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A SHEET-BEAM KLYSTRON PAPER DESIGN

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Abstract
What may be the first detailed cold test and computer simulation analysis of a Double Sheet Beam Klystron (DSBK) was performed at SLAC. The device was conceptually designed mechanically, and evaluated electrically for beam formation, gain, stability and efficiency. It is believed that the DSBK can be built at a relatively low cost for a future NLC collider and can produce at least 150 MW at 11.4 GHz with PPM focusing. Voltage and current are 450 kV and 640 A, respectively.

The Sheet Beam Klystron (SBK) is a device that has been considered as a microwave source for at least 60 years, but has never been fully designed or constructed. It was first proposed by Kovalenko in Russia in 1938 and revisited repeatedly over the years in the USSR, France and the US. The fact that no serious attempt was ever made to build and test an SBK can probably be attributed to the existence of alternatives and to perceived electrical and mechanical difficulties.

The principal electrical difficulties have been the large drift tube and overmoded cavities that the SBK requires. Also, designers have been concerned with the possibility that the sheet beam might be unstable suffering from diocotron break-up, or be difficult to contain laterally at the edges. Mechanical issues centered mostly at the gun, and the thermal design of a large cathode/heater package. Certainly, the construction of sheet-beam guns is beyond the capabilities of most universities and national laboratories. Industry, for the most part, has not taken on the SBK design problem, simply because other klystron types could serve existing requirements, or could be easily developed.

The chief virtue of the SBK is that its large lateral dimensions permit high power to be attained with low current densities in the cathode, and low power concentration in the cavities. This is the same advantage that multiple beam klystrons have over single-beam klystrons. The difference is that an SBK can be made with a fraction of the parts an MBK requires, or for that matter, that are normally used in an ordinary klystron.

At SLAC, the logistics of the Next Linear Collider (NLC) initially required several thousand 75-MW X-band klystrons for the 500 GeV versions of the machine. Gradually, as these tubes were built, put to use, and accumulated hours, confidence in their performance led to increases in the pulse length and the ratio of pulse compression. Today, the baseline NLC klystron has a pulse length of approximately 3 microseconds and the number of PPM-focused klystrons is approximately 1600. Obviously, this is still a large number of fairly complicated tubes. A klystron with twice the output would be very desirable, especially if a 1-TeV NLC were to be considered. However, 150 MW peak and a 50 kW average power at 11.4 GHz is uncomfortably high with a single beam and an output circuit with a one-centimeter bore. This is what motivated us to look very seriously into the SBK.

Through a process of parameter trade-offs, the design that has emerged employs two beams, each with an aspect ratio of 10:1 and perveance of 1.1×10^{-6} (0.11 micropervs per square). These are conservative numbers, and they are, in part, dictated by the necessity to use periodic focusing and to place magnets and polepieces at some distance from the beams in order to simplify the mechanical design and allow water-cooling in the space between the circuit and the magnet stack.

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As a matter of fact, mechanical considerations formed the basis for the overall design of this DSBK (Double Sheet Beam Klystron). Referring to Figs. 1 and 2, it can be seen that the cavities, drift tunnels and collectors are fabricated on numerically controlled machines out of four (4) slabs of copper. The two klystrons making up the DSBK share the same vacuum plenum at the double gun, but are otherwise separate mechanically and electrically. The two halves of each klystron are separated by a fraction of a millimeter so that cavities and drift tubes can be pumped from vacuum manifolds running along the entire length of the rf sections and the collectors. This is possible because the TM modes in the cavities do not have rf currents crossing the surface where the two halves are separated. (The guns are shown gridded because the picture was drawn for a different version of the DSBK).

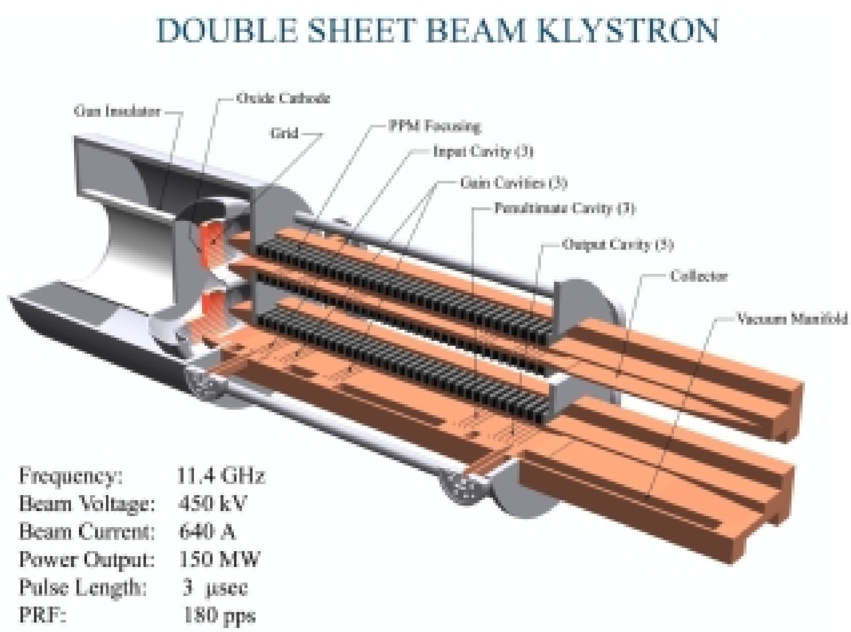


Fig. 1

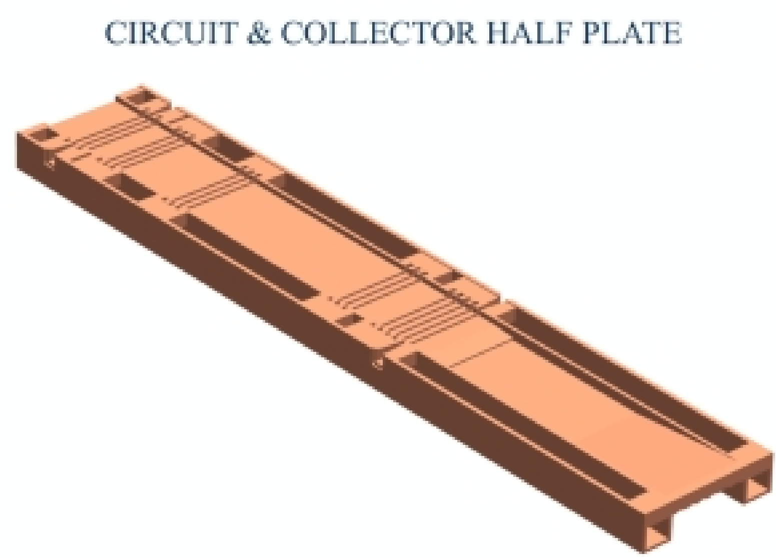


Fig. 2

These are twin 5-cavity klystrons, with all cavities of the extended type operating in the „-mode. The paper design consisted of a number of simulations and some cold testing. We wished to verify the following go, no-go conditions:

1. A gun can be designed with the necessary convergence and a low cathode current density.
2. The beam is well behaved and does not spread excessively laterally.
3. Cavities with sufficiently good R/Q and coupling coefficient can be designed, and provide a reasonably uniform field across the beam.
4. The klystron has good gain and efficiency.
5. The cavities are free of monotron oscillations for TM modes.

These were the conditions that had to be satisfied before prototype construction is attempted. Results are shown in the figures that follow.

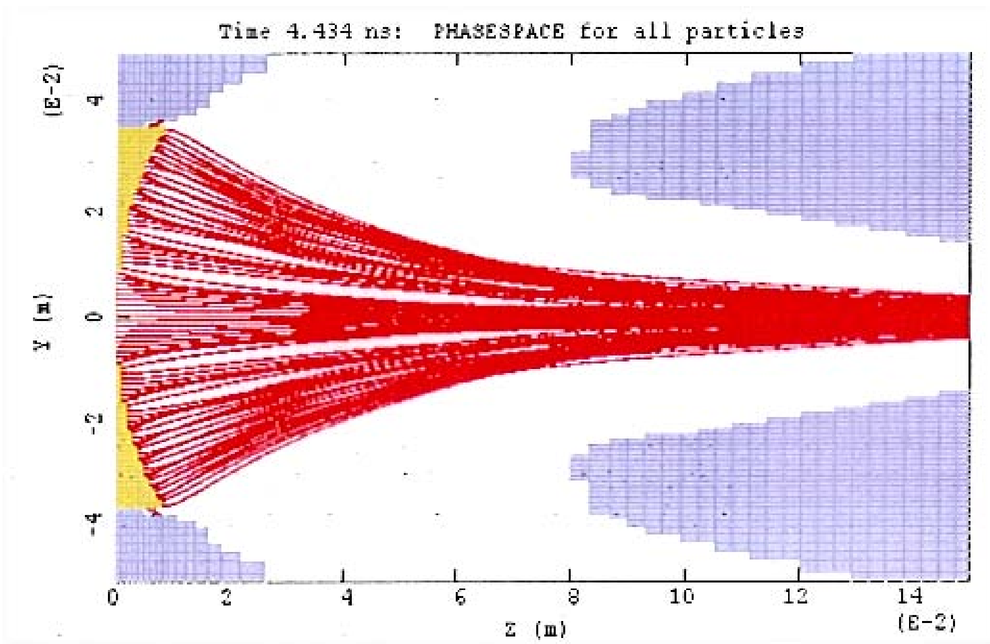


Fig. 3

1. Figure 3 shows a MAGIC 3D simulation of a gun which provides a beam 8-mm thick, 8-cm wide, with a beam current density of 50 A/cm^2, and an area convergence of 10, i.e. a cathode current density of 5 A/cm^2. The cathode surface is elliptical for good optics.
2. Lateral gun electrodes have not been designed as yet, but Fig. 4 shows that a beam artificially injected in the drift tunnel and immersed in a 3000 magnetic field is not spreading in a 10-cm distance and remains evenly distributed along its width. PPM simulations have not been performed as of yet, but PPM focusing is not expected to be a problem.
3. The cavities for the DSBK were at first designed as single cutoff waveguides. This is the method proposed at SLAC more than 15 years ago for providing a flat electric field across the width of the beam. A cold test model was constructed to test this scheme, as well as the isolation between cavities separated by varying lengths of a 1.2 x 9 cm drift tunnel (Fig.5) Cavity isolation was found to be more than 50 db in 5 cm of drift tube. However, GdfidL and MAGIC calculations showed that the coupling coefficient and R/Q were too low for a single cavity of the cutoff waveguide type. Figure 6 shows that the coupling coefficient for a transit angle of about 1 radian was only 0.09. Using triplet cutoff waveguides coupled capacitively

through the drift tube and operating in the „ mode corrected this. The coupling coefficient increased to 0.36 with an R/Q of 52 ohms. The light spots in the middle of the top view of the beam (Fig. 4) are a printer artifact.

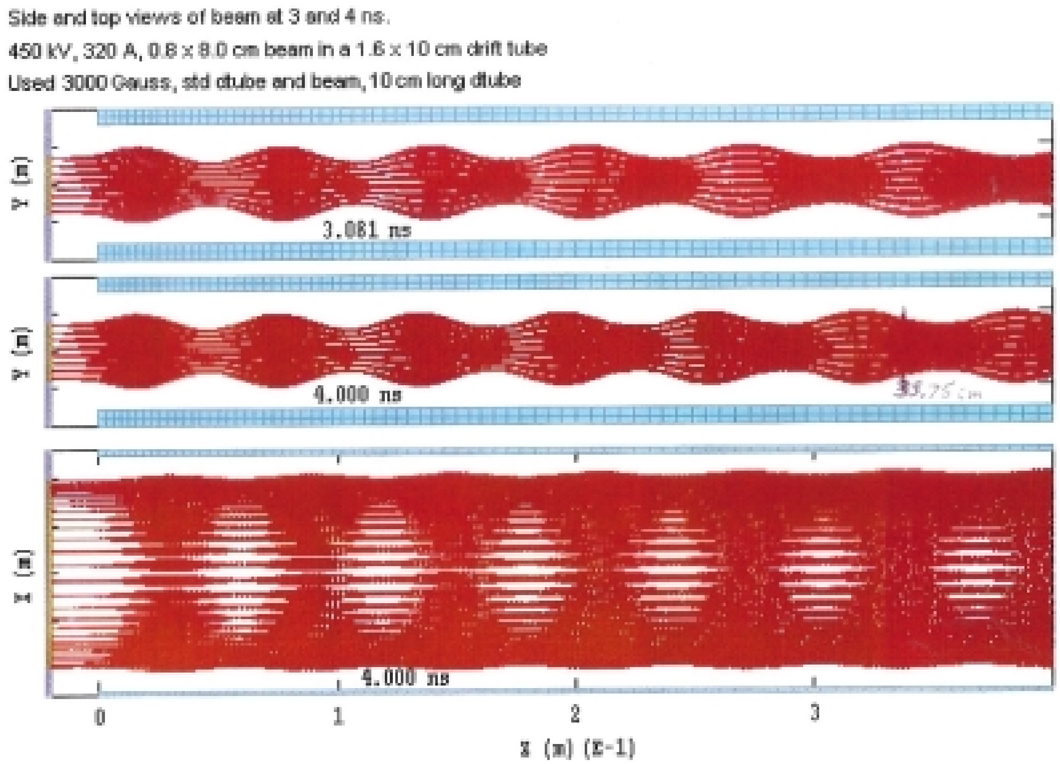


Fig. 4

4. With two of these cavities and an artificial beam, a MAGIC calculation produced a gain of about 18 db between two triplets spaced about 30 cm apart. Figure 7 shows the ratio of the rf current induced in the second cavity to the artificial rf current in the beam exciting the first cavity. We have inferred from these simulations the reduced plasma wavelength and beam loading parameters necessary to calculate small-signal gain. Using these in a standard gain vs. frequency calculation, we predict a 68+ db gain for the 5-cavity tube (Fig. 8 is on a separate page). Finally, a large-signal 3D-MAGIC simulation (Fig. 9) was run in which a beam modulated with an I_1/I_0 of 1 drives a triplet. The figure shows normal debunching, and Figure 10 indicates that this is evenly distributed across the width of the beam. A simulation for a higher value of I_1/Io will follow.

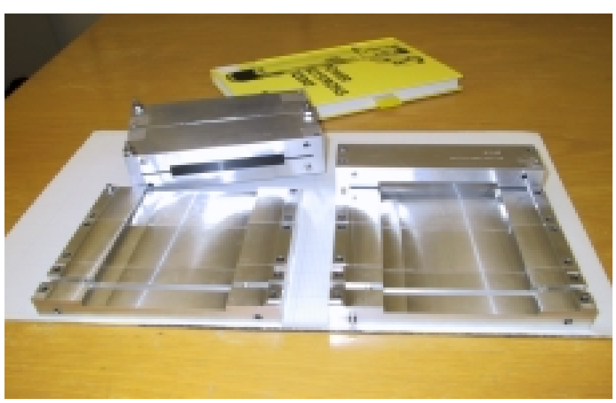
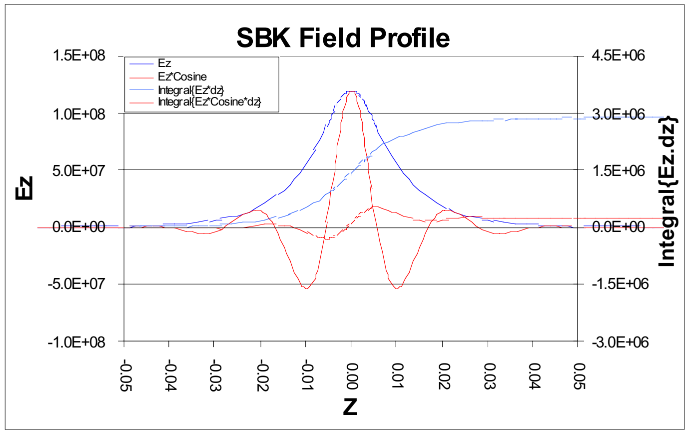


Fig. 5

Single Cavity   M = 0.088



Triple Cavity   M = 0.36

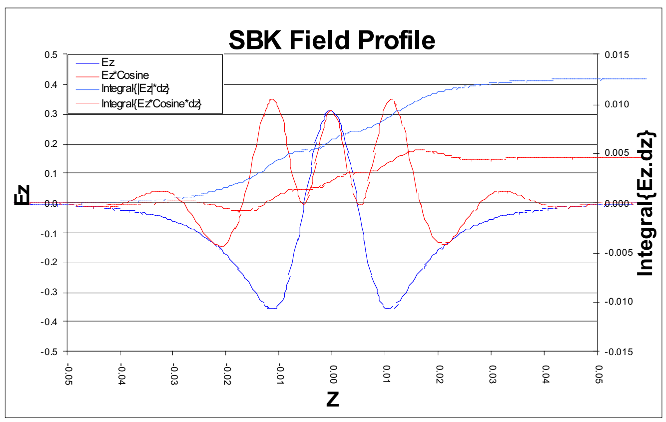


Fig. 6

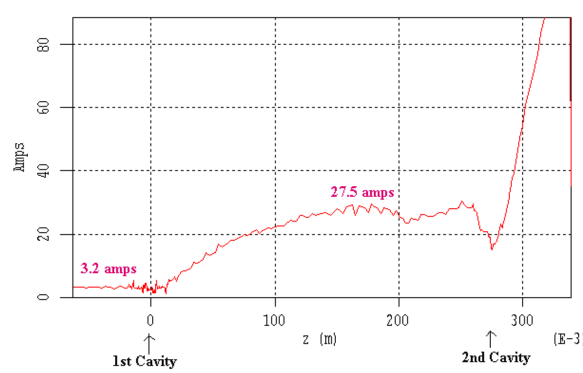


Fig. 7. RF current vs. Z.

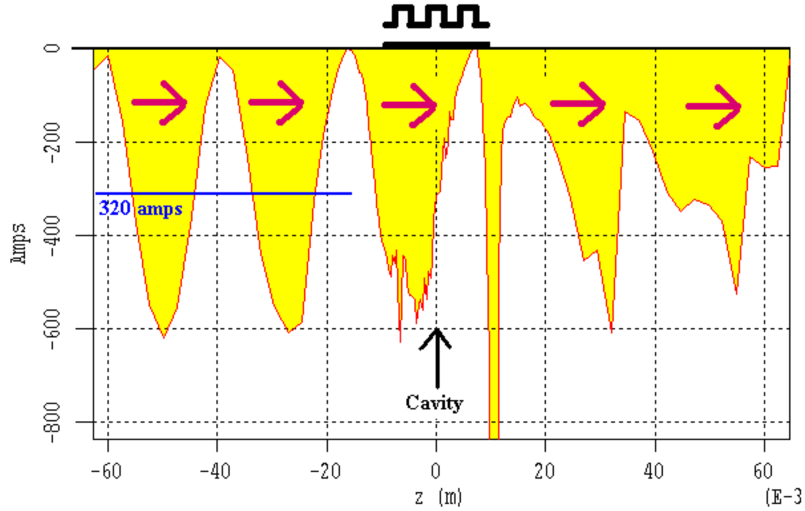


Fig. 9

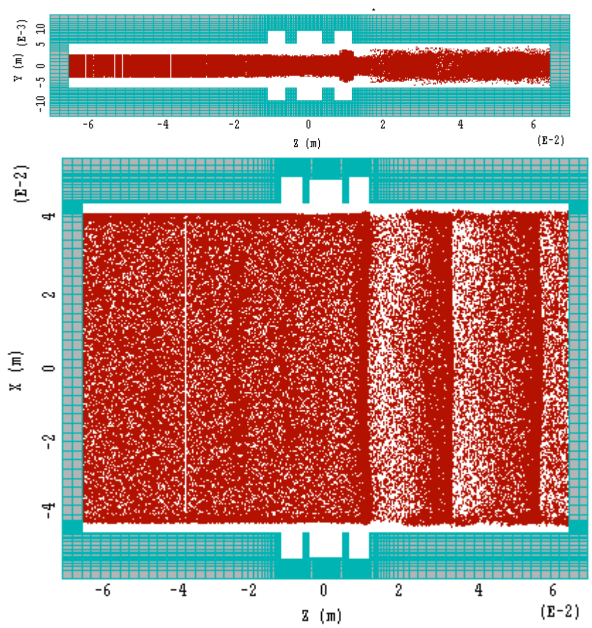


Fig. 10

One-half of an 11.4 GHz 150-MW DSBK (Coupling coefficient from GdfidL, beam loading, reduced plasma frequency from MAGIC)

--- **Data Inputs** -----------------------------------**GPSDRV02.MCD**

$Vo \equiv 450000$ **Beam Voltage (V)** — **Gun Microperveance (uA/V^1.5)** $K = 1.06$

$Io \equiv 320$ **Beam Current (A)** — **Beam current dens. A/cm^2** $Jo = 50$

$f0 \equiv 11.42$ **Center Frequency (GHz)**

$a \equiv 0.006$ **Drift tunnel half-height (meters)** — **Electron Prop. Constant (rad/m)** $\beta e = 282.604$

$b \equiv 0.004$ **Beam half-thickness (meters)** — **Radial propagation constant (rad/m)** $\gamma = 150.271$

$w \equiv 0.08$ **Beam width (meters)** — **Bunching wave number (rad/m)** $\beta q = 5.922$

$Ro := \frac{Vo}{Io}$

$\gamma \cdot a = 0.902$ $\quad \gamma \cdot b = 0.601$

Gap transit angle $2 \cdot \beta e \cdot d_1 = 3.109$

No of cavities: $N \equiv 5$

Beam resistance $Ro = 1.406 \times 10^3$ **ohms**

Brillouin field $Bbr = 368.297$ **Gauss**

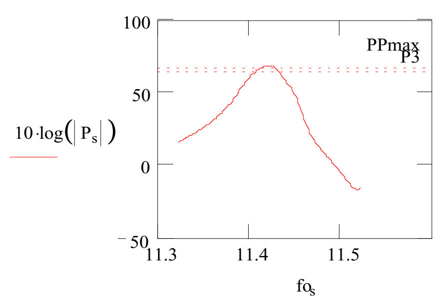
Plasma Frequency (rad/s) $\omega p = 2.425 \times 10^9$

$2 \cdot \gamma \cdot b = 1.202$

$S := \frac{a}{b}$ $\quad S = 1.5$ $\quad R \equiv 0.62$

$\frac{2 \cdot \pi \cdot f0 \cdot 10^9}{\omega q} = 47.723$

GAIN (DB) vs FREQUENCY



$\lambda q = 1.061$ **meters** $\quad \lambda p = 0.658$ **meters**

Gain $PPmax = 68.369$ **Db**

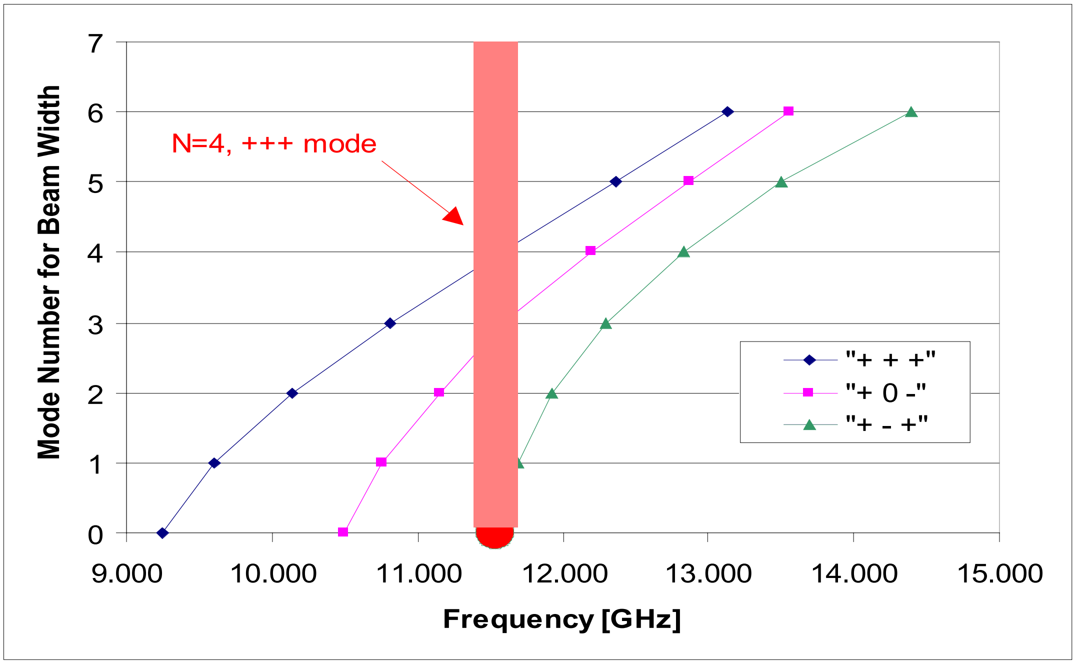
Power output @ 50% total efficiency: $0.5 \cdot Vo \cdot Io \cdot 10^{-9} = 0.072$ **GW**

Cavity Rs/Q	**External Q and Qo**		**Cavity Frequency (GHz)**	**Gap-Gap L (m)**
$RQ_1 \equiv 52.5$	$Qe_1 \equiv 805$	$Qo_1 \equiv 6550$	$f_1 \equiv 11.42$	$l_1 \equiv 0.0$
$RQ_2 \equiv 52.5$	$Qe_2 \equiv 1000$	$Qo_2 \equiv 6550$	$f_2 \equiv 11.4$	$l_2 \equiv 0.1$
$RQ_3 \equiv 52.5$	$Qe_3 \equiv 1000$	$Qo_3 \equiv 6550$	$f_3 \equiv 11.43$	$l_3 \equiv 0.1$
$RQ_4 \equiv 52.5$	$Qe_4 \equiv \infty$	$Qo_4 \equiv 6550$	$f_4 \equiv 11.45$	$l_4 \equiv 0.1$
$RQ_5 \equiv 52.5$	$Qe_5 \equiv 400$	$Qo_5 \equiv 6550$	$f_5 \equiv 11.42$	$l_{5.} \equiv 0.1$

--- **Data Output** ---

Beam loaded Q	**Gap Distance (m)**	**Coupling Coefficient (induced current)**	**Drift Length (degrees)**
$Qb_1 \equiv 918$	$Zg_1 = 0$	$M_1 = 0.357$	$\beta ql_1 = 0$
$Qb_2 \equiv 918$	$Zg_2 = 0.1$	$M_2 = 0.357$	$\beta ql_2 = 33.929$
$Qb_3 \equiv 918$	$Zg_3 = 0.2$	$M_3 = 0.357$	$\beta ql_3 = 33.929$
$Qb_4 \equiv 918$	$Zg_4 = 0.3$	$M_4 = 0.357$	$\beta ql_4 = 33.929$
$Qb_5 \equiv 918$	$Zg_5 = 0.4$	$M_5 = 0.357$	$\beta ql_5 = 33.929$

Fig. 8



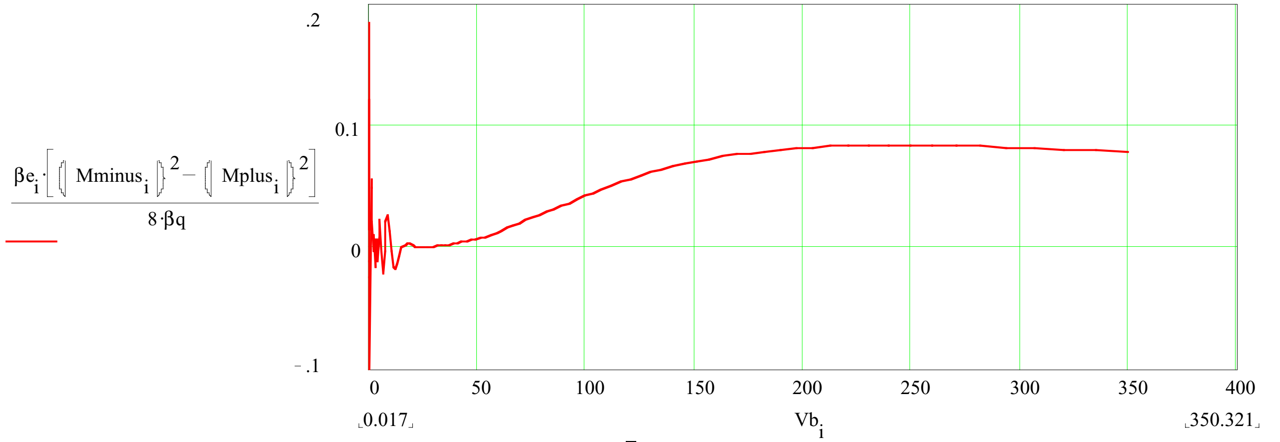
N	"+ + +"	"+ 0 -"	"+ - +"
0	9.245	10.502	**11.542**
1	9.598	10.762	11.689
2	10.143	11.152	11.930
3	10.817	11.575	12.292
4	**11.588**	12.193	12.827
5	12.358	12.876	13.497
6	13.129	13.558	14.394

Fig. 11

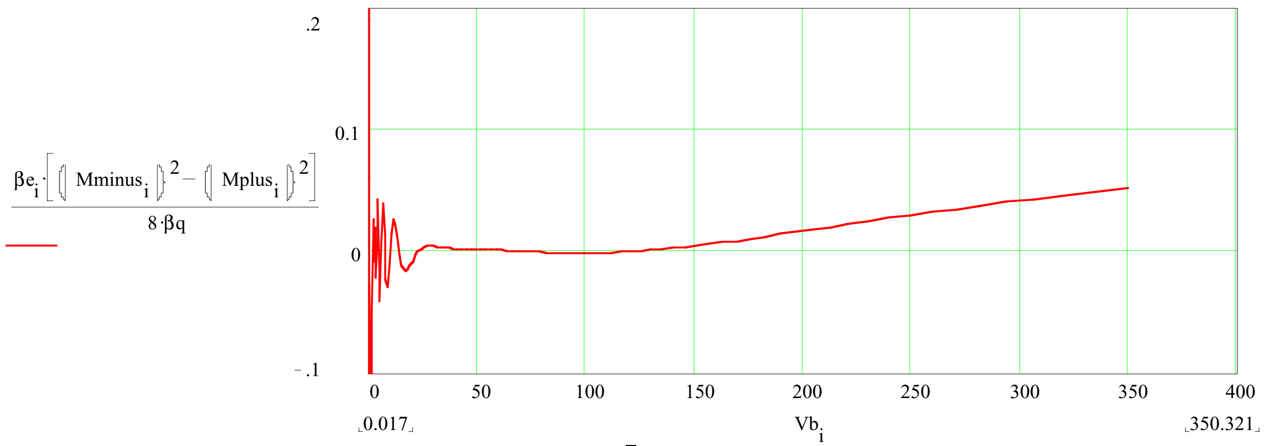
5. To test for stability in unloaded triplet cavities, a mode search was conducted using MAGIC (Fig. 11), and several of the TM modes were tested for negative beam loading, using GdfidL and the M^2_{minus} — M^2_{plus} criterion, the difference between the squares of the coupling coefficients for the fast and the slow space charge waves. (See Fig. 12). The slight differences in the frequencies between Fig. 12 and mode search and the stability tests in Fig. 12, are due to the fact that the structure used in Fig. 12, was tuned at 11.426 GHz, instead of 11.542 GHz.

Beam Coupling

pi-mode 11.4226



+0- mode N=0 and 2, 10.5203 and 11.2096



+++ mode N=4, 11.5735

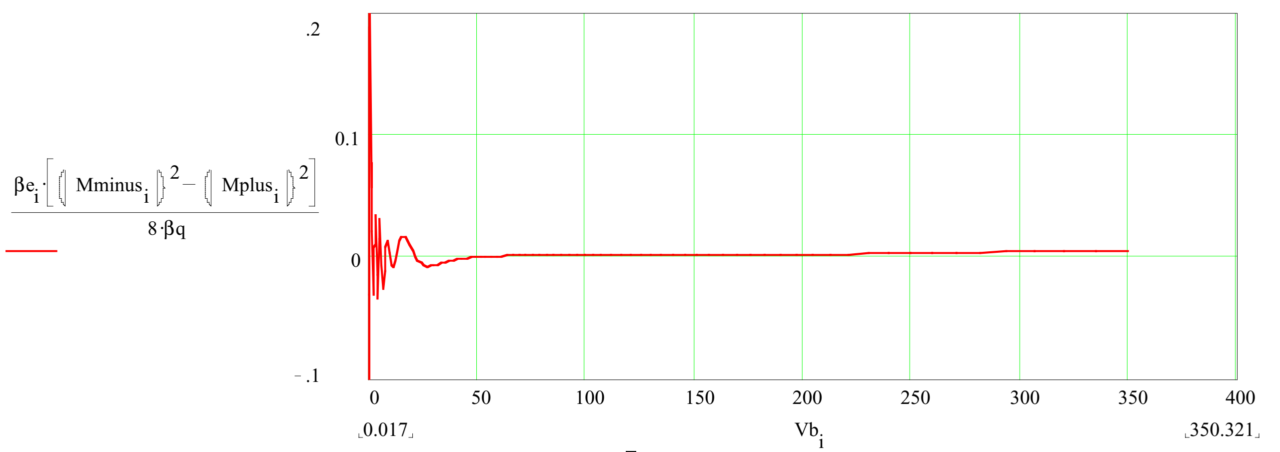


Fig. 12 Stability test examples

CONCLUSIONS

Although additional simulations will be necessary, it is clear the device has an excellent chance to work and should be built. This may take place in 2002.

APPENDIX 1 — LATE BREAKING RESULTS FROM MRC

Some recent results arrived from MRC which were too late to incorporate into the body of the paper, but too important to leave out. The first transmission from Dave Smithe of MRC, who was asked to drive a triplet cavity with a fully pre-bunched beam, is reproduced here without comment except to note that this is the first effort to run the simulation for full power. No attempts have been made to tune or otherwise adjust for maximum power.

A.1.1 OUTPUT POWER

Geometry: Resistive load filling each of the end cells.

Beam voltage = 450 kV, Beam current = 320 amps, I_1/I_0 = 1.8.

Output Power: 62.0 MWatts,
Wall Losses: 5.5 MWatts

A top view of the cavity geometry is shown in Fig. A.1.1.1. There is resistive load in each of the end cells.

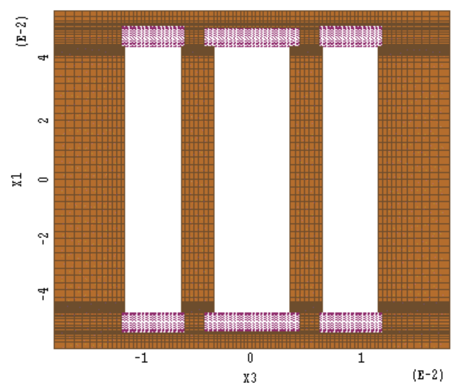


Fig. A.1.1.1

A pre-bunched beam is injected into the cavity, and it is rung up to saturation. Many runs were done to optimize the output power by varying the amount of resistance (cavity Q), and hot-test frequency-shift (+0.01%). The following figure (A.1.1.2) shows the time-history of cavity saturation. The first plot shows the sum of power to the end-cell load plus wall-losses, and the second plot shows just wall-losses.

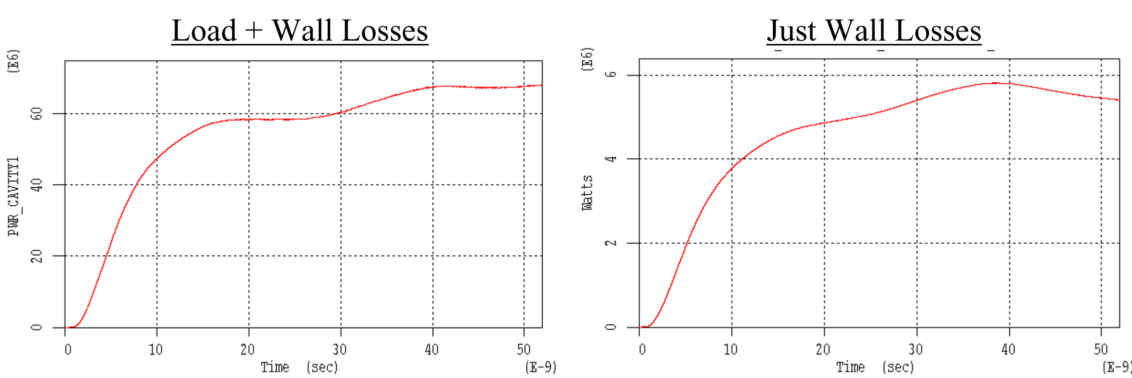


Fig. A.1.1.2

A view of the particles and current is shown below (Fig. A.1.1.3). The shape of the pre-bunched current is a sine wave, truncated below some value, and re-scaled to give the correct DC current. The particles are injected at a single energy of 450 kV.

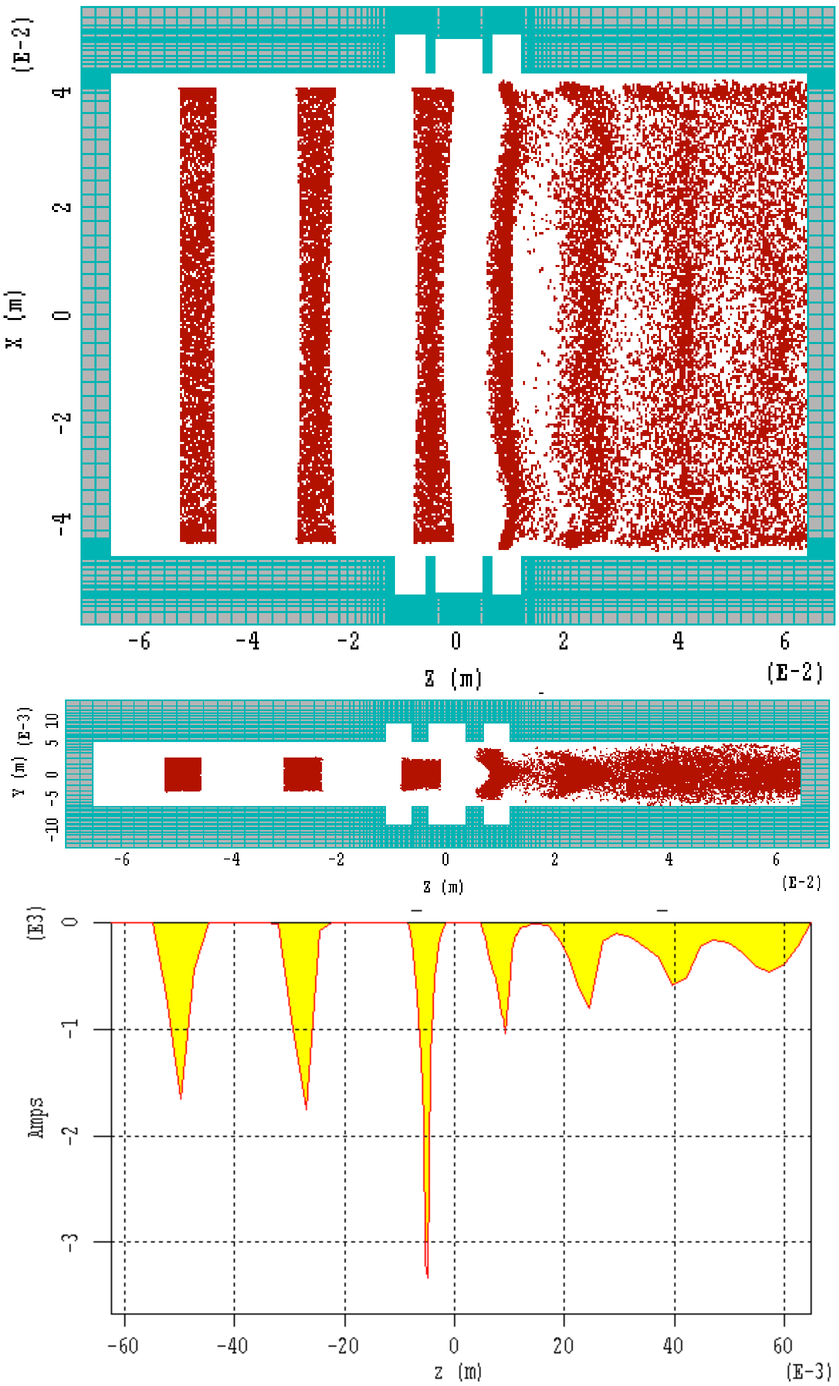


Fig. A.1.1.3

Shown below are views of particle-energy, average-energy-per-particle, and RF-current, down the length of the drift tube (Fig. A.1.1.4). Note that few, if any, particles are turned-around. About 47% of the original beam energy is lost, 43% to the output load, and 4% to copper wall losses. The RF current at the exit is about _ of the original pre-bunched RF current.

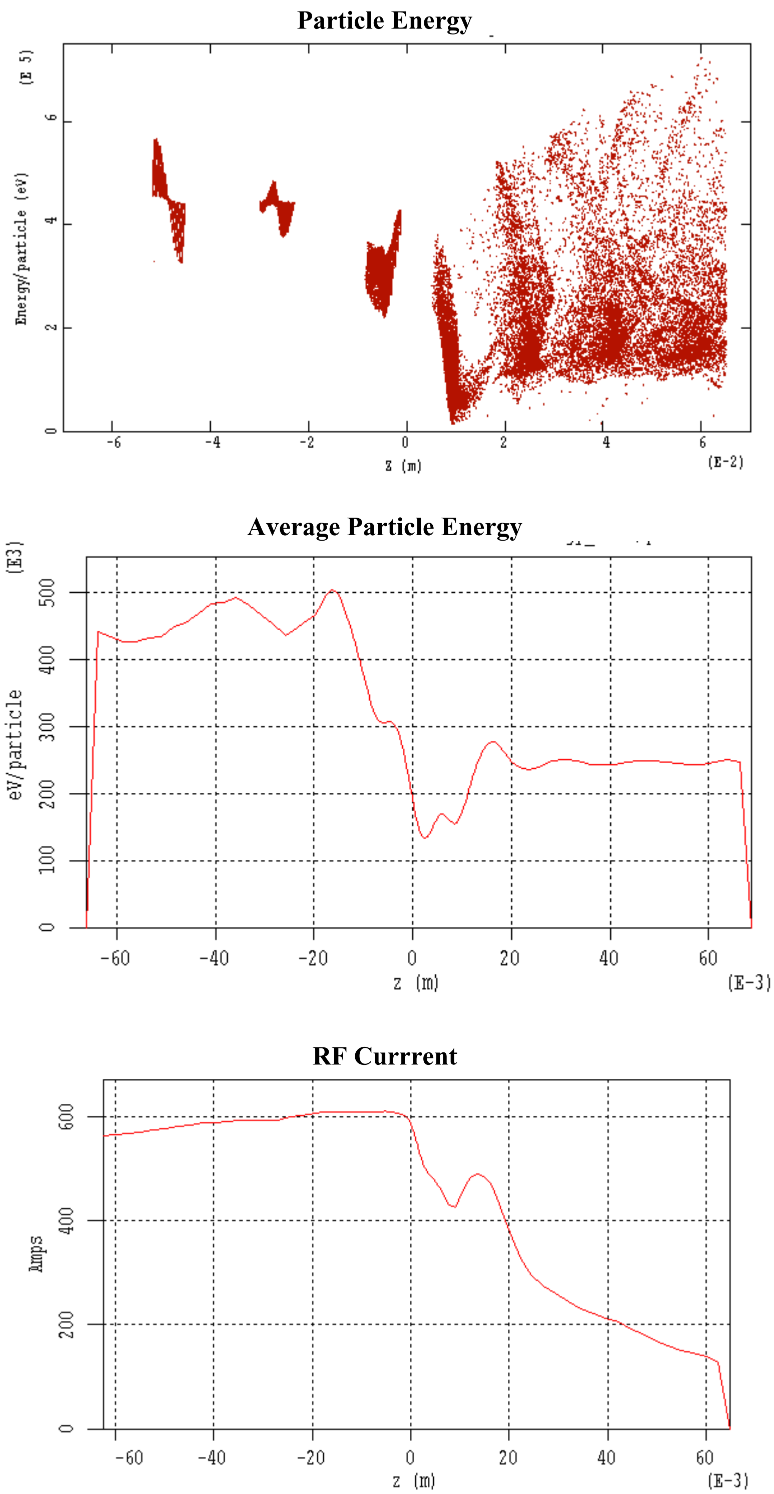


Fig. A.1.1.4

A.1.2 TEST OF CAVITY STABILITY

This is a final transmission from MRC (Fig. A.1.2.1). The objective here was to completely unbalance the beam to see whether modes might be excited in the cavity that would lead to oscillations. It can be seen from the treatment below that this did not happen.

Geometry: Unloaded, copper cavity.

Used _ of beam, e.g., missing right and lower halves, with no RF signal, other than the initial transient. The offset beam and the initial transient provide the seed for any unstable modes. The beam current density is the save as for the previous 450 kV, 320 amp runs.

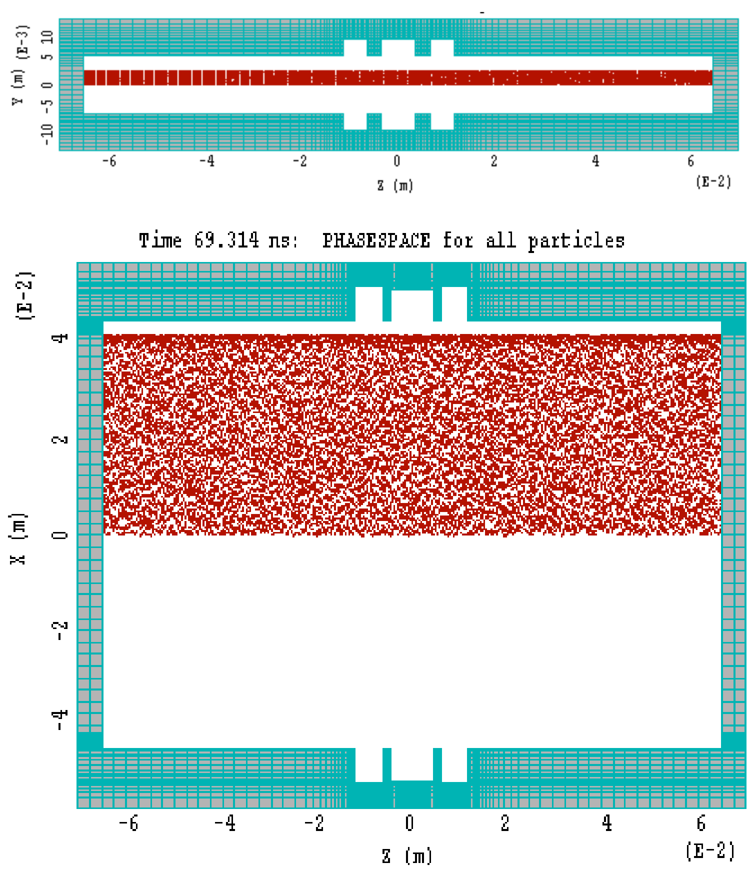


Fig. A.1.2.1

From previous simulations, it is already known that the system is stable at the operating mode, as the operating mode has been to seen to saturate in a conventional manner during small-signal analysis.

The simulation was run for 80 nanoseconds. Any linear instability would exhibit an *exponential* increase in the electromagnetic energy ($U_{em} = \_\varepsilon|\mathbf{E}|^2 + \_\mu|\mathbf{H}|^2$) stored within the cavity, as the instability mode grew in amplitude. *No such increase was observed.* The offset beam, in both X and Y directions, should couple strongly to virtually all conceivable modes, thus there is little chance that an instability exists, but is undetected, since the instability seed is quite strong.

Wall losses of copper have been included. Thus it is still possible that a perfectly conducting cavity might experience an instability, but that the copper wall-loss loaded system is stable.

Instead of an exponential rise in EM energy, a very slow, approximately *linear*, growth in electromagnetic energy was observed (Fig. A.1.2.2). This is typical of all unfiltered relativistic particle-in-cell simulations and is associated with growth of short-wavelength (grid-size) particle noise in a simulation. There is no identifiable cavity mode structure associated with particle noise (Fig. A.1.2.3).

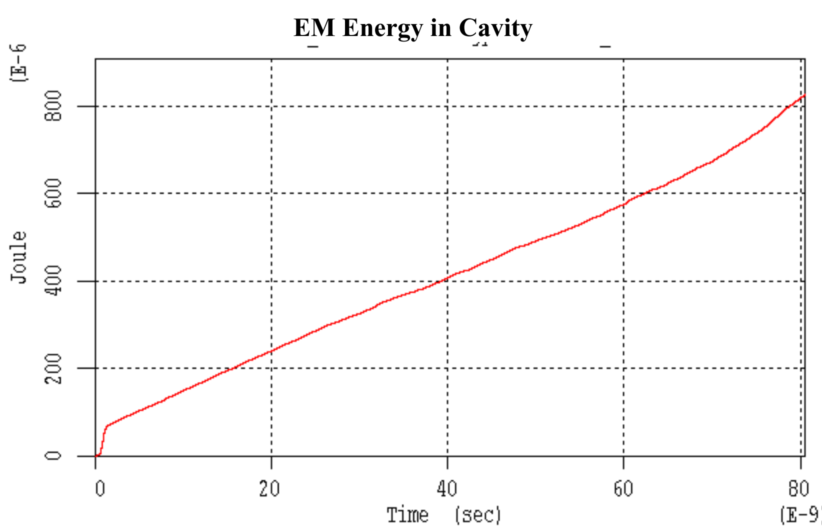
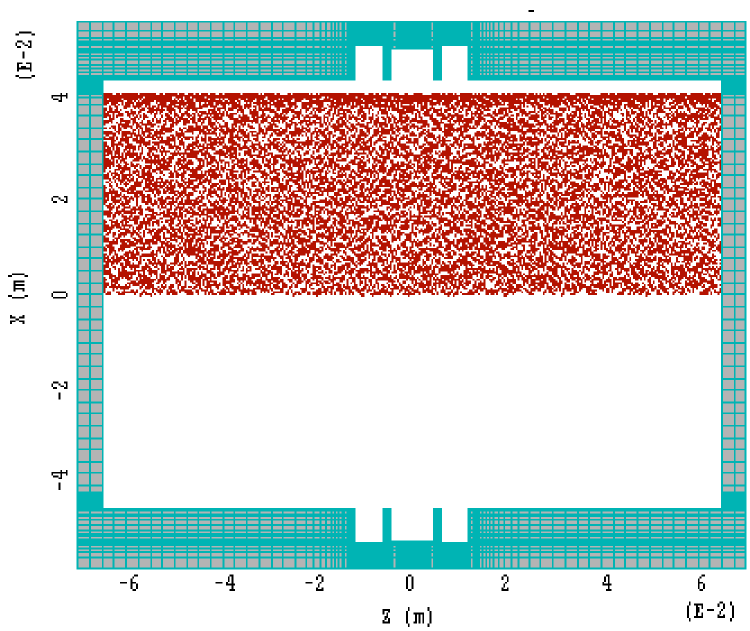


Fig. A.1.2.2

There is also no evidence of a coherent RF signal on the particle positions or energy after 80 nanoseconds.



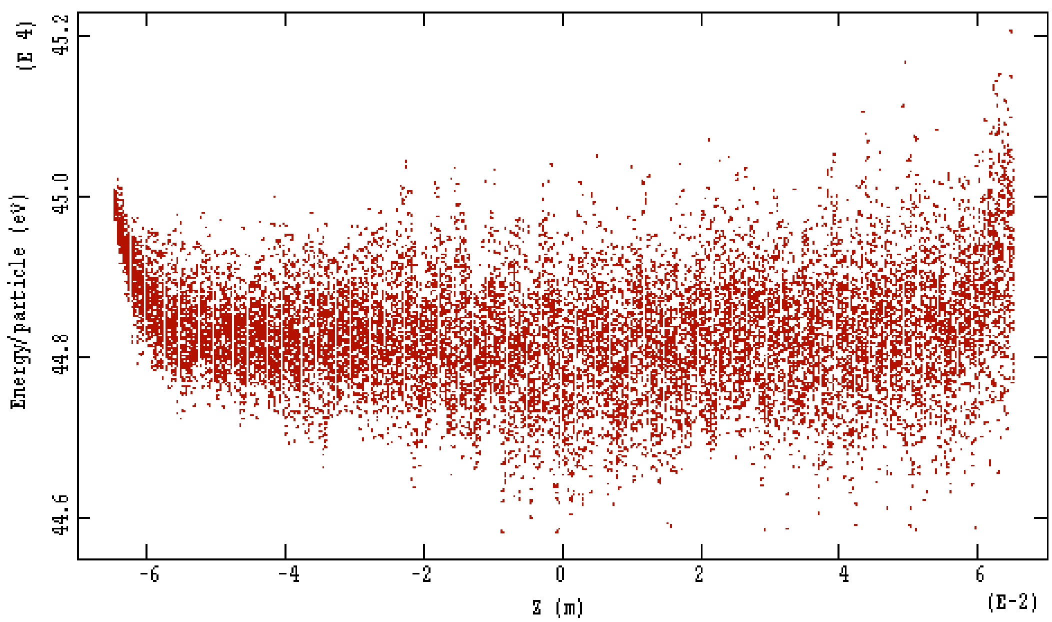


Fig. A.1.2.3

This result is for a single cavity. Instability associated with power propagation between two or more triple-cavities separated by rectangular drift tube has not been investigated here.

ACKNOWLEDGEMENTS

Thanks are due to Daryl Sprehn, who developed the gun optics, Mike Neubauer for the GdifdL simulations, David Smithe of MRC who performed the MAGIC simulations, and Randy Fowkes for the cold test work.