PRELIMINARY MODE DISTORTION MEASUREMENTS ON THE JEFFERSON LAB IRFEL

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Abstract

We previously reported analytical calculations of mirror distortion in a high power FEL with a near-concentric cavity. Naive assumptions about the FEL power vs. distortion led us to believe that mirror losses were much lower than expected. Recently we have directly measured the mode size and beam quality as a function of power using a resonator with a center wavelength of 5 microns. The resonator mirrors were calcium fluoride. This material exhibits a large amount of distortion for a given power but, due to the negative slope of refractive index vs. temperature, adds almost no optical phase distortion on the laser output. The mode in the cavity can thus be directly calculated from the measurements at the resonator output. The presence of angular jitter produced results inconsistent with cold cavity expectations. Removing the effects of the angular jitter produces results in reasonable agreement with analytical models assuming mirror losses comparable to the original expectations.

1. INTRODUCTION

In any high power FEL with a nearly concentric resonator one finds that the mirrors heat up and distort, changing their radii of curvature and their figure quality. To gain more insight into the mechanisms that limit power in a high power FEL we set out to measure the mode quality and Rayleigh range as a function of power. In previous work [1] we derived the change in the Rayleigh range and the growth in aberrations as a function of the mirror and FEL output properties. We found that these changes could be predicted using two main parameters. The first is the magnification $M \equiv 1+\left(L/2z_R\right)^2$ where L is the resonator length and z_R is the Rayleigh range.

This quantity is just the ratio of the spot size on the mirrors vs. the spot size at the waist. The second critical parameter is the mirror figure of merit given by the following relation:

$$F = \frac{k_{th}}{\alpha_e(h\alpha_B + \alpha_s + \alpha_s/t_c)} \tag{1}$$

where k_{th} is the thermal conductivity of the output coupler mirror substrate, h is the mirror thickness, t_c is the output coupler transmission, α_B is the bulk absorption coefficient, α_s is the coating absorption, and α_e is the thermal expansion coefficient of the mirror substrate. The quantity in parentheses is the total absorption of the mirror. The change in the Rayleigh range for a given laser output power P_l at a wavelength λ is then given by

$$\frac{\Delta z_R}{z_R} = \frac{1.17M}{16\sqrt{M-1}}\frac{P_l}{\lambda F} \tag{2}$$

The actual change in the Rayleigh range is larger than this due to the fact that the distorted mode now has a different magnification. For small changes, equation (2) is reasonably accurate but, for large changes the Rayleigh range of the distorted resonator, the equilibrium Rayleigh range must be calculated self-consistently. The dependence of the Rayleigh range vs. power for large changes is slightly faster than linear. The maximum aberration amplitude is given by:

$$\frac{\Delta z}{\lambda} = \frac{0.61}{8\pi}\frac{P_l}{\lambda F} \tag{3}$$

The following assumptions were made in deriving equations (2) and (3): 1.) The laser spot is centered on the laser mirror, 2.) the absorption is the same on both mirrors, and 3.) the system is in equilibrium. Using equations (2) and (3) we find that the FEL should lase well up to 250 W with calcium fluoride mirrors with 0.1% coating absorption and 0.05% bulk absorption. In fact the IR Demo produced 520 W with the CaF_2 mirrors so one might presume that the coating losses must be less than 0.05%. This presumption rests on the assumption that the FEL power saturates when the Rayleigh range changes by a factor of two from its cold cavity value. In fact, this is not necessarily true. There is no theoretical prediction of the FEL power vs. mirror distortion. The small signal gain is not very sensitive to the Rayleigh range for the IR Demo. The Rayleigh range can grow by a factor of 3.5 before the small signal gain drops by a factor of two. Even then the small signal gain is well above the saturated gain of 12%. If the Rayleigh range changes by this much, the aberration amplitude is predicted to be almost 6% of a wave. This will lead to an appreciable increase in the mode quality factor M^2, reducing the gain even more [2].

2. EXPERIMENTAL SETUP

In order to see a large change in Rayleigh range, we chose to operate with CaF_2 mirrors. These mirrors not only have a small figure of merit F but also exhibit a negative slope in the change in the refractive index vs. temperature. When the mirror heats up, the thickness increases in proportion to the temperature rise but the refractive index decreases just enough to almost cancel the increase in optical path length. The net effect is that the focal length of the output coupler is nearly independent of the mirror heating. This makes the measurement of the Rayleigh range much less ambiguous since one does not have to make any approximations about the heating-induced focussing of the mirror.

The design details of the IR Demo and its optical resonator have been reported in previous publications [3]. The cold cavity Rayleigh range calculated from the measured radii of curvature is 44±2 cm. This means the magnification for the cavity is 84. The mirrors are sufficiently close in radii that the waist is in the center of the resonator to within 2 cm. The gain is estimated to be 100% per pass from the turn on time and the efficiency vs. repetition rate [4].

We used a Coherent ModeMaster™ to measure the mode parameters. This device uses a spinning drum to slice the beam with two edges at right angle to each other. The 10% to 90% risetime is then used to infer the beam size. A lens is moved with respect to the rotating drum and the beam size is measured as a function of the lens position. From a fit to this curve the external waist diameter and the Rayleigh range can be found. From these two and the wavelength the mode quality M^2 can be found. The output from the FEL goes through a CaF_2 Brewster window and off one mirror with an *s*-plane bounce before emerging onto an optical bench. At that point we mounted a wedged CaF_2 plate. The front surface reflection was 7%. This beam was sent into the ModeMaster. Data was taken vs. power from 60 W to 520 W where the laser power saturated. The FEL power was almost independent of electron beam current from 4 to 4.8 mA. Previous measurements indicate that the CW laser efficiency peaks for 1.5 mA with the laser output at 350 W. The ModeMaster was then moved to the high reflector end of the resonator. The laser was operated at 4.6 microns where the high reflector has a transmission of 0.2%. The output from the resonator at this end exits the vacuum through a sapphire window with 80% transmission. The power was then steered into the ModeMaster using a remotely steered mirror. The upstream (output coupler end) arrangement did not have any steering on the CaF_2 plate so the resonator mode had to be steered to center the beam in the ModeMaster. This made the data much noisier than on the downstream (high reflector) end. On the other hand, the sapphire window on the high reflector end was not of high optical quality so some aberration was added to the beam on passing through it. On the high reflector end, data was taken from 100 W to 520 W. For power less than 100 W the ModeMaster signal was too noisy to get good data.

3. RAW DATA

In figure 1 we show the Rayleigh range vs. power for both the upstream and downstream ends of the resonator. The downstream data is much less noisy due to the ability to center the optical mode on the resonator mirrors. This reduces the drift in the resonator mode during a measurement. The data was quite reproducible however. Some data taken several months before at 4.8 microns shows very similar results to the upstream data. The apparent Rayleigh range is a factor of two smaller than the Rayleigh range in the cavity due to the defocusing in the output coupler. This implies that the cold cavity Rayleigh range, given by the zero-power extrapolation, is approximately 85 cm. This is a factor of two larger than the expected value mentioned above.

Note that the slope of the upstream and downstream data is nearly equal. This implies that the Rayleigh range in the direction of the electron beam is the same as in the opposite direction. This is a strong indication that guiding effects are negligible with a saturated gain of 12%.

In figure 2 we show the measured mode quality vs. power at the laser output. Surprisingly, the mode quality improves with power from a zero-power value of around 1.7 down to 1.3 at 300 W. The figure of the mirrors was measured before installation and was found to be λ/8 at 633 nm, which is λ/58 at the lasing wavelength. The effects of gain guiding or focussing should decrease with current so there is no reason to expect the mode quality to have a zero-current asymptote of 1.7. All other FELs have had nearly ideal mode quality[5].

In figure 3 we show the position of the waist as a function of power. If the Rayleigh range is growing as much as in figure 1, the apparent waist will shift from 290 to 300 cm from the mirror as the power increases. One therefore expects both curves to increase by about 10 cm. Instead, the upstream distance increases by around 20 cm and the downstream distance changes very little. This implies that the center of the optical mode moves 10 cm downstream as the mirrors heat up, indicating that the heating is larger in the output coupler. Using the analytical theory of an asymmetric resonator [6] we find that the output coupler absorbs approximately 15% more power than the high reflector. This may be due to a combination of the bulk absorption losses and the AR coating losses. If they are 0.1%/cm and 0.1% respectively and the coating absorption is 0.1% the difference would be explained. The absolute error in the distance from the mirrors (305 vs. 295 cm) is comparable to the typical error from the ModeMaster and is therefore not significant.

The waist position data is in reasonable agreement with expectations but the values of z_R and M^2 seem impossible to believe. The data are reproducible and stable over a period of months. We believe that the cause of this discrepancy is angular jitter in the laser output. If the pointing stability of the laser is not very good the spot will wander around at the waist during the measurement. This will increase the apparent spot size near the waist. This increases the measured Rayleigh range as well. Each of them will grow by the factor $\sqrt{1+(\delta/w_0)^2}$ where δ is the *rms* position jitter near the internal waist. Since the mode quality is the ratio of the waist size squared to the Rayleigh range, it will also grow by the same factor.

4. CORRECTED DATA

The angular jitter as measured by the ModeMaster is 160 μrad. The distance from the lens to the waist is 43 cm. If the source point is at infinity this leads to a position jitter of 69 microns. This value produced values of M^2 which were less than unity so a value of 67 microns was used for the upstream end. This altered the Rayleigh range so that the apparent Rayleigh range extrapolated to zero current was equal to 24 cm, which is very close to the calculated cold cavity value. For the downstream end it was found that a jitter of 93 microns was necessary to get the zero current asymptote to be the same as the upstream end. It is not clear why the jitter is different from the upstream end. Pointing stability measurements were not made for the downstream end. The corrected Rayleigh range data is shown in figure 4. Note how linear the Rayleigh range is vs. power. This is not expected since the model in reference [2] indicates that the growth of the Rayleigh range will have a term proportional to the square of the power as well. The linear dependence may be due to the mode size growth when the aberration becomes large. This will reduce the Rayleigh range growth for large distortions.

In figure 5 we show the mode quality vs. power for the corrected data. The mode quality for the output coupler end, which has a high quality window, is nearly ideal, as expected. It starts to rise at a power close to 350 W where the efficiency starts to drop off.

If the Rayleigh range data is used to estimate the figure of merit for the mirror, one finds that the mean figure of merit for the resonator mirrors is 0.036 kW/μm. This implies that the mirror coating losses are approximately 0.14%. This will be checked in the future using out mirror test stand, which is capable of accurately measuring cavity mirror losses of less than 0.1%.

5. CONCLUSIONS

The measurements of the change in the resonator properties with laser output power allow us to gain insight into the effect of mirror distortion on saturated laser power. From the change in the Rayleigh range derived from the corrected data one can calculate that the mirror losses are close to 0.1%. This is, within experimental error, in agreement with measurements carried out by China

Lake [7]. The Rayleigh range grows by a factor of 4 before the power vs. electron beam current saturates. The aberration expected for this much change is almost 8% of a wave so the laser power is probably limited by both the change in the Rayleigh range as well as the aberration induced by the mirror heating.

The measurements here also show no evidence for guiding and the change in Rayleigh range with power is almost perfectly linear. The mode quality at any given point in time is quite good but the effective mode quality is significantly worse. In the future we plan to try to track down the cause of the beam pointing stability jitter and to measure the mode quality and Rayleigh range vs. power for sapphire and zinc selenide mirrors.

Acknowledgements

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Figure Captions

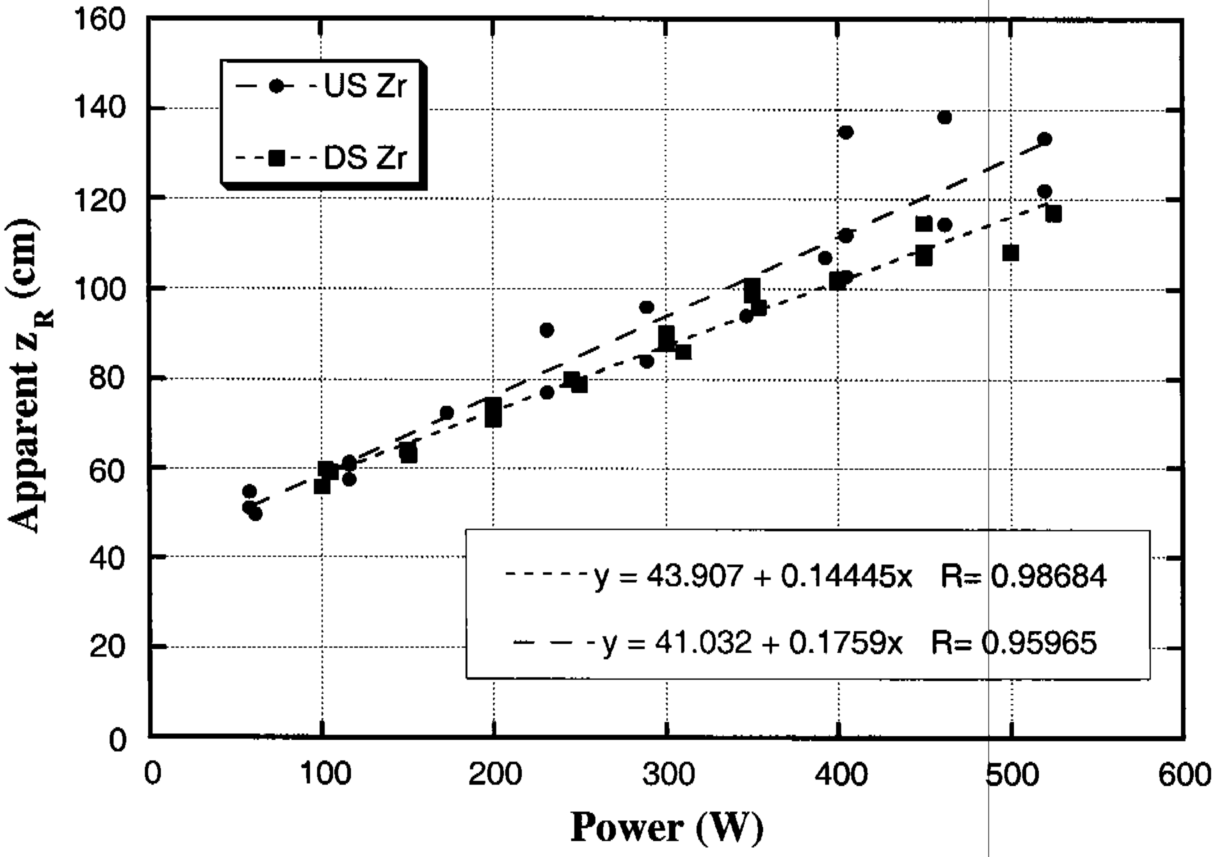
Figure 1. Rayleigh range from upstream (outcoupler end) and downstream (high reflector) ends is plotted. This is the transformed Rayleigh range after passing through the cavity mirror. The intracavity value is a factor of 2.0±0.05 larger.

Figure 2. Mode quality M^2 vs. power from output coupled end for each axis and for the average beam.

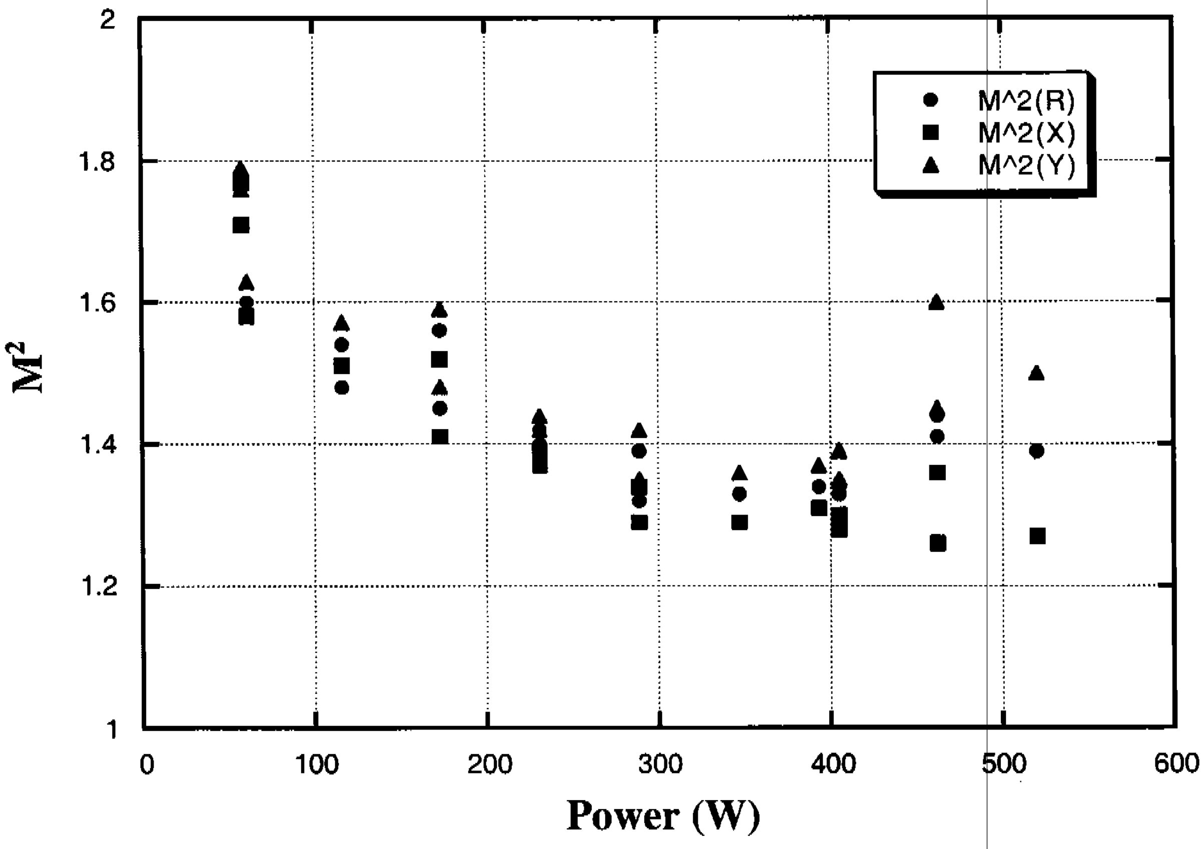
Figure 3. The waist position with respect to the cavity mirror is shown. We expect the apparent waist position to grow from 290 to 300 cm. Data indicates shift of waist by ~10 cm. This indicates that the heating in the output coupler might be around 15% larger than the high reflector.

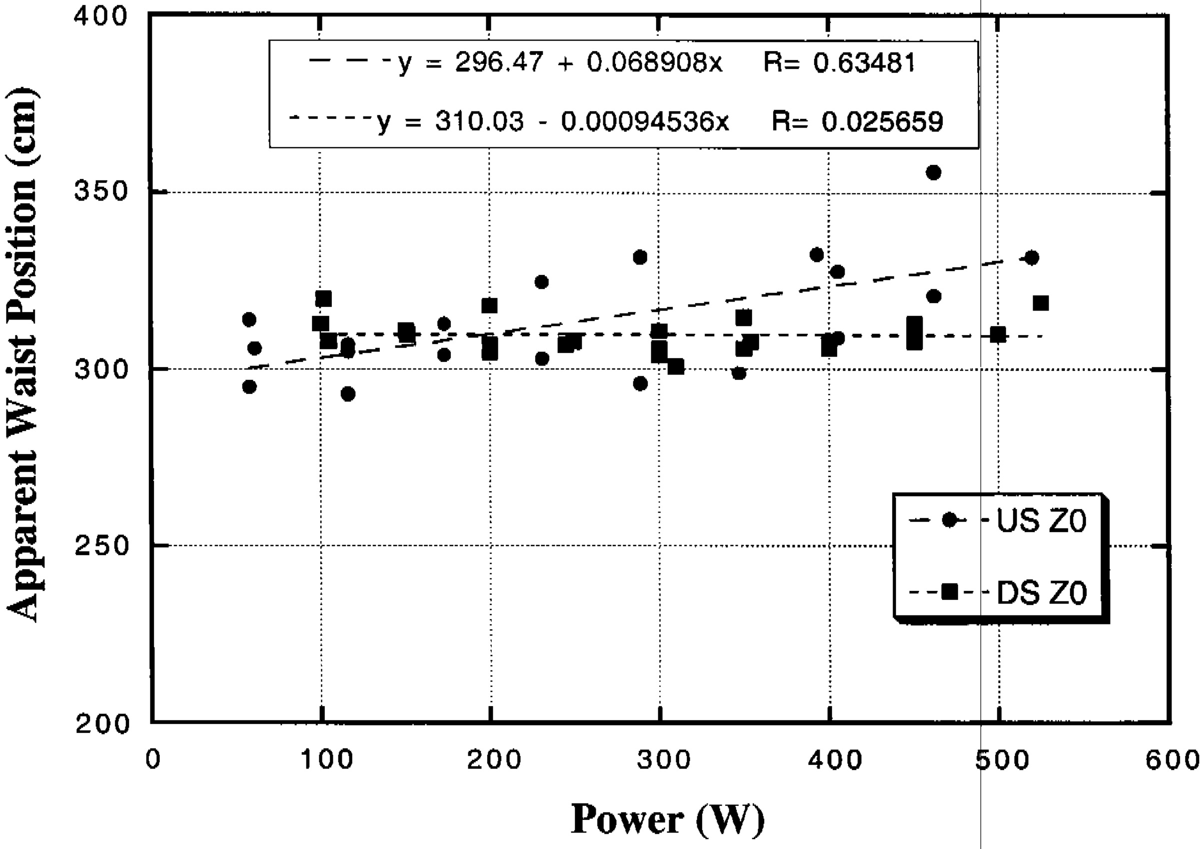
Figure 4. Rayleigh range data corrected for position jitter at the waist of the beam inside the ModeMaster. The zero power intercept is now close to the calculated cold cavity values.

Figure 5. Corrected Mode quality data vs. power. The beam is essentially an ideal Gaussian for power up to 350 W. For higher power the beam quality quickly degrades, presumably due to heating-induced aberrations.

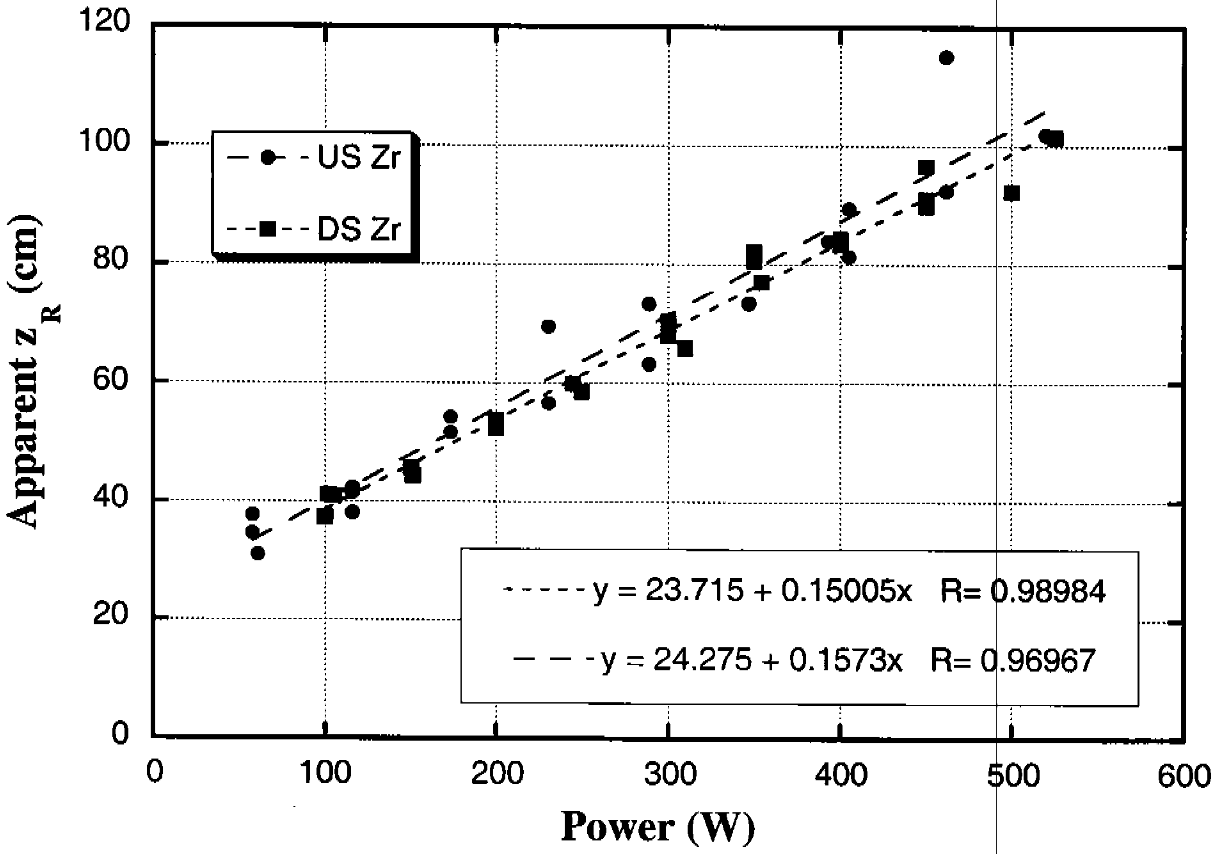


160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
Apparent z_R (cm)
Power (W)
US Zr
DS Zr
y = 43.907 + 0.14445x R= 0.98684
y = 41.032 + 0.1759x R= 0.95965

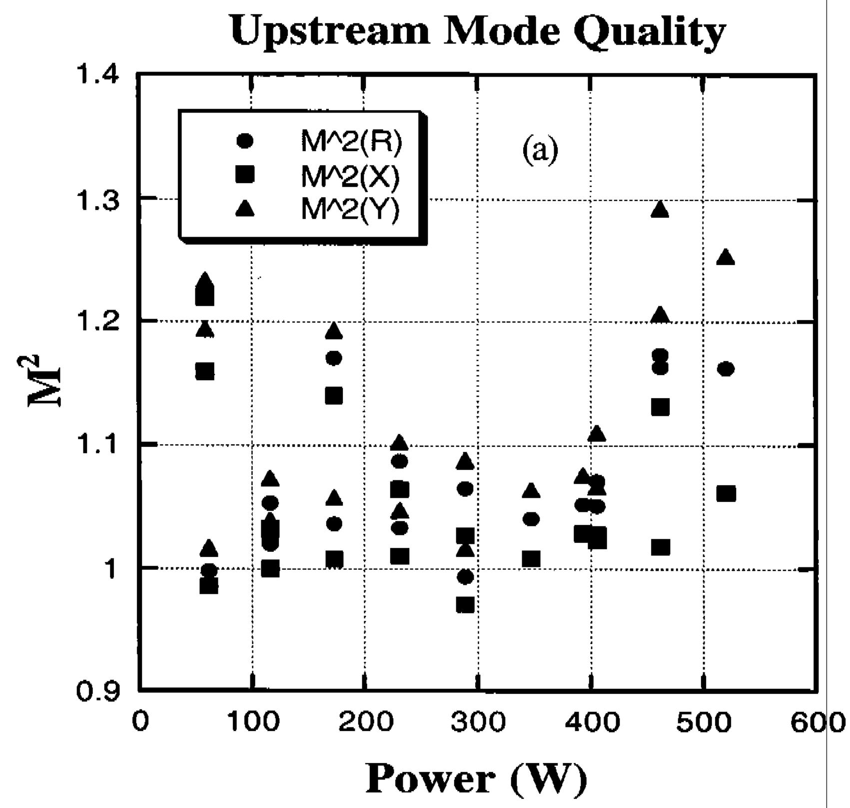

2
1.8
1.6
1.4
1.2
1
0
100
200
300
400
500
600
M²
Power (W)
● M^2(R)
■ M^2(X)
▲ M^2(Y)

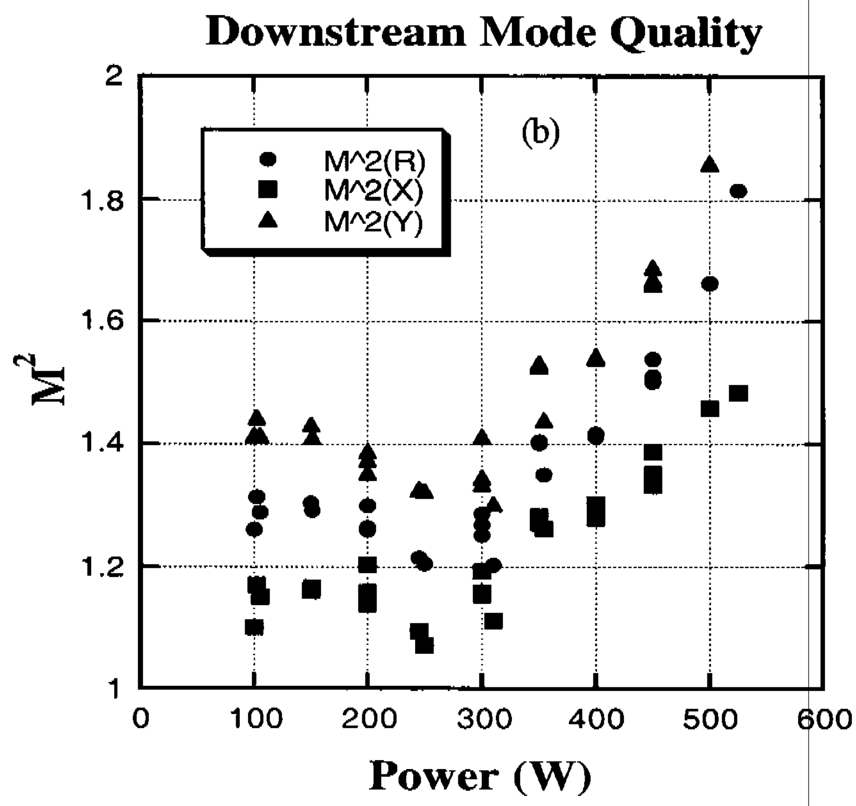


- - -y = 296.47 + 0.068908x R= 0.63481
-----y = 310.03 - 0.00094536x R= 0.025659
Apparent Waist Position (cm)
400
350
300
250
200
0
100
200
300
400
500
600
Power (W)
US Z0
DS Z0



120
100
80
60
40
20
0
Apparent z_R (cm)
0
100
200
300
400
500
600
Power (W)
US Zr
DS Zr
y = 23.715 + 0.15005x R= 0.98984
y = 24.275 + 0.1573x R= 0.96967


Upstream Mode Quality
1.4
1.3
1.2
1.1
1
0.9
M²
0
100
200
300
400
500
600
Power (W)
● M^2(R)
■ M^2(X)
▲ M^2(Y)
(a)


Downstream Mode Quality
2
1.8
1.6
1.4
1.2
1
M²
0
100
200
300
400
500
600
Power (W)
● M^2(R)
■ M^2(X)
▲ M^2(Y)
(b)