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CRYSTAL EXTRACTION AT THE TEVATRON[*]

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Abstract

Luminosity-driven channeling extraction was observed for the first time in a 900 GeV study at the Fermilab Tevatron carried out in the 1995-1996 period. This experiment, Fermilab E853, demonstrated that useful TeV level beams can be extracted from a superconducting accelerator during high luminosity collider operations without unduly affecting the background at the collider detectors. Multipass extraction was found to increase the efficiency of the process significantly. The beam extraction efficiency was in the range of 25%. The history of the experiment is reviewed. Special attention is paid to results related to collimation.

E853 HISTORY AND GOALS

In the early 1990's a fixed target experiment was proposed for the Superconducting Super Collider to study heavy flavor physics using a tiny fraction of the 20 TeV circulating beam extracted with bent crystal channeling. Conventional methods of beam extraction at such high energies posed problems with no obvious cost effective solutions. Since the new extraction scheme proposed for the SSC was not a proven technique, E853 at Fermilab was designed to study the feasibility of this approach. E853 was supported by the SSC program to test extraction at the Tevatron.

The goals of E853 were to extract one million 900 GeV/c protons/second with 10^{12} protons circulating in the Tevatron, to study the extraction efficiency, to show that the luminosity lifetime of the circulating beam was not adversely affected, and to investigate the backgrounds created at the two Tevatron collider experiments. Losses at these major collider experiments, CDF (one sixth of the ring upstream for protons) and D0 (one sixth of the ring downstream), had to be kept to a tolerable level. A central concern for E853 operation was that losses be minimized so that the superconducting Tevatron magnets were not quenched.

Parenthetically, this could well have been the most successful and effective experiment of the entire ill-fated SSC program. Some of the E853 successes included extracting significant beams from the Tevatron in parasitic, kicked, and RF-stimulated modes.

The experiment made the first-ever and, indeed, only observation of luminosity-driven extraction [1]. This was the highest energy particle channeling ever observed. Useful collimation studies were carried out and extensive information was developed on time-dependent behavior. All-in all the operation of the crystal septum was very robust.

There were significant constraints on where an inexpensive, parasitic extraction test could be placed in the Tevatron lattice. Any modification of the Tevatron vacuum system is expensive and requires rigorous attention to maintaining a very high vacuum. The C0 long straight section was chosen for E853 because it contained an existing 900 GeV abort system with an associated extraction line and dump that was not to be used in the 1994-1996 running period except at 150 GeV during collider injection tests. In addition there was free space along the abort beam line for instrumentation and cabling to a portakamp complex above ground for electronics and data acquisition. While this choice turned out to be quite successful it did have a problem. It would have been interesting to have more dispersion at the crystal so that longitudinal noise excitation studies could have been carried out.

The topics covered below include the details of the crystal extraction experiment. In addition the results for kick mode, luminosity-driven, RF-driven, and fiber-driven extraction will be reviewed. Information bearing on collimation will be discussed. Most of the information on channeling and time dependent effects [2] will be omitted. A complete report on the experiment appears in Carrigan et al. [3]

THE E853 EXPERIMENT

Fig. 1 shows the devices used for the E853 test in the Tevatron complex. E853 was located at C0. Note the positions of the colliding detectors CDF and D0. Loss monitors at these detectors were continuously monitored

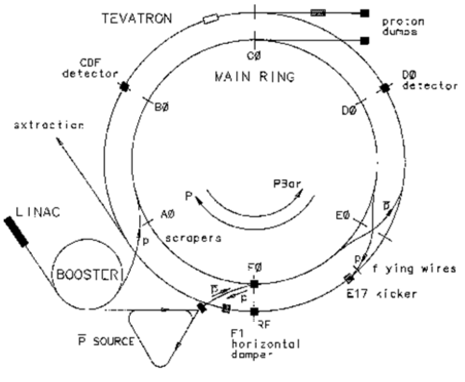

Figure 1: Schematic of the Fermilab accelerator complex showing the location of the crystal extraction experiment at C0.

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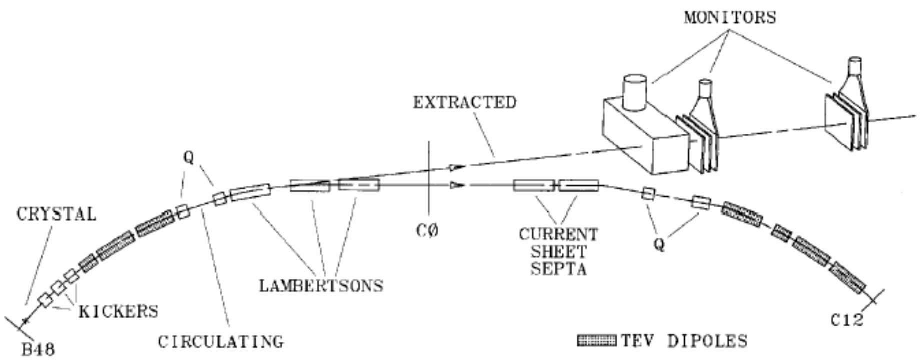

Figure 2: Schematic of the channeling extraction experiment at C0. The bent crystal is on the outside of the ring and deflects protons up through the quadrupoles (Q) into the field-free region of the Lambertson magnets. Downstream of the C0 midpoint the extracted protons are detected in two air gaps containing scintillators, a scintillating screen, and a SWIC.

during the experiment. There were scrapers at A0 and D17. A set of flying wires at E0 and E17 measured the beam size but also were used for fiber extraction. The damper at F1 was used for RF extraction. The E17 kicker provided a fast extraction device.

Fig. 2 shows the layout near C0. The abort magnet string replaced by the E853 crystal consisted of four 1.8 m long kicker modules with peak fields of 3.7 kG giving a total vertical deflection of 640 µrad. Removal of the upstream kicker module provided sufficient space for the crystal goniometer. The bent crystal was on the outside of the ring and deflected protons up through the quadrupoles (Q) into the field-free region of the Lambertson magnets. Extraction consisted of two parts: a vertical kick into the field-free region of the Lambertson magnet string and horizontal separation of the circulating beam from the extracted beam by the Lambertson string. After the Lambertson magnets the extracted beam traversed two instrumented air gaps approximately 100 meters downstream of the crystal and then entered a beam dump. The air gaps, separated by 40 meters, were instrumented with several scintillators. Thin movable counters could scan the beam profile. A fluorescent screen coupled to a CCD camera in the first air gap also provided a digital readout of the beam profile for run time diagnostics. There was already a segmented wire ion chamber (SWIC) in the second air gap as well as a toroid to measure beam current.

Kick mode was employed in the initial sessions of E853 [4]. The basic technique was to move the crystal in to a predetermined horizontal location close to the beam (4.5 to 6 σ_x from the beam center). The beam was then kicked horizontally a number of times by a fast kicker at E17 (see Fig. 1). At this distance from the crystal, the beam density was so small that no beam was observed to interact with the crystal on the first few kicks. However, after several hundred turns following a kick, the beam had grown in size as non-linearities in the machine gradually spread the beam to fill much of the phase space mapped out by the betatron oscillations. After about six such kicks, the beam size had grown by a factor 1.7 in the horizontal plane and a factor 1.2 in the vertical plane (resulting from the horizontal/vertical coupling in the Tevatron).

Fig. 3 shows fluorescent screen images of the extracted beam for the very first extraction using kick mode. The goniometer angle Θ_v was swept up through a 230 µrad scan, from 130 µrad below the peak to 100 µrad above the peak. The length of the dechanneling tail grows in the successive panels because the beam spot moves up and the Lambertson magnet aperture eclipses less of the dechanneled portion of the beam. The longest visible portion of the dechanneling tail is on the order of 10 mm.

The second extraction technique was called "diffusion mode", relying on either natural or stimulated diffusion during proton-only and proton-antiproton stores when E853 operated parasitically to the collider experiments. This diffusion was due to such effects as beam-gas scattering, beam-beam scattering and tune shift effects, magnetic field ripple, and imposed RF noise. In this mode, the crystal was slowly moved into the tail of the beam halo. Movement of the crystal was halted when an

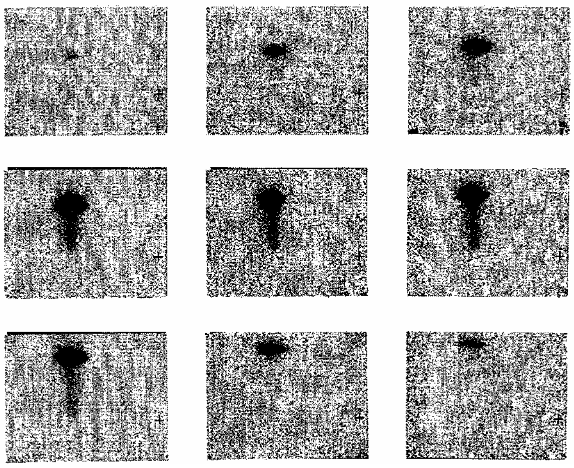

Figure 3: Fluorescent screen images of the extracted beam as Θ_v was swept up through a 230 µrad scan, from 130 µrad below the peak to 100 µrad above the peak. The length of the dechanneling tail grows because the beam spot moves up and the Lambertson magnet aperture eclipses less of it. For scale, the width of the dechanneling tail is 3 mm.

extraction rate adequate for the studies had been achieved. When operating parasitic to collider operations, this mode did not seriously affect the circulating proton beam lifetime.

LUMINOSITY-DRIVEN EXTRACTION

Early in the E853 runs we noticed that the extraction rate was higher when the beams were colliding than for the case where the crystal was placed at the same distance from the beam for a proton-only store. This was the first evidence for luminosity-driven extraction. This occurs because the colliding bunches produce scattering that drives protons from the beam core out into the halo. During collider runs this is normally scraped by the collimators. Indeed, it is the largest source of beam related background at a modern collider detector.

Since several factors such as beam-gas scattering influenced the extracted beam rate it was interesting to isolate luminosity from the other effects. The equivalent in a fixed target experiment would be a target in-target out measurement. Several approaches were considered; 1) changing the arrival times of the proton and antiproton bunches at the interaction points so they did not collide (cogging), 2) displacing the antiproton beam at the interactions points, and 3) eliminating some of the antiproton bunches and thereby removing the “target”. All of these required semi-dedicated running. Cogging was tried several times and led to ambiguous results because the proton beam invariably moved transversely at some point during the exercise due to lattice dispersion. No opportunity arose to try displacing the antiproton beam, but it might not have worked for the same reason cogging did not work. The approach which worked was to run with a special store with 36 proton bunches of which only six were colliding with three antiproton bunches.

Colliding and non-colliding proton bunches were observed during the same counting interval by employing two gates triggered on different bunches. With a typical bunch luminosity of $0.4*10^{30}$ $cm^{-2}s^{-1}$ and typical circulating proton and anti-proton bunch intensities of 4 to $6*10^{10}$ the extracted beam rate increased by factors of 4 to 8 for proton bunches that were colliding. The extraction rates resulting from collisions at CDF and at D0 were about the same.

Two sets of measurements were taken. The first set used a gate consisting of three windows each of 470 ns spaced evenly over a turn. Two such independent gates were employed. Typically one of the two gates was set on a colliding bunch and the other on a non-colliding bunch. With this arrangement collisions were detected that resulted from both the B0 and D0 interaction regions (set 1). Halfway through the measurements a different arrangement was adopted with only one window (rather than three equally spaced ones) to see the individual effects of D0 and CDF (set 2). The differing luminosities for the individual bunches also permitted the study of the extraction rate as a function of luminosity.

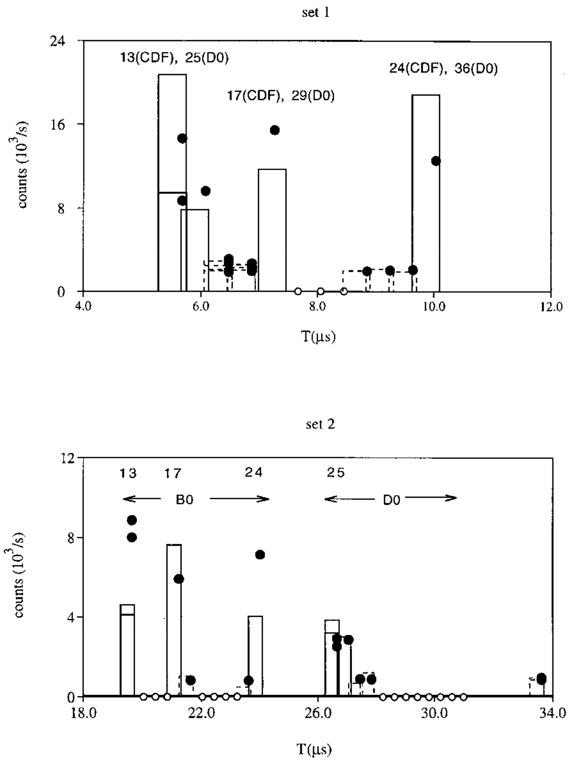

Figure 4: Illustration of the effect of colliding bunches on count rates for set 1 (CDF and D0 collisions combined) and set 2 (see text). Histograms are measured rates while dots are calculated based on bunch luminosities and a smoothed background. The histogram width is the gate length. The small open circles on the baselines indicate the times of unmeasured bunches. The vertical axis for set 2 is halved because only one bunch was counted. Numbers above a histogram indicate the proton bunch or bunches.

The count rate difference between colliding and non-colliding buckets is illustrated in Fig. 4. The measured count rates are compared to calculated rates based on luminosity plus an averaged background. Measured count rates are shown as histograms with the widths of the gates. Colliding cases are shown as solid histograms while proton-only cases are dashed. The difference between colliding and non-colliding buckets is clearly visible. It is clear that luminous bunches produced substantially more extracted beam.

Luminous bunches increased the rate to give a luminosity on/off ratio of 4.1. One way to quantify the luminosity on-off ratio is to ask how far the crystal would have had to be moved in to match a non-luminous bunch to the original luminous rate. Increasing the non-luminous count rate by a factor of 4 at $x_g = 2.5$ mm was equivalent to decreasing x_g by 0.4 mm or 0.7 σ_{max}.

Typically 10^{12} protons were circulating in six bunches in the luminosity-driven stores. The extraction rate was roughly 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 upstream of the crystal received no measurable background from the crystal, the

D0 “lost proton” monitor was sensitive to scattering from the crystal. Before the crystal was moved close to the beam D0 was usually already running at 80% of the conservative upper limit set by that experiment. D0 reached the beam loss limit when the extraction rate was between 50 and 150 kHz. However for a special end of store with D0 not taking data and $3*10^{12}$ protons circulating an extraction rate of 900 kHz was achieved. The D0 lost proton monitor exceeded its upper limit by a factor of 1.5 before the crystal was inserted and exceeded the limit by a factor of two after the crystal was inserted.

Note that the luminosity driven extraction is directly related to the principal collimation problem at the Tevatron and LHC.

RF-DRIVEN EXTRACTION

A horizontal damper located at F11 was also used in two E853 sessions to introduce RF noise in transverse phase space and thereby stimulate diffusion and increase the extraction rate. This characteristically decreased the beam lifetime substantially although it was still long enough for a typical study session. Significantly higher extraction rates were observed with the noise on. This approach could not be used for parasitic extraction owing to its destructive effect on the circulating beam.

The effect of turning the RF on or off was almost immediate and had a significant effect on the extracted beam. It was so significant that these tests were complicated by saturation problems in the larger principal counters even in a special proton-only store with 84 rather than 6 circulating bunches. However the small finger counters showed little or no evidence of saturation and also had a low background rate with noise off.

The rate was proportional to the square of the RF voltage as expected from the equations of motion in action angle variables [5]. Typically the rise time was on the order of 2-3 s and the decay time was of order 10 s after the beam was turned off.

It is interesting to compare luminosity and RF-driven extraction. This can be done by comparing the ratio of the rate with the driver on to the rate with no driver under the same conditions. As noted earlier for the luminosity case this ratio was 4.1 for $L_{pa} = 0.5*10^{30}$ $cm^{-2}s^{-1}$. In the RF-driven case the rate for the finger counter coincidence was $R = 15.2*V_{rf}^2 + 22$. A ratio of 4 is obtained for $V_{rf} = 2.1$ V.

FIBER-DRIVEN EXTRACTION

At Serpukhov Asseev demonstrated the use of a fiber at the edge of beam to multiply scatter halo out to the crystal [6]. In E853 we saw a substantial fast signal in the crystal extracted beam from the 30 micron carbon flying wires at E11 and E17 [7]. This is not the Asseev process since there is both beam edge and core scattering. However we did see the edges of the beam so that we could establish the process was practical in the Tevatron.

The fiber perturbs the beam in two ways. There is normal multiple scattering. There are also nuclear interactions at the level of about one in 10^5 passes. About 1 in 300 of these nuclear scatterings are at an angle small enough to stay in Tevatron. For the Tevatron flying wires it is these nuclear scatters that give rise to the early extraction signal, unlike the Asseev concept where multiple scattering over many collisions grows the beam. The flying wire extraction rates were consistent with the efficiency observed in other parts of E853.

BEAM HALO AND COLLIMATION

In E853 moving the crystal or the collimators gave information on the beam halo and an insight into how effective crystal collimation might be. Characteristically it took 5-7 kicks to produce extracted beam for a crystal to beam separation of 3.5 mm. When the crystal was retracted 200 microns the signal was typically cut by 4. The extraction rate recovered in several minutes. There was an immediate rise when the crystal moved in followed by 1/e decays of 0.5 to 5 hours.

We also studied collimation effects. Positioning of the three scraper collimators at D17 and A0 used to protect the collider experiments from beam halo was clearly interwoven with crystal position. When the crystal was effectively closer to the beam than the collimators the situation was different than when the crystal was shadowed by the collimators and diffusing beam was mostly lost on the collimators. For example a 5 mm retraction of the crystal (to well outside the collimators) lowered the rate precipitously, and even after 20 minutes there was no sign of increase.

In three study sessions the collimators were retracted almost simultaneously in small steps (typically 100 μm) near the end of the sessions by total amounts that varied from 0.5 to 1.2 mm. In all cases the extraction rate rose, but the rate of rise as a function of collimator position varied. This may have been a result of the fact that the collimators did not have the same initial settings in the three sessions. For example in sessions with crystal-beam separations of 5.3 and 5.5 mm the rate of rise per mm was in the 1-1.5 per mm range (so that the rate went from 2 to 2.5 times the initial value). Characteristically the D0 proton loss rate rose by 5% to 20% as the collimators were opened.

Studies of the time to reach equilibrium after a collimator move were complicated by relatively quick collimator changes with few measurements taken between adjustments. The time required to adjust the three collimators (on the order of 10 s) was also a limitation. Fast time plots and counting rate information indicated an initial fast rise of the count rate in less than 30 s, and perhaps much less. Information is available on only one relatively long quiescent period after a collimator move. Twenty minutes after completing a collimator moving session that had lasted 13 minutes the rate had risen by 30% (four times the estimated standard deviation of the measurement).

SUMMARY

E853 produced results in a number of areas. Parasitic luminosity-driven extraction was demonstrated and produced extraction rates in the 100 kHz range without unduly disturbing the collider detectors. For the same conditions this could potentially produce a 5-10 MHz parasitic extracted beam for TeV II conditions. RF and fiber-driven extraction were also investigated. Useful collimation information was developed.

We learned a lot in E853. Our experiences include the good, the bad, and the bland. In the bad category we found, as expected, that the interaction counters were very sensitive to beam motion. For kick mode operation we were often operating in a 10^8 - 10^9 protons per kick regime where special instrumentation would have been useful (and was not available). Beam halo behavior is often non-linear so simulations, particularly many turns after a kick, are complicated and sometimes impossible. The lattice location of the crystal is important. We understand that the location at RHIC was a problem [8]. The Tevatron crystal location was better but not perfect for some extraction techniques.

On the other hand there was lots of good news. Crystal extraction worked well at the Tevatron. The process was quite robust. The fact that extraction was observed in many different diffusion mode settings means crystal collimation can work. As we all now know, multiple pass crystal extraction (the Maxwell Demon of channeling) works. As a result crystal orientation is not as difficult as it might first appear. Finally channeling at this energy frontier behaves exactly like channeling at lower energies.

As far as the bland note that there is a large spectrum of time dependent behavior that has not been reviewed. Discussions of this as well as channeling behavior and extraction efficiency appear in the articles.

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