

# MEASUREMENTS OF HALO GENERATION FOR A PROTON BEAM IN A FODO CHANNEL\*

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## Abstract

An experimental effort has been undertaken to investigate the production of halo particles in a proton beam having significant space charge forces. The LEDA RFQ was used to inject a pulsed 6.7 MeV 15-75 mA beam into a linear FODO channel. Four matching quads at the input of this 52-quadrupole transport line were used to generate specific mismatch oscillations, believed to be a key mechanism in the generation of beam halo. A suite of diagnostics that provide beam profile measurements over a wide dynamic range enabled a detailed comparison of measurements with theoretical models.

## 1 INTRODUCTION

The generation of beam halo in intense proton beams is believed to be due to space-charge forces and is considered to be an important issue in present and future applications of such beams. Over the last decade a theoretical model for halo formation [1,2] has been developed which suggests halo particles can be driven by mismatch oscillations, however, no direct experimental verification of this model has, as yet, been carried out. To this end, we have undertaken an experiment using the Low Energy Demonstration Accelerator (LEDA) which produces up to 100 mA of current at 6.7 MeV to provide a test of the theoretical model.

Under matched conditions, the beam is expected to be transported along a linear transport channel with minimal emittance growth, and no significant change in the equilibrium distribution. However, under mismatched conditions, the imbalance of the external magnetic focusing force and the internal space-charge force will cause a mismatch oscillation, which in turn can nonlinearly drive particles out of the core and into a halo region surrounding the beam.

In this experiment we have set out to measure this effect by deliberately inducing mismatch oscillations at the beginning of an extended transport channel which

has been instrumented with a variety of beam diagnostics that can determine beam profiles over a wide dynamic range.

## 2 THEORETICAL EXPECTATIONS

According to the particle-core model, mismatch oscillations should immediately produce particles at large amplitude having a maximum extent in the halo region. The number density in this region is expected to slowly increase along the transport channel associated with emittance growth of the beam. Both the maximum extent of the halo particles and the rate at which the halo region is populated are expected to increase with the amplitude of the mismatch oscillations [3-5].

We parameterize the mismatch by defining a mismatch parameter  $\mu$ , which is the ratio of a particle's betatron amplitude under mismatch conditions to that when the beam is matched. Expectations from the theoretical model are that halo should not develop under matched beam conditions. Moreover, under mismatch conditions, the maximum extent of the halo quickly develops, but remains roughly constant along the channel. Halo development should occur in conjunction with emittance growth of the beam core.

## 3 EXPERIMENTAL ARRANGEMENT

The transport channel consists of 52 quadrupoles, the first four of which are adjustable to permit mismatching the beam from the RFQ as it passes into the transport channel and has been described in detail elsewhere [6]. An array of nine scanners is used to monitor beam profiles in two dimensions over the length of the transport channel. Details of the scanner design are given elsewhere in these proceedings [7,8]. A scanner consists of 33- $\mu$ m diameter carbon filaments for core measurements and scrapers for halo measurements. A biasing arrangement is used to maximize the dynamic range, which was carefully

optimized during these experiments. Taken together, the beam profile measurements permit a dynamic range of  $10^5$  or more.

Beam operation is limited to  $< 30\text{-}\mu\text{sec}$  macropulses to avoid thermionic emission from the wires. Profile data relies on shot-to-shot repeatability of the RFQ, which has been measured to be about  $\pm 1\%$ . Position jitter has also been shown to be less than  $\pm 0.1$  mm.

In this study there were two key steps. First it was necessary to find the matching conditions for the beam exiting the RFQ. This was done approximately by constructing empirical derivatives of the beam size as functions of the matching quad strengths. Settings for these quadrupoles were found that equalize beam sizes at the measurement points, producing a nominally matched beam. The second step in the procedure was then to use an envelope model to predict quad settings for a range of the mismatch parameter  $\mu$ . A typical profile consisting of data joined from both wire and scraper signals is shown in Fig. 1.

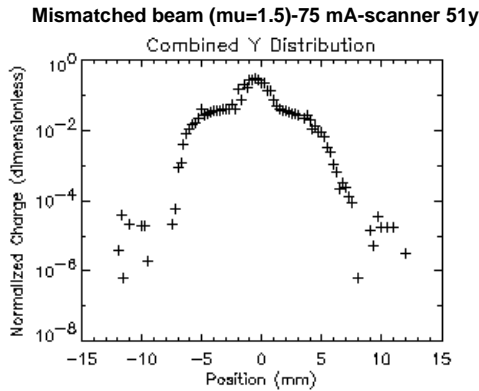


Fig. 1 Joined profiles with wire and scraper scanners showing a dynamic range from core to maximum extent of nearly six orders of magnitude.

#### 4 SUMMARY OF EXPERIMENTAL RESULTS

The beam profiles are characterized by strong halo formation of the sort shown in Fig. 1 for all but nearly matched cases. Moreover, the halo is observed to oscillate with the expected wavelength along the channel. Associated with the halo formation, at 75 mA peak current, emittance growth of the core of the beam also occurs as shown in Fig. 2. However, there is no rms emittance growth at 15 mA, even though halo is observed to form at low beam current.

In order to characterize the halo itself, we plot the maximum extent of the beam, as measured by the scrapers, as a function of mismatch parameter in Fig. 3. This indicates that the beam extent is minimal near matched conditions, however it should be noted that even in this case pedestals are evident in the beam profiles, as shown in Fig. 1. The extent of the halo is not observed to vary with current.

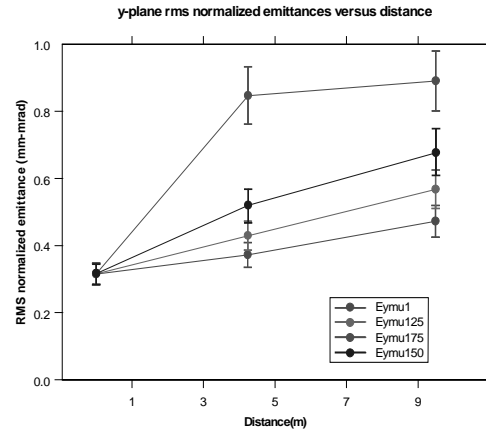


Fig. 2 Rms emittance growth in the vertical plane along the transport channel at 75 mA. While some emittance growth is expected in halo formation, the levels measured in this experiment are factors of two to four greater than found in simulations.

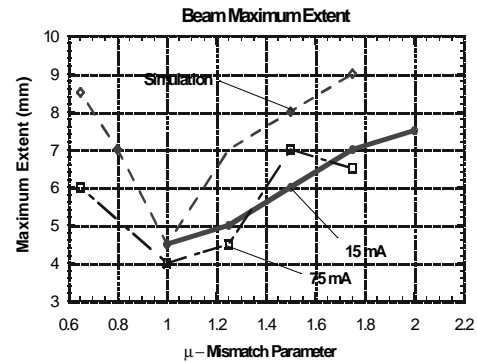


Fig. 3 Maximum extent of the beam as a function of mismatch parameter. A minimum occurs, as expected, near matched conditions. However, there is no variation of this parameter with current. The variation is qualitatively similar to simulation results (for 100 mA).

#### 5 PRELIMINARY COMPARISON TO THEORETICAL MODELS

Overall, the halo formation observed in this experiment has the expected trends given by theoretical predictions. However, the halo is observed to develop anomalously rapidly along the channel. There is indeed a minimum in the halo formed when the beam is nearly matched into the transport channel. Fig. 4 indicates that the halo is minimized at matched beam conditions. Halo is represented quantitatively by either of two ways: the fractional part of the beam which exceeds a Gaussian fit to the core of the beam or by a normalized moment of the difference from this Gaussian, dubbed the “S”-parameter, of the following form

$$S = \frac{\int (f_{data} - f_{gaussian})x^2 dx}{\int f_{gaussian}x^2 dx}.$$

When the halo does occur, it appears as broad pedestals in the profiles, and the amount of beam present in these pedestals qualitatively increases with the mismatch parameter.

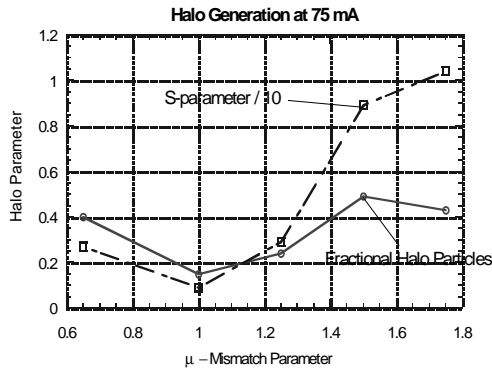


Fig. 4 Fractional halo at the end of the transport channel at 75 mA. See text for explanation.

However, the rate at which the halo forms appears to be unexpectedly high, and in fact there is no case where the beam remains exactly Gaussian throughout the transport channel. Associated with this halo growth, the core emittance increases at a rate considerably in excess of that predicted by simulations at 75 mA.

To explain these effects, it is possible that the halo is already formed within the RFQ by an unknown mechanism. One possibility is that the RFQ may be transmitting a significant number of off-energy particles, particularly because the rf fields are pulsed, permitting low energy particles to enter the transport channel. A simulation study indicated that rapid halo growth could occur under these circumstances, provided that approximately 10-20% of the beam were in a low energy tail of about 0.6-1 MeV width. However, direct-energy measurements of the beam energy spread with a resolution of about 200 KeV indicated that no significant low-energy tail existed.

Another possibility is the fact that strong halo formation may be occurring early in the injector as the beam is nonlinearly focused entering the RFQ. Indeed, simulation indicates rather good agreement with the measured profiles when such an input distribution is invoked. However, we do not have a direct measurement of the input beam into the RFQ and there is considerable latitude in choosing an appropriate beam distribution. A similar model has been

developed to explain earlier measurements of the beam profile directly at the exit of the RFQ [9]. At the present time, work is in progress to better understand the experimental results.

## 6 SUMMARY AND CONCLUSIONS

In this experiment we have shown that halo is readily formed in an intense beam in a linear transport channel when a mismatch occurs at the beginning of the channel. Our observations confirm the importance of matching an intense beam into a transport channel. Additionally, our results qualitatively support the particle-core model. While the process of halo production is consistent with theoretical predictions, our measurements show this effect occurs at a much faster rate than has been predicted. We conjecture that some of the observed halo may be generated before the beam has entered the transport channel, either in the RFQ or in the low energy portion of the injector. Work is in progress to determine the source of this halo, and how it may be further suppressed.

## 7 REFERENCES

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