A Comparison of Short Rayleigh Range FEL Performance with Simulations

S. V. Benson, P. Evtushenko, G. R. Neil, and M. Shinn
Thomas Jefferson National Accelerator Facility
Newport News VA
and
J. Blau, D. Burggraff, W. B. Colson,
P. P. Crooker, and J. Sans Aguilar
Naval Postgraduate School Monterey CA 93943 USA

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Motivation – 3D Simulations predict quite different performance vs. Rayleigh range vs. 1D simulations

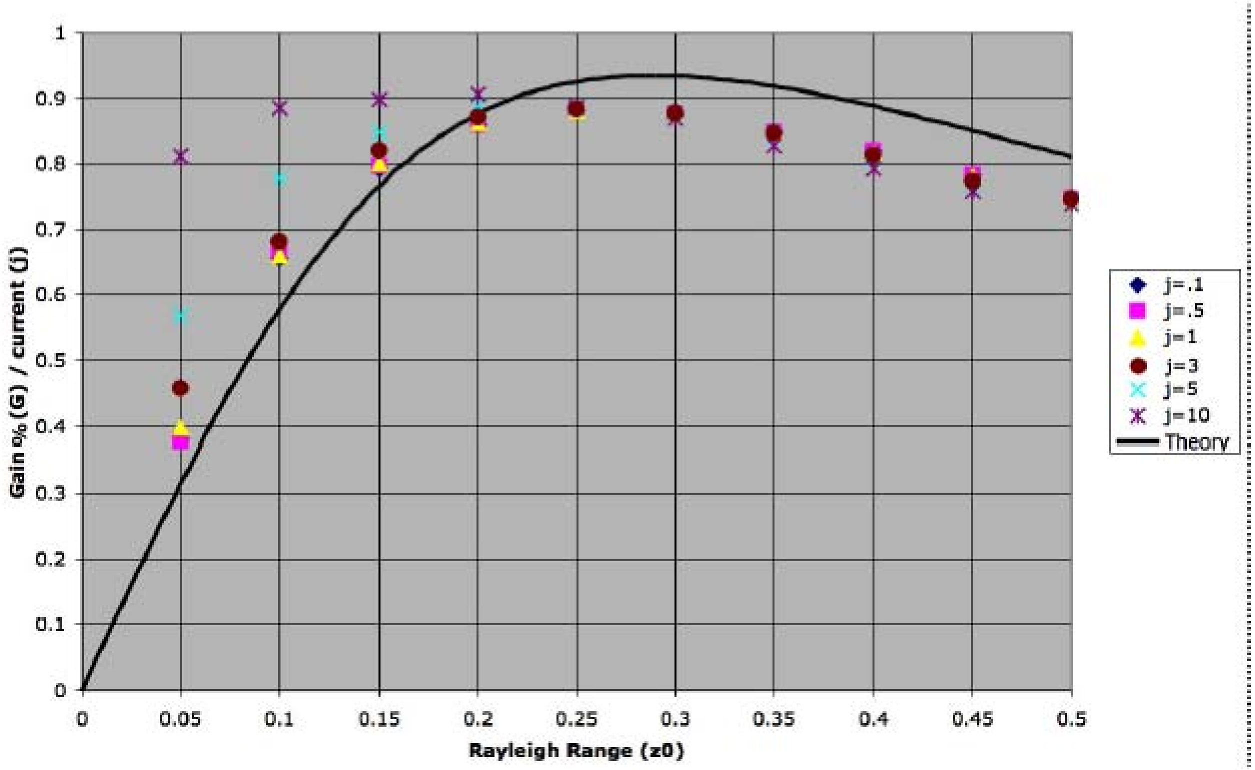


Figure 24. Gain curves for various Rayleigh lengths and dimensionless current values

W. B. Colson et al., "Short Rayleigh length free electron lasers,"
Physical Review Special Topics: Accelerators and Beams 9, 030703, 2006

Jefferson Lab Experiment

- Lase at 0.93 μm using 2.8 micron mirror set. The cavity length is 32.042m. Wiggler length is 1.65 m.
- The output coupler was a sapphire plano-concave substrate. The ROC of the concave side was 16.00±0.02 m.
- Vary radius of curvature of high reflector using deformable mirror assembly from 16.3 m to 16 m
- Measure gain, turn-on time, detuning curve length, and power vs. normalized Rayleigh range $z_0=z_R/L_W$.
- Take all data at very low average power to minimize change in the ROC due to mirror heating.
- Measured cavity losses were 6.1±0.2% for $z_0>0.2$

Rayleigh Range Calibration

- Three approaches to calibration:
  - Direct calculation from radius of curvature measurement. This is a problem for small z_0
  - Measure Mode size on mirrors and use

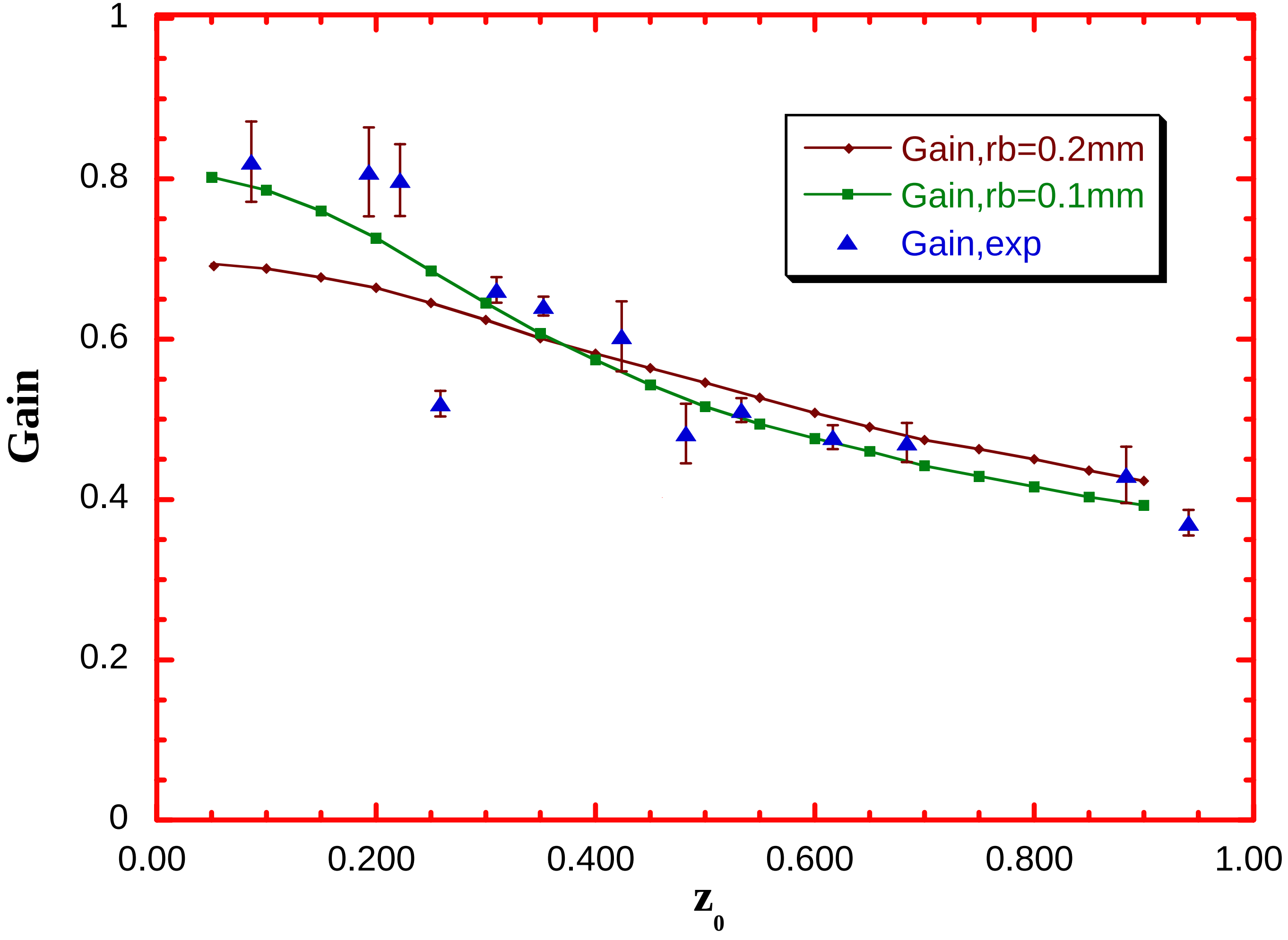
$$z_R = \frac{\pi w_m^2}{2\lambda}\left(1-\sqrt{1-\left(\frac{\lambda L}{\pi w_m^2}\right)^2}\right) \approx \frac{\lambda L^2}{4\pi w_m^2}$$

  - Measure mode rotation vs. mirror steering and use

$$M = 2\frac{\theta_r}{\theta_m} \qquad M = (1+(L/2z_R)^2)$$

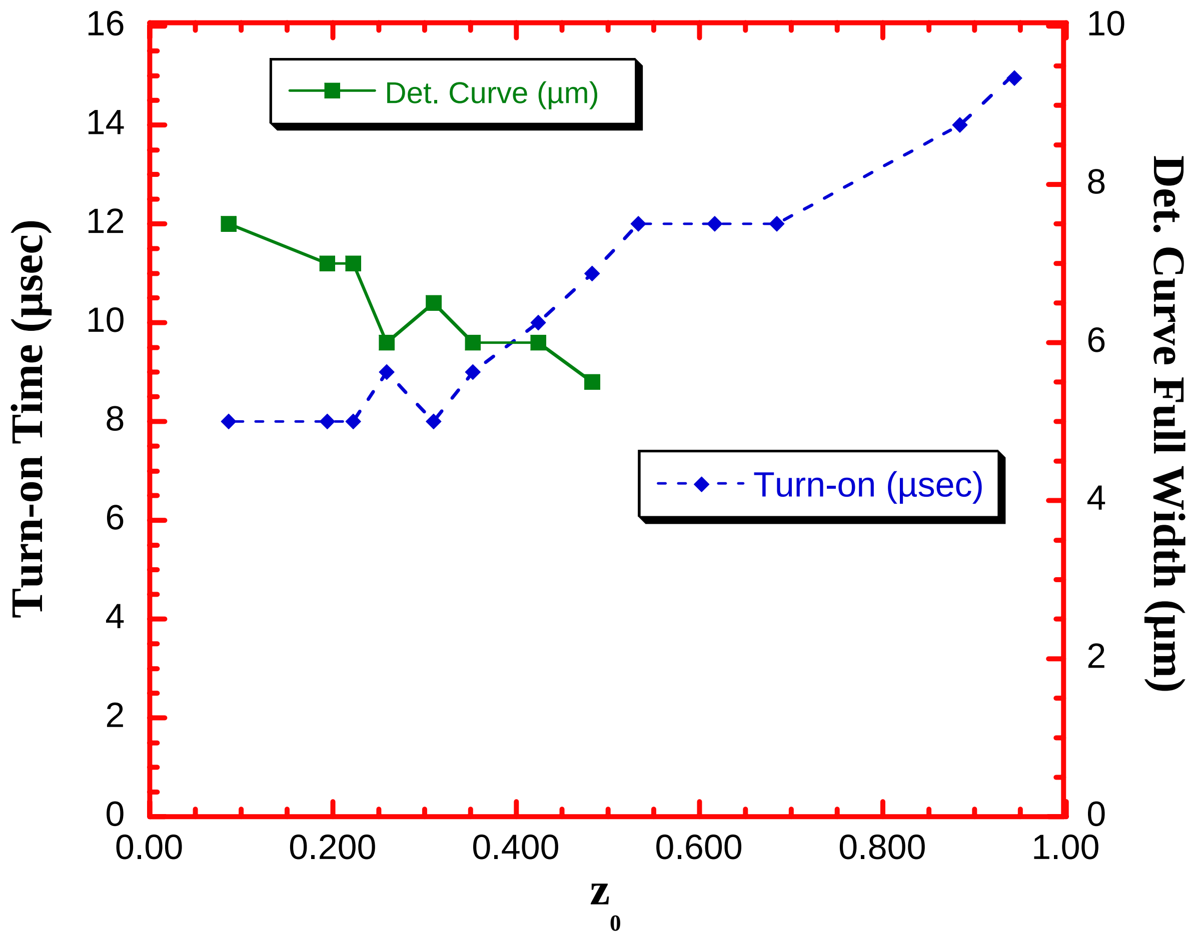
- The last method relies on the cold cavity mode matching the active cavity mode. We found that this is not the case. We use a scaling factor to make all 3 methods agree.

Gain vs. Rayleigh Range



Simulated gain is quite close to measured values.

Similar Performance Seen for Turn-on and Detuning Curve Width



Detuning curve width should be proportional to gain. Turn-on time should be inversely proportional to gain.

How Far Can One Tilt a Mode?

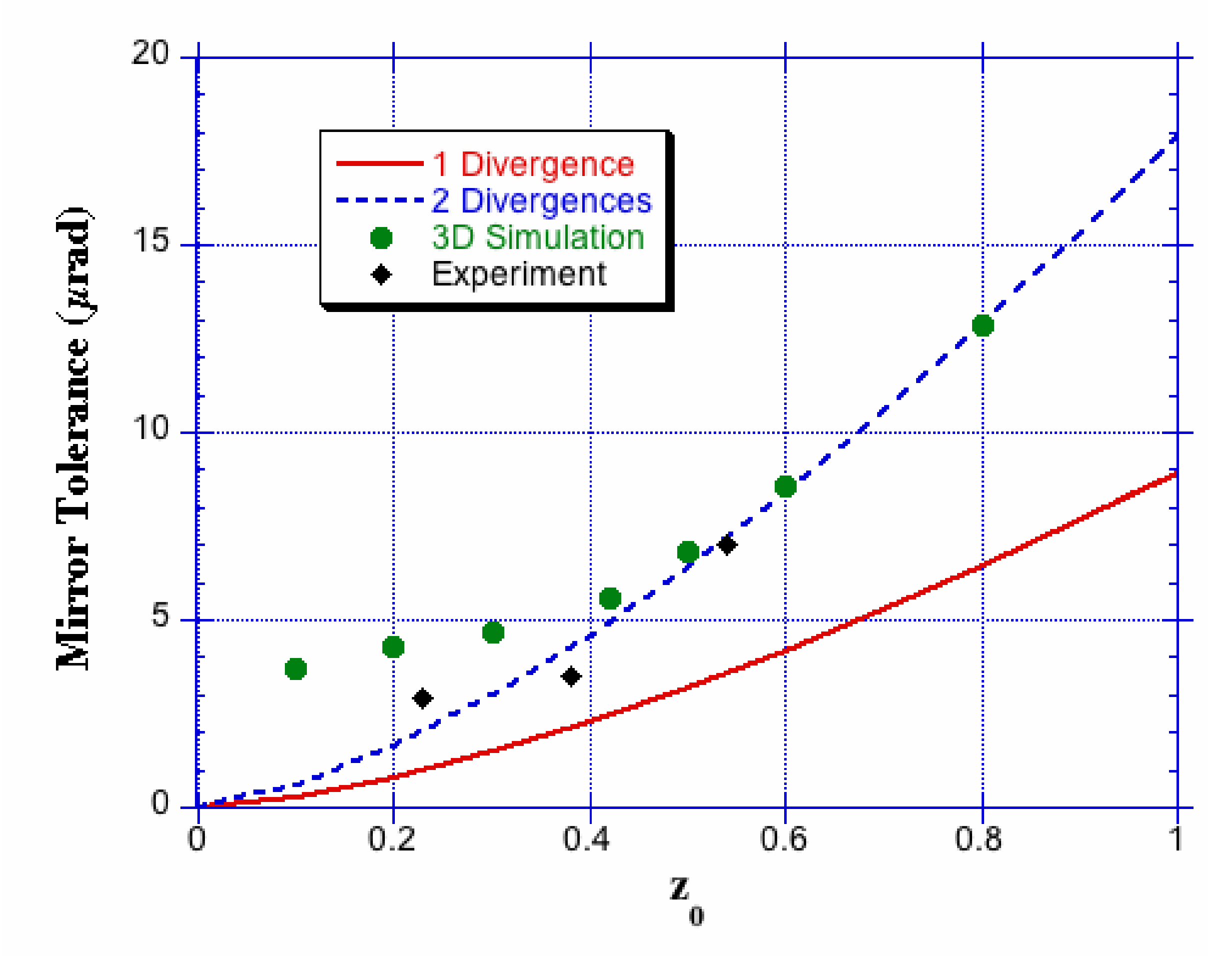
- A fundamental question of free-electron lasers is how far one can tilt an optical mode with respect to the electron beam (or *vice versa*).
- Simplistic thinking would say that things should get pretty bad if one tilts the electron beam or optical mode by one divergence of the optical mode.
- A simple analysis says that a crude estimate of the tolerance should be

$$\theta_m = 2\frac{\theta_d}{M}$$

$$\theta_d = \sqrt{\frac{\lambda}{\pi z_R}}$$

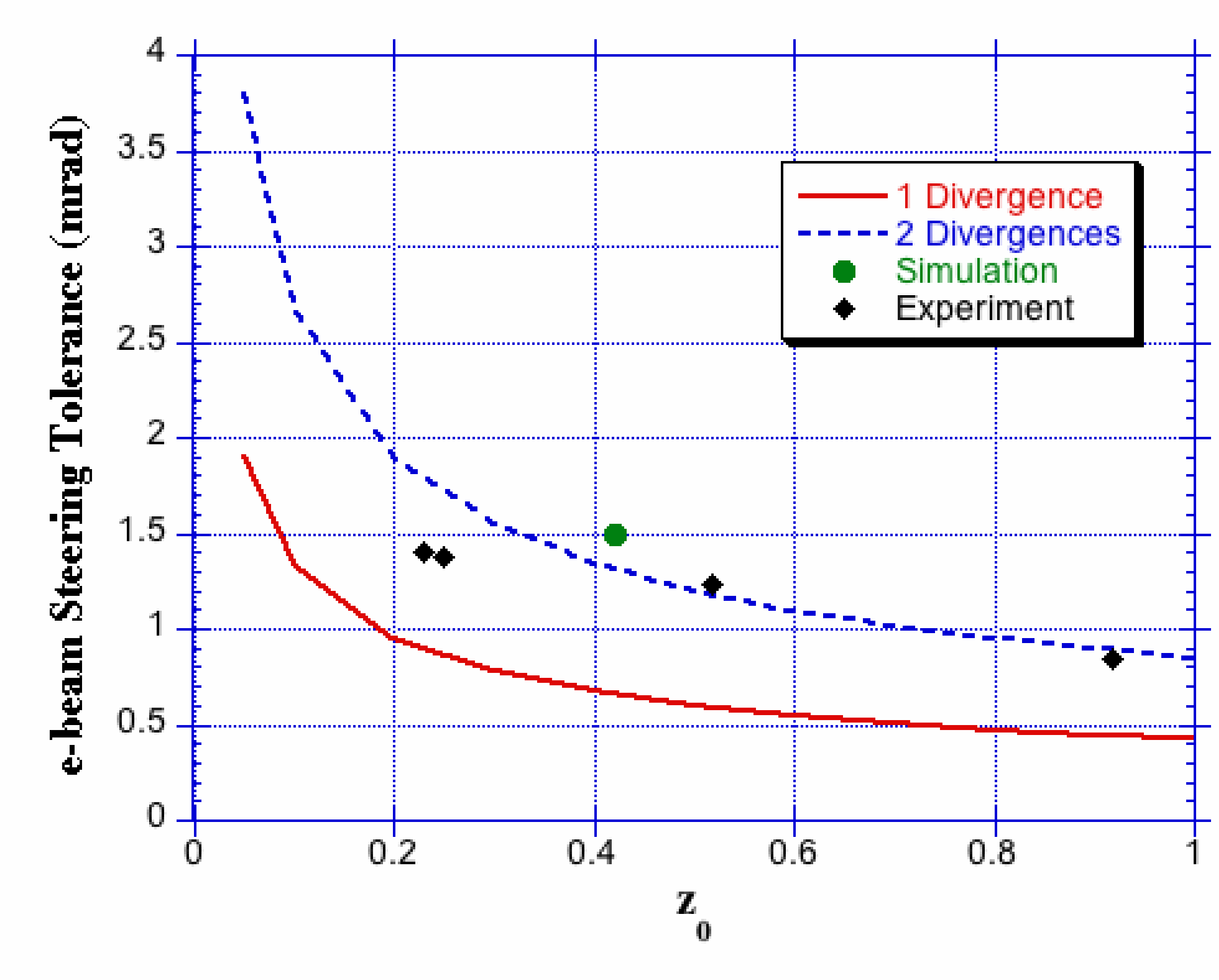
$$M = 1 + \left(\frac{L}{2z_R}\right)^2$$

Sensitivity to Mirror Tilt



HWHM of the gain vs. mirror steering. The red curve is proportional to the crude mode-rotation model.

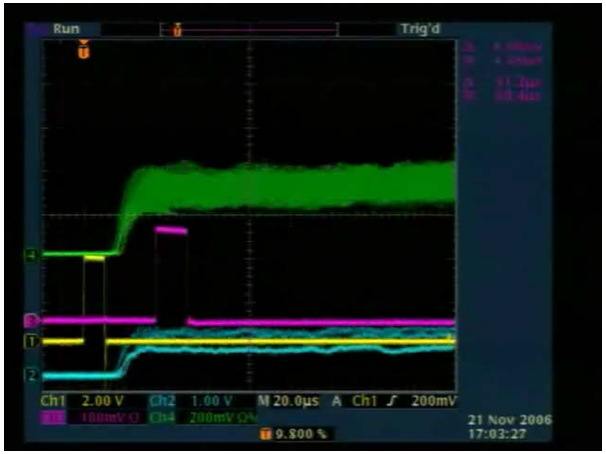
Sensitivity to Electron Beam Tilt



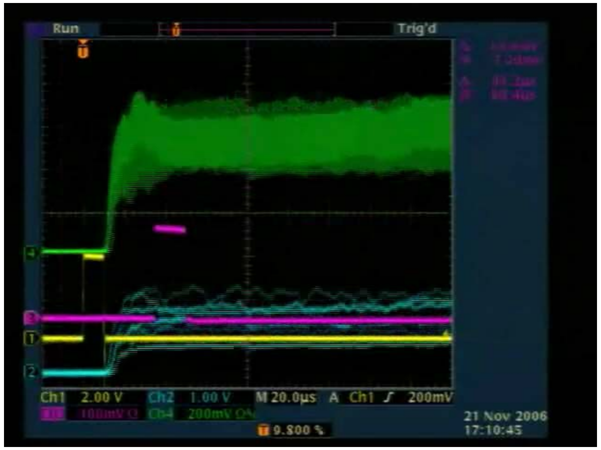
HWHM of gain vs. electron beam steering. The red curve corresponds to the crude mode-rotation model.

Total power and turn-on time vary little with resonator mode angle

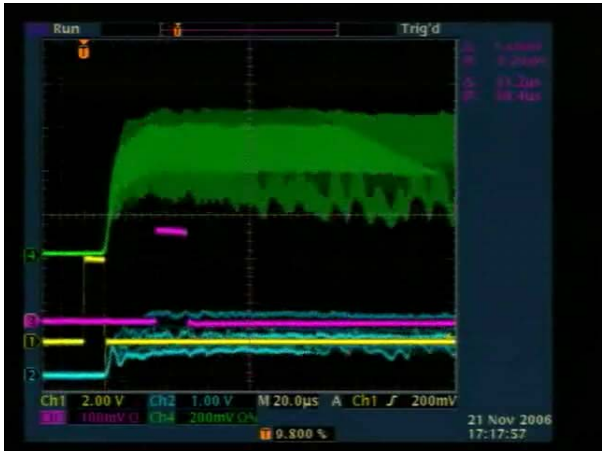
Blue trace is on-axis intensity, Green is total power



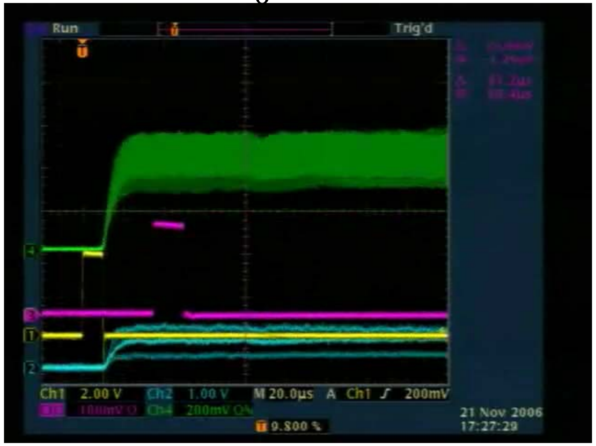
z_0=0.42



z_0=0.35



z_0=0.26

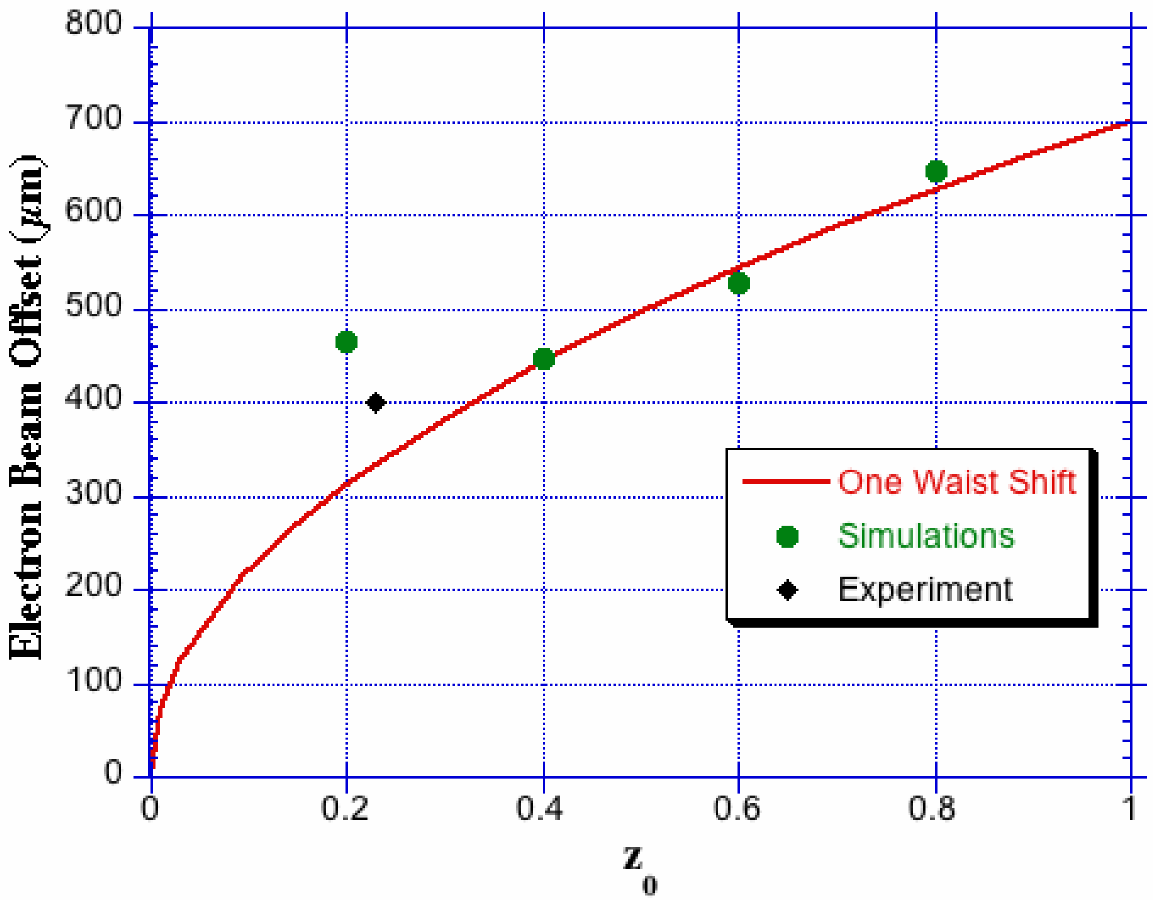


z_0=0.22

z_0=0.19

unstable

Gain vs. position



Crude model actually matches simulation well for large Rayleigh range. We don't have much data yet.

Other Observations

- The electron beam can be offset by one waist mode radius before the gain drops by a factor of 2. Experimental behavior qualitatively agrees with this.
- Even with half charge electron bunches the gain grows monotonically with decreasing Rayleigh range.
- Astigmatism at the level of $\lambda/20$ leads to a very astigmatic mode for very short Rayleigh range.
- Mirror vibrations at the 1 μrad level lead to large pointing errors for short Rayleigh range.
- The mode becomes more stable when the resonator goes unstable.

Conclusions

- Gain increases monotonically vs. Rayleigh range even when the cavity goes unstable.
- Agreement between the gain in simulations and measurements is quite good.
- The gain is not nearly as sensitive to mirror steering as one might expect but we need more data points to be able to conclude that there is good agreement between the experiment and simulations.