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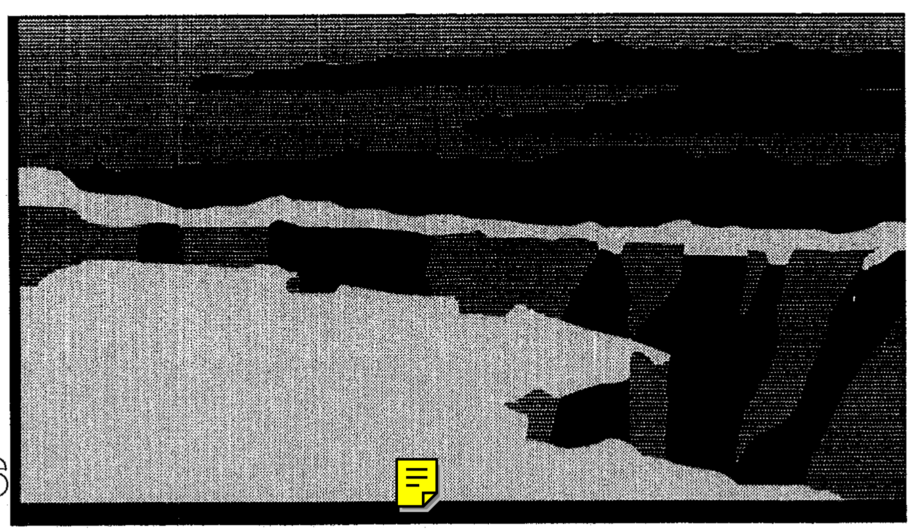

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EXPERIMENTAL STUDY OF PROTON-BEAM HALO INDUCED BY BEAM MISMATCH IN LEDA *

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Abstract

We report measurements of transverse beam halo in mismatched proton beams in a 52-quadrupole FODO transport channel following the 6.7-MeV LEDA RFQ. Beam profiles in both transverse planes are measured using beam-profile diagnostic devices that consist of a movable carbon filament for measurement of the dense beam core, and scraper plates for measurement of the halo. The gradients of the first four quadrupoles can be independently adjusted to mismatch the RFQ output beam into the beam-transport channel. The properties of the measured mismatched beam profiles in the transport channel will be compared with predictions from multiparticle beam-dynamics simulations.

1 INTRODUCTION

As a result of theoretical research during the past decade, we believe space-charge forces in mismatched beams are the main source of beam halo in high current proton beams. A beam is matched when there is a balance between the inwardly directed focusing force and the outwardly directed space-charge force plus a pressure force from the emittance. Beam mismatch corresponds to an imbalance in the forces, which acts in two ways. First, mismatch produces an immediate increase in particle transverse amplitudes and coherent oscillations of the rms beam sizes. Second, the nonlinear space-charge force seen by individual particles, acting while the beam is undergoing coherent rms-size oscillations, slowly drives some particles to even larger amplitudes; this mechanism has been described as a parametric resonance. The experiment will test these ideas by observing the properties of the beam after introducing a deliberate mismatch.

2 BEAM HALO EXPERIMENT

A 52 quadrupole FODO beam-transport channel was installed at the end of the Low-Energy Demonstration Accelerator (LEDA) 6.7-MeV, 350-MHz RFQ to carry out a first experimental study of beam-halo formation in a proton beam. [1, 2]The channel is long enough for the development of about 10 mismatch oscillations, enough to observe the initial stages of emittance growth and halo formation caused by mismatch. A large compliment of beam diagnostics is provided to monitor and measure its properties.[3] The key diagnostic component is a special transverse beam profile scanner [4]consisting of a thin 33m diameter carbon wire for measurement of the dense beam core and a pair of 1.5 mm thick scraper plates to provide greater sensitivity for measurement of the outer halo regions. Each wire and its associated pair of scraper plates are mounted on a common movable frame. As the protons pass through the wire a signal is induced from the secondary electron emission. The scraper plates are water cooled and are constructed of graphite brazed onto copper. A signal is induced by the beam protons that stop in the plates. The data from the wires and the plates are combined using computer software to produce a single distribution. The device has a large dynamic intensity range of at least 10000. Nine measurement stations, shown in Fig. 1, are located midway between pairs of quadrupoles, and at each location both the horizontal and vertical projected distributions are measured. The first station is located after quadrupole 4. The next four stations are located after quadrupoles 20, 22, 24, and 26, after the beam has debunched. The last four stations are located after quadrupoles 45, 47, 49, and 51.

Figure 1: Block diagram of the 52 quadrupole transport channel showing the locations of the 9 profile scanners.

Beam matching is done by adjusting the first four quadrupoles to produce equal rms sizes in x and in y in the final 8 scanners. We estimate a measurement uncertainty for the rms sizes of about 50μ, based mostly on transverse beam jitter. A least squares fitting procedure is used based on measurements of derivatives of rms sizes with respect to matching quadrupole gradients. The Courant-Snyder parameters of the matched beam can be calculated from the beam

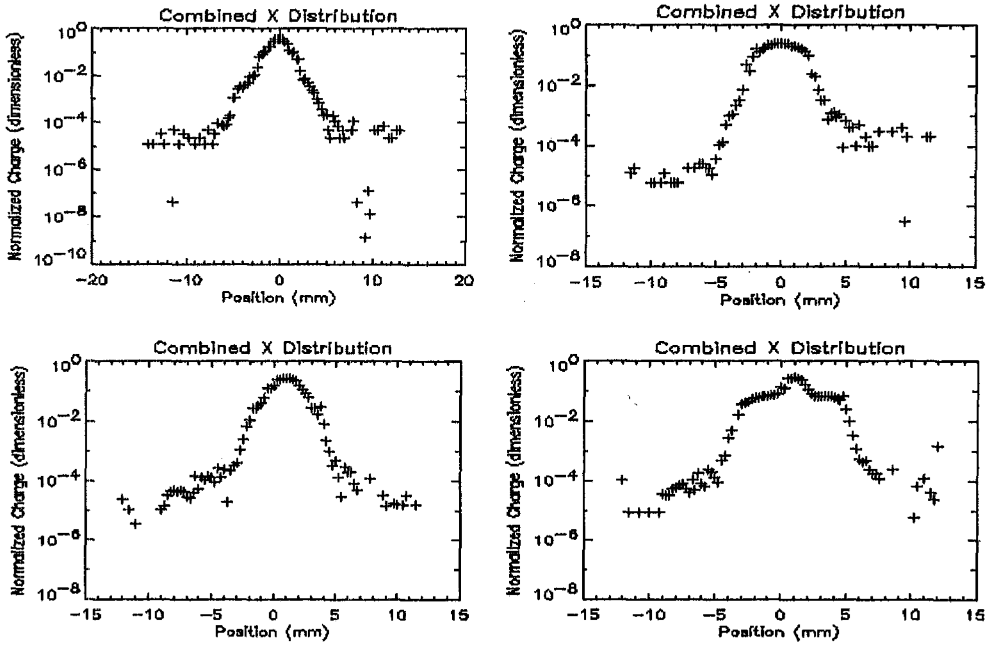

Figure 2: Measured beam profiles in x at 75 mA. a) scanner 22, μ=1.0, matched, b) scanner 22, μ=1.5 mismatched, scanner 51, μ=1.0 matched, scanner 51, μ=1.5 mismatched.

dynamics. Pure mode mismatches are calculated by scaling the Courant-Snyder parameters to the desired values and finding the setting of the matching quadrupoles that produce these values. For example, multiplying each of the four transverse Courant-Snyder parameters by the same factor produced a pure breathing mode mismatch. The mismatch strength is measured by a parameter μ, which equals the ratio of the rms size of the mismatched beam to the rms size of the matched beam.

The beam from the ion source is pulsed at 1 Hz to allow the use of interceptive beam diagnostics. The measurement cycle consists of the following steps. The CW RFQ is de-energized with an RF blanking pulse, and the 75-keV beam from the dc injector is injected into an unpowered RFQ as the injector beam approached a steady state. After about ~2 msec the RF blanking pulse is removed and the RFQ fields approach a steady state after about 5 μsec. The beam profile diagnostics are in a fixed position so only one wire or scraper is in the beam at a time; all other wires and scrapers are out of the beam pipe aperture. The wire or scraper in the beam accumulates beam-induced charge over about 30 μsec. Only the charge collected over the last 10 μsec, when the beam has approached a steady state, is selected for the recorded data. Then the dc injector is turned off, and the beam profile scanners are repositioned for the next cycle.

The beam profiles are used to characterize the beam with three quantities, 1) the rms emittance, 2) a dimensionless shape parameter called the kurtosis, and 3) the maximum detectable amplitude. Rms emittances at the RFQ exit are calculated from a least-squares procedure called the quad scan using rms-size measurements at scanner 4 from an array of different settings of the first four matching quadrupoles. Rms emittances at each of the two scanner clusters are calculated from a least-squares procedure using rms measurements at the four scanners in each cluster. The kurtosis is a function of the second and fourth moments of the distribution.[5] It is defined as $h=\langle x^4\rangle/\langle x^2\rangle^2-2$, and is equal to 0 for a K-V distribution and 1 for a Gaussian profile. A Gaussian profile with added tails results in h>1, but as the beam profile approaches a rectangular shape, h decreases and can become negative. The maximum detectable amplitude provides a lower limit to the extent of the beam, and is calculated from the intersection of the transverse beam profile with the background noise level. The intersection is determined from a statistical signal to noise parameter calculated for each data point.

3 INITIAL RESULTS FOR 75 MA

Measurements have been made at three beam currents, 16, 50, and 75 mA. In this paper we report the results at 75 mA. First, as shown in Fig. 2, the measured transverse profiles show unexpected structure in the form of shoulders in the semilog plots, and some asymmetric profiles. The shoulders and asymmetries are most prominent for the mismatched beams. Figures 3 and 4 show the x and y rms sizes at the different scanners for a matched and mismatched case, respectively. The rms emittances, shown in Fig. 5, grow along the channel with a growth rate that increases with increasing mismatch strength. The kurtosis (not shown) generally decreases with increasing mismatch strength, which can be qualitatively

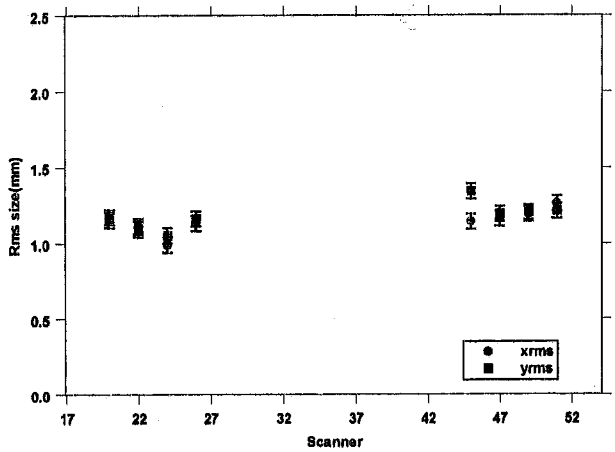

Figure 3: Rms displacements at the 8 profile scanners for matched beam case (μ=1.0) at 75 mA.

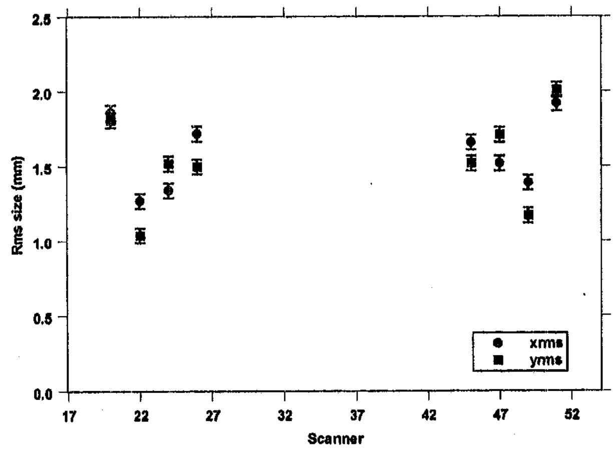

Figure 4: Rms displacements at the 8 profile scanners for breathing mode mismatch case (m=1.5) at 75 mA.

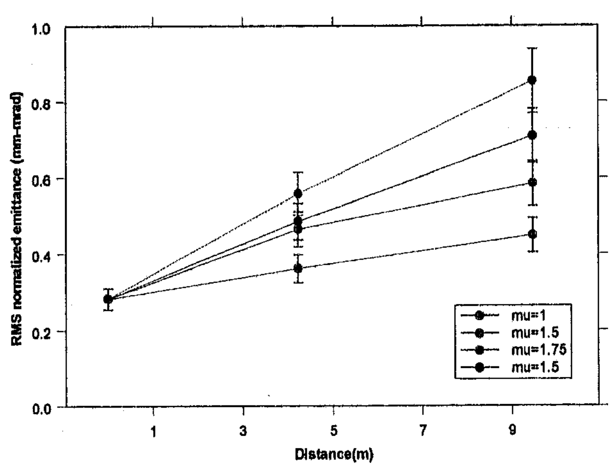

Figure 5. Rms normalized emittance in x (75mA) versus distance at different breathing mode mismatch strengths.

explained by the development of the shoulders, which makes the mismatched beam profiles more rectangular as the mismatch strength is increased. The maximum detectable amplitude is approximately what was expected from multiparticle simulations carried out prior to the experiment. The maximum amplitude shows no significant dependence on the mismatch strength.

4 MULTIPARTICLE SIMULATIONS

Multiparticle simulations in the transport channel were carried out using the IMPACT code with a 3D particle-in-cell space-charge subroutine. The simulations use 10 million particles and an input beam distribution based on a simulation through the RFQ. The measured results are not in good agreement with the simple simulations using the nominal output beam from the RFQ as the input beam. However, multiparticle simulations including lower energy particles, within about 1 MeV below the nominal 6.7-MeV design energy, show shoulders and asymmetries similar to the data, as shown in Fig.6. The simulations, given the right choices of the parameters, can reproduce emittance growth, halo growth, and the maximum amplitudes in the transport channel. Precise predictions by the simulation code would require more information about the beam properties, including the energy distribution of the beam.

Figure 6: Multiparticle simulations at 75 mA of the x beam profiles at all 9 scanners assuming a breathing mode mismatch with μ=1.5 for two different input beams. The dashed curves take the input beam as the nominal RFQ output beam from a simulation through the RFQ. The solid curves assume that 10% of the particles are distributed uniformly in energy from 6.0 to 6.7 MeV

5 SUMMARY

Based on our initial analysis, the experimental measurements of transverse beam profiles at 75 mA in the LEDA transport channel are consistent with space-charge forces acting in a mismatched beam, which contains a significant fraction, perhaps a few percent, of particles within about one MeV below the nominal RFQ output energy.

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