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Comment on Adiabatic expansion of longitudinal bunch shape oscillations

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Abstract

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; the first order perturbation analysis given in the paper is not suitable for quantitative comparison to the experimental observations. In this comment plausible values are selected for the longitudinal impedance and the beam pipe geometric factor for the AGS. The tracking code ESME is then used to model the conditions of the experiment. Discrepancy between the observed and the expected small amplitude synchrotron frequency in the AGS make it difficult to generate a precise comparison solely from the information in the paper.

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I. INTRODUCTION

The basic premise of the original 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 zero 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 of course 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. However, one may suppose that when beam current is high the adiabatic procedure is less susceptible to microwave instability.

The reported experimental results from the AGS at Brookhaven National Laboratory are in qualitative agreement with a first order perturbation treatment given in the original paper. The paper also expresses an interest in extending the investigation by multi-particle tracking. Since several computer programs exist for this kind of work, [2] it is questionable whether it is necessary to develop 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 note reports a preliminary look at the process using guesses for longitudinal impedance in the AGS. 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.

II. MULTIPARTICLE TRACKING

Table I is an expanded version of the table in the original paper which includes 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.

The experiment is not very much like the ideal model. For example, the paper gives the formula

$$\nu_s = \sqrt{(h|\eta|eV)/(2\pi\beta^2 E)} \ ,$$

according to which ν_s is $3.4 \cdot 10^{-4}$ instead of the quoted [*sic*] 0.23. This difference is not accounted for; it represents a significant uncertainty in how to match the experiment and the simulation. Possibilities include lowering the rf voltage to get the quoted synchrotron frequency and changing the modulation frequency in the simulation so that it has the same relation to the calculated value that the modulation frequency used in the experiment had to the experimental synchrotron frequency; neither of these served to give close agreement between simulation and the observations at the AGS. What has been done here is to use the machine parameters from Table I and adjust the modulation frequency for approximately the same level of quadrupole oscillation. The difference between the experimental modulation frequency and that used in the modeling is some measure of what remains to be explained in further work.

For a single bunch of $5 \cdot 10^{12}$ protons, image current and space charge forces could have a measurable effect. To make some plausible allowance for the longitudinal impedance offered by the beam tube and the space charge potential, an average beam radius of 1 cm, an equivalent beam tube radius of 6 cm, and a broadband impedance $Z_{\|}/n$ of 15 Ohm (Q = 1 resonance model) are assumed. Although these parameters are little better than guesses, the collective effects turn out unimportant for the results compared to the arbitrary selection of the modulating frequency.

The map used [3] is, of course, rather similar to eqs. 1 in Bai *et al.*, but the potential is not specialized to sinusoidal, and the focusing contains the nonlinearities arising from the dependence of the slip factor on momentum of both the particular particle mapped and the synchronous particle. The high frequency structure is intentionally smoothed out of the bunch by Bernstein polynomial smoothing to limit the collective effect to bucket shape distortion without the complication of possible spurious bunch breakup driven by statistical fluctuations in the macroparticle density, *i. e.* , numerical noise.

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 figures of the Bai *et al.* paper. The visual similarity between model results and the experimental data supports the idea that modeling could be helpful in further study of the excitation of bunch width oscillation in a real accelerator.

Fig. 1 shows 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 Bai *et al.* The obvious difference between the two figures results from the difference between the synchrotron frequencies. Fig. 2 is a phase plane plot which one may compare to the tomagraphic reconstruction in Fig. 5 of the paper. Fig. 3 shows the growth of the rms longitudinal emittance during the 0.2s during which the modulation percentage is raised linearly from zero to 80%. It may be seen that there is very little emittance growth in this case until the modulation is over 60% and that the total growth of $\sim$ 30% is not severe.

IV. IN FINE

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 most likely to be the efficient means to a credible detailed model.

TABLES

TABLE I. Basic parameters of the AGS experiment

Parameter	Symbol	Unit	Value
Species (protons)	p	...	...
Energy	E	GeV	24
Harmonic number	h	...	6
Number of bunches	...	...	1
Particles per bunch	...	...	$5 \cdot 10^{12}$
rms bunch area	ϵ_s	eVs	4
Slip factor	η	...	0.0153
Gap voltage	V_0	kV	190
Synchrotron tune (exptl.)	ν_s	...	$2.3 \cdot 10^{-4}$
Synchrotron tune (single particle)	...	...	$3.4 \cdot 10^{-4}$
Modulation tune (exptl.)	ν_m	...	$5 \cdot 10^{-4}$
Modulation tune (model)	...	...	$7.4 \cdot 10^{-4}$
Mean orbit radius	$R_\circ$	m	128.45
Beam circulation frequency	$f_\circ$	kHz	371.17
Transition γ	γ_T	...	7.71
Beam tube geometric factor (guess)	g	...	4.6
Broad band impedance (guess)	$Z_\parallel/n$	Ohm	15
Microwave cutoff freq. (guess)	f_c	GHz	1.5

Note: Entries in **bold face** are corrected; those in *itallics* are added.

FIGURES

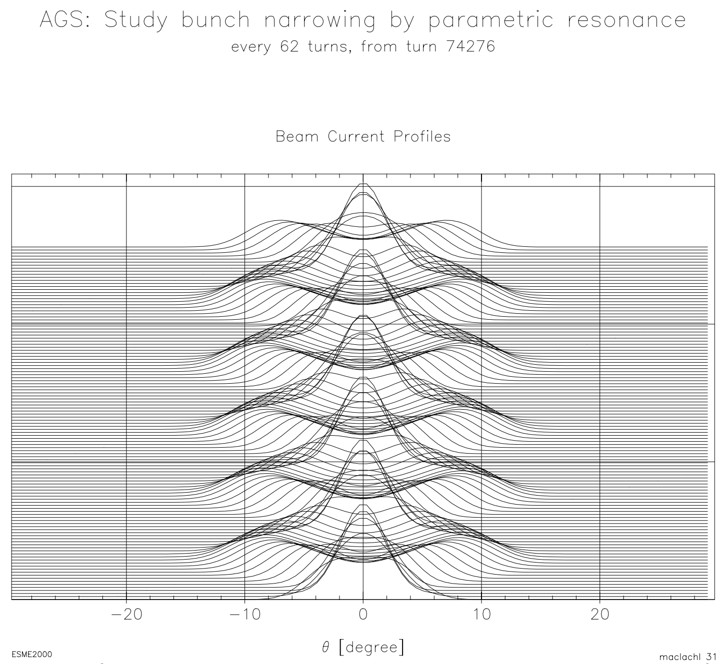

FIG. 1. Simulation of bunch shape at 167 μs intervals over 19.5 ms after the modulation of the rf amplitude has reached its final value of 80%, comparable to Fig. 4 of Bai *et al.* Abcissa is labeled with h=1 rf phase; it spans 0.45 μs. Note that the single particle small amplitude synchrotron frequency is nearly 50% higher than that observed in the AGS.

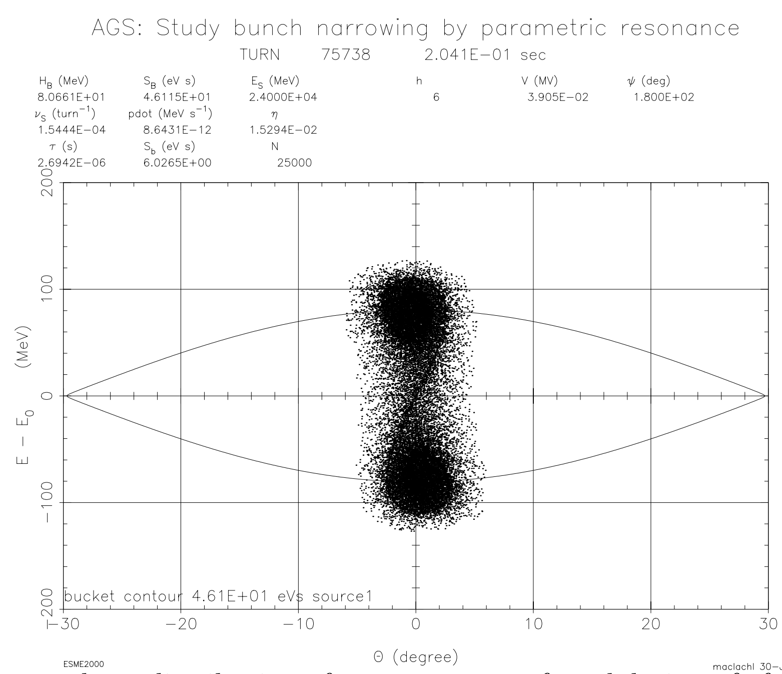

FIG. 2. Energy-phase distribution after 0.2 s ramp of modulation of rf amplitude from nil to 80%, comparable to Fig. 5 of Bai *et al.*

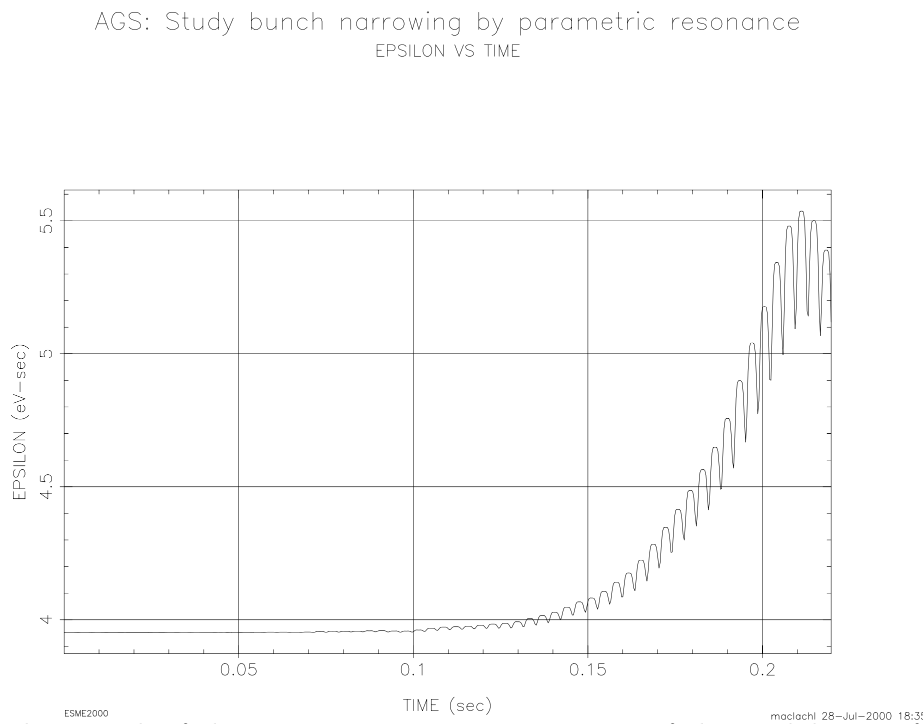

FIG. 3. The growth of the rms emittance over 0.2s ramp of the modulation of rf amplitude followed by 0.02s at the full modulation of 80%.

REFERENCES

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[3] J. MacLachlan, “Difference Equations for Longitudinal Motion in a Synchrotron”, Fermilab note FN-529 (1989)