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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, several instability scenarios are produced and their resulting effects on the RFQ capture efficiency is analyzed. From these scenarios, a stability requirement for the ARIEL pre-buncher harmonic voltages and phase is presented.

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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 at 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.

The ISAC RFQ longitudinal acceptance surface was defined by sending single particles through the RFQ in PARMTEQ for varying input values of energy and phase. The resulting surface was used to determine whether or not input particles would be captured by the RFQ. PARMELA was then used to compute the necessary pre-buncher voltages and phases on each of the 11, 23 and 35 MHz harmonic bunching frequencies to obtain a time-focus at the entrance of the RFQ. The pre-bunched particle distribution was then fed into a python script which computed the resulting capture by comparing the longitudinal distribution with the acceptance surface.

Finally, the voltages for each of the three bunching harmonics, in addition to their phases, were sampled 100 times by a Monte-Carlo method for four separate instability scenarios, spanning $\pm$ 0.5, 1, 2 and 3 volt-degree instabilities. By this, it is meant that the voltages and phases are randomly varied by the aformentioned quantities, relative to their optimal settings. The resulting perturbed beams were compared to the RFQ longitudinal acceptance surface and a capture effiency was computed. 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 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

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 quadrupole. See Figure 1 for the envelope overview.

this does not represent the finalized ARIEL beamline layout, it nevertheless simulates a 7m drift from pre-buncher to RFQ, using quadrupoles of identical length and aperture to the ISAC elements. Hence, this model will not reproduce realistic ISAC or ARIEL tunes, however the pre-buncher time focus at the RFQ will be dictated by the correct drift space.

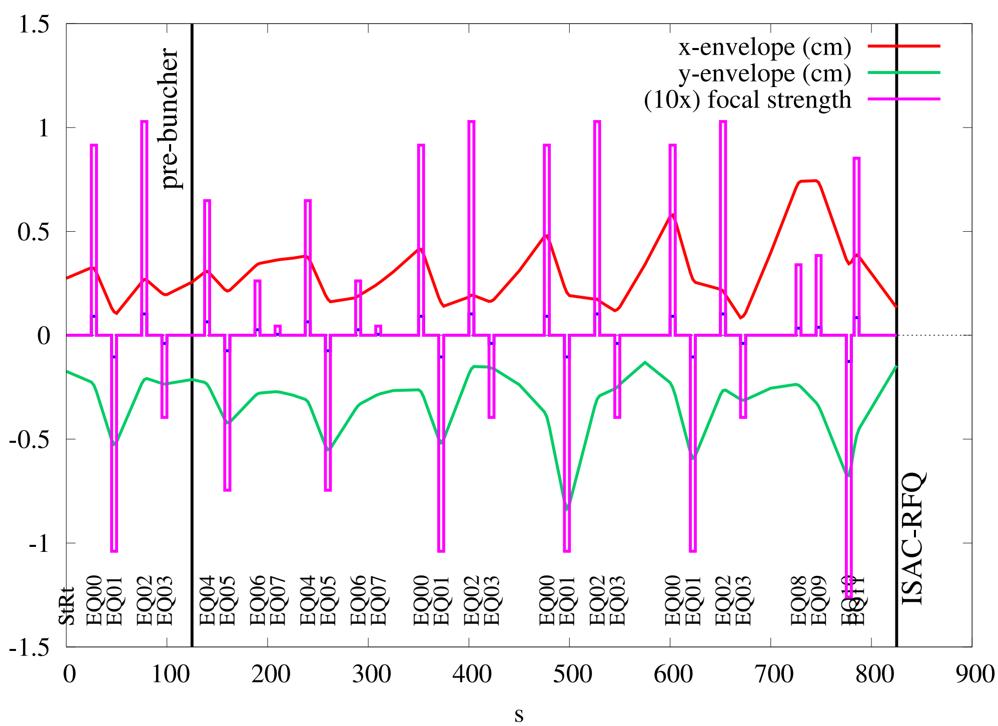

Figure 1: TRANSOPTR envelope simulation of the ARIEL pre-buncher tune to the ISAC RFQ, used for PARMELA simulation. Location of ARIEL pre-buncher marked with vertical black line at s = 125 cm.

TRANSOPTR was then run to produce the correct RFQ match [2], 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 to the RFQ match, for a total of 700 cm of drift, from pre-buncher to RFQ.

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 500 particles reaching the RFQ, with the correct transverse and longitudinal emittances.

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	256.6	8.0	1.1	0.99
23.56	108.2	188.0	0.41	0.44
35.34	38.9	8.0	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 [2]. *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 RFQ Longitudinal Acceptance

In order to compute the RFQ capture efficiency, the longitudinal acceptance was computed for optimal injection energy, or 2.05 keV/u for a beam of mass 30 MeV/c^2. This was done by sending a single particle through the RFQ at varying input values of (ϕ,E). The former was scanned over a phase domain of -600°,600° and an energy domain of ± 15% optimal energy. A mapping of (ϕ,E) for which particles successfully transmitted the RFQ, defined as having an output energy greater than 0.150 MeV/u and a phase within ±200° was produced and is shown in Figure 3.

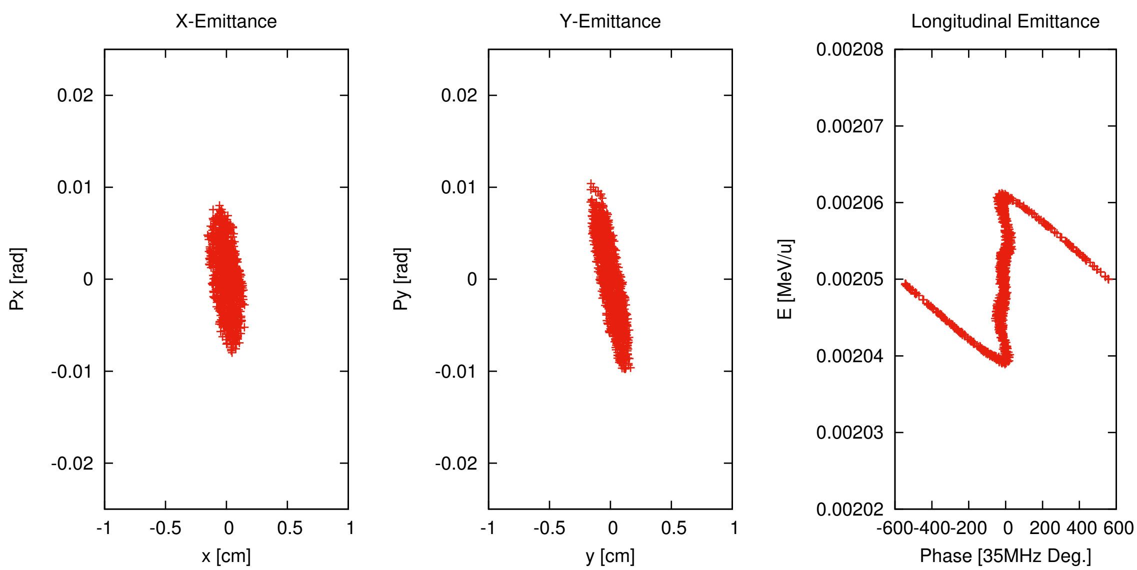

Figure 2: PARMELA output for mass 30 ARIEL prebunched beam. 1000 particles were used in this simulation.

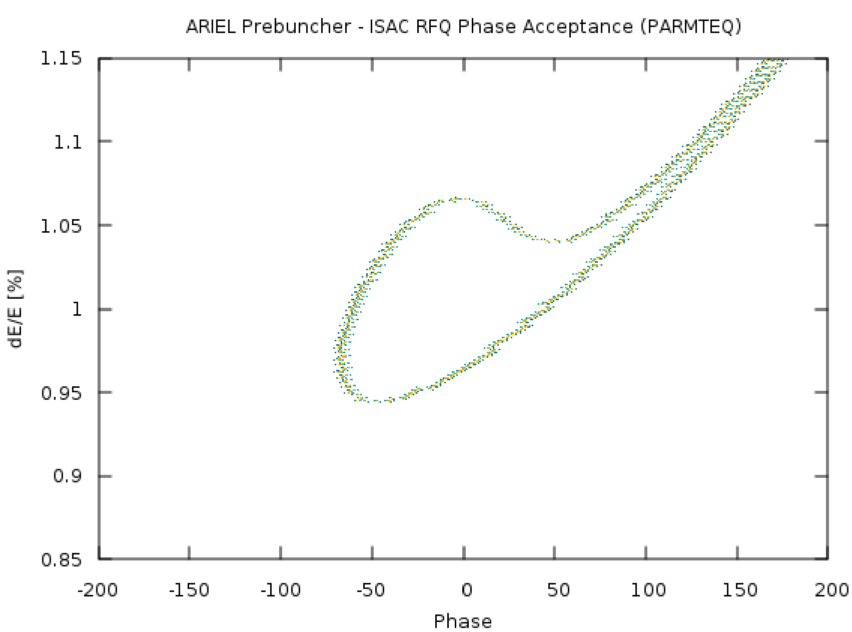

Figure 3: ISAC RFQ longitudinal acceptance as a function of phase and energy. 1000 particles were used to compute this distribution in PARMTEQ. Jagged features are a plotting artifact. Particles transmit within the outlined area, while outside they do not.

With the acceptance at hand, a python script was written to compute the capture efficiency of an arbitrary input particle distribution, speeding up the process of simulating ripples in the prebuncher harmonics. The alternative was to sequentially run PARMELA (pre-buncher) then PAMTEQ (RFQ), which would effectively double the computation time.

4 Pre-buncher Voltage and Phase Ripples

A Monte-Carlo routine was used to generete randomized phase and voltage variations on each of the three harmonics of the pre-buncher, enabling the simulation of varying levels of noise on the electronics. The routine works by varying the PARMELA input parameters for the pre-buncher and then executes the simulation. This can easily be iterated and, for this present simulation, was done for 100 iterations for each different noise scenario. These were chosen at ± 0.5, 1, 2, 3 volt-degrees. By volt-degrees, it is implied that both the voltage and phase of the given harmonic is unstable to the specified quantity, in their respective units (volts and degrees). It is also important to note that, for all of the above scenarios, one degree is defined in terms of its own harmonic. For instance, one degree for the second harmonic represents 1/360 of 23.8 MHz, in other words the instabilities are not normalized to the fundamental at 11.8 MHz. The resulting RFQ capture efficiency for each scenario is shown in Figure 4.

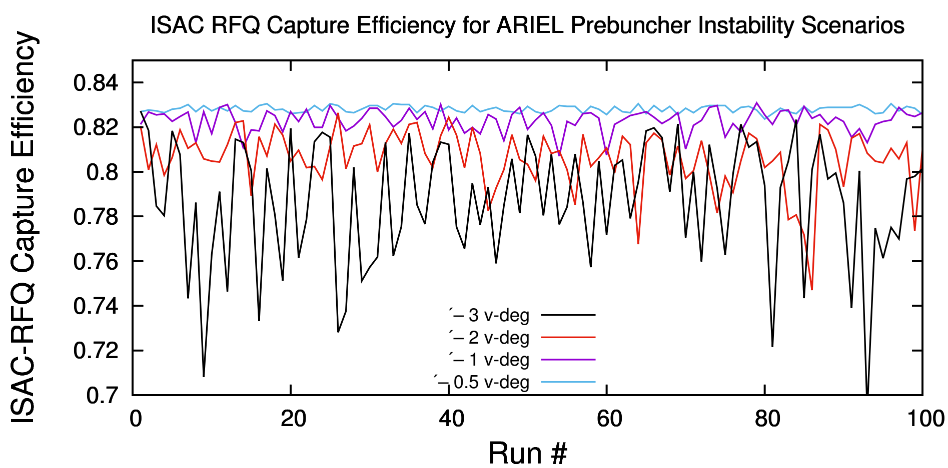

Figure 4: Four scenarios for ARIEL pre-buncher voltage and phase stability, showing ± 0.5 v-deg (blue), ± 1 v-deg (purple), ± 2 v-deg (red) and ± 3 v-deg (black). 1000 particles were used for each run.

The efficiencies shown in Figure 4 were then binned in capture efficiency intervals of 0.01 (one percent) for analysis. Figure 5 shows the number of runs with a given capture efficiency. A wider spread is indicative of higher resulting RFQ capture instability, while a narrower spread (and a higher total count) indicates more stable RFQ capture. As can be expected, when the stability criterion of the pre-buncher is relaxed, the resulting harmonic ripples cause variations in RFQ time-focus quality, thereby affecting the overall capture into the linac. As the amplitude of the ripples are decreased, one observes higher overall RFQ transmission and stability.

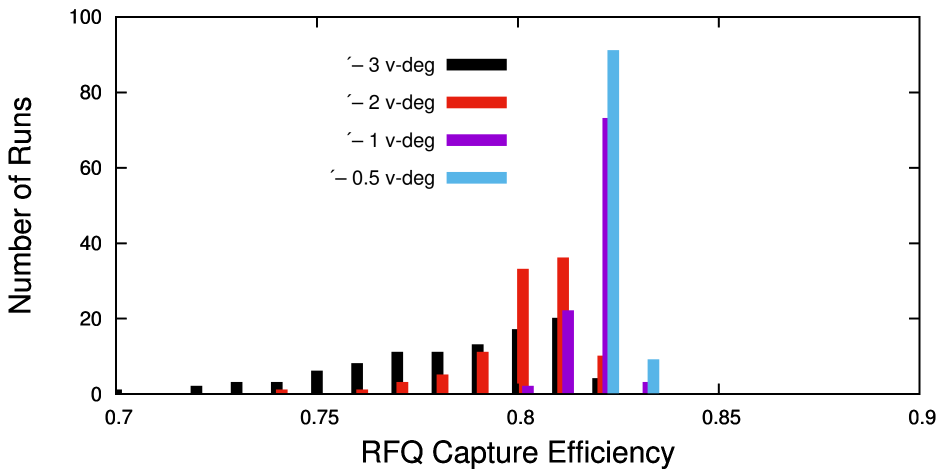

Figure 5: Four scenarios for ARIEL pre-buncher voltage and phase stability, showing ± 0.5 v-deg (blue), ± 1 v-deg (purple), ± 2 v-deg (red) and ± 3 v-deg (black). 1000 particles were used for each run. Histogram data was binned in RFQ capture efficiency intervals of 0.01, or 1%.

Inspection of Figure 5 shows the wide spread of the ±3 v-deg scenario, with resulting RFQ capture efficiencies ranging from 0.70 to 0.82, while the ± 2 v-deg case is marginally better, from 0.74 to 0.82. We note that for both aformentioned cases, the high degree of variability results in no more than 40% of runs remaining in one bin interval.

The situation notably improves for the ±1 v-deg scenario, where we observe both a significant narrowing of the capture efficiency spread, now spanning 0.80 to 0.83 and a corresponding increase in stability, with just under 80% of simulations in this case yielding a capture of 0.82. The ±0.5 v-deg case further narrows in spread, with all resulting capture efficiencies ranging between 0.82 and 0.83. The former scenario also produces the highest capture stability, with 90% of runs yielding 0.82.

5 Conclusion

During the process of conducting this simulation, much work had to go toward the optimization of the pre-buncher time-focus seen in Figure 2, namely ensuring that it was neither under or over-bunched, in other words ensuring that the time focus was as vertical as possible. Additionally, each harmonic had to be carefully tuned in phase to center the time-focus as much as possible to maximize RFQ capture efficiency, a process which was time-consuming.

The author notes that from an operational standpoint, there presently exist no mechanism for accelerator operators to directly inspect the RFQ time-focus (either for the ARIEL or ISAC pre-bunchers). It has also been highlighted[4] that a well established time-focus which has a slightly incorrect phase will result in added instability, due to the particle distribution being too close to the RFQ accpetance boundary. In the aformentioned case, small jitters in voltage or phase will result in particles proximal to the capture region boundary failing to be captured by the RFQ, thereby affecting the acceptance and transmission.

Adding to the above the known temperature-stability relationship for electronic components and the temperature variability in the ISAC experimental hall, which can vary by more than 10° in a day, along with the unknown temperature stability of the location where the as-yet unbuilt ARIEL pre-buncher electronics are to be located, a cautious and conservative approach should be favoured.

Therefore, it is the conclusion of this report that the ARIEL pre-buncher electronics are to be designed and manufactured with a stability of $\pm$ 0.5 volts and $\pm$ 0.5 degrees, to produce maximal possible RFQ capture stability.

It is further noted that the ISAC pre-buncher, whose electronics suffer frequent issues with stability and reproducibility [5] should also be built to a matching specification to those of the ARIEL pre-buncher.

References

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