Advanced Acceleration Concepts

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- R.H. Siemann (SLAC)
- W. D. Kimura (STI)
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- D. Sutter (DoE)
Outline

• Some brief guidelines

• Novel Acceleration Schemes: Concepts & Results

• Concluding Remarks
Guidelines

What will be presented next as Advanced Acceleration Concepts:

1. Focuses on gradients \( \geq 1 \text{ [GV/m]} \)
2. As reference: \( \text{SLC} \sim 20 \text{ [MV/m]} \)
   \( \text{NLC} \sim 50 \text{ [MV/m]} \)
3. Discuss \( e^- \) & \( e^+ \)
4. Optical regime
Inverse Radiation Processes

- Inverse Cerenkov (slow wave)
- Inverse FEL… (fast-wave)
- Inverse Transition Radiation (LEAP)
- Inverse Laser (Amplified Wake)

Space-Charge Wakes

- Laser Wake-Field
- Plasma Wake-Field
- Plasma Beat-Wave
- Resonant Absorption
Inverse Cerenkov: An Optical Acceleration Structure?!

- At optical wavelengths (1 µm) dielectrics have higher $E_{th}$.
  $E_{\text{max}} \approx 2 \text{GV/m} @ \leq 0.5\text{psec}$

- Frequency dependence of $\varepsilon$ leads to reduced wake effect since the # of modes drops: $10^5 \Rightarrow 10$

- Technion & SLAC

- Field Confinement
- Highest Symmetry
- Reduce Max. Field

No metals!!

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Inverse Radiation Processes

Figures of Merit -- Emittance & Planar Structures

• In an azimuthally symmetric structure, the ratio of the transverse force to the longitudinal force is virtually negligible since

\[
\left| \frac{F_\perp}{F_z} \right| \approx \frac{1}{4\gamma^2} \left( \frac{\omega}{c} R_b \right)
\]

• In a non-symmetric structure of a typical transverse dimension \(a\),

\[
\left| \frac{F_\perp}{F_z} \right| \approx \left( \frac{\omega}{c} a \right)^{-1}
\]
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Inverse Radiation Processes

Inverse Free Electron Laser (R. Palmer 1972)

- Electrons oscillate in a transverse magnetic field.
- Ponderomotive force may accelerate electrons.
- Acceleration: \( E_{\text{ACC}} \propto E_L B_w \lambda_w \gamma^{-1} \)
- Deceleration: \( E_{\text{DEC}} \propto B_w^2 \gamma \)
- Threshold: \( E_{\text{ACC}} > E_{\text{DEC}} \Rightarrow I > I_{th} \propto B_w^2 \lambda_w^{-2} \gamma^6 \)
- Example:
  \[
  B_w=1\,\text{T}, \lambda_w=2\,\text{cm} @ 1\,\text{TeV} \Rightarrow I_{th}=10^{25} \,\text{W/cm}^2 !
  \]
  \[
  B_w=1\,\text{T}, \lambda_w=2\,\text{cm} @ 1\,\text{GeV} \Rightarrow I_{th}=10^7 \,\text{W/cm}^2 .
  \]
Inverse Radiation Processes

Inverse Free Electron Laser

Kimura, PRL, 86, 4041 (2001)

- STELLA Experiment:
  BNL-ATF, STI & UCLA
- Goal: Staging optical modules

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Inverse Radiation Processes

Inverse Transition Radiation

LEAP: Laser driven Electron Accelerator Program (Stanford U.)

Huang & Byer APL 68, 753 (1996)

- Electron traversing a discontinuity generates radiation.
- Illuminating a geometric discontinuity may cause acceleration of an electron by proper choice of phase.

Lawson-Woodward: Interaction in finite-length region
The E163 Experiment (Stanford/SLAC/Tsing Hua)

Objective: To demonstrate laser driven electron acceleration in a dielectric structure in vacuum.

The acceleration cell: Two Gaussian beams of 800 nm laser light cross at 1.4° to form the acceleration field. Electrons are injected between the prisms into the crossed laser field.

Photonic Band Gap Fiber Accelerator (SLAC/Technion): Higher-order mode-free accelerator structure with good coupling impedance that can be fabricated by standard fiber bundle assembly methods.

Cerenkov Amplification Accelerator (Technion/SLAC): Cerenkov wake of triggering bunch is amplified in laser media, accelerating trailing bunch.

Lithographic Accelerator Structures (SLAC/Stanford): Lithographic, planar structures designed to use one laser pulse to accelerate many parallel electron bunches.

Ring Resonated Laser Accelerator (SLAC/Stanford): Laser accelerator embedded in ring resonator to use one laser pulse to accelerate many successive electron bunches.

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Inverse Radiation Processes

Inverse Laser: Wake Amplification Accelerator

Wake generation:
- Passive Medium
- Electron bunch
- EM wake

Pulse amplification:
- Input pulse
- Amplified pulse
- Active Medium

Wake amplification:
- Saturation
- Trigger bunch
- Active Medium
- Accelerated bunch
- Amplified Wake

Schächter & Siemann, PRL, 87, 134802 (2001)

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Inverse Radiation Processes

Inverse Laser: Wake Amplification Accelerator

Conceptual experiment proposed to ORION @ SLAC

Nd:YAG System

Flash-Lamp

Nd:YAG:
- 6mm diameter
- 10 cm length
- Nd – 10^{20} cm^{-3}
- 200 Joules

UNIFORM Beam:
- 10^9 electrons
- 30 GeV
- 5 Joules

Schächter & Siemann, PRL, 87, 134802 (2001)
Inverse Laser: Wake Amplification Accelerator

**Conceptual experiment proposed to ATF@BNL:**

- **Electron Beam**
- **CO₂**
- **0.3-0.5GW**
- **300 MW**
- **2m !!**
- **Pre-buncher**
- **IFEL**
- **Driving Laser Pulse**
- **0.1 μF; 20-25kV,**
  **20 Joule, 100nsec**
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Suggested first to use *SPACE-CHARGE WAVES* for the acceleration of electrons. Many variants have been considered:

**Plasma Beat Wave Accelerator**

**Self-Modulated Laser Wake-Field Accelerator**
*Sprangle, PRL, 72, 2887 (1994) -- NRL*

**Laser Wake-Field Accelerator**
*Tajima & Dawson, PRL, 43, 267(1979) -- UCLA*
Space-Charge Wakes

Plasma Beat Wave Accelerator


- Two laser pulses of different wavelength are beating in a plasma whose frequency corresponds to the difference between the two.
- The resulting resonant space-charge wave may accelerate electrons.
- Experiment:
  - 2MeV injected electrons (10 psec)
  - 2GV/m effective gradient along 1cm
- Other experiments:
  - Japan, Univ. of Osaka
  - UK, Imperial College
  - France, Ecole Politechnique
  - Canada, Chalk River Lab.

\[ \omega_1 - \omega_2 \approx \omega_{\text{plasma}} \]
Space-Charge Wakes

Self-Modulated Laser Wake-Field Acceleration

Sprangle, PRL, 72, 2887 (1994) -- NRL

- Intense laser pulse excites Forward Raman Instability that in turn “decays” into Stokes and Anti-Stokes modes that beat with pump wave to generate an intense electric field (SC).
- 1993 LLNL-UCLA
  Coverdale, PRL, 74, 4659(1995)
- 1994 Rutherford Appleton Laboratory
  30TW, 800fs, 5-15x10^{18} cm^{-3}.
  Outcome 94MeV
  Deduced gradient:
  \textit{150 GV/m} !
- Others
  NRL
  U. Michigan
  Ecole Politechnique (\textit{200 GV/m} !!)

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Space-Charge Wakes

Laser Wake Field Acceleration

*Tajima & Dawson, PRL, 43, 267 (1979)*

• Intense and short laser pulse generates a plasma wake that may accelerate electrons.

• 1996 Ecole Politechnique
  *Amiranoff PRL, 81, 995 (1998)*
  3MeV input
  4.6 MeV output
  Deduced gradient: *1.5 GV/m!!*

• Others
  U. Michigan
  LBL
  Japan: JERI, KEK
Space-Charge Wakes

Plasma Wake Field Acceleration

Repelled electrons

Space-Charge Wave

Intense Electron Pulse

Intense Laser Pulse

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Wide range of phenomena observed to date in E-157 and E162:

- Focusing of $e^-$ & $e^+$ beams; stable propagation through an extended plasma
- Electron beam deflection analogous to refraction @ boundary
- X-ray generation due to betatron motion in the blown-out plasma ion column
- Energy loss in the core and energy gain in the tail (>100 MeV/m) over 1.4m

X-ray Generation

 Beam Refraction

$\theta \propto 1/\sin \phi$

$\theta \approx \phi$
Still much to do in E164 (FFTB) and at the future ORION:

- Demonstrate $1/\sigma_z^2$ scaling law and $>\text{GeV/m}$ gradient $\Rightarrow$ E-164 (Spring 2003)
- Plasma source development: higher densities and hollow channels for positron
- Robustness against hose instability …

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Plasmas Have Extraordinary Potential

Investigating the physics and technologies that could allow us to apply the enormous fields generated in beam-plasma interactions to high energy physics via ideas such as:

**A 100 GeV-on-100 GeV e⁻e⁺ Collider Based on Plasma Afterburners**

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ORION Facility at NLCTA

Also FFTB !!

30GeV

1GeV ?

http://www-project.slac.stanford.edu/orion/
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Direct Laser Acceleration

Lasers promise extraordinary accelerating fields, provided efficient coupling structures can be developed.

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Concluding Remarks

• **Plasma** based schemes have promising perspectives with regard to a single module acceleration gradient (>100GV/m) however, emittance and phase control over many modules remain open questions. Other open questions: dark-current, instabilities, asymmetries, high rep. rate operation…. Great perspective as “afterburners” in existing accelerator; injectors… all plasma optical accelerator. **Not remote future!!**

• **Inverse radiation** schemes promise a “moderate” gradient (1GV/m) but preliminary results of staging optical modules seem very promising. Open questions: manufacturing constraints (asymmetry thus emittance), geometric and material tolerances, non-linear (Kerr) effect in dielectrics, ……

• **Wake amplification** in an active medium may prove to be of practical implementation since most of the **infra-structure** has been already developed by the communication and semi-conductors industry for low peak power but high average power: high-efficiency diode-lasers, materials for optical fibers and auxiliary equipment.
Concluding Remarks

- **Recycling (M. Tigner).** All laser based schemes rely on the fact that a relatively small fraction of the *energy stored in the laser cavity* is extracted and used in the *acceleration structure*. Conceptually, it seems possible to take advantage of the high intensity electromagnetic field that develops in the cavity and *incorporate the acceleration structure in the laser cavity*.

- According to estimates, the rep-rate of each macro-bunch is 1GHz and each macro-bunch is modulated at the resonant frequency of the medium (e.g. 1.06µm).

- The amount of energy transferred to the electrons or lost in the circuit is *compensated by the active medium* that amplifies the *narrow band wake* generated by the macro-bunch.
Concluding Remarks

- In the US, all this activity and much more, is part of the DoE’s 
  *Advanced Technology R&D Program*
  
  conducted by Dr. Dave Sutter.

- A list of US Institutions (from west to east):
  
  **SLAC/Stanford U**  **ANL**  **Maryland**
  **UCLA**  **Michigan**  **NRL**
  **LBL/UC Berkeley**  **MIT**  .....  
  **UCSD**  **BNL**
  **USC**  **Yale/Columbia**
Thank you!!

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