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1.0 SCOPE

1.1 This Technical Specification is for the design and fabrication of a fixed-gap, planar hybrid wiggler to be used on the CEBAF infrared demonstration free-electron laser (IR Demo FEL) .

1.2 The wiggler shall produce a resonant wavelength of 3 micrometers with a 42 MeV electron beam, with a full magnet gap of no less than 12 mm.

1.3 This Technical Specification covers the magnetic structure, including permanent magnets, poles, and end correctors (section 3.1), the mechanical interface including the backing beams alignment fiducials and support structure (section 3.2), compatibility with the wiggler vacuum chamber (section 3.3), and the mechanical and magnetic acceptance tests required of the contractor (section 4).

1.4 The production process should have the following milestones:

1.4.1 Magnetics design review. This shall occur no later than two months after award. At this design review the magnetic design will be analyzed and approved by the CEBAF technical representative. See section 4.1.1.

1.4.2 Mechanical design review. This shall occur no later than three months after award but may occur at the same time as the magnetics review. At this design review the mechanical design will be analyzed and approved by the CEBAF technical representative. See section 4.1.2.

1.4.3 Measurement review. A representative from CEBAF may witness the final measurements of the wiggler. This shall occur no later than 11 months after award.

1.4.4 Acceptance by CEBAF. Delivery shall occur no later than 12 months after award. The wiggler quality and the measurements shall be reviewed by CEBAF staff in no more than 30 days from arrival at CEBAF.

2.0 APPLICABLE DOCUMENTS

2.1 Contractor-supplied components and systems shall be in agreement with the applicable portions of the latest standards of:

2.1.1 Safety -Occupational Safety and Health Administration (OSHA) Standards, 29CFR 1900 through 1926.

2.1.2 Permanent Magnets - American Society for Testing and Materials (ASTM) Standard A340-65.

2.1.3 Pole pieces - American Society for Testing and Materials (ASTM) Standard A801-82, "Standard specification for iron cobalt high magnetic saturation alloys".

2.1.4 Welding - American Welding Society (ANSI/AWS) D I.2.

2.1.5 Mechanical - American Society for Testing and Materials (ASTM), Standards F738M-81(reapproved 1988) for stainless steel bolts, F468-84a for non-ferrous bolts, and F467-84 for non-ferrous nuts.

2.2 There are restrictions on the physical region that the wiggler may occupy. The physical interface between the wiggler and the accelerator is shown in:

2.2.1 CEBAF drawing No. 09510-D-0001, showing a plan layout and side view of the wiggler in the accelerator transport system in the vicinity of the wiggler. This drawing includes information about the coordinate system used in this technical specification. The *y* direction is vertical and the *x* direction is horizontal, directed to the right from the electron beam axis. The origin of the *x* and *y* axes is at the location of the electron beam.

2.2.2 CEBAF drawing No. 09510-C-0002, showing the cross-section of the vacuum chamber, for a minimum wiggler magnetic gap of 12 mm and the viewports necessary for diagnostic purposes.

2.3.3 CEBAF drawing No. 09510-C-0003, which shows a suggested scheme for supporting the wiggler and the required alignment fiducials for the wiggler. This drawing shows an H-frame support for the backing beams. A C-frame might also be used if the magnetic properties are not compromised.

3.0 TECHNICAL REQUIREMENTS

3.1 Magnetic Structure Requirements

3.1.1 The magnetic structure includes the periodic structure, which is the periodic arrangement of ferromagnetic poles and permanent magnets; and the end structures. The two halves of this structure shall be held rigidly such that the wiggler can be handled as a single unit for purposes of installation and alignment. (see section 3.2 for the specification for the stability of the mount).

3.1.2 The period length shall be 27.0 mm ± 50 micrometers, non-cumulative.

3.1.3 The effective number of periods shall be 40. This shall be measured by the calculated width of the spontaneous spectrum on axis and therefore includes the end correctors. There shall be even number of poles.

3.1.4 The overall length of the wiggler shall not exceed 115 cm. The overall width shall not exceed 35 cm and the overall height shall not exceed 25 cm.

3.1.5 The poles for the magnetic structures require:

3.1.5.1 The poles shall be fabricated from certified vanadium permendur.

3.1.5.2 After completion of the pole fabrication, the poles shall have a certified magnetic anneal following the procedure outlined in ASTM specification A801-82. Only minimal grinding is allowed after the magnetic anneal, and only if the poles are out of specification after the annealing process. The poles are to be free of any oxide layers and discoloration that are visible to the naked eye.

3.1.6 Permanent magnet blocks. Magnetic quantities in section 3.1.6 use SI units. The equation defining the vector quantities is $B = \mu_0(H + M)$ in SI units. The definitions of magnetic quantities in this technical specification correspond to those in ASTM Standard A340-65. The permanent magnet blocks used between the poles of the periodic magnetic structures and in the end assemblies require:

3.1.6.1 The permanent magnet blocks shall be fabricated from neodymium-iron-boron type magnetic material.

3.1.6.2 The permanent magnet blocks shall be stabilized so that there will be no irreversible degradation greater than 0.05% of the magnetic moments of the blocks after heating to 60°C.

3.1.6.3 Linearity of the nominal intrinsic induction $B_i = \mu_0 M = B - \mu_0 H$. After thermal stabilization, when the second quadrant $B_j(H)$ is fitted to a straight line in the region $-1.2H_c \leq H \leq 0$, B_i shall remain within 2.5% of this fitted straight line.

3.1.6.4 The total magnetic dipole moment [Amp-meter^2] Of each block shall be within 2.5% of the average value obtained for all the blocks at 24°C after stabilization.

3.1.6.5 The permanent magnet blocks shall be certified as being coated with a minimum thickness of 10 micrometers of nickel, tin, or another equally radiation- and corrosion-resistant metallic coating.

3.1.6.6 All permanent magnet shall be single blocks, no glued blocks will be accepted.

3.1.6.7 The permanent magnet block surfaces facing the magnetic gap shall have no more than 5% of their surface removed due to chips, burrs, nicks, or pits so as to not affect magnetic performance of the wiggler. There shall be no loose particles remaining at the edges or on the surfaces of the block. Contractor shall sort the magnet blocks so as to minimize the magnet block imperfections that face the electron beam.

3.1.6.8 At the magnetics design review (see section 4.1), contractor shall furnish the name of the manufacturer and the specific product name for the magnet block material to the technical representative for CEBAF's approval. At this time, the contractor shall also furnish *representative* magnetization data in SI units for the magnet blocks. These data shall include:

- Induction (B) versus magnetizing force (H) curves at both 20°C and approximately 60°C.
- Intrinsic induction ($B_i=\mu_0 M$) versus magnetizing force (H) at both 20°C and approximately 60°C.
- Reversible parallel permeability (dB/dH) at 20°C.
- Reversible temperature coefficients of coercive force (dH_C/dT) and intrinsic coercivity (dH_{Ci}/dT) at 20°C, 40°C, and 60°C.
- Reversible temperature coefficients of remanent induction (dB_r/dT) at 20°C.

Approval from CEBAF should occur in no more than one week.

3.1.6.9 Contractor shall measure the total magnetic dipole moment, including the direction of the dipole moment, of each block with a Helmholtz coil or with a system approved by the CEBAF technical representative at the magnetics design review. The precision in these measurements shall be 0.1% or better in the magnitude of the moment and 0.2° or better in the angle. The temperature of the block during these measurements shall also be measured to an accuracy of 0.3°C. Recommended Helmholtz coil diameter is 10 times the largest block dimension. The measurements of the total magnetic dipole moment shall be reported in Amp-meter^2. Contractor shall deliver to the technical representative at CEBAF two paper copies of the results of contractor's measurements of individual magnets, and a machine-readable copy of the data in the form described in section 4.3.9 of this specification. The coordinate system used to define the direction of the magnetic moment and its relation to the markings on the magnet block shall be clearly defined by contractor—a drawing is required.

3.1.6.10 Magnet blocks shall be identified by a number that is written non-removably on the block edge facing the magnetic gap. The direction of magnetization shall also be indicated on the block.

3.1.7 Wiggler Magnetic Performance. These requirements shall apply in a 'good field' region that ranges from -5 to +5 mm in the vertical (*y*) direction and from -2 to +2 mm in the horizontal (*x*) direction. The definition used for the normal (b_n) and skew (a_n) multipoles is:

$$\int dz(B_x + iB_y) = \sum_{n=0}^{\infty} (b_n + ia_n)(y + ix)^n,$$

where the limits of the integral in z are the same as the limits of the scans required in sections 4.2.7 and 4.2.8. The fields used in all field integrals are those in excess of the local magnetic field. The background field must be subtracted from the measured fields before doing the integrals (see Appendix A). These limits are also what is meant by the phrase "through the entire wiggler" in sections 3.1.7.3, 3.1.7.4, and 3.1.7.8. The desired *rms* field strength is 2800 G at a gap greater than 12 mm. The gap producing an *rms f*ield of 2800 G is referred to as the nominal gap.

3.1.7.1 The magnetic gap midplane *rms* field from the full field poles shall be a minimum of 2800 Gauss for a magnetic gap opening between the full field poles of 12 mm. If the *rms* field is not equal to 2800 G at a gap of 12 mm, the gap shall be increased until the *rms* field is equal to 2800±100 G.

3.1.7.2 The rms field strength may have harmonic content but no harmonic shall exceed 20% of the fundamental field component.

3.1.7.3 The vertical field integral [$\int B_y dz$] through the entire wiggler shall be less than 400 Gauss-cm at the nominal gap.

3.1.7.4 The horizontal field integral [$\int B_x dz$] through the entire wiggler shall be less than 400 Gauss-cm at the nominal gap.

3.1.7.5 The second field integral of the vertical field component (the mathematical expression is in Appendix A) shall be less than 5000 Gauss-cm^2 at the nominal gap.

3.1.7.6 The second field integral of the horizontal field component (the mathematical expression is in Appendix A) shall be less than 5000 Gauss-cm^2 at the nominal gap.

3.1.7.7 The field integral of the horizontal field component through the 4 periods at each end of the wiggler shall not exceed 200 Gauss-cm when averaged over the wiggler motion.

3.1.7.8 The integrated multipole fields through the entire wiggler shall be less than the following tolerances at the nominal gap.

n	Normal Component (b_n)	Skew Component (a_n)
1 (Quadrupole)	50 Gauss	50 Gauss
2 (Sextupole)	200 Gauss/cm	l 00 Gauss/cm
3 (Octupole)	300 Gauss/cm^2	300 Gauss/cm^2

3.1.7.9 The transverse field roll-off at the nominal gap and at the centers of the full field poles shall satisfy:

$$\left| 1 - \frac{B_x(y = \pm 5 \text{ mm})}{B_x(y = 0 \text{ mm})} \right| \leq 0.005$$

3.1.7.10 The rms optical phase error (defined in Appendix A) in the periodic magnetic structure (excluding the ends) shall be less than 5 degrees. The rms peak field variation (excluding the ends) shall satisfy, at the nominal gap,

$$\left(\frac{\Delta B_{\text{peak}}}{B_{\text{peak}}} \right)_{rms} \leq 0.005$$

3.1.7.11 In the periodic magnetic field, excluding 3 periods from each end, the averaged electron trajectory (i.e., averaged over each period to eliminate the periodic component) shall be straight within ± 100.0 micrometers in both the *x* and *y* directions for a 42 MeV beam, and the angle deviation of this averaged trajectory shall not be larger than ± 500.0 microradian for a 42 MeV beam. All magnetic measurement results used to confirm this requirement shall include the contribution of the earth's field.

3.1.7.12 The wiggler shall be equipped with end structures at both ends of the wiggler which not only satisfy the field integrals listed above but also minimize the deviation of the trajectory in the wiggler from the trajectory with no field present.

3.1.8 Ferromagnetic clamps, pins, screws, bolts, etc. shall be used with caution in the construction of the magnetic structure to avoid perturbing the center magnetic field.

3.1.9 The assembled magnetic structure shall not undergo any permanent demagnetization or other irreversible damage when exposed to temperature of up to 50 °C during, e.g., shipping or air-conditioning failure.

3.2 Mechanical Requirements: The mechanical structure must include backing beams to which the CEBAF supplied support structure attaches and some means to hold the two halves of the magnetic structure rigidly in place with respect to one another such as rails and gap spacers.

3.2.1 The relative position of the two backing beams must be held fixed by some rigid structure such as posts, rails, or a C-frame. The relative position of the backing beams in the *y-z* plane must reproduce to ±75 micrometers after disassembly and reassembly of the wiggler jaws. The design shall be sufficiently robust to hold this tolerance after several dozen cycles of disassembly and reassembly or after being subjected to a 5 G shock.

3.2.2 The gap of the wiggler shall be set at a value sufficient to produce an rms field of 2800±100 Gauss. The spacers which determine the wiggler gap must be replaceable by spacers with a different thickness so that the wiggler strength can be changed at a later date if this is desired by CEBAF. After disassembly and reassembly, the gap must be reproduced to within ±25 micrometers. As soon as the nominal gap is determined, the contractor must inform CEBAF so that the design of the vacuum chamber and support stand can be finalized.

3.2.3 For CEBAF personnel to align and position the wiggler, contractor shall provide alignment scribe lines and interfaces for alignment fiducials. These interfaces and scribe lines shall meet the following requirements:

3.2.3.1 The interfaces shall consist of bushings, Catalog No H-28-6-.2500 from Carr-Lane or equivalent, press fit into the backing beams. These will accept CEBAF survey targets.

3.2.3.2 The locations of the fiducial interfaces shall be approximately as shown in CEBAF drawing no. 09510-C-0003: two near each end of each backing beam on the side faces on each backing beam. The four pairs of fiducials shall be misaligned in the *z* direction by at least 10 mm.

3.2.3.3 The horizontal (*x*) distances of the centers of tooling balls (see section 3.1.9.5.4), inserted in each of the fiducial interfaces, from a plane, defined by a line (in the *y* direction) across the center of the face of the fifth pole from the upstream end and a point at the center of the face of the fifth pole from the downstream end of the wiggler, shall be the same to within 0.5 mm.

3.2.3.4 The contractor shall provide a flat surface at least 4 by 20 cm in size on the top surface of the wiggler structure which is perpendicular to the plane defined in paragraph 3.1.9.5.3 and to a line between the centers of the fifth pole from either end to within ±25 micrometers.

3.2.3.5 The contractor shall report, to an accuracy of ±25 micrometers, the three mutually perpendicular distances to the center of each tooling ball inserted in the fiducial bushings with respect to: the center of the pole tip surfaces of the

two poles that are the fifth ~~full-field~~ poles from either end of the device, and the pole immediately downstream of the center of the device. The tooling ball shall be type CL-1-SCB from Carr-Lane(0.500 inches {12.7 mm} in diameter, with the center of the ball 0.3125 ±.0002 inches {7.938±0.005 mm} above the bushing), or equivalent.

3.2.3.6 There shall be horizontal scribe lines at each end of each backing beam showing the geometrical center of the wiggler magnetic array in the *y* direction. The positions of these lines shall be accurate to ±50 micrometers. The lines shall still be visible after the backing beam is anodized.

3.2.4 The backing beam requirements include:

3.2.4.1 The backing beam shall be made of aluminum, 606 l T6, 2024 T8, or equivalent.

3.2.4.2 Backing beam weldments shall be in accordance with ANSI/AWS Dl.2-90.

3.2.4.3 The backing beam shall be anodized.

3.2.4.4 Each backing beam shall have four 5/8-11 tapped holes which can accept a lifting hook. There shall be two of these holes in the top of each backing beam and two in the side of each backing beam. The tapped holes shall be placed approximately one quarter of a wiggler length from either end.

3.2.4.5 When the design of the wiggler is complete the contractor must furnish dimensioned drawings to CEBAF sufficient to allow the design of the support interface.

3.3 Vacuum chamber interface. The following clearances must be maintained.

3.3.1 CEBAF drawing 09510-C-0002 indicates the stayclear for the vacuum chamber. The vacuum chamber will be at least 12 mm wide and at most 45 mm high over the entire length of the wiggler. Gap blocks and support rods must not intrude into this space.

3.3.2 Diagnostic ports above and below the main chamber will be situated between the 5th and 6th pole from either end and between the two center poles.. The contractor shall provide at least 40 mm of clearance in the *z* direction around the three locations.

3.3.3 In order to install the wiggler vacuum chamber, a method must exist of splitting and reassembling the wiggler in a controlled manner such that the relative location of the two jaws is maintained (see sections 3.2.1 and 3.2.2). Jacking screws must be provided for this purpose.

4.0 QUALITY ASSURANCE AND TEST REQUIREMENTS

4.1 Design Reviews. Two reviews are required; one review of the magnetic design and one of the mechanical design. They may be held either at the same time or separately.

4.1.1 When the wiggler magnetic design is complete, the contractor shall have a design review attended by the technical representative from CEBAF. The review shall cover the following topics:

4.1.1.1 The contractor shall indicate the source of the magnet material and present representative data on the characteristics of the material to be supplied.

4.1.1.2 The contractor shall describe the magnetic measurements to be made on the magnet blocks and the techniques that will be used to shim the wiggler field.

4.1.1.3 The contractor shall present calculations of the expected magnetic performance of the wiggler including the expected gap for rms fields of 2800 Gauss and 4000 Gauss , the internal fields inside the vanadium permandur, and the effects of imperfections in the magnet material or the physical structure.

4.1.1.4 The contractor shall present the means to be used to ensure the first and second field integrals at either end of the wiggler.

4.1.2 When the wiggler mechanical design is complete, the contractor shall have a design review attended by the technical representative from CEBAF. At this review the contractor shall describe the physical design and provide details on how the wiggler interfaces to the vacuum chamber and the mechanical supports.

4.2 Inspection and Preliminary Acceptance Tests

4.2.1 Contractor shall provide a certified report that specified or required dimensions of the completed wiggler given in sections 3.1.2, 3.1.4, and 3.3 of this specification are met.

4.2.2 Contractor shall provide a certified report that the required reproducibility of the relative position of the two wiggler jaws after disassembly and reassembly as described in sections 3.1.10 and 3.1.11 is maintained.

4.2.3 Contractor shall notify CEBAF at least 10 working days in advance of when all required acceptance tests are to be carried out, and CEBAF reserves the right to witness all required acceptance tests.

4.2.4 Upon receipt, CEBAF will mount the wiggler on CEBAF supplied supports and install the wiggler vacuum chamber. At that time the physical tolerances will be checked as part of the acceptance procedure.

4.3 Acceptance Test Magnetic Measurements

4.3.1 Contractor shall carry out a set of magnetic measurements with contractor's magnetic measuring equipment to verify that the magnetic performance requirements of section 3.1.7 of this specification are met. CEBAF reserves the right to have a representative on site during these measurements.

4.3.2 Contractor's magnetic measuring equipment shall include a Hall probe scanning system with the following capabilities:

4.3.2.1 Measuring field range from +8000 Gauss to -8000 Gauss.

4.3.2.2 Measuring field accuracy and reproducibility of a minimum of ±1 Gauss over the ±8000 Gauss range. A calibration curve showing the accuracy and linearity over the range of ±8000 Gauss shall be provided, both in hard copy and as described in section 4.2.9 of this specification. If the magnetic measurement data obtained using the Hall probe is reported to CEBAF in Gauss, no calibration curve need be provided.

4.3.2.3 Scanning capability to measure the field anywhere within a volume with respect to the center of the wiggler of ±0.65 m in length (z-direction), ±2 mm in width (x direction), and ±5 mm in height (y-direction).

4.3.2.4 Hall probe positioning accuracy and reproducibility in the z direction shall be 5 micrometers or better.

4.3.2.5 Hall probe positioning accuracy and reproducibility in the x and y directions shall be ±25 micrometers or better.

4.3.3 Contractor's magnetic measuring equipment shall include at least one long coil of uniform width and minimum length of 1.3 m, hereinafter referred to as "long coil", and at least one short coil of uniform width and suggested length of half a period. Contractor shall specify how coils will be calibrated and shall provide evidence that the coil is capable of measuring the multipole strengths with a resolution smaller than the specifications in section 3.1.7.8. Title to the short coils shall pass to CEBAF after acceptance of the wiggler.

4.3.4 Contractor shall carry out each set of scans or family of magnetic measurements in a 24°C±4°C environment, after the wiggler has remained in the 24±4 °C environment long enough to come to thermal equilibrium (or for at least 24 hours). The temperature at which the scans are taken shall be included in all reports of the scan data.

4.3.5 After wiggler completion, including tuning of the end correction, the contractor shall use the Hall probe to make horizontal field magnetic measurement scans in the wiggler magnetic gap on the wiggler midplane (x=0.0 mm) in the z direction at y = 0.0 mm. With

these scans, contractor shall verify that sections 3.1.7.1, 3.1.7.2, 3.1.7.4, 3.1.7.6, 3.1.7.7, 3.1.7.10, 3.1.7.11, and 3.1.7.12 of this specification are met at the nominal magnetic gap.

4.3.6 After wiggler completion including tuning of the end correction, contractor shall use the Hall probe to make a series of horizontal field magnetic measurement scans in the wiggler magnetic gap on the wiggler midplane (y=0.0 mm). At the nominal gap a minimum of eleven scans are to be made in the *z* direction from -0.65 m to +0.65 m with respect to the wiggler center at vertical offsets of -5.0 mm, -4.0 mm, -3.0 mm, -2.0 mm, -1.0 mm, 0.0 mm, +1.0 mm, +2.0 mm, +3.0 mm, +4.0 mm, and +5.0 mm in the *y* direction with respect to the wiggler center. With these scans, the contractor shall verify that the integrated dipole requirements of sections 3.1.7.4, 3.1.7.6, and 3.1.7.7, and the normal quadrupole, sextupole, and octupole requirements of section 3.1.7.8 of this specification are met at the nominal magnetic gap; and that the roll-off requirement of section 3.1.7.9 is met at the nominal gap.

4.3.7 After wiggler completion including tuning of the end correction, contractor shall use the short coil to make a series of horizontal field magnetic measurement scans in the wiggler magnetic gap. Scans are to be made in the *z* direction from -0.65 m to +0.65 m with respect to the wiggler center. As a minimum, scans are to be made at the following (*x*,*y*) coordinates (0.0 mm, -5.0), (0.0 , -4.0 mm), (0.0, -3.0 mm), (0.0, -2.0 mm), (0.0, -1.0 mm), (0.0, 0.0), (0.0, +1.0 mm), (0.0, +2.0 mm), (0.0, +3.0 mm), (0.0, +4.0 mm), and (0.0, +5.0 mm) with respect to the wiggler center. Contractor shall also use the short coil to make vertical field magnetic measurement scans at (*x*,*y*)=(0.0) at the nominal magnetic gap. With these scans, contractor shall verify that the requirements of sections 3.1.7.3, 3.1.7.4, 3.1.7.5, 3.1.7.6, 3.1.7.7, and 3.1.7.8 of this specification are met . Measurements made to verify sections 3.1.7.5 and 3.1.7.6 must be made with a coil that is approximately one-half period long or shorter; measurements made to verify sections 3.1.7.3, 3.1.7.4, 3.1.7.7,and 3.1.7.8 may be made with a coil that is several periods long.

4.3.8 After wiggler completion, including tuning of the end correction, contractor shall make long coil measurements of the vertical and horizontal field on the wiggler midplane (*x*=0.0), at *y values* of -5.0 mm, -4.0 mm, -3.0 mm, -2.0 mm, - 1.0 mm, 0.0, +1.0 mm, +2.0 mm, +3.0 mm, +4.0 mm, and +5.0 mm. With these long coil measurements, contractor shall verify that requirements of section 3.1.7.3, 3.1.7.4, and 3.1.7.8 are met.

4.3.9 All data, which include data from scans taken to verify sections 4.3.5 through 4.3.8 of this specification and the data required per sections 3.1.6.9 and 4.3.2.2 of this specification, shall meet the following requirements:

4.3.9.1 Data shall be provided to the technical representative at CEBAF on IBM PC-compatible 3.5 inch floppy disks or CD-ROM readable format.

4.3.9.2 The data shall be in ASCII format in the form of tables.

4.3.9.3 Each table shall have a header which describes the tabulated data, applicable environmental parameters, and other parameters relevant for the reproduction of the data.

4.3.10 Contractor shall deliver the measurement data at or before the time of the wiggler delivery. Verification of measurement data and contractor's analysis shall be carried out by CEBAF staff in no more than 30 days from the receipt of the wiggler at CEBAF.

5.0 PREPARATION AND DELIVERY

5.1 The contractor shall provide removable covers that are attached to the magnetic structure that will protect the exposed poles and permanent magnet material from damage.

5.2 The contractor shall attach a non-reversible temperature monitors that cover the range from 58°C to 77°C, Tempilabel No. 8MA-100/38 or equivalent, to the magnetic structure.

5.3 The contractor shall attach two, 5-G shock indicators, McMaster-Carr No. 1955T41 or equivalent, one at each end of the shipping crate.

5.4 The contractor shall specify the packaging of the completed wiggler suitable for the hazards of transportation and weather subject to CEBAF's review.

5.5 The contractor shall attach permanent tilt indicators to the shipping crate.

5.6 The contractor shall ship the completed wiggler via air when necessary, otherwise via an air ride flatbed truck. Contractor shall advise CEBAF as to shipper and shipping schedule. Any changes in shipping mode or schedule shall be with CEBAF knowledge and approval.

Appendix A DEFINITIONS

Wiggler Field Distribution:

The periodic magnetic field in an infinitely wide and infinitely long wiggler is given by:

$$B(x,z)=\sum_{n=0}^{\infty} B_{2n+1}\cos[(2n+1)kz]\cosh[(2n+1)kx] \qquad (1)$$

where $k = 2\pi/\lambda_u$ and λ_u is the wiggler period length.

The *rms* field, referred to by section 3.1.7.1, is defined by:

$$B_{rms}=\sqrt{\sum_{n=0}^{\infty}\frac{1}{2}\left(\frac{B_{2n+1}}{2n+1}\right)^2} \qquad (2)$$

Field Integrals:

The first field integrals are defined as:

$$S_x(z)=\int_{-\infty}^{z} B_x(z')dz' \qquad\qquad S_y(z)=\int_{-\infty}^{z} B_y(z')dz' \qquad (3)$$

The second field integrals, referred to by sections 3.1.7.4 and 3.1.7.5, are defined as:

$$D_x(z)=\int_{-\infty}^{z} S_x(z')dz' \qquad\qquad D_y(z)=\int_{-\infty}^{z} S_y(z')dz' \qquad (4)$$

where B_x is the horizontal and B_y the vertical field component. The integration is to be taken to and from a reference well outside the device where the device field is below 0. 1 Gauss.

Phase Error:

The phase error is to be evaluated in the periodic structure only. The five full field poles at either end are excluded. The reference trajectory for the perfect wiggler shall be calculated using a least squares fit of Eq. 1 to the measured magnetic field data, including all harmonics through the 11th. The magnetic measurements used to confirm that the phase error requirements are met shall include the contribution of the earth's magnetic field.

$$\varphi(z)=\frac{2\pi}{\lambda_R}\int_{-\infty}^{z} dz\sqrt{1+\left(\frac{dx}{dz}\right)^2+\left(\frac{dy}{dz}\right)^2} \qquad (5)$$

The integral calculates the length of the trajectory from a reference point beyond the end of the wiggler where the wiggler magnetic field is zero ('$-\infty$') to a point *z*. The wavelength of the first-harmonic radiation is λ_R.

The phase shift at a location *z* is given by:

$$\Delta\varphi(z) = \varphi(z)_{\text{real trajectory}} - \varphi(z)_{\text{reference trajectory}} \quad (6)$$

The average phase error is

$$\Delta\varphi_{ave} = \frac{1}{L}\int_0^L \Delta\varphi(z)dz\ , \quad (7)$$

where L is the length of periodic section of the wiggler. The root mean square phase error in a device, referred to by section 3.1.7.8, is defined by:

$$\Delta\varphi_{rms} = \sqrt{\frac{1}{L}\int_0^L \left(\Delta\varphi(z) - \Delta\varphi_{ave}\right)^2 dz}$$