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Comment on “Adiabatic excitation of longitudinal bunch shape oscillations”

J. A. MacLachlan
Fermi National Accelerator Laboratory, Box 500, Batavia, Illinois 60510

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This comment takes up the suggestion of the authors that it could be informative to model the excitation of the bunch shape oscillations using multiparticle tracking. The experiment they report employs an 80% modulation of the rf amplitude at approximately twice the synchrotron frequency; the first-order perturbation analysis given in the paper is not suitable for quantitative comparison to the experimental observations. The tracking code ESME is used to model the conditions of the experiment. The potential well distortion arising from image charge and current and a broadband longitudinal impedance of $Z_{\|}/n = 6\ \Omega$ was considered as an additional perturbation which also varies at the modulating frequency.

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I. INTRODUCTION

The basic premise of the subject paper [1] is that modulating the amplitude of the rf voltage in a synchrotron at a frequency near twice the synchrotron frequency with slow increase of the modulation percentage from near 0 to more than 50% can develop quadrupole mode (shape) oscillation without significant emittance growth. Either narrow or wide bunches can be selected according to the phase of the oscillation. Unfortunately, the desire to make very narrow bunches for, say, μ collider is frustrated by the oscillation of the extended bunch in the nonlinear region of the rf bucket. This problem can be addressed with a second harmonic rf system if the need justifies the cost. There is no discussion of the circumstances under which the adiabatic approach might be superior to a quarter period bunch rotation triggered by a sudden jump from low to high rf voltage.

The reported experimental results from the alternating gradient synchrotorn (AGS) at Brookhaven National Laboratory are in qualitative agreement with a first-order perturbation treatment given in the subject paper. The paper also expresses an interest in extending the investigation by multiparticle tracking. Since several computer programs exist for this kind of work [2], it is questionable whether it is necessary to develop a new code as the authors propose. In order to make a detailed comparison with the AGS experiment it is necessary to include, or at least consider, some of the effects of the beam current upon the particle motion. This paper reports a preliminary look at the process. A perfectly conducting wall and broadband longitudinal impedance do not affect the results in any interesting way, although small quantitative effects are observable. The purpose of the modeling reported below is to show that the means for answering many of the questions about the comparison of the analysis with the experiment are readily available. This comment does not address which are the interesting questions. The similarity between the simple model and the observations in the AGS is rather striking.

II. MULTIPARTICLE TRACKING

Table I is an expanded version of the table in Bai *et al.* [1] including a couple of corrections and added parameters used for defining the macroparticle model. Note also that the ν_s value before Eq. (6) should be divided by 1000, thus, likewise, the numbers in Eq. (6). For present purposes the single particle map used [3] is equivalent to that in Eq. (1) of Ref. [1].

For a single bunch of 5×10^{12} protons, image current and space charge forces will influence the dynamics by a potential well distortion which varies as the bunch length changes. To determine whether the influence of this additional synchronous perturbation is sufficient to require detailed treatment, the longitudinal impedance was modeled with a $Q = 1$ resonance at 1.5 GHz and $Z_{\|}/n$ of 6 Ω. The perfectly conducting wall term was estimated by assuming

TABLE I. Basic parameters of the AGS experiment. (Entries in bold are corrected; those in italic are added.)

Parameter	Symbol	Unit	Value
Species (protons)	p	···	···
Energy	E	GeV	24
Harmonic number	h	···	6
Number of bunches	···	···	1
Particles per bunch	···	···	5×10^{12}
rms bunch area	ϵ_s	eV s	4
Slip factor	η	···	0.0122
Gap voltage	V_0	kV	105
Gap voltage, peak	···	kV	190
Synchrotron tune	ν_s	···	2.3×10^{-4}
Modulation tune	ν_m	···	5×10^{-4}
Mean orbit radius	$R_\circ$	m	128.45
Beam circulation frequency	$f_\circ$	kHz	371.17
Transition γ	γ_T	···	8.5
Beam tube geometric factor (guess)	g	···	4.6
Broadband impedance	$Z_{\|}/n$	Ω	6
Microwave cutoff frequency (guess)	f_c	GHz	1.5

a uniform cylindrical current distribution of average radius 1 cm in a vacuum chamber of average radius 6 cm. The effect of the perfectly conducting wall was limited to low frequencies by Bernstein polynomial smoothing [4] of the azimuthal current distribution; thus, numerical noise was acceptable with only a few thousand macroparticles. These collective effects are small enough to be uninteresting for a preliminary comparison and are not discussed further.

III. COMPARISON OF AGS EXPERIMENT TO MULTIPARTICLE MODEL

The macroparticle model has been used to produce simulations of some of the AGS data shown in the figures of Ref. [1]. The visual similarity between model results and the experimental data encourages the idea that modeling could be helpful in further study of the excitation of bunch width oscillation in a real accelerator.

Figure 1shows the bunch width for 19.5 ms at 167 μs intervals after the modulation percentage has reached its 80% final value; it covers approximately the same time span as Fig. 4 from Ref. [1]. Figure 2 is a phase plane plot which one may compare to the tomographic reconstruction in Fig. 5 of Ref. [1]. Two interesting differences are readily apparent: the observed bunch shows a substantial disparity between the charge in the two lobes, and the filamentation is quite noticeable and asymmetric. Somewhat similar results were obtained for different parameters when phase feedback was incorrect.

Figure 3 shows the rms bunch length vs time during 0.14 s during which the amplitude modulation at 183 Hz rises linearly from 0 to 80% followed by 0.02 s in which the modulation is constant at 80%. The minimum bunch length decreases up to about 40% modulation; the maximum continues to increase throughout the modulation ramp, reflecting the greater separation of the lobes in the phase space distribution for large modulation. Figure 4 shows the rms longitudinal emittance during 0.14 s during which the modulation percentage is raised linearly from 0 to 80% followed by 0.14 s more when it is ramped back down. It may be seen that there is practically no emittance growth up to about 60% modulation and that some of the growth resulting from the lobe separation at greater modulation is recovered when the modulation is removed.

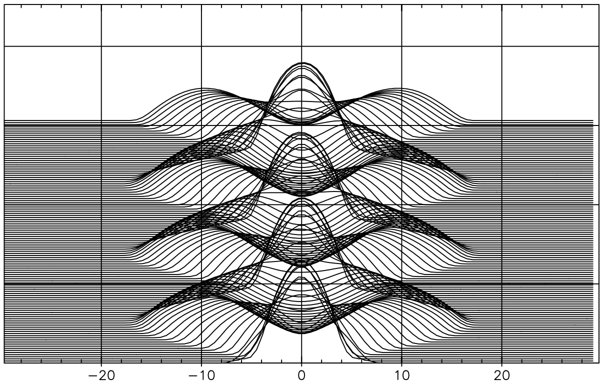

FIG. 1. Simulation of the bunch shape at 167 μs intervals during 19.5 ms after the modulation of the rf amplitude has reached its final value of 80%, comparable to Fig. 4 of Ref. [1]. The abscissa is labeled with degrees of azimuth; it spans 0.45 μs with time increasing from the bottom to the top of the figure.

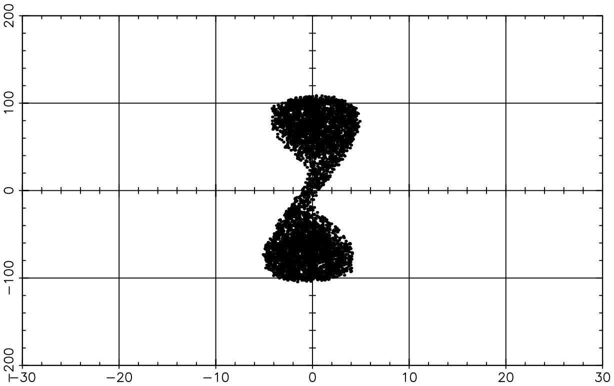

FIG. 2. Energy [MeV] vs phase [degrees of azimuth] distribution after 0.2 s ramp of modulation of rf amplitude from nil to 80%, comparable to Fig. 5 of Ref. [1].

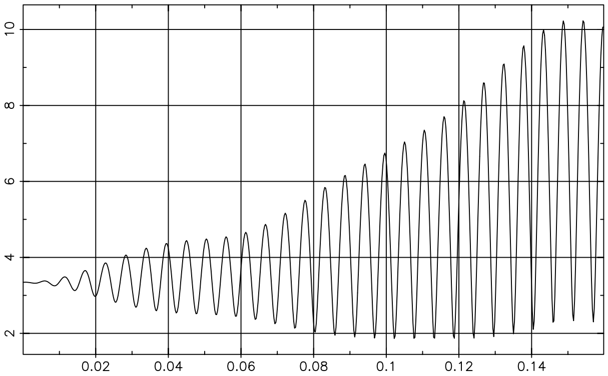

FIG. 3. rms bunch length [degrees of azimuth] during 0.14 s ramp of the modulation of rf amplitude followed by 0.02 s at the full modulation of 80%. The initial length of 25 ns reaches a minimum length of 14.2 ns.

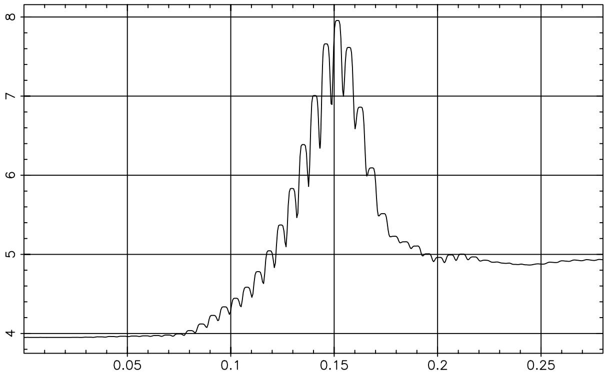

FIG. 4. rms emittance [eV s] during 0.14 s ramp of the modulation of rf amplitude from nil to 80% followed by 0.14 s ramp back to nil.

However, the distribution is subject to the nonlinear region of the rf waveform for several synchrotron periods, and filamentation leads to about 25% irreversible growth.

IV. IN FINE

The typical approach to bunch narrowing is nonadiabatic; viz, the rf amplitude is jumped suddenly for one quarter of a synchrotron period to produce a bunch rotation. Given that the change from least to greatest rf amplitude takes a quarter of a period in the adiabatic process, it is possible that the peak amplitude of 190 kV could be held for that length of time in the AGS. The result of rotating from a matched bunch of 4 eV s in a bucket at 10 kV to minimum width in a bucket at 190 kV is an rms bunch length of 10.5 ns compared to the 14.2 ns obtained in the adiabatic process. Thus, the bunch rotation will be preferable in general, but not necessarily under all circumstances.

The author does not have the detailed knowledge of the AGS to pursue the comparison of calculation and observation of the effects of high amplitude modulation of the rf voltage. However, it seems useful to remark that the beam behavior in the accelerator is governed by several mechanisms in addition to the amplitude modulation and that the development of a model with good quantitative predictions may require the inclusion of several of them. There are several existing codes which can be used for this type of investigation; unless contraindicated by special circumstances, the use of a time-tested modeling program is likely to be the efficient means to a credible detailed model.

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