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Extraction from the Fermilab Tevatron using Channeling with a Bent Crystal

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Abstract

Experiment 853 at Fermilab is approved to test the possibility of extracting very low intensity beams from the Tevatron using channeling in a bent crystal as the extraction device and RF modulations to move halo beam onto the crystal. The purpose of the experiment is to prove that the extraction technique is feasible, and that it does not create backgrounds for collider experiments which are unacceptable. In the first phase of the experiment, an unbent crystal has been inserted close to the beam at the site of the future bent crystal. In this paper we discuss the technological challenges of the bent crystal and measurements planned with both the unbent and bent crystals.

I. INTRODUCTION

In order to extract beam from the SSC Collider for B-meson high energy physics experiments while the major Collider experiments are taking data, it is necessary to design a system which extracts protons at an acceptable rate while not unduly impacting the luminosity or backgrounds. The replacement of a traditional septum magnet with a crystal in the SSC was first proposed in 1984 [1]. After a considerable amount of refinement [2,3] it was determined [4] that the east campus straight section of the SSC collider would be the optimum location for a crystal extraction system. Based on these studies, a proposal for an experiment which would use the extracted beam for B-meson physics was submitted to the SSC Laboratory [5].

Based in part on suggestions from the SSC laboratory, a test of crystal extraction of protons from a superconducting collider was proposed for the Tevatron. Partially funded by SSCL, this approved experiment E853 was approved for 72 hours of dedicated accelerator beam time during the Fermilab Collider Run Ib. While waiting for the fabrication of the bent crystal and positioning hardware, some preliminary experiments were completed parasitically during both proton only and Collider operations in the Tevatron. The results of those experiments are reported in a separate paper [6].

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*Operated by the Universities Research Association under contract with the U.S. Department of Energy.

II. TEVATRON SYSTEM DESIGN

A. Beamline

A sketch of the beamline geometry of the Tevatron Collider crystal extraction system is shown in figure 1. Protons in the halo of the beam distribution which intercept the bent crystal with the correct angle are deflected. These particles oscillate about the design orbit until they enter the Lambertson. Since the Lambertson magnet and the crystal are separated by an odd multiple of 90°, the angle generated by the bent crystal is exhibited as a position offset into the Lambertson field free region (figure 2). The circulating protons see the deflecting field of the Lambertson, which acts as one of the normal Tevatron dipoles. Protons in the field free region travel straight into the Tevatron C0 abort line toward the extracted beam detectors.

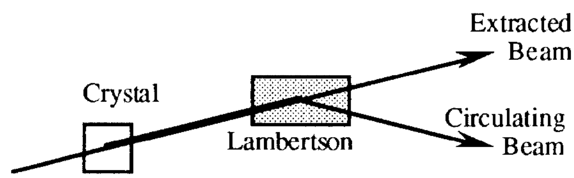

Figure 1: Sketch of the beamline geometry in the Tevatron Collider at the crystal extraction region.

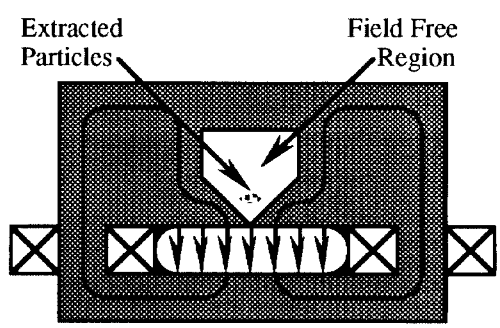

Figure 2: Sketch of a lambertson magnet, showing a portion of the magnetic flux lines generated by the bus bars pictured as crossed boxes.

B. Crystal

The crystal is positioned in the B48 straight section, replacing one of 4 proton abort kickers normally occupying that region. The monocrystal, aligned so that the protons will travel down the (1,1,0) planes, has the dimensions 30 mm long, 10 mm wide, and 3 mm thick. This alignment is produced by remotely controlled optical table positioners with a required precision of 0.24 mrad, which is the acceptance angle of the channels. The crystal is bent to create a 0.64 mrad deflection, requiring a sagitta of 1.6 microns. This sagitta is measured by means of optical interferometry. The crystal geometry and bender are shown in figure 3.

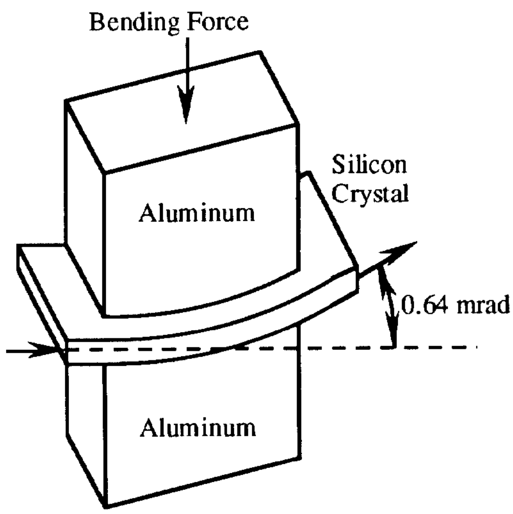

Figure 3: Drawing of the crystal in the holder which is designed to bend it without distorting the lattice structure.

A comprehensive analysis of the effect of the holder on the crystal lattice was recently completed [7]. The research used the materials program ANSYS to simulate the stresses and deformation in the crystal while being squeezed in the holder. It was found that due to the finite stiffness of the aluminum benders and the flap-back of the bent crystal, a design bend of 0.96 mrad was required to get an actual full bending angle of 0.64 mrad. Along the surface of the crystal facing the beam, the variation of this bend angle was negligible at the entrance and exit of the crystal due to the silicon overhang beyond the lengths of the aluminum pieces. The force required to accomplish this bend is less than 11 lbs, with a maximum stress in the crystal of less than 1500 psi.

This same study shows that at the crystal entrance at the top edge of the surface of the crystal facing the beam is closer to the beam than the bottom edge by 40 microns. Because this distortion is relatively constant from the entrance face up to the point where the holders start, this effect is not expected to affect the channeling efficiency. Of greater importance to channeling is the alignment and polishing of that surface. A particle must be strike deep enough into the crystal that it sees an uninterrupted lattice structure.

C. Abort Line Instrumentation

The Tevatron abort line was designed to maximum the angular acceptance of the aperture at the point of the kickers (and now of the crystal). Therefore, the beam in the abort line itself has very little divergence. To detect the particles sent into this channel, a pair of air gaps near the downstream end of the line have been inserted for instrumentation purposes. The heart of this equipment is a pair of active, segmented silicon counters, one in each air gap (which are separated by 40 m). Each channel of these detectors is read out by a FastBus crate of electronics physically located in the tunnel. The data acquisition trigger is derived from a set of plastic scintillators. A secondary diagnostic is a CCD camera imaging a fluorescent flag. The camera signal is digitized and stored by a computer as well as broadcast realtime over the Fermilab video distribution system.

In the Tevatron itself at B48 there are two monitors whose purpose it is to measure the interaction of the circulating protons with the crystal. The first is a loss monitor identical to those used in the Fermilab flying wire profile monitor systems [8], and is used to measure the turn-by-turn showers caused by inelastic collisions of circulating protons with the atoms in the crystal. The interaction rate measured by this counter will give crystal to beam halo proximity information. It may also act as a crystal angle diagnostic, where the inelastic scattering rate drops when the crystal is properly aligned and the majority of particles are being cleanly extracted. The second monitor is a phototube aimed at the crystal surface along the beam. By measuring the photon flux from the crystal caused by fluorescence, it is hoped that a direct measure of incident protons on the crystal is possible.

The C0 abort line is used for disposing of 150 GeV protons. Therefore, the detectors in the line must retract when the Tevatron is not in a 900 GeV store. This is accomplished with horizontal motion stages driven by standard stepping motors.

D. Diffusion

Probably the biggest challenge of the crystal extraction system is the diffusion of particles from the core of the beam into the halo. It is found in the Tevatron (and expected in the SSC storage ring) that there is an insufficient population of protons in the transverse or longitudinal halos of the beam available for extraction. Therefore, transverse or longitudinal external stimulation of beam diffusion are required. In the case of longitudinal excitation, the crystal must be placed at a high dispersion point of the magnet lattice.

This stimulation must not cause excessive background counting rates in the collider high energy physics detectors. Since detector backgrounds are extremely sensitive to tune, coupling, and chromaticity, changes in these parameters for such processes as resonant extraction are disallowed. In addition, the extraction process must be very efficient in order to provide the greatest flux possible to a future fixed target experiment while simultaneously maximizing the proton intensity and luminosity lifetimes during each store. Finally, because the fixed target experiment in the SSC will be rate limited to no more than one incident proton passage per RF bucket, a slow and steady method of extraction is necessary. Therefore, we and others at CERN [9,10] have come to the conclusion that the most promising technique of populating the halo is by generating amplitude dependent diffusion rates in either the longitudinal (SSC and Tevatron) or transverse (LHC and SPS) planes. By generating a signal which has a small effect at low amplitudes but generates large particle diffusion rates at greater oscillation amplitudes, luminosity lifetime can be preserved while creating a steady state population of particles which strike deep (greater than approximately 1 micron) into the crystal (hence avoiding surface irregularities and maximizing the extraction efficiency). This diffusion rate profile is generated by taking advantage of phase space nonlinearity which create amplitude dependent particle tunes. Since each particle only reacts to signals at their local resonant frequencies, frequency dependent signal power densities cause amplitude dependent diffusion rates. Though in most cases shaped random noise is utilized, it has been proposed to use more complicated waveforms [11] to improve the mean penetration depth into the crystal.

III. Experimental Goals

The goal of the Tevatron and SSC crystal extraction systems is to remove 10^{-6} of the circulating protons in the accelerator each second. In the Tevatron this amounts to 10^{6} protons/sec being extracted. The present Tevatron luminosity lifetime is approximately 18 hours. The above extraction rate corresponds to a proton beam intensity lifetime of 278 hours. Therefore, the luminosity lifetime during these extraction experiments should be roughly 17 hours, which is barely noticeable and falls within the normal range of luminosity lifetimes (observed variations during and between stores).

The main goal of the Tevatron experiment is to prove the feasibility of efficient and nondisruptive proton extraction from colliding beams. The Tevatron is perfect for such a study since, like the SSC Collider ring, it is superconducting, a collider, and has high energy physics experiments. The latter is a distinct advantage over the other crystal extraction experiment at CERN in that the presently active detectors have background monitor systems. Therefore, the luminosity lifetime and detector background rates measured in the Tevatron are directly applicable to estimates of SSC Collider effects.

Given our experience with applying RF noise and collimation to the beam during normal collider operations, it is anticipated that experiment setup work such as diffusion calibration, crystal alignment, and detector commissioning can occur parasitically. In this way the study time allocated to the experiment can be dedicated toward direct observation and manipulation of extracted beam.

IV. Present Status

With financial support from the SSC Laboratory, mechanical support from the Fermilab Accelerator Division, and approval for 72 hours of dedicated accelerator study time, experiment 853 is in the process of building all of the required hardware and fabricating the crystals. The micropositioning stages have been purchased and the required stands and vacuum chamber are under construction. The crystal holder design has not yet been finalized, nor has the method for measuring the total crystal deflection angle been tested. The detectors and associated electronics in the abort line are under construction.

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