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ELECTRON BEAM TRANSPORT FOR THE LBL IR-FEL*

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Abstract

The infrared free-electron laser (IR-FEL) proposed by LBL as part of the Combustion Dynamics Research Laboratory (CDRL) consists of a multiple-pass accelerator with superconducting cavities supplying a 55 MeV 12 mA beam to an undulator within a 24 meter optical cavity. Future options include deceleration through the same cavities for energy recovery and reducing the power in the beam dump. The electron transport system from the injector through the cavities and undulator must satisfy conditions of high order achromaticity, isochronicity, unity first-order transport matrix around the recirculation loop, variable betatron match into the undulator, ease of operation and economical implementation. This paper will present a workable solution that satisfies these requirements.

Introduction

The LBL IR-FEL serves the chemical sciences community by providing a λ = 3–50 μm beam with up to 600 watts of optical power. Two 500-MHz superconducting accelerator (SCA) cavities in a recirculating configuration provide an energy range of 20 to 55 MeV in a 40-pole, 2-meter undulator with a 5 cm period. Light generated within the 24.6 meter optical cavity has a frequency stability of 1 part in 10^4 due in part to the c.w. operation of the SCA.

The electron beam transport system takes the beam from the 6 MeV superconducting cavity injector through the two SCA sections in a two-pass recirculating configuration, through the undulator and to a high-power beam dump. Each SCA section adds up to 12 MeV to the beam which can reach 55 MeV in two-pass operation, with 6 MeV provided by the injector. The orbit length is be a multiple of $\beta\lambda$ and the transfer matrix around the loop is set to unity to reduce the tendency to transverse regenerative beam breakup in the SCA. Figure 1 shows the overall configuration of components in the shielding vault.

The bunch structure of the injector is preserved and a 1% momentum variation for rapid wavelength tuning must be accommodated, requiring the 180° arcs to be both achromatic and isochronous with third-order corrections to avoid significant transverse beam motion in the undulator.

The beam is focused to a waist in the center of each SCA structure to minimize coupling to the r.f. fringe field. The 180° arcs accommodate beam centroid monitors (strip-lines, e.g.) to monitor relative momentum shifts to a resolution of one part in 10^5 for active accelerator r.f. amplitude control.

A magnetic bunch compressor is included after the injector to provide some control of the bunch length and will also contain an energy defining slit to remove a low-energy tail from the beam.

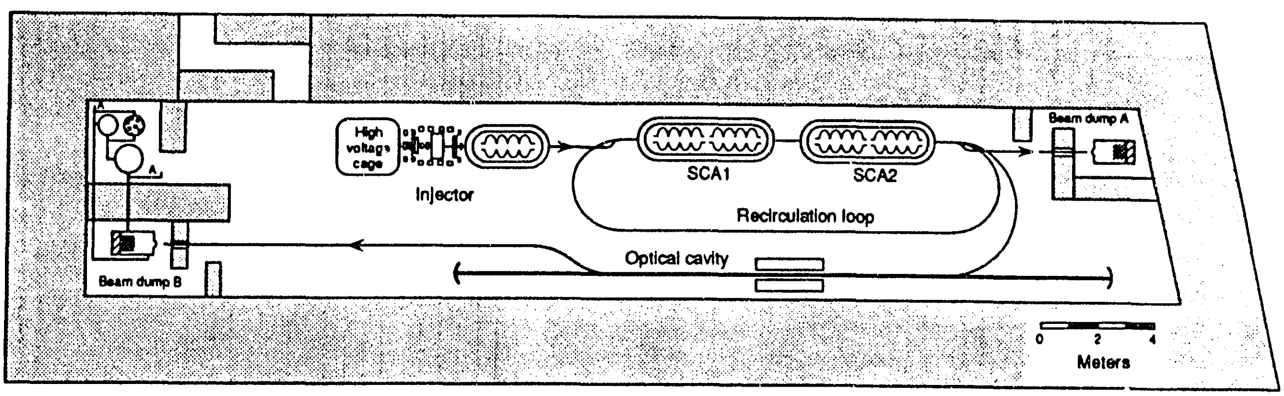

Figure 1. Overall Configuration of Components in Shielding Vault

Design Parameters

The requirements can be summarized as follows:

- The c.w. superconducting injector supplies a 6 MeV beam with $\varepsilon^n_{rms} = 30\,\pi$ mm-mrad with a 4% FWHM $\Delta P/P$, plus a long low-energy tail which is subsequently removed.
- A magnetic bunch compressor and energy slit follow the injector, removing any low energy tail more than 100 keV below the nominal 6 MeV, or about 20% of the current.
- Two 12-MeV 500 MHz SCA structures accelerate the beam at $\phi_s = 90°$ resulting in a $\Delta P/P$ of approximately 0.8% FWHM at 30 MeV.
- The beam will be recirculated through two 180° arcs and further accelerated to 55 MeV. An additional long wavelength undulator may be included in the 30 MeV return line at a future time.

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- The 180° arcs are achromatic and approximately isochronous. The chromatic correction limits the transverse or angular displacements to no more than 10% of the ellipse parameters for momentum changes of up to 1%.
- The path length around the recirculating orbit must be an integer multipole $\beta\lambda$ to satisfy the microtron condition.
- The transfer matrix of the recirculating loop is unity to avoid transverse beam breakup.
- The vertical beam betatron amplitude at the undulator β_y is varied over 0.33–0.73 meters as the gap spacing is changed with β_x constant at 1 meter.
- The 6, 30 and 55 MeV beams will be physically separated as soon as possible before and after the SCA sections and directed through their own transport channels.
- The 180° arcs will include diagnostic equipment (striplines, e.g.) to monitor relative momentum shifts to a precision of one part in 10^5.
- With beam power expected to top one-half megawatt at 55 MeV, the aperture will be at least 5σ throughout the entire beam line.
- The energy spread of the beam into the undulator at 55 MeV is 0.4% FWHM, and 2% after the undulator.
- Full power beam dumps will be provided at 6 MeV for SCA tuning, and at full energy after the undulator.
- The design will allow deceleration back down to 6 MeV to be added at a later time, saving r.f. power and activation of the high-energy beam dump.
- The overall size is constrained by clearance for the optical cavity and dewars, and by the 7 meter vault width.

Transport Line Configuration

The beam line is implemented in modules, each providing a specialized task. These modules include:

- 180° achromatic, isochronous arc, corrected to second order
- Transport lines between the SCA sections and the 180° arcs
- Transport line from the 180° arc to the undulator
- Beam separators at the end of the SCA sections
- Energy slit and magnetic compressor at the exit of the 6 MeV injector
- Transport line to the beam dumps

Figure 2 shows the configuration of magnetic elements in the beam transport system. The 6 MeV beam enters the combiner through an achromatic dogleg and is accelerated through the two SCA cavities to 18–30 MeV. The separator at the end of the SCA section directs the 6 MeV beam through the first 180° arc, the return line and the second 180° arc for a second pass through the accelerating cavities. The beam, now at an energy of 30 MeV, is separated from the 6 MeV beam, directed around the larger arc and to the undulator.

The optical axis of the undulator is translated 22.7 cm over from the exit of the 180° arc to provide clearance for the FEL cavity mirrors and their supports. The beam emerging from the undulator is achromatically translated 33.9 cm to pass around the mirror and directed to the beam dump.

The Arcs. Three arcs are provided, two symmetric units for the 30 MeV first pass and a 55 MeV arc which brings the beam to the undulator. Each arc is symmetric about its midpoint. The 30 MeV arc spans 2.35 meters and comprises 7 identical dipoles, 4 families of quadrupoles and one family of sextupoles. Seven dipoles helps achieve sufficient third order correction.

Each arc is achromatic and nearly isochronous to preserve beam emittance and bunch length and to allow a 1% fast energy tuning. To compensate the slight nonisochronism in the beam separators and the offset of the undulator optical axis from the exit position of the high energy 180° arc, an equal negative value of nonisochronism is introduced in each of the 180° arcs.

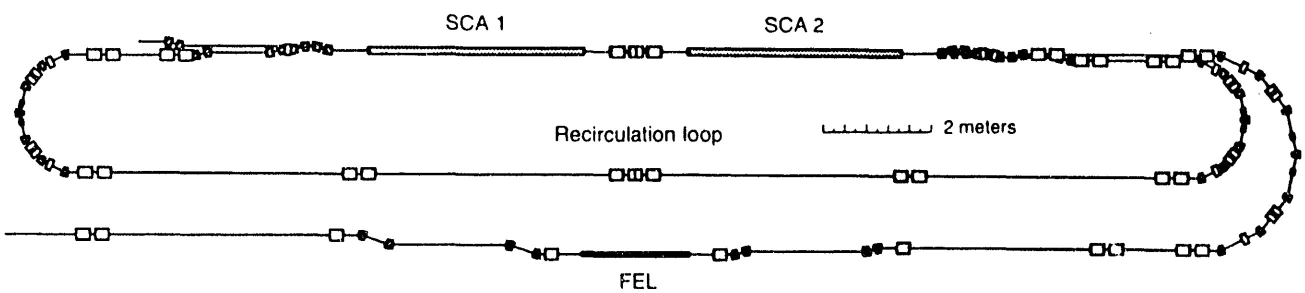

Figure 2. Configuration of Magnetic Elements in the Beam Transport System.

The achromatism of the arcs is corrected to second order by a pair of sextupoles straddling the central bending magnet. This correction also reduces the third order chromatic aberration significantly so that the beam displacement and angular error is held to within 10% of the ellipse parameters for momentum offsets of up to ±1.5%.

Focusing keeps β_x below 1 meter over most of the arc, with dispersion η_x peaking at 0.5 meter for stripline beam centroid monitors. Each 30 MeV arc is mechanically movable as a unit to trim the path length around the first loop to preserve the microtron condition.

The Transport Sections To and From the Arcs. The beam is matched from the accelerator section, through the beam separators into the 30 and 55 MeV arcs each by a pair of quadrupole doublets. After the first 30° arc, the beam is transported to the second 30 MeV 180° arc by a symmetric arrangement of quadrupole doublets (triplet at the symmetry point). The 30 MeV beam return path is reserved for a future second undulator and optical cavity.

The beam from the 55 MeV 180° arc is matched into the undulator by an arrangement of five quadrupoles and an achromatic four-dipole dogleg. The total transfer matrix around the 30 MeV loop is unity to suppress regenerative beam breakup in the SCA sections. The phase advance around the 30 MeV loop is a multiple of 2π and the betatron amplitudes β_x and β_y are adjusted to the optimal value of 6 meters in the middle of each SCA cavity.

The Final Partial Arc. The 55 MeV beam from the undulator is translated 33.9 cm from the optic axis by four identical dipoles in an achromatic four-bend dogleg similar to the 6 MeV injection offset.

The Beam Separators. The beam separator is the most complex element in the electron beam transport system. It must separate the orbits of the 6 MeV beam from those of the $6{+}\Delta E$ and the $6{+}2\Delta E$, where ΔE, the energy gain through the two SCA cavities, ranges up to 24 MeV. The separators divide three beams of adjustable energy into three fixed offset beam lines. The nominal 30 and 55 MeV beams have a 5σ stay-clear plus at least 1 cm magnetic septum width for further bending. The betatron function at the separators is about 12 meters in both planes, and the normalized rms emittance is 30π mm-mrad.

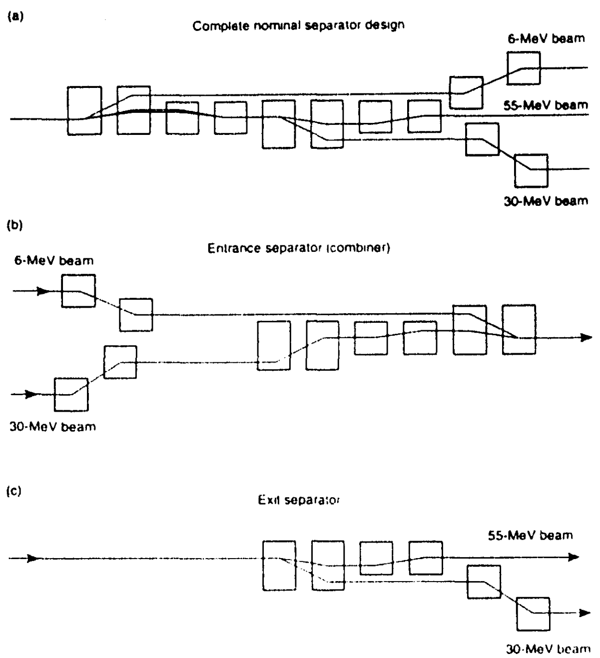

Figure 3. Separator Configurations: (a) Fully Loaded, (b) at Entrance and (c) Exit Ends of SCA.

Figure 3(a) shows the design of a complete device, which may be used in the future if deceleration and energy recovery is implemented. This device separates the 6 MeV beams from the other two, whose maximum energies are 30 and 55 MeV, and minimum energies are 18 and 30 MeV. Figures 3(b) and 3(c) show partial designs which are used at the entrance and exit of the accelerating section. Starting at the cavity and working outward, the first magnet group separates the 6 MeV injected beam, returning the 30 and 55 MeV beams to the axis, and the second set separates the 30 and 55 MeV beams, returning the 55 MeV beam to the axis. With a constant 6 MeV injection energy, the orbits of the two high energy beams are maintained outside of the separators for varying SCA energy gain with no mechanical motions required.

The 55 MeV beam is directed to the larger 180° arc and the 30 MeV beam is offset 19.8 cm toward the inside of the ring and directed to the smaller 180° arc. The worst-case separation of the two high energy beams is 4.2 cm in the middle of the second group of four dipoles when the SCA is operating at a 24 MeV energy gain. The two 180° arcs are identical, so the offset provided for the 30 MeV beam at each end of the SCA section must also be the same.

The bumps and doglegs are achromatic but not isochronous. An equal and opposite non-isochronism is introduced in the 180° arcs to provide an isochronous transport to the ring symmetry points. To preserve symmetry and to allow for the future energy recovery option, the separators are kept symmetric on each side of the SCA section.

Energy Slit and Magnetic Compressor. The 4-magnet translation for the 6 MeV beam also serves as a magnetic energy compressor and energy selection slit. The m_{56} matrix element for the translation will be set by the final choice of geometry at about 0.4 cm/%$\Delta p/p$, and the dispersion η_x is on the order of 0.33 meters where the matched beam amplitude β_x is about 0.55 meters.

Transport System to the Beam Dumps. The beam is transported to the beam dumps by an achromatic four bend dogleg, two sets of doublets and a beam scanner. With an average power of 650 kW at the highest energy and current, the beam must be spread over an area of at least 80 cm^2 at the dump. Raster scanning is probably the best solution, which avoids the precise steering problems and long transverse distribution tails associated with quadrupole or higher multipole beam spreaders. A scanning failure monitor is required to protect the target.

Inventory of Magnetic Elements. The dipoles are all short, typically 10 cm long, with modest fields and less than a 2 cm gap. The quadrupoles are typically 10 cm long with modest gradients less than 15 T/cm. Fifty-three quadrupoles in 33 families, and 49 dipoles in 8 families are required exclusive of the beam transport system from the injector and to the beam dumps.

Future Expandability. The design of the beam allows addition of a second undulator in the 30 MeV return line, adjacent to the installed one. In addition, the beam line configuration easily allows inclusion of an energy recovery deceleration option by adding one more 55 MeV 180° arc and decelerating the beam back down to 6 MeV, saving r.f. power and reducing the beam dump power and energy.

Reference

An Infrared Free-Electron-Laser for the Chemical Dynamics Research Laboratory Design Report, PUB-5335, Lawrence Berkeley Laboratory, April 1992

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