Proceedings of the 1999 Particle Accelerator Conference, New York, 1999

FERMILAB MAIN INJECTOR INSTRUMENTATION*

Ed Barsotti, Wim Blokland, Jim Crisp#, Brian Fellenz, Jim Fitzgerald, Gianni Tassotto, Greg Vogel,
and Jim Zagel, FNAL, Batavia, IL

Abstract

An overview of the instrumentation installed in the Fermilab Main Injector is presented. Efficiency, beam loss, average intensity, bunch intensity, position, betatron and synchrotron oscillation frequency, as well as transverse and longitudinal profiles are measured. Systems such as the Beamline Tuner and the Ionization Profile Monitor track changes through the accelerating cycle and analyze their rate of change.

1 INTENSITY MONITORS

1.1 DC Current Transformers

The DC current transformer (DCCT) used in Main Injector was designed at Fermilab for the Main Ring [2]. The device measures the second harmonic content from excitation windings to control a bucking current through magnetic cores surrounding the beam. The circuit is carefully balanced to maintain no net magnetic flux in the cores by making the bucking current exactly cancel the beam current. The bucking current is then a measure of the DC beam current. A careful balance of transformer coupling provides bandwidth from DC to several kilohertz.

A commercial current monitor was purchased for the Recycler ring (Bergoz, Crozet France). The unit has 100 kilohertz bandwidth, 7 decades of dynamic range, and .05% accuracy [3].

1.2 Torroids

Torroids (Pearson Electronics Inc., Palo Alto California) provide an inexpensive method of measuring beamline intensities and thus transfer efficiency. These devices are transformer coupled to the beam current and have no DC response. Their bandwidth is 40 hertz to 7 megahertz and they produce 1 volt per amp. A gated integrator is used to measure the total charge. Cable loss and matching, beam structure, limited bandwidth, and finite integration time result in 2% absolute accuracy. Relative accuracy is about ten times better. The calibration is adversely affected when secondary particles created by beam losses strike the torroid.

2 LOSS MONITORS

The same argon filled ion chamber (Troy-onics Inc., Kenvil, NJ) is used for Main Injector, beamline, and Tevatron loss monitors [4]. The sensitivity is 7e-8 coulombs per rad. The maximum signal is 100 rads "instantaneous dose rate" or 7e-6 coulombs of collected charge. Electronic noise limits the dynamic range to 6 decades.

2.1 Main Injector Loss Monitor Integrator

The daughter card used for the 250 Main Injector loss monitors has two channels. One channel provides a resetable integrator with a full scale output of 0.14 rads. An 8 bit A/D converter provides about 2 decades of dynamic range. The second channel provides a complicated decay integrator output to the MADC for time plotting. It has selectable gain advertised as .014 or 1.4 rads full scale. The response depends heavily on the time structure of the losses. Between 100 and 1000 hertz for example, the low gain setting produces full scale for 140 rads/second.

2.2 Beamline Loss Monitor Integrator

A new daughter card was designed and built for the 106 beamline loss monitors. It uses a "decaying integrator" circuit with a logarithmic response and a 1 decade per 30 msec decay time. The log amplifier has a 6 decade dynamic range. For losses shorter than 1 msec (as in the beamlines), 1 rad will produce the full scale output. For dc losses, the full scale output is 1000 rads/sec.

3 POSITION MONITORS

3.1 Position Detectors

To conserve tunnel space and maintain the beam pipe shape and minimize beam impedance, new detectors were designed that fit inside the downstream end of every quadrupole [5]. The 208 detectors measure 4 positions per betatron wavelength in both the horizontal and vertical planes.

The detector has four striplines that can be combined in pairs to measure either horizontal or vertical position at each quad. The plate width, position, and length were selected for best linearity and signal amplitude to match the Main Ring rf modules. The Main Injector bpm's provide about 0.7 db/mm for the ratio of A to B.

The four plate structure exhibits a pin cushion error which mirrors the field lines produced between the plates and the beam charge. This distortion couples the horizontal and vertical measurements for positions far off axis. Each detector was mapped with a set of 50 wire measurements at 5 mm spacing. This data was collected into a database and can be used to correct orbits with data from the orthogonal plane [6].

The Recycler ring uses a split tube design with separate horizontal and vertical geometry. Positions are

---

* Work supported by the U.S. Department of Energy under Contract No. DE-AC02-76CH03000

Email: crisp@fnal.gov

measured at 438 locations. The detector design allows a 500 volt clearing field to be applied to the bpm plates. Larger aperture detectors are required at 24 locations near injection and extraction points.

3.2 Position Electronics

The electronics from Main Ring were re used in the Main Injector. The system employs the AM to PM conversion technique to measure the relative amplitudes of the A and B detector signals and thus the beam position. The multibus system used to digitize the results are lacking in processing power, particularly by today's standards. However, a substantial savings was realized.

New position electronics using log amplifiers were developed for the Recycler [7]. Preamps are required in the tunnel in order to measure the position of unbunched beam using the rising and falling edges of the beam signal. Four positions are measured with a single CAMAC card. The log amp design is inexpensive but has ±.5 mm errors that depend on intensity and position. VME based computers and commercial digitizer cards with memory collect and process the data.

4 PROFILE MONITORS

4.1 Multiwires

A new paddle was designed for Main Injector multiwires with horizontal and vertical grids to allow simultaneous measurement of both planes. Each grid consists of 48 .003 inch diameter gold-tungsten wires with either 1 or 2 mm spacing. The distribution of charge is measured with a 96 channel integrator designed by the controls group for use in the Switchyard beamlines [8]. The central wire collects about 24 picocoulombs of charge for 5e11 protons.

4.2 Flying Wires

The Main Injector Flying Wires measure the transverse size of the particle beam used to calculate emittance [9], [10]. At separate horizontal and vertical locations, the system passes a 33 micron carbon monofilament (the 'wire') through the beam at speeds up to 10 m/s. Particles collide with the wire as it moves through the beam producing a cascade of secondary particles proportional to beam density. The secondary particles are measured with a scintillator paddle and photo multiplier tube. A 14-bit resolver measures the wire position with 0.022 degree angular resolution. The beam profile is a plot of photo multiplier tube output versus wire position. A non-linear fit is performed and the resulting summary data is made available to the accelerator network (ACNET) for use in calculating beam emittance.

4.3 Ionization Profile Monitors

The Main Injector and Recycler Ion Profile Monitors capture horizontal and vertical profiles at a once-per-turn sample rate [11], [12]. Microchannel plates are used to amplify the charge produced when the beam passes through the residual gas in the normal accelerator vacuum. The distribution of charge collected on a grid of conductors matches the beam profile. Current analysis include position, emittance (or sigma), 2D color intensity plot of raw data, single turn profiles for any turn during the cycle, and fourier transforms of bunch centroid (or tune).

An amplifier in the tunnel is required to convert the 140 nanoamp signal to the 0 to 5 volt 50Ω input of the A/D cards located in the equipment gallery. Sixty anode strips with 1.5 mm spacing are used to measure the transverse profile of the proton beam. Because the profile can be measured every Main Injector turn, each strip requires a dedicated amplifier and digitizer.

5 OTHER SYSTEMS

5.1 Sampled Bunch Display

The Sampled Bunch Display (SBD) is used to measure bunch intensities and longitudinal lengths of beam bunches. A wide band (3 kHz-6 GHz) longitudinal signal comes from a dedicated Resistive Wall Current Monitor. The signal is digitized by a LeCroy 9384L scope (4 GSamples/sec, 1 GHz analog bandwidth, 4 MByte segmentable memory with 100 usec re-arm time). A Macintosh computer running LabView does the processing and ACNET interface. Versatile, programmable acquisition timing is provided with a CAMAC 177 (TCLK-decoding) and a Kinetic Systems 3660 (programmable clock generator).

5.2 Fast Bunch Integrator

A real time intensity measuring system known as a Fast Bunch Integrator (FBI) was developed to determine the efficiency of this process and monitor when losses occur [13]. This system measures the intensity of both the original batch and the final individual bunch by using wide and narrow gated integrators [14]. A comparison of these two measurements provides the capture efficiency and indicates how much beam remained in adjacent RF buckets.

The FBI is a VME based system using a Motorola MVME-162LX embedded computer. The system supports fast time plots, snapshot plots and data logging of bunch intensity for all bunches as well as sums of bunch intensities for use as transfer qualifiers. The narrow gates provide the integrated intensity for individual bunches while the wide gates provide the integrated intensity for an adjustable sized batch centered on each narrow gated bunch.

5.3 Beamline Tuner

The Main Injector Beam Line Tuner (MIBLT) samples the integrated signals of vertical and horizontal beam position pickups using a Kinetics V440 60MHz digitizer. A LabView program analyzes the turn-by-turn position data and calculates the tunes, amplitudes and phase of the injection oscillation. The program has the capability to automatically make corrections for the next transfer. The integration of the pickup signal can be done using a low bandwidth RF module (batch resolution) or a high-bandwidth Fast-Integrator module (bucket resolution).

6 SPECIAL DEVICES

6.1 Wide Band Striplines

The Institute for High Energy Physics, near Moscow Russia, designed and built four stripline beam detectors for use at Fermilab [15]. A round geometry with two stripline plates allows installation as either horizontal or vertical detectors. Electrical feedthroughs at both ends of the 1.4 meter long striplines allow measurement of both proton and antiproton signals. The 1 gigahertz bandwidth and 9.3 nsec doublet separation allow measurement of high frequency structure within the beam bunches. The detectors are for general purpose use, two in the Main Injector and two in the Recycler.

The 60 degree wide plates intercept and carry about 1/6 of the beam image current. The peak amplitude on the 50Ω plates is 10 volts for 6e10 protons in a 3 nsec sigma gaussian bunch. A plate length of 1.4 meters (l/4 wavelength at the rf frequency of 53 MHz) is used to maximize the doublet separation. In the time domain, this allows observation of the bunch shape and changes in position along it's length. In the frequency domain, zero's in transmission occur when the plate is a multiple of 1/2 wavelengths long. This occurs at even harmonics of the rf frequency.

6.2 Resistive Wall Monitor

Resistive Wall Monitors were designed and built for the Fermilab Main Injector project [16]. These devices measure longitudinal beam current from 3 KHz to 4 GHz with a 1 ohm gap impedance. The new design provides a larger aperture and a calibration port to improve the accuracy of single bunch intensity measurements. Microwave absorber material is used to reduce interference from spurious electromagnetic waves traveling inside the beam tube. Several types of ferrite materials were evaluated for the absorber. Inexpensive ferrite rods were selected and assembled in an array forming the desired geometry without machining.

6.3 Schottky Detectors

A split tube detector is resonated through an inductor to provide a signal to the schottky receiver. The signal to noise ratio goes as the square root of the detector impedance which is proportional to it's Q. A Q of 300 is achievable, provides sufficient impedance, is reasonably stable with temperature, and has sufficient bandwidth. A center frequency of 21.4 MHz was chosen because of readily available crystal filters. The detected signal is dominated by coherent oscillations, not schottky noise as the name suggests.

7 REFERENCES

[1] http://ahse30.fnal.gov/home.html, RF&Instrumentation home page

[2] Webber, R.C., "Charged Particle Beam Current Monitoring Tutorial", Beam Inst. Workshop, Vancouver Canada, Oct. 1994.

[3] Unser, K.B., "The Parametric Current Transformer", AIP Acc. Instr. Conf. Proc., No. 252, 1991.

[4] Johnson, M., "Loss Monitors", AIP Acc. Inst. Conf. Proc. No. 212, 1989.

[5] Fitzgerald, J., Crisp, J. "A Compact BPM for the Fermilab Main Injector" IEEE PAC, 97CH36167, May 1997.

[6] Fitzgerald, J., Crisp, J., McCrory, E., Vogel, G. "BPM Testing, Analysis, and Correction", Beam Instrumentation Workshop, AIP Conf. Proc. No. 451, May 1998.

[7] Barsotti, E., Lackey, S., McClure, C., Meadowcroft, R., "Beam Position Monitors for the Fermilab Recycler Ring", Beam Instrumentation Workshop, AIP Conf. Proc. No. 451, May 1998

[8] Kissel, W., Lublinsky, B., Franck, A., "New SWIC Scanner/Controller System", presented at ICALEPCS 95, Chicago, IL, Oct. 1995.

[9] Vogel, G., Dey, J., "Flying Wires", IEEE PAC, 97CH36167, May 1997.

[10] Gannon, J., Crawford, C., Finley, D., Flora, R., Groves, T. , "Flying Wires at Fermilab", IEEE PAC, 1989

[11] Zagel, J., Crisp, J., Hahn, A., Hurh, P. :Fermilab Main Ring Ion Profile Monitor System. 1997 IEEE Part. Acc. Conf. 2166-8. May 1997.

[12] Zagel, J., Chen, D., Crisp, J. :Fermilab Booster Ion Profile Monitor System Using LabView. Beam Instrumentation Workshop. AIP Conf. Proc. 333. 384-90. October 1994.

[13] Utterback, J., Vogel, G., "Fast Bunch Integrator, A System for Measuring Bunch Intensities in Fermilab's Main Ring", presented at ICALEPCS 95, Chicago, IL, Oct. 1995.

[14] Vogel, G., Fellenz, B., Utterback, J., "A Multi-Batch Fast Bunch Integrator for the Fermilab Main Ring", Beam Instrumentation Workshop. AIP Conf. Proc. 390. 375-80. May 1996.

[15] Crisp, J., Gubrienko, K., Seleznev, V. :Stripline Detectors for Fermilab Main Injector. Proc. National 16th Conf. on Accelerators. Protvino, Russia. October 1998.

[16] Crisp, J., Fellenz, B. :An Improved Resistive Wall Monitor. Beam Instrumentation Workshop, AIP Conf. Proc. No. 451, May 1998.