A COMPUTER-AIDED DESIGN (CAD) TOOL FOR LINEAR OPTICS DESIGN

The lack of widely available CAD tools for Linear Optics design is hampering development in the field of Accelerator Physics. Such CAD tools have been used in many other fields for quite some time, e.g., by Mechanical Engineers since the mid-1960s. Industries where CAD tools have been widely adopted have seen increases in productivity, collaboration, and in the quality of the designs produced.

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1. ESSENTIAL REQUIREMENTS

To fulfil its basic purpose a Linear Optics design CAD tool must be able to:

1. Calculate, update, and display Beam Dynamics data in real-time.
2. Allow for interactive editing of the lattice structure being simulated.
3. Import and export lattice configurations in a consistent file format.

It is however desirable to expand upon these core requirements to develop a more complete and versatile solution. For example, supporting of a number of different lattice file formats as the Accelerator Physics community has yet to settle on a single standard file format.

2. DERIVED REQUIREMENTS

From discussion with Accelerator Physicists at Diamond, several specific user requirements have been derived:

1. The ability to display a graph of Linear Optics data that dynamically updates in response to changes. It is also desirable that the user can change which Linear Optics parameters are viewed on the graph.
2. The global Linear Optics data for the super-period, or lattice, should be clearly displayed.
3. The ability to select a specific element or 's-position', to display the local Linear Optics data at that location.
4. An intuitive visualisation of lattice structure, in which element types and lengths can be easily discerned. In this lattice representation, the elements should be selectable to display applicable fields and the values of those fields should be editable by the user.
5. The tool should integrate with existing Linear Optics simulation/optimisation software, to simplify the lattice development process and reduce the overhead of transferring prototype lattice structures between programs.

5. IMPLEMENTATION

With the requirements, use cases, and physics effectively captured, the software engineering task was relatively straightforward. The tool was based on existing accelerator simulation software and so the project was mostly focused on User Interface (UI) design, with production the GUI (Graphical User Interface) comprising the majority of development. The resulting software module, named VOLO (Visualiser and Optimizer for Linear Optics), was produced by a single Software Engineer in ~1.5 months of development time.

VOLO is written entirely in Python (PyQt was used for the GUI) and is hosted in an open-source, collaborative, repository (which can be found at www.github.com/dls-controls/volo). It makes use of ATIP (Accelerator Toolbox Interface for Pytac) to perform the lattice handling and physics simulations. ATIP is a fully Python based alternative to Matlab Middle Layer. ATIP achieves this by wrapping pyAT (the Python implementation of Accelerator Toolbox, which is existing accelerator simulation code) so that it can interface, as a data source, with Pytac (Python Toolkit for Accelerator Controls, which is high-level accelerator control software developed at Diamond). As a result of this, VOLO can use lattice files in all formats supported by pyAT (Elegant, .mat, 'repr' string, and Tracy formats). The software structure of VOLO can be seen in Fig. 1, and the GUI layout is shown in Fig. 2. Additionally, the VOLO module contains an optimiser, least squares regression, which is primed for future integration.

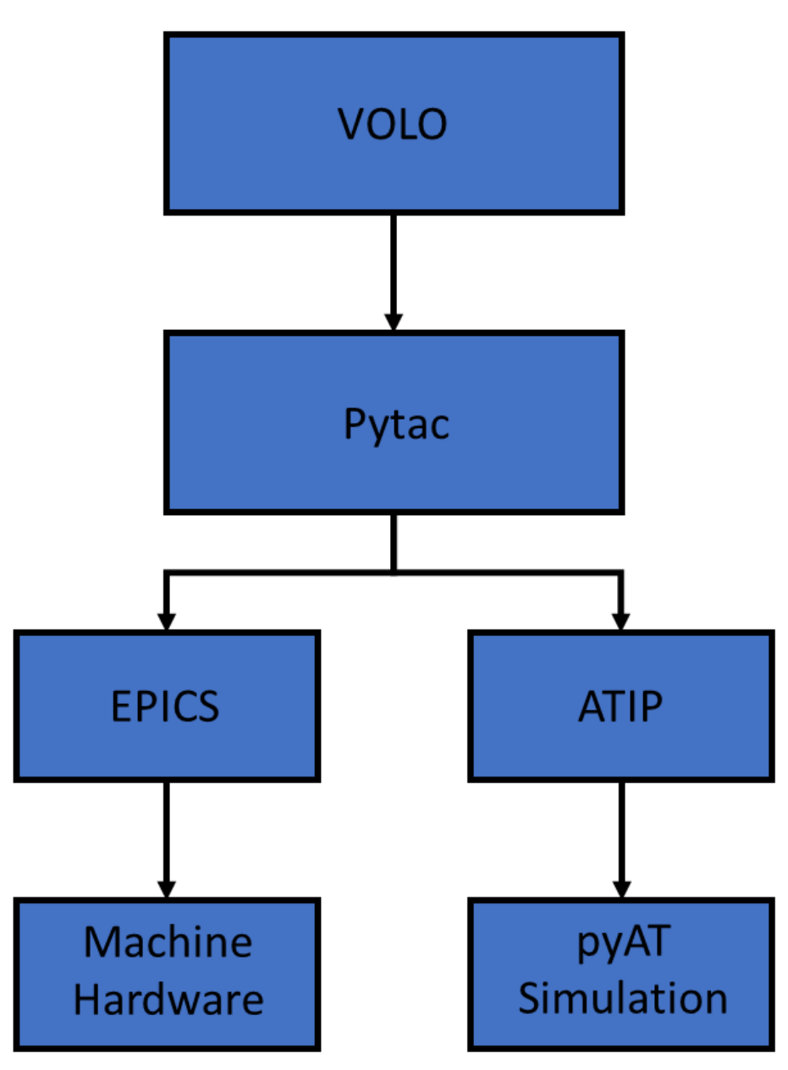
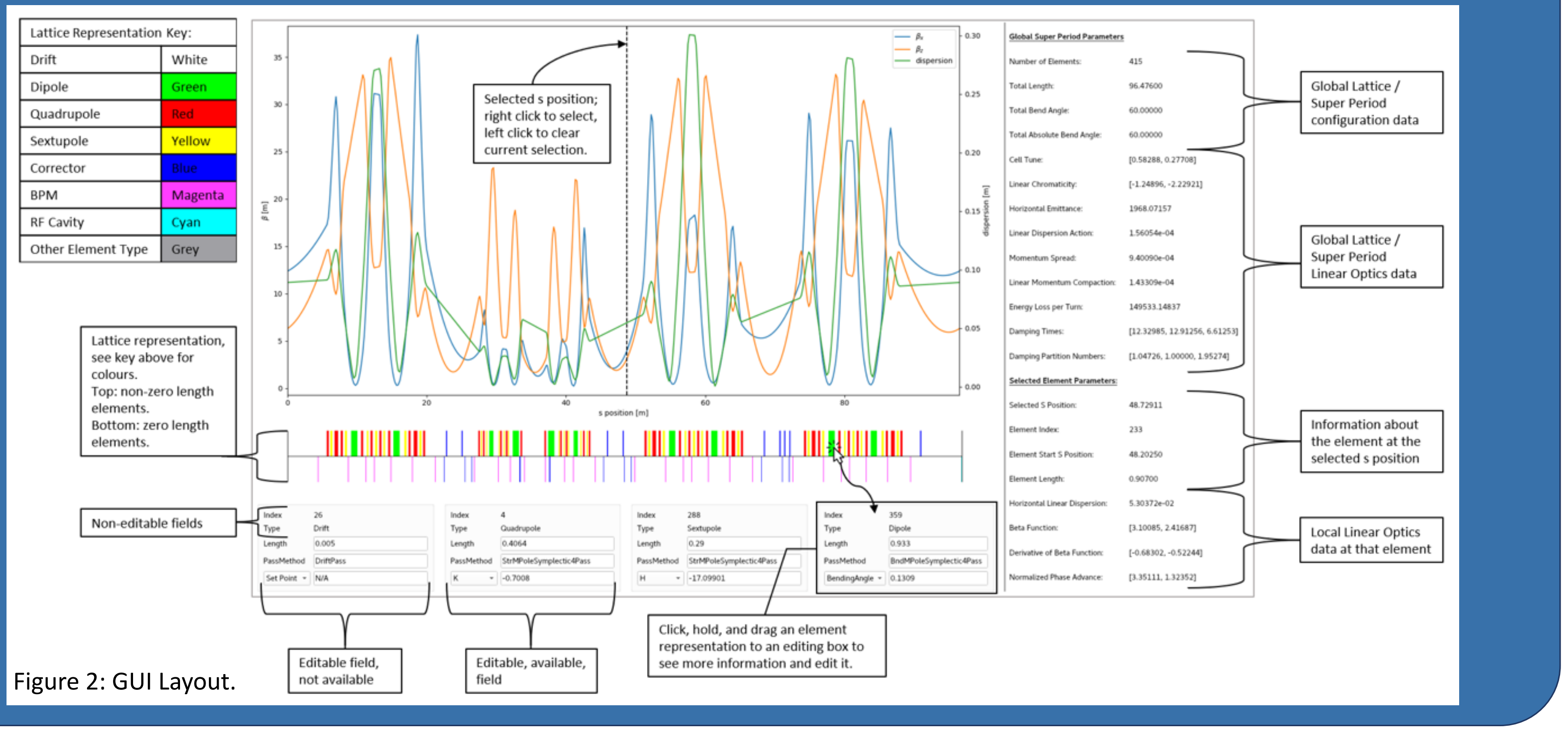


Figure 1: Software Hierarchy.



Lattice Representation Key:	
Drift	White
Dipole	Green
Quadrupole	Red
Sextupole	Yellow
Corrector	Blue
BPM	Magenta
RF Cavity	Cyan
Other Element Type	Grey

Global Super Period Parameters

Number of Elements:	415
Total Length:	96.47600
Total Bend Angle:	60.00000
Total Absolute Bend Angle:	60.00000
Cell Tune:	[0.58288, 0.27708]
Linear Chromaticity:	[-1.24896, -2.22921]
Horizontal Emittance:	1968.07157
Linear Dispersion Action:	1.56054e-04
Momentum Spread:	9.40090e-04
Linear Momentum Compaction:	1.43309e-04
Energy Loss per Turn:	149533.14837
Damping Times:	[12.32985, 12.91256, 6.61253]
Damping Partition Numbers:	[1.04726, 1.00000, 1.95274]

Selected Element Parameters:

Selected S Position:	48.72911
Element Index:	233
Element Start S Position:	48.20250
Element Length:	0.90700
Horizontal Linear Dispersion:	5.30372e-02
Beta Function:	[3.10085, 2.41687]
Derivative of Beta Function:	[-0.68302, -0.52244]
Normalized Phase Advance:	[3.35111, 1.32352]

Index	26	Index	4	Index	288	Index	359
Type	Drift	Type	Quadrupole	Type	Sextupole	Type	Dipole
Length	0.005	Length	0.4064	Length	0.29	Length	0.933
PassMethod	DriftPass	PassMethod	StrMPoleSymplectic4Pass	PassMethod	StrMPoleSymplectic4Pass	PassMethod	BndMPoleSymplectic4Pass
Set Point	N/A	K	-0.7008	H	-17.09901	BendingAngle	0.1309

Selected s position; right click to select, left click to clear current selection.

Lattice representation, see key above for colours. Top: non-zero length elements. Bottom: zero length elements.

Non-editable fields

Editable field, not available

Editable, available, field

Click, hold, and drag an element representation to an editing box to see more information and edit it.

Global Lattice / Super Period configuration data

Global Lattice / Super Period Linear Optics data

Information about the element at the selected s position

Local Linear Optics data at that element

Figure 2: GUI Layout.

3. USE CASES

A CAD tool for Linear Optics design would be primarily suited to creating and prototyping lattice configurations during accelerator conceptual design, but would see use adjusting and optimising lattices throughout an accelerator's lifecycle.

The specific use cases include: Beam Line Matching, Periodic Solution, Mirror Symmetric Periodic Solution, Reverse Bends, -I Transformer, and Higher-Order Achromat. For example, see Tab. 1 below for the parameters that would be optimised in the case of Beam Line Matching.

Parameter Name	Initial Value($\bar{a}_0$)	Final Value ($\bar{a}_1$)	Initial Value ($\bar{x}$)	Final Value ($\bar{y}$)	Delta
Element Length	$\bar{L}_0$	$\bar{L}_1$			
Bend Radius	$\bar{\rho}_0$	$\bar{\rho}_1$			
Gradient	$\bar{b}_{2,0}$	$\bar{b}_{2,1}$			
Dispersion			$\bar{\eta}_0$	$\bar{\eta}_1$	$\bar{\eta}_1 - \bar{\eta}_0$
Derivative of Dispersion			$\bar{\eta}'_0$	$\bar{\eta}'_1$	$\bar{\eta}'_1 - \bar{\eta}'_0$
Beta Function			$\bar{\beta}_0$	$\bar{\beta}_1$	$\bar{\beta}_1 - \bar{\beta}_0$
Dearivative of Beta Function			$\bar{\alpha}_0$	$\bar{\alpha}_1$	$\bar{\alpha}_1 - \bar{\alpha}_0$

Table 1: Beam Line Matching - Independent and Dependent Parameters.

4. PHYSICS

This is a concise summary of the physics intended to be understood by a Software Engineer in order to support development of the software needed to solve these equations efficiently. N.B. a range of software modules for this purpose already exist: Tracy, AT, Elegant, MAD etc.

The Equations of Motion are given by the Lorentz Force (Eq. 1):

$$\frac{d\bar{p}}{dt} = q\left(\bar{E} + \bar{v} \times \bar{B}\right), \qquad \bar{p} \equiv m_0\gamma\bar{v}, \qquad \gamma \equiv \frac{1}{\sqrt{1 - v^2/c_0^2}} \tag{1}$$

Which, for a transparent approach (straightforward generalisation for the nonlinear case), are integrated and expressed as a Lie Series (Eq. 2):

$$\bar{x}_1 = e^{L\mathscr{D}(-H_2)}\bar{x}_0 = M_{01}\bar{x}_0 \tag{2}$$

i.e., the Transport Matrix for the Quadratic Hamiltonian. For a Periodic System (the entire lattice or super period) the Poincaré Map is obtained by concatenating the Transport Matrices for the elements by matrix multiplication; which has the form (Eq. 3):

$$M + D = \begin{bmatrix} \cos(2\pi\nu_x) + \alpha\sin(2\pi\nu_x) & \beta_x\sin(2\pi\nu_x) \\ -\gamma_x\sin(2\pi\nu_x) & \cos(2\pi\nu_x) - \alpha_x\sin(2\pi\nu_x) \end{bmatrix} + \begin{bmatrix} m_{16} \\ m_{26} \end{bmatrix} \tag{3}$$

and is diagonalised (Floquet Space) into (Eq.4):

$$M = AR(2\pi\nu_x)A^{-1}, \qquad \tilde{D} \equiv A^{-1}\begin{bmatrix} m_{16} \\ m_{26} \end{bmatrix} \tag{4}$$

in which (Eq. 5):

$$A(s) = \begin{bmatrix} \sqrt{\beta_x(s)} & 0 \\ -\frac{\alpha_x(s)}{\sqrt{\beta_x(s)}} & \frac{1}{\sqrt{\beta_x(s)}} \end{bmatrix} \tag{5}$$

Having determined the Dispersion & Optics at the exit and entrance of the cell, they are then propagated with the transport matrices. The Radiation Effects (Energy Loss per Turn, Horizontal Emittance, Momentum Spread, Damping Times, and Partition Numbers) are then computed with the Sand's Formalism from the Synchrotron Integrals [I$_1$, I$_2$, I$_3$, I$_4$, I$_5$], which are obtained from the linear optics and magnet properties for the lattice.

Tabs. 2-4 show the parameters, and their respective equations, to be displayed numerically in the GUI side-pane.

Parameter Name	Symbol	Units
Beam Energy	E_b	[GeV]
Element Length	$L(s)$	[m]
Dipole Bend Radius	$\rho(s) = \frac{L}{\phi}$	[m]
Quadrupole Gradient	$b_2(s)$	[m^{-2}]

Table 2: Lattice Parameters (independent).

Parameter Name	Symbol	Units
Hor. Linear Dispersion	$\bar{\eta}(s) = e^{\mathscr{D}(-H)}\bar{\eta}_0 = M(s)\bar{\eta}_0 + D(s), \qquad \bar{\eta} \equiv [\eta_x, \eta'_x]$	[m]
Beta Function	$\bar{\beta}(s) \equiv [\beta_x(s), \beta_y(s)] = [a_{11}^2, a_{33}^2]$	[m]
Derivative of Beta Function	$\bar{\alpha}(s) \equiv -\frac{1}{2}\partial_s\bar{\beta}(s) = [\alpha_x(s), \alpha_y(s)] = [-a_{11}a_{21}, -a_{33}a_{43}]$	[.]
Normalized Phase Advance	$\bar{\nu}(s) \equiv \frac{\bar{\mu}(s)}{2\pi} = \left[\frac{\mu_x(s)}{2\pi}, \frac{\mu_y(s)}{2\pi}\right]$	[.]

Table 3: Local Linear Optics Design Parameters (dependent).

Parameter Name	Symbol	Units
Cell Tune	$\bar{\nu} \equiv \left[\frac{\mu_x(L_\text{tot})}{2\pi}, \frac{\mu_y(L_\text{tot})}{2\pi}\right] = \frac{\arccos\left(\frac{\text{Tr}\{M_{x,y}\}}{2}\right)}{2\pi}$	[.]
Linear Chromaticity	$\bar{\xi} \equiv [\xi_x, \xi_y] = \frac{\arccos\left(\frac{\text{Tr}\{M_{x,y}(\delta)\}}{2}\right) - 2\pi\nu_{x,y}}{\delta}$	[.]
Horizontal Emittance	$\varepsilon_x = C_\text{q}\gamma^2\frac{I_5}{j_xI_2} = C_\text{q}\gamma^2\frac{I_5}{I_2 - I_4}$	[pm · rad]
Linear Dispersion Action	$\mathscr{H}_x = \gamma_x\eta_x^2 + 2\alpha_x\eta_x\eta'_x + \beta_x\eta'^2_x$	[m]
Momentum Spread	$\sigma_{p_t}^2 = C_\text{q}\gamma^2\frac{I_3}{j_{p_t}I_2} = C_\text{q}\gamma^2\frac{I_3}{2I_2 + I_4}$	[.]
Linear Momentum Compaction	$\alpha_\text{c}(\delta) = \frac{1}{C}\oint\frac{\eta_x(s)}{\rho(s)}ds$	[.]
Energy Loss per Turn	$U_0 = \oint\frac{P_\gamma}{c_0}ds = \frac{C_\gamma E_0^4 I_2}{2\pi}$	[eV]
Damping Times	$\bar{\tau} \equiv [\tau_x, \tau_y, \tau_z] = \frac{1}{\alpha_k} = \frac{2E_0}{j_k\langle P_\gamma\rangle} = \frac{2T_0E_0}{j_kU_0} = \frac{4\pi T_0}{C_\gamma E_0^3 j_k I_2}$	[msec]
Damping Partition Numbers	$\bar{J} \equiv [J_x, J_y, J_z] = \left[1 - \frac{I_4}{I_2}, 1, 2 + \frac{I_4}{I_2}\right]$	[.]
Total Length	L_tot	[m]
Total Bend Angle	ϕ_tot	[°]
Total Absolute Bend Angle	$\sum\lvert\phi\rvert$	[°]

Table 4: Global Linear Optics Parameters (dependent).

6. CONCLUSION & OUTLOOK

Although VOLO is still in the prototype stage it comfortably fulfils the basic requirements and meets the majority of the further user specified requirements. The only user requirement not completely satisfied, at this time, is integration with existing accelerator simulation/optimisation software.

Currently there is only one-way integration as VOLO depends on and makes use of established software. Two-way integration is not yet possible as the output interface of VOLO remains undefined. Although the optimiser is currently run from a separate GUI or the command line, it is in the early stages of internal incorporation and there is also the possibility of future integration with pyAT.

In terms of future development there are three areas of focus, in order of attention:

1. Increase the utility of VOLO through more complete integration with a wider range of accelerator simulation software.
2. Inclusion of proposed novel features for the optimiser which would add innovative advanced functionality to streamline the accelerator conceptual design process.
3. Collect feedback from a wider audience to drive UI design improvement; currently, it has only been reviewed by a small group of Accelerator Physicists.

To date VOLO has seen testing and initial use in the Diamond Accelerator Physics group. However, the main purpose of this project is to increase the awareness, accessibility, and impact of CAD tools for Linear Optics Design within the Accelerator Physics community. As such, we would like to see wider adoption of these CAD tools by those who would benefit from them most, Accelerator Physicists. Although the motivation for the work originated from the conceptual design for an upgrade to a modern synchrotron light source, the protype CAD tool can be used with: synchrotrons in general, boosters (synchrotrons for the injection system), and transport lines. Potential applications include conceptual design, engineering design (e.g., ensuring that magnet strengths stay within engineering constraints), on-line model (for commissioning, operations, and beam studies), and upgrades (e.g., fine tuning of the optics in straight sections for better matching of insertion devices).