BEAM BASED ALIGNMENT STUDIES FOR THE CLARA FEL TEST FACILITY

J. K. Jones*, N. R. Thompson
ASTeC, STFC Daresbury Laboratory, Warrington, Cheshire WA4 4AD, UK

Abstract

The CLARA (Compact Linear Accelerator for Research and Applications) test facility is designed to experimentally demonstrate innovative FEL schemes for future light source applications. Such schemes can place strict requirements on the accelerator beam properties as well as the relative alignment of the beam in the FEL radiators and modulators. Beam-based alignment (BBA) of the FEL section is therefore an operational requirement for all advanced FEL facilities. In this paper we demonstrate results of CLARA BBA simulations, and also report initial simulation results from the use of non-linear algorithms to optimise the FEL performance directly.

INTRODUCTION

The CLARA test facility is a low energy linac-based FEL light source for the development of advanced FEL techniques and accelerator technology, under construction at Daresbury Laboratory in the UK. The facility is based on a 100 Hz, 5 MeV, RF photo-injector with three normal-conducting linac sections producing a final energy of up to 250 MeV. The FEL consists of 17 radiator sections, each of 0.66 m active length, with 2 seeding modulators preceding, and a possible FEL afterburner section post-radiatiors. The FEL is designed to emit at the shortest wavelength of 100 nm. More information on the proposed FEL-schemes to be investigated is given in [1] [2]. Each radiator section consists of both the undulator module (0.66 m) and an inter-undulator section containing a short delay chicane, corrector magnet, quadrupole and cavity BPM with a total length of 0.575 m. The final engineering layout of the inter-undulator section is still being determined, though to save space the dipole corrector is now combined with the quadrupole magnet. The quadrupole and cavity BPMs are both assumed to be on accurate mover assemblies. The radiator section has a constant internal diameter of 6 mm throughout. To restrict the FEL power reduction due to misalignments and subsequent orbit deviations to less than 2 %, a tolerance of less than 20 μm on the trajectory straightness has been determined for the radiator section of the lattice. This is significantly less than the expected mechanical alignment of 100 μm rms. Due to the relatively low energy of the CLARA facility, and the subsequently longer wavelength of emission, there is little to no spontaneous undulator radiation, and a very large divergence of the FEL light. This limits the photon diagnostics that can be performed, especially from the upstream end of the FEL. For this reason the use of beam-based alignment techniques is essential in the FEL section of the machine. In this paper we will demonstrate the results of a simulated correction algorithm to align the FEL radiator section to obtain the required 20 μm trajectory straightness. We also discuss the use of non-linear optimisation algorithms to achieve and maintain a trajectory that meets the FEL demands under the assumption that lasing has already been achieved.

* james.jones@stfc.ac.uk

ALIGNMENT TOLERANCES

The performance of the FEL has been studied with respect to errors in the trajectory straightness. The shortest operating wavelength of 100 nm is used as the FEL is most sensitive to errors at this tuning. The study was performed using Genesis 1.3 in steady state mode. The trajectory errors were introduced in two different ways:

- By adding an error Δx to the input position x_0. In this case the gaps between undulator modules were reduced to zero to give a smoother dependency of the output power on the error.
- By adding random quad position errors using the standard lattice.

The results were analysed in terms of normalised power (i.e. with respect to that with no errors) at saturation relative to the standard deviation of the trajectory offset from the axis, and are shown in Fig. 1. To satisfy the overall error budget the reduction in FEL power due to trajectory errors should be less than 2 %. From Fig. 1 it is seen that the rms trajectory error should therefore be less than 20 μm.

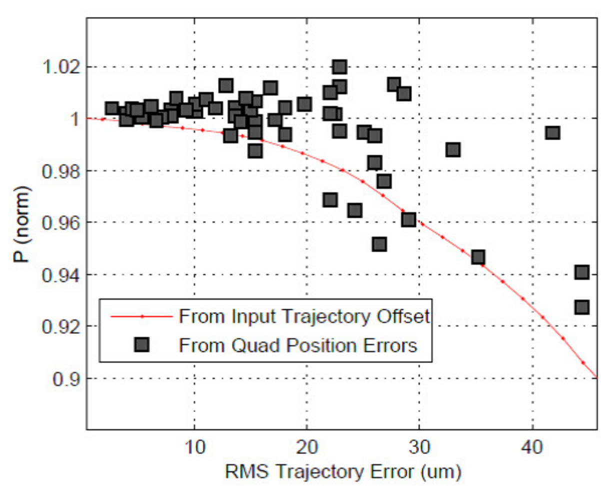

Figure 1: Normalised 100 nm FEL power with respect to rms trajectory error.

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ALIGNMENT STRATEGY

FEL alignment strategies have been studied extensively at other FEL facilities [3] [4] [5], primarily in the high energy regime. The low energy of the CLARA facility necessitates some modifications to the basic principles outlined at those other facilities. The principle relies on differentiating the beam trajectory errors, assuming that the undulator magnets are fully open, arising from quadrupole misalignments and BPM offsets, both of which have similar diagnostic fingerprints. In high energy machines this differentiation is done by changing the beam energy such that the lattice optics are modified from the nominal case, leading to a change in the measured beam position due to a quadrupole offset, but an invariance in the trajectory due to a BPM offset. The measured beam trajectory at 2 or more energies can then be decomposed, using Singular Value Decomposition [6]. The efficacy of this algorithm is dependent on the magnitude of the energy change, since we are interested in the magnitude of the trajectory change with energy. Small energy changes produce orbit differentials within the resolution of the BPMs or the noise envelope of the incoming beam jitter. At the maximum CLARA energy of 250 MeV, this procedure would be limited to a maximum energy change between 100 MeV and 250 MeV due to the FEL lattice optics. We therefore modify the procedure by varying, instead of the beam energy, the quadrupole focusing of the modulator section. This provides us with the required lattice optics change, but also allows us to effectively increase the beam energy to an equivalent of up to 400 MeV, significantly increasing the range of beam (equivalent) energies used in the algorithm. The algorithm itself comprises several response matrices: quadrupole offset vs. trajectory; BPM offset vs. trajectory; incoming beam jitter in position and angle vs. trajectory. Each matrix is taken at 3 equivalent energies and combined. The three combined response matrices are further combined into two global response matrices: the first (BBA) containing all three matrices, correcting quadrupole offsets, BPM offsets and initial beam offsets; the second (QC) for correction of only quadrupole offsets and initial beam offsets. The primary response matrix acts as a traditional BBA algorithm, whilst the second is used for trajectory correction using the quadrupole magnets as actuators. In both global response matrices the individual response matrices are normalised according to the standard deviation of the elements of each matrix before being inverted via SVD. We also use Tikhonov Regularization [7] to improve the conditioning of the final correction.

The methodology for correction is thus: measure and correct the trajectory using the QC inverted response matrix; measure and correct the quadrupole and BPM offsets using the BBA response matrix; perform a second QC-based correction of the orbit. Whilst this method produces consistent and well-corrected solutions it also has limitations in the final straightness of the solution. We therefore modify the BBA correction such that it is performed along a fitted straight line through the intermediate solution. An example correction is shown in Fig. 2, with the linear trend removed for clarity.

Table 1: List of Simulation Errors

Error	Magnitude
rms BPM misalignment	300 μm
rms quadrupole misalignment	300 μm
rms systematic initial Position / Angle error of incoming beam	100 μm / 100 μrad
rms random initial Position / Angle error of incoming beam	1 μm / 1 μrad
rms equivalent energy change jitter	3%
rms mover systematic / random error	0.1 % / 0.01 %
rms BPM rotation error	10 mrad

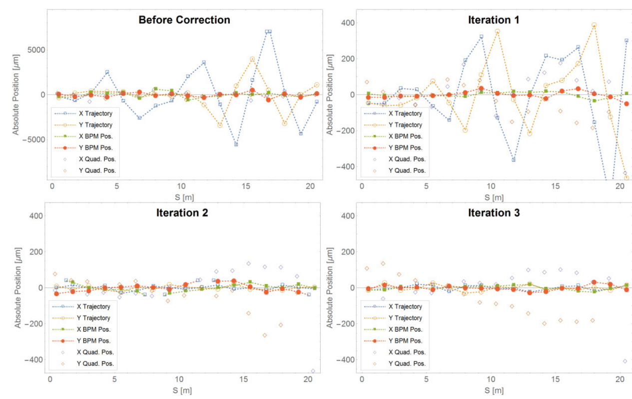

Figure 2: Example BBA correction showing before correction and after 3 subsequent iterations of correction with the linear trend removed.

RESULTS

Results are presented for four iterations of the complete BBA algorithm with the errors listed in Table 1.

Correction Iterations

The global response matrix is ill-conditioned leading to large offsets in the final solution. To combat this we use Tikhonov Regularization combined with an iterative correction procedure. The rms. position of the beam trajectory along with quadrupole magnets and BPMs (with the linear trend removed) are shown in Fig. 3 for standard errors and a BPM resolution of 2.5 μm. We see a clear convergence between three and four iterations of correction. The slow convergence rate is driven by both the BPM resolution and the launch position / angle errors.

BPM Resolution Requirement

One of the primary requirements for the simulation of the BBA algorithm is an accurate determination of the required cavity BPM resolution. The FEL section utilises 17 cavity BPMs with an internal diameter of 6 mm. The current design is based on an S-band cavity structure with an expected resolution of 1 μm at the CLARA maximum charge of 250 pC, but lower resolution at reduced charges. In Fig. 4

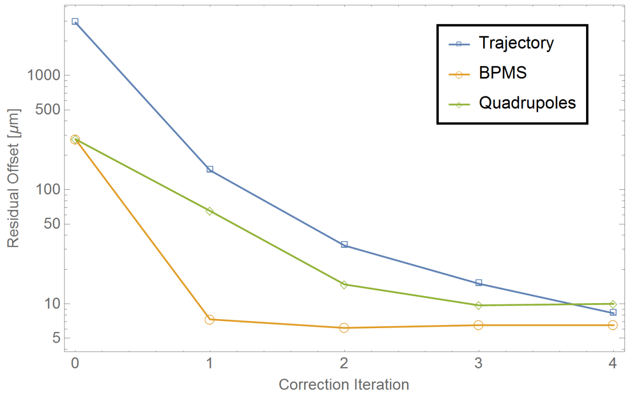

Figure 3: RMS residual positions of BPMs, quadrupoles and residual trajectories versus iteration number with the trend removed.

we show the rms residual trajectory after 4 iterations of the full BBA algorithm and with the linear trend removed. In general this trend is less than 10 μm / m, which is well within the acceptance of the FEL. The results show that we require a BPM resolution of around 2-3 μm to achieve the required trajectory straightness throughout the radiator section. We also note that the effects of reducing the BPM resolution below 1 μm are limited. This is driven by the random launch position and angle errors, which effectively limits the BPM resolution.

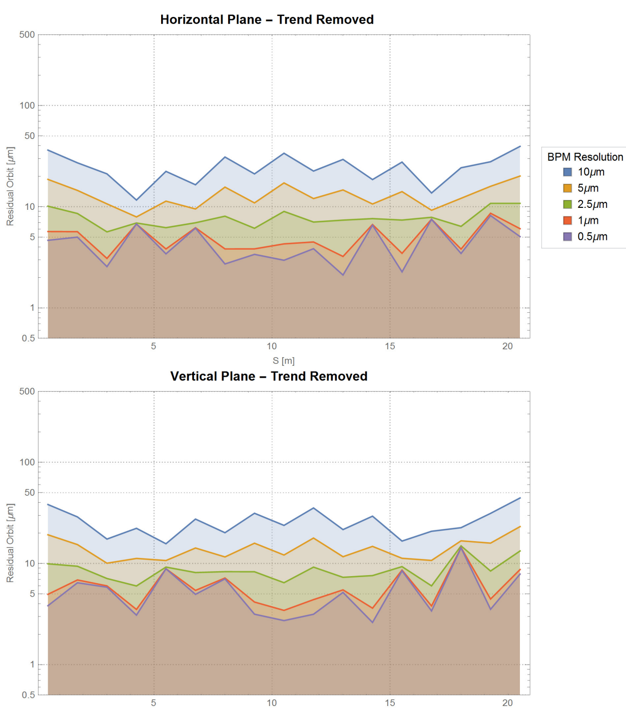

Figure 4: RMS residual trajectories after 4 iterations of BBA correction for various BPM resolutions.

NON-LINEAR OPTIMISATION ALGORITHMS

An alternative method of correcting for misalignments in the FEL is to directly optimise the measured FEL properties, using the quadrupole positions as actuators. We utilise a Nelder-Mead simplex algorithm [8] which as a heuristic algorithm can be trapped in local minima. To overcome noise issues we use a modified algorithm which includes a bracketed search function, whilst still using the standard (n-1)-vertex polytope search mechanism, including reflection, compression and expansion. The algorithm is used to minimise a simplified fitness function consisting of the FEL output power and band-width, which we assume are measurable averaged over many shots. The fitness function is given as:

$$f(E, BW) = -\sqrt{\frac{E+E_0}{E_0} + \sqrt{\frac{BW_0}{BW}}} \qquad (1)$$

Due to the requirements on being able to measure the FEL output, this methodology is only suitable for relatively small trajectory errors, characterised by the rms. quadrupole offset and shown in Fig. 1. In Fig. 5 we show the results for the bandwidth and power of the FEL with an initial random set of 100 μm rms. quadrupole offsets. This system clearly recovers the nominal power and bandwidth over several hundred iterations of the correction algorithm. A distinct advantage of these types of algorithms is that they are, to some extent, non-invasive to the beam and can be run during normal operation. There is an additional noise component added to the FEL output as the system drives towards the optima, but this may be acceptable in many scenarios to maintain a high average power.

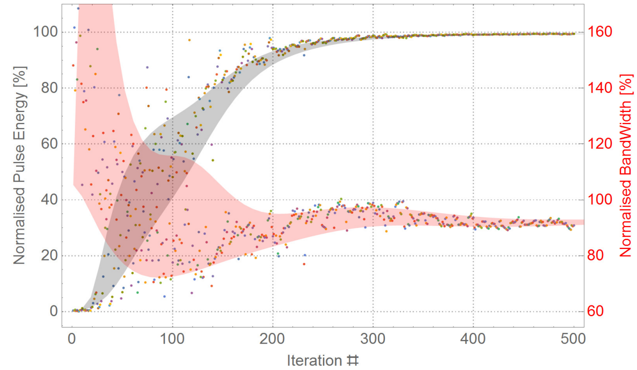

Figure 5: Example optimisation of the FEL power and bandwidth with 100 μm initial quadrupole errors.

SUMMARY

In this paper we have demonstrated the application of a beam-based alignment algorithm for the CLARA FEL radiator section. Modification of the nominal algorithm to use variation of the quadrupole current instead of the beam energy has been shown to produce adequate results. As part of the analysis we have shown that CLARA will require a cavity BPM resolution of 2-3 μm, which allows for alignment at potentially lower bunch charges. Finally we have demonstrated the use of optimisation algorithms to optimise the FEL peak power and bandwidth in a minimally invasive manner.

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