PIC Simulation Study of a 35 GHz, 200 kW Gyroklystron

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***Abstract*— A three-dimensional PIC simulation of a 35 GHz, 200 kW two cavity gyroklystron amplifier has been performed to study the electron beam and RF wave interaction behavior using a commercial PIC code 'MAGIC'. The electromagnetic field analysis of the RF structure in the absence of the electron beam and beam-wave interaction study in the presence of the electron beam have been carried out for the performance evaluation of the device. Electromagnetic field analysis has been done using the eigenmode solver, which ensures the structure operation in the desired TE_{01} operating mode at 35 GHz frequency. Electron beam and RF wave interaction simulation confirm that the present gyroklystron meet the required specification in terms of output power and gain. Moreover, the particles phase space behavior along the interaction length has been also demonstrated to realize the energy transfer phenomena. An output power around 200 kW at 34.95 GHz with ~35% efficiency and a bandwidth of 0.29% have been obtained considering no spread in electrons velocity. Our simulated result matches with the experimental values within 8%.**

***Index Terms*—** Fast-wave device, Microwave tube, Millimeter-wave high power amplifier, PIC simulation.

I. INTRODUCTION

Conventional microwave tubes, like, klystron, TWT, etc., are not capable of radiating high power in the millimeter and sub millimeter waves range. The RF power level reduces at the higher frequencies due to the limiting factors, like, DC power dissipation, RF losses, electron current density, heat transfer capability, material breakdown, etc. Efforts to narrow down this technological gap led to research and development of fast-wave microwave tubes operating in the millimeter-wave and sub-millimeter-wave frequency bands, for instance, gyrotron-devices based on CRM and Weibel instabilities. In gyro-devices, an electron beam moving in helical trajectories interacts with the transverse component of RF electric field supported by a waveguiding structure in the fast-wave regime. Gyroklystron is a fast-wave electron-beam device which combines the multi-cavity klystron configuration with the cyclotron resonance maser (CRM) instability energy extraction mechanism of the gyrotron. Its operation is similar to a conventional klystron except that electron bunching occurs in the transverse direction rather than in the axial direction and the overmoded cavities are used [1-2]. This scheme makes them useful at the higher frequencies with larger cavity dimensions. The schematic of a two cavity gyroklystron is shown in *Fig.* 1.

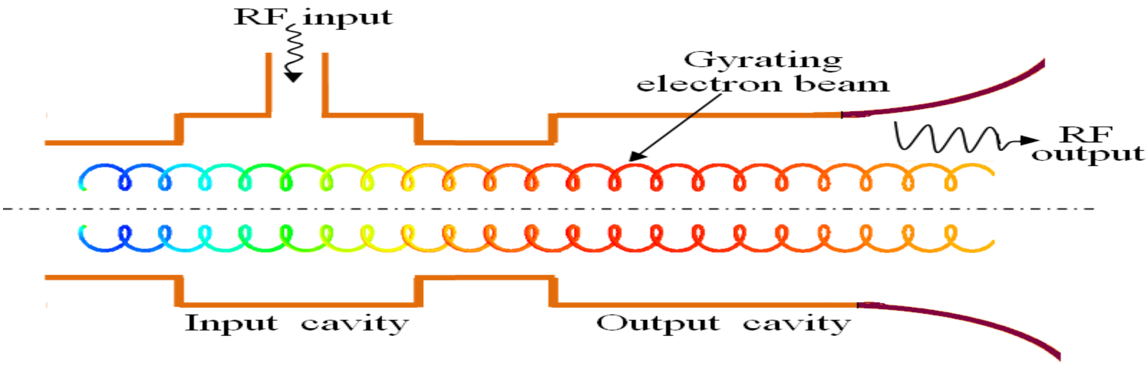

Fig. 1. Schematic of a two-cavity gyroklystron.

Presently, considerable research interests have grown up for the gyroklystrons due to their capabilities to provide high gain with moderate bandwidth in the mm-wave regime. Gyroklystron's applications include plasma heating, industrial heating, material processing, active plasma diagnostics, radar communications, particle accelerators, spectroscopy, etc. [2-3]. In the Ka-band regime, a two cavity gyroklystron had been successfully developed at IAP, Russia, which is capable of delivering an output power of 750 kW at center frequency 35 GHz in the TE_{021} mode with 24% efficiency and 20 dB gain [4]. Later on, a detailed study of 200 kW two-cavity, three cavity and four cavity Ka band gyroklystrons for millimeter wave radars was carried out at the Naval Research Laboratory of United States [5-7]. In the W band regime, a four-cavity gyroklystron amplifier producing 100 kW peak power and 10 kW average power at center frequency around 94 GHz with a bandwidth 700 MHz has been developed at the Naval Research Laboratory, USA for new high power radar named WARLOC [8]. Recently, Zasypkin *et al.* at the Institute of Applied Physics, Russia reported the experimental results of a 93.2 GHz gyroklystron amplifier operating in TE_{021} mode [9]. In this experiment, a peak output power of 340 kW with 27% efficiency, 23 dB saturated gain, and 0.41% (380 MHz) bandwidth was obtained using a 75 kV, 17 A electron beam [9].

To demonstrate the mathematical models for the design and analysis of gyroklystron using self-consistent as well as linear and nonlinear approaches; a number of literature have been published [10-14]. These approaches have also been adopted for the optimization of device efficiency and RF output power. With the advent of fast computers, particle-in-cell (PIC) simulation offers a lot of insight in understanding as well as supporting the established theories. Presently, PIC codes are widely used by the researchers to investigate the RF behavior of the gyro-devices and also helpful in optimizing the device performance. There are two-dimensional as well as three-dimensional codes. Some of these codes are CHICPIC, MAFIA, Particle Studio, MAGY and ARGUS. The simulation code MAGY developed at the University of Maryland and Naval Research Laboratory, is a large signal time-dependent multimode code used for simulation of slow and fast wave microwave tubes [15-16].

Here, a commercially available 3-D PIC code "MAGIC" has been used to study the RF behavior of

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a 35 GHz, 200 kW two-cavity gyroklystron. MAGIC is a user-configurable FDTD-PIC simulation code used for the modeling and simulation of beam wave interactions between space charge and EM fields [17]. The MAGIC software is effectively used for the PIC simulation of klystrons, magnetrons, gyrotrons and gyro- TWTs. Its implementation for the gyroklystron amplifiers have to be studied yet. Here, an experimentally reported two-cavity gyroklystron has been investigated using PIC simulation for this purpose [5]. The complete nonlinear behavior of the interaction mechanism in terms of saturation and efficiency of output electromagnetic radiation is clearly demonstrated. The eigenmode analysis (cold, in the absence of the electron beam) and the electron beam RF wave interaction analysis (hot, in the presence of the electron beam) have been carried out in detail for this purpose. The eigenmode and field analysis is performed in the absence of electron beam using eigenmode solver to ensure the device operation in the desired mode and frequency. The exact operating mode is confirmed by observing electric and magnetic field patterns and their variations along radial as well as in axial directions. Further, the electron beam and RF wave interaction simulation is carried out for the performance evaluation of the gyroklystron amplifier in all respects. The results obtained from the present study are validated with the experimental results reported in the literature [5].

II. PIC SIMULATION

The process of designing a gyroklystron includes the choice of the RF operating mode corresponding to the RF interaction structure, electron beam parameter, and magnetic field. The finalization of the RF interaction structure consists of several steps. First, the resonance frequency and quality factor with a desired field profile for each of the cavities are chosen. Based on this information, cavities shape, size and connecting drift tube radii are selected. To ascertain this, electromagnetic analysis of gyroklystron structure is carried out in the absence of the electron beam, also known as the cold analysis. The results obtained from the cold analysis are used to predict the electron beam and RF wave interaction behavior of the gyroklystron device in the presence of the electron beam which is also known as the hot analysis. At this point, the various device input parameters, such as, beam current, voltage, transverse to axial beam velocity ratio (pitch factor), guiding center radius and magnetic field values are judiciously chosen with the help of its parametric analysis. The operating current and the magnetic field are mainly decided by the start oscillation current criteria study, necessary for the stable operation of the device. The coupling coefficient curve helps us to launch the electron beam at optimum beam radius for maximum beam to mode coupling.

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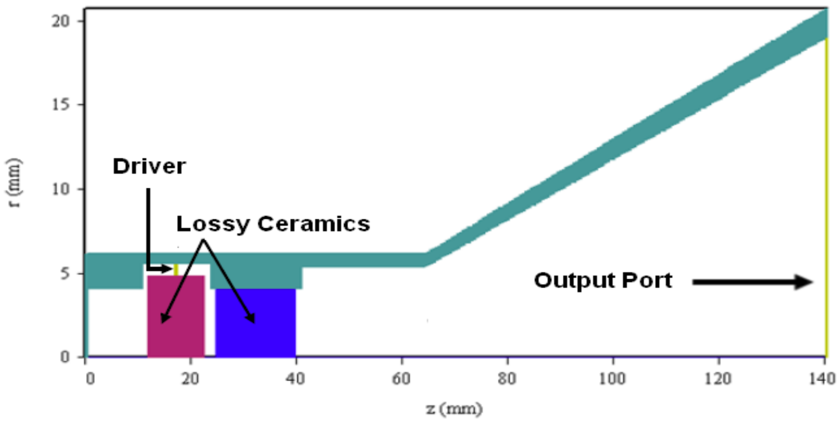

Fig. 2. Cross-section of a two cavity gyroklystron interaction structure.

A three-dimensional structure consisting of all-metal cylindrical cavities, is modelled using the cylindrical coordinate system (z, r, θ) for PIC simulation using 'MAGIC' code. Material properties of the cavities wall are typically assigned as metal (copper) to reduce the ohmic losses. The conductivity of the copper used in the simulation is taken as 5.8×10^7 S/m. A port has been assigned at the output taper end to observe the output signal. The cross-sectional view of the model used in the PIC simulation is shown in *Fig.* 2. Proper meshing is made for the discretization of the structure to get fast converging results. External loading in the RF input cavity is done to achieve the desired quality factor by observing the EM energy decay inside the cavity. Drift tube is externally loaded to avoid any cross-talk between the two cavities by absorbing the field leaked from the cavities. In 'MAGIC' software CONDUCTANCE command is used to define the lossy material. The CONDUCTANCE command specifies a finite conductivity (mhos/m) within an object. It must be a volume in a 3D simulation. The conductance may be entered by specifying the conductivity of the material. Conductivity will be applied only within the specified object and will result in an additional current as specified by Ohm' Law, $\mathbf{J} = \sigma\, \mathbf{E}$, which is applied to Ampere's Law as an additional current source. The ohmic power dissipated due to this conductance material allows us to achieve the desired quality factor [17]. In our simulation, we have used the conductance of material = 0.01 mhos/m for loading the input cavity. The conductance of material = 0.04 mhos/m has been taken for loading the drift tube.

The gyrating electron beam of desired guiding center radius is introduced at the input end of the interaction structure with the help of gyro beam emission command of this PIC code. The gyro emission produces a beam center axis parallel to the externally applied magnetic field. The external static magnetic field of strength 1.31 T is applied axially along the interaction structure. The typically selected design parameters for the present work are taken from the reported experimental results of J. J. Choi [5]. The RF input and output cavities lengths for the present gyroklystron are taken as 1.5λ and 2.75λ, respectively, for the operating TE_{01} mode resonating at 35 GHz [5]. The length of the RF output cavity is taken larger than that of the input cavity to enhance the electron beam and RF wave interaction process in the output cavity to get the maximum RF output power and efficiency. The input and output cavity radii are 5.6 mm and 5.35 mm, respectively. The drift tube is in cut-off to the operating mode with length equal to 1.7λ and radius equal to 4.1 mm. The present gyroklystron utilizes a gyrating electron beam of 70 kV, 8.2 A having the velocity pitch factor of 1.43 and beam radius equal to 2.65 mm.

III. RESULTS AND DISCUSSION

In order to study the electron beam and RF wave interaction mechanism in a two-cavity gyroklystron, firstly, the desired mode of operation at the desired operating frequency is selected by simulating the structure in the absence of the electron beam. Secondly, RF output power and the gain of the two-cavity gyroklystron are obtained by simulating the structure in the presence of the electron beam.

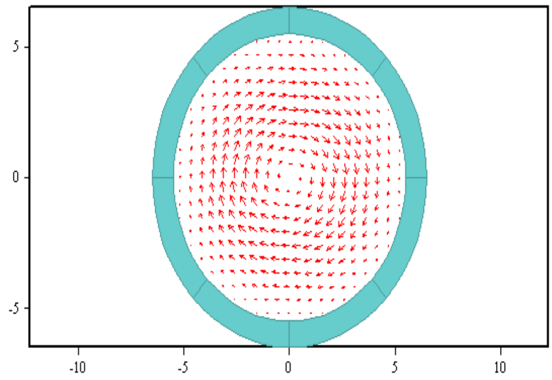

Fig. 3. Electric field distribution for input cavity of gyroklystron.

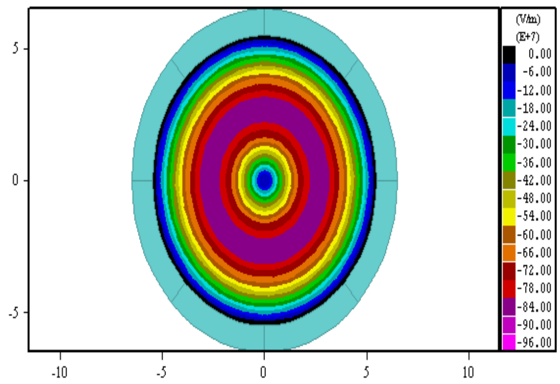

Fig. 4. Contour plot of electric field for input cavity of gyroklystron.

A. Eigenmode and Electromagnetic Fields

Electromagnetic simulation of the gyroklystron cavities has been carried out before the PIC simulation to observe the desired operating mode and resonant frequency in the absence of the beam using eigenmode analysis. Using this technique, the presence of the desired mode inside the cavities is confirmed by observing the electric field pattern. *Figs.* 3 and 4 show the vector and contour plots of electric field, respectively, of the input cavity of the gyroklystron which indicates that the desired TE_{01} mode is present inside the cavity. The overall quality factor of a cavity can be obtained using well known relation, $(Q_{total})^{-1} = (1/Q_{ohmic})^{-1} + (1/Q_{diffractive})^{-1}$. The diffractive quality factor for a closed cavity is usually very high. Therefore, the total quality factor of the cavity is approximately equal to the ohmic quality factor. The gyroklystron cavity is loaded with lossy ceramics to achieve the desired quality factor. The total quality factor of gyroklystron cavity is decided by making use of start oscillation criteria study. The quality factor is chosen in such a way that the device can operate in the stable region without going into the oscillation regime. In the present work, the loaded quality factor of the cavity is optimized to the desired value through external loading. For the estimation of the loaded quality factor, entire cavity volume is excited by a current driver placed at its center with

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excitation frequency 35 GHz. The decay of EM energy inside the cavity is observed for the estimation of the loaded quality factor. The EM energy decays slowly inside this cavity, which demonstrates the resonant behavior of the interaction structure. For our present simulation, loaded quality factor is obtained ~200. In *Fig*. 4, the required quality factor for the input cavity has been obtained.

B. Electron Beam and RF Wave Interaction

The hot analysis of gyroklystron is demonstrated by introducing the gyrating electron beam with a beam current of 8.2 A and beam voltage of 70 kV at the left end of the interaction structure. The guiding center radius used here is 2.65 mm. The velocity spread effects are assumed to be zero for carrying out the present simulation. Since, provision for the inclusion of velocity spread effects is not present with PIC code 'MAGIC'. In experimental devices, 5% to 10% velocity spread is always present, which deteriorates the electron bunching due to degradation in the quality of the electron beam as a result of which both output power and efficiency of the device decreases [10]. Here, eight beamlets are considered to perform the present simulation. *Fig.* 6 shows the cross sections of electron beamlets before interaction and *Fig.* 7 shows the cross sections of electron beamlets at the RF output port after the interaction time of 200 ns. The phase of all particles observed in each beamlets, confirm that all beamlets have a constant phase relationship with each other. *Fig*. 8 shows the time variation of electric field amplitude developed at the RF output cavity. The frequency of operation is validated by observing the Fourier transform of the azimuthal electric field component of the time growing signal at the RF input and output cavity. *Fig.* 9 shows the obtained frequency spectrum at the output cavity, characterized by single frequency component, peaked at 34.95 GHz, which validates the frequency and mode of operation in our case. The other noticeable peak of the electric field amplitude is found to be at 70 GHz, which is corresponding to TE_{02} mode of operation. It is clear from figure 9 the amplitude difference between TE_{01} and TE_{02} modes is good enough (~32 dB) to ensure that there will be no mode competition.

*Figs.*10 and 11 show the evolution of electronic energy and power along axes, respectively. It can be seen that at the output end, the net electron energy and power are decreasing, indicating an energy transfer from the electrons to the RF wave. The RF input signal is applied to the input cavity with the help of an input driver. The DRIVER command specifies a prescribed current-density source to drive electromagnetic fields in a local region of space. The desired mode corresponding to desired frequency and power can be excited with the help of this command. The power developed across this driver serves as the RF input power for our device. In our simulation, the RF input power is ~ 922 W. The hot beam results predict an output power corresponding to this input power is ~ 200 kW at 34.95 GHz. The growth rate of RF output power with time is shown in *Fig.* 12. The variation of RF output power and gain achieved as a function of input power using MAGIC code has been shown in *Fig.* 13. The bandwidth calculation of the device is done by plotting the output power and efficiency as a function of frequency (*Fig.* 14). The bandwidth obtained for this device is 0.29% (100 MHz). In order

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to validate the PIC results obtained here are compared with the experimental results of Choi *et al.* and large signal analysis (*Figs.* 13 and 14) [5, 10]. The present PIC results are in agreement with the experimental values as well as with those predicted by the large signal analytical model of the gyroklystron. The saturated output power, gain and bandwidth predications obtained from the PIC simulation are found matching with the analytical model along with the experimental results within 8%. Hence, PIC simulation can be used for the performance estimation of the gyroklystron amplifiers. In *Fig.* 15, the output power has been plotted as a function of output cavity quality factor (Q). The maximum output power is obtained ~ 200 kW at Q = 200.

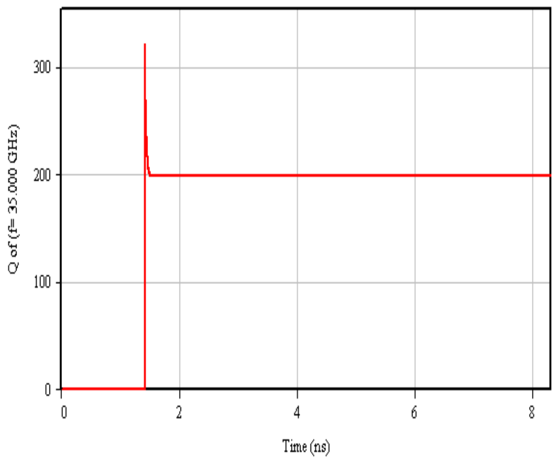

Fig. 5. Quality factor for input cavity of gyroklystron.

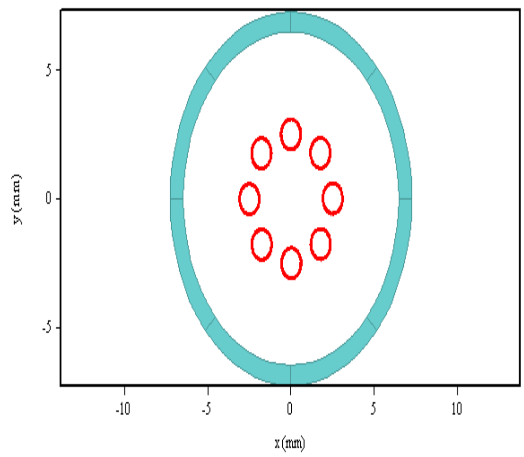

Fig. 6. Cross section of electron beamlets before interaction.

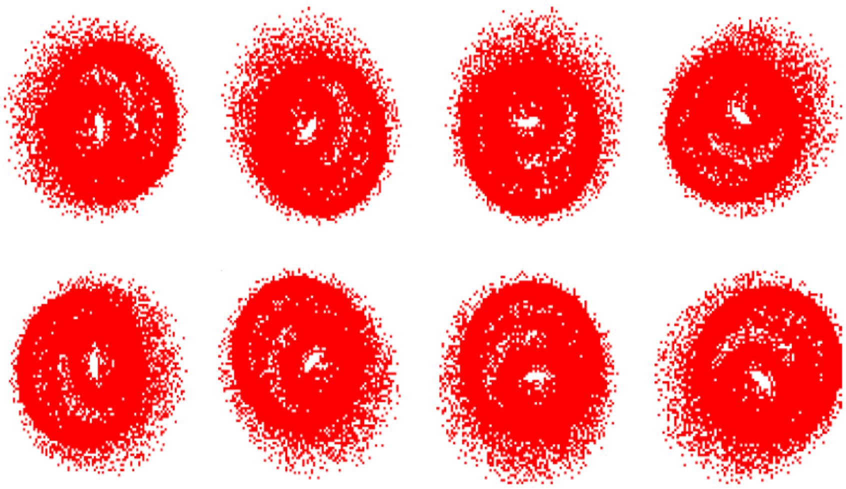

Fig. 7. Phase space of particles in beamlets observed at the end of simulation.

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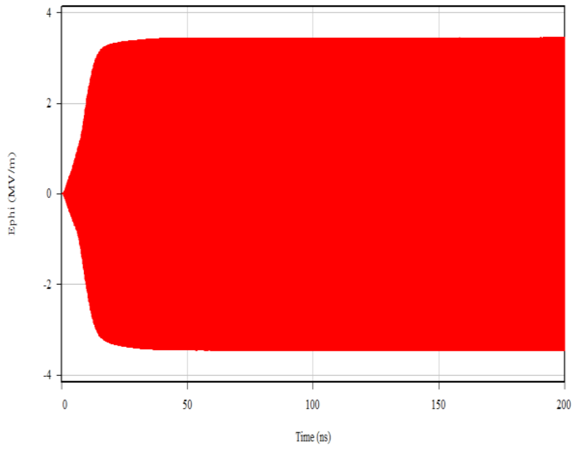

Fig. 8. Time domain variation of the field magnitude recorded using probe at the output cavity.

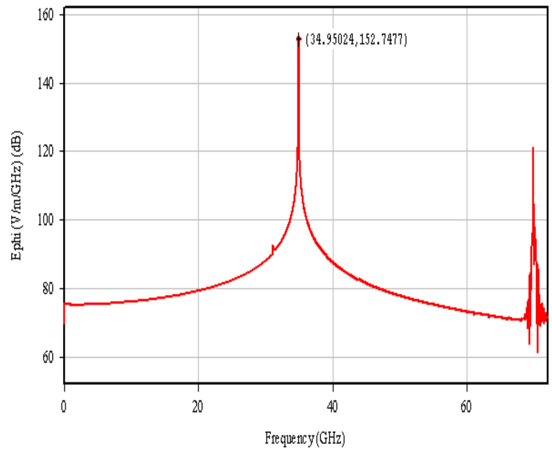

Fig. 9. Observed frequency spectrum of electric field at the output cavity.

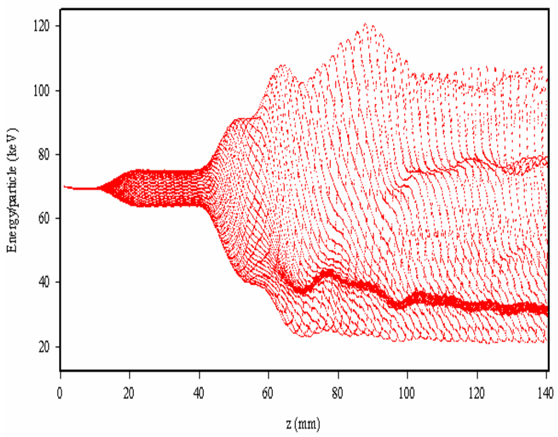

Fig. 10. Evolution of particles energy along axes.

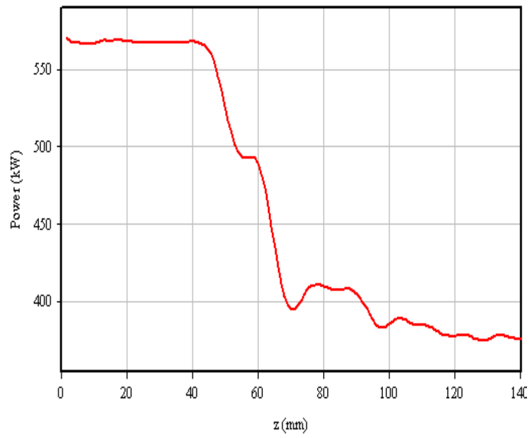

Fig. 11. Axial variation of electron positive power.

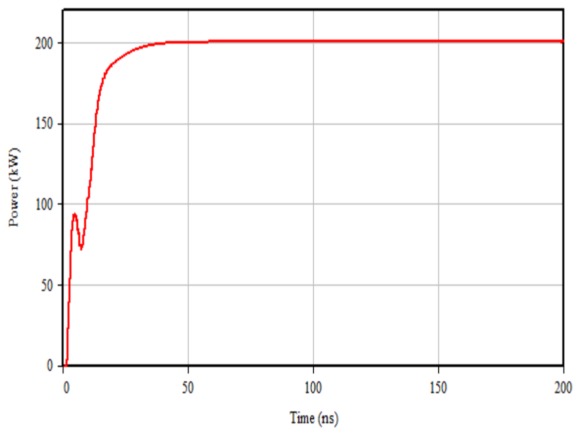

Fig. 12. RFoutput power.

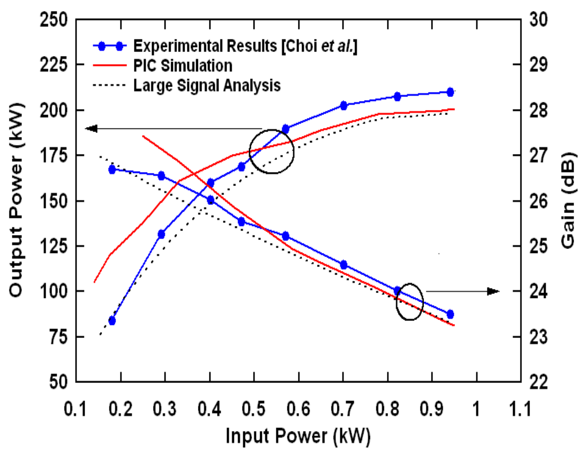

Fig. 13. Output power and gain as a function of the input power.

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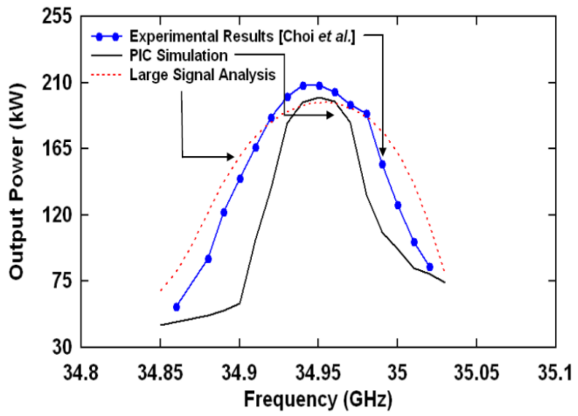

Fig. 14. Dependence of output power on frequency.

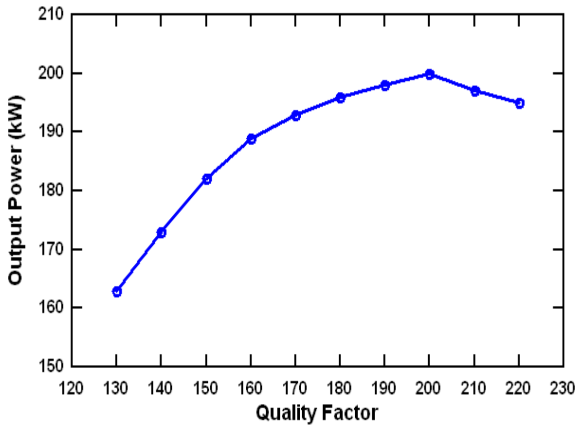

Fig. 15. Output power as a function of the quality factor of output cavity.

IV. CONCLUSION

PIC simulation studies of electron beam and RF wave interaction behavior for a cylindrical two cavity gyroklystron have been done using a three-dimensional commercial PIC code 'MAGIC'. Simulations have been performed in both the electron beam absent and present cases. In order to ensure the device operation at the desired mode, frequency and quality factor, the electron beam absent simulation is performed. The simulation is further extended to the electron beam present case to study the beam wave interaction behavior of the device under investigation. Bunching phenomena in phase space is explicitly observed along the interaction length. The Fourier transform of the time varying field developed across the output cavity confirms the exact frequency of operation in the beam present case. Our simulation demonstrates that the present gyroklystron produces an output power ~ 200 kW with 35% efficiency. The gain of the gyroklystron is ~ 23.4 dB and the bandwidth is 0.29%. The results obtained here matches within 8% with the reported experimental values.

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