# CIRCUIT ASPECTS OF THE NRL/INDUSTRIAL 94 GHz GYROKLYSTRON AMPLIFIER

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*Abstract*

A wide bandwidth, high average power W-band gyroklystron amplifier is currently under cooperative development by NRL, Litton Electron Devices, and Communication and Power Industries. The amplifier circuit is comprised of 4 stagger-tuned cavities operating in the fundamental $TE_{011}$ circular cavity mode. The input coupler is the first cavity of the circuit and must exhibit reasonable coupling strength between the $TE_{10}$ mode in rectangular waveguide and the desired $TE_{011}$ circular cavity mode over a better than 600 MHz bandwidth centered at 93.4 GHz, with high $TE_{01}$ mode purity. A single WR-8 rectangular waveguide drives a combined coaxial/cylindrical cavity system. The coaxial cavity resonating in the $TE_{411}$ mode is tightly coupled to the cylindrical cavity, excited to resonate in the $TE_{011}$ mode. The rf magnetic field couples the cavities through 4 azimuthally spaced apertures.

## 1 INTRODUCTION

Single aperture excitation of the $TE_{01}$ mode with high mode purity is difficult in a low Q cylindrical cavity. The logical step of splitting the excitation into several azimuthally separated apertures introduces a 'plumbing' complexity to precisely split the source power with the appropriate amplitude and phase. However, the amplitude and phase splitting can be accomplished via an intermediate coaxial cavity [1,2]. In the design discussed below, this coaxial cavity resonates in the $TE_{411}$ mode, and is tightly magnetically coupled to the cylindrical cavity via 4 rectangular apertures, equally spaced azimuthally. The coupling apertures are oriented 45° with respect to the single WR-8 rectangular drive waveguide. A schematic of the field solution region for the coupler is shown in Fig. 1, including the gun taper and a dielectric ring isolating Cavity 1 (the input coupler) and Cavity 2.

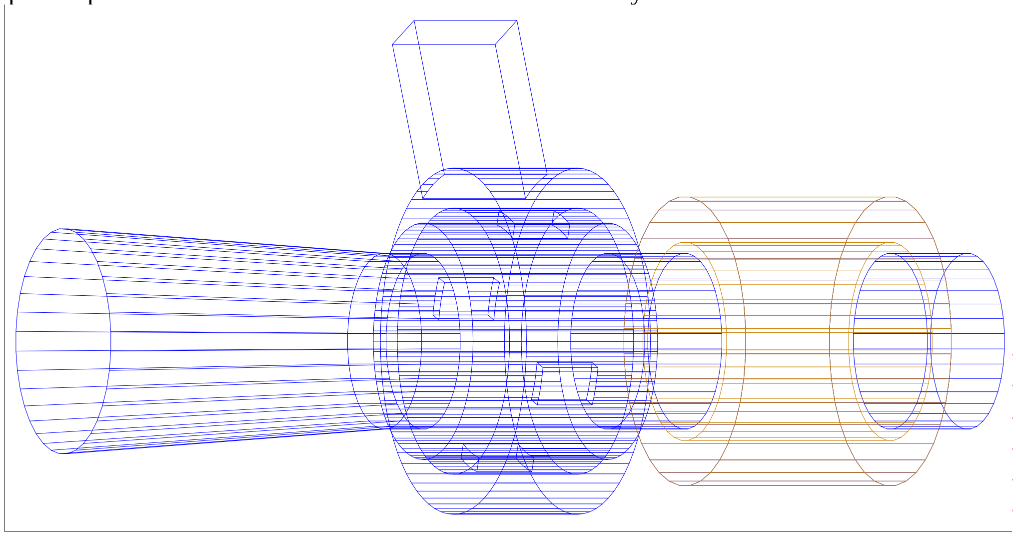

Figure 1: Schematic of input coupler geometry, including gun taper and drift tube dielectric. Vacuum/dielectric regions are shown.

Generally, a reduced geometry utilizing symmetry considerations, without taper and drift tube dielectric was modeled (see Fig. 2). Modeling tools include HFSS (High Frequency Structures Simulator) from HP [3] and ARGUS from SAIC [4]. HFSS is a finite element code that computes field distributions and S-parameters for passive 3D structures at a driven frequency. Material properties can be included. ARGUS is a 3D, volumetric simulation model for systems involving electric and magnetic fields and charged particles, including the capability to embed materials in the simulation region, with either time- or frequency-domain operation.

The cylindrical cavity radius and length are approximately set by gyroklystron performance calculations that determine the resonant frequency and Q of all cavities. Additionally, the wall thickness between the cylindrical and coaxial cavities is fixed at 10 mils for mechanical strength. This sets the inner radius of the coaxial cavity. For the initial simulation, the remaining coaxial cavity dimensions are chosen so that the unperturbed resonant frequency is the desired resonant frequency. The aperture width and height, coax cavity length and outer radius are adjusted to achieve the desired (cold) frequency and $Q_{ext}$, 93.4 GHz and 150, respectively, with better than 90% $TE_{01}$ mode purity. Large apertures are used in this design for tight coupling between the cylindrical and coaxial cavities. They are rectangular for simulation and fabrication convenience.

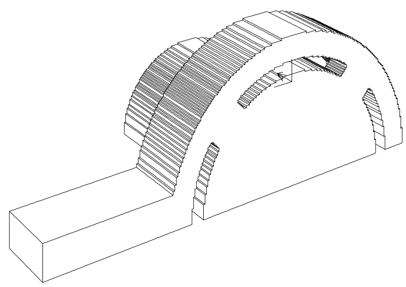

Figure 2: Input coupler simulation geometry for one quarter of the cavity.

## 2 SIMULATION METHODOLOGY

Both HFSS and ARGUS were used with various methods of solution to model many issues concerning the input coupler, including resonant frequencies, modes, Q's, resistive loading, mode purity, parameterization, and manufacturing tolerance. In particular, ARGUS and HFSS were used to model the Q and resonant frequency for the operating mode of the input coupler, as a means of benchmarking code performance for the coupler simulations. Excellent agreement was achieved between the two codes, where accuracy exceeding 0.1% was predicted.

Several techniques were employed with HFSS to determine the resonant frequency and Q of the $TE_{01}$ mode in the cylindrical cavity. As a first approximation, the stored electric field energy (proportional to $|\mathbf{E}|^2$) was integrated over the cavity and drift tube volumes when driven through the drive port at several frequencies. Frequency and Q, are determined from the peak and 'half-energy' points. A second method 'de-embeds' $S_{11}$ at the drive port to find the 'detuned short' position. The resonant frequency and Q are calculated from the phase of the reflection coefficient. HFSS has also been used to model a 'transmission' measurement by launching the $TE_{01}$ mode in the cylindrical cavity by evanescent coupling through the drift tube and 'receiving' at the rectangular port.

Resonant frequencies and Q's in ARGUS are determined from a variation of the 'detuned short' method due to Kroll and Yu [5,6]. Also, both HFSS and ARGUS were used to estimate the mode purity of the $TE_{011}$ circular cavity mode [7].

## 3 SIMULATION RESULTS

Performance of the input coupler is found using both HFSS and ARGUS to be quite sensitive to dimensions. The sensitivity of *f* and Q to slot dimensions and cylindrical cavity radius is shown in Figs. 3 & 4, respectively. Note that a 0.0006 cm change in radius shifts the resonant frequency by ~200 MHz. It is important that the slot angular orientation be within ~1° of 45° with respect to the input waveguide. A 1° slot rotation increases *f* by ~ 20 MHz and reduces Q by 3%. A 5° slot rotation increases *f* by ~ 36 MHz and reduces Q by 30%. A frequency and Q within +/- 100 MHz and +/- 50, respectively, of the design values are acceptable from overall circuit performance considerations.

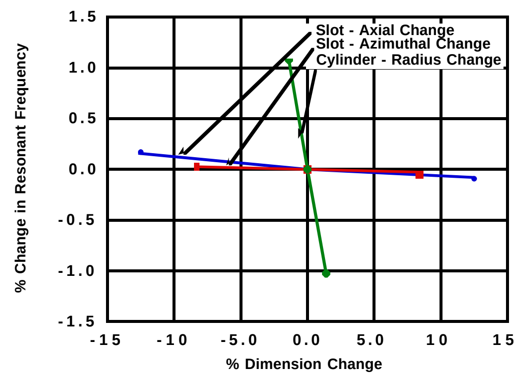


Figure 3: Resonant frequency change vs. dimensional change for a) slot axial size, b) slot azimuthal size, and c) cylinder radius.

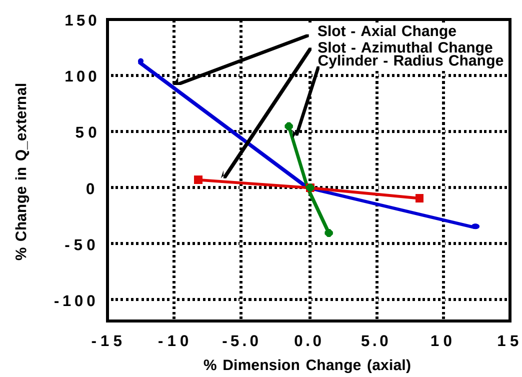


Figure 4: $Q_{ext}$ change vs. dimensional change for a) slot axial size, b) slot azimuthal size, and c) cylinder radius.

For the final design, the best compromise between coupling strength and bandwidth was achieved by 'stagger tuning' the cylindrical and coaxial cavities. The resonant frequency of the coaxial cavity was sufficiently higher than the cylindrical cavity that only ~ 10% of the combined stored energy is in the coaxial cavity over the nominal operating frequency range. For the final cavity dimensions, including stagger tuning, HFSS and ARGUS are in close agreement, as shown in Table 1.

| Simulation | Resonant frequency | Q |
|---|---|---|
| **HFSS (base case)** | 93.468 GHz | 149 |
| **HFSS (w/taper, dielectric)** | 93.467 GHz | 136 |
| **ARGUS (base case)** | 93.477 GHz | 157 |

Table 1. Resonant frequency and $Q_{ext}$ simulation results.

The calculated $TE_{01}$ mode purity is shown from both codes to be greater than 96% over a 600 MHz bandwidth. A color intensity plot of |**E**| through axial and transverse planes is shown in Fig. 5. The ohmic Q for the coupler is about 715, using 7.6e5 S/m for the conductivity of stainless steel in W-band. This conductivity is based on cold tests of simple cavities.

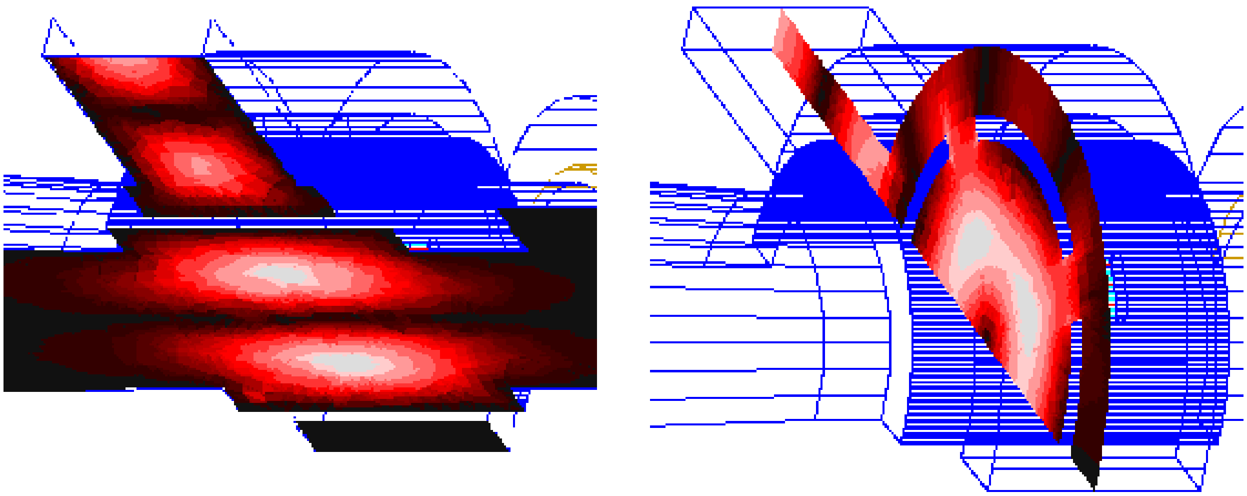

Figure 5. Intensity plot of |**E**| for transverse and axial cutplanes at 93.1 GHz.

## 4 COLD TEST RESULTS - SUMMARY

A prototype input coupler was constructed for testing. For the dimensions of this coupler, the calculated *f* and $Q_{ext}$ are approximately 93.14 GHz and 110 GHz, respectively, without wall resistivity. Based on other simulations with resistivity included, we expect *f* and $Q_{ext}$ to be 93.1 GHz and 95, respectively. Note that not all dimensions were available for simulation purposes, so that there is some uncertainty in these values.

The resonant frequency measured with a HP 8510C network analyzer, is 92.98 GHz in transmission mode and 92.96 GHz in reflection mode, in good agreement with predictions, although the test set-up is less than ideal. Power is injected into the drive port and a fraction of the power radiated from the drift tube is sampled with a WR8 waveguide for transmission mode measurements. $Q_{total}$ measured in transmission mode is 117, which implies $Q_{ext}$ ~ 140 if $Q_{ohm}$ is 715. More accurate comparisons between simulation and measurement will be made following modifications in the measurement hardware.

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