5th International Particle Accelerator Conference IPAC2014, Dresden, Germany JACoW Publishing
ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-THPME195

NONDESTRUCTIVE BEAM CURRENT MONITOR FOR THE 88-INCH CYCLOTRON*

M. Kireeff Covo, LBNL, Berkeley, CA 94720, USA

Abstract

A fast current transformer is mounted in the staging line of the Berkeley 88-inch isochronous cyclotron. The measured signal is amplified and connected to the input of a lock-in amplifier. The lock-in amplifier detects the signal vector from the input signal at the RF reference frequency of the cyclotron second harmonic. The magnitude of the signal detected is calibrated against a Faraday cup and shows the beam current leaving the cyclotron.

INTRODUCTION

The 88-Inch Cyclotron at Lawrence Berkeley National Laboratory is a sector-focused cyclotron with both light- and heavy-ion capabilities that supports a local research program in nuclear science and is the home of the Berkeley Accelerator Space Effects (BASE) Facility.

The cyclotron has three ion sources that have led to progressively higher intensities and charge states of heavier ions. The ions produced by the ion sources are injected inside the 88-inch cyclotron. After the ions enter the cyclotron, they are accelerated by a radiofrequency (RF) electric field and held to a spiral trajectory by a static magnetic field. The RF fields cause the ions to bunch up into packets. The ions gain velocity and the orbit increases with radius. The ions that are not synchronized with the RF are lost.

The cyclotron operates in the frequency range of 5.5 to 16.5 MHz, but it can operate using harmonic acceleration, so the energy range of the machine is limited only by the capabilities of the magnet, not the RF system.

Early on it was realized that the variable frequency of the cyclotron translated to a mass resolution of 1/3000, meaning that the cyclotron could separate most ions of near identical mass-to-charge ratio emanating from the ion source. The combination of cyclotron and ECR sources provide the unique ability to run "cocktails" of ions. A cocktail is a mixture of ions of near identical charge-to-mass ratio.

During the cyclotron operation, the ions are tuned out of the source together and the cyclotron acts as a charge-to-mass analyzer to separate them and provide different ion species and charge states for energy variable experiments.

The wide-band driven RF system for the 88-Inch cyclotron provides fast beam tuning, [1] allowing users to switch back and forth between several ion species of the same cocktail [2] with small adjustments of the accelerator frequency, so a new beam does not require retuning the whole accelerator and is accomplished in approximately one minute.

The next sections show a Fast Current Transformer (FCT) installed after the exit deflector to measure the beam current [3] of the cyclotron. The signal is filtered and amplified before it is processed by a lock-in amplifier and displayed in a computer.

FAST CURRENT TRANSFORMER

The Fast Current Transformer, model FCT-082-05:1-H from Bergoz Instrumentation,[4] is a toroidal core made of cobalt-based nanocrystalline and amorphous alloys of 82 mm inner diameter and a five turn coil wound, which has a gain of 5V/A. The bandwidth of the FCT is 32KHz to 700 MHz with typical rise time of 500 ps.

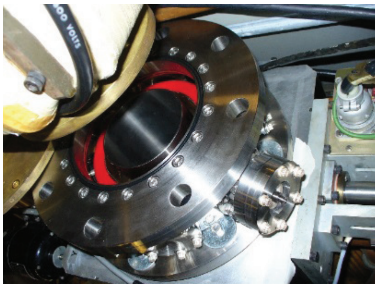

Figure 1: Fast Current Transformer.

The FCT is mounted inside a spherical octagon UHV vacuum chamber from Kimball Physics with a floating coaxial feedthrough, Fig. 1. The vacuum chamber is mounted in the staging line after the cyclotron deflectors, therefore all the beam leaving the cyclotron will cross it. An electrostatic shield, grounded only upstream, is installed and also protects the FCT from beam losses.

The signal from the FCT is amplified by two ultraband low noise amplifiers, model RLNA01M03GA from RF-Lambda. Each amplifier has a gain of 38 db, or voltage gain of 80, and have a high linearity and low noise figure (1.5 db).

The signal is sent to the control room by a low loss cable, Andrew Heliax, 7/8 in. diameter. Three ferrite toroids of material 43 with four turns are installed between the FCT and the heliax cable and work as a common-mode choke.

MEASUREMENTS

Figure 2 shows the beam current measurements with the FCT for a development run of $^{48}\mathrm{Ca}^{+11}$ with Cyclotron frequency of 15.73 MHz. The red line is the RF pick-up signal for timing purposes and uses the left hand ordinate. The green line is the current measured with the FCT and uses the right hand ordinate. The oscilloscope acquisition

---

*Work supported by the Director, Office of Science, Office of Nuclear Physics, Division of Nuclear Physics, US Department of Energy under Contract No. DE-AC02-05CH11231.

#mkireeffcovo@lbl.gov

is averaged over 16 samples to improve the signal to noise ratio. The background noise, obtained when a Faraday cup was blocking the beam in the axial line before the cyclotron, is subtracted from the FCT signal. The beam has a peak current of 95.3 µA and a full width half maximum of 5.6 ns, giving an average current of 10.4 µA.

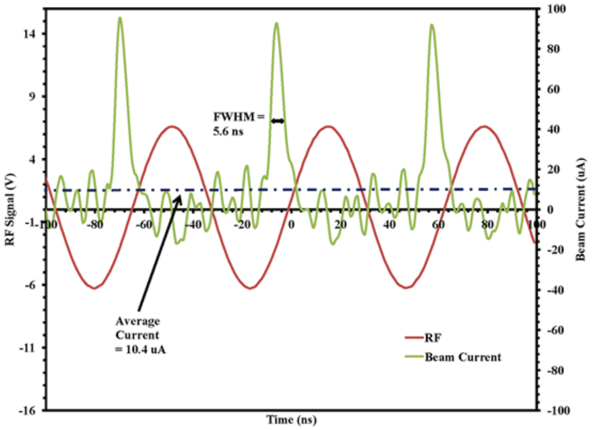

Figure 2: Beam current measurements with the FCT.

The FCT signal is then connected to a spectrum analyzer. Figure 3 shows the RF spectrum of the signal with and without the beam.

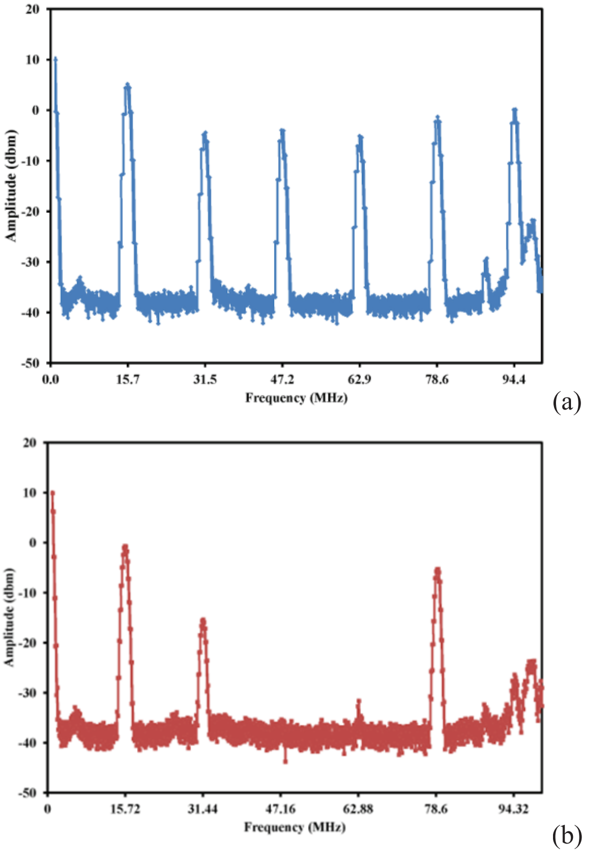

Figure 3: FCT spectrum measurements. (a) Spectrum of the FCT signal with beam leaving the cyclotron. (b) Spectrum of the FCT with beam blocked by a Faraday cup.

The sharp bunch shape with a duty cycle of 9% creates many harmonics, Fig. 3a, that can be measured because of the fast response of the FCT.

The spectrum without the beam, Fig. 3b, is obtained by blocking the beam with a Faraday Cup located in the axial line before the cyclotron. The spectrum obtained by blocking the beam with the FC agrees with measurements when the beam is turned off with the chopper. Noise present in these measurements are produced by the cyclotron.

Figure 4 shows the RF spectrum, obtained from a pick-up antenna inside the final power amplifier, before the RF is coupled with the cyclotron.

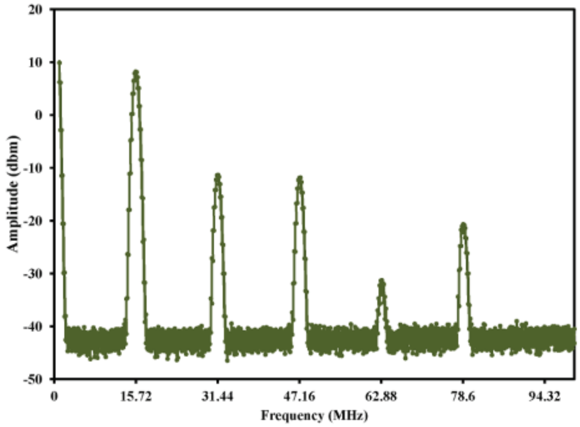

Figure 4: RF spectrum.

The 6th harmonic component is very low, nevertheless there is an induced beam noise in Fig. 3a and 3b.

BEAM CURRENT MONITOR

The FCT signal is finally connected to the input of the lock-in amplifier model SRS844 from Stanford Research Systems.[5] The lock-in reference signal is from a frequency synthesizer that is synchronized with the RF system. The frequency of the synthesizer is adjusted to the main frequency of the RF and its harmonics. The signal amplitude is measured and shown as red solid circles in Fig. 5. The blue solid line is the spectrum of the FCT signal measured with a spectrum analyzer.

The noise generated without beam crossing the FCT has components induced by the RF system and beam. The noise phase and amplitude changes with variations of any of these elements, moreover a small change in the cyclotron frequency during a cocktail tune will change the phase of the beam and noise signal. Therefore the amplitude is used to measure the amount of current because it is independent of the phase reference, which differs from previous work [6].

The beam current monitor is designed taking advantage of the fact that the spectrum of the second harmonic has a large dynamic range when the beam is turned on and off. Therefore the SR844 is adjusted for automatic harmonic detection of the 2f component and the fast fluctuations of the beam current, caused by plasma oscillations from the sources, are filtered by using a time constant of 1s with 24 dB/octave rolloff.

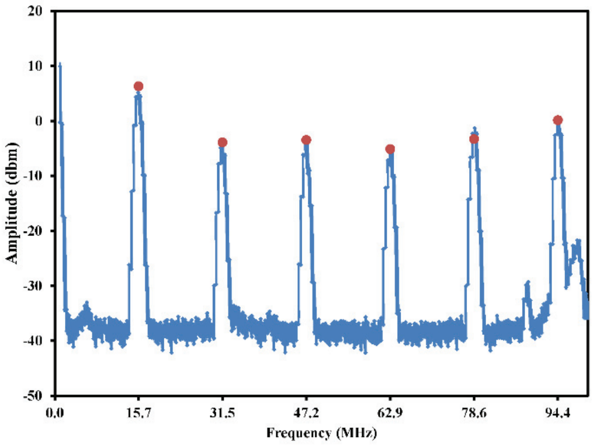

Figure 5: Fundamental and harmonic components of the FCT beam spectrum obtained with a spectrum analyzer (blue line) and a lock in amplifier (filled red circles) that used different reference signals from a synthesizer synchronized with the RF signal.

COMMISSIONING

The SR844 is a square wave detecting lock-in and detects all of the odd harmonics of the fundamental. As Fig. 3b shows the noise contribution to the signal measured , a low pass filter model BLP-70+ is added before the low noise amplifier to increase the signal-to-noise ratio by filtering high frequency noises generated by the cyclotron. One low noise amplifier, mode RLNA01M03GA, is also removed to decrease the noise figure.

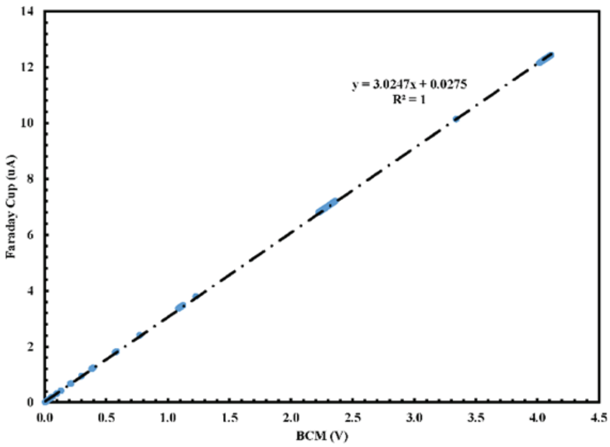

Figure 6: Beam current measured with the beam current monitor.

The sensitivity of the lock-in amplifier is set to the maximum and the output to measure the amplitude R of the signal. The current of the cyclotron was attenuated during the development run and a set of measurements were taken. Figure 6 shows a plot of the lock-in amplifier output voltage versus the current measured with a Faraday cup.

Later the output signal is sent to a computer and the current is calibrated against a Faraday cup before the acquisition starts. The computer shows the current measured over time and stores the data in files.

CONCLUSION

A fast current transformer is mounted after the deflectors of the 88-inch cyclotron. The signal is filtered, amplified, and sent to a lock-in amplifier that has a reference signal derived from the cyclotron RF signal.

The amplitude of the second harmonic is detected and calibrated against a Faraday cup. The beam current measured is displayed over time with a computer. The operators can detect beam current variations with the new beam current monitor and retune the beam to keep the current constant without interfering with the experiments.

ACKNOWLEDGMENT

The author would like to thank Brien Ninemire, Catherine R. Siero, Thomas Gimpel, and Scott M. Small for the cyclotron operation support, Adrian Hodkinson, Thomas Perry and John P. Garcia for the mechanical support, and Mark Regis and Brendan Ford for the electronic support.

REFERENCES

[1] M. Kireeff Covo, “Upgrade of the 88-Inch Cyclotron Power Amplifier,” Int. J. Microw. Wirel. Technol. 4 (2012) 553, doi:10.1017/S1759078712000505.
[2] D. Leitner-Wutte, M.A. McMahan, D. Argento, T. Gimpel, A. Guy, J. Morel, R. Siero, R. Thatcher, and C.M. Lyneis, LBNL, Berkeley, CA, USAD. Leitner et al., “Heavy Ion Cocktail Beams at the 88 Inch Cyclotron,” in *Proceedings of the 15th International Workshop on ECR Ion Sources*, Jyväskylä, Finland, Jun 12-14, 2002, Report LBNL-51451, 2002.
[3] C. Nantista and C. Adolphsen,” Beam Current Monitors in the Nlcta,” in *Proceedings of the 17th Particle Accelerator Conference*, Vancouver, Canada, May 12-16, 1997.
[4] Bergoz Precision Beam Instrumentation: Fast Current Transformer Datasheet.
[5] Stanford Research Systems: SR844 Lock In Amplifier User’s Manual.
[6] M. Wada, Y. Ishida, T. Nakamura, A. Takamine, A. Yoshida, and Y. Yamazaki, “Nondestructive intensity monitor for cyclotron beams,” RIKEN Accel. Prog. Rep. 38 (2005).