BUNCH SHORTENING EXPERIMENTS IN THE FERMILAB BOOSTER AND THE AGS

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Abstract

The proton driver for a muon collider [1,2] must be capable of producing 2.5 x 10 13 p/bunch on target (in 4 bunches) in order to reach the design luminosity in the collider ring. Additionally, the bunches are very short, with an rms of only ~1 ns, to match the longitudinal emittance requirements of downstream capture, cooling, and acceleration systems. This criterion along with the high intensity places constraints on the proton driver design which will require both theoretical and experimental verification. This paper will discuss the bunch shortening techniques to be tested experimentally, the impact of longitudinal space charge, and potential instabilities in such an accelerator.

1 INTRODUCTION

There has been great interest in developing high-intensity (~10^{14} protons per pulse) proton sources for neutron spallation sources, hadron factories, and muon colliders. Muon colliders also require rms bunch lengths as short as a nanosecond. Short bunch lengths limit the initial muon longitudinal phase space area, thereby enabling effective collection, cooling, transport, and acceleration, as described in ref [1]. Shorter proton bunches also allow capture of more highly polarized muon beams. This paper describes methods for producing short bunches and the experimental tests which are planned at the AGS and the Fermilab Booster.

Because of the conservation of longitudinal phase-space area, shorter bunches imply larger momentum spreads. For example, a Gaussian bunch with a longitudinal emittance of 1 eV-sec and an rms bunch length of 1 nsec at 8 GeV has a full momentum spread of about ±1.5%. Such momentum spreads are probably tolerable for a short time before extraction in a well-designed lattice.

2 BUNCHING

Bunch rotation has been used at Fermilab and elsewhare as a straightforward way to shorten bunches. In this method, the amplitude of the rf voltage is programmed to induce a rotation of the longitudinal phase space distribution in a stationary bucket. The efficacy of a simple bunch rotation is limited by the fact that the dependence of synchrotron frequency on amplitude in longitudinal phase space causes the distribution to distort into an S shape as it rotates.

Three methods are under consideration to reduce the bunch distortion during bunch rotation. These are: a) separate shears in energy and phase to minimize the motion in phase space required to produce the final bunch, b) augmenting the fundamental rf frequency with harmonic cavities which can cancel the nonlinearities, and c) compensating rotations above and below transition which cancel nonlinear effects.

The use of separate shears in momentum and phase requires that the transition gamma of the machine, γ_t, be changed between the two processes, using new lattices such as the FMC[3]. If necessary, the momentum dependence of the slip factor η of the lattice can be matched to that of the beam. A transition jump is also required in the third method.

Working close to transition has some obvious advantages: the beam is naturally shorter there and more bucket area is available. However, flattoping too close to transition energy should be avoided for two reasons: the synchrotron frequency is very low, so that bunch manipulations take too long; also, as described below, space charge effects below transition can prevent bunching unless they are compensated by inductive inserts[4-7].

3 LONGITUDINAL SPACE CHARGE

Below transition the longitudinal space charge force [4] is defocusing and thus opposes the effect of the rf voltage. Longitudinal space charge can strongly perturb, and perhaps prevent, the bunch rotation required to produce short proton bunches. The voltage produced on a particle in one turn by the longitudinal electric field due to space charge is

$$V_i = -\frac{Rg_0\lambda'}{2\varepsilon_0\gamma^2},$$

where g_0 = (1+2ln(b/a)), b is the vacuum chamber radius and a is the beam radius, λ' is the longitudinal charge density gradient, ε_0 is the permittivity of free space, γ is the relativistic factor and $2\pi R$ is the circumference of the ring. As the bunch is compressed over N turns, an individual particle in a bunch will lose (or gain) an amount of energy, shown in Fig 1, given by

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$$U = q\sum_{i=1}^{N} V_i = q\langle V\rangle N = q\langle V\rangle \frac{\Delta\phi_{\max}}{2\pi\eta\,\Delta p/p},$$

where $\langle V\rangle$ is the simple average of the space charge induced voltage per turn, during the compression process, q is the charge and U must be in units like W introduced below. The value of synchrotron phase at the start of the compression is $\Delta\phi_{max}$, and the expression in the denominator is the phase change per turn for a given slip factor η and momentum offset, $\Delta p/p$, since $\delta\phi_{turn}/2\pi = \delta f/f = \eta\ \Delta p/p$.

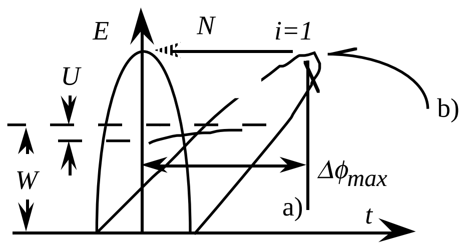

Figure 1, the final stage of bunching.

The complete expression can be written for a triangular bunch more explicitly in terms of the average charge density gradient $\langle\lambda'\rangle$ rather than the average voltage per turn $\langle V\rangle$, after expanding η as

$$U = \frac{qRg_0\langle\lambda'\rangle\Delta\phi_{\max}}{4\pi\varepsilon_0(1-\gamma^2/\gamma_t^2)\,\Delta p/p}.$$

As long as the energy loss by the particle is much less than the initial energy displacement from the center of the bunch, W, distortion of the bunch will be minimal. Thus the condition for bunching is that

$$\frac{U}{W} = \frac{qRg_0\langle\lambda'\rangle\Delta\phi_{\max}}{4\pi\varepsilon_0 W(1-\gamma^2/\gamma_t^2)\,\Delta p/p} < 1.$$

Values for the parameters can be obtained numerically for the AGS and the driver of the muon collider for a bunch compression using widths from FWHM / 2 = 10 ns down to 1 ns, Figure 2. The results show that if the bunching is done too close to γ_t it will proceed slowly and space charge will dominate, however if $|\gamma\text{-}\gamma_t|>0.2\gamma$, bunching can proceed.

Since the design of the accelerator enters into this expression as $R/W(1 - \gamma^2/\gamma_t^2)\Delta p/p$, the size of the ring should be minimized, likewise the momentum aperture and the difference between the operating and transition energy should be maximized. (Because the energy offset $W \approx \Delta p$, the momentum spread essentially enters with an exponent of 2). Thus one wants a lattice with an efficient packing factor for dipoles, magnets with a large aperture and the transition energy as far from the beam energy as possible during the final bunch rotation.

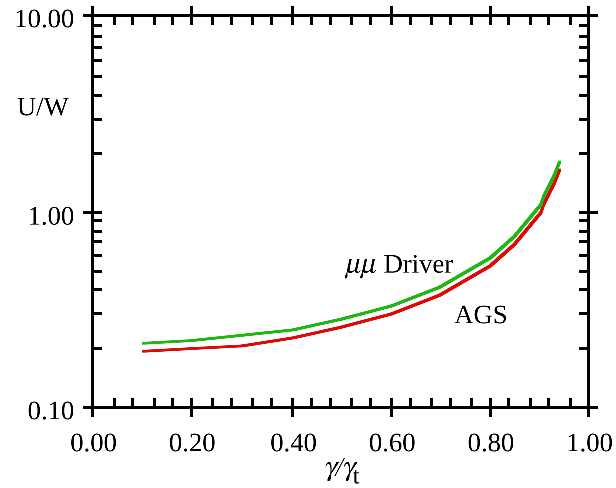

Fig 2. Degree of nonlinearity during bunching.

The third method under consideration, in which transition is jumped before the final bunch rotation, has the potential to put the space-charge voltage to good use to augment the rf bunching voltage. Alternatively, if inductive inserts are used to alleviate longitudinal space-charge effects, the above limitations can be circumvented.

4 OTHER INSTABILITIES

The bunch hitting the target will have a peak current of 1600 - 3200 A, which is significantly larger than is presently seen in synchrotrons. Although this current might be the cause of significant instabilities, the bunch will be stabilized by a number of effects.

The incoherent space charge tune shift

$$\Delta\nu_{inc} = \frac{3r_pN_t}{2AB\beta\gamma^2} \approx 0.2$$

will be large. By introducing Landau damping, this tune spread will tend to stabilize the beam against transverse resistive wall effects.

In synchrotron space, the bunch is stabilized by a large momentum spread. Since the approximate threshold for these instabilities is given by the Keil-Schnell relation

$$\frac{Z_\parallel}{n} = \frac{F|\eta|\beta^2E/e}{I_{pk}}\left(\frac{\Delta p}{p}\right)^2,$$

a constant phase space area would imply $I_{pk} \propto \Delta p/p$ for a vertical bunch, so the threshold $Z_\parallel/n \propto \Delta p/p$. Thus bunches become more stable as they are shortened.

In addition, it is assumed that the current will rise very rapidly in the final stages of bunching, and this period of time will be short relative to the growth time for known resonance effects.

4 EXPERIMENTAL TESTS

Bunch rotation schemes can be tested at both the AGS on high-intensity (~10^{13} p/bunch), long bunches (rms close to 20 ns) and on low-intensity, nanosecond bunches in the Fermilab Booster (~5×10^{10} p/bunch). The longitudinal structure of the beam will be measured using a resistive wall monitor, a fast analog scope with sequential triggering (25 μs rearm rate) and diagnostic software developed at Brookhaven (ref).

With this system, the longitudinal structure of the Fermilab Booster has been explored from injection to just below transition by accelerating to 4 GeV instead of the nominal 8-GeV extraction energy. Although the Booster gradient magnets cannot sustain a flattop, at least a millisecond of data can be obtained with little energy change before extraction. To effect a bunch rotation, the rf cavities can be quickly paraphased in opposite directions which cancels the net rf voltage seen by the beam. A "tumbling" bunch can be observed in Fig. 3 when the rf cavities are paraphased from a net rf voltage of 800 kV to 150 kV. Hardware is presently being developed and tested to unparaphase the rf cavities in order to recapture a shortened bunch.

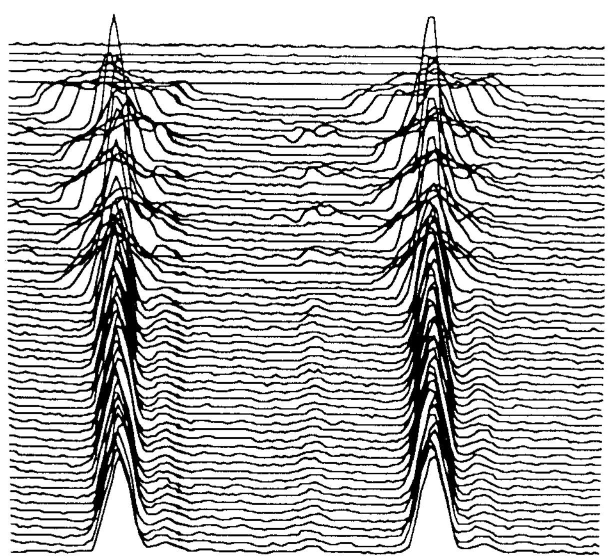

Figure 3. tumbling bunches in the Booster.

In the AGS, the gradient magnets can be programmed to maintain a flattop. During a flattop of 25-GeV kinetic energy, a bunch rotation will be effected using the rf cavities. Other techniques such as firing the γ_t jump system on the AGS to shorten the bunches by the shearing caused in crossing transition (rapidly) will also be investigated.

Expansion of the bunch can be accomplished either by turning down the rf and letting the beam expand in phase or by operating close to transition with the rf fully on, which expands the energy spread. Although the bunch will be truncated by the momentum aperture, rotation to a vertical orientation would then proceed to the extent allowed by longitudinal space charge. Both procedures would be studied as a function of proximity to transition and bunch intensity, with two dimensional reconstruction of bunch density from time dependence of the longitudinal current density.

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