Final Report

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Advanced Quasioptical Launcher System

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Introduction

Research is on going to develop efficient microwave and millimeter sources producing continuous power levels of one megawatt or greater. Driving this research is the need for an efficient plasma heating source for magnetically confined fusion plasmas. If available, these high-average power sources could find applications in other areas, such as space communications, high-resolution radar, high-directivity communications, and next generation of linear accelerators.

Current high power gyrotrons produce power in high-order TE modes (TEmn modes with m,n>>1). These modes cannot be efficiently transported in low loss transmission systems. In addition, it is advantageous to separate the RF transmission path from that of the spent electron beam within the gyrotron. Both these issues are typically addressed using an internal mode converter and step-cut launcher[i]. The internal converter uses perturbations of the waveguide surface to convert the mode output from the cavity into a set of modes whose combined fields have a Gaussian-like profile. This Gaussian-like profile can then be efficiently launched, focused, and guided by small mirrors inside the vacuum envelope of the gyrotron. Figure 1 depicts such a launcher and guide system. In this way, the RF power is converted to a mode more suitable for low loss transmission, and the RF beam is separated from the electron beam. This allows implementation of

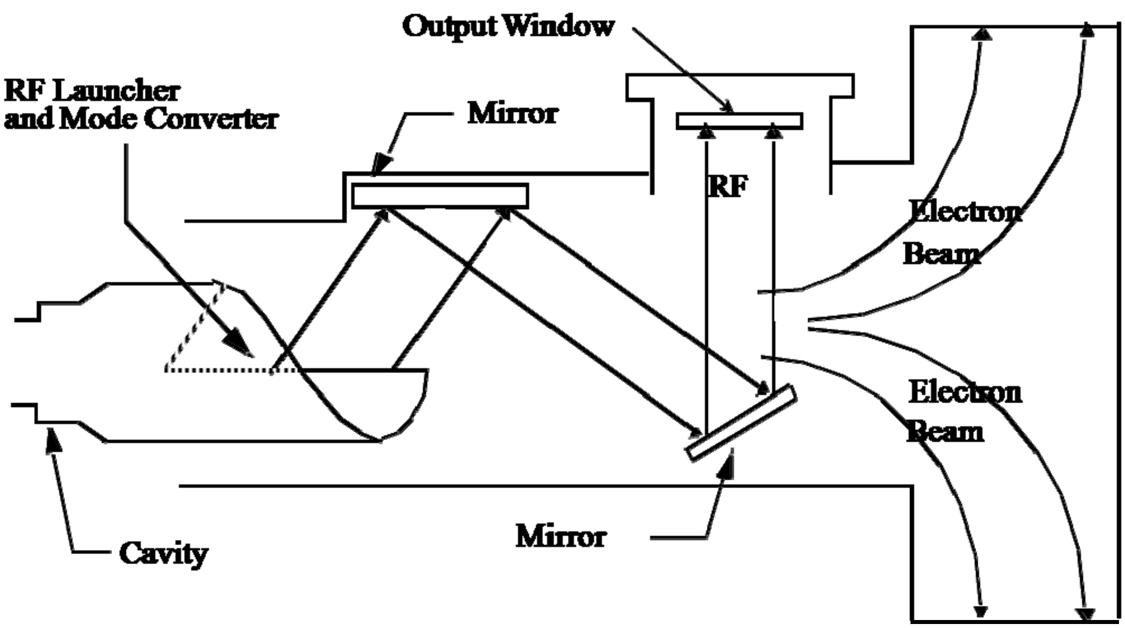

Figure 1 Internal mode converter and mirror transmission system for high-power gyrotron.

depressed collector and large surfaces for thermal dissipation without affecting the quality of the RF beam.

Calabazas Creek Research, Inc. (CCR) has previously developed an exact launcher analysis code (*Surf3d*) and an optimal synthesis code (*LOT*) for these quasi-optical (QO) converters[ii]. CCR developed commercial versions of the codes and they are currently in use by the main gyrotron developers in the US, Germany, Japan and India. QO launcher designs produced using these codes have substantial efficiency increases over earlier designs.

Equally significant, however, is the foundation these codes provide for designing new types of launcher systems with further improvements in performance and functionality. Examples of potential improvements include reducing sensitivity to machining tolerances of QO launchers, improving coupling efficiency to external corrugated waveguide systems, and developing QO launchers operable with multiple modes and frequencies. Achieving these objectives required developing new design/optimization algorithms and extending the functionality

In this Phase I and II of this program the following major achievements were obtained:

- Compact launcher design – QO launchers with significant reduction in length and having reduced sensitivity to machine tolerances
- Mirror analysis – Extension of *Surf3d* to allow full-wave analysis of mirror transmission line systems
- Multi-mode launcher analysis and design – Extensions to *LOT* to facilitate multi-mode launcher design for step-tunable gyrotrons
- Internal coupler design – A prototype design for coupling to corrugated waveguide inside the gyrotron vacuum envelope

Further details on these advanced QO launcher concepts are shown in the following sections.

The algorithms and codes developed as part of this program have been implemented into CCR's commercial launcher analysis and design tool suite (*Surf3d*/*LOT*). This code suite is installed at Communication& Power industries (CPI) in California, Karlsruhe Institute of Technology (KIT) in Germany and the Japan Atomic Energy Association (JAEA) in Japan, University of Wisconsin and Massachusetts Institute of Technology.

Compact Launcher

Existing high-efficiency mode converters and launchers are quite long, typically 200-300 mm. The mode converters in these launchers contain very small perturbations in the wall radius. These small deformations, on the order of 0.04 mm, are not much larger than the tolerance of computer numerically controlled (CNC) machines. As gyrotrons are constructed at higher frequencies, these wall deformations will become even smaller, which makes construction of high frequency launchers very challenging. Obtaining the desired design performance is problematic, because the uncertainty in the machining is a significant percentage (10%-20% for launchers at 110GHz) of the designed peak wall deformation. This uncertainty leads to variations in the performance of identically designed launchers. One solution is to measure the output of each launcher and design custom phase correcting mirrors. This is an expensive and time-consuming process. A more cost effective solution is design of reduced length launchers that use much larger deformations in the converter section.

Previous efforts to design compact launchers using CCR's *LOT* (Launcher Optimization Tool) have failed as the analysis method in *LOT* (coupled-mode/Stratton-Chu) uses first-order coupling terms which break down when the surface perturbations become on the order of a wavelength or larger. This breakdown leads to an incorrect result for the calculated radiated field. The solution is to use a full-wave analysis code to calculate the radiated field. CCRs *Surf3d* code which uses the surface integral approach provides such a code.

The primary task for enabling the design of compact launcher was integration of *Surf3d* analysis into the framework of the launcher optimization code, *LOT*. Additional tasks completed were optimization of *Surf3d* run time and implementation of parallel processing for decreased evaluation time of the numerical gradient used by the surface optimizer.

The new version of *LOT* with *Surf3d* integration has been tested on a 48 wavelength launcher (TE22,6 / 110GHz) which is about 30% shorter than typical launcher lengths. An initial optimization of the launcher was done using the default coupled-mode Stratton-Chu analysis. A good design was obtained with a 0.97 coupling factor to the Gaussian. However, when this design was analyzed using *Surf3d* the actual Gaussian coupling factor was actually 0.92. This design was then re-optimized with the new version of *LOT*. After 3 iterations the Gaussian content had increased to 0.98.

This release version of the code which implements this advance has already been used at CPI for advanced QO launcher design. Two new designs have been developed. The first was for a 95 GHz gyrotron used as a source in an USAF active denial system and the second was 170 GHz gyrotron for testing of ITER transmission line components at Oak Ridge National Laboratory. The new code was credited as enabling designs that were not possible with the original version of the code[iii].

Mirror Analysis Code Development

Existing QO launcher systems in gyrotrons include the launcher and three to four mirrors to shape and guide the RF beam for transmission through the output window. The designs typically use smooth analytic shapes for the first mirrors, with the last two mirrors employing synthesized surfaces to maximize Gaussian content. This results in a system where the alignment of the beam direction through the window cannot be decoupled from the alignment for best phase correction. Consequently, there is a trade-off between beam quality and proper beam steering. This is a fundamental flaw with the existing four-mirror design approach, which uses the last two mirrors for both phase correction and beam steering. Prior to the introduction of *Surf3d*, launcher design codes could not provide sufficiently accurate field information for synthesis of the mirrors for maximization of beam Gaussian content at the window. A measurement of the field at the position of the third mirror was used as input for the synthesis of the surfaces for mirrors three and four.

Synthesis of mirror surfaces requires calculation of the scattered field from the mirror surface. While it is possible to use existing codes for this calculation, it is preferable to do the calculation using an extended version of *Surf3d*. Existing codes are based on the induction theorem and an approximation of image theory. The approximations become worse with increasing mirror curvature and large surface deformations, which cause “shadowing” of the incident field. In addition, the time required for an exact mirror calculation in an upgraded version of *Surf3d* (based on the highly efficient multi-level fast multi-pole algorithm) is on the same order as required by the current codes. However, the original *Surf3d* code could not be used for this calculation, because it has only a waveguide mode as an incident source. The incident source field on a mirror is the Gaussian-like beam emanating from the launcher.

Modifications to *Surf3d* were implemented to allow this calculation. The main task was creation of a data structure that represented the radiated electromagnetic fields of a complex source (launcher or scattered off a mirror surface). These fields are represented as a multi-pole, plane wave expansion that allows rapid calculation of the radiated field at a desired point. From this incident field, the exact surface currents are calculated using the existing algorithms in the code. Finally, the total radiated field is obtained from the sum of the complex source electromagnetic field and scattered field of the induced surface currents on the mirror.

The launcher and mirror configuration shown in Figure 2 is used to demonstrate the significant computational advance that was obtained with the new code algorithms. This is a 95 GHz launcher and a single mirror with surface areas of 2560 and 1290 square wavelengths respectively. A *Surf3d* computation of the radiated field for the combined launcher and mirror took 82 minutes and 900 megabytes of memory on a 3 GHz PC. The *Surf3d* computation of the launcher alone to generate the incident field for a separate mirror calculation required 37 minutes and 630 megabytes. A separate mirror calculation using the new *Surf3d* code took 10 minutes and 210 megabytes of memory. The radiated field of the combined launcher and mirror calculation was essentially identical to that obtained by the two-step calculation of launcher calculation

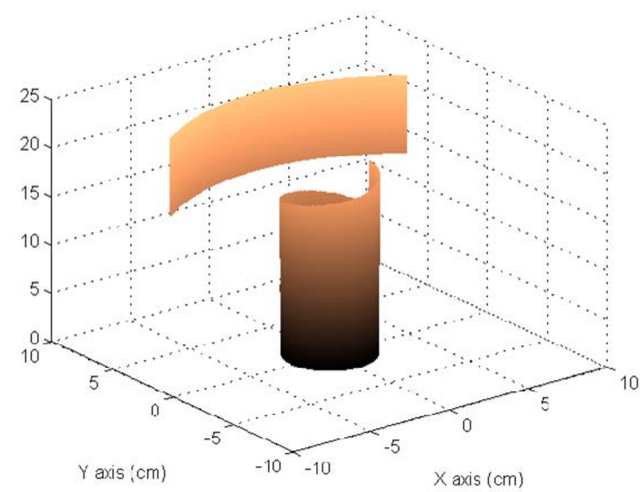

Figure 2 QO launcher and reflecting mirror.

followed by a mirror calculation. Separation of the launcher and mirror calculation allows an eight-fold decrease in the computation time to do one iteration of the mirror fields as part of a mirror synthesis process.

The commercial release of the additions to the *Surf3d* code was completed and it has been released to the Surf3d/LOT user community. This mirror analysis feature is already in use providing a final design check on the mirror transmission line designs at CPI and KIT.

Multi-Mode Launcher Design and Software

Several research institutions are investigating step-tunable gyrotrons for control of instabilities in plasma fusion devices, for plasma diagnostics, and for spectroscopy, including electron paramagnetic resonance spectroscopy. Since the gyrotron mode and frequency change with steptuning, the RF beam quality and position vary within the transmission system. To date the primary focus for improving the RF beam quality for multiple modes has involved synthesis of the mirrors following the QO mode launcher. However, the optimization techniques developed at CCR[iv] for single frequency converters should be applicable to multiple frequency systems. To test this hypothesis, the single frequency launcher optimization code *LOT* was modified to maximize Gaussian content of the radiated field for two frequencies (modes).

The test case was a prototype design for a gyrotron launcher for the ASDEX upgrade. KIT provided the prototype design which used the TE17,6 at 105 GHz and TE22,8 at 140 GHz. The launcher was 175 mm long with an initial radius of 19.3 mm (7.5% above cutoff) and a taper of 0.002 mm. The design was based on the analytic approach originated by Denisov[i]. The KIT design was used as an initial guess for optimization. The optimization goal function maximizes the far field, complex, Gaussian content of the two modes while minimizing the field intensity at the launcher cut. Equal weighting was given for the optimization goals of both modes. Significant improvements in the Gaussian content and reduction of fields at the launcher cut were obtained with this approach. The fractional Gaussian content for the TE17,6 mode increased from 0.732 to 0.979, and the fractional Gaussian content increased from 0.929 to 0.985 for the TE22,8 mode. The reduction of the field intensity at the launcher cut can be seen in Figure 3. The results clearly demonstrate that the optimization technique produces a superior design for the two-frequency case. It is also expected that similar improvements will be seen for multi-frequency cases.

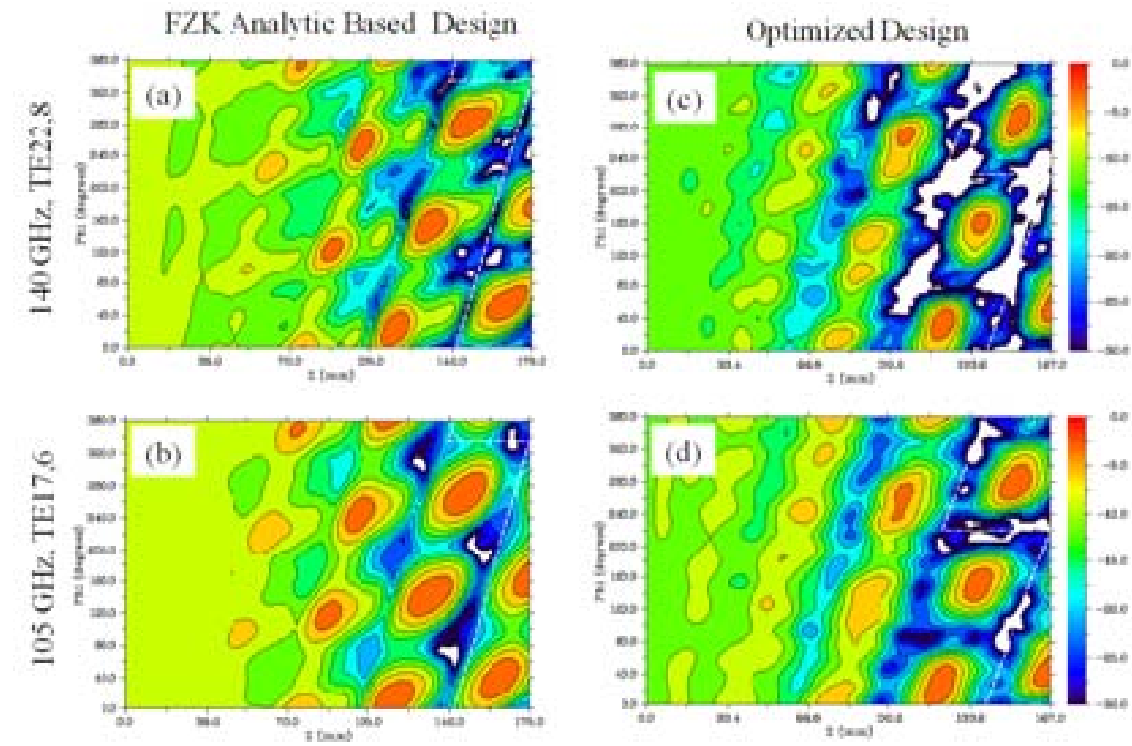

Figure 3 Field intensity of surface of multi-frequency launcher. Launcher spiral cut indicated by dashed white line. (a) FZK designed launcher for TE22,8 at 140GHz. (b) FZK designed launcher for TE17,6 at 105 GHz. (c) Optimized launcher for TE22,8 mod at 140 GHz. (d) Optimized launcher for TE17,6 mode at 105 GHz.

There is interest in exploring the use of a multi-frequency gyrotron for suppression of neo-classical tearing modes in the DIII-D experiment at General Atomics (GA). A design of a multi-frequency launcher with the frequencies of interest to GA was undertaken as part of this program in support of this research. This work was done in collaboration with the University of Wisconsin (UW), with CCR providing the launcher design and UW was to design the mirror transmission system and measurement.

The launcher design work was completed by CCR. A good multi-mode launcher design was achieved for the two modes of interest (TE22,6 at 110GHz and TE24,7 at 124.5GHz) with a high Gaussian beam quality and small azimuthal beam shift (1.2 degrees) and beam angle divergence differences (<5%). UW completed the design of a four-mirror transmission line for this launcher. Excellent Gaussian content at the output window was predicted (>99%) with minimal power clipping at the window. Mechanical design drawings were generated at CCR for the launcher and mirrors for a low-power test assembly (Figure 4). The drawings and a mode generator for multi-mode testing were provided to UW by CCR to enable low power testing of the design. The test at UW had not been completed at the time of this writing.

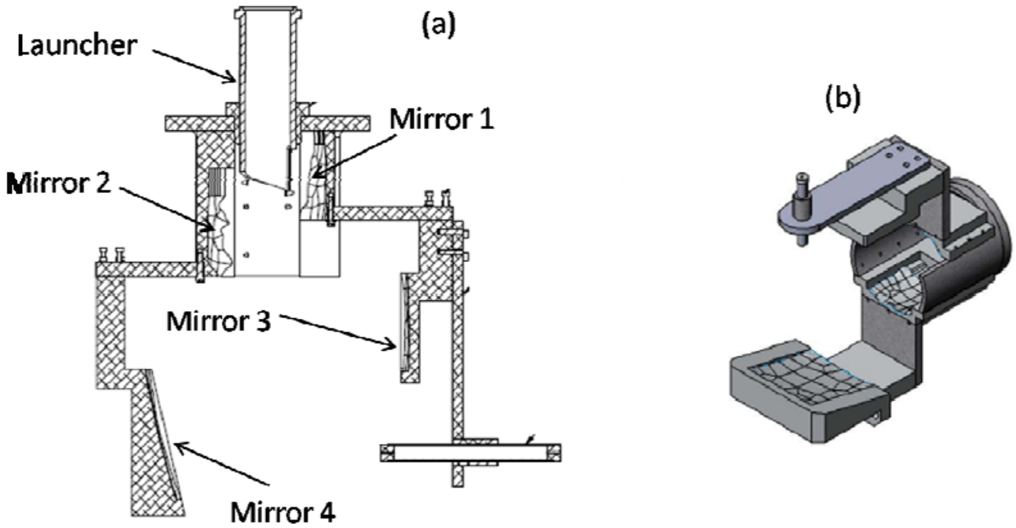

Figure 4 CAD design for low-power test of multi-mode launcher and mirror system. (a) 2-D drawing. (b) Solid model 3-d rendering.

A commercial release of the *LOT* code with multi-mode optimization was completed and released to the Surf3d/LOT user community. The techniques developed for multi-mode optimization of launchers have been published in the IEEE Transactions on Plasma Science[v].

Internal Coupler to Corrugated Waveguide

Modern high power gyrotrons produce power in high-order TE modes (TEmn modes with m,n>>1). These modes cannot be efficiently transported in a low loss transmission system. In addition, it is advantageous to separate the RF transmission from that of the spent electron beam within the gyrotron. Both these issues are typically addressed using an internal mode converter and step-cut launcher, which are commonly referred to as the QO launcher. The converter has small deformations in the waveguide surface to transform the high-order cavity mode into a set of modes whose combined fields have a Gaussian-like profile. The Gaussian-like beam can then be efficiently launched, focused, and guided by mirrors inside the vacuum envelope of the gyrotron. In this way, the RF power is converted to a mode more suitable for low loss transmission, and the RF beam is separated from the electron beam. This allows implementation of a depressed collector with large surfaces for thermal dissipation without affecting the quality of the RF beam. This method has been the primary technique for RF-electron beam separation in high power gyrotrons since the early 90's. The development of this technique was one of the key technologies enabling the development of MW level gyrotrons. However, it is a less than ideal solution.

There are several deficiencies in this technique such as internal diffraction losses, electron beam potential depression, and mirror alignment issues. Coupling to a HE11 corrugated waveguide mode inside the gyrotron could eliminate the aforementioned deficiencies in the current approach. In addition, substantial cost savings can be realized by eliminating the need for two to three adjustable mirrors in the gyrotron and the external mirror optical unit used to couple the output Gaussian beam to the corrugated waveguide transmission line. A final cost savings would be realized by the large reduction in the required diameter of the diamond material in the output window. Despite all the advantages an internal coupler would have over the existing QO launcher and mirror systems, there have been no designs to date using this approach. The most likely reason for this is because, at least until recently, there were not any full-wave RF computational tools capable of accurately analyzing the structures that would be required to construct an internal coupler. A full-wave analysis of the QO launcher is a formidable problem because of the large electrical surface area. The lengths of QO launchers range from 50 to 100 wavelengths with diameters of 10 to 20 wavelengths. Computation of the mode conversion and radiation from these launchers using conventional approaches such as volume finite-element or finite-difference full-wave codes would require 100's GBs of RAM and weeks of CPU time.

CCR's *Surf3d* code is based on the electric surface integral equation and the computation is accelerated by the multi-level fast multipole technique. The code has made high-accuracy analysis of QO launchers quite tractable with memory requirements of just a few GBs of RAM and only tens of minutes of CPU time. With this code the task of designing an internal coupling of the cavity power to corrugated waveguide became feasible on a typical high-end PC.

The approach used to generate a RF beam suitable for internal coupling to corrugated waveguide is based on a modification of the existing QO launcher technology. The radiated field from QO launchers, while Gaussian in profile, is highly elliptical with the azimuthal beam waist size typically a quarter to a fifth of the longitudinal waist size. In addition the azimuthal beam waist size is very narrow (on the order of a few wavelengths) so there is a rapid azimuthal divergence of the beam as it radiates from the launcher. In order to couple efficiently to the HE11 mode in a corrugated waveguide it is necessary to modify the radiated field from the launcher to greatly reduce the azimuthal beam divergence and ellipticity. This can be accomplished by modifying the latter part of the launcher design so the Gaussian beam is transformed to a less elliptical shape. Thus the length of the launcher is the same as the original launcher and maintains the same clearance from the electron beam. A single mirror placed on the outer envelope of the tube is then used to match the beam waist to the HE11 mode in the corrugated guide and tilt the output beam angle to be parallel to the tube axis (Figure 5).

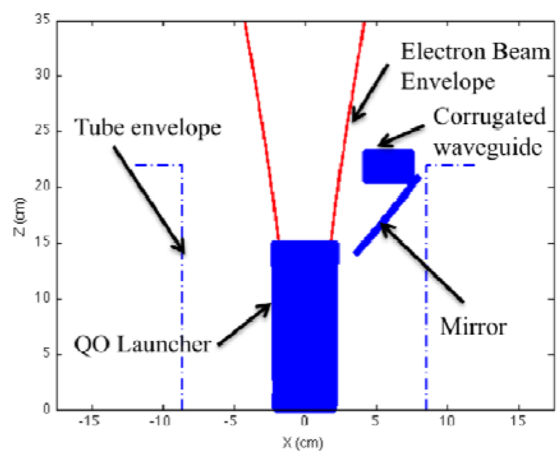

Figure 5 Internal coupler approach.

We have done a preliminary design to test the feasibility of the proposed coupling approach. The starting point was a 110 GHz QO launcher in a gyrotron currently in test at Massachusetts Institute of Technology Plasma Science and Fusion Center (MIT). The beam generated by this launcher has a waist size of 0.25 cm and 1.23 cm in the azimuthal and longitudinal directions respectively and radiates from the launcher with an angle of 65 degrees with respect to the tube axis. After modification of the launcher design the output beam waist was size was transformed to 0.9 cm and 1.0 cm in the azimuthal and longitudinal directions respectively.

The design of the single matching mirror was numerically optimized to provide maximum coupling to the HE11 mode in the corrugated waveguide. The coupling efficiency (power in HE11 mode / power in cavity mode) for the design is 97.4%. About 1.3% of the incident cavity power is not coupled into the waveguide. The HE11 mode purity is 98.8%. In this design only the latter part of the launcher and matching mirror were optimized. With optimization of the converter section of the QO launcher it is likely that the coupling efficiency and HE11 mode purity could be improved to better than 99%.

A mechanical design of the launcher to fit in the MIT tube has been completed and the parts have been built. A solid model of the coupler mechanical design is shown in Figure 6. Since the mirror is very close to the launcher, machining of the launcher and mirror was done in a single operation. This machining process insures proper alignment of the launcher and mirror focusing system. In addition to the launcher and mirror, a miter bend is used to connect the output power through the existing window design.

The completed assembly has been shipped to MIT. The low power testing of the coupler will is expected to take place in the summer of 2010 and integration and high power test in the tube later in the year.

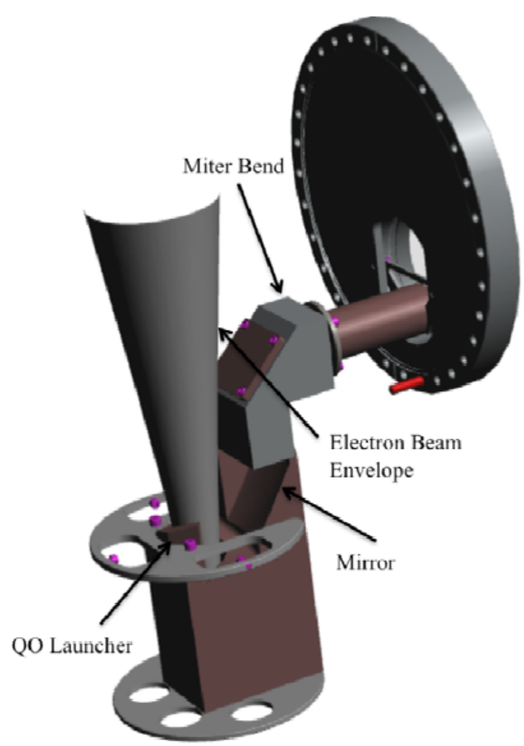

Figure 6 Solid model of internal coupler prototype.

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