Abstract: Data from experimental testing of a beamstick designed and built for a 670 GHz extended interaction klystron are compared against 2D and 3D beam optics simulations using the MICHELLE code. A methodology is presented to establish the “as-built” geometry from these comparisons. Excellent agreement with experimental beam current and transmission data is observed across a wide range of electrode voltages. The depressed collector achieved 99% energy recovery as designed.

Keywords: beamstick; simulation; MICHELLE; as-built; extended-interaction klystron

Introduction
The 3-D gun and collector code MICHELLE was employed in the design of the beamstick that will be the basis for a series of sub-mm wave extended-interaction klystrons [1]. This beamstick consists of (1) a magnetically-shielded electron gun that electrostatically compresses the emitted beam area by ~100 times to a current density of ~ 1 kA/cm² at the nominal 96 mA 25 kV operating point, (illustrated in Fig. 1), (2) a 1.15 T solenoidal focus 1.7-cm long transport section with a beam tunnel radius of 62.5 microns (an aspect ratio of 272), and (3) a novel two stage depressed collector with a single-collection stage that can recover 99% of transmitted current. To achieve the high compression ratio without interception, the gun includes an isolated focus electrode and a mod-anode. The focus electrode, with adjustable negative voltage relative to cathode, serves as the primary focusing lens. The mod-anode serves as a secondary lens for final electrostatic beam compression.

Figure 1: Beam optics at the nominal operating point (96 mA, 25 kV) with the design electron gun geometry.

The beamstick was fabricated by CPI/Canada and thoroughly tested at NRL [2]. This paper describes and summarizes our methodology to compare simulation results with measured beamstick performance. The two objectives of this work are: (1) to validate the MICHELLE code in this challenging emittance-dominated beam regime and, (2) to diagnose the “as-built” beamstick and make recommendations for future builds.

Electron Gun Modeling
Initial simulations with the design geometry using actual experimental electrode voltage settings show that measured beam current is substantially higher than those in the original design simulations. It is also found that a much higher focus electrode voltage depression than designed is required for good beam transmission. This behavior strongly suggests that the hot positions of the cathode and focus electrode are probably forward of their design points. To confirm the position of these electrodes, an experimental set of electrode voltages is selected for exploratory simulations with varying electrode positions to match up the simulated current with the measured cathode current, thereby establishing a potential baseline “as-built” gun geometry. The set selected for this purpose is -25.1 kV, -20.2 kV, and -110 V for cathode, mod-anode, and focus electrode, respectively. Actual measured cathode current for this case is 94 mA with 71% beam transmission. The resulting beam optics with the design geometry and with a likely “as-built” geometry is shown in Fig. 2.

Figure 2: MICHELLE simulations with design geometry (left) and a likely "as-built" geometry (right).

The difference in beam optics between the design geometry (42 mA and 42% transmission) and those of the potential “as-built” case (94 mA and 94.5% transmission) is quite remarkable1. This difference is primarily due to the fact that in the design the cathode is slightly recessed with respect to the focus electrode, whereas in this (inferred) as-built geometry the cathode is actually slightly forward. To conclusively establish this new geometry as the potential “as-built” gun geometry, a series of simulations was per-

1 Note that the simulated beam transmission in an axisymmetric gun model cannot be less than measured beam transmission, since there are always misalignments, tilts, etc.
formed for various electrode voltages to compare with test data. This comparison is illustrated in Fig. 3.

![Figure 3: Comparison of cathode current test data and simulated emitted current with "as-built" geometry for various cathode (bold) and mod-anode (italic) voltages in kV as a function of focus electrode voltage.](image)

The excellent agreement between test data and MICHELLE results strongly suggests that the cathode is indeed forward of where it was designed to be. To further confirm our finding, several Miriam curves of the gun were experimentally taken and analyzed to investigate the expansion rate of the cathode/focus electrode assembly. The result of this study confirms that the cathode in fact expands at a relatively faster rate than the focus electrode; explaining the observed performance of the gun.

**Beam Transport Modeling**

Once the “as-built” gun geometry is established, the beam phase-space information from the gun simulations is imported into 3-D beam transport studies. Again, a set of test data was selected to investigate possible scenarios for observed beam test transmission data. One likely scenario is illustrated in Figure 4, in which the beam tunnel is tilted by just 0.1° with respect to the magnetic axis. Here, the simulated cathode and transmitted currents are 68 mA and 55.2 mA, respectively. These are in good agreement with the corresponding test data of 69 mA and 54.5 mA for a 20.08 kV beam voltage.

![Figure 4: MICHELLE simulation of beam transport through a (1.7 cm long 62.5 microns radius) tunnel with 0.1° tilt. Beam cross-section at entrance (left) and exit (right).](image)

Further simulations have been performed and compared with test data as illustrated in Figure 5, which shows cathode and transmitted currents for three beam voltage settings (14.66, 20.08, and 25.1 kV) over a wide range of focus electrode voltages. The good agreement between simulated and measured results, both in values and shapes, lends credence that the 0.1° tilt between the beam tunnel and magnetic axis is most likely the other major cause, beside the displaced cathode described earlier, of the reduced beam transmission observed in the beamstick test.

![Figure 5: Comparison of MICHELLE cathode (solid) and transmitted (dash) currents with measured cathode (circles) and transmitted (triangles) currents.](image)

**Collector Performance**

The novel collector, shown in Figure 6, is a single-stage depressed collector with a non-collecting grading electrode [1]. It performed as designed: recovering 99% of the transmitted beam power without raising body current [2].

![Figure 6: High-efficiency collector design with MICHELLE](image)

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**References**
