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# FREE ELECTRON LASER EXPERIMENT at the NSLS 700 MeV ELECTRON STORAGE RING*

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## Abstract

A free electron laser experiment is described, to be performed with the 700 MeV electron storage ring of the National Synchrotron Light Source. The experiment is designed to study the parameters of the fel in an electron storage ring and the performance of this laser as a source of short wavelength radiation in the VUV region of the spectrum. The initial experiment will be carried out at a wave length of approximately 3000 Å, utilizing a permanent magnet undulator. For an average electron current of 1A distributed in three beam bunches, the small signal gain per pass (relative enhancement of the radiation intensity per electron bunch pass through the undulator) is calculated to be approximately 10%.

## 1. Introduction

An experiment test to prove the feasibility of a free electron laser (fel) in the ultra-violet, using the high energy beam of an electron storage ring is currently being prepared at the VUV-ring of the National Synchrotron Light Source.[1]

While the feasibility of a fel in which the electrons interact only once with the laser field has been shown by the Stanford experiment,[2] the case of a fel-storage ring system still lacks adequate experimental substantiation. Experiments are now in progress at Orsay[3] and Frascati.[4] The present experiment differs from these because of the larger current and current density available at The NSLS VUV-Storage ring thereby providing for larger values of the fel small signal gain over a large region of wavelengths

In the present experiment, it is intended to study in particular the following effects:
1. Increase of the electron energy spread and bunch length in the storage ring due to the interaction with the fel field, with corresponding limitation on the laser power. 2. Fluctuations in the emission of radiated photons at low laser power, particularly important at short wavelengths.

The experiment may lead to the optimization of parameters for a free electron laser and to the design of a dedicated storage ring to produce high intensity radiation in the very short wavelength region of far-UV to soft-X-rays.

## 2. Basic Fel Physics[5]

In a free electron laser, a beam of relativistic electrons of energy $\gamma$ enters an undulator magnet together with a laser beam of wavelength $\lambda$. We assume $\gamma$ to be near to a "resonant energy" $\gamma_r$ defined by

$$\lambda = \frac{\lambda_w}{2\gamma_r^2}\left(1 + k^2\right) \tag{1}$$

where $\lambda_w$ is the period of the undulator and k, the undulator parameter, is given by

$$k = \frac{e}{2\pi mc}\,\lambda_w \langle B\rangle \tag{2}$$

$\langle B\rangle$ being the r.m.s. field in the undulator.

In the undulator field, which in the electron rest frame appears as an incoming electromagnetic wave of wavelength near to $\lambda$, stimulated scattering takes place, with the result that the incoming laser beam is amplified at the expenses of the electron energy. Moreover, if an optical cavity is placed around the undulator, continuous amplifications of the radiation produced spontaneously by earlier electrons may result in a free electron laser oscillator.

The maximum gain per pass for a monochromatic electron beam, defined as the maximum relative amplification per pass of the radiation through the undulator, in the small signal limit, is given by

$$G_o\ (\%) = 0.184\,\frac{\lambda_w^{1/2}\lambda^{3/2}}{\Sigma}\, I_p\, \frac{k^2}{\left(1+k^2\right)^{3/2}}\, N^3 \tag{3}$$

Where $\Sigma$ is the transverse beam cross-section, $I_p$ the beam peak current and N the number of periods in the undulator.

With increasing electron energy spread and bunch length, the gain decreases until it becomes zero when the energy spread is of the order of $\frac{1}{2N}$. The effect on the gain and on the laser power of the electron beam-radiation field interaction in a storage ring has been studied theoretically by Renieri,[6] who has shown that the increase of the energy spread can be counterbalanced by the synchrotron radiation damping, and that it should be possible to obtain a steady state condition in which the laser power is related to the total synchrotron radiation loss in the storage ring, $U_o$, by

$$P = \frac{U_o I_o}{2N} \tag{4}$$

where $I_o$ is the average beam current in the storage ring.

The linewidth of the oscillator fel is determined by the length $2\sigma_{\parallel}$ of the electron bunches. It is

$$\frac{\delta\omega}{\omega} = \frac{\lambda}{\sigma_{\parallel}} \tag{5}$$

## 3. Layout of the Experiment

The fel experiment will be set up in one of the long straight sections of the VUV-storage ring of the National Synchrotron Light Source. It is the intent to carry the experiment out in two stages:

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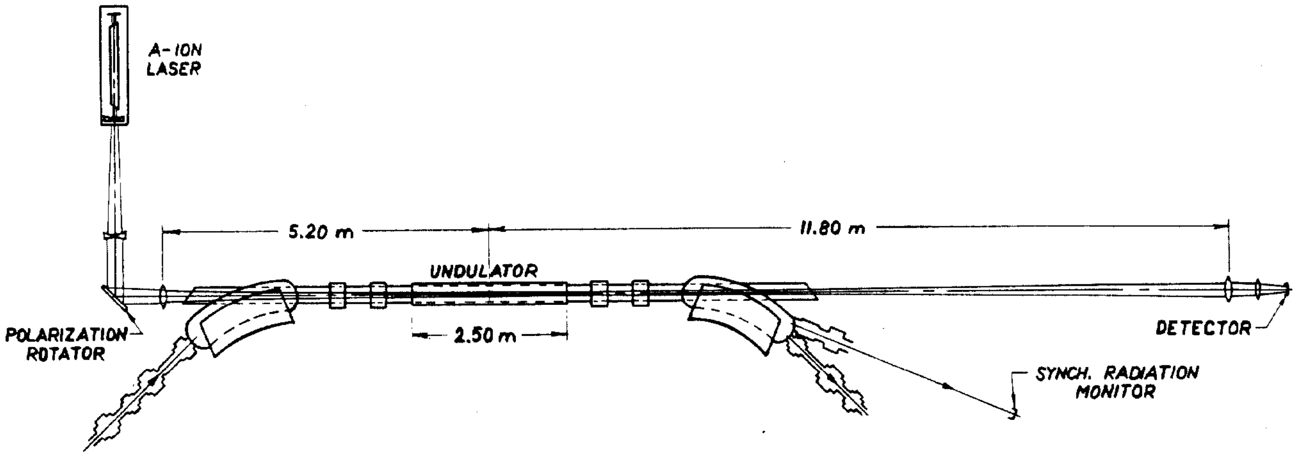


Figure 1. Schematic Layout for the fel Amplifier Experiment.

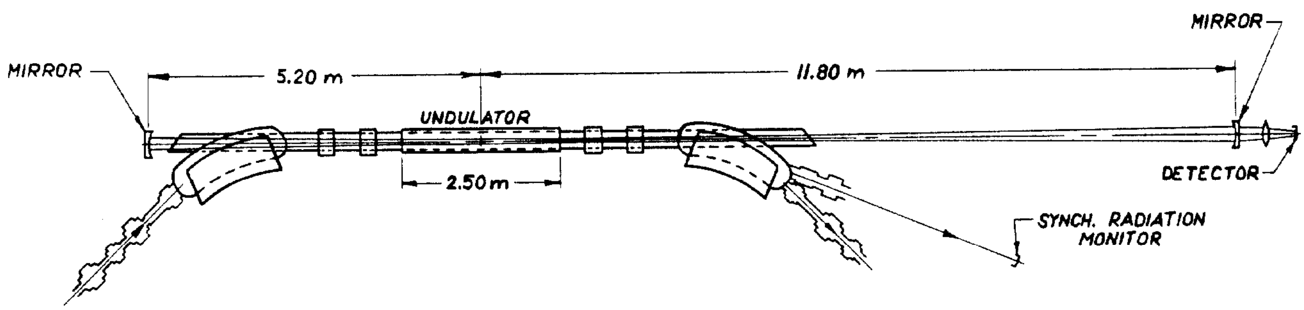


Figure 2. Schematic Layout for the fel Oscillator Experiment.

1. Amplifier experiment, in which an external CW ultra-violet laser will be employed to measure the gain. 2. Oscillator experiment.

Figures 1 and 2 show the arrangement of the various components in the VUV storage ring area.

In Table 1 we give some of the storage ring and associated electron beam parameters which are of interest for the experiment. The beam properties are given at 500 MeV, although it is planned to vary the energy between 300 and 500 MeV.

Table 1. VUV Storage Ring Parameters.

| | |
|---|---|
| Ring circumference | 51 m |
| Energy | 300 ÷ 500 MeV |
| No. of bunches | 3 |
| Average beam current | 1 A |
| Peak current per bunch | 108 A |
| Bunch length, $2\sigma_{\parallel}$ | 12 cm |
| Transv. beam cross-section, $\Sigma$ | .153 $mm^2$ |
| Sy. rad. energy loss, per turn, $U_0$ | 0.41 ÷ 3.2 KeV |
| Energy spread acceptance | ± 1.5% |

The undulator is a permanent magnet structure, with variable gap. Its characteristics are given in Table 2.

Table 2. Undulator Parameters.[7]

| | |
|---|---|
| Permanent Magnets | Rare-Earth-Cobalt(Rec) |
| Period, $\lambda_w$ | 6.5 cm |
| No. of periods, N | 38 |
| Full gap, g | 1 ÷ 6 cm |
| Max. field on median plane, $B_o$ | 0.7 ÷ 0.1 Tesla |
| Pole transverse width | 5 cm |

The undulator will be inserted in the high vacuum of the accelerating chamber, boxed in a thin-walled enclosure maintained to a lesser vacuum. This permits the smallest magnetic gap required for operation of the fel in the longer wavelength regions of the spectrum. A range of wavelength values will be available, in accordance with Equations (1) and (2), by adjustment of the gap g, and hence of k, and by varying the energy of the electrons.

The choice of a permanent magnet undulator limits the maximum field obtainable, compared to a superconducting undulator with the same field period. However, it provides for greater ease of operation and for greater simplicity to change the magnetic field configuration by rearranging part of the undulator structure with the objective, at a later stage, to test the Optical Klystron concept,[8] that could further increase the gain.

The optical cavity for the oscillator experiment must have a length equal to an integer multiple of half the distance between successive electron bunches in the storage ring, namely 8.5 m. The geometry of the ring did not readily allow for a 8.5 m long cavity, hence we have chosen 17 m as the cavity length. With this arrangement, two photon bunches will travel at the same time in the optical cavity between the mirrors, interacting at each passage through the undulator with every second electron bunch moving in the same direction. Clearly, in this case the cavity should have its center properly positioned to avoid head-on electron-photon collisions that would result in the production of high energy photons.[9]

For the amplifier experiment, using an external laser, the optical beam will be shaped in the interaction region, by means of lenses, in the same way as for the oscillator.

Optical design parameters for the oscillator cavity are given in Table 3.

Table 3. Fel Oscillator Optics.[10]

| | |
|---|---|
| Cavity length, $L_c$ | 17 m |
| Concave mirror radii | 5.50 & 11.93 m |
| Mirror locations from undulator center | 5.20 & 11.80 m |
| Waist size at undulator center, $w_o$ | 0.374 mm |
| Expected cavity losses at 3510 Å | 2% |

With the data of Tables 1 ÷ 3 and Equations (1) · (5), fel performance parameters as given in Table 4 are expected.

Table 4. Fel Expected Performances.

| | |
|---|---|
| Wavelength, $\lambda$ | 2500 ÷ 4500 Å |
| Small signal gain, $G_o$ | 6 ÷ 18 % |
| Saturated power (Oscillator), P | 5 ÷ 15 Watt |
| Line width, $\frac{\delta\omega}{\omega}$ | $10^{-6}$ |

Some values of the electron energy and of the small signal gain, for three values of the undulator parameter k, vs. laser wavelength are presented in Figure 3, where the assumption is made that the average beam current is 1 A, independent of electron energy.

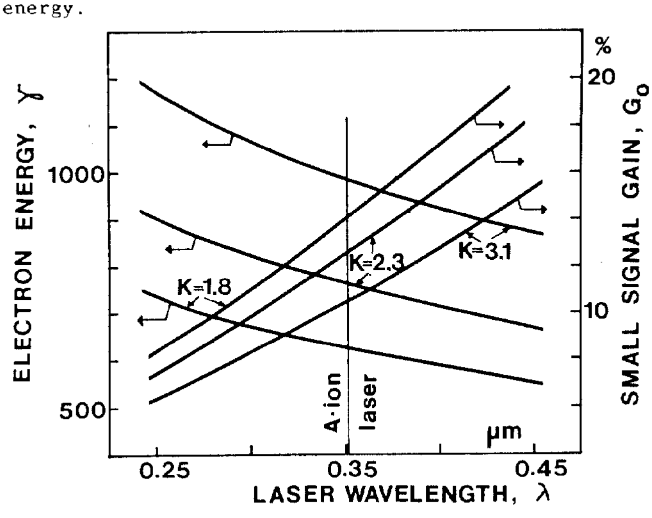


Figure 3. Electron energy, $\gamma$, and small signal gain, $G_o$, vs. wavelength, $\lambda$, for three values of k.

## 4. Experiment Status

Basic design for the fel experiment has been completed, detailed design of the undulator and optical cavity and acquisition of optical hardware, minicomputer control and data collection system is in program. It is expected to complete the assembly, test and calibration of all components during the current year and the first half of 1982, with the intent to start the amplifier and subsequently the oscillator experiment in the second half of 1982.

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