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Proposed ultraviolet free-electron laser at Brookhaven National Laboratory: a source for time-resolved biochemical spectroscopy

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Erik D. Johnson[‡*], William R. Laws[§] and John C. Sutherland[†]
National Synchrotron Light Source[‡] and Biology Department[†]
Brookhaven National Laboratory and the
Department of Biochemistry, Mount Sinai School of Medicine[§]

ABSTRACT

Brookhaven National Laboratory is designing an ultraviolet free-electron laser (UV-FEL) user facility that will provide pico-second and sub-picosecond pulses of coherent ultraviolet radiation for wavelengths from 300 to 75 nm. Pulse width will be variable from about 7 ps to ≈200 fs, with repetition rates as high as 10^4 Hz, single pulse energies >1 mJ and hence peak pulse power >200 MW and average beam power >10 W. The facility will be capable of "pump-probe" experiments utilizing the FEL radiation with: 1) synchronized auxiliary lasers, 2) a second, independently tunable FEL beam, or 3) broad-spectrum, high-intensity x-rays from the adjacent National Synchrotron Light Source. The UV-FEL consists of a high repetition rate recirculating superconducting linear accelerator which feeds pulses of electrons to two magnetic wigglers. Within these two devices, photons from tunable "conventional" lasers would be frequency multiplied and amplified. By synchronously tuning the seed laser and modulating the energy of the electron beam, tuning of as much as 60% in wavelength is possible between alternating pulses supplied to different experimental stations, with Fourier transform limited resolution. Thus, up to four independent experiments may operate at one time, each with independent control of the wavelength and pulse duration. The UV-FEL will make possible new avenues of inquiry in time resolved studies of diverse fields including chemical, surface, and solid state physics, biology and materials science. The experimental area is scheduled to include a station dedicated to biological research. The complement of experimental and support facilities required by the biology station will be determined by the interests of the user community.

1 Introduction

The proposal for a UV-FEL grew from the realization that neither existing lasers or synchrotrons, nor the third generation synchrotron radiation sources now under construction address all of the needs of scientists interested in the ultraviolet region of the spectrum, particularly the combination of continuous wavelength selection, high peak power and short pulse duration. Figure 1 summarizes the peak power of proposed and existing sources over 9 decades in wavelength. Several workshops have explored applications and source requirements in the 5 to 30 eV range.

A critical requirement is for very high peak power and short wavelength, especially for applications in chemical physics and non-linear optics [1]. The need for wavelength tuning with the ease and agility to which synchrotron radiation users have become accustomed was also strongly emphasized [1]. With these initial parameters in mind, the accelerator physics staff set about devising ways to produce this radiation [2]. Their design is for an FEL that has unique characteristics both in terms of possible applications, and in the range of radiation it could produce. In addition, the proposed location of the UV-FEL adjacent to the NSLS means that pump-probe experiments involving radiation from both sources will be possible. Each successive design has been reviewed in consultation with potential users in an iterative process to arrive at the design described in this paper.

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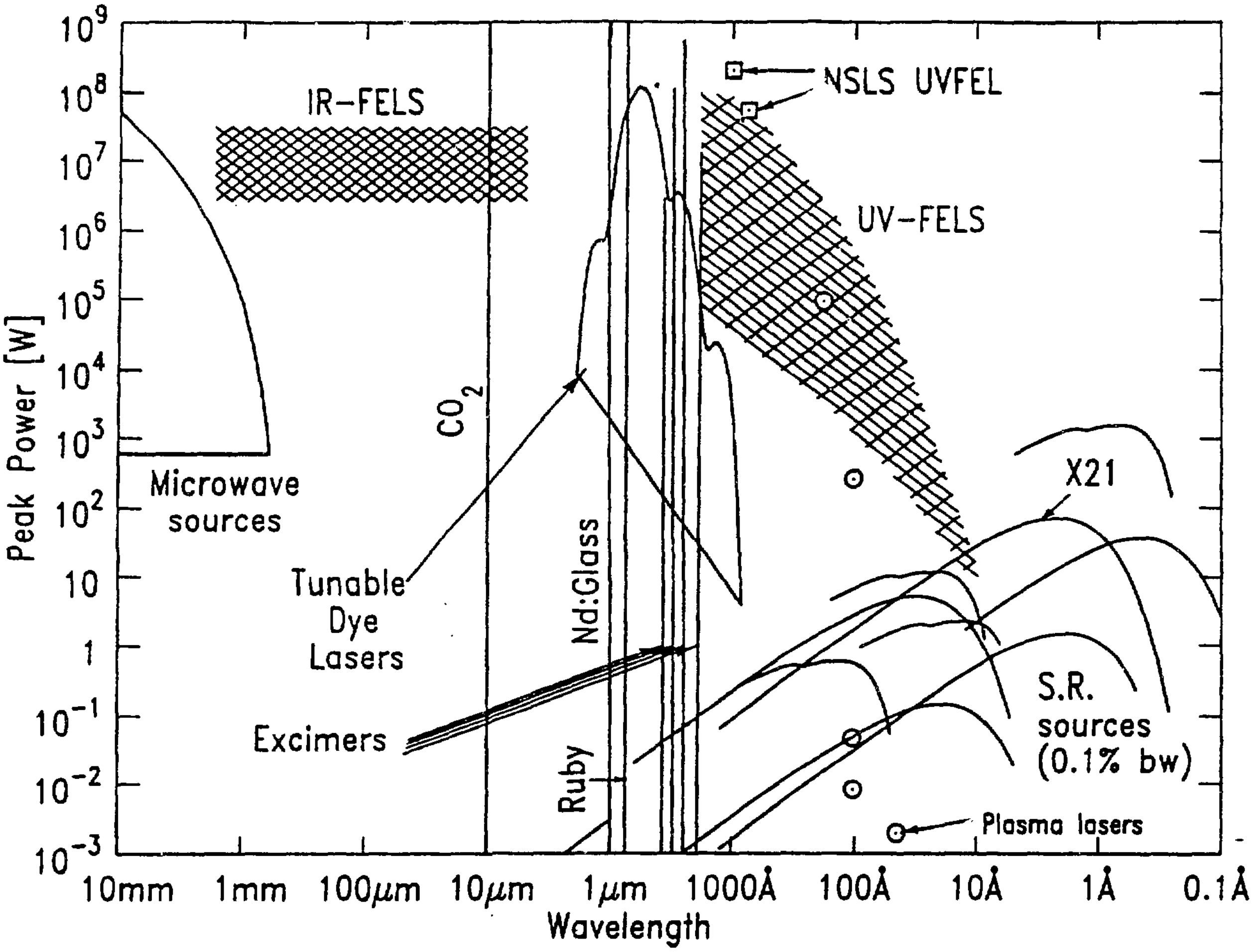

Figure 1. Comparison of Peak Power as a function of wavelength for existing and proposed radiation sources. Note the points for the NSLS UV-FEL described in this work, and the output curve for the X-21 wiggler which can be used in "pump-probe" experiments with the FEL. (Figure modified from reference 1.)

2 Basic Facility Description

To provide the peak power ($\approx 10^8$ Watts), wavelength tunability, and short pulse length (≤ 6 ps) required by many of the proposed experiments, a free electron laser (FEL) seemed the only choice. Because of the short wavelengths desired, a resonator scheme was deemed impractical, so a laser seeded single pass design was developed [3]. Overviews of the machine physics have appeared previously [3,4], while the detailed design study is provided in the conceptual design report [5], including not only the FEL, but the transport optics and experimental equipment required to perform the proposed experiments for the initial design. Figure 2 shows the layout of the accelerator.

The FEL utilizes the radiation of a conventional laser with a wavelength of e.g. 300 nm to energy modulate an electron beam inside a short periodic magnetic structure (wiggler) also resonant to 300 nm radiation. The energy modulation of the beam is converted into spatial bunching in a dispersive magnetic device which also introduces a strong third harmonic component at 100 nm. This beam of electrons enters a long wiggler resonant to 100 nm where the interaction between the electron beam and the wiggler results in coherent generation of e.g. 100 nm radiation followed by an exponential growth in intensity. The energy in the photon beam is extracted from the electron beam as they travel down the wiggler together. The loss of electron beam energy would spoil resonance condition and cause the photon beam intensity to saturate, in effect limiting the gain of the device. This effect can, however, be compensated by introducing tapering of the magnetic field in the last section of the wiggler to obtain the maximum possible energy extraction from the overall device. By synchronously changing the energy of the electron beam and the wavelength of the input seed laser, wavelength tuning of the output radiation is possible.

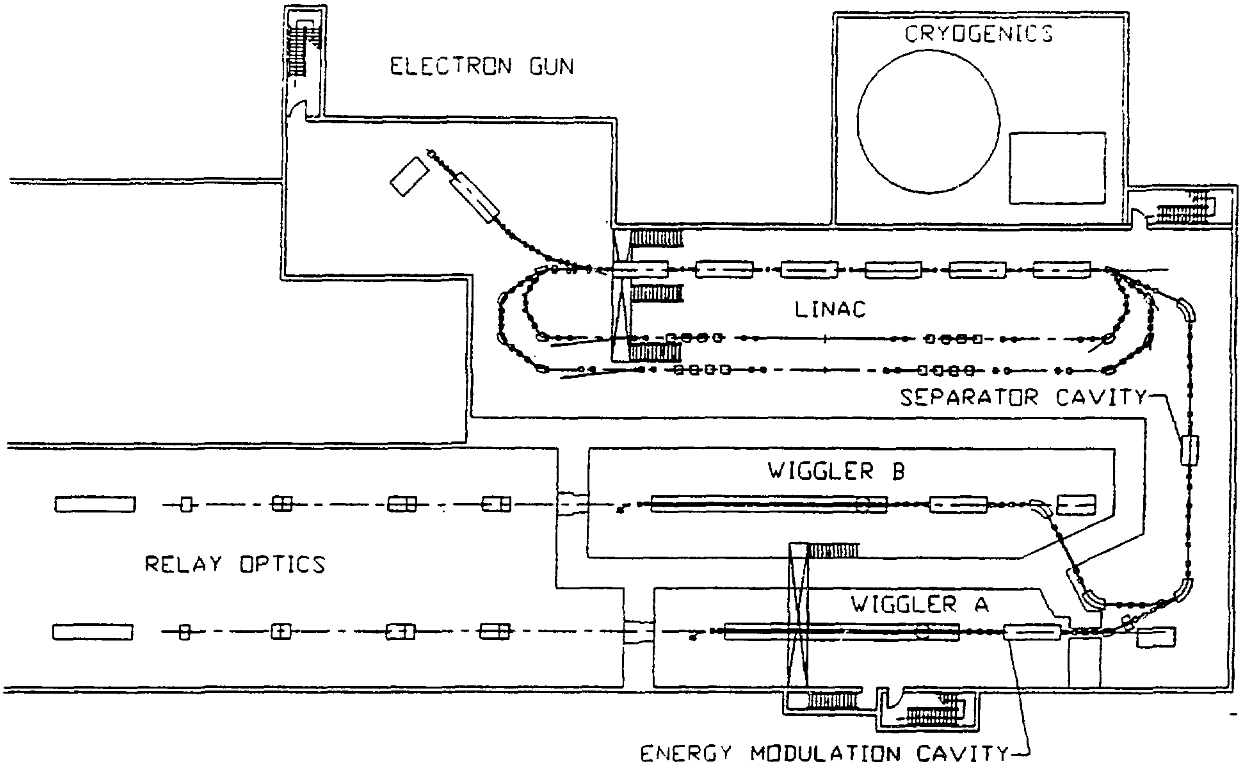

Figure 2. Plan view of accelerator components which are below grade level. The large wiggler magnets are 15 m long.

The electrons for the FEL are generated by a high repetition rate (10 kHz) laser photo-cathode electron gun which provides intense picosecond electron bunches (ca. 1-2 nC) that are further accelerated by a super-conducting linac with two recirculations, resulting in electron beams with energies as high as 285 MeV for the FEL. However, many pump-probe experiments employing conventional auxiliary lasers cannot fully utilize all of the output of the FEL since the repetition rates of these lasers are seldom greater than 1 kHz. Thus, the design provides for electron and photon beam multiplexing that allows for switching of alternating pulses between several users. The design employs two wigglers, and an extra energy modulating radio frequency cavity to separate two electron pulses at a septum magnet. Each wiggler can serve several users by switching of the optical beam.

Since each user could require different wavelength radiation for their experiment, additional radio frequency (rf) cavities were added before each wiggler to modulate the electron beam energy. By using several seed lasers coupled to the FEL through an optical switchyard, each user could control the tuning of their respective seed laser and, in concert with the energy modulation provided by the rf cavities, control the wavelength of the radiation delivered to the experiment. This arrangement allows the radiation from the FEL to be shared among up to four independent experimental stations simultaneously. A layout of the experimental area consisting of eight user laboratories is shown in figure 3.

The central feature of the proposed UV-FEL is the technology to produce a high quality electron beam, with the potential for a very high duty factor afforded by a superconducting linac. The UV-FEL itself uses only a small fraction of the possible duty cycle of the electron linac, so additional possible uses for the electron beam, including a high power infra-red FEL and the production of pulsed positrons, are currently under consideration.

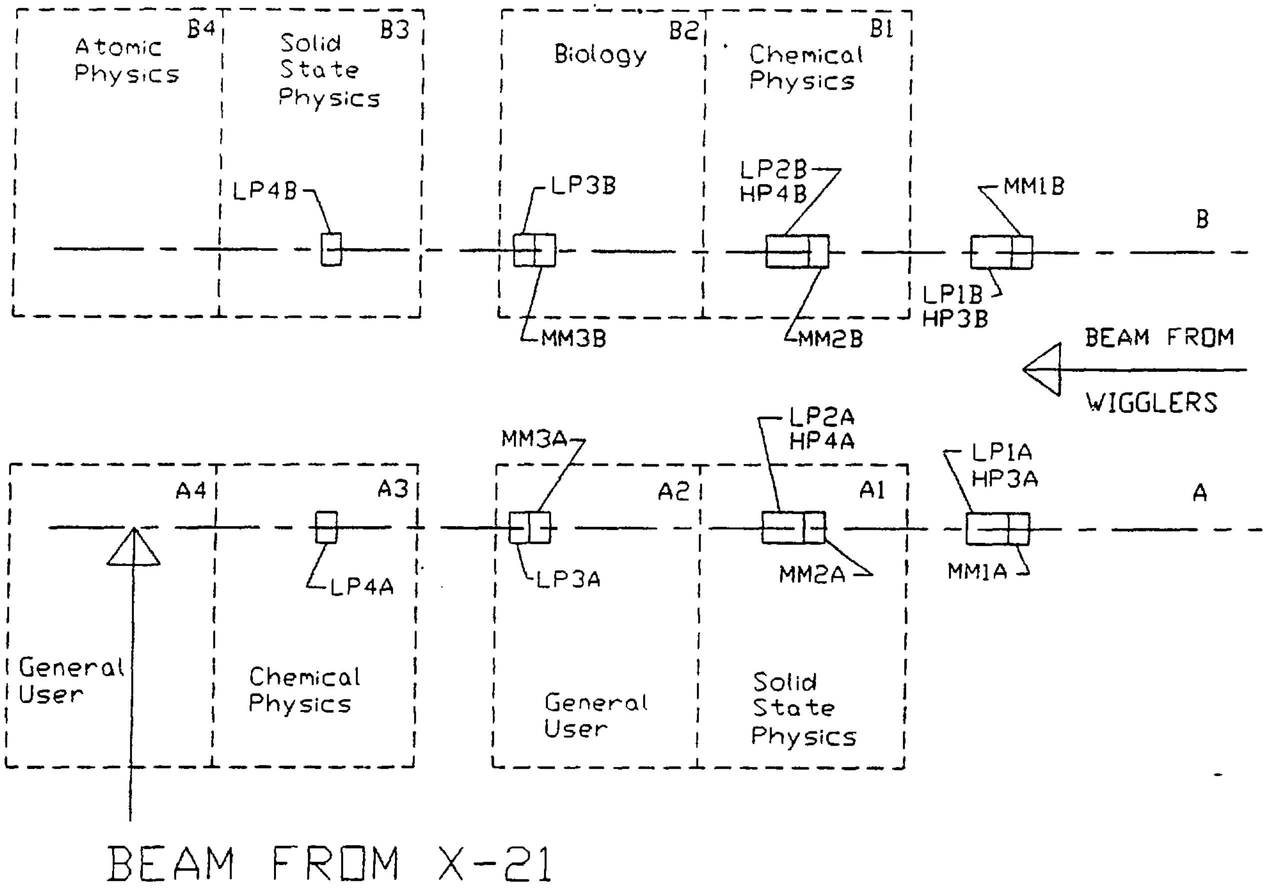

Figure 3. Plan view of laboratory space. The optical systems to relay the radiation to the laboratories are located below grade level, with the radiation deflected up to the user laboratories by mirrors (see section 3). The user laboratories are roughly 6 by 13 m.

3 Opportunities for experiments

To provide efficient use of the FEL output, an optical system has been devised which allows the photon beam to be relayed to several laboratories. The system takes advantage of the characteristics of the FEL radiation, and the placement of the laboratory space roughly 4.1 m above the accelerator. Four laboratories are served directly by each wiggler line. Parabolic mirrors are used to deflect the radiation up to the laboratories, and focus at the experimental station. The beam can be redirected to the horizontal plane and the focus modified by use of a Kirkpatrick-Biaez pair of mirrors. The parabolic focusing mirrors are mounted on manipulators so they can either be placed in the FEL beam, or removed so the light can be relayed on to the next experimental station. In this mode each FEL serves only one user at a time. Another optical system is under development which allows the beam to be multiplexed from pulse to pulse between each of the four users of a particular wiggler.

This is accomplished by interposing a pair of flat mirrors which are mounted in a rotating holder, shown schematically in figure 4. The incidence angle on these mirrors is only five degrees, so down to 50 nm the loss introduced by these mirrors is minimal. The mirrors are placed so that they produce a net vertical offset. The parabolic mirror can be lowered into the displaced beam and the radiation delivered to the experiment as previously described. The multiplexing mirrors can also be rotated so the FEL beam passes on to the next station to intercept either another multiplexing mirror or a stationary parabolic mirror. An arrangement of four pairs of mirrors mounted in a cylinder as shown needs to rotate at 37,500 RPM to provide a switching rate of 5 kHz, well within demonstrated limits for UHV rotating machinery. Each user of the system can select the desired wavelength by optical switching of their own FEL seed laser, and programming of the energy modulating cavities prior to the wiggler. In addition to selecting the energy of the FEL radiation, the user could control the pulse duration of their seed laser, and hence the duration of the FEL radiation.

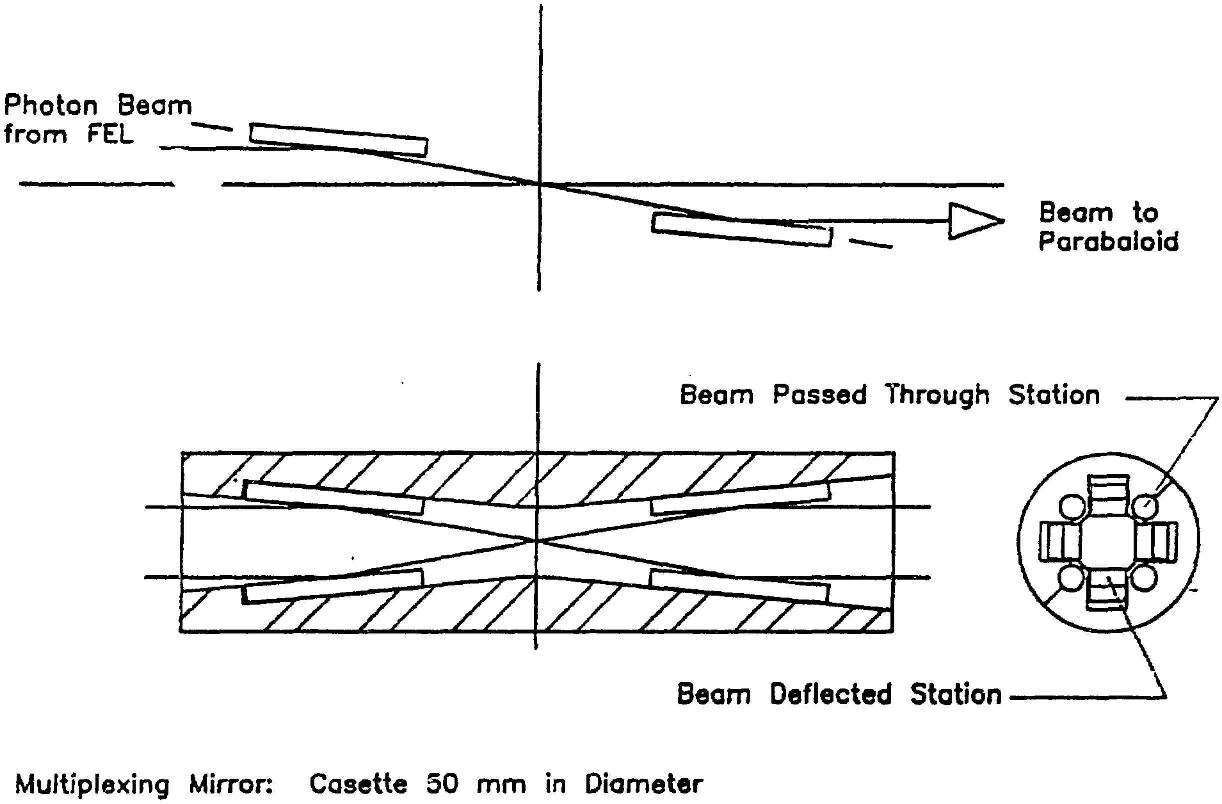

Figure 4. Schematic of Multiplexing mirror showing the beam path in the top panel, and the arrangement of four sets of mirrors and four transmission apertures in the bottom panel.

Plan views are provided in figure 3 which show the placement of the mirror tanks at the same elevation as the accelerator, with the laboratories above indicated as dotted lines. The two lines are designated A and B, with the following nomenclature for each tank. MM1A is the multiplexing mirror for the first station on branch A. LP1A is the first low energy parabaloid, serving the first laboratory on branch A. HP3A is the first high energy paraboloid on branch A which serves the third laboratory of the A branch, and so on. As shown, the incidence angle for the low energy parabaloids is 12.3 degrees, and 5.5 degrees on the high energy mirror. All of the parabaloids will be manufactured from silicon, while the flats in the multiplexing mirror systems are silicon carbide. At present, FEL on FEL experiments can be accomplished in the third and fourth laboratories of each line, by a roll of the opposing beamlines high energy mirror. This makes for an approximate path difference of 1.5 meters between the normal entrance point of the FEL beam, and the cross over beam.

The FEL facility will be built in close proximity to the NSLS as shown in figure 5. A pair of parabaloid mirrors would be employed to transport radiation from an insertion device in the X21 straight section to the B-4 station of the FEL facility. The radio frequency system of the FEL has been designed to operate at the 9th harmonic of the x-ray ring, so precise synchronization of pulses from the FEL and the insertion device is possible. The existing insertion device at X21 is the twin of the X25 hybrid wiggler, producing x-ray radiation with a critical energy of 4.7 keV and an intensity roughly a factor of 10 higher than that of a bending magnet beamline [6]. This extra intensity has been recently utilized in time resolved studies of macromolecules by Singer *et al.* [7].

The biology research station and its associated sample preparation area are shown schematically in figure 3 as laboratory B-2 which is a 6 by 13 m contiguous space around the FEL output mirror tank. This space can be partitioned as required, and additional laboratory space in the building, but removed from the experimental station can be provided. While the final configuration will reflect the interests and requirements of the user community, we envision standard biochemical equipment, *e.g.* balances, centrifuges, pH meter, spectrophotometer, fume hood, *etc.* In addition, facilities for cell tissue culture, *e.g.*, sterile hoods, incubators, and microscopes, may be required. The experimental area will provide for directing both the UV-FEL beam and auxiliary photon beams onto the sample while recording incident intensity, transmission, fluorescence, phosphorescence or scattering as functions of time or wavelength while controlling its composition (*e.g.* mixing), temperature (≈10° K to >100° C), pressure, or other relevant parameters.

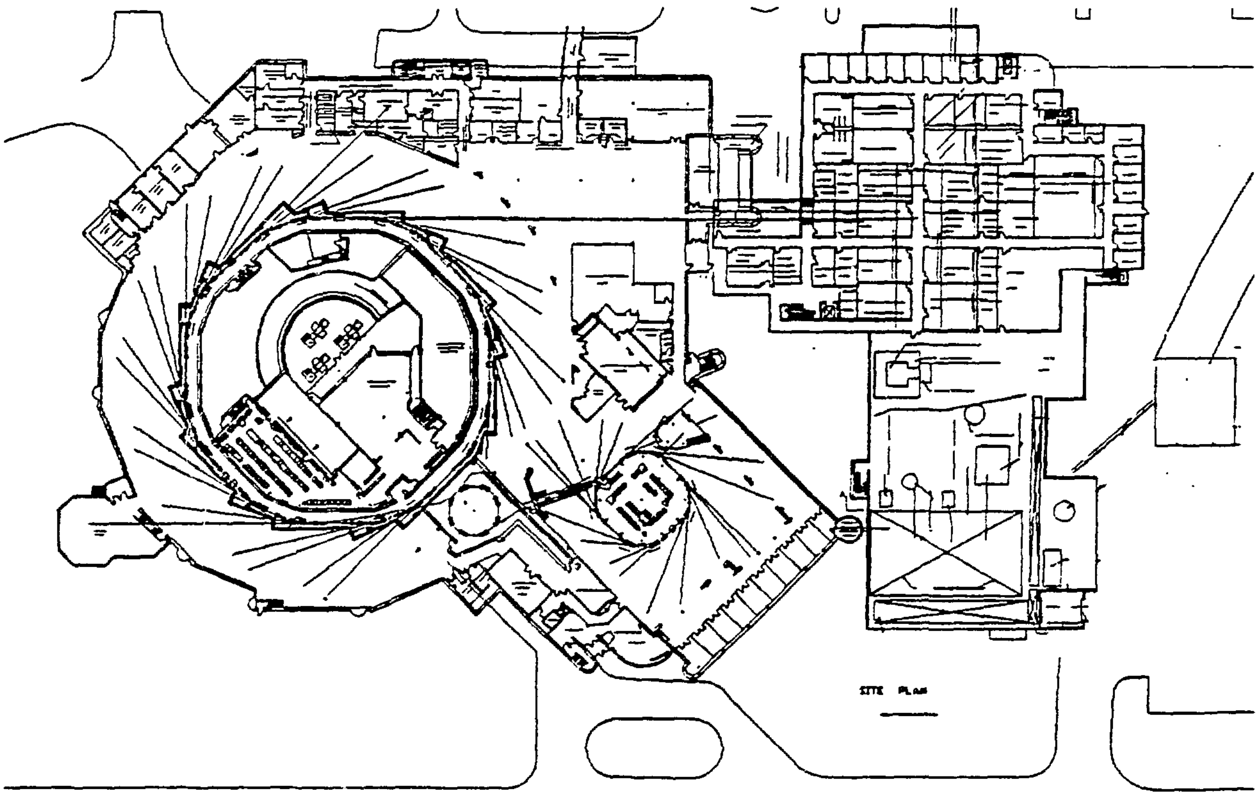

Figure 5. Plan view of the site for the proposed facility. On the left is the familiar profile of the NSLS (the x-ray ring, the largest of the three shown is 170 m in circumference) while on the right, accepting radiation from X21, is the FEL user facility.

4 Conclusions

The unique capabilities of the proposed UV-FEL will provide scientists in many fields new opportunities to study the structure of matter. In the case of biological systems, the ability to probe the biological and biochemical effects of UV radiation and the dynamical behavior of biological systems from the domain of milliseconds to femtoseconds is particularly exciting.

5 Acknowledgements

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