Optimisation Of ISIS Injector Linac RF Settings By Use Of A Beam Phase Monitoring System

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Abstract

The use of beam bunch phase monitoring in setting up the rf operating parameters of a multi-cavity linac is now an established technique [1-7]. This paper describes its application to the 70 MeV, four cavity, Alvarez linac used as an injector to the 800 MeV rapid cycling proton synchrotron of the ISIS spallation neutron source. A new method of using the phase measurement data, to determine the operating phase and amplitude of the cavity field, is used in a linac setting-up procedure operating under computer control.

1. INTRODUCTION

The operating settings of field amplitude and phase in each cavity of the ISIS injector linac were originally established by acceleration threshold measurements. In these, the minimum field level, with optimised phase, at which accelerated beam of the correct energy could still be detected was assumed to correspond to the condition for operation at zero synchronous phase angle. Appropriate adjustments were then made to set up the cavity for the desired synchronous phase angle. Subsequently, on many occasions, these settings have been empirically readjusted to optimise the injection of the beam into the synchrotron.

The process of establishing the acceleration threshold has been found to be imprecise and there are problems in applying the technique when there are errors in the level of accelerating field along the cavity length, which is the case in the ISIS linac. Repair work carried out on cavities 2 & 3 has perturbed the field distribution by up to 12% peak to peak, as measured by monitor loops along each cavity.

With the development at the laboratory of a beam signal monitor, small enough to install in the restricted space between linac cavities, it became possible to consider the use of beam phase measurements in setting up the linac. Although the so-called Δt procedure, as developed at Los Alamos for the high energy region of the LAMPF linac [1], was available, it was not clear that this particular technique would be suitable at low energies. In particular, when drifting a 10 MeV beam through the 10 to 30 MeV cavity with the cavity unexcited, as required by the Δt procedure, the debunching of the beam would appear to be too great to allow an accurate measurement of the bunch phase. A different technique in using beam phase measurements was thought to be required.

2. BEAM PHASE MONITORING SYSTEM

The beam monitor developed for the beam phase monitoring system consists of a toroidal ferrite core, mounted in the beam pipe, and having two diametrically positioned single turn windings coupled in parallel to a single coaxial output. The monitor typically gives a peak to peak voltage of 0.5 V into 50 ohms for a 200 MHz, 10 mA beam, as measured by a 300 MHz bandwidth oscilloscope.

The signals from 6 beam monitors and from 5 cavities including a debuncher, together with a signal from the 200 MHz reference oscillator, are fed to a signal multiplexer. This employs a system of coaxial switches designed to allow any two of the 12 signals to be selected for feeding to a phase monitor. The phase of one of the signals can be adjusted by a digital phase shifter.

The selected signals are first frequency-changed to 1 MHz, amplified and then limited before feeding to a phase-detector. This produces an analogue output, proportional to the time interval between the zero crossings of the two signals, and hence linear with phase over $\pm$ 90°. Control of the signal multiplexer and measurement of the phase detector output are both interfaced to the linac control computer.

3. METHOD OF LINAC OPTIMISATION

The first attempt to identify the cavity operating parameters was by generating curves of output beam phase versus cavity phase at different cavity field levels, such as those shown in Fig 1, and then trying to match these to theoretical curves computed by a single-particle dynamics program. The difficulty with this process is that the most characteristic parts of the curves lie at the extremities of the phase range, where a finite width beam bunch is least likely to be well represented by a single particle. The comparison is best made close to the synchronous phase angle, which lies near to the point of inflection in the curves.

These considerations have led to a process of seeking a match between the slopes of the measured and theoretical curves. Close to the synchronous phase angle the slopes of the curves in Fig 1 depend simply on the number of phase oscillations in the cavity, and it was thought that this would constitute a suitable identifying parameter, even in the case of a cavity which had significant errors in its detailed field distribution.

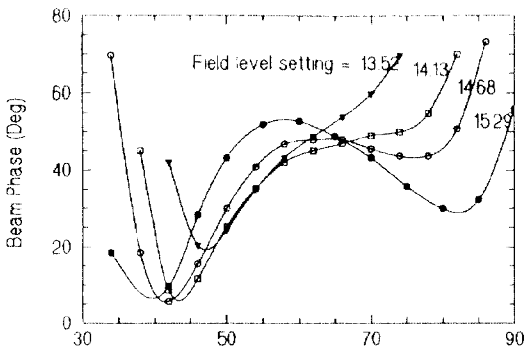

Fig. 1. Phase of beam at exit of Cavity 3 as function of cavity phase and field level.

The method adopted will be described with reference to the arrangement shown in in Fig 2, in which the first cavity is the one under investigation and the second cavity is unexcited and acts as a drift length. The following definitions are used,

ϕ_c = Phase of cavity field.
ϕ_1 = Phase of first beam monitor relative to cavity field.
ϕ_2 = Phase of second beam monitor relative to first.
E = Field level in cavity.

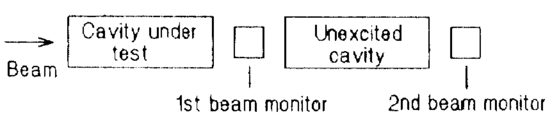

Fig. 2. Layout of beam monitors.

By making small changes to the cavity phase or the field level, each side of the set value, the following four coefficients can be measured,

$$C_1 = d\phi_1/d\phi_c, \quad C_2 = d\phi_2/d\phi_c,$$
$$C_3 = d\phi_1/(dE/E), \quad C_4 = d\phi_2/(dE/E).$$

A search may then be made for a set of computed coefficients which most closely matches the measured set of values, so as to identify the actual rf operating parameters of the cavity and hence enable it to be set to its design settings. To economise on computing time, an array of theoretical coefficients is pre-calculated, for a range of values of cavity field level and phase, and held on a data file. At the present time the array interval is chosen to be 0.5% in field level and 1° in phase. The measured coefficients are compared against each set of computed coefficients in turn and the best match found. This is defined as the point at which the quantity

$$\sum_{n=1}^{4} \left|\Delta C_n / C_n(mean)\right|$$

has the minimum value, where ΔC_n is the difference between the measured and calculated coefficients and each normalising factor $C_n(mean)$ is chosen to be roughly the mean value of $|C_n|$ over the search region.

4. LINAC OPTIMISATION RESULTS

The linac optimisation technique has been tested on each of the three cavities between 10 and 70 MeV. The technique was not considered suitable for the first 665 keV to 10 MeV cavity, since the 665 keV beam is only crudely bunched by a single cavity buncher and cannot be represented by single-particle dynamics.

The results of tests to establish the validity of the technique are illustrated by the measurements made on one cavity shown in Fig 3. On a plot of cavity field level against cavity phase, each arrow shows at one end the settings at which the cavity coefficients were measured and at the pointed end the cavity design settings as deduced from the matching process. The latter settings were those chosen to give a cavity synchronous phase angle of -30° with the input beam bunch entering the cavity at this phase.

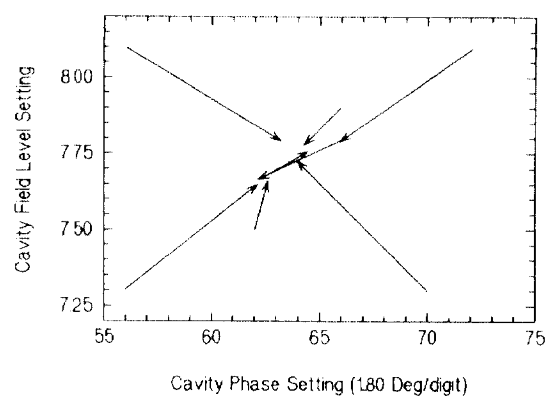

Fig. 3. Cavity 3 optimisation. Each arrow shows change in cavity settings resulting from single application of optimisation procedure.

It can be seen that the predicted cavity design settings are reasonably consistent starting from a wide range of initial settings. Similar results were obtained for the other linac cavities. Before working on any particular cavity the upstream part of the linac was first optimised and so, hopefully, provided the correct beam energy.

Fig 4 illustrates the result of applying repeated iterations of the optimisation procedure. There is rapid convergence to a region of uncertainty, which for cavities 2 to 4 is typically smaller than ± 3° in phase by ± 1% in field level.

The optimised cavity settings resulting from this work have now been adopted for the routine operation of the linac. As a result the linac output beam energy, as measured by the synchrotron, has changed from 69.57 MeV to 70.64 MeV, where the linac design energy is 70.44 MeV. Clearly, the linac had previously been operated with the beam executing a large coherent phase oscillation, with the likelihood of a distorted longitudinal beam emittance.

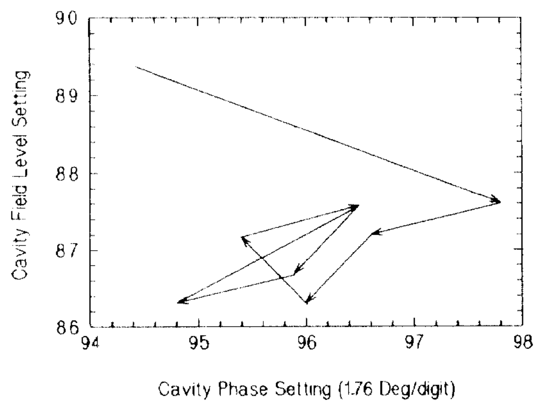

Fig. 4. Cavity 2 optimisation, showing result of repeated iterations of the optimisation procedure.

5. RESOLUTION AND ACCURACY

As a result of noise in the beam signals, measurements of beam phase show a random variation with a standard deviation in the range 0.2° to 0.6°. To improve accuracy in the above work, the average of 5 readings was taken for each phase measurement, and the average of between 3 and 8 values of the measured coefficients used in the matching routine. The resultant uncertainty in the values of the measured coefficients is sufficient to explain the degree of uncertainty found in determining the linac design settings such as is shown in Fig 4.

The accuracy could be further increased by taking even more measurements to improve the statistics. Another possibility would be to increase the size of the changes made to cavity field level and phase, when measuring the coefficients. Resultant non-linear effects would be of no concern provided that the theoretical coefficients were calculated using identical changes. In the above measurements the changes used, of ± 1% in field level and approximately ± 1.8° in phase, could be increased by at least a factor of 3. Finally, the intervals of field level and phase between the computed sets of coefficients could be reduced, or an interpolation technique employed. The nature of the beam noise is not understood but some reduction in its amplitude might also be possible.

An error in the energy of the beam entering the cavity under study would obviously provide a source of error in the optimisation process but, if necessary, such an error could be identified by including this variable in the data table of computed coefficients. Errors in cavity field distribution could also be taken into account but not, unfortunately, in the ISIS linac where the errors are not known with any degree of precision.

6. SUMMARY

A beam phase monitoring system has been installed on the ISIS injection linac and successfully used in correcting a long standing error in the longitudinal beam dynamics. Immediately following this event it was found possible to increase the operational beam intensity in the ISIS synchrotron from 1.60 x 10^{13} to 1.85 x 10^{13} particles per pulse, thus indicating a possible improvement in linac beam quality.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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