Nuclear Instruments and Methods in Physics Research A304 (1991) 233–237
North-Holland

# Design overview of a highly stable infrared free electron laser at LBL *

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An infrared free electron laser (IRFEL) is being designed for the Chemical Dynamics Research Laboratory (CDRL) at LBL. The FEL is based on a 50 MeV rf linac operating in synchronization to the Advanced Light Source (ALS), and will produce intense (100 μJ per micropulse), narrow bandwidth (narrower than 0.1%) radiation between 3 and 50 μm. In the design, we pay particular attention to the FEL stability issues and require that the fluctuations in electron beam energy and in timing be less then 0.05% and 0.1 ps, respectively. The FEL spectrum can then be stabilized to about $10^{-3}$, or if grating is used, to $10^{-4}$. We discuss various sources of fluctuations in the gun, the bunchers and the accelerator sections, as well as the feedback and feedforward schemes to reduce these fluctuations. The accelerator structure is chosen to be of the side-coupled, standing-wave type for easier control. The beam transport is made isochronous to avoid the coupling between the energy and the timing fluctuations.

## 1. Introduction

At LBL, we are designing an infrared free electron laser (FEL) as a part of the proposed Chemical Dynamics Research Laboratory (CDRL). CDRL is an integrated user facility for research in chemical dynamics with the goal of advancing the understanding of the combustion process. The FEL, which will be referred to as the CDRL-FEL, can be operated in synchronism with the vacuum ultraviolet radiation from the adjacent Advanced Light Source (ALS) [1], and also with other lasers. This capability, together with the tunability and the high intensity of the FEL output, will make the IRFEL a powerful tool to study reaction dynamics and molecular spectroscopy.

The main characteristics of the CDRL-FEL can be summarized as follows:

| | |
|---|---|
| Wavelength range: | $3 < \lambda < 50$ μm. |
| Micropulse energy: | 100 μJ at $\lambda = 3$ μm. |
| Micropulse duration: | $\tau = 10$ (25) ps. |
| Micropulse repetition rate: | 36.6 (18.3) MHz. |
| Macropulse duration: | 100 μs. |
| Macropulse repetition rate: | 60 Hz. |
| Average power: | 20 W. |
| Bandwidth: | transform limited. |

The time structure of the FEL pulses mimics that of the rf linac. The synchronism of the FEL pulses and the ALS pulses is achieved by filling the ALS storage ring with eight equally spaced bunches. The ALS pulses then have a repetition rate of 12.2 MHz and can be synchronized with every third FEL pulse.

As a user facility, the IRFEL for CDF must be reliable, and various forms of jitter in wavelength, in intensity and in direction must be reduced to an unusually low level. The jitter tolerance in wavelength, $\delta\lambda$, and in intensity, $\delta I$, are

$$\delta\lambda/\lambda < 10^{-3} \left(10^{-4} \text{ with grating}\right), \quad \text{and} \quad \delta I/I < 10^{-1}.$$

The jitter in the transverse position and in the angle should be less than one tenth of the spot size and the angular divergence, respectively. The wavelength tuning would also have to be relatively simple and straightforward. The design of the IRFEL for CDF therefore calls for a careful examination of all accelerator and FEL components.

## 2. Accelerator system

The accelerator for the IRFEL must provide very stable, bright and short electron beam pulses, with adjustable energy up to 56 MeV. The electron beam parameters are summarized as follows:

| | |
|---|---|
| Maximum energy: | 56 MeV. |
| Micropulse peak current: | 100 A. |
| Charge per micropulse: | 1 (2.5) nC. |
| Normalized rms emittance: | 20 mm mrad. |
| Energy spread ($\Delta E/E$, FWHM at 50 MeV): | 0.005. |

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* This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division, of the U.S. Department of Energy under Contract no. DE-AC03-76SF00098.

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The overall layout of the accelerator system is shown in fig. 1. It consists of a gun producing 1 A, 1 ns pulses, a bunching system consisting of two low-frequency bunchers (146.24 and 511.84 MHz) and an L-band buncher squeezing the pulses into 100 A, 10 ps bunches, and two 25 MeV linac tanks.

The main accelerating structure is chosen to be an L-band (1279.6 MHz), standing-wave structure. This choice is to ensure maximum stability and control of the electron beam; L-band linacs are inherently more stable than S-band linacs, and a standing-wave structure responds better to external control than a travelling-wave structure. The stability of an L-band, standing-wave structure in the FEL application has been demonstrated at LANL [2]. Our design adopts the sidecoupled cavity configuration of LANL.

Diagnostics on the accelerator can be divided into bunching, feedback and beam components. The feedback diagnostics are rf pickups in each of the rf structures. The signals from these pickups are mixed with the phase reference line to get amplitude and phase components. The bunching diagnostics unit consists primarily of a focusing coil and a spectrometer magnet after the fundamental buncher. With this, the amplitude and phase of each bunch can be measured and by varying the focus coil the emittance can be measured. There is steering between each structure with current and position measurement at the entrance of each. At the end of the accelerator, the energy, energy spread, energy stability and emittance are measured in another spectrometer and the bunch length is measured either with a fast rf deflection cavity or a streak camera.

The rf source for the accelerator must provide 100 μs pulses with a minimum level of ripple. We have selected the modulating anode klystron for this purpose. In this device, the klystron beam is switched with a low-current electrode called the modulating anode, and the output can be made as flat as possible except for a slight linear droop. Such a system is in operation at LANL [3]. Another approach is to pulse the cathode at the full operating voltage and current with a pulse-forming network (PFN). The disadvantage of this approach is that the transients and the ripples in the pulse voltage may not be completely removed, even by a careful tuning of PFN, and that the PFN would be rather bulky for a 100 μs macropulse.

A well defined turn-on procedure and ease of operation are required to make the FEL user-friendly and enable it to be operated routinely without time-consuming gymnastics. During the commissioning and initial operation, manual controls and diagnostics will be needed to understand the operation and to bring it into stable use. The next level of sophistication will be to have a computer interface to save and restore operating points of the machine. The next step is to have an on-line computer model of the machine transport and operation to identify problem areas and to allow flexible reconfiguration of the operating conditions. On top of this would be a system optimizer and problem-solving software. Once this system has been fully qualified, the operation can be routinely handled by trained operators.

## 3. Stability and control

To achieve the required FEL stability, fluctuations in the electron beam parameters need to be tightly controlled. The stability goal is as follows: Fluctuations occurring in a time scale slower than the cavity decay time $t_Q = 0.5$ μs, or equivalently at frequencies lower than $f_Q = 0.3$ MHz $(2\pi f_Q t_Q = 1)$, have a direct influence on the FEL output. These relatively slow fluctuations $\delta E$ in the electron beam energy, $\delta Q$ in the micropulse charge and $\delta T$ in the timing between the micropulses must be controlled with the following tolerances:

$$\delta E/E \leq 5 \times 10^{-4}, \qquad \delta T < 0.1 \text{ ps}, \qquad \text{and}$$
$$\delta Q/Q \leq 0.02,$$

where the variation $\delta$ refers to the FWHM values. The requirement on $\delta E$ comes from the wavelength stability, on $\delta T$ from the overlap requirement of the optical pulse

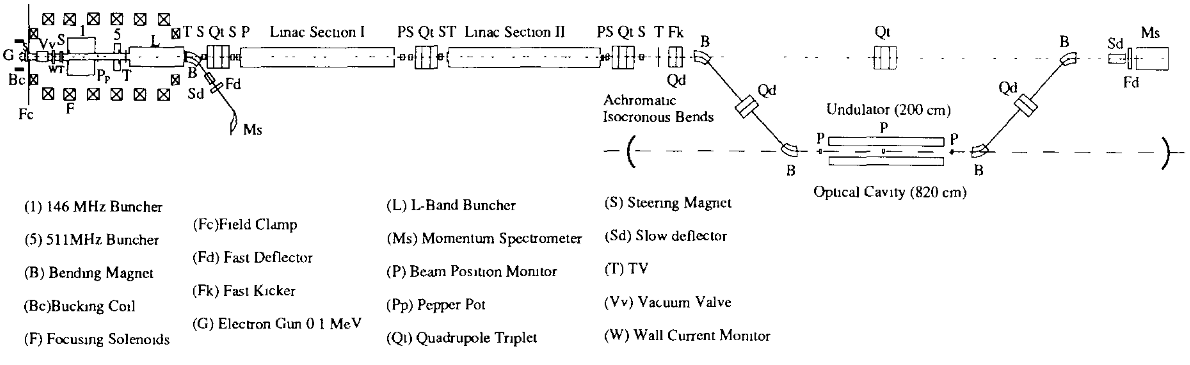

Fig. 1. Layout of the accelerator FEL system

and the electron pulse in the optical cavity (as determined from the width of the detuning curve) [4], and on $\delta Q$ from the intensity stability as well as from the energy stability through the beam loading effect. Notice that the requirement on $\delta T$ is on the *difference* of the micropulse arrival times. It is thus equivalent to a requirement on the error of the rf frequency. The effect of faster fluctuations, with frequencies higher than 0.3 MHz, is equivalent to inhomogeneous broadening. The requirements are therefore relaxed by an order of magnitude. Finally, we require that the electron beam position and the angle be stable to within one tenth of the beam size and the angular divergence, respectively.

The stability of the overall system will be achieved via passive regulation as well as active feedforward and feedback control in a layered fashion. First, wherever possible, voltages on rf and magnet power supplies will be regulated. Running at a submultiple of the electrical line frequency eases this requirement, as it greatly reduces the 60 Hz ripple. Regulating the water temperature in the cooling loops will allow sensitive temperature tuning, with a typical time constant of minutes. The required temperature stability is $\pm 1/2°$ F, achievable by modern standards. The required stability on the gun high voltage, gun current and grid voltage are:

$$(\delta V/V)_{\mathrm{HV}} \leq 0.002, \qquad \delta I/I \leq 2\%, \qquad \text{and}$$

$$\delta V/V\,|_{grid} \leq 0.01,$$

to ensure no more than 5 ps time jitter in the pulse comb time structure and adequate charge stability per micropulse. The master oscillator for the CDRL-FEL must have enough short- and long-term stability so that it is not a sizable component of either the intrinsic error signal in the feedback loops or the long-term drift. High spectral purity is required, such that the harmonics, subharmonics and multiples of the subharmonics are less than $-35$ dB, the single-sideband phase noise at 30 Hz offset is less than $-70$ dB, and the long-term stability is $1 \times 10^{-9}$ rad$^2$/Hz. The phase reference line needs to be temperature-controlled to 0.05°C to maintain long-term phase stability. Next, each accelerator and the bunching structure, including the gun, will be equipped with its own amplitude, phase and tuning control loops. Voltage regulation of the klystron will be effective in removing ripple, but there will remain significant droop over the macropulse (due to beam loading) which will then be corrected by a feedforward ramp in the amplitude and phase control loops. To achieve a $5 \times 10^{-4}$ relative energy stability of the linac, the various feedback loops will have to have significant gains (multiplicative gains in the range of 10–50) from dc to about 0.3 Mhz and tapering off to a value less than 1 beyond 2.5 MHz, determined by round-trip electronic delays in the loops. We believe that such feedback systems are technologically feasible to implement. They do, however, push the technology rather far and the ultimate limitation beyond $5 \times 10^{-4}$ will be determined by detector resolution errors for fluctuations of such small magnitude, availability of commercial amplifiers of suitable bandwidth and gain and the necessary control power to be installed.

In the next layer, in addition to all the above, we envision feedback from the optical beam at the FEL output to the electron beam and cavity mirrors. The necessary FEL diagnostics should provide information about time-resolved power, position, size, spectrum, polarization and pulse length over the 3 to 50 μm range.

In the last stage, one can envision the final wavelength selection and stabilization accomplished by incorporating frequency-selective elements such as gratings in the optical cavity.

## 4. Beam transport from linac to undulator

The optical design of the beam transport line from the linac exit to the undulator entrance should meet the following requirements:

(i) It must provide a horizontal offset in the electron beam so that is can be directed to the optical axis without interfering with mirrors.
(ii) It should not introduce timing jitter caused by the beam energy jitter – thus the transport should be isochronous.
(iii) It should not introduce jitter in transverse position and angle of the beam – thus the transport must be achromatic.
(iv) The transverse profile of the electron beam should be matched to the optical mode in the cavity.

We have worked out three achromatic beam transport designs with varying degrees of isochronicity and complexity [5]. The first design is a simple arrangement of four combined function bending magnets producing double S-bends. It has a limited offset (19 cm) and isochronicity (path difference in time per energy difference = 2 ps/%). The second design is another double S arrangement, but has more quadrupoles for a larger offset and also to make it linearly isochronous. The third one is similar to the one proposed in the FELIX study, but gives better performance as far as the isochronicity (0.4 ps/%) and the beam size are concerned. The matching to the optical beam will be accomplished by a quadrupole triplet placed at the end of the beam transport.

## 5. Undulator magnet and wavelength coverage

For the undulator magnet, we use the standard Halbach design [6] of SmCo–steel hybrid. The undulator has 40 periods, period length being 5 cm. The FEL wavelength at a fixed electron energy can be scanned between $\lambda = \lambda_{min}$ and $\lambda = \lambda_{max} = 2.15\lambda_{min}$ by varying the magnet gap from 31.8 to 20.5 mm. Thus the entire wavelength range of 3 to 50 μm can be covered by running the accelerator at four different energies, $E_e =$ 55.3, 39.1, 27.7 and 19.6 MeV.

The ease of the wavelength tuning is crucial for the operation of a user facility. The procedure for the wavelength tuning we envisage is as follows: The user specifies the desired wavelength or the tuning range. The required motion of the undulator gap is accomplished under automated computer control. The undulator scan at a given electron energy takes about one minute.

## 6. Optical system

FELs are intrinsically high-power devices and it is necessary to design the optical system and choose the materials that can handle the high intracavity power. The entire wavelength range should be covered with a minimum number of mirror changes. Finally, it is preferable to use optics that are easily available from commercial sources.

With these in mind, the solution we are proposing for the optical cavity is a linear arrangement of two mirrors. The parameters for the cavity are: the radius of curvature of the mirrors = 4.3 m, cavity length = 8.2 m, Rayleigh range $Z_R = 0.905$ m, the stability parameter $g_1 g_2 = 0.823$. With the micropulse repetition rate of 36.6 MHz, there will be two optical pulses in the optical cavity.

We are evaluating various schemes to couple out the optical beam in the entire wavelength range between 3 and 50 μm. Among these, the hole coupling based on all metal optics appears to be the most promising in view of its power handling and broadband capability. We have developed a computer code to analyze the performance of the hole coupling resonators, and found a preliminary hole–aperture combination that works over a wavelength range of a factor of 2 [7]. Another approach is to employ an unstable resonator [8]. Still another approach is to replace one of the mirrors by a grating in the Littrow configuration and use the zeroth-order reflection as the outcoupling [4]. Use of the grating has the additional advantage that it stabilizes the wavelength fluctuation as discussed in the next section.

## 7. FEL performance study

We have carried out an extensive study of the FEL performance using theoretical analysis as well as numerical calculation [4]. The numerical calculation was performed by using a simulation code originally developed by Benson [9]. A significant part of the study is to understand the effect of the electron beam fluctuation on the FEL fluctuation. We have calculated the variation in the FEL parameters caused by sinusoidal modulation in electron beam energy and timing between pulses. The study determined the tolerance limits on electron beam fluctuation.

It will be difficult to reduce the relative fluctuation in the electron beam energy to a level less than $5 \times 10^{-4}$ and the associated fluctuation in wavelength less than $1 \times 10^{-3}$ in a FEL based on a pulsed linac. However, it is possible to reduce the wavelength fluctuation significantly further by using a grating. Preliminary one-dimensional calculation indicates that the fluctuation can be reduced to $10^{-4}$ with a grating of bandwidth $10^{-2}$. This behavior has been observed at LANL [10], and can be explained with a simple model.

The FEL spectrum often exhibits sidebands at wavelength separated by $1/N$, $N$ being the number of the undulator periods, from the main line. The appearance of the sidebands, which could become chaotic, is a high-intensity phenomenon at saturation [11]. The sideband can be suppressed in various ways [12]; by increasing the cavity loss, by introducing a grating, or by detuning the cavity, i.e., by making the length of the cavity somewhat shorter than that determined by the synchronism with the electron pulses.

Since the FEL signal is developed from the initial noise, the output characteristics at saturation are expected to exhibit random fluctuation. Indeed, simulation shows that the position of the spectral peak fluctuates from shot to shot within some fraction of the gain bandwidth. However, the fluctuation disappears when the development of chaotic sidebands is suppressed by, for example, cavity detuning.

The FEL efficiency, the fraction of the electron beam's kinetic energy converted into the FEL output, is estimated to be about $1/2N$. Simulation result indicates that, when sidebands are suppressed by, for example, cavity detuning, the efficiency is about $1/4N$.

## Acknowledgements

We thank our colleagues at LBL and other laboratories, especially those listed below, for their generous help in this project: S. Benson, E. Szarmes, J. Bisognano, E. Bollt, J. Conrad, J. Goldstein, J. Haimson, L. Hensen, J. Hinkson, E. Hoyer, R. Miller, B. Taylor and R. Warren.

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