1st Experimental Evidence for
PASER: Particle Acceleration by
Stimulated Emission of Radiation

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Outline

- Motivation
- Essence of PASER
  - Macroscopic perspective
  - Microscopic perspective
  - Theoretical model
- Proof-of-principle experiment
  - Experimental setup
  - Experimental evidence
- Future directions
  - Boosting the gradient
  - PASER staging
- Concluding remarks
Motivation – Energy Sources

**Macroscopic Structures**

- Cavity (Circular Acc.)
- Coupled cavities (linear Acc.)
- Electron bunch (Wake-field Acc.)
- Laser pulse (Laser-plasma schemes)

**Microscopic Structures**

- Atom/molecule (Ar⁺, CO₂)
- Solid-State (Nd:YaG)
Motivation – Inverse Radiation Processes

ICA

Axicon lens
Laser pulse
e-bunch

PASER = Inverse-laser acceleration scheme

IFEL

Laser pulse
\[ \lambda_w \]
e-bunch

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Essence of PASER – Macr0

1. Passive Dielectric

\[ \text{Re}(\varepsilon_r) < \left( \frac{c}{V} \right)^2 \]
\[ \text{Im}(\varepsilon_r) = 0 \]
Decelerating Force

2. Resistive Material

\[ \text{Re}(\varepsilon_r) = 1 \]
\[ \text{Im}(\varepsilon_r) = -\frac{\sigma}{\varepsilon_0 \omega} < 0 \]
Decelerating Force

3. Active Medium

\[ \text{Re}(\varepsilon_r) >> \text{Im}(\varepsilon_r) \]
\[ \text{Im}(\varepsilon_r) > 0 \]
Accelerating Force

Schächter, PRE 53, p. 6427, 1996
Essence of PASER – Macro

1. Passive Dielectric
   - Cerenkov Radiation
   - Primary Field
   - Reaction Field
   - Broadband Field
   - Broadband Material

2. Resistive Material
   - Eddy currents
   - Primary Field
   - Reaction Field
   - Broadband Field
   - Broadband Material

3. Active Medium
   - Induced Polarization
   - Primary Field
   - Reaction Field
   - Narrowband Field
   - Narrowband Material

Train of bunches !!!
Essence of PASER – Micro

Banna, Berezovsky and Schächter, PRL 97, 134801, 2006
Essence of PASER – Theoretical Model

Assumptions

- Linear medium
- Medium has a single resonance
- No Cerenkov radiation
- Constant longitudinal velocity
- No transverse motion
- Uniform micro-bunches

Banna, Berezovsky and Schächter, PRE 74, 046501, 2006
Relative Change in Kinetic Energy

\[ \frac{\Delta E_k}{E_k} \approx \frac{4N_{el}}{\gamma - 1} \left[ d \left( \pi r_e^2 \right) \frac{W_{act}}{\hbar \omega_0} \right] \sin^2 \left( \pi \frac{\Delta}{\lambda_0} \right) \sin^2 \left( \frac{\pi M}{2\gamma^2} \right) F_\perp \left( 2\pi \frac{R_b}{\lambda_0} \right) \]

\[ r_e \equiv \frac{e^2}{4\pi \varepsilon_0 mc^2} \]

\[ F_\perp (u) \equiv \frac{2}{(u)^2} \left( 1 - 2I_1(u)K_1(u) \right) \]

Banna, Berezovsky and Schächter, PRE 74, 046501, 2006
Essence of PASER – Theoretical Model

Frequency Selection

\[ \Delta = 0.1\lambda_0, \quad E_k = 45 \text{ MeV} \]

\[ F_{\parallel}(\Omega, \beta, M, \Delta) = \text{sinc}^2\left(\frac{\Omega}{2\beta \Delta}\right) \text{sinc}^2\left(\frac{\Omega}{2\beta M}\right) \]

\[ \frac{1}{T_2} = 5 \times 10^8 \text{ sec}^{-1} \]

\[ M > 30 \]

@ CO\textsubscript{2} : \( \lambda_0 = 10.2 \ \mu\text{m} \); \( \lambda_1 = 9.2 \ \mu\text{m} \)

Banna, Berezovsky and Schächter, PRE 74, 046501, 2006

CO\textsubscript{2} relaxation time
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Experimental Setup

CO₂ LASER
0.5GW - 0.2 nsec

Wiggler

CO₂ active medium

Diagnostics

Accelerator
45 MeV - 5 psec

Macro bunch

Micro bunches

PASER cell

Accelerated micro bunches

Banna, Berezovsky and Schächter, PRL 97, 134801, 2006
Banna, Berezovsky and Schächter, PRE 74, 046501, 2006
PASER System

Glow-discharge

Gas mixture [CO₂ : N₂ : He]-[2:2:3] @ 0.25 atm

Diamond window of 1mm diameter and 2 micron thickness

Trigger pulse: 1.75 kV
**Experiment Parameters**

### e-beam Parameters
- Energy: 45 MeV
- Intrinsic energy spread: 0.03%
- Normalized emittance: 1.5 mm-mrad
- Charge – macro-bunch: 100 pC
- Pulse duration: 5 psec
- Focus size (rms): 100 microns

### Laser Pulse Parameters
- Wavelength: 10.2 microns
- Duration (FWHM): 200 psec
- Peak power: 0.5-1 GW

### PASER Cell Parameters
- Gas mixture pressure: 0.25 atm
- Gap between electrodes: 2.5 cm
- Electrodes size: 40 cm x 12 cm
- Window thickness: 2 microns
- Window diameter: 1 mm
- Discharge voltage: 25-30 kV
- Cell transmission: 50%-60%

Banna, Berezovsky and Schächter, PRL 97, 134801, 2006
Banna, Berezovsky and Schächter, PRE 74, 046501, 2006
PASER System Characteristics

Discharge Electrical Characteristics

Energy Stored in the Excited Gas

- CO$_2$:N$_2$:He = 2:2:3
- P = 0.25 atm
- P = 0.4 atm

Discharge Electrical Characteristics

- Anode voltage
- Energy
- Anode current
- Power

Time [nsec] 500 nsec

Arbitrary Units

Energy Density [J/cm$^3$ atm]

Applied Voltage [kV]

20 22 24 26 28 30

0.0 0.1 0.2 0.3 0.4
Experimental Evidence

~1.5% peak-to-peak energy modulation

Discharge off

~685keV

Direction of increasing energy

Discharge on

~845keV

2,000,000 collisions
Experimental Observation of Direct Particle Acceleration by Stimulated Emission of Radiation

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(Received 4 June 2006; published 28 September 2006)

We report the first experimental evidence for direct particle acceleration by stimulated emission of radiation. In the framework of this proof-of-principle experiment, a 45 MeV electron microbunch was modulated by a high-power CO2 laser and then injected into an excited CO2 gas mixture. The emerging microbunches experienced a 0.15% relative change in the kinetic energy, in a less than 40 cm long interaction region. According to our experimental results, a fraction of these electrons have gained more than 200 keV each, implying that such an electron has undergone an order of magnitude of $2 \times 10^6$ collisions of the second kind.

Particle Acceleration by Stimulated Emission of Radiation—PASER for Short

Particle Acceleration by Stimulated Emission of Radiation (PASER for short), a sort of particle analog of the laser process, has been demonstrated, for the first time, by a team of physicists from the Technion-Israel Institute of Technology using the accelerator facilities at the Brookhaven National Lab.
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Boosting the Gradient

### Optimizing the Energy Density

- **Apply beam focusing in the cell**
- **Improve excitation efficiency**
- **Increase the gas pressure**

### Optimizing # of Micro-bunches

- **Increase the amount of charge**
- **Improve bunching efficiency**
The phase of the wake is determined regardless the length of the drift region.

The wake-field phase corresponds to a decelerating force.

The wake-field phase corresponds to an accelerating force.
Staging of PASER Cells

- No external intervention for phase matching is required in PASER
- The phase of the accelerating field is established internally
- Staging PASER cells is natural
Solid-State PASER

Solid-State (Nd:YAG) PASER \( \lambda_0 = 1.06 \mu m \)

Advantages:
- 10 times more energetic photons
- Higher density of population inversion
- Electrons travel through vacuum tunnel
  - Eliminate windows and gas scattering (emittance)

Challenges:
- Micro-bunches at 1 micron wavelength
- Efficient interaction requires GeV electrons
Road Map

Proof-of-principle

0.5 [MV/m]

Learning curve

40-50 [MV/m]

Ultimate goal

1-2 [GV/m]
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Concluding Remarks

- PASER is a novel technique for accelerating relativistic particles
  - Requires only a train of electron micro-bunches with a spacing corresponding to the transition wavelength of the active medium.
  - No need for phase matching between the accelerated electrons and the active medium. Therefore, staging of PASER cells is natural.

- Proof-of-principle demonstration was achieved at BNL-ATF
  - Energy gain of 200 keV in the kinetic energy of a mono-energetic \(~45\) MeV macro-bunch was observed, corresponding to \(~2,000,000\) collisions of the second kind.
  - Experimental results are in very good agreement with an analytic model for the interaction of a train of micro-bunches with an active medium.

- Near future proposed program aims to
  - Boost the gradient up to 100MV/m based on gaseous medium.
  - Demonstrate staging of PASER cells.