2

CONF-9208142--17

LBL-32287
UC-406

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

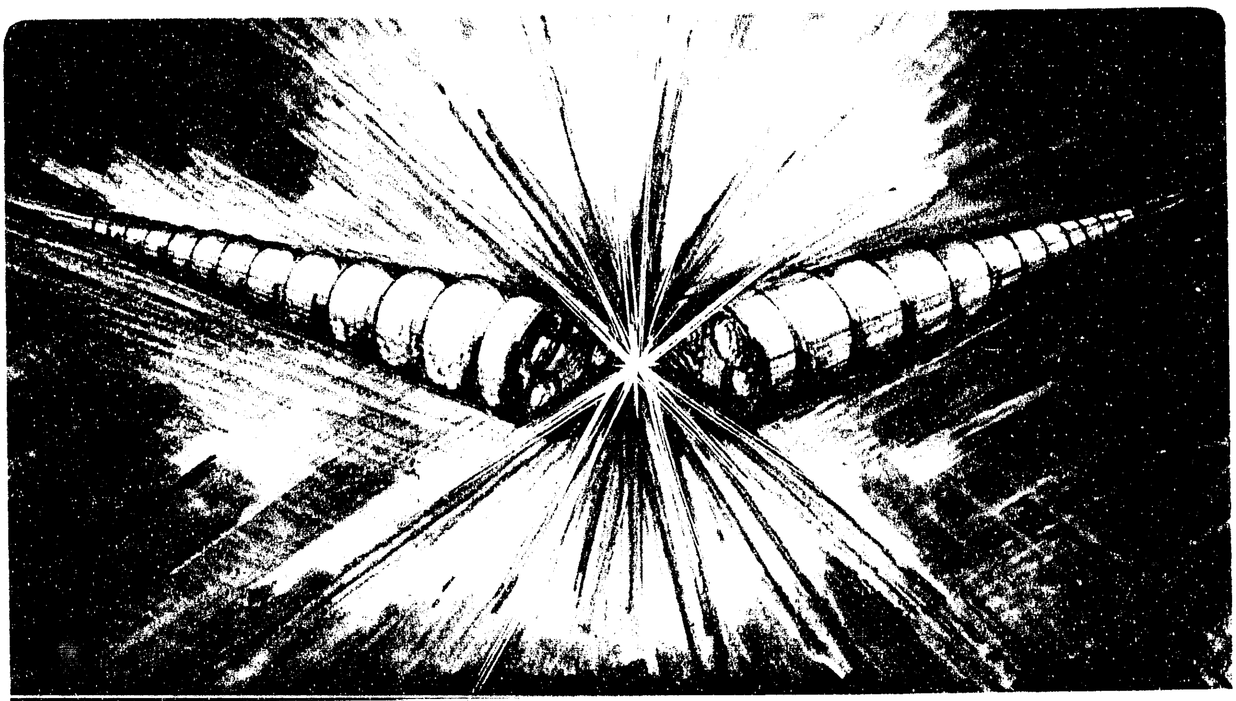
Accelerator & Fusion Research Division

Presented at the Fourteenth International Free Electron Laser Conference, Kobe, Japan, August 23–28, 1992, and to be published in the Proceedings

An Infrared Free Electron Laser System for the Proposed Chemical Dynamics Research Laboratory at LBL Based on a 500 MHz Superconducting Linac

K.-J. Kim, R. Byrns, S. Chattopadhyay, R. Donahue, J. Edighoffer, R. Gough, E. Hoyer, W. Leemans, J. Staples, B. Taylor, and M. Xie

September 1992



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

DISCLAIMER

LBL--32287

DE93 004723

AN INFRARED FREE ELECTRON LASER SYSTEM FOR THE PROPOSED CHEMICAL DYNAMICS RESEARCH LABORATORY AT LBL BASED ON A 500 MHz SUPERCONDUCTING LINAC*

K.-J. Kim, R. Byrns, S. Chattopadhyay, R. Donahue, J. Edighoffer, R. Gough, E. Hoyer, W. Leemans, J. Staples, B. Taylor, and M. Xie

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

Abstract

We describe a new design of the Infrared Free Electron Laser (IRFEL) for the proposed Chemical Dynamics Research Laboratory (CDRL) at LBL. The design and choice of parameters are dictated by the unique requirements of the CDRL scientific program. The accelerator system is based on the 500 MHz superconducting cavity technology to achieve a wavelength stability of 10^{-4}.

Presented at the 14th International FEL Conference, Kobe, Japan, 23-28 August, 1992.

* 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.

1. Introduction

This paper summarizes a new design of an infrared free-electron laser (IRFEL) for the proposed CDRL (Chemical Dynamics Research Laboratory) at LBL, based on a 500 MHz superconducting (SC) RF linac [1]. The primary motivation for adopting this approach is to meet the user requirement on wavelength stability equal to or better than one part in 10^4, which is difficult to meet with the previous design based on the room temperature RF technology [2]. In addition, the SCRF operates in CW mode, and hence delivers considerably higher average output power. It also allows flexible pulse formats that permit simultaneous multi-user operation.

The major parameters of the new CDRL-FEL are summarized in Table 1. The FEL will be installed in a basement vault of the CDRL building, to be constructed adjacent to the Advanced Light Source (ALS) facility at LBL. The IR pulses from the FEL can be synchronized with the UV and soft x-ray pulses from ALS, and also other conventional laser pulses at CDRL. The layout of the FEL in the vault of the CDRL building is shown in Fig. 1.

The accelerator - FEL system is summarized in section 2. The facility layout is discussed in section 3. Since the stringent requirement on electron beam stability was the main reason behind the choice of SCRF for CDRL-FEL, we devote section 4 for a comparative analysis of beam loading fluctuations in different RF structures. The analysis demonstrates clearly the need of SCRF technology in achieving the wavelength stability of one part in 10^4.

2. Accelerator-FEL System

The accelerator system starts from the injector consisting of a gun, bunchers and an energy slit. The electrons are produced in a conventional thermionic electron gun. The gun produces electron pulses with a duration of 1.5 ns, at an average current of 1.6 A (2.5 nC of charge). The pulses are squeezed into 33 ps, 30 A bunches by a sequence of three bunchers operating at frequencies of 61, 171 and 500 MHz. The first two bunchers operate at room temperature. The 500 MHz buncher is a 4-cell SCRF cavity in which the beam is bunched and accelerated to about 6 MeV. Before the main accelerator, a chicane with high-power energy slit is installed to remove the low energy tail on the bunches.

The main accelerator section consists of two SCRF accelerating modules in which the beam is accelerated to about 30 MeV. Each accelerating module is a dual cavity (4-cells per cavity) structure similar to that developed at DESY for HERA project [3]. Several manufacturers currently produce superconducting cavities, and most will guarantee performance at 5-6 MV/m and a Q_o of 2×10^9, which will satisfy our requirements for 5.25 MV/m and $Q_o = 2 \times 10^9$. We choose 4.5 K as the operating temperature for the SCRF cavities. A standard, 600 W helium refrigerator provides a sufficient reserve capacity and safety margin.

The 30 MeV beam is then recirculated by a beam transport section for a second pass through the accelerator section for a further acceleration to ~55 MeV. We have studied various beam instabilities associated with the recirculation, and determined that the instability thresholds are safely above the operating current of 2×12 mA for CDRL-FEL; The threshold for the HOM instability is about 1A for HOM coupler designed at DESY. Requiring the transverse transfer matrix of the recirculation loop to be an identity, the threshold of the transverse regeneration beam break-up instability is found to be about 340 mA [4].

The optics of the beam transport in the recirculation loop and in the path from the linac exit to the undulator must satisfy various constraints: It must be isochronous and achromatic to preserve the bunch structure. The achromatic correction must be sufficient to avoid significant beam motion while the beam energy changes by $\pm$ 1% for rapid wavelength tuning. The transfer matrix around the loop must be unity to suppress the beam break-up instability. The transverse profile of the electron beam needs to be matched to the transverse profile of the FEL optical beam, etc. Our design meets all of these requirements [5].

The electron beam interacts with the undulator magnetic field in the FEL optical cavity to generate coherent radiation. The FEL design must provide wide wavelength coverage while minimizing operational interruptions. At a fixed electron energy, the wavelength can be tuned between λ_{min} and $\lambda_{max} = 2.28\ \lambda_{min}$ by varying the magnet gap from 23 to 36 mm. The entire wavelength range from 3 to 50 μm can be covered by operating the accelerator at four different energies, 55.3 MeV, 39.1 MeV, 27.7 MeV and 19.6 MeV. By changing the electron beam energy by ± 1%, the wavelength can also be tuned by ± 2% in a fast tuning mode.

We have carried out extensive calculations to determine various characteristics of the CDRL-FEL, including the power, spectral characteristics, stability, etc. The calculation parallels closely to similar calculation for the previous design [6]. The spectrum will be transform limited by shortening the length of the optical cavity from that required for synchronization with the electron pulses. Taking into various efficiency factors, the FEL will deliver 100 μJ per pulse of optical energy to the experimental area. Since ease of tuning is a high priority for the CDRL-FEL, an essential feature of the design is an outcoupling scheme that covers the widest possible range of wavelengths. We adopted a hole-coupling approach after an extensive study of its performance [7].

We have initiated several experimental programs in support of the IRFEL design effort. These are the LBL-Stanford collaboration on development of novel diagnostics for FEL optical pulses [8], the Stanford-LBL-TRW-BNL collaboration on optimization of SC cavities for FEL [9], and experimental study of hole-coupling and resonator modes [10].

3. Facility Layout

The electron beam systems must be enclosed by a considerable thickness of radiation shielding to protect operators and users of the facility. The FEL will be housed in a concrete vault that also serves as part of the foundation of the CDRL building. The walls and roof of this vault will be formed with approximately 10 feet of conventional, poured-in-place concrete, and access to this area will be carefully controlled and monitored. Components inside the shielded vault include the injector and accelerator sections, all electron beam transport components, the undulator and optical cavity, and the electron beam dumps.

As shown in Fig. 1, separate shielding is provided at one end of the vault for a closed-loop water system used to operate two beam dumps. These dumps are identical and designed to safely absorb a 55-MeV beam with 800 kW of power. They are housed inside separate concrete bunkers within the main vault. One of these dumps is located near the exit of the accelerator and will be used primarily for commissioning, development, and debugging. The second dump is located near the point where the electron beam exits the optical cavity; this dump will become the primary dump once routine operation is established.

Space is also required outside the vault for a variety of power, control, and cryogenic systems, together with their associated equipment racks. Five commercially available 500-MHz power amplifiers, each utilizing two klystrons, are located in a 20 × 50 foot room just outside the shielding wall adjacent to the SCRF cavities. This room also houses the associated equipment racks, the klystron crowbar system, and water control systems for thermal stabilization of the room-temperature subharmonic bunchers. The power supplies for these bunchers are located nearby in a separate 20 × 20 foot room.

The cryogenic systems provide both helium at 4 K and liquid nitrogen at 80 K. Commerically purchased liquid nitrogen will be delivered by a house supply line from a nearby storage tank to points throughout the building. The helium will be generated on site by a 600-W refrigerator/compressor system. The helium system consists of the refrigerator/compressor, gaseous helium storage, and connecting cryogenic plumbing. The refrigerator is located in the basement level of the building approximately 70 feet from the cryostats in the vault. To isolate both noise and vibration, the compressor is located in a separate utility building approximately 200 feet away.

The FEL control room is located on the main floor of the building, directly above the FEL, and is adjacent to the experimental hall to promote good communication with the users.

4. Electron Beam Stability and Choice of SCRF

Our choice of superconducting RF structure is driven by the wavelength stability of one part in 10^4, which translates to electron energy fluctuations less than 5×10^{-5}. We have carefully evaluated various fluctuations in the accelerator system and determined that our design satisfies the requirement [1]. Here, we give a general comparative discussion of the beam loading fluctuations in different RF structures to demonstrate the need for SCRF to satisfy the above stability requirement.

Let f_c, V, R/Q, and Q_o be the resonant frequency, accelerating voltage, shunt impedance and unloaded Q of an RF cavity, respectively, and I_B be the beam current. The beam power gained in the cavity is therefore $P_B = I_B V$ and the power dissipated on the wall is $P_C = V^2/[(R/Q) Q_o]$. For an optimum coupling, the coupling coefficient is given by $\beta = 1 + P_B/P_C$ [11].

For fluctuations whose frequency f lies within the cavity bandwidth $\Delta f_c = f_c/2Q_L$ where $Q_L = Q_o/(1 + \beta)$, the fluctuation in the cavity voltage δV_B is related to the fluctuation in the beam current δI_B by $\delta V/V = -[(\beta-1)/(\beta+1)]\ \delta I_B/I_B$ [12]. The factor $(\beta-1)/(\beta+1)$, which will be referred to as the coefficient of the slow disturbance before feedback, is in general smaller than unity for a room temperature cavity (where $P_B << P_C$) while it is about unity for a superconducting cavity (where $P_B >> P_C$). After a feedback with a loop gain G, the fluctuation is reduced by a factor G. The factor $(1/G)(\beta-1)/(\beta+1)$, which will be referred to as the coefficient of the slow disturbance after feedback, is a measure of the RF stability.

The gain G (which falls off as 1/f) is limited by the requirement that it must decline to unity at the frequency f_1, where the loop phase shift become 180^o. Examining several factors contributing to the loop phase shifts (the length of the loop, the higher-order mode resonances, etc.), it is found that the frequency f_1 is about 1 MHz for the cases of interest [13]. The allowable gain is therefore $G = 1\ \text{MHz}/\Delta f_c$. Therefore the gain can be much higher in the superconducting case, resulting in a much smaller coefficient of the slow fluctuation after feedback than possible with the room temperature structures. This is the basic reason behind the superior stability performance of the superconducting RF system.

For faster fluctuations, $f > \Delta f_c$, the voltage fluctuation is given by $\delta V/V = (R/Q) (2\pi f_c q/2V)\ \delta q/q$, where q and δq is the charge and its fluctuation, respectively. The coefficient in front of $\delta q/q$ in this relation will be referred to as the coefficient of the fast disturbance. The coefficient of the fast disturbance scales as f_c^2. For the superconducting case, an accelerator system based on a lower RF frequency f_c is feasible because of the low cavity loss P_c. Thus, the superconducting option is also superior from the point of view of controlling fast fluctuations.

Table 2 provides a quantitative comparison of the stability performance of different RF options: (i) the previous CDRL-FEL design using room-temperature 1.3-GHz structures [2]; (ii) the new design discussed here; (iii) a possible CDRL-FEL design using superconducting 1.5-GHz structures; and (iv) the CEBAF accelerator design using superconducting 1.5-GHz structures [14]. For the room-temperature design, the coefficient of the slow disturbance after feedback is 7.2×10^{-3}. Assuming the current fluctuation to be about 0.1, we find that the fluctuations in the RF voltage can only be reduced to about 10^{-3}. For the superconducting CDRL design, the achievable stability is 2.5×10^{-5} (assuming $\delta I_B/I_B = 0.1$), which is smaller by more than an order of magnitude and also meets the constraints imposed by user requirements. The fast fluctuations are also smaller for the 0.5-GHz superconducting option because of the lower RF frequency.

The third column of Table 2 shows that the slow fluctuations after feedback for a possible CDRL design using superconducting structures of higher frequency are about 1.5×10^{-4} (assuming $\delta q/q = 0.1$), which does not meet the requirement. The stability improves for the CEBAF design (column 4), which also uses 1.5-GHz superconducting cavities, because the beam current for nuclear physics applications is lower. The beam current affects the stability because it influences the value of β.

[1] For detailed discussion, see "An Infrared Free-Electron Laser for CDRL," LBL preprint Pub-5335 (April 1992).

[2] K.-J. Kim, et al., Nucl. Instr. Meth. A304, 233 (1991).

[3] B. Dwersteg et al., Proc. IEEE Part. Acc. Conf., Washington DC, March 16-19, 1987, IEEE Catalog No. 78, CH2387-9, page 1716.

[4] G.A. Krafft and M. Xie, "Beam Breakup in a Superconducting IRFEL," LBL ESG TECH NOTE 176 (1991).

[5] J. Staples, J. Edighoffer and K.-J. Kim, "Electron Beam Transport for the LBL IR-FEL," paper presented at the 16th International Linac Conf., Ottawa, Canada (Aug. 23-28, 1992).

[6] K.-J. Kim and M. Xie, Nucl. Instr. Meth. A304, 146 (1991).

[7] M. Xie and K.-J. Kim, Nucl. Instr. Meth. A304, 792 (1991); Nucl. Instr. Meth. A318, 877 (1992); S. Krishnagopal et al., Nucl. Instr. Meth. A318, 661 (1992).

[8] W.P. Leemans, et al., "A Technique for Single-Pulse Spectrum and Pulse Width Measurements for an IRFEL," these proceedings.

[9] W. Barry, et al., "Field Profile and Loading Measurements on Higher Order Modes in a Two Cell 500 MHz Superconducting Structure," presented at the 16th International Linac Conf., Ottawa, Canada (Aug. 23-28, 1992).

[10] W.P. Leemans, et al., "Experiment and Simulation of Hole-Coupled Resonator Modes," these proceedings.

[11] P.B.Wilson, "High Energy Electron Linacs; Application to Storage Ring RF Systems and Linear Colliders," AIP Conf. Proceedings No. 87, page 450 (1982).

[12] G.A. Krafft, S.N. Simrock and K.L. Mahoney, in Proceedings of the 1990 Linac Conference, Alburquerque, NM, LANL report LA-12004-C (Conf.).

[13] We thank J.J. Bisognano, G.A. Krafft and S.N. Simrock for illuminating discussions clarifying this point.

[14] C. Leemans, "CEBAF Design Overview and Project Status," Proc. of the third Workshop on RF Superconductivity, Argonne, IL, 141 (1987).

Table 1

MAJOR CDRL-FEL PARAMETERS

Electron Beam	
Energy	55 MeV
Micropulse charge	1-2 nC
Micropulse length (FWHM)	33 ps
Micropulse rep. rate	6.1 MHz
Normalized rms emittance	11 mm-mr
Energy spread (FWHM)	0.35% at 55 MeV
SCR Cavity	
Frequency	500 MHz
Acc. gradient	5 MV/m
R/Q	125 Ω/m
Q_0	2×10^9
QL	1×10^6
Undulator	
Construction	Sm Co-Steel Hybrid
period length	5 cm
Number of periods	40
Bore diameter	21 mm
Magnet gap	23 mm
Range of K	0.9 - 2.1
Optical Cavity	
Length	24.6 m
Raleigh length	1 m
Coupling scheme	Hole coupling
Total loss	10%
Coupling efficiency	50%
FEL Output	
Wavelength range	3 - 50 μm
Pulse energy	100 μJ at 55 MeV
Av. Power	600 W
Bandwidth	Transform limited (0.1% at 10 μm)
Wavelength stability	$< 10^{-4}$
Intensity stability	< 0.1

Table 2

Accelerator performance parameters for four FEL designs

	CDRL RT 1.3 GHz	CDRL SC 0.5 GHz	CDRL SC 1.5 GHz	CEBAF SC 1.5 GHz
RF wavelength [m]	0.231	0.600	0.200	0.200
Q_0	2.0×10^4	2.0×10^9	2.0×10^9	2.4×10^9
R/Q (per cell) [Ω]	289	125	100	96
R (per cell) [MΩ]	5.78	2.5×10^5	2.0×10^5	2.3×10^5
Accelerating gradient [MV/m]	8	5.25	6	5
Voltage per cell [MV]	0.923	1.50	0.600	0.500
Power dissipated per cell [W]	1.47×10^5	9.0	1.80	1.09
Stored energy per cell [J]	0.361	5.73	0.382	0.276
Beam current [mA]	36	12	12	0.8
Power transferred to beam (per cell) [kW]	33.2	18.0	7.2	0.40
Coupling paramter, β	1.23	2000	4000	370
Loaded Q	8.99×10^3	9.99×10^5	5.00×10^5	6.48×10^6
Filling time [μs]	2.2	636	106	1370
Cavity bandwidth [kHz]	72.3	0.250	1.50	0.116
Coeff of fast disturbance (at 1 nC)	1.28×10^{-3}	1.31×10^{-4}	7.85×10^{-4}	9.04×10^{-4}
Allowed gain, G	13.8	4000	666	8630
Coeff of slow disturbance				
before feedback	0.1	1.0	1.0	1.0
after feedback	7.2×10^{-3}	2.5×10^{-4}	1.5×10^{-3}	1.2×10^{-4}

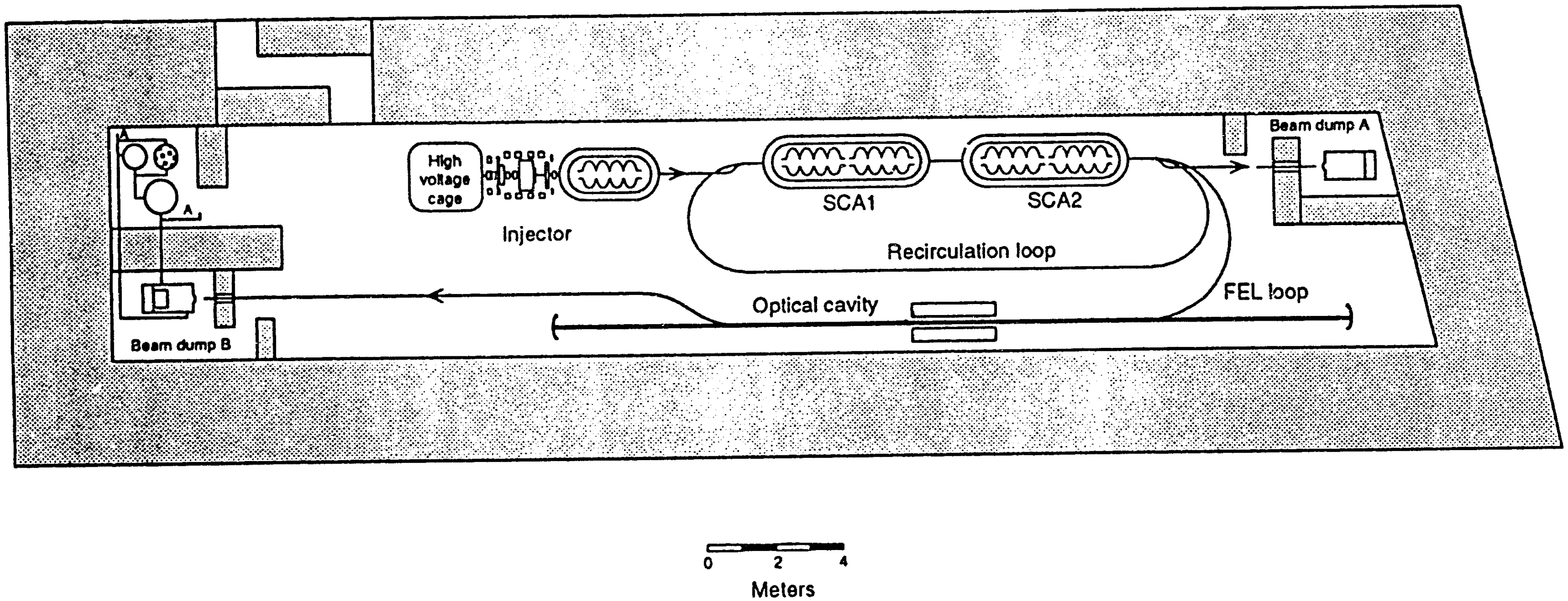


Fig. 1 Layout of IRFEL inside the Vault of the CDRL Building.

END

DATE
FILMED
02/19/93