ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THODB1

COMMISSIONING OF A 1.6 M LONG 16MM PERIOD SUPERCONDUCTING UNDULATOR AT THE AUSTRALIAN SYNCHROTRON

Y. E. Tan*, S. Porsa, D. Zhu, C. Kamma Lorger, Australian Synchrotron-ANSTO, Clayton, Australia
A. Grau, N. Glamann, KIT, Karlsruhe, Germany
W. Walter, A. Hobl, M. Kirchler, Bilfinger Noell GmbH, Germany

Abstract

A 1.6 m long 16 mm period superconducting undulator (SCU16) has been installed and commissioned at the Australian Synchrotron. The SCU16, developed by Bilfinger Noell GmbH, is based on the SCU20 currently operating at at KIT. The SCU16 is conduction cooled with a maximum on axis field of 1.084 T and a fixed effective vacuum gap of 5.6 mm. The design and performance of the longest superconducting undulator at a light source will be presented.

SCU16 DESIGN

The Australian Synchrotron (AS) [1] has been in operation for users since 2005 and in 2016 the BRIGHT beamline project launched to build six new beamlines. For the Biological Small Angle X- Ray Scattering (BioSAX) beamline a source at 12.4 keV located in one of the shorter straights (< 2.5 m) was needed. Based on known room temperature IVU performances and empirical equations by Bahrdt [2] (6 mm vacuum gap and 5th harmonic), a comparison of room temp vs cryogenic undulators was carried out and showed an expected improvement in the flux to the beamline by 36 % with a superconducting undulator (SCU). IVU/CPMUs have historically demonstrated the ability to achieve small RMS phase errors (< 5°) by shimming the poles [3]. While horizontal racetrack SCUs have yet to demonstrate shimming to to such values [4], vertical racetrack SCUs at the APS [5] have been able to achieve this goal. For the AS, SPECTRA [6] simulations showed an RMS phase error of 10° would result in a flux reduction of 10 % at the 5th harmonic and is considered acceptable if not ideal. With the recent successful development and demonstration of the conduction cooled SCU20 (designed and built by Bilfinger Noell) at KIT[7, 8], the SCU was selected for the beamline and the parameters are listed in Table 1.

The SCU16 is a vertical racetrack design with NbTi insulated SC wire (Nb-(47±1)wt%Ti) continuously wound around an iron core working at an operating current of 862 A and temperature margin of 1.7 K. Additional winding around the end poles (AUX) and a pair of SC horizontal Helmholtz coils (HH) in the insulation vacuum chamber (IVC) is used to correct vertical field integrals. SCU16 is cryogen-free and conduction cooled with two RDE-412D4 (thermal shield/leads; beam chamber) and two SRDE-418D4 (thermal-shield/leads; magnet) cold heads. A pair of 200 W heaters have been added to reduce the warm up period to 2.5 days. A combination of 36 Si-Diode/Cernox sensors is used for temperature sensing.

Table 1: Storage Ring and SCU16 parameters.

Parameter	Value
Electron Energy	3.03 GeV
Nat. Emittance / coupling	10.5 nmrad / 1.24%
$\beta_{x,y}$	8.92 m / 2.42 m
$\eta_{x,y}$	0.10 m / 0.00 m
Cryostat / Magnet length	2.5 m / 1.6 m
Magnet Period / Periods	16.01 mm / 98
Maximum Field / K	1.084 T / 1.62
Magnet Gap	8.0 mm
Horiz. / Vert. Vacuum Gap	60.0 mm / 5.6 mm
Field Stability (144 hr)	< 200 ppm
Horiz. roll-off (±10 mm)	< 0.35%
RMS Phase Error	10° - 15°

The 316LN electron beam chamber (EBC) was redesigned to increase the robustness under one atmosphere of differential pressure without lasting deformations. Both upper and lower surfaces facing the beam is coated with an additional 30 µm of copper to improve electrical and thermal conductivity. The tapered transitions to and from the storage ring chamber aperture is located external to the IVC to minimise RF heating.

Three Delta Elektronika SM 15-400 (15 V/400 A) power supplies arranged in series is used to power the SCU16. The primary passive quench protection system is a set of cold diodes that protect the superconductors coupled with Danfysik's four channel quench detector. The power supply is interlocked if a quench condition is detected (differential V> 100 mV for more than 10 ms) or magnet temperatures >4.25 K. The total static power consumption the SCU16 is approximately 30 kW.

Field Measurements

Magnetic measurements of the SCU16 were done with just the the cold mass at KIT's CASPER II facility [9] with a stretched wire system for integral measurements and hall probe for field profiles. The integrals and Cartesian quadrupole components are listed in Table 2 respectively. Technical issues, COVID delays and other time constraints meant that only two adjustments to the magnet array could be done to symmetrise the transverse roll-off and minimise the field amplitude variation along the length of the SCU. With

* eugene.tan@ansto.gov.au

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THODB1

the current corrections the RMS phase error is believe to 10° to 15° depending on AUX corrections. With additional shimming it would have been possible to reduce the phase error to less than 6°. Optimising SCU16 for peak brightness will be done when the beamline is ready to verify the new corrections.

COMMISSIONING

Cooldown took just under four days and resulted in a final IVC pressure of less than 10^{-6} mbar (see Figure 1). As the IVC pressure decreased below a pressure of 10^{-5} mbar periodic pressure spikes emerged as a result of trapped volumes in elements like the layered Mylar thermal shield. After a few months these spikes have largely disappeared. At the

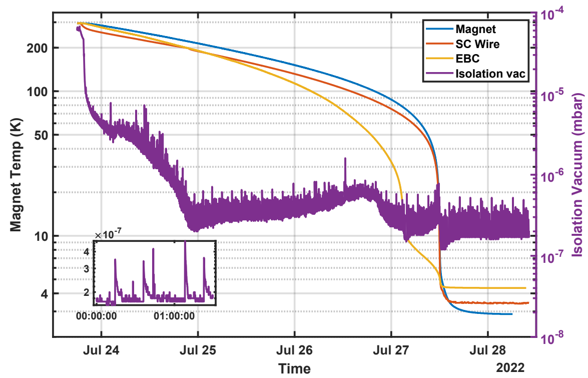

Figure 1: Cool down takes just under four days. Small vacuum spikes (inset) are likely the result of out-gassing from various trapped volumes within the IVC.

factory >40 quench training cycles were required however this has since settled and only requires 10 quench cycles to reach maximum field after the SCU warms up. During a quench the magnet/diode temperatures reach 20 K before cooling down to operational temperatures after 25 minutes. In one incident, a mis-configuration of the PSU resulted in the SCU16 quench trained to as high as 1.12 T (K = 1.673). The experience reinforced the need for an external DCCT to monitor the current (Ultrastab 866R + NI-6221).

The maximum ramp rate for the SCU16 is 4.5 A/s reaching full field in 3 minutes. The RMS and peak-to-peak field stability of 19 ppm and 170 ppm respectively was measured over a 160 hr time window during normal operation. An initial 45 minute warm-up period was observed before reaching the final stable operating current and a software based slow feedback will be sufficient to compensate this initial drift. A monotonic drift of the output current, as much at 200 ppm, over two weeks has also been observed and the source is still not understood.

A stretched wire system developed by KIT was used on site to confirm the field quality had not deviated significantly due to shipping, and was also used to verify the vertical aperture by touching the wire to the vacuum chamber's inner surfaces. After some corrections to the end flange positions the parallel gap was measured to be no larger than 5.6 mm. The impact of the aperture was a reduction in the beam lifetime of between 2% and 8% and no noticeable impact on injection efficiencies.

Vacuum conditioning after first beam was smooth reaching mid 10^{-8} mbar after a few days, and has since reached 10^{-9} mbar after six months. The equilibrium temperatures of the SCU16 at 1.084 T and 200 mA in the ring is shown in Figure 2 with magnets reaching temperatures < 3.5 °C. The temperature distribution at the EBC also shows elevated temperatures at the downstream end consistent with additional heat load from the upstream dipole synchrotron radiation.

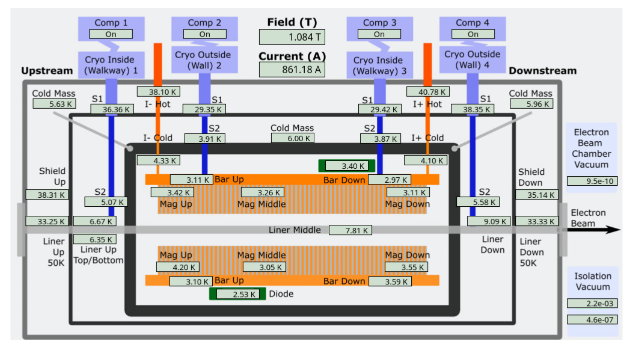

Figure 2: Control system graphical user interface showing the steady state temperatures for the SCU16 at 1.084 T and 200 mA in the storage ring.

Without a cryogen the impact of a loss of cooling is immediate and a test was done to study the effect of this failure. With 200 mA in the storage ring, the test showed the EBC pressure increased one order of magnitude in 5 minutes and dropped the beam lifetime to less than 5 hours and caused severe vertical beam instabilities. To mitigate this failure mode a PLC system is used to monitor the water flow and switch to a backup cooling system when needed.

Over the past 6 months of operations, the SCU16 has demonstrated a quench rate of 4.5 % (one quench from 18 beam dumps) and a controlled beam dump that directs the electron beam into a scraper is being implemented to eliminate beam dump related quenches.

Impact on Closed Orbit, Tunes and Impedance

After successive optimisations the maximum orbit changes have been kept to < 100 µm and with the fast orbit feedback system [10] (FOFB) the maximum disturbance is < 5 µm over the entire ramp. Figure 3 shows shows the impact of a quench on the beam position at the position with the largest response. The disturbance is too large for the FOFB system which attempts to correct the fault in the first 20 ms before stopping, but small enough it does not trigger a beam dump. Not shown in the figure is that after approximately 2 seconds, the AUX and HH coil also interlock, due to temperature, causing a second smaller distortion to the beam. The overall change in the horizontal and vertical tunes was $\nu_{x,y}$ = +0.0010, +0.0018 and is similar to other IVUs at the AS. No local quadrupole compensation is needed and only global tune correction will be used.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THODB1

Table 2: Stretched wire measurements of the field integrals and integrated quadrupole components with optimised trim coils.

Field (T)	B_y I1 (10^{-6} T m)	B_y I2 (10^{-6} Tm^2)	B_x I1 (10^{-6} T m)	B_x I2 (10^{-6} Tm^2)	k (mT)	k_s (mT)
0.325	21.80	-64.89	-102.80	-146.59	2	0.2
0.650	-7.48	30.17	-3.92	20.12	8	0.7
0.975	0.890	11.82	24.00	55.70	14	2.0
1.084	-0.32	-12.95	10.99	57.02	17	1.9

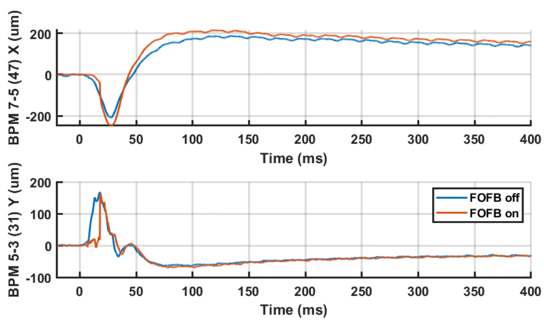

Figure 3: The maximum perturbation to the stored beam was recorded to be 250 µm (H) and 170 µm (V) which is below the orbit interlock limits. The disturbance is too large for the fast orbit feedback system manage.

The transverse impedance of the EBC is dominated in the vertical plane and is effectively a parallel plate model given the aspect ratio [11]. For our standard chamber (316LN) with a full vertical aperture of 32 mm and length of 3 m, the impedance is 0.013 MΩ. The new chamber's impedance is expected to increase to 0.059 MΩ[1]. Historically the total storage ring impedance is approximately 0.9 MΩ and the new chamber would have been a 5% increase. This change in impedance can be seen as a change in the single bunch tuneshift gradient by of $\Delta(d\nu_y/dI) = -0.020\ \mathrm{A}^{-1}$. Measurements have however showed a change that is five times greater at $-0.097\ \mathrm{A}^{-1}$, and this discrepancy is being investigated. Figure 5 shows the SCU16 as installed in the storage ring.

Beamline Measurements

The photon flux on sample after a double-multilayer monochromator (DMM) with a 1% FWHM bandpass was measured with a calibrated photodiode to be $\approx 10^{14}$ ph/s meeting the target for the beamline. The first measurement of the non-optimised photon spectrum is shown in Figure 4 without AUX or undulator vertical position optimisation.

CONCLUSION

The SCU16 has been designed and built by BNG and installed at the Australian Synchrotron for the BioSAX beamline. Cooling design is more than adequate operating well below design temperatures and the quench recovery time is of the order under 30 minutes with a slow feedforward system to compensate PSU warm up effect. In the coming months studies of the wider impact on the beam impedance and optimisation of the photon spectrum will be done via adjustment of the auxiliary coils and undulator position.

[1] Assuming copper foil with resistivity at cryogenic temperature of $0.0336 \times 10^{-8}\ \Omega$ (RRR of 50).

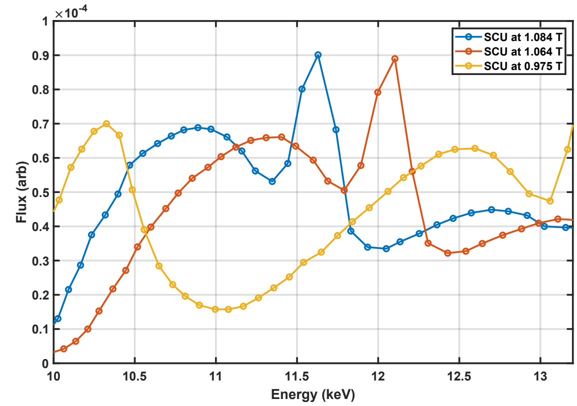

Figure 4: Preliminary beamline measurements of SCU16 spectrum after a DMM with a 1% FWHM bandpass at 1.084 T, 1.064 T and 0.975 T.

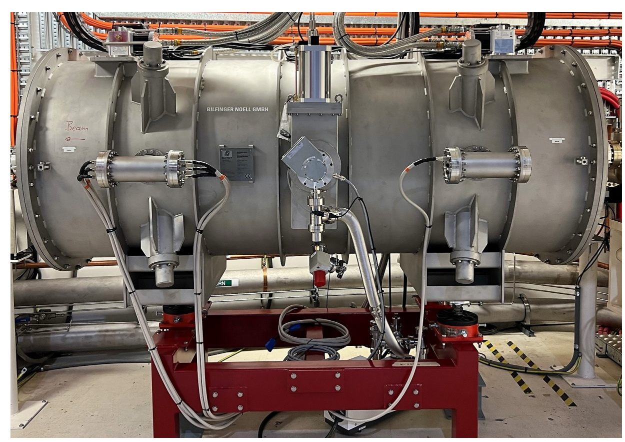

Figure 5: SCU16 installed in the storage ring.

ACKNOWLEDGEMENTS

The author would like to thank Mike Lafky and the Operators, and all engineering and technical teams at the AS and BNG. In particular Brian Jensen, Trent Smith, Jonathan McKinlay and Jason Wirthensohn.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THODB1

REFERENCES

[1] G. LeBlanc, M. J. Boland, and Y. E. Tan, "The Australian Synchrotron Project Storage Ring and Injection System Overview," in *Proc. EPAC'04*, (Lucerne, Switzerland, Jul. 2004), JACoW Publishing, Geneva, Switzerland. http://accelconf.web.cern.ch/e04/papers/THPKF005.pdf

[2] J. Bahrdt and E. Gluskin, "Cryogenic permanent magnet and superconducting undulators," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 907, pp. 149–168, 2018.

[3] J.-C. Huang *et al.*, "Force-compensating spring modules of self-contained type for small phase error performance in in-vacuum undulators," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 1013, p. 165 650, 2021, ISSN: 0168-9002. DOI: https://doi.org/10.1016/j.nima.2021.165650. https://www.sciencedirect.com/science/article/pii/S0168900221006355

[4] A. Bragin *et al.*, "Short-period superconducting undulator coils with neutral poles: Test results," *IEEE Transactions on Applied Superconductivity*, vol. 28, no. 4, pp. 1–4, 2018.

[5] M. Kasa, C. L. Doose, J. D. Fuerst, E. Gluskin, and Y. Ivanyushenkov, "Progress on the Magnetic Performance of Planar Superconducting Undulators," in *Proc. NAPAC'16*, (Chicago, IL, USA, Oct. 2016), JACoW Publishing, Geneva, Switzerland, pp. 477–479. DOI: 10.18429/JACoW-NAPAC2016-TUB4CO04. https://jacow.org/napac2016/papers/TUB4CO04.pdf

[6] T. Tanaka, "Major upgrade of the synchrotron radiation calculation code spectra," *Journal of Synchrotron Radiation*, vol. 28, no. 4, pp. 1267–1272, 2021.

[7] S. Casalbuoni *et al.*, "Superconducting undulators: From development towards a commercial product," *Synchrotron Radiation News*, vol. 31, no. 3, pp. 24–28, 2018.

[8] A. Grau *et al.*, "Full-scale conduction-cooled superconducting undulator coils—training, stability, and thermal behavior," *IEEE Transactions on Applied Superconductivity*, vol. 28, no. 3, pp. 1–4, 2018.

[9] A. Grau, S. Casalbuoni, N. Glamann, and D. S. de Jauregui, "Cryogenic, in-Vacuum Magnetic Measurement Setup for Superconducting Undulators," in *Proc. 10th International Particle Accelerator Conference (IPAC'19), Melbourne, Australia, 19-24 May 2019*, (Melbourne, Australia), ser. International Particle Accelerator Conference, https://doi.org/10.18429/JACoW-IPAC2019-TUPRB015, Geneva, Switzerland: JACoW Publishing, Jun. 2019, pp. 1709–1712, ISBN: 978-3-95450-208-0. DOI: doi:10.18429/JACoW-IPAC2019-TUPRB015. http://jacow.org/ipac2019/papers/tuprb015.pdf

[10] Y. E. Tan *et al.*, "Commissioning of the Fast Orbit Feedback System at the Australian Synchrotron," in *Proc. IPAC'17*, (Copenhagen, Denmark, May 2017), JACoW Publishing, Geneva, Switzerland, pp. 1770–1773. DOI: 10.18429/JACoW-IPAC2017-TUPIK040. https://jacow.org/ipac2017/papers/TUPIK040.pdf

[11] R. T. Dowd, M. J. Boland, G. LeBlanc, M. J. Spencer, and Y. E. Tan, "Single Bunch Studies at the Australian Synchrotron," in *Proc. EPAC'08*, (Genoa, Italy, Jun. 2008), JACoW Publishing, Geneva, Switzerland, pp. 1062–1064. https://jacow.org/e08/papers/TUPC010.pdf