PVC - AN ILC RF CRYOMODULE SOFTWARE SIMULATOR*

Justin Kien Keung†, Mitch Newcomer, University of Pennsylvania, Philadelphia, PA, 19104, USA
Sergei Nagaitsev, FNAL, Batavia, IL, 60510, USA
Nigel Lockyer, TRIUMF, Vancouver, BC, V6T 2A3, Canada

Abstract

We are developing the Penn Virtual Cavity (PVC). It is a software Superconducting RF (SRF) cavity simulator that simulates the effect of each component involved in controlling the precise oscillations of the 1.3 GHz fields in the cavities within a cryomodule. The simulator models the SRF cavity as lumped RLC circuits [1]. The effects of the components involved are simulated in PVC as time dependent changes of the current/voltage at the interface of the RLC circuits, as well as time dependent changes in the RLC values themselves. This simulator can be used as an expert tool to study cavity control issues, as well as a learning tool to get a general idea of the RF characteristics of the SRF cavities.

INTRODUCTION

Superconducting RF (SRF) cavities are being widely used in particle accelerators. It has uses from nuclear and high energy physics research in collider experiments (e.g. ILC), to biology and condensed matter research in light source experiments (e.g. XFEL). In order to maintain a flexible and reliable machine, a robust RF control system is indispensible.

In order to design a robust control system, all the perturbations must be understood and compensated for. For this reason, we have developed the Penn Virtual Cavity (PVC). It is a time domain software Superconducting RF cavity simulator that simulates the effect of each component involved in controlling the precise oscillations of the 1.3 GHz fields inside the cavities. This serves as a test bed to evaluate the performance of each candidate control system on neutralizing a variety of perturbations in different machine configurations.

PVC is being developed to support the R&D of the ILC. It simulates the RF characteristics of an eight SRF cavities ILC cryomodule in pulsed operation (Figure 1). These SRF cavities are the building blocks of the RF Unit, which is a set of three cryomodules. The RF Units are in turn the building blocks of the ILC. For 500 GeV center-of-mass operation in the ILC, more than three hundred RF Units are required for the electron and positron linacs each.

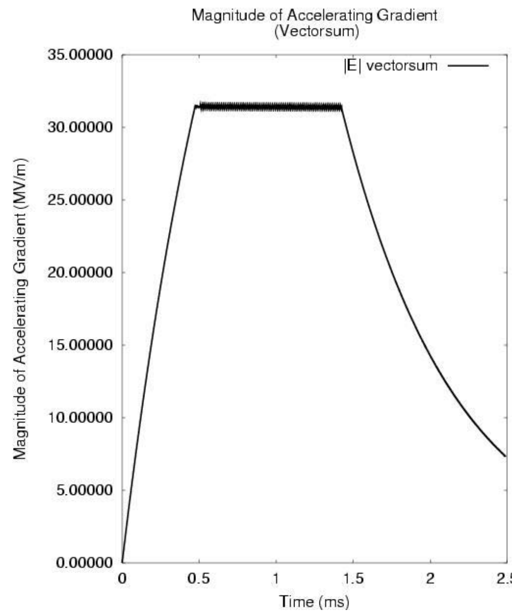

Figure 1: ILC RF pulsed operation with beam. The thicker line at the flattop is gradient fluctuations due to beam.

PVC: A SOFTWARE SRF CAVITY SIMULATOR

PVC is designed to help study SRF cavity control issues. It is important to study cavity control due to the need to maintain an accurate cavity gradient, since an inaccurate gradient will contribute to errors such as the beam energy spread. It should be noted that the PVC performs simulations based on a set of 138 parameters that can be easily modified to test new ideas or to reflect updated measurements. PVC will continually be improved to become a better approximation of a real cryomodule.

PVC is also intended to be a learning tool for non-experts to get a general idea of the RF characteristics of the SRF cavities. For this reason, a web interface is created to eliminate the need for software installation, along with several examples to easily get started.

The effects included in the simulation to date include: Vector Sum Control using Linear I/Q feedback with Adaptive Feedforward Tables, different Q-drop and Lorentz Detuning parameters for each individual cavity, fast piezo feedback, beam loading (pulsed, with random or correlated fluctuations), klystron power ripple and jitter, klystron power and phase turn on curve, klystron overshoot, cable and electronics delay, MO phase jitter propagated to LO and klystron, constant calibration errors at both the

* http://einstein.hep.upenn.edu/∼keungj/simulation.html
† keungj@hep.upenn.edu

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waveguide and ADC, as well as 8/9π mode at 1.2992 GHz (=1.3 GHz – 800 kHz).

The simulator models the SRF cavity [1] as lumped RLC circuits (Figure 2). The effects listed above are simulated as time dependent changes of the current/voltage at the interface of the RLC circuits, as well as time dependent changes in the RLC values themselves. These values and their dependencies are based on work of people from laboratories as well as from the industry.

These effects are implemented in several C++ classes with clearly defined interfaces, with the aim of enabling the straight forward verification and modification of component properties. For example, one can change the klystron properties simply by changing or replacing the existing member functions inside the klystron class.

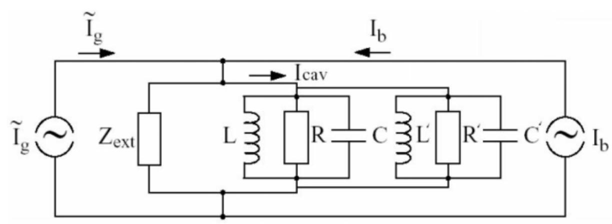

Figure 2: Thomas Schilcher's model of the cavity, with the new addition of an 8/9π mode.

STUDIES USING PVC

To maintain a stable field inside the SRF cavity, we need to consider the disturbances and correct for them. We can separate the disturbances into two categories, at the beam train to train timescale (repetitive errors) and at the beam pulse timescale (statistical errors). Repetitive errors are caused by processes reproducible from one beam train to another, these can be corrected by using feedforward techniques that deals with repetitive disturbances. However, random disturbances such as bunch charge fluctuations within the beam train can only be corrected with a feedback technique. The studies performed this year focused on trying to understand the capabilities and limitations of a feedback controller.

Examples of studies recently performed using the PVC include 1) a study on the effects of latency on the feedback stability of the 8/9π mode, 2) a study on the effects of bunch charge fluctuation on flattop gradient stability.

PVC STUDY 1: EFFECTS OF LATENCY ON THE FEEDBACK STABILITY OF THE 8/9π MODE

The latency is an important characteristic of the feedback loop, because it dictates how much the feedback can respond to change while maintaining stability.

We considered a I-Q feedback system with 100x proportional (linear) gain, designed to control the 1.3 GHz mode, but controlling an SRF cavity with two passband modes, the π mode at 1.3 GHz and the 8/9π mode at 1.2992 GHz (Figure 3). The RF source (klystron) provides 1.3 GHz RF power to the cavity, but the cavity passes energy at two bands, at 1.3 GHz and 1.2992 GHz. The feedback latency is varied and the stability is examined (Figure 4) .

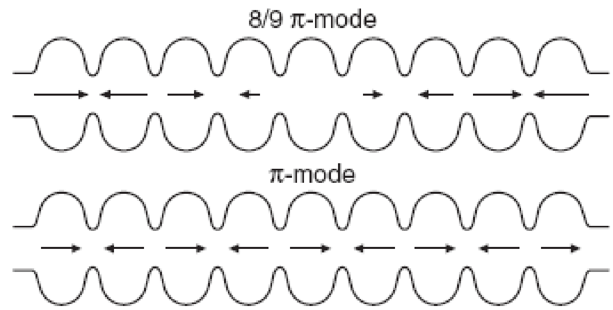

Figure 3: Illustration of the two passband modes included in the simulation, the π mode at 1.3 GHz and the 8/9π mode at 1.2992 GHz.

For a feedback latency of t_1, define the phase delay as $\phi_1 = 2\pi$ 800 kHz t_1. Then the feedback stability requirement for the 8/9π mode is that $\pi/2 + 2n\pi < \phi_1 < 3\pi/2 + 2n\pi$, n integer [2]. This can be directly compared to a study done at DESY [3].

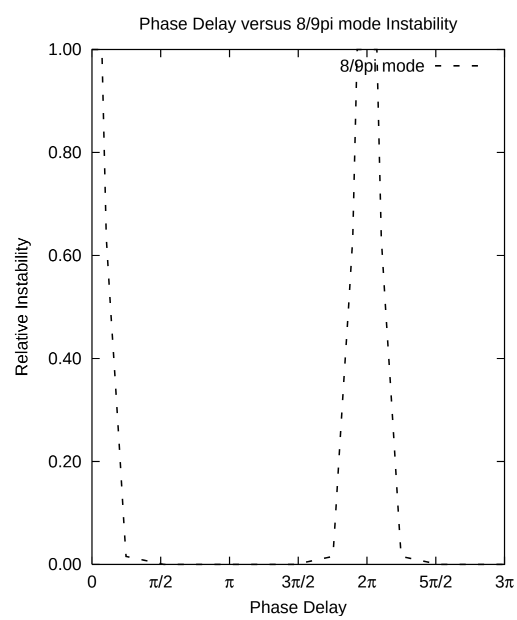

Figure 4: Summary of phase delay vs 8/9π mode stability.

PVC STUDY 2: EFFECTS OF BUNCH CHARGE FLUCTUATION ON FLATTOP GRADIENT STABILITY

Using the same system I-Q feedback system with 100x proportional gain as study 1, we examined the dependence of the flattop gradient error from random fluctuations in bunch-to-bunch charge. The fluctuations have a Gaussian distribution, with the beam current staying constant over the entire beam train. We considered two modes of operations, accelerating conditions and zero crossing conditions (beam phase at -90 degrees) [4].

For the case of a 31.5 MV/m accelerating gradient, the reverse voltage generated by a bunch charge on crest is given by equation 1 [5],

$$V_{bunch} = \frac{1}{2} q\omega_0 (\frac{r}{Q}) = 14.02\,\mathrm{kV/m} \tag{1}$$

where q is the bunch charge, nominally 3.2 nC with a 327 ns bunch spacing for the proposed ILC; ω_0 is the resonant frequency of the SRF cavity, which is $2\pi \times 1.3$ GHz; and $(\frac{r}{Q}) = \frac{V_{acc}}{I_{beam} Q_L}$ is the shunt impedance of the cavity, which is 1073 Ω for the TESLA cavity operating at 31.5 MV/m with beam current of $\frac{3.2\ \mathrm{nC}}{327\ \mathrm{ns}} = 9.786\ \mathrm{mA}$, and a $Q_L = 3 \times 10^6$. Therefore a 3.2 nC bunch charge causes a drop of 0.0445% in the accelerating gradient. This result is exactly reproduced by the PVC simulations.

For beam accelerating conditions, the beam phase should be adjusted to minimize wakefields. Wakefields are fields excited by the beam in the accelerating structure, they contribute to a significant portion of the total beam energy spread. Wakefield effects strongly depend upon the bunch length and the shape of the charge distribution [6]. This paper considers the case where all the 3.2 nC bunches have a Gaussian charge density distribution with $\sigma = 300\mu\mathrm{m}$. Using these parameters, the optimal acceleration phase for a beam with 3.2 nC bunches at 31.5MV/m is -5 degrees.

We investigated the relationship between the % RMS bunch-to-bunch charge fluctuations and % maximum flattop fluctuations, using beam phases of -5 degrees and -90 degrees, and the results are summarized in Figure 5.

In the operating conditions stated above, for accelerating conditions, a 5.6% bunch-to-bunch charge fluctuation doubles the flattop fluctuations, and a 11.2% fluctuation triples it. For zero crossing conditions, the effect is not as strong, however, since this beam at -90 degrees should only affects the phase, one may ask how it could affect the amplitude at all. This is due to the choice of the I-Q feedback system, which couples the amplitude and phase together. This points out the need to investigate the performance of I-Q feedback and amplitude-phase feedback under different conditions.

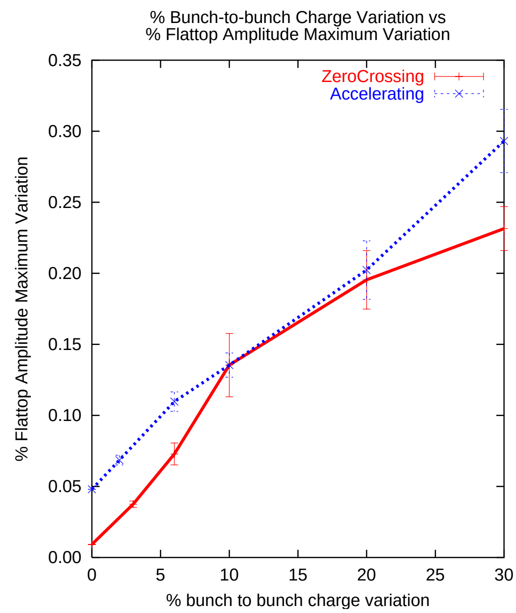

Figure 5: Summary of the RMS fluctuation in bunch-to-bunch charge and the maximum fluctuation in flattop amplitude. Error bars on each point give the range of 5 runs.

DISCUSSION

We have developed a software Superconducting RF (SRF) cavity simulator that simulates the effect of each component involved in controlling the precise oscillations of the 1.3 GHz fields in the cavities within a cryomodule. This simulator can be used as an expert tool to study cavity control issues, as well as a learning tool to get a general idea of the RF characteristics of the SRF cavities.

This simulator can help understand the effects of all the perturbations present, and how to compensate for them. In the quest to design a robust control system, this helps by serving as a test bed to evaluate the performance of each candidate control system on neutralizing a variety of perturbations in different machine configurations.

PVC aims to be a flexible RF simulation platform. The effects simulated are implemented in several C++ classes with clearly defined interfaces. This allows for straight forward modifications, should one wishes to operating with different components, or even in a different operating mode. We plan to demonstrate this in the near future, by adding the capability to simulate the CW operating mode using the same C++ classes.

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