Bandwidth Effects of Superconducting RF Cavity Controlled with a Vector Phase Modulator

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Introduction

This note examines the behavior of a HINS Superconducting Single Spoke Resonator that is driven with a vector phase modulator of limited bandwidth. This note is based on the model described in Beams Document 2910 "A Simple Model for a Superconducting RF cavity with a Vector Phase Modulator".

Vector Modulator Bandwidth

In the model described in Beams Document 2910, the bandwidth limitations of the vector modulators where described by a slew rate of the phase shifters on the shorted legs of the vector modulator. The slew rate of 1 degree per uS was used in the examples. The effect of this slew rate on vector modulator performance is minimal. A larger effect could be due to the limited bandwidth of the power supply driving the phase shifters of the vector modulator.

The most severe test of the effects of vector modulator bandwidth occurs when the beam current passing though the cavity is much different the value of beam current used to set the cavity coupling. For example in Beams Document 2910, the optimum coupling is set for a beam current of 15 mA. The gain of the vector modulator during fill and during the beam pulse is set to 0.9. If the cavity coupling is unchanged and the beam current passing though the cavity is dropped to 1 mA, the gain of the vector modulator during the beam pulse must drop by a factor of two. This requires the phase shifters in the vector modulator to each swing by about 40 degrees when the beam enters the cavity.

In this note, it will be assumed that the response of the power supply and phase shifters of the vector modulator can be described by a single pole low pass filter. The single pole filter is characterized by a specified rise time. To model this numerically, the phase shift of each of the phase shifters in the vector modulator evolve in time according to:

$$\phi_{out}(t+dt) = \phi_{out}(t) + \frac{\phi_{in}(t) - \phi_{out}(t)}{\tau} dt \qquad (1)$$

where ϕ_{out} is the actual phase shift and ϕ_{in} is the phase shift that is desired.

In the following examples, the cavity R/Q of 262 Ohms was used. This value is typical of a superconducting single spoke resonator used in HINS. The cavity voltage and synchronous phase angle were chosen from the design of the first cryomodule in HINS. The cavity voltage of 1472kV with a synchronous angle of 30 degrees was used. It was assumed that the cavity coupling would be optimized for optimum power transfer to the beam at a beam pulse current of 15mA. However, this example will look at the case when the beam current passing though the cavity is one tenth the optimum beam current. The loaded Q of the cavity is about 2.2×10^5 and the fill time of the loaded cavity is about 212uS. Beam injection time should be about 147uS after the generator current turns on. The beam pulse length is 1mS. This example will also assume that the cavity suffers a Lorentz detuning of 0.46 kHz/MV^2 which will detune the cavity by about 1 kHz at full gradient. Table 1 show parameters used in the simulation. Figure 1 shows the cavity voltage, Figure 2 shows the cavity voltage error, and Figure 3 shows the phase shifts for the case with a large bandwidth vector modulator.

Parameter	Value	Units
Cavity Voltage	1472	kV
Klystron Power	25.2	kW
R/Q	262	Ohms
Reference Beam Current	15	mA
Actual Beam Current	1.5	mA
Synchronous Phase Angle	30	degrees
Detuning Angle	-51.754	degrees
Generator phase during filling	8.4	degrees
Generator phase during beam	0	degrees
Vector modulator gain during filling	0.88	
Vector modulator gain during beam	0.479	
Vector modulator rise time	0.0005	mS
Beam injection time	0.147	mS
Beam Pulse Length	1	mS
Lorentz Detuning	0.46	kHz/MV^2

Table 1. Simulation Parameters.

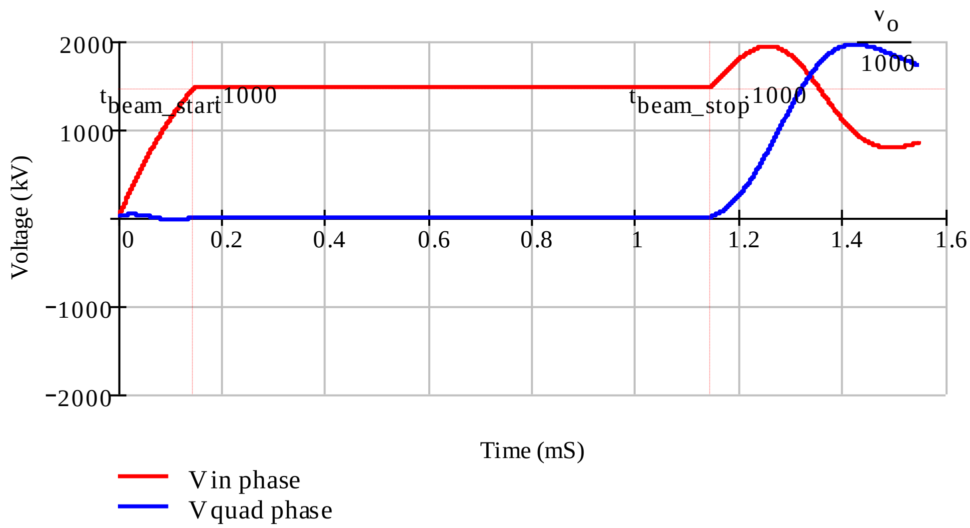

Figure 1. Cavity voltage for a large bandwidth vector modulator

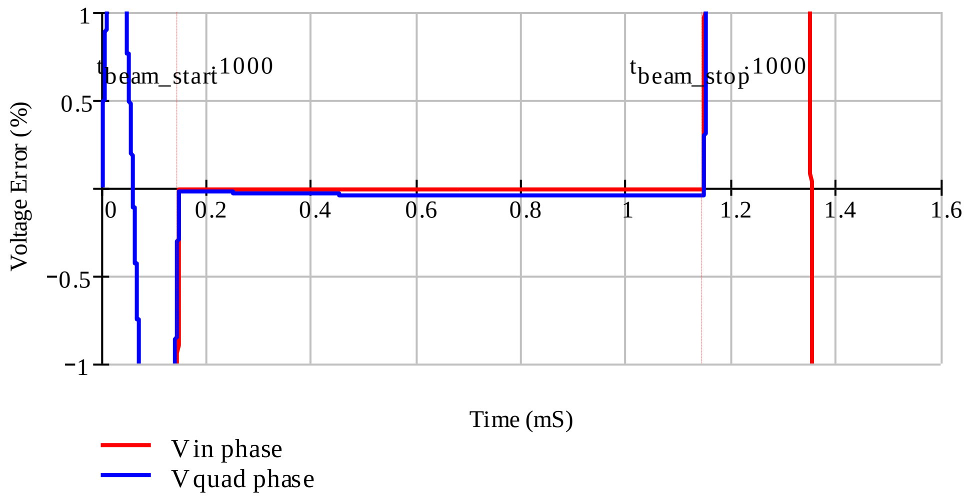

Figure 2. Cavity voltage error for a large bandwidth vector modulator.

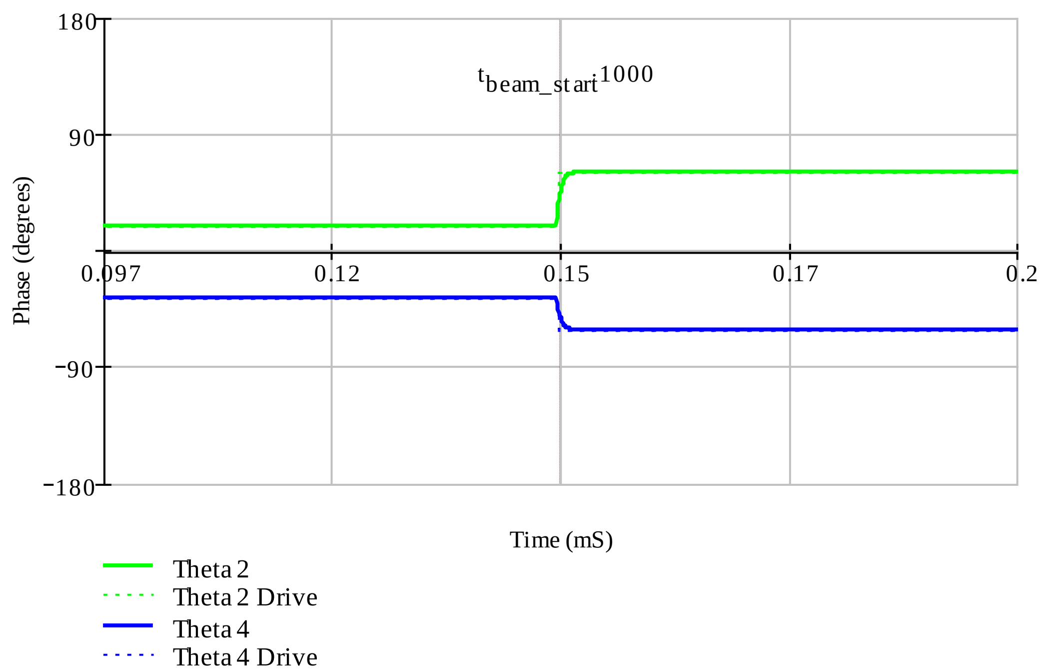

Figure 3. Phase shifts at beam injection for a large bandwidth vector modulator

Table 2 shows the parameter for a vector modulator with a rise time of 40uS (3dB bandwidth of 4kHz). To minimize the voltage error, it was determined empirically that the vector modulator should start ramping about 44uS ahead of beam injection. Figure 4 shows the cavity voltage, Figure 5 shows the cavity voltage error, and Figure 6 shows the phase shifts for the case in the vector modulator. The cavity voltage error exceeds 1% of the desired cavity voltage. In fact, the rise time of the vector modulator needs to be less than 7uS if the cavity voltage error is to be less than 1%.

Parameter	Value	Units
Cavity Voltage	1472	kV
Klystron Power	25.2	kW
R/Q	262	Ohms
Actual Beam Current	1.5	mA
Synchronous Phase Angle	30	degrees
Detuning Angle	-51.754	degrees
Generator phase during filling	8.4	degrees
Generator phase during beam	0	degrees
Vector modulator gain during filling	0.88	
Vector modulator gain during beam	0.479	
Vector modulator rise time	0.04	mS
Beam injection time	0.147	mS
Vector modulator start time	0.103	mS
Beam Pulse Length	1	mS
Lorentz Detuning	0.46	kHz/MV^2

Table 2. Parameters for a vector modulator with a 40uS rise time

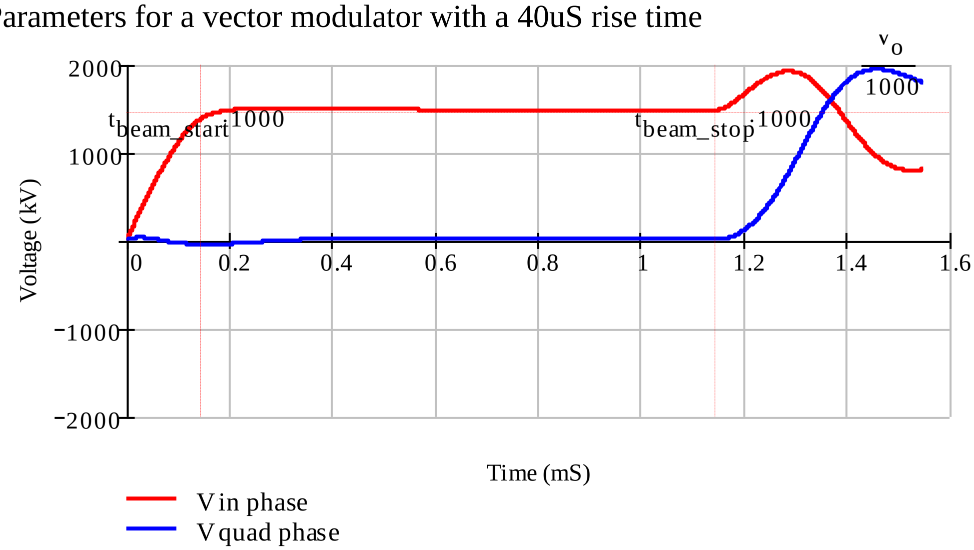

Figure 4. Cavity voltage for a vector modulator with a 40uS rise time.

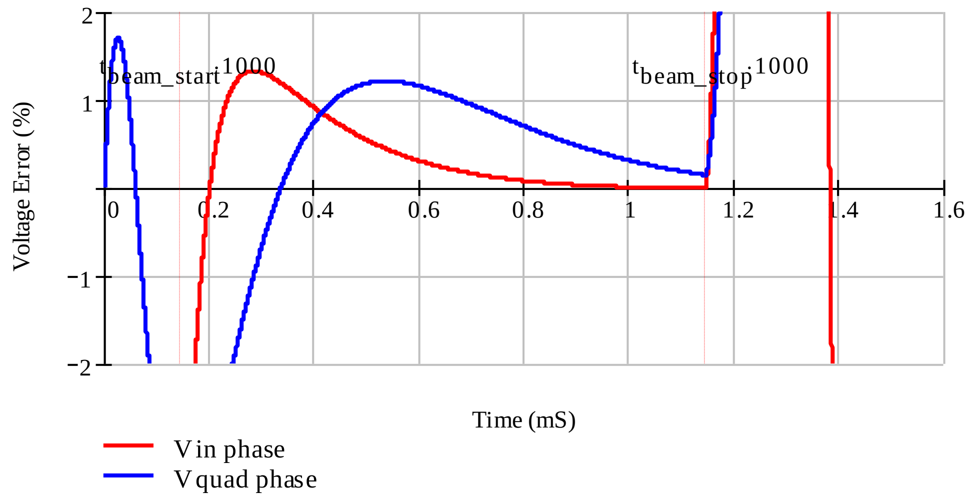

Figure 5. Voltage error for a vector modulator with a 40 uS rise time

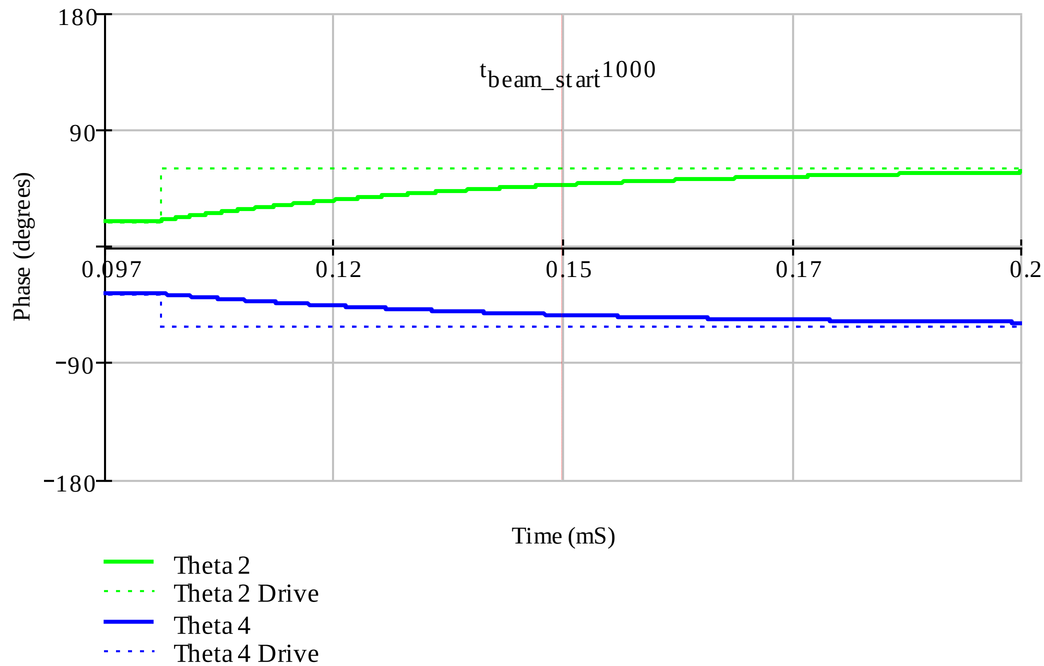

Figure 6. Phase shifts at beam injection for a vector modulator with a 40 uS rise time

Vector Modulator Pre-Pulse

The response of the vector modulator can be sped up if the drive to the vector modulator phase shifters is over-driven for a short period of time. For illustration, assume that a phase shifter of the vector modulator is at ϕ_0 at t=0 and it is desired to have the phase shifter at ϕ_1 at t=Δt. If a constant drive is applied to the phase shifter of a value ϕ_{pp} from t=0 to t= Δt, then:

$$(\phi_{pp} - \phi_1) = (\phi_1 - \phi_0)\frac{e^{-\frac{\Delta t}{\tau}}}{\left(1 - e^{-\frac{\Delta t}{\tau}}\right)} \tag{2}$$

for a rise time of τ. For example, if it is desired to reach ϕ_1 in a period of 0.5τ, then

$$(\phi_{pp} - \phi_1) = 1.54(\phi_1 - \phi_0) \tag{3}$$

An example of using a pre-pulse is shown in Table 3 and Figures 7-9. The rise time of the modulator in this example is 40uS. The pre –pulse width is 20uS. It was found empirically that centering the pre-pulse around beam injection time as shown in Figure 9 gave the best results. Also as shown in Figure 9, the pre-pulse shortens the transition to 20uS while keeping the drive phase still inside the range of the vector modulator. This reduction in transition time keeps the error voltage to less than 1% as shown in Figures 7-8.

Parameter	Value	Units
Cavity Voltage	1472	kV
Klystron Power	25.2	kW
R/Q	262	Ohms
Reference Beam Current	15	mA
Actual Beam Current	1.5	mA
Synchronous Phase Angle	30	degrees
Detuning Angle	-51.754	degrees
Generator phase during filling	8.4	degrees
Generator phase during beam	0	degrees
Vector modulator gain during filling	0.88	
Vector modulator gain during beam	0.479	
Vector modulator rise time	0.04	mS
Vector Modulator Pre-pulse	0.02	mS
Beam injection time	0.147	mS
Vector modulator start time	0.137	mS
Beam Pulse Length	1	mS
Lorentz Detuning	0.46	kHz/MV^2

Table 3. Parameters for a vector modulator with a 40uS rise time but width a 20uS pre-pulse.

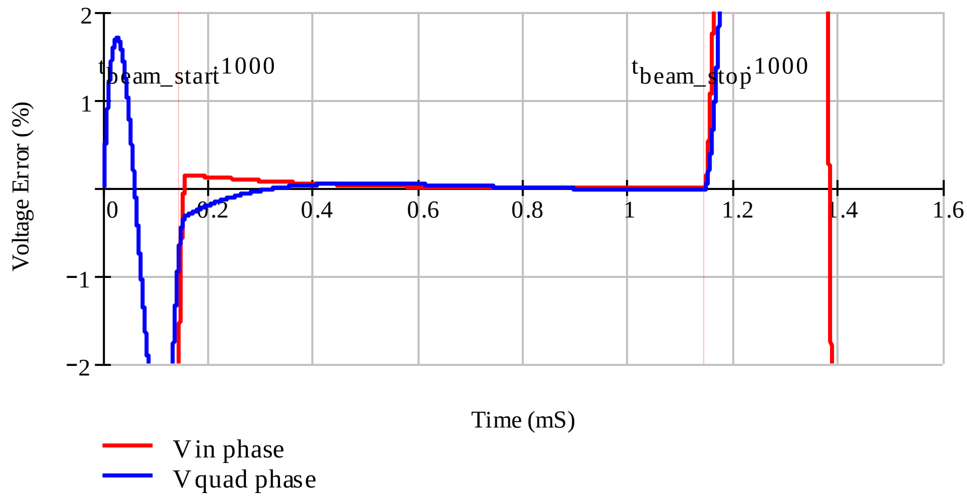

Figure 7. Error voltage for a vector modulator with a 40uS rise time but width a 20uS pre-pulse.

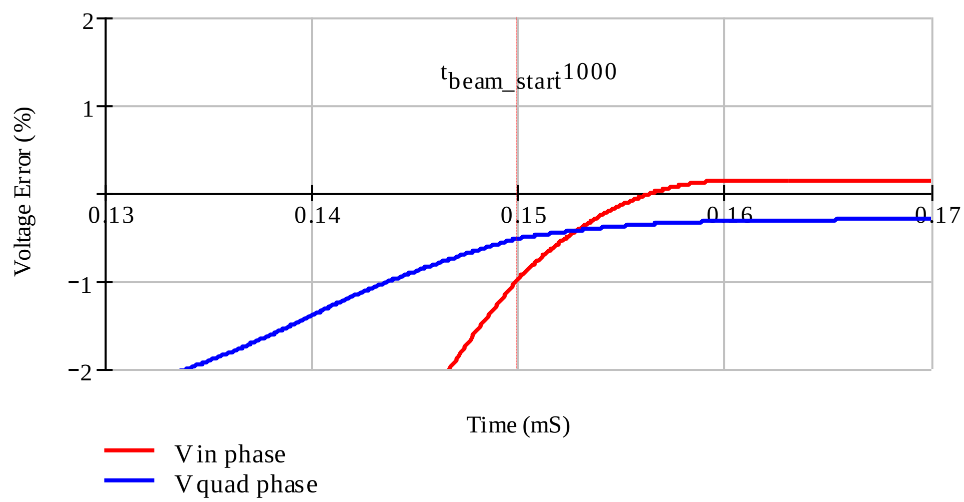

Figure 8. Error voltage for a vector modulator with a 40uS rise time but width a 20uS pre-pulse zoomed in around beam injection.

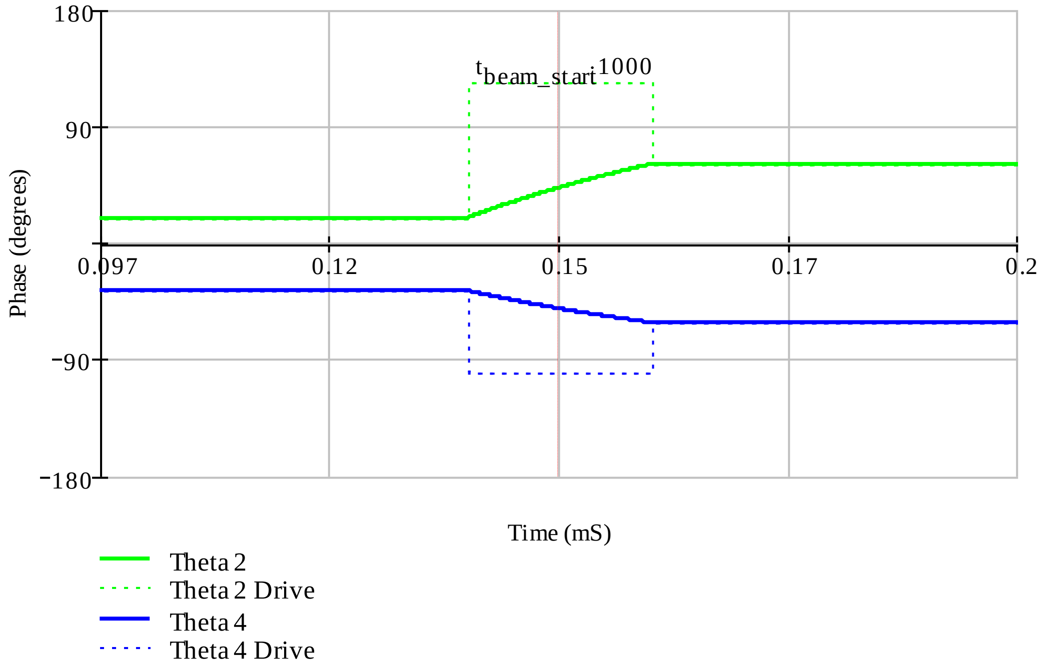

Figure 9. Vector Modulator phase shifts at beam injection for vector modulator with a 40 uS rise time but with a 20uS pre-pulse