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JITTER TOLERANCE FOR THE FEBE BEAMLINE ON CLARA

M.A. Johnson[1]*, J.K. Jones[1] and P.H. Williams[1]
ASTeC, STFC Daresbury Laboratory, Sci-Tech Daresbury, Warrington, UK
[1]also at the Cockcroft Institute, Sci-Tech Daresbury, Warrington, UK

Abstract

CLARA at STFC Daresbury Laboratory is a test facility for FEL research and novel accelerator technologies, providing high-quality electron bunches with charges up to 250 pC. Phase two of CLARA, which will bring the accelerator to its design energy (250 MeV) and repetition rate (100 Hz), is expected to begin commissioning in 2024. To maximise exploitation of the upgraded accelerator, a dedicated Full Energy Beam Exploitation (FEBE) beamline is currently being installed, featuring two large chambers where a high-power laser and advanced diagnostics will be available for user experiments that include investigation of novel plasma acceleration methods. Many experiments planned for CLARA-FEBE will require a high level of shot-to-shot beam stability, placing particular importance on the bunch time of arrival (tens of femtoseconds) and peak current (several kiloamperes). Accurate modelling of beam jitter will therefore be critical for the purposes of planning user experiments, and for future work to mitigate the dominant jitter sources in the machine. In this contribution, we investigate the jitter tolerance of CLARA-FEBE using start-to-end simulations of the accelerator complex.

INTRODUCTION

CLARA (the Compact Linear Accelerator for Research and Applications) is a high-brightness electron beam user facility under development at STFC Daresbury Laboratory [1]. To maximise its availability to users, the CLARA accelerator complex is being constructed in stages. Phase one, consisting of the CLARA front end (FE) [2,3], has been operational since 2018 and routinely provides bunches of up to 100 pC at 10 Hz and energies up to 35 MeV. Phase two, which will bring the accelerator to its design energy (250 MeV) and repetition rate (100 Hz) is currently under construction, and will begin commissioning with beam in early 2024.

Following a successful user run with the CLARA FE between 2018 – 2022, a dedicated Full Energy Beam Exploitation (FEBE) beamline is being installed to exploit the capabilities of the upgraded accelerator [4]. The FEBE experimental areas are specifically designed to accommodate user experiments investigating novel acceleration techniques. These experiments place strict requirements on the shot-to-shot beam stability, particularly with respect to the peak beam current and bunch arrival time jitter (~10 fs) [5,6].

Here, we investigate the jitter tolerance of the CLARA FEBE beamline using start-to-end simulations of the accelerator complex. A preliminary jitter tolerance study [7] was completed as part of the CLARA conceptual design in 2013.

* mark.johnson@stfc.ac.uk

Table 1: Assumed RMS jitter tolerances for each of the machine parameters considered in this study. Values with an asterix are based on measurements with the CLARA FE [3].

Parameter	RMS Jitter	
Photoinjector		
Initial bunch charge*	3.4%	
Laser spot size	5%	
Laser misalignment	100 µm	
Laser pulse duration	5%	
Laser timing jitter	200 fs	
RF Stations	**Voltage**	**Phase**
Gun*	0.035%	0.037°
Linac 1*	0.027%	0.057°
Linacs 2 – 4	0.05%	0.1°
X-band cavity	0.05%	0.3°

However, the accelerator layout has evolved significantly since then, with the relocation of the VBC relative to the RF accelerating structures, and the addition of the FEBE arc.

BASELINE SIMULATION

Figure 1 shows a schematic view of CLARA. The accelerator is comprised of a high repetition rate S-band RF photoinjector (PI) gun [8], followed by four S-band RF accelerating structures. A chicane-type variable bunch compressor (VBC) is located between the third and fourth accelerating structures, along with an X-band (4th harmonic) lineariser [9] for longitudinal phase space correction.

Start-to-end simulations of CLARA were carried out using several particle tracing codes, accessed through a python-based framework (*SimFrame*) developed at Daresbury Laboratory [10]. We primarily used ASTRA [11] to simulate low-energy sections of the machine (below 35 MeV) where space charge effects are significant. GPT [12] was used to validate these simulations, but was not used for start-to-end modelling in this particular study. At higher energies, ELEGANT [13] was employed for its computational speed and its inclusion of coherent synchrotron radiation (CSR) effects, which are important in both the VBC and FEBE arc.

CLARA was designed to maximise its flexibility for user experiments, and is therefore configurable to deliver a wide range of beam parameters. To inform modelling of the beam dynamics, several representative operating modes were defined based on the anticipated user requirements. Here, we describe simulations of a mode that delivers a peak current of 3.7 kA to the FEBE interaction point (IP) from an initial bunch charge of 250 pC, within a bunch length of 30.4 fs.

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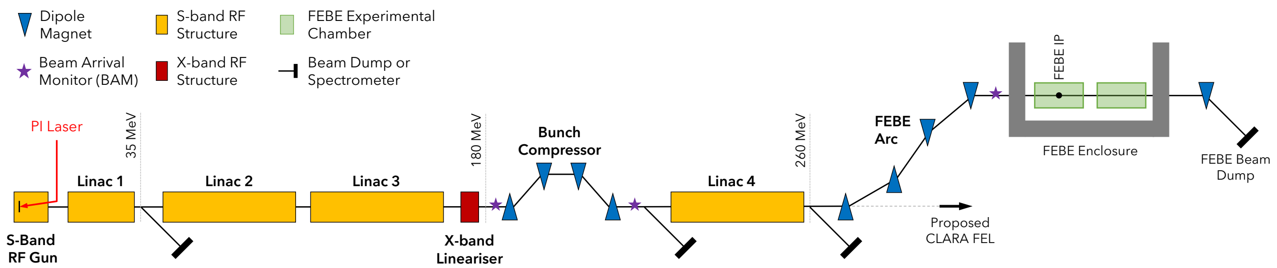

Figure 1: Schematic layout of the CLARA accelerator and FEBE beamline (not to scale). Accelerator components that are not directly relevant to this study are not shown.

JITTER SIMULATIONS

In line with the previous CLARA jitter study [7], tolerances for CLARA FEBE were estimated using a combination of parameters scans and simulations with randomly-generated jitter. In both cases, we assess the jitter on four key beam parameters along the accelerator: the beam momentum (p_z), fractional RMS momentum spread (σ_p/p_z), bunch time of arrival (t_{arr}), and RMS bunch length (σ_t).

Table 2: Mean and standard deviation of the beam parameters for 100 simulations with randomly generated jitter (Fig. 2). The time of arrival is stated as an absolute jitter.

Parameter	Mean	RMS Jitter
Beam momentum [MeV/c]	258	0.21%
Momentum spread [10^{-2}]	1.34	5.10%
Time of arrival [fs]	-	63.6
Bunch length [fs]	30.4	21.3%

Implementation

We broadly adopt the simulation methods used for the previous CLARA jitter analysis [7]. A brief summary is given here for completeness.

In this study, every simulation is referenced to a *fiducial* simulation, representing an ideal accelerator with no jitter. By default, ASTRA and ELEGANT will recalculate the on-crest phases of the RF structures at the start of each run. To model the effects of jitter, rather than deliberate changes in machine configuration, we retain the crests from the fiducial run for all other simulations. Varying the beam arrival time at a given cavity will therefore induce an RF phase shift.

Jitter was added to simulations of the accelerator by varying the simulation parameter associated with each jitter source. To propagate injector jitter into the main lattice, we require a consistent interface from ASTRA to ELEGANT that retains relevant information such as the bunch arrival time. ASTRA particle distributions were converted to ELEGANT SDDS format using the program `astra2elegant`, and then combined into a single file using `sddscombine`. The output of the fiducial simulation is stored as the first page of the file, and used to initialise a fiducial run in ELEGANT. The remaining pages are loaded separately, and represent injector simulations with one or more jitter sources.

Randomly Generated Jitter

To estimate the overall jitter on the beam properties, we generated a series of *replica* simulations that include randomly generated jitter on all of the machine parameters simultaneously. Each parameter was sampled from an uncorrelated normal distribution that reflects its expected stability during normal operation. At any point along the accelerator, we estimate the jitter on each beam parameter as its standard deviation across the set of replica simulations.

Table 1 lists the assumed tolerance for each machine parameter considered in this study. While several values in Table 1 are based on experimental data from the CLARA FE [3], most values are estimates based on the anticipated performance of various machine subsystems. We emphasize that many of these tolerances are conservative and likely to improve significantly during the first years of operation with CLARA.

Figure 2 shows the beam momentum and bunch arrival time at the FEBE IP for 100 simulations with randomly generated jitter. The mean and standard deviation of the beam parameters are listed in Table 2.

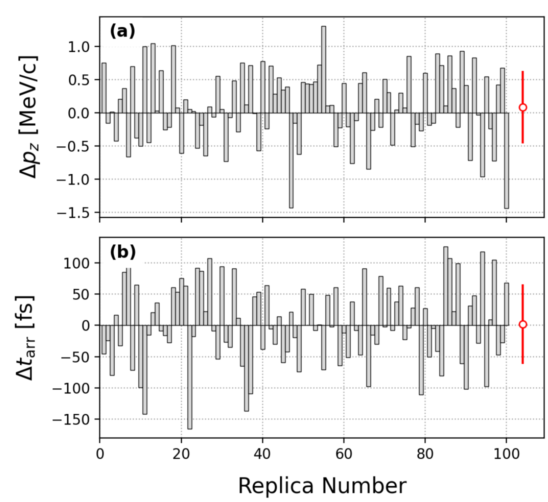

Figure 2: Change in the (a) beam momentum and (b) bunch arrival time at the FEBE IP, for 100 simulations with randomly-generated jitter. Values are plotted relative to a fiducial simulation with no jitter. The red markers (error bars) indicate the mean (RMS) of each parameter.

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Table 3: Effect of various jitter sources on the beam parameters at the FEBE IP. The values give the maximum change in the beam properties when each parameter is varied across its RMS tolerance (the full width of the shaded bands in Fig. 4).

Scanned Parameter	Δp_z [%]	$\Delta\left(\sigma_p/p\right)$ [%]	Δt_{arr} [fs]	$\Delta\sigma_t$ [%]
Photoinjector				
Initial Bunch Charge	0.12	3.02	2.53	7.96
Laser spot size	0.21	7.70	8.35	12.04
Laser misalignment	0.03	1.89	0.56	5.20
Laser pulse duration	0.05	5.78	1.89	10.75
Laser timing jitter	0.20	1.05	29.3	6.68
RF Stations				
Gun Voltage	<0.01	0.72	1.73	2.73
Gun Phase	0.02	1.01	1.13	3.39
Linac 1 Voltage	0.01	0.44	9.17	0.13
Linac 1 Phase	0.02	0.24	9.17	3.35
Linac 2 Voltage	0.02	1.03	46.7	2.47
Linac 2 Phase	0.02	3.17	31.5	5.03
Linac 3 Voltage	0.02	1.07	47.9	2.47
Linac 3 Phase	0.02	3.27	29.8	4.90
X-band Cavity Voltage	<0.01	0.79	9.96	0.95
X-band Cavity Phase	0.15	4.69	88.2	7.66
Linac 4 Voltage	0.03	0.93	13.9	0.46
Linac 4 Phase	0.02	1.10	7.04	0.16

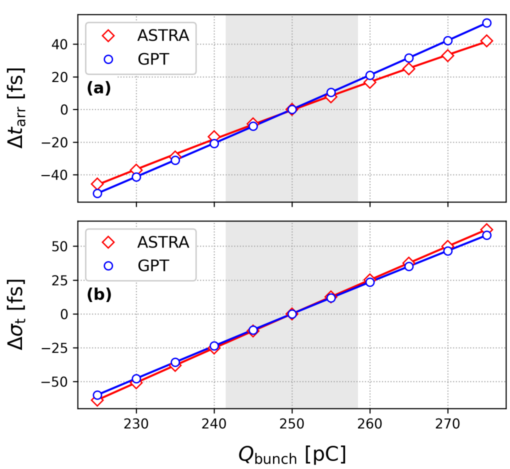

Figure 3: Change in (a) the bunch time of arrival and (b) the bunch length at the exit of linac 1, as a function of bunch charge jitter. The shaded regions indicate the expected RMS bunch charge jitter (see Table 1).

Parameter Scans

Simulated parameter scans were used to evaluate the effect of each jitter source in isolation from the other machine parameters. In each case, a single parameter was varied across a range two to three times larger its expected RMS jitter, while all other simulation parameters were held constant.

Figure 3 shows the effect of varying bunch charge jitter on the beam characteristics at the exit of linac 1 (see Fig. 1). The effects of each jitter source can be plotted at arbitrary points along the accelerator, as shown in Fig. 4. Table 3 summarises the effect of each parameter on the beam properties at the FEBE IP. As expected [14], the dominant sources of arrival time jitter are the RF stations before the VBC. Timing jitter arising from the injector (for example, from the PI laser timing jitter) is suppressed by the subsequent bunch compression stages.

CONCLUSIONS

Jitter estimates for the CLARA FEBE beamline have been calculated using start-to-end simulations of the accelerator. Our results indicate the initial performance of the machine, and will guide the development of feedback systems to mitigate the main sources of jitter. While the expected bunch arrival time jitter (~64 fs) will be acceptable for many experiments, our ultimate goal is to achieve state-of-the-art synchronization [15] to within 10 fs. Future work will include jitter calculations for other operating modes, and experimental validation on CLARA when beam is available in 2024.

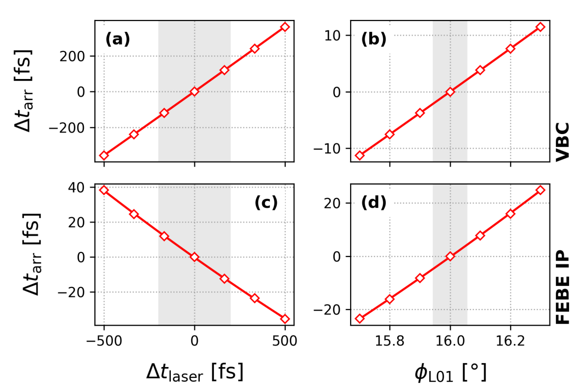

Figure 4: Change in the bunch arrival time at the VBC (top) and FEBE IP (bottom), plotted as functions of the PI laser timing jitter (left) and linac 1 phase jitter (right).

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