Chapter 15. Beam Instrumentation

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15.1. Introduction

The Proton Driver (PD) will produce 3×10^{13} protons 15 times per second. The extraction energy will be 12 GeV for Stage 1 and 16 GeV for Stage 2 operation. The 1.2 MW average beam power demands reliable instrumentation for commissioning and operation. Challenges for instrumentation include high beam intensity, fast repetition rate, short bunches, rapidly sweeping rf, high vacuum, and radiation environments. This study focuses on established techniques used in instruments with a proven reputation. Basic engineering issues rather than scientific novelties are emphasized. Operational experience of beam diagnostics in the FNAL Booster is exploited. A summary of Proton Driver and associated beam line instrumentation is provided in Table 15.1.

15.2. Beam Properties and Special Requirements

Instrumentation must cope with the following beam properties:

1. In the 400 MeV Injection Line:
   H^- beam is modulated at 201.25 MHz and contains 3.4×10^{13} ions in a 90 μs pulse repeated at 15 Hz. The beam will be chopped at 7.5 MHz in Stage 2 operation.

2. In the Synchrotron:
   Proton beam momentum changes from 400 MeV to 16 GeV with rotation periods changing from 3.3 to 2.4 μs. The 3×10^{13} protons will be divided into 126 - 53 MHz 12 GeV bunches in Stage 1 and 18 - 7.5 MHz 16 GeV bunches in Stage 2 operation. Normalized transverse emittance is 60 π mm-mrad. Beam losses must not exceed 10% at injection or 1% at extraction.

3. In the 12 (or 16) GeV Extraction Line:
   Single turn (2.4 μs) fast extracted beam of 3×10^{13} protons divided into 18 (or 126) bunches with an rms bunch length (σ) of 1 ns.

4. A pilot beam with 20 times lower intensity will be used to verify injection, acceleration and extraction efficiency. Instrumentation will require sufficient dynamic range to insure pilot beam measurements are consistent with those at operational intensities.

5. One important role of the instrumentation will be to provide information to an equipment protection system. This system must respond quickly to limit damage from losses of the 1.2 MW contained in the beam.

6. Because of large beam intensities and rapid pulse rates, equipment located in the tunnel could receive up to 50 Mrads through the 20-year life expectancy of the Proton Driver. Electronics located in the tunnel should be kept to a minimum to avoid failures and minimize personnel exposure.

7. The expected vacuum in the Proton Driver ring is 1×10^{-7} Torr. Devices exposed to vacuum may require baking at up to 150°C.

15.3. 400 MeV Injection Line

One Beam Position Monitor (BPM) and Beam Loss Monitor (BLM) will be installed at each of the 89 quads in the 400 MeV line. Beam Profile Monitors (BPrM) will be installed at every other quadrupole and one Beam Current Transformer (BCT) will be placed at each end of the Line.

15.3.1. BPM's

BPM's will be placed inside the poles of each quadrupole to measure position in the focusing plane. A shorted stripline design will be used to measure the 201.25 MHz frequency content of the beam. Each electrode will subtend 90 degrees of arc. Considering the beam velocity, the optimum stripline length is 310 mm resulting in an assembly length less than 400 mm. The outside diameter will be 2 or 3 cm larger than the clear aperture. A 60 mA beam will produce 1.5 volts at the BPM output. The signals will be transmitted through phase matched ½″ Heliax cables to AM/PM conversion receivers. The dynamic range of the receivers is sufficient to accommodate the anticipated 26 db range in beam intensity. The bandwidth of the position output must be sufficient to track the 7.5 MHz chop rate. A 12-bit digitizer sampling at 7.5 MHz throughout the 90 μsec spill should be adequate. Triggering can be performed by either beam synch clock events or pulses derived from the chopper power supply trigger. Position error from the BPM, cables, and electronics should be less than ±0.5 mm.

As an alternative, processing could be performed at double the Linac frequency (402.5 MHz). This allows shorter electrode length and reduces interference from the 201.25 MHz Linac rf system. Although the signal level is slightly lower, the approach was proven effective at BNL [1].

15.3.2. BLM's

For best sensitivity to beam loss, monitors will be placed downstream of each quad. Sealed, argon-filled, glass ionization tubes [2] will be used. They have been used for years at several laboratories: FNAL, BNL, LANL, and others. Argon filled chambers have faster time response (with electron collection), and larger dynamic range than the cheaper air filled type. Typically, they have 1 or 2 μsec response for electrons, 70 nano-Coulombs/Rad sensitivity, and are linear up to thousands of Rad/s. Such features are attractive for monitoring beam losses with one turn time resolution. Faster processing for a few monitors located near the injection area would be useful.

Loss monitor signals will be transmitted through coaxial cables to the equipment gallery. There are three signal-processing options presently used at Fermilab: linear amplifier, integrator with S&H, and logarithmic amplifier. An additional method to consider is digital integration based on monolithic synchronous V/F converters. This approach provides a four-decade dynamic range without gain change. The fast monitors should have programmable thresholds to provide alarm signals for the Equipment Protection System.

15.3.3. BCT's

Two BCT's will monitor beam line intensity, transfer line efficiency, and injection efficiency for each injected turn. The 3.4×10^{13} total intensity must be measured to 0.2% accuracy to verify that beam loss does not exceed the limit. This requires a time constant of more than 50 ms (low frequency cut-off less than 3 Hz). A 20 MHz high frequency response would resolve the time structure of the 7.5 MHz chopped beam. The sensitivity will be 1 V/A into 50 Ω. These bandwidth and accuracy requirements demand special attention.

15.3.4. BPrM's

Secondary Emission grids, slow wire scanners, and Ionization Profile Monitors (IPM) are used to measure the transverse profiles. The first two are a well established and accepted means of accurately measuring profiles of single pass proton beams. However, these devices will suffer from several problems with the high average current H^- ion beam: parasitic ion stripping, extreme heating, and declining secondary emission efficiency after exposure to 10^{19} particles. IPM's are non-destructive, do not suffer from these problems, and are used at FNAL [4, 5] and BNL [6] to continuously measure circulating beam.

Movable secondary emission grids at FNAL consist of 48 horizontal and 48 vertical 0.003″ diameter gold plated tungsten wires. At full Proton Driver beam intensity, these wires would reach 1600°C. Carbon wires would reach 850°C and Beryllium wires 300°C. Springs would be required to maintain wire tension at these temperatures. Thin walled, 0.5 mm diameter capillary tubes are commercially available and would exhibit lower temperature because of their larger surface area. The tubes are sufficiently stiff to be free extended from one end to avoid thermal expansion problems. Wire grids have a little less mass and less ion stripping, however. Grids based on either design should be used at reduced beam power for limited periods of time. Single plane monitors without collector foils are expected to strip about 2% of the ions. No more than two monitors should be placed in the beam at once.

About 100 picoCoulombs per 10^{12} ions will be collected on the center wire. Rapid multiple profiles with one turn resolution should be possible. Shielded multiconductor twisted pair cable will be used to transport collected charge to gated integrators located in the equipment gallery. Multiwire scanners at Fermilab have 96 parallel integrators followed by S&H circuits multiplexed into two fast 16-bit digitizers. Both horizontal and vertical profiles are measured using 48 wires each. Gain of 1, 10, or 100 can be selected remotely. Care should be exercised in the selection of cable to avoid problems with transient signals.

Single wire scanners will be used to measure profiles near the injection region. Carbon or Beryllium wires with 20 μm diameter would minimize beam blow-up from Coulomb scattering and could be used at intensities up to 10^{13} ions. The charge induced on the wire by secondary emission will be collected and the wire stepped to the next position after each beam injection. The desired profile resolution will determine the number of injection cycles required. Actuator triggering can be done from beam synchronized clock events. A useful watchdog tool for equipment protection could be implemented by monitoring the wire signal while it is parked at the periphery of the beam.

Only IPM's can be used to continuously monitor profiles at full beam intensity. This information may prove a useful input to the equipment protection system. HOT microchannel plates 100×80 mm in size with 10^4 charge gain are commercially available. About 2×10^5 ion pairs will be produced from 3×10^{13} beam particles passing through the expected geometry and vacuum. The charge collected from the MCP with 48 strips spaced 1.5 mm apart is comparable to that from secondary emission grids. The same cables, electronics, and applications programs can be used. The maximum lifetime charge obtainable from an MCP is 0.1 Coulombs/cm^2, equivalent to 8 years of continuous running.

A transverse electric field of 500 V/cm will direct positive ions to the surface of the first plate. The field can be made uniform with five equally spaced electrodes connected to voltage dividing resistors. One horizontal and one vertical IPM are recommended for the 400 MeV injection line.

15.4. Synchrotron

Many important phenomena in accelerator physics occur within or near the beam revolution period. Instrumentation for fast cycling high intensity machines should be capable of making measurements on turn-by-turn and, if possible, bunch-by-bunch basis. Assume one BPM and BLM for each of the approximately 100 quadrupoles. Tunes of 11.4 will provide just over 4 BPM's per betatron wavelength in each plane. Three IPM`s will be used to measure profiles on a turn-by-turn basis. One IPM per plane at low dispersion locations and one horizontal IPM at a high dispersion location will allow measurement and correction for momentum spread. Two BCT's with different frequency ranges will be used in the ring. A fast transformer will measure injection efficiency with turn-by-turn resolution. This transformer should resolve chopped beam and provide bunch-by-bunch extraction efficiency in Stage 2 operation. A slow transformer will measure intensity and acceleration losses with higher resolution. Tune measurement systems, a wide-band wall current monitor, and large bandwidth horizontal and vertical striplines should also be installed.

Diagnostic equipment such as a vector signal analyzer, network analyzer, and fast digital oscilloscope should be permanently installed and interfaced to the controls system. Installing certain instrumentation such as the Resistive Wall Monitor (RWM) and large bandwidth striplines near the low level rf system would provide a central location and facilitate sharing resources.

15.4.1. BPM's

Single plane BPM's will be nestled under the coil at the upstream end of each quad. The BPM will be mechanically indexed to the quadrupole to insure the location of the electrical center is known to better than 0.2 mm. Elliptically shaped, diagonally split, electrostatic pick-ups will provide both good linearity and low beam impedance. Electrodes will be made of stainless steel tubes 5 inch × 9 inch in cross section, 100 mm long, and 1 mm wall thickness. The electrodes are separated from the concentric outer tube with high-density alumina spacers. The electrode-to-ground capacitance is 160 ± 5 pF with 3.0 ± 0.1 mm spacers. Threaded plugs could be used to balance the capacitance. The 50 Ω output impedance and the 160 pF capacitance will differentiate the signals below 20 MHz. This will attenuate the 7.5 MHz signal for Stage 2 operation but should reduce the effect of losses on the plate and low frequency noise. A guard strip between electrodes could reduce the inter-electrode capacitance to 2 pF. An inter-electrode 4 kΩ compensating resistor will make the response independent of frequency. A built-in calibration ring could be used to simulate a centered beam. The total assembly would be 200 mm long and require three ceramic coaxial feed-throughs. The materials will withstand a 300° C bakeout. Low cost, 50 Ω, standard polyethylene cables can satisfy radiation requirements.

The BPM system could provide turn-by-turn position information for all 100 BPM’s on each of the 15,000 turns. Bunch-by-bunch measurements for Stage 2 operation may prove useful. The closed orbit would be determined by averaging several turns. Electronics based on the log-ratio technique is preferred for its ability to accommodate various rf running modes and beam structures. Calibration and software correction should be used to achieve required accuracy over the entire dynamic range. Experience with log-ratio processing has been gained at FNAL [7]. A new technique for wide band, time normalization [8] could be considered for bunch-by-bunch measurements. In this approach, both electrode signals are combined with different delays and the beam position information is converted into a pulse width. This method uses inexpensive fast ADC's. Critical time adjustment is the main limitation. Further study will be required.

The Beam Synch Clock, locked to the Low Level rf system, will be used to trigger the BPM’s. The data acquisition system will be based on VME or VXI. Anticipated accuracy of the position measurement is better than 1 mm on a single turn.

A Beam Line Tuner will measure turn-by-turn position at one horizontal and one vertical location and calculate betatron amplitudes and phases at injection. This data will be used to correct subsequent injections to correct slow repeatable errors in the 400 MeV Line. The Beam Line Tuner may require stand-alone position systems.

15.4.2. BLM's

The basic functions of the BLM system should be to minimize uncontrolled losses by providing data for tuning and disabling injection after high losses have occurred. About 110 monitors will be used: one downstream of each quadrupole and a few more at the injection, extraction, and collimation areas. Time response of 100 μs will be sufficient. Monitors located in the injection and extraction areas may benefit from faster detectors and should be read with one turn time resolution. The beam synch clock should be used to sample the BLM's. The BLM hardware would be similar to that used for the 400 MeV Line. Losses in the ring will vary over a large range and would benefit from fast logarithmic integrators. Inexpensive 8-bit ADC's should be adequate. Programmable comparators could produce an input to the equipment protection system. These comparators should not rely on software, as their reliability is critical.

15.4.3. BCT's

Bergoz [3] offers tape wound toroidal cores of high permeability amorphous alloy. A core with dimensions $245 \times 295 \times 22$ mm^3 would fit around the 9" beam pipe and provide: 0.1 ms time constant (1.5 kHz), sensitivity of 1 V/A into 50 Ω, and 15 ns rise time (10 MHz). The 2 Amp average beam current in the ring would produce a magnetic flux density of 0.3 Tesla at the inner surface of the core. Because the saturation value is 0.5 Tesla, the relative permeability of the core should be less than 10^5. Possible noise sources include: 60 Hz line, 15 Hz magnet power supply, rf systems, fast kicker magnets, and the beam image current. To reduce these effects, careful attention to grounding and shielding will be necessary. To reduce rf noise, the shield of the twinax cable should be connected to tunnel ground through a 20 nF capacitor.

Processing electronics for the fast BCT has challenging requirements: large dynamic range, necessity of base line restoration, variation of beam structure, and fast data flux. Two, gated, "ping-pong" integrators followed by fast 12-bit ADC's with S&H amplifiers will be used to measure turn-by-turn intensity. Variable gain, base line restoration, and an automatic calibration system will be required to measure turn-by-turn intensities to 0.2%. Again, triggering will require the beam synch clock. Delivered data includes turn-by-turn: intensity, injection efficiency, and extraction efficiency. Experience using 14-bit ADC's for fast intensity measurement has been gained at BNL [9]. This promising approach warrants further study.

The average circulating beam current could be obtained by numerically correcting the low frequency content of the fast BCT; however, the required resolution of 10^{-4} would not be realized. A DC Current Transformer (DCCT) is the best device for measuring beam intensity, or current, of circulating beam [10]. Commercially available DCCT's have 1 μA resolution, 15 μA noise, 50 μA long term drift, and 4 kHz bandwidth [3]. An 18-bit A/D converter would provide 8 μA resolution (1.6×10^8 particles at injection) with a 2 Amp range (3.0×10^{13} at extraction). To verify efficiency before full power operation a minimum of 1.6×10^{12} is required to obtain 10^{-4} resolution. The signal should be digitized at 1 kHz or faster. Data processing must account for the changing beam velocity as it is accelerated. The assembled detector will require 0.3 m and should be placed as close to the equipment gallery as possible.

15.4.4. IPM

The PD ring IPM's will be similar to those already in use at FNAL [4, 5]. Care will be required when locating and using the monitors. Tunnel locations should be chosen to minimize micro channel plate (MCP) damage from radiation and X-rays. Measuring turn-by-turn profiles at the output currents used by the 400 MeV line IPM's would quickly deplete the MCP's. Profile measurements should be done sparingly and plate voltage must be switched off immediately after the measurement. Because of faster drift times, turn-by-turn measurements may benefit from electron collection rather than the heavier ions. In this case, a magnetic field of 0.1 Tesla parallel to the electric field is necessary to reduce profile spreading caused by beam space charge. Simple Helmholtz coils could produce this field, but their influence on the proton beam must be removed with balanced corrector magnets before and after the IPM. The corrector magnets and the IPM will occupy 2 m of beam pipe. The IPM itself is 0.3 m in length.

The vertical IPM should be placed at DLS13, between quads Q1F and Q2D, where vertical beta is 31.2 m and dispersion is zero. One horizontal IPM will be placed at DLS23, where horizontal beta is 35 m and dispersion is also zero. The second horizontal IPM, used to measure momentum spread, will be placed at DR113, where dispersion is 2.68 m and horizontal beta is 24.47 m. Separate horizontal and vertical designs are necessary because of the aspect ratio of the PD beam pipe. The collector arrays will consist of 64 strips with 1.0 mm spacing for vertical and 1.5 mm for the horizontal IPM. Electronic design and data handling could be similar to IPM's developed for the FNAL Booster [5].

15.4.5. Resistive Wall Current Monitor

To observe the evolution of bunch shape and phase through the acceleration cycle, a wide-band Resistive Wall Monitor (RWM) will be installed. The low frequency limit is about 3 kHz and is determined by the permeability and size of the core and the gap impedance. The gap impedance is well controlled to more than 5 GHz. The beam's electric field lines spread with an angle estimated by $1/\gamma$. This has the effect of limiting the RWM bandwidth to 1.9 GHz with 400 MeV beam. The microwave cut off frequency for the 5" $\times$ 9" beam pipe is estimated to be 650 MHz. Above this frequency, microwave energy generated when the beam passes discontinuities will propagate through the beam pipe and contaminate the RWM signal. The elliptical shape of the beam pipe would cause "tails" on the RWM signal. A smooth transition from the elliptical pipe to the round RWM is recommended. Microwave absorber should be used in these transitions to attenuate spurious signals traveling along the beam pipe. Good quality cable such as 7/8" heliax should be used but kept as short as possible to minimize dispersion. A commercially available digitizer interfaced with the controls system will be used to perform general longitudinal measurements. The RWM signal will be used by the Sampled Bunch Display and by the Fast Bunch Integrator to automatically track bunch intensities and shapes [11].

The RWM should be located near the Low Level rf System to allow its use for the phase lock loop. This will insure the availability of an accurate low noise clock for measuring bunch-by-bunch intensities. The RWM would be useful for monitoring rf capture at injection as well as bunch compression at the extraction energy.

15.4.6. Fast Striplines

Two, one meter long, shorted, 50 Ω stripline BPM's should be installed for general-purpose diagnostics. The bandwidth will be limited by spreading of the beam's electric field and complicated above the 660 MHz cut off frequency of the beam pipe. The elliptical shape of the beam pipe suggests separate geometries for horizontal and vertical detectors. For 30° wide plates, horizontal plates should have a radius of 35 mm and vertical plates a radius of 205 mm to stiffen the plates and match the contour of the surrounding beam pipe. The striplines will be placed into a 9.5 inch × 5.5 inch elliptic stainless steel tube. Machinable ceramic such as Macor would be used for insulators because of its good electrical and vacuum properties. Type N vacuum feedthroughs will be used. Good quality cable such as 1/2 inch Heliax will transport the signal to hybrids located in the equipment gallery to produce sum and difference signals.

The striplines will be mounted in a 1.2 m section of beam pipe, as close to the equipment gallery as possible. It would be advantageous to have one region with circular beam pipe to install the wide band striplines and the RWM. Smooth transitions from the elliptical pipe to the round pipe could be used at both ends.

15.4.7. Tune Measurement

Tune measurements for both planes will be based on forced excitation of coherent transverse oscillations by a small angle kicker. An electrostatic pickup one-quarter betatron wavelength downstream of the kicker will monitor these oscillations. The tune system should work with a few tenths of a millimeter kick to avoid emittance growth. The Δ signal of the PU should have 250 kHz bandwidth centered between rotation harmonics. Considering the change in rotation frequency in the PD, using one of the lower rotation harmonics may be desirable. An FFT of 256 samples taken once per turn will provide 0.004 tune resolution. The amplitude of the FFT could be fed back to the kickers to limit emittance growth. The horizontal and vertical kickers will be one-meter long 50 Ω striplines.

15.4.8. Transverse Dampers

Transverse bunch-by-bunch active damping systems will be used to damp injection oscillations and coherent instabilities. Complete knowledge of the transverse impedance of the accelerator would be required to design a damper system with confidence. Without this, only a general approach can be considered [12, 13]. The dampers will consist of four basic parts: the stripline pick-ups, processing electronics, power amplifiers, and stripline kickers. Two important features are a 90° betatron phase advance between the pick-up and kicker locations and a time delay through the processing electronics which matches the beam flight time. The betatron phase advance will depend on the tune of the machine. Arbitrary tunes can be accommodated by combining the output from two pickups 90° apart with the ratio required to simulate the ideal position. This ratio can be dynamically programmed to track the tune. To accommodate the 3.3 to 2.4 μs change in rotation period, the processing electronics must incorporate a compensating variable delay. Much of the energy in the pick-up signals is not associated with correctable transverse motion. To obtain the required damping gain without overdriving the amplifiers, notch filters designed to remove energy at the rotation harmonics are required. Digital filters clocked in synch with the accelerating rf are used to form the notch filters. One feature of this approach is that the notches and the delay automatically track the revolution period. An additional phase correction may be required to account for the frequency dependent phase shift from pickup and kicker cables. A damper gain of 200 V/mm, one-meter long stripline kickers, and 1.5 kW amplifiers are consistent with other damper systems. All of the coupled bunch modes are represented within a bandwidth of one half of the rf frequency. Solid state amplifiers with sufficient power, bandwidth, and gain are economical, commercially available, and easy to work with.

The wide band striplines, tune measurement kickers, damper pick-ups, and damper kickers are similar and could benefit from a single design. Their lengths could be adjusted as needed.

15.5. 16 GeV Extraction Line

As in the 400 MeV line, one BPM and BLM will be installed at each of the 65 quads in the 12/16 GeV line. Beam Profile Monitors (BPrM) will be installed at every other quadrupole and one Beam Current Transformer (BCT) will be placed at each end of the Line. BLM's and BPrM's will be similar to the 400 MeV line. BCT's and BPM's would be similar to those used in the PD ring.

Upstream of each extraction magnet and at the exit window, four BPM's will measure radial position during extraction. Two bi-plane movable beam profile monitors will be mounted upstream of the first septum and at the exit window. Three BLM`s will be placed downstream of each extraction magnet and one close to the exit window.

The four extraction BPM's and the upstream BCT should be able to resolve changes during the 2.4 μs extraction turn. Other devices would be sampled once per extraction.

15.6. Equipment Protection System

Personnel protection and radiation limits will be enforced by a separate and independent system not discussed here.

The purpose of the Equipment Protection System (EPS) is to protect equipment and provide a safe means of increasing beam intensity while starting up the accelerator. The EPS will monitor selected devices and signals and inhibit subsequent injections or abort the beam when they are out of tolerance. Beam could be aborted by steering it into the collimator over several turns. Excessive beam loss, poor efficiency, bad vacuum, insufficient rf voltage, and key equipment status will likely be monitored. Indications of excessive coherent transverse oscillations from the damper or failures in the timing system may also be used. The EPS should be cast in hardware and consist of a permit loop with general purpose input chassis at key locations in the equipment galleries. The EPS system should respond in less than 100 μs. Hardware limits should be remotely controllable in a fashion easy to monitor and maintain.

Given the large power that can be delivered by the beam at high repetition rates, a hardware enforced, low intensity, low repetition rate mode of operation would be useful for turning the machine on or recovering from a trip. Different limits on loss and efficiency could be enforced while in this mode.

The controls system at FNAL has the ability to set alarms and limits on any device within the database. The value can be displayed in red, and/or alarmed and displayed on the alarm screen, and/or used to inhibit subsequent beam injection. This software system may take a few 15 Hz cycles to operate.

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Table 15.1. Instrumentation Summary

DEVICE/POSITION	QUAN-TITY	FEATURES	PROCESSING PARAMETERS, ACCURACY
400 MeV Line			
Position Monitors	89	Single plane stripline electrodes, L = 0.3 m	Integrated over injection, ± 0.5 mm
Intensity Monitors	2	BCT, 3Hz-20 MHz, 1 V/A, Integrating	Injection turn resolution, 0.1%
Profile Monitors	44	Movable single-plane grids, 48Be wires, 0.5 - 1.0 - 1.5 mm apart	Integrated over injection
	6	Slow single wire scanners, 3H+3V	0.5 mm resolution
	2	Ioniz. type, 1H+1V, MCP Ampl., 48 strips, 1.5 mm apart	Integrated over injection
Loss Monitors	89	Argon-filled Ion chambers, V = 0.11 cc	Integrated over injection
16 GeV Synchrotron			
Position Monitors	50H + 50V	Single plane elliptic electrostatic PU, at each quad, 100 mm length	Turn-by-turn measurements, ± 1.0 mm
Intensity Monitors	1	Fast BCT, 1.5 kHz-20 MHz, 5 V/A, 245 mm ID	Turn-by-turn measurements, 0.1% error
	1	DCCT, 245 mm ID	Resolution 10 µA, 500 Hz drift 5µA/24 h
Profile Monitors	2H + 1V	Ionization type, MCP Amplifier, 64 strips, 1 mm apart, L = 3 m	turn-by-turn time resolution
Loss Monitors	110	Argon-filled Ion chambers, V = 0.11 cc	Time resolution 0.1 ms
Wall Current Monitor	1	100 kHz – 0.6 GHz	1 GHz digital scope - based processing
Fast Striplines	2	1 m long, 50 Ω	Wide band diagnostics use
Tune Measurement	1H + 1V	Single plane elliptic electrostatic PU, 100 mm length, FEE	Resolution of 0.01 tune units, kick of a few tenths of a mm
Transverse Dampers	1H + 1V	Stripline, 1m long	Bunch-by-bunch active damping
12/16 GeV Line			
Position Monitors	4H	Single plane elliptic electrostatic PU`s	Bunch-by-bunch resolution, ±0.5 mm
	65	Single plane electrostatic PU`s	Integrated over spill, ±0.5 mm
Intensity Monitors	2	Fast BCT, 5 V/A	Bunch-by-bunch resolution, 0.1%
Profile Monitors	2	Movable bi – plane grids, 48H+48V wires, 1mm apart	Integrated over spill
	34	Movable single plane grids, 48wires, 1 mm apart	Integrated over spill
Loss Monitors	69	Argon-filled Ion chambers, V = 0.11cc	Integrated over spill