CONF-9009166--7

Presented at the 1990 International FEL Conference, Paris France,
September 17-21, 1990.

BNL--45161

DE91 001131

PROPOSED UV-FEL USER FACILITY AT BNL[*]

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ABSTRACT

The NSLS at Brookhaven National Laboratory is proposing the construction of a UV-FEL operating in the wavelength range from visible to 1000Å. Nano-Coulomb electron pulses will be generated at a laser photo-cathode RF gun at a repetition rate of 10 KHz. The 6 ps pulses will be accelerated to 250 MeV in a superconducting linac. The FEL consists of an exponential growth section followed by a tapered section. The amplifier input is a harmonic of a tunable visible laser generated either by nonlinear optical material or the non-linearity of the FEL itself. The FEL output in 10^{-4} bandwidth is 1 mJ per pulse, resulting in an average power of 10 watts. The availability of radiation with these characteristics would open up new opportunities in photochemistry, biology and nonlinear optics, as discussed in a recent workshop held at BNL.

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[*] This work was done under the auspices of the U.S. Department of Energy.

Scientific Motivation

In this paper, we describe an accelerator based UV/VUV radiation source capable of providing tunable, coherent radiation from 3000Å to 1000Å at near gigawatt peak powers. Unlike FEL's utilizing UV/VUV oscillator cavities, the laser amplifier scheme proposed here will provide high peak power VUV radiation with the mode structure, bandwidth and frequency stability of an input seed laser. Such a VUV source with peak energies near 1 mJ/pulse is well beyond conventional laser technology and could have an immediate impact on experimental studies of photo-induced processes in chemistry and physics. In the following section, we discuss applications of high intensity VUV radiation to photo-chemistry and photo-ionization for which the proposed source is ideally suited. For specific applications of FEL's to biology and physics, particularly surface physics, we refer the reader to previous VUV/FEL conference proceedings [1].

The study of UV and VUV (4000Å -1000Å) induced chemistry is largely driven by the fact that such radiation is sufficiently energetic to break most chemical bonds (≥ 70 kcal/mole). As a result, molecules photo-excited by UV/VUV light often undergo fragmentation into atomic and/or smaller molecular species. The radiation-induced atoms and molecular fragments are most often radical species with open shells and readily undergo reactions with surrounding molecules and surfaces. Photo-dissociation by energetic solar radiation is largely responsible for initiating the complex chemistry of the atmosphere as well as many naturally occurring mutations in biological systems. Investigations of the photo-dissociation process in which the initial state of the parent molecule and the final state distributions of the fragments are determined provide a detailed picture of the fragmentation dynamics at the quantum state level. Photo-dissociation also provides a probe of the reverse "half-reaction" in which two atomic or molecular species interact along a certain reaction coordinate and combine to form a new chemical bond. In general, the fate of molecules excited with UV/VUV radiation is an area of intense interest since it bears on all aspects of internal energy distribution within systems with large numbers of electronic and nuclear degrees of freedom.

For the most part, such studies have been performed with high peak-power laser systems.

e. g. Q-switched Nd:YAG or excimer laser pumped systems, which provide intense, tunable radiation from the near IR to the near UV (2000Å). For VUV radiation below 2000Å , upconversion of visible and near UV laser light is very inefficient (typically $\leq 10^{-5}$) with peak energies ($\leq$ 100 nJ) suitable for spectroscopic applications only. Consequently, very few studies with state-selective detection have been performed in the VUV, despite the importance of this wavelength region to atmospheric photochemistry, rarefied plasma dynamics and astrophysics.

Investigations of the primary photochemistry of small molecules generally require radiation with energies greater than 5 eV ($\lambda \leq$ 2480Å). In addition, the dissociation laser must be very intense in order to produce large yields of photo-fragments which can be subsequently probed by other spectroscopic techniques such as laser induced fluorescence (LIF) or resonant multiphoton ionization (REMPI). A VUV pulse intensity of ~ 1-10 mJ is estimated from the minimum yield of photo-products needed for LIF or REMPI detection with conventional UV/VIS probe lasers (~ 10^{10} per quantum state)[2]. Fixed-frequency excimer or Nd:YAG lasers producing 10–40 MW of peak power are typically used for such studies, however, only two intense excimer lines at 1930Å (ArF) and 1570Å (F_2) lie below the 2000Å . Clearly, a tunable VUV source with comparable power is needed to extend these studies into the VUV.

Given tunability down to 1000Å and pulse energies of ~ 1 mJ, it will be possible to investigate the photo-dissociation dynamics of small molecular systems important in atmospheric and combustion chemistry. The tunability of the source will allow selective excitation of Rydberg and valence states whereas previous state-resolved studies on systems such as H_2O were performed at fixed-frequencies determined by the laser (1930Å and 1570Å) and not by the spectroscopy of the molecule. By measuring the internal and translational energies (*scalar* correlations) and the spatial distributions (*vector* correlations) of the photo-fragments, it will be possible to determine the dynamics of the dissociation event and provide new tests for accurate potential surfaces [3]. In addition, these measurements can provide quantitative yields of alternative product channels, *e. g.* $O(^1D, ^3P)$ and OH(X, A, B) from H_2O, knowledge of which is important for modeling photochemically-driven reactions.

FEL Design

We shall describe two approaches using an FEL amplifier to produce a tunable source of high intensity radiation in the wavelength range from 1000 to 3000 Å. The first scheme utilizes a UV-seed at the operating wavelength. The second scheme uses a seed at three times the operating wavelength [4]. The harmonic generation of 1000 Å radiation from the 3000 Å seed is carried out in the beginning of the FEL. The two schemes are shown in Fig. 1.

For both schemes, we assume an input electron pulse of 256 MeV and length 2σ=6 ps from a superconducting linac with a laser driven photocathode RF gun. The electron beam has a peak current of 100 amp, normalized rms emittance 6 mm-mrad, and energy spread 0.1% FWHM.

The calculations reported in this paper have been carried out using the 3D computer code TDA [5]. We have modified [6] this code to enable calculations for the harmonic scheme. Furthermore, the numerical calculations were checked against a variational calculation of the FEL gain in the exponential regime [7] which incorporates the energy spread, emittance, and focussing of the electron beam, and the diffraction and guiding of the radiation. The harmonic generation and tapered section numerical calculations were checked against one-dimensional analytical models.

Let us first consider the case of a UV seed at 1000 Å. The FEL amplifier is comprised of a 21 m constant period wiggler. The magnetic field is constant over the first 11 m and the amplification in this section is exponential. The magnetic field is tapered quadratically over the last 10 m,

$$B_W = B_{W0}[1 - \eta \left(\frac{z - 11}{10} \right)^2]$$

with $\eta = 0.018$, yielding an approximately quadratic power growth. The peak magnetic field in the exponential section is $B_{W0} = 1.19T$, and the wiggler period throughout the FEL is $\lambda_W = 1.75$ cm.

In our design considerations, we optimized the position of the beginning of the tapered section, and the tapering coefficient η by individually varying these quantities to find the maximum output power.

We envision the wiggler magnet to be a superconducting device, with provision made for adjusting the strength of individual poles in the tapered section. The wiggler poles are shaped to give equal focusing in the horizontal and vertical planes. The input seed pulse at 1000 Å has a pulse length of $2\sigma = 6$ ps and an energy of 4 nJ corresponding to a peak power of 700 watts, in a bandwidth $\Delta\lambda/\lambda = 10^{-4}$. In the exponential section, the power gain length is 1.1 m, and the amplified power after 11 m has reached 2.5 MW, which is near, but before saturation of the exponential process. In the 10 m tapered section, the power is increased from the initial value of 2.5 MW to an output value of 160 MW. Given a pulse length of 6 ps this corresponds to about 1 mJ energy in the pulse. The exponential growth in the untapered section and the nearly quadratic growth in the tapered section are shown in Fig. 2.

One advantage of using a superconducting linac is that the energy variation within and between pulses can be kept well below 0.1% FWHM. If instead of using a superconducting linac, we used a conventional linac with an energy stability of 0.5% FWHM, then the output energy in a pulse would fluctuate with an average value of about 0.3 mJ, since on average only about 1/3 of the electron pulse will be within the gain bandwidth. Figure 3 shows the calculated dependence of the output power on detuning.

Let us discuss a little further the concept of local energy spread which determines the gain in our calculations. During the passage through the whole wiggler (~ 1000 wiggler periods) the slippage distance is only 0.1 mm, as compared with the bunch length of 2 mm. We call the energy spread within this slippage distance the local energy spread. Since the energy spread of the electron gun is about 20 KeV, and we do not expect this to be significantly increased in the linac, we believe 0.1% is a conservative estimate for the local energy spread (at 250 MeV, 20 keV energy spread gives the fractional energy spread 0.008%).

Let us now consider the case of using an initial seed pulse of 3000 Å wavelength. Third harmonic generation of 1000 Å radiation takes place in the FEL as we shall now describe. The FEL consists of an initial 2.5 m long wiggler resonant to 3000 Å , a dispersion section of length 20 cm and 4 KG magnetic field, and a second wiggler of length 20 m resonant to 1000 Å . The interaction of the 3000 Å seed pulse with the electron beam produces an energy modulation at 3000 Å . This energy modulation is converted into a spatial bunching with a strong third harmonic component at 1000 Å in the dispersion section. When this coherently bunched beam enters the second wiggler magnet, there is a rapid coherent generation of 1000 Å radiation within the first meter. This radiation process has a characteristic quadratic dependence on distance traversed in the wiggler. There is then a transition to exponential growth which continues until 8 m into the wiggler, where tapering begins.

The first wiggler magnet has a period length $\lambda_{W1} = 2.8$ cm, and a peak magnetic field of $B_{W1} = 1.13T$. The second wiggler has a period $\lambda_{W2} = 1.75$cm. Its field is $B_{W2} = 1.19T$ over the first 8 meters and

$$B_W = 1.19[1 - 0.016\left(\frac{z-8}{12}\right)^2]$$

over the last 12 m. This quadratic taper yields an approximately quadratic power growth. The initial seed pulse at 3000 Å has a power of 1.5 MW.

The peak to peak energy modulation of the electron beam exiting the first wiggler is $\Delta\gamma = 0.9$. In the dispersion section, this energy modulation produces a spatial bunching. Optimization has shown that one should take $d\psi/d\gamma \approx 1$, where $\psi = (k_s + k_W)z - k_s ct$ is the phase of the ponderomotive potential relative to the second wiggler with a resonant wavelength 1000 Å . This corresponds to 1 KG field in the 20 cm dispersion section.

An optimization has been carried out by varying the power of the input seed, the dispersion strength $d\psi/d\gamma$, the starting position of the tapered section and the tapering coefficient η. The generation and growth of the radiation in the second wiggler are also shown in Fig 2. The output power of 100 MW corresponds to about 600 μJ for a pulse of length 6 ps. After the initial fast power growth the harmonic generation scheme growth rate is smaller than the UV seed scheme due to the energy spread introduced by the pre-bunching.

We have also calculated the output power for a local energy spread of 0.05% FWHM. In Table 1 we present the performance of the UV FEL for various choices of parameters. In each case we optimize free parameters such as the tapering profile.

The laser driven photocathode RF gun being developed for the Accelerator Test Facility at BNL has a design current of 160 amp with a normalized emittance of 7 mm mrad. Assuming these values for the current and emittance and the conservative estimate 0.1% FWHM for the local energy spread, the optimized output power is found to be 300 MW, as given in Table 1.

The Linac and Seed Laser

At the energies required for a UV-FEL, the best combination of peak current, stability, energy spread and time structure is available from a superconducting linac at a low frequency, say about 500 MHz. With such a machine it is possible to run either short, sub-picosecond bunches or long, a few tens of picosecond bunches with little degradation of energy spread due to wake fields or fundamental mode curvature. At about 500 MHz it is possible to operate at 4.5K, simplifying the cryogenic system. Superconducting linacs are available commercially from a number of manufacturers and the cost (with a few recirculations) is competitive with room temperature linacs.

The low emittance electron beam needed for the UV-FEL will be generated by a laser-photocathode RF gun of the type which is being developed at BNL [8]. Simulations of the RF gun show that for a 6 ps bunch with a charge of 1 nano-Coulomb the normalized emittance at the exit of the gun is 7×10^{-6} m-rad and the energy spread σ_γ/γ is 4×10^{-3}. Recent work at BNL [9] has shown that the emittance of such a gun can be improved by more than a factor of 2 by providing a particular intensity profile of the laser pulse. We assume a normalized emittance of 6×10^{-6} m-rad and 100 A current. To attain 1000A the optimized linac energy is found to be 250 MeV.

The repetition rate of such a gun is determined mainly by the performance of the laser driving the photocathode. If the rate was not laser limited then the rf power dissipation would become a limiting factor. It is expected that such a gun could be operated at 10 KHz.

The linac structure would be similar to the HERA or ARES structure. These 500 MHz, four cell niobium structures have $R/Q = 470\Omega$ at the TM_{010} mode. These structures have demonstrated performance well over 5 MV/m at Q larger than 2×10^9. We shall assume conservatively a gradient of G=5 MV/m. At this gradient a bunch of charge q will change the voltage of the cavity by $\Delta V/V = q\omega R/Q/(2V)$. The voltage change for the 1.2 m structure at 5 MV/m beam loaded by a 1 nC bunch will be a negligible 10^{-4}. Thus beam loading is not expected to contribute to the bunch to bunch energy spread. The accelerating field and phase stabilizations in a cw operated superconducting linac are excellent and can reach the 10^{-4} level.

The wake field induced energy spread can be estimated by $2qk_{||}$ where $k_{||}$ of a single cavity cell is given by $k_{||}(Volt/pC) = 5.9 \times 10^{-3}\sqrt{g/\sigma}/a$ where g, a are the cell length and aperture radius in meters and σ is the bunch length in meters. Since the superconducting cavity has four cells we divide $k_{||}$ by $\sqrt{4}$ to get an effective wake loss factor per cell. We use $g = 0.32$ m, $a = 0.085$ m, $\sigma = 10^{-3}$ m and get $k_{||} = 0.62$ V/pC. For a 1 nC bunch this would lead to an energy spread $\Delta\gamma/\gamma = 2qk_{||}/gG = 7\ 10^{-4}$ This energy spread can be corrected by a proper choice of the stable phase to about one tenth of this value to better then 10^{-4}. The energy spread produced by the curvature of the rf waveform is less than 5×10^{-5} due to the low frequency of the linac.

To reduce the cost of the linac a recirculation scheme with about three passes through the linac will be used. This arrangement has additional advantages, such as the possibility of extracting bunches at various energies, destined for a number of FELs operating at various wavelengths as well as the option to do bunch compression at an intermediate energy.

The accelerator and wiggler set-up are shown schematically in Fig. 4. The laser photocathode rf gun will provide an energy of 5 to 10 MeV. The superconducting linac, comprised of about 11 sections, will provide an energy gain of about 80 MeV per pass. In the final pass the energy will be modulated at a slightly lower frequency (a harmonic of the gun repetition rate) to enable beam switching between a number of independent FELs. Only two wigglers are shown for simplicity.

The seed laser system must perform within the limits defined by a critical set of input criteria. these include high repetition-rate (kHz), high peak energy ($\geq 25\mu J$), picosecond pulse duration and tunability from 0.3 to 1.0 μm. Solid state regenerative amplifiers are capable of producing high peak powers while meeting the goals of kilohertz operation [10]. The heart of our seed laser system will be based on this technology operating on both Nd:YLF and Ti:Sapphire. Our approach for generating high repetition-rate, high power laser pulses is to inject a small fraction of energy from a mode-locked Nd:YLF or dye oscillator into a multi-pass cw-pumped regenerative amplifier. Such an amplifier can produce 10^9 gain or pulse energies in the mJ level. The wavelength generated from the primary amplifier stages will extend from 0.6 to 1.0 μm. Application of standard nonlinear techniques will provide tunability down to 0.3 μm with efficiencies from 25 to 40 % . Production of VUV seed radiation down to 0.1 μm will be accomplished by third-harmonic generation in inert gases. Although such techniques are inherently inefficient, we estimate that our system will produce pulse energies in the nJ range.

Acknowledgment

The authors would like to thank J.S. Wurtele for providing us with the computer code TDA and K.M. Yang for his help with the computer runs.

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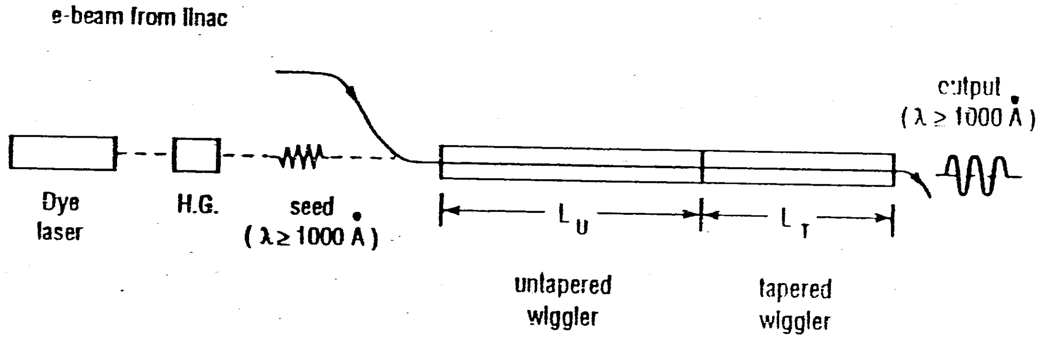
Table 1. FEL Parameters at 1000 Å

	UV Seed	Harmonic Generation	Harmonic Generation	Harmonic Generation
Current (Amp.)	100	100	100	160
Input wavelength (Å)	1000	3000	3000	3000
Input power (MW)	0.0007	1.5	0.5	0.9
FWHM local energy spread (%)	0.1	0.1	0.05	0.1
Dispersion $d\psi/d\gamma$	-	1	5	2
Length of untapered section (m)	11	8	6	8
Length of tapered section (m)	10	12	14	12
Tapering (%)	1.8	1.6	3.0	2.6
Output power (MW)	160	100	220	300
Output energy in a 6 ps pulse (mJ)	1.0	0.6	1.3	1.8

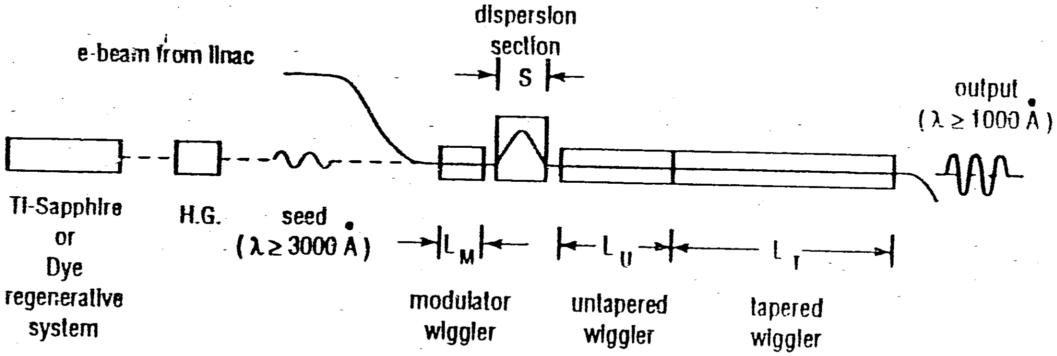
Figure Captions

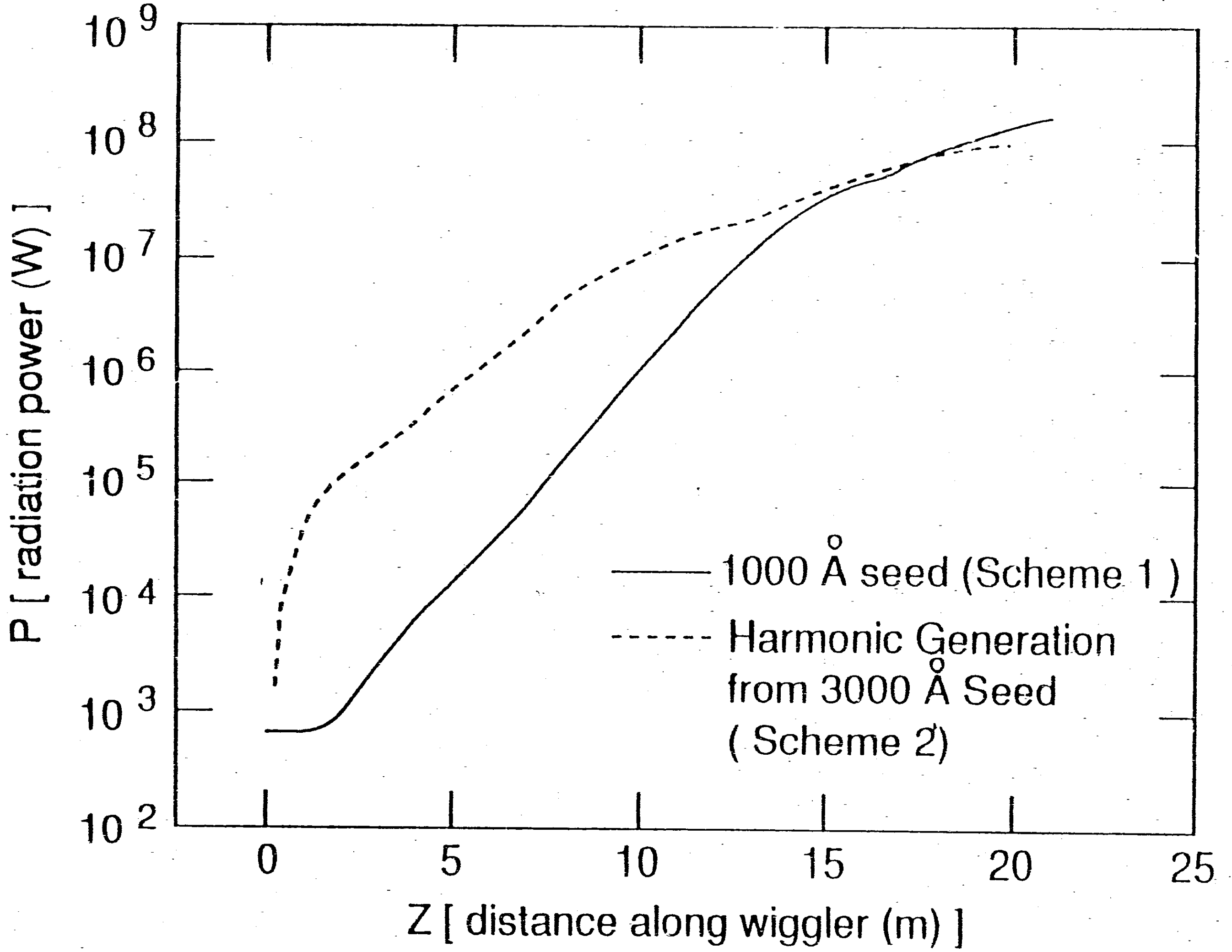
1. Schematic diagram of the two configurations of the UV FEL amplifier.
2. Radiation power vs. position along the wiggler for the two schemes of UV FEL.
3. Final radiation power vs. electron energy detuning in the 1000 Å seed scheme UV FEL.
4. Schematic diagram of the UV FEL facility and its recirculating electron linac.

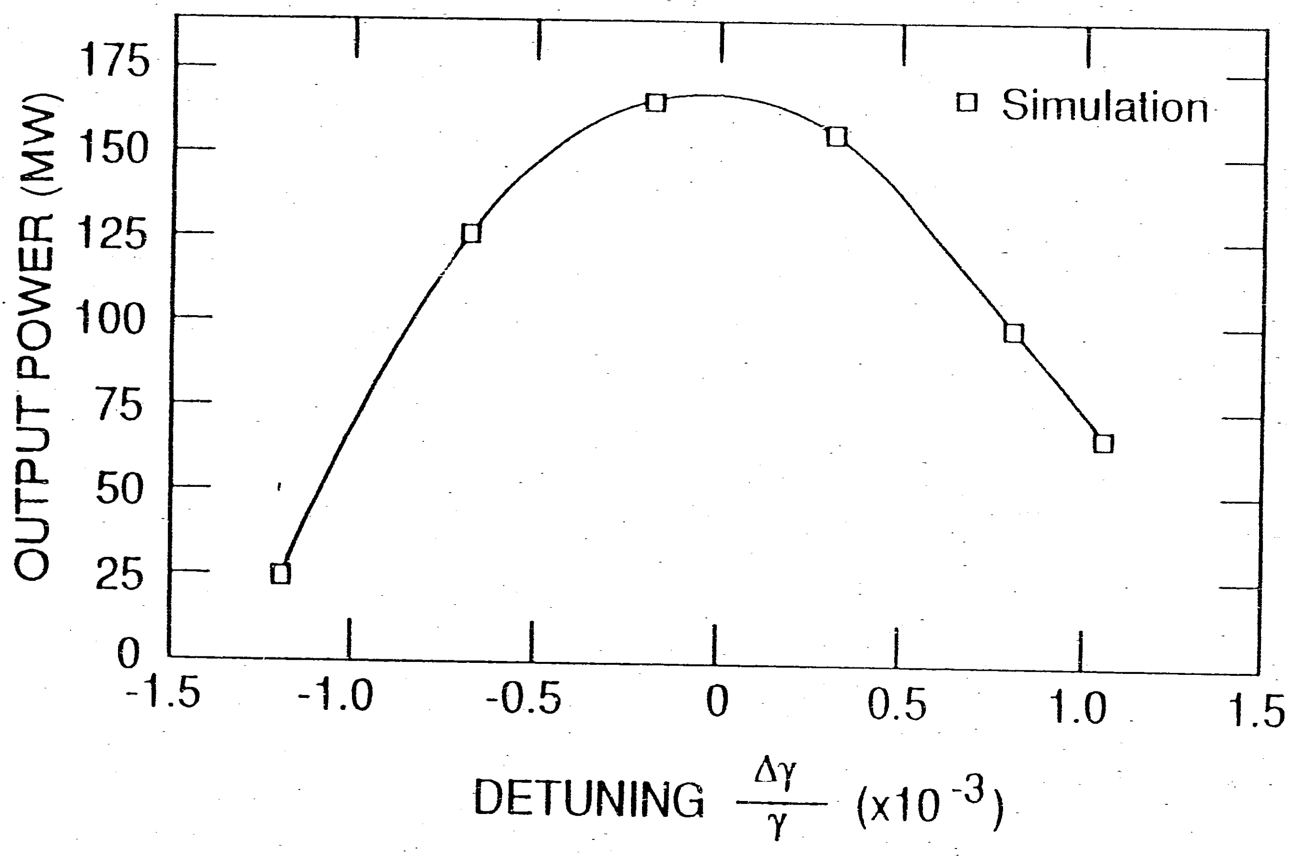
Scheme 1

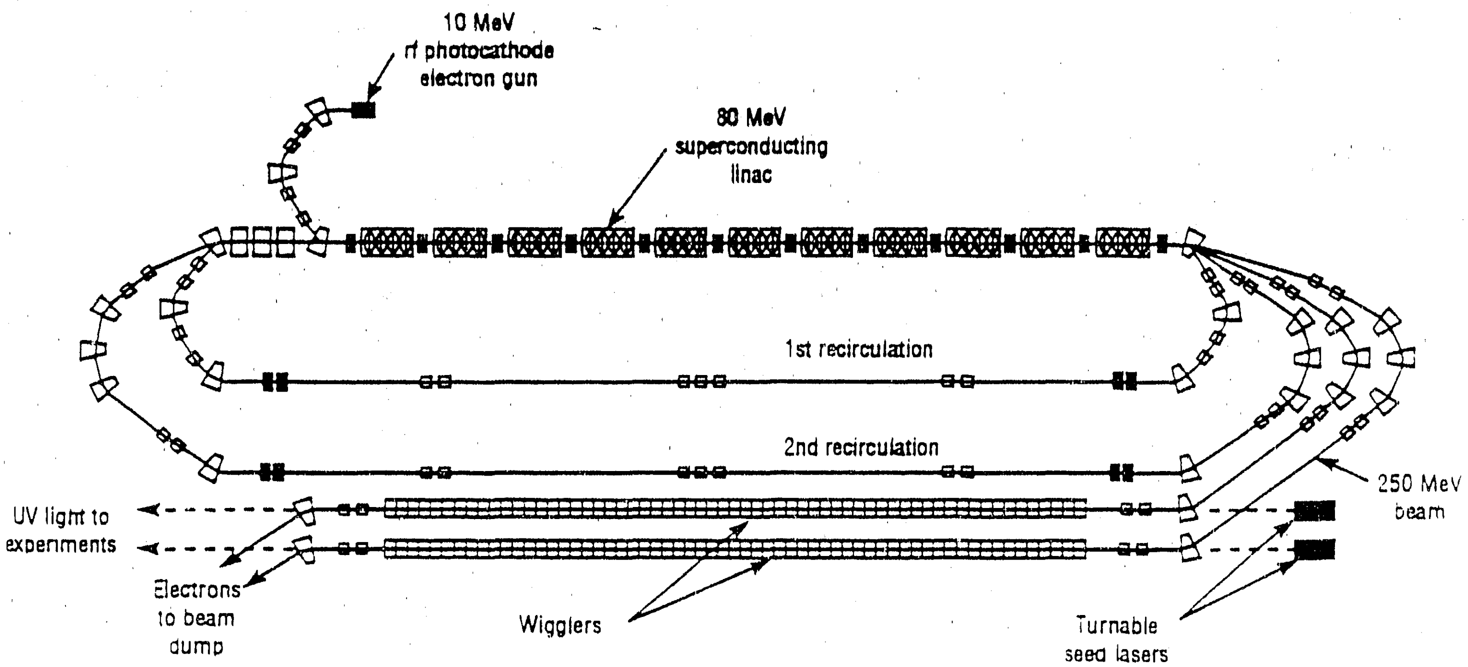


Scheme 2




10 9
10 8
10 7
10 6
10 5
10 4
10 3
10 2
P [radiation power (W)]
0
5
10
15
20
25
Z [distance along wiggler (m)]
1000 Å seed (Scheme 1)
Harmonic Generation
from 3000 Å Seed
(Scheme 2)


OUTPUT POWER (MW)
0
25
50
75
100
125
150
175
-1.5
-1.0
-0.5
0
0.5
1.0
1.5
DETUNING $\frac{\Delta\gamma}{\gamma}$ $(x10^{-3})$
□ Simulation


10 MeV
rf photocathode
electron gun
80 MeV
superconducting
linac
1st recirculation
2nd recirculation
250 MeV
beam
UV light to
experiments
Electrons
to beam
dump
Wigglers
Turnable
seed lasers

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