IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

GAIN MEASUREMENT ON THE ACO STORAGE RING LASER

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We report the results of the first gain measurements on the free electron laser being assembled on the storage ring ACO. The largest measured peak gain, averaged over the laser mode, is $\hat{G} = 4.3 \times 10^{-4}$ per pass. No laser induced bunch lengthening is observed within the experimental accuracy of 50 psec under a laser intensity of 1.6 kw/cm² and under the conditions of strong anomalous bunch lengthening $(\sigma_\tau/\sigma_\tau(I=0)) = 6.8 - 4.2$.

Since the first operation of a Free Electron Laser at Stanford[1,2] in 1976 and 1977, a significant effort on the part of a number of groups worldwide has been applied to the development of the theory of the device. However, due to the scarcity of adequate quality high energy electron beam sources, the difficulties involved in working with such machines, and the consequent planning time involved in setting up an experiment, three years elapsed during which the explosive growth of our theoretical understanding remained unsupported by further experimental work[3].

The present work is a result of a LURE-Stanford collaboration undertaken in 1979 to build and examine the characteristics of a storage ring free electron laser on the storage ring ACO[4]. A 23 period superconducting undulator with a 4 cm wavelength and 4 kg design field[5] was at that time under construction. The undulator was mounted on ACO in the straight section as shown in Fig. 1, and the characteristics of the spontaneous emission were measured[6] both at the injection energy, 240 Mev, and at 150 Mev. In this paper, we report the measurement of the gain of the storage ring laser in the visible region of the spectrum. (We are informed of a similar experiment on VEPP 3 in Novosibirsk, which apparently has yielded inconclusive results).

In view of the small gain anticipated for the ACO system, the gain measurement apparatus has been designed to have a signal-to-noise ratio unity for a peak gain of 3×10^{-6}. Since the low current bunch length in ACO is .21 nsec (FWHM) at 150 Mev while the orbit time is $T_o = 73.3$ nsec, this implies unity signal-to-noise for a mean gain of 10^{-8}, a performance exceeded by our present apparatus.

The experimental layout is shown in Fig. 2. A linear polarized CW argon laser operating at either 4880 A° or 5145 A° is focussed to a waist in the center of the undulator with its direction of propagation aligned along the axis of the electron beam. A portion of the laser beam is amplified each time a stored electron bunch passes through the undulator. The amplified beam is focussed on a detector, and a signal is observed with a synchronous detector at either 13.6 or 27.3 MHz according to the number of bunches stored in ACO at the time. The spontaneous radiation[6] emitted by the electrons has the same time structure as the gain, but is typically orders of magnitude larger. To eliminate the spontaneous signal, the laser is chopped at low frequency, and the difference signal, which is proportional to the gain only, is extracted by a second synchronous detector. The energy of ACO is then swept across the resonance energy, and the antisymmetric gain curve is observed.

The detector is coupled to a resonant 10-1 impedance transformer to reduce the noise bandwidth at the preamp and increase the sensitivity of the system at the signal frequency. The RF signal is then amplified and mixed with a reference signal generated from the frequency synthesizer which drives the ACO RF cavity. It is filtered at 100 Hz with a band pass filter, and the gain signal is extracted and filtered in a lock-in amplifier slaved to the chopper. A second, low frequency signal proportional to the total incident power is extracted from the bias circuit of the diode, and used to calibrate the system.

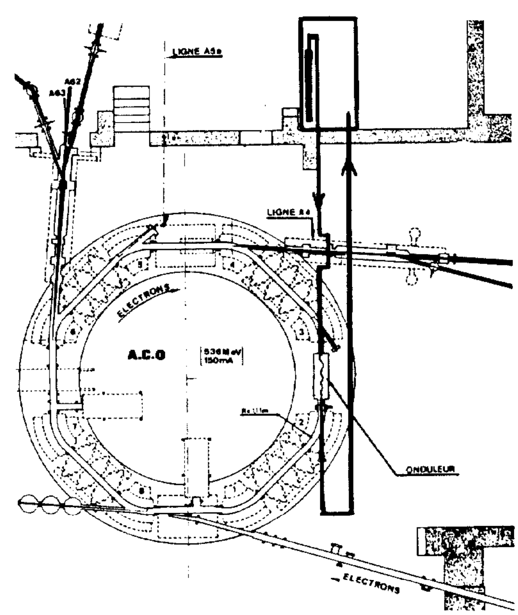

Figure 1 :
Placement of undulator and gain measurement beam lines.

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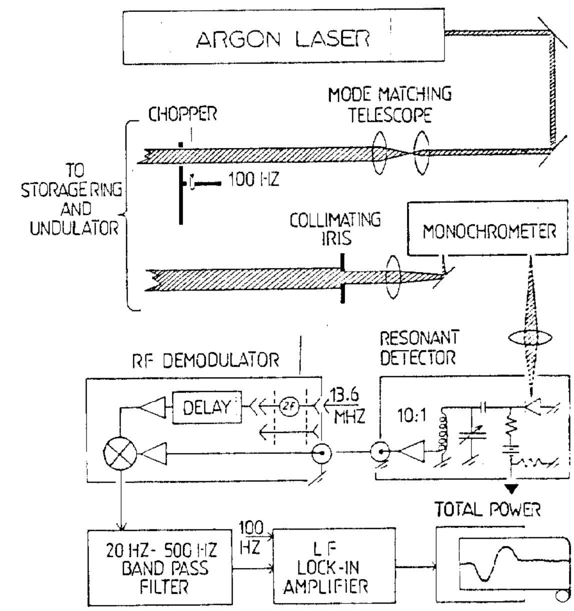

Figure 2 : Simplified schematic diagram of experiment.

The detector is a 350 MHz photoconductive silicon diode. The diodes renders the system susceptible to a peculiar kind of feedthrough which must be avoided. The argon laser, by far the largest signal impinging on the diode, creates a large number of carriers in the depletion zone, modulating the impedance of the diode in phase with the chopper. The spontaneous radiation, the next largest signal, and already in phase with the RF, produces a small signal modulated at the chopper frequency due to the impedance modulation, and appears as a distortion in the gain measurement. Fortunately, it is possible to separate the gain signal from the spontaneous feedthrough by their opposite symmetries about the resonance energy. The small symmetric distortion evident in the gain signal of Fig. 3 is the residual effect of this feedthrough. In future experiments, it is planned to use a vacuum photodiode which is not susceptible to impedance modulation if the space charge limited region is avoided.

It is important to reduce the ratio of the spontaneous to the gain signal power received at the detector in order to reduce feedthrough and avoid saturation on the mixer in the high frequency synchronous detector. Two means exist to accomplish this goal.

The spontaneous emission half angle for the laser frequency at the $1/e^2$ point

$$\theta_s = \frac{1}{\gamma}\sqrt{\frac{2.2}{N\pi}\left(1 + \frac{K^2}{2}\right)} \qquad (1)$$

is typically larger than the laser divergence angle $\theta_l = \lambda/\pi w_0$ where $\gamma = E/mc^2$ is the reduced electron energy, N is the number of magnet periods, $K = eB/mc^2q$, B is the undulator magnetic field amplitude, $q = 2\pi/\lambda_0$ is the undulator wave number, λ is the laser wavelength and w_0 is the laser beam radius parameter ($E = {}^{0}E_0 \exp(-r^2/w_0{}^2)$).

An iris placed in the far field of the interaction region and aligned to the laser axis is closed down on the laser mode to take advantage of the beam size difference, reducing the spontaneous-to-gain power ratio by the factor 13.

Since the laser bandwidth is extremely narrow, use of a monochromator to filter the spontaneous radiation from the unwanted frequency bands results in a further improvement limited only by the the resolution $\Delta\lambda$ of the monochrometer to $(\Delta\lambda/\lambda)N$, producing another factor of 70 on the power ratio.

The detection system is calibrated with the synchrotron radiation produced in the fringing fields of the two adjacent dipole magnets which is captured in the optical transport system used for the gain measurement. This beam is chopped creating a signal that mimics the time structure of the gain, and a signal V^o_{RF} is observed through the detection system. At the same time, the total incident power at 100 Hz produces the signal level V^o_{LF} at the output of a low frequency lock-in. In this case, we know that the power seen by the RF system is equal to the total incident power. A measured RF signal V_{RF} corresponds, according to our calibration, to a total amplified power in the LF port of $(V_{RF}/V^o_{RF})V^o_{LF}$. The average gain $\bar{G}$ of the FEL amplifier is then the ratio of the total amplified power to the total laser power V_{LF}

$$\bar{G} = \frac{V_{RF}}{V^o_{RF}} \frac{V^o_{LF}}{V_{LF}} \qquad (2)$$

The instantaneous peak gain averaged over the laser mode is then

$$\hat{G} = \bar{G}\,\frac{T_o}{mT}\sqrt{\frac{4\ln 2}{\pi}} \qquad (3)$$

where m is the number of bunches stored, T is the full bunch length at half maximum, and where a Gaussian bunch shape has been assumed.

Alignment is carried out with the aid of the directional characteristics of the spontaneous radiation of the undulator. An iris is placed immediately at the exit window of the vacuum chamber, and aligned to the axis of the beam in the undulator by centering it on the clearly visible annular structure of the radiation[6]. Closing down this aperture forms the spontaneous radiation into a narrow blue or green beam following the axis of the electron beam. A second iris is then aligned to this beam near the detector, and the argon laser is adjusted to pass through the two irises. We estimate the alignment accuracy obtained by this technique to be very good in angle : $\pm$ 40 μrad, but rather lacking in the transverse location of the laser beam waist on the electron beam : ± .3 mm. Since this latter error is somewhat larger than the root mean square transverse dimension of the electron beam, a rather large scatter is observed in the measured gain. The final alignment proceedure would be a small adjustment of the laser transverse position with a distant mirror so that the angle remains within the acceptance (1). This step, which has not yet been done due to the lack of differential micrometers for beam steering, can only be accomplished using the gain signal itself as diagnostic.

In order to obtain the results shown in this paper, it was necessary to modify ACO so that its operation would be stable at 150 Mev, 40% lower than the design energy. An old set of sextupoles has been brought into

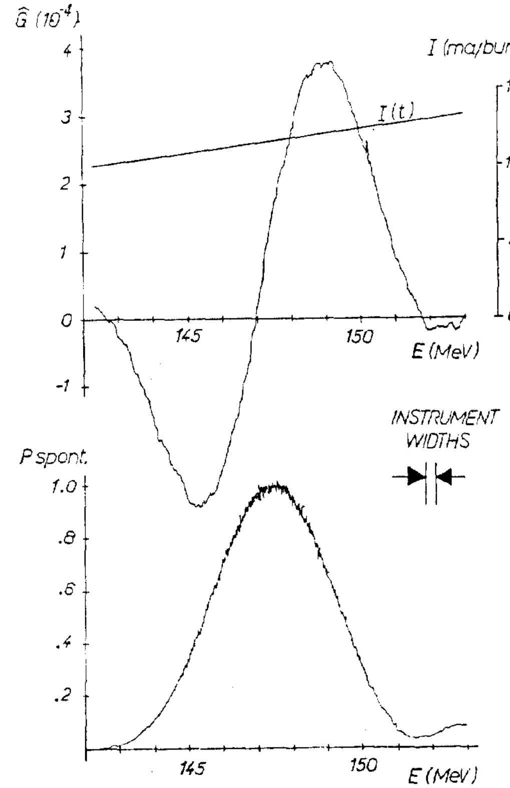

Figure 3 : Gain and spontaneous spectrum vs energy.

operation to annul the chromaticity, and the machine's optical characteristics have been recalibrated. Nonetheless, it has been found to be extremely difficult to store large amounts of current at low energy. In a typical injection cycle, 150 ma/bunch will be injected at 240 Mev, 40 ma will remain after the reduction of the energy, during which the sextupoles are controlled by hand, and 10 ma will remain to be utilized due to the poor lifetime after the undulator has been lowered and turned on. Steps are being taken to increase the lifetime of the beam in the undulator, caused in part by a poor vacuum, and to retain more current for use in the experiments.

A series of measurements performed at two visible wavelengths and three values of magnetic field are summarized in Table 1. Figure 3 shows the gain trace obtained on injection 7 of 9/28, along with the associated spontaneous emission trace taken from the RF demodulator. The superimposed trace of current vs. time shows a lifetime of 9 min, obviously a handicap in obtaining the data.

Both curves are approximately 40% broader than predicted. Magnetic field measurements indicate an S shaped deformation of the central electron trajectory in the undulator, which appears to explain this effect[7]. If this additional broadening is taken into account, the measured gain confirms very closely to the theory[8].

A series of measurements of the laser bunch lengthening was also performed during runs 7, 8 and 9 of 9/28. While the electrons were subjected to intensities up to 1.6 kw/cm^2, no effect was observed within the experimental error of 50 psec. The alignment problem does not explain the total absence of an effect[8]. A more likely explanation is that the effect was hidden in the response of the other bunch lengthening mechanisms to the incipient charge density reduction entailed by the laser heating process. The anomalous bunch lengthening observed during the measurements lay in the range $(\sigma_\tau / \sigma_\tau$ (I=0)) = 6.8 - 4.2.

TABLE 1

Injection	λ(A°)	K	$\overline{G}$(10^{-6})	$\hat{G}$(10^{-4})	I(ma/bunch)
4 (9/80)	4880	1.49	.2	.3	1.6
6	"	"	7.3	4.3	9.6
"	"	"	5.1	3.6	6.8
7	"	"	7.4	3.8	12.2
8	4880	1.72	2.4	1.0	18.
"	"	"	1.4	.8	10.6
"	"	"	.7	.8	3.0
9	"	"	3.8	2.1	10.0
"	"	"	2.9	1.9	7.6
10	5145	1.72	1.2	.6	11.2
5 (11/80)	4880	1.59	.62	.26	5.0

To obtain oscillation at these extremely small gains would require the acquisition and preservation of a set of truly exceptional cavity mirrors. The gain can be increased through the use of an optical klystron[9] in the place of the present undulator, and work is now under way to accomplish this. The gain apparatus will be required as a diagnostic for any forseeable storage ring laser operation, and it is being prepared, as much as possible, for routine use.

It is a pleasure to acknowledge the frequent help of the DCI storage ring physics group, and the LURE staff. This work has been supported by the DGRST, Contract 79-7-1063, the DRET, Contract 79-073, and the AFOSR, Contract F49620-80-C-0068.

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