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Final Report for the NRL Quasioptical Gyrotron Program

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The quasioptical gyrotron (QOG) has been under development as a high power, tunable source for tokamak plasma heating applications. In the QOG the conventional cylindrical gyrotron cavity is replaced with a Fabry-Perot type resonator formed by a pair of open mirrors. This has a number of advantages for high power operation including large interaction volume, low Ohmic heating density, and inherent separation of the electron and radiation beams. Prior to the FY91 effort, the quasioptical gyrotron was investigated in the single-cavity, free-running oscillator (FRO) configuration. As such, the QOG produced 600 kW at frequency of 120 GHz and an efficiency of 8% with peak multimode and single-mode efficiencies of 12% and 9%, respectively, obtained at lower power. Frequency tuning from 90–130 GHz was demonstrated. The addition of a simple, single-stage depressed collector raised the peak efficiency to 16%. Analysis of these results indicated that the experimental efficiencies are less considerably less (at least a factor of two) than theoretical expectations. Given the critical importance of source efficiency for large-scale ECH applications, understanding the causes of the low QOG efficiency and finding ways of improving it became a top priority for the current NRL program. As a result of this emphasis, we temporarily deferred the evaluation of output coupling methods for the QOG.

Significant changes in the experiment were introduced during this contract period in order to investigate efficiency enhancement. The experimental modifications adopted for this investigation included adding an open-mirror prebunching resonator, which can be driven by an 85 GHz, 1.5 kW Extended Interaction Oscillator, and capacitive probes to measure the electron beam velocity pitch ratio, or "alpha." The prebunching resonator can provide greatly enhanced control of the main-cavity mode, and its detuning, by the technique of mode priming. As a result of our investigation of mode priming and oscillation start-up conditions, we have been able to increase the peak QOG efficiency to 17.9% while operating in a single longitudinal mode.

The prebunching cavity benefits the operation of the QOG in several ways: i) It allows mode priming of the main cavity which is highly overmoded with many modes in the interaction bandwidth; ii) it can enhance the phase bunching of the beam to enhance the efficiency of the interaction; and iii) it can be used to obtain phase and frequency-locked operation. Our initial studies of this configuration have emphasized the study of mode priming as being of greatest interest to the ECH application. Mode priming can have a strong effect on the steady-state efficiency when the main cavity has several modes in the interaction bandwidth. This is because the interaction efficiency depends critically on the detuning of the resonance condition with greater detuning being associated with higher efficiency. However, less detuned modes typically have higher linear growth rates and may suppress the more detuned modes during start-up. The effect of the prebunching cavity is to provide a boost to the desired main cavity mode which allows it to overcome the less detuned, lower efficiency modes. Once the desired mode grows to large amplitude, it is able to suppress the competing modes without a prebunched beam.

The quasioptical prebunching resonator chosen for the first tests of prebunching was designed to operate stably at a frequency of 85 GHz, a voltage of 70 kV, a beam current of 10 A, and an alpha of 1.5. The Q factor is relatively low for a Fabry-Perot resonator, about 2000 at 85 GHz, in order to increase the self-oscillation threshold current. Experimental operation is basically as designed with operation at higher current possible using lower alpha. Operation could be extended to higher power by simply reducing the size of the prebunching cavity mirrors. The output cavity was tilted 2% from the perpendicular orientation to enhance single-mode stability and coupling to the prebunched beam. The QOG pulse consisted of a

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4 μsec rise and a 13 μsec flat-top. The EIO pulse length was 2 μsec and was typically applied during the QOG start-up. A typical operating sequence consisted of first finding a single-mode FRO operating point for the QOG and then increasing the detuning until mode hopping or switching occurred. The EIO signal was then used during start-up to restore stable single-mode operation and the detuning was further increased until the onset of further mode hopping. Typical efficiency results include 12.5% efficiency at 7.25 A as an unprimed FRO, and 15.1% at 6 A while primed by the EIO. Interestingly, the highest detuning and efficiencies (up to 17.9%) were obtained in a FRO regime characterized by high alpha during start-up. EIO priming was ineffective in this regime which was characterized by higher than usual cathode electric fields during start-up. Our understanding of this regime is still incomplete but it appears that a high detuning mode is able to grow during the voltage rise as a result of the high alpha condition. The general conclusions of our work to date is that the prebunching resonator allows for more precise control of start-up conditions, giving rise to better efficiency and mode selectivity.

Our measurements of the beam alpha using the capacitive probe confirm our expectation from trajectory simulations that high alphas, ≥ 1.5, are achievable in our configuration. This indicates that low beam alpha is not the main reason for low efficiency in the QOG. At higher currents the prebunching resonator models the effect of a drift-tube oscillation. The rf fields associated with prebuncher-cavity oscillations can be much larger than the rf fields generated by the EIO. Strong oscillations in the prebuncher produce a signature in the output pulse of the main cavity and reduce the efficiency of the main cavity interaction when the cavity frequencies are different. Another new feature of our experiment compared to previous NRL results is the observation of second harmonic emission under certain conditions. We also find that our best results are unexpectedly sensitive to mirror alignment which may perhaps be related to competition with the second harmonic.

In the area of output coupling, we have assessed two basic approaches: 1) mirror edge diffraction and 2) the use of a Littrow-mount diffraction grating. The former is used in our current experiments but a reflector is needed to obtain an output mode suitable for low-loss transmission. This approach should be compatible with significant frequency tuning. The diffraction grating approach, on the other hand, appears to be limited to a single frequency, but it yields a Gaussian output mode directly and should be highly selective either for or against higher harmonic interactions. An important element of either design will be the use of a larger resonator with the mirrors placed outside the magnet dewar cross-bore. This will involve a mirror separation of greater than 80 cm. This change is also required for obtaining low ohmic losses and for testing the effects of higher mode density on operation. Some of the hardware for the new cross-bore has been designed.

The importance of our present work is that it represents new insight into the factors controlling the efficiency of quasioptical gyrotrons. We have demonstrated that the technique of mode priming provides a method for improving efficiency via enhanced mode detuning and leads to more stable single-mode operation of highly overmoded resonators. The latter feature is an important consideration for output coupler and rf transmission system optimization and can make the QOG less sensitive to external influences such as window reflections. We have shown that a prebunching resonator is readily implemented in the quasioptical configuration. It is relatively free of the problems of spurious modes and cross-talk which plague over-moded prebunching cavities in conventional gyrotrons. The observation of almost 18% efficiency represents a doubling of our previous best single-mode results. Further improvements are expected from the optimization of start-up conditions and the study of the effects of the second harmonic interaction. A detailed description of the technical results obtained during this program are given the NRL Memorandum Report 6793-93-7387.