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COLLIMATION STUDIES WITH HOLLOW ELECTRON BEAMS*

G. Stancari†, G. Annala, T. R. Johnson, G. W. Saewert, V. Shiltsev, D. A. Still, A. Valishev
Fermi National Accelerator Laboratory, Batavia, IL 60150, USA

Abstract

Recent experimental studies at the Fermilab Tevatron collider have shown that magnetically confined hollow electron beams can act as a new kind of collimator for high-intensity beams in storage rings. In a hollow electron beam collimator, electrons enclose the circulating beam. Their electric charge kicks halo particles transversely. If their distribution is axially symmetric, the beam core is unaffected. This device is complementary to conventional two-stage collimation systems: the electron beam can be placed arbitrarily close to the circulating beam; and particle removal is smooth, so that the device is a diffusion enhancer rather than a hard aperture limitation. The concept was tested in the Tevatron collider using a hollow electron gun installed in one of the existing electron lenses. We describe some of the technical aspects of hollow-beam scraping and the results of recent measurements.

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 electric charge of the electrons kicks halo particles transversely. If the hollow distribution is axially symmetric, the core of the circulating beam is unperturbed. For typical parameters, the kick given to 980-GeV protons is of the order of 0.2 μrad.

In a conventional two-stage collimation scheme, primary collimators 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. These systems offer robust shielding of sensitive components. They are also very efficient in reducing beam losses at the experiments. However, they have 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.

The hollow electron beam collimator addresses these limitations. A magnetically confined electron beam can be

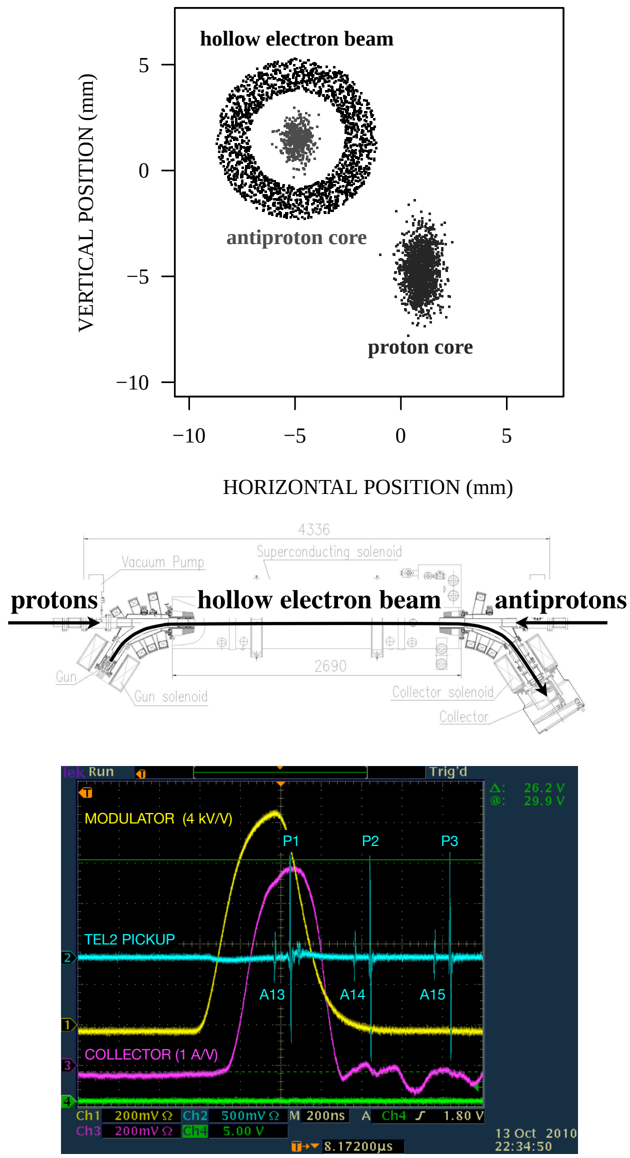

Figure 1: (top) Transverse beam layout. (center) Tevatron electron lens. (bottom) Example of pulse synchronization: modulator voltage (yellow), shortest possible pulse; electron current at the collector (magenta); beam pickup signal (cyan) showing proton and antiproton bunches (P1–P3 and A13–A15) and the derivative of the electron pulse.

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† On leave from Istituto Nazionale di Fisica Nucleare, Sezione di Ferrara, Italy. E-mail: stancari@fnal.gov.

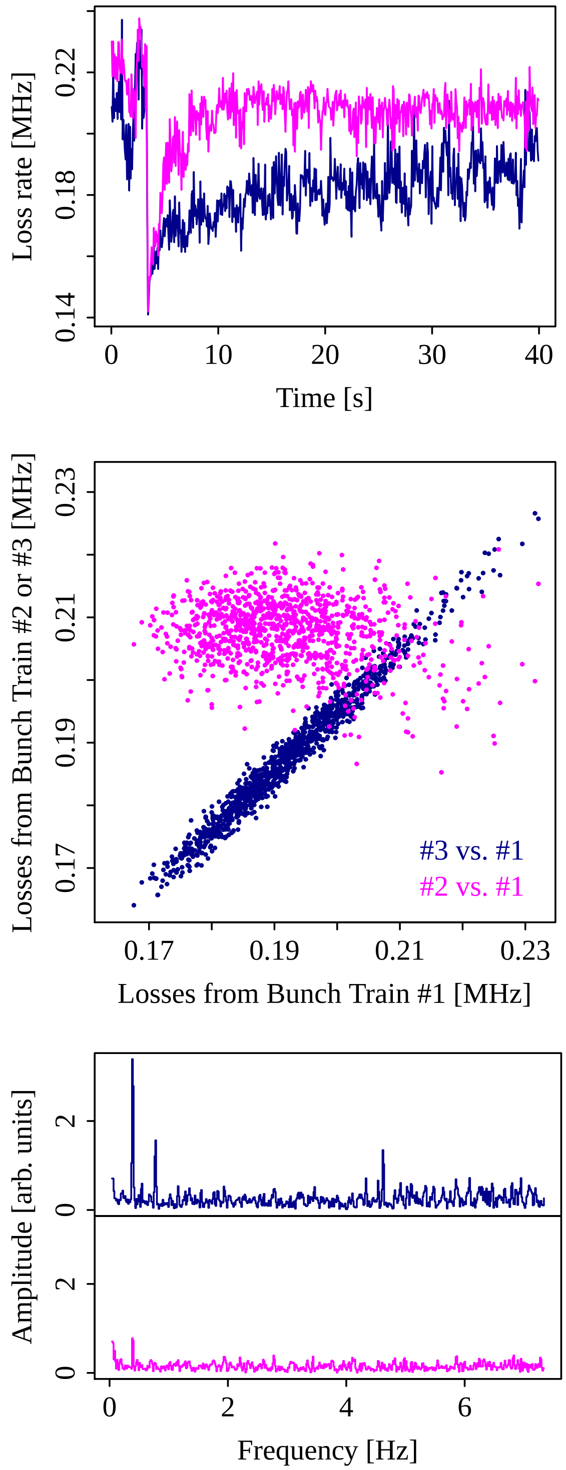

Figure 2: Loss rates recorded during HEBC studies in Tevatron Store 8749 (20 May 2011). (top) Loss rates vs. time during an outward collimator step for control bunch train #1 (blue) and for the affected bunch train #2 (magenta). (center) Correlations among loss monitors over the course of 74 s of steady state, with collimators at fixed positions. (bottom) Fourier spectrum of losses from trains #1 (blue) and #2 (magenta), same data as center plot.

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. Moreover, if halo tails are suppressed, the beam and the sensitive components in the machine become less vulnerable to beam jitter or to the loss spikes generated during collimator setup.

The concept was tested experimentally at the Fermilab Tevatron collider between October 2010 and September 2011. Preliminary results were reported in Ref. [4]. In this paper, we describe the status of the project and focus on different aspects of the hollow beam collimation phenomena.

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 bored through its convex surface. The gun was tested and characterized in 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.

In the electron lens, protons and antiprotons are separated transversely and in time. The transverse separation is about 9 mm. The radius of the hole is controlled by the ratio of solenoid fields in the gun and in the overlap region. Three corrector coils are used to align the electron beam with the circulating beam. A special high-voltage modulator with rise times of 200 ns allows one to synchronize the electron pulse with practically any bunch or group of bunches (Figure 1, bottom).

The experiments were carried out with the electron pulses acting on antiproton bunches: their smaller transverse size (achieved with stochastic and electron cooling) allowed one to explore a wider range of hole sizes and confining fields; and the position of the electron lens with respect to the Tevatron collimation system was more favorable for antiproton capture.

The first experiments were dedicated to testing the synchronization and alignment procedures, which are crucial for HEBC operation. In spite of the different time structure of the electron and antiproton pulses, the beam position measurements were found to be reliable and reproducible by observing loss rates and beam lifetimes as a function of the electron-lens corrector settings. Alignment was done manually and took a few minutes, yielding relative alignments of better than 0.1 mm, or 1/5 of the root-mean-square transverse size of the circulating beam. Tolerances of a few tens of microns are achievable if necessary.

It was demonstrated that many studies could be done parasitically during regular collider stores. No instabilities or emittance growth were observed at nominal antiproton intensities (10^{11} particles/bunch) and electron beam currents up to 1 A when the beams were aligned. This was true for both the affected antiproton bunch and for the proton bunch outside the electron beam.

We measured the behavior of the device under different experimental conditions: beam currents, relative alignments, hole sizes, pulsing patterns, and collimator system configurations. The main effects of the HEBC are the particle removal rate (typically, a few percent per hour) and halo scraping without perturbing the core. These effects are discussed in detail in Ref. [4]. Here, we focus on the enhancement of diffusion and on the time structure and correlations of losses.

Diffusion rates as a function of particle amplitude can be measured by observing the time evolution of losses as collimators are moved in small steps [5, 6]. The main features of the response of local losses to small collimator steps in the diffusion regime are a sharp peak (or dip in the case of collimator retraction) and a transient proportional to the inverse square root of time. From the transient time, which is a function of collimator position, the diffusion rate at the location of the collimator can be extracted. We are interested in how the diffusion rate is changed by the hollow electron lens. For this reason, new scintillator paddles were installed near one of the antiproton secondary collimators. Losses were gated to individual bunch trains and recorded at 15 Hz. Because many other observables are already gated (bunch intensities, luminosities, losses at the experiments) this device enabled us to measure diffusion rates, collimation efficiencies and loss spikes simultaneously for the bunch trains affected by the electron beam and for the control bunch trains.

An example of what can be observed by comparing losses from different bunch trains is shown in Figure 2 (top). The primary antiproton collimator was moved vertically outward by 50 μm. All other collimators were retracted. The electron lens was aligned and synchronized with only one of the bunch trains (#2), with a peak current of 0.9 A. The difference in diffusion times between the affected and the control bunch train is apparent. It corresponds to an enhancement of the diffusion rate by about a factor 10. The steady-state loss rate is proportional to the product of the local diffusion coefficient and the gradient of the beam population. The fact that it is only 10% higher for the affected train indicates that the halo population was greatly reduced.

Further insight in the distribution of these losses comes from the analysis of their correlation. The blue points in Figure 2 (center) show the losses coming from the 2 control trains (#3 vs. #1) in steady state conditions (transient ended, collimators fixed). One can see random fluctuations of the order of a few kilohertz out of 0.2 MHz, but the main effect is a very high correlation, which can be attributed to beam jitter — bunches oscillating coherently. The hollow beam eliminates this correlation, and even introduces a negative correlation for the loss spikes. This effect is interpreted as an increase in diffusion (higher average losses) and a decrease in tail population (reduced sensitivity to beam jitter).

Beam jitter is also apparent in the Fourier spectrum of gated losses (Figure 2, bottom). Normally, the spectra show peaks corresponding to mechanical vibrations caused, for instance, by the Main Injector acceleration ramp (0.4 Hz) or by the compressors of the Central Helium Liquefier (4.6 Hz). The electron beam acting on the second bunch train suppresses these periodic losses. This is another manifestation of the reduction of tails.

These are just a few examples of the great progress in understanding of hollow beam collimation that took place in the last few months. Many more observations were made on halo removal rates, effects on the core, diffusion, fluctuations, and collimation efficiency.

In collaboration with the LHC Collimation Working Group, we are investigating whether, after the end of the Tevaron run, the electron-lens equipment can be transfered to CERN to continue the experimental program in one of the rings. For the LHC, a hollow electron beam collimator could provide a gradual pre-scraping before collisions or collimator setup. It could also potentially improve the efficiency of ion collimation. To extend the flexibility of the device, a larger electron gun was designed. It has an outer diameter of 25 mm and an inner diameter of 13.5 mm. It will provide currents of up to 3 A at 5 kV. It will be tested in the Fermilab electron-lens test stand to investigate possible technical issues. In parallel with the experimental program, to understand the scraping mechanisms in detail, we are comparing tracking simulations in the Tevatron with the large amout of observations that was collected. This will provide the basis for studies of feasibility and possible benefits for the LHC.

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