Cherenkov Radiation in a Surface Wave Accelerator Based on Silicon Carbide (SWABSiC)

T. Wang, K. Lai, V. Khudik, and G. Shvets

Department of Physics, University of Texas at Austin
tianh_wang@utexas.edu

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Outline and Motivation

- Introduction to SWABSiC
- Cherenkov radiation studies
- Wakefield acceleration scheme

Motivation:

- Utilize surface phonons supported by SiC to create a high-gradient, uniform accelerating field for particle acceleration.

- Study how the Cherenkov radiation of the surface waves are distributed in space. In particular, the angular distribution and the influence of channel size to the radiation behavior.
Introduction to SWABSiC

**SWABSiC: Surface Wave Accelerator Based on Silicon Carbide**

- SiC has negative permittivity in mid-IR reststrahlen band:

  $$\varepsilon(\omega) = \varepsilon_{\infty} \frac{\omega_{OL}^2 - \omega^2 + i\gamma \omega}{\omega_{OT}^2 - \omega^2 + i\gamma \omega}$$

  - $$\varepsilon_{\infty} = 6.7$$
  - $$\omega_{OL} = 29.1 \text{ THz}$$
  - $$\omega_{OT} = 23.9 \text{ THz}$$
  - $$\gamma = 0.14 \text{ THz}$$

- SiC-Vacuum interface can support mid-IR surface wave (Surface Phonon-Polaritons/SPPs)

  - $$\varepsilon_0 > 0$$
  - $$\varepsilon_1 < 0$$

  Utilize the two interfaces

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Introduction to SWABSiC

- Why Silicon Carbide:
  - No need of outer metal confining wall;
  - High thermal and electric breakdown threshold: 1000 C & 300 MeV/m;
  - High resistive quality factor $Q_r \approx 350$;
  - High thermoconductivity: 3.8 W/cm/K;

- Application:
  - Mid-IR radiation source;
  - Wakefield acceleration;
  - Laser driven acceleration;

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Eigenmodes of the Surface Waves

- **TM EigenModes:**

  - Accelerating mode
  - Deflecting/dipole mode

  Panofsky- Wenzel theorem: $V_\perp (W_x) = \frac{\partial}{\partial x} (W_\perp)$; Deflection kick = transverse variation of the longitudinal kick

- **Field dependence:**

  $E_\parallel, \vec{H} \propto e^{i(k_\parallel \cdot \vec{r}_\parallel - \omega t)}$; 
  $\begin{cases} E_\parallel, \vec{H} \propto e^{-q_1 z} \text{; in SiC} \\ E_\parallel, \vec{H} \propto e^{q_0 z} + Ae^{-q_0 z} \text{; in vacuum} \end{cases}$; 
  $\begin{cases} q_0 = \sqrt{k_\parallel^2 - k_0^2} \\ q_1 = \sqrt{k_\parallel^2 - \epsilon k_0^2} \end{cases}$

- **Impose boundary condition:** $E_x$, $H_y$ continuity

  $D_A: \epsilon_1 \cosh(q_0) + \frac{q_1}{q_0} \sinh(q_0) = 0$; $D_D: \epsilon_1 \sinh(q_0) + \frac{q_1}{q_0} \cosh(q_0) = 0$
Resonant Excitation by Relativistic Charge

- Resonant condition (phase matching):
  \[ \omega(\vec{k}_{\parallel}) = \vec{k}_{\parallel} \cdot \vec{v} = k_x v \]

- Summing over eigenmodes: Green’s function
  \[ \vec{E}_{\parallel} = \int d\vec{k}_{\parallel} e^{ik_y y + i\omega \left( \frac{x}{v} - t \right)} \tilde{E}(\omega, k_y) \]

- Dispersions of surface waves at resonant excitation, \( v = c \)

\[ L_{prop} = \frac{1}{2} Im \left( \frac{\omega}{c} \right)^{-1} \approx 360 \mu m \]

Narrow-band mid-IR radiation:
- A mode: 26.3 THz ± 1%
- D mode: 26.3 THz ± 7%

\[ \Delta = 10 \mu m \]
Space Distribution of Coherent Cherenkov Radiation of SPPs

Angular spectrum (stationary phase method):

\[
\vec{E}_\parallel = \int d\vec{k}_\parallel e^{ik_y y + i\omega \left( \frac{x}{v} - t \right)} \tilde{E}(\omega, k_y) \implies \frac{\partial \omega(k_y)}{\partial k_y} \frac{1}{v} = \frac{y}{vt-x} = \cot(\theta)
\]
Space Distribution of Coherent Cherenkov Radiation of SPPs

- Angular spectrum (stationary phase method):
  \[
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  \]

- Radiation angle is the multi-valued function of frequency:

![Graph showing angular spectrum and radiation angle](image)

- Accelerating Mode

- Two waves beating behavior

![Diagram showing two waves beating](image)
Space Distribution of Coherent Cherenkov Radiation of SPPs

Angular spectrum (stationary phase method):

\[
\vec{E}_\parallel = \int d\vec{k}_\parallel e^{i k_y y + i \omega (\frac{x}{v} - t)} \tilde{E}(\omega, k_y) \implies \frac{\partial \omega(k_y)}{\partial k_y} \frac{1}{v} = \frac{y}{vt-x} = \cot(\theta)
\]

Radiation angle is the monotonic function of frequency:

Deflecting Mode

No beating when v approaches c.
Space Distribution of Coherent Cherenkov Radiation of SPPs

- Angular spectrum (stationary phase method):
  \[ \vec{E}_\parallel = \int d\vec{k}_\parallel e^{ik_yy+i\omega(x-vt)} \vec{E}(\omega,k_y) \Rightarrow \frac{\partial \omega(k_y)}{\partial k_y} \frac{1}{v} = \frac{y}{vt-x} = \cot(\theta) \]
  Gap: 10\text{um}

- Radiation angle is the multi-valued function of frequency:

\[ \theta(\text{Degree}) \begin{array}{cccc}
\lambda_{\Omega L} & 11 & 11.5 & 12 \\
\lambda_{\Omega T} & 70 & 78 & 86 & 90 \\
\end{array} \]

\[ \beta=1.00 \quad \beta=0.95 \quad \beta=0.90 \]

Deflecting Mode

Beating reappears when velocity decreases

D Mode, E (a.u)
Properties of Cherenkov radiation of the surface waves

- \( \nu_e \downarrow, \theta_c \uparrow; \)  
- \( \nu_e \downarrow, f_{\text{beat}} \uparrow \)

Different beating behavior

- \( \theta_c \) of A mode > \( \theta_c \) of D mode

- Gap: 10\( \mu \)m
Reverse CR Regime of Small Channel SWABSiC

- Small channel SWABSiC: “left-handed” waveguide.

\[ \vec{v}_g \cdot \hat{k} < 0; \; \epsilon_{eff} < 0, \; \mu_{eff} < 0 \]

- Accelerating mode Cherenkov radiation reverses.

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Reverse CR Regime of Small Channel SWABSiC

10\(\mu m\)

- Energy flux directions in SiC and vacuum are opposite.
- \(\vec{S}_{SiC} < \vec{S}_{vacuum} \Rightarrow V_g > 0\)
Reverse CR Regime of Small Channel SWABSiC

10μm
- Energy flux directions in SiC and vacuum are opposite.
- $\vec{S}_{SiC} < \vec{S}_{vacuum} \Rightarrow V_g > 0$

1μm
- Energy flux directions in SiC and vacuum are opposite.
- $\vec{S}_{SiC} > \vec{S}_{vacuum} \Rightarrow V_g < 0$
Part II, Accelerating Scheme and Structure Parameters

- The accelerating mode surface wave is used for two-beam/bunch-train acceleration:

- The deflecting mode is responsible for BBU instability.

- Benefits of slab geometry:
  - Deflecting mode can be suppressed by wide(ribbon-like) beam: \[ \sigma_y \gg \sigma_x. \]
  - Transverse field can be also suppressed by wide beam.

### Channel

<table>
<thead>
<tr>
<th>Channel</th>
<th>6( \mu )m</th>
<th>10( \mu )m</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-axis Gradient</td>
<td>225MeV/m</td>
<td>123MeV/m</td>
</tr>
<tr>
<td>Surface Gradient</td>
<td>307MeV/m</td>
<td>183MeV/m</td>
</tr>
<tr>
<td>Peak ( E_y/E_x )</td>
<td>0.05</td>
<td>0.17</td>
</tr>
<tr>
<td>Steady Power</td>
<td>33kW</td>
<td>18kW</td>
</tr>
<tr>
<td>Propagation Length</td>
<td>360( \mu )m</td>
<td>366( \mu )m</td>
</tr>
</tbody>
</table>
Experimental Progress

- The SWABSiC structure has been manufactured, and beam tested at ATF, Brookhaven
- Promising throughput is achieved (>12%) (9μm gap)
- Post-scan preformed, no visible damage

We have developed 3D wakefield code for SWABSiC by using analytic Green’s functions.
Experimental Progress

- The SWABSiC structure has been manufactured, and beam tested at ATF, Brookhaven
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Throughput Test Setup in ATF Chamber

- We have developed 3D wakefield code for SWABSiC by using analytic Green’s functions

More details about experiment --> K Lai, Poster 3-1S: “Progress of Surface Wave Accelerator Based on Silicon Carbide”, This afternoon
We studied the Cherenkov radiation of two surface modes in SWABSiC:

- Velocity dependence, angular spectrum and the beating behavior are investigated.
- Ordinary and reverse CR regime are studied.

The promise of the structure for wakefield acceleration was also discussed:

- High-gradient wakefield and high-power narrowband mid-IR radiation
- The future experiment: verify the surface wave excitation by diagnosing the beam distribution and energies.
Thanks