CHAPTER 6

EXTRACTION OF ANTIPROTONS FROM THE ACCUMULATOR AND TRANSFER TO THE MAIN RING

6.1 Accumulator Beam Manipulation and Extraction

Prior to extraction of the first $\bar{p}$ bunch, a nearly Gaussian distribution of $\bar{p}$'s will exist in the core. The density can be characterized by two numbers, the total number of $\bar{p}$'s in the core, N_o, and the rms energy spread, σ. If ε represents the energy difference between the particle energy and the most probable energy of the particles in the core, then the density function $\psi(\varepsilon)$ can be written as

$$\psi(\varepsilon) = \frac{N_o}{(2\pi)^{1/2}\,\sigma} \exp\left(-\frac{\varepsilon^2}{2\sigma^2}\right) \qquad (6.1)$$

The example presented here uses the following values for these parameters: $\sigma = 2.0$ MeV, $N_o = 4.5 \times 10^{11}$ and $\psi(0) = 10^5 \mathrm{eV}^{-1}$. Because we want to extract an assembly with the smallest longitudinal emittance, we begin the adiabatic capture with a bucket centered at the peak of the distribution. We plan to extract a single bunch containing 8×10^{10} $\bar{p}$'s. These $\bar{p}$'s exist within a range of ±452.5 keV. The revolution period of the ring is 1.59 μsec, so the longitudinal emittance of the core region selected is 1.44 eV-sec. The Accumulator parameters which are used in this calculation are $\bar{R} = 75.4716$ m, $\eta = 0.02$, $E_s = 8.938$ GeV, and $\Delta p/p \approx 1.6\%$ (Δp) = 142 MeV/c) from core to extraction orbit. Because η (i.e. $\gamma_t^{-2}-\gamma^{-2}$) varies over the aperture, the rf parameters determining bucket areas must be varied accordingly.

The rf voltage required to develop a single bucket of area 1.44 eV-sec at harmonic h is $V = 2.44\ h^3$. At $h = 1$, only 2.44 V is required and it may be difficult to establish such a low voltage with sufficient precision to control accurately the number of $\bar{p}$'s extracted. We propose to extract using a single $h = 2$ bucket with the remaining bucket suppressed. The required rf voltage is 19.5 V. Following adiabatic capture, a moving bucket will be established for deceleration to the extraction orbit.

The time required for this unstacking process depends upon the choice of rf voltage and synchronous phase angle. In order to minimize both the disturbance of the stacked $\bar{p}$'s and the particle loss from the moving bucket, the bucket will be moved very slowly, with a small phase angle. After the first $\bar{p}$ bunch has been extracted and placed in the Tevatron at 150 GeV, the duration that this bunch is required to reside in the Tevatron at low field depends upon the time required to extract the remaining bunches from the core. If the lifetime at 150 GeV is not long enough, it may be necessary to accelerate the process. Optimization of this time can only be accomplished after the Energy Saver and the Antiproton Source are operational. The rf voltage required to maintain the specified bucket area, the deceleration rate, and the time required for deceleration to the extraction orbit are shown in Table 6-I for several synchronous phase angles.

TABLE 6-I RF PARAMETERS FOR DECELERATION TO THE EXTRACTION ORBIT (CONSTANT BUCKET AREA 1.44 EV-SEC.)

ϕ_s (deg)	$\Gamma=\sin\phi_s$	$\alpha(\Gamma)$	V_{rf}(volts)	Decel.Rate (MeV/sec)	Decel.Time (sec)
10	0.1736	0.696	36.2	3.33	43
20	0.3420	0.4918	72	12.93	11
30	0.500	0.3334	157	41.1	3.5

Frequency and phase control of the rf system during unstacking may be improved by a phase-lock system that partially locks the system to the coherent component of beam current. Since this component of current is of order 10 mA, detection and phase locking should not be technically difficult. The bunch length during the unstacking process will be about 500 nsec.

A bunch of 1.44 eV-sec area is too large to accelerate in the Main Ring without large loss and dilution. It is therefore necessary to subdivide the bunch into smaller ones. This subdivision is accomplished by adiabatically capturing the h = 2 bunch into h = 84 (53 MHz) buckets supplied by the same rf system used for the injection stacking. The resulting bunches can be synchronously transferred into standard Main Ring buckets. The optimum number of bunches, which depends on the longitudinal emittance to be transferred and details of a later recombination process, lies in the range of 11 to 13. On the other hand, the bunch produced by the 100-V suppressed-bucket cavity spans many more 53-MHz buckets; between 500 V and 1 kV is required to shorten the bunch. The additional 900 V is generated by a fixed-frequency h = 2 system. Although this system forms two adjacent buckets, only one will contain antiprotons because of the prebunching provided by the suppressed-bucket cavity. The 1-kV bucket height is about 12 MeV or ±0.13%, so these buckets have negligible effect on the remaining cooled core. The momentum spread of the shortened h = 2 bunch is $\Delta p/p = 5.2 \times 10^{-4}$, easily accepted by the Main Ring.

After the eleven to thirteen 53-MHz bunches have been established on the extraction orbit, the extraction kicker shutter is closed, isolating the bunches from the accumulated beam. The bunches are then extracted and delivered to synchronized Main Ring buckets.

Movement of the isolated extraction bucket through part of the stack results in partial replacement of the antiproton density in the core by displacement deceleration from the stack above. Moreover, the cooling system quickly fills the depleted region left by the extracted bunch. During the acceleration of the extracted beam to 150 GeV and prior to the next extraction, core cooling systems will re-establish adequate core density.

The single bucket rf wave consists of one complete sinusoidal wave with a period of one half the rotation period. Because the fundamental frequency is 0.632 MHz, such a wave can easily be generated with Fourier components below 100 MHz. The accelerating structure may consist of an insulating gap in the beam pipe in parallel with a 50 Ω resistance of sufficient power-dissipating capability. This structure will be contained within a shielded enclosure with sufficiently high shunt inductance (introduced by high-permeability ferrite) so that the load presented to a broad-band amplifier will be essentially real over the operating range. The power requirements will be less than 100 W. The 50 Ω real impedance presented to the beam by this structure is well within the longitudinal-stability impedance limit.

The additional 900 V at h=2 is required only at a single frequency at the extraction momentum. It will be developed by a single ferrite-loaded resonant accelerating cavity with a shunt impedance of 1 kΩ. This shunt impedance meets the beam-stability requirement and the required voltage can be developed with an excitation power of 400 W.

After the single antiproton bunch has been narrowed to span the desired number of 53-MHz buckets, the h = 84 system is turned on adiabatically over 30 msec to 120 kV. The initial 1.5 eV-sec bunch, 244 nsec wide, shown in its h = 2 bucket in Fig. 6-2, is subdivided into thirteen h = 84 bunches. An intermediate stage in this operation is shown in Fig. 6-3 with the central h = 84 bucket indicated. The h = 2 voltage can be left unchanged. At this stage, the distribution lies just within a "ruffled" separatrix, the bucket arising from the sum of the two voltages. The final emittances of the five central bunches are approximately 0.15 eV-second and the outermost bunches are approximately 0.05 eV-sec. At the end of this process, the bunches are matched to 500-kV Main Ring buckets.

Extraction from the Accumulator occurs using a 2.1336 m long shuttered kicker and a 2.921 m long Lambertson magnet. The extraction orbit is rf displaced radially outward by 0.825% in Δp/p. At station A20 in the high dispersion straight section (See Fig. 5-1), the extraction closed orbit is displaced 71.5 mm outward. The orbit parameters are β_x=7.06 m, β_y=6.63 m, and $\alpha_x=\alpha_y=0$. A shuttered kicker centered 6.32 m downstream of station A20 gives the extracted beam an inward kick of 2.5 mrad and moves the extraction orbit to a position of x=37.19 mm, x_0=-0.002 mrad at the entrance to the Lambertson magnet. Figure 6-1 shows the extraction orbit. The Lambertson then bends the beam up by 100 mrad.

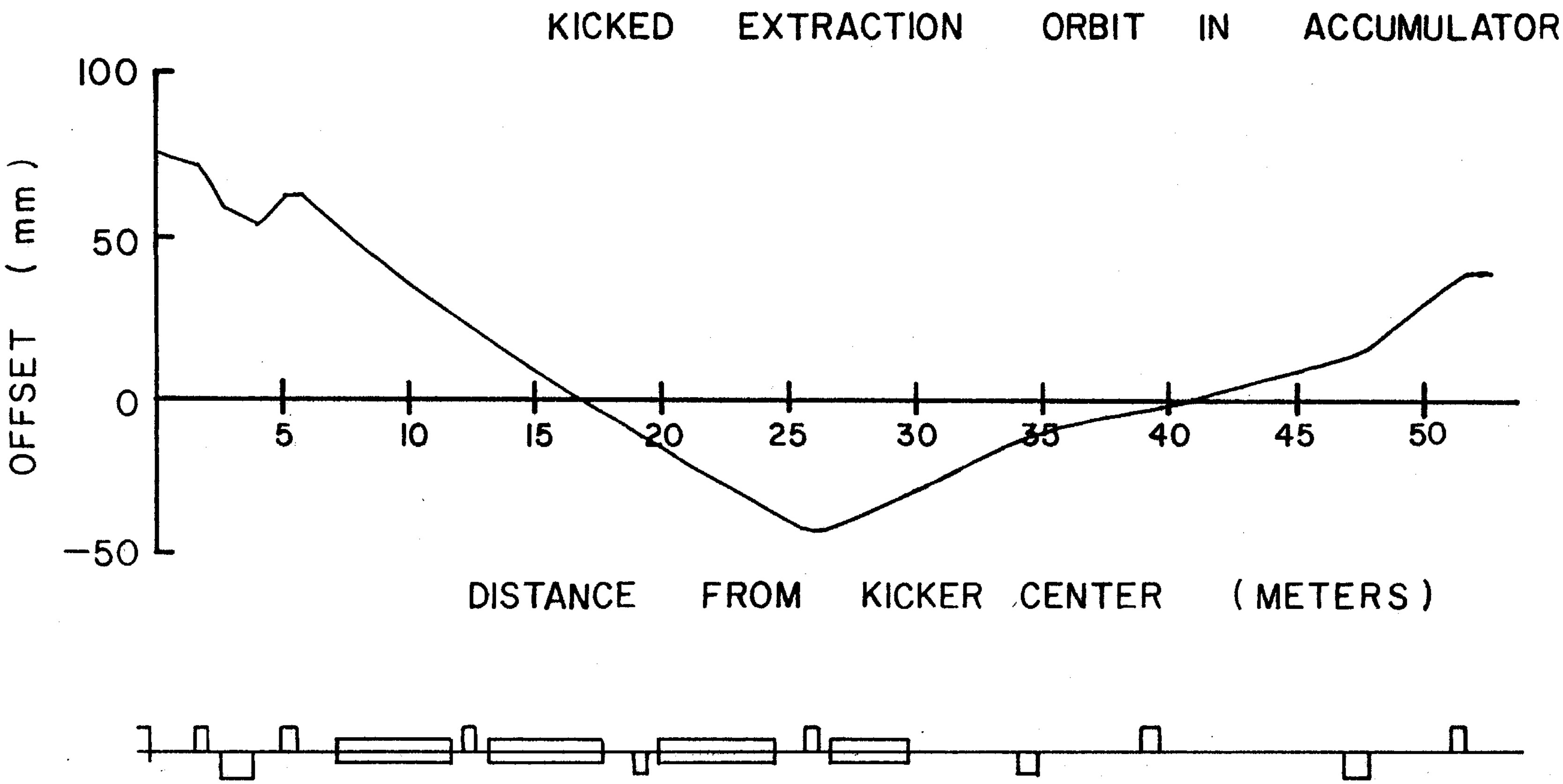
KICKED EXTRACTION ORBIT IN ACCUMULATOR
OFFSET (mm)
100
50
0
−50
5
10
15
20
25
30
35
40
45
50
DISTANCE FROM KICKER CENTER (METERS)

Figure 6-1

6.2 Main Ring Acceleration and Bunch Recombination

6.2.1 Introduction. We describe here the acceleration in the Main Ring of the several contiguous antiproton bunches that will constitute a single bunch in the Tevatron and the process whereby that single bunch is formed before extraction. Statements containing numerical values refer to the same illustrative example used in the preceding section, that is, 11 to 13 bunches with a total emittance of about 1.5 eV-sec.

6.2.2 Injection and Acceleration. The injection process is similar to injection from the Booster except that the Main Ring RF is phase-locked to the Accumulator. The injected intensity is lower by a factor of 20, and the batch is about 1/7 as long as a Booster batch. These differences require that the Main Ring be tuned differently from the $\bar{p}$-production mode, but do not represent unreasonable requirements for the same rf system. In addition, the Main Ring voltage should be about 500 kV to match the bucket produced by the h = 84 system in the Accumulator.

The longitudinal emittance is expected to increase by a factor of about 1.5 during acceleration. Recent studies in the Main Ring and careful simulation of transition crossing both indicate that bunches with initial longitudinal emittance in the range 0.2 to 0.3 eV-sec are diluted by a factor of about 1.25 between injection and γ=21, above transition. This dilution is accompanied by a slight bunch-to-bucket shape mismatch so that further dilution resulting from coherent bunch motion within the bucket results in the total dilution during acceleration of a factor of approximately 1.5.

6.2.3 Bunch Recombination at 150 GeV. At 150 GeV, the Main Ring field is held on flat top while the 13 adjacent bunches are coalesced into a single bunch. The h=1113 rf voltage is reduced slowly over a period of 0.1 seconds to about 12 kV by counterphasing equal numbers of rf cavities. At this voltage, the bucket containing the center bunch is nearly full. Adjacent buckets are not quite full and the total longitudinal emittance of all the bunches is about 2.2 eV-sec. At this time, the h=53 rf system is turned on at a voltage level (700 V) such that the h=53 bucket is matched to a 2.2 eV-sec distribution extending over the filled h=1113 buckets, 245 nsec. At the same time the counterphased Main Ring rf voltage is turned off and replaced by a single small h=1113 rf cavity at 12 kV. The voltage of this cavity is then lowered slowly to (nominally) zero so that the adjacent bunches are adiabatically debunched into matched orbits in the h=53 bucket. A simulation of this process, starting with bunch distributions derived from previously simulated acceleration is shown in Figs. 6-5 and 6-6. The result is a uniform bunch of about 2.4 eV-sec matched to the h=53 bucket and spanning a range $\pm 2\pi/3$ radians.

The next step in the bunch-coalescence procedure is to rotate the extended low momentum spread distribution into a vertical strip with sufficiently short time duration so that it can be contained within a single 53-Mhz (h = 1113) bucket. Because the bunch initially spans a range

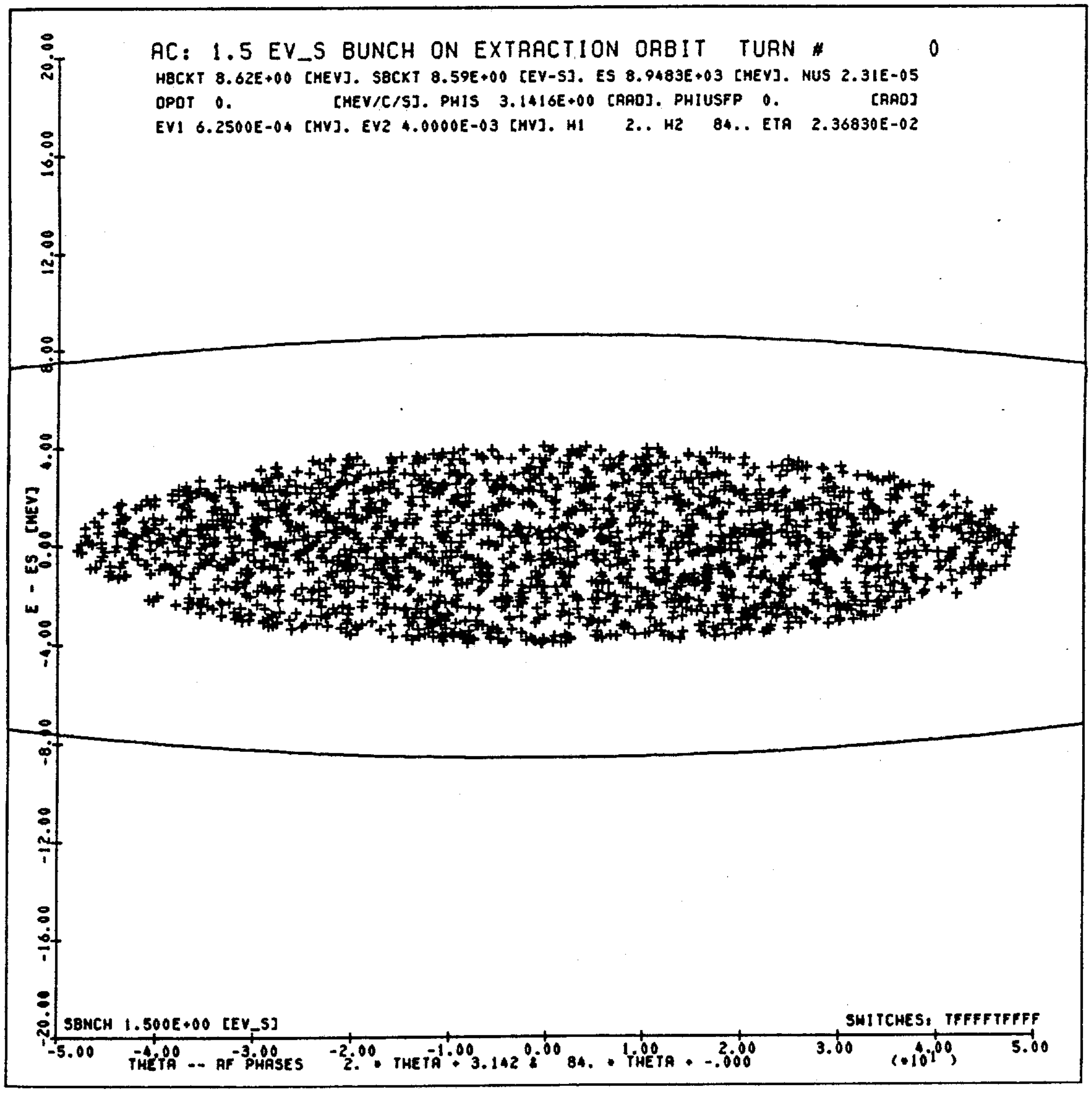
AC: 1.5 EV_S BUNCH ON EXTRACTION ORBIT TURN # 0
HBCKT 8.62E+00 [MEV]. SBCKT 8.59E+00 [EV-S]. ES 8.9483E+03 [MEV]. NUS 2.31E-05
OPDT 0. [MEV/C/S]. PHIS 3.1416E+00 [RAD]. PHIUSFP 0. [RAD]
EV1 6.2500E-04 [MV]. EV2 4.0000E-03 [MV]. H1 2.. H2 84.. ETA 2.36830E-02
20.00
16.00
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
-16.00
-20.00
E - ES [MEV]
SBNCH 1.500E+00 [EV_S]
SWITCHES: TFFFFTFFFF
-5.00
-4.00
-3.00
-2.00
-1.00
0.00
1.00
2.00
3.00
4.00
5.00
THETA -- RF PHASES 2. * THETA + 3.142 & 84. * THETA + -.000
(*10^1)

Figure 6-2

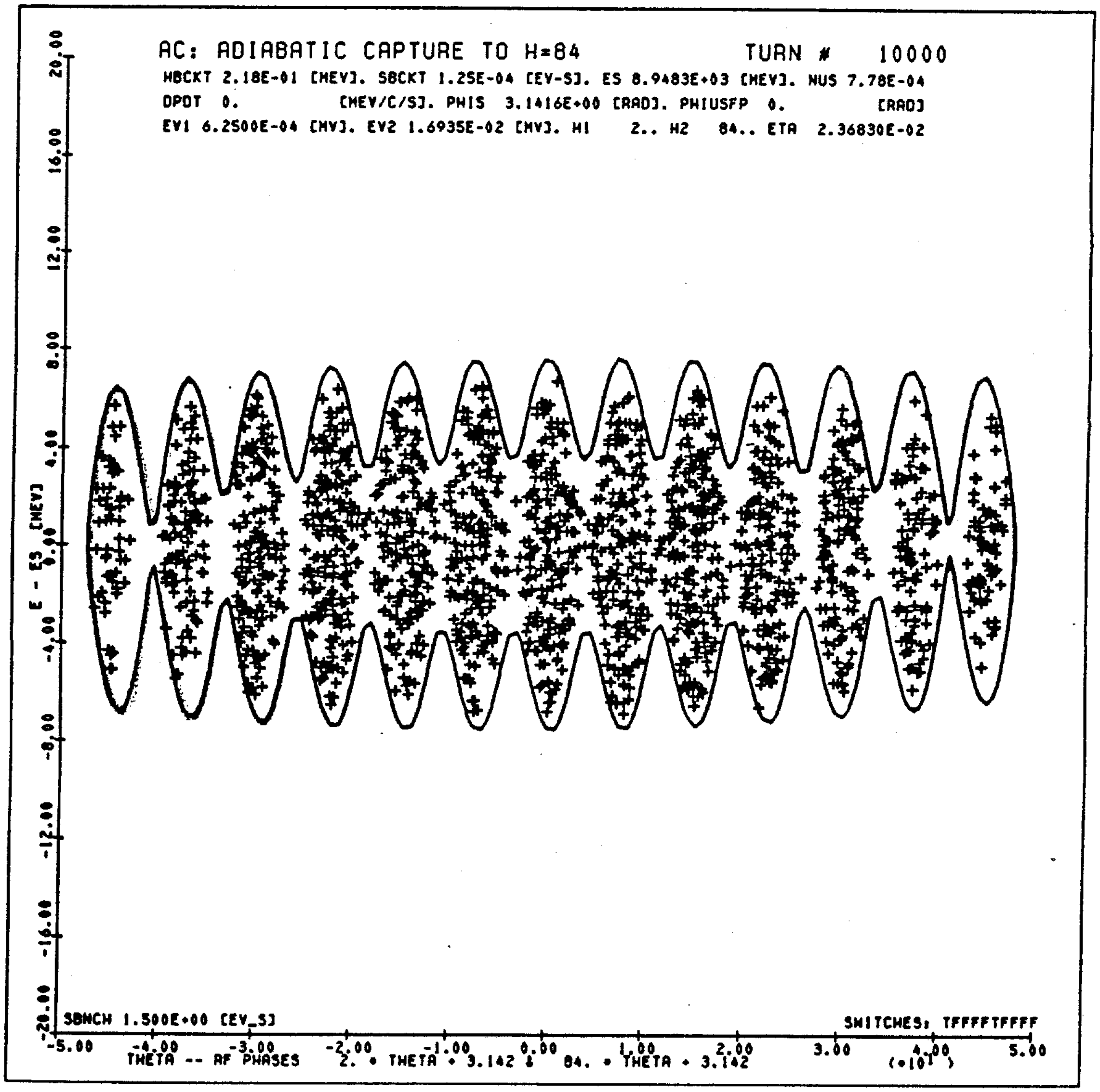
AC: ADIABATIC CAPTURE TO H=84
TURN # 10000
HBCKT 2.18E-01 [MEV]. SBCKT 1.25E-04 [EV-S]. ES 8.9483E+03 [MEV]. NUS 7.78E-04
DPDT 0. [MEV/C/S]. PHIS 3.1416E+00 [RAD]. PHIUSFP 0. [RAD]
EV1 6.2500E-04 [MV]. EV2 1.6935E-02 [MV]. H1 2.. H2 84.. ETA 2.36830E-02
E - ES [MEV]
20.00
16.00
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
-16.00
-20.00
SBNCH 1.500E+00 [EV_S]
SWITCHES: TFFFFTFFFF
-5.00
-4.00
-3.00
-2.00
-1.00
0.00
1.00
2.00
3.00
4.00
5.00
THETA -- RF PHASES 2. * THETA + 3.142 & 84. * THETA + 3.142
(*10^1)

Figure 6-3

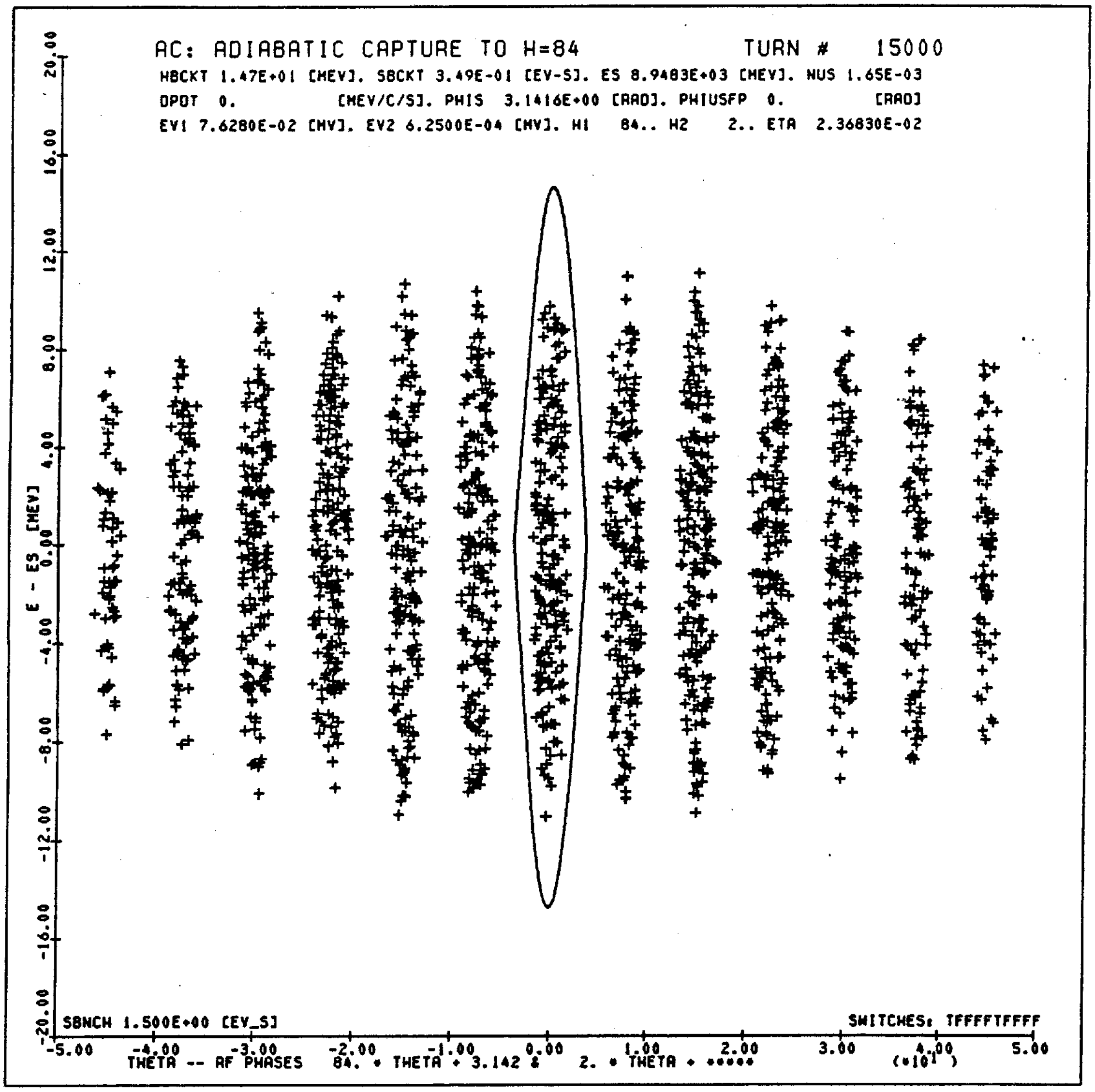
AC: ADIABATIC CAPTURE TO H=84 TURN # 15000
HBCKT 1.47E+01 [MEV]. SBCKT 3.49E-01 [EV-S]. ES 8.9483E+03 [MEV]. NUS 1.65E-03
DPDT 0. [MEV/C/S]. PHIS 3.1416E+00 [RAD]. PHIUSFP 0. [RAD]
EV1 7.6280E-02 [MV]. EV2 6.2500E-04 [MV]. H1 84.. H2 2.. ETA 2.36830E-02
E - ES [MEV]
20.00
16.00
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
-16.00
-20.00
SBNCH 1.500E+00 [EV_S]
SWITCHES: TFFFFTFFFF
-5.00
-4.00
-3.00
-2.00
-1.00
0.00
1.00
2.00
3.00
4.00
5.00
THETA -- RF PHASES 84. * THETA + 3.142 & 2. * THETA + *****
(*10¹)

Figure 6-4

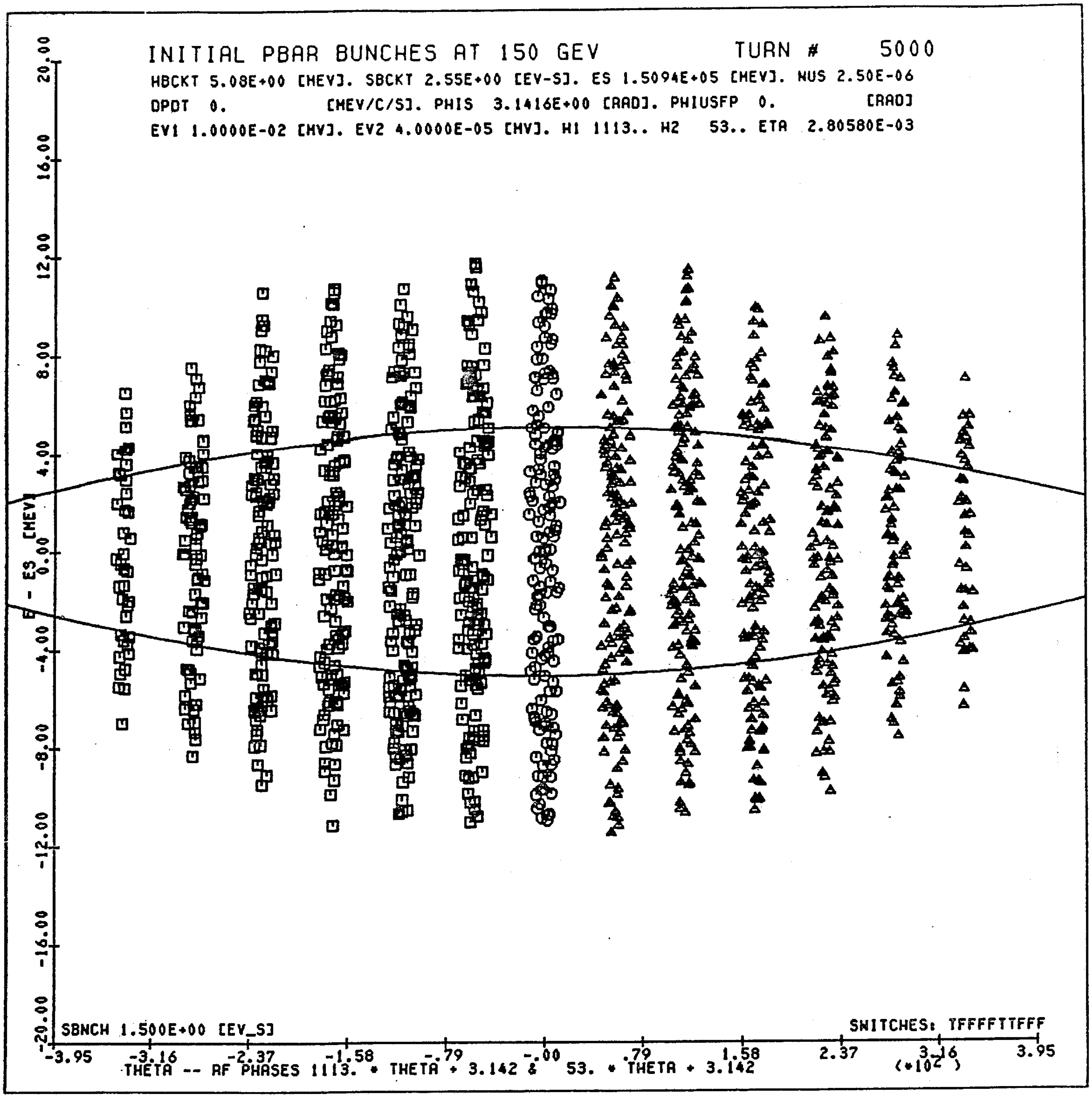

Figure 6-5 Adjacent antiproton bunches prior to final h=1113 debunching. The bucket outline shown is an h=53 bucket which will match the distribution of the coalesced bunches. The particles in the lefthand bunches have been indicated by squares, those in the center bunch by octogons, and those in the righthand bunches by triangles to aid in interpretation of the coalesced distribution shown in the following figere

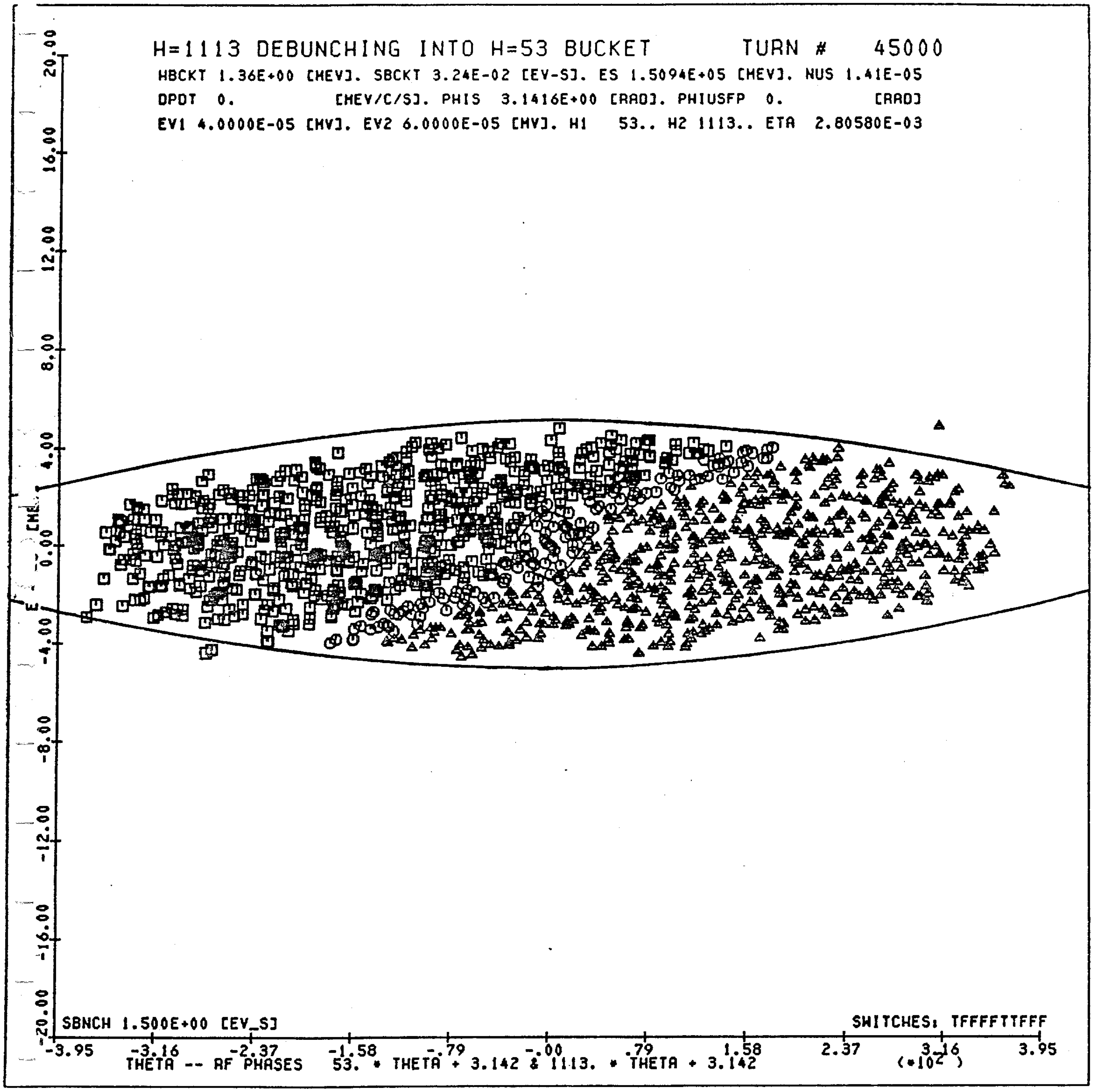

Figure 6-6 The antiproton distribution within the h=53 bucket following slow removal of the h=1113 rf voltage. The bunch extends over ± 13/21 π radians within within the bucket and the longitudinal emittance (95%) is about 2 eV-sec. Particles originating from h-1113 bunch left of the central bunch are indicated by squares, those from the central bunch by octagons, and those from the right-hand bunches by triangles.

of ±2π/3 radians in the h = 53 bucket, rotation within a h = 53 bucket created by a sinusoidal rf voltage at 2.53 MHz would not be satisfactory because of the spread in phase-oscillation period. Antiprotons on the outer edges of the distribution would lag behind those nearer the center and the vertical strip would be decidedly S-shaped. In order to "linearize" the synchrotron motion, the rf cavity wave-shape has been augmented with appropriate amounts of second, third, and fourth harmonics so that the rf gap voltage is linear to within about 10 percent between ±0.63π radians. In this circumstance, particles within the linear portion of the wave move with harmonic motion of nearly constant period so that the entire distribution reaches maximum momentum spread and minimum time spread at approximately the same time.

In Fig. 6-7, a simulated result of such a rotation is shown. The rf voltage used for this simulation was composed of a fundamental h = 53 voltage of 22.8 kV and a second-harmonic component of 4.9 kV at the correct phase angle for optimum linearization.

In Fig. 6-8, we show the results of a preliminary experiment in bunch coalescing. The experiment is done at h = 159 using four adjacent proton bunches. The successive oscilloscope traces starting at the bottom of the pictures show two or four proton bunches merging into a single bunch of larger intensity and emittance, as expected. Since the bucket covered only seven h = 1113 bucket lengths, the four bunches extended farther into the bucket than is proposed. This results in a more nonlinear process than will occur in the proposed scheme.

Following recapture, the rf voltage is raised to 1 MV. As a result, the bunch length shrinks to 12 nsec full width, and the bunch height grows to ±166 MeV, corresponding to a momentum spread $\Delta p/p$ of $\pm 1.1 \times 10^{-3}$. The bunch parameters are ideal for injection into pre-established matching buckets in the Tevatron.

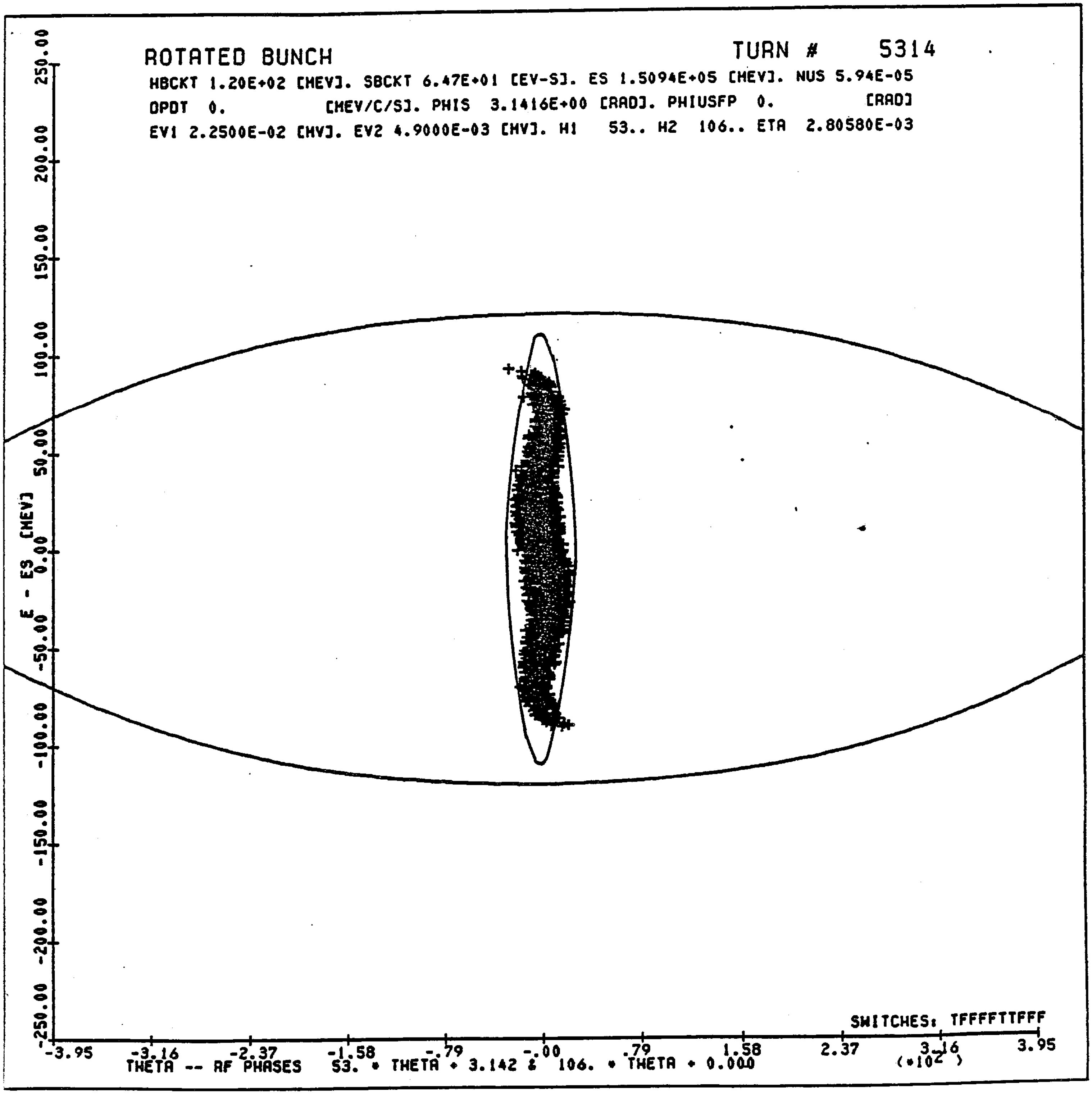

Figure 6-7 Antiproton distribution following bunch rotation in h=53 bucket. The rotated distribution has a full length of about 16 nsec and spans an energy range of ±100 MeV.

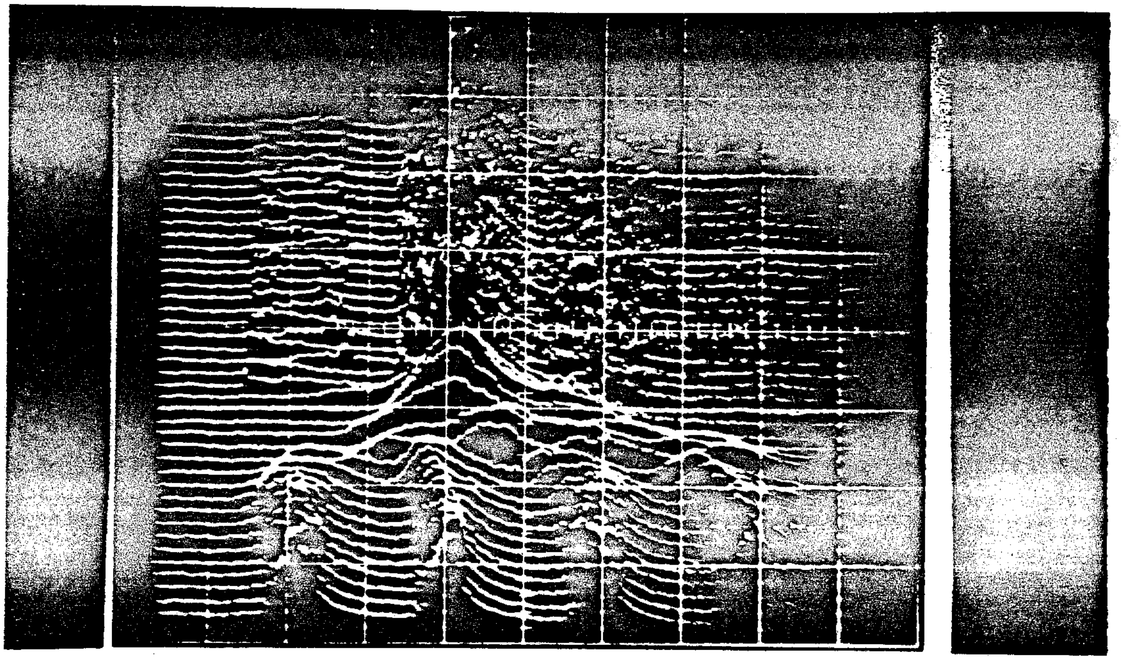

Figure 6-8a

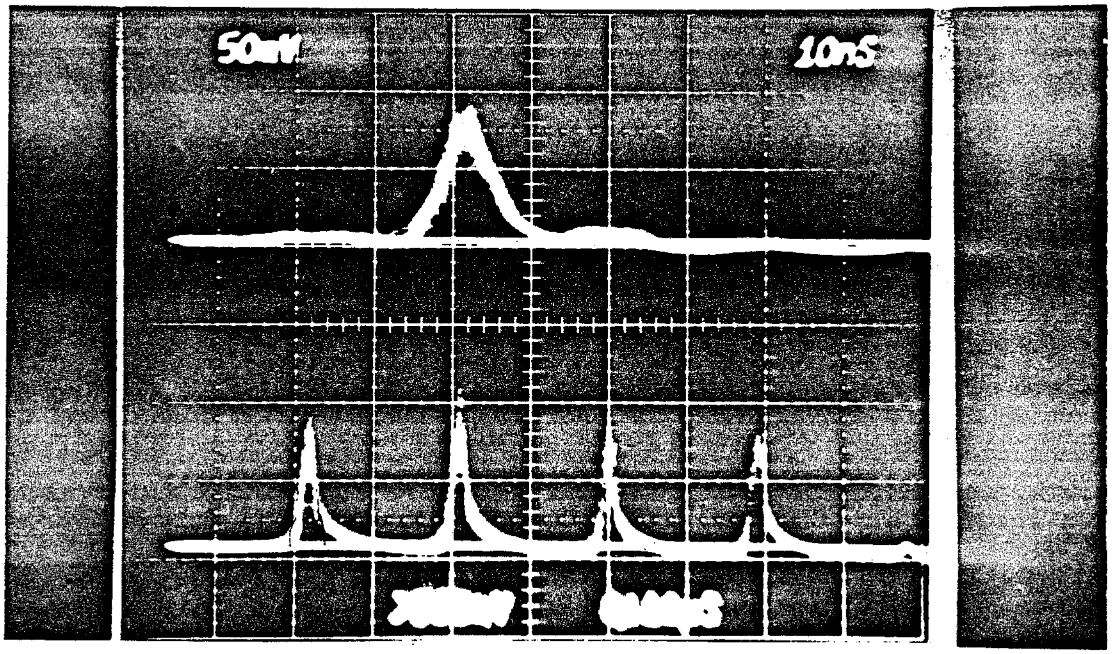

Figure 6-8b

Figure 6-8 Results of an early experiment in coalescing adjacent 53 MHz bunches in a lower harmonic bucket. The experiment was done at h=159 (7.5 MHz) where the lower harmonic bucket spans seven 53 MHz buckets. (a) The evolution of the coalescing process, time progressing upwards in 5ms steps. (b) The four bunches .1s before and .1s after coalescing. The coalescing efficiency (ratio of areas under the peaks) is about 90%. The time base is 10ns per major division in both pictures.