Laser Ion Acceleration

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Advent of collective acceleration (1956)

COHERENT PRINCIPLE OF ACCELERATION OF CHARGED PARTICLES

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This paper will include a very brief description of a new principle regarding the acceleration of charged particles.

In all existing accelerators of charged particles, the constant and varying electric field accelerating them is created by a powerful external source, and hence the strength of the field is independent, in the first approximation, of the number of particles which are being accelerated.

In resonance accelerators, the electromagnetic field has to be synchronized with the movement of the particles (this is of particular importance in linear accelerators). Finally, none of the existing methods permits the acceleration of neutral bunches of particles.

A new principle of particle acceleration is set forth below. Its distinctive feature lies in the fact that the particle-accelerating electric field is produced by the interaction of a geometrically small group of accelerated particles with another group of charges, plasma or an electromagnetic wave. This method has a number of important features. It appears, in the first place, that the magnitude of the accelerating field produced by this interaction and acting on each particle depends on the number...

Theoretical studies of various aspects of the coherent acceleration method have been made by M. S. Raburkovskii, A. A. Kolomenetski, B. M. Bulotovski, L. V. Kovrizhnikh and I. V. Yankov, as well as by A. I. Akhiezer, T. Fainberg and their collaborators. The calculations made by these theoretical workers shed light on a number of complicated problems connected with the development of the different variants of this new acceleration principle, and it therefore seems appropriate to describe the new method despite the fact that a great many problems involved still await solution.

1. Acceleration of charged bunches by means of the medium

It was pointed out in a paper by Tamm that the loss of energy by particles due to Cerenkov radiation could be reversed, i.e. the medium travelling at a great velocity past charged particles should be able to convey energy to the latter. Up to now, however, no attention has been paid to the possibility of developing an acceleration process of this kind by using a high density electron beam (plasma) as the moving medium. Of course, if a single charge e is
Prehistoric activities (1973-75,...84)

Collective acceleration suggested:
Veksler (1956)
(ion energy)~ (M/m)(electron energy)

Many experimental attempts (~’70s):
led to no such amplification
(ion energy)~ (several)x(electron)

Mako-Tajima analysis (1978;1984)
sudden acceleration, ions untrapped,
electrons return, while some run away
→ #1 gradual acceleration necessary

→ #2 electron acceleration possible
with trapping (with Tajima-Dawson field), more tolerant for sudden process
Path once trodden

Collective acceleration of ions by electron beam

F. Mako / T. Tajima

Ions left out, while electrons shoot backward

→ laser electron acceleration (1979)

→ laser ion acceleration of limited ion mass (2009)
Example of solid target (ca. 1999)

A few hundreds MeV protons and GeV Al are generated by petawatt laser with the Al foil coated with hydrogen.

<table>
<thead>
<tr>
<th>Laser power</th>
<th>( a_0 = 10 )</th>
<th>( a_0 = 30 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy conversion</td>
<td>21%</td>
<td>31%</td>
</tr>
<tr>
<td>ion; electron;</td>
<td>6%</td>
<td>14%</td>
</tr>
<tr>
<td>peak (average) energy</td>
<td>15%</td>
<td>17%</td>
</tr>
<tr>
<td>( H^+; ) (-)</td>
<td>-</td>
<td>0.4 GeV</td>
</tr>
<tr>
<td>( Al^{10+}; ) (-)</td>
<td>-</td>
<td>(115 MeV)</td>
</tr>
<tr>
<td>electron;</td>
<td>1.5 MeV</td>
<td>2 GeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(430 MeV)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20 MeV</td>
</tr>
</tbody>
</table>

Tajima: LLNL (1999)
Toward Less Sudden Acceleration (ca. 1999)

Energy conversion and acceleration of particles is strongly dependent on the state of the thin foil surface.

<table>
<thead>
<tr>
<th>$a_0$ = 30</th>
<th>target type</th>
<th>$\text{Al}^{10+}(56\text{nm})$ solid</th>
<th>$\text{Al}^{10+}(2240\text{nm})$ gas</th>
<th>$\text{Al}^{10+}(112\text{nm})$ cluster</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_{0x} = 69$</td>
<td>energy conversion</td>
<td>24%</td>
<td>50%</td>
<td>31%</td>
</tr>
<tr>
<td>electron density</td>
<td>ion;</td>
<td>8%</td>
<td>4%</td>
<td>14%</td>
</tr>
<tr>
<td>Al solid ; $6 \times 10^{22}\text{cm}^{-3}$ (416$n_c$)</td>
<td>electron;</td>
<td>16%</td>
<td>46%</td>
<td>17%</td>
</tr>
<tr>
<td>gas ; $1.5 \times 10^{22}\text{cm}^{-3}$ (10.4$n_c$)</td>
<td>peak (average) energy</td>
<td>0.4GeV (95MeV)</td>
<td>0.2GeV (58MeV)</td>
<td>0.8GeV (115MeV)</td>
</tr>
<tr>
<td>culster; $3 \times 10^{22}\text{cm}^{-3}$ (208$n_c$)</td>
<td>$\text{H}^+$;</td>
<td>2GeV (500MeV)</td>
<td>1GeV (130MeV)</td>
<td>2GeV (500MeV)</td>
</tr>
<tr>
<td>$\text{H}^+$ solid ; $4.6 \times 10^{22}\text{cm}^{-3}$ (31.8$n_c$)</td>
<td>$\text{Al}^{10+}$;</td>
<td>15 MeV</td>
<td>25 MeV</td>
<td></td>
</tr>
<tr>
<td>$n_c$: cut off density ; $1.4 \times 10^{21}\text{cm}^{-3}$</td>
<td>electron;</td>
<td>15 MeV</td>
<td>25 MeV</td>
<td>20 MeV</td>
</tr>
</tbody>
</table>

Recent breakthroughs
From incoherent (or heating) of electrons
to Coherent drive of them

CAIL (Coherent Acceleration of Ions by Laser)

TNSA (Target Normal Sheath Acceleration)

Taiima et al., 2009
Comparison of the phase space dynamics: toward more Adiabatic Acceleration

TNSA

(metallic boundary)

Ion trapping width:

\[ v_{tr,ion} \sim c \sqrt{a_0(m/M)} \]

Optimal Thickness Scaling

Normalized thickness $\sigma \sim a_0$

Maximal energy of protons (MeV)

LLNL (redef. $I_{\text{peak}}$)

CUOS (redef. $I_{\text{peak}}$)

$\sigma$

$\Delta L_{55} (\text{MeV}) \ a = eE/m_e \omega c$

(T. Esirkepov et al. 2006)
Recent Experimental Breakthroughs

Leadership by Dieter Habs

LMU, MPQ, Max-Born Institute, LANL, RAL, PMRC

Nanometer target: DLC
Sharp contrast laser double plasma mirrors

More coherent electron dynamics in $\sigma \sim a_0$
Recent experiments in CAIL Regime

Ultrathin film: $\sigma = a_0$, where $\sigma = d n / \lambda n_c \ (\xi = \sigma / a_0)$

High laser contrast: not to destroy ultrathin target

MAP + MBI

(Steinke et al., 2009; Henig et al., 2009)
Conversion efficiency of laser to ion energy

Two orders of magnitude higher efficiency in CAIL

Conversion efficiency of laser energy to ion energy comparing results from thick targets and the TNSA mechanism to measurements with ultra-thin targets in the regime of CAIL (red diamonds and line).

Fig. 11. Maximum cutoff energies of ions given in MeV/u as a function of laser pulse duration. The energy gain by CAIL experiments is embedded with red dots in the predicted curves of TNSA. Note that in shorter pulses, energies by CAIL are more than an order of magnitude higher than TNSA.
Laser-Thin Foil Interaction

X. Yan et al., 2009
Toward monoenergy spectrum

- Circularly polarized laser irradiation
  more adiabatic acceleration → more monoenergy

Carbon spectrum for three consecutive shots using circular polarized light at $5 \times 10^{19}$ W/cm$^2$ and a DLC foil target thickness of 5.9 nm
Coherent electron dynamics

Electron dynamics from thin foil: 3 clear patterns

Expanded target

Electron divergence angle

Electron divergence angle

Laser

laser transmitted
Characterization of coherent dynamics of electrons

Coherence parameter: $\alpha$

Dimensionless thickness parameter normalized to $a_0$
Energy Gain in Laser Ion acceleration: CAIL (Coherent Acceleration of Ions by Laser) regime

- When electron dynamics by laser drive is sufficiently coherent, with coherence parameter $\alpha$ of electrons, the ion energy in terms of electron energy is:

$$\varepsilon_{\text{max},i} = (2\alpha + 1) Q \varepsilon_0$$

Ion energy

(the more coherent the electron motion, the higher the ion energy)

$$\varepsilon_0 = mc^2 \left( \sqrt{1 + a_0^2} - 1 \right)$$

Electron energy = ponderomotive energy

$$\varepsilon_{\text{max},i} = (2\alpha + 1) Q \varepsilon_0(t_1) \left( (1 + \omega_L t_1)^{1/2\alpha+1} - 1 \right)$$

$\alpha$ maximizes at $\xi = 1$
CAIL Theory Prediction

CAIL (Coherent Acceleration of Ions by Laser) theory has definitive prediction of max energies

Tajima et al. (2009)

For the case of LANL experiment prediction (relative long pulse with nm targets)
Gradual dynamics of the ponderomotive bucket

Ponderomotive Force

Electrostatic Trapping of ions

Yan et al. (2008)
Synchrotron oscillations in the bucket

Laser drives accelerating bucket, more adiabatic trapping structure

(a,b,c) Evolution of phase space distribution for protons, the 1st, 2nd and 3rd oscillation period are 8, 8 and 10 T respectively.

(d) Energy spectrum of protons.

Yan et al. (2008)

Monoenergy spectrum

(a,b,c) Evolution of phase space distribution for protons, the 1st, 2nd and 3rd oscillation period are 8, 8 and 10 T respectively.
(d) Energy spectrum of protons.
Circularly polarized laser driven

**CP laser** drives ions out of ultrathin (nm) foil **adiabatically**

Monoenergy peak emerges

![Graph showing ion population and momentum](image)

**Ion population**

![Graph showing ion momentum](image)

**Ion momentum**

\[ V_{i, tr} = c\sqrt{(a_0 m/M)} \]

(X. Yan et al: 2009)

Bucket trapping ions

Ponderomotive force drives electrons,
Electrostatic force nearly cancels
Slowly accelerating bucket formed
Phase space of carbon ions in 2D

Trapped in the bucket

Bucket breaks down by runaway e-

Longitudinal phase space of carbon ions in 2D simulations. (a) Stable bucket structure of synchrotron oscillation; (b) Collapse of the accelerating bucket when the plasma becomes hot (due to the bending of the target)
Toward more adiabatic acceleration

The more adiabatic, the longer accelerated, the higher energy

Energy by CP tends to increase as $\sim a_0^2$
Monoenergetic electron bunch

Ultrathin (2nm) foil irradiation drives monoenergetic electrons

CP

MAP + MBI

(Kiefer et al, 2009)
Adiabatic (Gradual) Acceleration
from #1 lesson of Mako-Tajima problem

Accelerating structure

Inefficient if suddenly accelerated

Efficient when gradually accelerated

Lesson #1: gradual acceleration → Relevant for ions

(protons)

(cf. human trapping width: $v_{tr, human} \sim 1 \text{ m/s} \ll c_s$)
Adiabatic acceleration (2)

Thick metal target

Most experimental configurations of proton acceleration (2000-2009)

Innovation (“Adiabatic Acceleration”) (2009-)

= Method to make the electrons within ion trapping width

However, in ELI automatic

\[ v_{tr, ion} \sim c \sqrt{a_0 (m/M)} \sim c \]

(ultrarelativistic \( a_0 \sim M/m \))
An optimization toward adiabatic acceleration

Laser Pulse Conditions

\[ a_0 = \frac{\int n dl}{n_{cr} \lambda} = \frac{n l_{pl}}{n_{cr} \lambda} \]

Adiabatic laser-plasma interaction

\[ v_g(x) = c \sqrt{\omega^2 - \omega_{pe}^2(x)} \]

\[ n(x) = n_0 \exp \left[ -\pi \frac{m_e}{m_i} \frac{x}{\lambda} \left( R \frac{1}{\lambda} \right)^{1/2} \right] \]

(Tajima, Bulanov, Esirkepov, 2007)
Relativity Helps Acceleration (for Ions, too!)

In relativistic regime, photon x electrons and even protons couple stronger.

(Tajima, 1999 @LLNL; Esirkepov et al., PRL, 2004)

Strong fields: rectifies laser to longitudinal fields.
Monoenergy beam from double layer target

Double layer target (metal layer with smaller hydrogen (or light Z metarial))

Esirkepov et al. (2002)
Laser Piston (radiation pressure) Acceleration

Radiation dominant regime

Esirkepov et al. (2004)
Nanostructured target

(Habs, 2009)
Cluster Target Irradiation

Y. Fukuda et al. (2009)
Order of magnitude energy gain

With a modest (140mJ) laser, to go beyond 15MeV/nucleon by cluster target

FIG. 3 (color online). The ion energy spectrum obtained by the TOF method. The inset shows TOF spectrum obtained in one laser shot which registers 1.5 MeV/u ion signal. A saturated signal around the flight time $t = 5$ is caused by hard x rays emitted from the laser-cluster interaction region.

Fukuda et al. (PRL 2009)
Fig. 15

(a) Probe beam, Off-axis parabola, Cluster jet, FSSR, Laser beam

(b) Laser beam, Z = 8.5 mm, Z = 5.5 mm, Z = 3.5 mm, Z = 1.5 mm, Z = 0.7 mm

(c) X = 4.0 mm, 3.8 mm, 2.1 mm, 1.8 mm, 1.3 mm

Faenov et al., 2009
Cluster ions strongly energized

Faenov et al., 2009

Fig. 11
Laser-carbon cluster interaction

$a_0=4$

Ion energy ~ pulse length (laser energy)

Kishimoto (2009)
Maximum energy vs. laser intensity

Consistent to the Theory by Yan et al. (2009), though it is based on thin film case

\[ \varepsilon_{\text{max}} = (2\alpha + 1)Q\sqrt{1 + a_0^2} \]
**Ion Energy spectrum r=125 μm**

Ion Energy Distribution

- **fEilog_a4_l820-Nxy128-p1m_r125nm**
- **Energy [keV]**

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- **t=100 [fsec]**
- **t=300 [fsec]**

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- **fEilog_a4_l820-Nxy128-p1m**
- **Energy [keV]**

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- **t=500 [fsec]**
- **t=700 [fsec]**

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**Energy [keV]**

- **114.9MeV**
- **150.98MeV**
- **171.71MeV**
- **178.84MeV**
Cluster target scaling: ion energy ~ 1/(cluster radius)

Kishimoto, Tajima (2009)
Laser particle therapy (image-guided diagnosis→irradiation→dose verification) targeting at smaller pre-metastasis tumors with more accuracy
X-ray IMRT                  Proton IMRT

prostate cancer    rectum

January 20, 2010: “Relativistic Engineering”
February: “High Field Science”
March: “Photonuclear Physics”
April: “Medical Applications”

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Merci Beaucoup et a la Prochaine Fois!