# Tilted Pulse-Front Phase-matching in Three Dimensions: Overcoming The Cherenkov Angle Restrictions

Steven P. Jamison[1], David A. Walsh[2], Edward W. Snedden[2]
[1]Department of Physics, Lancaster University, Lancaster LA1 4YW, United Kingdom
[2]Accelerator Science and Technology Centre, Science and Technology Facilities Council, Daresbury Laboratory, Warrington, WA4 4AD, UK

***Abstract*—We consider the non-linear generation of THz with tilted pulse-fronts in three dimensions and show that, contrary to the widely held expectations, coherent phase matching can be obtained for pulse-front tilt angles other the Cherenkov angle.**

## I. INTRODUCTION

Effecient generation of high-field strength THz pulses are of interest for non-linear THz spectroscopy, and for application to THz driven particle acceleration. For many of the widely used non-linear materials with large non-linear coefficients phase-matching conditions preclude co-linear phase matching. For transversely narrow optical pump beams materials such as LiNbO3 give rise to THz emission in a Cherenkov cone around the drive laser. For transversely extended beams tilted pulse fronts are required to maintain efficient generation, and also have the desirable result of producing a planar front THz emission.

The generation of THz with tilted pulse fronts has been widely studied and exploited for over a decade [1-6]. It is generally accepted that to obtain the efficiency gains the pulse front tilt must match the Cherenkov angle of the material.

Recently, Walsh et al demonstrated a 'travelling source' THz generation concept for particle acceleration [7]. The generation scheme explicitly utilized a pulse-front tilt with tilt angle exceeding the Cherenkov angle, raising questions on the nature of the phase-matching efficiency. Here we show analytically, and also numerically through finite-difference time-domain modeling examples, that pulse-front tilt generation can meet the phase-matching condition whenever the tilt-angle exceeds the Cherenkov angle.

## II. RESULTS

Previous derivations of Cherenkov angle pulse-front tilt phase-matching have generally started from a two dimensional construction, requiring that the phase-fronts of the generated THz coherently reinforce in the 2-dimensional plane[1]. Similarly, published numerical modeling of the generation process has tended to assume a two-dimensional symmetry [2,3]. However for a 1-dimesional 'pencil-beam' excitation a 3 dimensional Cherenkov cone of emission is produced. By an explicitly three-dimensional construction of the Huygens-like emission throughout a finite, 3-dimensional volume it is possible to show analytically that constructive interference (i.e. phase-matching) can be obtained whenever the pulse-front tilt exceeds the Cherenkov angle. In Fig 1 we show results from a three dimensional FDTD modeling with pulse-front tilt equal to, and exceeding, the cherenkov angle. A planar wave THz emission is obtained in both cases, and with equal efficiency and field strength.

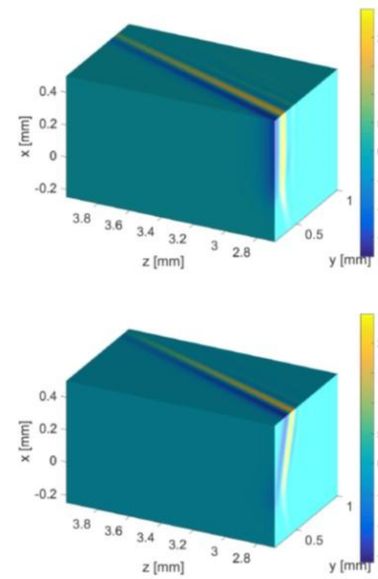


**Fig. 1.** THz generation of a planar front with differing pulse front tilt angle. Optical pulse propagation direction is in the z-direction. (a) with pulse-front tilt matching the Cherenkov angle of the material, with tilt in the z-x plane. (b) with a pulse front tilt exceeding the Cherenkov angle. The pulse-front tilt has projection components in both the zx- and zy-planes. The angle projected into the zx-plane is at the Cherenkov angle.

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