A COMPACT, MODULAR ELECTRON BEAM DELAY LINE FOR USE IN NOVEL FREE-ELECTRON LASER SCHEMES

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Abstract

Two Free-Electron Laser (FEL) schemes have been proposed, for the generation of atto-second pulse trains [1] and for the improvement of the longitudinal coherence of SASE FELs [2], in which repeated electron delays are implemented within the undulator lattice. To obtain the maximum performance and flexibility from these schemes it is advantageous to use an electron delay line that satisfies the isochronicity conditions, as well as being compact, modular and variable. In this paper we present initial designs for such a system, along with simulations of its performance. We investigate both in-undulator and out-of-undulator designs, and compare the applicability of each for various aspects of the FEL design, as well as commenting on the mechanical and magnetic implications of the schemes.

INTRODUCTION

In this paper we present the design of a variable electron delay-line for possible use in two related novel FEL schemes. The first scheme is the Mode-Locked Amplifier FEL [1] in which equal delays are used between undulator modules to repeatedly delay the electron bunch with respect to the co-propagating FEL radiation. For chicane delay δ and natural slippage in the undulator l then a set of $N = 2(l + \delta)/l - 1$ axial modes are generated in the radiation spectrum which can then be phase-locked via the introduction of a modulation with frequency matched to the mode spacing. In the temporal domain this is equivalent to a modulation with period $s = l + \delta$. This modulation can be in the electron bunch energy [1] or current profile [3]. The phase locked axial modes synthesise a train of separated radiation spikes of spacing s and duration $\Delta t \approx (l + \delta)/(2c\sqrt{N})$). Thus, by varying the delay δ, the spacing and duration of the pulses in the train can be controlled. The second scheme is a method of improving the longitudinal coherence in SASE FELs [2]. Here delays are used as a method of artificially increasing the total slippage during the FEL interaction with the result that the coherence length of the FEL output pulse is greatly increased and the spectral bandwidth greatly reduced. In this scheme it is advantageous to vary the individual delays in a pseudo-random manner. This prohibits the growth of the axial mode structure which would otherwise generate pulse-train structure in the output pulse: in effect the mode spacing varies as the FEL pulse develops, so that the off-resonance modes do not survive amplification whereas the resonant mode continues to narrow.

For the most flexible application in these schemes the electron delay line should therefore have certain features. It should be isochronous, to preserve the FEL-induced micro-bunching in the electron bunch for repeated large delays. It should be modular, such that many delay-lines can be implemented with minimal disruption to the undulator lattice. It should be compact, such that the inter-undulator spacing is not significantly increased. Finally it should be variable - this will allow macroscopic control of the temporal profile of the FEL pulse train structure in the Mode-Locked FEL and allow the pseudo-randomisation of the delays in the scheme to improve the coherence of SASE FELs.

The required parameters used in the work in this paper are derived from a feasibility study to demonstrate both of these FEL schemes on a low energy test accelerator such as the 250 MeV CLARA proposed at Daresbury Laboratory [4]. Here it is assumed that for the easy availability of single shot photon pulse diagnostics the output wavelength may be as long as 400~nm. Each undulator in the standard lattice has approximately 100 periods so the slippage in each undulator is 40μm. From simulation studies the number of modes required for synthesis of a train of clearly separated pulses is $N \geq 9$ thus from the expressions above the delay should satisfy $\delta \geq 4l$. Thus a realistic assessment of the maximum delay required in each delay line is 160μm.

To reduce the *minimum* pulse durations from the mode-locked FEL scheme the slippage in each undulator l should be reduced as much as possible by reducing the number of undulator periods. Such a push towards short undulators is incompatible with standard FEL lattices where typically each undulator module is designed to be longer than a power gain length. A possibility to overcome this problem is to introduce delay sections within the undulator itself, in effect splitting one undulator into smaller undulator sections separated by delays. Previous work on electron delay lines has studied magnetic phase shifters in undulators which provide a few wavelengths of delay in a compact space, but with the drawback of limited flexibility. This paper will therefore also investigate new designs for much stronger in-undulator delays, comparing their performance and flexibility to the out-of-undulator designs. Assessment will be made of the tolerances of the proposed solutions.

OUT-OF-UNDULATOR DELAY-LINE

The proposed variable delay-line is composed of up to 16 large-aperture quadrupole magnets arranged in a standard chicane structure, along with 6 additional quadrupoles for optics matching. The 16 main quadrupoles are offset from the main axis of the beamline to provide a bending force. Additionally, all 16 quadrupoles are mounted on precision movers to allow for variations in the quadrupole positions. A schematic of

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the layout is shown in Fig. 1. The design is a minimised in longitudinal space, and as such represents an extreme of the possible solutions. Increasing the available space for the delay-line relaxes somewhat all of the parameters presented here.

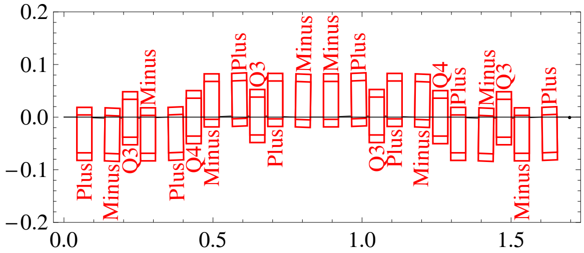

Figure 1: Layout of a double-chicane delay-line.

An example optics design for such a delay-line is shown in Fig. 2.

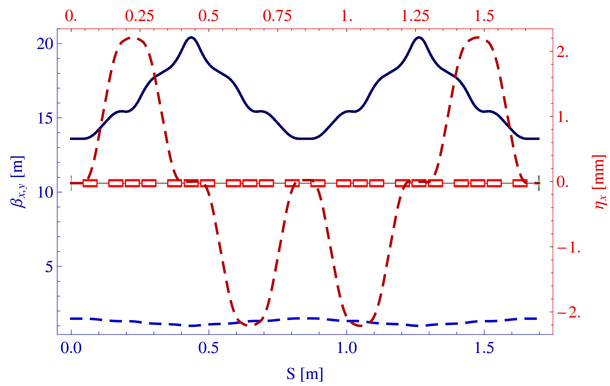

Figure 2: Optics layout for the delay-line showing the β-functions (x-long dash, y-short dash) and the dispersion.

The trajectory and angle for a 250 MeV electron beam is shown in Fig. 3.

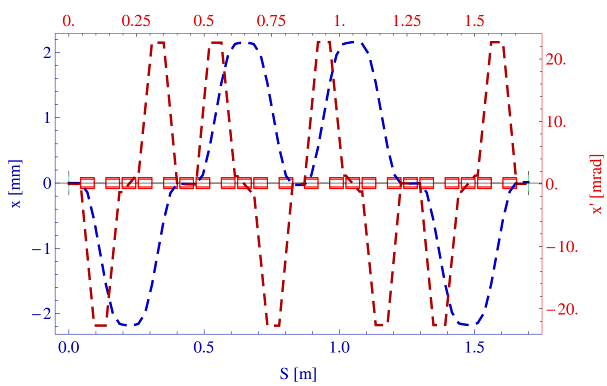

Figure 3: Beam position and angle through the delay-line.

Table 1 gives example offset and quadrupole strengths for a 250 MeV electron delay-line of 160 µm (400 wavelengths at 400 nm), and with the Twiss parameters shown in Fig. 2.

The delay-line time delay can be varied by changing the amplitude of the quadrupole offset, and the change in delay time is quadratic in offset amplitude.

Table 1: Example Quadrupole Parameters

Type	**K1 (m^{-2})**	**Offset (mm)**
Minus	14.4	-31.8
Plus	-14.9	30.6
Quad-3	23.6	0
Quad-4	-39.3	0

The system is designed to be linearly isochronous and, as such, the three dominating linear terms are small or approximately zero at the end of the system, as shown in Fig. 4.

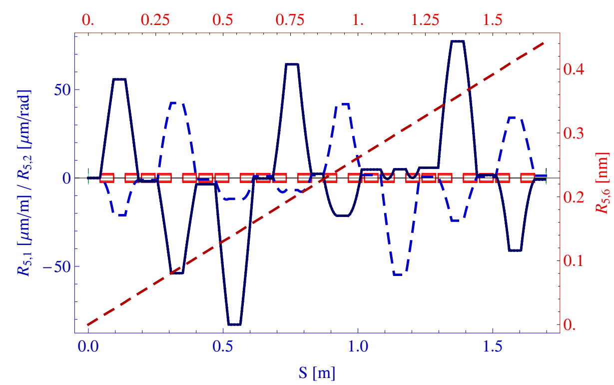

Figure 4: Cumulative time-dependant terms for a 160 µm delay-line.

IN-UNDULATOR DELAY-LINE

A permanent magnet based delay can be made with high-field magnet blocks for a much reduced longitudinal footprint. By orientating the delay-line perpendicular to the undulator it can be placed anywhere along the undulator length. The mechanical design, however, must still fit inside the undulator jaws. The required delay can be varied by changing the magnetic gap subject to mechanical limitations. Assuming a 250 MeV electron beam, the maximum delay for a B_r = 1.3 T device, at 6mm gap, is ~15µm, or 40 wavelengths at 400nm. Fig. 5 shows the field profile for a single delay-line module. The associated beam trajectory and divergence (for a 250 MeV electron beam at minimum gap) are illustrated in Fig. 6. The electron delay can be varied by increasing the magnetic gap of the phase-shifter, which is, again, quadratic in gap.

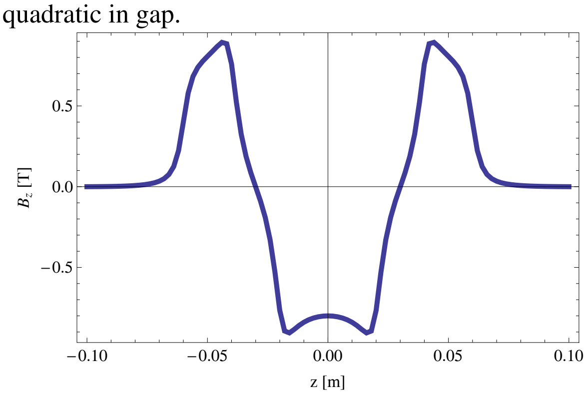

Figure 5: Field profile for a 15µm delay-line.

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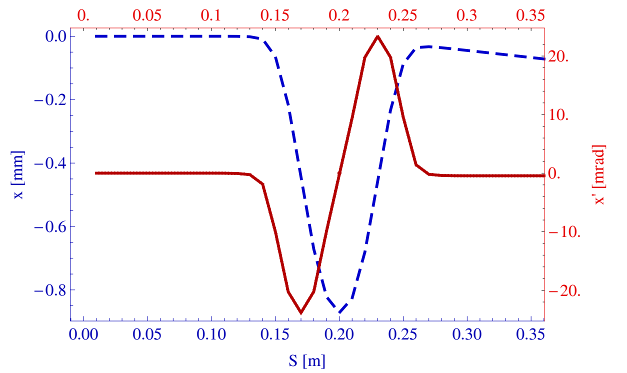

Figure 6: Beam trajectory and divergence for a 15µm delay-line at 250MeV.

TOLERANCES

Analysis of the variation in delay due to incoming beam errors is analysed for both in- and out-of-undulator designs. In Fig. 7 we compare the change in delay at a given point, expressed in units of 400nm wavelength, for 2 different types of error. We compare the relative errors for the 15µm in-undulator delay-line to the 160µm out-of-undulator delay-line. We make no allowances for the difference in longitudinal length of each system.

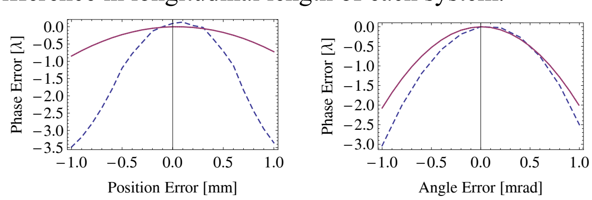

Figure 7: Tolerances for a 15µm in-undulator delay (blue) and a 160µm out-of-undulator delay-line (red).

Analysis of the robustness of the design to quadrupole errors has also been analysed. Figure 8 parameterises the change in time delay for a change in the quadrupole field of each of the 16 offset quadrupoles – the quadrupoles in order are 2x(Red, Green, Blue, Brown, Black, Dark Yellow, Orange, Purple) as well as a change in quadrupole position. Figure 9 shows the change in Twiss parameters at the exit of the delay-line parameterised through the B_{mag} parameter:

$$B_{mag} = \frac{1}{2}(\beta\gamma_0 - 2\alpha\alpha_0 + \gamma\beta_0) \qquad (1)$$

Comparison of the two plots in Fig. 8 show a similar dependence of the delay on the quadrupole position and gradient. It is thus possible to compensate an error in gradient, with a change in the quadrupole positions, and vice-versa. As an example of this, Fig. 10 shows the tolerance to quadrupole gradients where the quadrupole is moved by the opposite magnitude to the gradient error. Even in this simple case, the magnitude of the delay-error is reduced significantly in most cases.

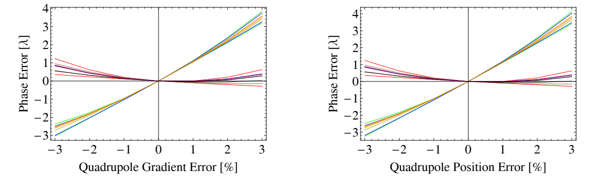

Figure 8: Relative change in delay-time vs. quadrupole gradient and position.

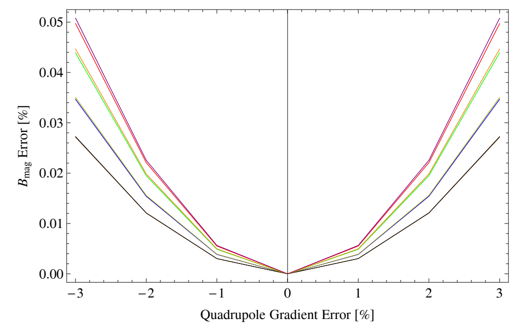

Figure 9: B_{mag} parameterisation of the change in final twiss parameters vs quadrupole gradient.

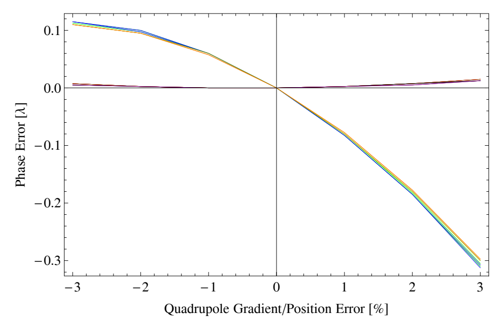

Figure 10: Phase error with compensated gradient errors.

CONCLUSION

In this paper we have presented a possible design for 2 electron delay-lines for use in FEL light sources. Both delay lines satisfy the criteria of being ~isochronous, flexible and relatively compact. One design is based on movable quadrupoles and compares favourably to the second design of in-undulator phase-shifter designs based on strong permanent-magnet dipoles. Both designs are robust to possible errors. The mechanical layout of the quadrupole design does not seem to be un-realistic, but an engineering assessment of the system will need to be finalised. In any case, extension of the longitudinal space should reduce difficulties with the current design.

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