A HIGH-ENERGY BEAM TRANSPORT SYSTEM[*]

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Summary

The High-Energy Beam Transport (HEBT) system for the Fusion Materials Irradiation Test (FMIT) Facility is to be installed at the Hanford Engineering Development Laboratory (HEDL) at Richland, Washington. The linear accelerator must transport a large emittance, high-current, high-power, continuous-duty deuteron beam with a large energy spread either to a lithium target or a beam stop.[1] A periodic quadrupole and bending-magnet system provides the beam transport and focusing on target with small beam aberrations. A special rf cavity will spread the energy in the beam so that the Bragg Peak is distributed within the lithium target. Operation of the rf control system, the Energy Dispersion Cavity (EDC), and the beam transport magnet will be tested on the beam stop during accelerator turn-on. Characterizing the beam will require extensions of beam diagnostic techniques and noninterceptive sensors. Provisions are being made in the facility for suspending the transport system from overhead supports using a cluster system to simplify maintenance and alignment techniques.

Introduction

The HEBT system (Fig. 1) contains four subsystems: the EDC, the beam transport optics and other beam-line components, a beam spreader (a quad doublet), a beam stop, and the HEBT support system. The EDC must create a large energy spread in the beam delivered to the target. The beam optics must transport a large emittance, 100-mA deuteron beam with large energy spread at either 20 or 35 MeV to one of the two lithium targets or to a beam stop. The lithium target requires an incident 1-cm by 3-cm FWHM Gaussian spot whereas the beam stop requires a 16-in diameter circular spot. The beam spreader and beam stop have been provided for tune-up using a pulsed beam. A minimum 2.1-m (7-ft) clearance must be maintained between the support structure and the HEBT hardware to allow component maintenance.

The Periodic Beam Transport System

The primary design consideration in the beam transport system is minimization of beam spill to prevent unacceptably high activation of components. The use of a magnetic transport system with an acceptance equal to or greater than the maximum possible output emittance of the accelerator is the best way to accomplish this minimization of beam spill; however, care must be taken so excessively large apertures do not drive the magnet costs too high. Magnet apertures are minimized with a properly matched beam in a periodic system. Although such systems often appear to be complicated at first glance, they are invariably cheaper to build because of the smaller aperture requirements, relaxed tolerances, shared power supplies, and many identical components.

The simplest method of transporting the beam the relatively short distance to the first bending magnet is to extend the periodic structure of the linac. The quadrupoles are slightly weakened to compensate for the lack of rf defocusing. A matched beam in the accelerator will, therefore, be nearly matched in this section. The periodic quad structure offers the advantage that diagnostics in this section can give the operator an indication of the beam conditions inside the machine because of the nearly identical focusing structure.

The bending magnet system is also periodic, consisting of four identical magnets with the angles of bend of the second and fourth magnets reversed. Vertical focusing is provided by the downstream edge angle of each magnet. The edge angles are adjusted so that the phase shift of a single-bend cell is 90° in both planes. The calculations were done using the computer code, TRANSPORT.[2] This arrangement is achromatic because any system composed of n identical cells of phase shift μ such that $n\mu = 360°$ is automatically achromatic and all second-order geometric aberrations are also zero. Second-order chromatic aberrations can be

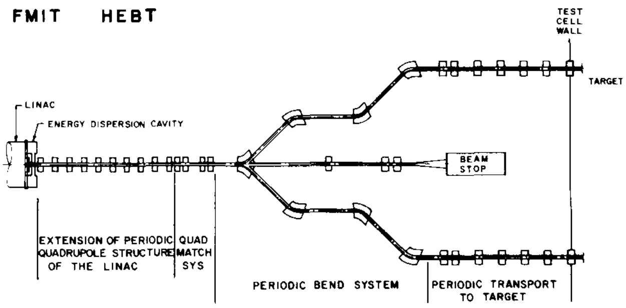

Fig. 1. The FMIT HEBT.

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corrected easily with the introduction of sextupoles[3] but this is unnecessary in the present case.

The bending magnet apertures remain quite small because there are no quadrupoles in the region of high dispersion. All four bending-magnets can be run in series on a single power supply. A mirror image of the bend system provides the transport to the second target cell.

The quadrupole array following the linac is matched to the bending-magnet system using a scheme devised by K. L. Brown.[4] The required matching conditions are determined from the transform matrix, R, of a single cell. The Courant-Snyder parameters are

$$\cos \mu_x = \frac{1}{2} (R_{11} + R_{22}) \quad ,$$

$$\alpha_x = \frac{1}{2} \frac{(R_{11} - R_{22})}{\sin \mu_x} \quad , \text{ and}$$

$$\beta_x = \frac{R_{12}}{\sin \mu_x} \quad ,$$

with similar equations for the y-plane. The matching system is constructed by placing a matching quadrupole ,Q1, midway between waists of the periodic quadrupole system (where $\beta_x = \beta_y$, $\alpha_x = -\alpha_y$) and a second quadrupole, Q2, at the corresponding location in the bending-magnet system. Two fixed-strength quadrupoles are added to complete the matching system, which has a 90° phase shift in both planes from the center of Q1 to the center of Q2. This procedure essentially decouples the two matching conditions, with Q1 controlling β (in both planes) and Q2 controlling α at the match point, which is at the center of Q2. The drifts at each end of the matching system were varied slightly to compensate for the fact that a quadrupole does not behave quite like a thin lens with $F_x = -F_y$.

Transport from the last bending magnet to the target can be accomplished in a number of ways. The last four quadrupoles are adjusted to obtain the desired spot size at the target. The large energy spread and the potentially large emittance coupled with the relatively small (1-cm vertical spot required at the target) require that chromatic and third-order geometric aberrations be considered. Calculations were made using the computer code TURTLE[5] with modifications to include the bimodal momentum distribution. The results indicated that, depending on the emittance, it may be impossible to achieve the desired spot size if the last quadrupoles are too far from the target unless the aberrations are corrected. Correction of the aberrations could be done with sextupoles and octupoles but a much simpler procedure is to place the last quadrupole close to the target (within 50 cm) in which case the aberrations are negligible.

Other Systems

Energy Dispersion Cavity

The EDC is a special rf cavity at the end of the linac that operates at a frequency slightly different from the 80 MHz of the accelerator itself, so that the energy dispersion is a "beat" of a few MHz. The cavity is a TM_{010} resonator that has a gap about equal to the last gap of the drift-tube linac. The EDC is amplitude controlled but not phase controlled. Frequency control is not critical. The current design creates a ±750-keV spread in beam energy with a dispersion profile that is a strong function of the inherent linac dispersion and a weak function of beat frequency. Positioning the cavity at the end of the linac permits its use for either beam-line branch.

Beam Stop

A beam spreader and a beam stop have been provided for initial tune-up purposes using an H_2^+ beam in a pulsed mode or a very low, steady state current of deuterons. Because the fill time of the linac tanks is under 2 ms, 10-ms pulse widths can be used to exercise adequately the operation of the rf control system, the set points of the drift-tube quads in the linac, and the HEBT up to the first bending magnet. The short pulse widths allow low duty-factor operation at full peak power, which greatly simplifies the design, construction, and expected lifetime of the beam stop. The beam stop will utilize the calorimeter principle and resembles the Lawrence Berkeley Laboratory designs, which consist of two thick and angled copper plates joined at the apex.[7]

Beam Diagnostics

Monitoring the progress of the transported beam will require noninterceptive sensors such as current transformers, magnetic position monitors, inductive pickups, and spill detectors. The information and feedback from these sensors must be processed through the control system and then returned to beam-handling elements with sufficient speed and sensitivity to correct out-of-bounds conditions with minimal spill of the deuteron beam. The feasibility of providing profiles of the density distribution within the beam by viewing (and digitizing) the light emitted from recombination processes of ionized residual gases in the beam tube is being studied. Three such optical profiles may be converted to a two-dimensional density plot and three or four such density plots from differing transport conditions may be reconstructed to give emittance information.

Further requirements for the diagnostics system include measurement of longitudinal phase, and verification of the required energy spread on target. The shape of the beam spot on target must be well defined because it is the source both of 3.5 MW of lithium target heating and of the product neutrons. These measurements must be made reliably in the presence of quite intense neutron fields.

Beam-line Suspension System

The facility is being designed to allow the transport system to be suspended from overhead supports to facilitate mechanized maintenance of activated components. The transport support system is a grid of I-beams supported by the walls of the building. Alternate methods are being studied for attaching the beam-line components to the support system and a variety of mounts have been proposed. The mounting stand will give all degrees of freedom of movement to the element to allow for its proper alignment.

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