HIGH LUMINOSITY OPERATION, BEAM-BEAM EFFECTS AND THEIR COMPENSATION IN TEVATRON*

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Abstract

Over the past 2 years the Tevatron peak luminosity steadily progressed and reached the level of $3.15 \cdot 10^{32}$ cm^2 s^{-1} which exceeds the Run II Upgrade goal. We discuss the collider performance, illustrate limitations and understanding of beam-beam effects and present experimental results of compensation of the beam-beam effects by electron lenses - a technique of great interest for the LHC.

TEVATRON RUN II PERFORMANCE

Since the beginning of the Collider Run II [1] in 2001, the Tevatron has delivered over 4.2 fb^{-1} of integrated luminosity to both CDF and D0 experiments. The goal is to deliver between 5.8 fb^{-1} and 6.7 fb^{-1} to the experiments by the end of Run II which is currently scheduled for October 2009, or between 7.3 fb^{-1} and 8.8 fb^{-1} if an extra year of operation will be permitted (the spread reflects less and more optimistic projections). All major improvements which were part of the Run II Upgrade project [2] had been finished in 2006-2007. Since then, the performance of the complex continues to improve (see Fig.1): weekly integrated luminosity is up by some 25% (record of 56.1 pb^{-1}/wk compared to 46 pb^{-1}/wk in 2007), peak luminosity is up 8% (from $2.92 \cdot 10^{32}$ cm^{-2} s^{-1} in 2007), average antiproton production rate is up 15% (from $1.93 \cdot 10^{11}$/hr to $2.21 \cdot 10^{11}$/hr, with maximum hourly rate exceeding $2.7 \cdot 10^{11}$/hr).

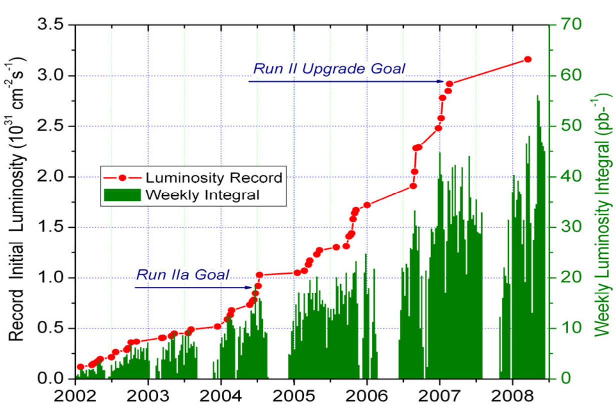

Figure 1: Tevatron peak and weekly integrated luminosity in 2002-2008.

The description of the Tevatron collider complex operation, main parameters and summary of progress prior to 2007 can be found in [1-4]. Below we outline recent and possible future improvements in various machines.

Antiprotons

Six accelerators are employed in production and collection of antiprotons for the Collider. Recent gains in the production rate came from: i) installation of two-turn notch filters in the Debuncher Ring's stochastic momentum cooling system; ii) "centering" of 2 kicker tanks and installation of new gain/phase equalizers in the Accumulator 2-4 GHz stack-tail stochastic cooling system which does momentum stacking; iii) automatisation of regular (every ~2 hrs) antiproton stack transfers from Accumulator to Recycler which now take <2 minutes compared to 20-30 min in 2007. The Recycler ring is the only source of antiprotons for the Tevatron and after recent upgrade of the transverse feedback system (bandwidth of the resistive wall instability damper increased from 35 MHz to 70 MHz) it is capable of accumulating more than $4.5 \cdot 10^{12}$ antiprotons. Operational tune-up of the 4.5 MeV 0.1A electron cooling system has led to a faster longitudinal cooling and smaller equilibrium transverse emittance which is currently ~0.3 π μm rms (about 0.1 π μm improvement compared to 2007). Change of the Recycler working point (betatron tunes) and optimization of the 2-4 GHz transverse stochastic cooling system resulted in improvement of the beam lifetime to ~600 hours. As a result of improvements, almost 98% of the stored antiprotons can now be sent to the Tevatron, compared to 92% a year ago. Following experiment's demand, an adaptive feed-forward barrier-bucket RF waveform correction system has been developed to equalize extracted bunch intensities to better than 10% [5].

Protons

Parameters of the proton bunches delivered to the Tevatron from Main Injector and Booster have been quite stable recently - some (260-270) 10^9/bunch with 2.5-3 π μm rms transverse emittance. Recent major improvements in these machines were made during the 2007 shutdown to prepare for a higher proton flux operation for 8 GeV and 120 neutrino experiments. E.g. the rapid cycling 8GeV Booster synchrotron has been equipped with stronger and faster multipole magnets (dipole, quadrupole and sextupoles – with slew rates 2-10 times the old ones) – yet only ¼ of all the required correctors were installed during 2007 shutdown. An injection orbit bump system was upgraded to run at 15 Hz.

The "11-batch" slip-staking technique is now operational in Main Injector [6] and pushed the proton power on NuMI experiment fixed target to 350 kW at 120 GeV (operation is parallel to proton delivery for the Collider and antiproton production). A new, two-stage collimation system – with two 0.25 mm W primary and 4

*Work supported by the US DoE contract No. DE-AC02-07CH11359
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1.1 m long 20 tons steel secondary collimators - was installed during the 2007 shutdown and is now operational with collimation efficiency >90%. The collimators can each scrape about 600 Watts of un-captured beam power left over from the high-intensity slip-stacking and this is essential for going up to 400 kW operation. [7].

Collider and Operation Strategy

Beam-beam interactions between two beams are the major source of the Tevatron inefficiencies [8] which currently account for ~20-30% of integrated luminosity loss. They are discussed below and also presented in more detail (including modelling results) in [9]. The most notable improvements in the Tevatron include commissioning of the 2nd order chromaticity correction circuits [10] which eliminated momentum dependence of beta-functions in IPs and improved luminosity lifetime; and low beta optics correction in February 2008 which allowed equalization of CDF and D0 luminosities to 1-3% level (7-10% previously); to get rid of 6 cm dispersion at the D0 IP and to re-establish minimum beta-functions at the values of β^*=29 cm (were as large as 32 cm before). Stabilization of the Tevatron orbits in and between the stores has greatly improved repeatability of shot setups.

Tremendous effort from the Run II operations team has been put into making operations more reliable (e.g., preventive maintenance), assure quick recovery from small and big failures (there were 4 in FY08 which took the complex down for several days each time, including 10 days no-luminosity period in December 2007 to replace a failed SC dipole magnet in the A4 sector. Speeding up mechanics the mechanics of beam transfers, injection, energy ramp, low-beta squeeze and scraping have reduced the HEP shot setup time from 2.5 hrs in 2007 to about 1 hr 45 min now. As the result of numerous operational improvements, an average time in collisions is approaching 100 hours/week.

To conclude the Collider performance section, one can list possible improvements which altogether can increase weekly luminosity to the level of 60-70 pb^{-1} per week before the end of the Run II: i) commissioning of individual band equalizers in the stochastic momentum cooling system of the Debuncher and the Accumulator transverse cooling system; ii) completion of installation of fast corrector magnets in the Booster together with commissioning of transverse and longitudinal dampers to keep beam stable while crossing transition energy; iii) increase of the proton brightness by scraping 8 GeV protons in the Main Injector by recently installed collimators; iv) further optimization of the operation strategy – e.g. increase of the average Recycler antiproton stash size for the Tevatron shots or/and variation of the store length; v) better focusing optics matching during injection in the Tevatron; vi) faster loading of protons into the Tevatron by injecting them in batches (of 2); vii) making the beam-beam compensation (BBC) by the Tevatron Electron Lenses (TEL) operational.

BEAM-BEAM EFFECTS

Beam-beam effects in the Tevatron Run II are a complex mix of head-on and long-range effects [8]. Over the years, the Tevatron beam-beam parameter, the tune shift $\xi=2Nr_p/4\pi\varepsilon_n$, has grown to record high – for hadron colliders - values: i) in the Collider Run Ia (6x6 bunches, 12 head-on collisions) it was ξ_a=0.025 (about 0.002 per IP) and ξ_p=0.018 (about 0.0015 per IP) [11]; ii) then, in the Run Ib (6x6 bunches, 2 head-on collisions and 10 parasitic ones), ξ_a=0.018 (about 0.009 per IP) and ξ_p=0.011 (about 0.005 per IP) were achieved [12]; iii) early in the Run II (2001-2005, 36x36 bunches, 2 head-on collisions [8]) they were ξ_a=0.020 (about 0.010 per IP) and ξ_p =0.004 (about 0.002 per IP).

Currently (mid-2008), the range of store-to-store variations is ξ_a=0.020-0.024 (i.e. 0.010-0.012 per IP), ξ_p =0.018-0.024 (i.e. 0.009-0.012 per IP) [13]. Notably, the parameters are about the same for protons and antiprotons. In addition to the overall tune shift, the long-range collisions result in significant bunch-by-bunch tune spread of about dQ_a=0.006 and dQ_p =0.003 [8].

Head-On Beam-Beam Effects

Head-on collisions at two main IPs (B0 and D0) result in either blowups of the protons and antiprotons (so called "scallops" [8]), excessive losses or both. Usual treatment of the "scallop" effect is to keep betatron tunes of both beams below (but as close as possible) 5th order resonance lines of $Q_{x,y}$=0.6. The available tune space between 7/12th and 3/5th resonances is only ΔQ=0.017 that is less proton tune tunespread $\delta Q\sim\xi_p$ =0.018-0.024.

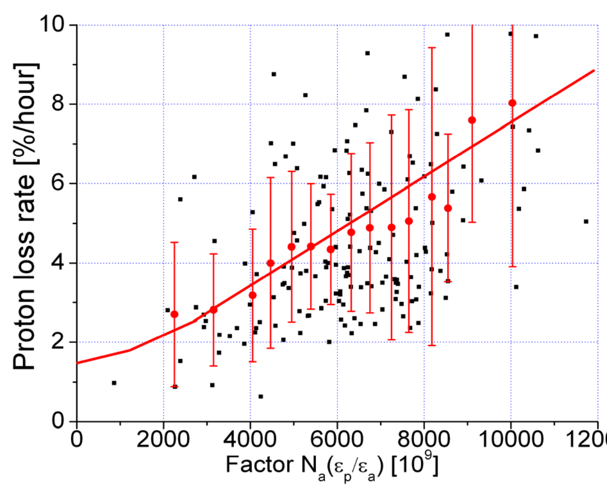

Figure 2: Proton-bunch intensity loss rates at the beginning of the Tevatron stores (FY08) vs factor *F*.

As a result, the 12th order resonances lead to high proton losses, dominating any other source of the loss in the Collider. Fig.2 demonstrates that the loss rate (%/hour averaged over the first 2 hours in the HEP stores) of protons grows with increase of the product of antiproton intensity and ratio of proton and antiproton emittances

$F=N_a(\varepsilon_p/\varepsilon_a)$. Due to significantly smaller emittance ($\varepsilon_a \sim\varepsilon_p/3$), antiprotons' tunespread is much less than ξ_a and antiproton losses are negligible with a proper choice of antiproton working point. High proton losses became intolerable for the machine and detector operation early in the FY08 run when antiproton emittances in the Tevatron dropped to record low values of about ε_a ~0.8πμm rms (due to improvements in the pbar cooling in the Recycler and reduction of emittance growth on several injections along the accelerator chain). To reduce the losses, a special source of transverse noise (called "Pbar Jacker") was introduced into operation which is turned on right after beams reach 980 GeV, before collisions initiated, and blows the antiproton emittance to acceptable level of ε_a~1.2πμm rms (compare with ε_p~3πμm rms).

Long-Range Beam-Beam Effects

The proton losses are especially high at the beginning of HEP stores where the positive proton tune shift due to focusing by antiprotons at the main IPs is the strongest. Due to numerous long-range interactions of the two beams (they share Tevatron vacuum pipe) the losses greatly differ from bunch to bunch – the effect which can not be corrected by choice of the proton working point or by the "Pbar Jacker".

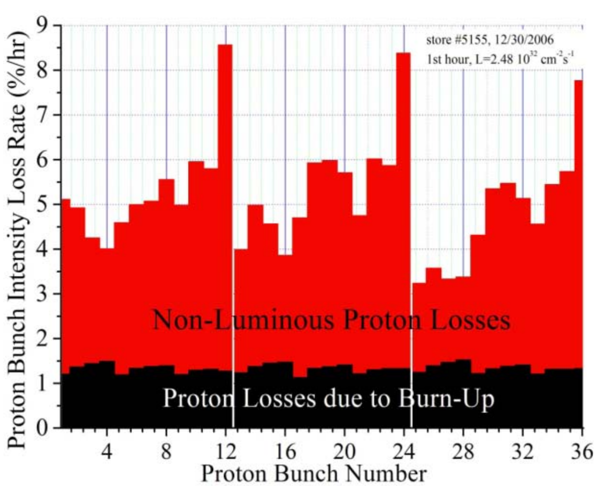

Figure 3: Proton-bunch intensity loss rates at the beginning of the Tevatron store #5155, Dec. 30, 2006, with initial luminosity $2.5\cdot10^{32}$ cm^{-2} s^{-1}.

Fig. 3 shows a typical distribution of proton loss rates at the beginning of an HEP store. In the Tevatron, 36 bunches in each beam are arranged in 3 trains of 12 bunches separated by 2.6 μs long abort gaps. Proton bunches #12, 24, and 36 at the end of each bunch train typically lose about 9% of their intensity per hour while other bunches lose only (4-6)% /hr. These losses are a very significant part of the total luminosity decay rate of about 20% per hour (again, at the beginning of the high luminosity stores). The losses due to luminosity burnup are much smaller (1.1–1.5%/hr). Fig.3 shows large bunch-to-bunch variations in the beam-beam induced proton losses within each bunch train but similar rates for equivalent bunches, e.g. #12, 24, and 36.

BBC BY TEVATRON ELECTRON LENS

Electron lenses were proposed for compensation of both long-range and head-on beam-beam effects in the Tevatron collider [14]. The lens employs a low energy $\beta_e=v/c <<1$ beam of electrons which collides with the high-energy bunches over ~2 m of length. The electron-beam current can easily be adjusted between each of the bunches, equalizing the bunch-to-bunch differences (e.g. in tunes or in lifetime [15]). Two Tevatron Electron Lenses (TELs) have been built and installed in two different locations of the Tevatron ring, A11 and F48. The high-energy protons are focused by the TEL and experience a positive betatron tune shift as big as dQ_p = 0.003-0.009 though significant BBC effect does not typically require more than dQ_p=0.0015 induced by 0.6A of the current in a 2 m long 5 kV electron beam [16].

To achieve a significant improvement of the proton lifetime, we set ~4 mm diameter electron beam (with smooth transverse edges) on the proton orbit with <0.2 mm accuracy and generate ~0.6 μs pulse of electron current pulsed on the proton bunch of interest. Other bunches are left not affected.

The last proton bunches in each train typically have the lowest vertical tune, while the first ones exhibit the lowest horizontal tune. Fig.4 shows what happens when TEL2, being the vertical beam-beam compensation device, is set to affect the proton bunch #12 (P12).

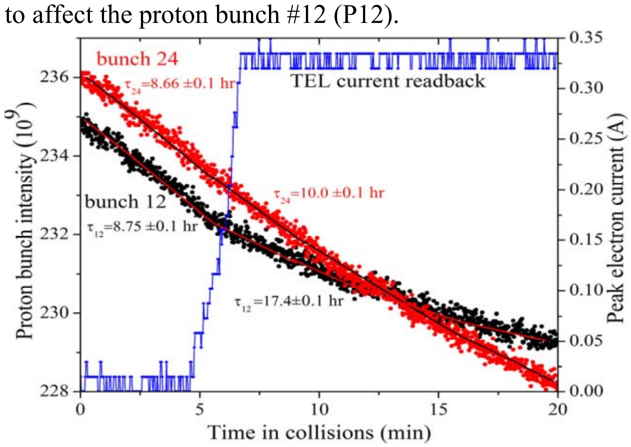

Figure 4: Effect of TEL2 on proton intensity decay.

As soon as TEL2 electron current is turned on a significant change of slope of P12 intensity decay was observed. This change corresponds to a lifetime improvement of about 100%. This result has been confirmed in several beam studies. Such an effect can be explained by a positive tune shift of about 0.0014 introduced by the TEL2. However, it is not yet clear whether the tuneshift is the only mechanism responsible for the significant lifetime improvement because, for example, the TEL2 operation resulted in bunch #12 having one of the lowest loss rates among all bunches [16], while its tune – even after being shifted up by TEL – was still lower than for other bunches.

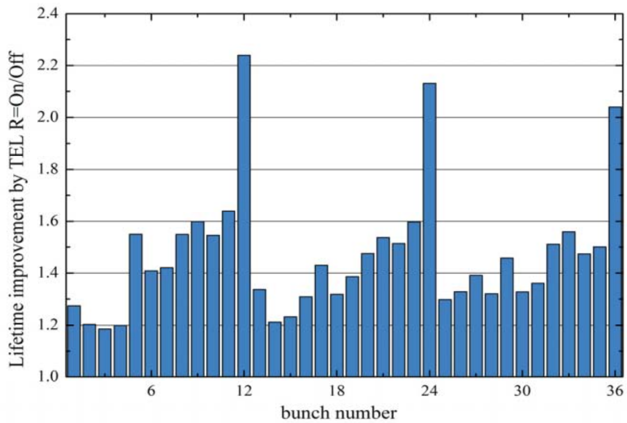

Figure 5: Proton bunch lifetime improvements due to the DC beam in TEL-2 J=0.3A early in store #5183.

In another very high luminosity Tevatron store #5183, we operated TEL-2 in DC regime with J_e=0.3A – thus, providing the same effect on all proton bunches in the beam – and has been regularly turned off and on. When the TEL-2 was turned on at the very beginning of the store, it improved the intensity lifetime of bunches P12, P24 and P36 by as much as R=2.2 times. As expected, other bunches experienced smaller improvements, but the fact that R>1 for all of them is noteworthy. Turning TEL off and on for some 20 min has showed that improvement due to BBC lasts for 8-10 hours into the store. Remarkably, in a separate beam studies we introduced a detectable emittance growth due to electron current fluctuations, but still observed a similar-scale proton lifetime improvement.

In a normal running condition, the fluctuations are small (<1% at low frequencies and <0.1% at high frequencies), the emittance growth is not detectable, and electron lens causes not only a significant reduction of the proton intensity loss rates, but improvements of the luminosity lifetime τ_L=$L/(dL/dt)$ as well – e.g. by about 10% at the beginning of the store [16].

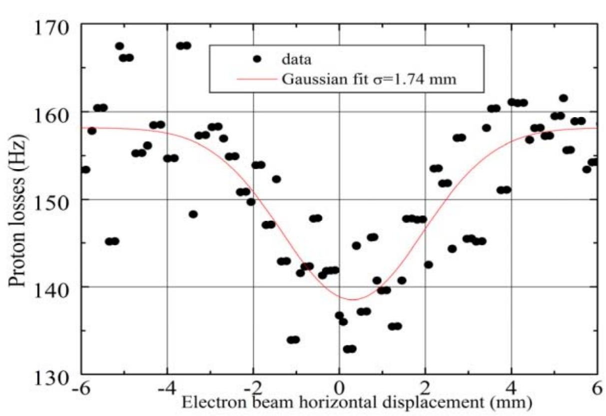

Figure 6: Dependence of proton bunch #13 losses on horizontal position of TEL-1 electron beam.

Comparable improvement of the proton intensity lifetime (up to 40%) has been observed in experiments performed with TEL-1. The only design difference between the two lenses is that the TEL-1 bending section has a 90 degree angle between the gun solenoid and the main solenoid while this angle is about 57 degrees for TEL-2. TEL-1 is installed in a location with large horizontal beta-function and mostly shifts horizontal proton tune up. As the proton horizontal tunes are lower by $\Delta Q_x \approx (0.002\text{-}0.003)$ for the bunches at the beginning of the bunch trains, P1, P13, and P25 [8], the TEL-1 effect is the largest for them. The reduction of the global proton loss rates due to the TELs can easily be seen by the local halo loss rate detectors installed in the D0 and CDF detectors, which can measure the losses on a bunch-by-bunch basis. These halo loss rates are proportional to (dN_p/dt). Figure 26 shows the dependence of D0 proton loss rate on the TEL-1 electron beam position. In this experiment, the loss rate of P13 dropped by about 20% once a 0.6A electron beam is set on the proton orbit. The effect vanishes if the electron beam is displaced from the proton orbit by more than 4 mm.

The numerical simulations [17] have reproduced the observed 2-fold increase of the proton lifetime with the TELs. The weak-strong multiparticle LIFETRAC code makes full advantage of the current knowledge of the Tevatron optics by using the measured beta-functions and helical orbits in order to compute the transfer maps for tracking particles between the IPs and to calculate the beam-beam kick. The code has been extensively used to study beam-beam effects in the Tevatron [18].

The next step of the BBC program is to incorporate the Tevatron Electron Lenses into the routine operation of the Tevatron collider. That awaits completion of the high repetition rate HV pulser development [19]. The new pulser will allow the TEL operation with more than one proton bunch (ideally, with up to 36).

BEAM-BEAM COMPENSATION IN LHC, OTHER APPLICATION

The versatility of the electron lenses allows their use for many other purposes. In the Tevatron, one of the TELs is in routine use for the removal of unwanted DC beam particles leaking out of RF buckets into abort gaps between the bunch trains [20].

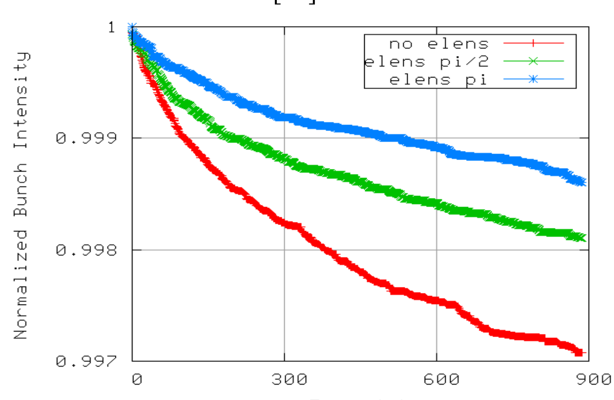

Figure 7: LHC lifetime improvements by electron lens at ξ_p/IP=0.0075 (from Ref. [23], courtesy of A.Valishev)

Head-on BBC with electron lenses has been proposed for the LHC luminosity upgrade [21]. E.g. only 2.4 A of DC current with Gaussian transverse distribution matching the proton is required in the electron lens to compensate head-on effects at twice the LHC nominal bunch intensities. In combination with current carrying wires for long-range beam-beam compensation, the electron lenses will allow reaching higher collider luminosities without a significant increase of particle loss rates or emittance growth rates. Particle tracking with LIFETRAC shows that an electron lens can improve the LHC beam lifetime by factor of 1.6 to 2.2 (depending on the betatron phase advance between the IP and location of the lens) at twice the nominal bunch intensity – see Fig.7 – and by almost an order of magnitude at three times the intensity ξ_p/IP=0.01 [23].

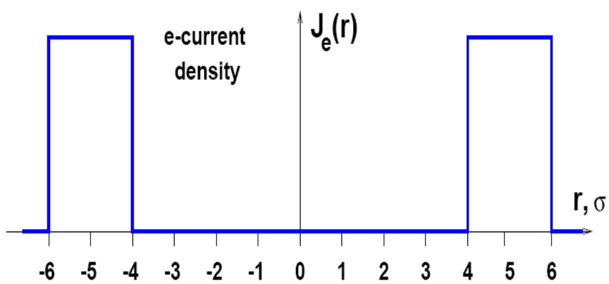

Figure 8: Hollow electron beam collimator for LHC.

An ideal round hollow electron beam – depicted in Fig.8 - can be used for particle collimation [24]. It has no electric or magnetic fields inside and has strongly nonlinear fields outside. The speed of diffusion of the large amplitude particles (protons or ions, in the case of LHC, which traverse the non-zero electric field region) can be greatly enhanced if the electron current varies in sync with betatron oscillations or at the nearest non-linear resonance line. Such a collimation system shows good efficiency in simulations [25], and has advantages compared to standard schemes as it can work for both ion and proton beams due to its purely electromagnetic nature (no nuclear interactions) and it allows to reduce the machine impedance either by replacing primary collimators or placing them farther away from the beams. Note that electron beam is "refreshable", no beam incident can damage it, contrary to metal or carbon collimators.

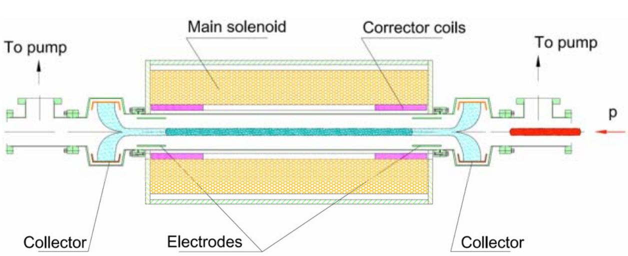

Figure 9: Electron column for space-charge compensation.

Electron lenses were also proposed for space-charge compensation (SCC) in high intensity proton synchrotrons [26]. Electron columns (EC) [27] were proposed to form electron charge distribution needed for the SCC by containing ionization electrons in a strong longitudinal magnetic field trap – see Fig.9. Strong solenoid field keeps freshly born electrons on the magnetic field lines (thus, the e-density follows the Gaussian one of the protons) and negative voltage on electrodes prevent longitudinal escape. Numerical simulations show that installation of 24 or 12 short ECs can effectively compensate emittance blow-up of Fermilab's Booster high intensity proton beam [28].

Author sincerely thankful to C.Gattuso, W.Pellico, V.Kamerdzhiev, J.Crawford, G.Kuznetsov, L.Vorobiev, K.Gollwitzer, R.Moore, A.Valishev, J.Annala, L.Prost, D.Broemmelsiek, A.Shemyakin, Yu.Alexahin, V.Kapin, J.P.Koutchouk, U.Dorda, W.Fischer, V.Papadimitriou, A.Kabel for their input and many useful discussions.

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