DESIGN OF A SUPERCONDUCTING LINEAR ACCELERATOR FOR AN INFRARED FREE ELECTRON LASER OF THE PROPOSED CHEMICAL DYNAMICS RESEARCH LABORATORY AT LBL*

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Abstract

An accelerator complex has recently been designed at LBL as part of an Infrared Free Electron Laser facility in support of a proposed Chemical Dynamics Research Laboratory. We will outline the choice of parameters and design philosophy, which are strongly driven by the demand of reliable and spectrally stable operation of the FEL for very special scientific experiments. The design is based on a 500 MHz recirculating superconducting electron linac with highest energy reach of about 60 MeV. The accelerator is injected with beams prepared by a specially designed gun-buncher system and incorporates a near-isochronous and achromatic recirculation line tunable over a wide range of beam energies. The stability issues considered to arrive at the specific design will be outlined.

1. Introduction

This paper provides a brief description of a recent design of a superconducting linac-based system as part of an infrared free-electron laser (IRFEL) for the proposed Chemical Dynamics Research Laboratory (CDRL) at LBL [1]. The heart of the system is a driver based on a 500 MHz superconducting radio-frequency (SCRF) linac, with recirculation loops. 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 a previously carried-out design based on the room temperature RF technology [2]. In addition, the CW mode of operation of the SCRF allows delivery of considerably higher average output power and flexible pulse formats that permit simultaneous multi-user operation.

The major parameters of the new CDRL-FEL are summarized in Table 1. The FEL is planned to 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 proposed for the CDRL. The layout of the SCRF linac-FEL system in the vault of the CDRL building is shown in Fig. 1.

We summarize the linac-FEL system in section 2. Section 3 is devoted to issues of stability, the stringent requirements of which led to the choice of SCRF for the CDRL-FEL. We close with words on present activities and outlook in section 4.

2. Linac-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 the HERA project [3]. Several manufactures 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 further acceleration to ~55 MeV. The magnetic 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 need to be matched to the transverse profile of the FEL optical beam, etc. Our design meets all of these requirements [4].

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}

* 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.

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 CDRL-FEL, including the power, spectral characteristics, stability, etc. [1]. The spectrum will be transform-limited by shortening the length of the optical cavity from that required for synchronization with electron pulses. Taking into account various efficiency factors, the FEL will deliver 100 μJ per pulse of optical energy to 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 [5].

The design of the concrete shielding, high power beam dumps and the cryogenic system have been given careful engineering considerations.

3. Stability Issues

The major stability issues are associated with the coherent collective stability of the high average current electron beam and the FEL wavelength stability arising from electron energy fluctuations in the superconducting linac.

We have studied various coherent beam instabilities including ones associated with the recirculation, and determined that the instability thresholds are safely above the operating current of 2 × 12 mA for the CDRL-FEL. The threshold for the HOM instability is about 1 A for HOM couplers designed at DESY. Requiring the transverse transfer matrix of the recirculation loop to be an identity, the threshold of the transverse regenerative beam break-up instability is found to be about 340 mA [6].

Our choice of superconducting RF structure is driven by the wavelength stability requirement of one part in 10^4, which translates to a required electron relative energy fluctuation of less than 5×10^{-5}. The selection of a low-frequency (500 MHz) structure, based on standing-wave superconducting cavities is a result of a thorough and careful consideration of this issue. Standing-Wave structures usually allow better control, compared with travelling-wave structures or waveguides. The choice of a superconducting, rather than room-temperature, structure was based on considerations of electron beam energy stability: Continuous-Wave (CW) operation of SC cavities allows more time for feedback control, as well as a higher feedback loop gain over a narrower bandwidth, and hence assures better stability. The frequency choice of the accelerator was again based predominantly on stability considerations: Low frequencies imply large transverse dimensions and a greater cavity volume. Thus, the cavity stores more energy, relative to the beam, and wake-field effects arising from the proximity of metallic boundaries to the beam are minimized — both of which improve stability. The cost penalty due to larger structures is not significant for superconducting cavities.

We have carefully evaluated various fluctuations in the accelerator system (e.g. beam loading fluctuations in the RF structures, etc.). The detailed analysis [1] demonstrated to us the need for SCRF as well as determined that our specific design satisfies the stability requirements for 'fast' and 'slow' fluctuations relative to the cavity response time.

4. Outlook

To date, the LBL CDRL-IRFEL represents a careful and detailed design, the first of its kind, of a free electron laser as a dedicated user facility with the issues of reliability, stability and specific experimental needs given the highest priority. We have jointly 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 [7], the Stanford-LBL-TRW-BNL collaboration on optimization of SC cavities for FEL [8], an experimental study of hole-coupling and resonator modes [9] in the Optics Laboratory of the Exploratory Studies Group at LBL and an emerging collaboration with CEBAF on IRFEL studies at the front-end of the CEBAF accelerator complex.

5. References

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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	5.25 MV/m
R/Q	125 Ω/m
Q_0	2×10^9
Q_L	1×10^6
Undulator	
Construction	SmCo-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

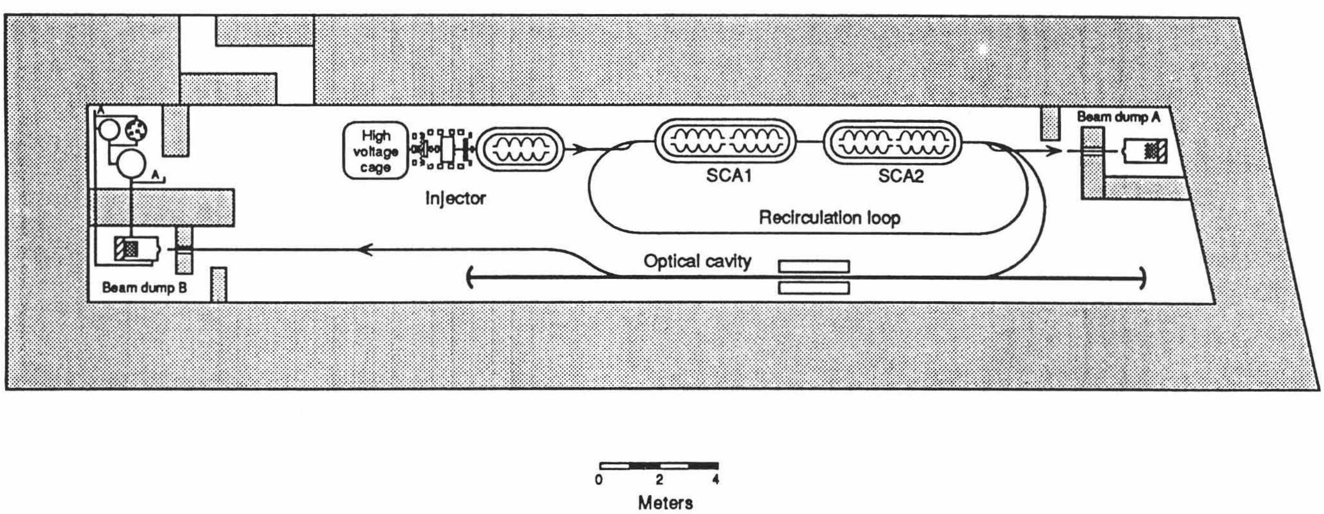

Fig. 1: Layout of IRFEL inside the Vault of the CDRL Building.