Fourier Analysis of the OMEGA Beam Timing Interferometer Data
(Master's thesis)

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FOURIER ANALYSIS OF THE OMEGA BEAM TIMIMG INTERFEROMETER DATA

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The OMEGA LASER system is a 24 beam Neodymium glass LASER used for Inertial Confinement Fusion experiments. One of the more important factors in these experiments is the high degree of symmetry needed to implode a sperical target. That involves not only the generation of many LASER pulses with the same energy and profile, but equally important is the need for these pulses to arrive at the target at the same instant in time. Because the laser pulse is approximately 1/2 a nanosecond in duration, and the scientists would like less than a ten percent error in the pulse overlay at the target, conventional means of timing up the beams with photodiodes is pushed past its limitations. As a result an interferometric method was developed to time these beams to within a few picoseconds of each other.

The methodology of the system is simple enough in principle. A continuous wave (C.W.) LASER is sent into two of the beams and directed at a spherical target. When the beams are focused at the center of the target they reflect back upon themselves, travel back through the system and recombine to form an interference pattern, which is then sampled by a detector. Appendix A describes this sampling technique. All this constitutes a standard Twyman-Green interferometer with a C.W. YAG LASER source. (fig.1)

In a standard interferometer the visibiltiy of the fringes created by the constructive and destructive interference is expressed as the difference between the maximum and minimum fringe intensities over their sum.

$$V=\frac{I(max)-I(min)}{I(max)+I(min)}$$

The intensity of the created fringes is expressed as a function of the LASER's spectral content B(s) { defined as the set of longitudinal modes existing in the LASER and their relative magnitudes } and the difference in path length between the two beams (l). The general solution for the fringe intensity is;

$$I(l)=<_{<s} B(s)x\{1+cos[ls2pi]\}$$

where 's' is the wave number at which the LASER can operate.

Therefore, when the spectal content of a LASER is constant, as one varies the reference beam path length, and hense the relative path difference between the two beams (l), the fringe intensity can be calculated at each point. From these intensities, a visibility curve can be generated as a function of the path difference.

That is how the system works in theory. However, shortly after installation it was found that there were far more peaks occuring on the visibility curve than would be predicted by the theory. Ideally there would only be a peak every 1.923 meters, (twice the LASER cavity length). This is because the relationship between I(l) and B(s) is based on a Fourier transform. If B(s) has a comb-like structure due to the disrete nature of longitudinal modes, then I(l) { and hense V } will also have a comb structure where the peak spacings are the inverse of the longitudinal mode spacings, which are defined as twice the cavity length of the LASER.

During timing scans that we ran on the system, peaks occured roughly every 300 millimeters, and around these peaks there occured smaller signals. Considering that the beam passes through the path length adjusting system (PLAS) four times, the distance between peaks of actual PLAS movement is approximately 75 mm. It becomes very easy to misjudge which of these signals comes from the actual zero path difference (ZPD), when you realize that the overall beam path from YAG to detector is roughly 140 meters! See fig.2.

To aid in the understanding of how the parameters of the LASER effect the visibility curve, a program was writen that would simulate a visibility curve for any given spectal content of the LASER. The first two parameters of the LASER that would obviously effect the visibility curve form were; the width of the frequency space at which the LASER was running, and also the distance between longitudinal modes that existed in the LASER.

As we varied these parameters, the resultant curves concurred with theory. Indeed, the visibility peak spacing varied as the inverse of the l-mode spacing. (see figure 3.) Also the width of the visibility peaks varied as the inverse of the width of the operating frequency space. (see figure 4.) This stands to reason since the addition of more l-modes only causes more destructive interference and as such any peaks due to constructive interference would be reduced in width.

Because the narrowest Z.P.D. peak on the visibility curve would allow us the highest accuracy in setting the beams to equal path length, it is to our advantage to have as wide a spectral content to the LASER as possible. The easiest way to effect the content is by varying the current of the pump lamps in the LASER cavity. With increased current you can take the LASER from a few lines, out to a bandwidth of roughly half an angstrom. To increase our bandwidth to the maximum, which would be the width of the fluorescence curve (~8 angstroms), an inter-cavity scanning etalon was installed. An etalon in this case, is a very thin piece of glass with parallel sides. As light enters, it is reflected back and forth inside the glass and interfers with itself. Depending on its wavelength, and the size of the etalon, the light will be either rejected from the etalon or transmitted. Fig. 5 explains the functional relationships of this process. Inside the LASER cavity this etalon will when stationary, allow only a very finite band of wavelength to lase. As it is tilted however the passed wavelengths are shifted, and other lines would then have a higher gain co-efficient. If the scanning of the etalon is done very fast (~ 2 kHz.) with respect to the interferometer sampling then because of the time averaging, it looks as though you have a LASER with a much larger bandwidth. The thickness of the etalon is severly constrained by the fluorescence curve of Nd.YAG (fig. 6). Although we want a large bandwidth, it would only complicate matters by having as complex a sigma field as the fluorescence curve itself. The seperation of the 1.0641u and 1.0615u lines is 26 angstroms, and allowing for the perverbial factor of two, this dictates that the etalon should have a periodicity of transmission equal to at least 50 angstroms. Using the the formula from fig. 5 leaves us with an etalon that is at most 50 microns thick, a very thin etalon indeed, but allows for an overall uncomplicated frequency space (spectral content B(s)).

Having this understanding of the parameter space of the system, it was now possible to start the data analysis. Since the availability of the entire OMEGA system is rather low for experimental purposes, especially for open ended projects such as the one we were undertaking, we devised an experimental set-up which used only a subset of the entire LASER system, (fig.7). An fortunate benefit of this was to improve signal levels by not having as many optical losses in the beam paths. The reflector mirrors could be installed in very short order, and typically a scan could be accomplished from cold start in under thirty minutes. Unfortunately, the PLAS scanning range is physically limited to ~152 mm, so to get a longer scan of the visibility function, one has to shorten or lengthen the reference beam by moving the reflecting mirror also. Doing this we acquired the data over larger areas and 'paisted' the plots together, fig. 2a. We confirmed that indeed the visibility peaks occured at an interval of 295 mm.

The theory being as straight forward as it is, indicated that there was some element in the LASER that was causing the l-mode spacing to appear much larger than it should be. Beacause of the inverse relationship between the l-mode spacing and the cavity length, this argued that we had an effective round trip cavity length of only 295 mm. An etalon of very large proportions could have this effect, but there certainly appeared to be no such device in our cavity.

A closer inspection of the LASER cavity indicated that a possible cause might be the LASER rod itself, or a resonance built up between one face of the rod and one of the cavity mirrors. Measurements of the system indicated that the latter was not the problem, but that the rod itself could be if its index of refraction were high enough. Measurement of rod was easily accomplished, (79mm) , but the index of the glass was unknown not only to ourselves but the the manufacturer. Text references indicated a probable index of 1.82. The etalon bandpass periodicity therefore which is equal to twice the rod length times its index, turns out to be 288 mm, very close to our mysterious etalon round trip length. It was soon discovered that the rod's ends were cut with no wedge, maximizing the etalon effect.

Now we had an etalon which could cause the modulation of the frequency space, but we were unsure of the modulation depth. It turned out that that the rod had anti-reflection (A.R.) coatings on either surface to minimize internal cavity losses. Thus, with the reflectivity equal to zero, the Finesse becomes two. (see equation in fig. 5) The Finesse is merely the ratio of the separation of transmission peaks over the width of the peaks. The curve of fig. 5 shows us that a Finesse of two yields a modulation depth of 50% and is sinusoidal in form.

Therefore a first cut at seeing how the theoretical visibility curve would look for this system, we set the longitudenal mode spacing equal to the inverse of the round trip path length of the LASER rod. (1-mode spacing = .00347 mm-1) The results of this are pictured in fig. 8. Indeed the major peak spacing do occur at the same interval as the data that we get from the interferometer.

Given that agreement, a more complicated form of the sigma space might be used to explain the other smaller but significant peaks in the real data. This time we allow all modes from the LASER cavity exist, (1-mode spacing = .00054 mm-1) but we modulate the sigma field by the transmission function of the LASER rod assuming a low finesse due to the anti-reflection coatings on the rod's surfaces, (F=2). The hope here is to generate not only the cavity peaks every 1980 mm., but also create peaks at the 300 mm. intervals due to the modulation periodicity caused by the LASER rod. The results are in fig. 9.

Unfortunately this simulation generated data that was less than what I had hoped for. Although the cavity generated peaks remained, only the rod generated peaks nearest the cavity peaks developed into anything significant. A possible explaination for this may be too much destructive interferance resulting from the 1-modes of low modulation depth which probably wouldn't lase in the real LASER. As such the next step is to add a threshhold level to the rod modulation function to simulate the gain over loss line which naturaly occurs in the LASER. Not having a good feeling for where to set this parameter, I varied it thoughout the range of modulation and witnessed the results. See fig. 10.

The results are as anticipated. With a larger threshhold the developement of the "rod peaks" increases. Furthermore, when threshhold goes over 90 %, the creation of sattelite peaks occurs. Although they are not of the same spacing as those created by our experimental set-up, their form is essentially the same. It should be noted that these simulations were run with a LASER bandwidth of roughly 1 angstrom for speed of calculations, and the real LASER has a probable bandwidth of 8 -> 11 angstroms.

The next step is to vary both the threshhold level and the bandwidth, because these are directly related to the two major operating parameters of the LASER system, namely lamp current and the magnitude of the vibrating etalon swing. Seeing how these parameters effect the signal magnitudes and positions, will help direct us to our own operating parameter values, and may tell us why the sattelite peaks we have do not occur as the code predicts. See figure 11 for these results. It would appear from this data that the width of all the peaks is a function of the bandwidth, and the number of peaks is a function of the level of the threshhold. The spacing of all the peaks seems locked to these parameters, and it is not a perfect duplicate of our experimental data. Clearly there must be other effects that we have not added to our model, the most obvious of which is Q-swiching and gain depletion which have been observed as the etalon swings out of the allowed 1-mode space and back into it.

---------------------- CONCLUSIONS ---------------------

My primary goal in this project was to develope a means by which we might explain the numerous peaks in the OMEGA LASER beam timing data, so that in the future actions might be taken to simplify the resultant visibility curves generated. To accomplich this, I created a computer model of the interferometer which used the frequency components of the LASER to generate through a Fourier transformation the visibility function. In the process of attempting to simulate the data, the program went through several revisions, but the resulting code predicts the following;

a.) the proper position of the LASER cavity peaks

b.) the proper position of the LASER rod peaks

c.) the formation of tertiary peaks caused by the existance of a variable lasing threshhold

d.) the proper relationships in magnitude between all peaks

e.) the proper relationship between the bandwidth of the LASER and the relative width of the peaks.

The one thing that the code fails to do properly, is to predict the proper position of the tertiary peaks formed by the lasing threshhold. Future work in this area may find the solution, but for now this remains unsolved.

The bottom line of the research is that we now have every reason to believe that peculiar peaks in the beam timing traces are due to the LASER rod acting as an etalon in the cavity. The solution to the problem, is a relacement of the rod, or recutting of its faces with a few degrees of wedge so that the etalon effects are minimized. This would leave us with a trace where the only peaks generated would be spaced at twice the LASER cavity length.

APPENDIX A.

SIGNAL DETECTION OF THE BEAM TIMING INTERFEROMETER

When the two beams of the interferometer recombine, they create a field of fringes the spacing of which is related to the angle between the beams. If this angle is kept small by accurate alignment, then the fringe size can be assumed to be a significant fraction of the field size. Our beam size at the detection plane is 64 mm in diameter, making the use of a small area photodiode (gigahertz responce) as the intrument of detection. As the PLAS in the reference beam is moved a wavelength of the LASER, the fringes in the field will move one fringe width. A stationary detector in the center of the field will generate a current output linearly proportional to the variation of the fringe intensity. With a constantly moving PLAS, an a.c. signal is generated of constant frequency which is proportional to the speed of the PLAS, and the signal level is proportional to the visibility of the fringes.

The electronics of the system consists of the following filters, and devices;

1.) A 240 Hz. notch to keep fluorescent room lights out.

2.) A notch filter to keep out the fundamental frequency of the vibrating etalon. (~1.8 kHz.)

3.) A high pass filter to keep out low frequencies caused by air turbulence in the LASER Bay. (< 1500 Hz.)

4.) A low pass filter to keep out any higher order harmonics generated by the vibrating etalon system. (> 200 Hz.)

5.) The remaining frequencies are passed to an RMS converter which gives us a d.c. offset for the magnitude of the a.c. signal.

6.) A low pass filter as noise suppression on the output of the RMS->DC converter (> 2 hz.)

7.) This signal is passed to a plotter and a digitizer along with the position of the moving PLAS so that curves of the resulting visibility function can be plotted.

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The OMEGA LASER Operations Team

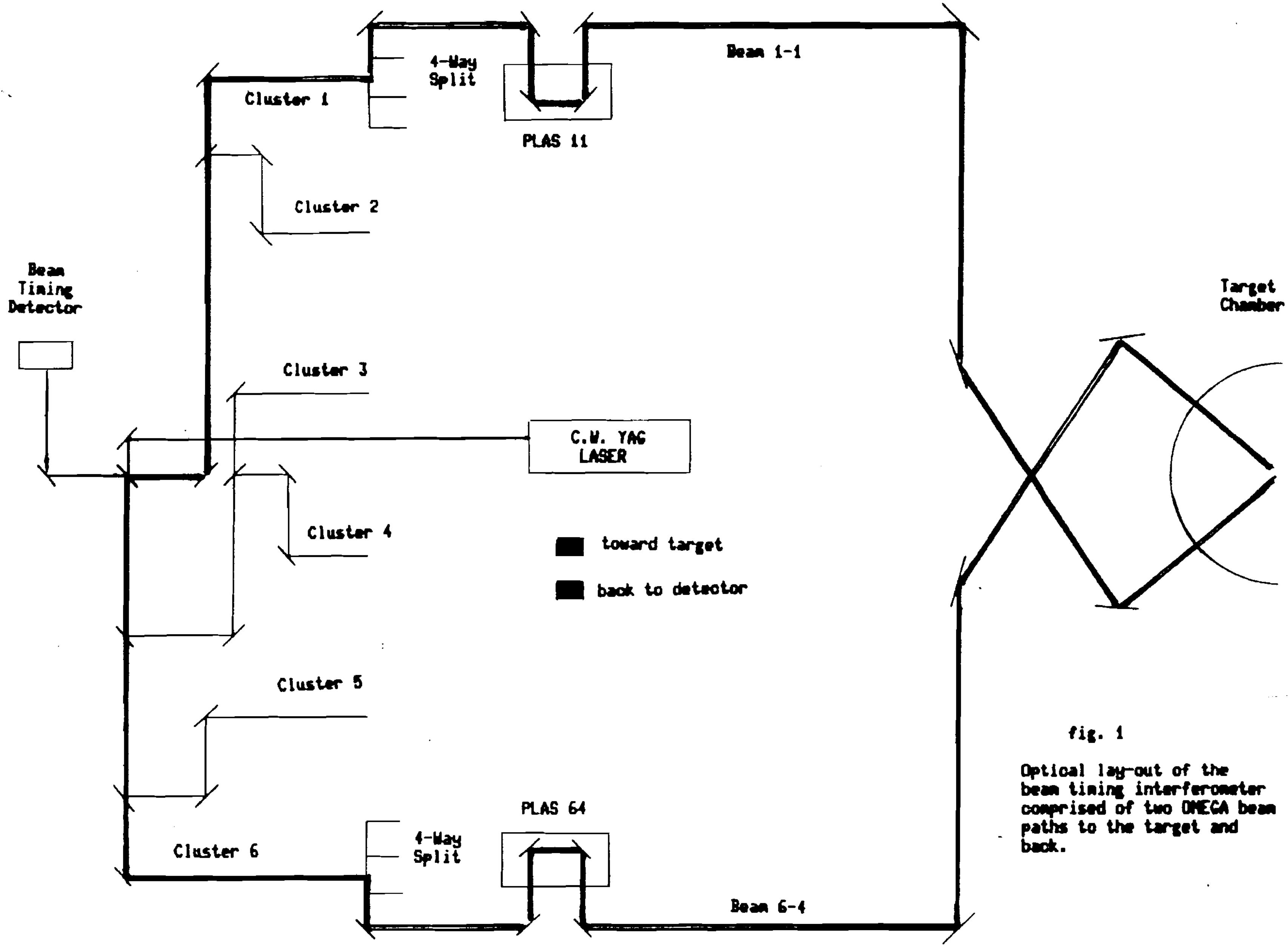


fig. 1

Optical lay-out of the beam timing interferometer comprised of two OMEGA beam paths to the target and back.

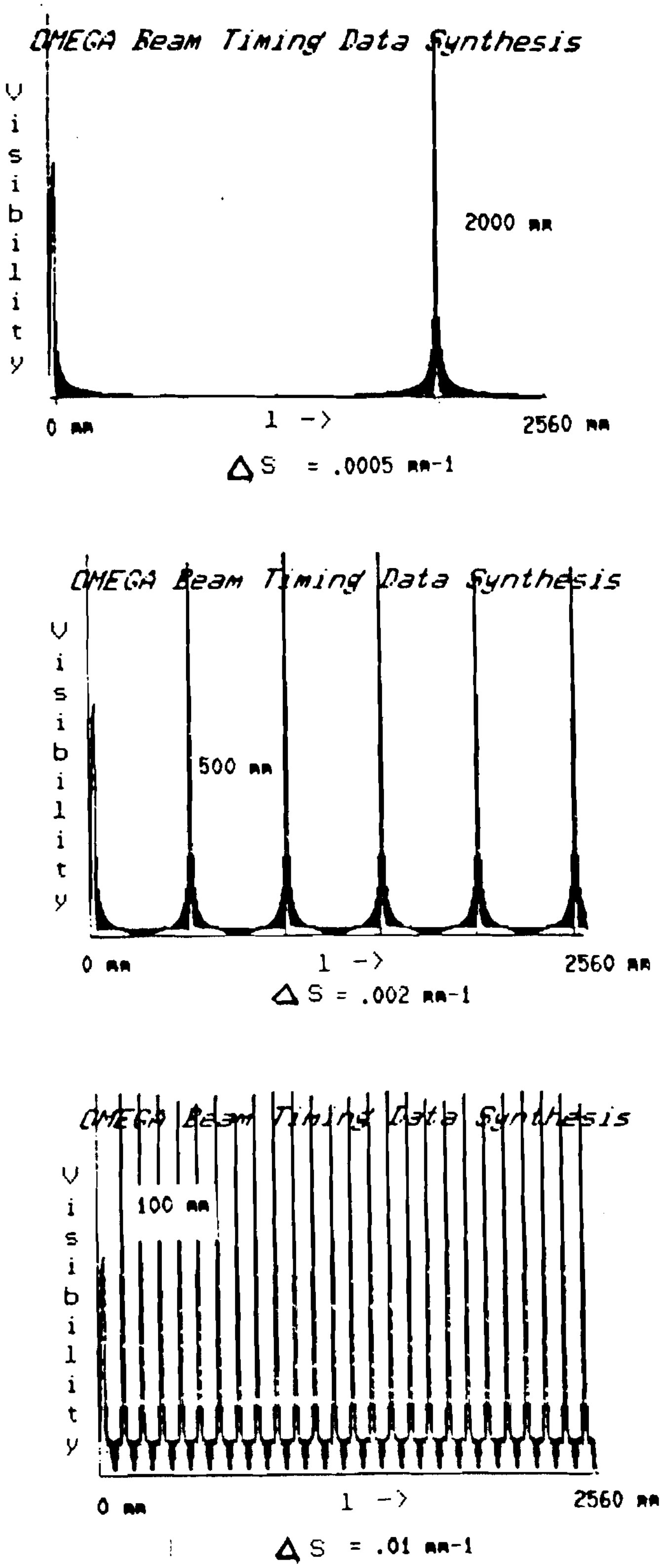
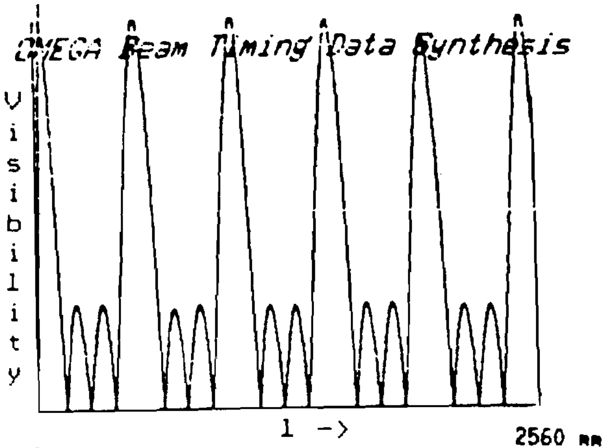
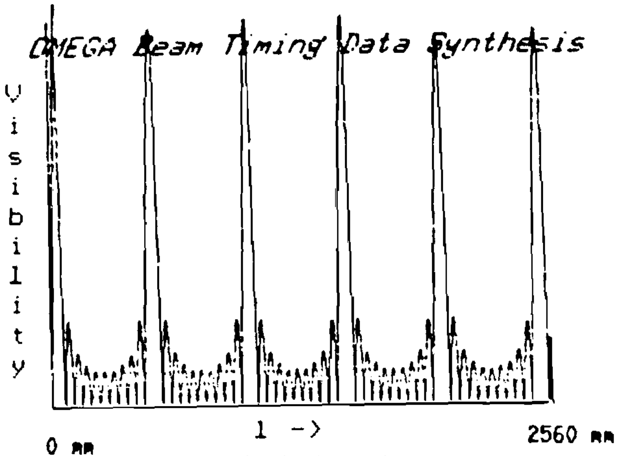


figure 3

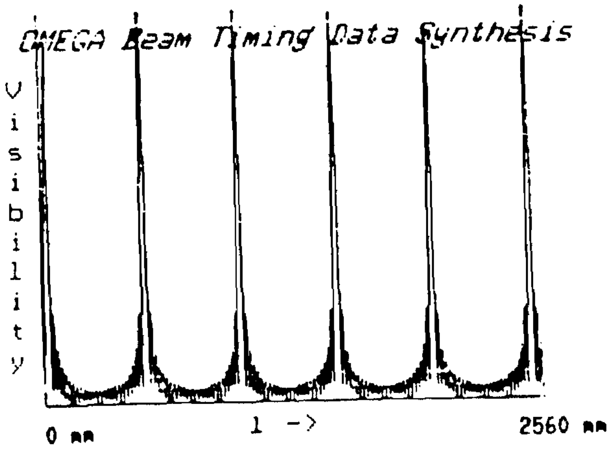
These traces indicate the peak position is related inversely to the l-mode spacing, given a constant width of .1 mm-1 for the frequency space of the LASER.



spectral width = .007 mm-1



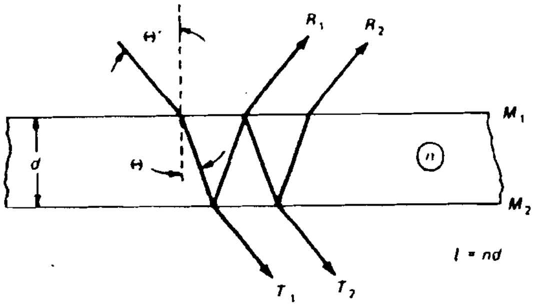
spectral width = .02 mm-1



spectral width = .05 mm-1

figure 4

These traces show the inverse relationship between the width of the operating frequency space and the width of the peaks in the visibility curves. Note that because B(s) has a step function shape and the visibility curve is its Fourier transform, its peaks take the shape of sinc functions. The l-mode spacing was held constant at .002 mm-1 for these runs.



$$F = \pi\left\{2\arcsin\left[\frac{2+4r}{(1-r)^2}\right]^{-1/2}\right\}^{-1} \approx \frac{\pi(r)^{1/2}}{(1-r)}$$

$$\Delta\lambda = \frac{\lambda_0^2}{2nd\cos\Theta} \qquad \delta\lambda = \frac{\Delta\lambda}{F}$$

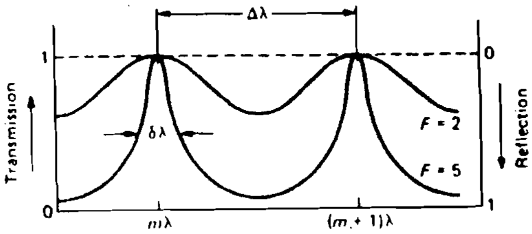


fig. 5

Etalon transmission as a function of phase difference which is related to the angle of the incident beam, its wavelength, and the etalon parameters.

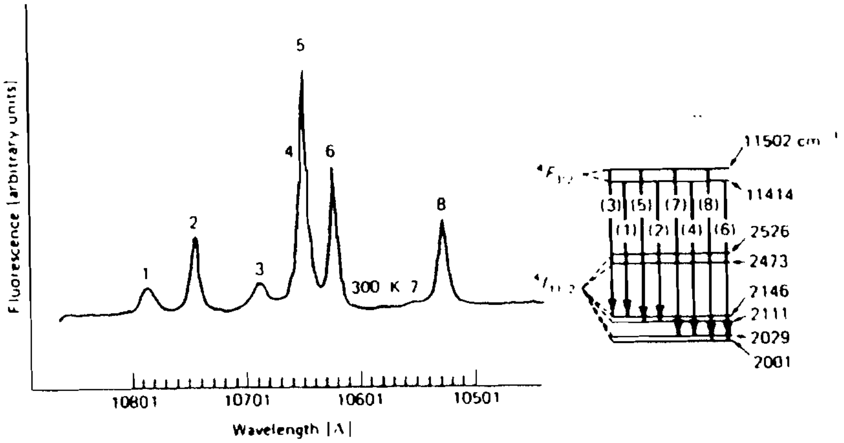


fig. 6

Fluorescence spectrum of Nd+3 in YAG at 300 K in the region of 1.06u

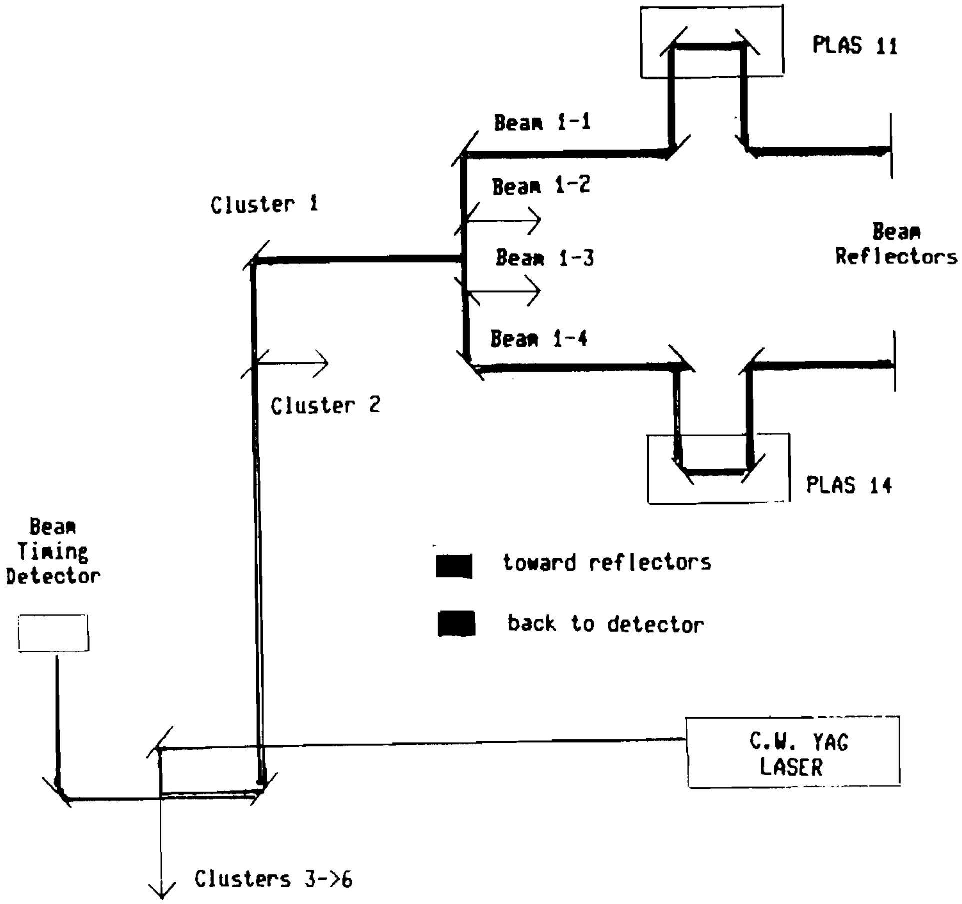


fig. 7

Experimental set-up of the beam timing interferometer used to facilitate the rapid collection of data and take advantage of increased signal levels.

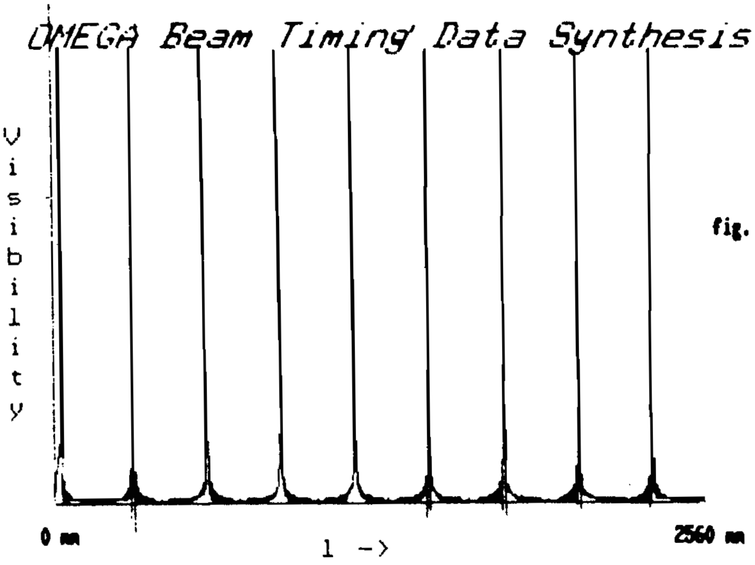


fig. 8 Visibility curve generated for a cavity equal to the LASER rod round trip optical path. (294mm) This is equivalent to a l-mode spacing of 0.00347 mm-1. The spectral width = 0.5mm-1 (5A)

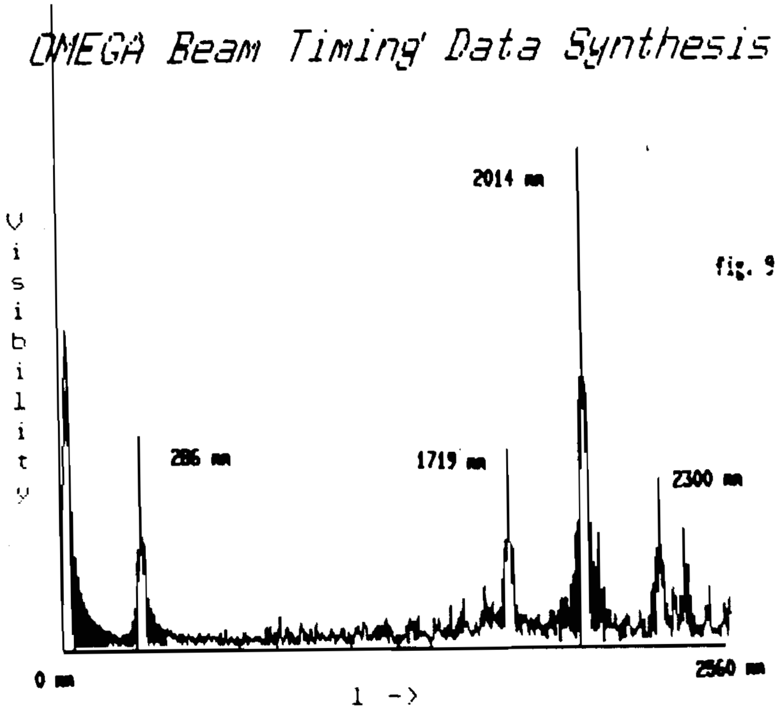


fig. 9 Visibility curve generated for a large cavity (2000 mm), but modulated by an inter-cavity etalon of 294 mm with a Finesse equal to 2. The spectral width = 0.1 mm-1 (1 A)

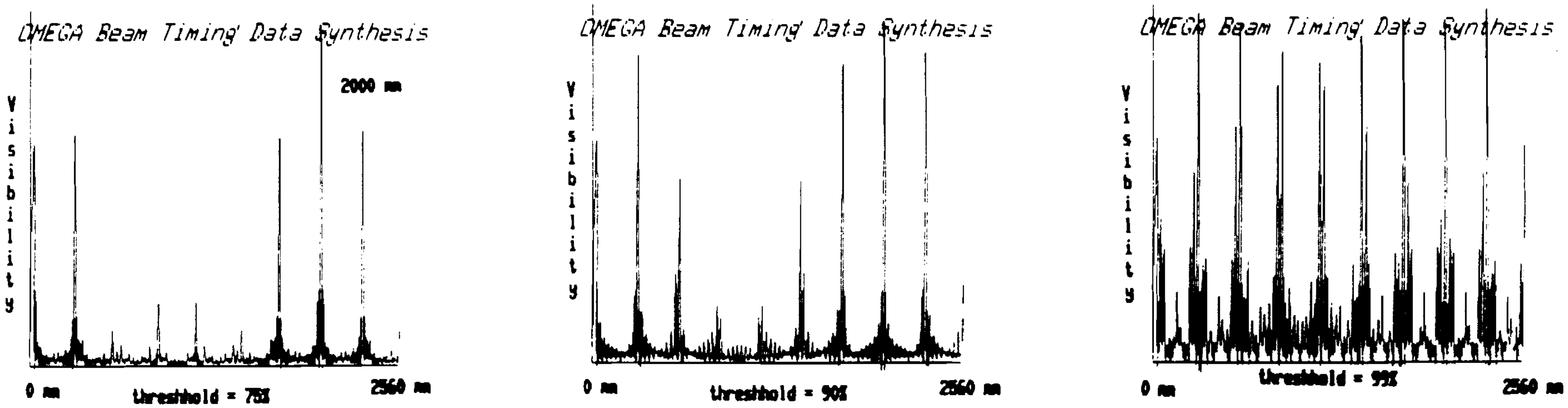


fig. 10a These curves indicate the growth of 'rod' peaks (those separated by approx. 300 mm) as threshhold for lasing increases from 75% to 90% to 99%. Note, the major peaks at 2000 mm which go unchanged are caused by the main LASER cavity.

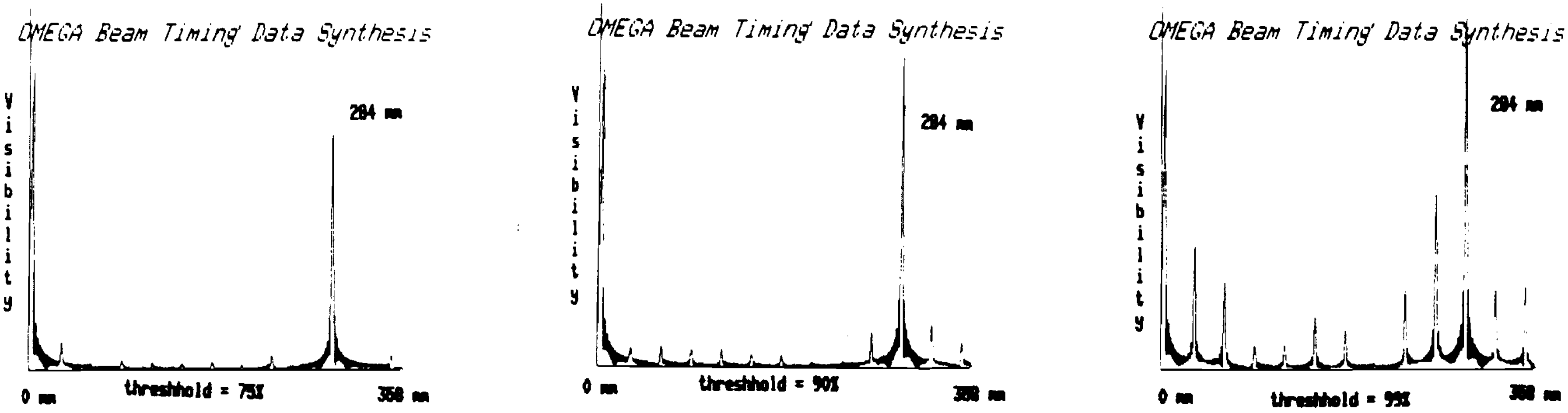


fig. 10b Looking at only the first 356 mm of the above traces, the growth of the tertiary peaks is also evident as lasing threshhold increases. The most radical growth occuring only after 98% is reached.

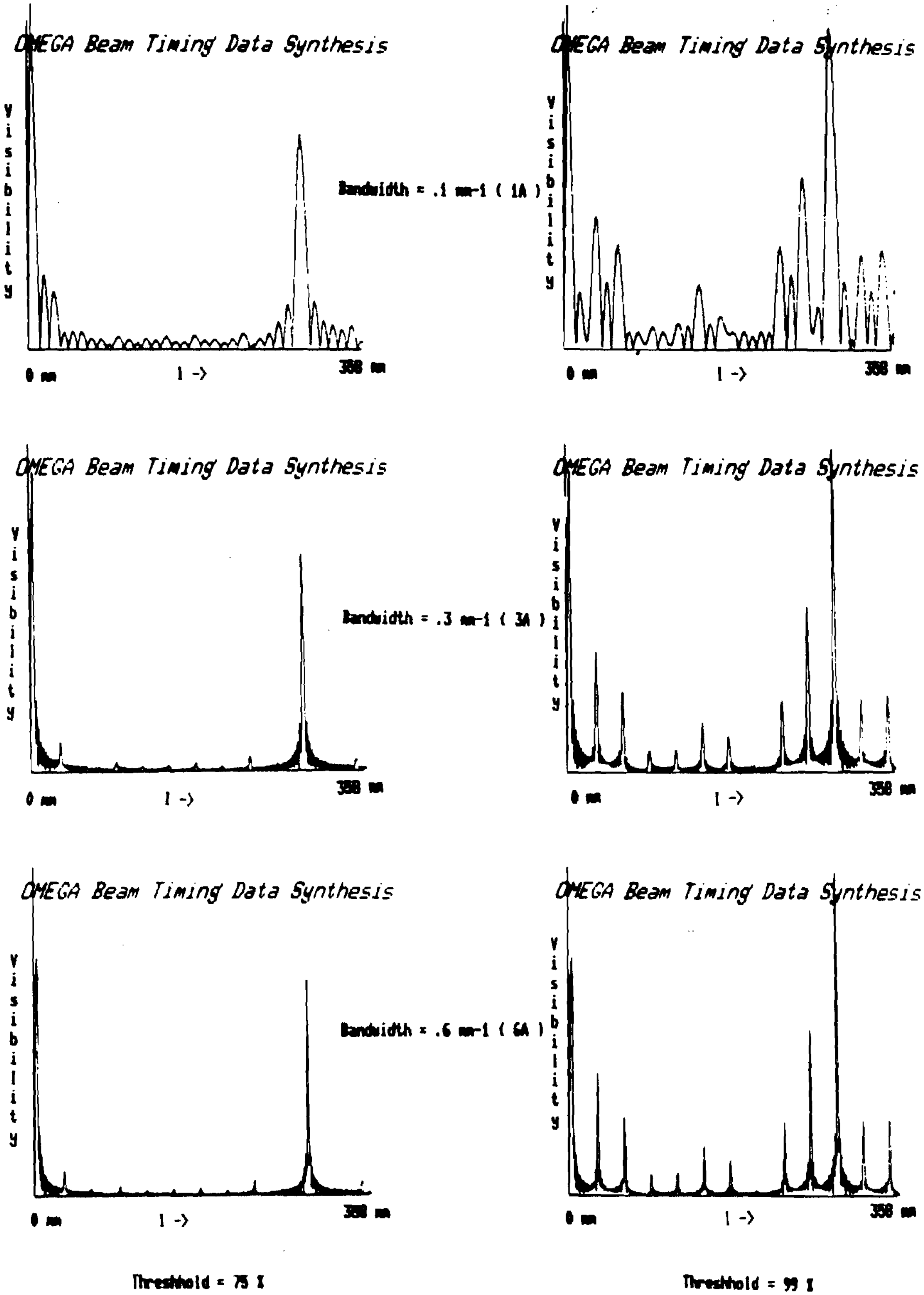


fig. 11 These graphs show the change in the visibility curve due to variations of two parameters; Bandwidth and Threshhold. As we have seen Threshhold creates more peaks, but for different bandwidths the peak formation is exactly the same except for their width, which is linearly proportional to the bandwidth