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Measurement of beam loading at the SNS superconducting linac for a beam with $\beta<1$ ☆

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ABSTRACT

When a beam passes through superconducting cavities, it excites beam induced fields in the cavities. A systematic study is performed to study the beam loading effects with $\beta<1$ beam on the $\beta=0.81$ superconducting cavities of the Spallation Neutron Source (SNS) linac. The analysis indicates that the shunt impedance equation is still valid even for a beam with β well below 1. It is also shown that the induced field level is consistent with the estimation and its effect on the beam dynamics is consistent with the model.

1. Introduction

For a superconducting linac, the beam loading effect is an important factor for tuning the cavities and also for the low-level rf control. When a charge passes through a cavity, it can excite various modes of cavity field. The excited modes can be monopole modes, dipole modes, etc. A charge q passing through a cavity induces voltage V_q for a monopole mode with mode frequency ω_n, quality factor Q, and shunt impedance (R/Q) where V_q is given by [1]

$$V_q = \mp \frac{q\omega_n}{2}(R/Q)\exp\left(\mathrm{i}\omega_n t - \frac{\omega_n t}{2Q}\right). \tag{1}$$

When a series of charges (beam bunches) pass through a cavity, the induced voltage is a summation of the all the induced voltage of individual bunche as is given in Eq. (2). The accumulated beam induced voltage in Eq. (2) can decelerate or accelerate the beam and affect the beam arrival time at the downstream beam line elements

$$V_q = \sum_m \mp \frac{q\omega_n}{2}(R/Q)\exp\left(\mathrm{i}\omega_n T_m - \frac{\omega_n T_m}{2Q}\right) \tag{2}$$

where T_m is the time when the m-th beam bunch with charge q passes through the cavity since the first beam bunch passes.

The wake field and bunch energy-loss effect for beams with $\beta<1$ is relatively unknown, while the effects are well known for the $\beta=1$ beam. It is believed that loss factors of a beam bunch moving through a cavity with $\beta<1$ are lower than those with $\beta=1$, because the energy loss should vanish as $\beta\to 0$. Time domain codes like MAFIA [2] and ABCI [3] can handle only cases with $\beta=1$. The main difficulty in numerical time-domain computation for $\beta<1$ is to formulate proper boundary conditions at the open ends of the beam pipe. Kurennoy [4] calculated bunch energy loss for particle beams with $\beta<1$, and showed that

$$\frac{k_s(\beta,\sigma)}{k_s(1,\sigma)} = \exp\left[-\left(\frac{\omega_s\sigma}{c}\right)^2 \frac{1}{\beta^2\gamma^2}\right]\frac{(R/Q)(\beta)}{(R/Q)(1)} \tag{3}$$

where $k_s(\beta,\sigma)$ is the loss factor of mode s and σ is one half of rms bunch length of a Gaussian beam. Here β and γ are relativistic factors. Eq. (3) was derived from the closed-cavity approximation in the frequency domain and can be applied to real problems only when the loss factor is dominated by the lowest resonances, below the pipe cutoff, e.g., for a cavity with narrow beam pipes. For the reasonably short bunches expected at SNS [5] linac where the rms phase width is $<3^\circ$ at the fundamental frequency, the exponential term in Eq. (3) is close to unity. Furthermore, it is a reasonable approximation to use

$$(R/Q)(\beta) = \frac{2c^2}{\varepsilon_0\omega^3}\frac{\left|\int_0^l \mathrm{e}^{-\mathrm{i}\omega z/\beta c}E_z\,\mathrm{d}z\right|^2}{\int_V E^2\,\mathrm{d}V} \tag{4}$$

to estimate the shunt impedance of the mode for the SNS H^- (or proton) beam with $\beta<1$. In the previous works studying the cumulative beam breakup of the SNS superconducting linac, the

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shunt impedance of Eq. (4) was also used for the same reason [6,7]. For the estimation of the shunt impedance, an ideal cavity field E_z was assumed without field tilt and with perfect field flatness. But in reality each cavity may have tolerable imperfections, leading to a certain field tilt and limited field flatness.

Testing whether the shunt impedance expression of Eq. (4) is accurate for a beam with $\beta<1$ could be indispensable in determining the rf set-point of superconducting cavities. One technique to determine the rf set-point is based on the phase scan technique, making a 360° scan of cavity rf field phase and recording the beam arrival time at the downstream beam position phase monitors (BPMs). At SNS, BPMs were designed to measure the beam phase as well as the transverse offset. Doing this involves beam drifting through unpowered cavities between the BPMs as shown in Fig. 1, making beam loading effects of unpowered cavities very relevant. It is important to understand the influence of the beam loading effects, which can affect the beam arrival time through beam loading effects.

In this paper, we consider only monopole modes and their effect on beam energy loss and the phase scan, because monopole modes accelerate/decelerate beam bunches while dipole modes deflect beam bunches, etc. It turns out that only the passband modes especially the fundamental mode contribute most and other monopole modes make a negligible contribution because of small (R/Q) values or ω_n being away from multiples of the cavity fundamental mode frequency ω_o. We compare the induced field level and its effect on beam arrival time at the downstream BPMs with the measured data. We intend to experimentally verify the validity of the shunt impedance of Eq. (4) even for a beam with $\beta<1$. Part of the study was previously presented at a conference [8].

2. Beam loading effect for a beam with $\beta<1$

When a beam pulse passes through a cavity, it induces a field in such a way that the beam is decelerated. Beam loading effects are studied in a systematic manner with a $\beta<1$ beam of the SNS Superconducting Linac. We check the validity of the shunt impedance formula of the monopole mode for a $\beta<1$ beam by comparing the delay in the beam arrival time at the downstream BPMs induced by the deceleration of the beam loading.

Measurements of beam loading effects were performed at two different places of the SNS superconducting linac, one at the entrance of the high beta section with a 440.8 MeV H^- beam ($\beta=0.733$) and the other with an 815 MeV H^- beam ($\beta=0.845$). Fig. 1 shows the schematic drawing of the phase scan for a $\beta=0.81$ cavity. The cavities that are already set and rf powered are marked as "t". The cavity being scanned marked as "s" is rf powered and the downstream unpowered cavities are marked as "u". As the beam passes through the cavities, it excites induced fields in the cavities. When the turned-off cavities are not detuned, a train of beam bunches coherently builds up the rf field in the cavity and decelerates the beam, delaying beam arrival time at downstream BPMs.

For the beam loading measurement, we recorded the rf signal from the pickup probes in the superconducting cavities that were off as the beam induced field was excited. Also the beam bunch arrival times at the BPMs were recorded as a function of time. And the induced field level in the cavity was recorded and compared with the simulation. Simulation was done by direct summation of the beam loading effect of each beam bunche from the beam current profile in Figs. 2 and 4, using Eqs. (2) and (4). The cavity voltage drop thus calculated was used to correct the beam energy and the beam arrival time downstream.

Fig. 2 shows the beam current profile of a 330 μs-long unchopped beam pulse used for the study. The peak current was 17 mA. For the measurement all the superconducting cavities in the high beta section, which consists of the cryomodules 12–23, were turned off without detuning for maximum beam loading effect. The rf phase of the last superconducting cavity of the cryomodule 11, which is 11c, was varied from −180° to 180° and the beam arrival times at the downstream BPMs were measured. Fig. 3 displays the measured 360° phase scan data taken at two different times "A" and "B" of the beam bunch train (see the Fig. 2) which were measured using the BPM12 located after the cryomodule 12. The delay in the beam arrival time is well illustrated for the "B" part of beam pulse with respect to the "A" part of beam pulse due to the beam loading effect. The induced field decelerates the beam and the "B" part of beam pulse arrives later than the "A" part thus shifting upward in Fig. 3. The BPM beam phase difference between the "B" and "A" part of beam pulse was measured and compared with the model. The measurement data agree well with the simulation results. For instance, the average BPM phase (time) difference measured at the BPM12 is Average $(\phi_{\rm BPM12}(B)-\phi_{\rm BPM12}(A))=8.52^\circ$ (8.09° simulation) and at the BPM13 Average $(\phi_{\rm BPM13}(B)-\phi_{\rm BPM13}(A))=30.44^\circ$ (30.08° simulation). The BPM12 and BPM13 are located after the cryomodule 12 and 13, respectively. This measurement confirms that the shunt impedance formula is also quite accurate for a beam with $\beta=0.733$ well below 1.

At SNS, we routinely use ~10 mA, 10 μs beam pulse to do the phase scan of the superconducting cavities to determine the rf amplitude and phase. This study confirms that this kind of beam through two unpowered cryomodules indeed does not affect the arrival time significantly, usually $<1^\circ$.

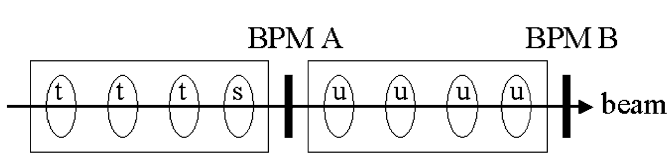

Fig. 1. Schematic drawing of the phase scan. The "u" cavities between BPM A and BPM B are unpowered, and those with "t" are already tuned. The "s" cavity just upstream of BPM A is being scanned.

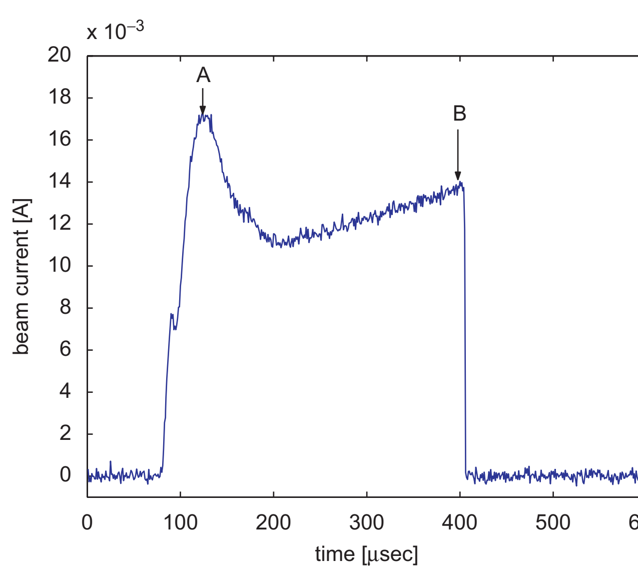

Fig. 2. Plot of the beam current vs. time of a 330 μs long unchopped beam pulse. The points A and B indicate where the phase scan data are taken, which is displayed in Fig. 3. The point A (B) is 50 (330) μs from the beginning of the beam pulse. This beam current was provided by ion source used then. Lately the SNS linac has routinely delivered beam with peak current of about 38 mA.