

BEAM STUDIES WITH ELECTRON COLUMNS *

V. Shiltsev[#], A. Valishev, G. Kuznetsov, FNAL, Batavia, IL 60510, U.S.A.
 V. Kamedzhiev, FZ-Juelich, IKP, Germany, A. Romanov, BINP, Novosibirsk, Russia

Abstract

We report preliminary results of experimental studies of "electron columns" in the Tevatron and in a specialized test setup. In the Tevatron, a beam of 150 GeV protons ionizes residual gas and ionization electrons are stored in an electrostatic trap immersed into strong longitudinal magnetic field. Shifts of proton betatron frequencies are observed. In the test setup, we observe effects pointing to accumulation and escape of ionization electrons.

ELECTRON COLUMNS

Compensation of space charge forces in high current proton beams is possible if a) the relative fraction of the electron charge w.r.t. the proton charge is equal to $\langle \eta \rangle = 1/\gamma^2$ where γ is relativistic factor of protons; b) the electron charge distribution is the same as the proton one (ideally, in all three dimensions); c) the electron-proton system is dynamically stable. Neutralization by ionization electrons – those which are born by ionization of residual gas by charged beam – is suggested [1,2] in the configuration with very strong longitudinal magnetic field which assures the e-p stability.

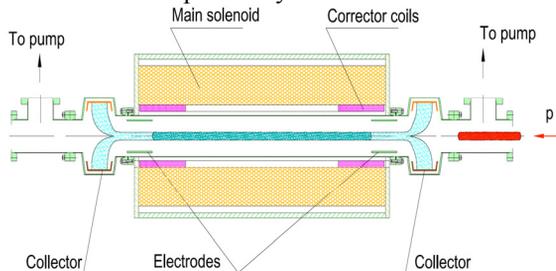


Figure 1: Layout of an "electron column".

The longitudinal magnetic field which is supposed to be strong enough to keep electrons from escaping from the transverse position they are born at and suppress the e-p instability, but at the same time weak enough to allow ions escape and not affect the process of charge compensation. For most common existing accelerators where high energy protons are guided and focused by transverse fields of magnetic dipoles and quadrupoles, there is a possibility to satisfy the compensation condition *on average* by having many space charge compensating elements (SCC) around the ring – ideally, one per every superperiod of the focusing lattice.

Schematically, the compensation device - an "electron column" [1] - may look as shown in Fig. 1 and consist of a solenoid magnet, a pair of ring- or cylinder-shape electrodes to control the accumulation of electrons (by applying negative voltage $-U$), a controlled leak to vary

vacuum conditions at the location of the electron column (EC), electron collectors and vacuum ports for possible differential pumping. If the B -field is strong enough, than the transverse charge distribution of accumulated ionization electrons follows the proton one as shown in Fig. 2 (right) for $\eta_0 = 0.5, 1, 1.5$. The system of electrodes may be more complex than just two rings and for example provide desired distribution of potential along the z -axis. Voltages can be made time-dependent to track changes of proton beam parameters (energy, size, etc). The solenoid field distribution can be varied too in order to reduce x-y coupling it introduces.

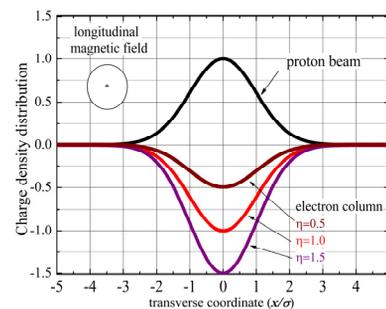


Figure 2: Ideal transverse distributions of electric charge in circulating proton beam and accumulated in "an electron column".

Accumulation of ionization electrons along the magnetic field lines is the key point of the proposal. It is understood that various processes may prevent that and diffuse the distribution and prevent electron storage – e.g. the electron scattering on residual gas molecules, collisions with electrostatic potential of the confinement electrodes, "dragging" by the proton beam, accumulation of "tertiary" electrons (those born in collisions of the initial ionization electrons with vacuum molecules or in a possible Penning-like discharge process), etc. In an attempt to explore the issues we performed a series of studies with 150 GeV proton beam circulating in the Tevatron and ionizing gas inside Tevatron Electron Lens (TEL) which can be arranged in configuration similar to the desired one (shown in Fig. 1).

TEVATRON STUDIES WITH TEL

Detailed description of TELs can be found in [3]. For the purpose of our study it is important that it has a 3T longitudinal field over about 2 m of the Tevatron circumference and has several electrostatic electrodes, voltages on which can be remotely controlled – see Fig.3. During the studies, the electron gun and electron collector of the TEL were shut off and set at the ground potential (so, no intentional electron current through the system was initiated). Voltages on both sides of split-cylinder

*Work supported by Fermi Research Alliance, LLC under DOE Contract DE-AC02-07CH11359
[#]shiltsev@fnal.gov

electrodes (neighbouring “holey electrodes” in Fig. 3) were varied from zero to about -2kV.

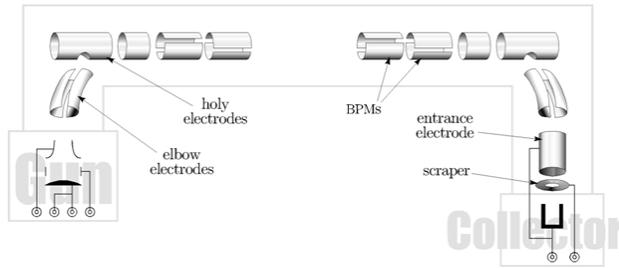


Figure 3: System of electrodes inside TEL (from [3]).

Accumulation of electrons due to ionization by the 150 GeV protons should lead to a positive proton (e.g. vertical) tuneshift of about:

$$dQ_y = + \frac{N_e r_p \beta_y}{4\pi\gamma\sigma^2} \approx +0.0067 \cdot U[kV] \quad (1)$$

where r_p is the classic proton radius $1.53 \cdot 10^{-18}$ m, $\sigma \approx 1.5$ mm is the rms proton beam and electron column radius, $\beta \approx 100$ m is the vertical beta-function at the location of the TEL, and N_e is the total number of electrons accumulated if the voltage on the confinement electrodes is set to $-U$:

$$N_e = \frac{U[V]}{30(1+2\ln\frac{a}{\sigma})} \cdot \frac{L_{ec}}{ec} \approx 1.8 \cdot 10^{11} \cdot U[kV] \quad (2)$$

The estimates above are valid under the assumption that the electron charge distribution follows the proton one as depicted in Fig. 2.

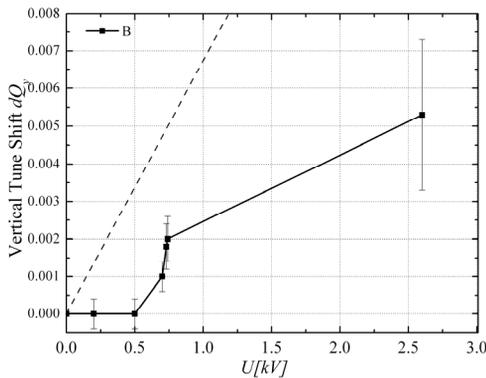


Figure 4: Summary of tuneshift vs U[kV] measurements. Dashed line – Eq.(1).

The Tevatron studies have revealed that: a) the tune shift can indeed be observed, it is positive (that is consistent with accumulation of electrons near the proton beam), but the shift is less than half of what is expected from Eq.(1) – see Fig. 4; b) at the nominal vacuum pressure in the TEL of about $3 \cdot 10^{-9}$ Torr no tuneshift is observed with any voltage on the electrodes up to -2.6 kV; c) after special measures were made to decrease the vacuum to $5 \cdot 10^{-8}$ Torr (this was achieved by either sending electron current from the TEL e-gun into the walls of the TEL vacuum chamber or, less disruptively,

by heating the vacuum chamber inside the TEL by sending some 3-5 A of DC current through a special heating wire attached to the walls), the tuneshift can be observed but only if the voltage exceeds -700V; d) during such attempts, significant vacuum instability was observed (local vacuum pressure went up to $5 \cdot 10^{-6}$ Torr) accompanied by the proton beam instability – shown in Fig. 5 - which led either to the emittance growth of about 4π mm mrad/s (95% normalized) or even to a proton beam loss, presumably, due to beam scraping.

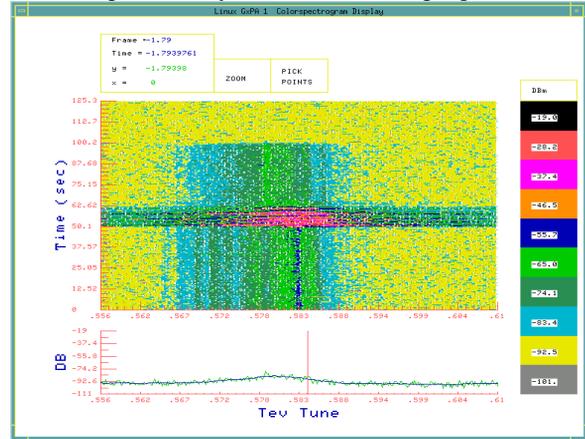


Figure 5: Color coded 21 MHz Schottky spectra of the vertical motion of the 150 GeV beam of protons in the Tevatron during space-charge neutralization study. The beam injection time is at the top (“waterfall” plot). Range of the vertical tunes on the horizontal axis is from 0.556 to 0.61. Some 40 sec after injection the vacuum was worsened in the Tevatron Electron Lens setup and the Schottky power went up. After that, the average tune of the beam increased by approximately 0.005.

Such an unexpected phenomena (instability flashes) indicated an incomplete understanding of the physical processes inside the ionized and magnetized plasma. To explore them in greater detail without using much of precious Tevatron operation time, the studies were moved to a TEL bench test setup.

TEST BENCH STUDIES

The facility for bench testing the TELs’ electron guns and collectors is described in [4]. It consists of electron gun, some 2 m long grounded drift tube and electron beam collector. The system is immersed in 0.2-0.4 T longitudinal magnetic field of three normal conducting solenoids. Fig. 6 shows placement of various electrodes in the test setup.

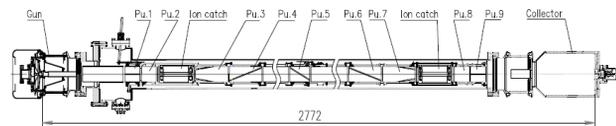


Figure 6: Test setup (left to right): electron gun; pickups (PU) 1, 2; ion removal electrodes (not employed in this study); PU’s 3, 4, 5, 6, 7; ion removal electrodes (not employed); PU’s 8,9; electron beam collector.

During the studies the electron gun cathode was kept at -2.3 kV DC, electron gun anode was grounded – that resulted in about 100 mA of DC electron current; electron collector and all pick-up (PU) electrodes except PU3 and 7 were grounded, too. The voltages on both halves of pickup electrodes PU3 and 7 were independently set at the negative potentials varied from 0 to -500V.

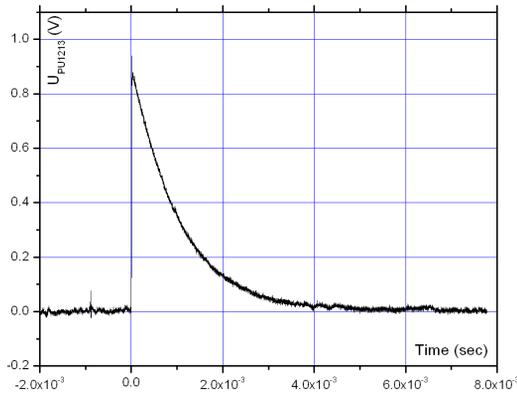


Figure 7: Signal on PU4 after quick switch off of the -400V trap voltage on PU7.

Figure 7 shows an exemplary signal on PU4 after quick switch off of the -400V trap voltage on PU7. Such a change of the voltage opens up the trap and allows electrons accumulated between PU3 and PU7 to flow into the beam collector in less than 1 μ s. As the result of the reduction of the total negative charge inside the 13cm long PU4, a positive voltage with peak amplitude of 0.9 V is detected by a 1 MOhm input resistance scope. The signal decays with the characteristic time of $RC=1\text{MOhm}\cdot 0.96\text{nF}\approx 1\text{ms}$ and indicates that the charge accumulated inside the electrode was $Q=0.9\text{V}/0.96\text{nF}\approx 1\text{nC}$ (here we take the pick-up to ground capacitance of $C=0.96\text{nF}$). For comparison, the charge of the 0.1A main electron beam inside the same electrode is about 0.5nC.

Figure 8 shows that the PU4 signal grows with the trap voltage, so more charge accumulated at the higher voltages on PU3 and PU7. The dependence is not linear as expected from Eq.(2) – probably because of significant deterioration of the vacuum pressure at higher voltages (see dashed line in Fig.8).

SUMMARY

The first studies with the Tevatron Electron Lens configured to work as “electron column” had shown significant accumulation of electrons inside an electrostatic trap in 3T longitudinal magnetic field. These negatively charged electrons moved vertical tune of 150 GeV proton beam upward by as much as +0.005. At the same time, the system of electrons and protons showed strong instability which usually resulted in significant deterioration of the TEL vacuum (due to electron/ion bombardment of the vacuum chamber walls)

and reduction of the proton lifetime (due to fast emittance growth and scraping).

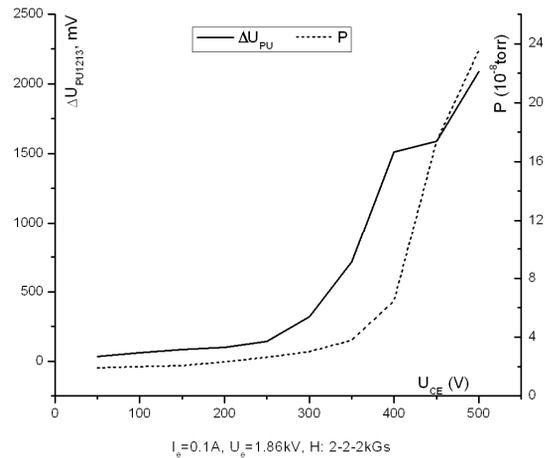


Figure 8: Peak amplitude of the PU4 signal after switch off of the trap voltage on PU7 vs. the trap voltage (solid line); vacuum pressure (dashed line).

To understand the phenomena beam studies have been started at the test bench which has similar configuration but operates with electron beam (rather than proton beam) which ionizes the vacuum and employs significantly smaller longitudinal magnetic field (up to 0.4T). The first studies had shown accumulation of negative space charge with confined electrodes set at negative voltage. The amount of charge depends on the voltages, the main electron beam current and magnetic field. Further studies at the test setup and in the TELs are needed to understand the dynamics of the multi-component plasma in the “electron columns”. Theoretical analysis is very much due, too.

ACKNOWLEDGMENTS

Authors are thankful to A. Shemyakin for numerous useful discussions and to G. Saewert and A. Netepenko for assistance in carrying out beam studies in the Tevatron and at the test facility.

REFERENCES

- [1] V. Shiltsev, PAC’07, Albuquerque, p. 1159 (2007); <http://www.JACoW.org>
- [2] V.Shiltsev et al., Proc. Advanced Accelerator Concept Workshop, AIP Proceedings 1086, p. 649 (2008).
- [3] V. Shiltsev et al., Phys Rev ST AB 11, 103501 (2008).
- [4] C.Crawford et al., PAC’99, New York, p. 237 (1999); <http://www.JACoW.org>