Fermilab Recycler Ring

Technical Design Report

November 1996

Revision 1.2

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1. Introduction

This report describes the technical design of the Fermilab Recycler Ring. The purpose of the Recycler is to augment the luminosity increase anticipated from the implementation of the Fermi III upgrade project, which has as its main component the Fermilab Main Injector construction project.

The Recycler is a fixed 8 GeV kinetic energy storage ring. It is located in the Main Injector tunnel directly above the Main Injector beamline, near the ceiling. The construction schedule calls for the installation of the Recycler ring during the installation of the Main Injector. This aggressive construction schedule is made possible by the exclusive use of permanent magnets in the ring lattice, removing the need for expensive conventional iron/copper magnet construction along with the related power supplies, cooling water system, and electrical safety systems. The location, operating energy, and mode of construction are chosen to minimize operational impacts on both Fermilab's ongoing High Energy Physics program and the Main Injector construction project.

1.1 Role in the Fermilab III Program

The Tevatron Collider provides the highest energy collisions in the world. To fully exploit this unique tool, Fermilab is committed to a program of accelerator upgrades for the purpose of increasing the Collider luminosity. Over the past 7 years the luminosity has been increased from a typical peak of $1.6\text{x}10^{30}$ $cm^{-2}sec^{-1}$ in 1989 to over $2\text{x}10^{31}$ $cm^{-2}sec^{-1}$ during 1995. Note that the original design peak luminosity of the Tevatron Collider was $1.0\text{x}10^{30}$ $cm^{-2}sec^{-1}$.

The Main Injector will supply a larger flux of protons for antiproton production, more intense proton bunches for use in the Collider, and a higher efficiency acceleration of antiprotons. The role of the Recycler ring is to provide more antiprotons for the Tevatron, which proportionally increases the luminosity. This is accomplished by acting as a high reliability post-Accumulator and receptacle for recycled antiprotons from the previous Collider store. Prior to the development of the Recycler ring, the peak luminosity goal of the Fermi III upgrade program was $8\text{x}10^{31}$ cm^{-2} sec^{-1}. With the construction of the Recycler ring, a typical peak luminosity of $2\text{x}10^{32}$ cm^{-2} sec^{-1} is expected. This factor of 2-3 increase in luminosity comes from the availability of more antiprotons at Tevatron injection. The Reycler is also the foundation of future accelerator upgrades which can generate another order of magnitude luminosity increase up to an ultimate goal of greater than $1\text{x}10^{33}$ $cm^{-2}sec^{-1}$. This report documents the design of the new fixed-energy Recycler storage ring to be placed in the Main Injector tunnel.

Figure 1.1 displays the history of the typical peak luminosity as a function of time since 1989, which shows an exponential growth with a doubling time of 1.5 years. With the addition of the Recycler ring and its commissioning along with the Main Injector, the Tevatron Collider will be able to remain on this exponential slope. The first open point represents the initial typical peak luminosity goal of the Main Injector project. The second open point represents the luminosity goal of $2\text{x}10^{32}$ $cm^{-2}sec^{-1}$ during Collider Run II when the Recycler is added to the picture. It should be possible, with further accelerator upgrades, to achieve a luminosity of 1×10^{33} $cm^{-2}sec^{-1}$, which is the highest luminosity open point in figure 1.1.

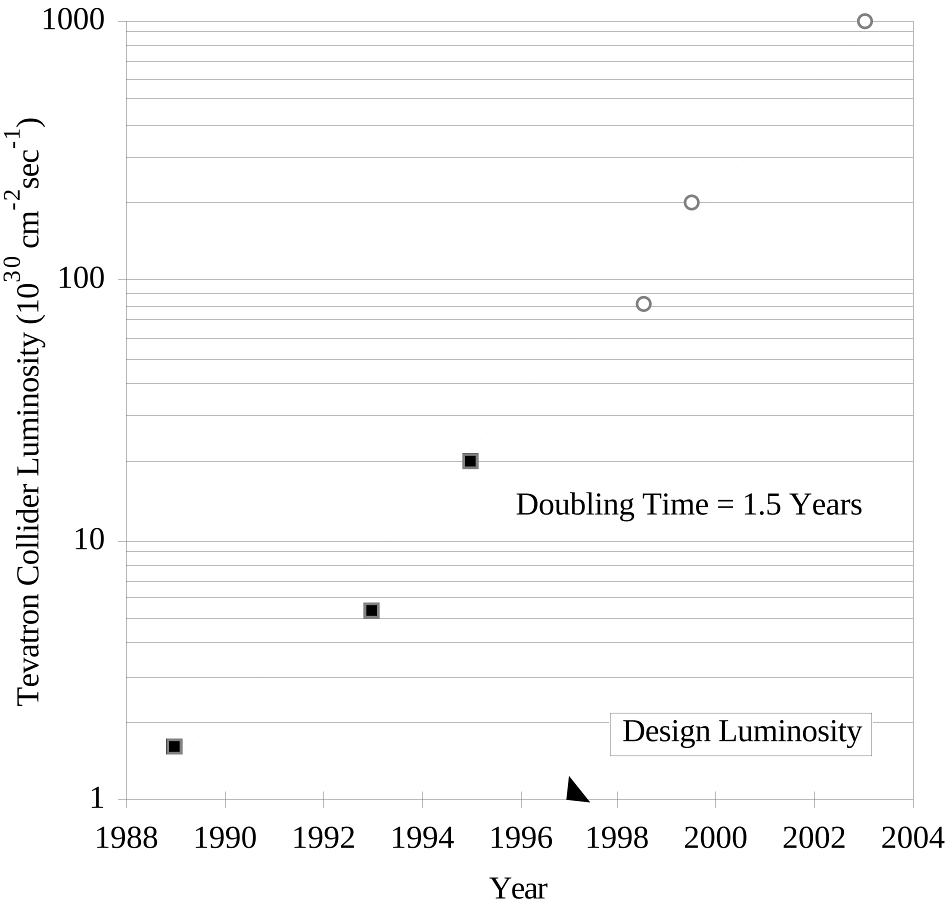

Figure 1.1: Tevatron Collider luminosity as a function of time. The filled circles are measured "best typical" peak luminosities, the line is an exponential fit to the data, and the open points represent goals for the future.

1.2. Performance

The Recycler ring parameter list is given in table 1.1. The placement and design of the ring were chosen to minimize its impact on the existing high energy physics program. This minimization takes place mostly in the areas of project cost and schedule. After the end of the present fixed target run, the only scheduled prolonged accelerator shutdown before the start of LHC operations at CERN is the 1998 Main Injector connection to the Tevatron. In the interest of accumulating the maximum amount of integrated luminosity before the LHC is publishing high energy physics results, an additional Tevatron shutdown for installation of the Recycler would be highly undesirable. By using as many of the already established Main Injector subsystem and lattice designs as possible, the ability to finish the Recycler installation before the completion of the Main Injector is made possible.

Table 1.1: Recycler ring parameter list.

Circumference	3319.400	m
Momentum	8.889	GeV/c
Number of Antiprotons	2.5×10^{12}	
Maximum Beta Function	55	m
Maximum Dispersion Function	2.0	m
Horizontal Phase Advance per Cell	86.8	degrees
Vertical Phase Advance per Cell	79.3	degrees
Nominal Horizontal Tune	25.425	
Nominal Vertical Tune	24.415	
Nominal Horizontal Chromaticity	-2	
Nominal Vertical Chromaticity	-2	
Transition Gamma	20.7	
Transverse Admittance	40	π mmmr
Fractional Momentum Aperture	1%	
Superperiodicity	2	
Number of Straight Sections	8	
Number of Standard Cells in Straight Sections	18	
Number of Standard Cells in Arcs	54	
Number of Dispersion Suppression Cells	32	
Length of Standard Cells	34.576	m
Length of Dispersion Suppression Cells	25.933	m
Number of Gradient Magnets	108/108/128	
Magnetic Length of Gradient Magnets	4.267/4.267/2.845	m
Bend Field of Gradient Magnets	1.45/1.45/1.45	kG
Quadrupole Field of Gradient Magnets	3.6/-3.6/7.1	kG/m
Sextupole Field of Gradient Magnets	3.3/-5.9/0	kG/m^2
Number of Lattice Quadrupoles	72	
Magnetic Length of Quadrupoles	0.5	m
Strength of Quadrupoles	30	kG/m

The other, more important, means of insuring prompt construction of the Recycler ring is to keep the cost very low. In order to achieve this feat, all subsystems must be designed to be simultaneously lower cost. For instance, the biggest cost savings comes from placing the Recycler ring in the Main Injector tunnel and avoiding civil construction. Taking advantage of the fact that this ring operates at a fixed momentum, the magnets are built using permanent strontium ferrite magnets. By designing the magnets to require very little human labor in their construction, a substantial cost reduction is realized. Minimizing the number of magnets is accomplished by merging the quadrupole and dipole functions into gradient magnets. Because the magnetic field is permanent, no power supplies, LCW cooling systems, power distribution cables, or electrical safety systems are required. Since the permanent magnets are very stable against time and temperature, distributed correction magnets are also not needed.

In addition, technological advancements in beam pipe preparation have led to superior vacuum pressures at lower cost. Stochastic cooling is employed to provide the phase space density necessary for Tevatron Collider operations. By recycling many of the components used in the Tevatron bunched beam stochastic cooling R&D project, and minimizing the design costs for the pickup and kicker tanks by copying old Accumulator tanks, the cost of this subsystem is also minimized. The cost of instrumentation is also reduced through technological innovation, but these saving are reinvested back into the ring to provide more detailed and precise measurements of beam parameters.

The design kinetic energy of the Recycler ring is precisely 8.000 GeV. This is the design kinetic energy of the Accumulator, as well as the injection kinetic energy of the Main Injector and extraction kinetic energy of the Booster. In the past considerable debate has occurred regarding the measurement and synchronization of this energy between these accelerators. With the planned construction of the Recycler with fixed field permanent magnets, an unambiguous energy reference is installed into the Fermilab accelerator complex. All other accelerators will be energy matched to the Recycler.

1.3. Operational Roles

The purpose of the Recycler is to further increase the luminosity of the Tevatron Collider over the luminosity goals of the Main Injector by itself. The majority of the luminosity improvement comes from the ability to inject more antiprotons into the Tevatron each store.

The first role of the Recycler is to act as a high reliability storage ring for antiprotons. Because there are few power sensitive components, there are virtually no mechanisms for inadvertent beam loss. Studying the data from the existing Antiproton Source complex, composed of the Debuncher and Accumulator rings, a couple of recent statistics ratify this concern.

In 35 weeks of running, the total number of antiprotons stacked was 16.72×10^{13}. In the same time interval, the total number of antiprotons lost or dumped was 2.42×10^{13}, which is 14.5% of antiprotons stacked. Additionally, there were 506 hours of Antiproton Source downtime out of a total of 9552 hours of operation (5.3% downtime). It is not impossible to lose the beam in the Recycler, so some of the types of failures found in the Accumulator will also occur in the Recycler. Therefore, the percentage improvement in antiproton availability with the use of the Recycler will not be the full 14.5%.

The second role of the Recycler is to act like a post-Accumulator ring. As the stack size in the Accumulator ring increases, there comes a point when the stacking rate starts to decrease. By emptying the contents of the Accumulator into the Recycler periodically, the Accumulator is always operating in its optimum antiproton intensity regime.

The third role of the Recycler, and by far the leading factor in luminosity increase, is to act as a receptacle for antiprotons left over at the end of Tevatron stores. By cooling these antiprotons and reintegrating them into the Recycler stack, the effective stacking rate, and hence the luminosity, is more than doubled.

1.4. Organization of this Report

This report is organized into four chapters. Chapter 1 is the introduction. Chapter 2 is the summary of the accelerator physics issues of the Recycler ring and beamlines. Chapter 3 contains a description of the technical component subsystems as well as overviews of design specifications. Discussions and descriptions of technical component subsystems are organized to follow the Work Breakdown Structure (WBS) of the project. All technical components are contained in WBS category 3.1. The third digit of the WBS describes the component type: 1=magnets, 2=vacuum, 3=power supplies, etc. Chapter 4 summarizes the civil construction for the Recycler.