First observation of luminosity-driven extraction using channeling with a bent crystal

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Luminosity-driven channeling extraction has been observed for the first time using a 900 GeV circulating proton beam at the superconducting Fermilab Tevatron. The extraction efficiency was found to be about 30%. A 150 kHz beam was obtained during luminosity-driven extraction with a tolerable background rate at the collider experiments. A 900 kHz beam was obtained when the background limits were doubled. This is the highest energy at which channeling has been observed. [S1098-4402(98)00003-2]

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I. INTRODUCTION

Since the original suggestion of bent crystal channeling [1] there has been interest in exploiting the technique for accelerator extraction. While the planar channeling critical angle is small, 5.8 μrad at 900 GeV for the Si(111) plane compared to the Tevatron beam divergence of $\sim$10 μrad, this is less of a limitation than might be thought. Many unchanneled particles multiple scatter in the crystal and remain in the accelerator to channel on a later pass, since the rms multiple scattering angle is only 10.8 μrad. Such multiple-pass extraction was first seen as an effect in simulations [2] and confirmed in experiments at CERN [3].

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Extraction with a bent crystal placed close to the beam is particularly interesting for colliders where there is enough halo to create significant external beams with little impact on the luminosity. During the Superconductor Super Collider (SSC) planning stage such a technique was proposed for construction of a 20 TeV proton beam for beauty production [4]. The experiment reported here, E853 at the superconducting Tevatron, was undertaken to investigate that possibility at 900 GeV.

II. EXPERIMENT

The E853 layout [5] is shown in Fig. 1. The bent crystal was located at the beginning of an existing beam abort line. The extracted beam was monitored at two air gaps with scintillators to count the entire beam and with thin “finger” counters to measure the beam widths. A pair of scintillators called the “interaction monitor” was also positioned below the crystal to count inelastic interactions of the beam with the crystal.

Crystals were prepared at the Petersburg Nuclear Physics Institute [6]. One crystal was mounted in a goniometer with 4 degrees of freedom so that it could be translated and rotated with small step sizes. The crystal was cut so that the (111) atomic plane was parallel with the top optical surface of the crystal. The beam side was optically flat. The 39 mm long, 3 mm high, 9 mm wide crystal was bent through a vertical angle of 642 $\pm$ 5 μrad with a four point bender (see Fig. 1).

Several mechanisms were available to drive the halo beam onto the crystal. A fast kicker magnet could provide transverse kicks of 0.5 mm at the crystal for an individual bunch. Results of these studies have already been published [7]. Noise sources such as beam-gas scattering, power supply modulation, and magnetic field nonlinearities also produced beam growth, called natural diffusion. Diffusion could be stimulated with an RF electrical horizontal damper. Most importantly, proton-antiproton collisions at the collider detectors created halo.

In operation the crystal was gradually moved horizontally into the halo from the outside of the ring. Note that in contrast with the CERN experiment, the crystal moved into the beam in the horizontal plane but bent the beam up, so that any lack of parallelism between the atomic planes and the top optical surface would not reduce the extraction efficiency. The final distance of the crystal from the beam center was between 4 and 7 mm (5 to 8 times the σ_H of the beam), depending on the beam intensity or the luminosity, which changes by a factor of 2 during a 20-hour store. This distance was chosen so as to maximize the extraction rate consistent with other constraints (see below).

Figure 2 shows a vertical beam profile obtained with a finger counter scan. The beam width was $\sigma_V = 0.25$ mm after correcting for the height of the finger counter, compared with a calculated width of 0.23 mm. A tail is visible below the beam resulting from such factors as horizontal misalignment and dechanneling. The bottom of the tail was cut off by the Lambertson magnets at $y = 8$ mm. The number of particles in the visible tail is 20% of the peak. A simulation of the experiment [8] predicted 25%.

The crystal was aligned to the circulating beam by scanning the crystal through the vertical angle Θ_V. Figure 3 (bottom) shows the counting rate in the coincidence of counters in the two air gaps as a function of Θ_V. The simulation predicts a σ_V of 21 to 24 μrad compared to the 32 μrad measured in Fig. 3.

III. EXTRACTION RATES

We have measured extraction rates under three conditions: extraction driven by natural diffusion during proton-only stores, RF noise-driven diffusion during a

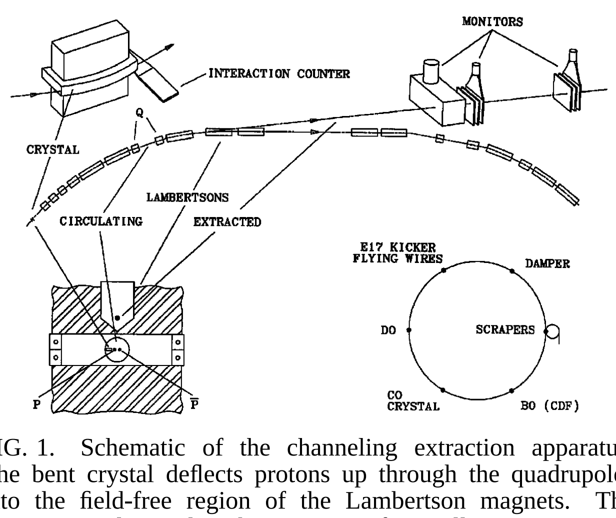

FIG. 1. Schematic of the channeling extraction apparatus. The bent crystal deflects protons up through the quadrupoles into the field-free region of the Lambertson magnets. The protons are detected with a system of scintillators in two air gaps separated by 40 m. The inset shows the location of the crystal extraction system, the fast kicker, the RF damper, and the collider experiments at B0 (CDF) and D0.

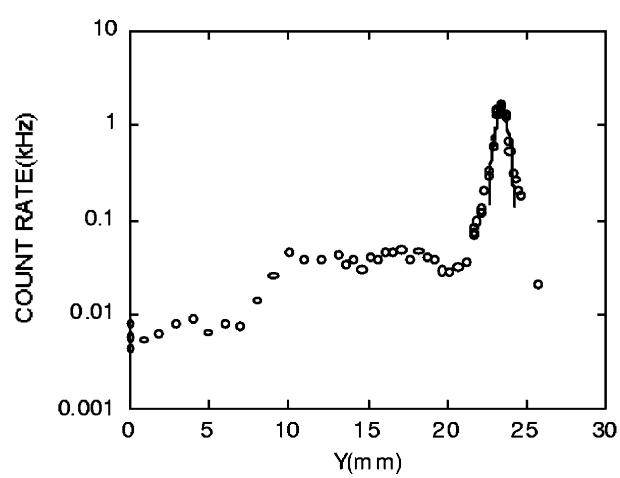

FIG. 2. Vertical profile of the extracted beam taken with a thin finger counter. Note the tail extending below the main peak. The solid line is a Gaussian fit to the data in the peak region.

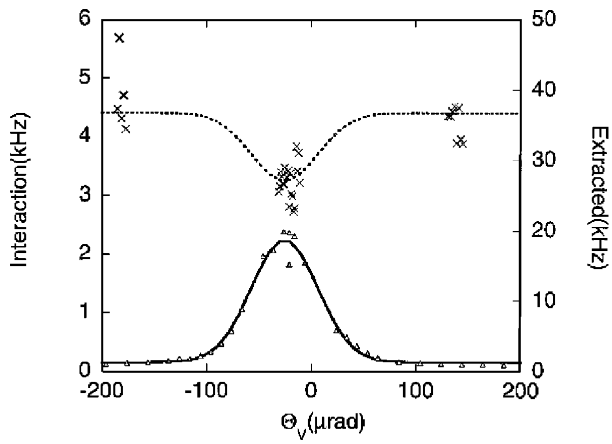

FIG. 3. The lower data set (right ordinate) is the counting rate in a coincidence between scintillators in the two air gaps as the vertical angle of the crystal was varied. The solid curve is a fit to a Gaussian plus a flat background. The upper data set (left ordinate) is the counting rate in the interaction monitor at three different vertical angles. The dotted curve is a Gaussian of the same width and central value as the solid curve.

proton-only store, and luminosity-driven extraction during proton-antiproton stores.

In a typical proton-only store, 10^{11} protons were circulating in six bunches. The extraction rate was 200 kHz. Higher rates could have been achieved by moving the crystal closer to the beam, but with only six bunches a rate of 287 kHz corresponded to extracting on average one proton per bunch, and the counters could not count more than one particle per bunch.

To mitigate this limitation, a special proton-only store was arranged with 10^{11} protons circulating in 84 bunches. Additional diffusion was induced by transverse RF horizontal noise using an electrical damper, creating an rms diffusion rate at the crystal of 0.023 μm per turn. The extraction rate achieved was greater than 450 kHz.

In the luminosity-driven stores, typically 10^{12} protons were circulating in six bunches. The maximum extraction rate achieved was 150 kHz. In this mode the limitation was the impact of particles scattered from the crystal in creating backgrounds for the operating collider experiments. Although the CDF experiment was not affected, the D0 "lost protons" monitor reached the conservative limit set by that experiment at an extraction rate between 50 and 150 kHz.

This limitation was removed during a special store with 36 proton bunches and three antiproton bunches during which D0 was not taking data. There were 3×10^{12} protons circulating, and an extraction rate of 900 kHz was achieved. The D0 lost proton monitor exceeded its upper limit by a factor of 2.

During that same store, the extraction rate was also studied as a function of luminosity. Only six of the 36 proton bunches were colliding with antiprotons. Colliding and noncolliding proton bunches were observed during the same counting interval. The extracted beam rate increased by factors of 4 to 8 for proton bunches that were colliding with antiprotons.

IV. EXTRACTION EFFICIENCY

Another purpose of this experiment was to measure the extraction efficiency. Efficiencies up to 15.4% were measured in a recent CERN 120 GeV experiment [3]. "Efficiency" in this context is defined in two ways. One practical definition, which we call the "extraction efficiency," is the extraction rate divided by the increase in the total circulating beam loss rate after the crystal was inserted. This definition was used by CERN.

The major contribution to lowering this efficiency was from protons which interacted inelastically with the crystal (12.9% of an interaction length) on one of their several passes through the crystal. A second contribution was from protons which dechanneled after being bent through approximately 50 to 350 μrad. A third contribution is from protons which were fully channeled but left the crystal through the beam-side surface because they had a large negative horizontal angle, called hereafter the "surface loss" contribution.

While the numerator was straightforward to measure, determining the change in the total loss rate from the accelerator was difficult. The variation with time of the loss rates before the crystal was inserted, resulting from various instabilities in the accelerator, usually exceeded the difference between the crystal out and in loss rates. No measurements of this efficiency were possible.

A second way to measure the efficiency is to compare the number of protons that interact with the crystal when its vertical angle is not aligned to the beam with the number that interact when it is aligned for maximum channeling. Fewer interactions are observed when the crystal is well aligned with the beam because the channeled protons do not come close to nuclei [9]. We call this the "channeling efficiency" and define it as the difference between the aligned and unaligned interaction monitor rate divided by the unaligned rate.

The surface loss mentioned above does not lower this efficiency, and the dechanneling losses contribute only partially (once a proton has dechanneled after channeling through part of the crystal, it has less than 12.9% probability of a nuclear interaction). Thus we expect this efficiency to be slightly higher than the extraction efficiency (by a factor of about 1.13 in a simple model).

In operation, the interaction counter rates were sensitive to fluctuations arising from such effects as small horizontal fluctuations of the circulating beam. Some of these effects could change in an unpredictable way in the time it took to do a typical Θ_V scan. To mitigate this time dependence, the best measurements were obtained by moving the crystal quickly back and forth from an aligned to a very unaligned vertical angle. An example of such data from a luminosity-driven store is shown in Fig. 3 (top). These data were taken within minutes after the Θ_V scan shown in Fig. 3 (bottom). No time dependence in the data was discernible.

In two stores in which the extraction was luminosity driven, the channeling efficiencies were 24 ± 8% (Fig. 3) and 35 ± 11%. During the 84-bunch proton-only fill, the efficiency was 32 ± 9%. The errors in these efficiencies are derived from the rms scatter of the many data points about their average value. The simulation [8] predicted an extraction efficiency of 35% for a realistic crystal. The same simulation program gives a value consistent with the efficiency measured at 120 GeV at CERN [10].

V. CONCLUSIONS

In summary, this experiment has observed luminosity-driven crystal extraction and demonstrated crystal extraction in a superconducting accelerator for the first time. No heat load on the cryogenics from the interactions in the crystal was observed. This is the highest energy channeling experiment ever carried out. The extraction efficiency has been measured and found to be significantly higher than at lower energies and consistent with a simulation incorporating multiple-pass extraction.

A parasitic extraction rate of 150 kHz has been achieved without impact on the collider experiments. A sixfold increase in this extraction rate will occur when the Tevatron changes from six bunches to 36 bunches, and additional increases could be realized if additional collimators are installed and the D0 lost proton limit can be increased.

Crystal extraction efficiencies are high enough to make this technique an interesting candidate for several applications. One such possibility is using a crystal as an active primary collimator [11]. The use of crystals to extract protons to generate neutrino beams has also been investigated [12]. A continuous 1 TeV proton beam of order 1 MHz could be extracted from the upgraded Tevatron collider into the fixed target areas with no significant impact on collider detector operations [13]. This might be quite useful as a test beam for Large Hadron Collider (LHC) detectors. One report [14] has suggested that an experiment operating in such a beam could produce 10^7 charm candidates per year. A proposal for a B physics experiment using such a system was considered for the LHC at CERN. The proposal was rejected because of uncertainties about the impact of crystal extraction on a TeV-scale superconducting collider. With the completion of this experiment these concerns should now be significantly reduced.

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