Chapter 2

The collider: Tevatron

Tevatron is the machine at Fermilab that provides the collisions we study. It collides protons with antiprotons at a center-of-mass energy ($\sqrt{s}$) of 1.8 TeV [45],[46]. At present, it is the highest center-of-mass energy available anywhere in the world. In this chapter, we shall present a sketchy overview of the principles of operation of the Tevatron in the collider mode.

The collider at Fermilab, shown in Figure 2.1, is a sophisticated device consisting of seven major components: (1) A Cockroft-Walton accelerator (the Pre-accelerator), (2) A linear accelerator (the Linac), (3) The Booster synchrotron, (4) The Main Ring synchrotron, (5) The Antiproton Source, (6) The Antiproton Debuncher, and (7) The Tevatron Ring.

First, H^- ions are created in an "ion source" by passing Hydrogen gas over a catalytic surface in the presence of free electrons. These ions are released into the pre-accelerator which produces a static electric field to propel the ions to 750 KeV. The ions are then injected into the 150 meter long Linac. This device induces an oscillating electric field between a series of electrodes

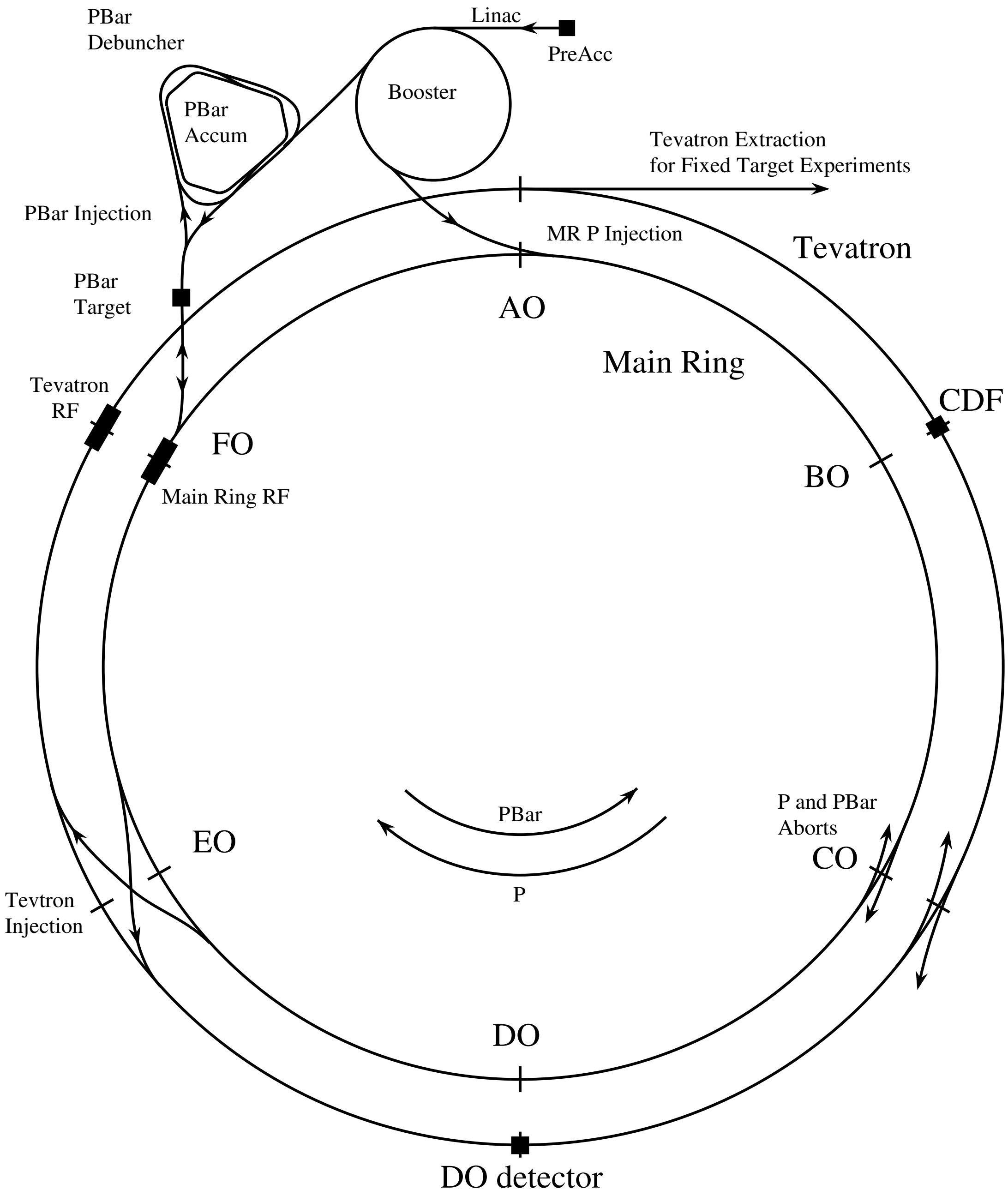

Figure 2.1: The Tevatron at Fermilab (collider mode)

which accelerates the ions to 200 MeV. The H^- ions are then sent through a carbon foil which strips both the electrons off each ion. What come out of the carbon foil are protons (H^+ ions). The protons are steered into the Booster synchrotron ring (500 meters in circumference). A synchrotron is a cyclic accelerator in which the particles are confined to a closed orbit by a series of bending magnets. Quadrupole focusing fields keep the beam from diverging. On each pass around the ring, the particle's energy is increased by acceleration in a set of synchronized Radio Frequency (RF) cavities. As the momentum increases, the magnetic field in the bending magnets must be increased to keep the particles in the ring:

$$p = qBr \tag{2.1}$$

where p is the particle momentum, q its charge, B the magnetic field and r the radius of curvature. Hence, the maximum particle energy is limited by the strength of the magnetic field and the radius of the ring. Protons exiting the Booster have an energy of 8 GeV. These protons are injected into the Main Ring (MR) which is a synchrotron consisting of more than 1,000 conventional copper-coiled magnets in a ring 6 Km in circumference. The MR accelerates the protons and coalesces them into shorter bunches. When the protons have attained 120 GeV, the bunches are extracted and directed onto a nickel/copper target creating about 2×10^7 antiprotons per bunch. For every 10^6 protons which strike the target, only about 20 antiprotons make it to the next step. A cylinder of liquid lithium creates a focusing magnetic field from a pulsed current of 600,000 amperes. This acts as a lens which keeps the antiproton beam from diverging. Following this treatment, the antiprotons are injected into the first of two antiproton storage rings.

This first ring is known as the "Debuncher" which uses sophisticated RF techniques to "squeeze" the antiproton beam further into as compact a phase space as possible. This process is known as "cooling". The Debuncher uses two cooling processes. The first, called "debunching", was invented at Fermilab. As a bunch of antiprotons circulates around the ring, computer controlled RF manipulations reduce fluctuations in the longitudinal component of the antiproton momenta. The second process, known as "stochastic cooling", restricts the transverse oscillations of the antiproton beam. Fluctuations in the circulating current are detected by sensors which send correction signals to "kicker" electrodes that, on the average, adjust the path of the wayward particle. When the process is complete, the antiprotons form a ring that looks almost static in a rotating frame of reference. The "cooled" antiprotons are transferred into the antiproton storage ring known as the "Accumulator" 2×10^{10} at a time. The Debuncher and the Accumulator are in the same tunnel which is 520 meters in circumference. Several different systems within the Accumulator provide further cooling and increase the density of the antiprotons by a factor of about 10^6. It takes four to six hours for the antiproton population in the Accumulator to reach $\sim 2 \times 10^{11}$ which is enough for a "shot" into the MR.

Next, the antiprotons are transferred to the MR, accelerated to 150 GeV and then injected into the Tevatron, travelling in the direction opposite to that of the protons. The Tevatron is in the same tunnel as the MR, but uses much stronger superconducting magnets which, operating at a temperature of 4.7 K, produce a field of $\sim$ 4 Tesla. In the final step, the 6 bunches of protons (typically 1×10^{11} per bunch) and six bunches of antiprotons (typically 5×10^{10} per bunch) are simultaneously raised to full energy i.e. 0.9 TeV for run the 1992-1993 run (christened "run 1A"). Once at full energy, the beams are squeezed very hard at two beam crossing points, BØ (CDF) and DØ . Due to all the manipulation, the beams freshly injected into the Tevatron carry a considerable amount of halo and other debris which must be removed. This is accomplished by a process known as "scraping" whereby metal plates collimate the beam. This must be performed before the detectors start collecting data. Over time, the beams decrease in density due to scattering with residual beam gases in the vacuum tube, beam-beam effects (obeying the second law of thermodynamics) and $p\bar{p}$ collisions. The typical lifetime of a beam is approximately 20 hours after which its quality falls below the lowest acceptable standard. During this time, the antiproton source runs continuously so that a "stack" of antiprotons is ready when the next shot is needed. Thanks to improvements in several aspects of the accelerator system, run 1A saw a record instantaneous luminosity ($\sim 9.0 \times 10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$), a record stacking rate (4.54×10^{10}/hour), and a record Integrated Luminosity in a week (1.48 pb^{-1}).