TRANSIENT STUDY OF BEAM LOADING AND FEED-FORWARD LLRF CONTROL OF ARIEL SUPERCONDUCTING RF e-LINAC

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Abstract

ARIEL e-LINAC is a ½ MW-class SRF accelerator operated at 10 mA of average current. In the initial commissioning, e-LINAC will be tested with increasing duty factors from 0.1% up to CW mode. During the pulsed mode operation, beam loading causes cavity gradient fluctuation and therefore transient behaviour of SRF Cavity gradient needs to be studied in order to determine how the Low-level RF (LLRF) should be implemented. Performance of LLRF control system with and without non-adaptive feed-forward are simulated to determine the resulting beam energy spread and experimental measurements are proposed to measure the increase of beam size due to beam loading.

INTRODUCTION

ARIEL e-LINAC will produce a 50 MeV electron beam as the photo-fission driver for Rare Isotope Beams (RIB) production [1]. Electron beam is first accelerated up to an energy of 10 MeV through an injector cryomodule (ICM) containing a single 9-cell SRF cavity, and further accelerated with two accelerating cryomodules (ACM), each containing two 9-cell SRF cavities, up to an energy of 50 MeV. The schematic of the e-LINAC is shown in Fig. 1. Initial commissioning of the e-LINAC will be tested with pulsed beam operation for cavity conditioning and the duty factor will be increased gradually up to CW mode.

The ARIEL e-LINAC is dominated by RF beam loading with ½ MW of beam power. During pulsed operation, beam loading causes cavity voltage to fluctuate and this result to an increase of the beam energy spread at the cavity output as shown in Fig. 2. This cavity voltage fluctuation is usually too fast to be controlled by feedback loop alone. Both feedback and additional feedforward control is needed to minimize voltage fluctuation and it is therefore studied in this simulation.

The effect of the beam loading can be observed directly from the increase in beam size as electron beam passed through a bending magnet. Experiments are proposed at the output of ICM to measure beam size coming out of a single beam loaded cavity. A combination of beam profile monitor (view screen) and BPM (beam position monitor) will be used to measure integrated and time snapshot of the beam energy.

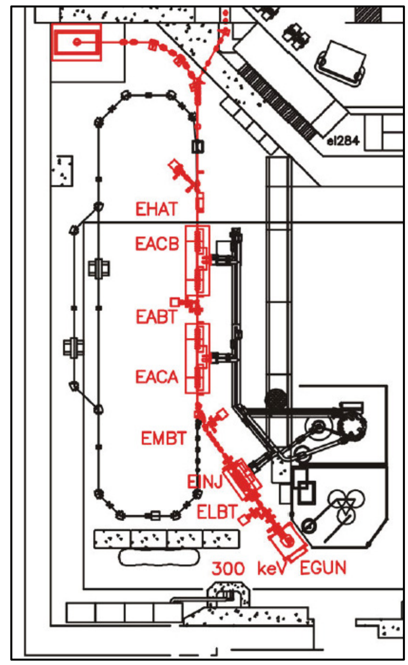

Figure 1: ARIEL e-LINAC layout.

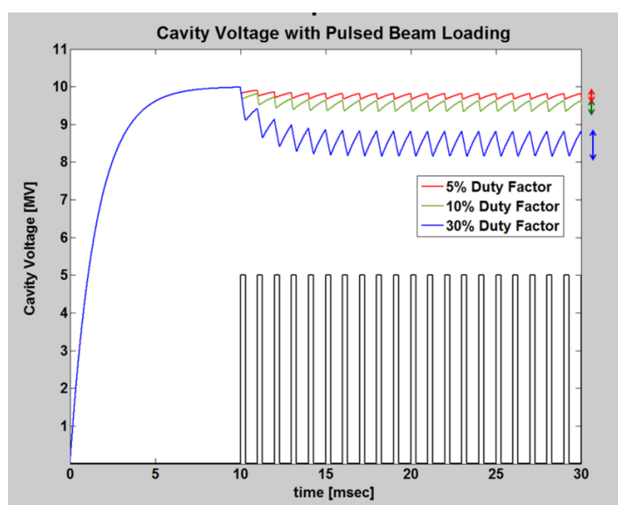

Figure 2: Cavity voltage fluctuation at different pulsed beam duty factor. Shown in black colour is the beam pulse (not drawn to scale) at 30% duty factor and injected 10 msec after RF power is turned on. Double headed arrows illustrate the measure of beam spread.

SRF CAVITY CONTROL SIMULATION

Cavity and LLRF Control Model

Resonant cavity is modelled as an equivalent RLC circuit with generator and beam current sources. Cavity voltage as a superposition of both generator and beam induced voltage can be expressed in frequency domain as:

$$V_{cav} = \frac{1}{s\tau + 1 - j\Delta\omega\tau}\left(\frac{\Gamma+1}{2}\right)\left(v_f - i_B Z_{ext} e^{j\phi}\right), (1)$$

with v_f : forward voltage, i_B : beam current at 10 mA, τ : cavity filling time. Z_{ext} : external impedance at optimum coupling, $\Delta\omega$ =0 on resonance, ϕ = 0 for on-crest beam acceleration, and Γ : reflection coefficient ~ 1 for superconducting cavity. Cavity parameters used in this simulation are described in details elsewhere [2].

Block diagram of control system with both feedback and feedforward input are shown in Fig. 3. All simulations are carried out in MATLAB. Digital LLRF controller is modelled as PI (Proportional Integral) controller with a sampling rate at nominal operating value of 400 kHz. PI controller zero location are chosen to cancel cavity pole: K_i/K_p = $1/\tau$, where K_i and K_p are integral and proportional gain, respectively. Discretized plant, $H_{plant}(z)$, includes both klystron, modelled as low pass filter with 1MHz bandwidth, and beam-loaded cavity.

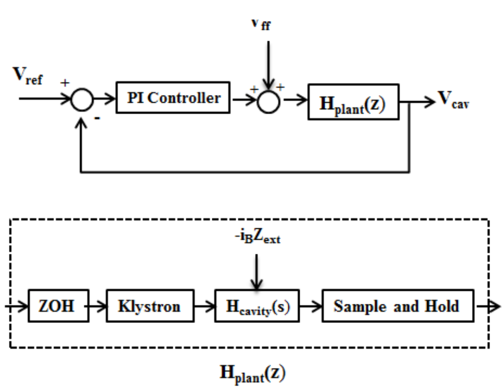

Figure 3: Above: Feedback and feedforward block diagram. Below: Discretized model of beam-loaded cavity and klystron.

Feedback and Feed-forward Simulations

Simulation results without additional non-adaptive feedforward control (PI-controller only) are shown in Fig. 4 for duty factors ranging from 0.5% up to 50% at beam current of 10 mA (with 1 kHz repetition rate). Cavity voltage error can be reduced by increasing K_p. In practice, however, K_p is limited by stability, digital transport delay, and integrator wind-up due to large value of K_i. Further analysis of PI-controller stability (using frequency response method) would require experimental measurements of transport delay. In this simulation, however, it is shown that PI-controller alone is not adequate to meet the voltage error requirement of ΔV/V < 0.25% for beam pulse with duty factor larger than 1%.

Non-adaptive feed-forward control is simulated in combination with PI feedback control. Input parameters for this simulation are the predicted value of incoming beam current at 10 mA, K_p value (fixed at gain value of 5), and different feed-forward signal timing schemes. 'Normal' indicates timing the feed-forward signal at the same time with the incoming beam pulse, while 'delayed' and 'advanced' shift the feed-forward signal 50 µsec after and before the beam pulse, respectively. Simulation results, illustrated in Fig. 5, compare different timing methods with open and feedback loop performance. Only 'extended' timing mode, where feed-forward signal is sent to the cavity 50 µsec before the beam current input and turned off 50 µsec after, that significant reduction in cavity voltage error can meet the ΔV/V requirement up to 20% duty factor.

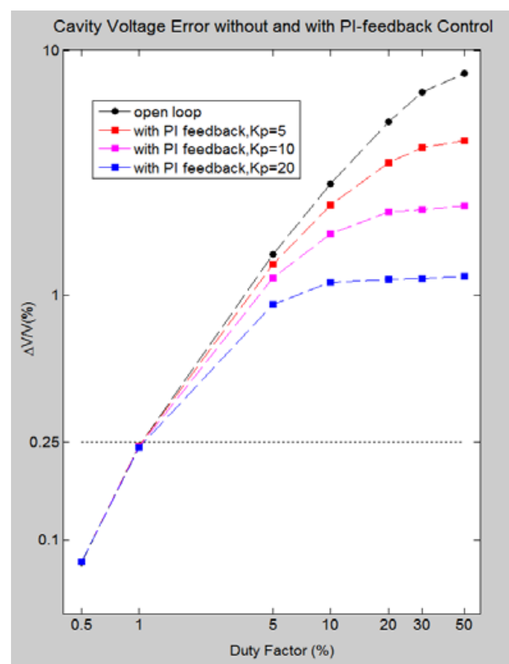

Figure 4: Cavity voltage errors with different PI controller gain values. Dashed horizontal line indicates voltage error control requirement.

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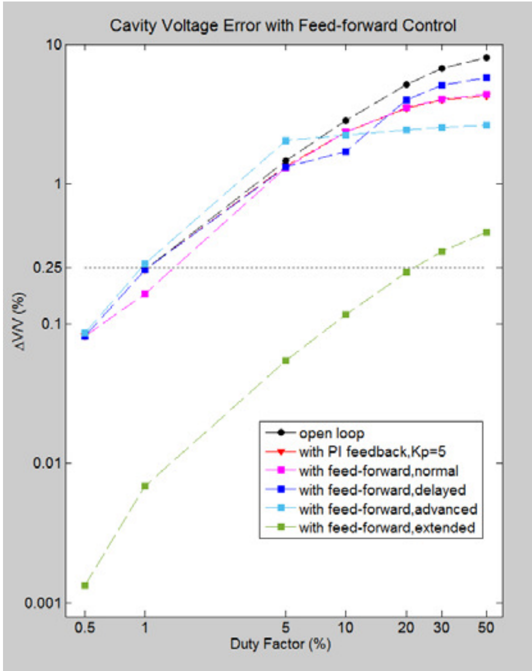

Figure 5: Cavity voltage errors with additional feed-forward control and different timing modes.

BEAM ENERGY SPREAD

Proposed Experiments

Experimental measurements of beam energy spread due to beam loading are planned for upcoming ARIEL e-LINAC commissioning schedule. Beam energy spread from beam loading of a single SRF cavity can be performed at the output of ICM and measured after passing the beam through EMBT bending magnet towards the beam dump (EMBD). Layout of e-linac section up to EMBT is shown in Fig. 6.

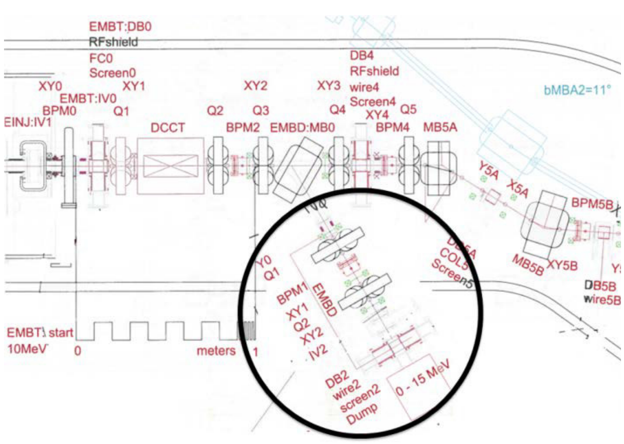

Figure 6: EMBT section of e-linac. Location of beam dump diagnostics are shown in black circle.

View screen and BPM (Beam Position Monitor) can be used to obtain both the integrated beam energy spread and time resolution of the beam energy fluctuation within the pulse. Details of the beam diagnostics design are specified in [3]. View screen design also allows external trigger to study different slices of beam pulses [4]. The ranges of duty factors that can be studied, however, are limited by minimum exposure time and BPM are needed to measure energy variations within the pulse at low duty factors. LLRF control performance with additional feedforward could then be tested as compared with simulation results presented above.

Calculated Beam Sizes

Beam loading contributes to an additional momentum (energy) spread and shifting of the centroid energy. This result to a significant increase of transverse beam size as electron beam passed through the bending dipole magnet. Calculated value for transverse beam size can be obtained with OptiM by specifying the EMBT optics components, centroid energy, and momentum (energy) spread [5].

Estimated RMS values of beam size measured at the EMBD (E-linac Medium Beam Dump) are summarized in Table 1 under all three control conditions. Values above the voltage error requirement (above 1% duty factor for open loop, no controller, and PI feedback control) are also given to show the significant increase of beam sizes if proper control signal ('extended' mode of feedforward) is not implemented in the ICM's LLRF control system.

Table 1: Estimated Beam Loading Contribution to Transverse Beam Size Measured at EMBD

Duty Factor	Open Loop		PI feedback		Feed-forward ('extended')	
	ΔV/V (%)	Beam size (mm)	ΔV/V (%)	Beam size (mm)	ΔV/V (%)	Beam size (mm)
0.5%	0.081	0.97	0.081	0.98	0.001	0.02
1%	0.24	2.90	0.24	2.91	0.006	0.08
5%	1.47	17.60	1.34	16.05	0.05	0.64
10%	2.85	33.93	2.33	27.91	0.12	1.39
20%	5.12	60.54	3.47	41.67	0.23	2.79

CONCLUSION

Transient effect of beam loading to cavity voltage fluctuations has been studied. Digital LLRF system has been modelled and simulated with both PI-feedback and feed-forward control. Feedback control alone is shown not adequate in meeting the cavity voltage error requirement and only feedforward control with 'extended' signal is effective in minimizing the voltage error up to 20% duty factor.

Beam size increase due to beam loading has also been estimated with real optics components at EMBT section of the e-LINAC. Experimental measurements of transverse beam size due to beam loading are proposed at the EMBT utilizing both view screen and BPM to obtain the time averaged and time resolution of beam spread within the pulse. This will then be correlated with the performance of LLRF feedback-feedforward control system.

REFERENCES

[1] M. Marchetto, et al., "Commissioning and Operation of the ARIEL Electron LINAC at TRIUMF", Proceedings of IPAC2015, Richmond, USA, (2015).

[2] P. Kolb, et al., "1.3 GHz SRF Cavity Tests for ARIEL at TRIUMF", Proceedings of SRF2013, Paris, France (2013).

[3] J. M. Abernathy, et al., "Beam Diagnostic Systems for the TRIUMF e-LINAC", Proceedings of IPAC2012, New Orleans, USA (2012).

[4] D. Storey. A view screen beam profile monitor for the ARIEL e-linac at TRIUMF. Master's thesis, University of Victoria, 2011.

[5] V. Lebedev, OptiM - http://www-bdnew.fnal.gov/pbar/organizationalchart/lebedev/OptiM/optim.htm

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