Tevatron Status and Future Plans

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1. Collider Run I

Fermilab has just completed a very successful 1992-1996 Collider Run I which has led to the discovery of the top quark [1, 2] along with many other remarkable physics results. A typical luminosity of $2 \times 10^{31}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ was achieved with 7×10^{10} antiprotons in each of 6 bunches. The total integrated luminosity delivered to both the CDF and DØ collider detectors was about $150\,\mathrm{pb}^{-1}$ (see Fig. 1). The collider reliability was such that 72.6% (421 of 580) of the stores were ended intentionally. Table 1 lists the operational performance of the Collider at the end of Run-I, accompanied by operational goals for the complex following construction of the Main Injector and Recycler rings and a completion of the Tevatron33 project [3]. Typical luminosity at the beginning of a store translates to integrated luminosity with a 33% duty factor.

Fundamental limitations are related to the total head-on beam-beam tune shift seen by antiprotons ξ and to the total number of antiprotons in the collider that is a product of the number of bunches and the number of $\overline{p}$'s per bunch, $N_b \times N_{\overline{p}}$. The beam-beam tune shift that can be tolerated by the antiprotons is believed to be limited by the tune space available between resonances up to about tenth order. Approximately 0.024 has been achieved in the past. For a given total number of antiprotons the luminosity does not depend upon the number of bunches.

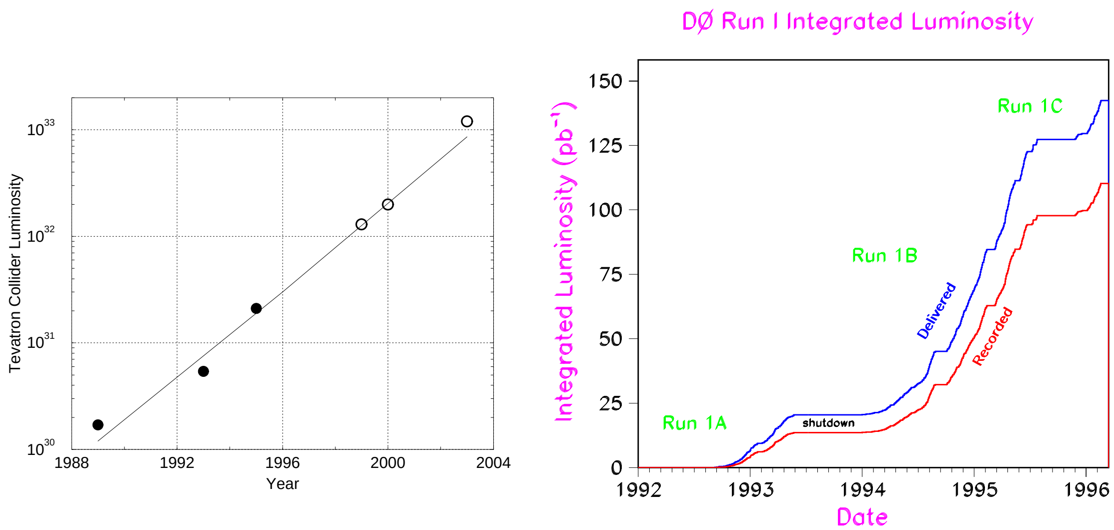

Figure 1: (a) Fermilab luminosity performance: actual 1988/89, 1990/91 and 1993/95 (solid symbols) and predicted MI through TeV33 (open symbols); (b) The Run-I delivered and recorded integrated luminosity in the DØ detector.

Table 1: Parameters of Fermilab Collider

Parameter	Run-IB	Run-II (MI)	RUN-II (MI+Recycler)	TeV33
Beam energy (TeV)	0.9	1.0	1.0	1.0
N_b	6	36	36	108
N_p, 10^{11} per bunch	2.3	2.7	2.7	2.7
$N_{\overline{p}}$, 10^{10} per bunch	5.5	3.0	7.0	variable
ϵ_p, π mm-mrad	23	20	20	20
$\epsilon_{\overline{p}}$, π mm-mrad	13	15	15	20
rms bunch length, m	0.60	0.43	0.38	0.18
β^*, m	0.35	0.35	0.35	0.35
θ_x=θ_y, μrad	0	0	0	$\pm$100
Bunch spacing, nsec	3500	396	396	132
Int/crossing	2.7	2.3	5.8	8.7
$\overline{p}$ tune shift	0.015	0.020	0.022	0.022
$\mathcal{L}$, cm^{-2} s^{-1}	2.1×10^{31}	8.1×10^{31}	2.0×10^{32}	1.2×10^{33}
$\mathcal{L}$, pb^{-1} week^{-1}	4.2	16.3	41.0	246

The Collider performance at the end of Run-IB represents a significant increase relative to the previous collider runs (1988-89 and 1992-93) and is attributable to completion of the linac energy upgrade from 200 MeV to 400 MeV, the Main Ring bunch coalescing system upgrade (higher voltage cavities) and other improvements within the complex. The linac upgrade has led directly to increased proton bunch intensity delivered from the Booster and through the Main Ring. The direct results have been more intense proton bunches 2.32×10^{11} *vs* 1.2×10^{11} in collision and a significant increase in the number of protons targeted for antiproton production 3.3×10^{12} *vs* 2.0×10^{12} every 2.4 seconds. Work done on transfer cogging also improved the proton intensity. The increase in targeted protons, improved $\overline{p}$ yield and imroved by a factor of three stacking rate have supported an increase in the antiproton production rate (from about $4\times10^{10}\,\overline{p}$/hr to about $6\times10^{10}\,\overline{p}$/hr) and an increase in the size of antiproton bunches in collision (5.5×10^{10} *vs* 3.1×10^{10}).

Some luminosity was lost in the run due to the fact that one of the low-β triplet quadrupoles at CDF was inadvertently rolled by 7 mrad. This resulted in a reduction in the luminosity by about a factor of two at CDF and lesser amount at DØ. Once this error was corrected, the peak luminosity reached $\sim 2\times10^{31}$ cm^{-2} s^{-1}, i. e. about a factor of two higher compared to the best peak luminosity of Run-IA (1992-93).

With the number of bunches N_b=6 in Run-I there were twelve potential proton-antiproton collision points in the Tevatron. Ten of these were avoided through the utilization of electrostatic separators. As a result the currently achieved antiproton tune shift, 0.015, is somewhat below the 0.024 achieved prior to the implementation of separators. This means that collider performance is not currently limited by beam-beam effect, but rather by our ability to preserve emittances and coalesce high intensity bunches. One expects that increases of 50% or so in N_p/ϵ_p are possible before beam-beam limitations set in. Long range beam-beam effects were not significant during Collider Run-I operation.

Antiproton availability currently, and through the foreseeable future, represents the primary impediment to increased luminosity. As Fig 2(a) shows the luminosity in the Tevatron is still proportional to the total antiproton intensity. The total number of an-

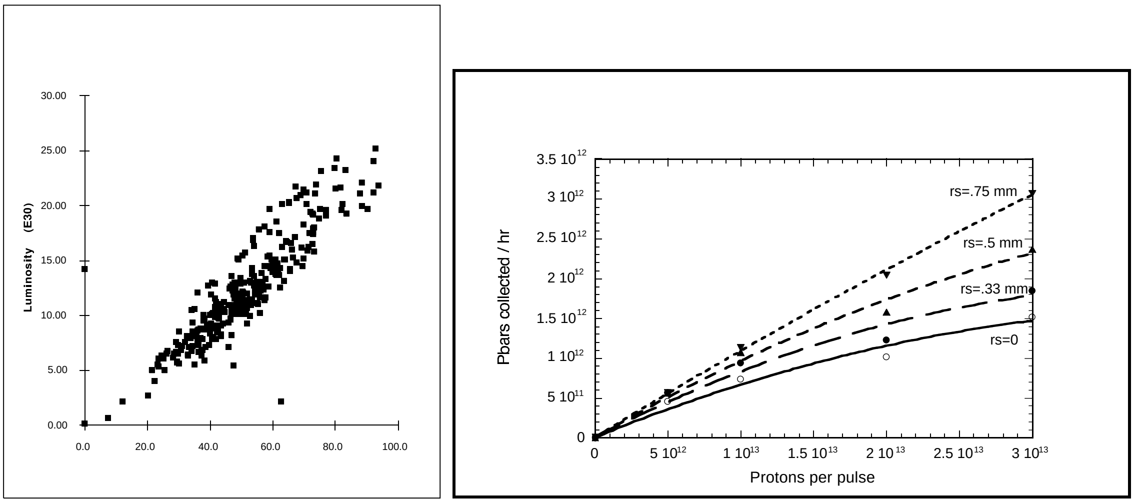

Figure 2: (a) Tevatron luminosity *vs* antiproton intensity in $10^9\,\overline{p}$/bunch; (b) Number of $\overline{p}$'s collected in debuncher without sweeping system (currently) and for several sweep radii assuming upgraded antiproton source parameters.

tiprotons in the Collider is determined by the product of the antiproton production rate, the typical store duration, and the transmission efficiency from the Antiproton Accumulator to low-β in the Tevatron. Typical store lengths of 11 hours, an average stacking rate of $5{\times}10^{10}\,\overline{p}$/hr, and an antiproton transmission efficiency of 70% led to the current average availability of antiprotons. Increase of this quantity via improvements of the antiproton source (Fig. 2(b)) is one of the main task in the future upgrades (see below).

2. Fixed Target Run

The beam energy for the current fixed target run, begun in May 1996, is 800 GeV. The intensity goal is $3{\times}10^{13}$ protons per pulse, with reliable delivery of $2.5{\times}10^{13}$. The intensity of 2.0×10^{13} is achieved in the mid-October of 1996. The slow resonant extraction spill length is 20 seconds with a Tevatron cycle time of about 60 seconds. Some of the beam is resonantly extracted in a fast mode which takes the beam out in about 1 msec. Several of these fast pulses are interspersed in the slow spill.

The intensity goal is ambitious but probably not unattainable. The previous best intensity was 1.8×10^{13} ppp, with reliable delivery of 1.5×10^{13} protons per pulse. Beam instabilities in the Tevatron, if not controlled, will limit the intensity. Longitudinal and transverse coupled bunch dipole mode instabilities are typically observed at intensities of 1.0×10^{13} or more. These instabilities have been suppressed by bunch spreading and active feedback (beam dampers). The suppression of instabilities is still an area of active development.

The fixed target beam operation is alternated with the civil construction for the new 8 GeV beam transfer line between the Booster and the Main Injector. The Booster operated at nights and weekends when the construction work was paused. Startup proceeded smoothly for the most part. One unusual feature of the startup was to run 150 GeV beam to the E815 target train to help align it. For this special mode, beam was extracted from the Main Ring, injected into the Tevatron and extracted to the Switchyard after passing through only 2/3 of the Tevatron.

It is intended to operate this fixed target run for a total of 13 months before the shutdown scheduled for February 1998 to the complete the Main Injector. This fixed target run represents the end of an era which started in 1983 with the first extracted beam from the Tevatron.

3. Collider Run-II

To meet the goals of the Fermilab high energy physics research program through the 1990's and into the twenty first century, a phased upgrade of the Fermilab accelerator complex has commenced. The goals established for the upgrade are to provide at least a factor of 100 increase in luminosity over the original $1\times10^{30}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ design goal of the Tevatron collider, accompanied by a threefold increase over the original 2×10^{13} goal for Tevatron fixed target beams. The first phase of the upgrade program is now complete. The second phase of the upgrade program involves the replacement of the existing Main Ring with a new accelerator, the Main Injector (MI) to provide Collider Run-II parameters listed in Table 1. The Main Injector (a large aperture, rapid cycling proton synchrotron designed specifically to address the fundamental limitations inherent in the present Main Ring) is designed also to provide a slow (or fast) resonantly extracted 120 GeV beam containing 3×10^{13} protons with a 2.9 (or 1.9) second cycle time. Current planning now also envisions the integration into the complex of a new antiproton accumulator ring, the Recycler. The construction and operation of such a ring could reasonably be expected to yield a luminosity of $2\times10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ based on enhanced antiproton production, storage, and recovery capabilities.

The plan is to finish the Main Injector in March 1999, and collide beams at 2 TeV in the center of mass shortly thereafter. The goal is to deliver $2\,\mathrm{fb}^{-1}$ on tape to each of the CDF and DØ detectors. It will start with 36 bunches per beam with a minimum spacing of 392 nsec, and may finish with as many as 108 bunches per beam with a minimum spacing of 132 nsec. The Main Injector project is progressing very well. By October 1996:

- *Magnets:* 237 of 344 dipole magnets are complete; 80 of 80 new quadrupoles are complete; 45 of 45 8 GeV permanent magnet dipoles are assembled; production of special magnets started.
- *Other components:* LCW installation into the tunnel is 95% complete; 185 dipole magnets are installed; prototype RF station operational in the Main Ring for more than two years.
- *Civil construction:* the ring enclosure is complete; service building construction is 60% complete; 8 GeV transfer line is complete.

Two basic strategies are followed to achieve the Run-II performance goals: 1) select a proton density that produces an antiproton beam-beam tune shift near to the maximum believed achievable; and 2) accumulate and deliver to the Tevatron the maximum number of antiprotons that can be provided, either through direct production or through recovery at the end of collider stores. The β^* at the interaction point is assumed to remain at the present value of 35 cm. Reduction to 25 cm could produce an increase up to about 30% in luminosity but is not considered now. The bunch length shown in Table 1 is based on a possible achievement of a longitudinal emittance of 0.5 eV-sec in both the proton and antiproton beams. This would represent a significant reduction as compared to the currently achieved ~ 5 eV-sec and is a consequence of longitudinal cooling of both the proton and antiproton beams utilizing the electron cooling in the Recycler ring. The RF upgrade is an alternative as well as a possible operation with a longitudinal emittance of 2 eV-sec.

The goal for Run-II is 1 TeV per beam. During a study period in Collider Run-I, a proton beam was stored at 980 GeV. During the fixed target startup (taking advantage of the periods when beam operation was prevented due to the civil construction) the upper limit of the Tevatron energy was pursued. Further improvements in energy are expected as inadequately performing magnets are identified and either replaced or swapped with other magnets. Because the total cooling capacity is limited, it is desirable to operate some cryogenic loops colder than others to favor weaker magnets. The swapping technique takes optimum advantage of temperature differences in the various cryogenics loops. These differences are due to deliberately running various cryogenic loops colder than others, or due to the temperature profile within a cryogenic loop. Superconducting magnets perform at a higher current when they are colder. If all these are successful, one may achieve 1 TeV per beam.

In order to provide for increase in the antiproton stacking rate several improvements are planned for the Antiproton Source. A beam sweeping system will be built so that the antiproton production target can handle the higher protons intensities from the Main Injector (see results in Fig. 2(b)). The Debuncher (which is the first stage of stochastic cooling will have a cycle time commensurate with the Main Injector) will have an upgrade which includes further cryogenic cooling of the electronics and which provides for pick-ups and kickers with gaps which dynamically vary with the transverse beam size. The Accumulator will have an upgrade to the stacktail system and its lattice.

In Run-I more than half of the antiprotons remained at the end of collider stores and they were simply dumped. An idea for recovering these antiprotons has lead to the concept of a ring to recycle a large fraction of these antiprotons. The Recycler is an 8 GeV antiproton storage ring to be installed above the Main Injector in the same 3.3 km circumference tunnel. Since the beam enclosure is designed for 150 GeV, it is possible to use low field magnets for an 8 GeV ring. Since it is also a storage ring, it is possible to use permanent magnets. This ring will allow for the recovery of antiprotons from the Tevatron, and it is expected that this will gain a factor of 2 to 2.5 in the luminosity. It is intended to install the Recycler at the same time as the Main Injector. Initial implementation is based on the proven technology of stochastic cooling. It is expected to replace it or augment it with electron cooling when the R&D has proven out on this newer technology.

4. Tevatron33

The goal of the TeV33 project is to develop a plan for the Fermilab Tevatron Collider beyond the year 2000 when the Main Injector project will be finished and collider Run-II is expected to be well underway. The assumed goal is 30 fb^{-1} of $p\overline{p}$ collisions at 2 TeV in the center of mass system by the year 2006. The major considerations in the project are [3]:

1. The antiproton production rate must be improved by about a factor of 5.
2. The antiproton cooling must be improved to accommodate the increased flux. The current plan is to use 4-8 GHz stochastic cooling in the existing Debuncher and Accumulator Rings, and electron cooling in the Recycler Ring.
3. The existing detector technology (with modest upgrades) must be capable of analyzing the collisions for rare processes. The important considerations for the accelerator are:
   - limiting number of interactions per crossing to a sufficiently small value by using roughly 100 bunches in the Tevatron;
   - reducing the peak luminosity (luminosity leveling) to further reduce the number of interactions per crossing;
   - maintaining low backgrounds from beam lost from mechanisms other than beam-beam interactions.
4. It is necessary to keep the proton and antiproton beams well separated in the Tevatron except at the desired collision points. Obtaining adequate separation becomes increasingly difficult as the number of bunches is increased to 100 or more bunches.

The TeV33 performance goals are listed in Table 1. Slip stacking, increased antiproton accepatance via improved 9 T lithium lenses and increased from 17π to 32π mm-mrad acceptance of the the AP2 beam line and the Debuncher and beam sweeping on the target will allow to dramatically increase a number of $\overline{p}$'s collected in the Debuncher (see Fig. 2). Electron cooling, refined bunch loading structure, introduction of a $\pm 100\mu$rad crossing angle at the IP to avoid deleterious effects of the long-range beam-beam interactions with the increased number of bunches are the most crucial issues in the TeV33 project.

The performance of a TeV33 scenario is determined by the average production rate of events that can be analyzed to study interesting physics processes. The store parameters affect strongly the Collider performance. Proton and antiproton beam loss in the machine and through collisions at the IPs, and emittance growth due to intrabeam and beam-gas scattering contribute to the luminosity lifetime. Fig. 3(a) shows the luminosity as a function of time in a store for various $\overline{p}$ intensities. The luminosity drops sharply in the first few hours of the store. It is important that a substantial fraction of the antiprotons remain at the end of the store. With a recapturing the bulk of these $\overline{p}$'s for re-injection into the Tevatron, the integrated luminosity will depend entirely on the $\overline{p}$ production rate for a wide range of initial store parameters.

The growth rate of transverse emittance is shown in Fig. 3(b). The RF upgrade increases the momentum spread of the beam and also the peak current. For longitudinal intrabeam scattering, the effect of the momentum spread is more important, and the intrabeam scattering growth is greatly reduced. The opposite is true for transverse intrabeam scattering, and the RF upgrade has the fastest heating rate of any of the scenarios considered. The case with the very small initial longitudinal emittance (0.5 eV-sec) lies between these two cases.

The factors affecting the integrated luminosity include proton and antiproton intensities, transverse emittance, bunch length, β^*, crossing angle, intra-beam scattering and $\overline{p}$

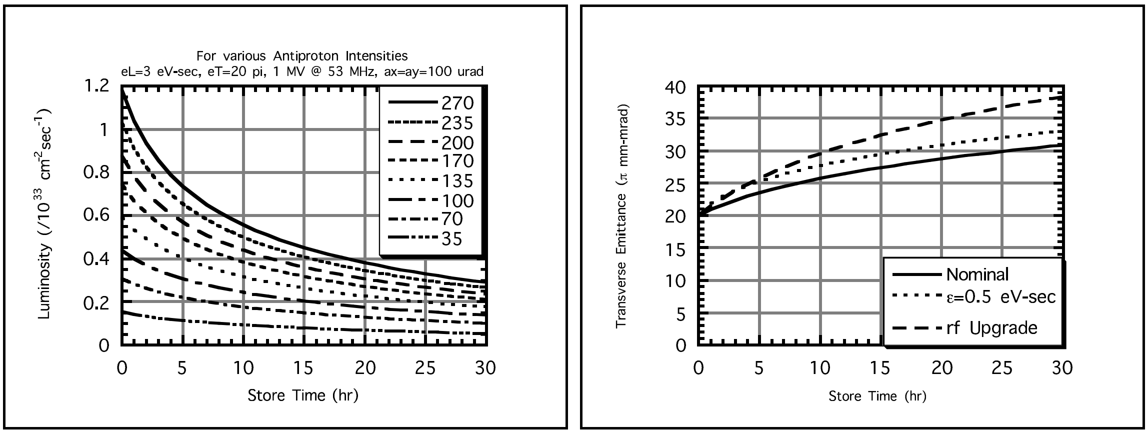

Figure 3: (a) Tev33 luminosity *vs* time in a store for the varying antiproton intensities as indicated in the legend in $10^9\,\overline{p}$'s; (b) The time dependence of the TeV33 transverse emittance.

lifetime. The peak luminosity of $10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ with 100 proton and antiproton bunches results in about 10 interactions per bunch crossing. It is difficult (and expensive) to build high performance detectors to operate in this environment. One possible operational scenario involves a technique known as *luminosity leveling*. The idea is that the luminosity is held at a maximum value - say $0.5\times10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ - during the initial part of the store and kept constant for as long as possible. One straight-forward method of accomplishing this goal is to dynamically adjust the value of β^* as the store progresses. The luminosity is kept constant until the minimum value of β^* is achieved. A simulation of luminosity leveling is shown in Fig. 4 [3] for the nominal parameters of Table 1. The loss of luminosity from intrabeam scattering and residual gas effects is the same for both stores, but the luminosity limited store retains more antiprotons (fewer collisions) and has a higher luminosity later in the store.

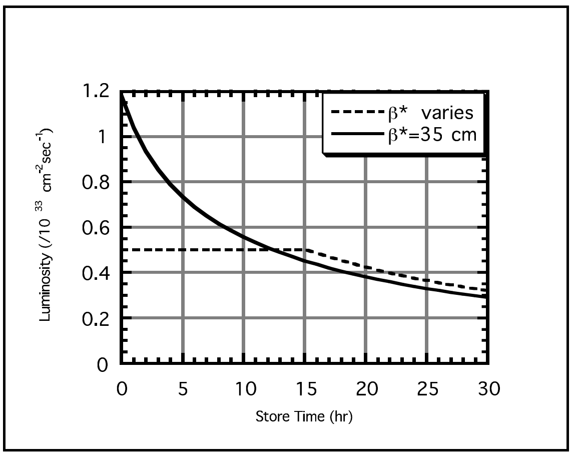

Figure 4: The luminosity in a store with the nominal initial parameters and $N_{\overline{p}}=2.7\times10^{11}$ is compared to an otherwise identical store where β^* is varied to maintain a constant luminosity of $0.5\times10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ for as long as possible keeping $\beta^*>35\,\mathrm{cm}$.

The limited store yields 23.2 pb^{-1} in 13.9 hours for an average luminosity of 1.66 pb^{-1}/hr compared to 33.5 pb^{-1} in 15.2 hr and an average luminosity of 2.19 pb^{-1}/hr. The average luminosity obtained with a luminosity leveled store is less sensitive to the initial antiproton bunch intensity than a unleveled store, but the highest integrated luminosity is obtained in either case with the highest possible initial antiproton intensity. The loss of integrated luminosity from leveling depends on the store parameters: the importance of the antiproton intensity to the lifetime, the amount of luminosity reduction desired, and the length of the store.

5. Detector Upgrades

The upgrade of both Fermilab Collider detectors, CDF and DØ, is a key element of the attack on physics in the new high luminosity Main Injector environment. There are comprehensive upgrade plans for CDF and DØ based on individual strengths of each detector, enhancing the tracking and triggering capabilities. Construction is now underway on a number of the detector systems.

6. Conclusions

A rational plan exists for enhanced utilization of the Fermilab complex in the 1990s and into the first decade of the next century. The first upgrade stage has been successfuly completed supporting a luminosity in the Tevatron more than a factor of ten beyond the original design goal. By the end of the decade one can look forward to:

- A luminosity of up to $2 \times 10^{32}\,cm^{-2}\,s^{-1}$ in the Tevatron Collider, supported by the Main Injector and Recycler rings.
- A fixed target program based on 120 GeV up to 3×10^{13} proton beam, coincident with collider operation, providing a unique capability in the realm of rare K-decay and neutrino oscillation physics, with the NuMI project started in 1999.
- A platform for enhancements that will meet the future needs of the U.S. high energy physics community for ever improved collider performance.
- Considerable R&D toward the TeV33 project with a luminosity in the $1{\times}10^{33}\,cm^{-2}\,s^{-1}$ domain.
- Considerable superconducting magnet R&D aligned on the LHC.
- An extensive design and optimization program for a muon collider project.

7. Acknowledgments

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References

[1] F. Abe et al. (CDF Collaboration), 'Observation of Top Quark Production in $p\overline{p}$ Collisions', Phys. Rev. Letters, vol. 74, 2626 (1995).

[2] S. Abachi et al. (DØ Collaboration), 'Observation of the Top Quark', Phys. Rev. Letters, vol. 74, 2632 (1995).

[3] P. Bagley et al., 'Summary of the TeV33 Working Group', Snowmass, July 1996.