VECTOR SUM CONTROL OF AN 8 GeV SUPERCONDUCTING PROTON LINAC*

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Abstract

Fermilab is investigating the feasibility of an economical 8 GeV superconducting linac for H-. In order to reduce the construction costs it is considered to fan out the rf power to a string of accelerating structures per klystron. Below 1 GeV the individual fluctuations of the cavities will be compensated by high power phase shifters, above 1 GeV the longitudinal dynamics are sufficiently benign to consider omitting the phaseshifters. The impact of this setup on the field stability of individual cavities and ultimately the beam energy has been studied.

INTRODUCTION

At Fermilab studies are underway for the design of a so-called Proton Driver to replace the existing accelerator chain up to the Main Injector. The new accelerator is supposed to increase the beam power after the Main Injector by a factor of 5. One design option calls for a superconducting linac to deliver 2 MW of beam power at 8 GeV [1]. It is foreseen to accelerate H^- ions and inject via stripping.

To keep the project economically feasible it is planned to reduce the number of klystrons necessary by operating multiple cavities from one klystron. In that way it is very similar to the TESLA proposal for the Linear Collider, only that in the case of H^- the feasibility of such a system is not as clear as it is with electrons. In contrast to electrons the ions are not ultra-relativistic. This means that their velocity changes along the linac but more importantly it fluctuates as the energy fluctuates. Therefore the arrival phase of the beam depends on the upstream acceleration. This makes vector sum control difficult.

A simulation tool has been developed [2] to enable studies of the rf controls under the circumstances just described.

LINAC DESIGN

The desing of the Proton Driver is still evolving, with substantial changes between versions. The version treated here has four cavity types in the superconducting part. The beam is injected at 87 Mev into a section with elliptical cavities with design beta of 0.47 and a frequency of 805 MHz. There are sixteen cavities in this section all powered by a single klystron[1]. There are two more sections operating at 805 MHz, one for $\beta = 0.61$ and one for $\beta = 0.81$. The first type was developed for the Rare Isotope Accelerator (RIA), the latter two are used in the Spallation Neutron Source (SNS). In these sections each klystron drives twelve cavities. At 1.3 GeV the beam is injected into a section with cavities of design beta 1.0 and a frequency of 1.2075 GHz. These would be scaled TESLA cavities. A selection of parameters is summarized in table 1. The beam current is 25 mA and the linac is pulsed with beam pulses of 800 μs.

Table 1: List of selected parameters of the cavities under study.

cavity β	0.47	0.61	0.81	1.0
No.of cavities	16	36	64	288
No.of klystrons	1	3	8	24
average acc. voltage $[MV]$	6.9	11.3	18.6	25.2
energy after section $[MeV]$	174	400	1320	8075
cav. length $[m]$	0.525	0.682	0.906	1.118
No. of cells	6	6	6	9
power per cavity $[kW]$	160	260	440	605
K $[Hz/MV^2]$	11.9	6.2	0.85	1.0

Because there are only four different types of cavities, in most cases they are mismatched to the beam. This means that in most cases the actual energy gain in a cavity is smaller than its voltage. This leads to another challenge for the cavity grouping: The beam loading differs from cavity to cavity.

To prevent the beam from debunching phase focusing has to be applied. This is achieved by off-crest acceleration. A consequence of that is a transversely defocusing force by the rf field depending on the rf phase.

Because of these effects it is necessary to assist the klystron by high power modulators to allow for individual cavity control. With the simulations reported in this paper it was confirmed that these modulators are only needed in the first three sections of the linac. In the biggest part of the accelerator,the section with the beta 1.0 cavities, the beam is already stiff enough to get along without individual cavity control.

HIGH POWER RF MODULATOR

Figure 5 shows the working principle of the high power RF modulator [3]. It works by recombining two partial waves after they experienced a variable phase shift. The amplitude and phase modulation can be written as

$$P = P_0 \exp\left(i(\psi_1 + \psi 2)/2\right) \cdot \cos\left((\psi_1 - \psi_2)/2\right). \quad (1)$$

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[1] This is a deviation from the original design

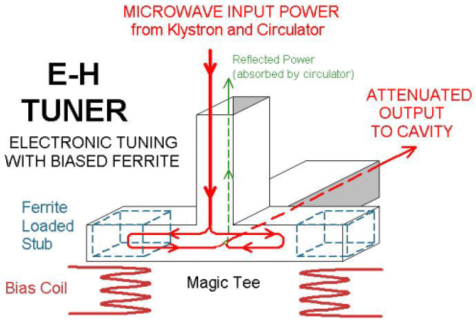

Figure 1: Working principle of the high power rf modulator.

It is foreseen to have individual phaseshifts of ±45° to achieve a maximum attenuation of 3dB. For optimal performance of the control loops one would like to run at a working point of $\psi_1 - \psi_2 \approx 45°$. This would result in a constant loss of 3dB, which seems unacceptable. The lowest losses would occur at a working point of $0°$. But then the incremental gain of the amplitude loop, which is proportional to $\sin((\psi_1 - \psi_2)/2)$, would vanish. Furthermore a crossing of the two phases would flip the feedback from negative to positive, making the loop unstable. A good compromise seems to be a value around $10°$. In the simulation all modulators in one rf unit are lowered as soon as one of them approaches the $10°$ phase difference.

Another problem is the response time of the phaseshifters. The ferrites have to be biased by an external magnetic field to achieve the phase shift. Solenoid magnets are being constructed to achieve this. They have an inductivity of 1 mH and require currents in the order of 100 A, with variations around ±20 A to achieve the required modulation. With a power supply voltage of 150 V the 20 A can be reachd within 130 μs which corresponds to a slew rate of $45°/133\,\mu s$. There will probably be a screening effect by the waveguide around the ferrite which acts like a low pass filter. A time constant of 20 μs is expected. A second filter with time constant 10 μs will suppress voltage spikes from the power supply. The control loop has to cope with these long delays. The present results were generated with a proportional/differential feedback. Other types of controllers are being investigated. To compensate for the lower differential gain at smaller attenuation, the feedback gain in the amplitude loop is increased when the phase dfference gets smaller.

RESULTS

In figure 2 the beam energy at the exit of the 8 GeV linac. For each time step the weighted average of all macroparticles is plotted. This result was obtained with a grouping of 12 cavities per klystron in the beta-1-section. In this section there are no modulators at the cavities, the field control is done globally for the 12 cavities. There is a systematic increase of the energies towards the end of the pulse. The acceptance of the Main Injector is ±10 MeV, so this correlated movement is acceptable. In figure 3 the histogram of all particle energies in the same pulse is shown. The whole distribution fits easily into the acceptance window. The motion of the mean energy is due to the vector sum control in the high-beta section. Particularly the first 2-3 rf modules are to blame. With some very delicate tuning of all individual cavities it should be possible to suppress the effect completely. For the result in figures 2 and 3 the optimization was stopped when the requirements were fulfilled.

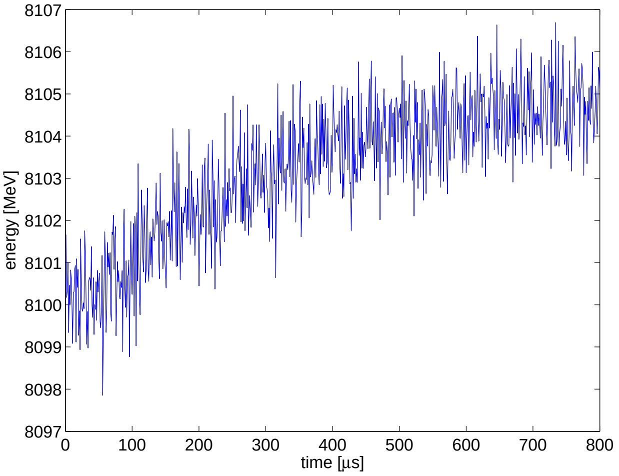

Figure 2: Beam energy at the exit of the linac. The weighted average energy of all macroparticle is plotted for each time step of the simulation. The fast fluctuations are due to fast fluctuations of the incoming beam which are transferred to the end of the beamline.

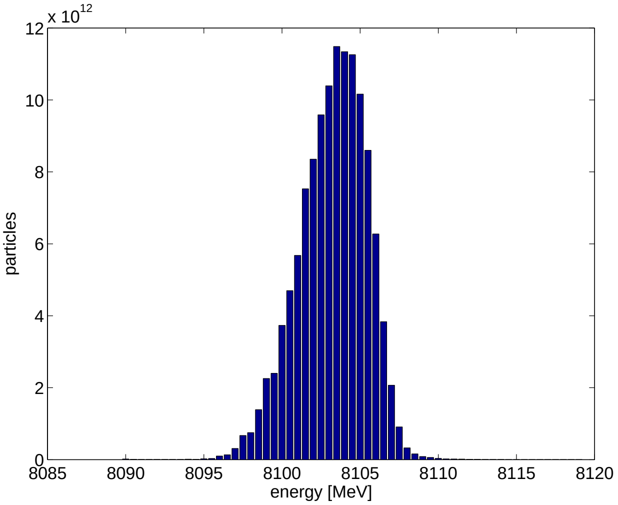

Figure 3: Histogram of the particle energies at the exit of the linac. The bunch centroids move according to figure 2.

There are fast fluctuations on top of this slow movement. These can be attributed to the fluctuations of the incoming beam. They are modelled as white noise up to the nyquist frequency. Although the high frequency components are too fast for the cavities to follow, they are passed along in the simulation to avoid any prejudice in the selection of the cutoff. The same applies to microphonics.

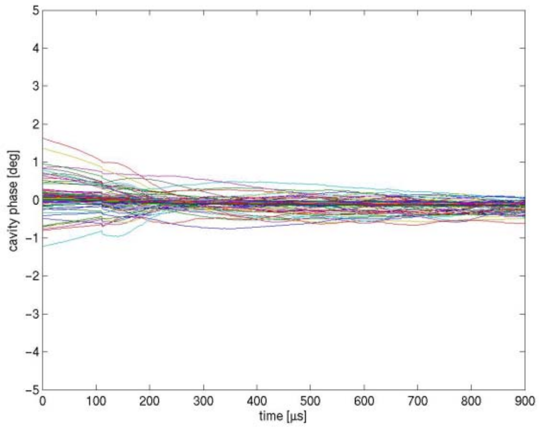

Figure 4: Phases of the low beta ($\beta < 1$) cavities. The phaseshifter response time was 100 μs in this simulation.

The low beta cavities are controlled by high power modulators. In figure 4 one can see the stability of the phases of the individual cavities that could be achieved with a slew rate of the phase shifters of $45°/100\,\mu s$. The motion of the phase shifters can be seen in figure 5. Actually in this picture only the first 16 are depicted to avoid excessive cluttering of the plot. There are two phaseshifters per cavity. In the figure the two ways of motion on these shifters can be observed: Moving the shifters parallel provides a net phaseshift, moving them antiparallel provides attenuation. In this picture the minimum offset between the phase shifters is zero. A better setting requires $10°$ or more to achieve a better amplitude control.

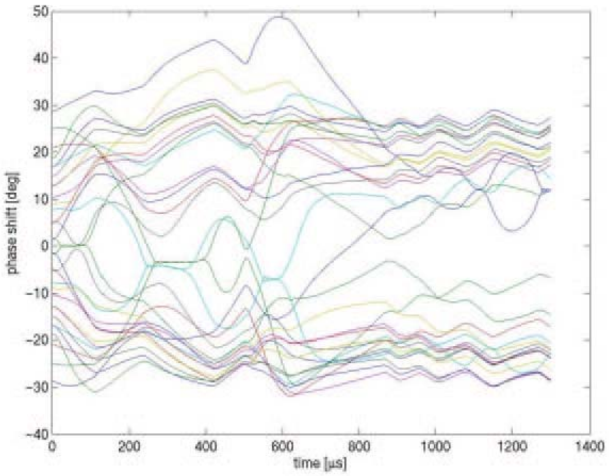

Figure 5: Phase shifter action on the first sixteen cavities of the linac. There are two phase shifters per cavity.

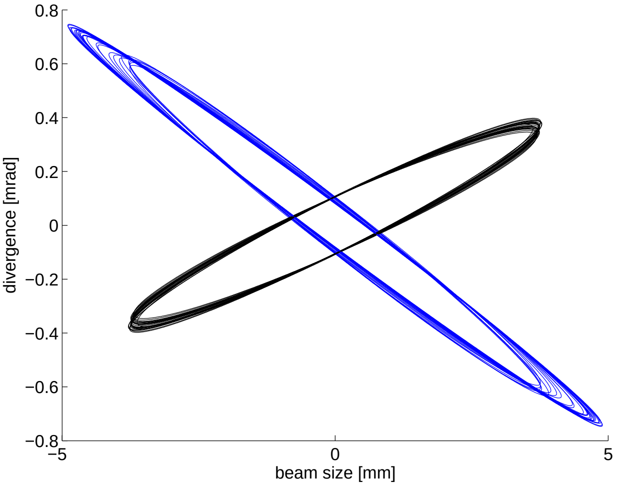

Figure 6: Output of TRACE3D for the transverse phasespace ellipse after the first 50 cavities of the beta=1 section. There are twelve cavities fed by one klystron.

For more thorough simulations including the transverse phase space, it is possible to export the results of the field simulation to other programs. Figure 6 shows the result of a TRACE3D simulation based on the field fluctuations in the first 30 cavities of the high beta section. The TRACE3D input file used for this simulation is the same that was used in [4]. There was a concern that the fluctuations of the cavities in the rf modules without individual cavity control may cause fluctuations of the transverse phase space too big to be tolerated. Although the final answer has to await simulation of the whole beamline, preliminarily it seems that there is no problem.

CONCLUSION

Simulations have been performed to study the feasibility of rf controls for the planned superconducting proton driver linac at Fermilab. At the beginning of the study the rf controls were considered one of the big uncertainties of the project. Although the simulations are not completely finished yet, a big part of the concerns could be resolved already. Results from the rf simulations will be fed into complete start-to-end simulations.

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