ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEPL073

THE MAX-IV LINAC WITH VARIABLE BUNCH COMPRESSORS

A. Dixon*[1], University of Liverpool, Liverpool, United Kingdom
P. H. Williams[1,2], ASTeC, Warrington, United Kingdom
S. Thorin, MAX IV Laboratory, Lund, Sweden
T. K. Charles[1], University of Liverpool, Liverpool, United Kingdom
[1] also at Cockcroft Institution, Warrington, United Kingdom
[2] also at STFC Daresbury Laboratory, Warrington, United Kingdom

Abstract

Recent studies have shown that accelerating +19° off-crest in all RF cavities in the MAX-IV linac reduces voltage-induced timing jitter from the klystrons. The current bunch compressors in the linac have fixed first-order longitudinal dispersion, and the RF phase is varied to control the amount of compression. Variable bunch compressor designs have been considered at MAX-IV in recent years, these would allow us to regain control over compression while the accelerating phase is fixed to reduce timing jitter. Particle tracking studies have been performed on the MAX-IV linac with the addition of arc-like variable bunch compressors.

INTRODUCTION

The Soft X-ray Laser (SXL) project is a proposed free-electron laser (FEL) upgrade to the MAX-IV facility [1, 2], which will use the existing 3 GeV linac to provide the electron bunches. The SXL will operate in three beam modes: (1A) 100 pC high compression and high charge, (1B) 10 pC high compression and low charge and (2) 100 pC low compression and de-chirped, the highly compressed modes (1A and 1B) are especially sensitive to timing jitter [1]. The layout of the MAX-IV linac is shown in Fig. 1, where SP03 is the beamline for the SXL.

The linac utilises a two-stage bunch compression scheme to achieve the required compression, the two bunch compressors (BC's) have fixed first-order longitudinal dispersion R_{56} (see Table 1) and the compression is controlled by varying the RF phase in the cavities before each bunch compressor. Studies on the MAX-IV linac indicate that there is a 'magic angle' where the voltage-induced timing jitter from the klystrons is minimised [1], this angle is +19° off-crest in all RF cavities. Choosing to minimise timing jitter by accelerating at a fixed RF phase would then fix the overall compression of the linac, as the R_{56} of each bunch compressors is fixed, so it would be of interest to regain control of the compression in the linac. This can be achieved with variable R_{56} bunch compressors which are been considered at MAX-IV as part of SXL upgrade. Ref. [3] outlines two designs that could be used to retrofit R_{56} variability into existing bunch compressors.

In this paper we will study the R_{56} required in the first and second bunch compressor to achieve the same peak current as in the existing linac, while accelerating +19° off-crest in all RF cavities, we will refer to this compression scheme as the 'variable bunch compressor' or 'VBC' scheme. ELEGANT [4] will be used to perform particle tracking simulations of each compression scheme, which will then be compared.

VARIABLE BUNCH COMPRESSOR

The first and second bunch compressor (BC1 and BC2) in the MAX-IV linac are both comprised of two multi-bend achromats, as such they have an arc-like R_{56} in which compression is achieved when the head of the bunch has greater energy than the tail of the bunch. Throughout this paper, we will use the same sign convention as ELEGANT, where arc-like R_{56} is positive, and chicane-like has a negative R_{56} [3, 4]. Reference [3] proposed two methods to retrofit R_{56} variability into the first bunch compressor, named the *additional dipole* and the *additional quadrupole* solutions. The additional magnets (either dipoles or quadrupoles) are placed within each double bend of the existing bunch compressors, where the bend angle or quadrupole strength can be varied to control the R_{56} of the bunch compressors. It was found that the strong focusing required in the *additional quadrupole* solution led to large emittance growth, $\Delta\varepsilon_{n,x} = 10^2$ mm mrad and $\Delta\varepsilon_{n,y} = 10^3$ mm mrad from an initial emittance of $\varepsilon_{n,x} = 10^{-1}$ mm mrad and $\varepsilon_{n,y} = 10^{-1}$ mm mrad, respectively. Where as $\varepsilon_{n,x}$ and $\varepsilon_{n,y}$ were preserved in the *additional dipole* case [3]. Due to this we have only considered the *additional dipole* solution in this paper. As the first and second bunch compressors have similar layouts, we are able to retrofit R_{56} variability to the second bunch compressor in the same way as the first bunch compressor. For more details on the variable bunch compressor design, refer to Ref. [3].

Table 1: The Longitudinal Dispersion Properties of the Existing BC1 and BC2, and Accelerating +24° and +21.5° Off-crest in Linac 1 and 2, Respectively

Location	R_{56} [cm]	T_{566} [cm]	U_{5666} [cm]
BC1	3.23	10.73	-29.11
BC2	2.60	-8.60	87.16

The off-crest accelerating phase and longitudinal dispersion of the existing accelerating structures and bunch compressors for the SXL are summarised in Table 1. Operated in the (1B) mode, the 10 pC electron bunch has a final rms bunch length of $\sigma_t = 4.24$ fs and a peak current of 3.5 kA.

* sgadixon@liverpool.ac.uk

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEPL073

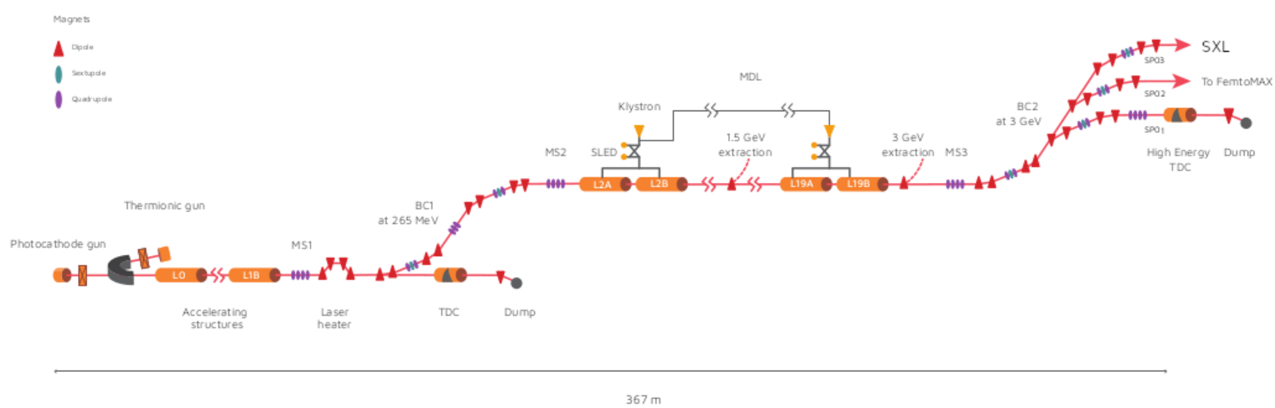

Figure 1: Layout of the MAX-IV linac, showing the beamlines to the short-pulse facility (SP02/FemtoMAX) and the soft X-ray laser (SP03) (modified from [1]).

In the VBC scheme, the off-crest accelerating phase is 19°, which is lower than the off-crest phase in the existing compression scheme (see Table 1). The R_{56} in the first and/or second bunch compressor needs to increase to compensate for smaller energy chirp. The *additional dipole* solution proposed in Ref. [3] does not allow for increased arc-like R_{56}, this can be seen in Fig. 2.

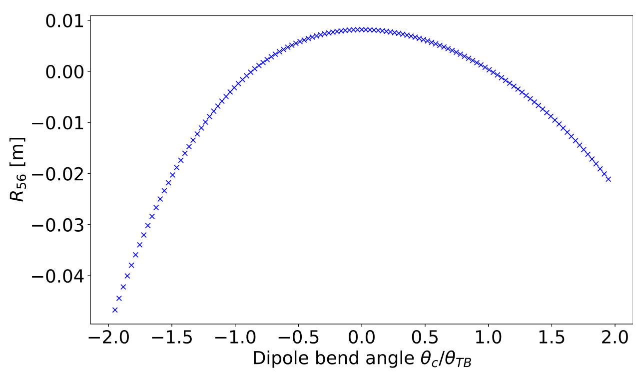

Figure 2: R_{56} of the triple bends in the first variable bunch compressors as a function of centre bend angle θ_c.

$\theta_{TB} = 0.154$ mrad is the net bend angle of each triple bend in the variable bunch compressor, and θ_c is bend angle of the additional dipole at the centre. The variable bunch compressors have four triple bends, with each contributing equally to the final R_{56}. For the triple bend, the maximum arc-like $R_{56,max} = 8$ mm at $\theta_c/\theta_{TB} = 0$, which is $\frac{1}{4}R_{56}$ of the existing bunch compressor configuration. Increased arc-like R_{56} can be achieved with the addition of combined function dipoles rather than flat dipoles. Using dipoles with a quadrupole component allows us to increase horizontal dispersion (R_{16}) in the following dipole, which generates more R_{56} [3, 5]. Unlike the *additional quadrupole* solution in Ref. [3], the additional focusing from the combined function dipole did not introduce any significant chromatic errors (which we will see in Fig. 5). We can achieve the same amount of compression by only increasing the R_{56} in the first bunch compressor. As such, we will only consider increased R_{56} a requirement for the first bunch compressor, and the second bunch compressor will use flat dipoles. The off-crest accelerating phases and longitudinal dispersion of the VBC scheme with variable bunch compressors are shown in Table 2.

Table 2: The Longitudinal Dispersion Properties of Variable BC1 and BC2, and Accelerating +19° Off-crest in All Linacs

Location	R_{56} [cm]	T_{566} [cm]	U_{5666} [cm]
BC1	4.01	15.01	-48.20
BC2	2.60	5.99	-24.14

PARTICLE TRACKING

Simulations of the two schemes are performed using `ELEGANT`, the first is the existing compression scheme and the second is with variable bunch compressors, both with a 10 pC electron bunch. The off-crest accelerating phases and longitudinal dispersion parameters are shown in Tables 1 and 2, respectively. The horizontal and vertical β-function for the two cases are shown in Fig.3.

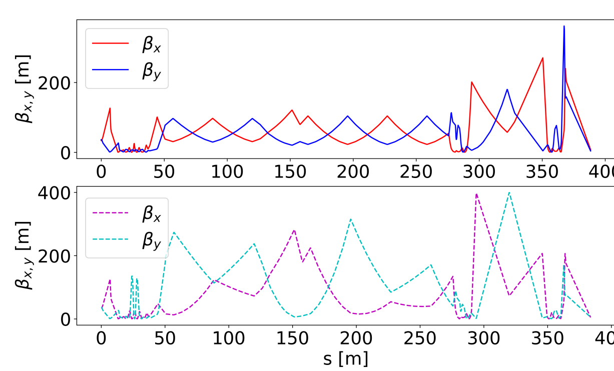

Figure 3: (Top) β_x (red solid line) and β_y (blue solid line) in the existing SXL linac, and (bottom) β_x (purple dashed line) and β_y (cyan dashed line) in the linac with variable bunch compressors.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEPL073

The final longitudinal phase space and current profile for the existing linac is shown at the top of Fig. 4. The final rms bunch length is $\sigma_t = 4.24$ fs, a peak current of 4 kA and final rms energy spread is $\sigma_\delta = 0.148$ %. The final longitudinal phase space and current profile for the variable bunch compressor scheme is shown at the bottom of Fig. 4. The final rms bunch length is $\sigma_t = 5.57$ fs, a peak current of 4 kA and final rms energy spread is $\sigma_\delta = 0.114$ %.

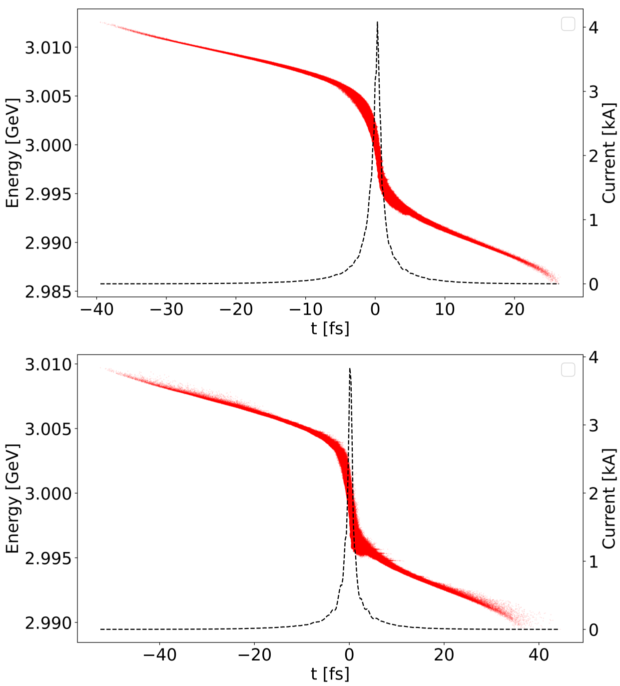

Figure 4: (Top) Longitudinal phase space (red dots) and current profile (black dashed line) at the end of the existing linac. (Bottom) Longitudinal phase space (red dots) and current profile (black dashed line) at the end of the linac with variable bunch compressors.

The same peak current was achieved for the two schemes, however the rms bunch length is 31.4 % larger when variable bunch compressors were used compared to the existing bunch compressors. The final rms energy spread is reduced by 23.0 % in the VBC scheme compared to the existing compression scheme, this is a result of accelerating closer to crest in all RF cavities, generating a smaller energy chirp.

For slices of the beam in the range $-20\,\text{fs} < t < 20\,\text{fs}$, the normalised slice emittance is unchanged for the two compression schemes, as seen in Fig. 5. The addition of combined function dipoles with a quadrupole component did not lead to any significant chromatic effects, like those seen in the *additional quadrupole* solution [3]. This due to the the chromatic dependence of the Twiss parameters being well managed [3, 6, 7]. The increase in number of dipoles in the variable bunch compressors had no significant effects on CSR-induced emittance growth, for this configuration.

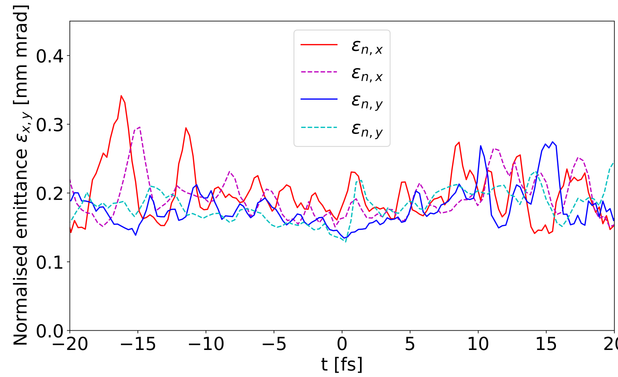

Figure 5: Normalised slice horizontal emittance $\varepsilon_{n,x}$ for the existing linac (solid red line) and variable bunch compressor scheme (dashed purple line). Normalised slice vertical emittance $\varepsilon_{n,y}$ for the existing linac (solid blue line) and variable bunch compressor scheme (dashed cyan line).

CONCLUSION

Minimising voltage-induced timing jitter is an important concern being considered for SXL project, in particular for ultra-short bunches. Accelerating +19° off-crest in all RF cavities has been proposed to minimise voltage-induced timing jitter in the MAX-IV linac. We found $R_{56} = 4.01$ cm in the first bunch compressor and $R_{56} = 2.60$ cm in the second bunch compressor were required to produce a peak current of 4 kA, while the accelerating phase was set to minimise timing jitter. This could be achieved using a modified design of the *additional dipole* variable bunch compressor from Ref. [3]. In the first bunch compressor, this meant the addition of a combined function dipole with a quadrupole component instead of flat dipole, as this allowed an increase in arc-like R_{56}. This modification was not made for the second bunch compressor. The compression scheme using the variable bunch compressors showed no change in horizontal and vertical slice emittance in the range $-20\,\text{fs} < t < 20\,\text{fs}$. Further work will be done to see if we can use the octupoles in the variable bunch compressors to linearise the longitudinal phase space.

REFERENCES

[1] "The Soft X-ray Laser @ MAX-IV: Conceptual Design Report," 2021. `https://www.maxiv.lu.se/soft-x-ray-laser/`

[2] W. Qin *et al.*, "The FEL in the SXL project at MAX IV," *J. Synchrotron Radiat.*, vol. 28, no. 3, pp. 707–717, 2021. `doi:10.1107/S1600577521003465`

[3] P. H. Williams, G. Pérez-Segurana, I. R. Bailey, S. Thorin, B. Kyle, and J. B. Svensson, "Arclike variable bunch compressors," *Phys. Rev. Accel. Beams*, vol. 23, no. 10, p. 100 701, 2020. `doi:10.1103/PhysRevAccelBeams.23.100701`

[4] M. Borland, "User's Manual for elegant," *Advanced Photon Source*, p. 567, `https://www.aps.anl.gov/Accelerator-Operations-Physics/Software`

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEPL073

[5] A. Wolski, *Beam Dynamics in High Energy Particle Accelerators*. Imperial College Press ; Distributed by World Scientific, 2014.

[6] J. Björklund Svensson, T. K. Charles, O. Lundh, and S. Thorin, "Third-order double-achromat bunch compressors for broadband beams," *Phys. Rev. Accel. Beams*, vol. 22, no. 10, p. 104 401, 2019. doi:10.1103/PhysRevAccelBeams.22.104401

[7] C. A. Lindstrøm and E. Adli, "Design of general apochromatic drift-quadrupole beam lines," *Phys. Rev. Accel. Beams*, vol. 19, no. 7, p. 071 002, 2016. doi:10.1103/PhysRevAccelBeams.19.071002