FERMILAB-CONF-04-560-PPD

Proceedings of EPAC 2004, Lucerne, Switzerland

SIMULATION OF RF CONTROL OF A SUPERCONDUCTING LINAC FOR RELATIVISTIC PARTICLES*

P.C. Bauer, G.W. Foster, M. Hüning†, FNAL, Batavia, IL 60510, USA

Abstract

We present a code to simulate the rf field and field control in a superconducting linac for relativistic heavy particles. In such a linac the field stability is strongly influenced by the longitudinal beam dynamics. So the code has to simulate both the field and the beam dynamics with the resulting varying beam loading. Other effects included in the simulation are microphonics and Lorentz force detuning. The code can simulate both single cavity and vector sum control.

INTRODUCTION

The demands on the field stability of proton- and heavy ion linacs are different than those in electron linacs. Because of the large mass of the particles their speed is considerably smaller than c along a large fraction if not the entire length of the linac. Because of this fluctuations in the energy gain at any point of the accelerator can have a large impact on the arrival phase of the beam downstream. This has implications both for the energy gain as well as the beam loading in the corresponding acceleration structures.

At Fermilab the design of a 8 GeV superconducting proton linac is being studied [1]. One core element of the design is the use of a rf fan-out from one klystron to several cavities. In this setup with its inherent field fluctuations of individual cavities the above considerations become especially relevant. It is immediately clear that high power correction elements will be required to allow control of individual cavities. But is this true for the entire linac? What are the exact requirements for these correction elements? What energy stability can be expected at the end of the linac?

To answer these and other questions a simulation tool has been developed which is capable of simulating both the relativistic motion of particles as well as the field control of the superconducting rf cavities. It was dubbed "SCREAM" for **s**uperconducting **re**lativistic particle **a**ccelerator si**m**ulation.

A "plugin" simulates the high power rf modulator, internally referred to as phaseshifter although it has to be capable of modulating both amplitude and phase. The devices envisaged have a non-neglectable dynamic response. This is simulated as well.

The code described here is not the first of its kind [2], but for a number of reasons it seemed wise to create something new.

WORKING PRINCIPLE

The tool mainly consists of MATLAB functions and scripts. This allows for easy implementation with little programming overhead. The longitudinal beam dynamics are simulated in a c-function that can be called from the MATLAB code. This is done with the hope that execution times may be shorter, and indeed an increased speed of the simulation was observed.

The simulation works in time steps of typically one microsecond, but other stepsizes can be chosen. The delay of the feedback loop is automatically set to the stepsize. It is assumed that nowadays 1 μs loop delays can be achieved even with digital systems. With the field values reached at the end of the previous time step the beam is tracked through the linac. The beam can be made up from one or more macroparticles, each carrying a fraction of the total bunch charge. Even when in the real machine there are several bunches during one time step, in the simulation all charge is represented by one bigger bunch. The beam loading is equivalent. The energy gain in each cavity is calculated by the accelerating voltage, the arrival and cavity phase

$$\triangle E = V \cdot T \cdot \cos(\varphi), \tag{1}$$

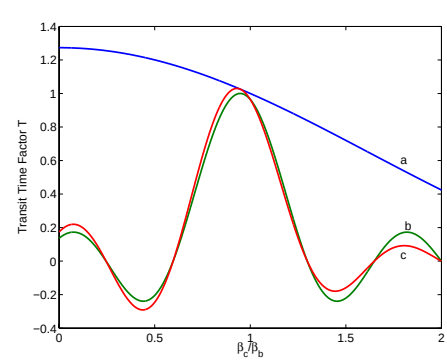

Figure 1: Transit time factor T of a 6-cell standing wave structure. The optimum is found at a ratio $\beta_{cavity}/\beta_{beam}$ slightly smaller than one. The overall factor (c) is made up by the effect of individual cells (a) and the effect due to coupling 6 cells (b).

* Work supported by Department of Energy contract DE-AC02-76CH03000

† mhuening@fnal.gov

and the transit time factor of the cavity

$$T = \underbrace{\frac{4}{\pi}\frac{\cos\left(\pi/2\beta_c/\beta_b\right)}{1-\left(\beta_c/\beta_b\right)^2}}_{\text{single cell}}\underbrace{\frac{\sin\left(N\pi/2(1-\beta_c/\beta_b)\right)}{N\sin\left(\pi/2(1-\beta_c/\beta_b)\right)}}_{\text{multiple cell}}, \quad (2)$$

with β_c the beta for which the cavity is optimized, β_b the beta of the particle, and N the number of cells. The above formula is correct for a standing wave structure with $E_z = E_0\cos(kz)\cos(\omega t)$ and a ratio of peak voltage to acceleratin voltage of 2. The maximum of T is normalized to 1. Figure 1 shows the transit time factor of a 6-cell structure. The variation of the factor with β is dominated by the cell-to-cell effects. Therefore it seems justified to use the same factor for all types of cavities.

The phase φ is the phase of the rf at the time the particle crosses the center of the cavity – either the center of the middle cell or the center between the two middle cells, depending if the number of cells is even or odd. At the end of the function the energies, arrival times, and transit time factors of all macroparticles in all cavities are returned to the main function.

The main function then calculates the beam loading based on this information. Given the field values at the end of the previous time step the rf control loop – presently a pure proportional feedback with a feedforward for beam loading compensation – is simulated. With the rf signals being constant during one time step, the development of the cavity field is

$$V_{k+1} = (V_k - V_b - V_{rf})\exp\big((\omega_{1/2} + i\triangle\omega)t\big) + V_{rf}, \quad (3)$$

with V_k the cavity voltage at the k-th time step, V_b the beam loading, V_{rf} the forward power, $\omega_{1/2}$ the bandwidth, and $\triangle\omega$ the detuning of the cavity. Obviously the first step of the simulation is only performed after the filling time of the cavity when the beam is switched on.

Due to the large off-crest phase required for phase focusing there is considerable transverse focusing by the rf field. Therefore fluctuations in the cavity fields can also have a big impact on the transverse phase space. Also the model in this program is somewhat restricted, it is missing space charge effects for example. To account for this it is necessary to export the data of field amplitudes and phases to other, more complete, simulation programs. To date it is possible to export to TRACE3D, but other codes can be supported, too. A short script is provided that takes the output of the simulation and places it at the appropriate places in an existing TRACE3D input file.

Because the focus of the simulation is not the beam but the rf controls, and to keep the computation time and programming effort reasonable, the beam dynamics in the code were restricted to the absolute minimum. Also it is desirable to check the results of the simulation with another, independent and well tested code.

SOME TECHNICALITIES

After the main function has calculated the feedback loop for the klystrons, a script is called that simulates the feedback loop for the individual cavities and the dynamics of the high power rf modulator. The modulator is made out of two phase shifters which act independently on one half of the forward power respectively [3]. Its action on the forward power for the respective cavity is multiplicative with a factor

$$P = P_0\exp\left(i(\psi_1+\psi_2)/2\right)\cdot\cos\left((\psi_1-\psi_2)/2\right). \quad (4)$$

Initial phase offsets are absorbed into ψ_1 and ψ_2. It is advantageous to enforce a minimal difference between the two phases. If the phases come too close to each other the incremental gain diminishes, with adversal effects on the field stability. Should the phase difference flip sign, the loop could even become unstable. A non-zero phase difference causes loss of rf power, but the benefits for the feedback loop might outweight it. In addition to that, the amplitude feedback loop adjusts the gain to always maintain approximately the same overall loop gain.

The program needs a lot of input data. It is read from coma separated value lists (csv-files). In this way it is possible to create the input files by spreadsheet programs, any ASCII editor, or by any program capable of writing custom files.

The bunches are made up of macroparticles. Their definition is part of the input file. Currently 73 macroparticles are used. In the incoming phasespace they are distributed along a star with 8 beams, with one particle located at every $0\ldots9$ units from the center. The relative weight of the particles is chosen such that they represent a 2D gaussian distribution with σ one unit. Each macroparticle represents the charge in a slice $[r-0.5, r+0.5)$ times $[\varphi-\pi/8, \varphi+\pi/8)$. The phasespace is stretched in the time and energy coordinate according to the assumed RMS values of the incoming beam.

FLUCTUATIONS

A key function of the program is to accumulate statistics on cavity fields and beam properties with fluctuations of main parameters of the system. The quantities allowed to fluctuate are the cavity tuning, the beam initial energy, the beam input phase, the beam current, and the Lorentz force detuning. The latter is different from all others in that it is fixed once the accelerator is built. Therefore it is generated once and then kept constant over several runs. There are two nested loops to do this.

The other quantities are newly generated for each run. A distinction is made between coherent and incoherent fluctuations. The coherent fluctuations are generated once per simulation, the incoherent once every time step. The fluctuations are generated with normally distributed random numbers, with the standard deviation of the distribution given in the input file. The state of the random number generator is saved with the results.

The figure 2 shows a comparison between coherent and incoherent fluctuations of the incoming beam. It consists of two correlation plots of the incoming and outgoing energy fluctuations. Due to the small bandwidth of the system there may be the concern that slow fluctuations feed back onto themselves by causing large fluctuations of the field. The slope of the correlation plot between the input and output errors should then be bigger for the coherent ones. It turns out that they are about equal, apparently the controls do their job.

RESULTS

In figure 3 one sees the cavity voltages of 12 cavities fed by a single klystron. The cavities shown are $\beta = 1$ cavities at a beam energy of 1.3 GeV. At this energy the mismatch between beam and cavities is still relatively large and varies along the rf group. To compensate for the difference in beamloading each cavity is operated at a different gradient, approximately

$$V_{cav} = V_{ave}/\sqrt{T\left(\beta_{beam}\right)}, \tag{5}$$

which is achieved by tuning the loaded Q slightly off the optimum and varying the power P from the equal distribution,

$$Q_L = Q_L^{(0)}/\sqrt{T\left(\beta_{beam}\right)} \qquad P = P_0/\sqrt{T\left(\beta_{beam}\right)}. \tag{6}$$

In this way the ratio between filling and flat top is similar for all cavities, which reduces the slopes on the gradients during flat top.

The figure 4 shows an example for a phase space plot. It shows how regular areas in phase space get distorted along the acceleration. Had the input areas been extended a little bit further it would have curled around the center of the bunch and eventually been lost. Due to fluctuations of the rf fields the stable region shrinks.

CONCLUSION

A tool has been created to simulate rf control of a superconducting linac for relativistic beams. It can be used for many different types of such accelerators, but special emphasis is in the control of multiple cavities per klystron. A high power rf modulator for individual cavity control can be modeled. The tool has been used in the design study for a superconducting linac version of the proton driver at Fermilab [4]. A more detailed description of the program can be found in [5].

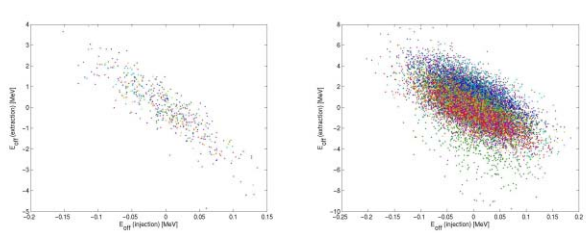

Figure 2: Transport of incoming fluctuations to the end of the linac. The simulation distinguishes between coherent and incoherent fluctuations. Note the different scale of the two plots.

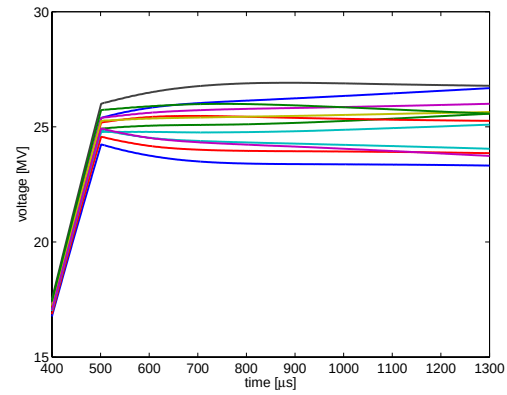

Figure 3: Cavity fields amplitudes with an rf fan out from one klystron to several cavities. The vector sum is kept constant to better than 10^{-3}, but individual cavities fluctuate. The spread in voltages is intentional.

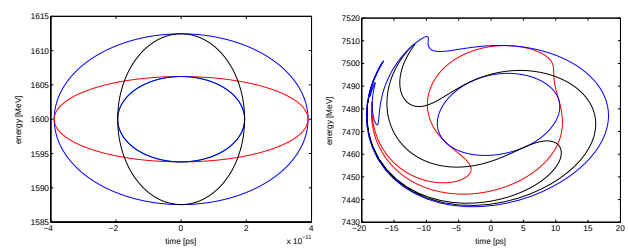

Figure 4: Longitudinal phase space at the input and output of the high beta section of a 8 GeV proton linac. Due to the nonlinear curvature of the accelerating fields the regular structures at the input get distorted along the way.

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