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Abstract

Motivated by the work of Saldin, Schneidmiller and Yurkov, we have measured the detuning curve widths, spectral characteristics, efficiency, and energy spread as a function of the taper for low and high Q resonators in the IR Demo FEL at Jefferson Lab. Both positive and negative tapers were used. Gain and frequency agreed surprisingly well with the predictions of a single mode theory. The efficiency agreed reasonably well for a negative taper with a high Q resonator but disagreed for lower Q values both due to the large slippage parameter and the non-ideal resonator Q. We saw better efficiency for a negative taper than for the same positive taper. The energy spread induced in the beam, normalized to the efficiency is larger for the positive taper than for the corresponding negative taper. This indicates that a negative taper is preferred over a positive taper in an energy recovery FEL.

1. Introduction

In the early days of free-electron lasers (FELs) Kroll, Morton, and Rosenbluth, using analogies to accelerator physics [1] suggested using variable parameter wigglers to enhance the efficiency of FELs. The theory of the tapered wiggler FEL [2] assumed a single frequency, plane wave input and was thus applicable to amplifiers. The phase displacement scheme [3] also assumed a plane wave, though pulsed effects were considered. The two schemes share one common feature. They assume a well-defined bucket as an initial condition. However, the small-signal gain at the optimal saturated frequency was smaller than the saturated gain, so oscillators had a startup problem [4]. The first tapered oscillator therefore used a multi-component design that enhanced the small signal gain at the appropriate frequency and produced a good trapping fraction [5]. Later, high efficiency (up to 45%) was achieved in an amplifier experiment at Livermore [6]. In 1995, experimental studies at FELIX and Orsay [7] and theoretical studies by Saldin, Schneidmiller, and Yurkov [8] showed that a mild negative taper should produce better extraction efficiency than a positive taper. The authors in ref. [8] showed that there was a mismatch between the optimal frequency for small signal gain and the optimal frequency for saturated lasing for the case of a positive tapered wiggler, leading to poor performance for mildly tapered FEL oscillators. There is no such mismatch for a moderately inverse tapered oscillator, allowing it to operate more efficiently.

In many experiments, inserting a wedge in the wiggler gap, leaving the untapered gap at either the front or back end, provides the taper. In this case, the ratio of the small signal gain of the tapered wiggler to that of the untapered wiggler is independent of which end is opened. Similarly, the frequency for maximum small signal gain is the same for the two cases. This frequency decreases for both positive and negative tapers since the maximum field is being held constant.

The analysis in ref [8] motivated us to look at the behavior in the IR Demo FEL [9] at Jefferson Lab with a linear taper. We created the taper by introducing a linear gap change. The taper is only slightly non-linear and the magnetic field quality is still excellent. One major difference between our FEL and the analysis in reference [8] is the assumption of a single frequency. The IR Demo FEL has quite short electron pulses and operates in the high slippage regime with broad spectra. In this regime, the FEL tends to develop very short micropulses that pass over the electrons in much less than one pass through the laser. An electron therefore effectively sees a shorter wiggler. This can enhance the efficiency of the untapered FEL and can negate the effects of a taper since the electrons do not see a significant taper during the time that the optical field is present. Another difference is that the maximum wiggler field is a constant vs. taper while, in ref. [8], the entrance wiggler field is constant. Finally, the resonator Q for most of our data was lower than in ref. [8]. This should result in lower efficiencies for the IR Demo for most tapers.

Since the IR Demo FEL utilizes energy recovery, the overall performance is sensitive to the *total* energy spread at the output of the FEL. Experiments with step-tapered oscillators indicated that the *rms* energy spread was smaller for an inverse step taper than for an untapered FEL for the same power [7]. We were therefore quite interested to see if an inverse taper could provide enhanced efficiency while maintaining or even decreasing the exhaust energy spread.

2. Description of the experiment

The IR Demo FEL and accelerator are described in reference [9]. Two experimental runs with the laser were carried out. In the first, the laser was operated at wavelengths near 3 microns with a resonator Q of 10. Three tapers of both signs were studied. Exhaust energy profiles were obtained by looking at a viewer downstream of the FEL when lasing with pulsed beam. In the second set of experiments, the laser was operated near 6 microns. One positive taper and two negative tapers were studied with a resonator Q of 10 and one of each was studied with a resonator Q of 50. In each case, slit scans of the exhaust beam energy spread enabled us to measure the exhaust energy spectrum of the laser.

For each taper the laser was optimized with pulsed lasing conditions (typically 1 msec. pulses at 60 Hz). At this power level, slightly higher electron losses could be tolerated and mirror-heating effects were negligible compared to CW operation. With almost 19,000 cavity round trips during the macropulse the laser had plenty of time to reach an equilibrium state. The average power as a function of cavity length detuning was measured. For the case of no taper or a weak taper, the detuning curve was also measured for a 9.4 MHz micropulse frequency where two resonator passes are required for each gain pass. For each taper we measured spectra at the peak of the detuning curve and one third and two thirds of the way out on the curve. The exhaust energy spreads were measured at several points on the detuning curve. Finally, the performance with CW lasing was optimized and measured.

Tapers were obtained by the insertion of precision shims at either end of the wiggler. Dial gauges on either side of the wiggler measured the position and gap of the wiggler for each taper. The variation of the wiggler field with respect to gap is known so the field taper can be calculated from the gap taper. The actual taper will be exponential instead of linear, but with a taper of only 10% the linear taper is an excellent approximation to the exponential taper. The resonant energy prediction will differ by less than 0.1% from the actual resonant energy for a resonant energy taper of 5% (10% field taper).

3. Experimental results

Dattoli has shown that the total length of the detuning curve should be linearly proportional to the gain [10]. We have found that this is not true when the gain-to-loss ratio is very large, but we can increase the losses by doubling the number of passes for each gain pass. If this is done, the results are fairly consistent with Dattoli's theory. The detuning curve length vs. the normalized taper strength is shown in figure 1 along with the relative gain vs. taper calculated from theory. The normalized taper strength b as defined in ref [8] is the change in the normalized resonant energy, i.e. $b=\nu_f-\nu_i$ where ν_i and ν_f are the normalized resonant energies at beginning and end of the wiggler respectively. The agreement is quite good considering the inaccuracies of this method. Also note that the gain was independent of the sign of the taper as expected from theory.

The normalized efficiency $2N\eta$ is shown in figure 2 for a negative taper, along with the dependence from ref. [8] using the same dimensionless parameters. The efficiency for no taper is actually much higher than for the single frequency theory, due to short pulse effects similar to those described in ref. [11]. This effect persists as the taper is increased but the efficiency goes down. This is presumably due to the fact that the gain-to-loss ratio is decreasing. This lowers the fraction of electrons contributing to the interaction and lowers the effectiveness of the short pulse effects and the tapered operation. When the cavity Q is raised so that the gain-to-loss is the same as that of the untapered case we find that the efficiency agrees quite well with the single frequency model. No CW data is shown for the Q=50 resonator since the mirror heating greatly limited the efficiency.

In figure 3 we show the efficiency vs. taper for the positive taper runs. The general behavior is similar to the negative taper runs. The efficiency is highest for an untapered configuration and falls off as the taper increases. The efficiency is uniformly less than the negative taper for all value of the taper. The efficiency for the case of the high Q resonator is surprisingly low. Higher efficiency was limited by the inability to recirculate beam due to the occasional strong lasing accompanied by an extremely large exhaust energy spread. The optical spectrum was at least 3% in width but was extremely noisy at any one wavelength as if the wavelength was jumping around from pulse to pulse. There was also some evidence for synchrotron detrapping at some cavity lengths.

As noted above, the inverse taper is expected to have a smaller energy spread at the FEL exit. In addition, the distributions for a positive taper, a negative taper, and no taper should be qualitatively different. We took slit scans and viewer images at a dispersed location to study the distributions. We found that the untapered case has a nearly top hat energy distribution. In general, the energy distributions varied with the cavity length and the degree of taper. The general trend was for the positive taper to have a low energy tail and the negative taper to have a high-energy tail and a very sharp low energy edge. The positive taper typically has a double humped distribution with a decelerated bucket and a second peak corresponding to the untrapped electrons. The positive tapers usually showed evidence of poor trapping efficiency.

If the full width of the energy distribution for each taper at the peak of the detuning curve is divided by the laser efficiency, one has a measure of how appropriate the wiggler is for energy recovery (lower ratios are preferred). The ratios for all our configurations are shown in figure 4. The lowest numbers are for an untapered wiggler, a mild negative taper, or the strong negative taper with a high cavity Q. The general trend is towards a higher ratio for the positive taper and a lower ratio for the corresponding negative taper. One might expect the positive taper ratio to be much lower than it is. The problem is that the trapping efficiency is rather poor as noted above.

As pointed out in ref. [8] the wavelength for maximum small signal gain is not the correct wavelength for optimum large signal operation with a positive taper, leading to poor efficiency. One might think, however, that the large spectral bandwidth present in an FEL with a large slippage parameter might allow the saturated signal to move over to a frequency where the saturated gain is higher. That this was not the case is evident in figure 5. In this figure we show the shift in frequency from that of an untapered wiggler for a similar point in the cavity length detuning curve. The curves are the shift in the frequency for the maximum small signal gain as a function of taper. The points taken with a very large taper shows that the jump at b=26 occurs in the experiment. The spectrum does not approach the wavelength necessary for the tapered FEL to operate most efficiently. The points for b=31 have a large uncertainty since the wavelength jumped around rapidly with time.

4. Conclusions

Some of the predictions of the single frequency model for linearly tapered oscillators are borne out by the experimental results. The gain is independent of the sign of the taper and the reduction of the gain, as measured by the length of the cavity length detuning curve, matches predictions well. The negative taper is clearly superior to the positive with respect to efficiency and exhaust energy spread. Finally, the saturated wavelength is close to the wavelength for largest small signal gain even for a system with very broad bandwidth. This is really surprising given the broadband nature of the IR Demo FEL.

We did not expect the experimental efficiency to be the same as that predicted in ref. [8] due to the relatively low Q and the large slippage parameter. The behavior seen as the gain decreases is what one might expect for an untapered system with a large slippage. When the Q was raised to match the gain-to-loss ratio of the untapered configuration, however, the efficiency of the negative taper matched that of ref. [8] well. The surprise is that the high Q positive taper did not work well. This was due to a very poor trapping fraction, which appears to have been due to synchrotron-betatron detrapping. The stochastic nature of this led to extremely unstable operation in both power and wavelength.

How appropriate is a tapered wiggler for an FEL with energy recovery? The positive taper is clearly poorly suited due to its unstable operation, its low efficiency, and its large exhaust energy spread. The negative taper worked as well as the untapered wiggler but, in the case of the optimal taper, the Q had to be raised. This limited the average power of the device due to mirror heating. It should be noted however that the fact that the negative taper has a high energy tail and a sharp low energy edge means that the system can be pushed very hard without leading to a beam-loss instability in the RF system. A recirculating linac is stable to losses on the high energy edge. A system with longer micropulses would also benefit from a negative taper since the efficiency of the laser in the absence of a taper would not be as high.

5. Acknowledgements

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6. References

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Figure 1. The theoretical gain vs. the absolute value of the taper and the experimental detuning curve length relative to that for no taper are shown. The gain is the same for both positive and negative tapers. The kink in the curve occurs when the gain peak shifts from peak to peak as described in ref [8].

Figure 2. The experimental normalized efficiency $2N\eta$ vs. taper strength is shown. The curve is scaled from the one in ref. [8]. The circles are CW efficiencies, the diamonds are pulsed efficiency and the triangles are the pulsed efficiency for the case of Q=50. The filled symbols are taken at 3 μm and the empty ones at 6 μm. Two of the symbols are slightly offset at b=0 for clarity.

Figure 3. The experimental normalized efficiency vs. taper strength for a positive taper is shown. The curve is scaled from ref [8]. The symbol definition is the same as for figure 2.

Figure 4. Ratio of the full-width of the exhaust energy spectrum to the efficiency at the peak of the cavity length detuning curve. Only pulsed efficiencies were used since the energy spreads could only be measured using pulsed beam.

Figure 5. Normalized frequency detuning shift versus taper strength. The curves correspond to the frequency expected if the frequency varies with the peak of the small signal gain. Circles are the shift at the peak of the detuning curve. Squares and diamonds are for spectra one third and two thirds of the way out on the detuning curve.

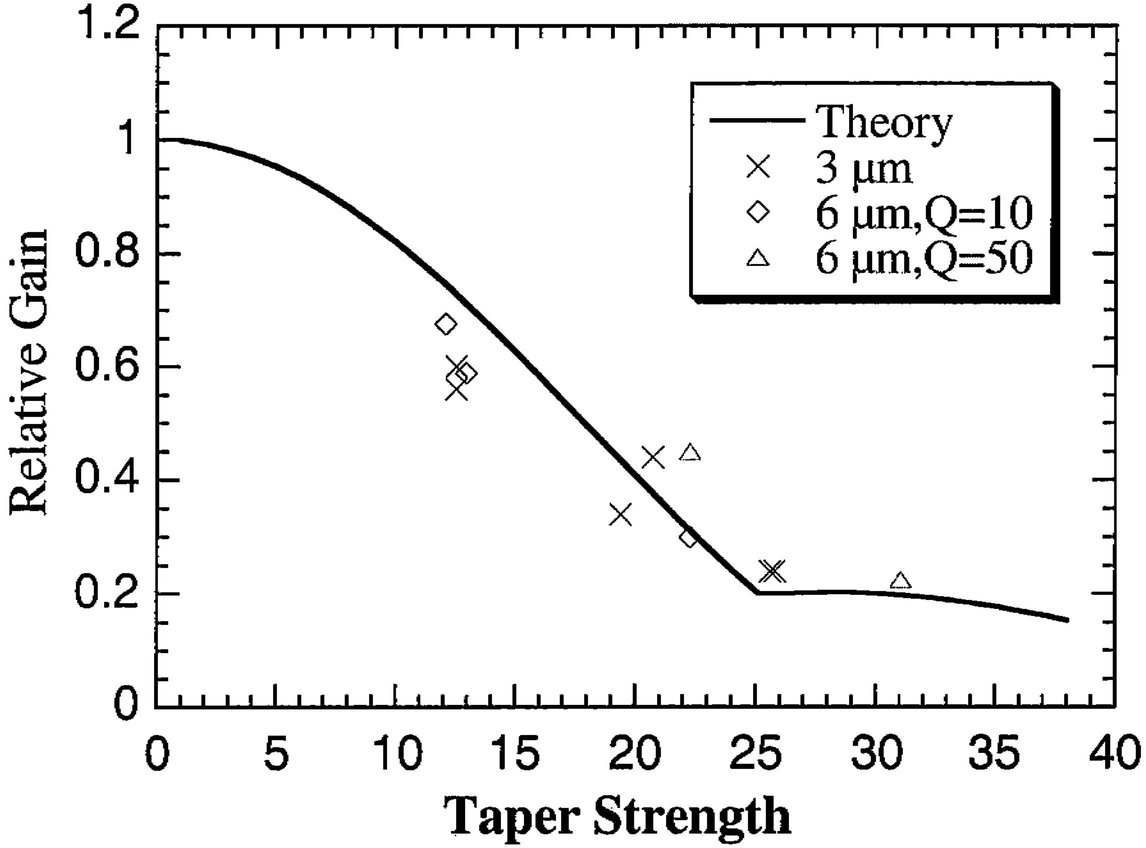
1.2
1
0.8
0.6
0.4
0.2
0
Relative Gain
0
5
10
15
20
25
30
35
40
Taper Strength
Theory
3 μm
6 μm,Q=10
6 μm,Q=50

Figure 1

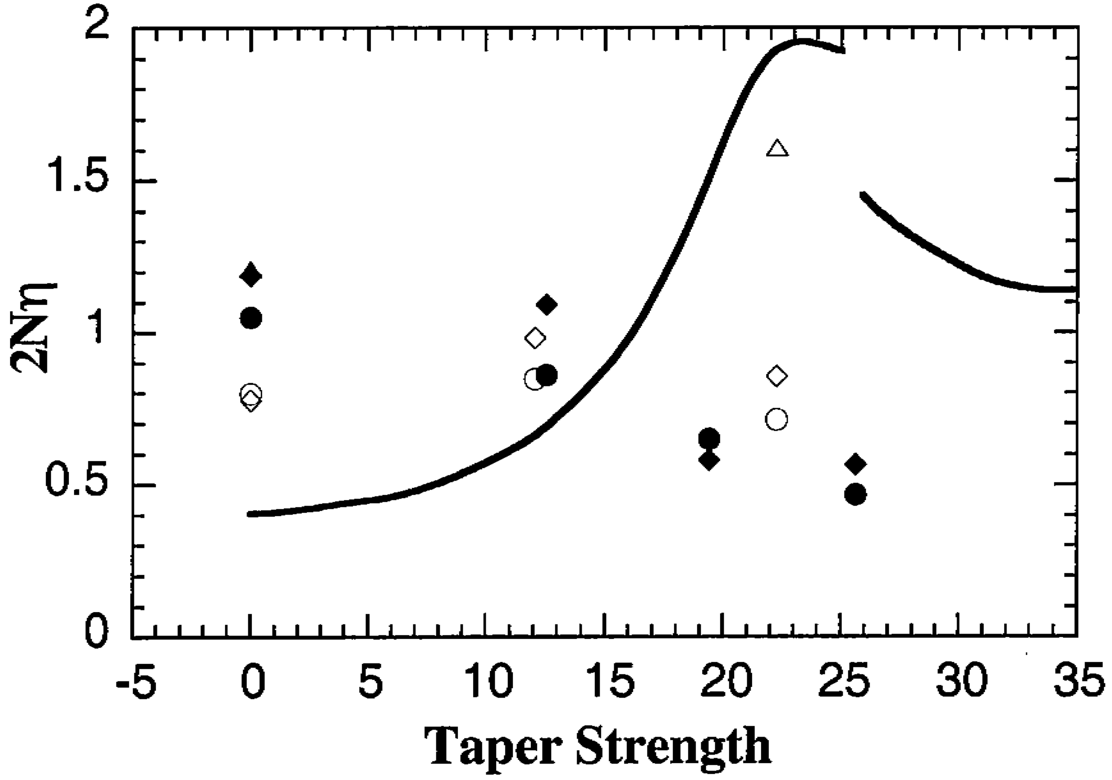

Figure 2

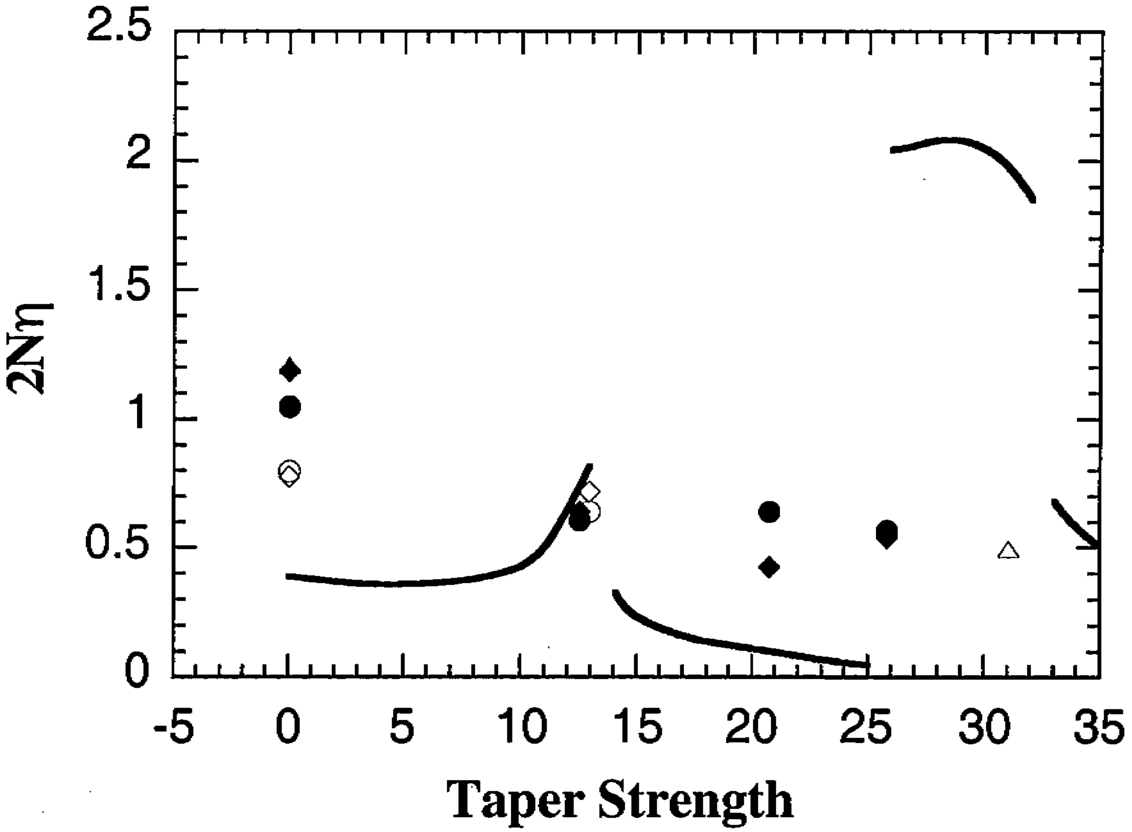

Figure 3

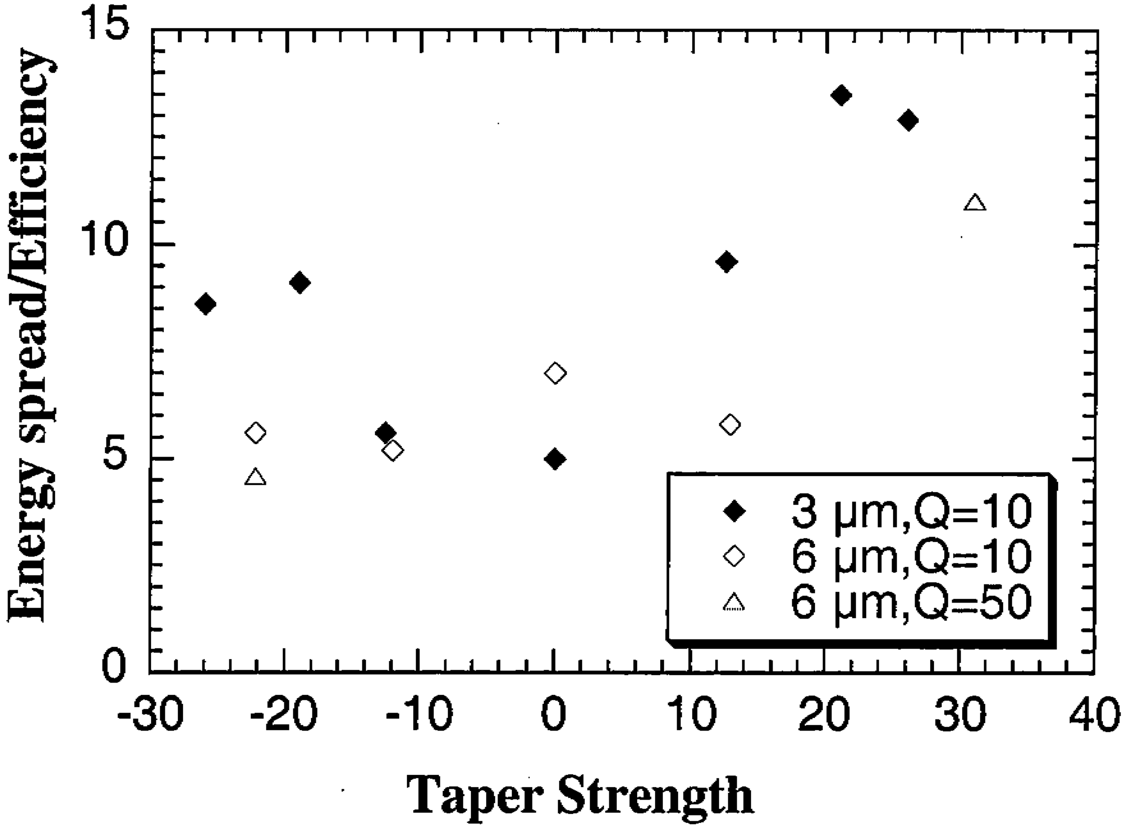
Energy spread/Efficiency
15
10
5
0
-30
-20
-10
0
10
20
30
40
Taper Strength
◆ 3 µm,Q=10
◇ 6 µm,Q=10
△ 6 µm,Q=50

Figure 4

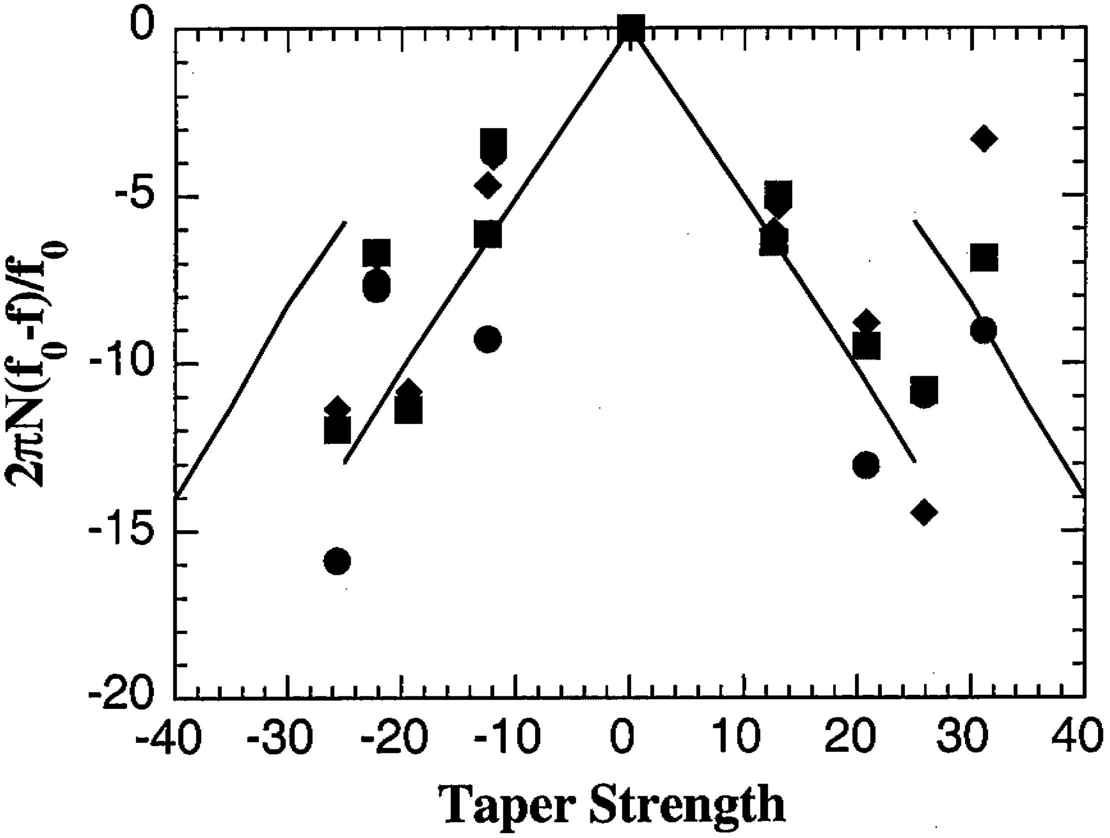

Figure 5