Introduction to the Recycler Ring

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Recycler Vacuum Workshop/Internal Review Huddle

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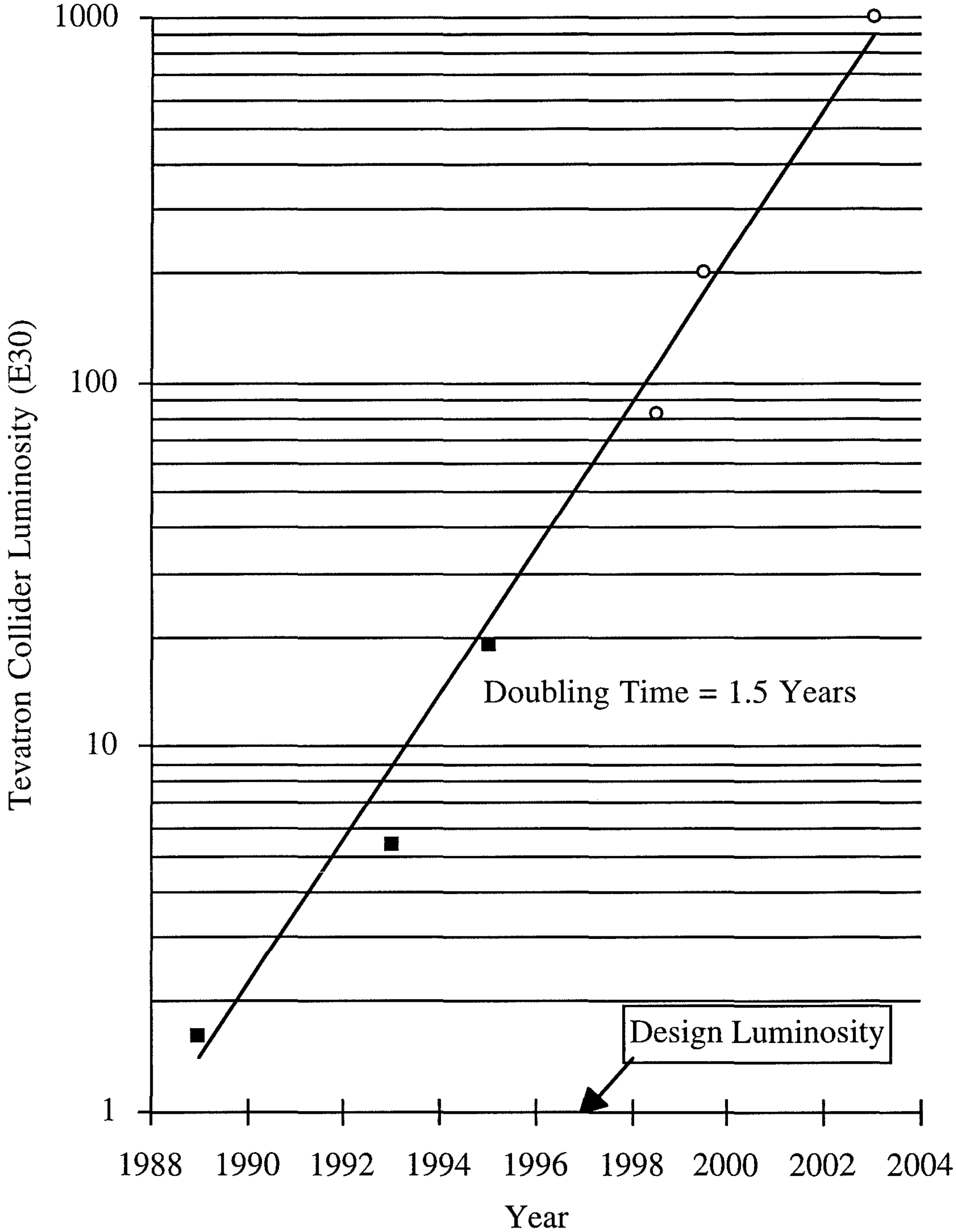
Fermilab Luminosity Performance: Past and Future



Increasing Tevatron Collider Luminosity

Parameter	Run I	MI	Tev*
N_p Protons/Bunch (E9)	250	330	270
N_a Pbars/Bunch (E9)	60	36	66
ε_p Proton Emittance (π mmmr)	24	30	18
ε_a Pbar Emittance (π mmmr)	15	15	15
β^* Beta @ IP (cm)	35	35	35
E_o Beam Energy (GeV)	900	1000	1000
N_b Bunches/Beam	6	36	36(108)
σ_s Proton Bunch Length (cm)	50	45	45
σ_s Pbar Bunch Length (cm)	50	45	33
N_{IP} Interaction Regions	2	2	2
ΔT Bunch Spacing (ns)	3500	395	395(132)
Luminosity Form Factors	0.65	0.69	0.72
Lo Peak Lum (E30 cm^{-2} s^{-1})	19	83	**200**
$\int L$ Integrated Lum (pb^{-1}/week)	3.8	17	**40**
Interactions/Crossing (@ 49 mb)	3.2	2.4	5.7
Total Pbar Tune Shift	0.015	0.016	0.023
Total Proton Tune Shift	0.005	0.003	0.006
Total Pbar Intensity (E10)	36	130	238
Pbar Loss Rate (E10/hr @ 78mb)	1.0	4.6	11
Scenario	actual FNAL	Main Injector design	with Recycler added

Motivation for the Recycler

$$L=\frac{N_P(N_A B)f_o(\beta_r\gamma_r)}{2\pi\beta^*\left(\varepsilon_{nP}+\varepsilon_{nA}\right)}H\left(\frac{\beta^*}{\sigma_s}\right)\frac{1}{\sqrt{1+\frac{2\alpha^2\sigma_s^2(\beta_r\gamma_r)}{\beta^*\left(\varepsilon_{nP}+\varepsilon_{nA}\right)}}}$$

where α is the crossing half-angle, the transverse beam sizes $\sigma_{x,y}$ is related to β^* and the rms normalized emittance ε_n by the equation

$$\sigma_{x,y}^2=\beta^*\frac{\varepsilon_n}{(\beta_r\gamma_r)}$$

and H is the hour-glass factor which has the form

$$H(x)=\sqrt{\pi}\,x[1-\Phi(x)]\,e^{x^2}$$

The ultimate limit to luminosity in hadron colliders to date has been the been the beam-beam interaction. This limit has been a total beam-beam linear beam-beam tune shift ξ of approximately 0.025 where (r_p=1.535x10^{-18} m)

$$\xi=\frac{r_p}{4\pi}\frac{N}{\varepsilon_n}N_{IP}$$

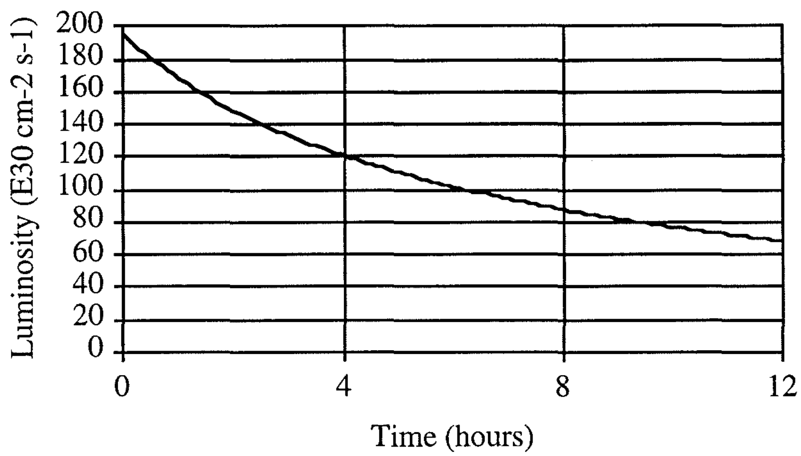
The ratio of the proton bunch intensity to emittance is limited by the total beam-beam tune shift suffered at all interaction regions. Plugging the equation for this tune shift into the equation for luminosity per interaction region yields the result

$$L=\frac{(N_A B)}{N_{IP}\beta^*}\frac{2\xi_{max}f_o(\beta_r\gamma_r)}{r_p\left(1+\frac{\varepsilon_{nA}}{\varepsilon_{nP}}\right)}L$$

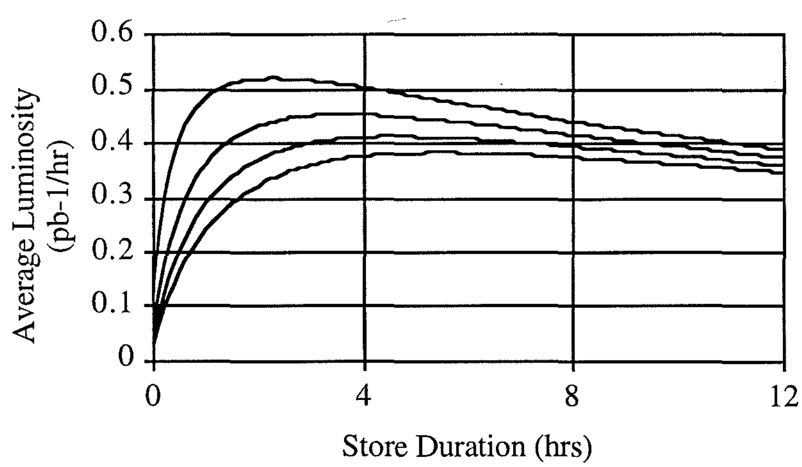
where the factors whose values can be modified appear in the left fraction. The quantity ($N_A B$) is just the total antiproton intensity injected into the Tevatron, independent of the bunch spacing.

Standard Operation Scenario

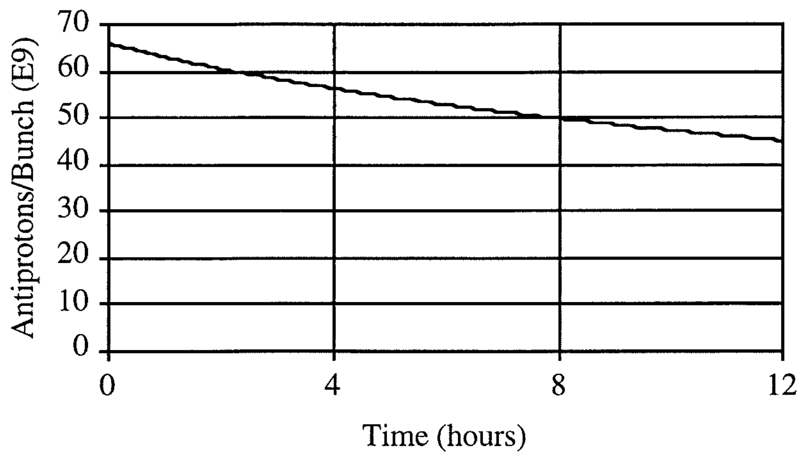
The standard approach to producing luminosity is to run at the minimum beta-star, a constant value, over the entire store. In this scenario one expects the luminosity to always decrease, as shown in the following figure.



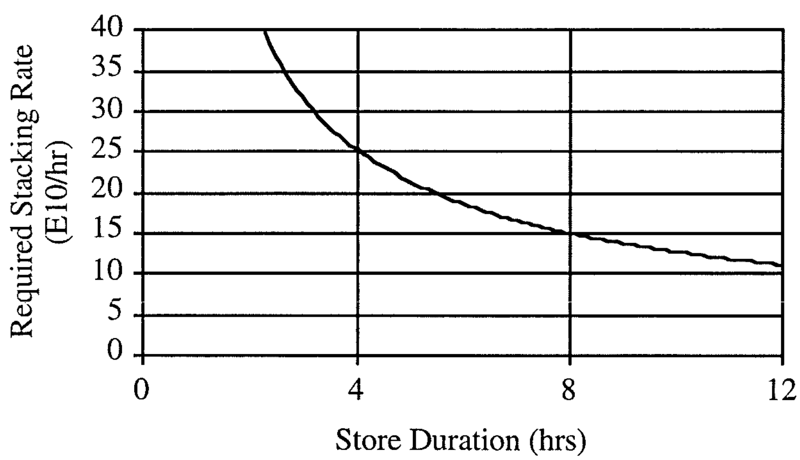
Under these conditions, assuming antiproton recycling, a 90% antiproton acceleration efficiency, and a 80% antiproton deceleration efficiency, the average luminosity vs. store length can be calculated. The different curves correspond to assumptions of 0.5 (top), 1, 1.5, and 2 hour (bottom) Tevatron turn-around (deceleration, injection, acceleration, scraping) times.



The evolution of the antiproton bunch intensity, which is crucial to recycling efficacy, is predicted to be dominated by particle loss due to proton-antiproton collisions at the interaction points. At the end of a 7 hour store, approximately 80% of the antiprotons are still in the Tevatron.



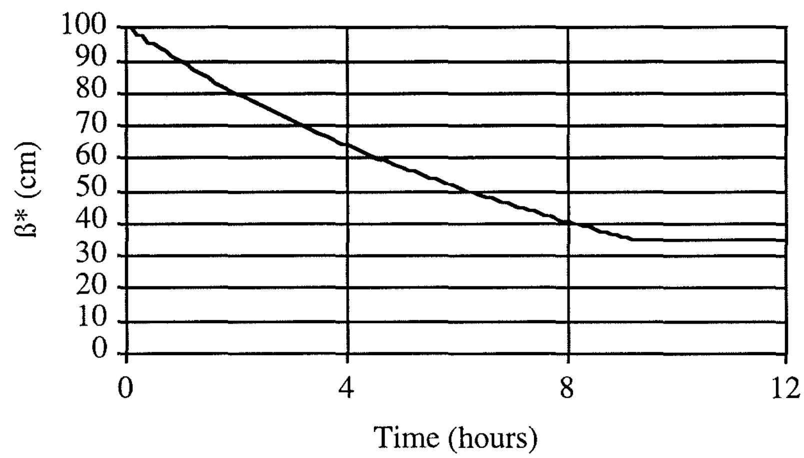
Given the number of antiprotons needed to generate the goal luminosity and given the anticipated optimum store length, the antiproton stacking rate need to produce the number of antiprotons needed for continuous operations can be predicted.



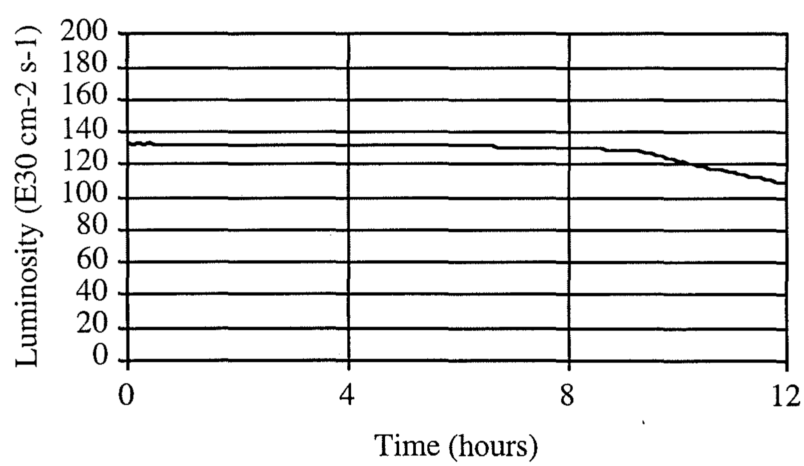
The above scenario is the nominal operational proposal for Run II. The Recycler ring design is based on this scenario. But a new scenario which aims to improve the operations of the HEP detectors is being considered. At the present time it is referred to as Luminosity Leveling.

Luminosity Leveling

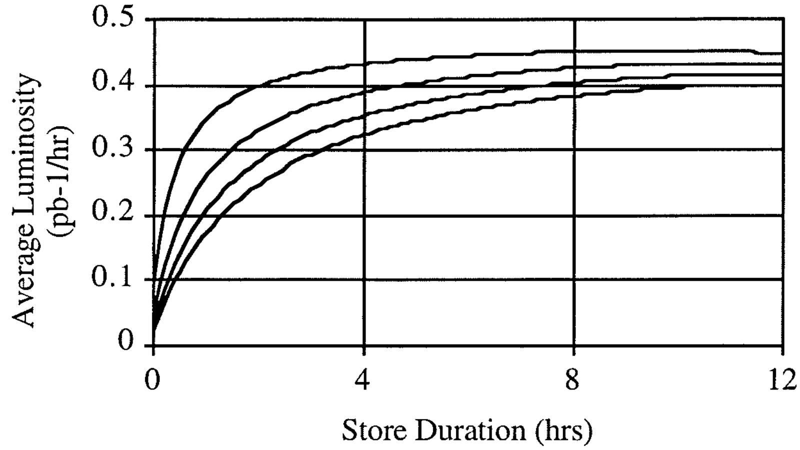
In luminosity leveling the beta-star is continuously varied with the goal of maintaining a constant luminosity over some period of time. If one has the goal of maintaining the same average luminosity at the optimum store length for the same stacking rate, the beta-star evolution required is shown in the figure below.



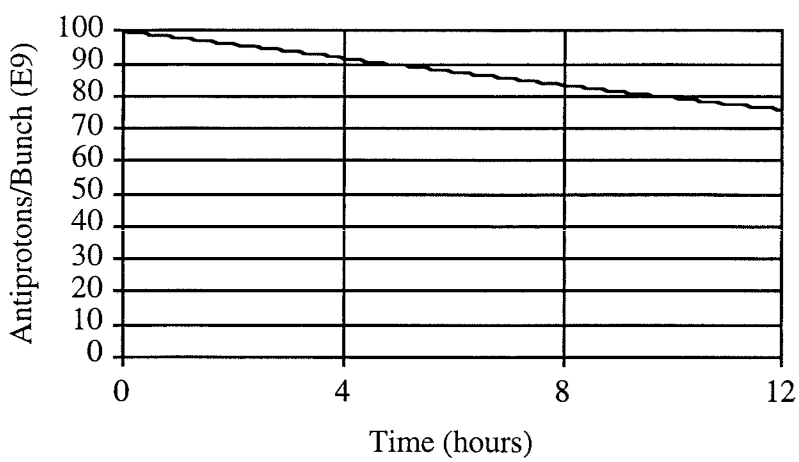
The luminosity profile which results from this continuously varying beta-star is also shown below. The peak luminosity is at 65% of the peak luminosity in the nominal case. Therefore, the largest average number of interactions per crossing anticipated during Run II decreases from 5.7 to 3.7, as compared to the typical peak number of 3.2 during the last collider run.



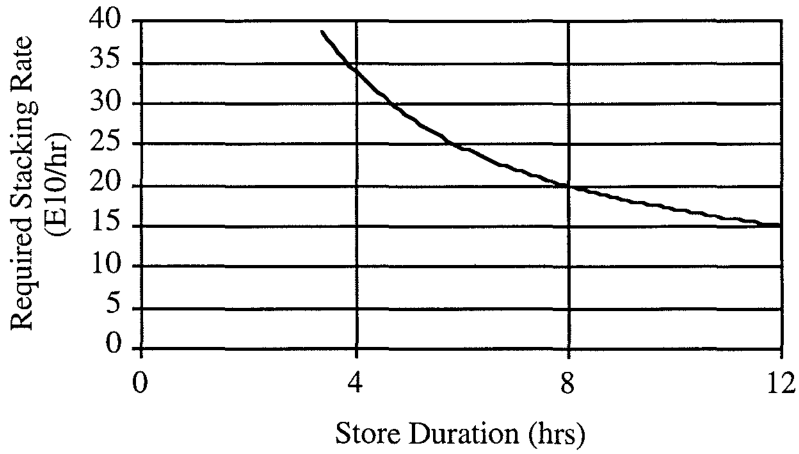
The average luminosity vs. store length is dramatically stretched in time when luminosity leveling is invoked. Note that the optimum store length has increased to approximately 11-12 hours, and the sensitivity of the peak average luminosity to Tevatron Collider turn-around time is reduced considerably.



As one might expect, for the optimum store length the antiproton loss is predicted to be the same percentage as in the nominal operational mode. Note that because the optimum store length is longer but the assumed stacking rate was held constant, the antiproton bunch intensity has increased by 50%.

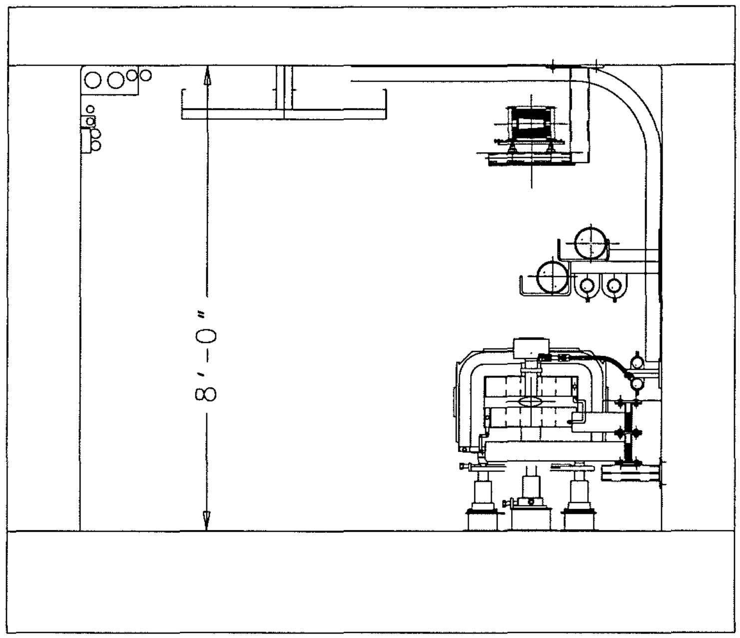


The required stacking rate for continuous operations at the same luminosity is shown below as a function of store length.

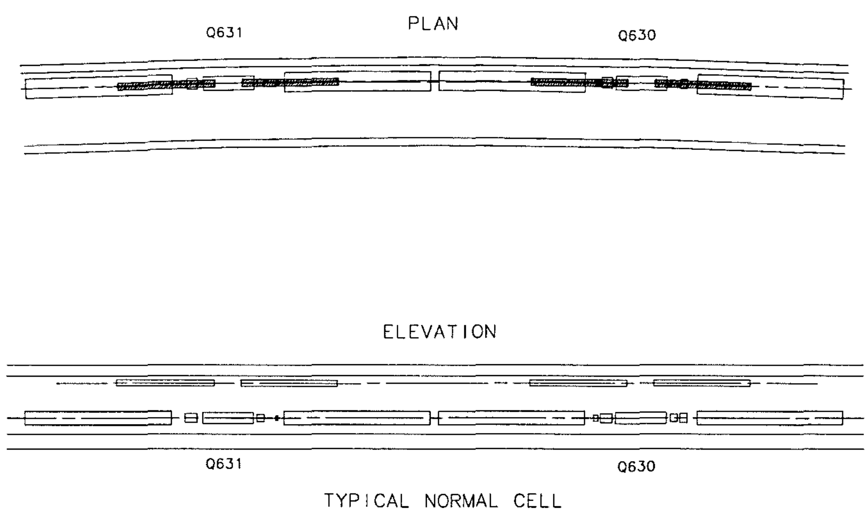


In order to verify the operations needed for the key step in all of this, antiproton recycling, studies of antiproton deceleration are important. There are studies being organized by **Jerry Annala** (Tevatron) and **Ionis Kourbanis** (Main Ring) to begin testing the beam dynamics, machine hardware, and control software necessary to meet Run II expectations.

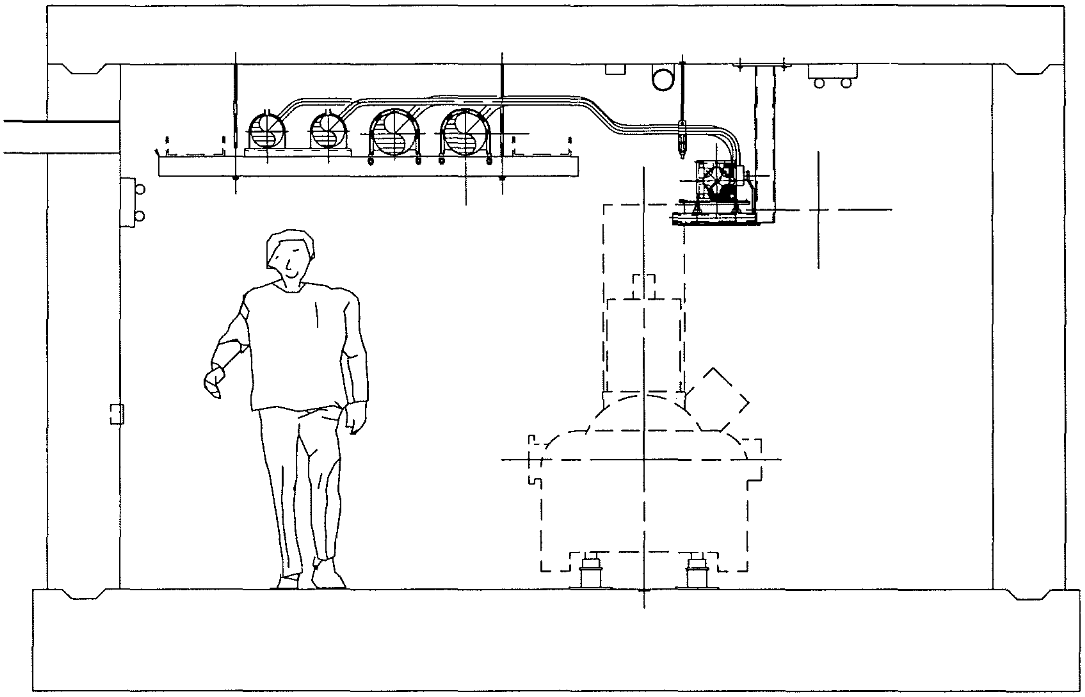
Especially important for Run II operations is the development of the controls software and associated hardware which will orchestrate all of the various operations into one smooth symphony.



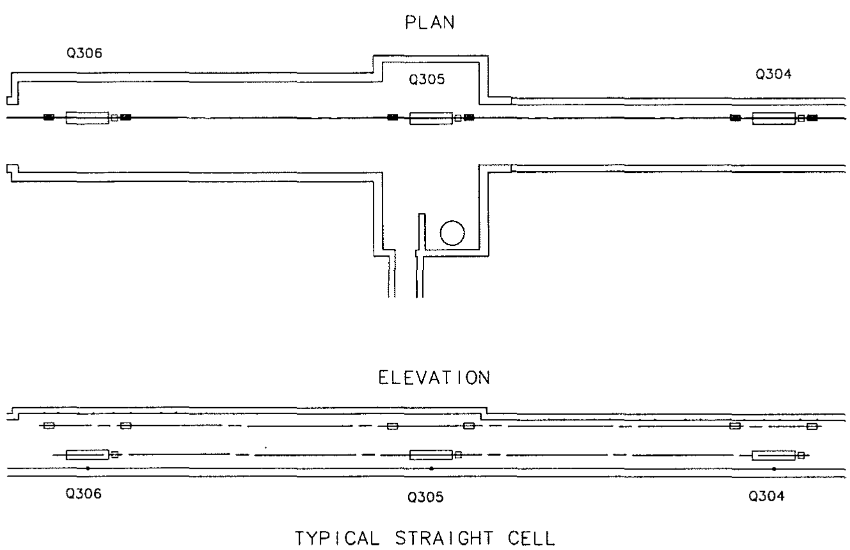
Tunnel cross-section in a standard arc cell showing a Main Injector dipole near the floor and a Recycler gradient magnet above it and near the ceiling.



Plan and elevation views of both the Recycler and Main Injector beamlines. Note that the top magnets (shaded magnets in the plan view) are the Recycler gradient magnets.

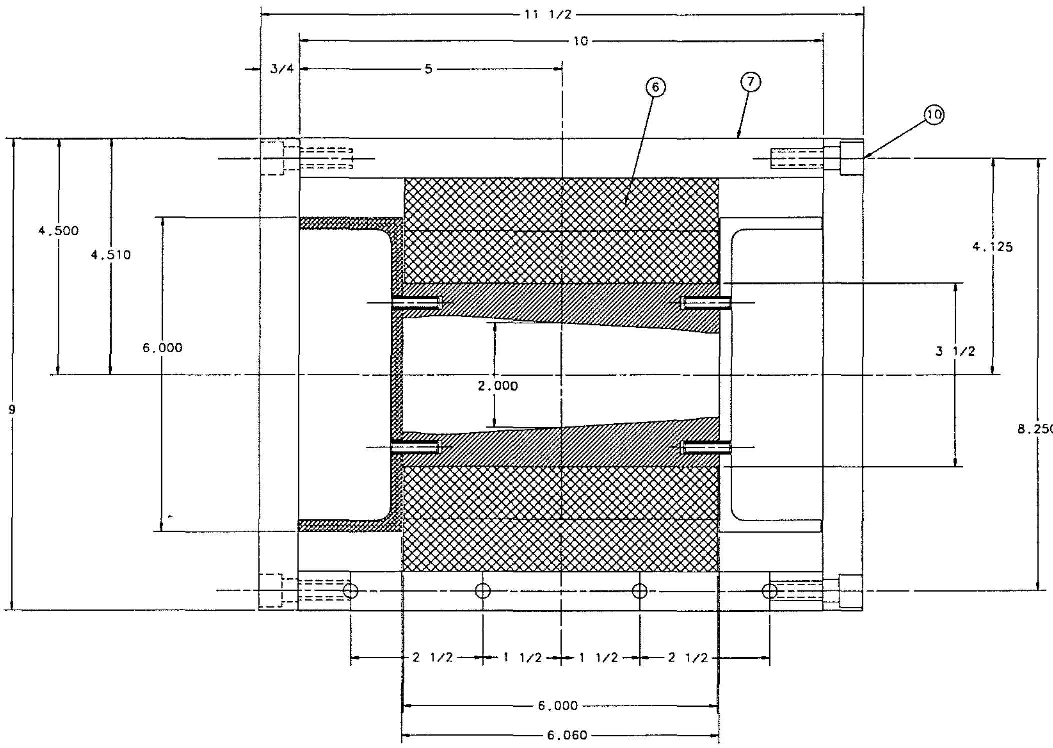


Tunnel cross-section at the MI-60 straight sections showing the Main Injector RF cavities with the Recycler ring quadrupoles above and to the radial outside.

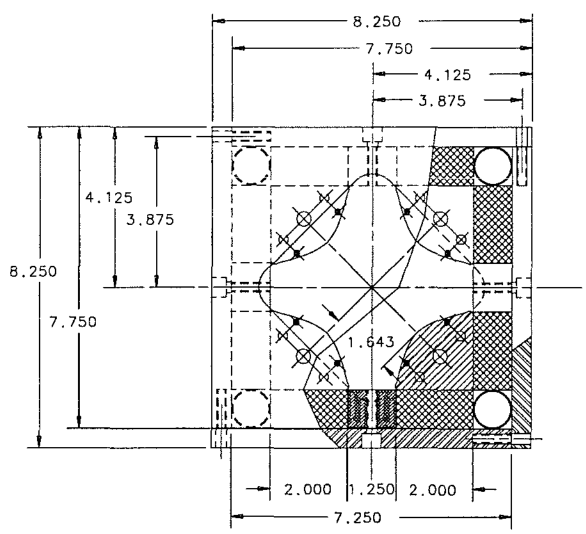


Plan and elevation views of the Main Injector (open frames) and Recycler (shaded rectangles) magnet deployments in a standard straight section.

Permanent Magnets



Gradient magnet profile. These magnets are composed of double bricks on the top and bottom, and no side bricks.

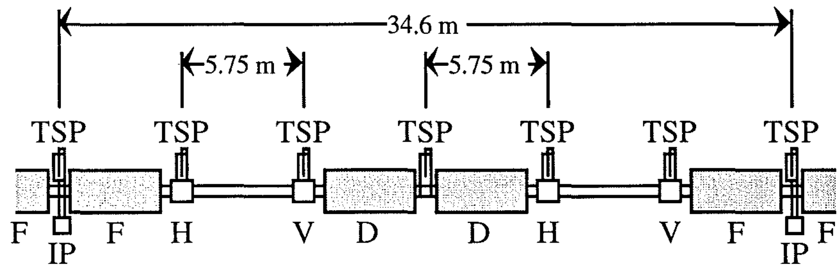


Quadrupole magnet profile. These magnets are composed of two partial strontium ferrite permanent magnet bricks per pole.

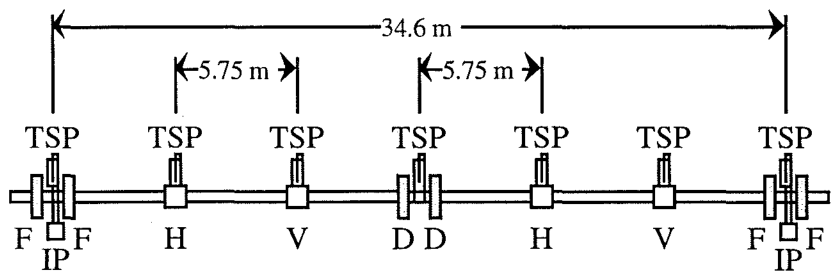
Vacuum System

In response to recommendations from the Leemann committee, the vacuum system has been modified dramatically. Basically, the committee was concerned that though the average vacuum goal of 1×10^{-9} Torr was acceptable from the point of view of beam intensity lifetime and emittance growth, it was not sufficient for ion trapping effects.

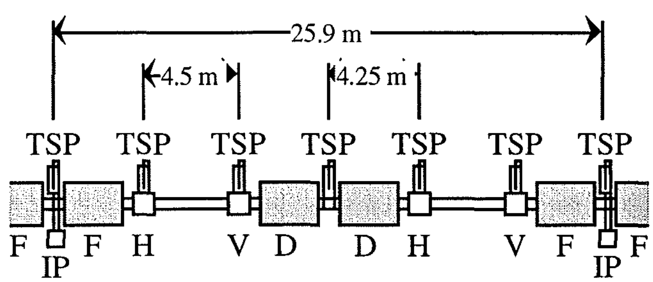
Therefore, the number of pumps has been increased from 1 ion pump/cell to 6 titanium sublimation pumps + 1 ion pump/cell, for 10x pressure reduction.



Sketch of the vacuum system in a normal arc cell. The horizontal (H) and vertical (V) BPMs have attached to them titanium sublimation pumps (TSP) in order to maintain a low average pressure and to minimize the number of tunnel welds.



Sketch of the vacuum system in a normal straight section cell.



Sketch of the vacuum system in a dispersion suppresser cell.

Correction Systems

Correction Dipoles

At Fermilab two accelerators operate at high fields without correction dipoles. Both the Booster and Main Ring can correct their orbits at injection, but at flattop the positions of the magnets determine the closed orbit. It is observed that the flattop orbit is very stable with time, indicating that a non-ramping accelerator does not need an **extensive** system of powered correctors. In the Recycler 24 powered orbit control dipoles are planned around the 3 transfer Lambertsons. This is enough corrector coverage for harmonic orbit control and aperture scanning in conjunction with the beam loss monitor system. These correctors are also used to perform beta function measurements around the ring. There are also a total of 24 correction dipoles in the 3 Recycler transfer lines.

Tune Adjusting Quadrupoles

An elegant design for a phase trombone has been worked out. With quadrupoles turned up at most by 50%, a tune change range of ±0.5 units was calculated. The location of this trombone is the MI-60 long straight. The plan is to implement a phase trombone with a tuning range of ±0.1 units using 9 old Main Ring correction quadrupoles, one at each straight section quadrupole location.

Coupling Adjustment

Local coupling can be corrected locally around the ring by moving magnets. The same algorithms developed at FNAL for the FFTB studies can be applied in the Recycler at commissioning to determine the magnet moves. For diagnostic purposes two skew quadrupoles are added to the ring for global coupling studies.

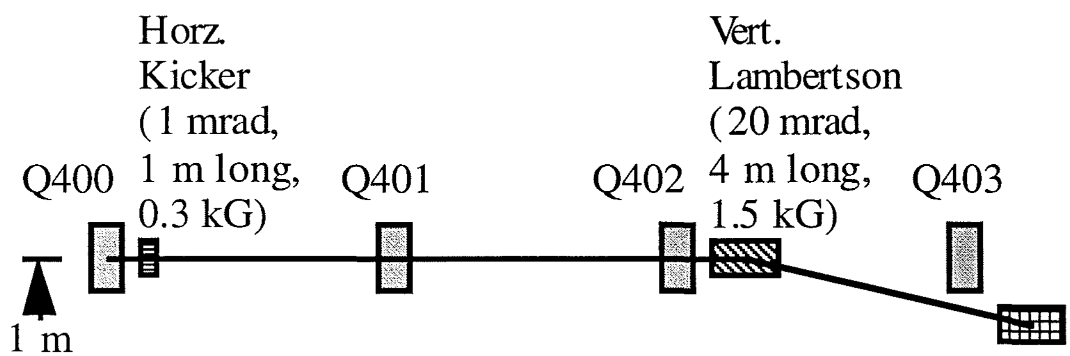
Chromaticity Adjustment

Old Main Ring correction sextupoles are used to generate ±5 units of chromaticity tuning for diagnostic purposes. A total of 8 focussing and 16 defocussing sextupoles are required.

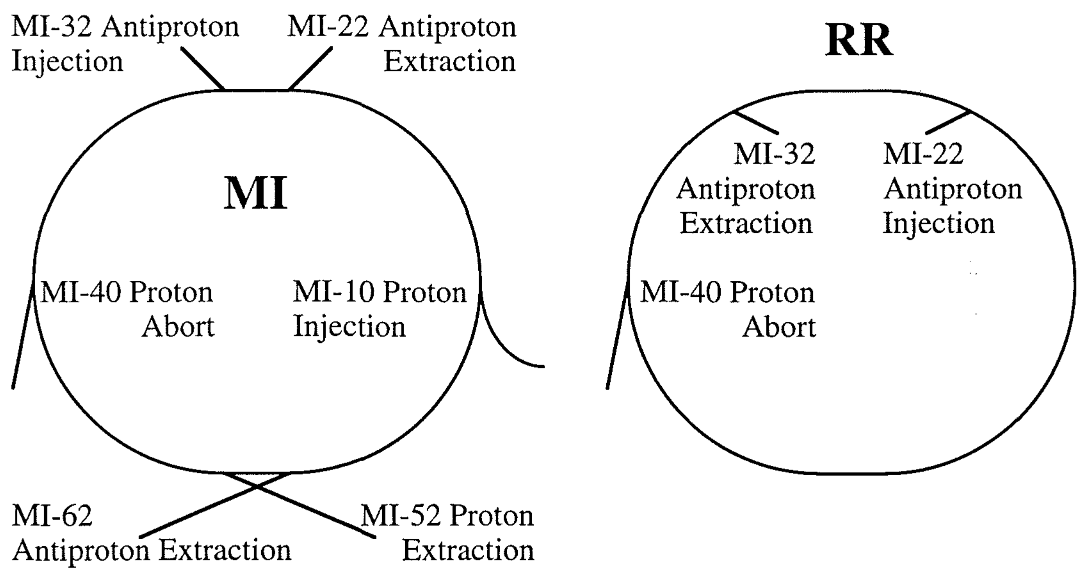
Beam Transfers

Geometry

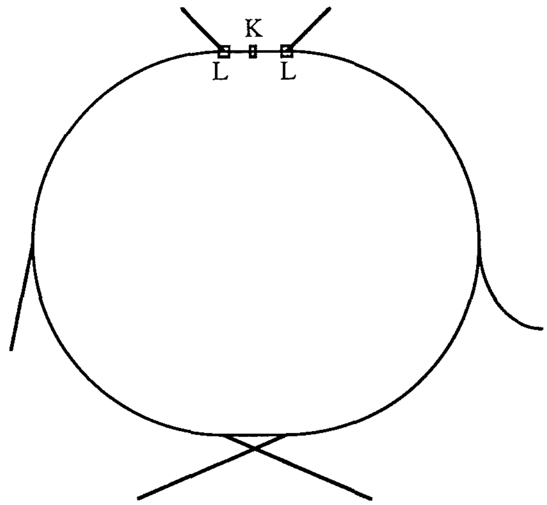
The basic transfer geometry is shown in the figure below (this particular design is for the proton abort at MI-40). The two components required are a 300 Gauss, 1 m long kicker magnet and a 1.5 kGauss, 4 m long Lambertson. The Lambertson is constructed with permanent magnets.



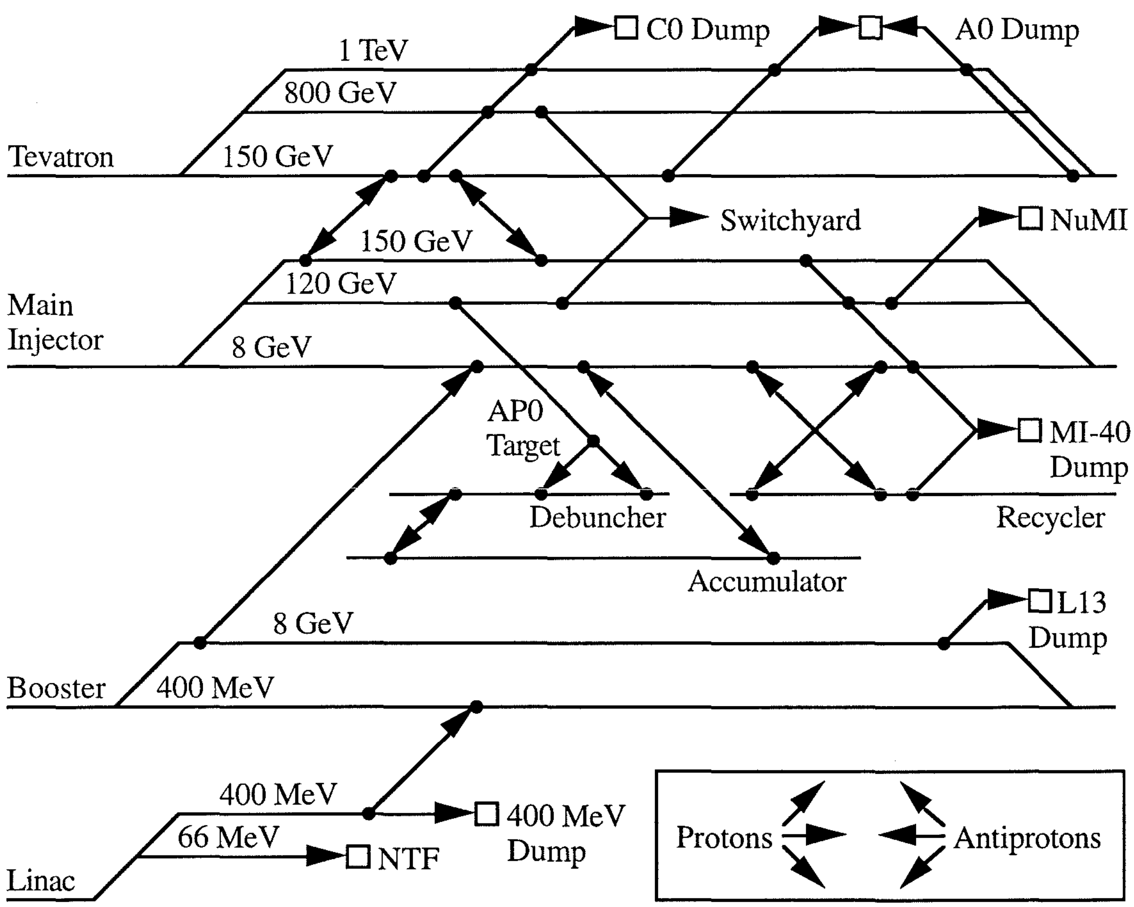
There are 3 transfer lines into and out of the Recyler ring



Only 2 kickers are needed in the Recycler ring at MI-20 and MI-40. One additional kicker is needed in the Main Injector at MI-30. These kickers service two transfer lines, both protons and antiprotons, and protons delivered to the abort dump at MI-40. The sketch below shows the relative geometry of the kickers and Lambertsons.



A summary of all possible beam transfers after commissioning of the Recycler is shown in the figure below.

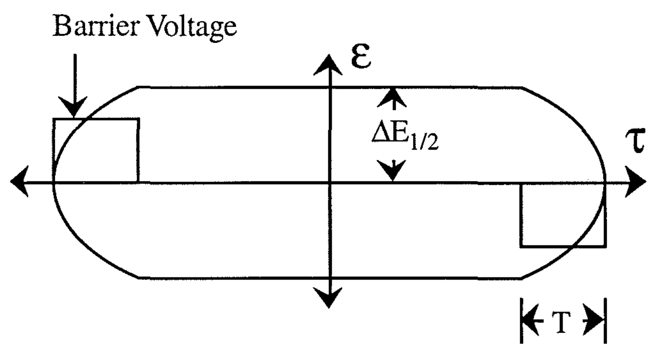


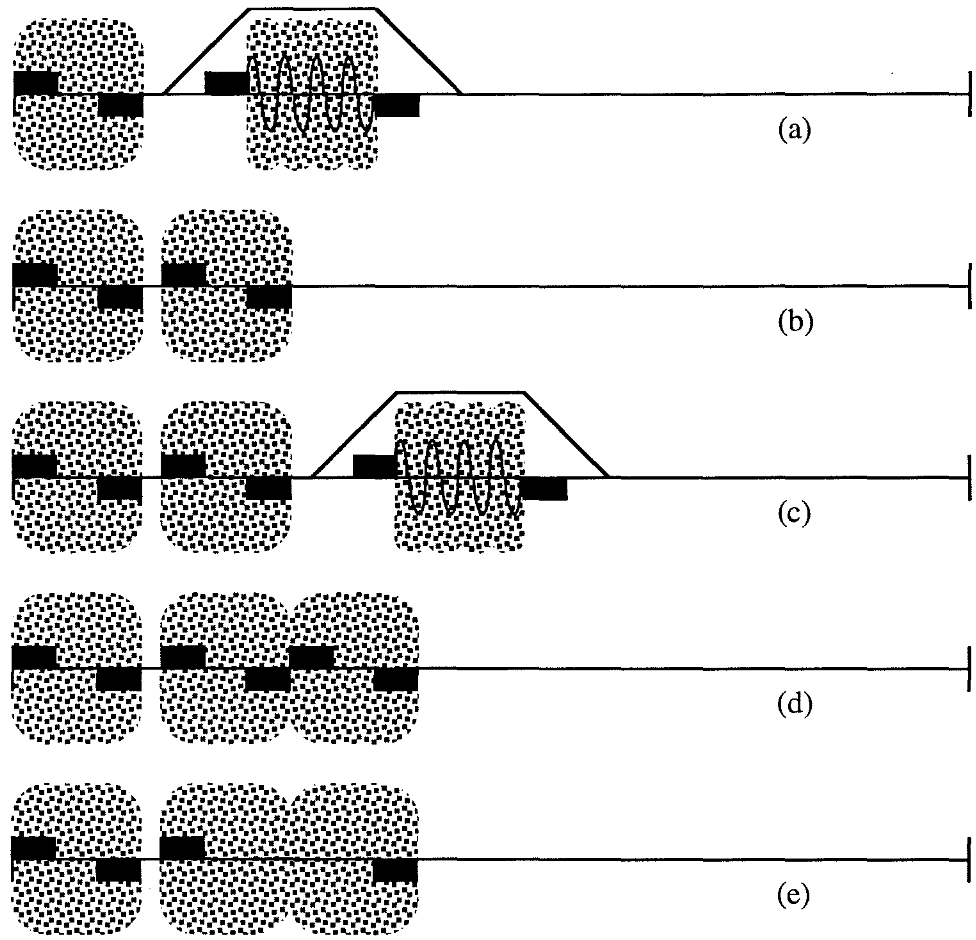
RF

The RF system is composed of a 2 kV maximum voltage broadband longitudinal kicker structure composed of four 50Ω gaps. At less than 40 kW peak, this is a rather straightforward high level system. The low level RF system is virtually identical to the Main Injector system which is presently running the Main Ring.

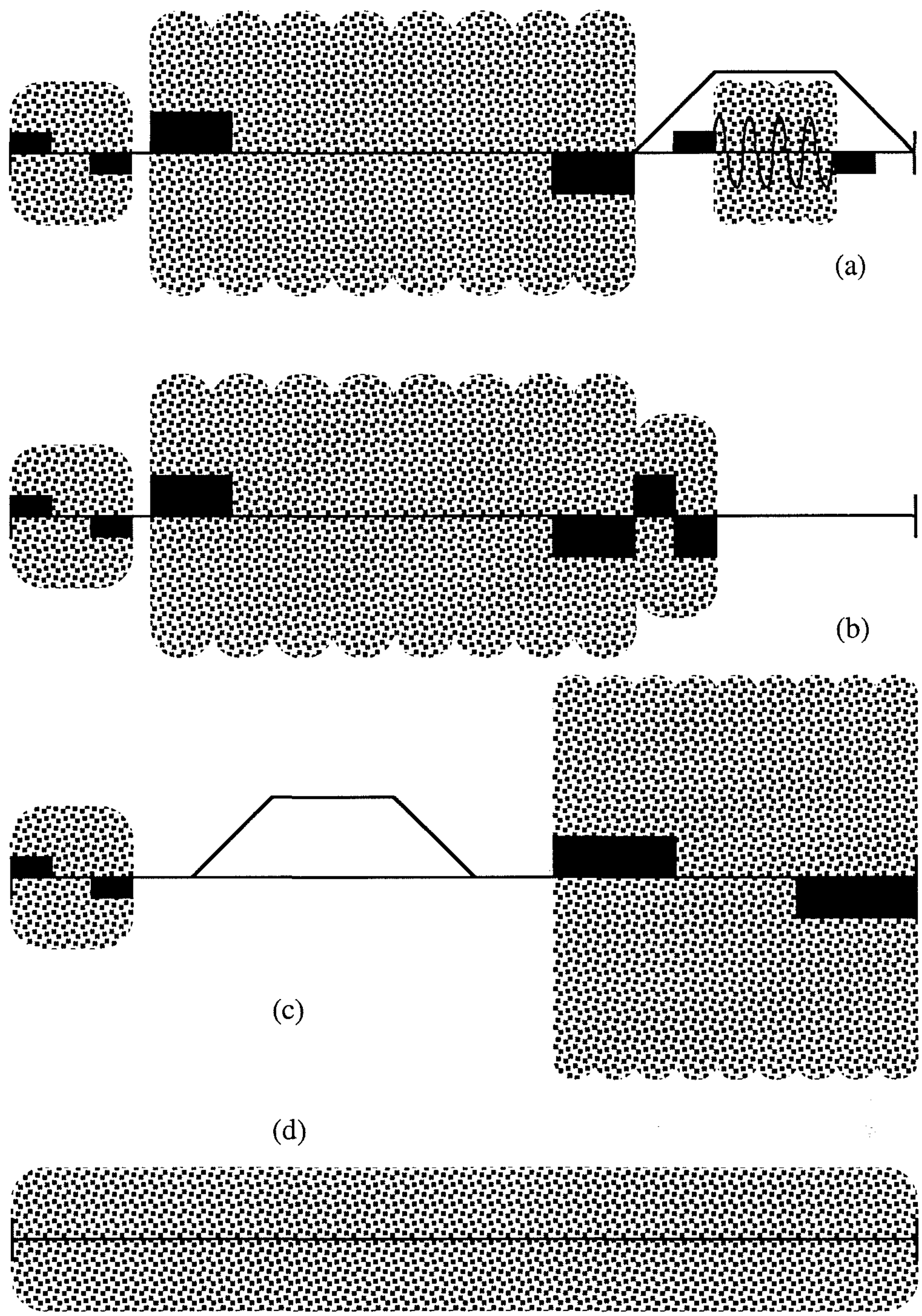
The purpose of the system is to generate barrier buckets for operations such as antiproton stacking and recycling. The barrier bucket system is also used to maintain a gap in the longitudinal distribution of the beam to guard against ion trapping.

$$\Delta E_{1/2} = \sqrt{\frac{T}{T_o}\frac{2\beta_r^2}{\eta} e V_o E_o}$$





The above figure shows recycling of antiproton batches from the Main Injector. The leftmost charge distribution is always the cooled antiprotons. The shown Recycler injection kicker waveform has a rise-time and fall-time of 1 μsec. Note that the recycling process never requires more than 3 pairs of barrier voltage pulses.



The above figure shows the end of the process of antiproton recycling from the Main Injector/Tevatron. The leftmost charge distribution is always the cooled antiprotons. In (d) the cooled antiprotons have already been injected into the Tevatron Collider and the recycled antiprotons have been debunched.

Stochastic Cooling

Mission

The need for emittance cooling in the Recycler is driven by three issues:

1) Emittance of Recycled Antiprotons

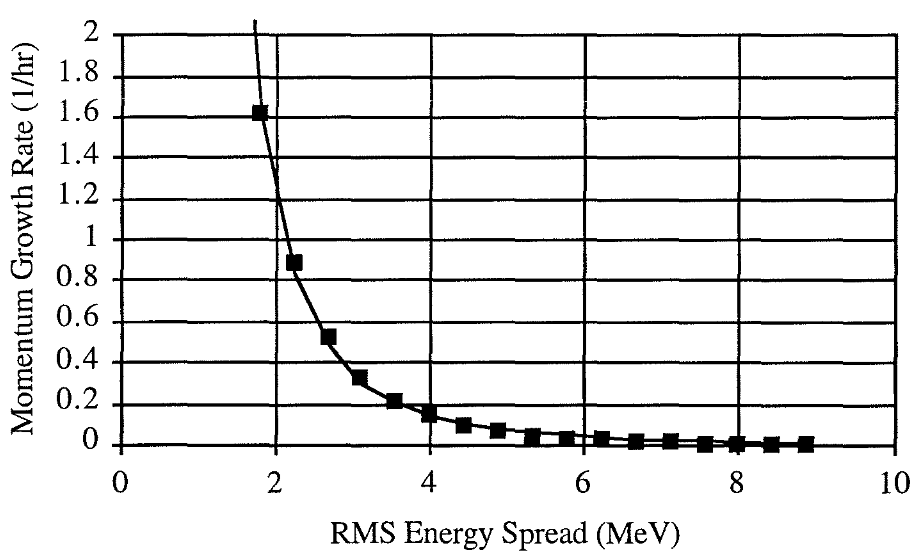
2) Emittance of Stacked Accumulator Antiprotons

3) Intrabeam Scattering

The transverse emittance and momentum spread of the recycled antiprotons need to be reduced by 1/e in the seven hour store length. A stochastic cooling damping rate in all 3 dimensions of roughly seven hours is needed.

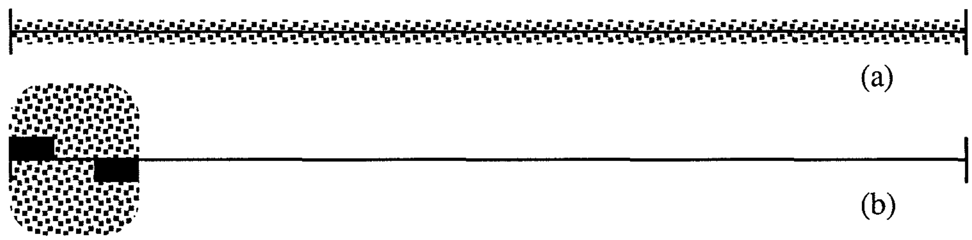
At the antiproton intensities needed to achieve the higher luminosity goal the **momentum spread** of the stacked antiprotons from the Accumulator ring is too large to effectively use for Tevatron stores. The **transverse** beam emittance is still injected below the target value of 10 π mmmr. A momentum damping time of a few hours is required.

Intrabeam scattering has been calculated by a number of people and applied to the Recycler by **Pat Colestock**. The transverse emittances shrinks, while the longitudinal emittance growth rates are rather large.



Barrier Bucket Compression

A fit to the curve of longitudinal emittance growth rate vs energy spread indicates a cubic increase in growth rate with decreasing energy spread. This cubic dependence indicates that it is more effective to maintain a large momentum spread and longitudinal compress the beam as the longitudinal emittance is reduced via stochastic or electron cooling.



Sketch of the beam distribution around the Recycler ring without (a) and with (b) a barrier bucket longitudinal voltage system (hard to call an RF system) employed to compress the beam.

The "RF system" used to generate the voltage pulses which form the longitudinal phase space barrier bucket is composed of four 50Ω gaps. Stochastic cooling simulations assume this compression scheme.

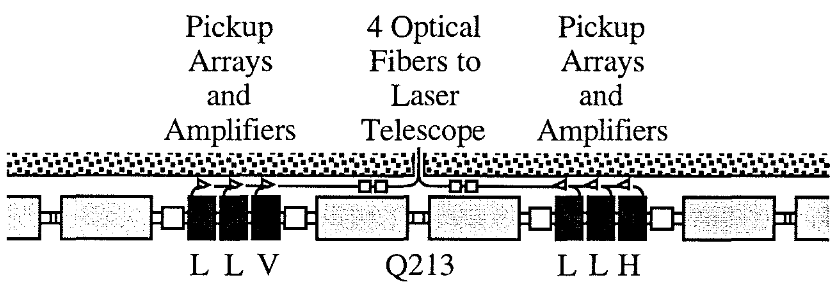
Because of the novel nature of this longitudinal cooling scheme, tests in the Accumulator ring are planned.

Hardware

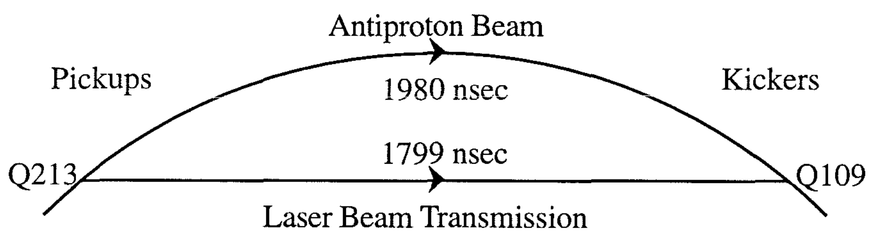
The calculations of stochastic cooling indicate that the following systems are required requiring the following pickup and kicker hardware.

Plane	Band (GHz)	Pickup Tanks	Kicker Tanks	Pickup Electrodes	Kicker Electrodes
Horz	2-4	1	1	32	32
Vert	2-4	1	1	32	32
Mom	1-2	2	2	32	32
Mom	0.5-1	2	2	16	16
	Total	6	6		

The tunnel arrangement of these tanks, each 48" long and patterned after the Accumulator, are shown below.



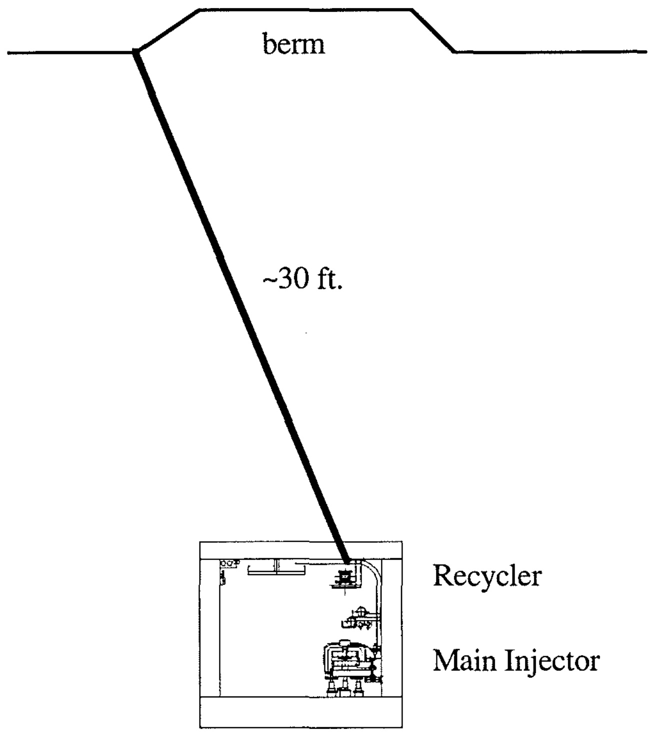
The mode of signal transmission assumed is via optical fiber and direct laser beam propagation across the ring.

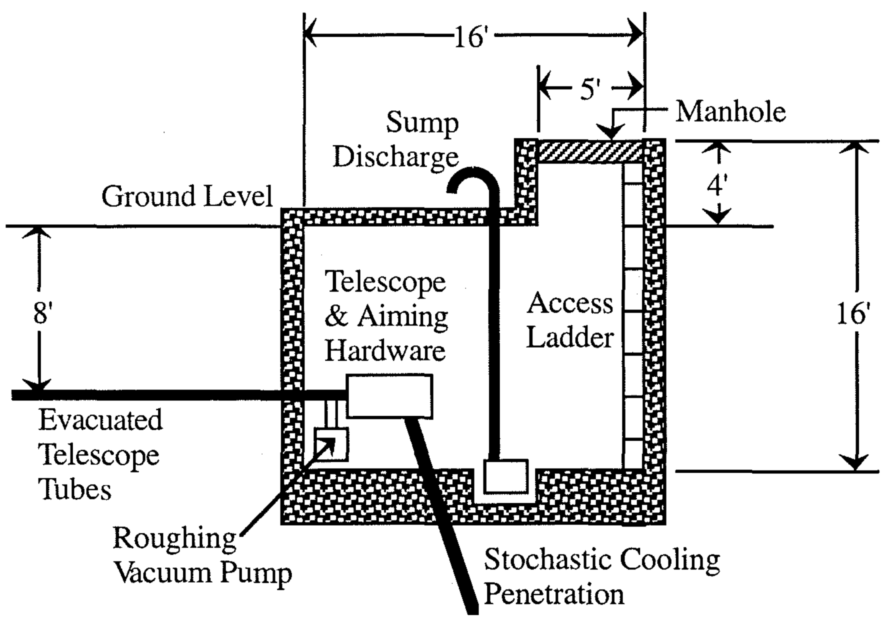


Optical fiber transmission of stochastic cooling signals is well established. Tests at launching a fiber signal into a discrete optical system which aims a beam across a ring have occurred.

Civil Construction

The civil construction associated with the stochastic cooling, which is the only civil construction in the project, is sketched below.





Instrumentation

Even though the goal is to build this machine at a low cost, it would be a serious mistake to eliminate or compromise beam instrumentation. This is especially true at commissioning. Therefore, just as in the case of the magnets and vacuum system, it is necessary to employ non-standard technology to make the desired instrumentation less expensive while maintaining system performance specifications.

- **BPM System**

  This is a low bandwidth system sensitive to the beam current modulation induced by the suppressed bucket RF gap. A log-amp based reciever followed by a sample-and-hold allows readout via the standard control system multiplexed ADC system. Because of this architecture, every BPM can be used to meaure the closed orbit, first turn trajectory, or turn-by-turn oscillations, though not all simultaneously.

- **Resistive Wall Monitors**

  These monitors are used to study the longitudinal beam spectrum over a broad frequency range (3 kHz - 6 GHz).

- **Transverse Stripline Pickups**

  These monitors are used to monitor the horizontal and vertical beam spectra over a broad frequency range.

- **Residual Gas Ionization Profile Monitors**

  Unlike flying wires, which have the unfortunate fault mode in which the wire stops in the middle of the beam and either vaporizes or eliminates the beam, these monitors are relatively passive. The plan if for one in each plane in a zero dispersion straight section.

- **DCCT**

  This is used to accurately measure the DC current in the Recycler ring.

- **Toroids**

  The mission of the toroids is to measure all transfer efficiencies.