REQUIREMENTS FOR THE RF CONTROL OF THE VECTOR SUM FOR SUPERCONDUCTING PROTON LINACS

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Abstract

Superconducting accelerator technology has demonstrated its superior performance in large scale machines such as CEBA at TJNAF and is increasingly used for new accelerator designs. Until now this technology has found its main application in electron accelerators. However nowadays proton accelerator designs for the European Spallation Source (ESS) and the Accelerator Driven Transmutation Technology (ADTT) also study the feasibility of superconducting linacs. In contrast to the highly relativistic electron beams the proton beam exhibits an increased susceptibility to voltage fluctuations in the acceleration system induced by microphonics and dynamic Lorentz force detuning. Although low beam loss is an important criterion for linac design, studies of the longitudinal dynamics appear to be a good indicator for beam stability in presence of fluctuations of the accelerating field. Control of the vector sum of multiple cavities driven by one klystron is desirable for cost reasons but does not allow for control of individual cavity fields. In this paper we study the performance of such a system.

1 INTRODUCTION

The technology of proton accelerators has progressed considerably in the past three decades [1]. Several high intensity proton accelerators with high peak or average beam currents of the order of 100 mA are presently under study for applications such as: spallation neutron sources, kaon factory, nuclear transmutation technology, energy amplifier, and muon collider drivers. The implementation of superconducting acceleration systems [2,3] appears to be attractive since it could lead to substantial cost savings in machine operation especially if multiple cavities are driven by one common high power klystron.

An important design criterion for a high intensity proton linac is beam loss control since the beam loss should not exceed 1 nA/m to allow for hands-on maintenance after a long operation period. Particle loss is caused by a small number of particles outside the dense beam core, called the beam halo. The origin and formation and dynamics of the halo have been studied intensively and significant progress has been made in recent years. In superconducting linacs where multiple cavities are driven by a single klystron beam loss may be enhanced by microphonics which are a result of mechanical vibration modulating the resonance frequency of the high Q cavities. In this paper we develop a simple model to determine the impact of fluctuations of the accelerating field on beam energy. For simplicity only the longitudinal dynamics of the bunch centroid are analyzed. Bunches with excessive energy deviations are considered as potential candidates for beam loss. An important result of this model is an upper limit for the microphonics noise levels permitted for accelerator operation.

2 BEAM DYNAMICS MODEL

The energy gain of the bunch centroid when passing a single cavity can be described as

$$\Delta V = V_o \cdot T \cdot \cos(\phi_S),$$

where V_o is the cavity voltage, T is the transit time factor, and ϕ_S the phase angle between beam current and accelerating field. The transit time factor is a function of the bunch velocity $\beta = v/c$ and the phase angle depends also on β according to $\Delta\phi = (2\pi f L)/(c\beta)$, where f is the operating frequency of the rf cavities, and L the drift space between the center of two adjacent cavities. Thereby the dynamics inside the cavities have been approximated by a cavity with length zero and the surrounding drift space.

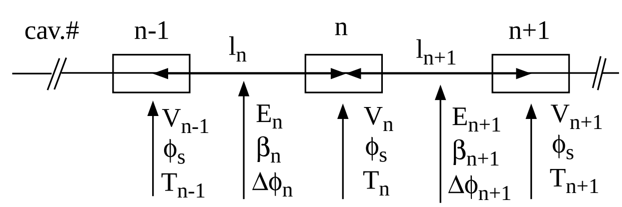

Figure 1: Definition of parameters used for the beam dynamics model.

Changes in transit time factor due to finite cavity length are however considered. For a given linac configuration one can calculate the deviations of beam energy, bunch velocity, and phase of the accelerating field with respect to a reference particle.

$$E_{n+1} = E_n + V_n \cdot \cos(\Delta\phi_n + \phi_s) \cdot T_n(\beta_n)$$

$$\beta_{n+1} = \sqrt{1 - \frac{m_p^2 c^4}{(E_{n+1})^2}}$$

$$\Delta\phi_{n+1} = \Delta\phi_n + \frac{2\pi f l_n}{c} \cdot \left(\frac{1}{\beta_n} - \frac{1}{\beta_{ref}}\right)$$

In the model the transit time factor of a m-cell cavity is derived from the transit time factor $T_1(\beta)$ of a single cell cavity as:

$$T(\beta) = T_1(\beta)2 \cdot \frac{\cos\left(\frac{m-1}{2}(x-\alpha)\right) - \cos\left(\frac{m+1}{2}(x-\alpha)\right)}{m \cdot (1-\cos(x-\alpha))}$$

with

$$T_1 = \frac{\sin(x/2)}{(x/2)} \text{ for } E(z) = \text{const.}, \; x = \frac{2\pi L_n}{\beta\lambda}, \; \alpha = \frac{k}{m}\pi$$

k=1...m depending on selected passband mode. Here k/m=1 i.e. $\alpha = \pi$ for a standing wave structure. L_n is the length of the cavity.

3 LINAC PARAMETERS

To determine the impact of fluctuations of the accelerating field on the longitudinal dynamics of the bunch centroid the parameters of two recently proposed linac designs have been selected (see Table 1).

4 SIMULATION RESULTS

Based on the beam dynamics model and the sample linac parameters the quantities of interest have been determined for several cases:

1. stochastic cavity amplitude and phase errors along the linac with uniform distribution. The simulation has been performed with various sets of errors for injector and linac.
2. stochastic cavity amplitude and phase errors along linac but the vector-sum of an ensemble of 2 or 4 cavities perfectly regulated.

Table 1: Sample Linac Parameters

	LINAC 1	LINAC 2
Frequency [MHz]	700	700
Linac Energy [MeV]	1700	1300
Number of cavities	102 & 308	166
Number of cells / cavity	5 & 5	5
Injection energy [MeV]	211 & 470	70
Beta of cavity	0.64 & 0.82	0.37 .. 0.91
Cav. centroid spacing [m]	2.0 & 2.1	0.5 .. 1.36
Synchronouse phase [deg]	-35 & -30	-20
Energy gain/cav. [MV]	2.5 & 4.0	3.9 .. 9.8
Cavity gradient [MV/m]	5.2 & 5.9	10

The deviation of the final linac energy from the reference energy can be used to determine the potential for beam loss. The simulations show that small field fluctuations result in a moderate increase in energy spread while larger errors - depending on the distribution along the linac - may result in basically zero energy gain in the linac due to phase slippage. Particles which do not experience a net energy gain in the linac are likely to be lost due to the lack of rf focusing. Some of the results of the simulations for the different case studies are shown in Table 2. The probability of beam loss is equivalent to linac energy gain less than 90%.

Table 2: Linac Energy Spread (Bunch-to-Bunch) and Particle Loss

Injector Error[1]		Linac cavity error[1]		probability of energy gain < 90% $[10^{-5}]$ [2]						σ_E/E $[10^{-4}]$					
$\Delta\phi$[°]	ΔE [%]	$\Delta\phi$[°]	ΔV [%]	no control[3]		vector-sum (2)[4]		vector-sum (4)[4]		no control[3]		vector-sum (2)[4]		vector-sum (4)[4]	
		Linac type:		1	2	1	2	1	2	1	2	1	2	1	2
1	1	1	1	12	-	-	-	-	-	18	11	18	8.7	18	9.1
1	1	3	3	24	-	-	-	-	-	22	25	18	9.4	19	12
1	1	5	5	270	13	-	-	-	-	27	42	18	11	19	16
1	1	7	7	1580	30	-	-	-	-	33	57	18	12	20	21
1	1	10	10	9500	610	-	-	10	7.8	40	72	19	15	21	31
0	0	1	5	- 5	- 5	- 5	- 5	- 5	- 5	15	29	1.8	6.2	4.0	11
0	0	5	5	- 5	- 5	- 5	- 5	- 5	- 5	20	39	2.3	7.8	5.2	15
0	0	1	10	300	120	- 5	- 5	- 5	- 5	28	54	3.4	10	7.6	20
0.5	5	1	5	- 5	- 5	- 5	- 5	- 5	- 5	19	30	10	10	11	14
0.5	5	5	10	1600	1400	- 5	- 5	- 5	- 5	33	61	10	14	14	24
0	0	0.1	1	- 5	- 5	- 5	- 5	- 5	- 5	3.2	7	0.7	4	1.7	4.5
0.5	5	0.1	1	- 5	- 5	- 5	- 5	- 5	- 5	10	10	9.7	8.9	9.7	9.0
1	5	0.1	1	- 5	- 5	- 5	- 5	- 5	- 5	19	12	18	11	18	11
1	5	1	5	80	- 5	- 5	- 5	- 5	- 5	23	31	18	12	19	15
5	5	0.1	0.1	80000	60000	80000	60000	80000	60000	27	41	25	41	26	41

[1]All errors assume a uniform distribution; [2]total number of runs is 100000 [3]no rf feedack applied; [4]vector-sum of 2 repectively 4 cavities is perfectly regulated; [5] number of runs only 12000;

The number of random error sets for most simulations has been 100000 which means there is still a chance of the order of 10^{-5} that a bunch might get lost. The table shows that for a reasonable phase and amplitude injection error of 1 deg. and 1% respectively the linac can tolerate phase and amplitude perturbation levels of severals degrees and percent. A summary of the results is shown in Figure 2.

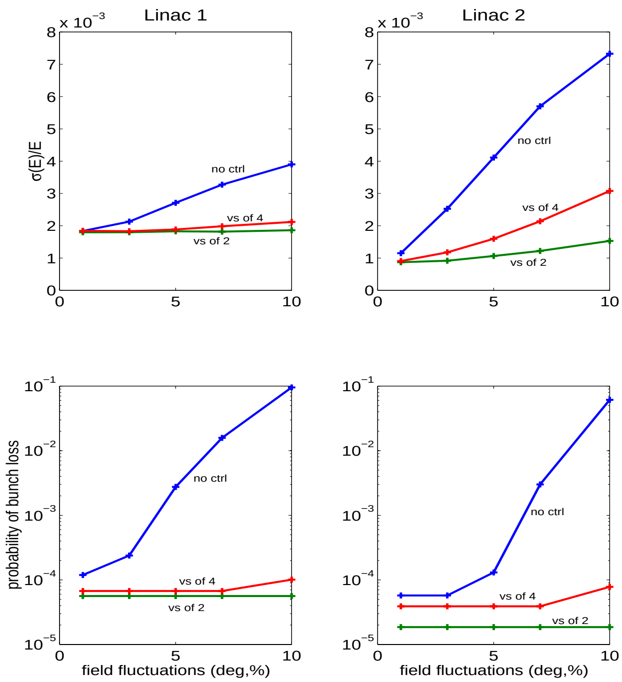

Figure 2: Energy spread and bunch loss as function of amplitude and phase errors in the linacs.

5 CONSIDERATIONS FOR THE CONTROL OF THE VECTOR SUM

The rf control for the vector sum of multiple cavities can be improved significantly if the energy gain and the beam arrival time or beam phase at the entrance of the following ensemble of multiple cavities can be controlled. This can be accomplished by control of the vector sum amplitude and phase which provide linear independent control of the beam energy gain and beam phase in the vicinity of the synchronous phase.

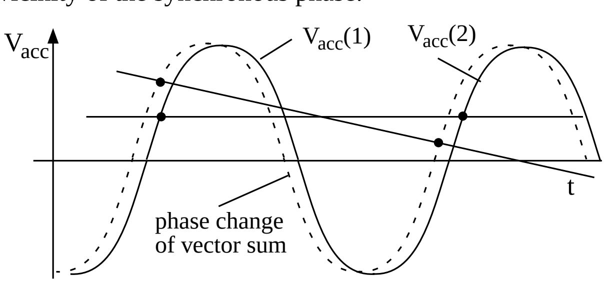

Figure 3: Principle of beam energy and beam phase control

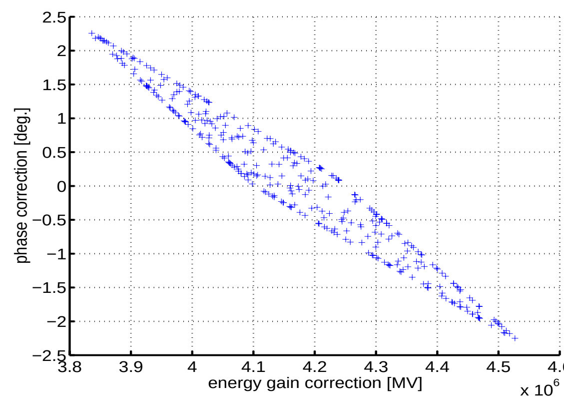

Figure 4: Energy gain and beam phase correction range at the low energy end of Linac 1. The vector sum of 2 cavities is controlled and varied by ±3 deg. in phase and ±10% in amplitude.

The principle of beam energy and beam phase control is shown in Figure 3. A change in cavity phase or amplitude will result in the arrival time at the following cavity. With proper choice of vector sum amplitude and phase the energy and beam phase at the following cavity can be controlled within the boundaries shown in Figure 4. The control range is larger at the low energy end of the linac.

6 CONCLUSION

The control of microphonics and Lorentz force detuning in superconducting cavities for proton accelerators has been a major concern. This is especially true if only vector sum of several cavities which are driven by one common klystron is controlled. The simple model presented for the analysis of the accelerating mode driven longitudinal dynamics of the bunch centroid has shown that surprisingly large levels of microphonics are acceptable even in the case of vector sum control of 4 cavities.

REFERENCES

[1] M. Pabst and K. Bongardt, *Halo simulation in a realistic proton linac design*, PAC97, Vancouver, B.C., Canada, May 12-16, 1997, in print.

[2] G.P.Lawrence and T.P. Wangler, *Integrated Normal-conducting/Superconducting High-Power Proton Linac for the APT Project*, PAC97, Vancouver, B.C., Canada, May 12-16, 1997, in print.

[3] B. Aminov, A. Gamp, E. Haebel, H. Heinrichs, H. Piel, J. Pouryamout, Th. Schilcher, D.L. Schrage, G.Schulz, S. Simrock, C.H. Rode and R. Röth, *Conceptual Design of the Superconducting High Energy Linear H⁻-Accelerator for the Future European Spallation Source (ESS)*, ESS 96-60-L, 1996.