1.6-TeV COLLISIONS - THE ACCELERATOR PERSPECTIVE

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As a brand-new graduate student at the University of California in Berkeley in 1961, I was greatly impressed that my assigned advisor was to be Owen Chamberlain, who had won the Nobel Prize for collaborating on the discovery of the antiproton at the Bevatron in 1955. I was even more appreciative that Professor Chamberlain would spend a long time discussing academic plans with a green student from the Midwest. (In the midst of that conversation, the phone rang, and a frantic hunt for the source of the noise ensued amongst enormous stacks of papers and notebooks. My co-workers will avow that I have emulated Dr. Chamberlain at least in the matter of office clutter.)

Enrico Fermi is often credited with the suggestion that the Bevatron be built with a high enough energy to allow production of antiprotons, should they exist. As it was, in that first experiment of Chamberlain, Segre, Wiegand, and Ypsilantis, with the low intensity of a new accelerator and a beam energy barely above threshold, the antiprotons trickled in at a very slow rate. The candidate events were recorded in the form of photographs of oscilloscope traces showing pulses from velocity-sensitive detectors. In retrospect, the methods seem pretty crude, but I remember being impressed as a student with the complexity of the experiment.

Later, while working on my thesis experiment, I remember suggesting to Denis Keefe that antiprotons could be made to collide with the protons in the Bevatron. "The rate would be too low," he replied, and the speed of his response led me to believe that I was not the first person to have thought of the idea. Of course I did not know then that 20 years later, at a Midwestern lab named in Fermi's honor, I would be privileged to help make antiproton-proton collisions occur at beam energies more than 100 times those of the Bevatron. This is a personal account of some of the activities of many dedicated people in the Main Control Room and the RF Building at F0 that contributed to that achievement.

Chronologically, I suppose the story begins on August 28th, although a tremendous amount of preparatory work had already gone on before that date. To begin with, as the Design Report attests, the Tevatron had been designed and built with colliding beams in mind. Also, extensive modifications to the Main Ring and the Tevatron had already been accomplished on previous shutdowns, including the CDF Collision Hall and detector installation, the beam-squeezing quadrupoles at B0, the D0 overpass, the antiproton beam transfer system from the Main Ring to the Tevatron, and the system at F17 for extraction of protons to the production target and injection of antiprotons from the source. Furthermore, extensive studies related to the collider mode as

SEQUENCING

SEQUENCER	40 TIMERS (KICKERS, ABORT, RF, LAMBERTSONS, BUMPS) HALT/CONTINUE Q1 POLARITY REVERSAL ν's, ξ's, COUPLING STORE NUMBER, DURATION TIME LOG FILE
COORDINATE ACCELERATOR COMPLEX	DETERMINE CYCLE TYPE FOR BOOSTER, MR, TEV. AND ACCUMULATOR LATER
TEV COORDINATION	BUS CURRENT WAVEFORM RF CURVES 29 TIMERS, 11 CIRCUITS (ν's, ξ's, COUPLING, EXTRACTION) BØQ1 CURRENT 216 DIPOLE CORRECTION ELEMENT TIME/ENERGY SLOTS
LOW BETA SEQUENCE	4 LOW BETA CIRCUITS 6 ν, ξ, COUPLING CIRCUITS 20 CORRECTION DIPOLE CIRCUITS
SEQUENCED DATA ACQUISITION	MR & TEV BEAM POSITION MONITOR INFORMATION AND MORE LATER
AND MORE LATER	

This flow chart (courtesy of Dave Finley) shows some of the steps necessary for Tevatron operation as a collider.

well as Antiproton Source tests had been possible, many of them parasitic to the fixed-target program, thanks in part to a flexible time-line generator which allowed multiple Main Ring ramps of different types between Tevatron injection cycles. The number and type of Main Ring ramps were a subject of almost daily negotiation. The parasitic studies included sending protons backwards down the various beam transport lines to simulate the antiprotons that would eventually be carried, as well as optimizing the beam storage lifetimes in the Tevatron and testing the beam-squeezing techniques at B0.

Still, it was not until the 28th that our undivided attention could be devoted to the colliding-beams test. The demise of the fixed-target program a few days prematurely as a result of a Tevatron magnet problem was met with poorly-disguised glee in the Accelerator Division. People were clearly anxious to get on with the job.

In cognizance of the hyperbolic accounts of our forthcoming efforts that had appeared in the popular press, someone entitled the new commissioning log book the "Large-scale antimatter production log." Daily meetings were held in the Dungeon at 4:30 p.m. to discuss prospects, problems, plans, and priorities. Helen Edwards orchestrated the show, coordinating, cajoling, and convincing. She made it look easy. (I saw a man on TV once, juggling chain saws; he made it look easy, too.) I was impressed by the honesty with which people divulged their problems and the general spirit of cooperation which led people to adjust their plans in response to the setbacks of others. Equally striking was the rate of progress, the almost daily litany of new technical achievements. Still it was a race that was clearly going down to the wire. In fact, the present long shutdown was postponed more than once because of the anticipation of eventual success.

One concern was the antiproton accumulation rate. Despite our best efforts, the Booster would only produce about two trillion protons for antiproton production per cycle; worst yet, the Main Ring would only accelerate about half of them. This was about half the number called for in the Tevatron I design report; the Main Ring cycle rate was also set conservatively at half the value called for in the Tevatron I design. With the Antiproton Source falling further large factors below the design accumulation rate, it soon became apparent that special measures would be necessary to cope with the small numbers of antiprotons. Special high-gain detectors had been implemented to give information about the behavior of the antiproton beam in the rings. However, the antiproton-beam signals were still too small to control the feedback loops in the Main Ring low-level rf. At a memorable meeting, Helen Edwards suggested that we use protons in the Main Ring simultaneously with the antiprotons as "guide dogs" for the feeble antimatter beams. Hectic efforts ensued, soon successful,

to reconfigure the rf and recalculate a slower Main Ring ramp, since half the cavities would be used to accelerate each beam.

Many of the new beam gymnastics involved the rf and thus led to seemingly chaotic activity at F0. The necessary manipulations included "bunch rotation," whereby proton bunches are shortened before striking the antiproton production target; "cogging," which moves bunches azimuthally in the Main Ring so that, after transfer to the Tevatron, they will meet at the straight sections; "coalescing," or merging many bunches into a single intense bunch at 150 GeV in the Main Ring, and bidirectional acceleration in the Tevatron (and, as it turned out, in the Main Ring, too). Synchronization of the beams was aided by a new beam-sync lock.

One modest contribution resulted from a request, months before, from John Elias to show him how to reduce the radiation dose to the CDF detector. I showed him how easy it was to move the beam around locally in the Main Ring with "three-bumps" to minimize losses. He was apparently so impressed that I became the unofficial defender of their multimillion dollar detector against radiation damage. Later, as the Main Ring intensity was coaxed higher, it became more difficult to control losses near B0. There were times when, as a last resort, I scraped the beam against the wall elsewhere to reduce losses where they mattered most. Finally, I accidentally discovered, while doing resonance corrections to improve the intensity, that the correctors for the half-integer tune lines could be used to make the beam smaller in the Main Ring at B0. Fortunately, this expertise will probably be rendered obsolete by the new B0 overpass.

Rol Johnson had written an application program which he called a "sequencer," shown on page 5. It looked like a wish list of all the things that needed to be done to accomplish colliding beams. Almost magically, interrupting under a line in the list invoked other programs to implement one of the many required beam manipulations. This process was supplemented with frequently refined recipes describing what to do at each step.

Activities in the Main Control Room alternated between long slow periods of antiproton production and frantic periods of attempting to inject and accelerate the antiprotons. During the antiproton production shifts we also ran cycles for testing the other acceleration modes. Beam was getting lost during the radial excursions necessary for cogging. The instability could be prevented by raising the current in the Main Ring chromaticity-correcting sextupoles, but that caused the sextupoles to drop like flies due to overheating. Finally, Howie Pfeffer found a ramp which cured the problem (rather than the sextupoles).

During the last production sequence on Saturday, October 12th, the antiproton stack had reached a record number of more

than ten billion pbars, which prompted a celebration featuring Dejan Trbojevic's Yugoslavian plum brandy.

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                          THU  13-FEB-86  10:22

T48                 COLLIDING BEAM SEQUENCER                  *FTP**COPIES*
        *ch-plot            *log                                *filedit *COMND
*Help                                                  store  100
*set at 150/inject protns  *D69 f 15 *Stop@8.3 *T48 f  1
*store those protons                              *T48 f  2
*test rev injectn Tev-MR   *D69 f 12              *T48 f  3
*test rev injectn MR-Acc   *D69 f 13              *T48 f  4
*inject coalesced pbars    *D69 f 14              *T48 f  5
*store those ANTIprotons              *Cont>80    *T48 f  6 *D69 f 11
*ramp to 800 GeV and store *Cont@8.3 *Stop@53    *T48 f  7
*turn on low beta          *T111f  7 *B0 Newst   *Q1 revpl *T111f  8
*vary parameters  .384 .4   12   1   -2.85 5     *T111f  3 *B0 Newst
*recover from low beta     *T111f  2 *B0 new     *Q1 norpl
*recover from store        *D69 f 16 *Cont@8.3   *T49 f  7 *T48 f  8
*prepare for fixed target  *D69 f  1 *T49 f  1   *T48 f  9
---------utilities--------
*freeze squeeze            *allstop  *B0 contn
*Kill Beam                 *ABTCUP
*fly wire                  *T46 f  1
*get closed orbit          *T39
*start VAX SDA             *startSDA *stop SDA *EVT 5E   *EVT 5F

     Log Entry:
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The console TV image of Rol Johnson's sequencer program, which implements the Tevatron colliding-beam mode.

Another round of extracting the antiprotons from the source, in shots of less than a billion at a time, then commenced. Dave Finley orchestrated the operators manning the consoles, each assigned to perform particular operations and take specific scope pictures and hard copies of computer displays. An intense analysis of the pictures followed each shot to figure out how far the antiprotons had gotten and to calculate better settings and develop better strategies for the next shot. For example, the beam diagnostics for the pbars yielded immensely valuable information about how to correct transverse and longitudinal injection errors. Our poring over the pictures must have been a little like what happened in that first antiproton experiment thirty years ago. Through it all, the Director puffed on his pipe, patiently waiting and watching. The phones were abuzz with questions about what was observed at the RF Building and by the experimenters at CDF and elsewhere.

It seemed almost anticlimactic, or maybe just hard to believe, when Roy Schwitters finally called from CDF to say that they had observed a confirmed antiproton-proton collision event. Hard copies of the reconstructed event soon arrived in

the control room to convince us. More events trickled in later. Remarkably, the whole test run had used only about 25 shots and about 20 billion antiprotons, one fifth the number required in a single bunch to achieve the design luminosity. Nobody had to twist my arm when the invitation to B0 for champagne and sake appeared on channel 13. Facing a 4 a.m. to 4 p.m. shift without benefit of prior sleep, I was delighted when Leon decided to declare victory and begin the shutdown.

STATISTICS

DATE	STORE	P-BARS USED (E8)	COMMENT
5 OCT	-	10	MR SEM'S IN
"	-	10	~1 TURN MR
"	-	10	~100 TURNS MR
P-BARS CIRCULATED IN MAIN RING			
8 OCT	74-1	19	BAD ACCUM. TO MR TRANSFER
"	74-2	13	ACCELERATED IN MR
P-BARS ACCELERATED IN MAIN RING			
10 OCT	80	8	P-BARS IN TEV
"	82	6	NO GOOD
11 OCT	83	7	" "
"	84	2	" "
12 OCT	88	6.8	WRONG ACCUM. TO MR TIMING
"	89	6.5	BAD MR COGGING LOSS
P-BARS IN TEVATRON WITH MULTIPLE TURNS			
12 OCT	90	6.6	TEV COGGING PROBLEM: Q1 TRIPS
P-BARS TO 800 GEV			
12 OCT	91	5.1	MR COGGING PROBLEMS
"	92	8.4	DIED IN MR
"	93	7.4	NO PROTONS IN MR
"	94	6.6	TEV COGGING PROBLEMS
"	95	5.6	P-BARS AT LOW-BETA
CDF HAS P/P-BAR EVENTS			
13 OCT	97	8.0	SHORT RUN: GO FOR MORE P-BARS
"	98	6.7	NO GOOD
"	99	13.5	LAST STORE

TOTALS: 2E10 P-BARS USED
23 CDF EVENTS

This list (also provided by Dave Finley) of the antiproton "shots" illustrates the rate of progress toward the goal of achieving collisions in the Tevatron.