# INNER UNDULATOR ELECTRON DIAGNOSTIC STATIONS

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## Abstract

As part of the Boeing/Spectra Technology free-electron laser (FEL) program, stations have been built for electron diagnostics within the undulator. The hybrid undulator design imposes stringent requirements on applied steering and focusing, since external fields cannot be linearly superimposed. In order to avoid any appreciable gain loss in the FEL, the space reserved for the diagnostics is severely restricted. We have established the performance requirements for the undulator diagnostics. The resulting design incorporates electromagnetic beam-position monitors, "pop-in" targets, steering, quadrupole trim, and vacuum pumping in a 4.0 cm longitudinal gap. The steering and diagnostics have been built with the design goal of aligning the electron beam to the optical mode of the cavity to better than one tenth (30 $\mu$m) of an electron beam diameter.

## Introduction

The operation of the free-electron laser places very stringent requirements on the alignment of the electron beam and the incident optical beam. The need for precise alignment and control of the electron beam has shown to be a issue in several experiments [1-3]. The electron beam constraints become even more rigorous as the output is scaled to shorter and shorter wavelengths [4]. Misalignment of the optical beam and the electron beam in the FEL results in a significant reduction in the laser's performance [3,5]. Misalignment of the electron beam, improper matching of the e-beam to the undulator entrance conditions, or steering errors present in the magnetic field of the undulator cause an increase in the apparent emittance of the electron beam [6]. This apparent increase in emittance decreases the gain by degrading the overlap of the electron beam to the optical beam and by causing an increase in the effective energy spread [4]. In FEL systems the alignment can strongly influence the overall performance in both the small-signal regime and the saturated regime [6].

One electron beam alignment technique which has been used in pure rare-earth permanent magnet (REPM) undulators [7] consists of superimposing trim coils over the length of the undulator and providing fluorescent screens inside the undulator [2,8]. This technique, however, will not work for hybrid (steel and REPM) undulators [7] since external fields cannot be linearly superimposed as a result of the presence of the highly permeable material. In order to overcome this problem, we have designed a system which allows for electron diagnostic stations throughout the length of the hybrid undulator without significant loss of gain.

Figure 1 is a photograph showing a portion of the partially assembled subsections of the tapered hybrid undulator (THUNDER) built as part of the Boeing/Spectra Technology visible FEL project [9]. Shown on either side of the subsection are the adjacent diagnostic stations. The diagnostic stations, which contain both field trim elements, beam position monitors, and intercepting targets, are placed in small gaps along the undulator. The length of these gaps has been phased to minimize their influence on the gain. We discuss here the operational requirements and design of the diagnostic stations for THUNDER.

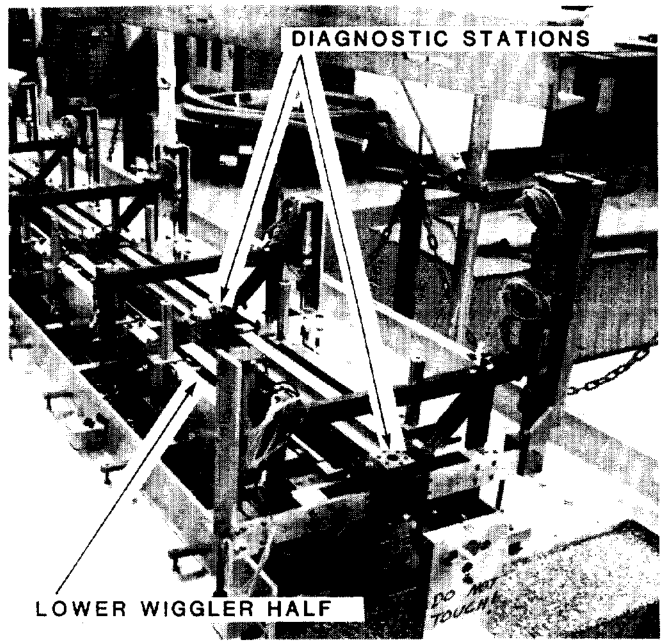


Figure 1. Photograph of the portion of the partially assembled tapered hybrid undulator (THUNDER) showing a portion of the magnetic system, vacuum system and electron beam diagnostic stations.

## Design Considerations

Since the diagnostic stations replace undulator periods which would normally fill these longitudinal gaps, their length L must be commensurate with an integer or half-integer optical phase slip, $\Delta\psi/2\pi$, of the electrons

$$\frac{\Delta\psi}{2\pi} = \frac{L}{2\lambda_s}\left(\frac{1}{\gamma^2} + \langle\theta^2\rangle\right) = \frac{n}{2} \qquad [1]$$

In Eq. 1, $\lambda_s$ is the optical wavelength, $\gamma$ is the electron energy measured in units of its rest energy $mc^2$, and $\langle\theta^2\rangle$ is the average of the square of the angle of electron trajectory throughout the gap. This criteria avoids dephasing which can cause detrapping or interference effects resulting in a possible gain or extraction loss throughout the undulator. The optical klystron [10] exploits these interference effects with a large dispersive gap between sections to achieve enhanced gain, but only at the expense of decreased extraction [10].

THUNDER has been designed to operate at various magnetic tapers. Since the longitudinal gaps are fixed at an optimum length for a specific taper prescription, the saturated gain of other tapers will be slightly reduced. For example, gaps for which $\Delta\psi=\pi$ that have been optimized for a 6% resonant energy taper along the undulator result in a 3% reduction in the untapered small-signal gain and a 8% reduction in the saturated gain for a 12% taper. The small-signal gain of the tapered prescriptions remains essentially unchanged since it originates principally in the first two subsections of the undulator [6].



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An additional complication of the hybrid undulator is that the highly permeable material shunts the field provided for steering and focusing at the individual stations. Figure 2(a) plots the measured steering fields of a diagnostic station. For the design parameters of 120 MeV electron energy and 0.5 $\mu$m optical wavelength, the space available for the diagnostics $\pi$-phase gaps is limited to about 4.0 cm. This small spacing results in the distortion of the steering fields shown in Fig. 2(a). Shunting of applied quadrupole fields is also observed. Figure 2(b) shows the geometry of the station and undulator used during the measurements. From Fig. 2(a) it is seen that the elements are capable of providing a steering field sixteen times (1600 G-cm) larger than steering errors allowed in an undulator subsection.

In order to provide additional emittance acceptance, it is advantageous to provide two-plane focusing in the undulator [4]. Because of the field shunting and limited space, the diagnostic stations cannot reliably provide the complete focusing strength required for equal two-plane focusing. The required focusing in the undulator is provided by canting the hybrid pole pieces [11]. The diagnostic stations provide only steering and quadrupole trim.

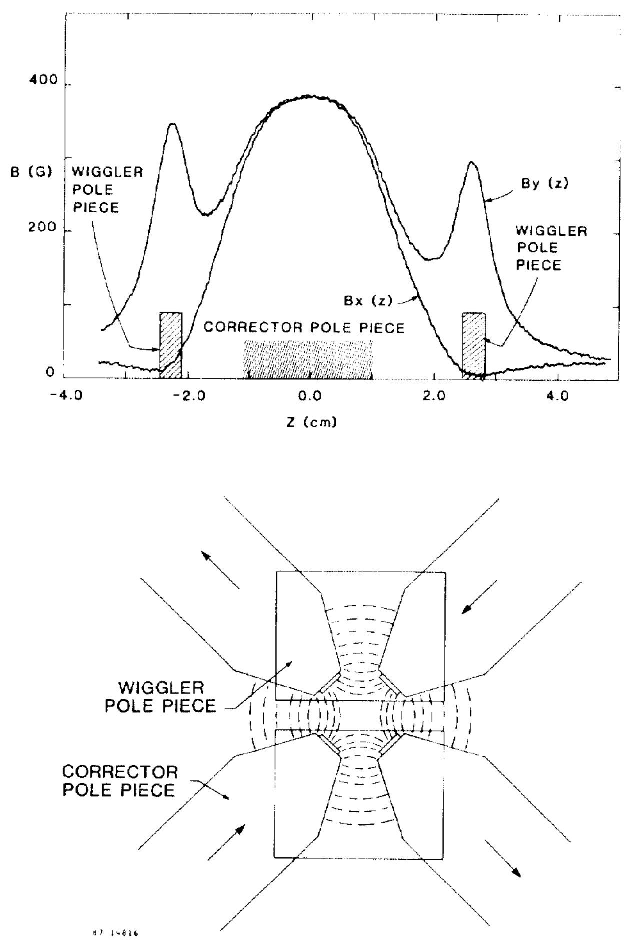



Figure 2. (a) Magnetic measurements of a diagnostic station showing shunting introduced on steering fields by the adjacent undulator subsections. The dashed line is the unshunted configuration. (b) Geometry of an installed diagnostic station showing the proximity of the adjacent undulator poles which give give to the shunting.

## Physical Description

Figure 3(a) is a photograph of the entire diagnostic station and Fig. 3(b) is a detail of the central portion identifying the major elements. A "pop-in" target, a fluorescent screen or Cerenkov cell, provides visual information on the profile and size of the electron beam with respect to the alignment laser beam that also is imaged on the screen. The first and last diagnostic stations, one of which is pictured in Fig. 3, also have pop-in apertures which provide alignment targets for the alignment of the optical cavity with the undulator centerline. Additionally, in each station, stripline electrode beam position monitors are provided which are based on designs employed at SLAC [12,13]. These provide position information without disrupting either the electron beam or laser. The striplines are mounted on the tips of the poles of the steering elements to conserve space. The stripline monitors themselves are set back from the nominal beam tube diameter so that they cannot be struck directly by the electron beam and suffer thermal distortions. The bench-test calibration suggests that the resolution of the strips will be of the same order as the design goal of 30 $\mu$m, but the effective resolution remains to be proved with the actual electron beam and operating conditions.

Based on calculations and comparison with the equivalent designs employed at SLAC [12]The electron beam diagnostic station housings are fabricated from 316 stainless steel. Round low-carbon iron pole pieces are inserted radially through holes in the cylinder wall and vacuum brazed into place using an induction furnace. After brazing, the pole pieces and housing are machined to their final dimensions to maintain tolerances. All C-ring grooves and screw holes are added during this final machining phase. The pole pieces are brazed through the housing in order to allow the magnetic flux-bearing elements to extend as close to the electron beam as possible while providing sufficient room for the electron beam position screens.

The beam position monitors are 3 mm wide stainless steel strips mounted slightly beyond the ends of the pole pieces. The spacing of each strip from the end of the pole piece maintains a 50 $\Omega$ impedance. The strips are attached directly to the pole pieces with a screw and a clamping bar at one end and to a feedthrough via a pin jack at the other. A ceramic retainer and spacers maintain the mechanical positioning of the striplines within the housing. The coaxial vacuum feedthrough is welded into a custom fitting with an SMA connector. The fittings are screwed into the outside end of the four low-carbon iron pole pieces and sealed with lead plated metal C-rings. The flux return paths are clamped to the side of the permendur poles to permit access to the feedthroughs. The geometry maintains a 50 $\Omega$ impedance throughout.

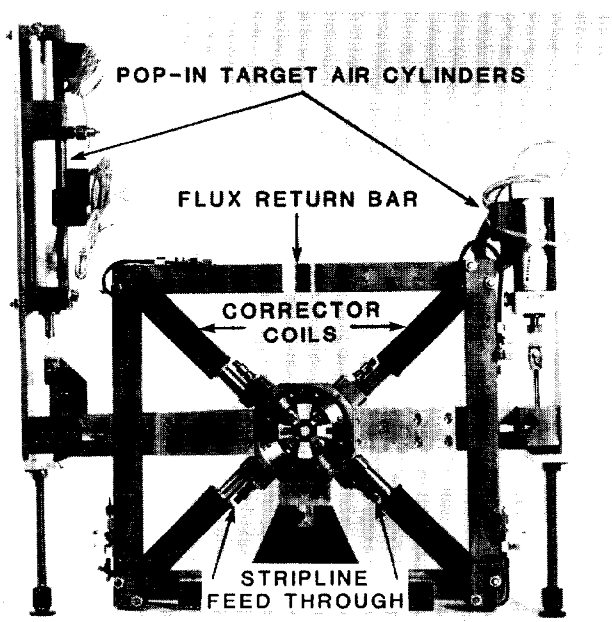
Two radial ports drilled through the housing cylinder between the pole pieces provide access for the "pop-in" target, a viewport, and vacuum pumping. Vacuum bellows allow sufficient travel for retraction of the target well away from the electron beam and stripline monitors. An externally adjustable "stop" provides positioning of the target inside the diagnostic station.

## Installation

An electron beam diagnostic station assembly is mounted on a pedestal between each undulator subsection and at each end of the undulator. The stations will be aligned to the beam line and the pedestals clamped in place. The stations are then removed from their pedestals so that the electron beam tube/diaphragm assembly can be attached.

The stainless steel electron beam tube is a 3/16 inch diameter tube that has been brazed into a thin stainless steel diaphragm at each end. This diaphragm is clamped to the diagnostic station housing using a round flange. Each beam tube/diaphragm assembly will be made 1/2 to 1 millimeter shorter than is actually required between each diagnostic station. This insures that the beam tubes will be in tension during the assembly of all eleven electron beam diagnostic stations into the undulator.

Each station is then replaced and clamped to its respective pedestal, positioning being assured by alignment pins in the pedestal. Atmospheric loading on each diaphragm section will not overstress the beam tube, but will tend to pull each tube section straight.



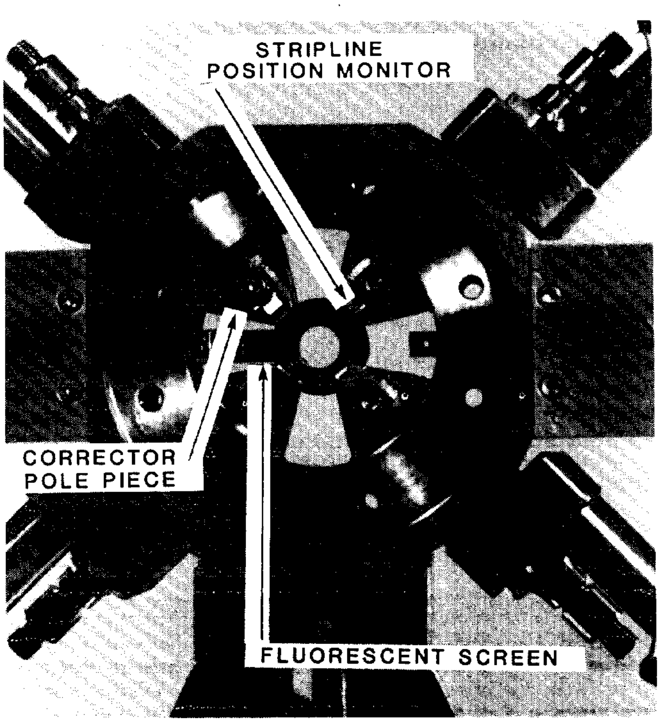




Figure 3. (a) Photograph of the combined function diagnostic station. (b) Detail of central portion of diagnostic station.

## Conclusion

Stringent requirements on e-beam alignment in short wavelength FELs necessitate the use of diagnostic stations along the undulator length. We have built a system which meets the requirements without impact on system performance. The diagnostic stations for the tapered hybrid undulator are completely installed. Mock-up measurements and previously demonstrated technology give confidence in the final performance of these stations. Their actual performance characteristics will shortly be verified with the actual electron beam as oscillator studies begin.

## Acknowledgements

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