DESIGN AND OPTIMISATION OF THE LATTICE FOR THE UK-XFEL SPREADER

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Abstract

The UK-XFEL spreader will distribute 1 MHz bunches between ten undulator beamlines. Each of the different paths through the spreader must transport an electron bunch to the undulator with minimal increase in the emittance and energy spread, whilst also conforming to various geometry constraints. To minimise the energy spread/emittance growth, the design was optimised to mitigate the effect of coherent synchrotron radiation (CSR). This was done by control of the phase advance between repeated sections, and by cancelling CSR kicks using a single kick CSR model. Due to the number of constraints that needed to be adhered to, an optimisation tool was developed to aid in the design of the optics. This paper will give an overview of the optimisation tool, show the design of different sections of the spreader, and then show the results of beam tracking.

UK-XFEL SPREADER LAYOUT

The UK-XFEL spreader will distribute electron bunches between 10 undulator lines [1–3]. FEL 2-6 can be seen in Fig. 1. Only half of design is seen in the figure, the design will be mirrored over x=0. The spacing between two adjacent lines is 8 m. The photon optics will distribute the FEL pulses from each undulator line to numerous end stations, therefore, it was decided that 8 m of space would be needed between the lines so that there would be enough space to fit the end stations.

The straight ahead line (FEL-1) is not included in the spreader design, but is reserved for matter under extreme conditions (MEC) experiments that require high charge bunches. It was decided to put the MEC line on the straight ahead line so that the high charge bunches would not pass through the arc sections where they would be affected by CSR.

FEL-2 is made up of two undulator lines (FEL-2 and FEL-2s) separated by 3 m. This is for two colour pump-probe operation with pulse widely separated in both energy and time. There is a variable path length adjuster (VPLA) chicane along FEL-2s, this allows control over the pump probe separation.

BEAM DYNAMICS AND CSR CANCELLATION

The design of the UK-XFEL spreader was separated into subsections. The separation of the lattice into subsections allowed for the beamline to be optimised in parts, which where then connected together to form a full line using the matching sections. Using subsections simplified the design due to the repeated patterns within the lattice. FEL's 3-6 all follow the same design, just with an additional straight subsection per line along the main diagonal. The subsections are all isochronous and the dispersion is cancelled. The maximum value of the beta function in each subsection was kept as low as possible without interfering with any other constraints. The lengths of the drift sections were set so that the spacing between adjacent lines was 8 m. The linear optics was also designed in way so that the effects of CSR were mitigated.

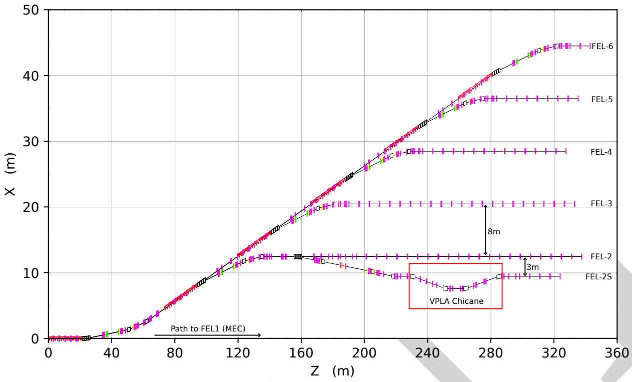

Figure 1: Layout of the beam spreader of the UK XFEL.

CSR Mitigation Within a Subsection

CSR occurs when the bunch is transported through a dipole magnet. The radiation emitted by the electrons at the back of the bunch interacts with the electrons at the front of the bunch. This causes energy loss, and as a result, the bunch is steered too much by the dipole. Therefore, the bunch exits the dipole with a kick in both x and p_x. Due to the horizontal offset when leaving the dipole, the bunch is kicked further by any subsequent quadrupoles it passes through. The kicks from all of the elements add up over the length of a subsection, causing the beam to become deformed and an increase in emittance.

To mitigate the kicks caused by CSR over the length of a subsection, the strengths of the quadrupoles were tuned so that the horizontal kick was cancelled at the exit of the last dipole within the subsection. This was done using a simplified model of the CSR, where the energy loss is applied to the bunch as a single kick at the center of the dipole. The resulting kick in x and p_x, through the second half of the dipole and any subsequent quadrupoles, was calculated using transport matrices.

The energy loss was initially estimated using analytical formula, which can be found in [4], but it was found that

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this did not accurately model the energy loss modelled in simulations. Simulations were run using BMAD [5]. The analytical formula was used as a first guess, and the required quadrupole strengths to cancel the kick were calculated. A simulation was run where a normally distributed bunch was tracked through the subsection, and the mean energy loss of the bunch in the dipoles was calculated. The quadrupole strengths were then re-calculated using the simulated values of energy loss in the dipoles. The process was repeated until there was a sufficient agreement between the model and the simulation results.

CSR Mitigation Along a Full FEL Line

This process was effective at mitigating the kicks caused by CSR over the length of a subsection, however, due to an imperfect model, further mitigation was required over the length of an entire line. This was done by controlling the phase advance between an arc subsection, and its reverse arc subsection. The phase advance of the matching sections was set to be $2\pi - \phi$, where ϕ was phase advance of the preceding subsection. This ensured that the phase advance between an arc subsection, and its reverse arc was always a multiple of 2π. Using this design, part of the bunch received a kick in the first arc subsection, then it received a second equal and opposite kick in the reverse arc [6].

Non-Linear Correction

After the linear optics were finalised, sextupoles were added to the lattice in locations with high dispersion and their strengths were set to cancel the T166, T266 and T566.

OPTIMISATION OF THE LATTICE

The subsections were designed using an optimisation script written in python. A set of optimisation goals were defined and split into two categories. The first category was a list of strong conditions that needed to be solved exactly. An example of a strong condition was that the dispersion and its gradient must be exactly zero at the end of the subsection. The second category was a list of weak conditions. A figure of merit function was defined for the weak conditions which returned a high value for bad solutions and a low value for good solutions. An example of a weak condition was to minimise the maximum value of beta function over the entire subsection.

For each of the strong conditions, a single optimisation parameter was picked to be associated with the solution. For example, the strength of a quadrupole could be picked to find a solution where the dispersion was zero at the end of the lattice. The optimisation parameters not used for satisfying strong conditions were the input to a minimisation routine. Therefore, there were two arrays of optimisation parameters. Array S used for satisfying the strong conditions, with the length of S being equal to the number of strong conditions. The remainder of the parameters made up array W, the weak optimisation parameters. A guess for the values of array W would be passed into a function which calculated the exact values for the parameters in the S array needed to satisfy the strong conditions for the given set of parameters in W. The figure of merit was then calculated. A minimiser (Nelder-Mead [7] or Powell [8]) was then used to find the values of W to minimise the figure of merit.

The use of two steps in the optimisation process ensured that the strong conditions were always satisfied by the solution and that there were no cases where the maximum value of the beta function was minimised at the expense of a non-zero dispersion at the end of the subsection.

TWO COLOUR OPERATION

One feature of the UK-XFEL design is two colour operation, with FEL pulses widely separated in both energy and time. This is achieved using two undulator lines and directing the photon beams to the same end station using the photon optics. The two lines must be placed close to each other (≈3 m apart).

Two separate electron bunches are injected into closely separated RF buckets in the LINAC (1.3 GHz) using two injectors. A transverse deflecting cavity (TDC) operating at a quarter of the frequency of the LINAC is used to separate the bunches. The leading bunch enters the TDC on crest and is deflected onto FEL-2s. The trailing bunch enters the cavity on the zero crossing and continues along FEL-2. The trailing bunch recieves a head-tail kick from the TDC due to entering on the zero crossing. This is corrected by a second TDC placed at a π phase advance downstream. The leading bunch travels through a dogleg with a higher path length than the straight ahead line. This partly reduces the temporal separation between the two bunches. The leading bunch then travels through a VPLA chicane, which delays the bunch further. When the VPLA is fully extended, it will delay the leading bunch enough so that the two bunches will leave the spreader simultaneously. The path length of the chicane can be adjusted to control the separation of the two pulses. This scheme is illustrated in Fig. 2.

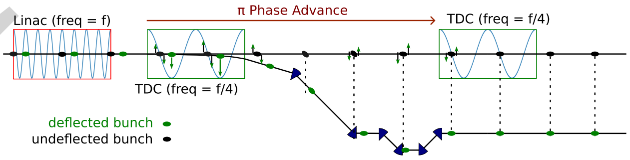

Figure 2: Bunches for two colour operation at various points during their passage through the spreader to FEL-2 and FEL-2S.

The trailing bunch has to be injected on the zero crossing of the TDC. This is achieved by injecting the second bunch an odd number of RF buckets after the first. To achieve the minimum separation, the two bunches have to be injected into adjacent RF buckets, however, much larger pulse separations can be achieved by injecting the trailing bunch into later (odd) RF buckets. The delay from the bucket selection and the delay from the VPLA can be combined to provide a range of possible delays. Ideally, the VPLA would be able to provide a delay over the range of 2 RF buckets, which would allow a full continuous range of delays to be achieved. Due to the spatial requirements and the effect on the beam transport, this was not practical. The maximum delay from the VPLA was made just large enough so that simultaneous pulses could be achieved. The result is a continuous band of possible pulse separations, as discrete intervals of 2 RF buckets. The possible separation between the pump and probe using this setup can be seen in figure 3.

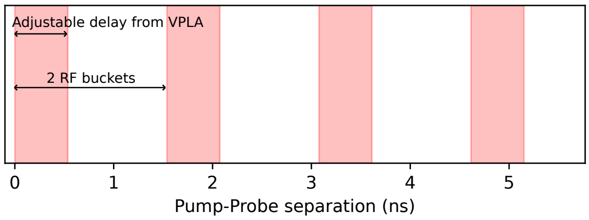

Figure 3: Time separation between pulses in the two colour operation mode, using a combination of changes of electron bunch separation in the linac and path length changes using an adjustable chicane.

TRACKING SIMULATIONS

Tracking simulations were set up to determine the effectiveness of the steps taken to reduce emittance growth. The results shown here are after tracking normally distributed bunch through FEL-6 (the longest line not associated with a special operation mode). The phase space of the beam before and after tracking can be seen in Fig. 4.

The bottom axes on figure show some deformation of the longitudinal phase space due to the energy loss caused by CSR. The top axes show that the horizontal phase space is still centered on zero after tracking, meaning that the kicks due to the CSR were successfully cancelled by the optics.

The slice properties of the bunch are an important factor in determining whether a bunch will lase or not. The horizontal slice emittance, the slice energy spread and the longitudinal current profile can be seen in Fig. 5.

Figure 5 shows that there is no noticeable increase in the energy spread and the current profile, however there was a 10 % growth in the emittance. Despite the growth in emittance, the slice properties are still within acceptable limits, and that transport of a bunch through FEL-6 would not degrade the bunch quality enough to prevent lasing.

FUTURE WORK

Further tracking studies will be done to assess the beam transport along the other FEL lines. Tracking studies will also be run using a bunch that has previously been tracked through the UK-XFEL bunch compressors; to assess the effect that a more realistic bunch distribution has on the tracking results.

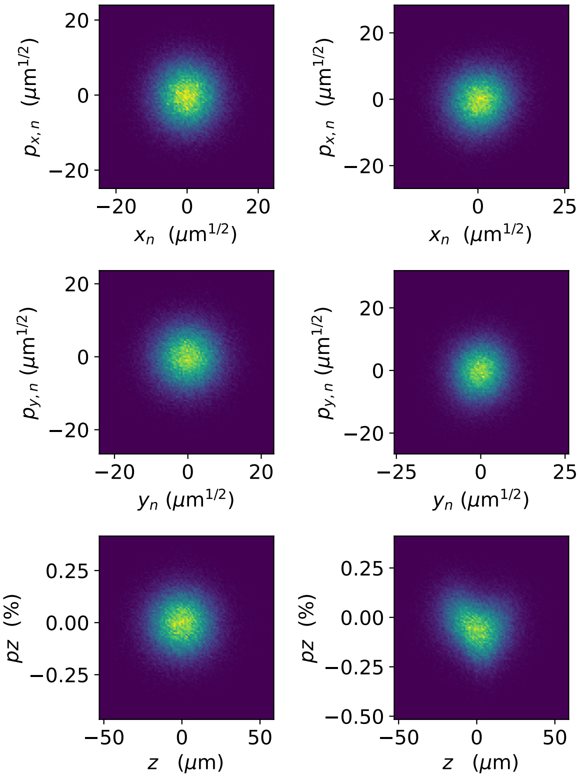

Figure 4: The normalised phase space plots of a gaussian bunch before tracking (left) and after tracking (right) through FEL-6 of the UK-XFEL spreader. Shown are the (top) horizontal, (middle) vertical and (bottom) longitudinal phase spaces.

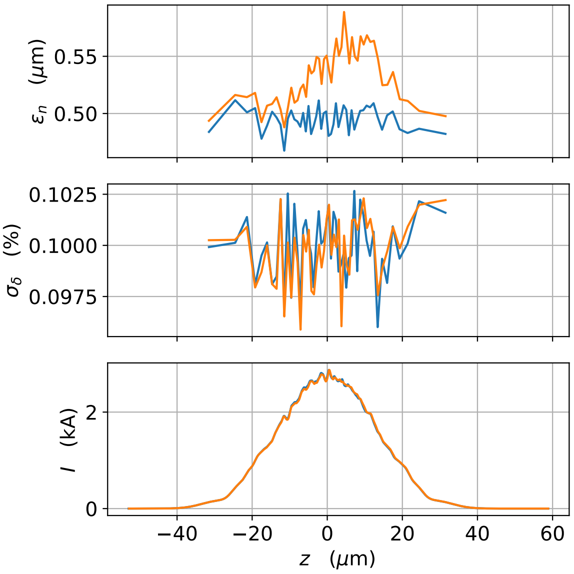

Figure 5: The slice properties of the gaussian bunch before (blue) and after (orange) tracking through FEL-6 of the UK-XFEL spreader. Shown are the (top) horizontal emittance, (middle) energy spread and (bottom) current profile of the bunch.

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