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Design and Beam Test Results of CHESS Compact Undulator.

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Abstract. We developed, built and beam tested a novel, compact, in-vacuum undulator magnet based on an adjustable phase (AP) scheme. The undulator is 1 m long with a 5mm gap. It has a pure permanent magnet structure with 24.4mm period and 1.1 Tesla maximum peak field. The device consists of two planar magnet arrays mounted on rails inside of a rectangular box-like frame with 156 mm x 146 mm dimensions. The undulator magnet is enclosed in a 273 mm (10.75") diameter cylindrical vacuum vessel with a driver mechanism placed outside. In May 2012 the CHESS Compact Undulator (CCU) was installed in Cornell Electron Storage Ring and beam tested. During four weeks of dedicated run we evaluated undulator radiation properties as well as magnetic, mechanical and vacuum properties of the undulator magnet. We also studied the effect of the CCU on storage ring beam. The spectral characteristics and intensity of radiation were found to be in very good agreement with expected. The magnet demonstrated reproducibility of undulator parameter K at 1.4 x10^{-4} level. It was also found that the undulator K parameter change does not affect electron beam orbit and betatron tunes.

1. Introduction

To address the needs of the CHESS upgrade we designed and built the Cornell Compact Undulator (CCU). It is of adjustable phase (AP) type [1], 1 meter long, in-vacuum, has planar PPM structure and has a number of novel features.

Instead of traditional massive C-frame, CCU has compact and rigid r***ectangular box-like*** frame. Two magnet arrays are mounted inside on miniature sliders. The magnetic field is controlled by the displacement of one magnet array relative to other along beam axis. The use of a box-shape frame provides compactness and excellent mechanical integrity. The problem of limited access to the magnetic field region around beam axis needed for magnetic field measurement and tuning was resolved in the way described in [3].

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The CCU magnetic structure is comprised of ***inexpensive, simply shaped Nd-Fe-B permanent magnet blocks***. Blocks are ***soldered*** to the copper holders according to procedure developed in [4]. The holders, in turn have features for accurate positioning needed for magnetic field tuning. Compared with gluing, soldering provides stronger bonding and UHV compatibility. Mechanical fastening of PM blocks would require a more complex design and would increase significantly the cost and the size of undulator.

Because motion has only one degree of freedom, for undulator K parameter tuning we used a ***single stepping motor driver*** with feedback through an accurate positioning gauge. This simplicity resulted in excellent position reproducibility. The x-ray spectra measurement indicated that the undulator parameter K can be reproduced with 1.4e-4 accuracy. This accuracy requires magnet array position repeatability better than one micron.

CCU performance was beam tested during a dedicated four week test run from April 22 to May 24 2012. The experience and results obtained in the course of the test and described in the following sections, helped us better understand various aspects of the undulator operation. Acquired knowledge will be used in the design of the next CCU type magnets.

2. General Information

The cross-section of the CCU magnet is depicted on Figure 1. A description of some of components is given in the caption, more details can be found in [3].

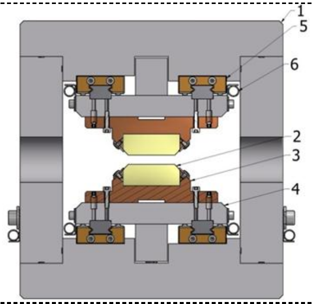

Figure 1. CHESS Compact Undulator cross-section: (1) – thick aluminum plates comprising the undulator frame; (2) – permanent magnet blocks soldered to copper holders (3); (4) – base plates holding PM block/holder assemblies; (5) – miniature rails; (6) – cooling lines. Outer frame dimensions are 152mm x 146mm. Gap between magnets is 5mm.

The undulator assembly, tuning and vacuum baking were done in clean room in 12GeV Annex. On April 24, 2012 the magnet was moved into CESR tunnel and installed in the storage ring. In the direction of electron beam undulator emitted radiation into CHESS "A"-line and in the direction of positron beam into "G"-line. The CCU assembly was equipped with a pair of RF-shielded gate valves, and was baked at 70°C for one-week to achieve a base vacuum pressure in low 10^{-9} torr. After installation in the storage ring, the two connecting short beam pipes were baked to 150°C for 24-hour.

Figure 2. Undulator body on assembly bench in clean room in 12 GeV Annex.

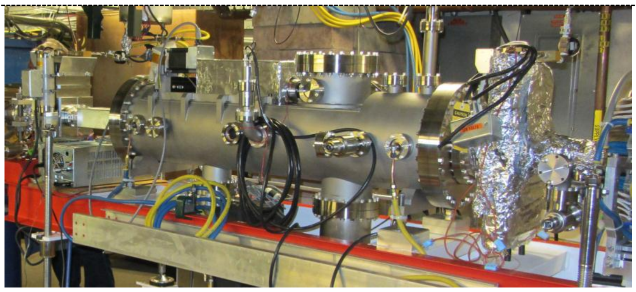

Figure 3. CHESS Compact Undulator installed in Cornell Electron Storage Ring.

Figures 2 and 3 depict assembled undulator body and undulator in vacuum vessel installed in storage ring.

3. Undulator Basic Properties

Two aspects of undulator operation were evaluated in the test. We characterized undulator radiation properties and studied undulator interaction with storage ring beams.

3.1. Measured and calculated X-ray spectra

Most of the characterization of radiation was done at the CHESS "A2" station. For spectra measurement, we defined an on-axis 0.2x0.2 mm slit 18.3 m downstream of the undulator and 2 m upstream of the double-bounce Si-111 monochromator. The monochromator energy was scanned over a range of 8.6 to 25keV, measuring the rocking curve of the second monochromator crystal at each energy. The x-ray flux was measured in the A2 hutch using a nitrogen-filled ion chamber. The measured ion chamber counts were normalized to the storage ring current. The flux was computed from theoretical ion chamber sensitivity based on the photo absorption cross section for nitrogen [5] and a W-value of 34.6 eV/ion pair. This measured flux was then finally corrected for sources of attenuation along the beamline, including beryllium windows, graphite filter, helium flight path, and air.

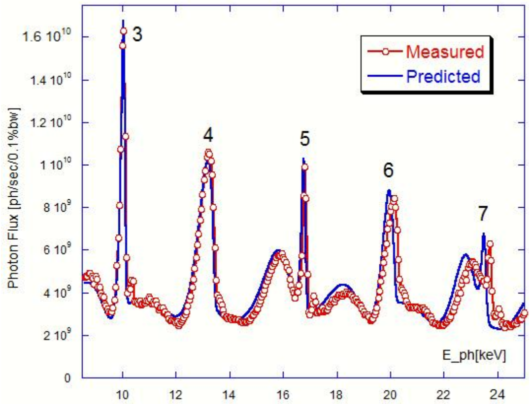

Figure 3. Measured x-ray spectra and predicted for ideal undulator magnetic field. Numbers indicate radiation harmonic orders.

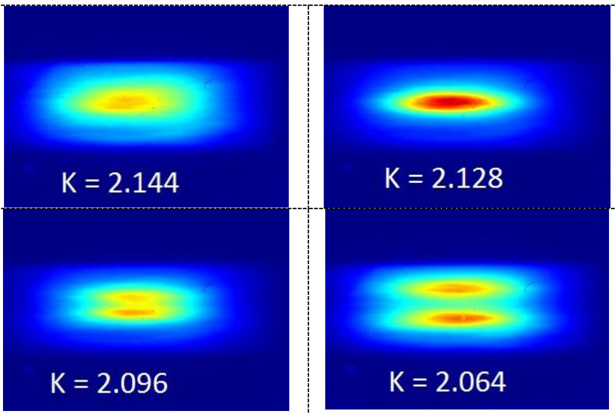

Figure 4. Spatial distribution of 10keV photon flux for various undulator K parameter.

The resulting measured and calculated x-ray spectra are presented in Figure 3. At the time of measurement the undulator was tuned to 71.35^0 phase (K =2.130) to move third harmonic's energy slightly above 10keV. In the calculations we assumed an ideal undulator magnetic field, 1% coupling and beam current as in experiment. Calculations were made with software SPECTRA [6].

The good agreement between measured and predicted undulator spectra up to 7-th harmonics indicated satisfactory undulator magnetic field quality.

Another experiment was the observation of the spatial distribution of 3rd harmonics as a function of the undulator parameter K. In this experiment we fixed monochromator energy at 10keV and scanned K (by moving magnet array) from 2.144 to 2.080. The series of images in Figure 4 show dynamics of 10keV photon flux spatial distribution generated by 3-rd harmonics undulator radiation. The observed distribution is in good agreement with prediction. This also confirmed adequate undulator magnetic field quality

3.2. K parameter reproducibility

Undulator parameter reproducibility is very critical to the operation. It directly depends on accuracy of the mechanical motion. To evaluate this, we set monochromator to 30.491 keV photon energy and made a number of undulator scans in the range from 121.69 to 123.56 degrees (K parameter was changing from 1.2763 to 1.2388). In this range, the 5-th harmonic of undulator radiation is crossing the selected energy and the dependence of the peak locations of photon counting rate on undulator phase can be used for the reproducibility evaluation. Data obtained from six scans are depicted in Figure 5.

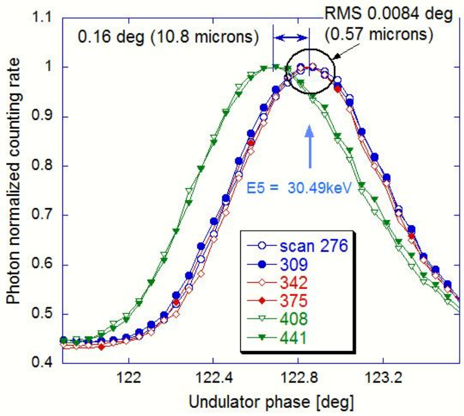

Figure 5. Photon normalized counting rate as function of undulator phase (magnet array displacement) with monohromator energy set to 30.49keV

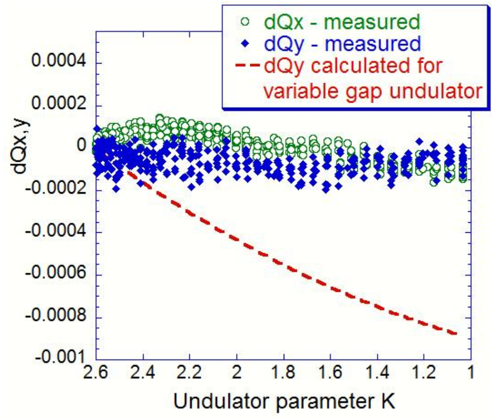

Figure 6. Measured horizontal (dQy) and vertical (dQx) electron beam betatron tune variations versus K. Dashed line – calculated vertical tune change for variable gap undulator

Scans 276, 309 and 342, 375 were made after the undulator was moved through the standard cycle: from 121.69^0 (8.3 mm displacement) to 0^0 (0 mm) and back. Analysis indicated that the spread in peak locations of these scans is just 0.0084^0 (RMS). Assuming that this spread is due to errors in magnet array position, we can estimate RMS of these errors as just 0.57 microns. That corresponds to 1.4×10^{-4} of K variation. The latter number agrees with the result from magnetic field measurement described in [3]. Two scans, 408 and 441, were made after a non-standard motion cycle. From 123.56^0 phase the undulator was moved to 140^0, then back. The non-standard motion cycle caused -0.16^0 (-10.8 microns) shift in harmonics location. The shift suggests the presence of ~10 microns backlash in the moving system which can be avoided if the undulator is moved through the standard path.

3.3. Interaction with storage ring beam.

One of the properties of AP type undulators predicted in [1] is the independence of the beam focusing on K parameter. To check it, we measured electron beam betatron tunes as a function of K. The measurement results, together with vertical tune variation calculated for variable gap undulator, (see dashed line) are depicted on Figure 6. The data confirm that in an AP structure the K parameter change does not affect storage ring beam focusing.

Prior to installation into storage ring, we measured CCU first magnetic field integrals on bench with a Hall probe. The measurements showed the field integrals variation with K at 0.1 Gm level or less. We estimated electron beam orbit displacement due to this to be below 3 microns. In experiment, the data indicated peak-to-peak ~5 microns orbit variation with K change. Taking into account the measurement errors (~3 microns) we estimated the upper limit on orbit variation as 2 microns and on the first magnetic field integral change less than 0.1 Gm. The negligible first magnetic field integral variation with K agrees with observations reported in [2].

4. Conclusion

We developed, constructed and beam tested a new type of PPM planar undulator magnet (CHESS Compact Undulator) that is much more compact, lighter and less expensive than conventional undulators operated at storage rings. The magnet demonstrated excellent magnetic and mechanical properties. The measured undulator radiation characteristics are in a very good agreement with predicted. This type of undulator magnet can also be used at other facilities.

5. Acknowledgment

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6. References

[1] R. Carr, NIMA 306, 391 (1991)

[2] R. Carr, H.-D. Nuhn and J. Corbett, “First Test Results for an Adjustable Phase Undulator”, In Proc. EPAC 92, p. 489. Available on web: http://accelconf.web.cern.ch/AccelConf/e92/PDF/EPAC1992_0489.PDF

[3] A. Temnykh et al., “Compact Undulator for Cornell High Energy Synchrotron Source”, IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 22, NO. 3, JUNE 2012. Available on web: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=06112670

[4] A. Temnykh, US Patent 7,896,224

[5] W.T. Elam, B.D. Ravel and J.R. Sieber, Radiation Physics and Chemistry, 63 (2), 121 (2002)

[6] T. Tanaka and H. Kitamura, J. Synchrotron Radiation 8 (2001) 1221