The monotron as a gridded microwave tube

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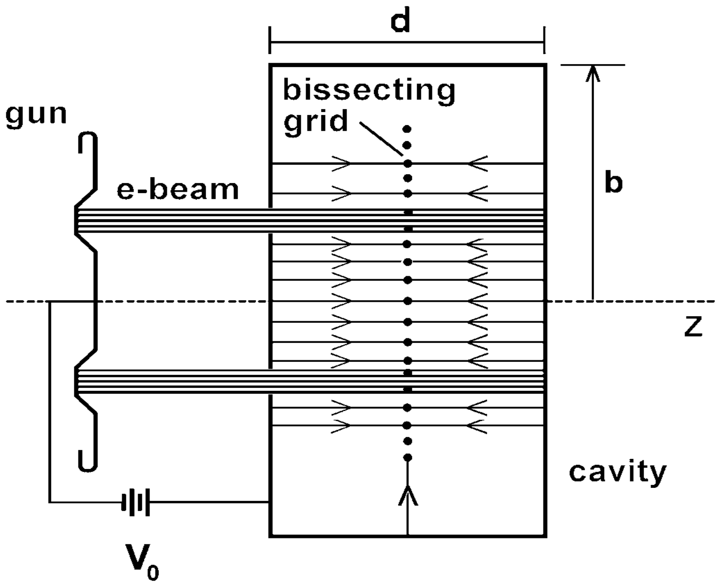
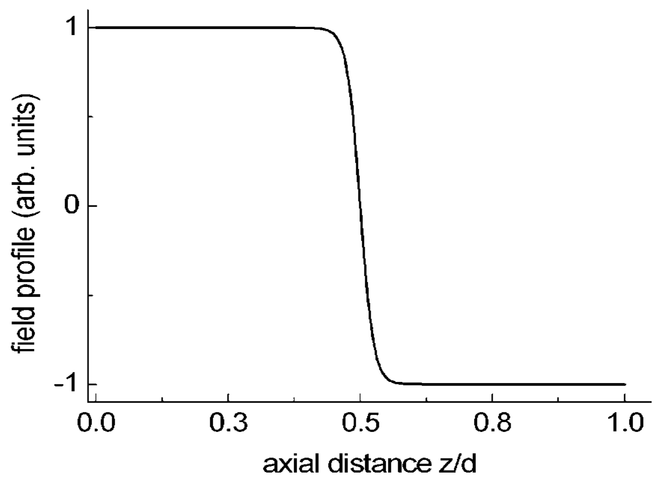
Abstract-The simplest of the microwaves tubes, the monotron consists of a circular cylindrical cavity driven by a linear electron beam. Without needing an externally applied magnetic field and operating in circular TM0n0 modes, the device yields the maximal electronic efficiency of 20.0 %. But upon insertion of a bisecting grid into the cavity, this work demonstrates that such a device can reach the electronic efficiency of 40.0%. Specifically discussed are the design and operating characteristics of split-cavity monotrons driven by 10 keV, 50-70A current beams. Dictated by the injection beam energy, the optimum cavity aspect ratio of length/radius=0.37 is central to achieving single π-mode operation while suppressing competing TM0n0 modes. Based onn one-dimensional analysis, a 9.2 GHz split-cavity monotron is synthesized with the cavity capacitively coupled to an output TM01 waveguide for external utilization of the RF power internally generated at 40.0% conversion efficiency. Numerical particle-in-cell simulation with a 0.4-cm thick, 70-A current beam crossing a transparent grid gives the overall efficiency of 35.7% relative to 700kW input beam power.

CNPq FAPESP

EFFICIENCY CALCULATION





$$\frac{dp}{dt} = qE(z)\cos(2\pi t/T + \varphi)$$

$$\frac{dz}{dt} = \frac{p(t)c}{\sqrt{m^2c^2 + p^2}}$$

$$\tilde{p} = p/mc \qquad \tilde{t} = 2\pi t/T \qquad \tilde{z} = z\omega/c$$

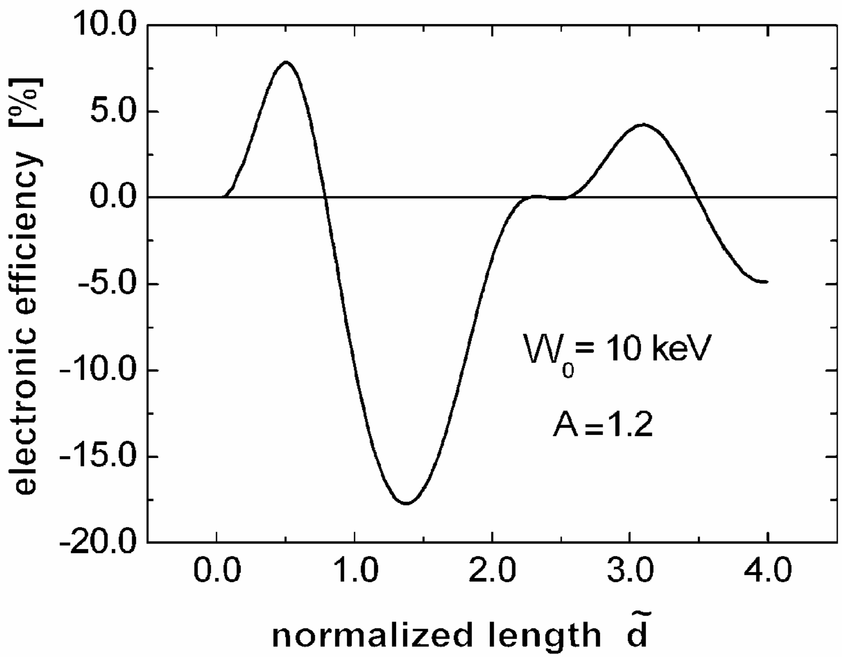
$$\frac{d\tilde{p}}{d\tilde{t}} = \left[\frac{A}{\tilde{d}}\frac{W_0}{mc^2}\right]\tanh[\,40(\tilde{z} - \tilde{d}/2)]\cos(\tilde{t} + \varphi) = 0$$

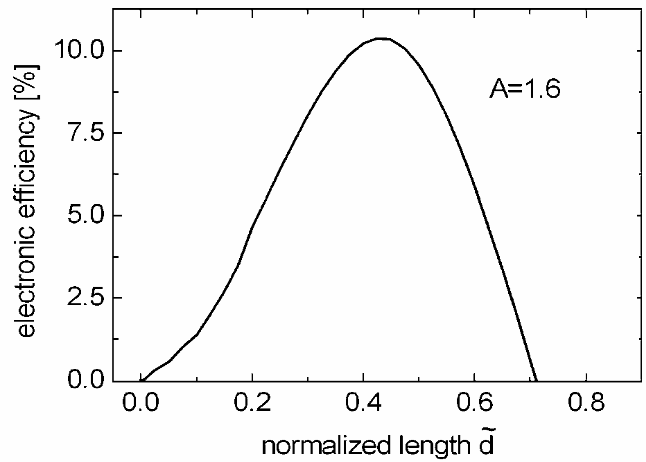
$$W_S = mc^2(\sqrt{1 + (p(\tau)/mc)^2} - 1)$$

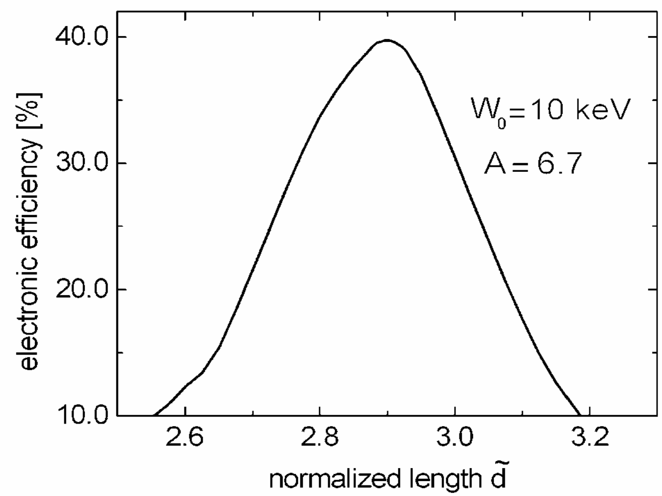
$$\langle W_B \rangle = \frac{1}{2\pi}\int_0^{2\pi} W_S(\tau)d\varphi$$

$$\eta_{el} = 1 - \langle W_B \rangle / W_0$$

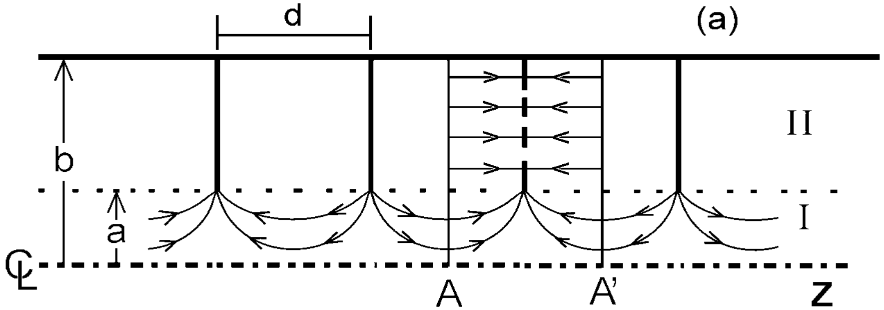
THE SECOND REGION OF HIGHER-EFFICIENCY REGIME







RESONANCES OF THE π-MODE TWIN CAVITIES

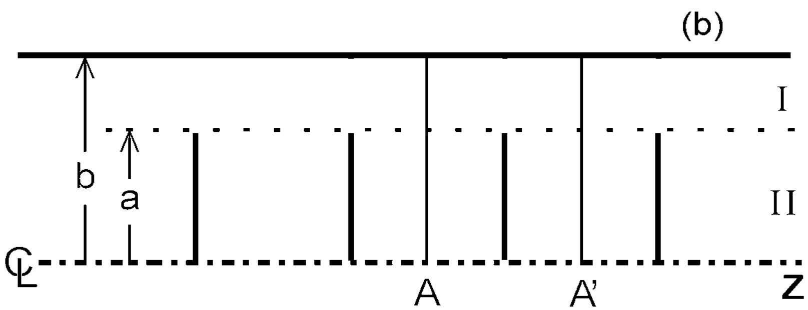


$$E_Z^{II} = B^{II}\left[J_0(kr) - \frac{J_0(kb)}{N_0(kb)}N_0(kr)\right]\exp(i\omega t)$$

$$H_\Phi^{II} = iB^{II}\sqrt{\frac{\varepsilon_0}{\mu_0}}\left[J_1(kr) - \frac{J_0(kb)}{N_0(kb)}N_1(kr)\right]\exp(i\omega t)$$

$$E_Z^{I} = A^{I}J_0(k_\perp r)\exp[-i(\beta z - \omega t)]$$

$$H_\Phi^{I} = i\frac{A^{I}k}{\sqrt{\mu_0/\varepsilon_0}\,k_\perp}J_1(k_\perp r)\exp[-i(\beta z - \omega t)]$$



$$E_Z^{I} = C^{I}\{N_0(k_\perp b)J_0(k_\perp r) - J_0(k_\perp b)N_0(k_\perp r)\}\exp[j(\omega t - \beta z)]$$

$$H_\Phi^{I} = -jC^{I}\frac{k}{k_\perp}\sqrt{\frac{\varepsilon_0}{\mu_0}}\{N_0(k_\perp b)J_1(k_\perp r) - J_0(k_\perp b)N_1(k_\perp r)\}\exp[j(\omega t - \beta z)]$$

$$E_Z^{II} = D^{II}J_0(kr) \qquad H_\Phi^{II} = jD^{II}\sqrt{\frac{\varepsilon_0}{\mu_0}}J_1(kr)$$

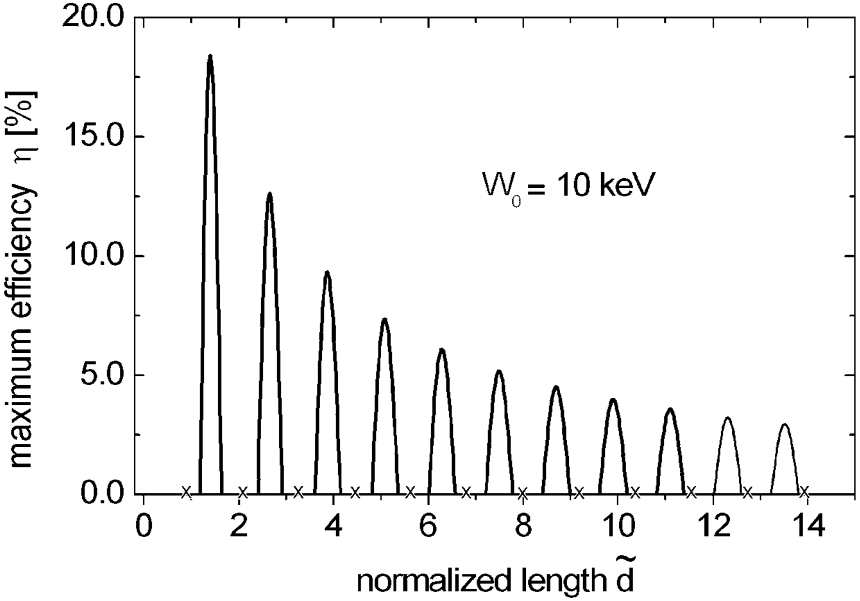
Matching the surface impedances $-E_z/H_\Phi$ at r=a

$$\frac{kJ_1(k_\perp a)}{k_\perp J_0(k_\perp a)} = \frac{J_1(ka)N_0(kb) - J_0(kb)N_1(ka)}{J_0(ka)N_0(kb) - J_0(kb)N_0(ka)} \qquad \text{(a)}$$

$$\frac{J_1(ka)}{J_0(ka)} = \frac{k}{k_\perp}\,\frac{N_0(k_\perp b)J_1(k_\perp a) - J_0(k_\perp b)N_1(k_\perp a)}{N_0(k_\perp b)J_0(k_\perp a) - J_0(k_\perp b)N_0(k_\perp a)} \qquad \text{(b)}$$

The corrugated surface is represented in terms of a surface boundary condition, thereby converting a two-media problem into a single one, from which we can determine the transverse wavenumber $k = \sqrt{k_\perp{}^2 + (\pi/d)^2}$ from the cavity and grid dimensions *a*, *b* and *d*.

OPTIMUM CAVITY ASPECT-RATIO



Maximal electronic efficiency versus normalized length for circular TM_{0n0} modes at the injection beam energy of 10 keV. Crosses on axis refer to TM_{0n0}-mode cavities with aspect ratio length/radius=0.37.

Competing TM_{020} mode oscillates at the resonant frequency $\omega = c\chi_{0n}/b$, which combined with $\tilde{d} = \omega d / c$ gives $\tilde{d}_n = (d/b)\chi_{0n}$

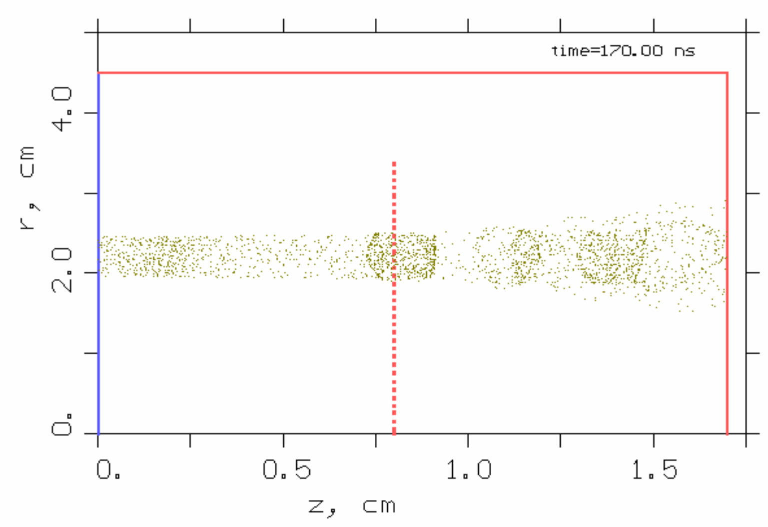
Hence, in cavities of aspect ratio $d/b = \tilde{d}/\chi_{0n}$ with $\tilde{d}$ lying midway between adjacent humps, TM_{0n0} modes are hardly excited. To get a sequence of $\tilde{d} = \chi_{0n}(d/b)$ values (*n=1,2,...*) between humps, the optimum value $(d/b)_{opt}$=0.37 has been selected and taken as the design aspect ratio of π-mode cavities operating at beam energy of 10 keV.

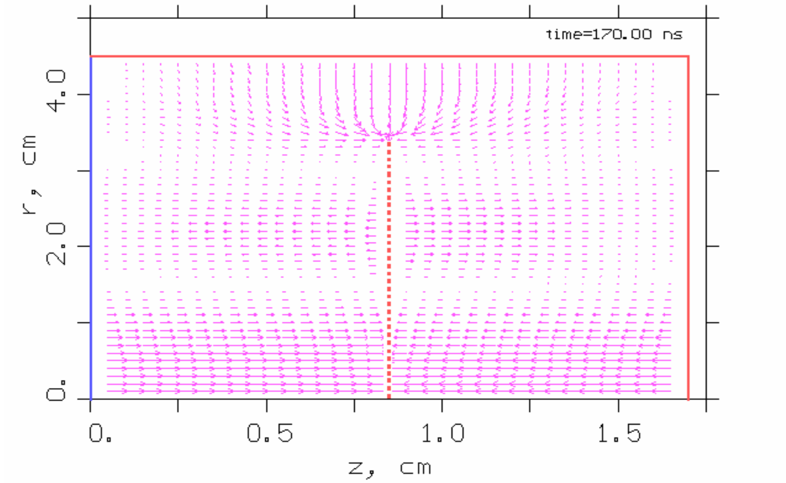
Therefore, the optimum wave number is $k_\pi = 7.8/b$

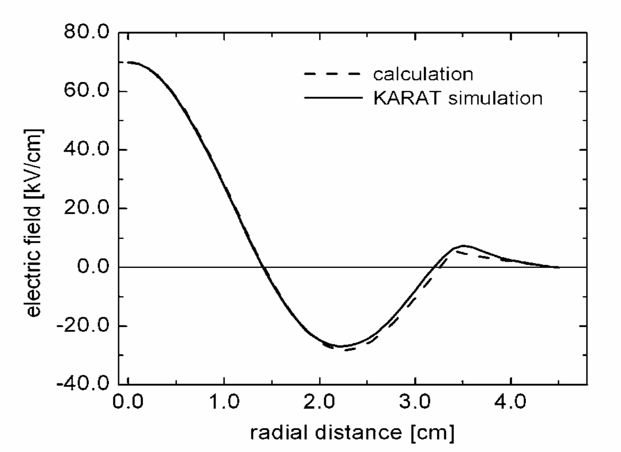
Using k_π in the dispersion relation corresponding to the grid with a center hole of radius *a*, one gets *a/b*=0.52; alternatively, the dispersion relation for the grid with annular slot (of width b-a) gives *a/b*=0.75.

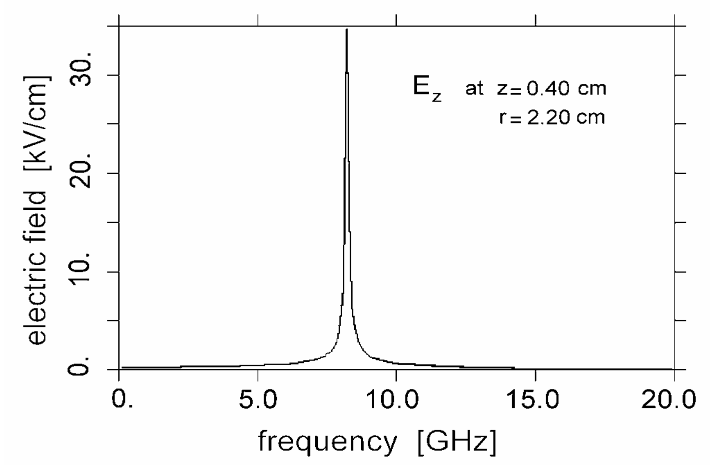
NUMERICAL SIMULATION

The physical system is run on a spatial grid of square cells 0.5 mm size with over 3000 macroparticles representing the beam electrons. Neither plasma formation nor secondary electron emission are included in the simulations, which also assumes the grid to be transparent.

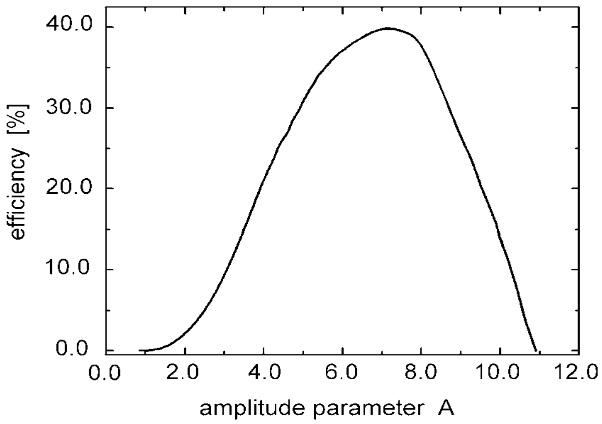




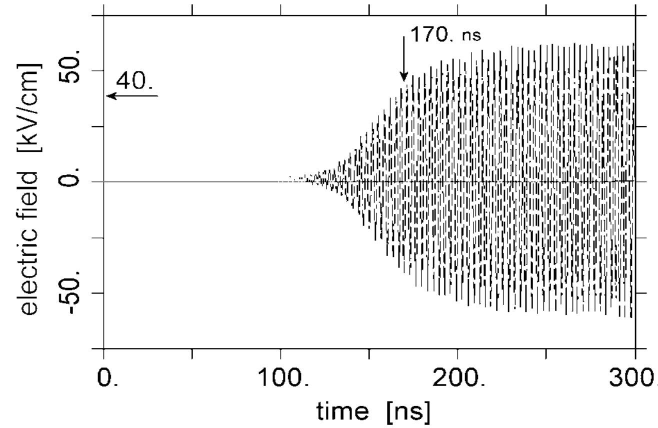




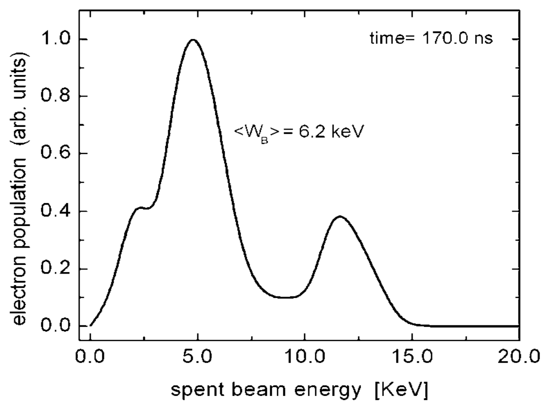
OPTIMAL ELECTRIC FIELD AMPLITUDE



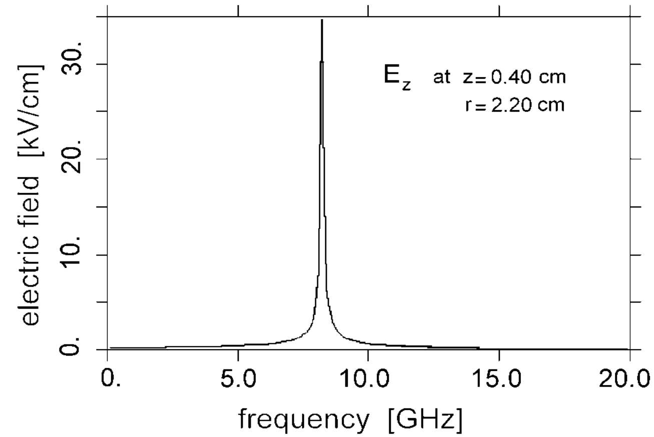
Efficiency at W_0=10 keV and d=2.9 as function of the amplitude A



Time history of electric field at z=0.40 cm, r=1.20 cm in the gridded cavity with annular slot

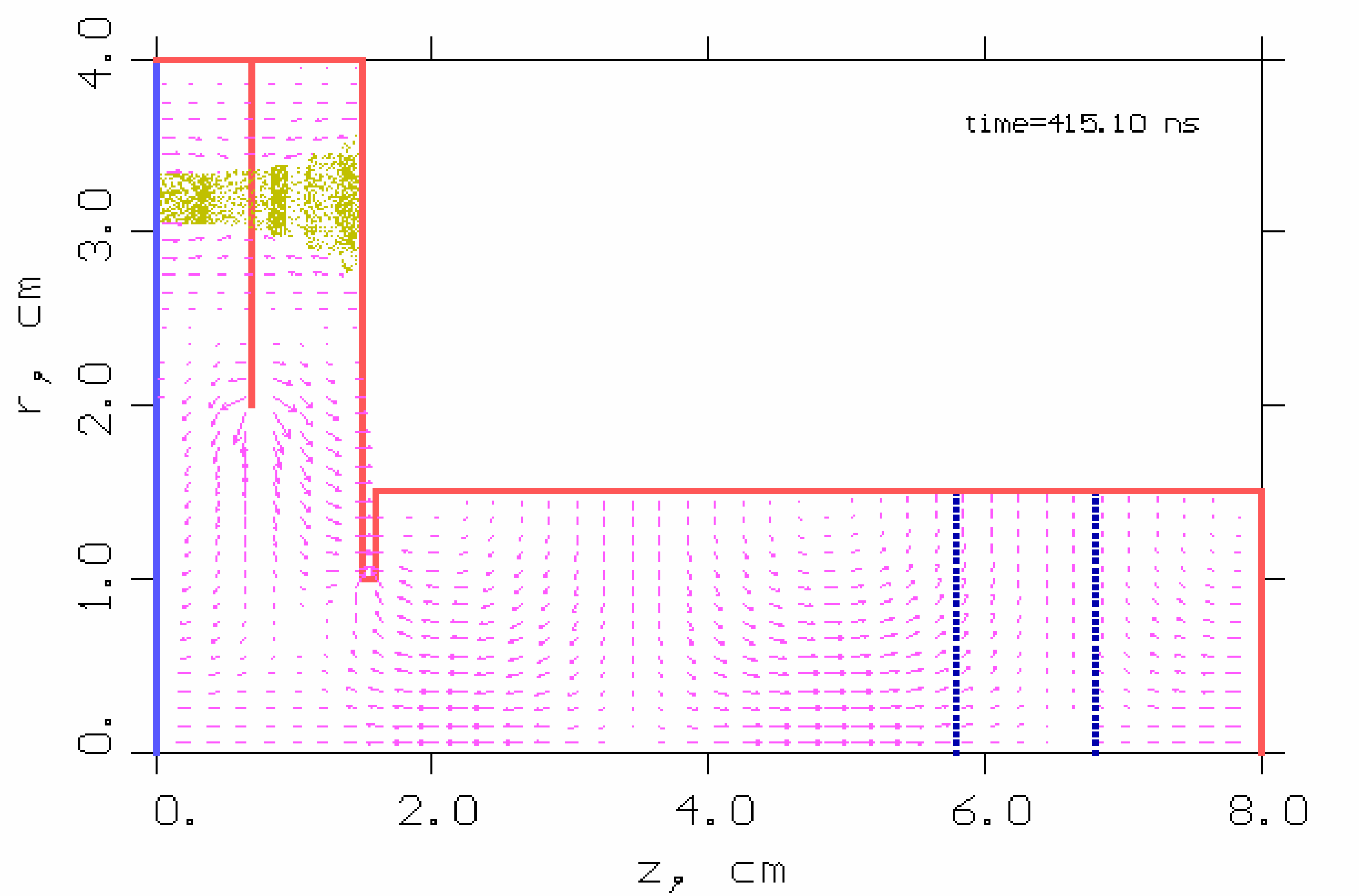


Energy distribution of collected electrons



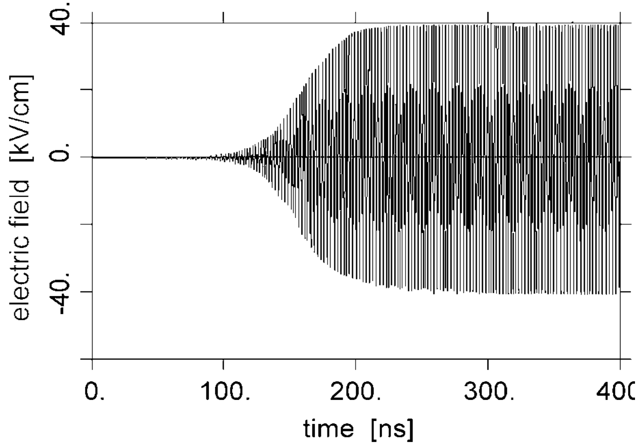
Frequency spectrum of electric field at z=0.40cm, r=2.20 cm

TWIN-CAVITY MONOTRON COUPLED TO AN OUTPUT WAVEGUIDE

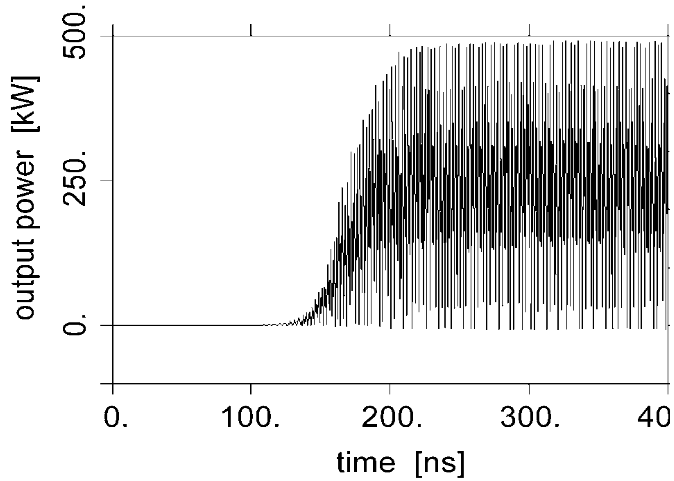


The hollow symmetric beam, 0.4-cm thick and carrying a 70-A current, is centered at r=0.0 with a 3.2-cm radius. The system is synthesized so that the saturation field reaches the optimum value of 40.0 kV/cm

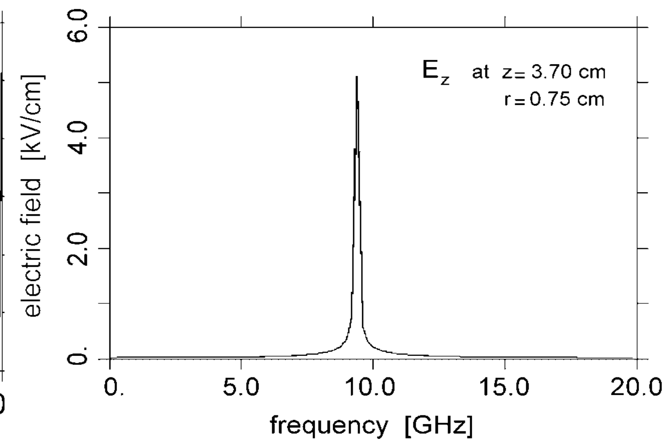
OPERATING AND OUTPUT CHARACTERISTICS



Total time history of electric field at z=0.4 cm, r=3.2 cm in the central shell of the annular electron beam



At z=3.7 cm, the total time history of output power. The average power level of 250.0kW yields the overall efficiency of 35.7 % relative to the injection beam power of 70.0 kW



Frequency spectrum of electric field at z=3.70 cm and r= 0.75 cm

CONCLUSIONS

The split-cavity monotron can be thought of two gridless monotrons in tandem, where the fields oscillate π radians out of phase in the adjacent partitions.

The beam injection energy W_0 dictates the optimum aspect ratio length/radius while suppressing competing TM_{0n0} modes.

At W_0=*10 keV*, the best ratio *d/b=0.37* yields the wavenumber k_π , which in turn defines the cold cavity eigenfrequency through $f=(GHz)=(15/\pi)7.8/b(cm)$

Following the design parameters provided by one-dimensional analysis, a 9.2 GHz monotron has been synthesized by properly selecting the radius (1.0 cm) and thickness (0.1 cm) of the coupling iris so that the resulting field amplitude (in the central shell of the annular beam) might reach the optim1010um saturation value of 40.0 kV/cm.

PIC simulation with a 0.4-cm thick, 70-A current beam has given the overall efficiency of 35.7% relative to 700 kW input beam power