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Simulation of ARIEL Prebuncher Voltage and Phase Instability Through The ISAC RFQ

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Abstract: Voltage and phase instabilities in the proposed ARIEL prebuncher are simulated using a multiparticle simulation. Using a monte-carlo method, the effect of a ± 1V, 1° instability on the RFQ output is analyzed.

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1 Introduction

Unlike most Radiofrequency Quadrupole (RFQ) accelerators, the ISAC RFQ operates with only a booster and accelerator section [1]. The advantage is an overall reduction in length, however the cost to pay is twofold. First, an external bunching cavity must be operated upstream to pre-bunch the beam. Second, the time-focussing introduces a higher sensitivity to space-charge effects. While the latter is, a priori, not an issue at an ISOL facility such as ISAC, the former is a more immediate concern. Longitudinal bunching efficiency largely depends upon the ability of the prebuncher to effectively modulate and thus time focus beam bunches a the RFQ entrance. Instabilities in either of the harmonic bunching frequencies have the potential to compromise RFQ acceleration, be it transmission, output energy or time/energy spectrum profile.

This document investigates a specification for voltage and phase stability for the ARIEL pre-buncher, intended to time focus ARIEL beams to the ISAC RFQ for post-acceleration. Multi-particle simulations were run from the pre-buncher through the ISAC RFQ, using two separate particle-tracking codes: PARMELA for the pre-buncher and PARMTEQ for the linac.

PARMELA was used to compute the necessary pre-buncher voltages and phases on each of the 11, 23 and 35MHz harmonic bunching frequencies to obtain a time-focus at the entrance of the RFQ. The pre-bunched particle distribution was then fed into PARMTEQ for simulated RFQ acceleration to 0.153MeV/u, the design energy of the MEBT section at ISAC.

Finally, the voltages for each of the three bunching harmonics, in addition to their phases, were sampled 100 times by a Monte-Carlo method, spanning ±1V and $\pm1^\circ$ for each harmonic, simulating instability on the pre-buncher. The resulting perturbed beams were accelerated through the RFQ and analyzed. From the obtained data, a specification for ARIEL pre-buncher stability was elaborated.

2 Simulation

The PARMELA simulation was generated by using TRANSOPTR to compute a rudimentary 7m drift tune from the pre-buncher to the RFQ entrance. First, a 125 cm periodic section was constructed, listed in Table 2. This periodic section was repeated 3 times back-to-back for beam transport, with a 4th modified section added at the end. The former modified the spacing between the last two quadrupoles to 1 inch, roughly reproducing the RFQ actual RFQ matching quadrupoles ILT:Q3 and ILT:Q4, with the final drift distance adjusted to 37.25 cm. This arrangement results in a 5m overall travel distance, reproducing the ISAC pre-buncher arrangement and was used for calibration.

A 200 cm extension was added after the prebuncher and before the ISAC transport, consisting of two back-to-back, one meter long transport sections, also outlined in Table 2. While this does not represent the actual, finalized ARIEL beamline layout, it nevertheless represents a 7m drift from pre-buncher to RFQ, using quadrupoles of identical length and aperture to the ISAC electrostatic quadrupoles. Hence, this model will not reporduce realistic ISAC or ARIEL tunes, however the pre-buncher time focus at the RFQ will be dictated by the correct drift space.

ISAC Periodic Transport			ARIEL 100 cm Transport			ISAC RFQ Match		
Element	L [cm]	Setpt.	Element	L [cm]	Setpt.	Element	L [cm]	Setpt.
Drift	25.0		Drift	12.5		Drift	25.0	
EQuad	5.0	EQ00	EQuad	5.0	EQ04	EQuad	5.0	EQ08
Drift	15.0		Drift	15.0		Drift	15.0	
EQuad	5.0	EQ01	EQuad	5.0	EQ05	EQuad	5.0	EQ09
Drift	25.0		Drift	25.0		Drift	25.0	
EQuad	5.0	EQ02	EQuad	5.0	EQ06	EQuad	5.0	EQ10
Drift	15.0		Drift	15.0		Drift	2.75	
EQuad	5.0	EQ03	EQuad	5.0	EQ07	EQuad	5.0	EQ11
Drift	25.0		Drift	12.5		Drift	37.25	
Total [cm]		125.0	Total [cm]		100.0	Total [cm]		125.0

Table 1: TRANSOPTR transport sections, where L denotes the element length. All electrostatic quadrupoles have an aperture of 2.54 cm, or 1 inch. Column Setpt. shows the setpoint code for each quadrupoles. See Figure 1 for the envelope overview.

TRANSOPTR was then run to produce the correct RFQ match [3], keeping the transverse beam dimensions below 0.8 cm to minimize transverse aberrations. The resulting RMS envelope is shown in Figure 1. A 125 cm segment starts off the tune, up to the pre-buncher, followed by 2 back-to-back ARIEL periodic sections (200 cm), followed by 4 ISAC periodic sections, with the last one corresponding the the RFQ match, for a total of 700 cm of drift, from pre-buncher to RFQ.

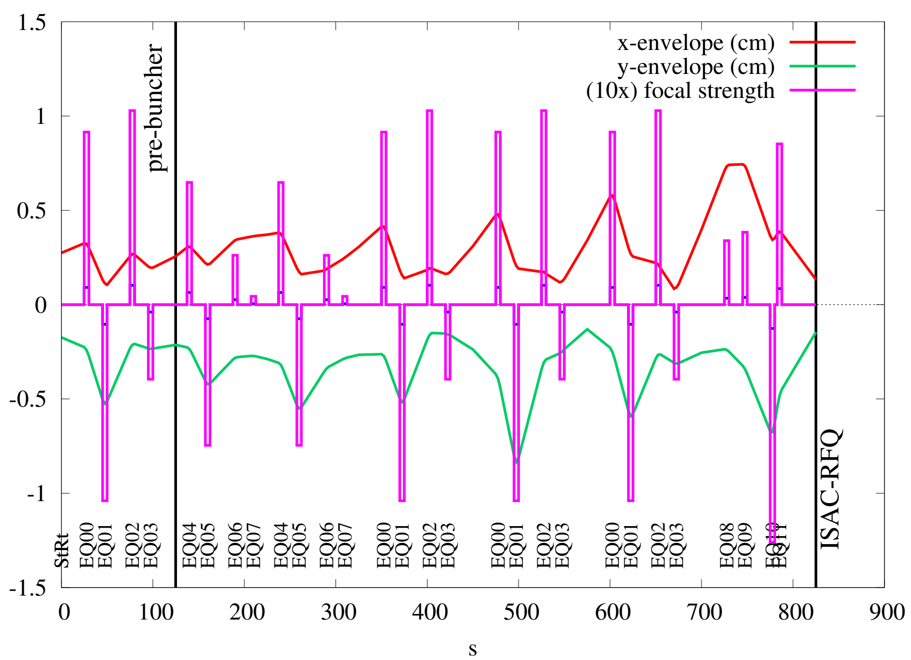

Figure 1: TRANSOPTR envelope simulation of the ARIEL pre-buncher tune to the ISAC RFQ, used for PARMELA simulation. Location of ARIEL pre-buncher marked with vertical black line at s = 125 cm.

PARMELA was then supplied with the computed electrostatic quadrupole setpoints, in a run file simulating the identical transport beamline as used in TRANSOPTR. The pre-buncher simulation resulted in roughly 6000 particles entering the RFQ, with the correct transverse and longitudinal emittances.

A TRIUMF modified PARMTEQ, modelling the ISAC RFQ, was used in conjunction with relax3D [2] to generate electric field distributions corresponding to the input radial matcher and exit high energy cells. Each randomized run resulted in an output particle distribution from which the output energy and time spectra were integrated using python. Spectra from each run were integrated and qualitatively compared to the nominal scenario. Transmission through the RFQ was also tracked.

A Gaussian fit on the time and energy spectra was then performed using a nonlinear least-squares fit algorithm. The variation of these spectra was then analyzed versus simulated pre-buncher instability and used to quantify a stability specification.

2.1 Prebuncher Implementation in PARMELA

The pre-buncher was simulated as a 37.5 cm drift space, in which three discrete simulated bunching harmonics were centrally located. A mass 30 beam with charge state 1 (the limit of the ISAC RFQ) was then simulated flying through the prebuncher and associated transport line. Optimal values for the known ISAC prebuncher case, involving a 5m drift to the RFQ were scaled linearly by a factor 5/7 to obtain the new voltages. Phases had to be manually adjusted to obtain an optimal output. The bunching frequencies, associated voltages and phases used for an RFQ time focus are listed in Table 2.1. In addition, Table 2.1 contains the theoretical and measured transit-time factors from the ISAC pre-buncher, as reference.

Harmonic [MHz]	Voltage* [V]	Phase [deg]	Tn (Theory)	Tn (Measured)
11.78	236.1	-204.7	1.1	0.99
23.56	54.08	-607.3	0.41	0.44
35.34	18.02	-692.2	0.24	0.23

Table 2: ARIEL pre-buncher parameters, as used in PARMELA for mass 30 beam injection in the ISAC-RFQ. TTF values obtained from [3]. *note: PARMELA does not take into account transit time factors, thus these voltages are for simulation purposes only. Actual pre-buncher voltages must take TTF into account.

3 Simulation Results

The PARMTEQ output for mass 30 acceleration is shown in Figure 2. The three plots at the bottom show the injection emittances at 2.04 keV/u while the three top figures show output emittances at 0.153 MeV/u. The pre-buncher parameters used for this simulation are those of Table 2.1.

The simulated ARIEL injected beam agrees well with known behavior from ISAC beams. The output longitudinal emittances closely match simulated ISAC behavior, likewise for the transverse emittances.

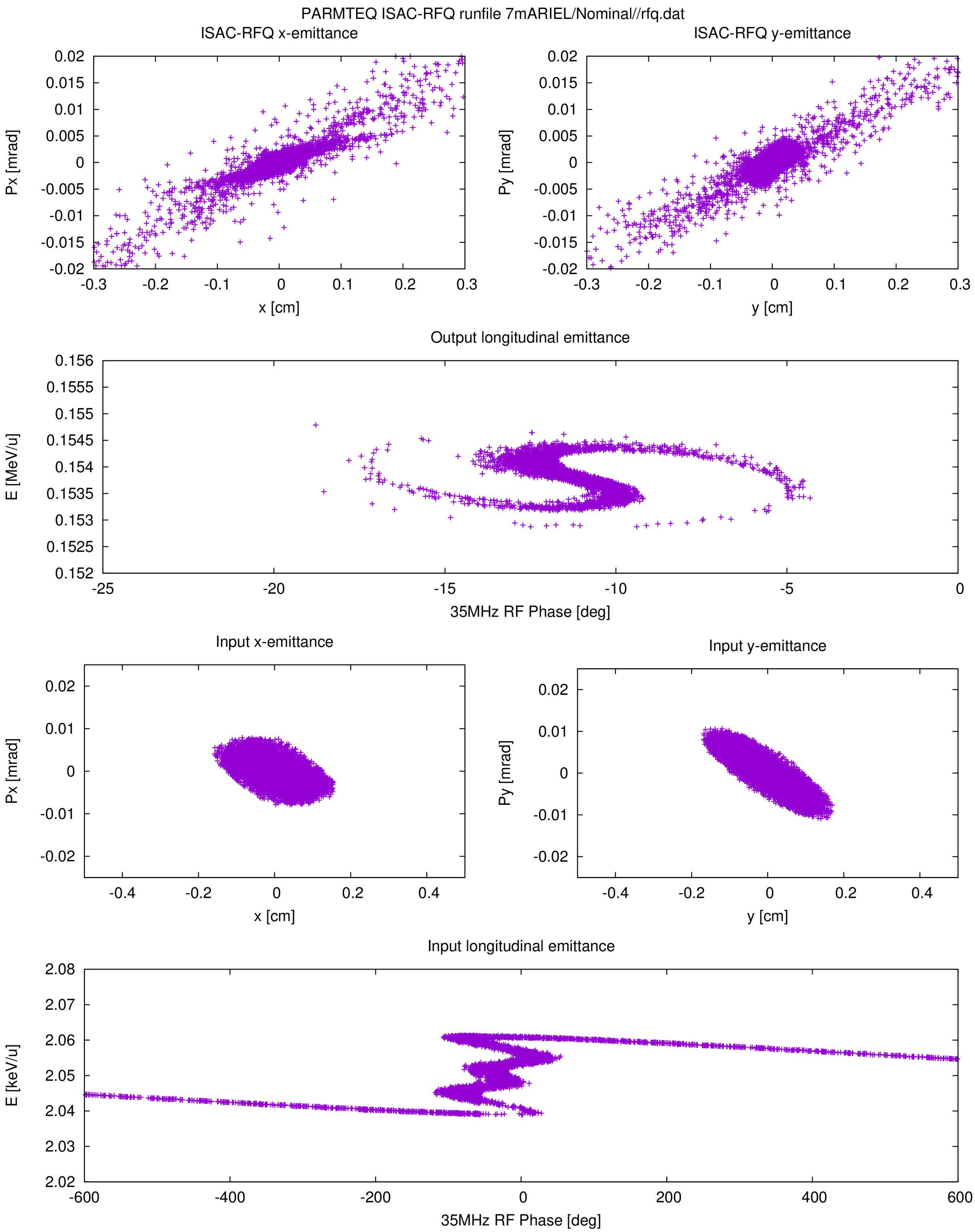

Figure 2: PARMTEQ output for mass 30 ARIEL prebunched beam. The three top figures show the output x,y emittances, and the longitudinal emittance. The three bottom figures show the input x,y and longitudinal emittances. 5000 particles were used in this simulation.

The Monte-Carlo sampling was repeated 100 times with randomized voltages and phases of $\pm 1\%$ and $\pm 1^\circ$, respectively. The resulting phase-space coverage of the simulation is presented in Figure 3.

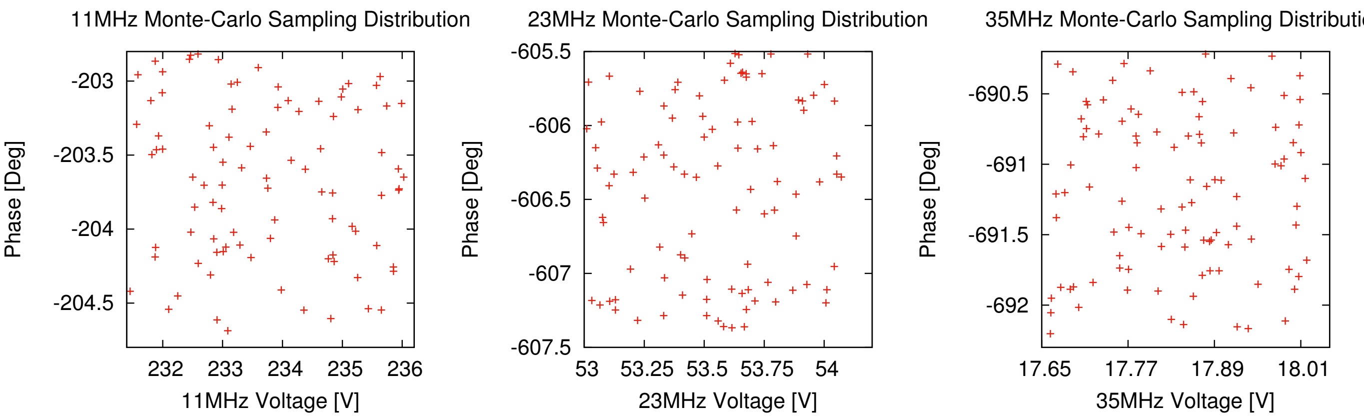

Figure 3: 11, 23 & 35MHz Monte-Carlo sampling for phase vs. voltage with 100 PARMELA/PARMTEQ runs.

Each of the 100 time and energy spectra from the simulation were then integrated over all runs, providing a full trace of the resulting RFQ output spectra with the modelled prebuncher voltage and phase ripple. These traces are shown in Figures 4 and 5 for both energy and time, respectively, and are compared to the nominal RFQ output with the ARIEL prebuncher operating at nominal setpoint.

Visual inspection of Figures 4 & 5 reveal that the resulting centroid and width of the cumulative perturbed spectra, compared to the nominal case, are roughly identical. A more quantitative analysis was also carried out. Both the output time and energy spectra were fit with standard Gaussians to extract centroids, amplitudes and widths. The Gaussian parameters were then plotted for each run, as shown in Figure 4 for energy and Figure 5 for time.

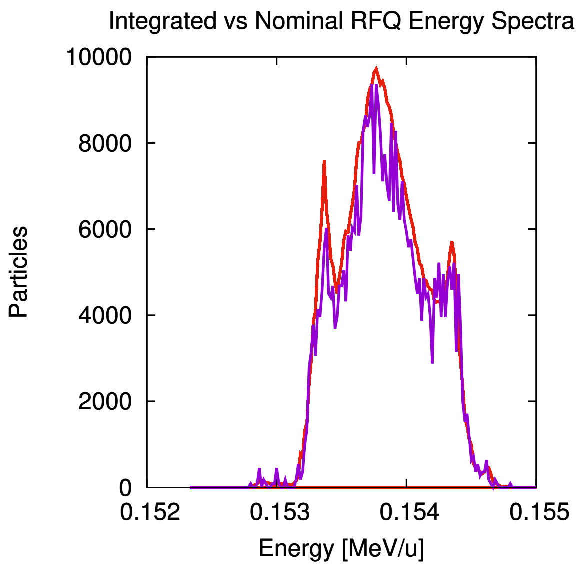

Figure 4: Cumulative output RFQ energy spectrum (red) produced by integration of each individual run, corresponding to a ± 1V,1° ripple on the ARIEL prebuncher. The spectrum is compared to the nominal case (purple), which has been scaled vertically for visual comparison.

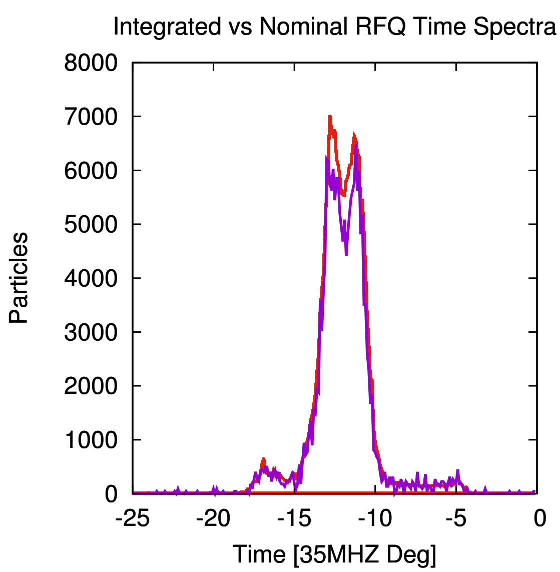

Figure 5: Cumulative output RFQ time spectrum (red) produced by integration of each individual run, corresponding to a ± 1V,1° ripple on the ARIEL prebuncher. The spectrum is compared to the nominal case (purple), which has been scaled vertically for visual comparison.

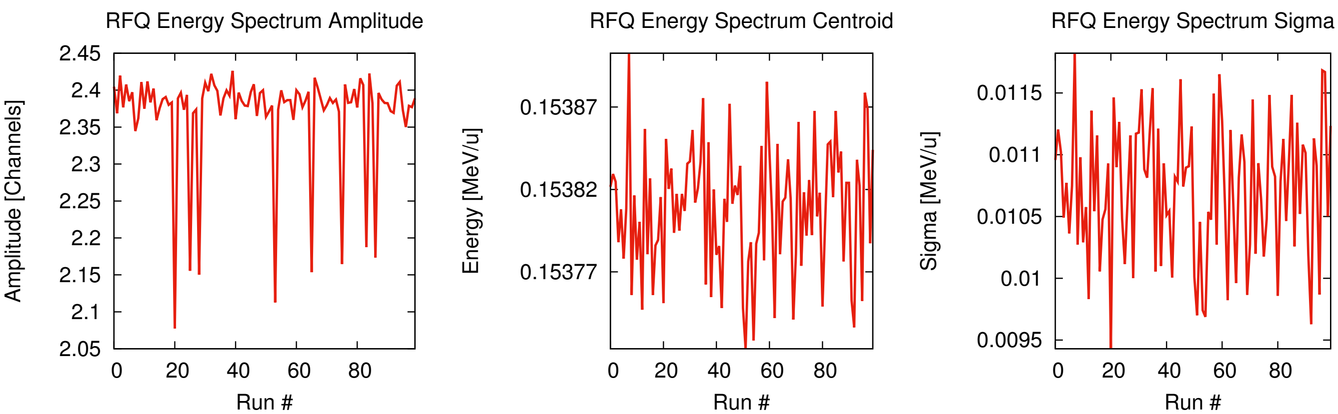

Figure 6: Gaussian fit parameters for output RFQ energy spectrum of 100 PARMELA/PARMTEQ runs with ±1%,1° Monte-Carlo sampling for voltage and phase, respectively.

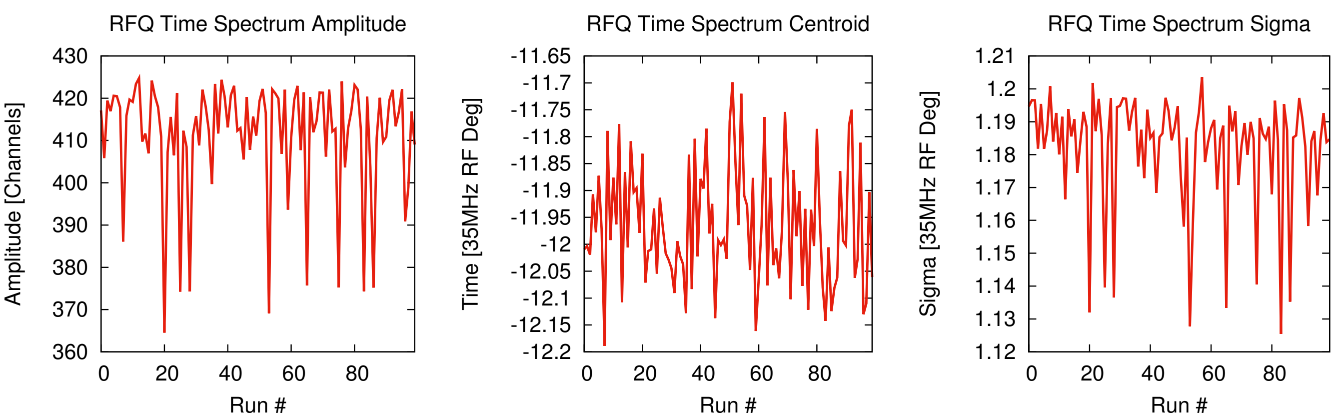

Figure 7: Gaussian fit parameters for output RFQ time spectrum of 100 PARMELA/PARMTEQ runs with ±1%,1° Monte-Carlo sampling for voltage and phase, respectively.

The energy spectrum output of the RFQ remains stable within 0.1 % of the RFQ output energy. Save for a few excursions on the order of 10%, the vast majority of the energy spectrum widths (Figure 6, right) was found to lie within roughly 4% of the nominal case. On the other hand, the time spectrum centroid varies by 0.4° (35MHz), representing a time shift of roughly 30 picoseconds. The time spectrum width varied by roughly 6%, again with the largest excursions being negative (smaller output width). For both cases, the dithering of the output spectra was insufficient to cause an appreciable increase in integrated spectral width (Figures 4 and 5).

Figure 8 shows the measured RFQ transmission for each sequential run. The 1% voltage and 1° phase variations were found to result in an RFQ transmission variation on the order of 3%.

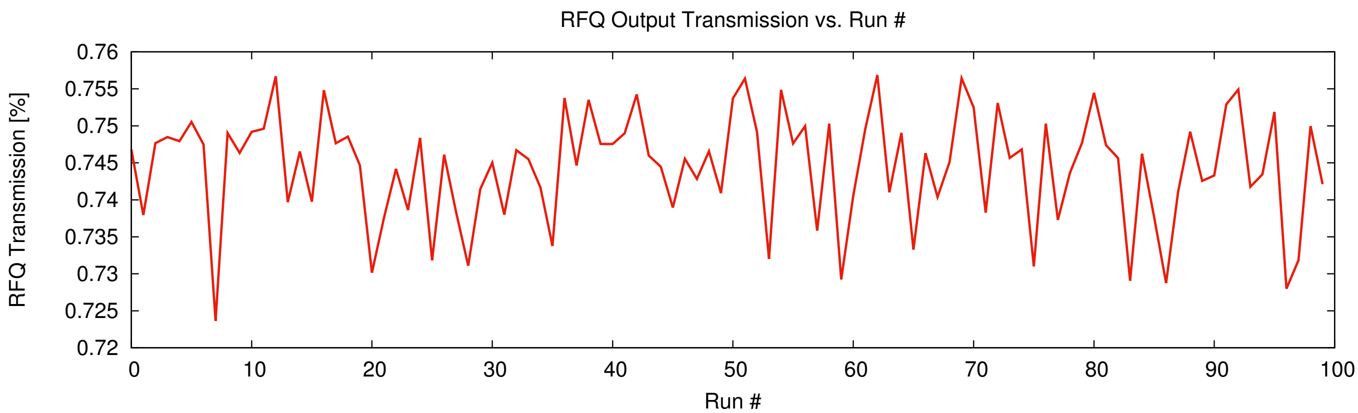

Figure 8: Simulated RFQ Transmission of 100 PARMELA/PARMTEQ runs with ±1%,1° Monte-Carlo sampling for voltage and phase, respectively.

4 Conclusion

From the above discussed simulation and analysis, it is concluded that a variation of ±1V, ±1° on any of the 11, 23 or 35MHz ARIEL prebuncher harmonics will not produce a substantial perturbation to the ISAC RFQ output, and are therefore acceptable.

Monte-Carlo simulations of such ripples on the ARIEL prebuncher predict that such a voltage and phase variation will result in an RFQ output energy shift on the order of 0.1% and a time centroid shift on the order of less than one degree 35MHz RF. While the individual perturbed spectra had maximal outlying width variations on the order of 10% and 6% for energy and time, respectively, most simulated runs fall well within these intervals.

Integrated over time, the resulting perturbations on the RFQ output energy and time spectrum, including centroid and width variations, are not discernable compared to the nominal output case in which prebuncher voltage is held at optimal settings. The high stability of the centroids minimizes the perceptible effect of these variations over time.

References

[1] L. Root. Beam Dynamics Feasibility Study for A Pre-RFQ Subharmonic Buncher. Technical Report TRI-DN-96-09, TRIUMF, 1996.

[2] Koscielniak S. Root L. Lee R. Laxdal R. Grguric I. Beam Dynamics of the TRIUMF ISAC RFQ. Technical Report LINAC96, 402-404, TRIUMF, 1996.

[3] L. Root. Initial Operation of the RFQ Pre-buncher With a $^{14}N^{+1}$ Beam. Technical Report TRI-DN-ISAC-00-05, TRIUMF, 1998.