HIGH AVERAGE POWER OPERATION OF A SCRAPER-OUTCOUPLED FREE- ELECTRON LASER

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Abstract
We describe the design, construction, and operation of a high average power free-electron laser using scraper outcoupling. Using the FEL in this all-reflective configuration, we achieved approximately 2 kW of stable output at 10 um. Measurements of gain, loss, and output mode will be compared with our models.

INTRODUCTION

Compared to other high average power laser systems, an advantage of a free-electron laser (FEL) is there are no heat dissipation issues within the gain medium. However, when operated in an oscillator configuration, one must mitigate and manage the effects of absorbed photons and the resultant thermally induced distortion of the otherwise spherical mirror surface. Previous analysis [1] and experiment [2] have shown that this distortion, when sufficiently large, causes the output to saturate. The obvious solution, to obtain low loss coatings and substrates, isn't always possible at certain wavelength ranges. For example, at 10.6 µm, the best outcoupler (OC) designs still have absorption levels in excess of 0.1% [3], which limits the extracted power to less than 10 kW [4]. In other wavelength regions such as the deep UV (< 150 nm) suitable substrates for outcoupling the output don't exist.

In these cases, some other scheme for outcoupling the laser radiation from the resonator must be used. In FELs, hole outcoupling is traditional [5], but is not particularly efficient. For many high average power lasers it is customary to use a scraper mirror intracavity, *i.e.*, an annular mirror were some fraction of the center of the laser mode is transmitted, and the wings of the mode are reflected out of the cavity. [6] Usually scraper outcoupling is used in positive branch unstable resonators, where the gain is very high and the outcoupling fraction may be large, *e.g.*, > 30%. The gain in the majority of FELs is not so high, and the wiggler in the FEL requires a negative branch unstable resonator, which adds its own complications. We chose to use our existing near-concentric resonator and place the scraper mirror close to one of the end mirrors. Only one theoretical paper [7] has been published on the use of an annular scraper, but to our knowledge there are no experimental results. Therefore, we analyzed this cavity configuration to confirm that we would get efficient and stable output. Finding that it was stable, we then proceeded to build and test it.

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DESIGN AND IMPLEMENTATION

The optical cavity configuration we modeled is shown in Fig, 1, and the resonator parameters are shown in Table 1. We chose to operate at ~ 10 µm, as we had been commissioning the IR Upgrade FEL at this wavelength using a conventional, transmissive outcoupling optical cavity, and had mirrors readily available.

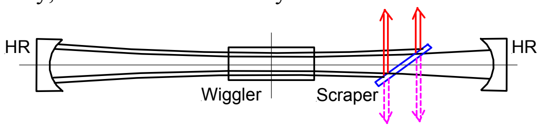

Figure 1 Schematic layout of the FEL optical cavity with an annular scraper. The solid arrows denote the outcoupled beam, the dashed arrows denote the diffracted beam that strikes the rear of the scraper.

Table 1 FEL resonator parameters

Parameter	Value
Cavity length	32.042 m
Rayleigh range	3 m
Mirror radius of curvature	16.6 m
Scraper position	15.4 m
Scraper outcoupling	10%

Given the single pass gain of our optical klystron was ~ 30%, and the extraction efficiency is highest when the outcoupling fraction is ~ 1/3 the gain [8], we designed the scraper to intercept 10% of the optical mode. This was done using the following analytical expressions [6]:

The power transmitted for a gaussian beam of $1/e^2$ radius ω through a circular aperture of radius a is given by:

$$P_{trans} = 1 - \exp\left(\frac{-2a^2}{\omega^2}\right) \quad (1)$$

In our case, we want $P_{trans} = 0.9$, so a = 1.07ω.
At the position of the scraper (z=15.4m), the mode size is given by:

$$\omega(z) = \omega_0 \left[1 + \left(\frac{\lambda z}{\pi \omega_0^2} \right)^2 \right]^{\frac{1}{2}} \tag{2}$$

For our resonator configuration, $\omega_0 = 0.003$ m, and with $\lambda = 10$ µm, $\omega(z) = 1.66$ cm. From the relationship between a and ω, the radius of the hole in the scraper is. 1.78 cm. This was the starting point for our simulations. Simulations were carried out in both ZEMAX [9] and GLAD [10], with similar results. Given our interest in determining the losses due to diffraction, we primarily used GLAD. Since we were most interested in determining if the configuration was stable, we did the calculations in a cold cavity, *i.e.,* no gain. Rather than let the power in the cavity decrease on each pass, we simply reinitialized the power after each pass and let the mode develop until the losses (and power) converged to a steady state. These diffractive losses occur at two points, first when the mode traverses the scraper, and then as it approaches the wiggler vacuum chamber.

As the intracavity average power may be as high as 100 kW, the scraper should be thermally conductive and water cooled. We chose copper for the substrate, with a simple loop of copper tube brazed to its periphery for cooling. (Fig. 2). To have high reflectivity, the scraper was gold coated, using a RF magnetron deposition process. As the wavelength is long, the surfaces did not have to be polished to a high degree of flatness or smoothness. Specifications are given in Table 2. The polishing and coating were done in-house, and the optical specifications checked using a Wyko RTI4100 laser interferometer and NT1100 noncontact profilometer. We met or exceeded specifications; the mirror figure was 3 waves at 633 nm, and the roughness was 1 µm rms.

Table 2 Scraper specifications

Item	Parameter
Material:	Cu
Diameter:	3.500 in (+ 0 in, - 0.005 in)
Edge thickness:	0.500 in (+0 in, - 0.005 in)
Mirror figure:	10λ @ 632.8 nm
Surface roughness:	≤ 1 µm rms

Actuation of the scraper was on a modified "ultraviewer"; a linear insertion device that repeatedly maintains alignment of the pitch and yaw axes to better than 50 µrad. The outcoupled beam was in the horizontal plane, and intercepted into a diagnostic beam dump (a power meter with position sensing). Readout of the input and output temperatures is in our EPICS control system.

As mentioned earlier, as the mode traverses the scraper there will be diffraction, which after reflection from the end mirror does not pass through the scraper aperture but instead falls on the back of the scraper. Based on simulations, this amounts to ~ 10% of the intracavity power outcoupled by the scraper. This reflected laser light passed through an AR-coated viewport and was absorbed by a Molectron PM5K power probe. This system had a faster response time than the diagnostic beam dump.

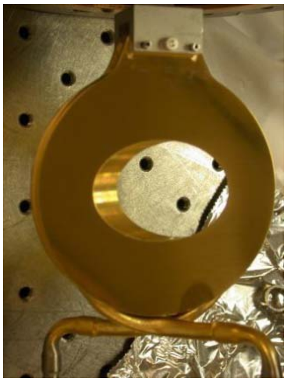

Figure 2 The scraper mirror. The mirror is moved in the vertical direction. At the bottom of the scraper is the cooling loop.

An IR camera imaged the surface. We could also use this radiation to study the laser dynamics. When operating in a macropulsed mode we could insert a mirror before the power probe and focus the light onto a Judson J15D12 cryogenically-cooled MCT detector.

RESULTS

Gain and loss measurements

Getting this system to lase was quite easy. In macropulsed mode, the output from the MCT detector (Fig. 3) was used to optimize the system.

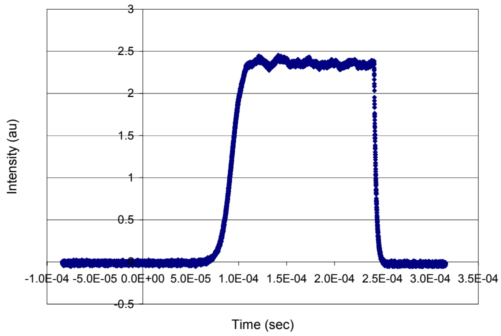

Figure 3 FEL output during a 250 µs macropulse.

We recorded the rise and decay of the macropulsed output at higher resolution to determine the gain and loss. This is shown in Figs 4 and 5, respectively.

Analysis of the FEL output's rise and fall allowed us to determine the gain and loss/pass. These values are 16% and 8%, respectively. The error bar on the measurements is +/- 1%. The lower than calculated gain was unanticipated, since we had measured higher gain at this wavelength when operating the resonator with a transmissive outcoupler. We believe this was due to the accelerator setup.

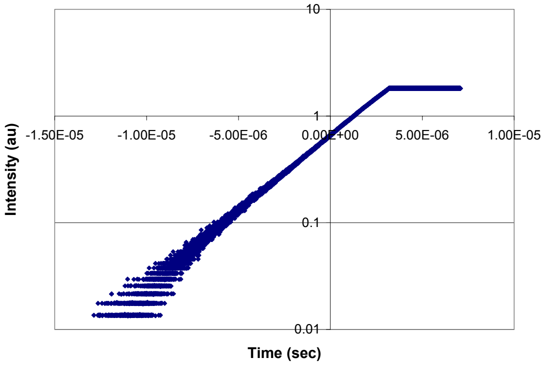

Figure 4 FEL start up

High average power operation

When operating at high average power, we found the power probe and IR camera was beneficial in optimizing the total output. Fig. 6 shows an image from the IR camera viewing the power probe.

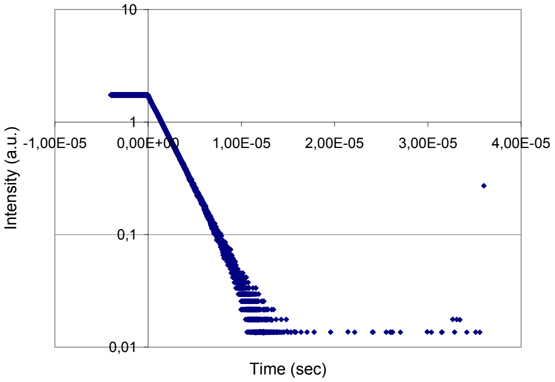

Figure 5 FEL decay

When operating at high average power, we found the power probe and IR camera was beneficial in optimizing the total output. Fig. 6 shows an image from the IR camera viewing the power probe.
So long as the image remained circular, the mirrors were well aligned and we had the highest output power - as measured on both the diagnostic dump and the diffracted light power probe. The highest power measured was ~1750 W, as inferred by measuring 139 W with the fast power probe, and using an experimentally determined ratio between the diffracted to outcoupled light of 1:12.5. A typical power trend is shown in Fig. 7. Once we were above 1 kW average power, note that each push up in power was rather short, only a few minutes in length. What was occurring was that both cavity mirrors would

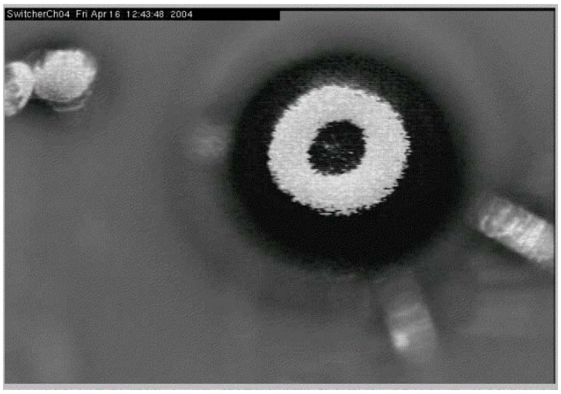

Figure 6 IR image of light reflecting from the rear of the scraper onto a power probe.

pitch as the mirrors absorbed power, and the cavity length would drift, first shorter, then longer. This made optimization problematic, and usually the cause of the laser shutting off was the cavity length. Once the laser was off, the mirrors would cool off and drift in the opposite direction. Fortunately, we were able to track this drift and could get the cavity realigned quickly.

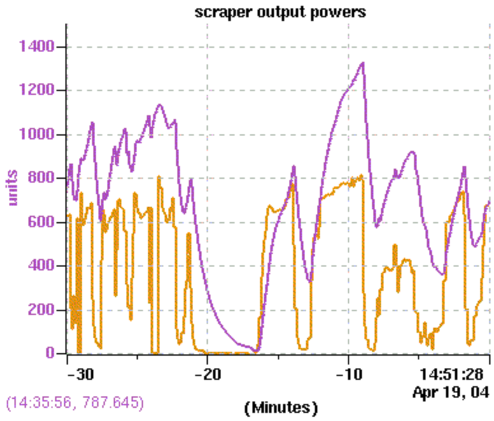

Figure 7 Power trends. The purple trace is the outcoupled light from the scraper. The yellow trace is the power from the diffracted light off the rear of the scraper (0-200W scale).

Why was this occurring? Subsequent to testing the scraper outcoupler, we added IR viewports and cameras that enabled us to image the interior of the optical cavity mirror vacuum vessels. What we found was that scattered light was scattered into a wide enough cone that it fell on the poorly cooled mirror fixturing hardware. These components warmed up and as they expanded, they caused the cavity length to grow longer. The more rapid shortening of the cavity length was the result of absorption of laser light (and in the case of the downstream mirror and its deforming assembly, THz and second harmonic light as well), that causes a thermal bump in the center of each mirror. The magnitude of this bump (for each mirror) is of order 1 um, and develops in the course of a few seconds, forcing us to initially lengthen the cavity. There were other signs that the scattered (and absorbed) light was excessive. We saw pressure transients (as measured by the ion pumps) that correlated with strong lasing. In addition, enough scattered light was absorbed in a calcium fluoride vacuum viewport situated just upstream of the wiggler (part of the OCMMS hardware [11]) that it shattered. Clearly, better control of scattered light needs to be in place. We are designing water-cooled absorbing shields that will be placed before the mirror plane to minimize the heating effects we saw. Treating the beam tube in the vicinity of the scraper, so it absorbs scattered light, is being contemplated as well.

We can determine the amount of power absorbed by measuring the flow rate and temperature rise in the water that cools each cavity mirror. When lasing with a power of 1500 W, the mirror upstream of the wiggler absorbed ~ 120 W, while the downstream mirror absorbed 310 W, the highest value we have ever measured. We were able to partially compensate for the thermal bump by actively deforming each mirror. Due to the high absorption (~ 1.7% of the intracavity power for the downstream mirror) the uncompensated aberration lowered the lasing efficiency to the point that we decided to pursue lasing at a shorter wavelength, where we had better mirrors. Much lower loss 10 µm HR mirrors (absorption < 300 ppm) are available, and we are procuring them.

Table 3 Comparison between optical modeling and experimental results

	Model	**Experiment**
Loss/pass	11%	8%
Outcoupled/diffracted power	10	12.5

CONCLUSIONS

We found that operation of a FEL in a scraper-outcoupled near-concentric cavity configuration lased easily, and produced stable output. Experimentally derived values for the loss and ratio of outcoupled to diffracted light were in good agreement (Table 3) with the values from our simulations. The outcoupling efficiency of 92% is much higher than obtainable with a hole-outcoupler mirror. We found that this cavity configuration, using two high reflectors with backplane cooling and active ROC control allowed us to outcouple ~ 1.75 kW. With a more conventional, edge-cooled transmissive outcoupler with 0.4% loss, we could only achieve 0.7 kW. If we had better mitigated the effects of scattered light, and had lower loss coatings, we would have easily achieved higher output powers. Clearly, this demonstration proves that the annular scraper outcoupler can be used to produce high average power in wavelength regions where substrate and/or coating absorption precludes the use of a transmissive outcoupler.

ACKNOWLEDGEMENT

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