INTENSE SHEET ELECTRON BEAM TRANSPORT IN A PERIODICALLY CUSPED MAGNETIC FIELD *

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Abstract

We explore periodically cusped magnetic (PCM) fields in the regime of a Ka-Band coupled-cavity travelling wave tube (beam current = 3.5A, voltage = 19.5kV, 10:1 beam aspect ratio). We use finite-element beam optics code MICHELLE to simulate the 3-dimensional beam optics for the beam transport within a PCM field. Realistic 3-dimensional magnetic fields have been considered to determine the practicality of these designs. We present the methodology used to focus and transport a thermal beam from a shielded-cathode, high aspect-ratio electron gun.

INTRODUCTION

Electron beams with large transverse aspect ratios (sheet-beams) are of interest for use in RF sources, accelerators, and free-electron laser applications. Focusing an intense, relatively low voltage (i.e. > 300A/cm^2, ≤ 20kV) sheet electron beam is difficult, and only solenoidal focusing over distances of several cm has been successfully used to date.[1-4] If periodic permanent magnets could be used instead of a permanent magnet solenoid, the overall size and weight of the magnetic structure would be substantially reduced and transport over longer distances might become practical [5].

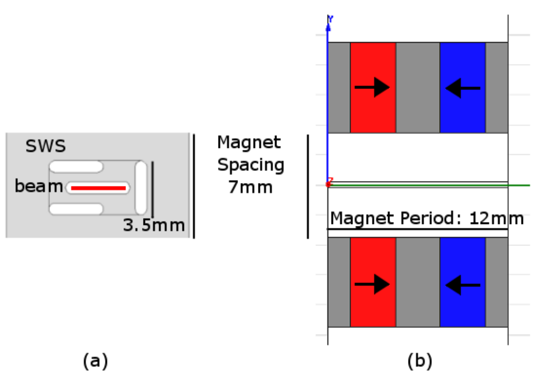

Figure 1: a) Generic Ka-Band sheet-beam slow-wave structure geometry (end view). b) 2D Magnet configuration with realistic dimensions (magnet period, magnet spacing) – arrows represent direction of magnet polarization (side view).

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The electron beam that we wish to transport has the following parameters: beam current = 3.5A, voltage = 19.5kV, beam height = 0.3mm, beam width = 4.0mm. These are the same parameters achieved by Nguyen and Pasour et al. [1,2] with strong permanent magnet solenoid focusing (8.5kG), and this is a realizable gun at the voltages desired, and has been demonstrated [3]. This is a very strong magnetic field, as compared with the sheet-beam Brillioun Field calculated to be 1.5kG.

The goal of this study is to find what measure of focusing is realizable for an intense sheet-beam with PCM focusing. To this end, we assume a beam tunnel within a slow-wave structure with outer dimension 7mm (Fig. 1a). This provides a lower limit on the magnet spacing (Fig. 1b), and therefore a limit on the magnetic field intensity. The magnet period is similarly limited by materials and machining technology, and also affects the available field intensity within the beam tunnel. Here, we set the period at 12 mm and analyze the magnetic field using a finite-element magnetic field solver, Maxwell [6]. By adjusting the magnet height, we can easily produce the 1.5kG Brillioun field within the beam tunnel region and go 20-30% beyond without saturating the pole-pieces. However, the magnet period is dangerously large when considering PPM instability [5].

1-DIMENSION ANALYTICAL FOCUSING

An analytical, laminar sheet-beam that is infinite in the wide-dimension has a force equation [7],

$$y'' = K_y - {k_{c0}}^2 \left(b(z)\right)^2 y,$$

where K_y is a measure of the defocusing charge,

$$K_y = \frac{qJ}{2m\varepsilon_0 v_z},$$

J is the current per unit width, k_{c0} is the cyclotron wavenumber,

$$k_{c0} = \frac{qB_{rms}}{mv_z},$$

and $b(z)$ is the magnetic field shape with rms value of one.

The force equation can be solved numerically using a simple leap-frog integration and assuming an initial beam height. The results of a set of simulations with increasing magnetic field are included in Fig. 2. Also marked are the analytical value for the Brillioun Magnetic-Field and the area of observed PPM instability.

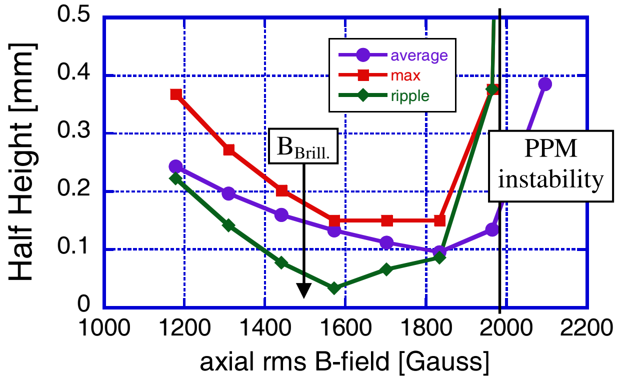

Figure 2: Results of 1D Numerical PPM Transport

2-D MICHELLE SIMULATIONS

A set of 2D beam-optics simulations were performed using the finite-element code MICHELLE[8]. The 2D magnetic field was produced using realistic magnetic materials in the finite-element magnetic field solver Maxwell[6], exported to a table, and scaled linearly in magnitude within MICHELLE. The electron beam used in these initial simulations is an artificial beam created from a non-convergent gun with nearly constant beam-height (both laminar and "thermal" emission models were tested). The beam is transported through a straight 4cm-long section of a flat beam-tunnel of nominal Ka-band size (specifically 0.9mm tall). Note that this propagation distance is only 3.3 periods long, so a steady-state solution is not achieved. However, this distance is sufficient for the Ka-band circuit we envision.

The 2D results presented in Fig. 3 are very similar to the predicted 1D results in terms of the shape near the Brillioun-field value, and also in the appearance of a PPM instability at approximately the same magnetic field value. The particle trajectories (not pictured here) also indicate the PPM instability for larger magnetic fields, as they exhibit a growing beam scallop with a period close to the magnetic field period.

3-D MICHELLE SIMULATIONS – LAMINAR BEAM

A series of 3D beam-optics simulations were performed with MICHELLE – the simplest using a laminar, elliptical beam, created numerically to fully account for the space charge depression of the beam. The beam is propagated through a straight rectangular beam-tunnel of dimension 0.9mm x 5.0mm. The 3D magnetic field is created with the 3D capabilities of the Maxwell field solver – both periodic boundaries and a realistic, finite stack of periodic magnets were used with agreement between methods.

The initial 3D simulations were accomplished with minimal side-focusing (or none – as the extrusion of the 2D magnetic field solution) with currents measured vs. rms magnetic field strength plotted in Fig. 4. The currents represent a measure of how well the beam is transported and whether the fractions of the beam lost is collected on the top and bottom (wide surfaces), or the left and right sides (short surfaces). For small magnetic field, the beam quickly expands into the top/bottom due to space-charge. As the magnetic field increases the beam is better confined in the short-dimension (as predicted by 1D and 2D analyses), but shears quickly into the side-walls. It can be seen that the optimum field is near the predicted Brillioun field, but is somewhat smaller.

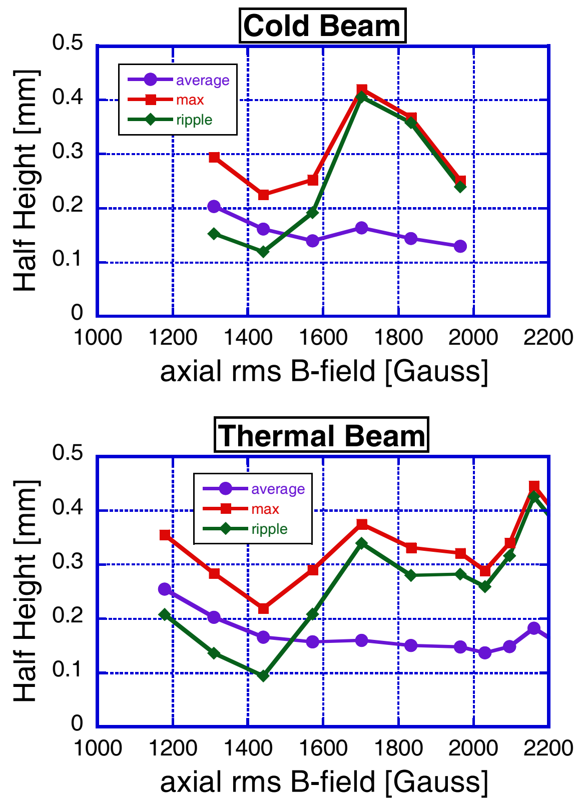

Figure 3: Results of MICHELLE 2D PPM transport simulations with scaled 2D magnetic fields – infinite sheet beam approximation. a) Cold (laminar) Beam. b) Thermally-emitted Beam.

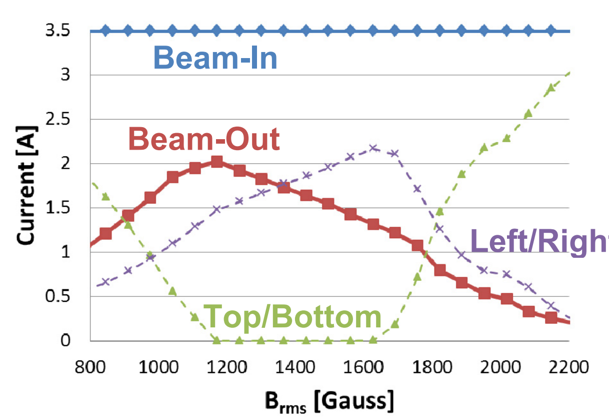

Figure 4: Beam-Interception results of MICHELLE PPM transport simulations with scaled 2D magnetic fields extruded from 2D field solution – no side-focusing fields.

Focusing in the wide-dimension is accomplished by alternately offsetting the pole-pieces as suggested by Booske et al. [5]. Simulations with an "infinite" periodic stack were accomplished with magnetic symmetry boundaries, and injecting a laminar (shielded) beam into the periodic field.

Creating a uniformly periodic magnetic field with finite length and magnetically shielded gun-region required some adjustments to the magnet strengths (*e.g.,* by adjusting the heights of individual magnets) and monitoring the magnetic field components on axis and at the beam edges and corners. These full 3D magnetic simulations were evaluated with both linear and nonlinear materials to assess the realities of saturation within the pole-pieces. We found that realistically a 12mm period PCM would produce the required Brillioun field on axis without saturating, but that a 10mm period PCM would saturate before producing the required magnetic field for the given magnet-spacing (refer to Fig. 1 for geometry). This determined the lower-limit on magnet period for this study.

The results from a series of 3D beam-optics simulations with varying rms axial magnetic field strength are illustrated in Fig. 5. The key result of this plot is the depiction of a range of magnetic field strengths over which the entire beam is transported successfully, indicating that the side-focusing is successful. Unfortunately, the side-focusing (the y-component of the magnetic field) is linearly scaled along with the dominant focusing of the beam (the x-component of the magnetic field), so for increasing values of magnetic field, the beam becomes over-focused in the wide-dimension and becomes less sheet-like. The other point to observe from this plot is that, similar to the 2D-field/3D-beam case above, the optimal solution occurs somewhat below the Brillioun-field value. This is likely the result of the distortion of the sheet-beam during transport.

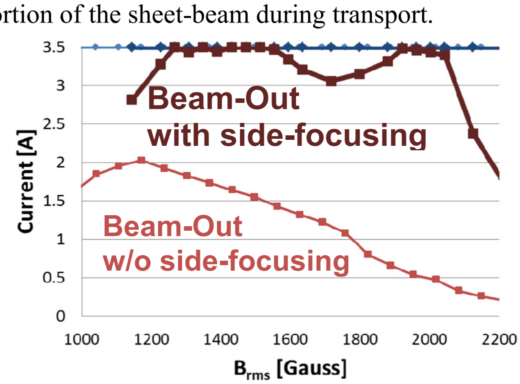

Figure 5: Results of MICHELLE PPM transport simulations with scaled 3D magnetic fields, both with and without side-focusing fields.

3-D MICHELLE SIMULATIONS – AVAILABLE GUN

As a case with a slightly more realistic thermal sheet-electron beam, we used the electron gun designed by Nguyen[2] for the electron source. The original design for this gun intended for very strong solenoidal focusing, which worked very well at capturing the thermal beam (98% transport demonstrated[3]). However, as we see from simulations, the thermal emittance is quite large due in part to the large beam convergence. For realistic magnetic fields optimized to this beam, the best PCM transport achieved thus far was 83% for the 4cm transport section.

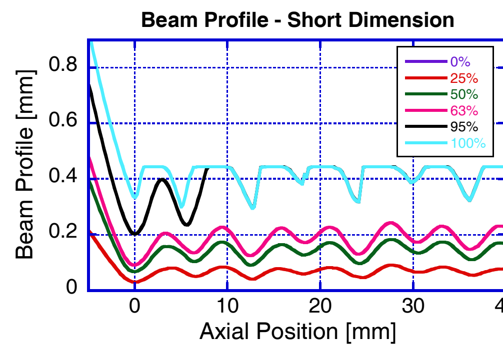

Figure 6: Beam-height profiles vs. axial position for the thermal gun of Nguyen with PPM focusing fields.

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