EXPERIMENTAL STUDY OF MAGNETICALLY CONFINED HOLLOW ELECTRON BEAMS IN THE TEVATRON AS COLLIMATORS FOR INTENSE HIGH-ENERGY HADRON BEAMS*

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Abstract

Magnetically confined hollow electron beams for controlled halo removal in high-energy colliders such as the Tevatron or the LHC may extend traditional collimation systems beyond the intensity limits imposed by tolerable losses. They may also improve collimation performance by suppressing loss spikes due to beam jitter and by increasing capture efficiency. A hollow electron gun was designed and tested at Fermilab for this purpose. It was installed in one of the Tevatron electron lenses in the summer of 2010. We present the results of the first experimental tests of the hollow-beam collimation concept on 980-GeV antiproton bunches in the Tevatron.

We are studying hollow electron beams as a new kind of collimator for high-intensity beams in storage rings and colliders [1, 2]. In a hollow electron beam collimator (HEBC), electrons enclose the circulating beam (Figure 1). The electron beam is generated by a pulsed electron gun and transported with strong axial magnetic fields, in an arrangement similar to electron cooling or to the existing Tevatron electron lenses [3]. The electrons' electric charge kicks halo particles transversely. If the hollow distribution is axially symmetric, the core of the circulating beam is unperturbed. For typical parameters, the kick experienced by 980-GeV protons is of the order of 0.2 μrad.

In a conventional two-stage collimation scheme, primary collimators (targets) impart random transverse kicks due to multiple scattering. The affected particles have increasing oscillation amplitudes and a large fraction of them is caught by the secondary collimators (absorbers). These systems offer robust shielding of sensitive components. They are also very efficient in reducing beam losses at the experiments. However, this two-stage system has limitiations. In high-power accelerators, no material can be placed too close to the beam. The minimum distance is limited by instantaneous loss rates, radiation damage, and by the electromagnetic impedance of the device. Another problem is beam jitter. The orbit of the circulating beam oscillates due to ground motion and other vibrations. Even with active orbit stabilization, the beam centroid may oscillate by tens of microns. This translates into periodic bursts of losses at aperture restrictions.

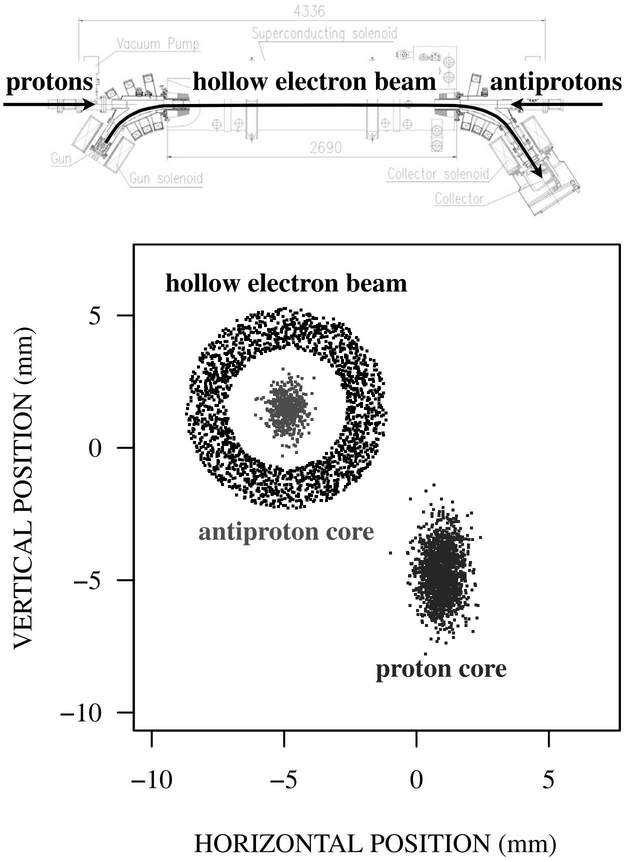

Figure 1: Layout of the beams in the Tevatron.

With the hollow electron beam collimator we are trying to address these limitations. We are studying whether this concept is viable as a complement to conventional systems. A magnetically confined electron beam is stiff, and it can be placed very close to, and even overlap with, the circulating beam. The intensity of the transverse kicks is tunable, making the device act more like a 'soft collimator' or a 'diffusion enhancer', rather than a hard aperture limitation.

After some preliminary modeling and simulations, we decided to test this concept experimentally. A 15-mm-diameter hollow electron gun was designed and built in 2009. It is a tungsten dispenser cathode with a 9-mm-diameter hole. The gun was tested and characterized in

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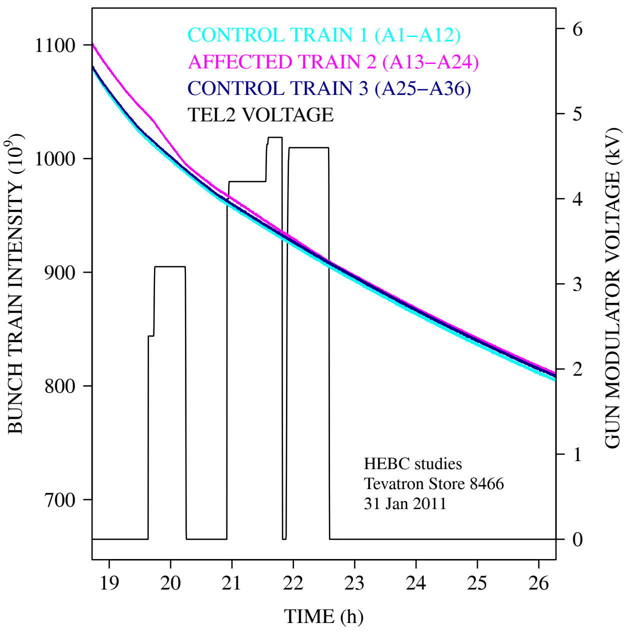

Figure 2: Bunch train intensities.

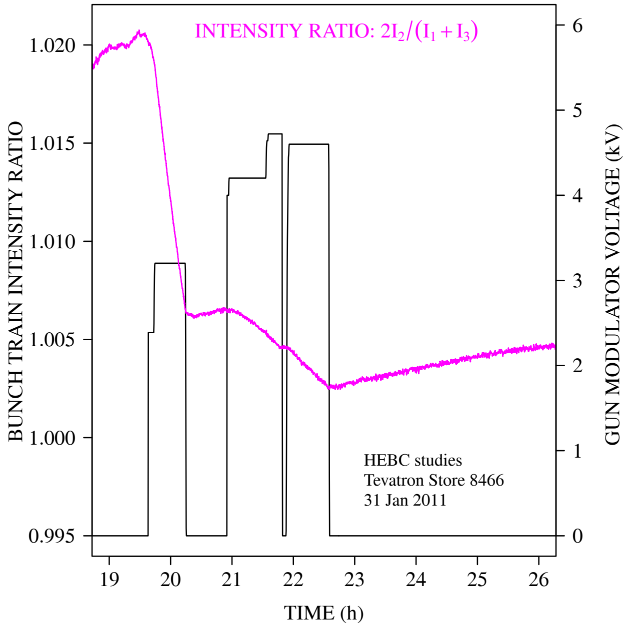

Figure 3: Relative intensity of the affected train.

the Fermilab electron lens test stand. The peak current delivered by this gun is 1.1 A at 5 kV. We installed the gun in one of the Tevatron electron lenses in August 2010.

There are 2 electron lenses in the Tevatron, TEL1 and TEL2. The electron beams are pulsed and can be timed with any bunch or group of bunches. TEL1 is used during normal operations for cleaning the abort gap [4]. TEL2 is a backup for TEL1 and it was used for studies. Experiments began in October 2010.

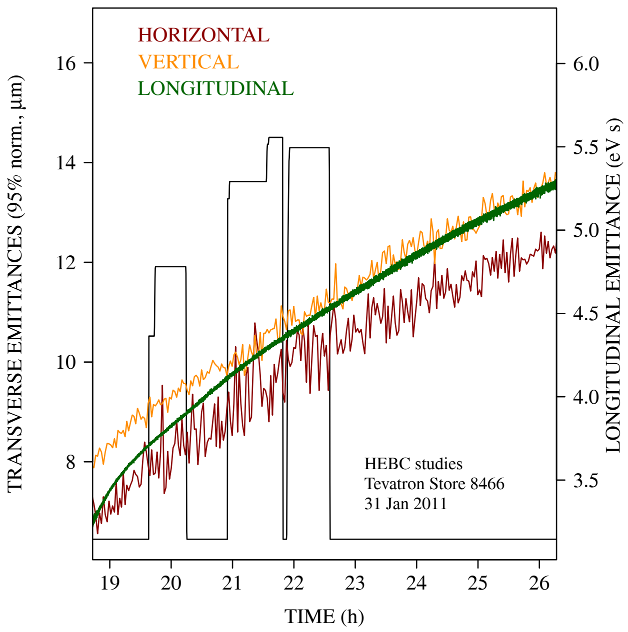

Figure 4: Emittance evolution of the affected train.

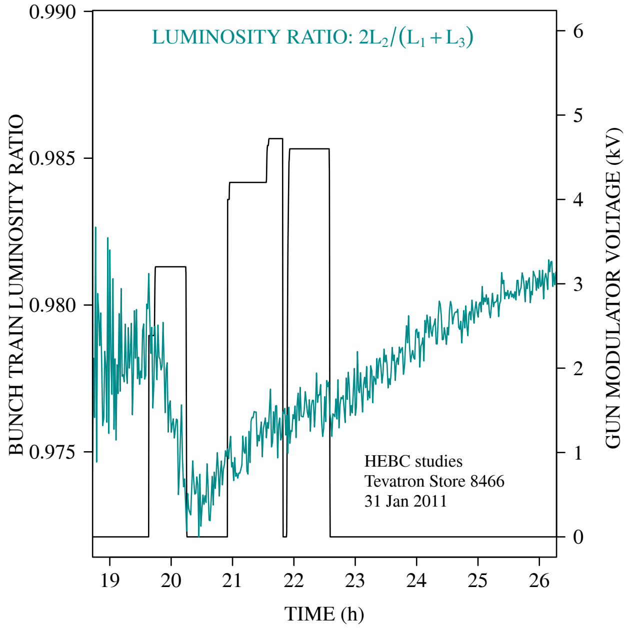

Figure 5: Relative luminosity of the affected train.

We have tested the device under various experimental conditions, by varying the beam current, the alignment, the hole size, the pulsing pattern, and the collimator system configurations. Here we will focus on some examples of the electron beam acting on antiproton bunches.

The first question we addressed is the removal rate. In the experiment described in Figure 2, the electron lens was turned on the second antiproton bunch train about 1 hour after the beginning of a regular collider store. The size of the hole was 4.5σ and 5σ, respectively, where σ is the vertical r.m.s. beam size. The hole size is controlled by the ratio of magnetic fields in the gun and main solenoids. Figure 2 shows the intensity of each bunch train as a function

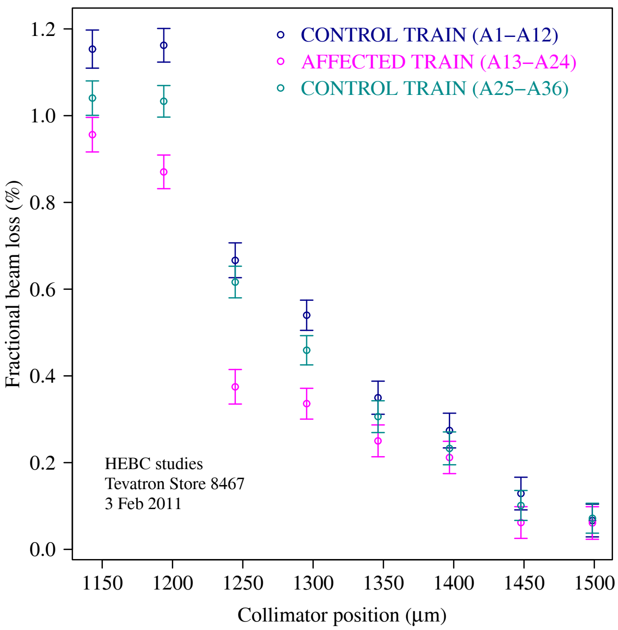

Figure 6: Fractional beam loss during a collimator scan.

of time. The black trace is the TEL2 voltage. One can already see that train number 2 is being scraped. To isolate the effect of the hollow beam, the ratio between the intensity of the affected train and the average intensity of the other two trains is shown in Figure 3. One clearly sees the smooth scraping effect: in this example, 2.5%/h with the 4.5σ hole, and 0.32%/h with the larger hole size.

The other important question is whether there are any adverse effects on the core of the circulating beam. This is a concern because the overlap region is not a perfect hollow cylinder. We approached the problem from three points of view. First, we looked at the evolution of the emittances. In Figure 4, the emittances for the affected bunch train are shown. If there is emittance growth produced by the electron beam, it is much smaller than that driven by other factors, mainly beam-beam and intrabeam scattering.

Secondly, we compared beam scraping with the corresponding decrease in luminosity. Luminosity is proportional to the product of antiproton and proton populations, and inversely proportional to the squared rms of the overlap region. If antiprotons are removed and the other factors are unchanged, luminosity should decrease by the same relative amount. If the hollow beam causes emittance growth or proton loss, luminosity should decrease even more. A smaller relative change in luminosity, or no change, are clear indications of halo scraping. In Figure 5, one can see how the luminosity for the affected bunch changed with time relative to the other bunch trains. During the first scrape with small hole, intensity was reduced by 1.4%, whereas luminosity only decreased by 0.57%. In the second experiment with 5σ hole, a 0.39% reduction in intensity was accompanied by no detectable change in luminosity, or less than 0.05%.

The third approach is to try to measure the halo population directly. This can be done by scanning a collimator in small steps and observing the corresponding beam loss. In Figure 6, one can see the results of a collimator scan. The hollow beam was acting on the second bunch train with a 3.5σ hole. A vertical antiproton collimator was moved downward in 50-micron steps. All other collimators were retracted. Figure 6 shows how much beam was lost at each step for each of the 3 bunch trains. About 1% of the total intensity was scraped by the hollow-beam, but one can see that there is a region in which the population of the affected train is about 40% lower than the other trains. As expected, populations tend to be equal towards the beam axis and far away from it, and the ratio of populations in the two control trains is constant. The time evolution of losses can also be used to estimate the diffusion rate as a function of amplitude [5], and we have started to use this technique to measure the effect of the hollow beam.

The alignment procedures, which are crucial for HEBC operation, were found to be reliable. No instabilities or emittance growth were observed at nominal antiproton intensities (10^{11} particles/bunch) and electron beam currents up to 1 A. Most of the studies were done parasitically during regular collider stores.

We have observed the scraping effect of the hollow-beam collimator. Our experiments show that it is possible to remove particles from the halo without significantly affecting the core. We plan to continue the experimental study in the next few months, compatibly with the Tevatron run schedule. We want to compare diffusion measurements with and without electron lens; study the capture efficiency as a function of hole size; and measure the effect on protons. In parallel, we are designing a larger cathode and expanding our modeling and simulations efforts.

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