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Outline of Lecture on Laser Plasmas Physics

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Outline of Lecture on Laser Plasmas Physics

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• Introduction for laser plasma physics
  - laser science, fusion & laser plasma accelerator-
• Physics of Fast Ignition:
  1. Relativistic laser plasma interactions
  2. Generation of intense relativistic electron and
     ion beams in dense plasmas
  3. Self generated magnetic fields and electron transport

ICTP, Trieste, Italy, 12, July, 2010
Development of Laser Technology

Ultra high intensity opens new plasma world

Fast ignition laser fusion
Quick plasma heating

CPA

D. Strickland and G. Mourou,
1986, Opt. Commun. 56, 212

G. A. Mourou, C. P. J. Barty, and M. D. Perry,
1998, Phys. Today 51, 22
Relativistic Lasers Plasmas

Morphology of Laser Plasmas

Laser Wake Acc. /Astro-Plasmas

Fusion

NIF

HiPER

Fast ignition/FIREX

Laser electron acceleration

Photon bubble

Ion sheath acceleration


Laser Wakefield Acceleration

Matlis et al. (2009)
Advanced accelerator with laser plasma acceleration

Conventional RF accelerator matured
Stable and high repetition rate
Max. E-field $\max \approx$ a few MeV/m
Limited by Breakdown
Large scale radiation shielding

Laser Accelerator
Compact, local shielding
Point source, ultra short pulse
Low repetition rate, unstable, pre-mature

Experiments by M. Downer (PRL, 2006)

RF cavity

Laser plasma acceleration

1 m

100 µm

Courtesy of W. Mori & L. da Silva
History of Laser Fusion

1960: Laser innovation (Maiman)
1972: Implosion concept (J. Nuckolls)
       GXII, Nova, OMEGA, and so on
       Japan and US: T> 10keV and $10^{13} \sim 10^{14}$ neutrons
High-density demo
       US      100-200 times liquid density
       Japan   600 times liquid density
1990~: NIF, LMJ construction
       Fast ignition was proposed.
2000~: Ignition demonstration
       Central ignition
       Fast ignition

NIF project, LMJ project, SNL-Z project
FIREX, OMEGA-EP, HiPER

Thermonuclear ignition in laboratory will happen in 2011.
Laser Fusion Plasma Conditions

• Burning fraction \( \phi = (n_0 <\sigma v > t/2) / (1 + n_0 <\sigma v > t/2) \)
  for fusion reaction time \( t \sim R/4C_s \) and reaction rate: \(<\sigma v>\)

• \( \phi = \rho R/(A + \rho R) \), for DT fuel radius: \( R \), sound speed: \( C_s \), and
  \( A = 10/(T/10 \text{ keV})^2 \text{ g/cm}^2 \) for temperature \( T \)

• “Name of the Game” is compression, because
  DT mass: \( M_f = 4 \pi R^3 \rho/3 = 4.19(\rho R)^3/\rho^2 \sim 33/\rho^2 \text{ [g]} \),
  when \( \rho R = 2\text{ g/cm}^2 \) for high gain.

  \[ M_f \sim 0.8 \text{ kg}, \text{ for } \rho = 0.2 \text{ g/cm}^3, \text{ H- bomb!!} \]
  \[ M_f \sim 4.5 \text{ mg}, \text{ for } \rho = 400 \text{ g/cm}^3, T<1\text{ keV (2 times fermi energy)} \]
  (2000times solid density implosion)

• Hot spark ignition: \( \rho R = 0.4\text{g/cm}^2 \),
  \( \rho = 100 \text{ g/cm}^3 \), \( T>5\text{keV}, \text{ mass } 0.6\text{mg} \)
Two ways of Ignition in Laser Fusion

Ultra intense short pulse laser
Peta watt laser
M.Tabak, 1994 POP

The same thickness yields the same Q.

Central ignition
Short pulse laser
Self ignition

Fast ignition


Neutron Yield vs Heating Laser Power (PW)
Relativistic laser plasma physics in Fast ignition

Critical plasma physics in Fast Ignition

Ultra intense laser - plasma interactions;  laser propagation, generations of high energy electron and ions, and transport

<table>
<thead>
<tr>
<th>Laser intensity;  $I_L = 10^{16} \text{ W/ } \pi r_h^2 \sim 2 \times 10^{20} \text{ W/cm}^2$</th>
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| Electron energy;  $\varepsilon_r = (\gamma - 1)mc^2$ ,  
  $\gamma = [1 + (eA/mc)^2]^{1/2} = [1 + I_L/(2.4 \times 10^{18} \text{ W/cm}^2)]^{1/2}$  
  So, $\varepsilon_r \sim 3\sim5$ MeV near the cut off. |

Super dense plasma is heated by relativistic electron beam and/or ion beam.

Beam current $\sim 1 \text{ GA}$
Experimental Results and Issues

X-ray pinhole camera observing from the cone side (time integrated)

Laser pre-pulse of ~100mJ with 3ns duration produces pre-plasmas

- High electron slope $T_h$
- Large spot size of electron beam

500 µm (cartoons overlaid)
Requirements for fast heating

Assume hot spark area density: $\rho r_h: 0.6 \text{ g/cm}^2$

[Electron heat deposition range]

Imploded plasma density: 1000 times solid density

$\rho_h \sim 200 \text{ g/cm}^3$

Hot spark radius: $r_h \sim 30 \mu\text{m}$

$2 \rho r_h \sim 1.2 \text{ g/cm}^2 \rightarrow \text{range} \rightarrow \varepsilon_h < 3 \text{MeV}$, i.e. not too high energy

• Total energy of DT hot spark: $3N_hT_h \sim 5 \text{kJ} \rightarrow 10 \text{kJ}$
  • where $N_h \sim 2 \times 10^{18}$, $T_h \sim 10 \text{keV}$
  • Heating efficiency of 10% then: total laser energy: 100 kJ

[Electron beam geometry]

Heating e-beam diameter: $60 \mu\text{m}$

Distance from heat deposition point to hot spark: $100 \mu\text{m}$

Beam divergence full angle: $0.6 \text{ radian} \sim 30^\circ$
Bremsstrahlung diagnostic* confirms low hot electron temperature

- Fast electrons produce bremsstrahlung in target
- Detected with image plates interleaved with filters
- Detector response modeled with $T_h$ and $n_e$ as variables

Wilks scaling

$$T_{\text{hot}} (\text{MeV}) = 0.5(1+I_L/(2.3\times10^{18}\text{W/cm}^2))^{1/2}-1$$

Single temperature fit shows hot electron temperature follows Beg’s scaling†: $T(\text{MeV}) = 0.215(I_{18})^{1/3}$

*C. Chen et al., HTPD conference 2008
Model predicts intense laser pulse moderates electron energy

- Simulations show high intensity beams compress the laser plasma interface
- So electrons escape EM field before attaining ponderomotive energy
- Energy reduction: \( \propto \frac{\text{skin\_depth}}{\text{acceleration\_length}} \)

\[ \Rightarrow \text{Good coupling to compressed target} \]

After R. Stephens, 2008 US-Japan

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\( ^{\dagger} \) B. Chrisman et al., PoP 15, 056309 (2008)

\( ^{\dagger\dagger} \) M. Haines et al., submitted to PRL (2008)

\( ^{\ddagger} \) P. Mulser arXiv 0805.1815v1 13May 2008
Hot electron generation

Collisionless absorption mechanisms:

1) Stimulated Raman Scattering (forward Raman: wake filed), and Two Plasmon decay:
   
   \[
   \text{em wave} \rightarrow \text{epw} + \text{emw} \rightarrow \text{hot electron}
   \]
   
   [Long scale under density plasma, fast process]

2) Parametric decay instability:

   \[
   \text{em wave} \rightarrow \text{epw} + i\omega \rightarrow \text{hot electron}
   \]

   [Long scale critical density plasma, slow process, but if \( > 10^{24} \text{W/cm}^2 \), fast ?]

3) Resonance absorption: sharp density gradient.

   \[
   \text{em wave} \rightarrow \text{epw} \rightarrow \text{hot electron}
   \]

   [Finite scale length plasma, non relativistic]

4) Brunel absorption/JXB absorption (Brunel, 1987, PRL), Vacuum heating (stochastic heating) (Gibon 1992), so on

   particle oscillation \(<\) laser oscillation (\( \omega_0 \) and/or \( 2\omega_0 \) fields) are de-phase.

   \[
   \text{emw} \rightarrow \text{hot electron}
   \]

   [Relativistic, short scale length \( L<\lambda \)] (P. Mulser etal, PRL, 2008)
Collective laser absorption of short pulse laser

Revisit the resonance absorption for P-polarized relativistic laser light at an oblique incidence.


Realtivistic electron and X-ray higher harmonics
HEDS – $T^3$: Hot electron generation

Steep, highly overdense plasma.
Absorption up to 80%!

New mechanism?

8 fs, $5 \times 10^{16}$ W cm$^{-2}$
$10^{-5}$ picosecond contrast

After R. Kumar, TIFER: Cherchez et al. PRL, 100, 245001 (2008)
Hard X-Ray Yield and Second Harmonic signals vs. Plasma scale length (time delay of main pulse)

Observe dip in second harmonic and peak in X-ray Yield at ~ 24 ps

X-ray yield is enhanced by two orders of magnitude

Second Harmonic dips to half its maximum value
Plasma waves couple light to itself

Higher harmonic generation (SHG) via the *plasma density oscillation*…..

\[ \omega_{\text{light}} + \omega_{\text{pl}} = 2 \omega_{\text{light}}, \ 3 \omega_{\text{light}} \]

(\(\omega_{\text{pl}} = \omega_{\text{light}}\) or \(2\omega_{\text{light}}\) at critical layer)

The *stronger* the plasma wave, the *stronger* the HHG

*HHG - essentially at the relativistic critical layer*
The mechanism of collisionless absorption

Plasma wave breaking accelerates (heating) hot electrons, since phase relation of field oscillation and electron oscillation is no more $\pi/2$

When all electrons satisfy the above condition, it is "wave breaking".
Laser-Pulse-Induced Second-Harmonic and Hard X-Ray Emission: Role of Plasma-Wave Breaking

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(Received 29 August 2004; published 8 July 2005)
Collision-less absorption in highly relativistic regime is relevant to Fast Ignition

- There are very many experiments and simulations, but not well understood yet!
- In this regime, density profile steepening is essential → polarization dependent
- Steep plasma-vacuum surface oscillates by $2\omega_0$ oscillating ponderomotive force.→ Oscillating piston
- The oscillating mirror producing many higher harmonics→ many observation (Gibon etal, Gibbon, 1992)