RAMPRF: A Program for Synchronous Acceleration *

Miguel A. Furman
Lawrence Berkeley Laboratory, Berkeley, CA 94720

Abstract

We describe a family of standard FORTRAN programs that calculate bucket-related quantities as a function of time during acceleration, assuming it is adiabatic. The members of the family are distinguished by the type of input: One family member takes energy and total peak voltage as a function of time; another takes momentum and bucket area as a function of time, etc. The input is in free-format tabular form. The output is in standard ASCII form, in multi-column tables and x-y listings appropriate for plotting. Bunch-related quantities, such as energy spread and space-charge tune spread, are also calculated assuming that the bunches have a specified longitudinal emittance, and are small and matched to the bucket. Sample excitation curves for the SSC's low energy booster are presented.

I. Introduction

In this article we describe a family of programs that calculate a host of bucket-related and bunch-related quantities during synchronous (adiabatic) acceleration. These programs have been used, in part, in the design of the rf requirements of the SSC and its three boosters, and in the study of the longitudinal phase space dynamics and matching along the entire chain of ramping, from the exit from the linac through the top energy of the collider.

These programs are written in standard FORTRAN language, without recourse to special library functions. All input and output is in ASCII format. The output consists of physical quantities as a function of time; it comes in three forms: screen output, disk files in multi-column format, and x-y disk files suitable for graphics post-processing. A disadvantage is that the programs are not interactive, so that a fine-tuning of the rf voltage program in a specific design, for example, can become cumbersome. Nonadiabatic behavior, such as nonadiabatic or quasiadiabatic capture, transition crossing, bunch rotation and deliberate longitudinal emittance dilution, must be studied separately with multiparticle simulations.

*Work supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Superconducting Super Collider Division and High Energy Physics Division of the U.S. Department of Energy under Contracts DE-AC02-89ER40486 and DE-AC03-76SF00098, respectively.

0-7803-0135-8/91$01.00 ©IEEE

II. Basic Assumptions

There are two basic physical assumptions made in arriving at the equations [1] that are solved by these programs: (a) the non-synchronous particles in the bunch perform energy and phase oscillations around the synchronous particle in such a way that their energy change per turn is much smaller than the synchronous energy, and (b) if there is net acceleration, the energy and phase of the synchronous particle change slowly compared to the typical motion of the particles in longitudinal phase space. Assumption (a) allows replacing turn-by-turn changes of energy and phase by their time derivatives, and is equivalent to the assumption that the synchrotron period T_s is $\gg T$, where T is the revolution period of the synchronous particle. Assumption (b) means that the characteristic time τ for the variation of E is much larger than T_s. If the actual machine design has several cavities rather than one, assumption (b) allows one to combine them all into a single cavity for the purposes of the analysis.

To the extent that these two assumptions are valid, the acceleration process is "adiabatic," or "synchronous" [1]. The two assumptions are summarized by the inequalities

$$\tau \gg T_s \gg T \tag{1}$$

and their validity can be monitored, in practical applications, by computing the "adiabaticity" $\mathcal{A} \equiv T_s \dot{A}/A$ (A =bucket area), and the synchrotron tune ν_s (other definitions of adiabaticity are possible and often desireable). Then the synchronous acceleration assumptions are valid to the extent that $|\mathcal{A}| \ll 1$ and $\nu_s \ll 1$.

III. Description of the Programs

The bucket area function $\alpha(\phi_s)$ is approximated by a simple analytic expression [2] (ϕ_s = synchronous phase). The nontrivial intercept of the separatrix ϕ_ℓ (the left intercept, if the energy is below transition) is calculated by the successive approximation method *regula falsi*; since the other intercept is $\phi_r = \pi - \phi_s$, one gets the bucket width $\Delta\phi = \phi_r - \phi_\ell$. The bucket height is calculated from the familiar analytic formula [3].

Transition crossing is treated properly (ϕ_s jumps to $\pi - \phi_s$); in this case, however, the adiabaticity assumption needs to be monitored more carefully. Both real and imaginary γ_t are allowed.

Bunch quantities are calculated assuming that the bunch is small compared to the bucket, and is matched to it. The bunch shape can be chosen to be gaussian or parabolic.

The basic bunch quantities are the rms length σ_z and rms momentum spread σ_p; these are related by $\sigma_z\sigma_p = \epsilon_L$ =longitudinal emittance (=rms area/π), which is specified in the input table (this allows ϵ_L to be varied as a function of time so that one can simulate, for example, deliberate emittance dilution). The ratio σ_z/σ_p follows from the assumption that the bunch is matched to the bucket; thus σ_z and σ_p are obtained in a straightforward way.

Input

All four family members take as input certain global parameters such as circumference, tunes, average beta-functions, average bending radius, transition gamma, etc. In addition, they require certain other quantities as a function of time in tabular form. The four members of the family are distinguished by the type of tabular input required.

RAMPRFA has a "built-in" time dependence of the synchronous particle momentum of the form

$$p(t) = p_i + \tfrac{1}{2}(p_e - p_i)(1 - \cos(\pi t/T_r)) \qquad (2)$$

where p_i and p_e are the injection and extraction momenta, respectively, and T_r is the ramping time (*i.e.*, the time it takes for p to increase from p_i to p_e). In addition, a table of values must be provided in the form

$$t\ [\mathrm{s}] \quad A\ [\mathrm{eV\text{-}s}] \quad \dot{A}\ [\mathrm{eV}] \quad 6\pi\epsilon_L\ [\mathrm{eV\text{-}s}]$$

where A =bucket area, $\dot{A} = dA/dt$, $6\pi\epsilon_L$=95% longitudinal bunch area, and the units are as indicated.

RAMPRFB requires all input in the form of a table

$$t\ [\mathrm{s}] \quad E\ [\mathrm{eV}] \quad V\ [\mathrm{V}] \quad 6\pi\epsilon_L\ [\mathrm{eV\text{-}s}]$$

where E=total energy (=rest energy+kinetic energy) and V=total peak voltage.

RAMPRFC requires input in the form

$$t\ [\mathrm{s}] \quad E\ [\mathrm{eV}] \quad \dot{E}\ [\mathrm{eV/s}] \quad V\ [\mathrm{V}] \quad 6\pi\epsilon_L\ [\mathrm{eV\text{-}s}]$$

where $\dot{E} = dE/dt$.

RAMPRFD assumes that the momentum p varies with time as in Eq. (2), and that the rest of the input is in a table

$$t\ [\mathrm{s}] \quad V\ [\mathrm{V}] \quad 6\pi\epsilon_L\ [\mathrm{eV\text{-}s}]$$

RAMPRFA is suitable for synchrotrons whose magnets are powered by a resonant circuit, such as fast-cycling injectors. The specification of bucket area on input allows a good handle on this quantity, which is sometimes critical. RAMPRFD is similar, except that the basic input is V instead of A. In this case dA/dt (needed in the calculation of the adiabaticity) is obtained by finite differences.

RAMPRFB and RAMPRFC are suitable for synchrotrons with programmed ramps; the only difference between these two programs is in the absence or presence of $\dot{E}$ in the input file. In the case of RAMPRFB $\dot{E}$ is calculated by finite differences from the input table, so that a coarseness is thereby introduced. The assumption used

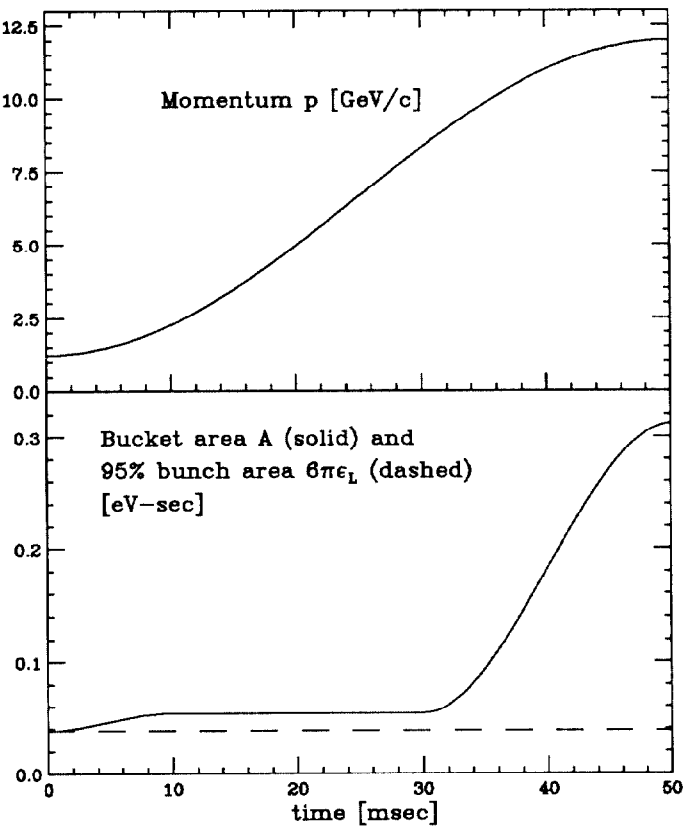

Figure 1: Input for program RAMPRFA, for a sample excitation of the SSC's LEB.

in RAMPRFC is that one can provide $\dot{E}$ from some analytic calculation for $E(t)$ (for example, if one uses a spline generator to produce the values of $E(t)$, the derivative can be easily calculated from the spline formula). RAMPRFB is more suited for the case in which one obtains the values of E and V from a source outside one's own control (for example, from the control program of a friend's synchrotron).

In all cases, the time intervals in the input tables *need not be uniform*; the proper weighting is used in the forward-backward algorithm for the computation of derivatives by finite differences.

Output

The output consists of three data sets: (a) Screen output with a few columns such as time, V, ϕ_s and space-charge tune spread. (b) Four disk files in multi-column format, called RAMPRFn.DAT, where $n = 1, 2, 3, 4$. (c) 23 disk files with x-y listings of physical quantities, suitable for graphics plotting; these files are called xxx.TOPDAT, where xxx is a mnemonic for the quantity listed.

RAMPRF1.DAT lists E, p, B (=dipole field), $\dot{E}$, $\dot{p}$, $\dot{B}$, β, γ and $\beta\gamma^2$ as functions of time. RAMPRF2.DAT lists ϕ_s, $\Delta\phi$, Δt and Δz (=bucket width in units of phase, time and length, respectively), A, ϕ_ℓ and ϕ_r (=left and right intercepts of the separatrix, respectively) and $\Delta p/p$ (=full

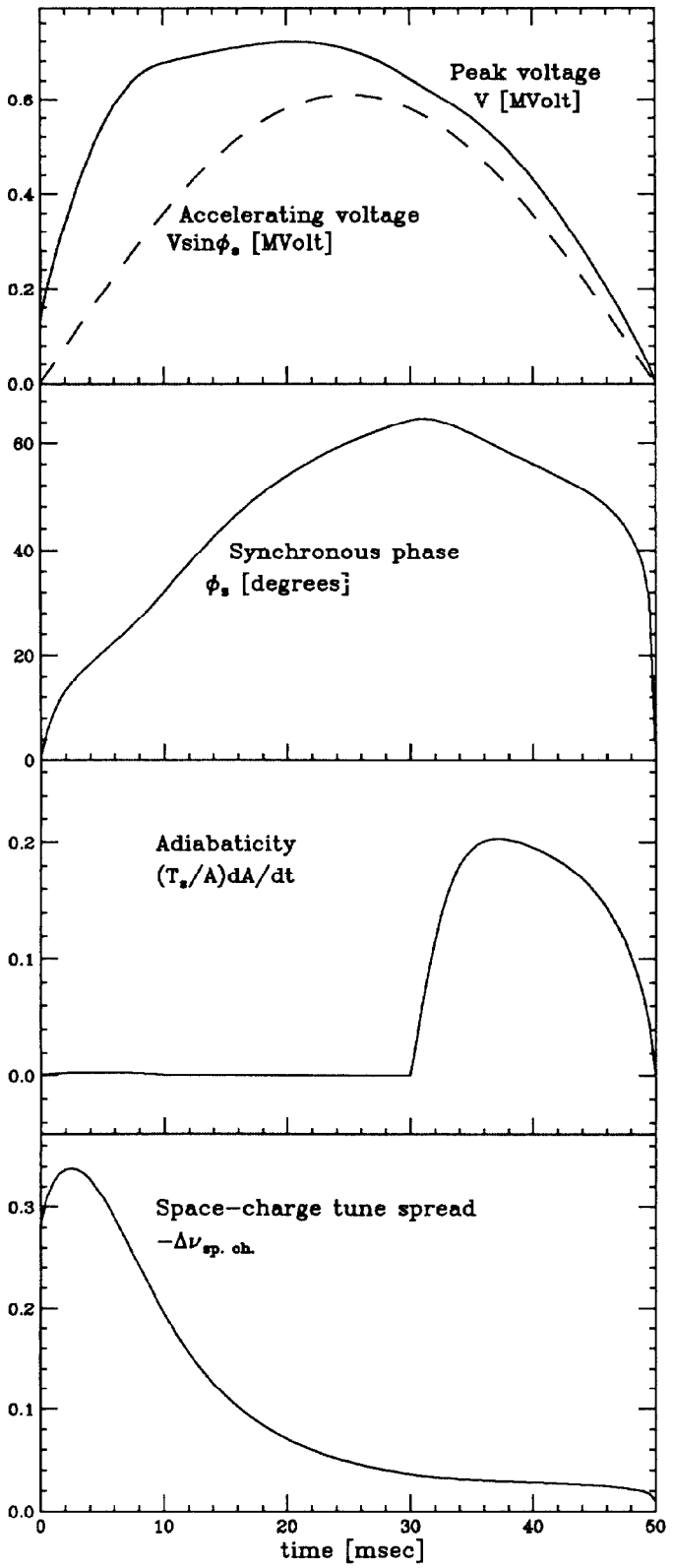

Figure 2: Some of the output corresponding to the input in Figure 1.

bucket height) as functions of time. RAMPRF3.DAT lists V, $f_{\rm rf}$ (=rf frequency), $\mathcal{A}$, $B_f \equiv I_{\rm peak}/I_{\rm av.}$ (=bunching factor), $\Delta\nu_{\rm sp.ch.}$ (=space-charge tune spread), σ_p/p, σ_z and σ_x, σ_y (=average rms bunch widths) as functions of time. RAMPRF4.DAT lists ν_s, f_s (=synchrotron frequency), $6\pi\epsilon_L$, $V\sin\phi_s$ (=accelerating voltage), longitudinal and transverse microwave instability thresholds $|Z_\parallel/n|$ and $|Z_\perp|$, and longitudinal and transverse mode-coupling instability thresholds $\mathrm{Im}(Z_\parallel/n)$ and $\mathrm{Im}(Z_\perp)$ as functions of time.

The xxx.TOPDAT files list the following quantities *vs.* time: V and $V\sin\phi_s$ (in one single file), $f_{\rm rf}$, A, $6\pi\epsilon_L$, A and $6\pi\epsilon_L$ in a single file, ΔE, $\Delta p/p$ (=full bucket height in energy and relative momentum, respectively), $\Delta\phi$, Δt, ν_s, f_s, $\mathcal{A}$, σ_p/p, σ_t (=rms bunch length in time units), B_f, $\Delta\nu_{\rm sp.ch.}$, p, B, $|Z_\parallel/n|$, $|Z_\perp|$, $\mathrm{Im}(Z_\parallel/n)$, and $\mathrm{Im}(Z_\perp)$. The last file lists V *vs.* $f_{\rm rf}$.

IV. An Example

The case presented here corresponds to an earlier design of the SSC's low-energy booster (June 1990 "point design") using RAMPRFA. In this case $p_i = 1.219$ GeV/c, $p_e = 12$ GeV/c, $T_r = 50$ msec, $\gamma_t = 14.5$ and the circumference is 540 m. At extraction the voltage drops to a very low value despite a relatively large bucket area because the energy comes close to transition ($\gamma_e = 12.8$). The bunching factor used to determine $\Delta\nu_{\rm sp.ch.}$ was obtained assuming a gaussian longitudinal distribution with emittance as shown in Figure 1; multiparticle simulations verified that this is a very good approximation for $t \gtrsim 0.5$ msec (important details at injection are not shown here; see Ref. [4]).

V. Acknowledgments

I am grateful to C. Ankenbrandt, A. Chao, M. Craddock, D. Edwards, H. Edwards, D. Finley, H. Foelsche, J. Griffin, R. Johnson, J. MacLachlan, N. K. Mahale, P. Martin, A. Maschke, P. Morton, S. Penner, A. Ruggiero and M. Syphers for many discussions. I am also grateful to A. Chao for the hospitality extended to me at the SSC Laboratory, where these programs were developed.

VI. References

[1] See, for example, H. Bruck, *Circular Particle Accelerators*, Los Alamos translation LA-TR-72-10 Rev.; D. A. Edwards and M. J. Syphers, *An Introduction to the Physics of Particle Accelerators*, 1988 USPAS.

[2] M. Furman, SSCL-N-758/ESG-170, in preparation.

[3] C. Bovet, R. Gouiran, I. Gumowski and K. H. Reich, CERN/MPS-SI/Int. DL/70/4.

[4] N. K. Mahale and M. Furman, these proceedings.