DEVELOPMENT OF A 10-m WEDGED-POLE UNDULATOR

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Abstract

A 10-m rare-earth permanent magnet hybrid undulator [1] called NISUS (Near-Infrared Scalable Undulator System) is being installed by Spectra Technology, Inc. (STI) for use in the Boeing Aerospace Company (BAC) free-electron laser (FEL) program series. The design has been optimized for operation at a 1-μm wavelength with the BAC accelerator parameters. A remotely-adjustable compound taper is utilized to achieve optimum startup gain and high saturated extraction. Notable improvements include the use of wedged poles for higher field strength and magnetically seamless structure which accommodates frequent two-plane steering correction without drift spaces. An important development is the finding that magnetic field errors can be substantially reduced using thin iron shims attached to the permanent magnets.

Introduction

Performance demands have increased for undulators. Long scalable undulators are becoming necessary for various applications. Modularity, field quality and serviceability are major requirements of an undulator system. A major goal of STI has been to build NISUS from modules which would allow easy scaling to longer lengths without redesign. The NISUS design parameters are listed in Table 1. The on-axis magnetic field strength is 5.6 kG in a 3.89 cm period and 1.44-cm gap.

Table 1
NISUS DESIGN PARAMETERS

UNDULATOR	
Length	10 m
Period	3.89 cm
Peak Field	5.6 kG
Gap	1.44 cm min.
Clear Aperture	1.14 cm
a_w (rms)	1.44 max
Energy Taper	Adjustable to 20%
E-BEAM	
Energy	121 Mev
Peak Current	500 A
Energy Spread	1% FW
Emittance	0.02 cm-rad ($\gamma\pi r\theta$)
PHOTONS	
Wavelength	1.06 μm
Rayleigh Range	3.7 m

The NISUS design includes a number of improvements relative to the technology used in the earlier tapered hybrid undulator (THUNDER) [2]. The use of the wedged-pole configuration [3] has provided a major increase in field strength, has reduced the harmonic content to less than two percent, and assures that no portion of the poles operate near saturation. Another major difference stems from an upgraded method of providing e-beam steering and focusing correction. The new NISUS magnetic structure is seamless, eliminating the drift spaces previously used to accommodate steering stations. This simplifies construction since careful phase tuning of drift spaces is unnecessary.

System Components

An isometric drawing of the assembled undulator is shown in Figure 1. The 10-m, 256 period undulator magnetic structure is built in 16 modules, each consisting of 16 periods. The entire structure rests on an optical table which is firmly mounted to the floor of the accelerator chamber. The optical table provides a rigid, vibration damped, and scalable platform. The modular arrays of vanadium permendur poles and samarium cobalt magnets are supported from above and below on long aluminum box beams. The upper box beam is rigidly held by six strongback support stanchions. The magnetic field may be tapered by varying the gap separation. Each remotely adjustable gap separation mechanism is attached to the box beam and moves an undulator half up and down. The mechanism consists of two rigid threaded-rod actuators driven by a worm-gear and ball nut assembly. Linear variable differential transformer (LVDT) gap sensors with 1-μm resolution provide closed-loop position feedback. The drive accuracy and reproducibility are expected to be equivalent to the resolution because the attractive force between undulator halves eliminates backlash. Each magnetic structure section is connected to its nearest neighbor by a tuning fork shaped flexure joint, which allows for angular variation between sections as the gap is tapered. The sides of the undulator are open for easy access to the vacuum chamber components.

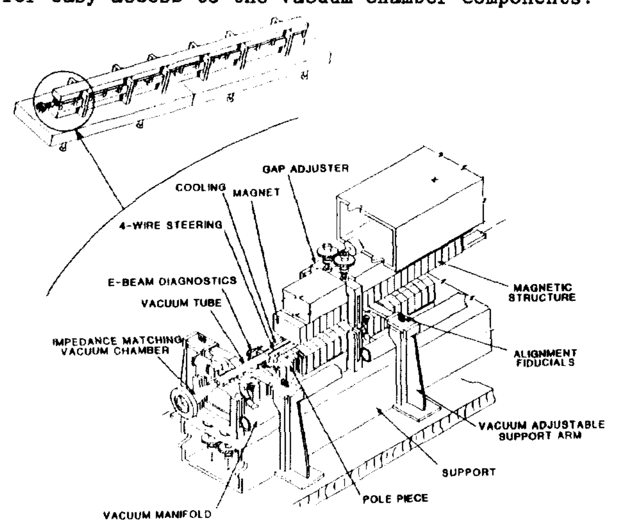

Figure 1

The NISUS vacuum system configuration is depicted in Figure 2. A 1.2-m length of vacuum tube section is shown, together with the associated 2-axis kinematic mount. Commensurate with the undulator section length, each vacuum tube section consists of two subassemblies. One subsection has a set of independently controlled steer-focus wires, the other has a pop-in target mount, and ports for non-

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interrupting beam diagnostics and pumping. Both fluorescent screens and non-contact stripline beam position monitors are used for e-beam sensing. Tests have shown that the lead C-rings achieve a leak-free seal tolerant of large misalignments between vacuum-tube sections. Each of the modular sections can be independently removed for servicing. Side contact cooling is provided.

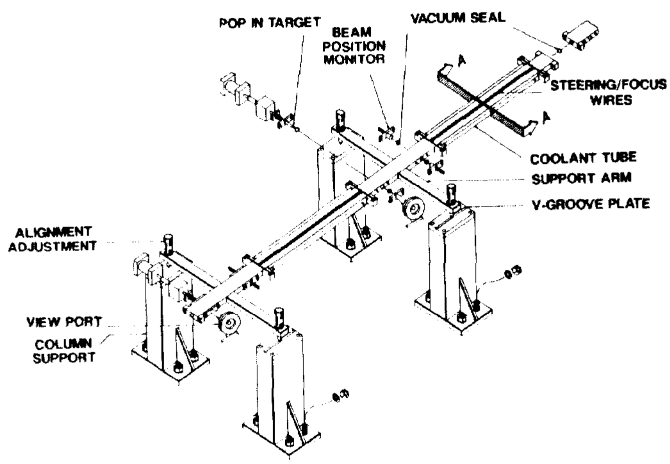

Figure 2

Two-plane steering correction is provided in NISUS by an efficient distributed coil system which is mounted directly on the vacuum chamber. The steering system consists of four wires mounted in close proximity to the pole tips, as suggested by Halbach [4]. Four copper ribbons are oriented at approximately 60 degrees with respect to the horizontal axis. The primary function of the wire ribbons is to supply e-beam steering. By changing the relative symmetries of the currents in each of the wires, steering or focusing fields at any angle can be generated.

A 16-pole mockup has been used to test the 4-wire steering system concept. The strength and field quality produced in both steering and focusing current configurations has been verified. The system is found to produce a horizontal steering field of 1.3 G/amp, which, at 10 A, provides over 300 G-cm of integrated steering field in a 25-cm length. In the mockup the poles are unpowered so that higher order moments in the steer-focus field distribution can be studied without being overpowered by the 5.6-kG primary field. Standard multipole analysis determined that higher order impurities generated by the 4-wire configuration are acceptably small. These moments are expected to contribute less than one percent change in e-beam radius over the 10-m undulator length. The main source of these impurities is wire misplacement.

The basic features of the NISUS magnetic structure were also first verified with a prototype. This mock-up verified achievement of the design 5.6-kG on-axis field strength using wedged poles. This strength for the fundamental field component is at least 15 percent higher than achievable with straight-poles at this gap to period ratio.

The prototype has also shown that two sections can be joined in a magnetically seamless manner and that the tuning fork shaped flexure joint between sections operates correctly when used to achieve a tapered field. The pole alignment, pinning and clamping techniques have been verified and the magnet insertion procedures determined. By replacing some of the poles with canted poles, the cant angle needed for equal two-plane focusing was established.

Canted-pole two-plane focusing has been selected over curved-pole focusing [5] for NISUS primarily because of the higher achievable on-axis field strength. The canted-pole system avoids a field strength limitation imposed by saturation of overhanging pole tips [6]. While curved poles minimize the resonant coupling between the synchrotron oscillations and betatron motion of trapped electrons, this is not a concern for the e-beam brightness and other parameters of interest [8]. Furthermore, canted poles together with the internal 4-wire steering and focusing system allows additional operational flexibility in an adjustable gap undulator. The available focusing trim allows the desired equal two-plane focusing condition to be maintained over all ranges of gap and e-beam energy.

A plot of the measured transverse field gradient produced by the canted poles in the 26-pole NISUS prototype is shown in Figure 3. Comparison with comparable data measured for THUNDER [2] reveals an interesting difference. In THUNDER the gradient is considerably more nonuniform with axial position; the gradient drops nearly to zero between the poles. This difference apparently results because the thickness of the straight poles used in THUNDER takes up a smaller fraction of the undulator period. The thicker NISUS wedged poles are considerably wider at the tip. For a pole tip cant angle of 10.8 mrad, the measured average gradient dB/dx in NISUS is about 100 G/cm and the peak gradient is approximately 130 G/cm.

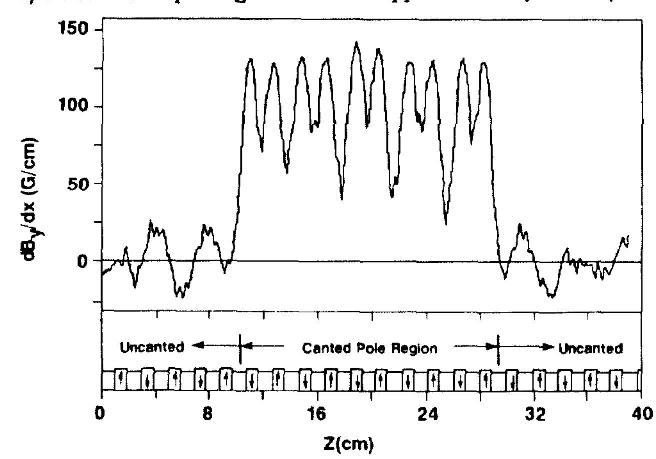

Figure 3

Based on these measurements, the desired nominal equal two-plane focusing condition is provided in NISUS by canting a total of 6 central poles out of 32 in each section. The required average gradient is so small that a subset of poles is canted in each undulator module in order to make the cant angle reproducible in manufacturing. E-beam transport is indistinguishable from fully distributed canting since the discrete canted pole regions occur frequently within the 9-m betatron period.

Field Shimming

In practice, undulator field quality has been limited by the presence of several undesirable factors, caused in part by inhomogeneities in the permanent magnets and pole imperfections. One of the most studied errors is that of the half-period integrals under each undulator pole [8]. Calculations of the effect of field errors in long undulators [9] show that it is highly desirable to improve the rms variation of these integrals from the typical values of 0.5 to 1.5 percent achieved in high field strength permanent magnet undulators. The techniques used to construct the current generation of undulators for 0.5 and 1-μm operation are not suitable for further extrapolation. These methods consist of tighter mechanical tolerances and higher rejection rates of the permanent magnets with resultant cost penalties. Magnet and pole interchange algorithms for error compensation have not been perfected and will be labor intensive at best. What is needed is a method of tuning an undulator to the desired fields after it has been assembled.

An important result of the NISUS magnetic structure prototype work is the finding that field errors can be dramatically reduced by a straightforward field tuning method. The basic concept is that thin iron shims are used to selectively shunt a small fraction of the field lines from regions where the field is higher than desired. The shims are placed on the surface of the magnets in the shallow recess between pole tips, thereby shunting field lines from one pole to another.The shims are easily placed or adjusted by hand, and are therefore a preferable tuning technique compared to magnet or pole interchange. With the large scalar potential difference between the poles, the shims are completely saturated and the number of field lines shunted is determined simply by their thickness. The field modification induced by the shim is largely confined to the region of two poles, and it has been shown experimentally that it is approximately linear in the shim thickness and additive with that of shims on neighboring poles.

Given that the field reduction is predictable, one can generate algorithms that modify the field in a predetermined way. Thus far, the shims have been applied to the problem of reducing the rms level of half period dipole field errors. By symmetry, the field modification has no integrated dipole component. However, the shims are still useful for correction of these steering errors. Shims allow a redistribution of any arbitrary dipole errors to a new distribution, which can be simply a constant (independent of axial position) error. This constant error can be canceled with an externally applied field of large spatial extent. Thus, the shims are a means for converting high spatial frequency errors to lower spatial frequencies where they can be dealt with by a simple bias field provided by the steering coils.

The capability of magnetic shims for correcting the primary field component has been demonstrated in the central region of the 26-pole NISUS mockup. Shown in Figure 4 are the half-period field integrals under the 18 central poles. Only the residual errors are shown, that is, the contribution of the best fit sine wave has been removed. The initial kick errors are shown as the points connected by the dotted lines. The quality of construction of this initial prototype was not as well controlled as NISUS itself, and prior to shimming the rms value of residuals compared to the underlying field is 1.3 percent. Following placement of appropriately chosen shims and one iteration, this value is reduced to 0.11 percent.

Conclusion

NISUS has achieved the goals of scalability, modularity, serviceability, and high field quality need for advanced FEL and Synchrotron radiation application. At the time of this writing, all of the undulator modules have been assembled and the last 5 meters are undergoing magnetic field testing. The first 5 meters were installed following its magnetic certification, in the fall of 1988, complete installation is anticipated by the fall of 1989 prior to full system operation. NISUS rms errors in the half-period field integrals can be substantially reduced using thin iron shims attached to the permanent magnets. A shimming algorithm has been demonstrated which allows arbitrary dipole steering errors to be redistributed into a constant dipole error which can be easily canceled by the internal steering coils in NISUS.

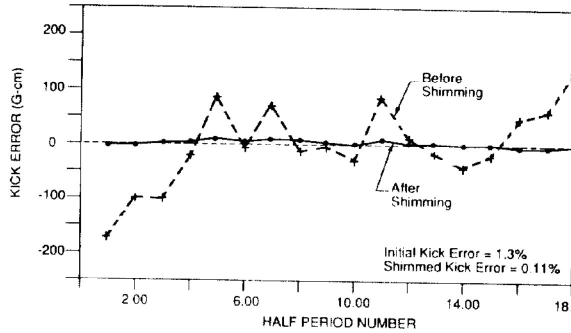

Figure 4

Acknowledgements

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