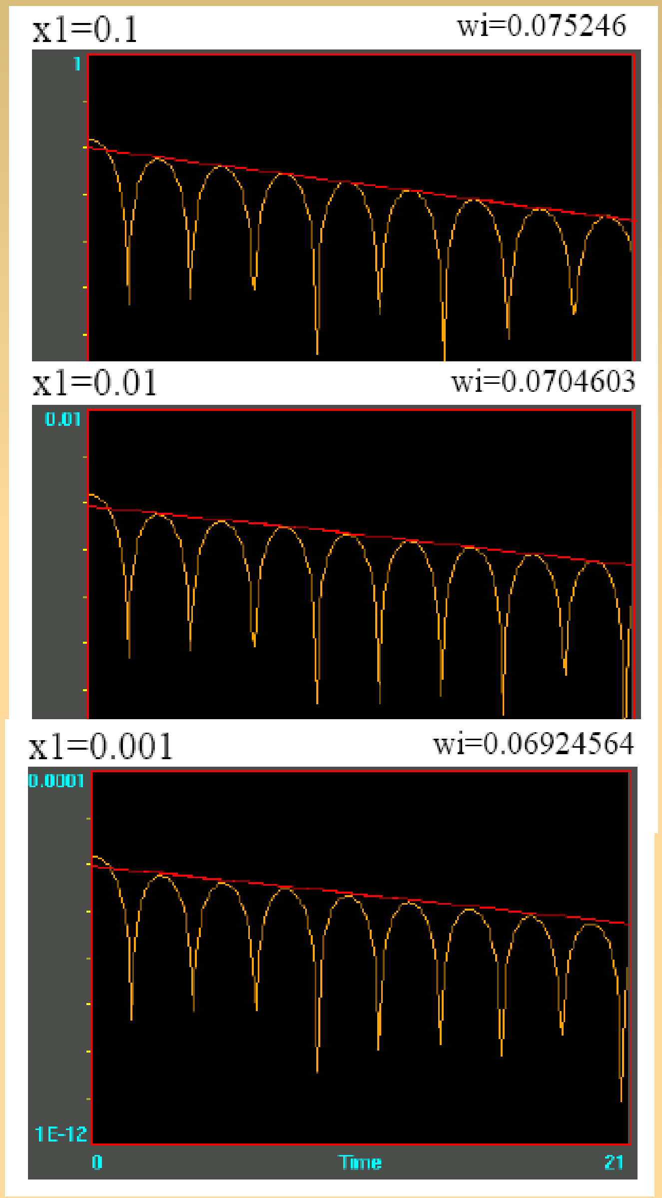
$$\rho(\mathbf{x}) \longrightarrow \rho(\mathbf{k}) \longrightarrow \phi(\mathbf{k}) \longrightarrow \phi(\mathbf{x}) \longrightarrow \mathbf{E}(\mathbf{x})$$

$$\begin{aligned} \mathbf{E}(\mathbf{k}) &= -i\mathbf{k}\phi(\mathbf{k}) \\ \phi(\mathbf{k}) &= \frac{\rho(\mathbf{k})}{\epsilon_0 k^2} \end{aligned}$$

Case 1: Landau Damping

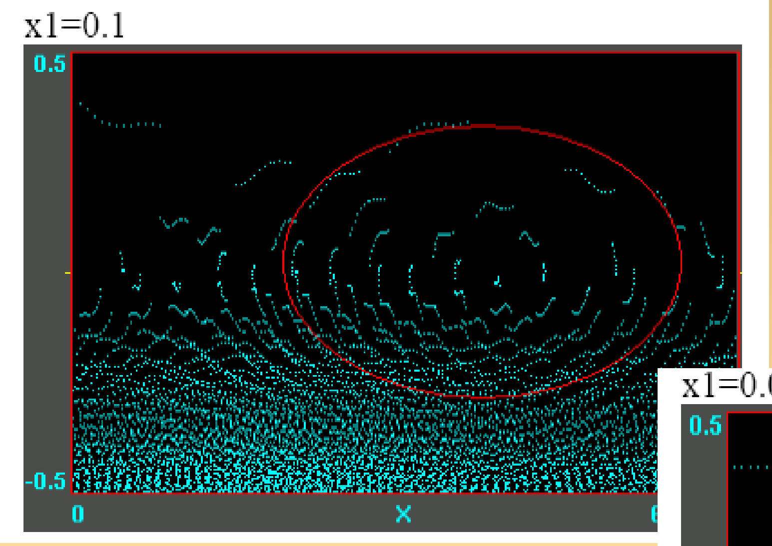
Damping rate of Waves

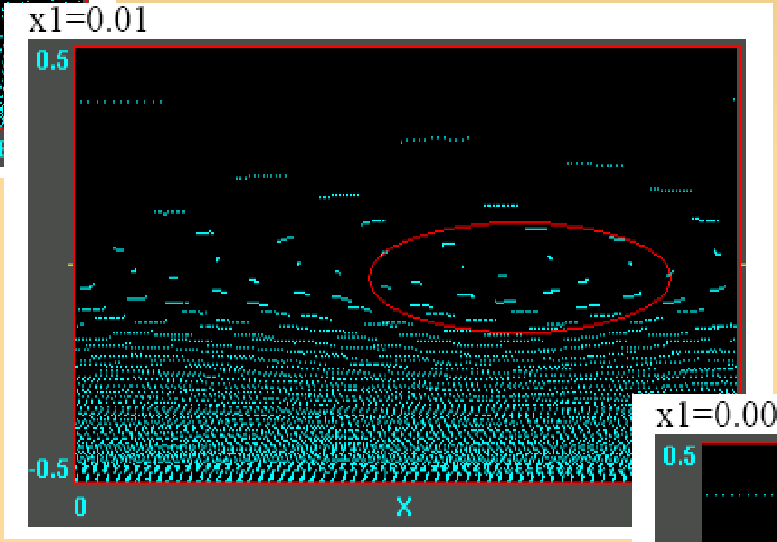




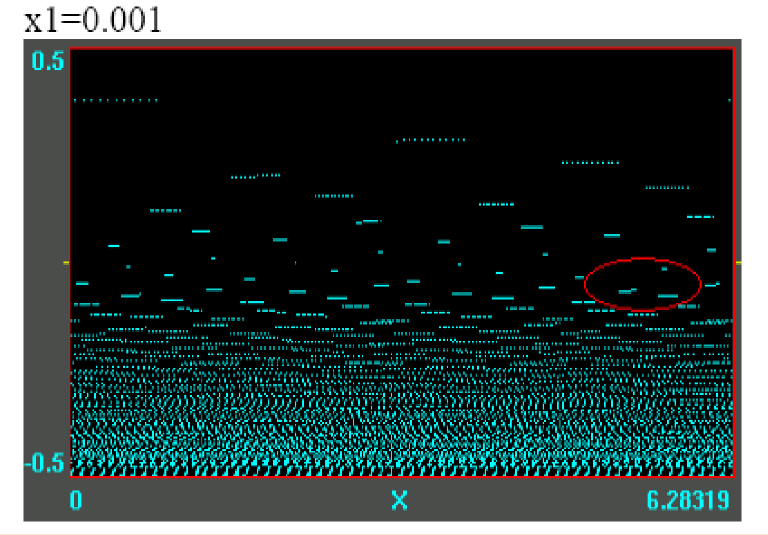
- N=100,000
- N=1,000,000
- c.f. Estacio

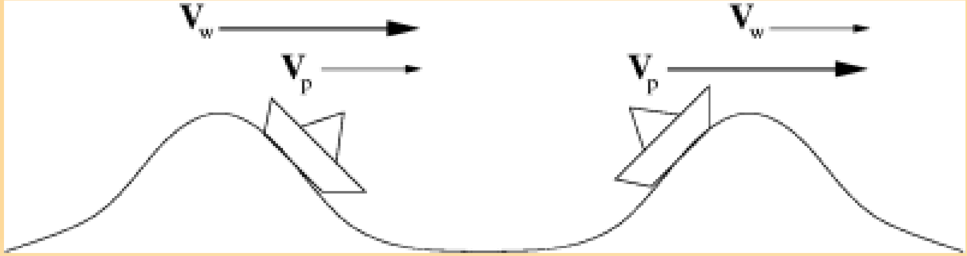
Case 1: Landau Damping
Trapping in Phase Space





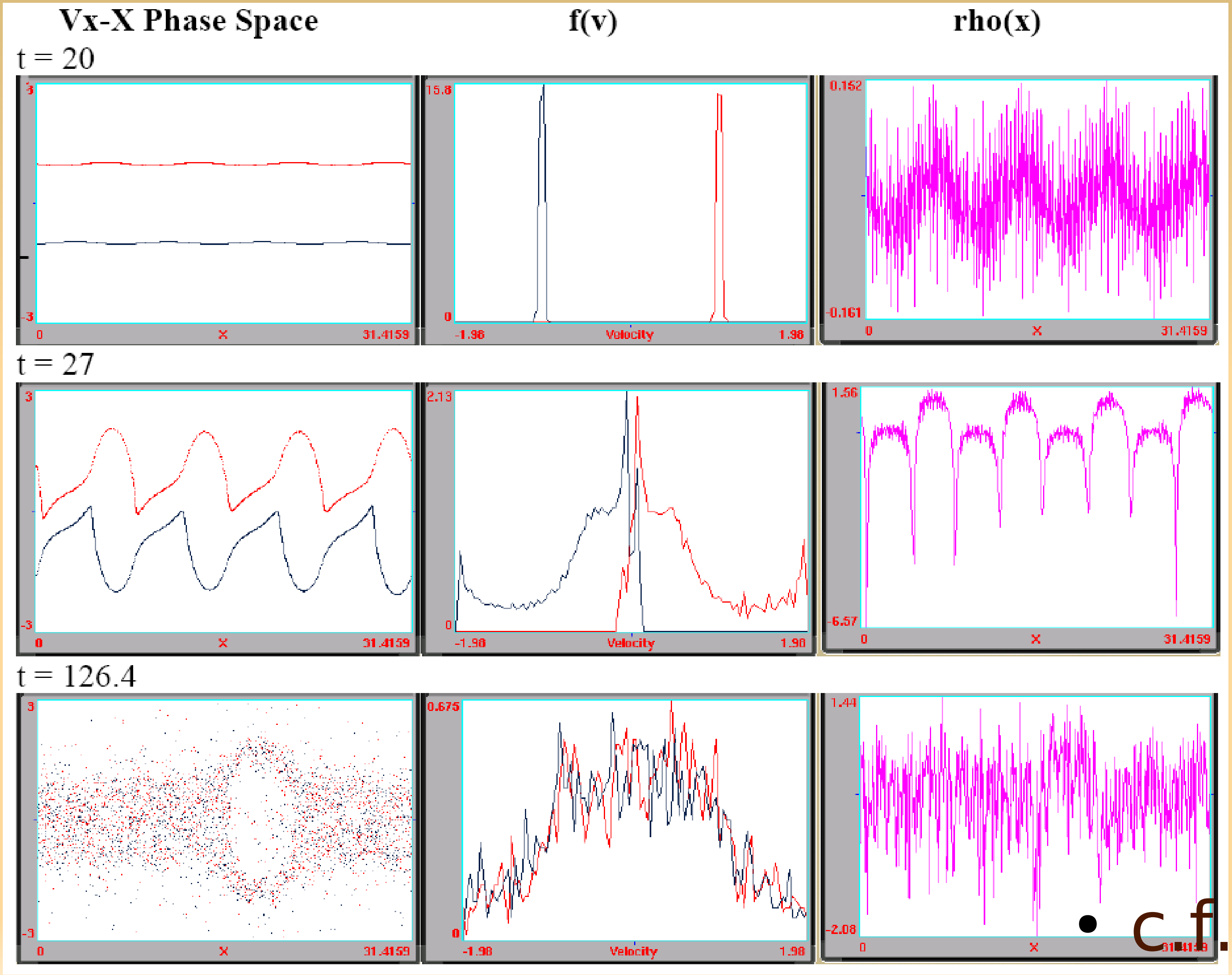
- c.f. Estacio





Case 2: Two-Stream Instability

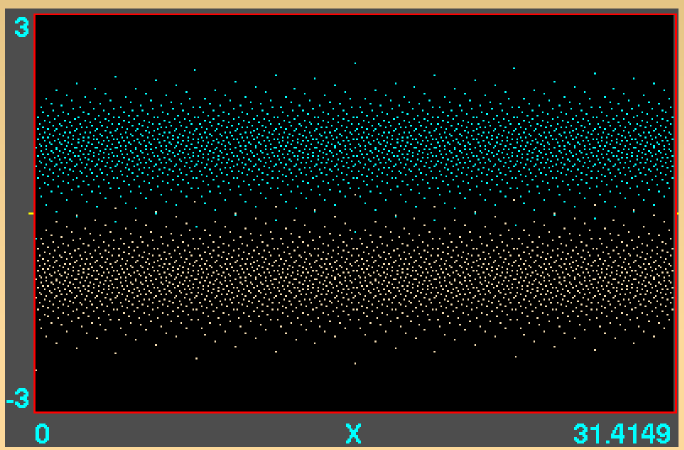
Cold electron plasma

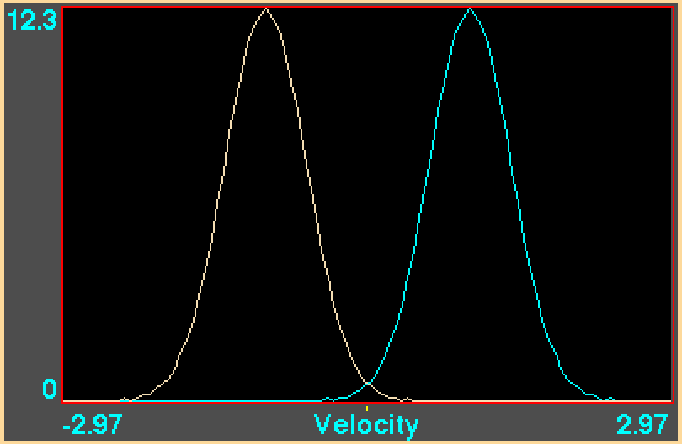


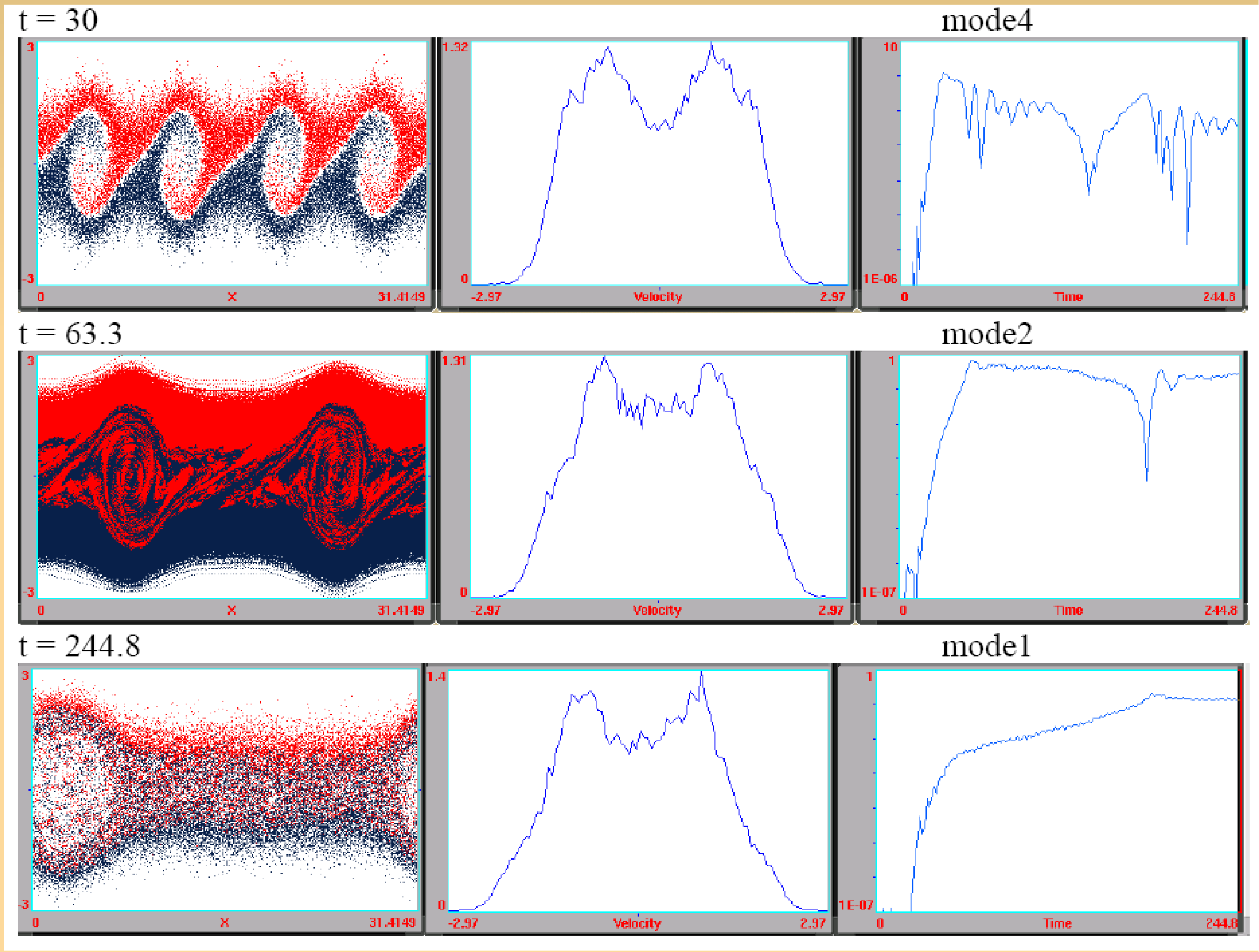
- c.f. Estacio

Case 2: Two-Stream Instability

Warm electron plasma







- c.f. Estacio

Sample Input File

Two-Stream Instability 2stream.inp

nsp – # part. species
l – system length
dt/nt – time step/#
ng – # grids
epsi – 1/epsilon

n – # particles
wp – plasma freq.
wc – cycl. freq.
qm – ratio q/m
v0 – drift velo.
v1/v2 – Gaussian
velo. around v0
x1 – pertubation

```
nsp------------l-----------dt-----nt---mmax---l/a---accum
2        31.415926535  0.1     300     5       0         1
ng-------iw-----ec------epsi------a1-----a2-----E0-----w0
512       1        0        1.00      0.00     0.00      0        0

SPECIES 1: Cold Electron Plasma

n------------nv2-----nlg-----mode
2048          0          1          1
wp------wc------qm------vt1------vt2-----v0
1.00     0.00     -1.00       0.0       0.001  1.00
x1----------v1-----thetax-----thetav
0.0001      0.0      0.00           0.00
nbins------vlower-------vupper
100            -2.00            2.00

SPECIES 2: Cold Electron Plasma

n------------nv2-----nlg-----mode
2048          0          1          1
wp------wc------qm------vt1------vt2-----v0
1.00     0.00     -1.00       0.0       0.00    -1.00
x1-----------v1-----thetax-----thetav
-0.0001      0.0      0.00           0.00
nbins------vlower-------vupper
100            -2.00            2.00
```

Plasma frequency $\omega_p^2 = \frac{nq^2}{\epsilon_0 m}$

Units in ES1 based on L, WP, EPSI, andQM

$$\begin{cases} U_t = \mathrm{WP}/w_p & \text{Time} \\ U_t = l/\mathrm{L} & \text{Length} \\ U_m = \epsilon_0\ \mathrm{EPSI}\ U_t^{-2} U_l^3 \left(\frac{e}{m_e}\right)^{-2} & \text{Mass} \\ U_q = \frac{1}{\mathrm{QM}} \frac{e}{m_e} U_m & \text{Charge} \end{cases}$$

e.g., real plasma, $l = 1000$ m, $w_p = 178$ kHz
set WP = 1

$$\begin{cases} U_t = 5.62\ \mu\mathrm{s} \\ U_l = 159\ \mathrm{m} \\ U_m = 3.63 \times 10^{-17}\ \mathrm{kg} \\ U_q = 6.42 \times 10^{-6}\ \mathrm{C} \end{cases}$$

Reference

- Plasma Physics vis Computer Simulation: C.K. Birdsall & A.B. Langdon (1985, book)
- Lecture notes on Computer Simulation Techniques: T. Oscarsson (2007, online)
- Particle Simulation in Plasma: E. Estacio (2003, online, summer program at UCB)

ES1@UCB http://langmuir.eecs.berkeley.edu/pub/codes/xes1/
MS http://sun.stanford.edu/~sasha/PHYS312/2007/Plasma_Computer_Codes/
Linux http://w3.pppl.gov/~hammett/courses/trieste01/es1-install-linux.html