Exotic Acceleration Concepts: from vacuum to structures to plasmas

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What Makes a Concept Exotic?

- **Unusual materials:**
  Cliché:
  1. Dielectrics and metals are the only choices for structure-based accelerators
  2. Plasma must have density between $10^{16} - 10^{19}$ cm$^{-3}$

- **Unusual drivers:**
  Cliché:
  1. Beatwave must be an intensity-modulated laser beam tuned to plasma wave resonance

- **Unusual combinations:**
  Cliché:
  1. Lasers + plasmas, microwaves + dielectrics & metals
List of Exotic Concepts

• Far-Field Vacuum and Almost-Vacuum Acceleration:
  1. Inverse Cherenkov Accelerator

• Exotic Structures
  1. Inverse Smith-Purcell and Open-Sided Dielectric Accelerators
  2. Photonic Bandgap (PBG) Accelerators

• Exotic Plasma Concepts
  1. Innovations in beatwave: detuned, auto-resonant, bi-stable, micro-bunched beam driven
  2. UIT \( \rightarrow \) millimeter-wave plasma accelerator

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Before building an advanced accelerator, choose your materials carefully!

- **Vacuum**: Lawson-Woodward-Palmer theorem requires boundaries, high intensities, gases, or magnetic fields.
- **“Hard” materials (metals, dielectrics, semiconductors)**: Pulsed heating, breakdown, difficulties with miniaturization.
- **Plasma**: Challenging to excite plasma waves, inject electrons into a short wavelength bucket.

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Limitations of vacuum acceleration

• Linear in electric field acceleration in vacuum is impossible (Lawson-Woodward-Palmer’s theorem)

\[ \vec{p}_1 - \vec{p}_0 = \omega \]

Cannot stop a photon in vacuum!

• Non-linear (ponderomotive) acceleration, a.k.a. Inverse Compton Scattering is possible \( \rightarrow \) injector applications

\[ \frac{dE}{dz} = \frac{30 \text{ GeV}}{\gamma} cm \left( \frac{P}{3 \times 10^{18} \text{ W/cm}^2} \right) \]

Useless for collider but could be used for injector applications

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Linear Acceleration: Stopping a Photon

• Can “stop” a photon in a medium → Inverse Cherenkov Accelerator

\[ \omega_{\text{rest}} = \gamma_{\text{frame}}(\omega - \mathbf{k} \cdot \mathbf{v}_{\text{frame}}) = 0 \]

\[ |\mathbf{k}| = n_{\text{gas}} \frac{\omega}{c} \]

Any acceleration technique is the inverse of a radiation process → radially polarized beam matches the Cherenkov emission cone

• Can accelerate near boundaries: Examples of Inverse Smith-Purcell, Surface Wave, and Photonic Bandgap Accelerators

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Inverse Smith-Purcell Accelerator

incident wave  evanescent wave  reflected wave

$\mathbf{q} \quad \mathbf{v} \quad d = 2\pi/k_u$

Image $q' = -\frac{\varepsilon - 1}{\varepsilon + 1} q$

- Convenient to excite (open structure)
- Metal or high-$\varepsilon$ dielectric gratings
- Non-resonant structure ($E_{\text{acc}} \sim E_{\text{inc}}$)
- Strong variation of $E_z$ with $x \to$ small $\varepsilon_n$

Evanescent wave has a sub-relativistic phase velocity $\to$ suitable for acceleration

$$v_{\text{ev}} = \frac{\omega}{\omega/c \cos(\theta) + k_u} = v$$

Experimental accomplishments: 10 $\mu$m radiation from 45 MeV beam at BNL (Fernow '97)

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Exotic Materials for ISPA

\[ q' = -\frac{\varepsilon - 1}{\varepsilon + 1} q \]

S-P Radiation produced totally by the image charge \( \rightarrow \) enhance the IC to enhance radiation \( \rightarrow \) enhance E-field at the charge

For RF/microwaves: thin-wire array mimics plasma:

\[ \varepsilon = 1 - \frac{\omega_p^2}{\omega^2} \]

\[ \omega_p^2 \approx \frac{16c^2}{d^2 \log(d^2/8r_0^2)} \]

• For 10.6 \( \mu \)m radiation use naturally-occurring SiC:

\[ \varepsilon = \varepsilon(\infty) \frac{\omega_i^2 - \omega^2}{\omega_i^2 - \omega_f^2} \]

Micro-machined SiC ablated by the 266-nm VUV laser, 60 pulses F=1.1 J/cm²

IC enhanced by using materials with \( \varepsilon < 0 \) in the desired frequency range

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Limitations of open planar structures

- In-plane TM waves with \( k_z \approx \omega/c \) do not deflect the beam: \( E_x = H_y \)
- In-plane TM waves with \( k_z = \omega/v \) are de-localized: \( \Delta x = \lambda \gamma \beta/2\pi \)
- They are almost transverse \( \Rightarrow \) can’t accelerate relativistic particles

For any point above grating: 
\[
E_z \propto \partial_x H_y \quad \text{and} \quad H_y \propto e^{-x\sqrt{k_z^2 + k_y^2 - \omega^2/c^2}}
\]
- Finite \( E_z \) \( \Rightarrow \) evanescence \( \Rightarrow \) oblique incidence \( k_y \neq 0 \)
- Finite \( \Rightarrow \) finite \( H_x \) \( \Rightarrow \) deflection force parallel to the grooves
- Synchrotron losses for high-\( \gamma \) beams \( \Rightarrow \) suitable as an injector only

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From open to open-sided structures

**Goals:**

- X-independent (in-plane) luminous wakes do not deflect the beam
- Enable x-dependent (deflecting) wakes to leak out → open-sided structure
- Increase shunt impedance by maximizing E_z/E_y
- Reduce or eliminate metallic components → lossy at high frequency
- Reduce E_y at the metal surface

Hill et.al., 2001

Rosenzweig et.al., 1995
2-D photonic bandgap accelerator: reversed fiber

**Advantages of PBGs:**

- Fundamental mode confined in vacuum through Bragg scattering by PC
- Can operate a defect mode with a frequency in the bandgap $\rightarrow$ lateral confinement of the fundamental
- Deleterious wakes will be outside of bandgap $\rightarrow$ not confined

E. Smirnova et. al. (MIT), metallic photonic fiber, 17 GHz

B. Cowan (SLAC), open-sided structure

E. Lin (SLAC), photonic fiber
Planar surface-wave accelerator

SiC ε < 0

3 µm

SiC ε < 0

SiC/vacuum SPP’s are excitable by a CO₂ laser

• No metal: confinement by ε < 0 material (SiC)
• Supports ω = kc mode \( \Rightarrow \) can accelerate relativistic particles
• Near field (small gap) \( \Rightarrow \) attractive ratio \( E_z/E_x \)
• Acceleration by surface phonon polaritons (SPP)

Coupling problems: (a) how do you couple 10.6 µm radiation into a 3 µm hole?? (b) SPP’s group velocity is very small \( \Rightarrow \) how will they get to the other end??

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Side-coupled surface wave accelerator

Incident CO₂ laser

SiC

Si

16 µm

2 µm

3 µm

800 µm

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Novelties in Plasma Beatwave Acceleration

• Detuned (driven) beatwave (UCLA)
  1. Less severe requirements on plasma homogeneity: plasma wave frequency determined by laser frequency detuning
  2. Advantageous for phase-locked injection

• Autoresonant beatwave excitation (UC Berkeley)
  1. Accesses plasma wave amplitudes beyond linear wavebreaking by slowly chirping the laser frequency
  2. Low-intensity very long laser pulses are used

• Relativistic bi-stability (UT-Austin)
  1. Achieves plasma waves close to wavebreaking using long pulses of above-threshold intensity
  2. Nonlinear “clean-up” of plasma wakes

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Phase-locking of externally injected electrons into the accelerating field of the plasma wave requires constant phase velocity.

\[
\frac{eE}{mc\Delta\omega} = \frac{\omega_p^2 a_1 a_2}{\omega_p^2 - \Delta\omega^2} \sin \Delta\omega(t - z/c) \approx a_1 a_2 \sin \Delta\omega(t - z/c)
\]

ON-RESONANCE phase velocity & amplitude of the RPW are sensitive to density \(\rightarrow\) energy spread of the e-beam.

OFF-RESONANCE pump pulse excites a “forced” oscillation \((\omega_{\text{plasma}} \gg \Delta\omega_{\text{beatwave}})\) \(\rightarrow\) phase & amplitude “locked” by laser
Robust Autoresonant Excitation in PBWA

Rosenbluth-Liu Relativistic Detuning Limit:
as plasma wave grows, its natural frequency
drops, and the beatwave is out of resonance

\[ \frac{E_{RL}}{E_{WB}} = \left( \frac{16a_1a_2}{3} \right)^{1/3} \]

Relativistic equation for electrostatic potential
\[ \phi = \frac{e\Phi}{mc^2} \] of an ultra-fast plasma wave

Laser beatwave:
\[ a^2 = \bar{a}^2 + \varepsilon \sin \psi(\zeta), \quad \text{where} \quad \psi(\zeta) = \int d\zeta \omega(\zeta) \]

chirped detuning

\[ \omega(\zeta) = \omega_p (1 - \alpha \zeta), \quad \text{where} \quad \zeta = \omega_p \left( t - z/c \right) \]

\[ \alpha < 0.15 \omega_p \left( \frac{\omega_p^2 E_1 E_2}{\omega_1 \omega_2 E_0^2} \right)^{4/3} \]

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Beatwave Generation of Plasma Waves Using Relativistic Bi-Stability

Beatwave strength $a = (e/m)^2 E_1 E_2 / 2 \omega_1 \omega_2$

Critical strength

$$a_{crit} = \frac{4\sqrt{2}}{9} \left( 1 - \frac{\omega^2}{\omega_p^2} \right)^{3/2}$$

Long detuned beatwave pulse with $a > a_{crit}$ of duration $T>>1/|\omega - \omega_p|$ leaves behind a strong plasma wake $\Rightarrow$ only because of relativistic effects!

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Microbunched beam driven beatwave

Instead of modulating laser intensity, use inverse FEL to micro-bunch an electron beam at the plasma wavelength

Modulated e-beam driven accelerator/injector

Energy into wake

Energy into driver

Front bunches excite the wake, middle bunches accelerate

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Microwaves and Plasmas: Unusual Match

- **Common pairings:** microwaves → dielectrics & metals, short-pulse lasers → plasmas
- **Trapping limit:** \( E_z = 10 \text{ MeV/m} \times f[\text{GHz}] \)
- **For frequencies above 100 GHz** fabricating conventional structures is hard → sub-mm features
- **In plasma frequencies are determined by plasma density:**
  \[ \lambda = 3\text{mm} \rightarrow 10^{14} \text{ cm}^{-3} \]

**Challenge:** Converting high power transversely polarized microwaves into longitudinally polarized plasma wave

**Usual ponderomotive coupling won’t work:**
- (1) plasma too dense \( \omega \sim \omega_p \)
- (2) pulses too long \( \omega_p \tau \gg 1 \)

**Solution:** Use magnetic field for mode conversion

**Extra benefit:** strong compression of EM waves due to \( v_g \ll c \)

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Undulator + Microwaves = Plasma Wave

Axial + undulator B-fields create a “slow wave” band for \( \omega = \omega_p = \Omega_0 \)

\[
\begin{align*}
B, T_1
\end{align*}
\]

Length of plasma, cm/2\(\pi\)

\[
\frac{n_p \text{ [cm}^{-3}\text{]}}{10^{13}} = 2a_1 \frac{B_0^2}{B_u} \Rightarrow
\]

for \(a_1 = 0.02\) \(E_z = 10\) MeV/m

\[
v_\phi = c / (1 - \lambda_1 / \lambda_u) \rightarrow \text{control of phase velocity} \rightarrow \text{possibility of ion acceleration}
\]

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PIC simulation of UIT: weak undulator

Parameters:

\[
\frac{\omega}{\Omega_0} = 1, \quad \frac{k_u c}{\omega} = 1.6 \quad \frac{eB_u}{mc\omega} = \frac{1}{50}
\]

\[\Rightarrow \quad \frac{\text{Group Velocity}}{\text{Light Speed}} = \frac{1}{50}\]

Note 10-fold compression of electric field \(E_Z/E_X\)

Linear prediction confirmed by PIC: weaker undulator results in higher energy compression ratio and higher accelerating field.

Is linear theory accurate?

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Decreasing undulator field $\rightarrow$ increasing accelerating gradient?

$B_c=1$ T

Nonlinear saturation for small $B_w$ $\rightarrow$ evidence of relativistic mass increase?


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Conclusions and Acknowledgements

As our field matures, there is still room for innovation in all AAC areas: drivers, materials, combinations thereof.

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Advanced Technology Program of HEP office of DOE
Direct laser acceleration in capillary channel

- **Idea**: use the free electrons contained in metal walls to excite a surface wave (Steinhauer et.al.) Metal wall enables confinement.

- **Problems**:
  - Oversized channel ($w \gg \lambda$) required for luminous propagation $\rightarrow$ small ratio $E_z/E_{\perp}$
  - Large $E_{\perp}$ may lead to heating of metallic wall

Radially polarized laser beam accelerates electrons

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