# MANIPULATING THE TWO-STREAM INSTABILITY FOR EFFICIENT TERAHERTZ GENERATION*

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*Abstract*

Particle beams have exhibited a two-stream instability for many decades; this undesirable trait has been well-understood for many years. We propose creating a scheme that uses a beam of electrons with two distinct energies that will develop the two-stream instability as a bunching mechanism. By controlling the beam parameters and seeding them with a low-level rf signal, a gain as high as 2.5 dB per centimeter is predicted. We show the theory behind this concept and recent progress in a developing experiment.

## INTRODUCTION

Terahertz-frequency sources have been the holy grail of mm-wave research for many years now. In the recent past, a great deal of emphasis has been placed on developing these sources for a variety of applications [1].

Terahertz generally refers to a range of several hundred GHz through perhaps 10 THz, which lies in a band that has shorter wavelengths than electronics and conventional structures, yet longer than the atomic scale. Because of this, sources in this band have eluded conventional electronics and atomic techniques (e.g. lasers) and remain an unexplored region of the EM spectrum.

Yet the number of applications of terahertz manipulation is vast and growing. Typically, these include remote sensing, communications, three-dimensional imaging, and directed energy. Discussions of THz applications are published frequently; they will not be regurgitated here [1,2].

The most common approach to building a high-power source that reaches to 1 THz is typically a TWT-type device, where an electron beam is pushed through a comb-like structure, and the coupling of the beam with the vanes generates traveling waves of a wavelength nearly matching that of the structure. However, the structure and the efficiency of coupling scale very poorly to short wavelengths.

We propose a terahertz-generation scheme that eliminates the need for any problematic structure while providing high-average power output to satisfy the desires of the THz-based applications.

## PHYSICAL DESCRIPTION

Figure 1 shows a three-dimensional model of the experiment currently being fabricated. The total beamline length, represented by the blue and red lines, is only a couple feet long. Two electron guns produce electron beams of slightly different energy. These beams are bent by a (green) dipole so that they merge and co-propagate. Then they get bent again and collected in a large-aperature collector.

The next section describes the theory of the interaction, and shows that Coulombic bunching should occur during the mixing process. These space-charge waves will radiate via coherent synchrotron radiation at the second bend. Instead of being dependent on shot noise to begin the process, we expect to steal a small percentage of the output radiation and reflect it back on the initial beam using one (yellow) mirror and a diffraction grating.

Seeding the beams at a specific frequency will allow that mode to self-select in the amplification process. Meanwhile, the majority of the radiative beam will be collected and analyzed. A number of variations are possible (frequency-modulated input, multi-mode mixing, etc), but in all cases, the setup is significantly less complex than conventional TWT-type techniques.

## LINEAR THEORY

We start by separating out the dc and ac components of each beam's density and velocity:

$$\eta_j = \eta_{0j} + \tilde{\eta}_j \,,\; v_j = v_{0j} + \tilde{v}_j \,,\text{ and } E = E_0 + \tilde{E} \,,$$

The continuity equation, Lorentz' law, and Poisson's equation can be written:

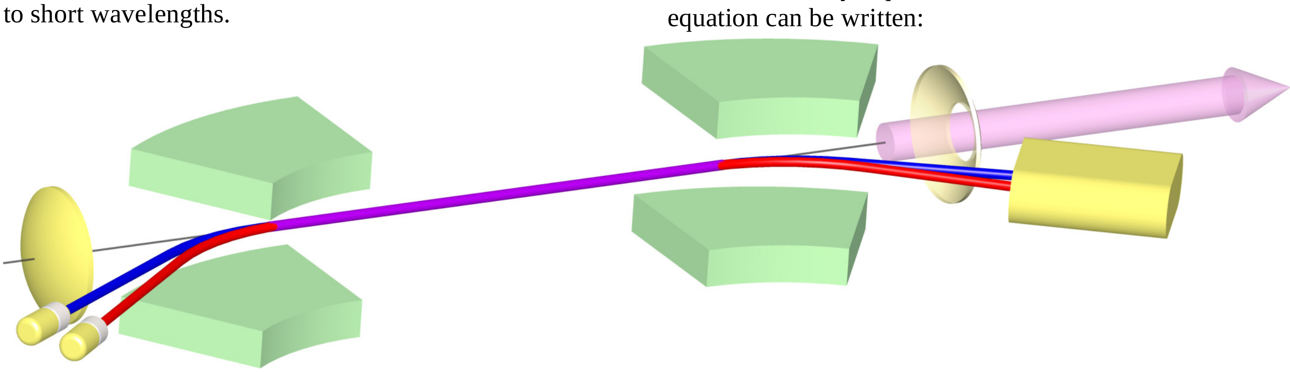

Figure 1: Model of the experimental beam layout. The two electron guns generate beams of slightly higher (blue) and lower (red) energies, which are then mixed (purple) through the interaction region. This middle portion is about 10-cm long, and the total apparatus is less than one meter in length.

$$\frac{\partial \eta_j}{\partial t} = -\frac{\partial}{\partial z}\eta_j v_j$$

$$\frac{\partial v_j}{\partial t} + v_j \frac{\partial}{\partial z} v_j = \left(\frac{q}{m}\right)\left(\vec{E} + \frac{\vec{v}}{c}\times\vec{B}\right)_z$$

$$\frac{\partial E}{\partial z} = \frac{q}{\varepsilon_0}\sum_j \eta_j .$$

Considering only longitudinal motion, these equations become:

$$\left(\omega - kv_{0j}\right)\tilde{\eta}_j = k\eta_{0j}\tilde{v}_j$$

$$-i\left(\omega - kv_{0j}\right)\tilde{v}_j = \left(\frac{q}{m}\right)\tilde{E}$$

$$ik\tilde{E} = \frac{q}{\varepsilon_0}\sum \tilde{\eta}_j .$$

If we define the average and difference quantities as:

$$\bar{v} \equiv \frac{v_{01}+v_{02}}{2}, \quad \Delta \equiv \frac{v_{01}-v_{02}}{2}, \text{ and } \Omega \equiv \omega - k\bar{v},$$

then the linearized equations can be rewritten as:

$$(\Omega - k\Delta)\tilde{\eta}_1 = k\eta_{01}\tilde{v}_1$$

$$(\Omega + k\Delta)\tilde{\eta}_2 = k\eta_{02}\tilde{v}_2$$

$$(\Omega - k\Delta)\tilde{v}_1 = i\left(\frac{q}{m}\right)\tilde{E}$$

$$(\Omega + k\Delta)\tilde{v}_2 = i\left(\frac{q}{m}\right)\tilde{E}$$

$$ik\tilde{E} = \frac{q}{\varepsilon_0}(\tilde{\eta}_1 + \tilde{\eta}_2).$$

Now the dispersion relation can be evaluated:

$$(\Omega - k\Delta)^2\tilde{\eta}_1 = \omega_{p1}^2(\tilde{\eta}_1 + \tilde{\eta}_2)$$

$$(\Omega + k\Delta)^2\tilde{\eta}_2 = \omega_{p2}^2(\tilde{\eta}_1 + \tilde{\eta}_2),$$

where $\omega_{p(1,2)}^2 \equiv q^2\eta_{0(1,2)}/\varepsilon_0 m$ are each beam's plasma frequencies.

Combining both parts of the last equation and assuming $\omega_{p1}^2 \approx \omega_{p2}^2$, we generate the dispersion relation:

$$\Omega^4 - 2\Omega^2\left(\omega_p^2 + k^2\Delta^2\right) + k^4\Delta^4 - 2k^2\Delta^2\omega_p^2 = 0 .$$

If $\Gamma$ is defined as:

$$\Gamma^2 \equiv \sqrt{1 + k^2\Delta^2\left(2\omega_p^2 - k^2\Delta^2\right)\Big/\left(\omega_p^2 + k^2\Delta^2\right)^2} - 1,$$

then the solution of the dispersion relation becomes $\Omega = \pm i\Gamma\sqrt{\omega_p^2 + k^2\Delta^2}$ or $k\bar{v} = \omega \pm i\Gamma\sqrt{\omega_p^2 + k^2\Delta^2}$. The velocity separation and growth approximation can thus be rewritten as:

$$k = \frac{\omega}{\bar{v}} \pm i\frac{\omega_p}{\bar{v}}\left(\frac{2-\sqrt{3}}{\sqrt{2}}\right)$$

and

$$\frac{\omega_p}{\bar{v}} = \frac{2}{b}\sqrt{\frac{I}{\beta^3 I_A}} .$$

Putting these together, the gain (in decibels) over a length $L$ becomes:

$$G = 20\cdot\log\left(\exp\left(\frac{2L}{b}\sqrt{\frac{I}{\beta^3 I_A}}\left(\frac{2-\sqrt{3}}{\sqrt{2}}\right)\right)\right).$$

$$G \approx 3.29\frac{L}{b}\sqrt{\frac{I}{\beta^3 I_A}}$$

For a beam of one-millimeter radius and one ampere, this is about $0.25\ \mathrm{dB/mm}$.

## CURRENT PROGRESS

For the past several months, 3D simulations have been analyzing the two-stream amplification process more completely than the linear theory. One-dimensional simulations have produced impressive results, which have been published elsewhere.

Simultaneously, the experimental demonstration of this method is nearly finished fabrication and assembly. Beam mixing and bunching is expected in the next year.

## REFERENCES

[1] M. Rosker, "Progress Towards a THz Imager," IMS 2007 Workshop (2007); www.darpa.mil/mto/ programs/tift/pdf/MTT_THz_Workshop.pdf.

[2] B. Carlsten, K. Bishofberger, R. Faehl, "Compact two-stream generator of mm and sub-mm wave radiation," Physics of Plasmas 15, 073102 (2008).

[3] K. Bishofberger, B. Carlsten, and R. Faehl, "Generation of millimeter and sub-millimeter radiation in a compact oscillator utilizing the two-stream instability," International Vacuum Electronics Conference 2008, April 2008, 164 (2008).