On-line Diagnoses of High Current-Density Beams

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Abstract

Los Alamos National Laboratory has proposed several cw-proton-beam facilities for production of tritium or transmutation of nuclear waste with beam-current densities of 8 mA/mm^2. The primary beam-diagnostics-instrumentation requirement for these facilities is provision of sufficient beam information to understand and minimize beam-loss. To accomplish this task, the beam-diagnostics instrumentation must measure beam parameters such as centroids and profiles, total integrated current, and particle loss. Noninterceptive techniques must be used for these measurements because the high-intensity cw beam will destroy any interceptive diagnostic device. Transverse and longitudinal centroid measurements have been developed for bunched beams by measuring and processing image currents on the accelerator walls. Transverse beam-profile measurement-techniques have also been developed using the interaction of the particle beam with the background gases near the beam region. This paper will discuss these on-line noninterceptive diagnostic techniques.

1. INTRODUCTION

A new generation of cw H^+-beam accelerators have been proposed whose primary purpose is to either produce tritium or transmute nuclear waste [1,2]. These accelerator designs have common components. Typically, the low energy beamlines contain a dc injector, and a 350-MHz radio frequency quadrupole (RFQ) and drift tube linac (DTL). The output beams from the DTLs are combined using various electromagnetic lenses to match and interleave the two beams. This transport area, known as the funnel, contains an RF deflector cavity which interleaves and bends each of the input beams to form a single output beam of twice the input bunching frequency. This bunched beam is further accelerated by two other 700-MHz accelerator structures. A bridge-coupled drift-tube linac (BCDTL) is injected with the funnel output beam and accelerates this beam to 100 MeV. The coupled cavity linac (CCL) accelerates the beam from 100 MeV to 1 GeV. The funnel output beamline also has a dc bending magnet which bends the beam into an offset beamline that is used to fully measure the beam entering the BCDTL.

Since these accelerators are production facilities, an overall facility requirement is that hands-on maintenance is necessary. To meet this requirement, the accelerator is designed with a beam radius 8 to 13 times smaller than that of the beam pipe radius. The combination of a smaller beam, high beam currents, and cw operation increases the average beam power density at the accelerator output to 8 MW/mm^2 (see Table 1).

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1.1. *Beam Diagnostics Requirements*

Beam diagnostic measurements for these accelerators consist of two types of beam instrumentation. Those beam measurements that characterize the beam during the initial start of the beam facility or during off-normal beam operation, and those beam measurements that are used during normal beam operation. The operational or on-line beam diagnostics measurements sense only the portion of the beam phase space required to establish and maintain normal daily beam operations. Due to the large quantity of beam energy deposited into robust materials like graphite (shown in Table 1), the on-line measurements are either non- or minimally-interceptive and therefore sense the beam without interfering with beam operation or increasing the amount of beam loss.

Table 1

Summary of the cw beam parameters for a 2-mm-rms wide beam (i.e., peak current densities of 8 mA/mm^2) from the output of each accelerator structure.

Acc. Structure	Avg. Current (mA)	Bunch Freq. (MHz)	Energy (MeV)	Power Density (kW/mm^2)	Dep. Power* (W)
Injector	100	DC	0.075	0.3	220
RFQ	100	350	7	28	48
DTL	100	350	20	80	21
Funnel	200	700	20	160	42
BCDTL	200	700	100	800	12
CCL	200	700	1000	8000	3

* Average beam power deposited in a 1-mmW x 1-mmH x 1-μmD volume of graphite by a cw proton beam.

The characterization beam diagnostics are capable of fully measuring the transverse or longitudinal beam phase-space and either fully or partially intercept the beam. Due to their interceptive nature, the characterization beam measurements must be operated under low-current-density or low-duty-factor pulsed-beam conditions. These operation conditions reduce their usefulness during normal beam operation. An offset beamline in the funnel output section has both on-line and characterization beam diagnostics.

Typically, the accelerator operator needs are nearly satisfied if the on-line beam diagnostics measure the first and second moments of the projected distributions for all six dimensions of the beam's phase space, number of particles contained in the beam, and the number of particles lost to the structure. However, in reality, there are a limited number of measurements that can be performed for these beam currents. Typical on-line measurements include beam current, beam loss, transverse and longitudinal centroids, transverse width and angular distributions. The longitudinal phase-space beam-parameters are difficult to measure without directly intercepting the beam. Due to the limited space, this paper will only discuss some of the on-line beam measurements specific to these accelerators.

2. ON-LINE BEAM MEASUREMENT TECHNIQUES

2.1. *Beam Current Measurements*

There are two common techniques for beam current measurements that are applicable for these accelerators. The primary and most reliable technique measures the average beam current by sensing the charge-particle bunch traveling through a toroidal transformer. Another technique measures the peak beam current of a micro-bunched beam by sensing the signal power of the fundamental bunching-frequency from a beam image-current-based electromagnetic-probe.

The toroidal-transformer beam-current measurements are split into two types of measurements. Dc or cw beam-current measurements sense beams with very low bandwidths. Pulsed beam current measurements sense beams with a broader bandwidth than that of the cw measurements. Since there have been several excellent papers describing the operation of these measurements, this paper will not provide details on this measurement operation [3,5]. Table 2 shows typical beam current measurement specifications and the current measurements' spectrums of sensitivity.

Table 2.

Feasible beam current measurement specifications includes resolution, accuracy, measurement range, sensitive spectrum, and bandwidth (BW) for these high intensity accelerators.

Technique	Res. (mA)	Acc. (mA)	Range (mA)	Spectrum (MHz)	BW (kHz)
dc/cw Toroid	<0.1	<0.5	0.1-200	<0.003	DC-3
Pulsed Toroid	<1	<2	1-200	$1X10^{-6}$-5	1-5000
Image Current	<0.5	<1	1-200	3.5 & 7	DC-5000

2.2. *Beam Loss Measurements*

The beam loss measurements have two functions [4,5]. They provide fast signals to an accelerator equipment protection system that typically shuts the beam off within a few microseconds so that beamline components are not damaged by the beam. Secondly, they provide a very sensitive tool for the fine tuning of the accelerator. There are two types of beam loss measurements: Those measurements based on sensing the ionizing radiation caused by the lost beam particles interacting with the beamline structures, and those based on sensing beam current differences at two different locations on the beamline. The radiation-based beam-loss measurements are very sensitive and have a very broad measurement range but are difficult to calibrate and are susceptible to saturation effects. The current difference techniques are easily calibrated but have a limited measurement range.

2.3. *Beam Centroid Measurements*

The centroids of the projected distributions in all six dimensions of the beam's phase space are acquired using an integrated measurement system. This system includes two four-lobed beam-image-current probes, associated sets of processing electronics, and a set of simple algorithms. Traditionally, only beam position information has been supplied by a single beam diagnostic measurement system. However, an improvement to the existing measurement technique has been developed that integrates all of the beam's phase-space centroid measurements [5]. Table 3 shows typical specifications for the centroid measurements.

Table 3.

Typical beam centroid measurement system specifications with a 1-MHz bandwidth for the processing electronics and 15-cm probe aperture and a 45° subtended lobe-angle.

Centroid	Res.	Acc.	Meas. Range	Dynamic Range(mA)
Position (mm)	0.05	0.25	± 5	200 to 1
Angle-1 meter drift (mrad)	0.07	0.4	± 5	200 to 1
Phase (° @ 350 MHz)	0.05	3.0	± 170	200 to 4
Energy-12 $\beta\lambda$ drift (% nom.)	0.005	0.02	± 8	200 to 4

The centroid-measurement beamline device, known as a microstrip or stripline, senses the bunched-beam image currents traveling down the beampipe. The microstrip has four lobes mounted opposite of each other on the horizontal and vertical axes. Each lobe is a microstripline or microstrip transmission line whose downstream end is terminated in the line's characteristic impedance. Until recently, mathematical models for cylindrical shaped microstrip probes did not include dependency on beam velocity. The beam velocity dependency is explained in ref. 2 and fig. 1 shows how a change in relative beam velocity, β, and bunching wavelength, λ, increases 5- and 25-mm radius probe-sensitivities with respect to the equivalent sensitivities at relativistic beam energies [6].

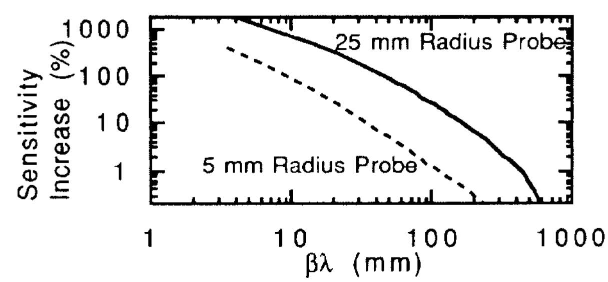

Figure 1. Probe sensitivity increases greater than those probe sensitivities for relativistic beams as a function of beam velocity and bunch wavelength for 5- and 25-mm radius probes.

The signal from each lobe is down-converted from the bunched-beam fundamental frequency to an intermediate frequency (IF). For beam position and trajectory angle information (i.e., the transverse phase-space centroids), difference-over-sum processing of the opposite lobe signals is performed on the IF signals. The trajectory angle is calculated from the measured beam position by two probes separated by a known drift distance. For output phase and energy information (i.e., longitudinal phase-space centroids), two different types of phase measurements are performed on the summed-lobe IF signals. The beams output phase is measured between a downstream microstrip probe and an nearby accelerating or bunching cavity-field signal. The beam energy is measured between two probes separated by a known drift distance. Simple algorithms convert the digitized signals from the associated electronics into the correct beam parameter.

2.4. *Transverse Profile Measurements*

There are two transverse profile techniques that are useful for these particular accelerators. For lower beam energies, a fluorescence-based video profile measurement provides on-line beam information [6].

Inelastic collisions between accelerated beam and residual gas in the vacuum chamber causes the residual gas to fluoresce. The gas fluorescence is proportional to the current density of the beam and residual gas pressure, and is a function of the beam energy. The beam energy function is based on the amount of beam energy deposited into the residual gas. Therefore, the amount of collectable light decreases as the beam velocity increases. At beam energies above 100-MeV for these beam current densities and vacuums of $<10^{-6}$ Torr, there is insufficient light produced by this technique.

Estimation techniques have been developed for calculating the signal to noise for the output signal from the video cameras. The amount of light that is generated by the beam/residual gas interaction is estimated by a series of calculations based on how much beam energy is deposited in a volume of residual gas. It has been experimentally found that approximately 8% of the beam energy that is deposited in the volume of gas is converted to light for interactions where N_2 is the dominant gas. The primary noise source is the initial optics or electronics devices such as microchannel-plate intensifiers or initial amplification stages of a camera that acquire the fluorescent-light based beam-profiles. Signal-to-noise ratios of 60:1 have been observed with a 25-mA, 300-μs pulsed beam and estimated N_2 partial pressures of 10^{-5} Torr.

It has been empirically discovered that the raw data can be fitted to the sum of two gaussian distributions. The first distribution describes the actual beam distribution and the second distribution describes a wider, lower-amplitude background-distribution. The beam distributions acquired from this fitting procedure compare favorably with independent transverse-emittance measurements. Although the cause of this added background distribution is not yet well understood, beam tests have shown that it is beam-induced and not a function of the measurement hardware.

The flying wire scanner will be the primary technique used for beam energies above 80 MeV. For energies below 80 MeV, the graphite fiber installed in the scanner cannot reach sufficient velocities without being destroyed by the deposited beam energy. For an 2-mm-rms, 200-mA, 60-MeV beam, a 50-μm carbon fiber traveling at 15 m/s will reach approximately 1700°C. This is approximately the maximum temperature a graphite fiber should reach without expecting some mass loss. This particular minimally-interceptive technique only perturbs the beam during the 600 μs the graphite fiber is swept through the beam [7,8].

2.5. *Longitudinal Phase-Space Measurements*

There are no noninterceptive measurements that can completely characterize either axis of the beam longitudinal phase-space without changing the beam transport tune for these beam current densities. There are, however, several techniques that can be used under pulsed beam and high peak current conditions [9,10]. There are also on-line techniques that can approximate the phase spread of the beam with good resolution but poor accuracy [5]. A separate beam-characterization beamline located near the funnel output is necessary just for these various techniques so that the beams longitudinal phase-space operation can verified.

4. SUMMARY

This paper has discussed various on-line measurement techniques for measuring 200-mA cw, H^+-beams. Adequate beam current and beam loss measurement techniques presently exist. Further improvements to the beam centroid measurements were discussed including that of integrating the beam energy and phase into traditional beam position measurements. On-line transverse-profile measurements were discussed including the residual-gas video-profile measurement. Finally, there are presently no on-line techniques for measuring longitudinal phase-space distributions for these beam current densities, however, there are off-line measurements located in the funnel output region.

5. REFERENCES

[1] George Lawrence, "Los Alamos High-Power Proton Linac Designs," to be published in the *International Conference on Accelerator-Driven Transmutation Technologies and Applications Proceedings*, Las Vegas, Nevada, July, 1994.

[2] K.C. Dominic Chan, et.al., "Accelerator Performance Demonstration Facility in Los Alamos," to be published in the*1994 Linear Accelerator Conference Proceedings* , Ibaraki, Japan.

[3] K. Unser, "The Parametric Current Transformer, a Beam Current Monitor Developed for LEP", AIP Conference Proceedings 252, pp. 266-276, 1991.

[4] Marvin Johnson, "Loss Monitors," *Accelerator Instrumentation*, AIP Conference Proceedings 212, , pp.156-181, 1989.

[5] J. D. Gilpatrick, et.al., "Experience with the Ground Test Accelerator Beam-Measurement Instrumentation," *1993 Beam Instrumentation Workshop*, Santa Fe, NM, October, 1993.

[6] D. P. Sandoval, et al., "Fluorescence-Based Video Profile Beam Diagnostics: Theory and Experience,"*1993 Beam Instrumentation Workshop*, Santa Fe, NM, October, 1993.

[7] J. Gannon, et. al., "Flying Wires at Fermilab," *1993 Particle Accelerator Conference Proceedings*, pp. 2480-2482, 1993.

[8] D. B. Barlow, et. al., "Prototype Flying-Wire Beam-Profile Monitor," *1993 Particle Accelerator Conference Proceedings*, Vol. 3, pp. 68-70, 1989.

[9] A.V. Feschenko and P. N. Ostroumov, "Bunch Shape Measuring Technique and Its Application for an Ion Linac Tuning," *1986 Linear Accelerator Conference Proceedings* , pp. 323-327.

[10] R. Connolly, et. al., "A Real-Time Longitudinal Phase-Space Measurement Technique for H^- Beams," *1991 IEEE Particle Accelerator Conference Proceedings*, pp. 1237-1239, 1991.