International Journal of Infrared and Millimeter Waves, Vol. 27, No. 5, May 2006 (© 2007)
DOI: 10.1007/s10762-006-9113-8

CONCEPTUAL DESIGN STUDIES OF AN 84 GHz, 500 kW, CW GYROTRON

M. V. Kartikeyan[1], G. Singh[2], E. Borie[3], B. Piosczyk[3] M. Thumm[3,4]

[1]*Department of Electronics & Computer Engineering Indian Institute of Technology, Roorkee 247 667, India*

[2]*Vacuum Electrophysics Laboratory, School of Physics Seoul National University, Seoul 151–742, Korea*

[3]*Forschungszentrum Karlsruhe, Association Euratom-FZK Institut für Hochleistungsimpuls und Mikrowellentechnik Hermann von Helmholtzplatz 1, D 76344 Eggenstein–Leopoldshafen Germany*

[4]*Universität Karlsruhe, IHE, Kaiserstr. 12, D 76128 Karlsruhe Germany*

Received 2 February 2006

Abstract

The feasibility of an 84 GHz, 500 kW, CW gyrotron for ECRH on an experimental tokamak will be presented in this paper. Mode competition and mode selection procedures are carefully investigated by considering various candidate modes and the $TE_{10,4}$ mode is chosen as the operating mode. A conventional cylindrical cavity resonator with weak input and output tapers and parabolic roundings is considered for interaction studies. Self–consistent, both single–mode and time–dependent, calculations are carried out and power and efficiencies are computed for a typical set of beam parameters. The results show that an output power of well over 500 kW, CW and efficiency around 40% can be reached without a depressed collector.

Keywords: Gyrotrons, High Power Microwaves, Electron Cyclotron Resonance Heating (ECRH)

Introduction

Gyrotrons are capable of providing hundreds of kilowatts of power at millimetric and sub–millimetric wavelengths. They are mainly used for plasma heating. Other applications include high power communications, industrial heating and material processing. For the past two decades, gyrotrons are considered as the most promising sources for electron cyclotron resonance heating (ECRH) of plasmas for thermonuclear fusion experiments in tokamaks and stellarators because of the distinct advantage that they provide power levels of more than 1 MW at frequencies 30–170 GHz with long pulse to CW range of output, which is the basic requirement for plasma heating [1,2]. The work presented in this paper is a technological extension of our earlier conceptual design of a device operating at both the fundamental and second cyclotron harmonics [3, 4] at 42 GHz. Gyrotrons operating at 84 GHz have been designed and developed by GYCOM (Russia) and CPI (USA) [5–9] respectively for plasma heating applications. Developmental work on low frequency gyrotrons operating at 84 GHz for fusion applications, has been reported recently [5]. Although this technology is now quite mature, it will be useful to carry out the basic design aspects which will lead to the conceptual design and later the design translation to an actual device. In this work, the feasibility design of an 84 GHz, 500 kW gyrotron operating in the $\mathrm{TE}_{10,4}$ mode, preferably with radial output coupling, is presented. This device could serve as a source for ECRH in systems which require a high power microwave source at 84 GHz, preferably in the form of a Gaussian beam. Similar gyrotrons operating at 82.6/84 GHz with 200/500 kW output power levels are employed or being used elsewhere in Tokamak and LHD systems respectively [10, 11].

The design parameters and goals are given in Table 1. Mode competition and mode selection are carefully studied; then cavity design and interaction computations are carried out. This is a preliminary feasibility study which indicates that the operation of such a gyrotron is possible and can give a power of 500 kW at nearly 40% efficiency. Moreover, by using a suitable depressed collector system, the efficiency can be increased considerably.

Mode Selection and Starting Current Calculations

The given frequency corresponds to a wavelength of 3.57 mm. For operation in the $\mathrm{TE}_{\mathrm{m,q}}$ mode, the cavity radius is related to λ by $R_0 = x_{m,q}\lambda/(2\pi)$ where x_{mq} is the q'th root of $J'_m(x)$. For operation at the first harmonic (s=1) the optimum electron beam radius is given by $R_e = x_{m\pm1,i}R_0/x_{m,q} =$

Table 1: Design parameters and goals for a $TE_{10,4}$ gyrotron.

Frequency	84	GHz
Output power	500 kW	CW
Diffraction Q (Q_D)	≈ 900	
Beam current (I_B)	15 – 20	A
Accelerating voltage (U_B)	65 – 70	kV
Magnetic field (interaction)	$\approx$ 3.2–3.3	T
Compression ratio (b)	≈ 14.0	
Beam radius (interaction, R_0)	6.09	mm
Velocity ratio (α)	1.35–1.45	
Total output efficiency	≈ 35	%
Estimated wall losses	$<$ 1.0	kW/cm^2
Overall losses	< 8	%

$x_{m\pm1,i}\lambda/(2\pi)$ (i=1 or 2). In general, the corotating mode (with the lower sign) is chosen, since this provides better coupling of the electron beam to the RF–field. Following standard mode selection procedures taking into account the design constraints [1], the $TE_{10,4}$ mode is chosen as the most promising candidate for the operating mode. It gives a cavity radius (R_0) around 13.52 mm. Other possibilities are operation with the $TE_{12,5}, TE_{15,n}$, $(n = 2, 3, 4)$ modes as reported earlier [2]. After a careful inspection of the mode spectrum for candidate modes, three modes, namely, $TE_{10,4}$, $TE_{12,5}$ and $TE_{15,4}$ appear to be particularly interesting. As far as the wall loading is concerned, all these modes tend to operate well within the limitation of 1 kW/cm^2 for ideal copper and one can produce a suitable transverse output coupling scheme effectively. This confirmed earlier studies that indicated that the $TE_{10,4}$ mode is good for operation at 140 GHz with an output power of around 500 kW [12, 13] (see also [2]). At 140 GHz the wall loading is too high for CW operation at 500 kW. However, a tube with that power was designed and successfully tested with pulse lengths up to 0.2 s with a single–stage depressed collector [14]. The mode competition issues are identical for the two cases.

As a next step, the starting currents [15] were computed for the candidate mode and possible competing modes that might prevent operation in the desired mode. After computing the starting currents by considering all the possible competing modes operating at 84 GHz at s=1, it became clear that the $TE_{10,4}$ was best separated from its competing neighbors (see Fig. 1). In

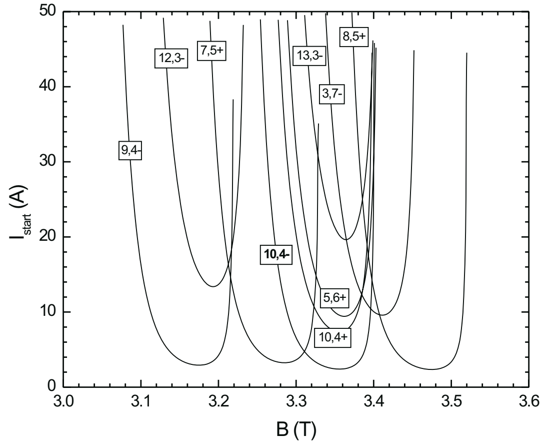

Figure 1: Starting current (I_{start}) as a function of magnetic field B for various modes with the beam radius (R_e) optimized for the $TE_{10,4-}$ mode gyrotron at 84 GHz. Here, $\alpha = 1.5$ and $U_b = 70$ keV. The sign $\pm$ after the mode indices indicates corotating (−) and counter–rotating (+) modes, respectively.

addition, the $TE_{10,4}$ mode operating at 84 GHz can also be used as a complementary dual regime mode to the $TE_{6,2}$ mode operating at 42 GHz, since these two modes form a similar caustic with nearly identical cavity radii and can be used for the dual–mode regime operation at 84 and 41.6 GHz respectively. Preliminary design calculations show that a dimpled–wall launcher with 15.0 mm input radius will work for both modes/frequencies.

Cavity Design and Interaction Computation Results

The cavity is a standard three section structure with an input taper and a uniform mid–section followed by an output uptaper. Parabolic smoothing of the input and output tapers is carried out to reduce unwanted mode conversion at sharp transitions. The beam–wave interaction takes place in the uniform mid–section where the RF–fields reach peak values. The uptaper with nonlinear contour connects the cavity with output waveguide and launcher of the quasi–optical output coupler. The optimum cavity design is carried out by computing the power and interaction efficiencies in cold cavity and self–consistent approximations for various parameters until a satisfactory cavity design compatible with the design goals such as efficiency, wall losses, output power etc. is obtained.

Table 2 shows the resonant frequency and quality factor for various lengths of the cavity mid–section (L_2); the lengths of the tapered sections were fixed at $L_1 = L_3 = 26$ mm, $\theta_1 = 2.3°$, $\theta_2 = 0°$, and $\theta_3 = 3.5°$. Roundings of length $D_1 = D_2 = 6$ mm were included at each transition. For the $TE_{10,4}$ mode at 84 GHz, the cavity radius was 13.52 mm.

Table 2: Frequency and quality factor as a function of resonator mid–section length.

L_2(mm)	f (GHz)	Q_D
22.00	84.020	810
22.50	84.015	852
23.00	84.011	895
23.50	84.006	940
24.00	84.002	986
24.50	83.998	1034
25.00	83.994	1084

Cold cavity design and self–consistent calculations [1, 16–19] for power and efficiency are carried out for a range of external parameters, namely: beam energy, beam velocity ratio α, beam current and applied magnetic field. Computations are carried out for three cavity mid–section lengths $L_2 = 22.0\,/\,23.0\,/\,24.00$ mm that give values of $Q_D = 810\,/\,895\,/\,986$ respectively. However, from the design goals and from Table 2, it is obvious that one can conveniently consider the cavity geometry corresponding to $Q_D = 895$ as the best choice to carry out the interaction computation.

Resonator geometry and cold–cavity field profile for the above cavity dimensions with $L_2 = 23$ mm give a $Q_D \approx 895$ and are shown in Fig. 2. The results of the cavity design based on self–consistent computations are shown in Figs.3–6. From these figures, it is evident that operation at the fundamental (s=1) at 84 GHz with the $TE_{10,4}$ mode as the operating mode gives well above 500 kW of cavity output power with around 40% efficiency. Calculated maximum wall losses are 0.7 kW/cm^2 at 500 kW.

In addition, time–dependent self–consistent (SELFT) calculations are carried out for various values of Q_D considering all the probable competing

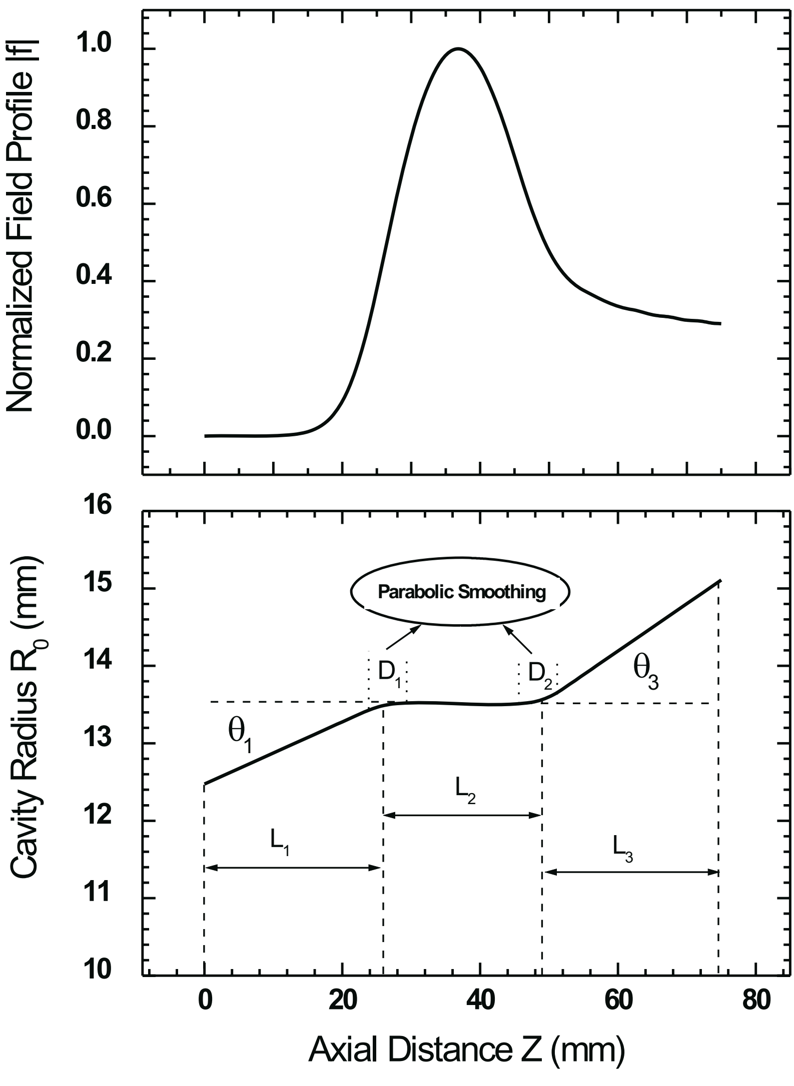

Figure 2: Resonator geometry and cavity field profile for a cavity with $Q_D = 895$.

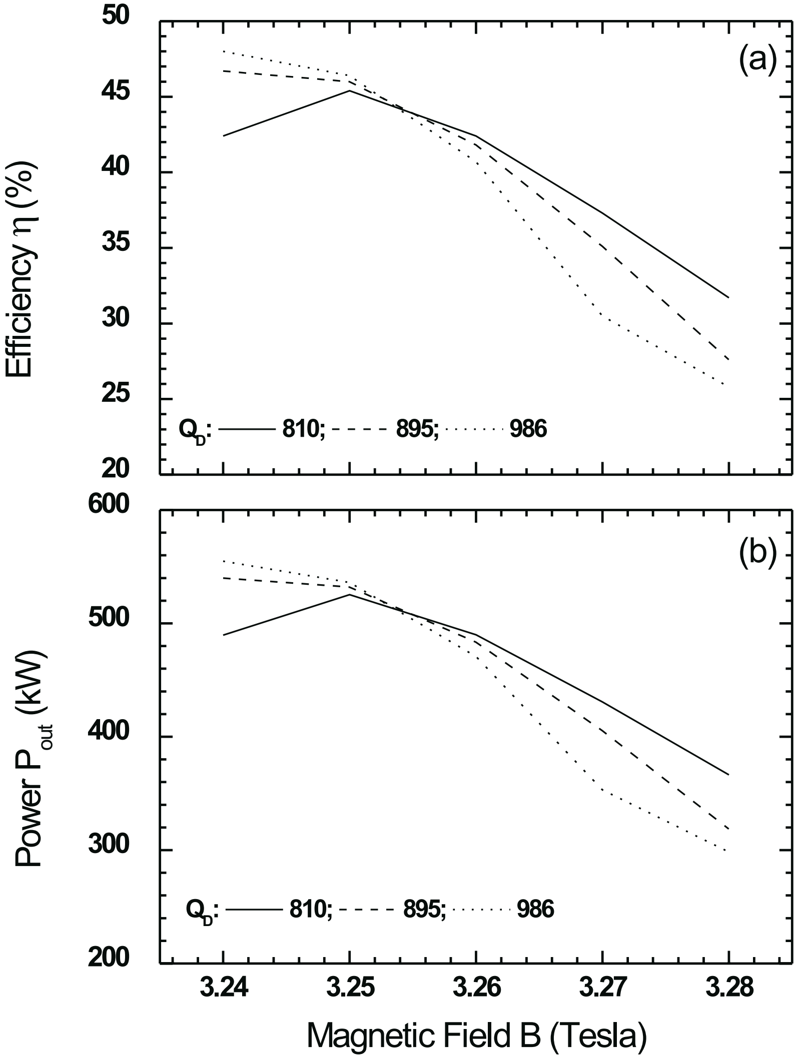

Figure 3: Cavity output power and efficiency as a function of magnetic field for various values of Q_D. Here, $U_B = 68$ kV, $I_B = 17$ A, and $\alpha = 1.40$.

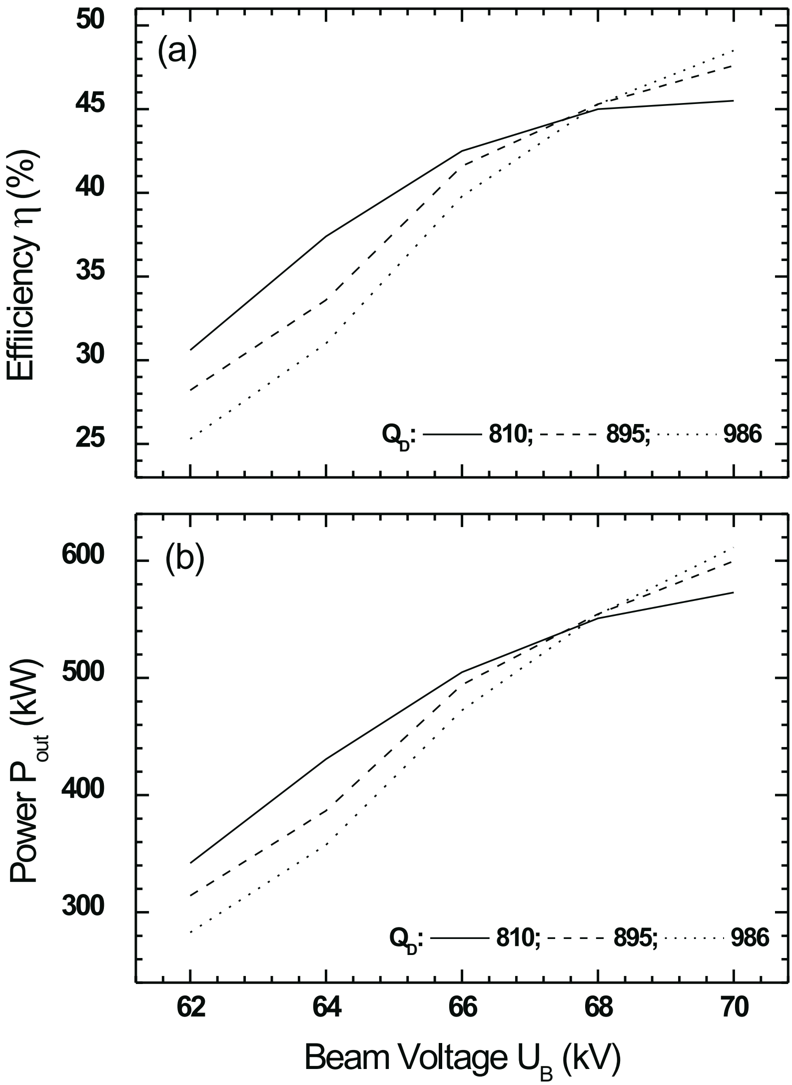

Figure 4: Cavity output power and efficiency as a function of beam voltage (U_B) for various values of Q_D. Here, $\mathrm{I_B}$ = 18 A, B = 3.25 T and $\alpha = 1.40$.

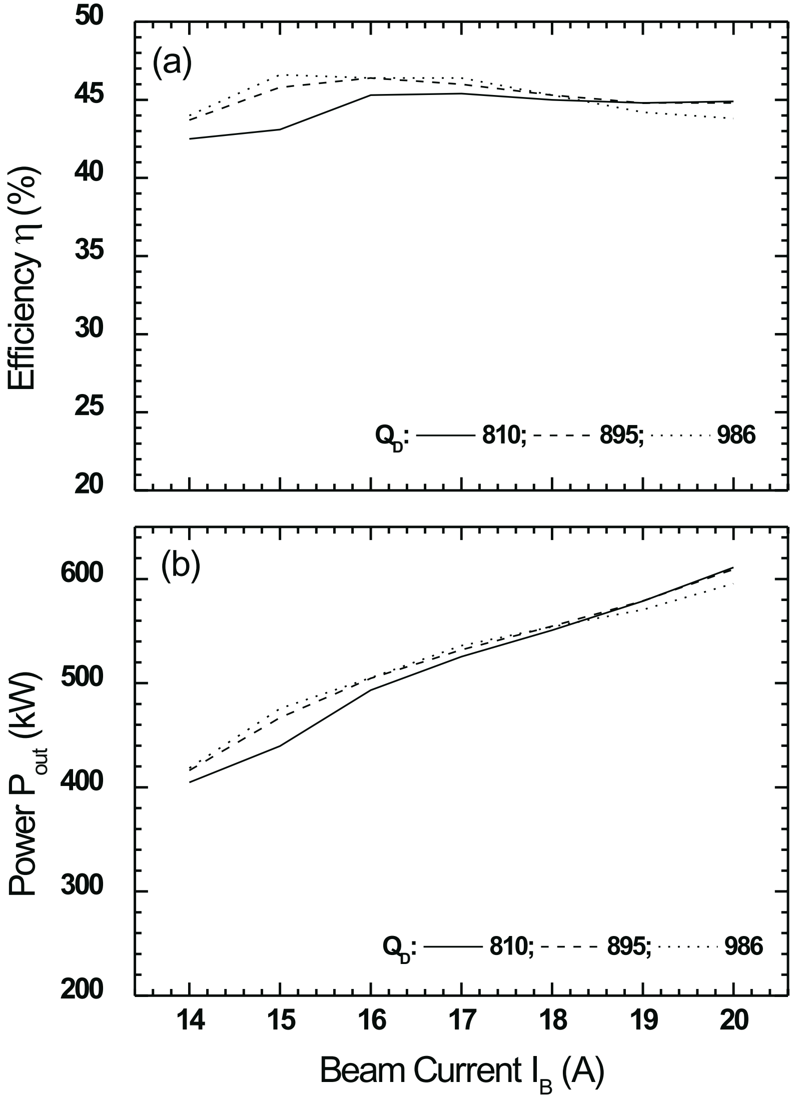

Figure 5: Cavity output power and efficiency as a function of beam current (I_B) for various values of Q_D. Here, U_B = 68 kV, $\alpha = 1.4$, and B = 3.25 T.

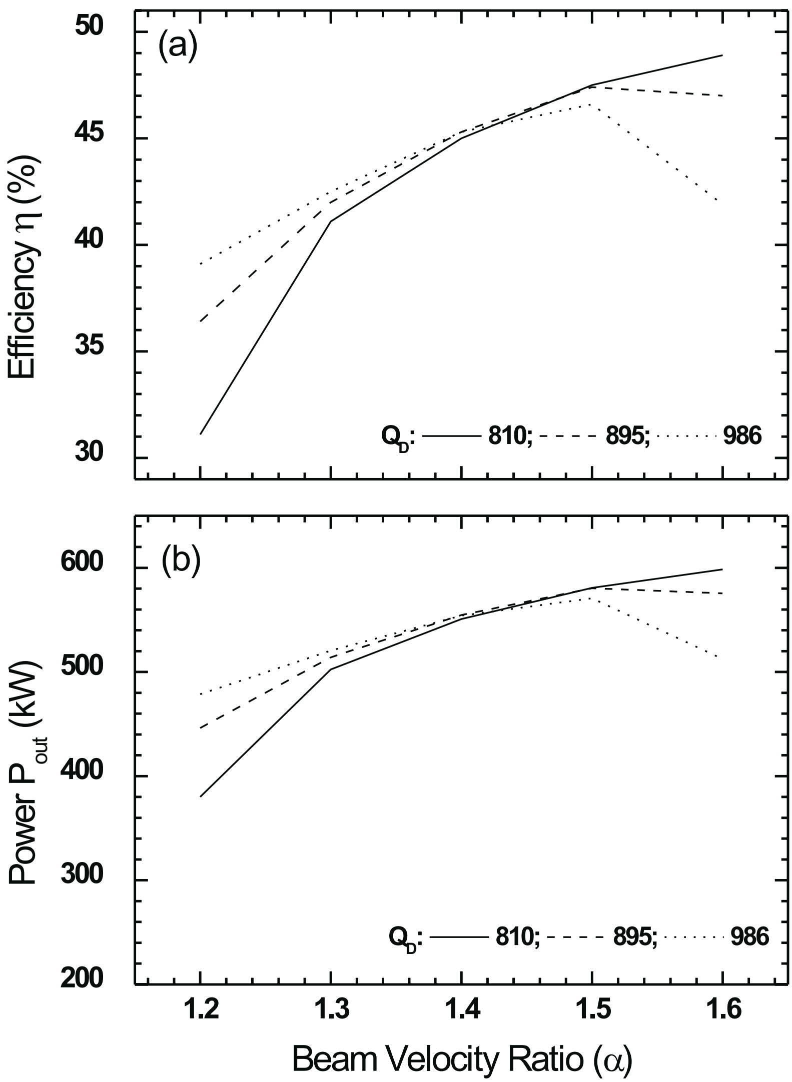

Figure 6: Cavity output power and efficiency as a function of beam α for various values of Q_D. Here, U_B = 68 kV, I_B = 18 A, and B = 3.25 T.

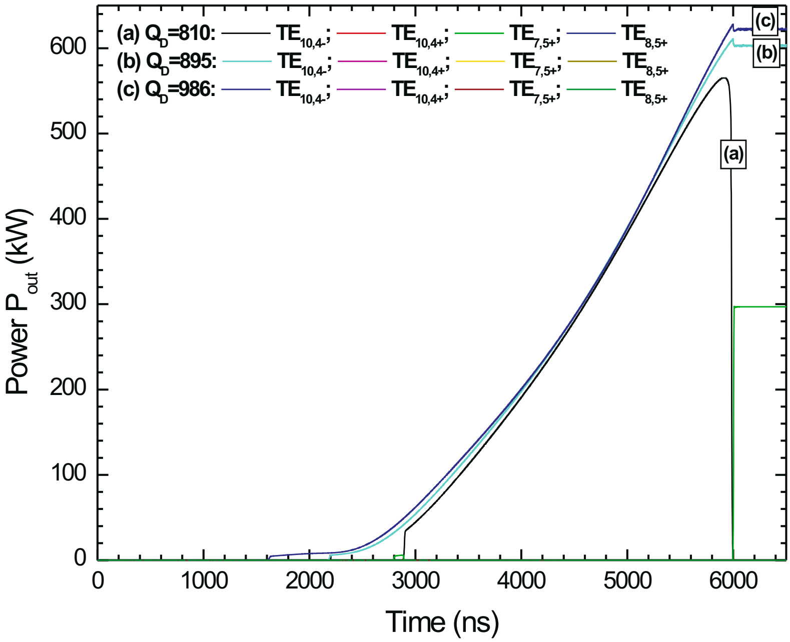

Figure 7: SELFT simulation results for a $TE_{10,4}$ gyrotron considering the probable competing modes. Here, $U_B = 30$–70 kV, α varies accordingly, $I_B = 18$ A and B = 3.25 T.

modes. Figure 7 shows the results of a simulation with SELFT [19] for the $TE_{10,4}$ mode along with probable competing modes. In these calculations, the beam energy is increased from 30 keV to 70 keV over a fictitious startup time of 6500 ns (typical voltage rise times are around 100 μs), and the velocity ratio varies accordingly. The beam current and magnetic field are held constant. The computations are carried out for three different cavity mid–section lengths which give three different diffractive quality factors ($Q_D = 810$, 895, 986). For all the geometries considered, the $TE_{10,4}$ mode oscillates well. However, these results indicate that stable operation of a gyrotron in the $TE_{10,4}$ mode at 84 GHz at power levels around 500 kW should be possible for cavity geometries with $Q_D = 895$ and 986 respectively.

It is planned to use a simple and cost effective magnet design using a single coil which gives the maximum required field at the center of the cavity and uses the stray field in the gun and collector region. An earlier feasibility study for a 42 GHz gyrotron [3,4] considered a magnetic compression ratio b around 12–14 between the emitter and the resonator. In the present study, we have also considered b to be around 12–15. A formal design of the MIG, guiding system, quasi–optical output coupler, and window are to be carried out after these interaction studies, and that work is in progress at the present time.

Conclusions

This work presents a feasibility design of a 84 GHz, 500 kW conventional cavity gyrotron operating in the $TE_{10,4}$ mode. Gyrotrons have been successfully operated in this mode elsewhere. The present study is limited to the mode selection, cavity design and interaction computation and the design study of other major sub–systems of this specific device is in progress. Since the conceptual design leading to the engineering design aspects is always a dynamic process involving a lot of trade-offs, final device integration may require some modifications to the conceptual design aspects.

References

[1] M.V. Kartikeyan, E. Borie, M.K. Thumm, "*Gyrotrons–High Power Microwave and Millimeter Wave Technology*," Springer–Verlag: Berlin, Germany, 2004.

[2] M. Thumm, "*State–of–the–art of high power gyro–devices and free electron masers update 2004*," Scientific Report FZKA 7097, Forschungszentrum Karlsruhe, Germany, February 2005.

[3] M.V. Kartikeyan, E. Borie, B. Piosczyk, O.S. Lamba, V.V.P. Singh, A. Möbius, H.N. Bandopadhyay, M. Thumm, "*Conceptual design of a 42 GHz, 200 kW gyrotron operating in the* $TE_{5,2}$ *mode*," Int. J. Electronics, vol. 87, pp. 709–723, 2000.

[4] M.V. Kartikeyan, E. Borie, O. Drumm, S. Illy, B. Piosczyk, M. Thumm, "*Design of a 42–GHz 200–kW gyrotron operating at the second harmonic*," IEEE Trans. MTT, vol. 52, no. 2, pp. 686–692, February 2004.

[5] V.I. Belousov, A.A. Bogdashov, G.G. Denisov, V.I. Kurbatov, V.I. Malygin, S.A. Malygin, V.B. Orlov, L.G. Popov, E.A. Solujanova, E.M. Tai, S.V. Usachev, "*The test results of the 84 GHz/200 kW/CW gyrotron*," Proc. 13th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, Nizhny Novgorod, Russia, May 17–20, pp. 388–392, 2004.

[6] A.G. Litvak, M.V. Agapova, G.G. Denisov, V.I. Kurbatov, E.M. Tai, S.A. Malygin, V.E. Myasnikov, V.I. Ilyin, S. Usachev, V.E. Zapevalov, "*New results in development of MW output power gyrotrons for fusion systems*," Proc. 27th Int. Conf. on Infrared and Millimeter Waves, San Diego, USA, 295–296, 2002.

[7] Yu Bykov, A. Eremeev, M. Glyavin, V. Kholoptsev, A. Luchinin, I. Plotnikov, G. Denisov, A. Bogdashev, G. Kalynova, V. Semenov, N. Zharova, "*24–84–GHz gyrotron systems for technological microwave applications*," IEEE Transactions on Plasma Science, vol. 32, no. 1, pp. 67–72, February 2004.

[8] G.G. Denisov, V.I. Belousov, A.V. Chirkov, A.G. Litvak, V.I. Malgin, M.Yu. Shmelyov, V.I. Kurbatov, I.V. Kazanskiy, E.A. Solujanova, E.M. Tai, "200 kW/CW gyrotrons and transmission line components for fusion systems," Proc. 6th IEEE Int. Cacuum Electronics Conf. (IVEC–2005), Noordwijk, The Netherlands, pp. 119–120, 2005.

[9] M. Blank, P. Borchard, P. Cahalan, S. Cauffman, T.S. Chu, K. Felch, H. Jory, "*Development and demonstration of gyrotron oscillators and amplifiers at CPI*," Proc. 5th Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod, ed. A.G. Litvak, Inst. of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, 2003, Vol. 1, pp. 7-15.

[10] D. Bora, Sunil Kumar, Raj Singh, K. Sathyanarayana, S.V. Kulkarni, A. Mukherjee, B.K. Shukla, J.P. Singh, Y.S.S. Srinivas, P. Khilar, M. Kushwah, Rajnish Kumar, R. Sugandhi, P. Chattopadhyay, Singh Raghuraj, H.M. Jadav, B. Kadia, Manoj Singh, Rajan Babu, P. Jatin, G. Agrajit, P. Biswas, A. Bhardwaj, D. Rathi, G. Siju, K. Parmar, A. Varia, S. Dani, D. Pragnesh, C. Virani, Harsida Patel, P. Dharmesh, A.R. Makwana, P. Kirit, M. Harsha, J. Soni, V. Yadav, D.S. Bhattacharya, M. Shmelev, V. Belousov, V. Kurbatov, Yu.

Belov, E. Tai, "*Cyclotron resonance heating systems for SST–1*," Nuclear Fusion, vol. 46, pp. S72–S84, 2006.

[11] Y Yoshimura, S Kubo, T Shimozuma, H Igami, T Mutoh, Y Nakamura, K Ohkubo, T Notake, Y Takita, S Kobayashi, S Ito, Y Mizuno, S Inagaki, M Kojima, M Kobayashi, S Sakakibara, T Tokuzawa, H Nakanishi, K Narihara, S Masuzaki, J Miyazawa, T Morisaki, A Komori, O Motojima and LHD experimental group, "*Achievement of One Hour Discharge with ECH on LHD*," Journal of Physics: Conference Series 25, pp. 189-197, 2005.

[12] E. Borie, O. Dumbrajs, R.K. Gupta, A. Möbius, B. Piosczyk, H. Wenzelburger, "*A High Power Gyrotron Operating in a Whispering Gallery Mode for KfK*," 14th Int. Conf. on Infrared and Millimeter Waves, M. V. Ortenberg, Ed., SPIE, vol. 1240, pp. 213–214, 1989.

[13] G. Gantenbein, E. Borie, G. Dammertz, M. Kuntze, H.U. Nickel,B. Piosczyk, M. Thumm, "*Experimental results and numerical simulations of a high power 140 GHz Gyrotron*," IEEE Trans. Plasma Science vol. 22, pp. 861–870, 1994.

[14] G. Dammertz, O. Braz, C.T. Iatrou, M. Kuntze, A. Möbius, B. Piosczyk, M. Thumm, "*Long–pulse operation of a 0.5 MW* $TE_{10,4}$ *gyrotron at 140 GHz*," IEEE Trans. Plasma Science, vol. 24, no. 3, pp. 570–578, June 1996.

[15] E. Borie, B. Jödicke, "*Comments on the Linear Theory of the Gyrotron*," IEEE Trans. Plasma Sci., vol. 16, pp. 116–121, 1988.

[16] E. Borie, in "*Gyrotron Oscillators – Their Principles and Practice*," Edited by C. J. Edgcombe, Taylor & Francis, London, 1993, Ch. 3.

[17] E. Borie, "*Self–Consistent Code for a 150 GHz Gyrotron*," Int. J. of Infrared and Millimeter Waves, vol. 7, pp. 1863–1879 , 1986.

[18] A.W. Fliflet, M.E. Read, K.R. Chu, and R. Seeley, "*A self–consistent field theory for gyrotron oscillators: application to a low Q gyromonotron*," Int. J. Electronics, vol. 53, pp. 505–521, 1982.

[19] S. Kern, "*Numerische Simulation der Gyrotron-Wechselwirkung in koaxialen Resonatoren*," Forschungszentrum Karlsruhe, Scientific Rep., FZKA 5837, Nov. 1996.