# Development of a Two-Dimensional, Time Dependent, Parallel Wave Propagation Code as an aid to Interpreting Reflectometry Data*

Jeff Nine[1], Raffi Nazikian, Ernest Valeo, Stephan Brunner, Charles Karney
*Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton NJ 08540-0451*
*[1]National Undergraduate Fellow, LeTourneau University, Longview, Texas, U.S.A.*

## Statement of the Problem

- Reflectometer (microwave scattering) measurements in large fusion scale plasmas has yielded exciting new results on the properties of plasma turbulence.
- Analytic models of wave reflection from plasma are inadequate to address many fundamental issues regarding the details of wave scattering.
- Wave propagation of microwaves in fusion scale plasmas typically involves system sizes consisting of 100s of wavelengths.
- Conventional (single processor) simulation of such large system size is inefficient
  - typically requires reduced system size for tractable computation.
  - Limitation of box size has driven much of the innovation in boundary condition algorithms.

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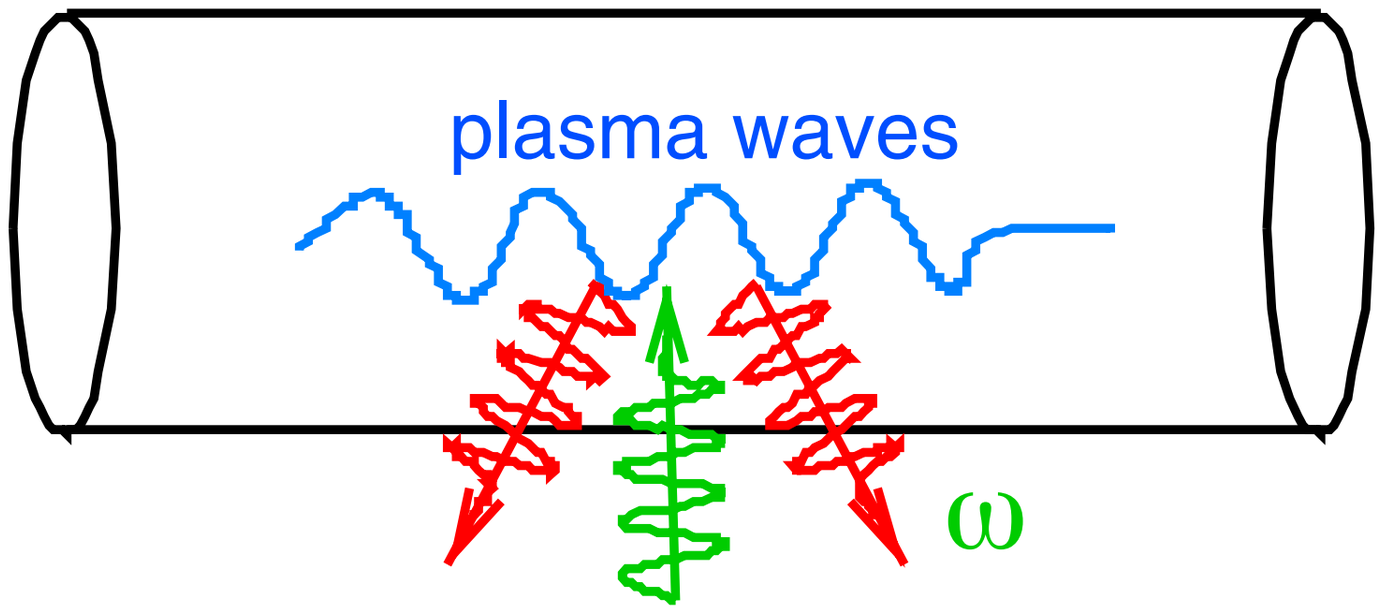
# The Two Dimensional Scalar Wave Equation: Wave Propagation in an Inhomogeneous Unmagnetized Plasma (Relevant for E||B propagation)




$$\left(\frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2} - \frac{\partial^2}{\partial y^2} + \frac{1}{c^2}\left[\omega_p^2 + \sigma\frac{\partial}{\partial t}\right]\right)E = 0$$

$\omega_p$ : plasma frequency.

$\sigma$ : absorbing boundary (hyperbolic tangent).

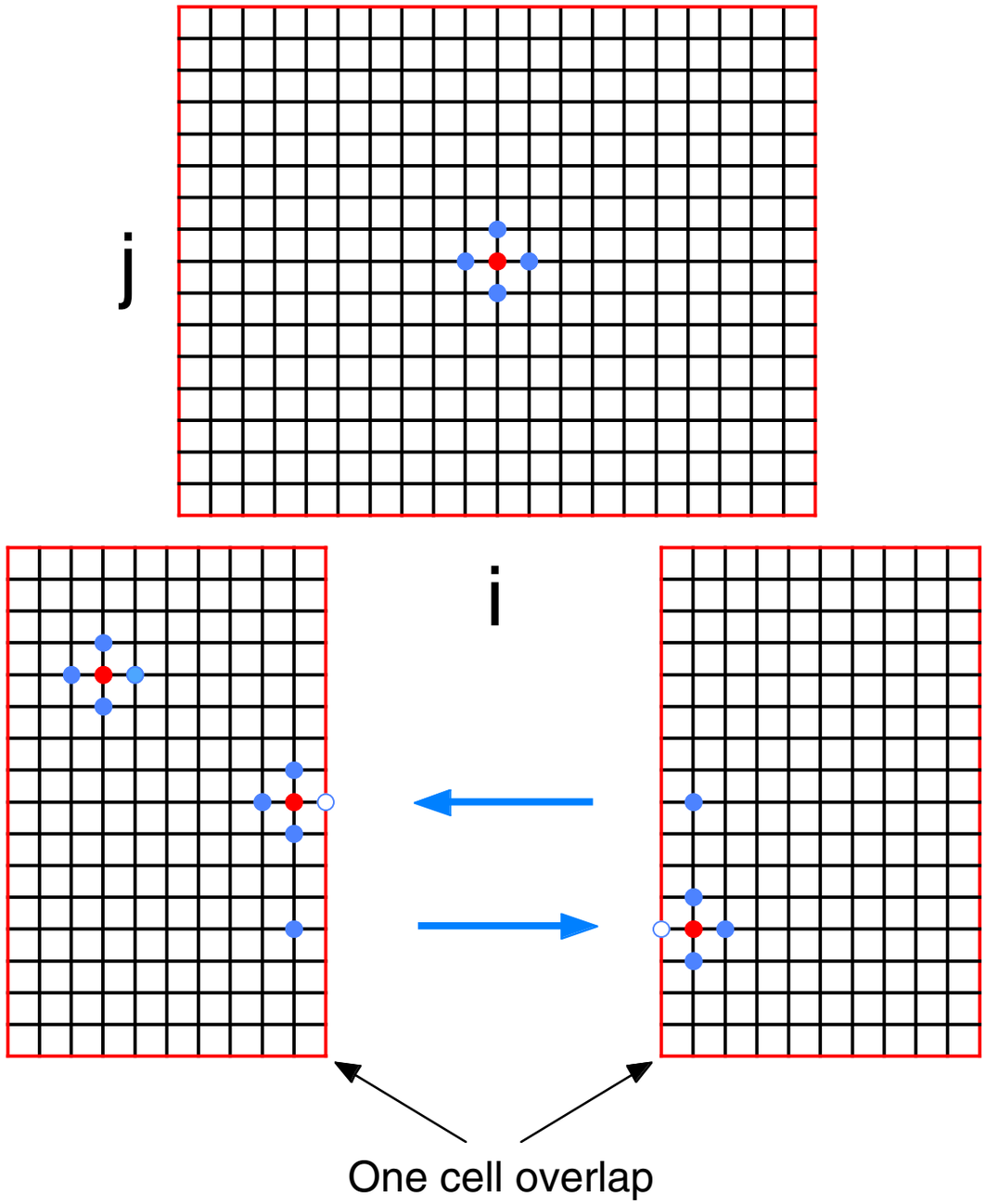
$E = e^{ik_0 x} e^{-(x-x_0)^2/w_x^2} e^{-(y-y_0)^2/w_y^2}$ : Initial condition (t = 0).

## The key issue for parallel computing is Communication: Fortran Program with Message-Passing Interface: MPI

- The time-dependent wave equation can be solved for all interior points of a region at a subsequent time if the field is prescribed at all points, including points on the boundary, at previous time(s).

- Multiple processors divide up the domain into sub-regions. The key idea is that the boundary of one sub-region represents an *interior* point of an adjacent region. When this interior point is evaluated, the result is communicated to the adjacent processor for performing the next iteration.

# Boundary points in one sub-region communicated from interior point in an adjacent region




Solving for the difference equation:
(Here $\omega_p$, $\sigma = 0$)

$E_{i,j,t+1} =$

$E_{i+1,j,t} + E_{i-1,j,t} - 2E_{i,j,t}$
$+$
$E_{i,j+1,t} + E_{i,j-1,t} - 2E_{i,j,t}$
$-$
$2E_{i,j,t} - E_{i,j,t-1}$

## Description of Parallel Computer (Puffin) Used for the Following Simulations

- Puffin consists of 8 PCs:

  Dual Intel Pentium III 450MHz CPU
  512MB RAM
  14.4GB IDE disk
  100Mb Ethernet card
  SVGA graphics card

and 1 PC with the following configuration:

  Dual Intel Pentium III 450MHz CPU
  512MB RAM
  SCSI interface
  14.4GB IDE disk + 18GB SCSI disk
  2 100Mb Ethernet cards
  AGP 8MB graphics card

- Linux Redhat 6.

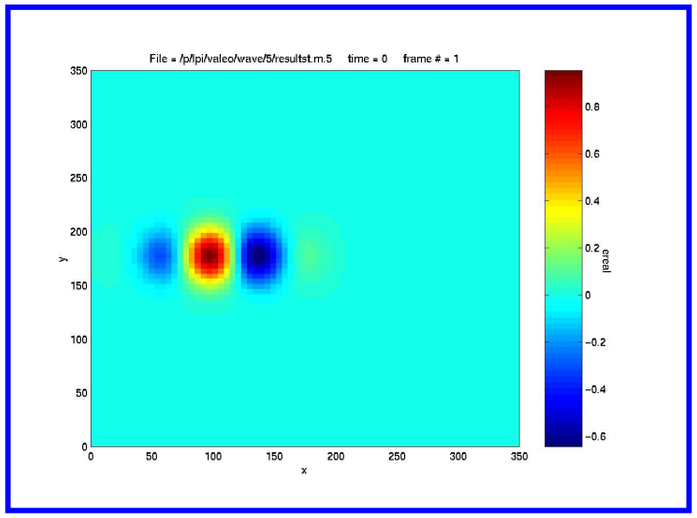
- NAG and Portland Group Fortran compilers.

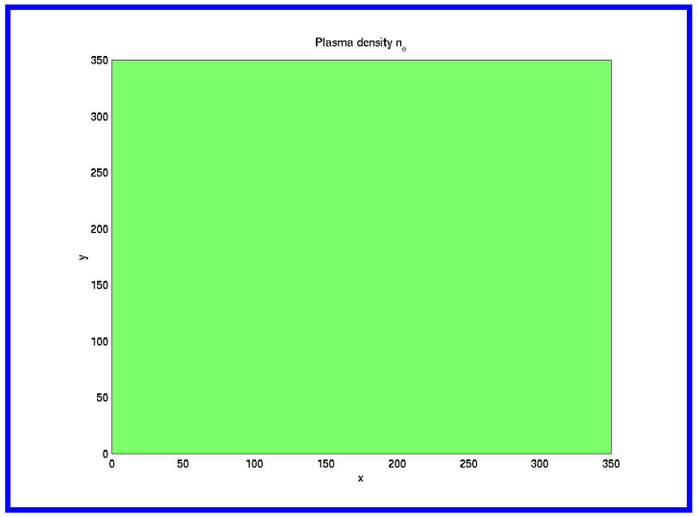
- MPI and PVM message passing libraries.

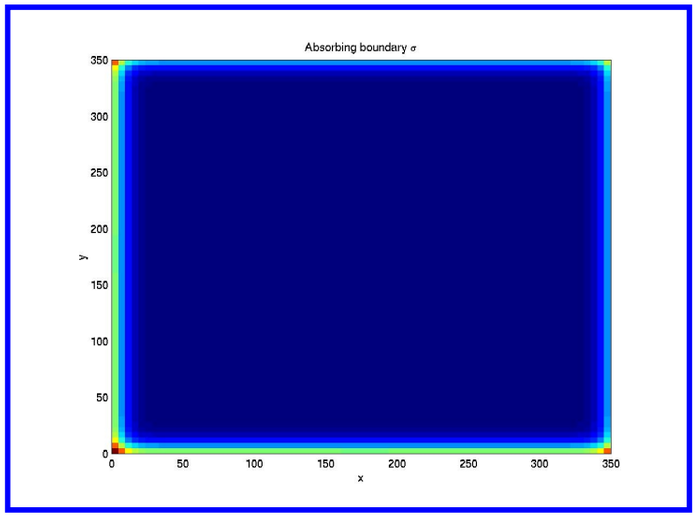
Puffin total cost: $25. k

# Case I: Test of Boundary Condition in vacuum with Sub-Wavelength Absorbing Boundary Region.

(CaseI&II: 75x75 grid/3x3 array/15000 time steps/45 sec.)




Real part of initial wave packet.

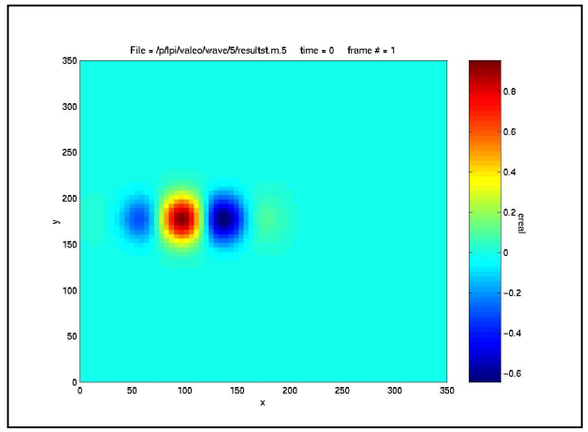
Density distribution, $n_e$=0.

Sub-wavelength Absorbing boundary region, $\sigma$.

Note that the reflected power is down 20 dB, even though the absorbing layer width is thinner than one wavelength.

# Case I: Time Sequence of Propagation and Absorption.

(Auto-scaled plots. Initial amp. ~1.0, Final amp. ~0.1.)

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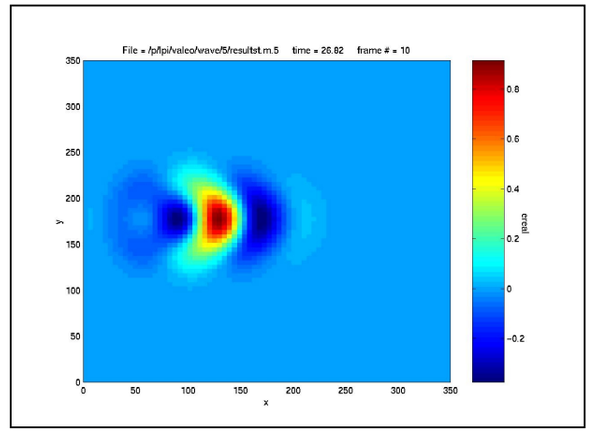


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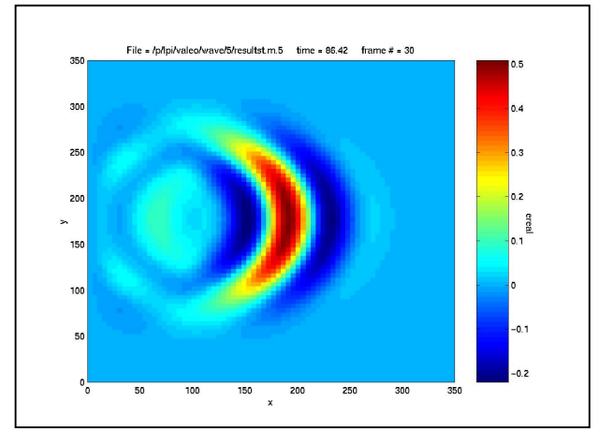


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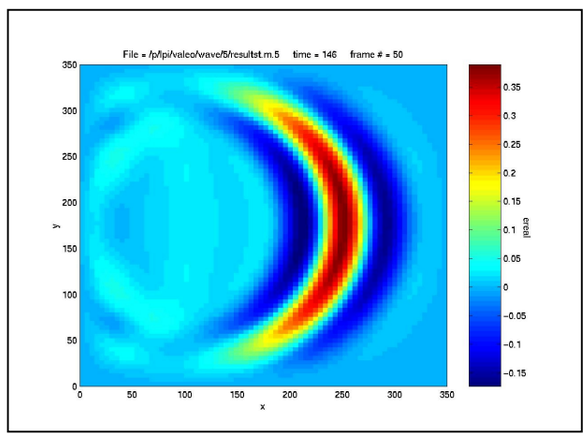


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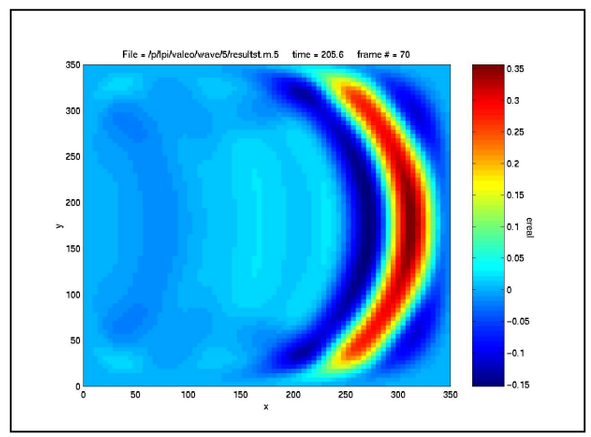


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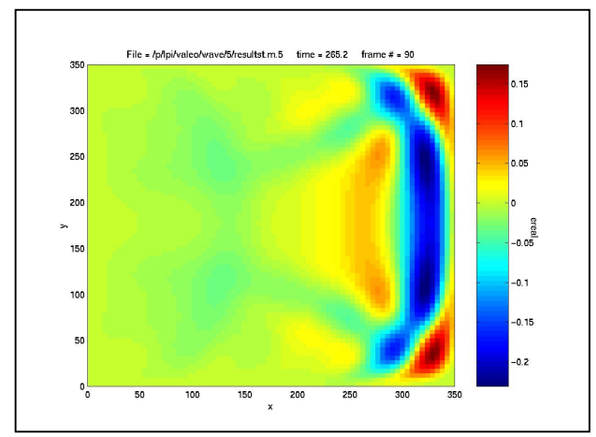


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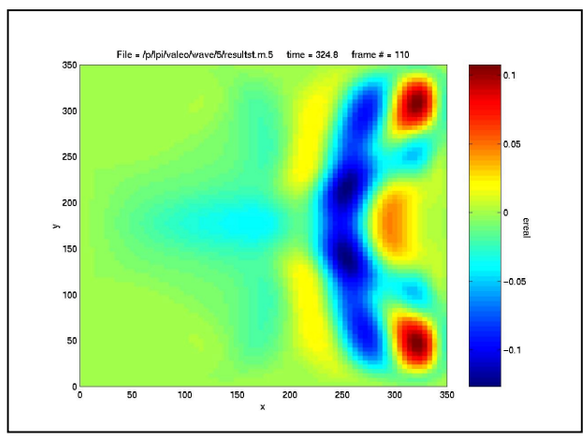


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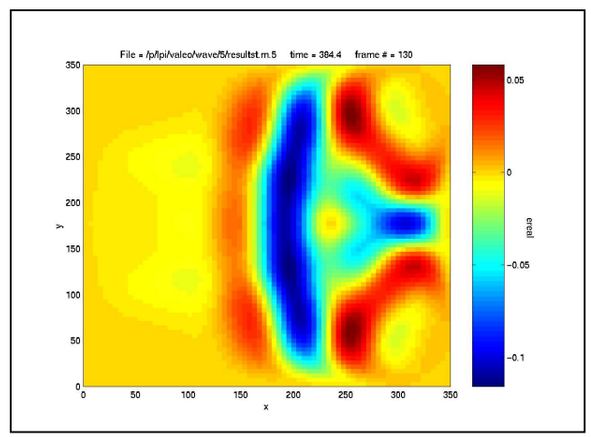


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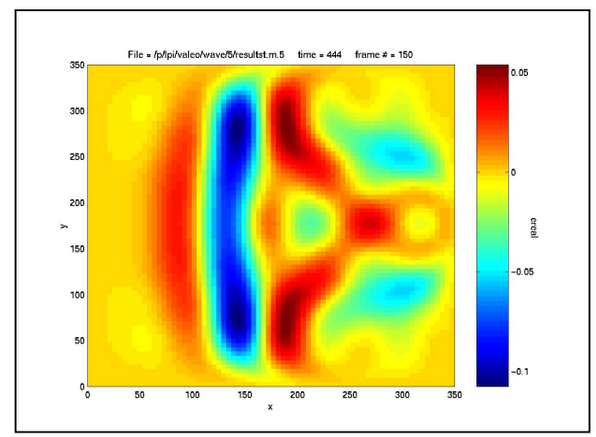


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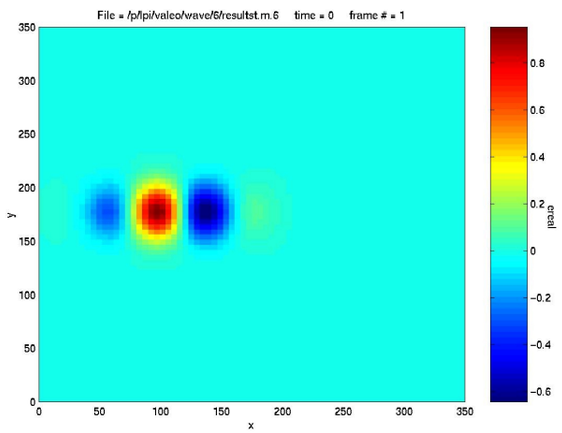
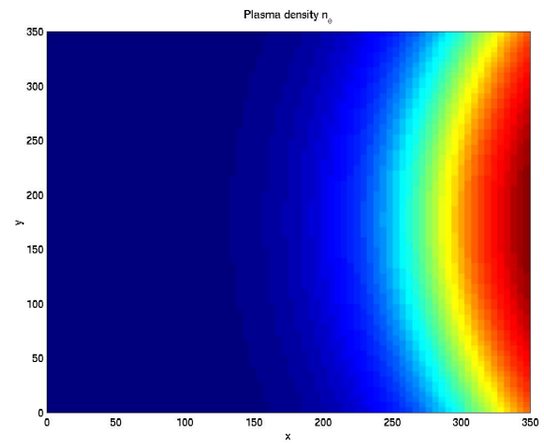
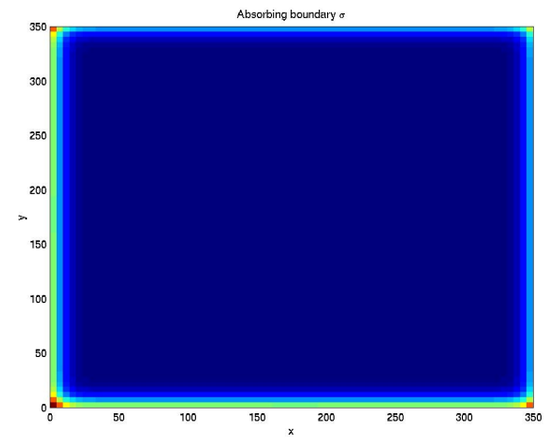
# Case II: Test of Wave Reflection from a Cutoff.




Initial wave packet, before propagation.

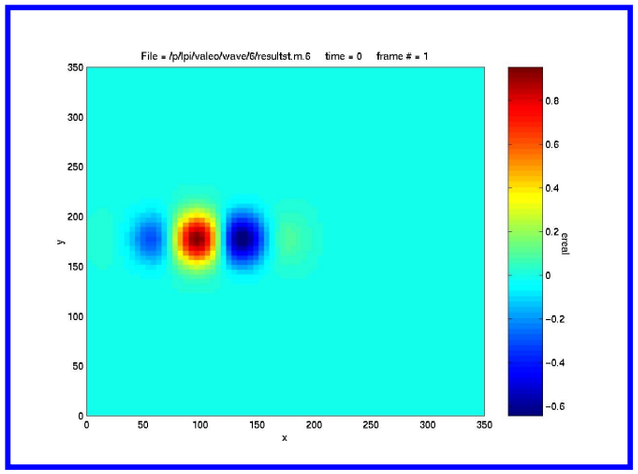



Density distribution.




Sub-wavelength Absorbing boundary region, $\sigma$.

# Case II: Time Sequence of Propagation and Reflection: Reflection takes place near edge of density.

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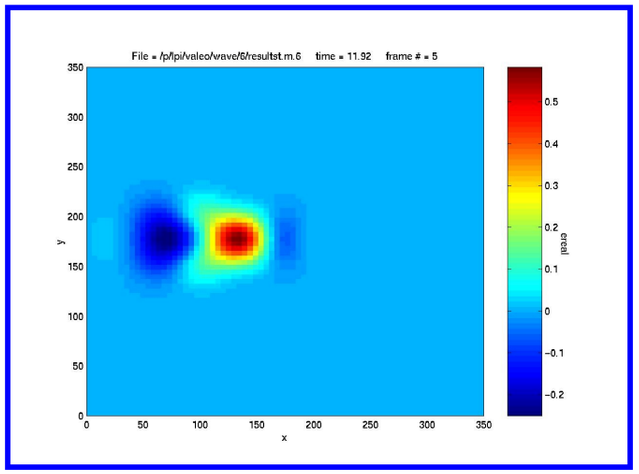


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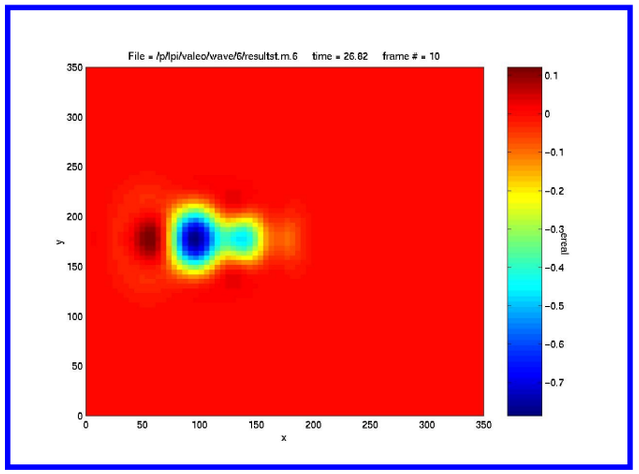


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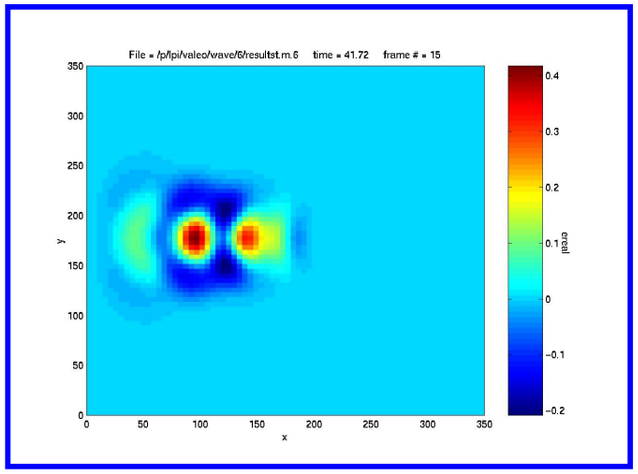


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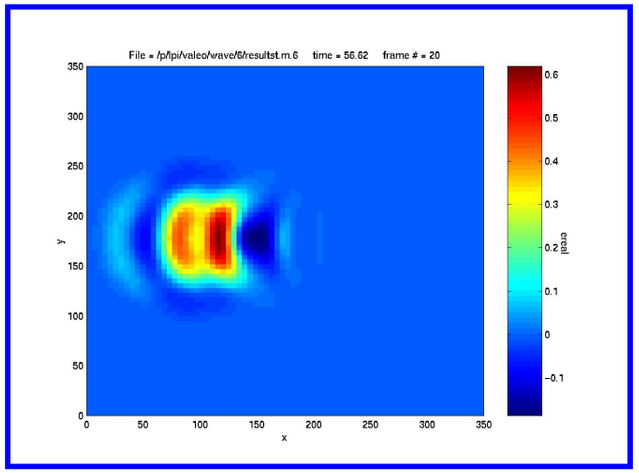


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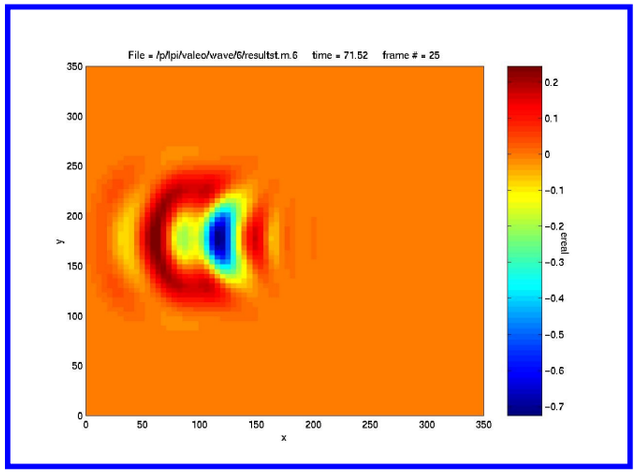


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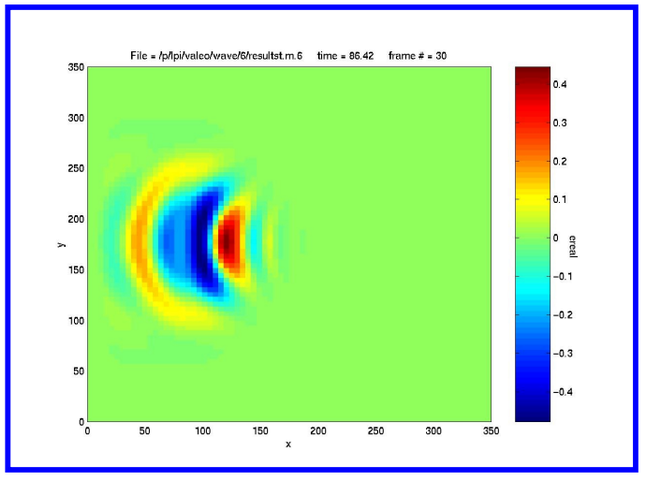


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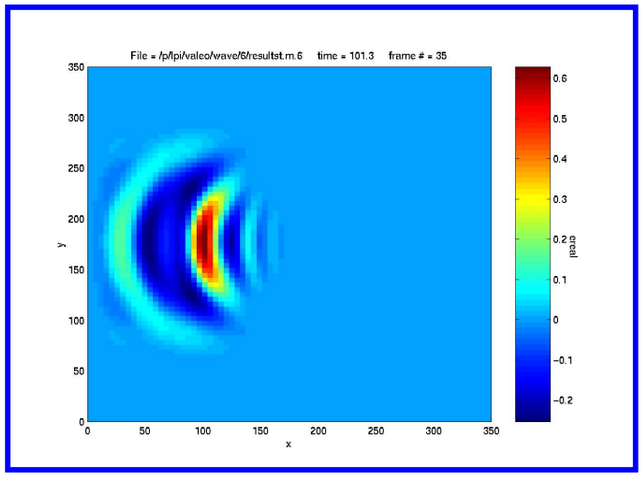


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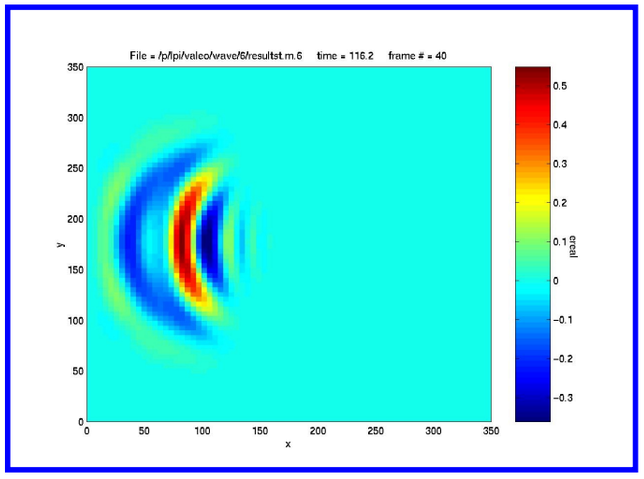


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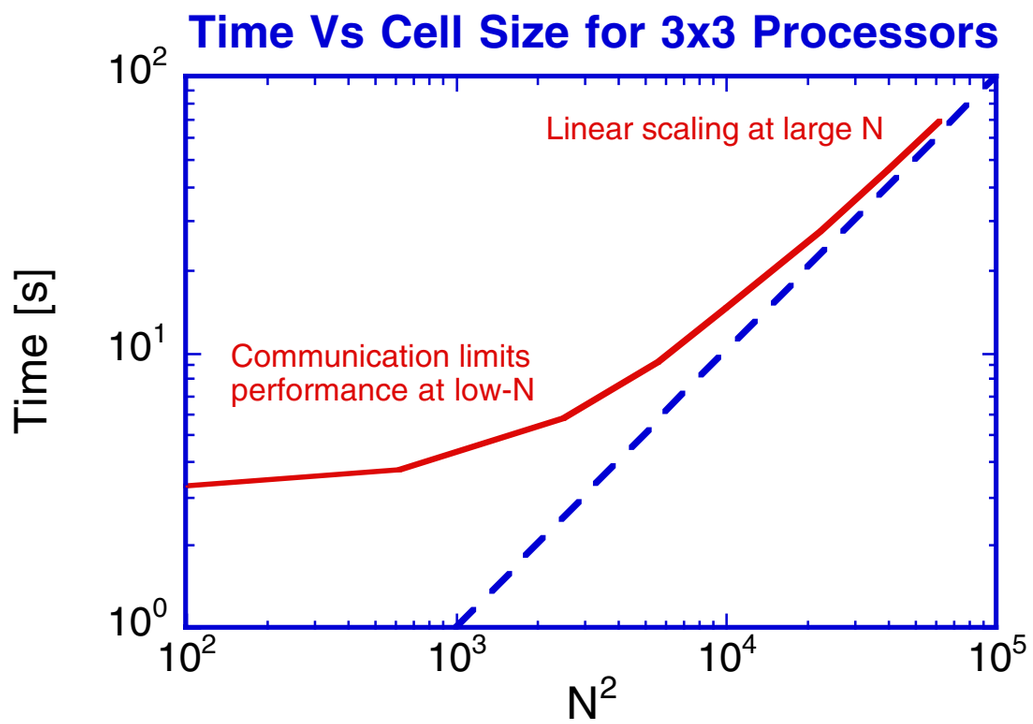
# Computation Time Vs Grid Size N per Cell for a 3x3 Array of Processors: 1000 Time Steps.




For cell dimension N, linear scaling occurs at large N.
Communication dominated at low-N.

# Summary

- New code has been developed for solving the scalar wave equation on a parallel processor for fusion plasma applications.

- Reflection from plasma simulated. Absorbing boundary condition yields reasonable results for large system size.

- Ideal (non-communication limited) scaling of computation time with system size confirmed for large system size on Puffin.

- Next step is to introduce fluctuations and benchmark to theory in slab geometry.