TWO-STAGE FREE-ELECTRON LASER DRIVEN BY AN ELECTROSTATIC ACCELERATOR

Isidoro Kimel, Luis R. Elias and Gerald Ramian
Quantum Institute, University of California, Santa Barbara, CA 93106

ABSTRACT. The UCSB 6 MeV pelletron, modified for electron beam recovery, is being used to drive a two-stage Free-Electron Laser (FEL). A new gun and electron collector have been installed for this experiment and, with new focusing in the accelerator tubes, a current of up to 20 A will be drawn from the accelerator. The first stage, with a 20 cm period helical undulator, will generate 10^7 W/cm^2 optical saturation power of 703 μm radiation. This radiation acts as an electromagnetic undulator for the second stage where the same beam of electrons will drive a second FEL of 1.08 μm. Calling λ_0 the undulator period, the wave length of the first stage radiation is $\lambda_1 \approx \lambda_0/2\gamma^2$, while the wave length generated in the second stage is $\lambda_2 \approx \lambda_1/4\gamma^2$. Thus the overall Doppler upshift in frequency is given by the factor $8\gamma^4$. For an electron energy of 6 MeV, this factor is $\sim 2\times10^5$. Both the principles of a two-stage FEL as well as experimental details are discussed.

1-INTRODUCTION

A 6 MeV electrostatic accelerator of the pelletron type is used for driving a single-stage Free-Electron Laser (FEL)[1] at the University of California, Santa Barbara (UCSB). The accelerator was modified for electron beam recovery with the installation of a deceleration tube and an electron collector. The same accelerator will shortly drive a two-stage FEL[2].

The single-stage FEL has been in operation at UCSB since 1984 and it lases almost at a single resonator mode with a fractional bandwidth of the order of 10^{-8}. As was recently shown[3], such narrow bandwidths are to be expected in FELs driven by long pulse accelerators. Single mode operation together with long coherent laser pulses will be an important factor for the success of the two stage FEL experiment presently under way at UCSB.

In the first stage (which is being assembled at the time of writing) with a helical undulator of N_0 periods of λ_0=20 cm, far infrared radiation of wavelength λ_1=703 μm will be generated. In the second stage, this radiation will act as a pump or electromagnetic undulator. Wiggling in the field of the pump, the electrons emit a second laser light of wavelength λ_2=1.08 μm.

For electrons of energy $E=\gamma mc^2$ the wavelength of the pump is $\lambda_1 \approx \lambda_0/2\gamma^2$ while in the second stage the laser wavelength is $\lambda_2 \approx \lambda_1/4\gamma^2 \approx \lambda_0/8\gamma^4$. Thus, in a TS FEL, the undulator virtual photons are successively Doppler upshifted in frequency by the factor $8\gamma^4$. The experiment will be performed with electrons of 6 Mev for which $8\gamma^4 \approx 2\times10^5$.

2-ELECTRON BEAM SYSTEM

In order to be able to recover almost all of the electron current after it goes through our FEL we need: 1) A very high quality electron beam. This puts very stringent requirements on the electron gun design. 2)Beam transport with the minimum possible of aberrations. 3) A very efficient collection of the electron beam after it goes through the deceleration column inside the accelerator tank. This is achieved with a carefully designed electron collector.

A-ELECTRON GUN. We had previously developed an electron gun capable of producing up to a 2 ampere current for 50 kilovolts between anode and cathode. This gun has been in operation since 1981[4] and the measured emittance was quite close to the calculated thermal value.

More recently we have developed a scaled up version of the old gun, with a similar perveance of 0.22 micropervs. The new gun is presently producing up to 2.5 A. After new focusing elements in the accelerator tubes are installed, the gun will be operated at the nominal current of 20 A for 200 KV.

A one inch diameter custom made concave cathode with a relatively low nominal loading of less than 4 amperes/cm^2 was chosen for the new gun in order to have high beam homogeneity. To facilitate pulsed operation of the gun, an intermediate aperture grid electrode (or modulating anode) was incorporated in the design. A voltage of 15 KV with respect to cathode (w.r.t.c.) on this electrode is required to turn the gun on, while -15 KV will shut the gun off.

A beam analyzer is being built to measure the emittance which is expected to be near the thermal (normalized) value of ϵ_n=18 mm-mrad.

B-BEAM TRANSPORT. The UCSB system has successfully handled the transport of a 1.25 ampere beam achieving a high degree of recovery (97%). For the new 20 A beam to be used for the two-stage experiment, new focusing elements will be added to the acceleration column to compensate for the increase in space charge spreading of the beam.

A computer code taking into account space charge and emittance, is used to model the electron trajectories and monitor the beam profile. Extra care is being taken in the design of bending magnets and focusing elements in order to transport the beam with a minimum of aberrations.

After passing through the FEL the energy of the electrons is decreased from 6 MeV to 200 KeV in the decelerating column where new focusing elements will also be placed in order to handle the more intense beam.

C-ELECTRON COLLECTOR. A unique feature of our system is a very good energy and current recovery of the electron beam. In order to recover the new 20 ampere beam we have developed a new collector. Besides the base plate, it has three stages at depressed voltages w.r.t.c., and the calculated energy collection efficiency is 75.5 %.

The collector was designed to accept electrons with kinetic energies between 80 and

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200 kV and RMS transverse velocity v_t to axial velocity v_z ratio of up to 0.07. The position of the collecting apertures and the angles of the plates at the apertures were designed to minimize the possibility of backward reflection.

3-DESIGN OF THE EXPERIMENT

To reduce the losses, we adopted free space mode configurations for both the pump and laser waves. Our first estimates were that we would need a resonator of length $L \sim 3.5$ m and the pump wave would have a wavelength of $\lambda_0 \sim 700\ \mu m$. In order to have diffraction losses of no more than 1% per round trip in that section, the Fresnel number $F = R^2/\lambda_1 L > 0.8$ [5], giving a bore radius $R > 4.4$ cm. We finally used a stainless steel tube of 3.5 inches diameter.

Estimating pump wave losses $\alpha_p \sim 3\%$ per pass, we required a net gain of 10% for an actual small signal gain of

$$G_1 = 4\times10^{-4}\ I K_1^2 N_1^3\ \lambda_0^2/\gamma^3 \langle W_p^2 \rangle = 13\%. \qquad (1)$$

In this equation: γ=electron energy/mc^2 =12.74, Current= I=20 A, Undulator period=λ_0=20 cm, N_1= number of periods of the undulator, K_1= undulator parameter, average pump radius squared=$\langle W_p^2 \rangle$=5cm^2.

In eq. (1) all parameters were fixed or estimated except for N_1 and K_1. A second equation containing these parameters is obtained from an analysis of the second stage gain and the saturated power flux of the pump wave. This flux (Poynting vector) can be written as [6]

$$S_1 = 3.42 \times 10^9 \text{ watts } (\gamma^2/\lambda_0\ K_1\ N_1^2)^2. \qquad (2)$$

When the pump reaches saturation, the small signal gain for the second-stage laser wave will be given by

$$G_1 = \frac{5.80\times10^{-14}\ L_2^3\ \lambda_0\ I\ S_1}{\gamma^3 \langle W_L^2 \rangle\ [1+(N_1\ \epsilon_n^2/\pi^2 r_{b2}^2)^2]}\ . \qquad (3)$$

The new parameters in this equation are: Length of second stage interaction region= L_2=1.4m, spot size of laser beam= W_L=1 mm, electron beam radius in second stage interaction region= r_{b2}=1 mm, normalized emittance ϵ_n=18 mm-mrad, number of wavelength of the pump as seen by the electrons in the second stage=$N_2 \approx 4000$. The gain depression for the laser wave due to the finite emittance is taken into account in the factor

$$[1+(N_2\ \epsilon_n^2/r_{b2}^2)^2]\ . \qquad (4)$$

We know that we cannot have a large gain for the second stage laser wave, so we required a modest G_2=10% which would result from a pump saturation flux $S_1 = 4.6 \times 10^7$ watts/cm^2. Once the required S_1 was fixed at that value and G_2=0.1, we were left with the system of eqs. (1) and (3) from which we obtained N_1 and K_1. The resulting value of N_1=12.7 was implemented by tapering at the ends a 14 period undulator. For the undulator parameter we got K_1=0.385 which corresponds to a magnetic induction B_1=206 Gauss. with this, we have all the parameters of the helical undulator.

4-EXPERIMENT

In order to check the performance of the pump wave, a single stage FEL experiment will be performed first. The parameters listed under FIRST STAGE in the table are also valid for this single stage experiment. We will shortly inaugurate a new 20 ampere electron beam line. The single stage experiment will allow us to optimize the beam transport maximizing the electron beam recovery while at the same time measuring the pump gain and saturation power.

After we are satisfied with the performance of the single stage experiment, we will add the second stage interaction region. The simplest is a straight line design with the electrons traveling in a straight path in succession first through the second stage interaction region and then through the first stage. This design is schematically shown in Fig. 1.

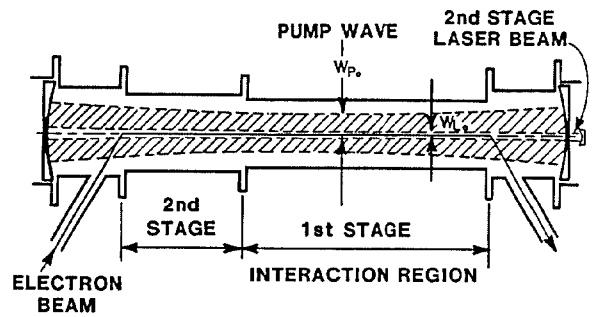

Fig. 1. Schematics of the two-stage resonator.

In the second stage it is advantageous to match the electron beam radius to the optical laser beam waist w_{L0}. Then, the gain of the second stage light would be

$$G_2 \sim \{r_{b2}^2[1+(N_2\ \epsilon_n^2/r_{b2}^2]\}^{-1}\ .$$

By maximizing the gain we get the optimum electron beam radius $r_{b2} = N_2^{1/2}\epsilon_n/\pi = 1$ mm.

The second stage will have appreciable gain when the power flux of the pump wave is of the order of 10^7 watt/cm^2. We estimate that it will take 16 μsec for the pump wave to reach that value.

5-ACCELERATOR VOLTAGE DROP

The electrostatic accelerator has a capacitance $C_{ap} = 2\times10^{-10}$F. Thus, calling R the fraction of the electron beam that is recovered, the voltage of the accelerator terminal drops according to $dV/dt = -I(1-R)/C_{ap}$ as the current I is extracted.

An optical mode starts lasing for a detuning parameter $\mu \sim 2.6$ and continues to lase until it drops out of the gain-minus-losses bandwidth for $\Delta\mu \sim -2$. This takes place in a time interval

$$t_{1m} = (-\Delta\mu) C_{ap}\ \ mc^2/4\ \ N_1\ e\ I(1-R)$$

Representative values of single mode lasing time as a function of recovery are:

R(%)	90	93	95	97
t_{1m}(μsec)	8.8	12.6	17.6	29.4

If we remember that we need 16 μsec for the pump wave to get to 10^7 watts/cm^2, then we see that we have to achieve at least 95% recovery in order to have appreciable second stage laser radiation.

We are presently developing a 25 kilovolt terminal voltage stabilizer that for 95% recovery will buy us an extra 5 μsec. After we test the voltage stabilizer concept, we have plans to build a much larger one of 150 kV (the limit is dictated by the availability of high voltage tubes) that will add as much as 30 μsec to a single mode lasing time

In conclusion we can say that with our electrostatic accelerator with electron beam recovery our system can produce longer pulses than other existing acceleration schemes. The pulse length being limited by the voltage drop of the terminal. Using voltage stabilizers we can further extend the length of the pulse of the pump radiation well beyond saturation. There is then enough power and time for the second stage laser light to develop.

The main working parameters of the two-stage FEL are listed in the table.

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TABLE. PARAMETERS OF THE-TWO STAGE EXPERIMENT

	FIRST STAGE (PUMP)	SECOND STAGE
Electron beam energy	6 MeV	same
Theoretical emittance	ϵ_n=18 mm-mrad	same
Current	I=20 A	same
Undulator parameter	K_1=0.373	K_2=4x10^{-3}
Pump period	λ_0=20 cm	λ_1=703 μm
Number of periods	N_1=14	N_2=3980
Wavelength	λ_1=703 μm	λ_2=1.08 μm
Small signal gain	G_1=12 %	G_2=10 %
Electron beam radius	r_{b1}=5 mm	r_{b2}=1 mm
Optical beam waist	w_{p0}=1.98 cm	w_{L0}=1 mm
Rayleigh lengh	Z_1=1.75 m	Z_2=2.91 m
Losses	α_1=3 %	α_2=2 %
Satur. flux(watts/cm2)	S_1=4.6x10^7	S_2=1.3x10^6
Power output (watts)	P_1=2x10^6	P_2=1.5x10^4