KINETIC SIMULATIONS OF SRS SATURATION

D. J. Strozzi[1], A. K. Ram, A. Bers, M. M. Shoucri*

Massachusetts Institute of Technology
Cambridge, MA 02139

**Institut de Recherche de l'Hydro Québec*
Varennes, Canada

Work supported in part by DoE Contract No. DE-FG02-91ER-54109

34th Anomalous Absorption Conference
Gleneden Beach, Oregon
Poster 4P16
6 May 2004

---

[1] email: dstrozzi@mit.edu. Poster available at www.mit.edu/~dstrozzi

Abstract

We are developing a 1-D Vlasov code, ELVIS, to study laser-plasma interactions. With kinetic electrons and fixed ions, SRS is bursty. The EPW is driven to large amplitudes and traps a significant amount of electrons in high-energy tails. This substantially increases the plasma kinetic energy. The EPW k spectrum broadens as SRS saturates, and develops a component at slightly lower k. We are still investigating the saturation mechanism in this 1-D kinetic model, and comparing recent experimental (Fernandez, Kirkwood) and numerical and theoretical (Rose, Russell, Vu, DuBois, Bezzerides) work.

Outline

- SRS: linear theory of growth
- ELVIS: 1D Vlasov Code
- Simulation Results: Seeded SRS

1-D SRS Growth: Linear Theory

- Undamped growth rate:

$$\gamma_0 = \tfrac{1}{4} k_e v_{osc,0} \left(\frac{\omega_e}{\omega_b}\right)^2$$

- Convective threshold:

$$\gamma_0^2 > \gamma_c^2 = \nu_b \nu_e$$

- Absolute threshold:

$$\gamma_0^2 > \gamma_a^2 = \tfrac{1}{4} |v_{gb} v_{ge}| \left(\frac{\nu_b}{|v_{gb}|} + \frac{\nu_e}{|v_{ge}|}\right)^2$$

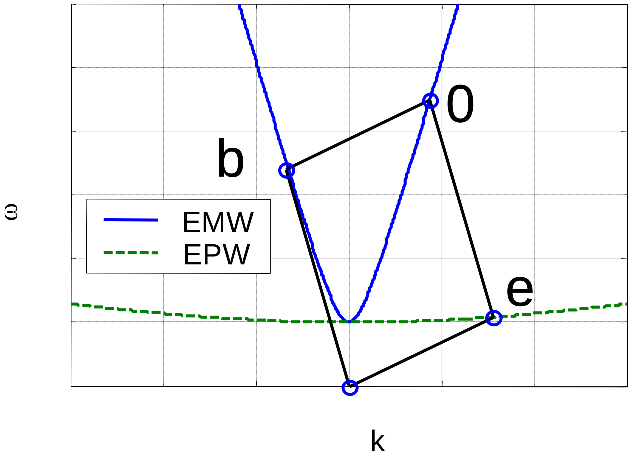
- Max. temporal growth rate:

$$\gamma = -\frac{\nu_b + \nu_e}{2} + \sqrt{\gamma_0^2 + \left(\frac{\nu_b - \nu_e}{2}\right)^2}$$

- Intensity threshold for absolute instability:

$$I_{cr} = 6(n_o m_e v_{Te}^2) \left(\frac{\nu_e}{\omega_p}\right)^2 \left(\frac{\omega_0 k_0 \omega_b}{k_b \omega_e k_e}\right)$$

0: laser
b: back EMW
e: EPW



- Undamped spatial growth rate:

$$K_0 = \frac{\gamma_0}{\sqrt{|v_{gb} v_{ge}|}}$$

- Spatial damping rates: $K_{b,e} = \nu_{b,e} / |v_{gb,e}|$
- Max. spatial growth rate:

$$K = -\frac{K_b + K_e}{2} + \sqrt{K_0^2 + \left(\frac{K_b - K_e}{2}\right)^2}$$

- Spatial gain over length L : $G = 2KL$
- Limit $\nu_b = 0$, $\nu_e \gg \gamma_0 \sqrt{|v_{ge}/v_{gb}|}$

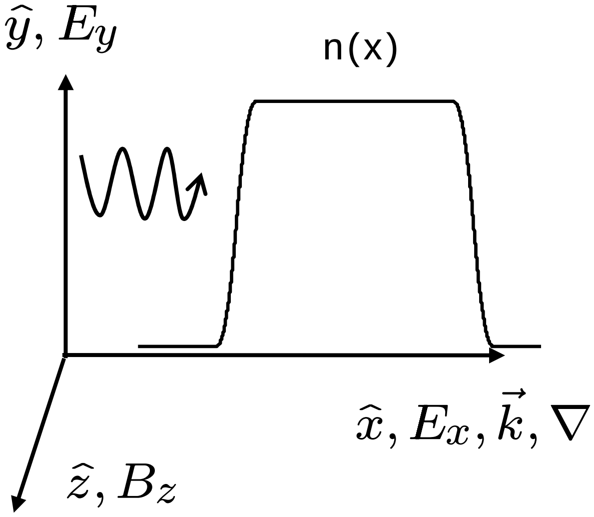
$$K \approx \frac{\gamma_0^2}{\nu_e |v_{gb}|} \qquad G \approx \frac{2L\gamma_0^2}{\nu_e |v_{gb}|}$$

ELVIS: 1D Vlasov Code

Eulerian-Lagrangian Vlasov Integrator w/ Splines

- 1D time-evolution code
- fixed or kinetic ions
- Vlasov (kinetic, collisionless) Equation in x:

$$\frac{\partial f}{\partial t} + v\frac{\partial f}{\partial x} + q(E_x + v_y B_z)\frac{\partial f}{\partial p} = 0$$



- Gauss' Law (solved in k-space):

$$\partial_x E_x = \frac{e}{\epsilon_0}(Z_i n_i - n_e)$$

- Transverse Maxwell Fields: fixed, linearly polarized in $\hat{y}$

$$E^{\pm} \equiv E_y \pm c B_z \qquad (\partial_t \pm c\partial_x)E^{\pm} = -\epsilon_0^{-1} J_y \qquad E^{\pm} = \text{right,left-moving}$$

- Transverse flow: cold beam, no collisional damping

$$m\partial_t v_y = qE_y$$

Elvis time-stepping

Follows Ghizzo, Bertrand, Shoucri et al, *Journ Comp Phys* **90**, 431 (1990)

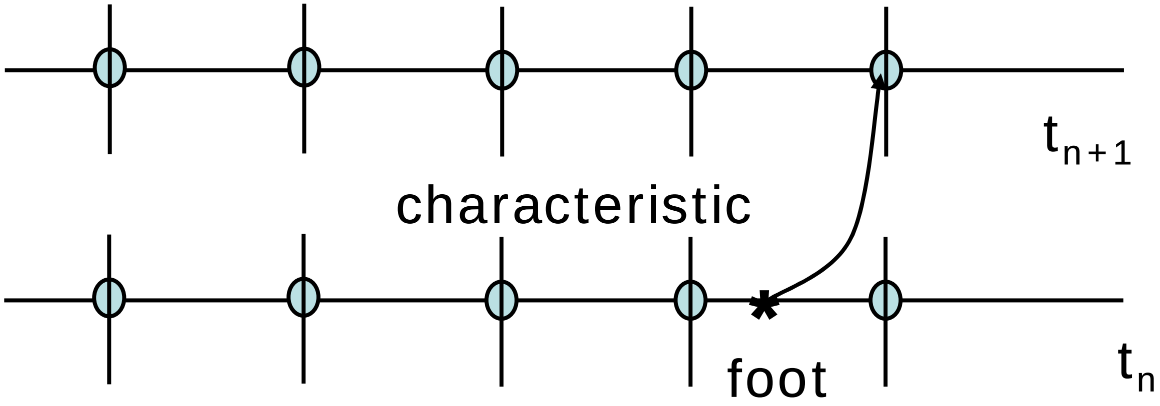
$$\begin{tikzcd}
\text{start} & 0 & 0^{+} & \frac{1}{2}^{-} & \frac{1}{2} & \frac{1}{2}^{+} & \text{end} & \\
f_{0-} \arrow[rr, "A"] & & f_{0+} \arrow[rrrr, "S"] & & & & f_{1-} & \\
n_0 & & & & n_{\frac{1}{2}} & & n_1 & \\
\rho_0 & & & & & & \rho_1 & \\
E_{x0} & & & & & & E_{x1} & \\
v_{y0}, v_{y\frac{1}{2}} \arrow[rrrrrr, "A_y"] & & & & & & v_{y\frac{3}{2}} \arrow[r] & v_{y1} \\
& & & & J_{y\frac{1}{2}} & & & \\
E_0^{\pm} \arrow[rrr, "M"] & & & E^{\pm}_{\frac{1}{2}-} \arrow[rr, "J"] & & E^{\pm}_{\frac{1}{2}+} \arrow[r, "M"] & E_1^{\pm} &
\end{tikzcd}$$

- Accelerate f_{0+} to f_{0-}
- Shift n_0 into n_{old}
- Free-stream f_{0+} to f_{1-}
- Calculate n_1, ρ_1, E_{x1}
- $n_{\frac{1}{2}} = \frac{1}{2}(n_0 + n_1)$
- Free-stream $E_0^{\pm}$ to $E^{\pm}_{\frac{1}{2}-}$
- $J_{y\frac{1}{2}} = \sum q_s v_{ys\frac{1}{2}} n_{s\frac{1}{2}}$
- Apply J_y kick to $E^{\pm}_{\frac{1}{2}-}$
- Free-stream $E^{\pm}_{\frac{1}{2}+}$ to $E_1^{\pm}$
- Accelerate $v_{y\frac{1}{2}}$ to $v_{y\frac{3}{2}}$

Evolving *f*: Method of Characteristics

- Vlasov eqn: f (# of particles) is constant along orbits =characteristic curves $X(t), P(t)$ where

$$\frac{dX}{dt} = V \qquad \frac{dP}{dt} = F$$



New value of *f* at gridpt
= value of *f* at foot of char.

- Operator splitting: first solve $(\partial_t + v\partial_x)f = 0$:
  $f^*(x,p) = f(x - v\ dt, p, t_n)$

- Then solve $(\partial_t + F\partial_p)f = 0$:
  $f(x,p,t_{n+1}) = f^*(x, p - F\ dt)$

- Use cubic spline interpolation for off-gridpt f at foot

Boundary Conditions in ELVIS

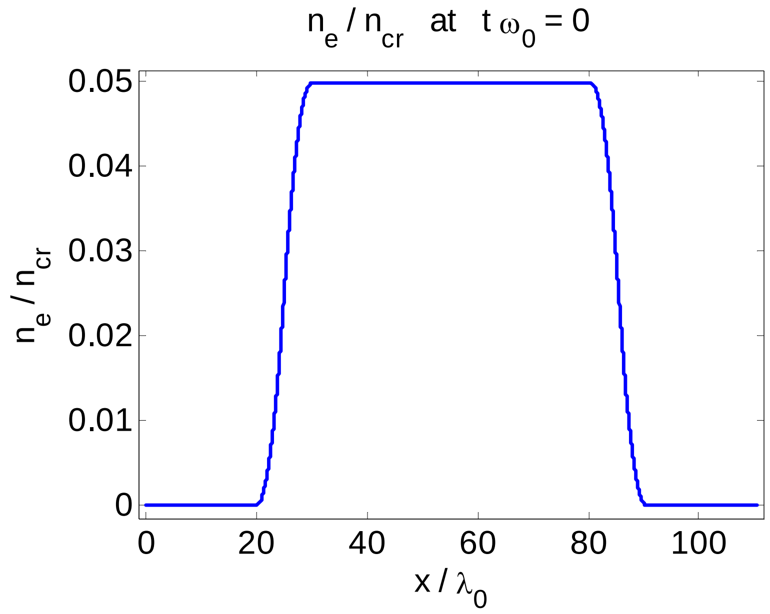
- f periodic in x: particles that leave box are recirculated at the other end.
- f finite in p: particles that are accelerated past p_{max} are lost, but replenished from Maxwellian at initial T_e
- Longitudinal E_x is periodic, solved for in k space with FFTW. $E_x(x=0)=0$, as is appropriate for finite plasma.

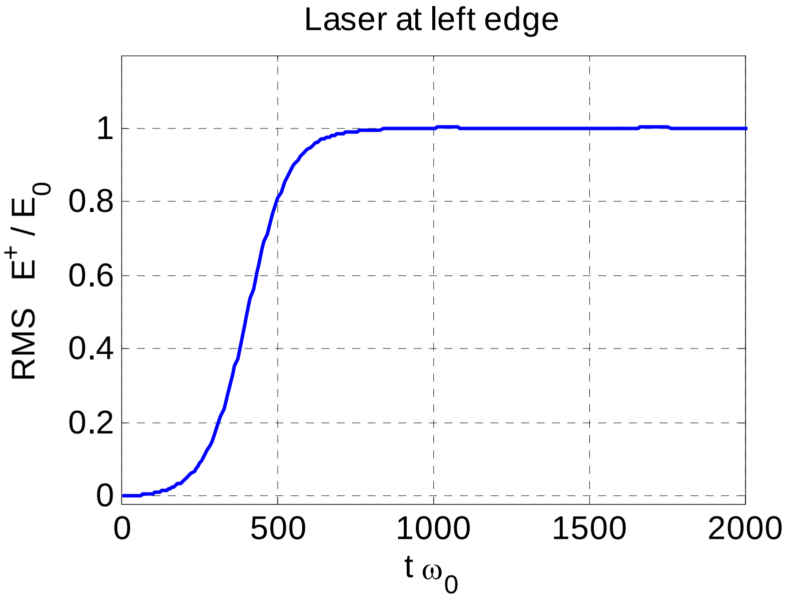
$$\rho(x) \to \rho(k) \to E(\neq 0) = \frac{\rho}{ik} \to E(x) \qquad E_x(x=0)=0$$

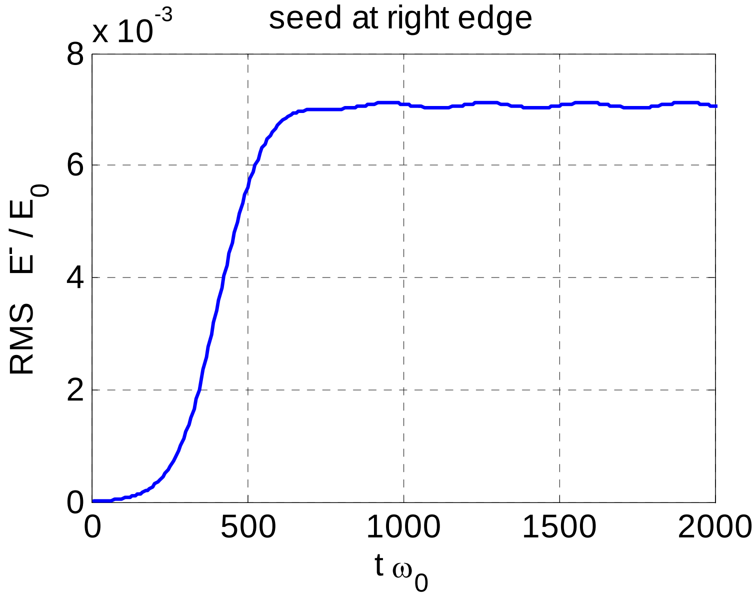
- $E^{\pm}$ are non-periodic. We specify E^{+} (E^{-}) versus t at left (right) edge and they are advected into plasma. No reflections at boundaries.

Base Case: $k_e \lambda_{De} = 0.24$

- flat-top density profile, laser (E^+) enters from left, SRS seed (E^-) from right


n_e / n_{cr} at $t\,\omega_0 = 0$


Laser at left edge

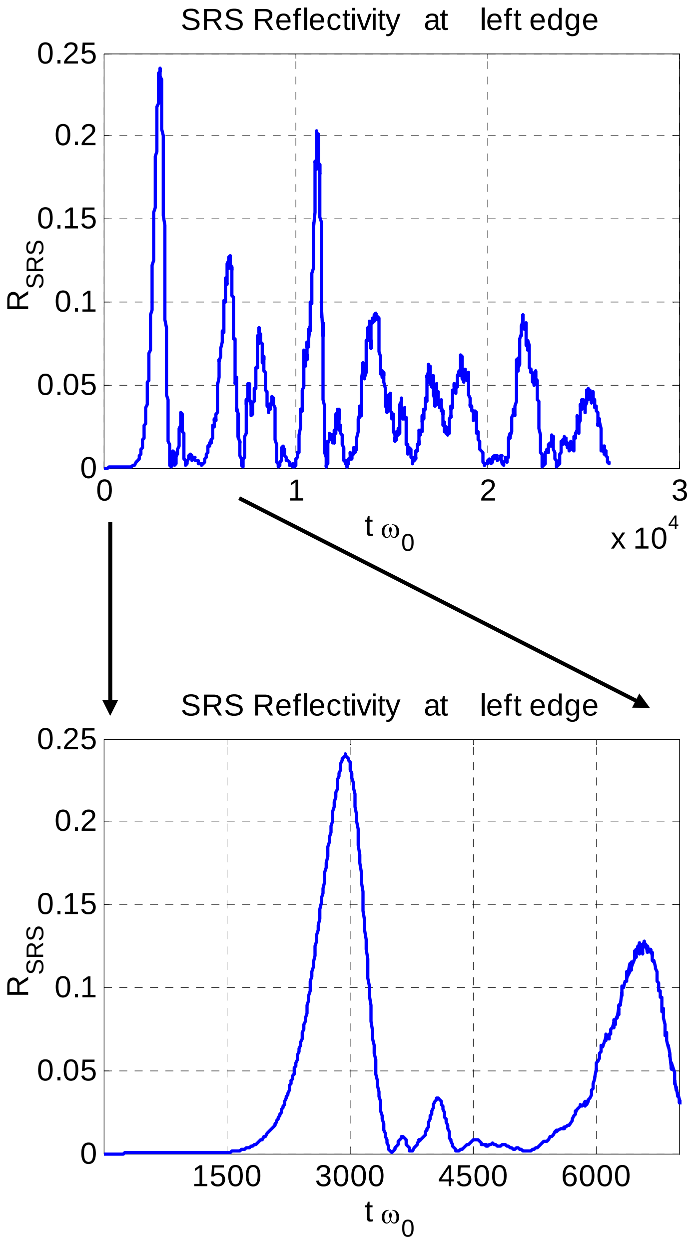

seed at right edge

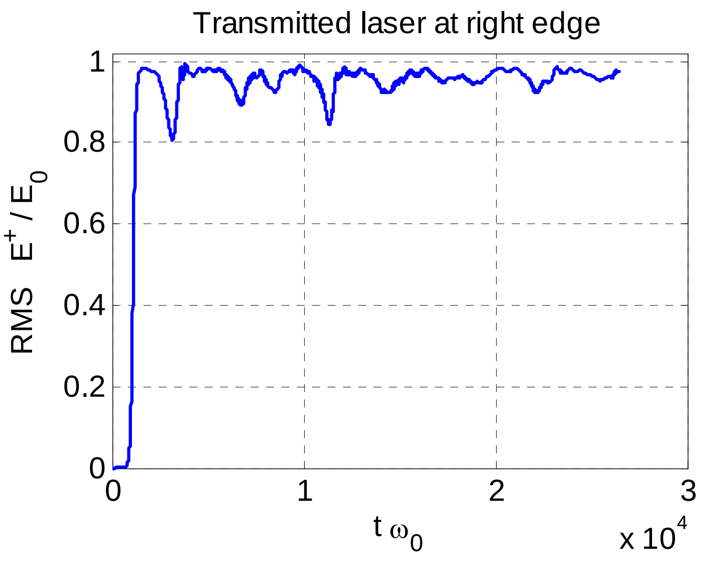
$I_0 = 2{\cdot}10^{15}$ W/cm^2
$\lambda_0 = 527$ nm
$I_{seed} = 10^{11}$ W/cm^2

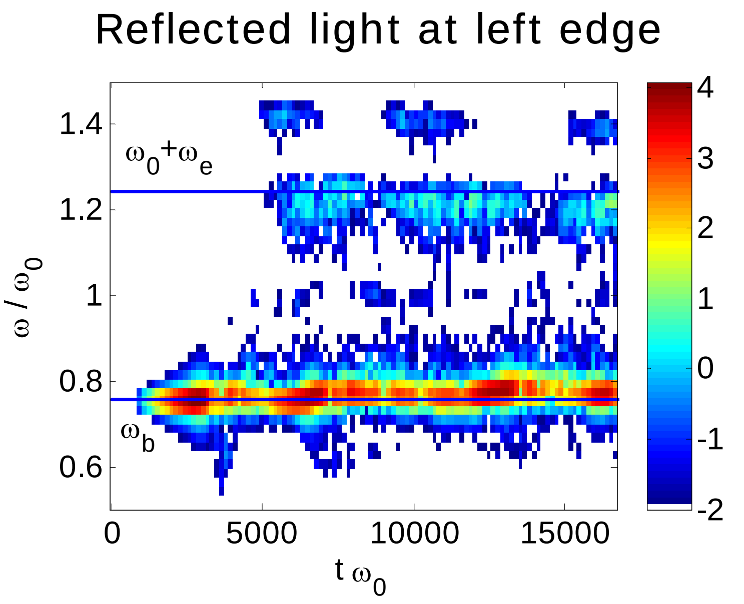
$T_e = 500$ eV
$n_e = 2{\cdot}\,10^{26}$ m^{-3}

$n_e/n_{cr} = 0.05$
$k_e\lambda_{De} = 0.24$
$I_{cr} = 9.1{\cdot}10^9$ W/cm^2

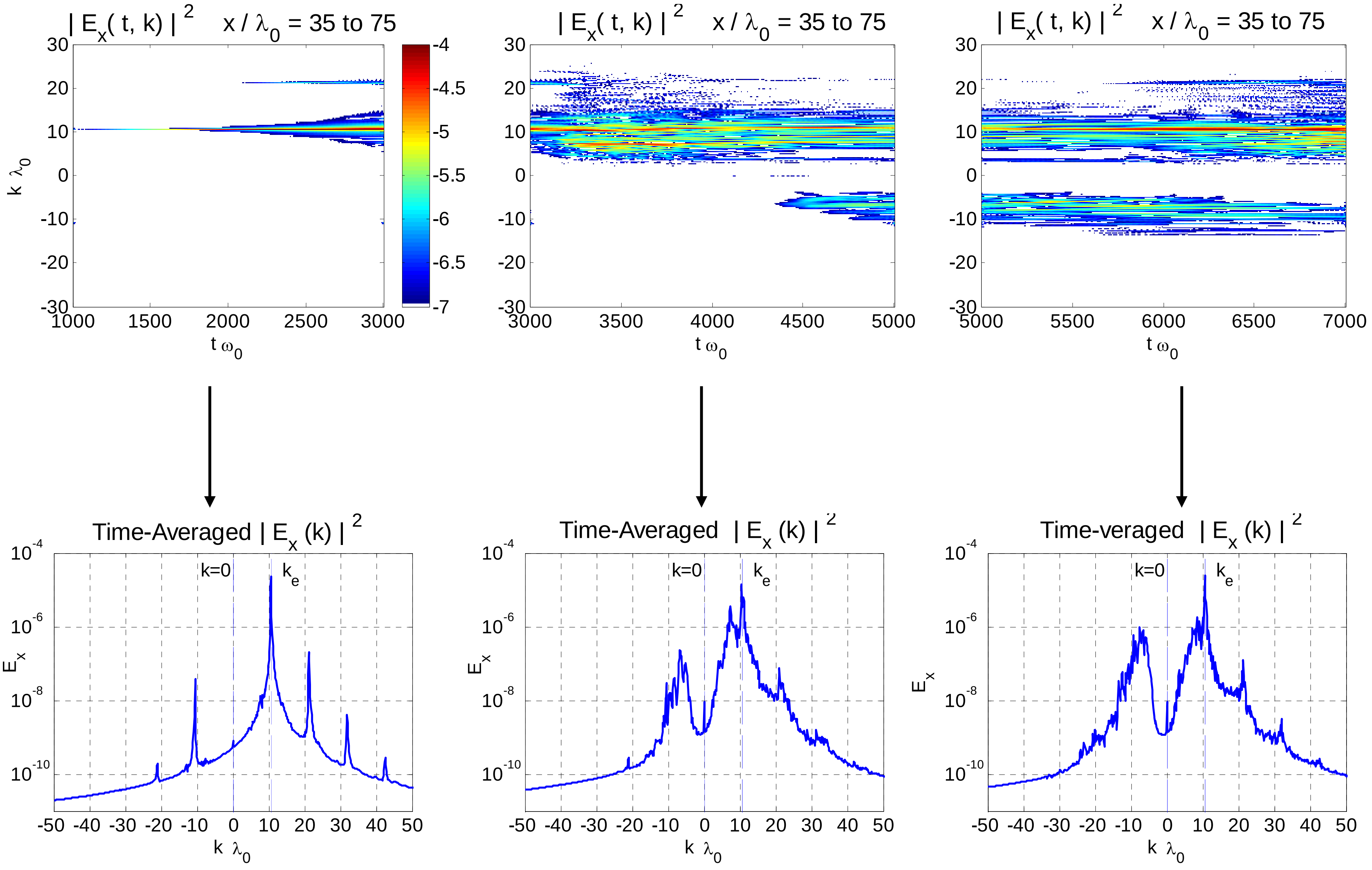
Base Case: Bursty SRS, Avg. Reflectivity = 3.6 %



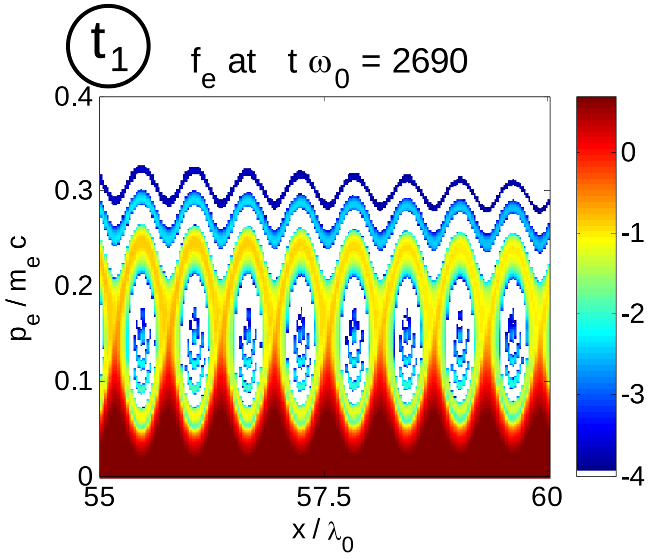


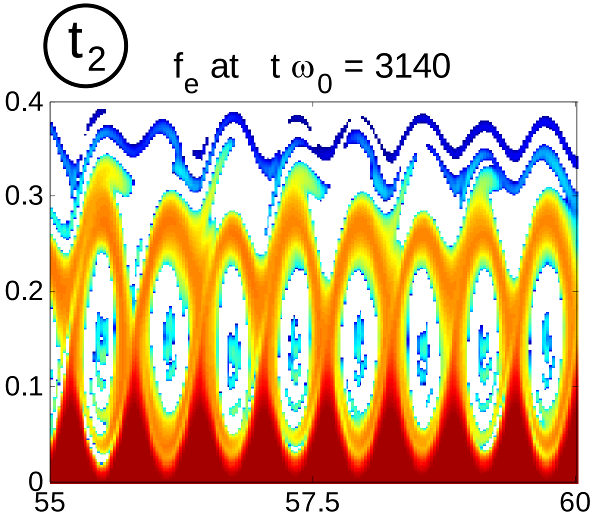


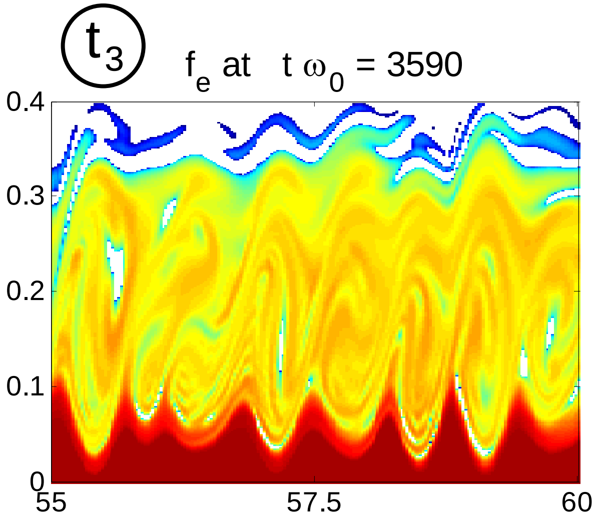
Electrostatic fields: bandwidth, harmonics, left-movers

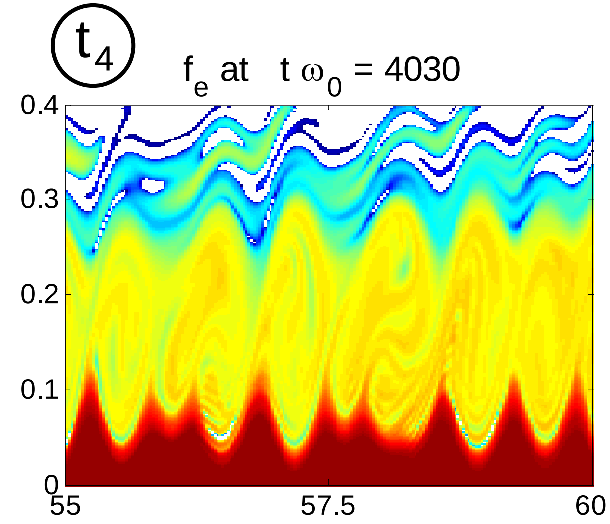


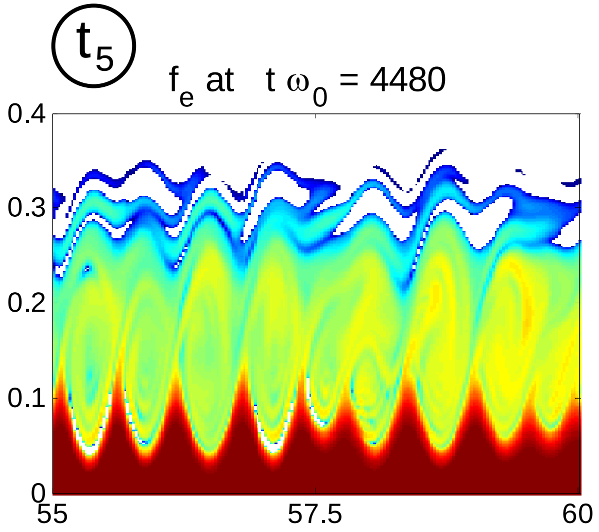
Phase Space: Trapping, Irregular Vortices

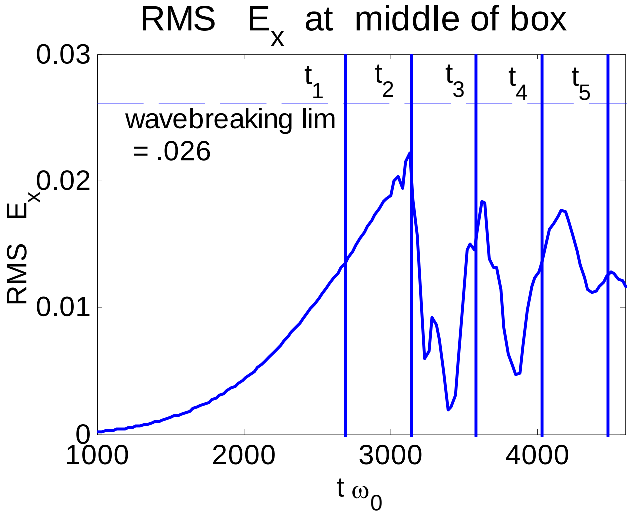

f_e at $t\,\omega_0 = 2690$


f_e at $t\,\omega_0 = 3140$

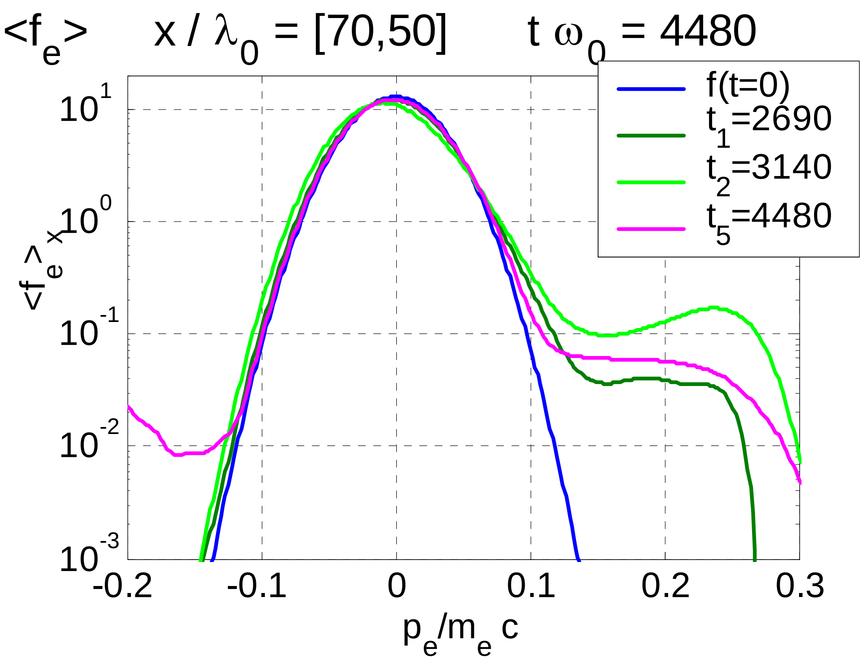

f_e at $t\,\omega_0 = 3590$

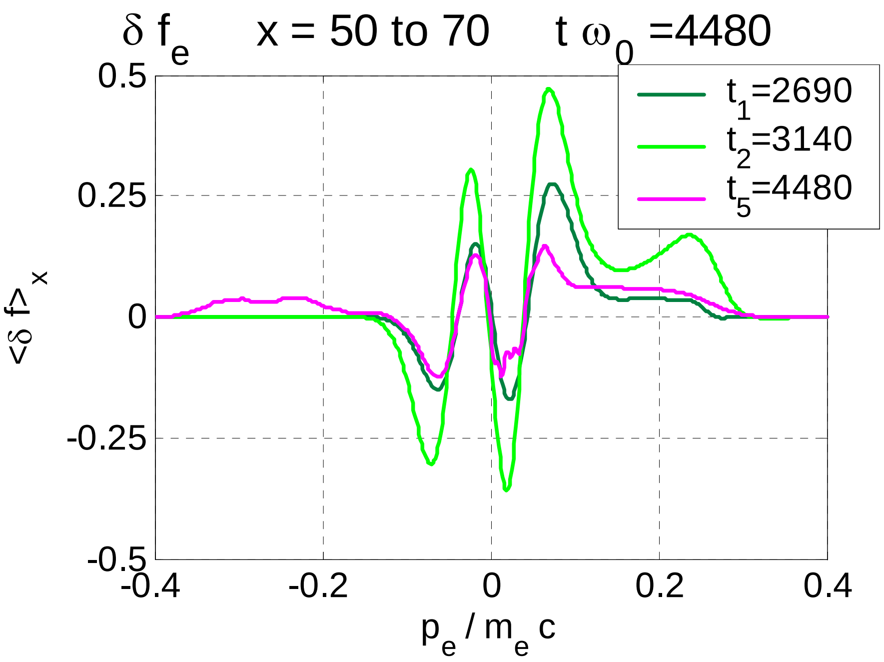

f_e at $t\,\omega_0 = 4030$

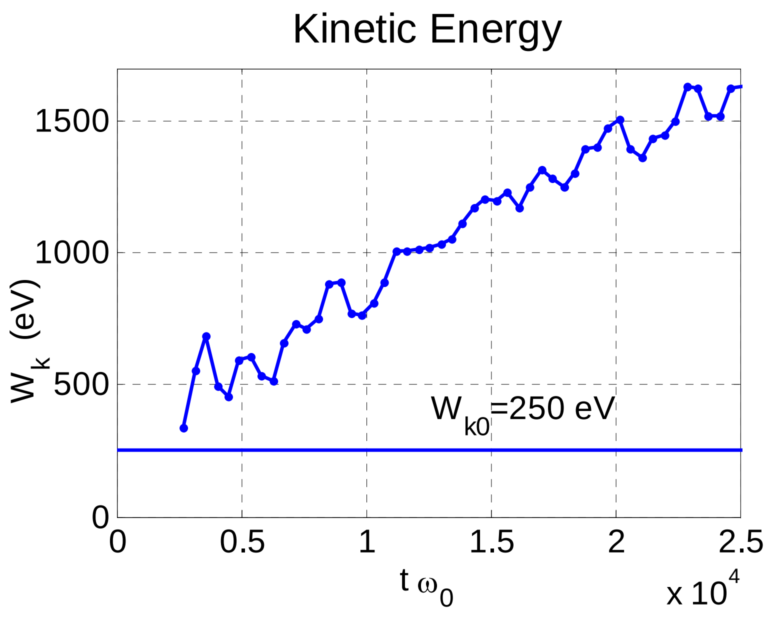

f_e at $t\,\omega_0 = 4480$


RMS E_x at middle of box

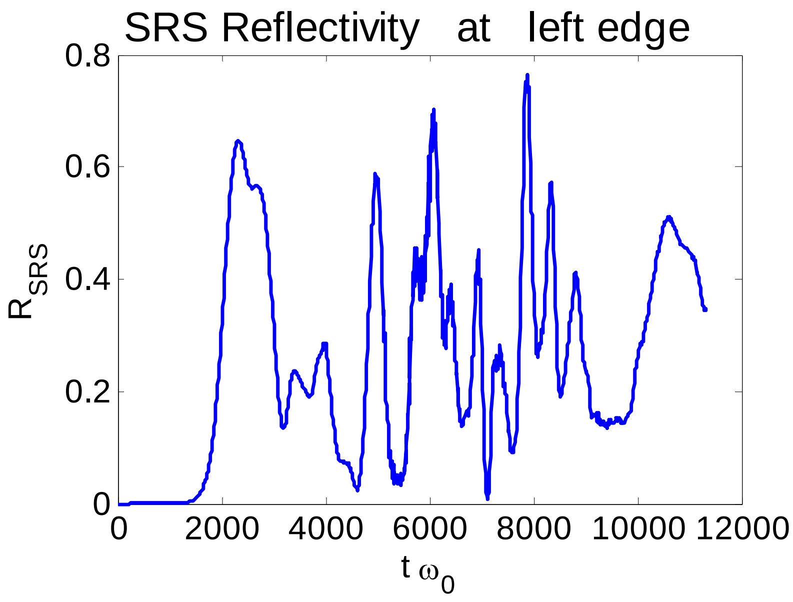
Spatially-Averaged f(p): Energetic Tails

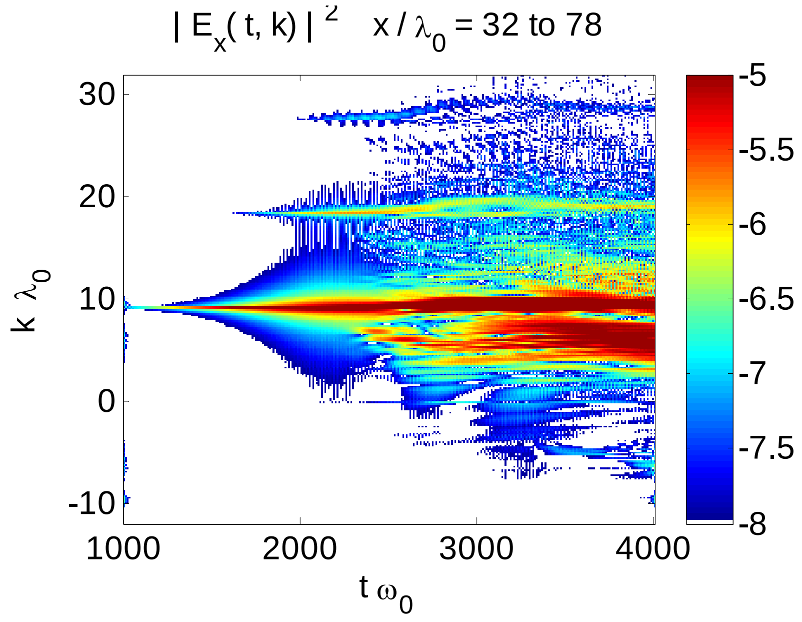


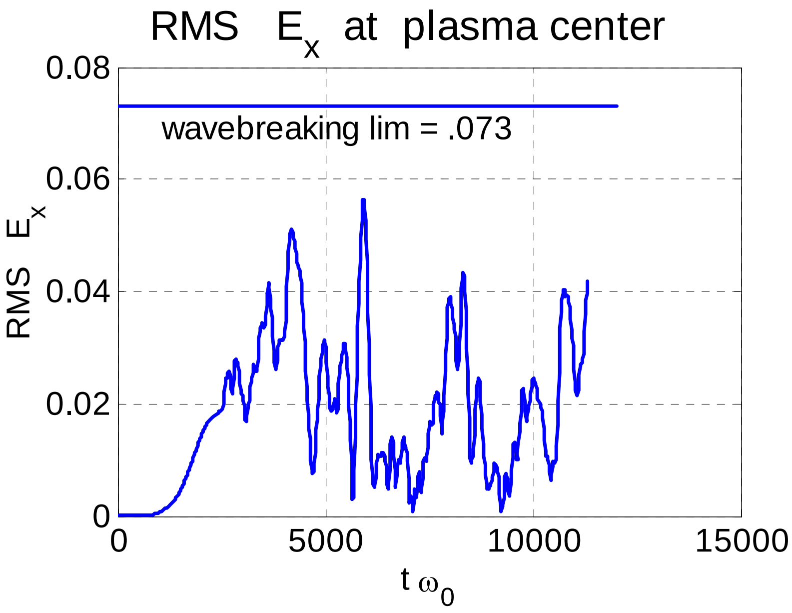




Lower $k_e\lambda_D$: Higher Reflectivity, Avg. = 25.8 %







I_0 = $2{\cdot}10^{15}$ W/cm^2

λ_0 = 527 nm

I_{seed} = 10^{11} W/cm^2

T_e = 500 eV

n_e = $5{\cdot}\,10^{26}$ m^{-3}

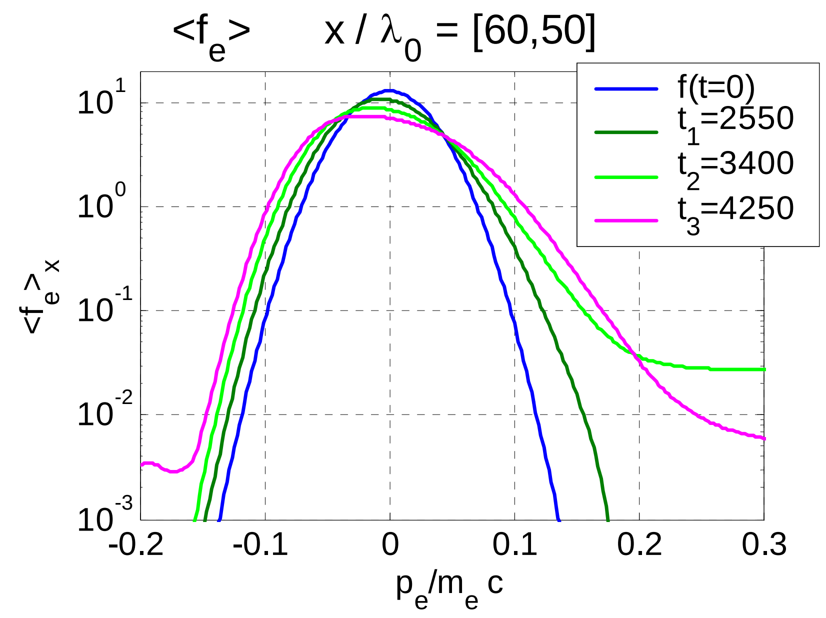
n_e/n_{cr} = 0.125

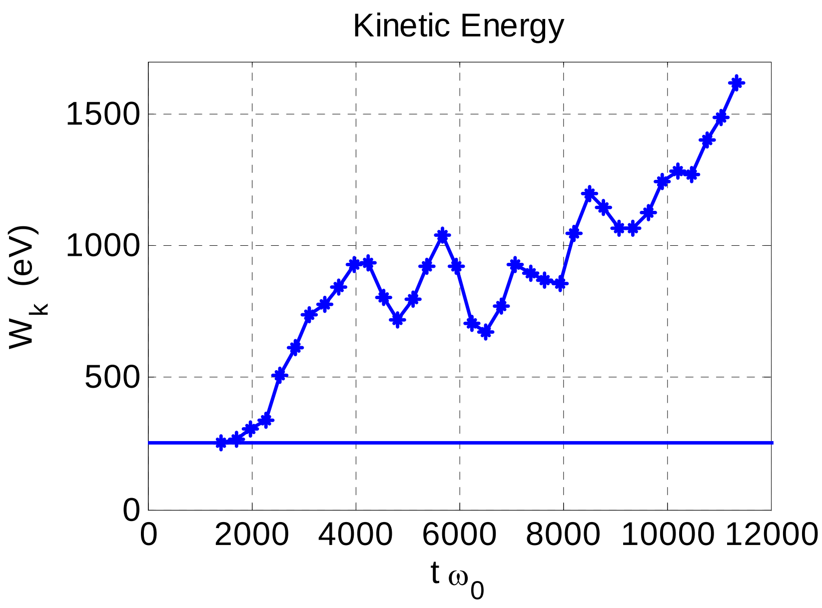
$k_e\lambda_{De}$ = 0.13

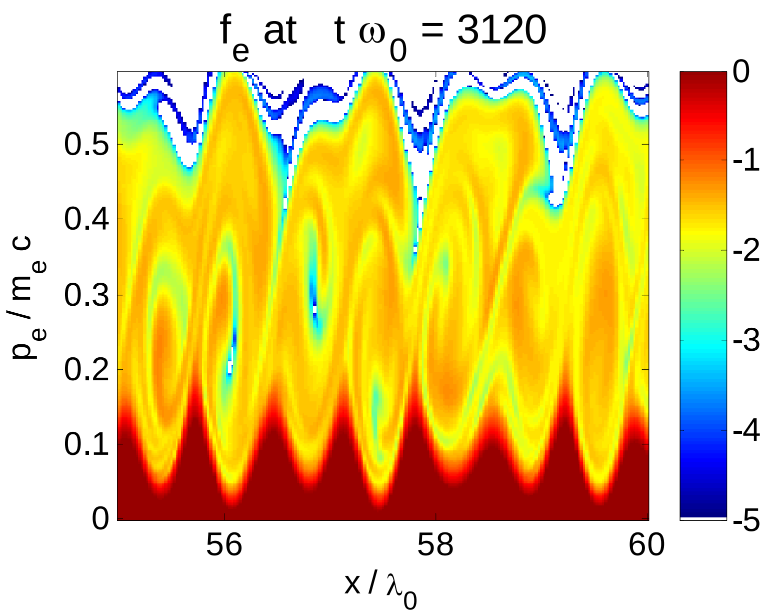
I_{cr} = $2.6{\cdot}10^3$ W/cm^2

Orange: different from base case

Low $k_e\lambda_{De}$: Phase Space







Future Work and Acknowledgements

Future Work:

- Noise: Seed laser is artificial. We will add realistic noise in the electrostatic and electromagnetic channels

- Ions: Ion dynamics (LDI, Langmuir collapse) are important in SRS saturation.

- How do ion saturation mechanisms compete with electron kinetic effects?

- Parallelization: Allow for longer runs, bigger plasmas.

We thank...

- Drs. Bedros Afeyan and Vlad Savchenko for a series of very helpful discussions
- The MIT Plasma Science and Fusion Center, and in particular Dr. John Wright, for providing us access to the Marshall theory cluster
- LLNL for providing DJS funding to attend the conference

Reprints/Comments: Please leave name and address