DELTA-PHI METHOD FOR THE IFMIF-LIPAC SRF-LINAC CAVITY TUNING

M. Valette, P.A.P. Nghiem, N. Chauvin, D. Uriot,
CEA Saclay, DSM/Irfu/SACM, Gif-surYvette, France

Abstract

In order to achieve the upcoming commissioning of the IFMIF-LIPAc prototype accelerator in Rokkasho, the accuracy and resolution required for all diagnostics must be determined. These specifications will depend on the accuracy at which the tuning parameters must be set and finally on the tuning errors that can be tolerated on the beam itself. We will here discuss the use of the Δφ method to tune the SRF Linac and the resolution requirements it implies for the BPMs. This method, using a relative time of flight measurement to assess the energy of the beam, has the advantages of allowing setting the beam energy and beam longitudinal focusing at once.

INTRODUCTION

The tuning precision of the SRF-Linac cavities directly affects the input beam to the HEBT and thus the final beam at the LIPAc accelerator end. For the IFMIF accelerators [1], it is furthermore critic, because the beam stability itself within the linac four cryomodules will critically depend on the beam accelerating and focusing in transverse as well as in longitudinal. In any case, beam characteristics and beam losses are dictated by this tuning.

The Δφ tuning method we plan to use is inspired from what was used at LANL and SNS [2] for general RF component tuning. It requires a set of beam mean energy measurements via time-of-flight measurements, i.e. measurements of beam arrival phase difference between two BPMs which directly give access to the beam mean energy. Having a relative measurement allows not knowing the absolute phase of the beam at cavity entrance. But the main advantage of this method is that it allows setting the acceleration rate and the longitudinal focusing at once.

In this report, the Δφ method is briefly recalled and their advantages and drawbacks discussed. Simulations of beam energy response to scans in RF phase and amplitude are performed, to which similar measurements must be compared during beam commissioning procedures, in order to choose the best appropriate cavity phase and amplitude. The resolution need for BPMs phase measurements is also calculated in order to be able to tune the cavities at the required tolerances.

LAYOUT DESCRIPTION AND SIMULATION PARAMETERS

The considered RF structure is the Superconducting Radio Frequency Linac of the IFMIF LIPAc accelerator. It is composed of a series of 8 superconducting cavities and solenoids. A detailed layout of the LIPAc cryomodule is presented in Fig. 1 [3]. Its purpose is to bring the beam from energy 5MeV to 9MeV. During the considered commissioning sequence [4], the SRF-Linac will be installed at its definitive position in the definitive configuration: it is preceded by the MEBT, set with nominal parameters for optimal acceleration in the cavities, and followed by the HEBT, starting with 3 quadrupoles and the Diagnostic plate. Note that there is a BPM in front of each solenoid. All the BPMs mentioned in this study are used as beam-phase meters, thus only the time resolution and accuracy are considered. Spatial resolution requirements will not be studied here and alignment issues are considered as done.

The simulations presented hereafter are performed using the TraceWin [5] code, with accelerator configuration, field maps and settings as of “Start-to-end beam dynamics simulations for the prototype accelerator of the IFMIF/EVEDA project” version 23 [6] which will be used as a nominal working point. The input particle distribution is obtained according to the mentioned report and associated simulation data.

TUNING OBJECTIVES AND ΔΦ METHOD

The latest beam dynamics studies in the presence of errors [7] suggest that tuning errors of about 1% in RF field amplitude and about 1° in field phase can be tolerated, meaning that an error of at least half this quantity must be observable in order to maintain correct acceleration and focussing of the beam.

The Δφ method [8] consists in varying the amplitude and the phase of a cavity while assessing the mean energy of the output beam with a time of flight measurement using downstream BPMs. The monitors we plan to use are the BPMs located in front of the solenoids around the downstream cavity. In this method all the downstream cavities must be switched off and completely detuned so that there are no beam loading effects. For the last cavity the BPMs of the D-plate are used as described in Fig. 2 (the first BPM in Q1 may also be used for a longer flight length).

The tuning should be done at full intensity but at very low duty cycle and chopper-shortened pulse length so that no damage is done to the SRF Linac in case of losses. Once both the BPMs used are synchronized the measured phase difference must be incremented by k times 360°, k corresponding to the number of RF periods the beam takes to reach one BPM from the previous one at considered energy. Once this is done, the energy is calculated using the following formula:

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$$E = \frac{E_0}{\sqrt{1-(\frac{2\pi * f * L}{c * \Delta\varphi})^2}} \qquad (1)$$

Where E_0 is the rest energy of the particle, f the frequency, Δφ the measured phase difference and L the distance between monitors, which is 68cm for the first seven cavities and 128 cm for the last one. This method allows to assess the beam energy at any RF phase and amplitude (φ,V) and thus to explore a wide area of settings. In order to tune a said cavity, a phase and amplitude scans are performed around their design values φ_0 and V_0.

SIMULATION RESULTS

Phase and amplitude scans were simulated for the first and last cavity within wide ranges.

Fig. 3 and Fig. 4 show for the first cavity, simulated beam phase differences at the two downstream BPMs, for (φ) and (V) scans, and the corresponding mean beam energies. Fig. 5 shows the phase signature for the last cavity.

The horizontal axis corresponds to the cavity RF phase offset φ- φ_0 relatively to the design phase φ_0. The RF-amplitude relative to its design value, V/V_0, is shown with the colour chart of the curves. The red curve gives the result for the nominal amplitude $V/V_0 = 1$. The horizontal green curve gives the result for the switched off cavity V=0.

During beam commissioning, the same measurements must be performed in the same configuration as in the present simulations, and the cavity amplitude/phase will be chosen so that the energy and the phase signature are the closest to the theoretical ones. In that way, the accelerating rate and the longitudinal focussing are set the closest to what was theoretically expected, even if the cavity electric field profile is different from simulations.

We can observe for the last cavity that though the energy is higher and thus the time of flight for a given distance shorter, the phase variation on the whole scan is about the same between the first and the last cavity, thanks to the longer distance between BPMs in the second case. This lets us anticipate that the situation for the seventh cavity is the most critical, due to short flight distance and almost maximum energy, using the D-plate BPMs in this case should be considered.

BPM RESOLUTION REQUIREMENTS

Focusing on the first cavity and a short range scan we can observe from Fig. 6 that the time of flight variation in a short range around design settings is linear relatively to the RF phase and amplitude. The distance between curves allows knowing the required resolution required for the BPMs.

As the objective is to have tuning errors on phase and amplitude below 1° and 1% respectively, we can say from the simulated data in Fig. 6 that Δφ must be known at a resolution of 1.51° and 0.68° respectively. The relative amplitude accuracy leads therefore to the most severe need in terms of BPM resolution. Moreover, as the time-of-flight measurement is in fact a difference of two arriving phases, thus the error is the quadratic sum of both errors; each BPM must then be able to measure the beam-phase at the required resolution for Δφ divided by$\sqrt{2}$.

In order to achieve a 1° and 1% accuracy on the RF field, a 0.48° resolution is therefore needed for phase measurements at BPMs. At a frequency of 175MHz, this resolution corresponds to 7.6 picoseconds which may be close to the limit of BPM resolution. This is nevertheless consistent with the 0.3° resolution asked to BPMs, resulting from several workshops between beam dynamics and beam instrumentation teams [9].

DISCUSSIONS

1. Observing phase variations of the order of a few picoseconds between two BPMs may be challenging when considering the lengths of cables in which the BPM signals must travel. A possibility to relax the needed resolution is to lengthen the time of flight by lengthening the distance between the BPMs, using for example non-consecutive BPMs.

Indeed, the required resolution is an almost-linear function of the flight length as shown in Fig. 7. The inconvenience of using further away monitors is the beam's strong defocusing in the absence of longitudinal focusing leading to a bigger bunch length, consequently to a much higher difficulty in precisely detecting the passing of the center of the bunch.

2. This study only focuses on phase and amplitude tuning in relative values. This is why resolution requirements are determined. An absolute calibration of the energy is necessary but not treated here. It can be done using the three D-plate BPMs, as described in [10].

3. Another way to assess the energy signature of the beam is to use the dipole after the diagnostic plate. But this may lead to other accuracy or resolution problems.

4. The present method can also be used for the tuning of the MEBT bunchers during commissioning, using the D-plate BPMs as described for the last cavity in this report. These bunchers can also be tuned in the final configuration by using the first BPMs in the SRF-Linac.

CONCLUSIONS

The Δφ method allows performing the cavity tuning in phase and amplitude in order to get a beam with energy and longitudinal focusing the closest to the design values.

Simulations of the energy signature of the beam lead to the conclusion that the BPMs resolution should be of the order of 0.5° in order to tune the RF phase and amplitude at the required accuracy of 1° and 1%.

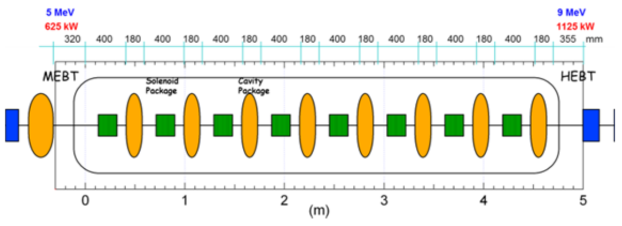

Figure 1: IFMIF-LIPAc SRF Linac Layout.

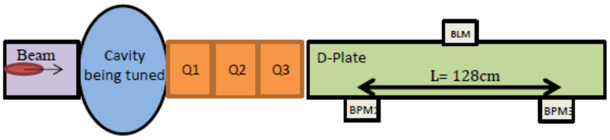

Figure 2: Configuration for the last cavity.

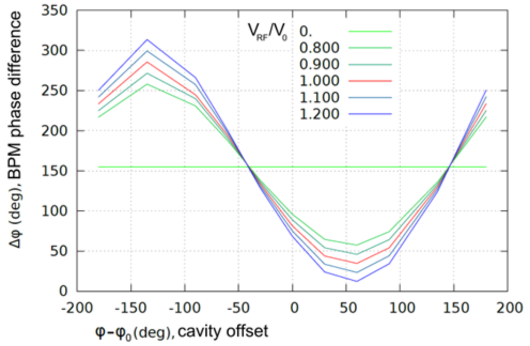

Figure 3: Phase signature for the first cavity.

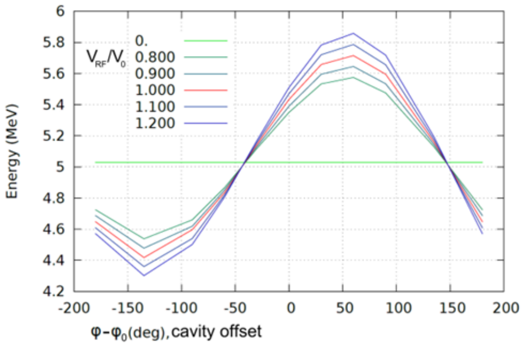

Figure 4: Energy signature for the first cavity.

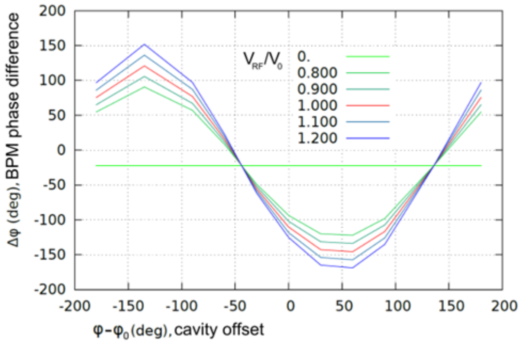

Figure 5: Phase signature for the last cavity.

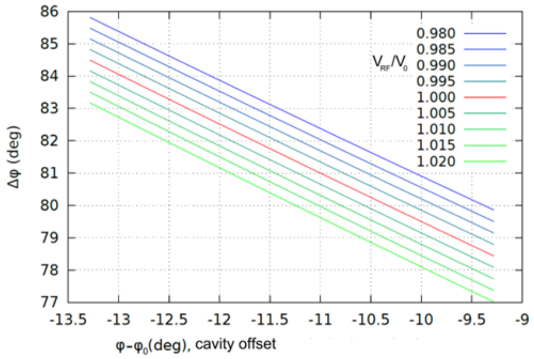

Figure 6: Short range scan for the first cavity.

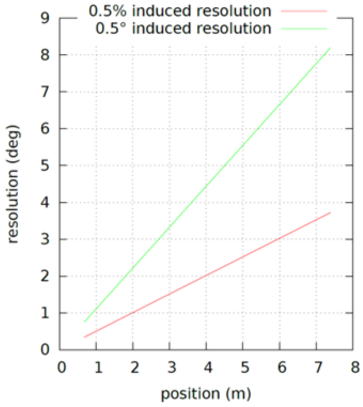

Figure 7: Required resolution as a function of flight length.

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