Application of Radio Frequency Superconductivity to Recirculating Linacs[*]

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I. Purposes of Recirculating Linear Accelerators (RLA's)

The recirculating linear accelerators discussed in this paper are continuous wave (CW) devices used to accelerate electrons. Recirculation through the RF accelerating structures is used because it reduces both capital and operating (electric power) costs. Such accelerators are used, at present, for two purposes: nuclear physics and free electron laser drivers.

II. Available Technologies and Selection

Beam requirements for nuclear physics include a high duty cycle (approaching 100%), high current (up to 200 μA), energy between 100 MeV and 16 GeV (one accelerator will normally cover only part of this range), a low normalized emittance (down to $2 \cdot 10^{-5}$ $\pi \cdot \gamma \cdot$m$\cdot$radians is useful), and a low energy spread (σ_E/E down to $2 \cdot 10^{-5}$ is useful).

Beam requirements for free electron lasers include high within-bunch peak currents (~1000 A) and low normalized emittance (~$2 \cdot 10^{-5}$ $\pi \cdot \gamma \cdot$m$\cdot$radians).

Technologies available for producing high duty cycle electron beams of the energies indicated include:

(1) Microtrons. This type of accelerator is excellent for the low end of the energy range, but produces excessive emittance growth at higher energies due to the large number of turns and the small bending radius.

(2) Synchrotrons. Synchrotrons are low current accelerators because the magnets must go through a full cycle for each batch of electrons accelerated, and cycle rates above 60 Hz are difficult to achieve. Flat-topping is required to produce a high duty cycle, and this further reduces the cycle rate.

(3) Pulsed stretcher rings. Such rings receive electrons from pulsed linacs. Due to the high current in the linac, the emittance is degraded by space charge effects. In addition, an energy spread occurs due to variations in klystron power output throughout the

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pulse. Variations within the pulse and from one pulse to the next would require very complex circuitry in the stretcher ring to damp out these disturbances and therby avoid an erratic output beam. The emittance and energy spread available with a pulse stretcher ring are significantly worse than those available from a recirculating linear accelerator.

(4) Recirculating linear accelerator. This type of accelerator produces a beam with excellent stability, low emittance, and low energy spread. These properties exist because the beam has a CW condition at all times, and there are minimal space charge effects and very small transients. Recirculating linear accelerators are practical only using superconducting RF because the power dissipation associated with supplying the required CW voltage would otherwise be prohibitive.

III. History of Recirculating Linear Accelerators

Since the existing RLA is well documented in the literature,[1] and all others are discussed in other papers at this workshop,[2,3,4,5] this paper deals primarily with general considerations pertaining to RLA's.

The existing machine at HEPL[1] has been extremely successful except for its unanticipated problem with multipacting. The stability and quality of the beam are outstanding.

The 130 MeV RLA under construction at Darmstadt[2] has produced a low energy beam using the first few cavities. The construction phase of the 4-pass, 4 GeV RLA at CEBAF[3] began in February, 1987. Planning and R & D directed toward a 2-4 GeV RLA at Saclay[4] is well under way. Funds for construction of a 25 MeV free electron laser (FEL) driver at Frascati[5] have been approved, and higher energies appropriate for nuclear physics are being considered.

IV. Developments in Radio Frequency Superconductivity Important to RLA's.

The most serious obstacle to adequate gradients for many years was multipacting, which limited gradients to around 2 MV/m/GHz. After extensive investigation, this multipacting was identified by Claude Lyneis at HEPL as one point multipacting near the equator of the cell. In 1979, a "spherically" shaped cavity developed at the

University of Genoa[6] did not exhibit multipacting. Using an extension of Lyneis's work, the absence of multipacting in the Genoa cavity was explained by Klein and Proch[7] at the University of Wuppertal. The "spherical" shape was further improved by Kneisel[8] with development of the "elliptical" cavity, which uses an elliptical dorsal profile in the iris region to minimize E_p/E_{acc}. The "elliptical" shape also avoided a surface perpendicular to the beam axis; this change greatly strengthened the cavity and improved rinsing during acid cleaning.

Higher order mode (HOM) couplers are essential to prevent beam instabilities. In their absence, the high intrinsic Q's of the HOM's ($\sim 10^9$) would destroy the beam at very low beam currents. Q_{ext} values of around 10^4 are needed to provide a stable beam with a reasonable safety margin. HOM couplers which penetrate cell walls cause enhanced magnetic fields which can result in thermal-magnetic breakdown at reduced accelerating gradients. Such penetrations can also induce local multipacting. Cavities in which both the fundamental and HOM couplers are placed on the beam pipe just outside the cell region were developed independently by Cornell[9] and DESY[10].

Another important improvement was in the area of electron beam welding. A "standard" electron beam weld uses a sharply focussed beam which generates a vapor column in the metal being welded. Cavities welded in this manner are commonly found to exhibit thermal-magnetic breakdown at $E_{acc} \simeq 1$ MV/m. This breakdown has been traced to two causes. One cause is that such welds generate significant spatter; this spatter can result in small niobium spheres fused to various places on the cavity surface. The poor thermal conduction away from these spheres results in breakdown at low fields. A second cause is that voids are frequently left in the weld by the vapor column. If one of these voids is opened but not removed by acid cleaning, enhanced magnetic and/or electric fields at the edge of the opening result. If the void is just below the surface but not opened, thermal conduction away from the niobium directly above the void is severely impaired, resulting in thermal-magnetic breakdown at a low field. Both of these problems have been obviated by a modification of the welding technique. The key feature of the modification is a spreading of the beam welder's electron beam so that no vapor column results. One version of the modified weld is the "rhombic raster,"[11] which rasters the beam at a

mixed 4 and 5 kHz rate. Another version is a defocussed beam, which also works well but is difficult to characterize in terms of a well defined diameter.

Surface defects are another area in which significant progress has been made. Such defects, which can be dielectric and/or metallic, generate heat and initiate thermal-magnetic breakdown at $E_{acc} \simeq 5$ MV/m with reactor grade niobium. The gradient limit caused by a given defect is approximately proportional to the square root of the thermal conductivity of the niobium. The thermal conductivity of niobium available from niobium manufacturers has increased by a factor of 12 above that of reactor grade niobium. This has been achieved by an increase in the number of ingot remelts, slower melting, carefully controlled rolling and annealing, and to a lesser extent, improvement of the vacuum in the ingot melting furnace. The thermal conductivity can typically be improved by an additional factor of 2-3 by post-processing. The post-processing is accomplished by placing a metal with high oxygen affinity, such as yttrium[12], titanium[13], or hafnium, in contact with the niobium surfaces and holding the niobium at a sufficient temperature to cause the oxygen to diffuse into the surface layer, where it is trapped. The surface layer is then removed. It has been postulated by Kneisel[14] that commercial Nb with high thermal conductivity has a surface layer with much lower thermal conductivity; this postulate would explain some CERN results[15] in which the Q_{BCS} was anomalously high. Some evidence to support Kneisel's hypothesis has been obtained by Padamsee[16]; these results suggest that the low conductivity layer is thick enough not to be removed in a normal acid cleaning. Post-processing avoids the presence of this low conductivity layer.

Improved surface condition has also contributed to improved gradients and Q's. This improved condition has been partially achieved by more careful handling of the niobium. Improved inspection procedures, including anodization to reveal surface inclusions, rust testing to reveal iron surface inclusions, careful visual inspections to find surface structural defects, and ultrasonic and/or X-ray inspection to find internal foreign inclusions and delaminations, have contributed to the improvement. Faster rinsing following acid cleaning reduces deposition of chemical residues. Dust control through use of laminar flow HEPA filtered cavity assembly areas, use of filtered air during cavity attachment to test apparatus, use of

electronic grade solvents, and use of rapid surface drying techniques, have contributed to clean surfaces. Field emission processing using a partial pressure of helium in the cavity was developed at HEPL[17] many years ago and is still frequently used to reduce field emission enhancement values. Hermetic assembly, a concept developed by Kneisel[18], consists of testing one or more cavities in a comparatively simple configuration in a vertical cryostat, where gravity keeps the liquid helium in place and where $Q=Q_o$ if all cavity and coupler parts are Nb, of warming up the cavity and closing beam line gate valves, and of then installing the cavity, under vacuum, with its tuner and other complex instrumentation into the beam cryostat. This procedure is believed to reduce the probability that contamination of the cavity will occur between the time of the first simple test and the relatively complex test in the beam cryostat.

V.   Design Considerations

An appropriate RF frequency is one of the first selections to be made. The lowest acceptable frequency depends on the number of experimental areas to receive alternately routed bunches, and on the resolving time of the experimental detectors. 300 MHz is the lowest acceptable frequency per experimental area, so that three areas, for example, require an RF frequency of at least 900 MHz.

With couplers on the beam pipes at the ends of the cell region, 5 is presently the maximum number of cells per cavity; more than 5 cells causes unacceptable sensitivity to dimensional errors for some HOM's, and can cause the fraction of stored RF energy in the vicinity of the HOM couplers to be so small that the associated HOM Q's are unacceptably high. With a relatively small number of cells, minimization of cavity and cryostat parts and of the number of control and interlock circuits favors large cells and, therefore, low RF frequencies. Minimization of material consumption favors high frequencies. Minimization of surface area per structure, and attendant probability of defects[19], favors high frequencies. Data supporting Wilson's theory is shown in Figure 1.

Q_{BCS} α f^{-2} favors low frequencies, but this effect can be partially compensated by the fact that Q_{BCS} is an exponential function of temperature. The geometrical shunt impedance, ZT^2/Q, is proportional to f, favoring high frequencies. Q_{Res}, the temperature-independent component of the Q, is roughly frequency independent. The static heat leak of the cryostat, the refrigerator capital cost, and sub-atmospheric and superfluid effects must be taken into account.

Considering all of the above-mentioned factors, a frequency of 1500 MHz and an operating temperature of 2.0K have been selected as optimum for CEBAF.

The number of passes in an RLA is another important design parameter. It should be recalled that the purpose of recirculation is to minimize the length of expensive RF structure; the required length of RF structure is inversely proportional to the number of passes. On the other hand, the total required length of arc magnets and associated power supplies, beam pipe, beam position monitors, etc., is directly proportional to the number of passes. The combination of these two considerations leads to a cost optimum and a roughly parabolic cost vs. passes curve. However, several non-cost factors should be considered. The emittance growth increases with an increasing number of passes through the arcs. Clean separation of the beamlets into their respective arc channels becomes more difficult with more passes. Tuning of the accelerator becomes more difficult with more passes. All of these considerations favor choosing a number of passes somewhat smaller than the cost-optimum number. The overall optimum for CEBAF, taking these factors into account, has been chosen to be 4 passes.

Beam instabilities are another important design consideration[20]. There are three principal types of instability which affect linacs: multi-pass, backward wave, and cumulative. Backward wave instability current thresholds are maximized by minimizing cavity lengths and decoupling separate cavities by using small diameter beam pipes between them. The cumulative instability is a noise amplification process which grows with distance along the linac and grows toward an asymptotic limit with time since the beam was turned on. The most serious instability in an RLA is the multi-pass instability.

A multi-pass instability occurs due to the following process: (1) a beam bunch passes off-axis through a cavity on its $(n+m)^{th}$ pass $(n>0, m>0)$; (2) the off-axis bunch deposits energy in a deflecting mode of the cavity; (3) the RF energy in the cavity introduces a transverse kick to a subsequent bunch in the beam on its nth pass; (4) this transverse kick is converted into a transverse displacement on the $(n+m)^{th}$ pass by betatron oscillations; and (5) due to damping of the RF energy in the transverse modes of the cavity by the finite Q of these modes, there is a threshold current at which the instability starts.

A number of factors affect the multi-pass instability threshold current. Higher injection energies increase the beam rigidity and reduce its ability to be deflected on the first pass. A high energy gain per pass increases the adiabatic damping of the betatron oscillations, and thereby reduces the transverse displacement of the beam on the $(n+m)^{th}$ pass. Short betatron wavelengths (i.e., tight focussing) reduce the conversion of a transverse kick into a transverse displacement. Low HOM Q_{ext} values damp the transverse energy faster. Low frequency RF and large holes between cavity cells provide lower geometrical impedances. A small number of passes (at fixed final energy) helps by increasing the energy gain per pass and hence the adiabatic damping between passes, and by reducing the number of passes on which a bunch can receive deflections and deposit deflecting mode energy in the cavity. Statistical or intentional spreads of the frequencies of the same HOM in different cavities limit the ability of the cavities to act coherently. The effectiveness of this spread is reduced as Q_{ext} is lowered because an increasing number of cavities then have HOM frequencies falling within a bandwidth of each other.

RLA's normally operate with very short bunches in order to minimize the beam energy spread associated with the curvature of the RF sine wave. A beam power spectrum extending up to 80 GHz is typical; this spectrum can extend even higher if there is internal transverse or longitudinal structure to the beam. Radiation of high frequency HOM's down the beam pipe cannot be relied upon to provide adequate damping because the beam pipe soon runs into another superconducting cavity, and the attenuation provided by the short length of beam pipe normally does not lower the Q of the HOM to an acceptably low value.

Destructive interference sometimes impedes the coupling of a cavity mode into a certain transmission mode of a HOM coupler. If the dimensions of the coupler opening are not very small compared to an RF wavelength, destructive interference with respect to one transmission line mode does not necessarily imply similar destructive interference with respect to another transmission mode. If one imagines that either a boundary surface near the coupler, or the location of the coupler itself, is displaced, the voltage coupled into a particular transmission mode of the coupler will vary as a quasi-sinusoidal function of this displacement. The associated Q_{ext} value will thus vary in a quasi-sine-squared manner. This, of course, is a rather crude approximation, but has an obvious physical basis. If one now makes the further assumption that the phase angle between the phase corresponding to maximum damping and the phase actually occurring is random, the probability of destructive interference suppressing transmission to a specified fraction of maximum damping can be computed. The probability of suppression by a factor ≥ 100 is 0.06377, and of suppression by a factor ≥ 1000 is 0.02014.

Using the above information, an estimate can be made of the importance of having multiple transmission line modes through which a particular cavity mode can have its energy extracted. First, the number of cavity modes needs to be determined. For this purpose, a five-cell, 1500 MHz cavity has been simulated using five rectangular cells coupled by very small beam holes; these cells have their TM_{110} mode (rectangular notation) at 1500 MHz, and are half a wavelength long.

Damping of the cavity modes is evaluated subject to two different assumptions: one is that there is only one transmission mode leading away from the HOM coupler at any frequency, and the other is that the number of transmission modes available is the number available in the HOM waveguides of the Cornell/CEBAF cavity.

The following quantity is now calculated: the net probability within each 1 GHz band that no cavity mode within that band has all available coupling line transmission modes suppressed by destructive interference by a factor ≥ 100 (or ≥ 1000). The probability over any frequency range of interest is then the product of the probabilities for all 1 GHz bands within that range.

The results of this calculation are quite dramatic:

(1) Above 5 GHz, coupling systems which provide a single transmission mode rapidly approach zero probability that such suppression of damping does not occur. Figure 2 shows the probability per 1 GHz interval that a factor of 100 suppression does not occur for damping of any cavity mode in the interval, and Figure 3 shows the same information for a factor of 1000. Note that the plots are semi-logarithmic. Also note that for a broader frequency range, the net probability is the product of probabilities for all 1 GHz intervals within the range. Each point on the plots represents the 1 GHz interval immediately above the frequency plotted.

(2) Above 5 GHz, coupling systems which provide the same number of transmission modes as that used on the Cornell/CEBAF cavity rapidly approach unity probability that such suppression of damping does not occur. Figures 4 and 5 are the counterparts of Figures 2 and 3, respectively.

Additional information which comes out of this calculation is the number of cavity modes per GHz, as shown in Figure 6. This mode density is expected to be comparable to the density in the actual cavity shape used. The total number of cavity modes below 80 GHz is 820,000. Figure 7 shows the average number of propagating waveguide modes within each 1 GHz interval. For a waveguide of the indicated cross-section, there are an average of 803 transmission modes available to each cavity mode for extraction of stored energy.

Although the calculation performed here involves some rough approximations, the fact that the two results are so drastically different indicates that these results are qualitatively significant. The performance of this calculation is important for several reasons: (1) some significant geometrical impedance values (ZT^2/Q) occur well above ~3 times the fundamental mode frequency; (2) meaningful calculations (using Superfish[21], URMEL[22], and MAFIA[23]) above ~3 times the fundamental mode frequency are extremely difficult because beam pipe boundary conditions are undefined, mechanical tolerances have a large effect, and available mesh densities rapidly become inadequate; and (3) meaningful measurements (using bead pulls) above ~3 times the fundamental mode frequency are extremely difficult because the bead dimensions must be small compared to the wavelength, and the associated perturbation becomes unacceptably

small. A statistical method of establishing that these modes will not cause instabilities is therefore important. Below ~3 times the fundamental frequency, the properties of the modes can be measured accurately and computed approximately, making it practical to alter coupler designs until acceptable results are obtained[24].

Note that a large number of transmission line propagating modes must be maintained all the way into the load; conversion to a single transmission mode before reaching the load could cause destructive interference at this location, effectively reducing the number of transmission line propagating modes available.

Another important RLA design consideration is the emittance. An injector which provides a low emittance and a short bunch length is essential, since no significant damping of the normalized emittance can be provided beyond this point. The short bunch length ($<1°$) is required to avoid introducing an energy spread due to the curvature of the RF waveform.

The combination of eta and beta functions in the arcs must be optimized so that emission of synchrotron radiation induces the smallest practical betatron amplitude increase. The highest energy to which the accelerator is likely to be upgraded should be considered in selecting the arc radius.

In order to obtain an energy stability better than 1 part in 10^4, a very high quality RF control system is required. The phase reference line must have a stability much better than $1°$ between any two points in the system. Cavity RF voltage measurement must be stable, at least short-term, to much better than 1 part in 10^4, particularly if errors in different cavities are correlated (e.g., due to tunnel temperature). If the long-term stability is not comparable to the short-term stability, slow total energy feedback from a spectrometer may be necessary.

High control bandwidths (unity loop gain at ~30 kHz) are required to minimize the effects of cavity microphonics. This is necessary because the fundamental mode Q_{ext} value is typically ~6•10^6. Alternatively, the cavity structure can be made more rigid, but this normally is not cost effective.

Lack of cylindrical symmetry of the RF fields in the cavity input coupler region causes differential deflection of the head and the tail of a bunch, thereby leading to an effective emittance growth. This effect can be compensated to first order by having input couplers

face in opposite directions in a +--+ or ++----++ pattern. This compensation is incomplete due to energy gain of the particles while passing through a cavity set and because the cavities are normally each set at a different gradient. A procedure exists[25] for introducing a slight change in the setpoint of each cavity, and thereby completely compensating for these effects by the end of each turn.

If RF separators are used to divert successive bunches to different end stations, and particularly if the separators do not operate at (n+1/2, where n is a small integer ≥ 0) times the frequency defined by the spacing of the bunches passing through the separator, minimal separator amplitudes must be used to avoid introducing an objectionable effective emittance spread into the bunches.

VI. Conclusions

Although an RLA was built and successfully operated many years ago, recent developments in RF superconductivity, which developments have raised practical gradients from 2 MV/m to 5 MV/m, have made RLA's with energies > 1 GeV economically feasible. RLA's using present superconducting RF technology are slightly less expensive and have substantially higher quality beams than stretcher rings fed by pulsed linacs.

RLA's for nuclear physics are under construction at Darmstadt and CEBAF, and are being planned at Saclay and Frascati.

Continuing progress in achieving higher gradients in superconducting RF cavities offers promise that the accelerators under construction can have their energy upgraded at moderate cost, after the physics in the initially accessible energy range has been explored.
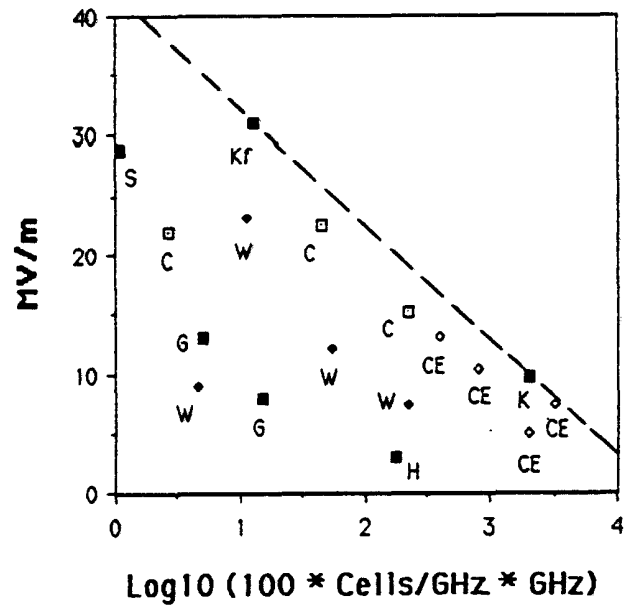
Figure 1: Best gradient performance achieved at various labs as a function of cavity surface area (number of cells divided by square of frequency). Note that envelope fits 22 MV/m - 10 MV/m • $\log_{10}$ (number of cells/(frequency in GHz)^2). C=Cornell, CE=CERN, G=Genoa, H=HEPL (Stanford), K=KEK, Kf=Kernforschungszentrum Karlsruhe, S=Siemens, W=Wuppertal.
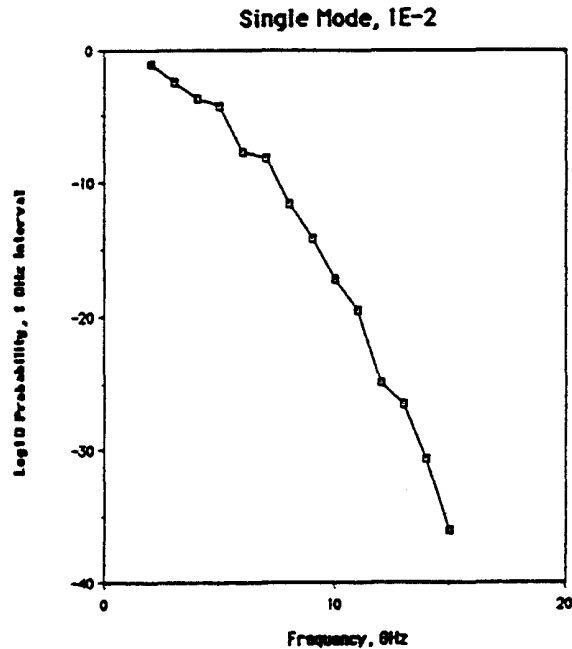

Single Mode, 1E-2

Figure 2: $\log_{10}$ of probability within a 1 GHz interval that no cavity mode has its damping reduced more than a factor of 100 by destructive interference, with a single transmission line mode available at all frequencies.
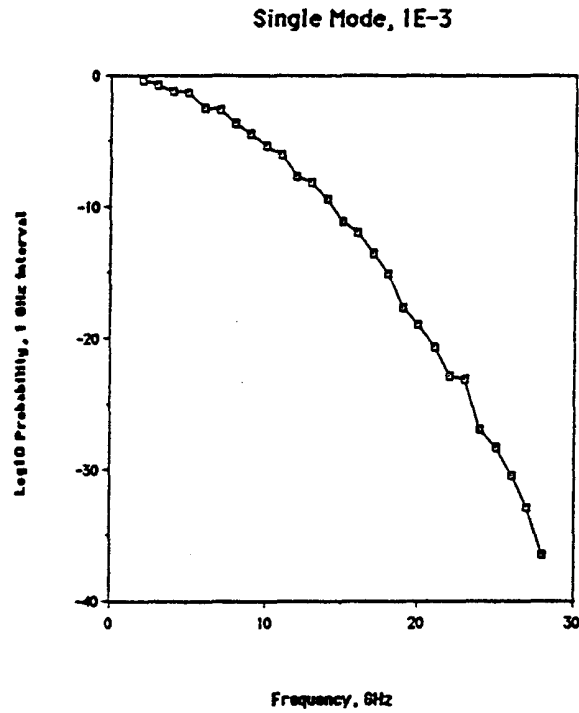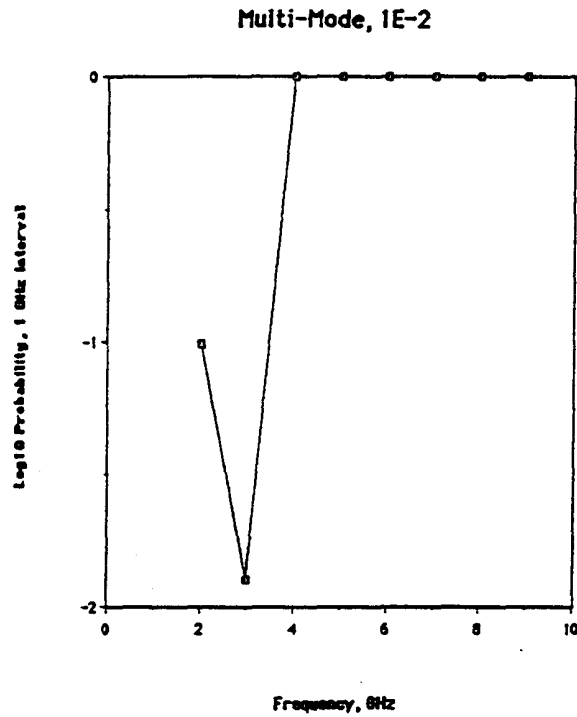
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Single Mode, IE-3

Figure 3: Log_{10} of probability within a 1 GHz interval that no cavity mode has its damping reduced more than a factor of 1000 by destructive interference, with a single transmission line mode available at all frequencies.

Multi-Mode, IE-2

Figure 4: Log_{10} of probability within a 1 GHz interval that no cavity mode has its damping reduced more than a factor of 100 by destructive interference with a 7.9 cm X 3.8 cm rectangular waveguide as the transmission line.
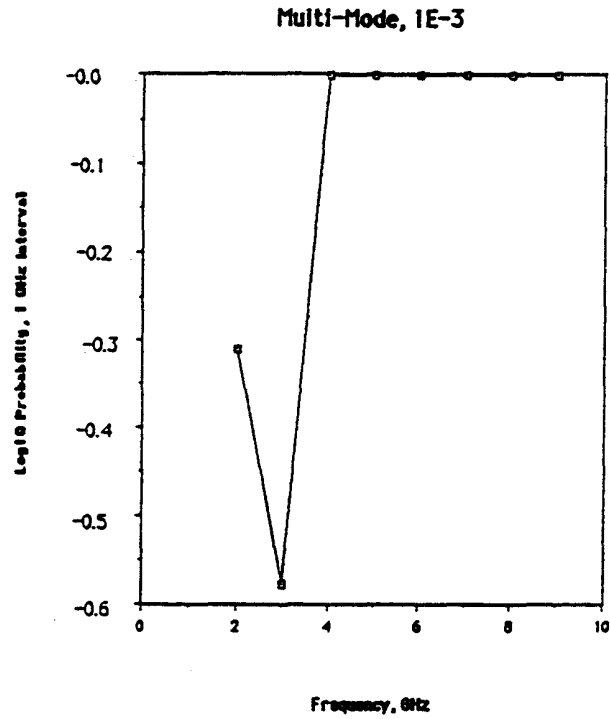
Multi-Mode, 1E-3

Figure 5:   Log$_{10}$ of probability within a 1 GHz interval that no cavity mode has its damping reduced more than a factor of 1000 by destructive interference, with a 7.9 cm X 3.8 cm rectangular waveguide as the transmission line.
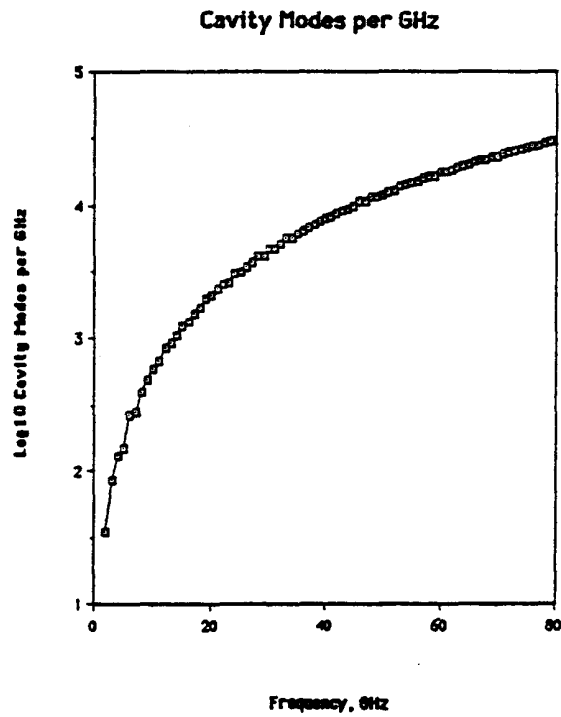
Cavity Modes per GHz

Figure 6:   Number of 5-cell cavity modes per GHz for a cavity with five $\lambda/2$-long rectangular cells having a fundamental frequency of 1500 MHz.
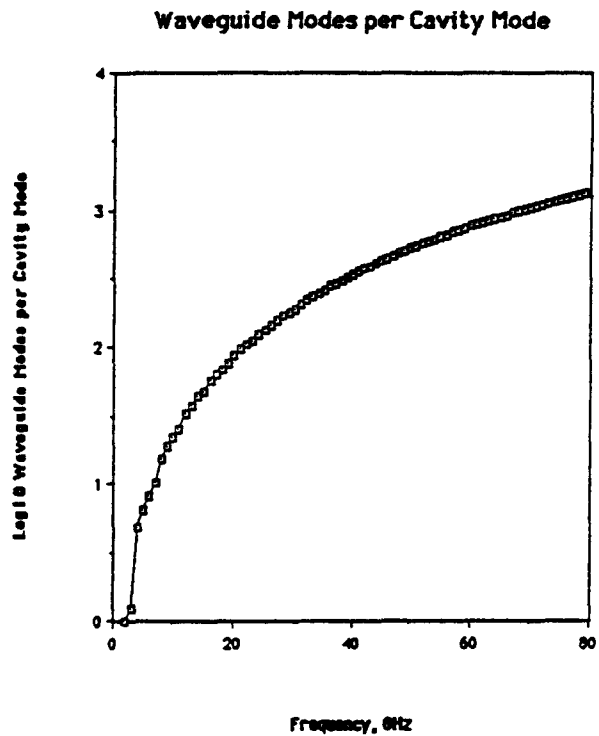
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Waveguide Modes per Cavity Mode

Figure 7: Average number of non-cutoff waveguide modes per cavity mode as a function of frequency.

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