LRP 514/95 March 1995

STARTUP METHODS FOR SINGLE-MODE GYROTRON OPERATION

D.R. Whaley, M.Q. Tran, S. Alberti, T.M. Tran,
T.M. Antonsen Jr., C. Tran

submitted for publication to
Phys. Rev. Lett.

Startup Methods for Single-Mode Gyrotron Operation

D. R. Whaley, M. Q. Tran, S. Alberti, T. M. Tran

Centre de Recherches en Physique des Plasmas,
Association Euratom-Confédération Suisse,
Ecole Polytechnique Fédérale de Lausanne,
21 Av. des Bains, CH-1007 Lausanne, Switzerland

T. M. Antonsen Jr.

Institute for Plasma Research and
Departments of Electrical Engineering and Physics,
U. of Maryland, College Park, MD 20742

C. Tran

Thomson Tubes Electroniques,
2, rue Latécoère - B.P. 23,
78140 Vélizy-Villacoublay Cedex, France

Experimental results of startup studies on a 118 GHz $TE_{22,6}$ gyrotron are presented and compared with theory. The theoretical excitation regimes of competing modes are computed in the energy-velocity-pitch-angle plane near the operation point. The startup paths through the plane are determined by the time evolution of the beam parameters during the startup phase. These startup paths are modified by changing the anode and cathode voltage rise from zero to their nominal values and are seen to determine the cavity oscillating mode. Experimental results show specifically that competition between the $TE_{22,6}$ and $TE_{-19,7}$ mode can be completely eliminated by using the proper startup method in a case where a typical triode startup results in oscillation in the competing $TE_{-19,7}$ mode. These new results are shown to be in excellent agreement with theory whose approach is general and therefore applicable to gyrotrons operating in any arbitrary cavity mode.

Electron cyclotron resonance heating and current drive of fusion plasmas require the development of gyrotrons operating at high frequency and high average power. These requirements necessitate the use of high-order gyrotron cavity modes. In the design and operation of such gyrotrons mode competition must be considered to assure oscillation in the proper mode. Oscillation in a competing mode can result in a decrease of interaction efficiency, degraded performance of the quasi-optical coupling system, change in oscillation frequency, increase in window reflection, decrease of coupling between window RF power and the RF transport system. The dense mode spectrum of high-order modes requires consideration of the temporal evolution of the beam parameters during the startup phase. Studies of the effect of startup on the behavior of cavity modes for high-order mode gyrotrons have been performed in [1] - [11]. In [10] the relative timing of the rise of the anode and cathode voltages in a quasioptical gyrotron was shown experimentally to favorably affect the final operating mode. In this Letter, we apply the theoretical approach presented in [11] to experimental startup studies of a 118 GHz 0.5 MW gyrotron tube.

In this study competition between the desired $TE_{22,6}$ operating mode and the competing $TE_{-19,7}$ mode is considered. Excitation regions of both modes are computed in the α-E plane where α is the velocity pitch ratio, $v_\perp/v_\parallel$, and E is the beam energy. The startup path through the α-E plane depends on the startup scenario - the method in which the anode and cathode voltages of the gyrotron are raised from zero to their nominal values. The choice of startup scenario determines the evolution of the beam energy, velocity pitch angle and beam current during the time-changing portion of the electron beam pulse. Depending on the path taken, one of the competing modes will be excited first and will grow to large amplitude. This mode can suppress all other competing modes even when the final beam parameters are such that another startup path would have resulted in excitation and oscillation of another mode.

The triode gun of a gyrotron allows for independent control over beam energy and electron velocity pitch angle. The excitation regime of the $TE_{22,6}$ mode is shown in Fig. 1 and has been computed in the α-E plane using the method described in [11] for the cavity of a 118 GHz gyrotron. For this figure, the geometry of the triode gun is required and the figure takes into account the changing beam current as one changes the beam α and energy. During the startup phase of the electron beam, the beam α and energy evolve from $\alpha = 0$, $E = 0$ to their nominal values of $\alpha = 1.5$, $E = 78$ keV. The 'startup path' that is taken as the beam moves through the α-E plane is dependent on the timing of the applied anode and cathode voltages. A typical triode startup, where the cathode voltage is established at its nominal value followed by the rise of the anode voltage, maintains a constant beam energy for all values of α and a vertical startup path to the nominal operation point is traced in the α-E plane as shown in Fig. 1 (labeled 'triode'). A 'timed' startup scenario is one in which the anode and cathode voltages are first brought to intermediate values, V_{A1} and V_{K1}, and then increased simultaneously to the nominal values V_{A2} and V_{K2} (shown later in Fig. 3). With this timed method, the startup path in the α-E plane is different than that of the typical triode scenario and is also shown in Fig. 1 (labeled 'timed'). As seen, the intermediate voltages, V_{A1} and V_{K1}, are chosen so as to remain outside of the excitation region of the $TE_{22,6}$ mode until the simultaneous rise to the nominal values begins. The choice of these intermediate voltage values determines the slope in the α-E plane with which the startup path approaches the nominal operation point and will be seen later to determine the oscillating mode.

The excitation region of any gyrotron cavity mode, such as the $TE_{22,6}$ mode shown in Fig. 1, is based on the calculation of starting current using the normalized variable method as described in [11]. This is derived from linear theory and assumes a Gaussian electric field profile of constant width. To validate this approach a fully non-linear time-dependent code [12] was used to determine the starting current as a function of beam energy for a typical timed startup, allowing for the consistent change of the beam α and current with energy as shown in Fig. 2(a). Figure 2(b) shows the starting current as a function of beam energy for both the theoretical and simulation results as well as the beam line for the startup. The good agreement between the two calculations demonstrates that the excitation of the $TE_{22,6}$ mode occurs in both cases at the same time in the startup. It should be noted that the theoretical approach is valid if the cavity filling time, Q/ω (~ 2ns for the 118 GHz gyrotron), is considerably shorter than the voltage ramp time scales so that the equilibrium states can be considered as established instantaneously.

Experimental verification of the results presented in [11] has been performed on a 118 GHz gyrotron with a triode electron gun [13]. The high voltage power supplies are capable of producing a triode startup as well as a timed startup with $7\ kV \leq V_{A1} \leq 17\ kV$ and $56\ kV \leq V_{K1} \leq 67\ kV$ for nominal parameters in both cases of $V_{A2} = 25$ kV, $V_{K2} = 81$ kV, $I_b = 20$ A, and $B = 4.7$ T. These nominal values correspond to $\alpha = 1.5$ and $E = 78$ keV with 3 keV space charge depression. Figures 3 show an experimental time trace of a timed startup. Fig. 3(a) is the oscilloscope trace of the voltages plotted in x-t, Fig. 3(b) is the same trace plotted in x-y resembling the startup paths of Fig. 1, and Fig. 3(c) shows the actual startup paths converted to the α-E plane using the method of [11]. The unexpected excursions of the startup path just before the point corresponding to the intermediate voltages, seen in Figs. 3(b) and (c), is due to a drop in the cathode voltage during the initial rise of the anode voltage to V_{A1}. This could not be corrected but since this takes place at or below V_{K1}, the startup behavior of the gyrotron is not affected by this effect.

Frequency measurements with a series HP70000 spectrum analyzer were used for mode identification and show the two most dominant modes of the gyrotron to be the desired $TE_{22,6}$ mode and the competing $TE_{-19,7}$ mode. The excitation regions for these two modes are therefore computed and are also shown in Fig. 3(c). Experimental observations suggest that the radius of the electron beam in the cavity, r_b, is several percent smaller than the optimum predicted value of $r_b = 0.51$ a and therefore the excitation regions of Fig. 3(c) are generated for $r_b = 0.49$ a. One can see that the startup path of the electron beam will move into the excitation region of one of the two modes first, exciting that mode before any other. The point at which the transition between the $TE_{22,6}$ mode and the $TE_{-19,7}$ mode occurs is labeled 'transition point'. Many startups, similar to that of Fig. 3(c), for a series of different V_{A1}, V_{K1} combinations were performed for equal final nominal anode and cathode voltages. This merely affects the startup path approaching the same operation point. It is seen experimentally that depending on the startup path chosen the tube oscillates in either in the $TE_{22,6}$ mode at a full power of $P_{rf} \sim 500$ kW at f = 118.0 GHz or in the $TE_{-19,7}$ mode at a reduced power of $P_{rf} \sim 100$ kW at f = 117.5 GHz. Once either mode is established it remains the oscillating mode for the remainder of the microwave pulse (limited in these experiments by the microwave load to $\Delta t = 4$ ms).

An enlargement of the region around the transition point of Fig. 3(c) is shown in Fig. 4 as well as the series of experimentally measured startup paths in a startup series with varying V_{A1} and V_{K1}. The values of V_{A1} and V_{K1} are chosen so that the paths lie on either side of the transition point. In the figure the paths which result in excitation in the $TE_{22,6}$ mode are shown as solid lines and the paths which result in excitation in the $TE_{-19,7}$ mode are shown as dotted lines. It is readily seen that all combinations of V_{A1}, V_{K1} passing first into the $TE_{22,6}$ excitation region result in oscillation in the proper $TE_{22,6}$ mode and combinations of V_{A1}, V_{K1} passing first into the $TE_{-19,7}$ excitation region result in oscillation of the $TE_{-19,7}$ mode. Table I summarizes the characteristics of startup in each of the two modes. In general a high V_{A1} and low V_{K1} eliminates the problem of competition with the $TE_{-19,7}$ mode. It should be noted that a typical triode startup, shown in Fig. 1, also results in low power oscillation of the $TE_{-19,7}$ mode.

Another experimental startup series was taken with the transition point of Fig. 4 moved in the α-E plane. This was accomplished by slightly increasing the beam compression and therefore decreasing the cavity beam radius. Startup in the $TE_{22,6}$ or the $TE_{-19,7}$ mode was again determined as a function of the startup path. The result is shown in Fig. 5. As in Fig. 4, Fig. 5 shows that only startup paths entering the excitation region of the $TE_{22,6}$ mode result in final oscillation of the $TE_{22,6}$ mode. Also, with the transition point changed in Fig. 5, combinations of V_{A1}, V_{K1} that, in Fig. 4 led to $TE_{22,6}$ oscillation, now result in oscillation of the $TE_{-19,7}$ mode as expected.

Experimental verification of mode selection during the startup of gyrotrons has been presented. A method of ensuring single mode oscillation in the correct mode while eliminating oscillation of competing modes is determined and compared with theory. By varying the temporal evolution of the electron beam parameters during startup, it is seen that one can effectively choose between different operating modes even for equal final nominal operating parameters. The optimum startup consists of a timed scenario where anode and cathode voltages are established at an intermediate value and then brought to their final operating voltages simultaneously. With the intermediate values correctly chosen, high power oscillation in the desired $TE_{22,6}$ mode occurs in a case where a typical triode startup results in low power oscillation in a competing mode. The location of the transition point in the α-E plane between the two competing modes has been computed and verified experimentally. The methods presented here, supported by these experimental results, provide a useful tool for determining optimum procedures for gyrotron startup.

The contribution and assistance during these tests of Drs. A. Dubrovin, P. Garin, E. Giguet, J.-M. Krieg, and H.-G. Mathews of Thomson Tubes Electroniques (TTE) and M. Pain of the CEA was greatly appreciated. Gyrotron operators F. Blanchard and F. Legrand were also of great help during the tests. The 118 GHz gyrotron was constructed in the framework of a joint development between the Associations Euratom - CEA Cadarache, Euratom - Swiss Confederation and TTE. Contributions of Dr. M. Thumm of FZK are greatly appreciated during this 118 GHz gyrotron development program. This work was partially supported by the Swiss National Science Foundation.

References

[1] G. S. Nusinovich, Elektronnaya Tekhnika, Ser. I, Elektronika SVCh, 44 (1974).

[2] E. Borie and B. Jödicke, Int. J. Infrared and Millimeter Waves **8**, 207 (1987).

[3] B. Levush and T. M. Antonsen Jr., IEEE Trans. Plasma Sci. **18**, 260 (1990).

[4] O. Dumbrajs and G. S. Nusinovich, IEEE Trans. Plasma Sci. **20**, 452 (1992).

[5] E. Borie *et al.*, Int. J. Electron. **72**, 687 (1992).

[6] G. Gantenbein *et al.*, in *Proceedings of the Sixteenth International Conference on Infrared and Millimeter Waves*, Lausanne, 1991, p. 264.

[7] A. W. Fliflet *et al.*, Phys. Rev. A **43,** 6166 (1991).

[8] K. E. Kreischer and R. J. Temkin, Int. J. Infrared and Millimeter Waves **2,** 175 (1981).

[9] M. Q. Tran, *et al.*, in *Proceedings of the International Workshop of Strong Microwaves in Plasmas*, Suzdal, 1990, p. 812.

[10] R. P. Fischer *et al.*, *Phys. Rev. Lett.* **72**, 2395, 1994.

[11] D. R. Whaley *et al.*, IEEE Trans. Plasma Sci. **22**, 850 (1994).

[12] S. Y. Cai *et al.*, Int. J. Electron. **72** 759, 1992.

[13] M. Pain *et al.*, in *Proceedings of the Eighteenth Symposium on Fusion Technology*, Karlsruhe, 1994, PA-051.

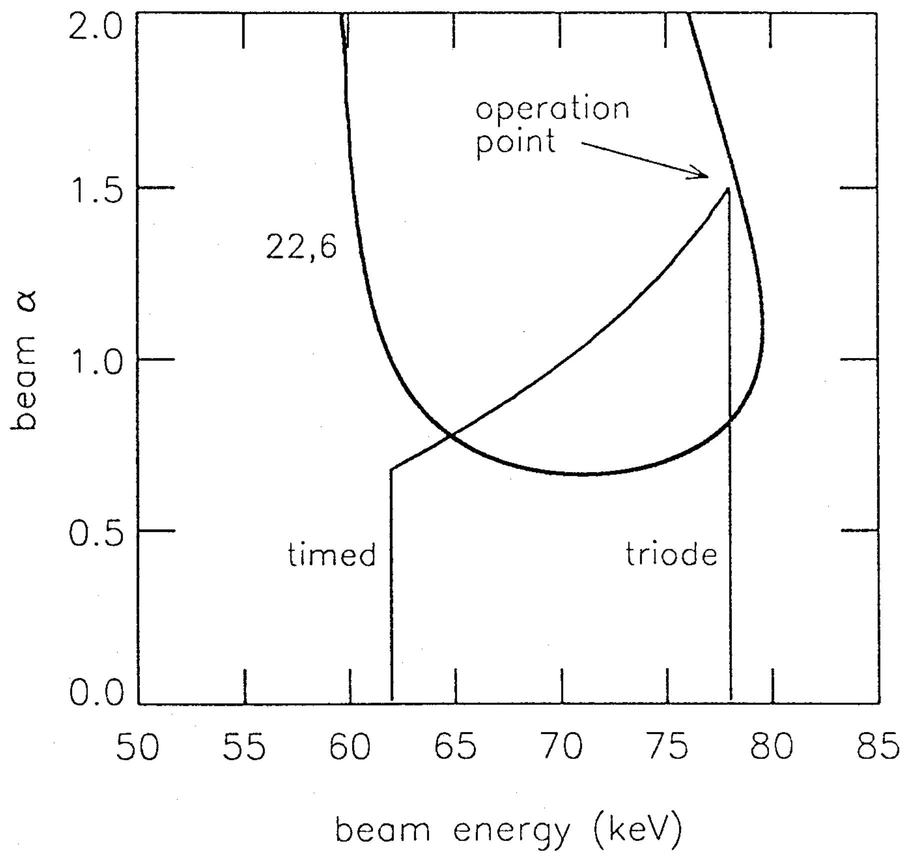

Figure 1. Excitation region of the $TE_{22,6}$ mode in the α-E plane with original design parameters $r_b = 0.51$ a (a = cavity radius) and B = 4.71 T. The startup paths for the triode and timed startup scenarios are also shown.

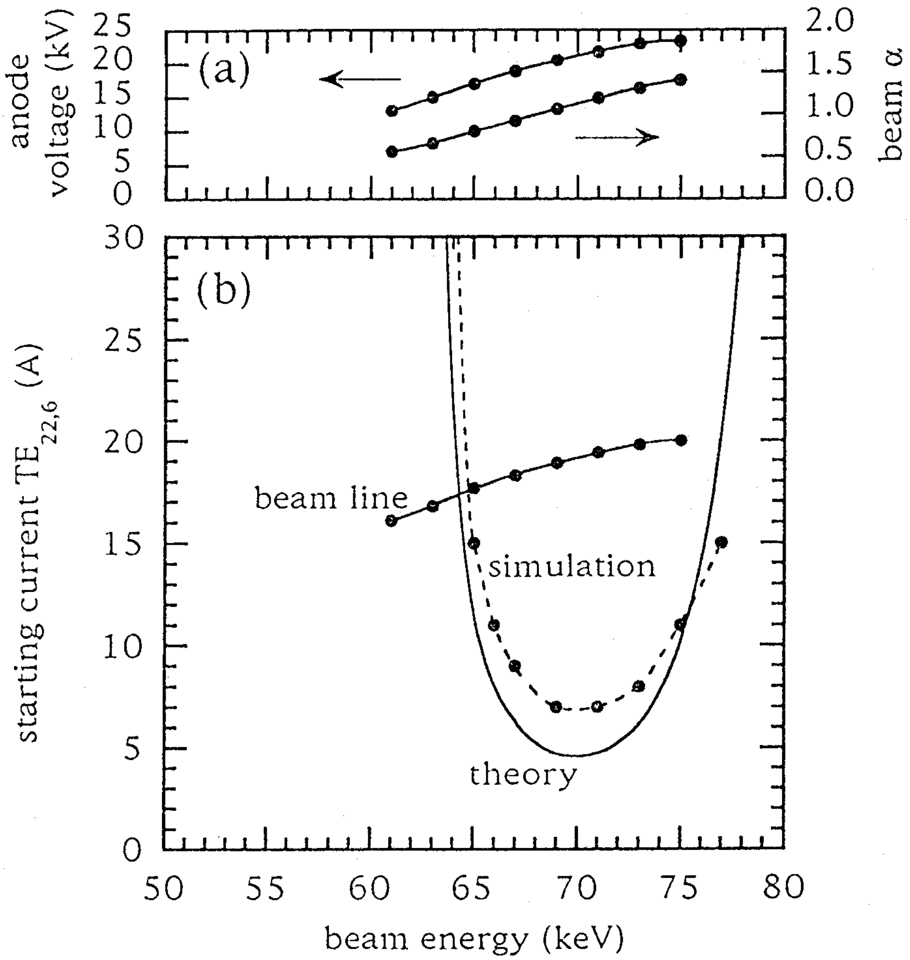

Figure 2. (a) anode voltage V_A and beam α vs. beam energy (b) theoretical starting current curve and starting current determined using time-dependent startup simulation code [12]. The beam line is also included showing the excitation of the $TE_{22,6}$ mode in the theoretical approximation to occur at the same time as in the simulation.

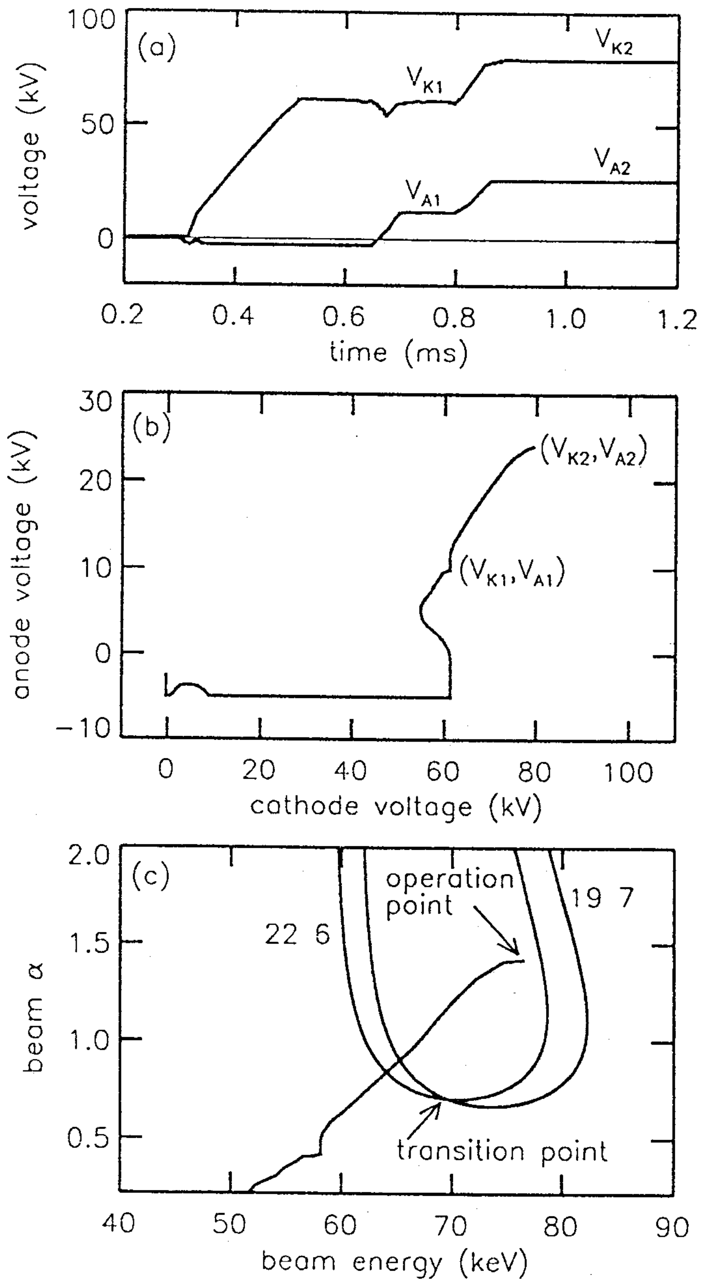

Figure 3. (a) experimental anode and cathode voltage forms for timed startup scenario. The polarity of the cathode voltage is negative. (b) voltages of (a) plotted in x-y (c) respective experimental startup path in the α-E plane. Excitation regions of the $TE_{22,6}$ and $TE_{-19,7}$ modes are also shown. Parameters are $B = 4.71$ T and $r_b = 0.49$ a.

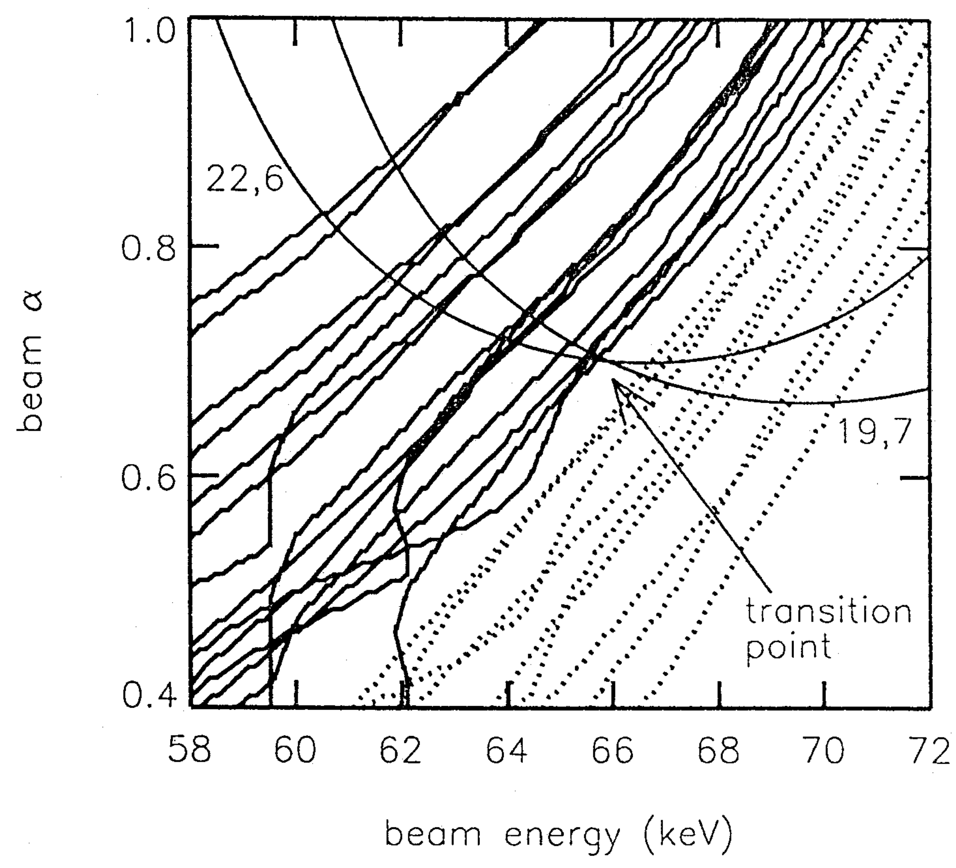

Figure 4. Expanded view of α-E plane near transition point. Each line represents the experimental startup path followed by a separate shot. Solid paths are shots that startup and oscillate in the $TE_{22,6}$ mode and dotted paths are shots that startup and oscillate in the $TE_{19,7}$ mode. Theoretical excitation regions for both modes are also shown. Model parameters are B=4.68 T and r_b = 0.49 a which correspond to a transition point of α=0.70, E=65.9keV.

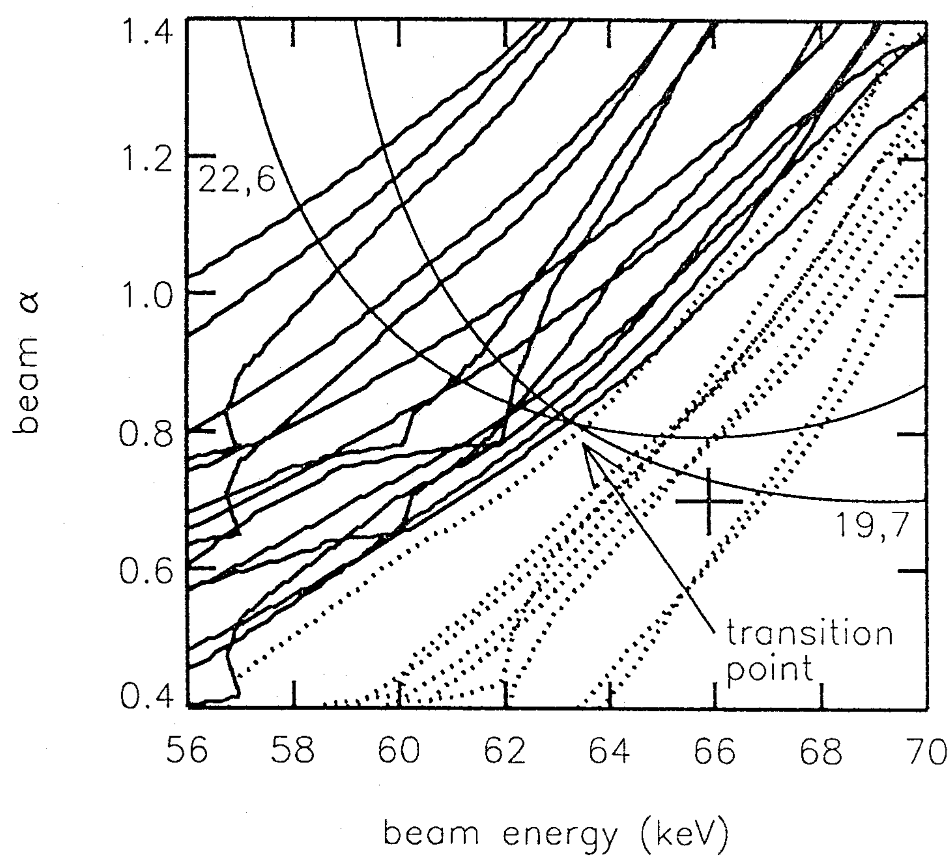

Figure 5. As with Fig. 4 for second startup series. The beam compression has been changed to decrease the beam radius in the cavity by 0.02 a. Model parameters are B=4.68 T and $r_b = 0.47$ a which correspond to a transition point of α=0.81, E=63.3keV. The transition point of the first startup series shown in Fig. 4 has been marked with a '+'.

beam parameters V_{A2}=25kV V_{K2}=81kV I_b=20A

timed startup method	mode	frequency	average RF power
high V_{A1} - low V_{K1}	$TE_{22,6}$	118.00 GHz	470 kW
low V_{A1} - high V_{K1}	$TE_{-19,7}$	117.50 GHz	103 kW

Table I. $TE_{22,6}$ and $TE_{19,7}$ mode characteristics of the 118 GHz gyrotron using different startup techniques.