Nuclear Instruments and Methods in Physics Research A318 (1992) 74–80
North-Holland

NUCLEAR
INSTRUMENTS
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IN PHYSICS
RESEARCH
Section A

# Final results of the Boeing and Los Alamos grazing incidence ring-resonator free electron laser experiment

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**Initial test results for the Boeing and Los Alamos grazing incidence ring-resonator FEL were presented at the 1990 FEL Conference. This work showed that the resonator pointing alignment accuracy required improvements to the resonator diagnostics to increase the alignment accuracy. The alignment technique was described, but lasing results with the more accurate alignment were not available at that time. This paper discusses more recent and final test results from the grazing-incidence ring-resonator experiment. With the new alignment techniques, the extraction was approximately seven times greater, and the FEL output exhibited much reduced temporal structure. Measurements show that FEL output and wavelength are sensitive to electron beam energy variations.**

## 1. Introduction

The purpose of this work was to test the difficulty of operating an grazing-incidence optical resonator cavity capable of withstanding the high incident optical fluxes produced in free electron lasers (FELs). A ring-resonator optical cavity using grazing incidence optics has been suggested as a possible design for high power FELs [1]. To study the practicality of this type of resonator, an operational resonator was designed, constructed and integrated into the existing free-electron laser facility at Boeing in Seattle, Washington.

In our contribution to the 1990 Free Electron Laser Conference we described initial lasing results at visible wavelengths for this FEL using a grazing incidence, ring-resonator optical cavity [2,3]. This early lasing data

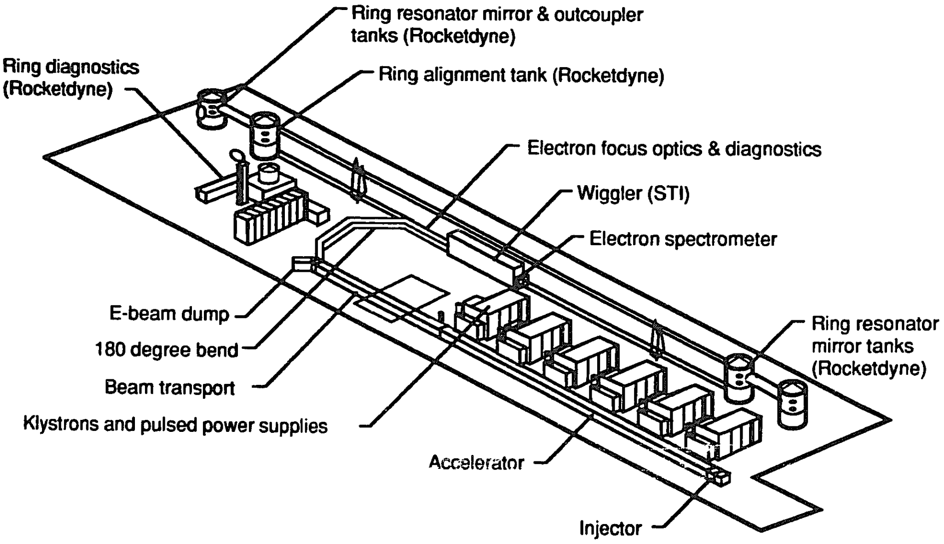

Fig. 1. Overview drawing of the Boeing free electron laser facility.

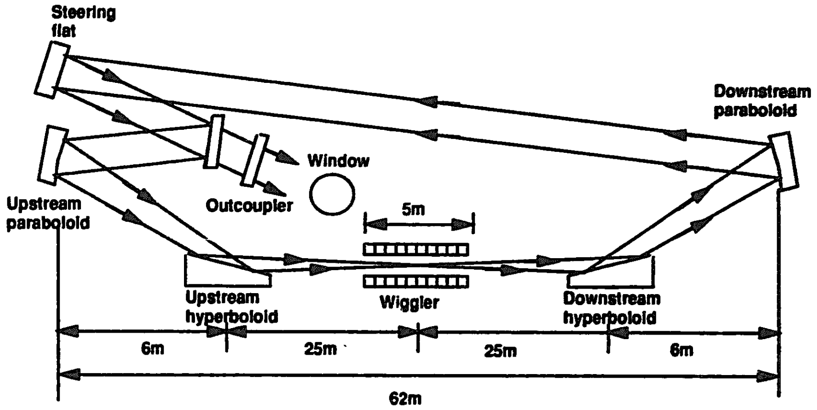

Fig. 2. Grazing incidence ring resonator.

exhibited a highly structured temporal output and unreliable initiation of lasing. Measurements reported last year indicated strong walking modes within the ring resonator optical cavity. Computer simulations demonstrated that a poorly aligned resonator would have startup difficulties, and if clipping of the outcoupled beam occurred, it would temporally structure the FEL output [4]. The models also showed if the small-signal gain was less than roughly twice the single-pass losses, the FEL output would be very sensitive to electron-beam variations [5].

However, the greatest experimental difficulty was achieving reliable startup of the FEL. Measurements and analysis showed the dominant problem lay with the pointing alignment of the ring resonator. This was corrected by the installation of a Pockels cell-chopped laser alignment beam to assure the pass-to-pass optical beams were aligned, and a reverse mirror viewed by a

Table 1
Electron beam, thunder wiggler and ring-resonator design parameters

| | |
|---|---|
| *Electron beam* | |
| Electron beam energy | 110 MeV |
| Repetition rate | 2 Hz |
| Macropulse length | 110 $\mu$s |
| Micropulse spacing | 443 ns |
| Emittance ($4\epsilon_{rms}$) | 100–120$\pi$ mm mrad |
| Macropulse energy jitter | 0.5–0.75% FWHM |
| Micropulse energy spread | 0.5% FWHM |
| Micropulse width | 12 ps FWHM |
| Micropulse charge | 3 ns |
| *Thunder wiggler* | |
| Length | 5 m (ten 50 cm sections) |
| Wiggler period | 2.18 cm |
| Number of periods | 220 |
| Peak magnetic field | 1.02 T |
| Wiggler parameter | 1.8 (peak) |
| Wiggler parameter | 1.31 (rms) |
| Betatron period | 5.6 m |
| Taper | 0% (during these tests) |
| *Ring resonator* | |
| Ring Rayleigh range | 240 cm |
| Hyperboloid focal length | − 105 cm |
| Paraboloid focal length | 698 cm |
| Telescope magnification | 7× |
| Hyperboloid-paraboloid spacing | 600 cm |
| Roundtrip path length/time | 133 m/443 ns |

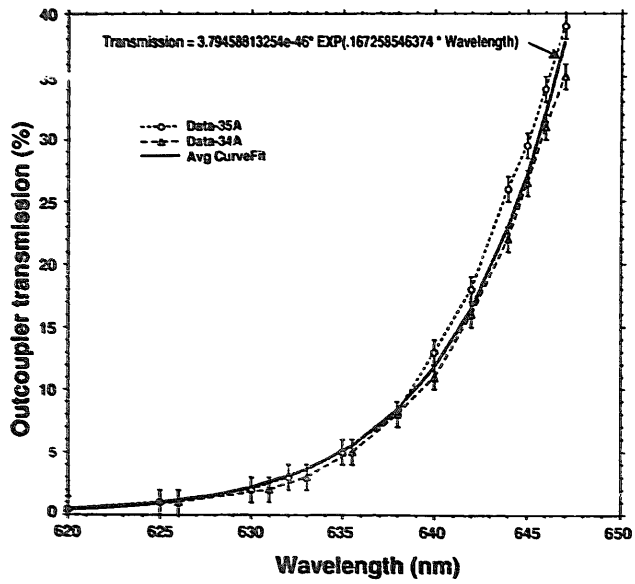

Fig. 3. Outcoupler transmission vs wavelength.

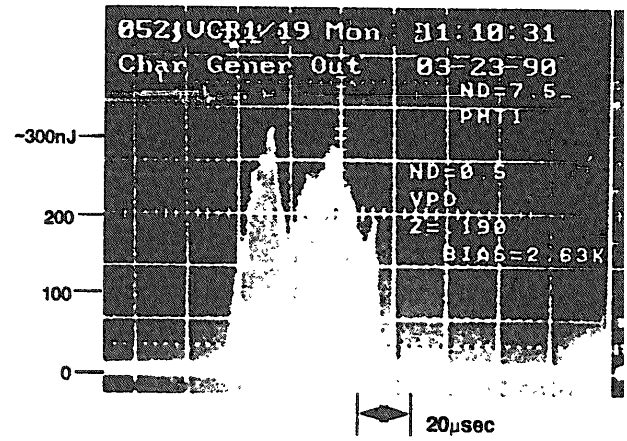

Fig. 4. Vacuum photodiode measurement of the optical macropulse during initial lasing tests.

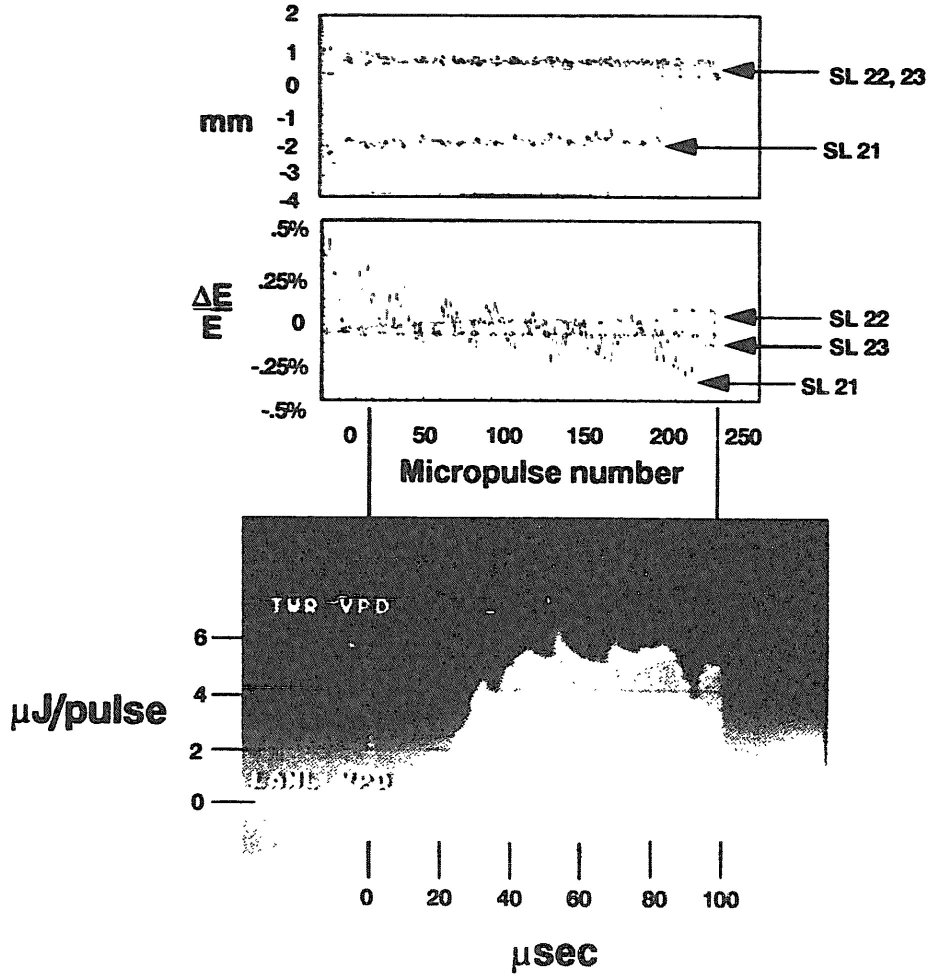

Fig. 5. FEL output and electron beam stripline data for electron macropulse energy (SL21) and position (SL22 and SL23) at two locations in front of the wiggler.

Table 2
Electron beam and lasing data for October 10, 11 and 12, 1990

| | Date | | |
|---|---|---|---|
| | Oct. 10 | Oct. 11 | Oct. 12 |
| *Electron beam* | | | |
| Energy [MeV] | 109.7 | 109.7 | 108.9 |
| Energy slew [%] | 0.25 | 0.5 | 0.25 |
| Micropulse charge (wiggler) [nC] | 3.1 | 2.9 | 3.0 |
| Pulse width (injector) [ps] | 16 | 15 | 15 |
| Peak current (wiggler) [A] | 197 | 193 | 200 |
| Normalized edge emittance ($4\epsilon_{rms}$) | | | |
| horizontal plane [mm mrad] | $107\pi$ | $117\pi$ | $149\pi$ |
| vertical plane [mm mrad] | $168\pi$ | $122\pi$ | $115\pi$ |
| Energy/micropulse [J] | 0.34 | 0.318 | 0.327 |
| *Optical beam* | | | |
| Wavelength [nm] | 637 | 635 | 645 |
| Spectral width [nm] | 2-4 | 2-4 | 10-12 |
| Lasing duration [μs] | 75-80 | 80-90 | 90 |
| Ringdown loss [%] | 30 | 25-30 | 45-50 |
| Net small signal gain [%] | 35-65 | 25 | 50-100 |
| Energy/micropulse [μJ] | – | 2-8 | 10-30 |
| Outcoupler transmission [%] | 8 | 5 | 30 |
| Extraction efficiency [%] | – | 0.0035-0.028 | 0.005-0.015 |

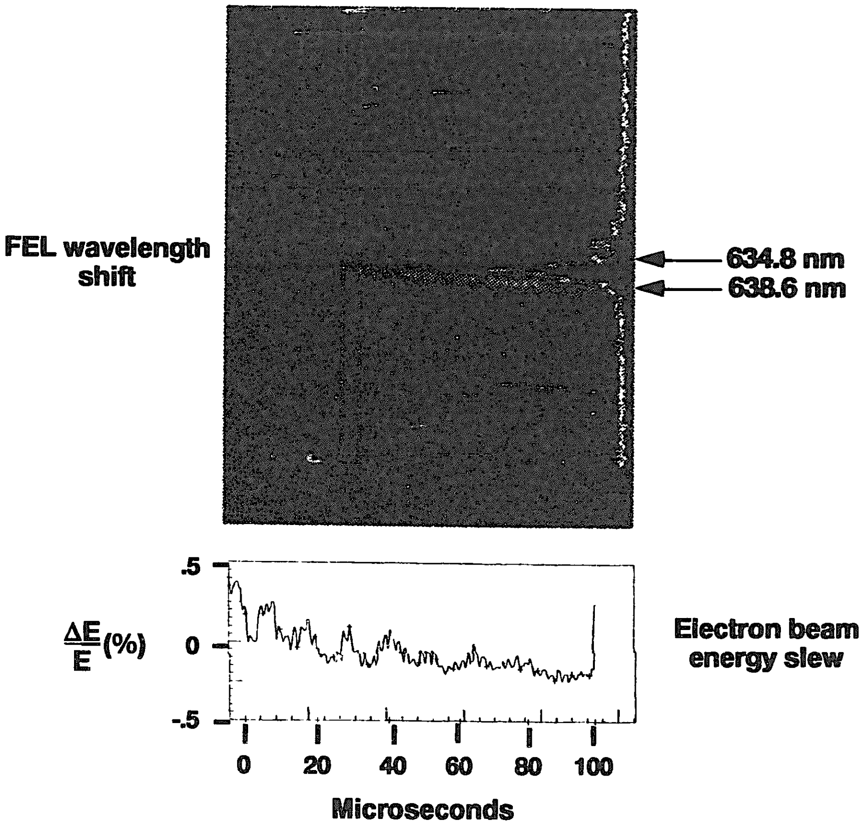

Fig. 6. The observed FEL wavelength shift is correlated with the electron beam energy slew.

movable camera to accurately determine the ring focus location [3]. This paper presents data of the improved FEL operation using these new alignment techniques.

## 2. Description of the grazing incidence ring-resonator FEL

The details of the Boeing and Los Alamos FEL experiment have been described elsewhere [6–11] and are briefly reviewed here.

Fig. 1 shows the laboratory layout of the 110 MeV electron accelerator using a thermionic gun followed by two stages of subharmonic bunching and a traveling wave buncher [6]. The wiggler is 5 m long comprised of ten 50 cm long sections. This is the same wiggler used in the concentric-cavity experiments [7–10]. The wiggler was untapered during the ring-resonator tests. The ring resonator [11] is contained in four large vacuum tanks, two at each end of the wiggler. The positions of the resonator optical elements are shown in fig. 2. The parameters for the accelerator, wiggler, and ring resonator are given in table 1.

The transmission of the outcoupling flat is strongly dependent upon wavelength to suppress sideband generation. This transmission, as a function of wavelength, is given in fig. 3.

## 3. Discussion of lasing results

This section discusses the more recent results of FEL operation with the pass-to-pass alignment system [2,3]. The methods used to prepare the electron beam and align the ring resonator have been described elsewhere [2,3,12,13].

The initial lasing performance of the ring-resonator experiment is illustrated in fig. 4. The vacuum-photodiode measurement showed considerable temporal structure and peak outcoupled energy of approximately 300 nJ, corresponding to only 0.0036% extraction efficiency [2]. In contrast, fig. 5 gives the FEL output on October 11, 1990 after using the chopped alignment beam to align the ring resonator in pass-to-pass and by locating the ring focus at the center of the wiggler. The outcoupled energy is roughly 20 times higher, the structure observed in fig. 4 is greatly diminished, and the lasing now occurs over 80 μs rather than 50 μs. Table 2 lists the electron beam and lasing results for three consecutive days of operation. The extraction efficiency in-

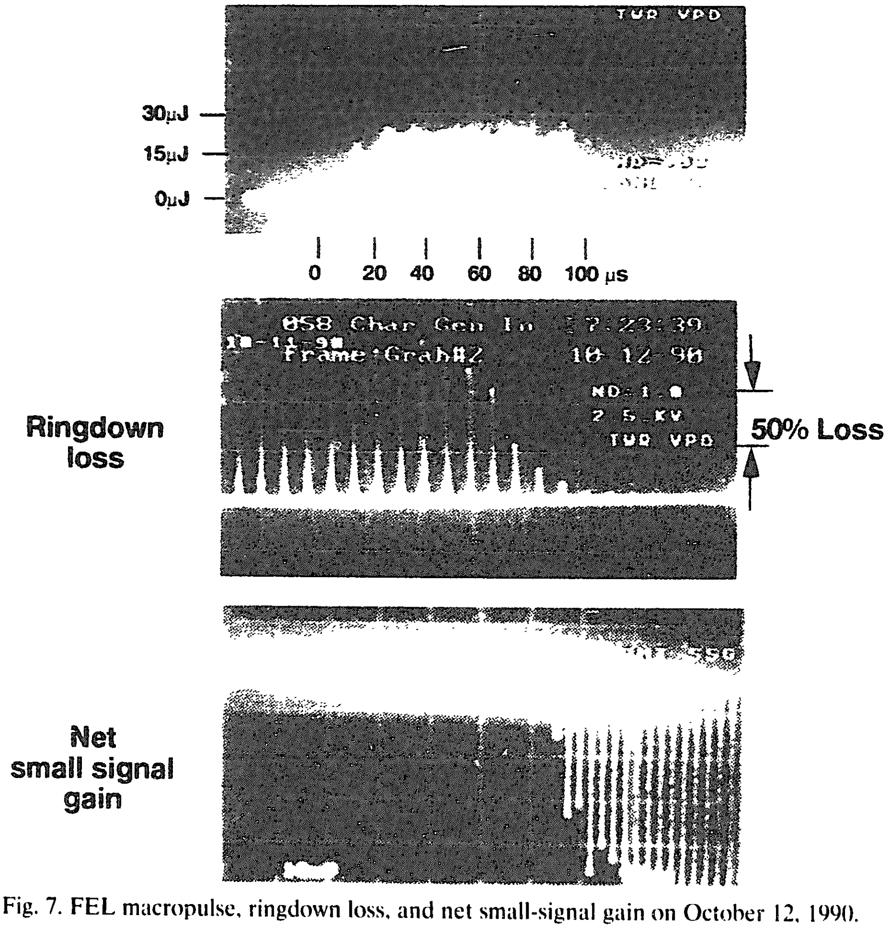

Fig. 7. FEL macropulse, ringdown loss, and net small-signal gain on October 12, 1990.

creased approximately seven times by using the new alignment techniques.

Electron beam stripline data is also plotted in fig. 5. Stripline 21 is located in the 180° bend and gives the energy slew and jitter during the macropulse. Striplines 22 and 23 are in front of the wiggler and provide information on the electron beam position and angle motion at the wiggler entrance [13]. The typical energy slew was 0.3% to 0.5% over 100 μs.

The effect of energy slew upon lasing wavelength is shown in fig. 6. Here a streak spectrometer image [14] is displayed with the macropulse energy slew. The electron energy falls by 0.3% causing a corresponding 0.6% increase in wavelength. This is expected since the wavelength depends upon the square of the beam energy.

The optical parameters given in table 2 show that, except for the last day of operation, the lasing wavelength was 635 nm, at which the outcoupler transmission was 5%. On October 12, the electron energy was too low by 1 MeV, resulting in a much higher outcoupler transmission of 30%. (See fig. 3.) This higher outcoupling fraction gives the much larger observed optical energy of 10–30 μJ per micropulse, but it does not explain the increased optical line width from 2–4 nm to 10–12 nm FWHM.

The October 12 optical output, ringdown loss and small-signal gain measurements are shown in fig. 7. The higher ringdown loss is consistent with the increased outcoupling at the longer wavelength (645 nm). However, this should not have affected the line width which was approximately five times greater on this day.

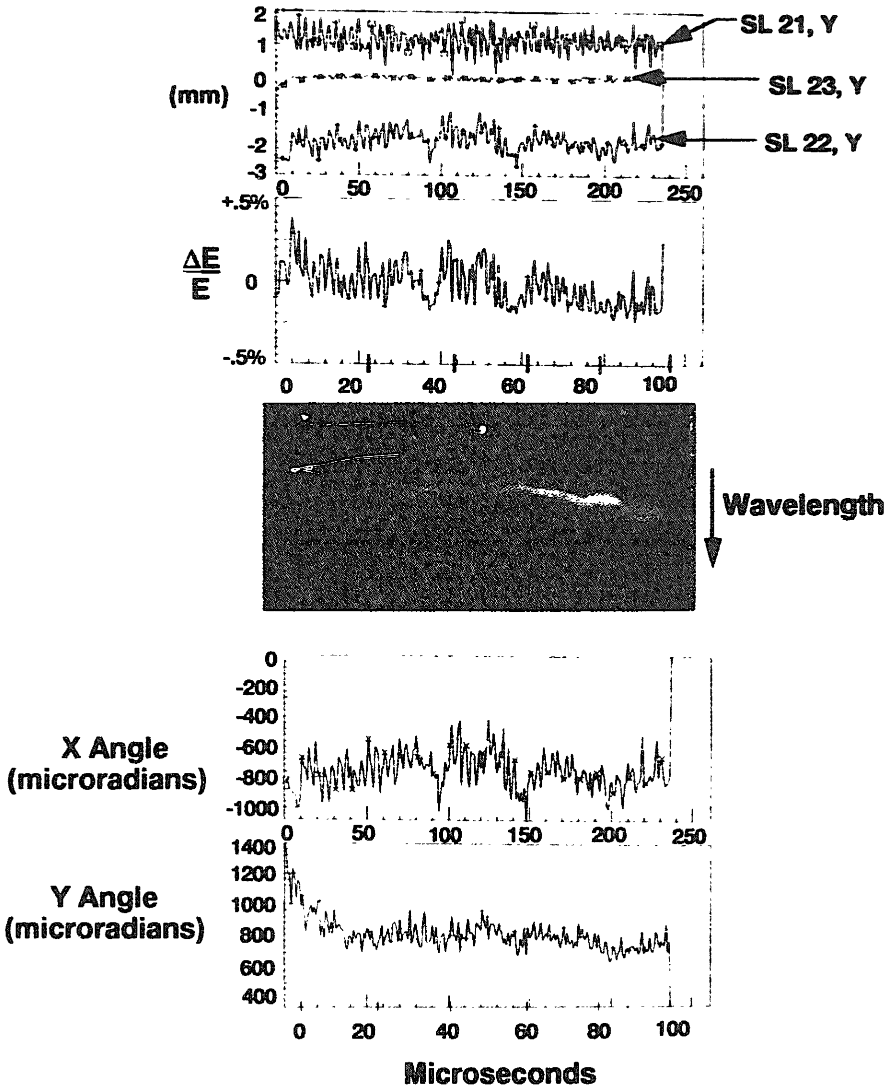

Fig. 8. Streak camera image of wavelength vs time correlated with the electron beam energy, position and angle stripline measurements. Excessive electron beam jitter slews the FEL wavelength.

A suggestion of excessive electron beam jitter is indicated in the small-signal gain which fluctuates wildly from pass to pass.

Comparing the streak spectrometer image with the stripline results, as in fig. 8, demonstrates the utility of coordinated optical and electron beam diagnostics. The streak camera image gives the spectral evolution of the FEL as the macropulse progresses; time increases to the right and longer wavelength is downward. The striplines clearly show that the electron beam had excessive energy jitter which caused large and fast position and angle motion at the wiggler. This motion is well correlated with the wavelength slewing and is the cause of the increased line width. The measured 400 μrad peak-to-peak angular jitter is at least ten times greater than the jitter for optimal ring resonator operation.

## 4. Summary and conclusions

The initial results of operating a FEL with a grazing incidence ring resonator exhibited a structured optical output, and startup was unreliable. Measurements were performed to separate electron-beam effects and ring-resonator effects. Calculations showed that startup problems were likely due to poor resonator alignment, while the structured lasing intensity was dominated by fluctuations in the electron beam. Therefore, efforts were made to develop an additional alignment laser producing a chopped beam to quantify the resonator's walking mode. This chopped beam not only demonstrated the presence of the pass-to-pass walking behavior, but also provided a means for correcting it by tipping the downstream paraboloid and the outcoupler flat. Renewed testing with the aligned, but still astigmatic resonator, resulted in reliable operation and a sevenfold increase in the extraction efficiency.

The next steps were to remove the remaining astigmatism, increase the bandwidth of the stabilization system, and upgrade the electron accelerator. This work was nearing completion when the direction of the FEL project changed, and the ring resonator experiment was discontinued. However, this decision was not the result of any fundamental technical shortcomings of using a grazing incidence ring resonator with an FEL. Therefore, the results presented here do not represent the capabilities of a fully optimized ring-resonator FEL.

## Acknowledgements

It is impossible to imagine making a device as complicated as an FEL work without the efforts of many talented and dedicated people. The authors would like to thank P. Johnson, K. McCrary, M. Bemes, R. Hawkins and A. Currie for building, maintaining and operating the FEL, L. Milliman and C. Lancaster for software support, and M. Bailey and D Schultz for installing and maintaining the various optical systems. There were also useful discussions with A Vetter, R. Kennedy, T. Buller, L. Tyson and A.D Yeremian. We also received helpful advice from J Slater, K. Robinson, D. Quimby, and D. Shemwell.

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