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DECELERATION OF ANTIPROTONS IN THE FERMILAB BOOSTER

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SUMMARY

Deceleration has been studied in longitudinal phase space by numerical simulation of the phase motion. Longitudinal acceptances as a function of the antiproton injection momentum, the transition energy and the ramp of the magnetic field are presented. Preliminary deceleration experiments with protons are discussed.

INTRODUCTION

As presently proposed, the antiproton facility at Fermilab will utilize electron cooling as a part of the collection scheme.[1] Antiprotons are to be produced at around 6 GeV/c by 80 GeV/c protons, and decelerated to 200 MeV, the normal injection energy of the Booster, for cooling and accumulation in a separate ring. As deceleration is to take place in the Booster, its acceptance in longitudinal and transverse phase space will be a factor in the maximum accumulation rate of antiprotons.

A computer program was used to simulate the behavior of antiprotons in the longitudinal phase space. The purpose was to study the Booster acceptance, the optimum momentum for injection and the magnetic field ramp, and the effects of crossing the transition.

NUMERICAL METHOD

The equations of phase motion of particles were written in terms of the canonical variables, the differences in phase, q, and angular momentum, y.

An ensemble of 200 particles was generated for each case studied, either on an ellipse defined by input parameters $\pm q_{max}$ and $\pm y_{max}$ (unmatched input); or around a trajectory in phase space as defined by one input parameter, $+q_{max}$, (matched input). Matched inputs were used with injection momenta away from transition by at least 0.25 GeV/c.

The maximum step for integration is taken as one revolution in the machine. The minimum number of integration steps was determined requiring that an ensemble of particles of area much smaller than the bucket area at $\bar{p}$ injection, taken below transition, be decelerated to 200 MeV without dilution of the longitudinal emittance. The RF cavities are assumed to be uniformly distributed around the ring. This is an approximation as 18 RF stations are in one half of the ring only. The amount of RF voltage is obtained from interpolation on the curve of voltage vs. frequency, shown in Figure 1. The curve is an approximation of the actual voltage and reflects the variation of the cavity characteristics with frequency.

Higher order terms have been included in the equation of motion.[2] The Johnsen coefficient α_2 was determined by measuring the chromaticity of the Booster near transition using the approximate relation[3]

$$\alpha_2 \simeq 1 - 2 \, . \, \xi_0 - \Delta\xi$$

where ξ_0 is the horizontal chromaticity of the linear machine and $\Delta\xi$ is the change due to the sextupole fields. We obtained a value of α_2 = -0.2, far from the ideal value of -1.5 for which there is no second-order effect.

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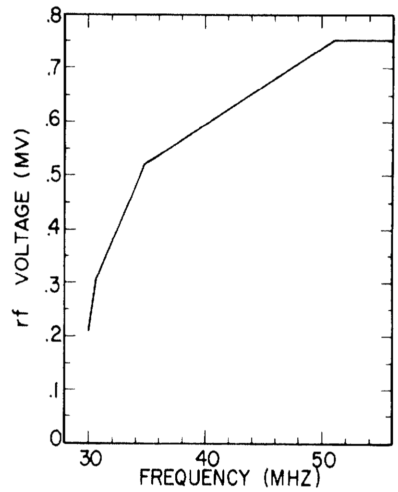

Fig. 1. Total Booster RF voltage vs. frequency used in the numerical calculations.

ANTIPROTON INJECTION MOMENTUM

Antiprotons will be produced by protons from the Main Ring. The time structure of the protons will then be transferred to the $\bar{p}$, i.e., $\bar{p}$ will be produced in bunches at the same frequency and with the bunch length of the main ring protons. For the synchronous transfer of $\bar{p}$ bunches into $h_{\bar{p}}$ Booster buckets, it can be shown that the antiproton's velocity $\beta_{\bar{p}}c$ can be expressed as a function of the velocity of the primary protons $\beta_p c$ and the harmonic number used for proton acceleration h_p.

$$\beta_{\bar{p}} = h_p \, \beta_p / \, h_{\bar{p}}$$

This is valid only for a synchronous transfer between the Booster and the Main Ring. For normal Booster acceleration h_p = 84 and for 80 GeV/c protons we obtain,

$h_{\bar{p}}$	$\beta_{\bar{p}}$	$p_{\bar{p}}$(GeV/c)
85	0.9882	6.045
86	0.9767	4.268
87	0.9655	3.476

NUMERICAL RESULTS

The results of the deceleration calculations for the cases listed above, and some higher harmonic numbers for comparison, are summarized in Figures 2 and 3. Figure 2 corresponds to matched inputs labeled as a function of the harmonic number, and plotted in the Δp/p (relative momentum) and "q" plane. Each point represents the maximum beam area decelerated with no losses. The corresponding value in [eVs] is given for each point. All cases are for deceleration with the normal magnet ramp up to 8.89 GeV/c and transition momentum at its nominal value of 5.02 GeV/c. The dotted lines indicate the direction of increased beam area resulting in losses. The importance of the Main Ring

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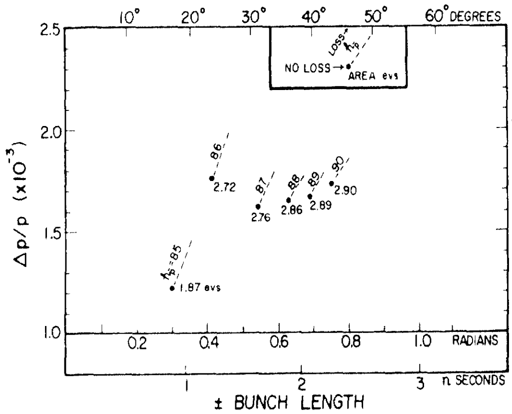

Fig. 2. Longitudinal acceptance for deceleration of $\bar{p}$ as a function of harmonic number for matched bunches.

bunch length can also be seen in Figure 2. In order to decelerate 6.05 GeV/c $\bar{p}$, as proposed, without losses the bunch length will be required to be less than ± 0.3 rad. This should be compared with the present bunch length at 80 GeV/c of about ± 0.4 rad. The increase in Booster acceptance for larger harmonic numbers, which corresponds to lower $\bar{p}$ injection momenta, is due to higher frequencies throughout the cycle. This results in higher RF voltages and lower phase angles for deceleration.

In Figure 3 we summarize the effect of different values of the peak momentum of the Booster ramp and of the transition energy for harmonic numbers 85 and 86. The regions of acceptance with no losses for unmatched inputs and transition momenta close to injection are indicated by the shaded areas. A larger $\Delta p/p$ acceptance is obtained at the expense of the one in bunch length. Capturing a larger fraction of the produced $\bar{p}$ in the Booster by increasing the $\Delta p/p$ acceptance depends on the minimum bunch length that can be obtained in the Main Ring. Injection at the peak of the ramp, as opposed to during the decreasing field, increases the $\Delta p/p$ acceptance by ~ 25% with little effect on the accepted bunch length.

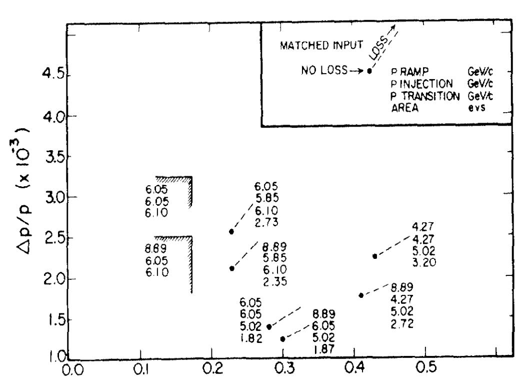

Fig. 3. Longitudinal acceptance for deceleration vs. magnet ramp and transition energy for matched and unmatched (shaded area) bunches.

In conclusion the most important single parameter in selecting the injection conditions for antiproton deceleration is the bunch length in the Main Ring at 80 GeV/c. The production cross sections should also be considered for deciding whether injecting lower momentum $\bar{p}$, for deceleration into a larger acceptance would result in an increase in the number of antiprotons accumulated.

DECELERATION EXPERIMENT

The Fermilab Booster is a rapid cycling proton synchrotron with a 15 Hz resonant magnetic field. Acceleration from 200 MeV to 8 GeV with harmonic number of 84 requires the RF system to operate between the frequencies of 30.1 MHz and 52.8 MHz.

The experiment is intended to prove that the Booster can decelerate particles and to clarify design criteria for new instrumentation and modifications. Only the initial phase of the planned studies has been completed.

Protons are injected and accelerated in the normal manner. With the extraction devices switched off, the protons remain bunched in the accelerator. Deceleration takes place in the downgoing part of the ramp following acceleration. This operation requires symmetric programs for all ramped devices around the maximum energy point. It also requires a full cycle on the RF cavities and a double crossing of transition, the first during acceleration and the second during deceleration.

The new low level RF system for the Booster[4] was used for the experiment. This system has the capability of producing the necessary curves to control the frequency, feedback loops, cavity tuning bias supplies and RF voltage over the full cycle in addition to performing the double transition phase jump.

For stability of the phase motion, the sign of the slope of the RF voltage at the synchronous phase depends only on whether the energy is below or above transition energy.

In practice, as shown in Figure 4, transition phase jumps $\Delta\varphi_A$ and $\Delta\varphi_D$ are the result of two hardware operations at transition times: i) During acceleration, the phase of the RF voltage is shifted by π; during deceleration the original phase is restored. ii) The beam-RF relative phase changes sign during acceleration from φ_{tA} to $-\varphi_{tA}$; the reverse takes place during deceleration from $-\varphi_{tD}$ to φ_{tD}.

These RF manipulations for double transition crossing were successfully implemented and 1.0×10^{12} protons were decelerated from 8.0 GeV to 4.0 GeV with no significant losses. The lower energy for deceleration was determined by the lack of regulation in the power supplies for the RF cavity tuners for rapidly decreasing frequency. The beam-RF relative phase signal and the charge in the accelerator for the full acceleration-deceleration cycle are shown in Figure 5. Losses are observed at injection time and again towards the end of deceleration.

The transition phase jump during acceleration is clearly seen. The second phase jump during deceleration can be seen just before the signal is affected by the phase errors caused by the RF cavities not tracking the frequency.

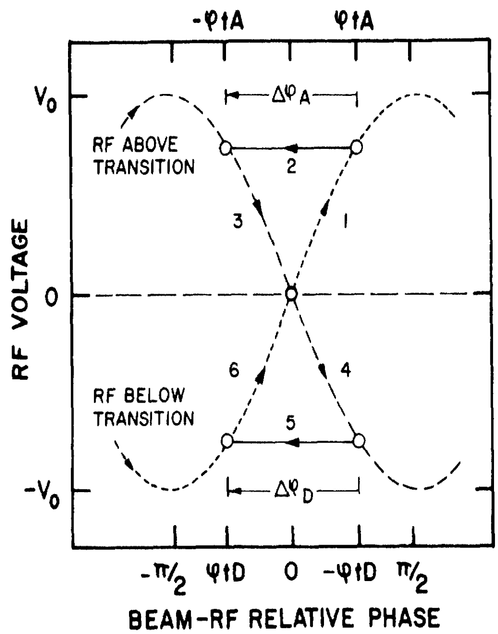

Fig. 4. RF voltage vs. beam-RF relative phase for a full acceleration (1,2,3) and deceleration (4,5,6) cycle.

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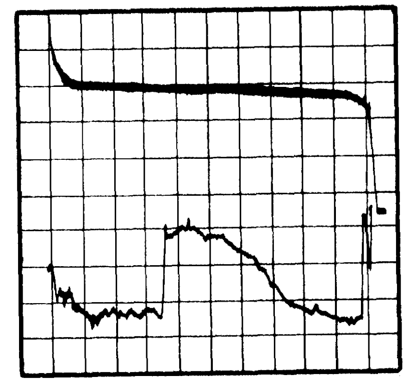

Fig. 5. Acceleration of protons to 8.0 GeV followed by deceleration to 4.0 GeV. Upper trace: charge in the machine. Lower trace: beam-RF relative phase signal with two transition phase jumps. Sweeps 5 ms/div.

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