Laser target interactions, and space/solar physics simulation experiments (Seed funding project)

A progress report presented by Charles Chiu

- **Laser-target**: Boris Breizman, Alex Arefiev, Mykhailo Formyts'kyi & CC.
  - BA-model: **Laser-cluster-ansatz** states that $R \ll \lambda$ and $\omega_p \ll \omega$. It leads to predict various characteristic features in laser-cluster interaction. The model was proposed prior to the report period. It is the cornerstone of present work.
  - Novel 2D-PIC code has been developed by MF based on BA model. Based on these two tools, we explore features in temporal development of laser-cluster interaction and investigate potential application to 3d-harmonic absorption experiment. Work in progress was reported by MF at 2003 Int. Sherwood Fusion Theory Conf. [http://gazoo.ph.utexas.edu/~fomisha/Sherwood2003.ppt](http://gazoo.ph.utexas.edu/~fomisha/Sherwood2003.ppt)

- **Solar-physics simulation experiment**: Wendell Horton, Manish Ithawa & CC
  An experimental simulation of Solar-wind-magnetospheric interaction is being studied. Several sets of numerical estimates are given to show feasibility of the experiment. Study of relevant properties of solar wind is in progress.
Breizman-Arefiev model for electron dynamics in micro-clusters

B.N. Breizman and A.V. Arefiev, Plasma Physics Reports, July 2003
http://peaches.ph.utexas.edu/ifs/ifsreports/950_Breizman.pdf

Electron response time is much shorter than the ion response time!

Key assumptions (typically satisfied in cluster experiments):

- Cluster size $R$ is much smaller than the laser wave-length $\lambda$: $R \ll \lambda$
- Laser frequency $\omega$ is much smaller than the electron plasma frequency $\omega_{pe}$: $\omega \ll \omega_{pe}$
Model predictions

- Extracted electrons escape if $\xi = \frac{eE_0}{m\omega^2} \gg R$
- The remaining electrons form a cold conducting core
- The core displacement adjusts instantaneously to the laser field
- If $\xi = \frac{eE_0}{m\omega^2} \ll R$, then the extracted electrons return to the cluster and undergo stochastic (“vacuum”) heating

Numerical simulation is needed to investigate:

- ion dynamics affected by the electrons
- stochastic electron heating quantitatively
- resonant features in electron response
3D simulation of an axisymmetric cluster

**Assumptions:**
- Laser electric field is uniform in space and it is a given function of time
- Electron and ion contributions are electrostatic
- Cluster is fully ionized
- Electrons and ions are “macroparticles”
- Binary collisions neglected
- Boundary conditions: dipole expansion

“Macroparticles” may be identical

or their weight may vary in \( r \)

Every “particle” corresponds to a physical ring:
Electron core formation and electron leakage due to ion expansion

- Monotonically increasing field extracts electrons as the core contracts (① → ③)
- No contraction in constant field (③ → ④)
- Ion expansion reduces the potential well for the electron core
- The excess electrons leak out of the well and leave the cluster
Ion expansion anisotropy

**Large amplitude pulse**

\[ \xi = eE_0/m\omega^2 >> R \]

- Electrostatic space-charge field (averaged over the electron core oscillations) is anisotropic
- The average accelerating force for the ions at point A is larger than at point B.

Ions expand predominantly **across** the laser field.

**Small amplitude pulse**

\[ \xi = eE_0/m\omega^2 << R \]

- Hot electron pressure is anisotropic with \( P_\parallel > P_\perp \).
- The electrons pull the ions primarily **along** the laser field.
Electron heating and anisotropic ion expansion

Extracted electrons undergo vacuum heating

Vacuum heating produces electron pressure anisotropy $P_\parallel > P_\perp$

Pulled by heated electrons, ions gain larger momentum along the laser field

Each point corresponds to an ion

Electron momentum distribution

Ion angular distribution
Third harmonic generation

- Start with an electron core inside a uniform ion cluster
- The core eigenfrequency is $\omega_{pe}/\sqrt{3}$
- Core oscillations become nonlinear due to nonuniform ion expansion
- Choose laser frequency as $\omega_0 = \omega_{pe}(t=0)/(3.4\sqrt{3})$
- Ion expansion reduces $\omega_{pe}$
- Resonant response occurs when $\omega_{pe}(t)/\sqrt{3}$ reaches $3\omega_0$
- Near $t=15\tau_0$, the equation of motion for the core is approx. given by:
  $$\ddot{x} + \omega_{pe}^2 \frac{x}{\sqrt{3}} = \alpha x^3 + f(t)\sin \omega t$$

Laser field is harmonic

Dipole moment oscillates at $\omega_0$ and $3\omega_0$

Cluster radiates at $3\omega_0$!
Experimental Setup

Terrestrial magnetosphere acts as a magnetic obstacle to the solar wind. This leads to the creation of shock, the dynamo EMF and the acceleration of charged particles.

Measure B by Faraday Rotation:

\[ \frac{d\phi}{dz} = \frac{\omega_{ce}}{2c} \left( \frac{\lambda}{\lambda_p} \right)^2 \approx 1 \frac{\text{rad}}{m} \]

\[ \lambda(\text{mm}) \approx \frac{0.2}{\sqrt{n_{14}B(T)}} \]

For \( n=10^{14}/\text{cm}^3 \), \( B=0.01 \text{ T}, \lambda \sim 2\text{mm} \).
Solar-wind-magnetosphere simulation

- Setup: We will consider both 2D-dipole and 3D-dipole.
  - Dipole(2D) surface at \( r_s = 1\text{ cm} \), \( M \)-pause at \( R_{mp} = 10\text{ cm} \).
  - Dipole(3D) surface at \( r_s = 1\text{ cm} \), \( M \)-pause at \( R_{mp} = 8\text{ cm} \).
- Assumed: Mach number \( \sim 3 \), percent into M-sphere \( \eta \sim 1\% \).
- Parameters of wind protons: \( \{ n_{sw}, K \} \), where \( n_{sw} = n_j \times 10^j \), \( K \) in eV.

1. Shock at Magnetopause

<table>
<thead>
<tr>
<th>Dipoles: ( R_s = 1\text{ cm} )</th>
<th>2D dipole, ( R_{mp} = 10\text{ cm} )</th>
<th>3D, 8cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters: ( { n_{sw}, K } )</td>
<td>( 10\text{eV}, n_{16} )</td>
<td>( 100\text{eV}, n_{14} )</td>
</tr>
</tbody>
</table>

### Pressure balance at magnetopause

- \( u_{sw} = \left( \frac{2K}{m_p} \right)^{1/2} \), in km/s
  - \( 44 \) | \( 140 \) | \( 44 \) | \( 44 \)
- \( p_{mp} = n_{sw} K \), in Pa
  - \( 1.6 \times 10^4 \) | \( 1.6 \times 10^3 \) | \( 1.6 \times 10^2 \) | \( 1.6 \times 10^2 \)
- \( B_{mp} = (2\mu_0 p_{mp})^{1/2} \), in T
  - \( 0.2 \) | \( 0.06 \) | \( 0.02 \) | \( 0.2 \)
- \( B_s = B_{mp} \left( \frac{R_{mp}}{R_s} \right)^D \), in T
  - \( 20 \) | \( 6 \) | \( 2 \) | \( 10 \)
2. Wind flow, M-spheric thermal energy and Dynamo EMF

<table>
<thead>
<tr>
<th>Parameters: ( { n_{sw}, K } )</th>
<th>( 10 \text{eV}, n_{16} )</th>
<th>( 100 \text{eV}, n_{14} )</th>
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<th>( 10 \text{ eV}, n_{14} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 2D-/3D)-Dipoles: ( R_s = 1 \text{ cm} )</td>
<td>( D=2, R_{mp} = 10 \text{ cm} )</td>
<td>( D=3, 8 \text{ cm} )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mean-free-path, proton gyro-radius, shock thickness.

| \( \text{mfp} = 0.35 \left( \frac{K (e^2 v)^2}{n_{15}} \right) \), in cm | 3.5 | 35000 | 350 | 350 |
| \( \rho_p \left( \frac{R_{mp}}{2} \right) = \left( \frac{m_p u_{sw}}{e B_s} \right) \left( \frac{R_{mp}}{2 R_s} \right)^D \), in cm | 0.06 | 0.57 | 2.2 | 0.28 |
| \( \text{thickness} = \left( \frac{c}{\omega_p} \right) = \frac{0.7}{\sqrt{n_{15}}} \), in cm | 0.22 | 2.2 | 2.2 | 2.2 |

Power flow and m-sphere heating by laser pulse.

| \( P_{mp} = u_{sw} n_{sw} K \left( \pi R_{mp}^2 \right) \), in W | \( 2.2 \times 10^7 \) | \( 7 \times 10^6 \) | \( 2.2 \times 10^5 \) | \( 1.4 \times 10^5 \) |
| \( \Omega_{mag} = \left( \frac{4}{3} \pi R_{mp}^3 \right) \), in \( \text{cm}^3 \) | \( 4.2 \times 10^3 \) | \( 4.2 \times 10^3 \) | \( 4.2 \times 10^3 \) | \( 2.1 \times 10^3 \) |
| \( N_{mag} = \eta n_{sw} \Omega_{mag} \), in \( \text{cm}^3 \) | \( 4.2 \times 10^{17} \) | \( 4.2 \times 10^{15} \) | \( 4.2 \times 10^{15} \) | \( 2.1 \times 10^{15} \) |
| \( T = \left( \frac{K}{\text{mach}^2} \right) \), in eV | 1.1 | 11.1 | 1.1 | 1.1 |
| \( W_{mag} = N_{mag} T \), in J | \( 7.4 \times 10^{-2} \) | \( 7.4 \times 10^{-3} \) | \( 7.4 \times 10^{-4} \) | \( 3.8 \times 10^{-4} \) |
| Pulse: \( \tau = \left( \frac{W_{mag}}{P_{mp}} \right) \), in ns | 3.4 | 1.1 | 3.4 | 2.7 |

EMF generated in the Dynamo Model.

| \( L_y \approx 10 R_{mp} \), in cm | 100 | 100 | 100 | 80 |
| \( eV_{dyn} = e u_{sw} B_{mp} L_y \), in keV | 8.8 | 8.8 | 8.8 | 0.70 |
Parker's solar wind model

The solar wind is the result of a pressure difference between the solar corona and interstellar space.

From continuity and momentum conservation, the solar wind velocity $u$ is determined from:

$$\left(u^2 - \frac{2kT}{m}\right) \frac{1}{u} \frac{du}{dr} = \frac{4kT}{mr} - \frac{GM_{\text{Sun}}}{r^2}$$

The solar wind is such that the velocity is always increasing with distance from the sun:

$$\frac{du}{dr} > 0$$

The speed is supersonic for:

$$r > r_c \equiv \frac{GM_{\text{Sun}} m}{4kT}$$

At Earth's radius $\left(\frac{r}{r_c} = 37.3\right)$ with a corona temperature: 1E6 K, sound speed is 128.5 km/s wind speed 450 km/s $\left(\frac{u}{\sqrt{2kT / m}} \approx 3.7\right)$. 

![Solar Wind Flow Velocity](Image)