Proceedings of the Linear Accelerator Conference 1990, Albuquerque, New Mexico, USA

DIAGNOSTICS FOR HIGH-BRIGHTNESS BEAMS*

R. E. Shafer
Los Alamos National Laboratory, Los Alamos, NM 87545

ABSTRACT

Special techniques are required for beam diagnostics on high-brightness particle beams. Examples of high-brightness beams include low-emittance proton linacs (either pulsed or CW), electron linacs suitable for free-electron-laser applications, and future linear colliders. Non-interceptive and minimally-interceptive techniques for measuring beam current, position, profile, and transverse and longitudinal emittance will be reviewed. Included will be stripline, wire scanner, laser neutralization, beam-beam scattering, interceptive micrograting, spontaneous emission, optical transition radiation, and other techniques.

INTRODUCTION

Beam diagnostics for high-brightness beams is becoming an increasingly important topic as accelerator physicists improve the designs of low-emittance particle accelerators. The diagnostics must be able to measure the characteristics of low-emittance beams to confirm the accelerator design. Permanently-installed diagnostics must be able to characterize the beam without intercepting the beam or causing emittance dilution.

First, we need to define the characteristics of a high-brightness beam. High-brightness here means a high density of particles per unit 6-D phase space, 4 transverse and 2 longitudinal. Because high-brightness applies to individual bunches, it is not synonymous with high-average-current beams, although achieving simultaneous high brightness and high average current is often desirable. A good example of a high brightness requirement without high average beam current is the high-energy linear collider, in which individual electron and positron bunches are collided in a final focus.

There are three requirements for achieving high brightness beams; optimized accelerator operating parameters, design of accelerator and beamline components that minimize emittance degradation, and minimal variations in bunch-to-bunch characteristics.

Beam diagnostics measurements can be divided into the following three categories:

Centroid measurement	current and charge position and angle synchronous phase energy
Profile measurement	energy bunch width bunch length bunch divergence
Emittance measurement	transverse longitudinal

In addition, bunch-to-bunch jitter in any of the above centroids can lead to dilution of the single-bunch emittance, unless the jitter can be eliminated or corrected. Although beam-current jitter may not appear to be correlated to any of the 6-D emittance parameters, it can couple into them via beam loading in accelerator RF cavities as well as via space-charge effects.

This paper reviews beam diagnostics techniques for high-brightness beams, with examples given for three representative high-brightness accelerator applications: proton and H$^-$ linear accelerators, high-energy linear colliders, and free-electron-laser linear accelerators.

Good general review papers on the subject of beam diagnostics can be found elsewhere in the literature.[1-7] Because there is not enough space in this paper to present a complete review, the reader is referred to these papers, and only a few select topics will be discussed here.

CENTROID MEASUREMENTS

BEAM CURRENT AND CHARGE

Beam-current measurements are straight forward, and have been reviewed elsewhere.[8] Pulsed (i.e., low duty cycle) linac beams are easily measured with standard tape-wound or ferrite toroids, with the beam current representing a single-turn primary. Active feedback to the toroid secondary winding is often employed to increase the L/R time constant, and special laminating techniques are used to increase the high-frequency bandwidth. For CW applications, the non-linear properties of flux-gates have been employed to achieve a DC current-measurement capability, with accuracies of a few microamps. For single bunches, ballistic integration of the toroid signal (e.g. by shunting the toroid with a capacitor) yields a signal whose amplitude is independent of the bunch shape and proportional to the total charge. This method has been used to measure the total charge in individual sub-nanosecond-long bunches at LEP, for example.

BEAM POSITION

Generally, the largest quantity of beam diagnostics in an accelerator facility is used for beam position monitoring. Non-interceptive beam pickup electrode structures include[9]

Capacitive (also called electrostatic) pickups
Magnetic (window frame) pickups
Linear response (special form of capacitive) pickups
Button pickups (often used in electron machines)
Stripline (directional coupler) pickups
Slot-coupled (Bethe-hole-coupled) pickups
Resonant-cavity pickups

The best broad-band pickup frequency response is available in the impedance-matched stripline and slot-coupled designs, and for this reason these designs have been used in anti-proton stochastic-cooling applications. The best linearity (output amplitude vs. beam displacement from center) is available in the diagonally-cut-electrode design that has a linear difference-over-sum response to displacement. Impedance-matched designs provide the best control of beam coupling impedances, and therefore are preferred where a low "Z/n" is desired.

---

* Work supported by the US Department of Energy, Office of High Energy and Nuclear Physics.

The choice of beam-position-processing electronics plays an important role in the overall system performance. The "standard" processing technique is the difference-over-sum method, which can be implemented either by digitizing each electrode signal separately, or by using analog or RF techniques to form RF or video (analog) difference and sum signals. These signals can then be digitized, or the ratio can be obtained using analog techniques. These circuits have a limited dynamic range and real-time bandwidth, although the acquisition bandwidth can be very high.

A second method that has been used recently on the Fermilab accelerators, and also on the LEP ring at CERN, is phase-quadrature processing (also known as amplitude-modulation-to-phase-modulation or AM/PM processing). In this method, amplitude disparities are converted to phase disparities in a passive circuit, and the phase disparity is measured using mono-pulse radar techniques. This approach, which is a frequency-domain rather than a time-domain technique, has a large dynamic range (up to 60 dB), as well as a real-time bandwidth of about 10% of the processing frequency. It is relatively costly, and requires phase matching of the signal cables. Because the circuit measures the signal-amplitude ratio from the two opposing electrodes, the output is normalized to beam current. This technique has been used on single beam bunches by using narrow-band bandpass filters that "ring" when excited by the bipolar-doublet signal from a single bunch.[10]

A third signal-processing method recently being investigated is log-ratio processing, which appears to be more linear in displacement than either difference-over-sum or AM/PM when used with stripline electrodes in a circular geometry. Like AM/PM, it is a frequency-domain method, and is more applicable to multi-bunch rather than single-bunch beams. Also, like the AM/PM method, log-ratio processing provides a real-time beam-current-normalized analog signal that is free of digitizing errors, and capable of high resolution.

In general, the resolution limit δx is determined by the signal-to-noise ratio, and may be written as

$$\delta_x = \frac{r}{2\sqrt{2}}\left(\frac{P_N}{P_S}\right)^{\frac{1}{2}}$$

where P_N and P_S are the noise and signal powers respectively, and "r" is the pickup aperture radius. For AM/PM and log-ratio, P_N is typically about 15 dB above thermal (kTB) noise because of the presence of electronic noise, when EMI and RFI are properly shielded out. For example, a 1 MHz real-time bandwidth position signal with 1-µm resolution can be obtained for a 50 mA beam in a "quarter-wavelength" stripline electrode pickup with a 1-cm aperture radius. Beam sizes in future linear colliders are expected to be in the 1 to 2 µm range[11], and the pulse-to-pulse beam position jitter must be controlled to a fraction of this. It appears that with proper design of beam position electrodes and electronics, the necessary resolution is obtainable.

Accuracy of non-intercepting beam position measurements is generally limited to about 1% of the aperture radius by such effects as mechanical tolerances and alignment, cable attenuation disparity, and electronics offsets and drifts. Direct injection of calibration signals into pickups may reduce the cable and electronic contributions by a factor of 10.

SYNCHRONOUS PHASE

The beam-synchronous-phase angle (the relative phase of the beam-bunch RF structure and the accelerator RF cavity fields) is an important measurement for optimizing the performance of linear accelerators. The synchronous-phase angle can be measured with an accuracy of about 50 ps, and with a resolution of about 5 ps (e.g., about 8° and 0.8° respectively at 425 MHz), using either stripline pickups or low-Q RF cavities.

BEAM ENERGY

Beam energy is usually obtained by measuring beam rigidity in magnetic fields. At low energies, however, where β is substantially less than 1, time-of-flight techniques can be used. An example of this is using two striplines (or low-Q RF cavities) with 50-ps time-measurement accuracy to measure the phase delay of the RF modulation between two pickups. For example, with 50-ps measurement accuracy and a flight path of 3.5 meters, the energy of a 10-MeV proton beam can be measured to about ± 10 keV.

In free-electron-laser linacs, It is also possible to use the measurement of the spontaneous emission wavelength in wigglers to measure the energy of an electron beam. The spontaneous emission wavelength is approximately the wiggler period divided by $2\gamma^2$.[12] The emission wavelength can be measured using optical spectroscopy techniques. The natural linewidth is approximately the emission wavelength divided by the number of wiggler periods, and can be less than 1% for a wiggler with over 100 periods. For example, with a 5-cm wiggler period and $\gamma = 200$, the spontaneous emission wavelength is about 600 nm. With several hundred wiggler periods, energy-measurement accuracies in the range of ±0.1% are possible.

PROFILE MEASUREMENTS

TRANSVERSE BEAM PROFILES

The wire scanner is the most widely used device for obtaining transverse beam profiles. In this method, a single 10-to-100-µm-diameter wire is moved through the beam in a controlled manner, and either the current induced in the wire or the radiation caused by the beam hitting the wire is measured. The major shortcoming of wire scanners is that the wire may not survive in high intensity beams. For low-duty-cycle accelerators, the wire is stepped through the beam in small increments, thus obtaining a profile over many beam pulses. Low-Z wires (e.g., carbon) are often used because the multiple scattering is low and the heat capacity and melting point are high. If a large radiation yield is preferred, high-Z materials (e.g., tungsten) are used. Position and profile resolution of a few µm is possible. For CW beam applications in which the stepped wire would melt, or the multiple scattering could cause excessive emittance blowup, the wire is moved through the beam at a high velocity, often exceeding 10 m/s. In this case the temporal profile of either the induced wire current or the radiation produced as a result of nuclear scattering is a good representation of the beam profile. Stepping wire scanners are now being used in the SLAC linac to check beam profile and alignment.

Wire scanners can also be used at the intersecting point of two colliding beams, such as at SLC. Because the bremsstrahlung radiation is highly collimated, the temporal overlap of the two radiation patterns is a measure of the relative alignment of the two colliding beams. Unlike beam-beam scattering (see below), the temporal profile measurements of the two beams are not convoluted, so independent measurements of the two beam sizes are possible. The resolution of wire scanner measurements is presently limited to perhaps 10 μm or more, due to the wire diameter.

Because the beam size is so small at the collision point in linear colliders, special methods must be used to measure profiles. At SLC, the deflection of one beam by the other at the final focus as the beams are scanned across one another provides a good measure of both the beam overlap and the convoluted beam profile. Resolution of several μm has been achieved. This method does not depend on any dimension other than the beam sizes themselves, and can therefore be extended to sub-μm beams.

At SLAC, the transverse wakefield effect creates a head-tail relative displacement of the beam centroid. By placing a deflector magnets and fluorescent screens at the proper locations in the magnetic lattice, the x, x', y, and x' profiles of individual bunches can be observed on fluorescent screens.[13]

Beam profile measurements in future linear colliders pose a particularly difficult problem because the beams are expected to have rms widths of 1 to 2 μm in the linac, and 10 or 20 nm at the final focus.[11] Buon[14] has proposed observing the yield and velocities of electrons and ions in the ionized residual gas, because these parameters depend on the beam size and the electric fields surrounding the beam. This method does not seem to be extrapolatable to very small beams, however, because electric fields in excess of 10^9 V/cm will produce field-emission ionization. Another proposal is to use a target composed of many very narrow parallel stripes of high-Z material on a thin low-Z backing (e.g., gratings of gold on polymer). High-energy beam bunches will destroy the stripe, so the grating is moved continuously through the beam. The bremsstrahlung yield will depend on what percentage of the beam hits the high Z stripes. If the beam size is of the order of or smaller than the stripe spacing, there will be large pulse-to-pulse fluctuations in the bremsstrahlung yield. These fluctuations can be correlated to the beam size. Feature sizes of the order of 0.06 μm have been achieved in semiconductor lithography using synchrotron light sources, so gratings of this size are possible.

Laser beams have been used to neutralize segments of H^- beams, because the threshold for photo-dissociation of H^- is about 0.75 eV, and the maximum cross section is about 40 megabarns at 1.5 eV. A 100 ns-long, 10 mJ laser pulse focused to a narrow waist is sufficient to neutralize a longitudinal slice of the beam completely. A Nd:YAG laser at 1.06 μm has been used for this purpose.[15] After neutralization, the charged beam is separated magnetically from the neutral beam, and the yield of neutral hydrogen is measured. For transverse profile measurements, the obtainable resolution of this "massless slit" is of the order of 50 μm because of the confocal parameter of the laser beam.

Other bunch profile measurement techniques include residual gas ionization and fluorescence. The ionization measurement usually involves collecting the ions or electrons on a multi-channel plate. The residual gas fluorescence method typically uses video cameras and CCDs, sometimes with image intensifiers. These measurements suffer from senitivity to beam halos, lack of resolution, and sensitivity to the electric field of high-current beams.

For highly relativistic electron beams such as are used in free electron lasers, both spontaneous (wiggler) emission and optical transition radiation (OTR) have been successfully used to measure both beam size and beam divergence profiles. When the beam passes through a thin metallic foil, optical-wavelength radiation is emitted from both surfaces of the foil.[16] The radiation is emitted in narrow cones whose opening half-angles are about $1/\gamma$. If the foil is tilted at 45° relative to the beam, the backward radiation cone is emitted at right angles to the beam, while the forward cone is at 0°. The video image obtained by focusing at the point of emission yields a two-dimensional profile of the beam size. Focusing at infinity, however, yields a two-dimensional hollow circle representing the opening angle of the radiation cone. The width of the line is related to both the beam energy spread ($d\gamma/\gamma$) and the angular divergence. Observation of polarized coherent interference patterns in two-foil OTR interferograms yields direct information on the transverse beam divergence. In this case, the interference is between the radiation emitted from the front surface of the upstream foil, and the back surface of the downstream foil, both of which are tilted at 45° with respect to the beam. Measurement is made by observing the OTR at right angles to the beam from the back surface of the downstream foil.

BUNCH LENGTH MEASUREMENTS

Non-interceptive bunch-length measurements can be made by coupling to the electromagnetic field of the beam in either the time or frequency domain. For highly relativistic beams, the measurement is limited only by the pickup response. In the time domain, either real-time or sampling oscilloscopes can be used. In the frequency domain, spectrum analysis can be used to measure the Fourier harmonics of the beam-bunching frequency.

Wall-current monitors that monitor the temporal profile of the beam-image currents in the beam-pipe wall flowing through a resistive path have achieved bandwidths up to 6 GHz.[17] The pickup is made up of 10 or more parallel resistors across a ceramic gap, and has a total resistance of a few ohms. This measurement method is generally limited to the frequencies below the beam-pipe waveguide-cutoff frequency (TE_{11} and TM_{01} modes).

For low-velocity beams, the EM field of the beam is no longer Lorentz-contracted to a TEM wave, but has a finite longitudinal extent at the beam-pipe wall, thus limiting the frequency response to (3 dB cutoff point)[18]

$$I_0\left(\frac{\omega r}{\beta\gamma c}\right) \le \sqrt{2}$$

where $\beta\gamma$ is the relativistic factor, c is the speed of light, r is the half-aperture of the pickup device, and $I_o(\text{arg})$ is the modified Bessel function of order zero. As an example, the cutoff frequency (arg = 1.22) for a 10 MeV proton beam in a 1-cm-radius aperture is about 850 MHz.

To overcome the "Bessel factor" limitation for the low-velocity beams mentioned above, it is possible to obtain good time resolution by measuring the temporal profile of secondary-emission electrons from the ions striking a thin wire. Resolution of about 1° in phase at 200 MHz (15 ps) was recently obtained at the Moscow Meson Factory on a 20-MeV proton beam.[19] In this case, the wire was biased at -4 kV, and a 600 MHz RF deflector was phase-locked to the accelerator RF to deflect the secondary-emission electrons across a narrow slit. A similar system is being built for use on the Fermilab Linac upgrade.[20]

Totally-interceptive bunch-length measurements can be made using Faraday cups either in a coaxial transmission-line geometry, or a stripline geometry in which the beam (a low-energy ion beam in this case) strikes the stripline transversely.[21]

A laser can also be used to measure the longitudinal bunch profile of a H$^-$ beam. In this case, very short laser pulses synchronized to the beam RF structure are required. Again, magnetic separation of the charged beam is required, and the yield of neutral hydrogen is measured. A plot of the yield of neutrals vs. the RF phase of the laser pulse provides the bunch-length-profile information.

Streak cameras, with temporal resolution under 2 ps, have been successfully used to observe the very short bunches in electron accelerators such as SLAC and free-electron-laser linacs. The signal source for streak cameras is typically spontaneous emission, synchrotron light, or Cerenkov light.

ENERGY PROFILES

Energy profile measurements generally require using a device that has momentum dispersion. An example is the energy spread measurement at SLAC, which utilizes a wiggler in a dispersive section of the magnetic lattice. The wiggler x-rays from single bunches of electrons or positrons impinge on a fluorescent screen, and are viewed by TV cameras.[13]

Very fast Nd:YAG laser pulses (<20 ps) have been used to neutralize slices of individual bunches of H$^-$ beams.[15] At low energies, the energy profile of these slices can be measured by letting the neutral hydrogen drift to a coaxial Faraday cup many meters away. The temporal profile of the Faraday cup signal is directly related to the velocity profile, and hence the energy profile, of the neutralized beam. At higher energies, the neutrals must be stripped to protons at the entrance to a magnetic spectrometer after being separated from the H$^-$ beam, and the momentum profile measured.

EMITTANCE MEASUREMENTS

TRANSVERSE EMITTANCE

Slit-and-collector and slit-slit systems are the traditional methods for measuring transverse emittance of high brightness ion beams, but this method is limited to beams with a low average beam power because of the slit heating. However, a slit-slit system is presently being used on the CW RFQ at CRNL.[22] Wire shadows ("negative slits") on fluorescent screens are similarly limited. For this reason, other methods have been used.

Tomographic techniques have also been used to measure transverse emittance. In this method, the transverse profile of the beam is measured at several points in a drift space or a matched strong-focusing lattice near a waist in the beam. The evolution of the transverse phase space ellipse as the beam passes through the waist can then be estimated, yielding the emittance. If the beam is space-charge dominated, then the emittance may not be preserved as the beam passes through a narrow waist, however. In this case a better measurement is obtained by measuring the beam envelope at several points in a matched strong-focusing lattice. Wire scanners can be used for this purpose.

A variation of the waist measurement mentioned above is to vary the focusing strength of the magnetic lattice in order to move the beam waist through a single profile measurement device. This method also is limited to beams in which the emittance is preserved in passing through a waist.

It is possible to reconstruct the transverse beam emittance if the second moment of the beam profile can be measured at several points. In principal, this can be done using non-interceptive electromagnetic pickups whose response is very well understood. In particular, Miller[23] proposed such a technique using stripline pickup electrodes, but no measurement using this technique has yet been reported in the literature.

For the special case of H$^-$ beams, the laser-neutralization technique mentioned above has been used successfully in combination with a standard slit and collector.[24] In this case a 100-nsec segment of the entire beam is neutralized immediately in front of a bending magnet. A narrow slit is placed in the neutral beam immediately downstream of the magnet, and a collector, which may be a multiwire harp, a segmented Faraday cup, or a fluorescent screen, is placed at a suitable distance downstream. This approach limits the beam power on the slits. It is important in this case to minimize the distance between the neutralization point and the slits, because the emittance ellipse is shearing in the x and y coordinates between the two points, and can become quite elongated by the time it reaches the slit. Unlike the conventional slit-type transverse-emittance-measuring systems, this laser neutralization approach can be a permanently-installed diagnostic, because it has a minimal effect on the H$^-$ beam.

LONGITUDINAL EMITTANCE

The most difficult measurement to make on particle beams is longitudinal emittance, which requires simultaneous correlated measurements on both the bunch longitudinal profile and the energy spread.

For H$^-$ beams, it is possible to combine bunch length and energy profile measurements mentioned above using a mode-locked Nd:YAG laser at 1.06 µm. For low energies, the energy spectrum can be obtained using a pulsed laser and time of flight.[15] At higher energies, the obtainable resolution from time of flight is inadequate, and a CW mode-locked laser and a momentum spectrometer must be used.[24]

Other methods include the use of RF deflection, either of the beam itself or in a streak camera. RF deflection of a beam in a dispersive region onto a fluorescent screen provides longitudinal emittance information. In this method, the phase resolution is limited by the transverse emittance. Streak cameras can be used with a wiggler in a dispersive beamline, can also yield longitudinal emittance information.

BEAM JITTER

Although beam jitter is not a basic characteristic of beam bunches, like beam current, energy, or position, beam jitter deserves special attention because it can adversely affect the performance of the accelerator.

Sources of jitter may be vibration or ground motion (microtremors), RF amplitude or phase noise, fluctuations in magnet current, etc. Jitter in one beam parameter can couple into others. Beam current bunch-to-bunch fluctuations can cause RF-cavity-amplitude fluctuations via beam loading, and therefore couple into energy jitter. Energy jitter can couple into beam position jitter in beam optics that have residual (non-zero) dispersion. For high-brightness beams, beam profiles and emittance ellipses often depend on the space-charge density, and therefore beam current.

For these reasons, it is very important to understand the possible sources of jitter, and design the beam diagnostics to be able to observe it if it is present. Vibration and ground motion are generally below 100 Hz, but plasma oscillations in H$^-$ sources are often in the 10 to 20 MHz range. For free-electron-laser linacs, the beam-bunch separation is typically 10 to 50 ns, but bunch-to-bunch phase jitter must be controlled to of the order of 1 ps.

REFERENCES

1. J. Borer and R. Jung, "Diagnostics," CERN Publication 84-15, P. 385 (1984).
2. G. Lambertson, "Dynamic Devices, Pickups and Kickers," AIP Conference Proceedings #153, M. Month, Ed., P. 1413 (1987).
3. R. Littauer, "Beam Instrumentation," AIP Conference Proceedings #105, M. Month, Ed., P. 869 (1983).
4. R. H. Siemann, "Bunched Beam Diagnostics," AIP Conference Proceedings #184, M. Month, Ed., P. 430 (1989).
5. J. L. Pellegrin, "Review of Accelerator Instrumentation," Proceedings of the 10th International Conference on High Energy Accelerators, CERN, P. 459 (1980).
6. "Frontiers of Particle Beams; Observation, Diagnosis, and Correction," Proceedings of the Joint U. S. - CERN School on Particle Accelerators, M. Month and S. Turner, Eds., Springer Verlag Lecture Notes in Physics #343 (1989).
7. Proceedings of the 1989 Beam Instrumentation Workshop, AIP Conference Proceedings # 212, R. Witkover, Ed. (1990).
8. K. B. Unser, "Design and Preliminary Tests of a Beam Intensity Monitor for LEP," Proceedings of the 1989 IEEE Particle Accelerator Conference, Chicago, P. 71, (1989). See also R. Talman, "Beam Current Monitors," Ref.7, P. 1.
9. R. E. Shafer, "Beam Position Monitoring," Ref. 7, P. 26.
10. R. E. Shafer, S. P. Jachim, and R. C. Webber, "An RF Beam Position Measurement Module for the Fermilab Tevatron." Proceedings of the 1981 IEEE Particle Accelerator Conference, IEEE Trans. Nucl. Sci. Vol. NS-28, P. 2323 (1981)
11. R. D. Ruth, "Beam Dynamics in Linear Colliders," these proceedings.
12. C. A. Brau, "Free-Electron Lasers," Academic Press (1990). See also J. L. Pellegrini, "Linacs for Free-Electron Lasers," these proceedings.
13. E. J. Soderstrom et al., "Fast Energy Spectrum and Transverse Beam Profile Monitoring at SLC," Proceedings of the 1989 IEEE Particle Accelerator Conference, Chicago, P. 1864 (1989). See also J. T. Seeman, "The Stanford Linear Collider," these proceedings.
14. J. Buon, "The Possibility of Measuring Very Small Spot Sizes Using Gas Ionization at Future Linear Colliders," Particle Accelerators Vol. 31, P. 39 (1990).
15. W. B. Cottingame et al., "Non-Interceptive Techniques for Measurement of Longitudinal Parameters of Intense H^- Beams," Proceedings of the 1985 IEEE Particle Accelerator Conference, IEEE Trans. Nucl. Sci. Vol. NS-32, P. 1871 (1985).
16. R. B. Fiorito et al., "Optical Transition Radiation Measurements on the Los Alamos Free Electron Laser," Proceedings of the 1989 IEEE Particle Accelerator Conference, Chicago, P. 65 (1989).
17. C. D. Moore et al., "Single Bunch Intensity Measurement using an Improved Wall Current Monitor," Proceedings of the 1989 IEEE Particle Accelerator Conference, Chicago, P. 1513. See also R. C. Webber, Ref. 7, P. 85.
18. A. Hofmann and T. Risselada, "Measuring the ISR Impedance at Very High Frequencies," Proceedings of the 1983 IEEE Particle Accelerator Conference, IEEE Trans. Nucl. Sci. Vol. NS-30, P. 2400 (1983).
19. Private communication, A. Feschenko, INR, Academy of Sciences, USSR (1990).
20. E. S. McCrory and G. Lee, "Diagnostics for the 400 MeV FNAL Linac," these proceedings.
21. J. M. Bogaty, R. C. Pardo, and B. E. Clifft, "A very Wide Bandwidth Faraday Cup for Low Velocity Beams," these proceedings.
22. G. M. Arbique et al., "Beam Performance and Measurements on the RFQ1 Accelerator," these proceedings.
23. R. H. Miller et al., "Non-intercepting Emittance Monitor," Proceedings of the 12th International Conference on High Energy Accelerators, Fermilab, P. 602 (1983).
24. D. Sandoval, private communication (1990).