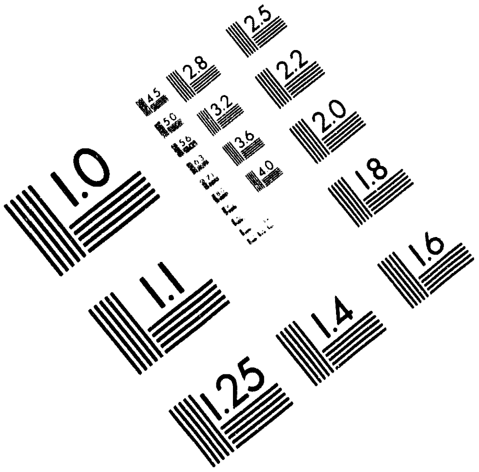

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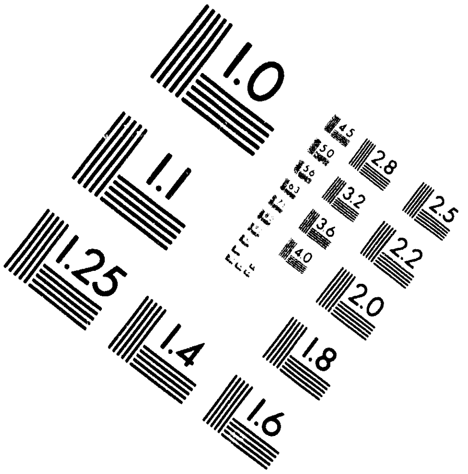

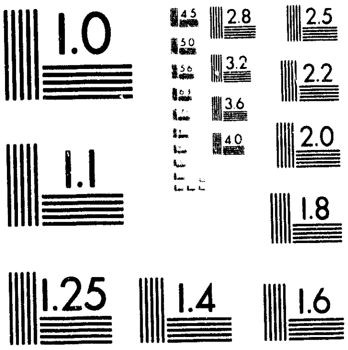

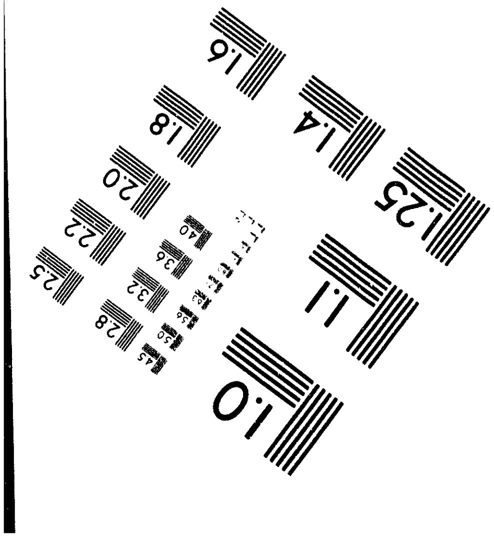

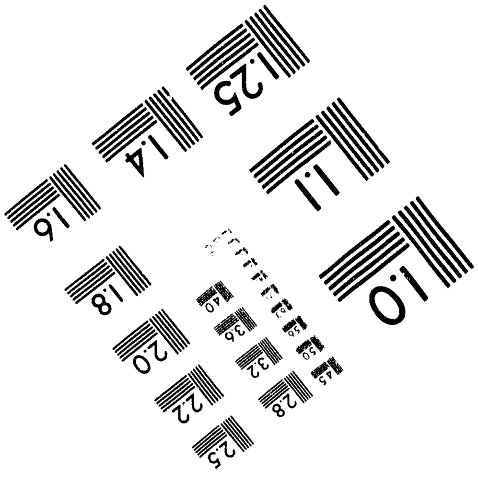

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ROUGH DRAFT

Online 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 greater than 5 mA/mm^2. The primary beam-diagnostics-instrumentation requirement for these facilities is provision of sufficient sufficient beam information to understand and minimize beam-loss. To accomplish this task, the beam-diagnostics instrumentation must measure beam parameters such as the centroids and profiles, total integrated current, and particle loss. Noninterceptive techniques must be used for diagnosis of high-intensity CW beam at low energies due to the large quantity of power deposited in an interceptive diagnostic device by the beam. 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 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]. This accelerator designs have common accelerator 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 a 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.

Since these accelerators are production facilities, an overall facility requirement is that hands-on maintenance is necessary. To meet this requirement, the accelerator was 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 (see Table 1).

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 at the output of each of the accelerator structures.

Acc. Structure	Avg. Current (mA)	Bunch Freq. (MHz)	Energy (MeV)	Power Density (kW/mm)	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.

Typically, the accelerator operator needs are nearly satisfied if the on-line beam measurements 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 in this beam current. 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 discuss some of the on-line beam measurements specific to these accelerators.

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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 measurments. Since there have been several excellent papers describing the operation of these measurements, the paper will not provide details on this measurement operation [2,5]. Table 2 shows typical beam current measurement specifications and their spectrum of sensitivity.

Table 2.

Feasible beam current measurement specifications that 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. *Beamloss Measurements*

The beam loss measurements have two functions. They provide fast signals to an accelerator equipment protection system that typically shuts the beam off within 10-µs so that beamline components are not damaged by the beam. Secondly, they provide a very sensitive tuning tool for the fine tuning of the accelerator. There are two types of beamloss 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. The current difference techniques are easily calibrated but have a limited measurement range. Several excellent papers have also been written on these measurements [3,4].

2.3. *Beam Centroid Measurements*

The centroids of the projected distributions in all six dimensions of the beam's phase space are acquired using two four-lobed beam-image-current probes and associated sets of processing electronics. Traditionally, only beam position information has been supplied by a single beam diagnostic measurement system. However, an improvement to the existing beam position 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[5].

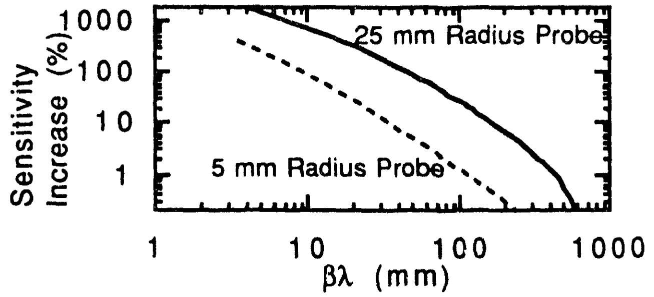

Figure 1. Increases to probe sensitivity due to the beam velocity for 5- and 25-mm radius probes.

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.

2.4. *Transverse Profile Measurements*

There are two transverse profile techniques that will be useful for these particular accelerators. For lower beam energies, a fluorescence-based video profile measurement provides on-line beam information [6]. At energies above approximately 80 MeV, flying wire scanner provides beam profile information [1].

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 range of the beam in the residual gas. Therefore, the amount of collectable light decreases as the beam velocity increases. Typical gas pressures at which this measurement can operate are between 10^{-7} and 10^{-5} Torr. Intensified charge-coupled-device (CCD) cameras acquire the fluorescent-light based beam-profiles which are digitized by control system hardware.

It has been empirically discovered that the raw data can be least-squares 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-emittence measurements. Although the cause of this added background distribution is not well understood, beam tests have shown that it is beam-induced and not a function of the measurement hardware.

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 the microchannel-plate intensifier and the initial amplification stage of the CCD camera. 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.

The flying wire scanner will be the primary technique used in the BCDTL and the CCL for beam energies above 80 MeV. For energies below 80 MeV, a graphite fiber cannot reach sufficient velocities without being destroyed by the energy deposited into the fiber by the beam. For an 2-mm-rms, 200-mA beam, a 50-µm carbon fiber traveling at 15 m/s will reach approximately 1700°C with 60-MeV beam impinging on the fiber. This is about 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 when the facility operators ask for newly acquired profile information [7].

2.5. *Transverse Angular Divergence Measurements*

Angular distribution or divergence and emittance RMS measurements may also be acquired if three profile measurements are made in a periodic optical transport system.

2.6. *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 in this regime of beam current. There are, however, several techniques that can be used under pulsed beam and high peak current conditions [8,9]. 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 were discussed to the beam centroid measurements 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 presently are no on-line techniques for measuring longitudinal phase-space distributions for this regime of beam species and current, however, there are off-line measurement techniques that are to be located in the funnel output region.

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