STATUS OF TEVATRON COLLIDER RUN II AND NOVEL TECHNOLOGIES FOR LUMINOSITY UPGRADES*

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Abstract

Over the past 2 years the Tevatron peak luminosity steadily progressed and reached the level of 85e30 cm-2s-1 which was the original Run IIa goal. Over 0.56fb-1 have being delivered to each CDF and D0 experiments since the beginning of the Run II. In parallel to the Collider operation, we have started a project of the luminosity upgrade which should lead to peak luminosities of about 270e30 and total integrated luminosity of 4.4-8.5 fb-1 through FY2009. In this paper we describe the status of the Tevatron Collider complex, essence of the upgrades and novel accelerator technologies to be employed.

STATUS OF RUN II AND UPGRADES

Fig.1 shows progress of the Tevatron peak luminosity since start of Run II on March 1, 2001. One can see that the Run IIa peak luminosity goal [1] for the collider without electron cooling in the Recycler Ring (RR) has been achieved in June 2004. The progress was a result of more than a dozen improvements in the injectors and the Tevatron itself, each giving a 5-25% performance boost. The improvements have often been introduced during regular shutdown periods (e.g., 10 weeks long one in Fall 2003).

Besides luminosity production, the Run II team has also been working on commissioning of the 8GeV Recycler ring which is critical for the future of Run II and installation, commissioning and beam running for two neutrino experiments, MiniBooNE and NuMI.

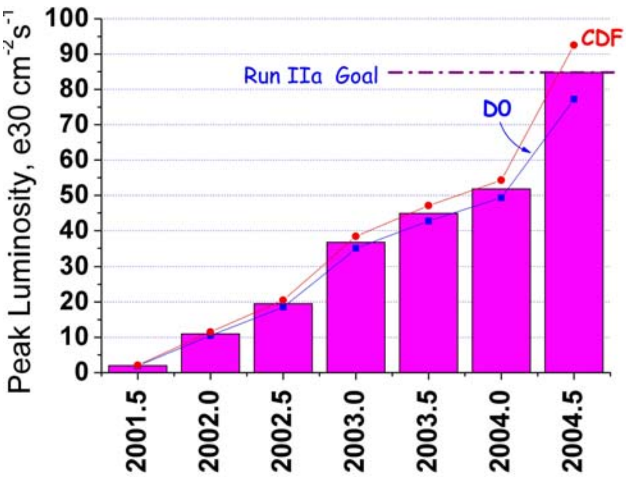

Fig.1: Tevatron luminosity progress in Run II

Since 2003, all future improvements were gathered under an umbrella of the Run II Luminosity Upgrade project. Major focus of the upgrade is 3-4 fold increase of number of antiprotons with help of the electron cooling in the 8 GeV Recycler Ring (RR). Comparison of the current Tevatron performance with the Upgrade goal is given in Table 1. The spread in the final integrated luminosity numbers from 4.4 to 8.5 fb-1 through FY2009 reflects “base” and “design” projections.

The mechanics of the Tevatron collider complex operation can be found elsewhere [2]. Below we describe recent improvements in various machines and upgrade plans.

Table 1: Tevatron Collider Parameters

Parameter	Present	Upgrade	units
Peak luminosity	85e30	270e30	$cm^{-2}\ s^{-1}$
Integrated luminosity	18	47	pb^{-1}/wk
Total $\int L\,dt$	0.56	4.4-8.8	fb^{-1}
Beam Energy	980	980	GeV
Number of bunches	36x36	36x36	
Protons/bunch	260e9	270e9	
Anti-Protons/bunch	34	127	
Proton emittance,95%	19	20	π μm
Pbar emittance, 95%	17	20	π μm
β^* at IP	35	35	cm
Hour-glass factor	0.68	0.65	
Pbar production rate	13.5e10	45e10	1/hr

Antiproton Source and Recycler

Recent improvement of the antiproton source include removal of Secondary Emission Monitors (SEMs) removed from antiproton transfer line AP3 and saved 1.5-2 π μm (or about 10%) in pbar emittance for HEP stores; stochastic cooling upgrade and installation of optical notch filter in the Debuncher ring together with core transverse cooling upgrade in the Accumulator (AA) led to some 20% improvement of the stacking rate at higher stacks >100e10 (now about 10e10/hr at 100e10). Greatly improved reliability of the Tevatron and the antiproton source itself (periods of continuous operations of AA without failures are as long as 2 months nowdays) allows longer stacking periods and higher pbar stack sizes available for record high luminosity operation of the Collider complex (maximum ever achieved 246e10 pbars). Fig.2 shows a typical stacking cycle of the AA which lasts about 30 hours. The Antiproton source

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upgrades are focused on i) increase of the antiproton collection efficiency from the Ni target – for that a 1000T/m Li lens has been prototyped and tested, and will be employed in 2005; ii) opening apertures in the transfer lines and Debuncher ring (during Fall'03 shutdown) and motorized quadrupole stands for beam-based alignment allowed to increase aperture of the AP2 line and the Debuncher from 19.5/11.8$\pi\mu$m to 17.9/24.3$\pi\mu$m, more

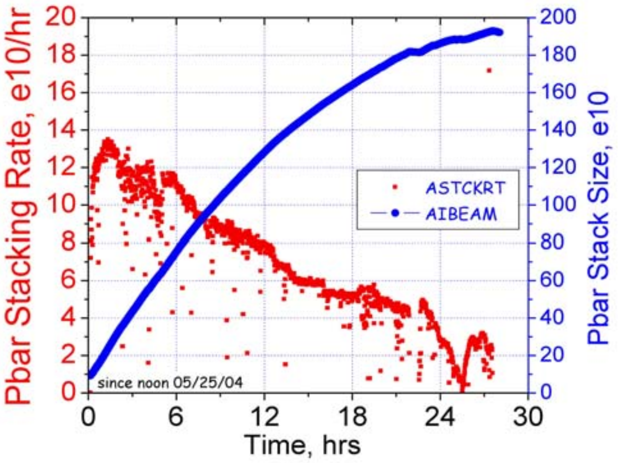

Fig.2: Typical cycle of Antiproton Accumulator operation

work scheduled in the Debuncher injection region during Fall'04 shutdown; and iii) cooling upgrade in the Debuncher and AA which should result in 3 fold increase of the zero-stack stacking rate. The AA function then will be to accumulate fast and do frequent transfers of antiprotons to the Recycler at the rate of 40e10/hr.

Both electron and stochastic cooling systems will be employed to make the Recycler Ring to be the second antiproton storage ring which will eventually deliver antiprotons for HEP stores. The stochastic cooling system [3] works in 0.5-2GHz band longitudinally and 2-4GHz transversely but its efficiency drops at larger stack sizes (at present, the maximum stack in the RR was 150e10 antiprotons, while the Run II Upgrade goal is 600e10). To prepare the RR for operation with the electron cooling, vacuum problems were fixed by ring-wide baking during the Fall'03 shutdown, average vacuum improved to 2e-10 Torr (vacuum beam lifetime is now about 500 hrs) and transverse emittance growth reduced from 10 $\pi\mu$m/hr to 3 $\pi\mu$m/hr that meets specs for the e-cooling in the RR. In 2003, about 200 RR BPM electronics cards have been upgraded and the beam position measurement accuracy improved to about 10 microns rms. Extensive beam studies needed to commission the RR for electron cooling required some 20% of the antiproton production timeline, but that paid off: efficiency of pbar transfer from AA too RR and from RR to the Main Injector (MI) now exceeds 90%, minimum longitudinal emittance of 60eVsec achieved without electron cooling (goal is 54eVs for 180e10), studies on instabilities have been performed. There were 3 shots into the Tevatron with luminosities up to 66e30 when antiprotons for HEP were taken either from the RR or from both RR and AA. More such "mixed shots" are planned in 2004. The electron cooling system will be installed in the RR during Fall'04 shutdown [4].

Proton Source and Main Injector

Performance of the rapid cycling 8GeV Booster synchrotron has been significantly improved recently and record intensity of 6e12 protons per pulse has been achieved (the Run II Handbook goal was 5e12 [1]). Beam losses limit the intensity because of the above ground radiation, damage and activation of equipment. In parallel to the Collider operation, Booster delivers protons to neutrino experiments MiniBooNe(running) and NuMI (2005) which will eventually require 9 times more protons than the Run II demand. A system of collimators, installed in 2003, reduces the tunnel activation by more than 50%. Modification of injection bump "dogleg" magnets, re-alignment, orbit control and installation of larger aperture elements at injection area also helped to reduce losses. Reliability issues with 200MHz Burle 7835 RF tubes and 800 MHz Varian VKP-7955 and Litton 5859 klystrons were of a concern at the end of 2003, but presently mostly solved as larger stock of spares has been built. Booster RF system will be upgraded in 2005-06 when larger aperture RF cavities will be designed,

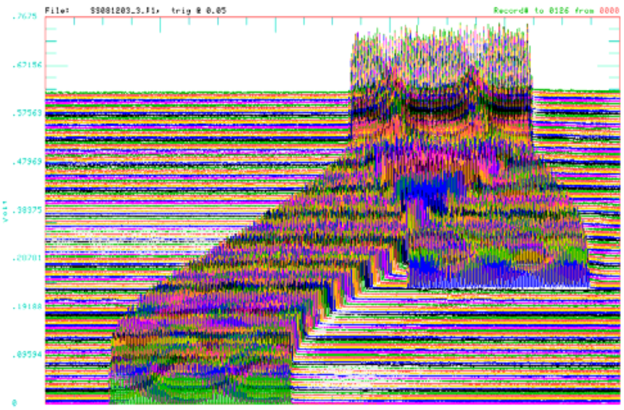

Fig.3: Slip-stacking of 6e12 protons in Main Injector

prototyped, installed and commissioned.

Over the past 1.5 years, there was significant progress with 150 GeV Main Injector: a) installation and commissioning of an longitudinal instability damper which is important for protons (now we don't need to blow up long emittance by 20-40% to be stable at transition), b) transverse damper to control resistive wall coupled bunch instability [5], c) beam loading compensation now works on the ramp and during coalescing and helps to reduce proton longitudinal emittance on the pbar production target by almost factor of 2; d) 2.5 MHz pbar transfers from AA to MI replaced 53 MHz transfers and now fewer 53 MHz pbar bunches are needed for coalescing resulting in 5% increase of the pbar coalescing efficiency. Further reduction of the longitudinal emittance of coalesced antiproton bunches extracted in the Tevatron is thought to be possible with 2.5MHz acceleration in MI to some intermediate energy. The most important Upgrade project in the MI is slip-stacking – a method to overlap two batches (bunch trains) injected at two different energies in the same ring, and, thus, to double proton bunch intensity directed onto pbar production target [6]. The slip-stacking studies are finished, the method works well and gives promising results with upto 6.5e12 protons per pulse so far – see Fig.3. The goal for the Upgrade is 8e12/pulse on target. More than 2 batch slip-stacking is also under consideration.

Tevatron

A number of recent Tevatron ring improvements paid

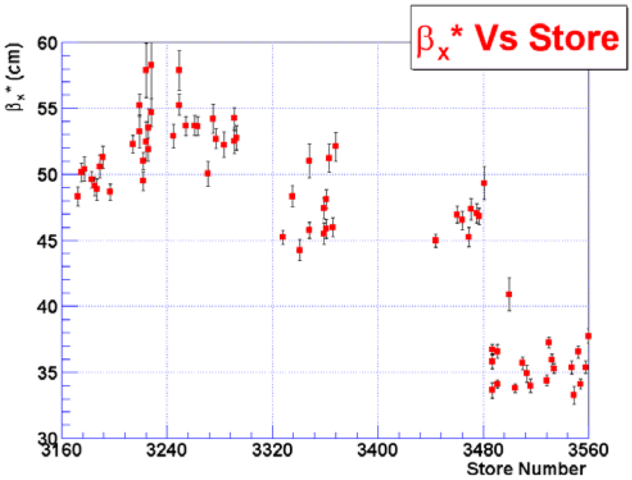

Fig.4: β* as fit parameter of D0 luminous region analysis in stores from Jan., 13 to June 5, 2004, co-urtesy of J.Estrada, A.Chandra (D0 collaboration)

off and determined 2.4-fold increase of peak luminosity in 2003-04. First, removal of C0 Lambertson magnets (Jan'03) and installation of thin conducting liners in F0 Lambertsons (Fall'03) reduced the transverse impedance of the ring from about 6MOhm/m to about 1MOhm/m. As the result, more than 20% increase of the proton bunch intensity has become possible without excitation of weak head-tail instability [7]. Then, the reduction of current in S6 sextupole feeddown circuit and implementation of a modified helical separation scheme on the ramp led to 10% improvement of the pbar transfer efficiency from 150 to 980 GeV. Comprehensive re-alignment of magnets and 0.1mm adjustment of vertical position of a cold-mass in 106 SC dipoles ("re-shimming"), pre-calculated rolls of 4 quadrupoles in the P1 proton injection line, optics correction at injection energy of 150GeV – all these measures allowed to reduce proton and pbar emittance dilution at injection (about 2-4 π μm and 1-2 π μm, correspondingly), open available aperture and reduce losses at 150 GeV and early on ramp. Together with desensitizing of the Tevatron RF power amplifiers to power glitches and replacement of all flaw design VFCs (voltage to frequency converter cards used in quench protection system) all that greatly improved reliability of the Tevatron which is now able to run 24-36 hours HEP stores, and availability to 120 and sometimes 140 hours per week - almost two times longer than in 2003 and before. As the result, the AA gets time to accumulate larger stacks of antiprotons. All that combined gave more than 35% increase in peak luminosity early in 2004. Finally, in April-May 2004 we have corrected beam optics in order to bring beta-functions at both IPs from 42-48 cm to the design value of 35 cm – see evolution of the observed β^* by D0 detector in Fig.4. That gave another 15-20% boost in peak luminosity. Luminous region analysis results provided off-line by both CDF and D0 detectors were very helpful for the β^* tuneup. In Decemeber 2003, in a response to the CDF collaboration request, we realigned B0 low-beta quadrupoles such that vertical beam position at the IP moved by 4.3mm down to the center of the CDF detector. As the result, the CDF b-tagging efficiency (equivalent to luminosity) increased by 20%.

Currently, the biggest operational issues for the Tevatron are the beam-beam effects, which are responsible for almost 10% pbar loss on the ramp and 10-20% reduction in luminosity lifetime and peak luminosity early in stores due to fast proton losses and pbar emittance blowup at collisions ("scallops", see in next Section). The upgrade projects to address these issues are: measurements and correction of chromaticity snap-back and other field harmonics variations on the Tevatron ramp, at injection energy and at flat top [8]; increase of helix separation by installation of additional HV separator modules, polarity switches and running at higher voltage; project of Beam-Beam Compensation (BBC) with Tevatron Electron Lenses (TELs, see below). The upgrade includes aggressive plan to improve Tevatron beam diagnostics: upgrade of the BPM electronics cards, installation of Ionization Profile Monitors in the Tevatron and Optical Transition Radiation Monitors in injection lines, development of Abort Gap Monitor, 1.7GHz Schottky detector [9], on-line hydrostatic level systems to detect motion of all low-beta quadrupoles and nearby arc quadrupoles; tunetracker, head-tail chromaticity monitor, upgrade of Beam Loss Monitors. Besides that, regular vacuum improvements and survey and re-alignment are anticipated.

TEVATRON ELECTRON LENS

The BBC in the Tevatron proton-antiproton collider assumes installation of two electron lenses with pulsed and variable currents to compensated bunch-by-bunch tune variation in antiproton beam [10]. In spring 2001 the first TEL had been installed in the Tevatron tunnel and commissioned (see Fig. 5). Detailed description of magnetic, vacuum and electron beam system of the TEL, its diagnostics and operation can be found in [11,12], see also references therein.

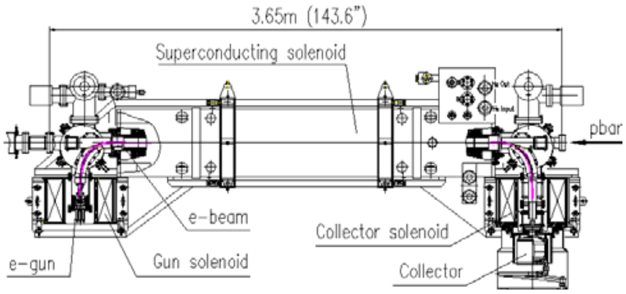

Figure 5: The first Tevatron Electron Lens

Project progress in 2001-2003

In the first series of beam studies in 2001-2002, we achieved tuneshifts for 980 GeV protons of about dQ=+0.008 with ~3 A of the electron beam current. The original 10kV electron gun generated constant current density distribution in 3.4 mm diameter beam over 2m long interaction region. The tuneshift dependence on electron current and energy, on electron beam position and timing is in a good agreement with theory [10]:

$$dQ_{x,y} = \mp \frac{\beta_{x,y}}{2\pi} \cdot \frac{1 \pm \beta_e}{\beta_e} \cdot \frac{J_e L_e r_p}{e \cdot c \cdot a_e^2 \cdot \gamma_p} \qquad (1)$$

In 2002 the TEL was found to very effective in cleaning DC beam which consists of particles slowly leaking from RF buckets at 980 GeV and circulating all around the ring unsynchronized with RF – see Fig.6. Since then, the TEL is being operationally used for the DC beam cleaning in every Tevatron HEP store [13].

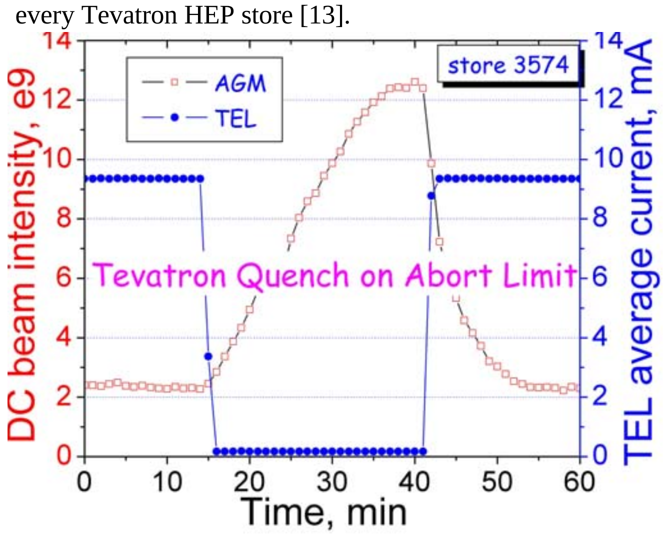

Fig.6: DC beam in abort gap with/without TEL

The proton lifetime in the first TEL experiments was not satisfactory - about 24 hours at the best. Later we proved that the limiting factor was nonlinear beam-beam effects due to sharp edges of the electron beam complicated by inaccurate electron beam alignment with respect to (anti)protons. This effect spurred the design of a new electron gun with Gaussian-shaped transverse current profile which was installed and good proton lifetimes exceeding 120 hours over broader area of Tevatron working points were demonstrated.

BBC: suppression of "scallops"

The very first evidence of successful BBC was suppression of vertical emittance growth of antiproton bunches tuneshifted by the TEL.

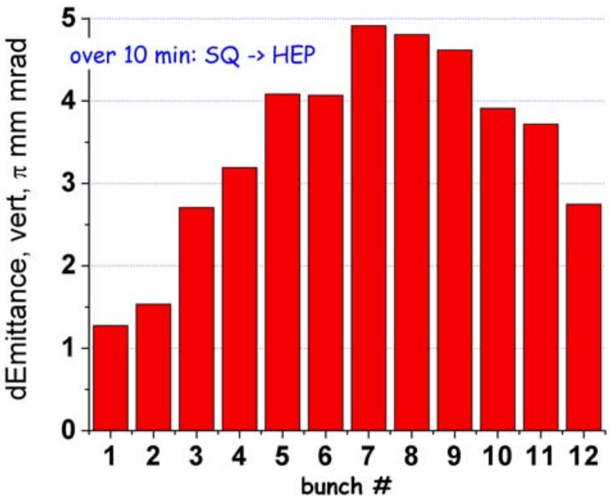

Fig.7: Emittance growth along pbar bunch train

The transverse antiproton emittance growth, after 980 GeV beams are brought to collision, is caused by beam-beam interaction and occurs in the Tevatron when proton bunch intensity exceeds 180e9 [14]. Figure 7 shows emittance growth rate of 12 antiproton bunches in the first 10 minutes in store #3231. Because of 3-fold symmetry of proton loading, the emittance growth rates are the same within 5-20% for corresponding bunches in different trains (e.g. for #1,13,25 or for #2,14,26, etc). One can see that blowup rates are smaller for bunches closer to the end or start of the train. After about 0.5-1 hour the blowup flattens out, and distribution of pbar emittances over different bunches looks like three "scallops". The effect is dependent on antiproton tunes— particularly how close one of them is to some important resonance. For a typical working point of Q_x=0.582, Q_y=0.590, 5th order (0.600), 7th order (0.5714) and 12th order (0.583) resonances play major role in the pbar beam dynamics. There was observed that vertical tune changes as small as -0.002 often resulted in a reduction of the amplitude of the "scallops." Smaller but still quite definite "scallops" were also seen in protons.

The TEL was used at the beginning of several HEP stores in attempt to reduce the "scallops." The TEL with about 0.6A of current was timed on a single pbar bunch at the beginning of the Tevatron stores and *we observed that the TEL can slow vertical emittance growth of the antiproton bunch it was timed on.*

Fig. 8 presents evolution of vertical rms sizes of three antiproton bunches #9, 21 and 33 over the first 34 minutes after "initiating collisions" in store #2540 (May 13, 2003). The TEL was acting only on bunch #33. The size has been measured with use of SyncLite Monitor. Corresponding emittance growth was 4.1 π mm mrad/hr for bunch #9, 2.2π mm mrad/hr and only 1.0 π mm mrad/hr for #33. At the beam parameters: current 0.6 A, energy 4.5kV, rms e-beam size 0.8 mm, interaction region length 2.05 m – expected maximum horizontal pbar tune shift was about -(0.003-0.004), vertical -0.001 (estimated). After 34 minutes the TEL was turned off, and emittances of all three bunches leveled.

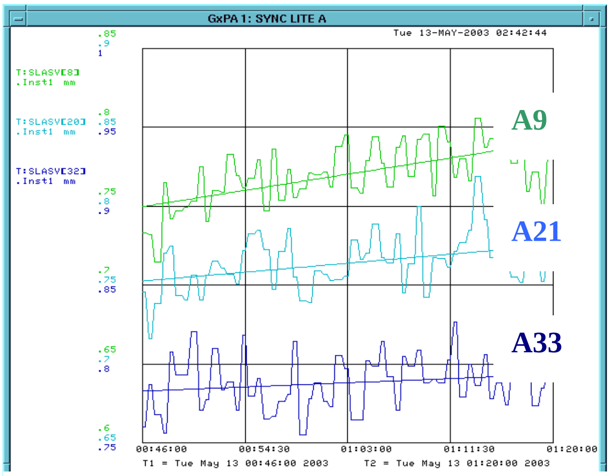

Fig.8: Vertical size of three pbar bunches in store 2540

There were six attempts to do the BBC at the beginning of the HEP stores. There were no "scallops" in three stores: #2445, #2490, and #2495, and though the TEL was acting on antiprotons, we observed no effect on emittance growth, as well as pbar losses and lifetime. After that was fixed, we had "scallops" and the TEL on bunch #33 in three stores and we suppressed the vertical emittance growth in #2540, effect was neutral in #2546, and somewhat negative (faster emittance growth) in #2549. Again, the effect of the TEL is obvious, though not well controlled as it can be negative as well as positive. The uncertainty is due to insufficiently precise centering of electron beam on antiprotons. Pbar orbit at F48 can migrate by up to 0.5 mm over a time scale of 12 hours and up to 1 mm over a scale of few days to a week. Alos, electrical centers of the TEL BPMs are dependent on the signal bandwidth, and the difference between short pbar pulse position and long electron pulse position can not be determined with accuracy better than 0.5-1.5 mm (though, resolution of the BPMs for any of the beams alone is about 30 microns). Such errors in positioning of σ=0.8 mm electron beam wrt σ=0.5 mm pbar bunch may result, for example, in significant variation of the TEL-induced tuneshift and even in changing sign of the tuneshift.

We plan to continue experimental studies of the Beam-Beam Compensation with the TEL at F48 which can be used not only for suppression of the "scallops" but also at the other stages of the Tevatron cycle (at injection energy, ramp, squeeze, during collisions). We may want to explore Beam-Beam Compensation for protons as well. We plan to improve the TEL BPMs and perfect bunch-by-bunch tune diagnostics with 1.7 GHz Schottky detector [9]. Fabrication of the second electron lens in collaboration of IHEP (Protvino) is underway and will be finished by the end of 2004. After extensive tests, the 2nd TEL will be installed in sector A11. We also plan to develop new 15kV HV modulator and a new electron gun combining flattop and smooth "Gaussian" tails.

SUMMARY

Number of improvements in the injectors and the collider itself led to the 4-fold Tevatron peak luminosity growth since Summer 2002 upto the original Run IIa goal (without Recycler) of 85e31 cm-2s-1. Total Run II integrated luminosity exceeded 0.56 fb-1 in each CDF and D0 detector. The cornerstone of the luminosity upgrade plan is the electron cooling in the Recycler ring supported by numerous improvements in other accelerators. The goals of the upgrade are peak luminosity of about 270e30 and total Run II luminosity integral of 4.4-8.5 fb-1 through FY2009.

The Beam-Beam Compensation with Tevatron Electron Lenses showed promising results but needs significant hardware and diagnostics upgrades and more beam studies before being helpful operationally.

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