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PREPARATION AND STUDY OF BUNCHES CONTAINING 10^{11} PROTONS IN THE FERMILAB MAIN RING

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Summary

A scenario for combining four adjacent bunches in the Fermilab main ring into a single bunch containing 10^{11} protons is described. This is to be done using a 7th sub-harmonic rf cavity. First experimental results of the procedure are shown.

Introduction

The $\overline{p}p$ program at Fermilab proposes to collide several bunches of anti-protons (3,6, or possibly 12) with an equal number of proton bunches in the Tevatron at 2 TeV c.m. energy. The total number of anti-protons will be 10^{11} and it is proposed to have 10^{11} protons in each of the proton bunches.[1)] At present, the Fermilab accelerator operates at slightly greater than 2.5×10^{13} protons per pulse with about 1080 bunches (i.e. 1080 of the 1113 main ring buckets occupied). This results in an average proton number per bunch of about 2.5×10^{10}. In order to achieve the required 10^{11} protons per bunch, it is proposed that the protons in several groups of four adjacent bunches (quartets) be coalesced and re-captured in normal (h=1113) buckets before injection into the Tevatron. Injection into the Tevatron will be done at 150 GeV so it is reasonable to do the bunch coalescence at fixed magnetic field at 150 GeV just before injection. It is preferable to do the bunch coalescing at relatively high energy rather than at injection energy (8 GeV) for several reasons; the beam size is smaller relative to the available aperature, the ratio of longitudinal emittance to available rf bucket area is favorable, and the necessity for accelerating heavily populated bunches through transition is eliminated. In experiments of a similar nature at CERN, the advisability of avoiding transition crossing with dense bunches has been noted.[2,3)]

Since it is possible to select which buckets will contain a significant number of protons by selectively expelling unwanted protons before acceleration, the required number of quartets can be established at the desired azimuthal locations before beginning the acceleration cycle.[4)] This procedure is absolutely necessary. In order to coalesce the adjacent bunches, it is necessary to reduce their momentum spread to the minimum possible value by lowering the rf amplitude to an extremely small value. If a large fraction of the buckets contain proton bunches the resultant beam excitation of the high shunt impedance accelerating cavities prevents lowering the voltage to the required value. Furthermore, it would be extremely difficult to remove the unwanted protons from the machine with sufficient precision at 150 GeV and if those protons were to remain in the machine but not well contained in buckets, the injection process into the tevatron would almost certainly quench the super-conducting magnet.

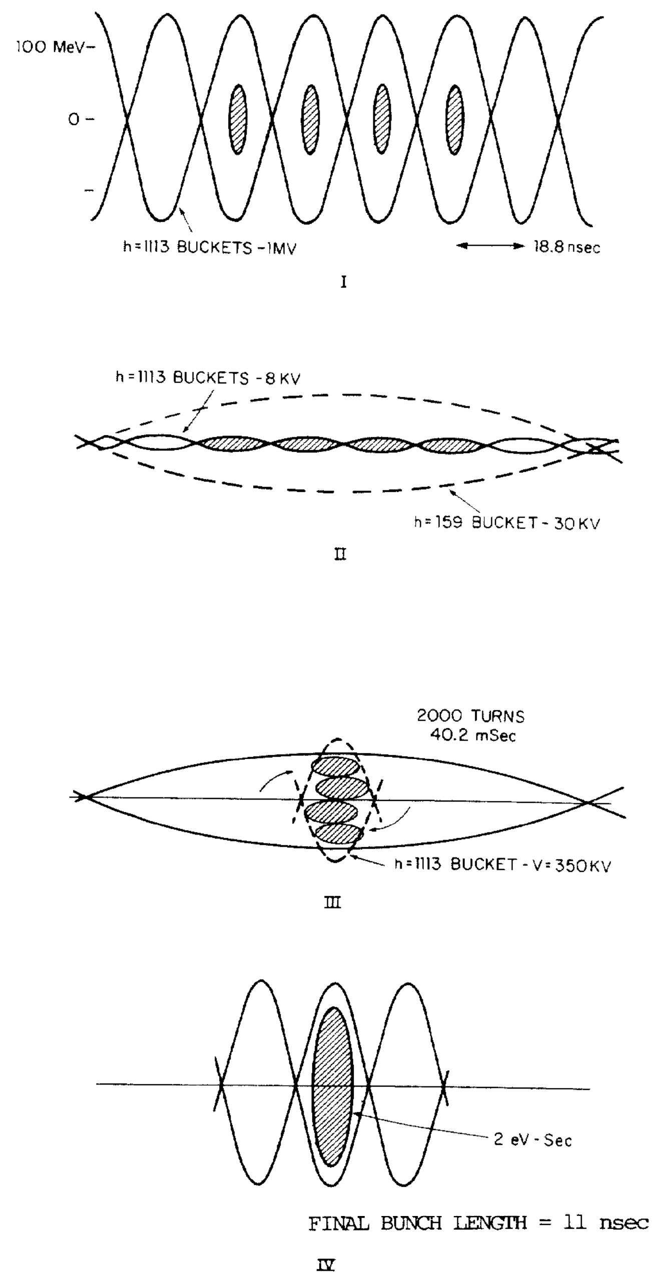

Figure 1. Bunch coalescing scenario. Bucket areas and occupied phase space are roughly to scale.

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Coalescing Scenario

The four step procedure for coalescing quartets is shown in Figure 1. (The procedures described here are at 100 GeV instead of 150 GeV because we have well established machine parameters at 100 GeV and the experiments are slightly less expensive in electric power cost). Step I shows a series of h=1113 (53.102 MHz) buckets, four of which contain bunches of protons. The stationary bucket of voltage is 1 MV resulting in a bucket height of 144 MeV. (In this paper we use coordinates of energy ΔE and time ΔT to describe the phase spaces. Because we are dealing with more than one harmonic number, these coordinates are more convenient than ΔW (eV-sec) and radians ($\Delta\phi$)). We have assumed that each of the bunches has a longitudinal emittance of 0.3 eV-sec consistant with recent measurements.[4] These bunches, initially matched to a 1 MV bucket, will have a half-height of 46.7 MeV and a half width of 4 nsec, roughly as shown.

Step II shows the 0.3 eV sec bunches matched to an rf bucket which has been reduced in amplitude until the bucket area equals the bunch area. The bunch and bucket height is now 12.5 MeV. Shown also in part II is a dashed line representing a sub-harmonic bucket encompassing seven of the original buckets. Because the original harmonic number h=1113=(3)(7)(53) a 7th sub-harmonic bucket (h=159) will remain fixed in phase with respect to the original buckets. (Had the original harmonic number been a prime, this sub-harmonic operation would have been impossible). The sub-harmonic bucket shown has a height ΔE=66 MeV requiring the application of 30 kV at 7.58 MHz. When the h=1113 voltage reduction is complete, the voltage creating that bucket is removed and the h=159 voltage is applied suddenly at full amplitude.

Step III shows the proton distribution within the sub-harmonic bucket after slightly more than one-quarter of one synchrotron period. This requires 2000 turns or 41.8 msec. The distributions with larger momentum deviation are those which started farthest from the bucket center and have consequently lagged slightly due to synchrotron tune spread. Computer simulations of this rotation have established 2000 turns to be an optimun period for establishing the narrowest charge distribution. Initially the charge in the h=159 bucket extends over 4/7 of the bucket length. (In $\Delta\phi$, ΔW coordinates $\Delta\phi=4\pi/7$ radians). In a 66 MeV bucket, this distribution should reach a maximum energy deviation of 66 $\sin(\Delta\phi/2)$=51.6 MeV. Computer simulations have verified that this indeed happens and the distribution shown in part III is a good representation of the simulation. The rotated charge extends in energy over approximately 104 MeV and in time over about 19 nsec so the phase space area covered is about 2 eV Sec.. At this time the h=159 rf voltage is removed and h=1113 buckets are re-applied at an amplitude which matches as well as possible the rotated distribution. The dashed line in part III represents a 2 eV-sec h=1113 bucket, requiring the application of 340 KV. Because we have coalesced an even number of bunches in an odd-numbered sub-harmonic bucket, the center of the coalesced bunches have moved azimuthally π radians from the original position and the re-applied h=1113 bucket must be shifted in phase accordingly or the coalesced bunch will arrive at the unstable fixed point.

Part IV of Figure 1 shows the coalesced bunch distribution after the h=1113 rf voltage has been raised to 1 MV. The total bunch width of a 2 eV-sec distribution matched to a 3.36 eV-sec bucket (1 MV) will be 11 nsec and the energy half-height will be 114 MeV. At 100 GeV this amounts to a total $\Delta P/P$ of 0.12 percent, small with respect to the momentum aperture of the ring, about 0.5 percent.

A density dilution of about a factor of two has occurred in the process so while the final energy half-height is 114 MeV as opposed to 47 MeV for the original bunches the peak current, as indicated on a beam current detector, will have increased by only a factor of about 1.3.

After acceleration to 1 TeV, this distribution is to be stored in buckets generated by about 1.2 MV. At 1 TeV the 1.2 MV bucket height will be 495 MeV and a 2 eV-sec bunch, matched to such a bucket, will have a total length of 5.7 nsec.

Computer simulations were done also for coalesence of five adjacent bunches in a seventh sub-harmonic bucket. In that case all of the center three bunches and about half of each of the outer two bunches could be recaptured so there is no advantage over coalescing four bunches.

Experimental Coalescing

Because of a severe limitation in the operating schedule of the Fermilab accelerator, only about eight hours of accelerator time have been available for this experiment. Consequently, the results presented here must be considered to be preliminary.

The accelerator was operated in just the manner described above, with a flat field region of greater than one second at 100 GeV. Only one group of four bunches was accelerated. The h=159 rf voltage was provided by an inherited Princeton Pennsylvania Accelerator (PPA) accelerating cavity installed in the ring for this purpose.

The seventh sub-harmonic rf voltage was obtained by doubling the frequency of the operational low-level rf output voltage and then dividing by 14 with a gated 100 MHz pre-det scaler. The scaler was preset to a given configuration at the beginning of each acceleration cycle by a pulse signaling the appearance of the first beam bunch in the ring. The low-level rf system is subsequently phase locked to the beam in the ring so even though the first pulse was not to be one of the quartet to be coalesced, the phase of the sub-harmonic rf voltage always remained fixed with respect to any given bunch in the machine and specifically to the four bunches to be coalesced. (The bunch "knock-out" process does not completely remove the unwanted bunches from the ring, but reduces their amplitude by a factor approaching one-hundred. The 60 db dynamic range of the low-level rf system is adequate to allow phase locking to the intensity attenuated beam). During the 40 msec coalescing period the beam phase information received by the low level rf system is useless so the system must operate "open loop" on a computer generated frequency program. Following coalescence, the beam has a sufficient Fourier component on its seventh harmonic so that the low-level rf system can again be phase-locked to the beam.

The h=1113 rf voltage was reduced by the large factor required by simultaneously rotating the phase of the gap voltage of adjacent pairs of cavities to $\pm 90^{\circ}$ and reducing to a minimum the amplitude excitation of all 18 rf stations. In Figure 2 the rf waveforms of both the h=1113 and the h=159 systems is shown. The h=1113 voltage is reduced during a period of 0.1 seconds to less than 10 KV, then the excitation is removed entirely. At that time the rf drive voltage from the sub-harmonic scaler is gated into the PPA cavity for 42 msec. Following that the h=1113 voltage

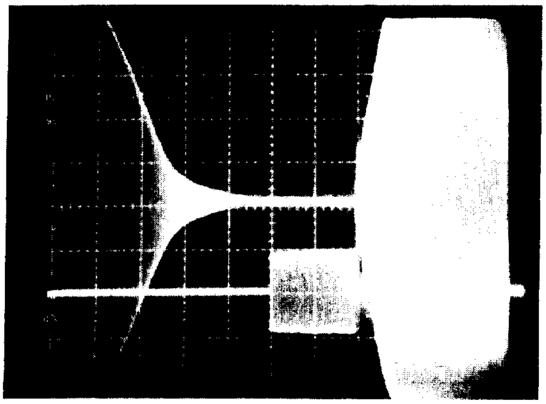

Figure 2. Top trace is the h=1113 (53.1 MHz) rf voltage during the coalescing process. The sweep rate is 40 msec per div. and the vertical calibration is 250 KV per div.. Bottom trace is the h=159 (7.58 MHz) rf wave. The amplitude is 30 KV.

is reapplied at 340 KV and raised smoothly to 1 MV in approximately 50 msec.

Unfortunately, it was not possible during this time limited experiment to switch the phase of the reapplied rf voltage as required because several matching phase jumps would have been required in areas of the low-level rf system which were not easily accessable. To compensate for this, the phase of the h=159 cavity was adjusted in the direction to optimize capture of five initial bunches and the h=1113 rf was reapplied with its original phase, locating the coalesced bunch at the azimuthal location of one of two center bunches of the original quartet. This is equivalent to coalescing five bunches with one of the outermost initial bunches missing. Therefore 3.5 of the original 4 bunches should be coalesced resulting in an efficiency of 0.875.

Results and Conclusions

Figure 3a is a mountain range picture of the evolution of a quartet covering a period of 0.2 seconds during the coalescing process. The traces are spaced 5 msec apart starting 40 msec before application of the h=159 coalescing bucket. In Figure 3b the bunches are shown at 0.1 seconds before the coalescing process and at 0.1 seconds after completion. These pictures are representative of many such events observed during the experiment. The bunches have an initial width of 4 nsec as expected (the longer tail on the bunch pictures is an artifact of the detector used to observe the bunches). The average area of the initial bunches is approximately 160 mV-nsec giving a total area of 640 mV-nsec.. The coalesced bunch appears to be about 14 nsec at its base, slightly wider than the simulation prediction and its height appears to be about equal to that of the initial bunches so that its area is about 560 mV-nsec.. This results in a coalescing efficiency for this event of approximately 0.875 which is just the expected result. More detailed analysis of many events yields slightly larger collection efficiency of about 0.9..

The beam detector used in this experiment has been calibrated by observing the average bunch area displayed with many bunches in the accelerator (~1000) and dividing by the measured number of bunches and the beam intensity as measured by a standard beam current transformer. The sensity is $0.6x10^8$ protons/mV-nsec so the intensity of the coalesced bunch shown is about $3.4x10^{10}$ protons, about a factor of three lower than the ultimate requirement.

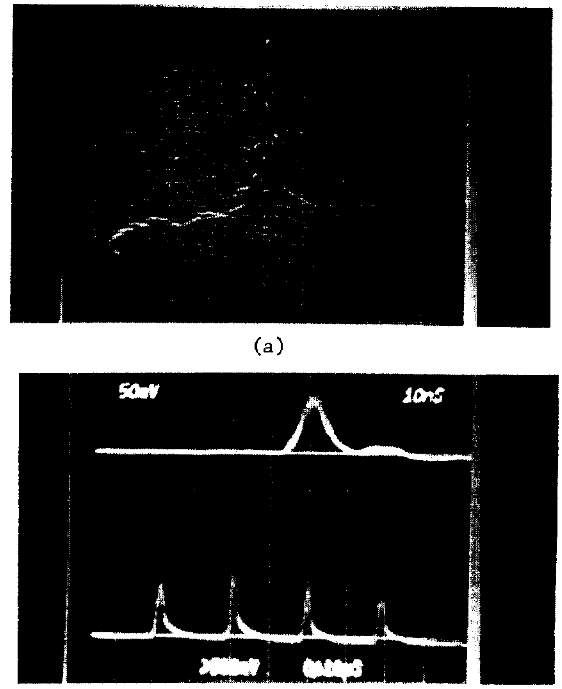

Figure 3. a) Time evolution of bunch coalescence. Traces are 5 msec apart and sweep rate is 10 nsec per division. b) Bunch quartet 0.1 sec. before and 0.1 sec after coalescing. Sweep rate 10 nsec per division.

We conclude from this brief experiment that the procedures for coalescing several adjacent bunches in the Fermilab main ring are straightforward and managable. The process is easily understood and well represented by computer simulation. The dilution observed in this experiment is slightly larger than that which was anticipated, probably due to the phase shift problems described. Further study at higher intensity will be required to determine whether this technique will be adequate to provide the required 10^{11} proton bunches in the Tevatron with acceptable bunch length.

Acknowledgements

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