Injector Upgrade Phase 1 Settings for 130 kV Gun HV

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The Phase 1 CEBAF Injector Upgrade focuses on the beam line between the gun and the captured solenoid MFA0I03 upstream of the Chopper 1 RF cavity and retains the pre-upgrade injector beam line downstream from MFA0I03 onward. One of the main goals of Phase 1 is to move the Prebuncher RF cavity downstream of the Wien system. Phase 2 will concentrate on the beam line downstream of the choppers removing the Capture RF cavity, shifting the position of the Buncher RF cavity, and replacing the quarter cryomodule (2 Cornell-style 5-cell cavities) with the booster (1 2-cell and 1 7-cell cavity). The chopping system may be upgraded in Phase 2 or at a later date. This note provides settings to use for Phase 1 for the RF and solenoids up to and including the cavities in the quarter cryomodule. It also provides an indication of the robustness of the settings provided with the results of an RF settings sensitivity study.

1 Settings For Wiens OFF

Phase 1 will be completed and commissioned with the gun HV at 130 kV and 200 kV, and for the 2021 Physics run, the gun HV will be 130 kV. The optimal set up for the Physics run with the Wien system OFF and the FG spin solenoids (MFG1I04A and MFG1I04B) set for 0° ($+45^\circ - 45^\circ = 0^\circ$) comes from optimizations performed using the General Particle Tracer (GPT) suite of programs [1]. The selected optimal settings for the RF, solenoids, and quadrupoles through the quarter cryomodule are provided in Tables 1, 2, and 3. Suggested (but not necessarily recommended) settings from the optimization for the quadrupoles between the quarter cryomodule and the first full cryomodule are in Table 4.

Table 1: Relative phases for RF elements.

Element	**Phase Reference**	**Phase Offset (°)**	**Comment**
Prebuncher	bunching zero-crossing	0	on zero-crossing
Buncher	bunching zero-crossing	-46.5	toward deceleration
Capture	crest	$+4.3$	debunching
1^{st} 5-cell	crest	-27.2	bunching
2^{nd} 5-cell	crest	-0.9	bunching

Table 2: Amplitude/GSETs for RF elements.

Element	**Setting Type**	**Setting**	**Comment**
Prebuncher	peak amplitude	44000	0.00080× 5.5e7 (field map peak amplitude 5.5e7 (V/m (? units))
Buncher	peak amplitude	320901 V/m	field map peak amplitude 6.37349e+07 V/m corresponds to U at 1 J
Capture	peak amplitude	3422460	Arb. Units
1^{st} 5-cell	GSET	7.367 MV/m	
2^{nd} 5-cell	GSET	4.086 MV/m	

Table 3: Solenoid and quadrupole settings (Wiens OFF and $\sum$FGs=0°).

Element	**Setting (mA or A(*))**	**Comment**
MFX2I01	1823.535	
MFX1I03	-1721.738	
MQW1I03*	0*	
MQW1I04*	0*	
MFG1I04A	958.85	+45°
MFG1I04B	-971.06	−45°
MQW1I05*	0*	
MQW1I06*	0*	
MFX0I01	1433.196	
MFA0I03	-1235.411	
MFD0I04*	0.771*	
MFA0I05	-868.621	
MFA0I06	1309.225	
MFL0I07	-2041.882	

Table 4: Reference settings for the quadrupoles between the quarter and the first full cryomodule.

Element	**Setting (G cm)**
MQS0L01	50.271
MQJ0L01	35.769
MQS0L01A	2.407
MQJ0L02	-174.662
MQS0L02	6.228
MQJ0L02A	185.249
MQS0L02B	45.395
MQJ0L03A	-79.332
MQS0L03	21.533
MQJ0L03	52.758
MQS0L04	7.092
MQJ0L04	2.064

2 Simulated Beam Characteristics for Wiens OFF

Figures 1, 2, and 3 show the bunchlength (σ_t), average kinetic energy ($\bar{E_k}$), energy spread ($\sigma_{E_k}/\bar{E_k}$), beam sizes (σ_x and σ_y), and normalized transverse emittances (ε_{n_x} and ε_{n_y}) for the optimal solution (Wiens OFF). For speed and to roughly approximate the expected beam characteristics for 170 μAmp beam current at 499 MHz, the simulations in the optimization were performed with 250 macroparticles, and the solution results were checked with simulations using 1000 and 10000 macroparticles. Increasing the number of macroparticles increases the accuracy of the calculated space charge effects and exposes subtle responses to the set ups found by the optimization, so the beam characteristics such as bunchlength and transmission achieved during the optimization (see Table 6) typically degrade with an increased number of macroparticles. The figures in this section show results calculated with 10000 macroparticles.

Beam transmission approximated by the number of active macroparticles in the simulation is better than 99% as shown in Figure 4. In the optimization and subsequent verification simulations, the aperture sizes for A1 and A2 are smaller than the installed apertures, so transmission in the machine should not be a significant issue.

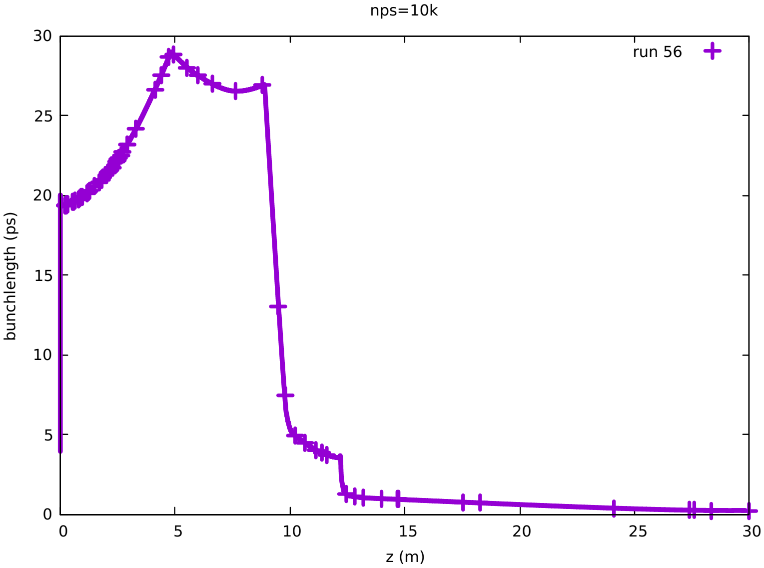
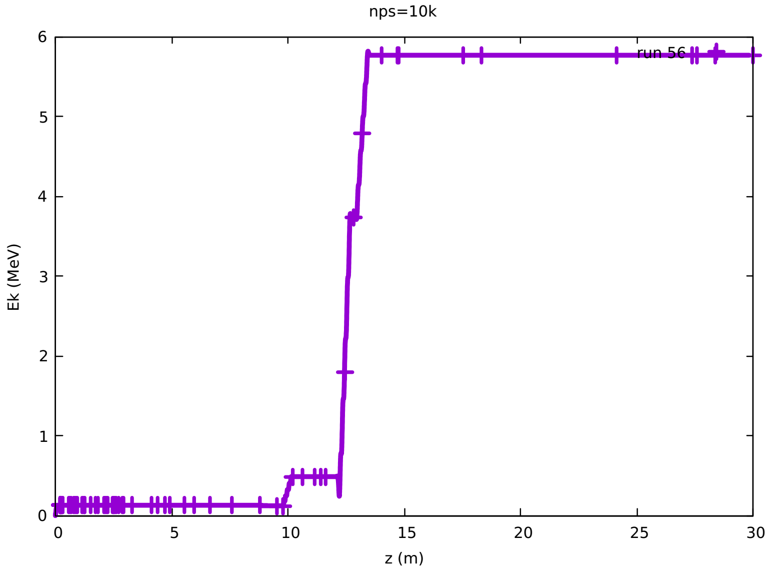
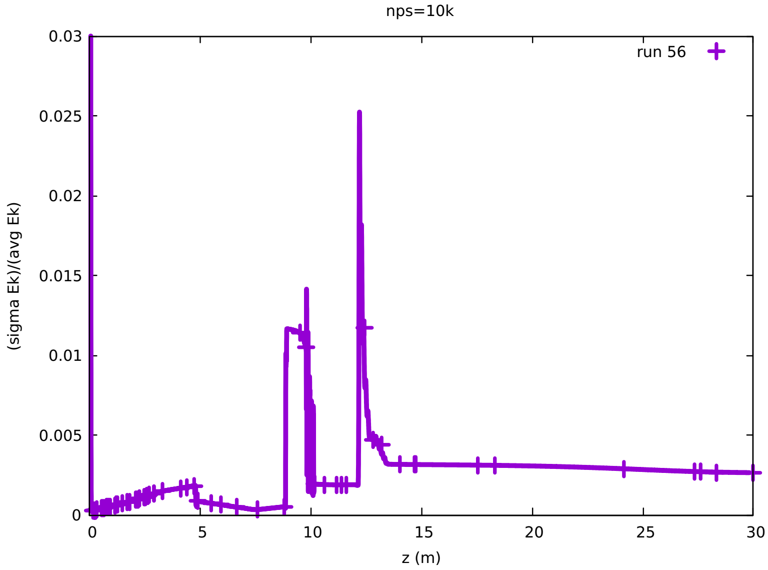


Figure 1: Bunchlength (σ_t) with Wiens OFF. The bunchlength upstream of the full module is 0.25 ps.

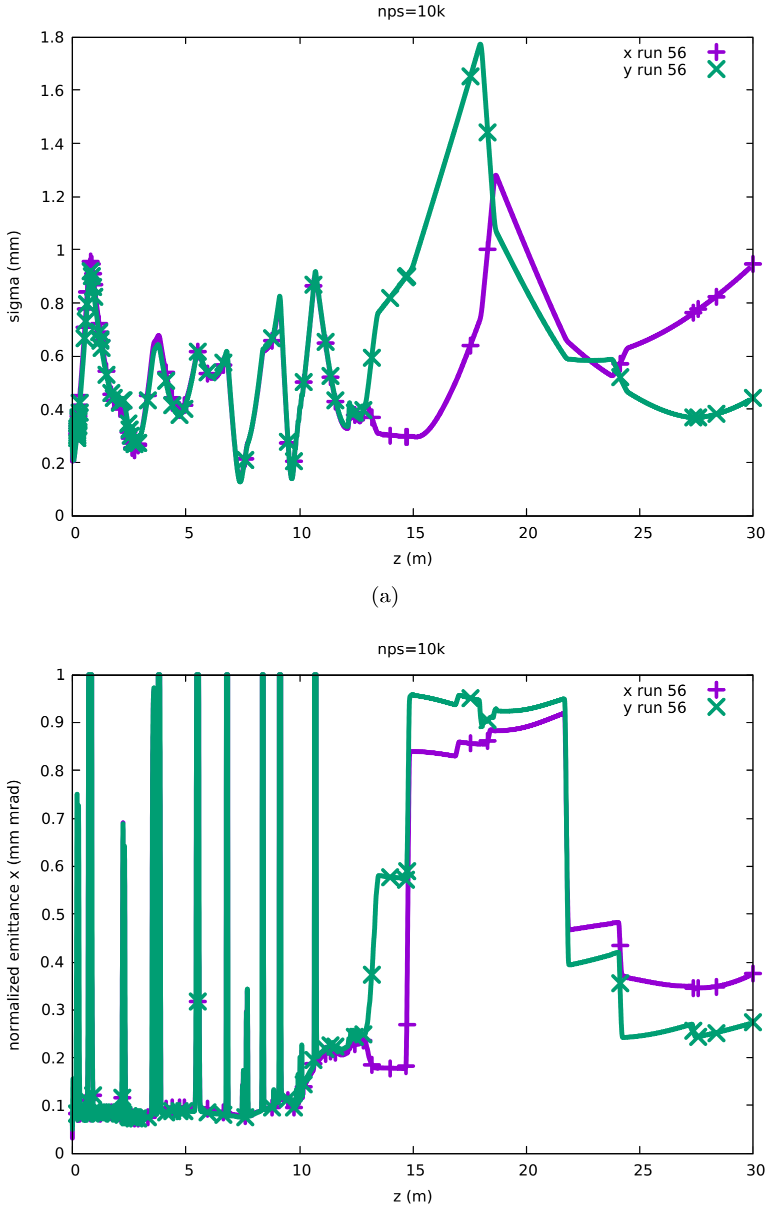


(a)



(b)

Figure 2: (a) Average kinetic energy ($\bar{E_k}$) and (b) energy spread ($\sigma_{E_k}/\bar{E_k}$) with Wiens OFF.



(a)

(b)

Figure 3: (a) Beam sizes (σ_x and σ_y) and (b) normalized emittances (ε_{n_x} and ε_{n_y}) with Wiens OFF.

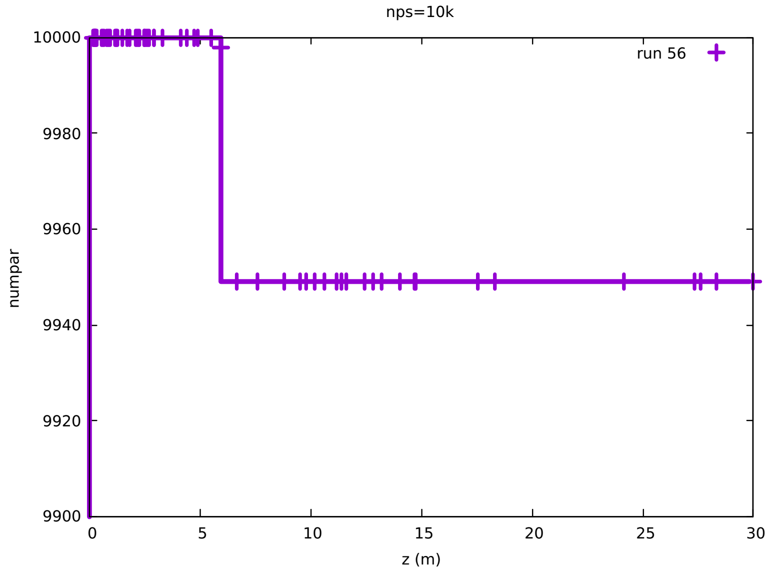


Figure 4: Estimate of beam transmission for 170 μA at 499 MHz with Wiens OFF.

3 Wien Quadrupole Settings for Vertical Wien ON at 90°

Rough settings for the Vertical Wien quadrupoles to use with this set up when the Vertical Wien is ON at 90° are listed in Table 5. The table provides settings for two FG cases: $\sum$FGs=0° and $\sum$FGs=+90°. To change between the two FG configurations, flip the sign of the second FG setting (see Table 3).

Table 5: Rough Wien quadrupole settings (Vertical Wien ON +90°).

Element	**$\sum$FGs=0° Setting (A)**	**$\sum$FGs=+90° Setting (A)**
MQW1I03	−0.3	−0.2
MQW1I04	−0.5	−1.1

4 RF Setting Sensitivity for Wiens OFF

Comparisons between the optimal solution and subopitmal RF configurations show how the set up might respond to changes in RF settings. A likely scenario producing a suboptimal set up is a single element with an incorrect setting. This study modeled this single point error looking at the effect of changing one setting of one RF element per simulation. All simulations including the optimal solution used 1000 macroparticles.

A single point change in amplitude or GSET is straightforward to model because the amplitudes and GSETs are independent. Phases, on the other hand, are related to timing and are intrinsically relative to each other. Therefore, simulating a single phase change in one element requires counter phase adjustments for downstream elements. For example, a $+5°$ change in Prebuncher phase requires a compensating $-5°$ offset for the phases of the Buncher, Capture, and quarter cavities to restore their optimal phases.

Errors in set up can produce a range of beam characteristics from drastic and untransportable to viable and transportable. Table 6 lists the relaxed criteria used in this study to identify candidate viable and transportable solutions. The table also provides the optimization goals for reference.

Table 7 summarizes the simulated responses that met the criteria in Table 6, and the ranges provided serve as estimates for RF setting variation that are tolerable (but not optimal). The set up is relatively insensitive to changes in Prebuncher and Capture phases and is quite sensitive to the Buncher and quarter cavity phases. There is flexibility in the amplitude or GSET settings for all cavities except the Capture amplitude.

Table 6: Criteria for acceptable beam characteristics upstream of the first full cryomodule in the Injector

Beam Characteristic	**Sensitivity Limit**	**Optimization Goal**
beam transmission	$\geq 99.9\%$	$\geq 99.9\%$
transverse emittance	≤ 1 mm mrad	≤ 0.25 mm mrad
bunchlength	≤ 1 ps	≤ 0.5 ps
$\bar{E}_k$	not considered	5.5 to 7.5 MeV
σ_{E_k}	see $\sigma_{E_k}/\bar{E}_k$	≤ 50 keV
$\sigma_{E_k}/\bar{E}_k$	comparable to optimal case	not specified since use σ_{E_k}

Table 7: Acceptable RF setting ranges (relative to the optimal settings). Note "[" and "]" mean end points are included, and "(" and ")" mean end points are excluded.

Element	**Phase Offset Range (°)**	**Amplitude/GSET Percent Variation Range (%)**
Prebuncher	$[-10, 7]$	± 20
Buncher	± 1	± 5
Capture	$[-5, 7]$	$[-1, 1)$
1^{st} 5-cell	± 1	$[-5, 10]$
2^{nd} 5-cell	± 2	± 20

5 Acknowledgements

5.1 Field Maps

Gabreil Palacios-Serrano provided field maps for the gun. Shaoheng Wang, Haipeng Wang, and Frank Marhauser provided field maps for the Prebuncher, Buncher, and 5-cell RF cavities. (The Capture field map is based on the Fourier coefficient description of the Capture originally used in the CEBAF PARMELA model.) Jay Benesch provided field maps for the solenoids (FA, FD, FG, FL, and FX), Wien quadrupoles (QW), Wien dipole, and Wien HV.

5.2 Beam Line Positions

Many individuals contributed to positioning the elements on the beam line. A very incomplete list (in addition to ourselves) includes: Phil Adderley, Joe Grames, Chris Gould, Shaun Gregory, Gary Hays, Carlos Hernandez-Garcia, Lakshmi Lalitha, Danny Machie, Marcy Stutzman, Dennis Turner, and Yan Wang.

References

[1] Pulsar Physics, General Particle Tracer, `http://www.pulsar.nl/gpt`.