# BEAM PROFILE MEASUREMENT WITH FLYING WIRES AT THE FERMILAB RECYCLER RING*

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*Abstract*

Flying wires were installed at the Fermilab Recycler Ring for transverse beam profile measurement for both proton and antiproton beams. The following note describes the system configuration, calibration and resolution of the flying wire system, interactions between the wires and the beam, as well as analysis of the transverse beam profile in the presence of a stochastic cooling system.

## INTRODUCTION

The Fermilab Recycler is a 3.3-km 8.9-GeV/c fixed momentum storage ring located in the Fermilab Main Injector tunnel [1]. Table 1 presents relevant Recycler parameters. The Run II Luminosity Upgrade Plan requires the Recycler to play a key role as the repository of large stacks of antiprotons ($6\times10^{12}$) with the appropriate phase space characteristics to be used in collider stores. For beam stability and efficiency in generating a bright antiproton beam, it is critical to have precise knowledge of the transverse emittances and beam profile. In addition to the existing 1.75 GHz transverse Schottky detector [2], the flying wires were installed during the August 2004 shutdown after thorough vacuum and mechanical tests were performed on the system. The system has been in operation since the start-up in November, 2004.

Table 1: Recycler ring parameters

| Parameter | Value | Units |
|---|---|---|
| Average $\beta$-function, $\beta_{ave}$ | 30 | m |
| Max. dispersion | 2 | m |
| Transition, $\gamma_t$ | 20.7 | |
| Typ. transverse beam emittances (n, 95%), $\varepsilon_n$ | 3-7 | π mm-mrad |
| Number of antiprotons | ≤ 6 | $10^{12}$ |

## SYSTEM DESCRIPTION

The Recycler flying wire system, which is based on the Flying wire systems installed earlier in the Antiproton Source and the Tevatron [3], consists of two cans (for horizontal and vertical measurements) installed at low dispersion locations. Each can is equipped with an ion pump and a TSP for vacuum maintenance. The cans have been loaded with ferrite for mode damping [4]. The system utilizes rotary motion to move the wires through the beam; the wires are 33 micron monofilament carbon fiber attached to aluminum forks with 133mm radius, which are directly driven; the axis of rotation is about 63.5 mm from the center of the beampipe. Each measurement consists of moving the wire through 540 degrees of which 180 degrees is constant speed (7 rps) while making two passes through the beam. The DC servo motor is operated in closed loop using a magnetic resolver mounted on its shaft. The resolver signal is converted to 14 bit resolution, which translates to a position resolution of 51 microns. Motion is transferred into the vacuum chamber via a bellows feedthrough to maintain the required vacuum of 0.1 nanotorr. The system is equipped with four scintillation counters (2 per plane) to measure both proton and antiproton beams. Light produced in the scintillator from secondary particle cascades is read by Hamamatsu R5380 low gain, high current PMT's. The light intensity vs. position data is analyzed and stored on a PC, interfaced with the user through the Fermilab ACNET system. User selectable filters have been installed to attenuate the light intensity by 90 and 60 percent to achieve the required measurement range for the Recycler beam. As low as $1\times10^{10}$ particles can be measured reliably. A pulsed LED calibration system is included to monitor the scintillator condition and PMT gain. A 21 slot VME crate handles all the real time data acquisition. It holds the Fermilab specific timing module which can initiate a fly on any decoded clock event, and synchronizes the data acquisition to machine beam synchronous clock. In addition it contains the analog to digital converters (ADC), integrators for the photo multiplier tube signals, and the resolver interface position (RIPFifo) module for each wire. The ADC and RIPFifo modules contain buffers to collect the real time data which are later read into the PC for analysis via the VME to PCI interface slot 0 crate controller. All the instrument settings, readings, and analysis are accomplished on a commercial rack mount PC.

## DATA ACQUISITION AND ANALYSIS

The user loads a specification file for data acquisition, including the timing reference with respect to an accelerator event, a delay from the beam revolution marker, photo-multiplier high voltages and optical filter type. Data acquisition can be triggered with an accelerator event or on demand. A peak/background finding algorithm is applied to fit the intensity vs. position data to a Gaussian plus a linear background. The background data is acquired with each set of data, by fitting a line to points on both sides of the found peak. Figure 1 shows a typical display of a Recycler Flying

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wire measurement, in this case an antiproton beam. The horizontal axis is in millimeter, while the vertical axis is scaled intensity. The analysis program finds the peak and background, performs the fit to acquire the σ (the rms beam size for a Gaussian beam) and μ (beam centroid position), and computes the 95% normalized emittance based on the input of the local beta function and beam energy:

$$\varepsilon_{trans.}(95\%, normalized) = \frac{6\pi\sigma^2(\beta\gamma)}{\beta_{lattice}} \qquad (1)$$

In this equation $\beta_{\mathrm{lattice}}$ is the local beta function, which is based on the design lattice value. The quality of the fit is represented by a chi-square parameter and also observable by the user. Data sets are stored on the PC in a circular buffer available for further analysis.

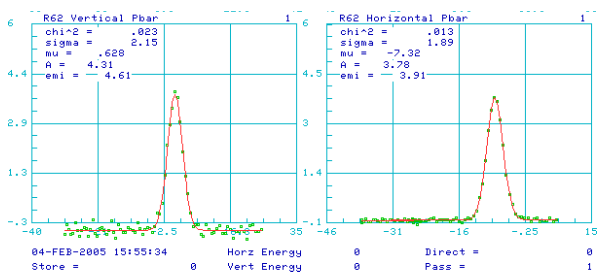


Figure 1: The ACNET program display for the Flying wire measurements of an antiproton beam.

## SYSTEMATIC UNCERTAINTIES

The systematic uncertainty in the beam width measurement caused by position uncertainties from the resolver and the feedthrough have been estimated by convoluting a Gaussian profile with teststand measurements of the position errors. The teststand measurements compared the input shaft position from the resolver to the position of the fork shaft using an encoder [5] and the position of the wire on the fork using an optical shadowing technique [6]. The combined uncertainty in the beam sigma is about 2% with the current magnetic resolver and bellows feedthrough (which dominates), or about 4% in emittance. Uncertainty of the lattice functions at the Flying wire locations also contributes to the calculated emittance (1). BPM Turn-by-turn lattice function measurements [7] have been made to verify that the lattice functions at the Flying wire locations are within a few percent of the design values.

## COMPARISON WITH OTHER EMITTANCE MEASUREMENTS

Initial check on the horizontal scale of the Flying wire measurements were made using local three bumps. The estimated uncertainty in the calculated bump displacement is about 5%. It was observed that the peak displacement measured by the Flying Wires is linear to the three bump amplitude, with a slope of a few percent from unity in both planes (Fig. 2).

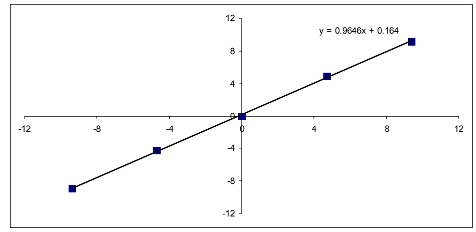


Figure 2: Peak position measured with the horizontal Flying wire vs. calculated three-bump displacement. The slope from the linear fit is 0.965. The data is similar for the vertical.

The Flying wire emittance measurements were compared to the 1.75 GHz Schottky detector system previously installed in the Recycler. This detector has been calibrated with a mechanical scraper system and beam [8]. The tradition at Fermilab is to report the 95% normalized emittances. The Schottky detector measures the rms size of the beam, and converts it to the 95% normalized emittance based on the assumption that the beam distribution is Gaussian. The Flying wires measure the profile of the beam and obtain the σ from the Gaussian fit. It was verified that the two detectors agreed to within 10% when measuring a cooled antiproton beam, which has a known Gaussian profile. Furthermore, it was demonstrated that the two detectors diverge when the transverse profile was known to be non-Gaussian, with the Schottky detector reporting larger emittances when the distribution had a tail bias (large rms), and the Flying wires reporting larger emittances when the tails of the distribution was truncated (small rms).

During operations the Recycler uses the 1.75 GHz Schottky system for emittance monitoring for all dimensions. The phenomenon of IBS (intrabeam scattering) is an important consideration for the Recycler operation [9]. One of the key utilizations for the Flying wires is the measurement of the transverse emittances when the rms momentum spread of the beam is more than 4 MeV/c, at which point the betatron bands (n ~ 20,000) overlap and it becomes impossible to measure the band power accurately due to the loss of baseline information.

## BEAM-WIRE INTERACTIONS

Next, we consider the effects of the carbon wire on the antiproton beam.

### *Ionization Energy Loss*

The energy loss due to ionization can be directly computed from the known charge number and density of the wire material if the specifics were known. However, a method has been developed in the Recycler to precisely measure the ionization energy loss by fitting to the Landau distribution [10]. Figure 3 shows the logarithmic longitudinal energy spectra of the beam measured with the 1.75 GHz Schottky detector before and after 5 Flying wire operations in both planes, a total of 20 wire crossings of the beam. The asymmetry in the final distribution represents an ionization loss of 0.088 +/-


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0.004 MeV, which agrees well with a scattering medium with a charge number of six and density of 1.70 +/- 0.08 g/cm$^3$.

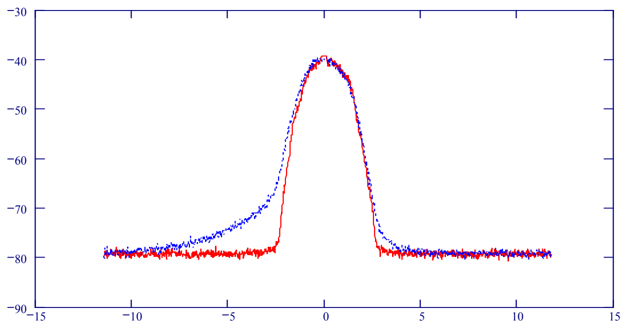


Figure 3: The measured energy spectra of the beam before (red trace) and after 20 wire crossings of the beam (blue trace). The vertical axis is on logarithmic scale. The horizontal unit is in MeV. The computed total ionization energy loss based on the analysis of the Landau distribution is 0.088 +/- 0.004 MeV.

### *Transverse Emittance Growth Due to Multiple Coulomb Scattering*

The emittance growth caused by a wire passing through the beam is [11]

$$\frac{1}{\pi}\Delta\varepsilon_N = 3\gamma\beta\cdot\left(\frac{f\cdot d}{v_x}\right)\cdot\left(\frac{13.6\,\mathrm{MeV}}{pv_s}\right)^2\cdot\left(\frac{\pi\cdot d/4}{L_{rad}}\right) \qquad (2)$$

Here $v_s$ is the speed of the particles; d, $v_x$ are the diameter and transverse projection of the wire velocity on the beam; *f, p* are the revolution frequency and momentum of the particles; $L_{rad}$ is the radiation length of the scattering medium scaled to the measured density of 1.78g/cm$^3$. The calculated emittance growth based on this formula is about 0.8 +/- 0.04 π-mm-mrad per operation, or 4 wire crossings of the beam when measuring both planes. Actual measurements with the Schottky detector showed about 60% of the calculated emittance growth, while the Flying wire measurements showed about 40% of the calculated growth. Studies have been planned to further understand these results.

### *Particle Loss Due to Nuclear Interaction*

The fractional beam loss during a wire traversal due to nuclear interaction is

$$\text{Fractional loss} = \frac{\mathrm{f}(\pi\cdot d/4)^2}{v_x\cdot L_{\mathrm{int}}} \qquad (3)$$

Here $L_{int}$ is the nuclear interaction length, and all other variables are defined in (2). For the Recycler Flying wire system this fraction is about $4\times10^{-5}$, which for $100\times10^{10}$ particles is about 0.56 microamp. This is below the resolution of the Recycler DCCT (Direct Current Transformer), which has a specified resolution of 1 microamp. This amount of beam loss, however, is detectable with the Schottky detector, which can resolve the loss in principle when there is more than $10\times10^{10}$ particles in the machine. A study plan has been made to make this measurement when operationally feasible.

## UPGRADE ITEMS

An upgrade plan is being considered to improve the performance of the Flying wire system. The main items include smaller wire diameter to reduce emittance growth, better feedthroughs to reduce position uncertainty [5], and more flexible data analysis in which an rms calculation of the beam size is made in addition to the current fitting routine.

## CONCLUSION

The Recycler Flying wire system was installed in August, 2004 and has been in operation since November, 2004. It has been demonstrated that accurate and stable measurements of the beam profile can be made with this system. Due to the measurement induced transverse emittance growth, the frequency of measurements and studies is limited. Future upgrades are being planned to make the system more versatile.

## ACKNOWLEDGEMENT

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## REFERENCES

[1] Jackson, G., “The Fermilab Recycler Ring Technical Design Report,” Fermilab-TM-1991, Nov. 1996.

[2] Cullerton, E. and Pasquinelli, R., “A 1.75 GHz Schottky Detector for the Recycler,” Fermilab RF department technical note, Dec. 2003.

[3] Blokland, W., “A New Flying Wire System for the Tevatron,” Proceeding, PAC 1997.

[4] Crisp, J., “Beam Impedance of the Flying Wire Can,” Fermilab-TM-2212, May 2003.

[5] Wilson, P., “Recycler Flying Wire Status,” Fermilab Beams-doc-969-v1, Jan. 2004.

[6] Pischalnikov, Yu. et al, “Optical Calibration of Wire Position as Part of FWM Testing at IB1 (TD/I&C),” Internal Memo, 2003.

[7] Yang, M., “Lattice Function Measurement with TBT BPM Data,” Fermilab-TM-1922, 1995.

[8] Hu, M., “Calibration of the Recycler Transverse Schottky Detectors,” Fermilab Beams-doc-372-v2, Jun. 2004.

[9] Hu, M. and Nagaitsev, S., “Observation of Longitudinal Diffusion and Cooling Due to Intra-Beam Scattering at the Fermilab Recycler Ring”, these proceedings.

[10] Hu, M., et al, “Beam-based Vacuum Measurement at the Fermilab Recycler Ring,” Fermilab-FN-0758-ad, Aug. 2004.

[11] Syphers, M. and Eddy, N., “Emittance Growth Due to Tevatron Flying Wires”, Fermilab Beams-doc-1199-v2, Sep. 2004.