ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPRB113

TOOLBOX FOR OPTIMIZATION OF RF EFFICIENCY FOR LINACS

J. Ögren*, A. Latina, D. Schulte
CERN, Geneva, Switzerland

Abstract

We present a toolbox for optimizing the RF efficiency for linacs and as an example we use it to re-optimize the Compact Linear Collider booster linac. We have implemented a numerical model of a SLED-type pulse compressor that can generate a single or a double pulse. Together with the CERN CLICopti library, an RF structure parameter estimator, we created the toolbox which enables thorough optimizations of linacs in terms of RF efficiency, beam stability, and cost simultaneously, via a simple and concise Octave script. This toolbox was created for the optimization of X-band-based linacs, however it can also be used at lower frequencies, e.g. in the S- and in the C- bands of frequencies.

INTRODUCTION

For normal-conducting linacs the RF system becomes an important driver of the overall power consumption and total cost. For the Compact Linear Collider (CLIC) [1,2] a global optimization was performed. It is a non-trivial task with many parameters: dimensions, gradient and lengths of the accelerating structures which in turn affects the needed pulse length delivered by klystrons and pulse compressors. Here we present a common toolbox including pulse compressors and accelerating structure parameters.

RF TOOLBOX

The RF Toolbox is a combination of scripts for RF pulse compressors written in Octave [3] and an already existing library, CLICopti [4], for accelerating structure parameters, which now also can be conveniently accessed via Octave.

Pulse Compressor

We have implemented Octave scripts [5] for a SLED-type pulse compressor [6] that can output both a single- and double-pulse modes. In a pulse compressor the RF energy is stored in two cavities and by flipping the phase of the input signal the stored amplitude constructively interferes with the incoming signal resulting in a short output pulse with higher power. By changing the coupling, pulse separation and phase ramp a flat single- or double-pulse with maximum energy can be obtained. We use a built-in Octave optimizer for determining the pulse compressor parameters. Figure 1 shows the input and output power signals for a double pulse.

CLICopti

CLICopti is an RF structure parameter estimator that can estimate RF structure parameters based on inputs such as cell type, cell length, apertures, tapering and number of cells.

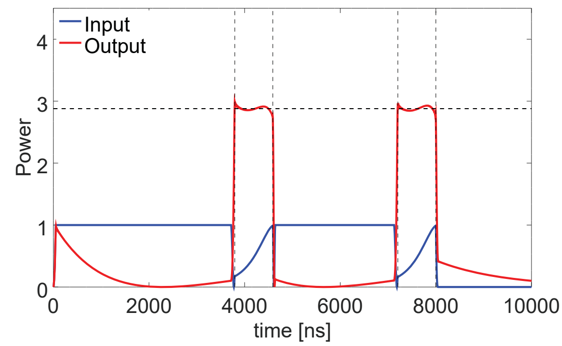

Figure 1: Example of pulse compressor input and output power signals. In this case a 2 GHz 8 µs klystron pulse is compressed to two 800 ns long pulses with a gain factor of 2.9.

From these inputs, the software returns parameters such as filling time, RF power needed for a given gradient, efficiency, etc. CLICopti, originally written in C++ as a binary shared library, was recently interfaced to Octave and Python using the Simplified Wrapper and Interface Generator (SWIG), which is a software development tool for building scripting language interfaces to C and C++ programs [7]. This significantly eased the use of the library, and made it promptly accessible from high-level scripting languages designed for scientific computations such as Octave. The following lines of Octave script show how CLICopti can be used to retrieve useful information related to an RF structure:

```
%rf structure parameters
frequency = 11.9942; % GHz, X-band
G = 66e6; % V/m, gradient
a = 0.1; % average a/lambda
d = 0.11; % average thickness/cell length
n_cell = 60; % number of cells per structure
beam_current = 1.65; % A, beam peak current

% initialize the library
base = CellBase('DB/TD_12GHz.dat', frequency);
as = AccelStructure(base, n_cell, a, 0.0, d, 0.0);

% inquire the library
filling_time = as.getTrise() + as.getTfill() % s
power_unloaded = as.getPowerUnloaded(G*as.getL()) % W
power_loaded = as.getPowerLoaded(G*as.getL(), beam_current) % W
t_beam = as.getMaxAllowableBeamTime(power_loaded).time % s
```

The CLICopti estimator is open source and freely available [8].

OPTIMIZING THE CLIC BOOSTER LINAC

For a given accelerating structure geometry one can estimate the head-tail instability for a given set of beam parameters. Following the reasoning for multi-bunch instability

* jim.ogren@cern.ch

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPRB113

Table 1: The CLIC 380 GeV Booster Linac Beam Parameters

Beam energy [GeV]	2.86 to 9.0
Bunch length [µm]	300
Particles per bunch [10^9]	5.2
Number of bunches	352
Train length [ns]	176

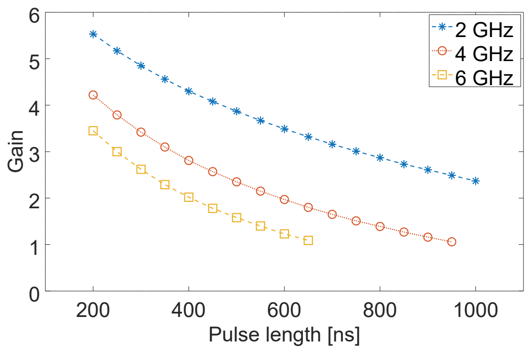

Figure 2: Gains for different pulse lengths of the compressed double-pulse for three different RF frequencies.

in [9] one can compute the kick amplitude as

$$A = \int_0^L \frac{\beta}{2E} ds \langle W_\perp \rangle N e^2, \tag{1}$$

where $\langle W_\perp \rangle$ is the short-range transverse wakefield. The margin of stability is higher for higher beam energy, lower beam current or stronger focusing. For stability one requires $A \ll 1$ and for our parameter scan in the next section we used $A < 0.4$ as a limit.

In the CLIC injector chain the bunches of the beams are compressed in the first bunch compressor after exiting the damping rings. Then the booster linac accelerates the 300 µm long bunches of the electron and positron beams from 2.86 GeV to 9.0 GeV before the second bunch compressor and the main linacs. In the baseline design the booster linac is based on 2 GHz RF frequency and it is assumed that the pulse compressors generate a double pulse (c.f. Fig. 1) such that the electron and positron beams, separated in time, both can be accelerated within a single klystron pulse. The CLIC booster linac beam parameters are summarized in Table 1. In this example we review this RF design and explore options of using 4 GHz and 6 GHz in addition to the baseline 2 GHz.

Using the pulse compressor scripts we generated a gain table with the power gains for different pulse lengths of the compressed double-pulse. Figure 2 shows the gains for the different RF frequencies. It can be seen that a shorter pulse provides a higher gain (at cost of lower efficiency), if compared to a longer pulse. We assumed 50 MW for all klystrons and a $1/f$ scaling for the pulse length. The klystron parameters are summarized in Table 2.

Different RF frequencies require different lattice designs. Typically, higher frequencies require stronger focusing, due to the stronger wakefields induced by the smaller apertures. Since also the beam pipe aperture can be smaller, the focusing magnets can reach higher gradients and one can envisage stronger focusing while preserving the fill factor. To treat the lattices equally we assumed that all cases have the same quadrupole fill factor of 5%. For FODO cells with a fill factor FF the average beta function can be computed as

$$\langle \beta \rangle = \sqrt{\frac{8\, P/q\, r_0 \sin(\phi/2)}{B_{\text{poletip}} \sin^2(\phi)\, FF}} \tag{2}$$

where P/q is the rigidity of the reference particle. The strongest focusing occurs for a phase advance of $\phi \approx 70.5°$. We use quite conservative values with $B_{\text{poletip}} = 0.8$ T and $r_0 = \lambda_{RF}/3$ to keep the magnet apertures larger than the apertures of the accelerating structures.

For the cost estimate we used a simplified cost model, where we assumed that two klystrons combine to an RF unit with a fixed price per klystron and that the cost of tunnel scales linearly with its length (L_{RF}). Then the cost can be calculated according to

$$\text{Cost} = 2C_{\text{klystron}} N_{\text{RF}} + L_{\text{RF}} C_L \tag{3}$$

where we assume $C_{\text{klystron}} = 300$ kCHF as the cost per klystron and $C_L = 50$ kCHF/m as the cost of tunnel.

Parameters Scan

For the CLIC booster linac beam parameters we scanned over a large set of accelerating structure parameters:

- $0.08 \le \langle a \rangle / \lambda \le 0.22$
- $0.11 \le \langle d \rangle / h \le 0.4$
- $10 \le$ gradient [MV/m] ≤ 60
- $10 \le N_{\text{cell}} \le 200$

where $\langle a \rangle / \lambda$ is the average iris aperture normalized to wavelength and $\langle d \rangle / h$ is the average iris thickness normalized to cell length for the tapered structures. For each cell configuration we looped over a set of gradients and for different number of cells per structure, N_{cell}, for a total of over 100 million structures. For each we retrieved the power required, filling time, and checked if there is sufficient single-bunch stability (i.e. eq. 1). Furthermore we also checked that the maximum allowable beam time (how long RF pulse the structure can sustain with a breakdown rate below the threshold value specified for the CLIC main linac) is long enough to accommodate beam pulse length and structure filling time. Structures that did not fulfill the requirements or had too long filling times were immediately discarded. Given a needed RF pulse length we used the gains from the pulse compressor and computed an RF configuration, i.e. how many structures can a single RF unit consisting of two klystrons feed, we discarded inefficient configurations. As a last step, we selected the 30% most efficient solutions.

Figure 3 shows the results from the parameter scan for the booster linac for three different RF frequencies: 2, 4 and 6 GHz. Due to limits of beam stability only the lower frequency cases gave acceptable solutions for low $\langle a \rangle / \lambda$. Higher frequency allows for higher gradients but due to

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPRB113

Table 2: Cost optima for the three different cases. For reference we also show the 2 GHz baseline design.

Parameter	Baseline	2 GHz	4 GHz	6 GHz
Assumptions				
Klystron power [MW]	50	50	50	50
Klystron pulse [µs]	8.0	8.0	4.2	3.0
$\langle\beta\rangle$ [m]	16	14	10	8
Cost optima				
Gradient [MV/m]	14.8	18	20	26
$\langle a\rangle/\lambda$	0.11	0.09	0.13	0.17
Number of cells	30	16	48	122
Structure length [m]	1.5	0.80	1.20	2.03
RF active length [m]	414	341	307	236
Stability condition	0.10	0.16	0.38	0.37
Filling time [ns]	430	369	172	123
Number of structures	276	427	256	116
Structure efficiency [%]	24	20	36	40
Power (loaded) [MW]	54	38	56	130
Total power [GW]	4.9	4.9	5.1	6.4
Number of klystrons	98	98	102	128
Cost [a.u.]	50	46	46	50

limits in beam stability the structures with higher gradients might require a larger aperture yielding worse efficiency. Table 2 shows the cost optima for the different frequencies as well as the baseline design for reference.

Cost Optimization

Optimizing for cost we found a 2 GHz option cheaper than the baseline, as well as a 4 GHz option of comparable cost. It is interesting to note that higher frequencies, although shortening the linac thanks to the larger gradients, require higher installed klystron power due to the shorter pulses delivered from the klystrons.

The results of this cost optimization depended both on the assumptions made and on parameters that are not easy to estimate, e.g. the klystrons specifications and cost. The main purpose of this example was to demonstrate the procedure and usage of the toolbox. There might also be additional constraints to be taken into consideration and that are outside the scope of this paper. Nonetheless, the results of the booster linac optimization demonstrated that there might be a cheaper 2 GHz option compared to the baseline. Furthermore, a 4 GHz option could also be an interesting alternative with similar cost. Higher frequencies than 6 GHz were considered but gave unsatisfactory results due to poorer transverse beam stability.

CONCLUSIONS

We have created an Octave toolbox for RF optimization for normal-conducting linacs. The toolbox consists of a pulse compressor model and an interface to the CERN CLICopti library for RF parameter estimation for accelerating structures. As an example we optimized the RF system for the CLIC booster linac and found potential improvements with respect to the baseline design.

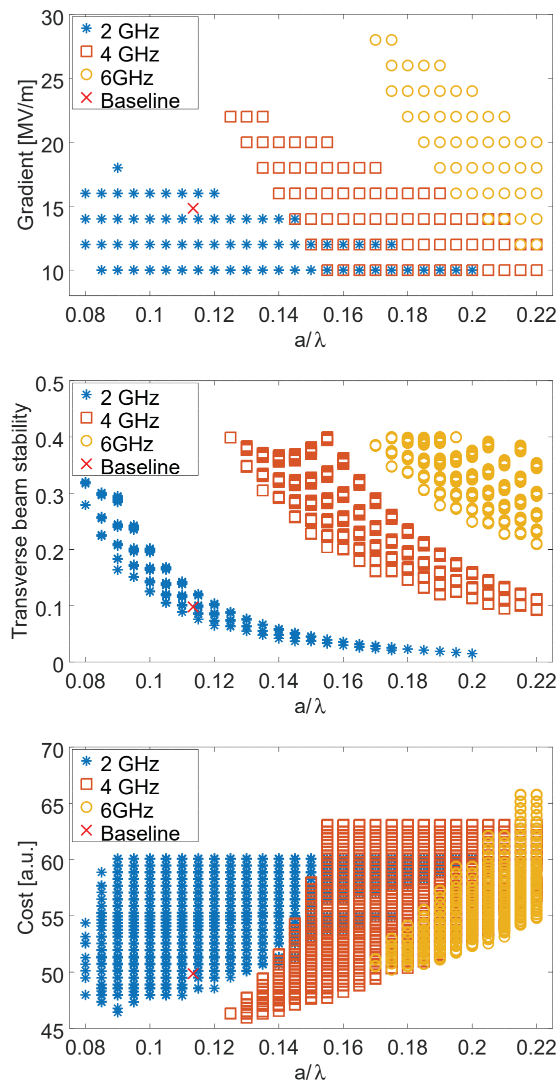

Figure 3: Results from the parameter scan. The plots show structures with different iris apertures and gradients (top), margins of transverse beam stability (middle) and costs (bottom).

ACKNOWLEDGMENT

The authors thank Steffen Doebert for his inputs.

REFERENCES

[1] L. Linssen *et al.*, "The CLIC Programme: Towards a Staged e+e- Linear Collider Exploring the Terascale : CLIC Conceptual Design Report", CERN, Switzerland, CERN-2012-005, 2012.

[2] "Updated baseline for a staged Compact Linear Collider", edited by P.N. Burrows, P. Lebrun, L. Linssen, D. Schulte, E. Sicking, S. Stapnes, M.A. Thomson, CERN, Switzerland, CERN–2016–004, 2016.

[3] J. W. Eaton, D. Bateman, S. Hauberg, R. Wehbring "GNU Octave version 4.2.1 manual: a high-level interactive language for numerical computations", 2017. `https://www.gnu.org/software/octave/doc/v4.2.1/`

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPRB113

[4] K. Sjobak and A. Grudiev, "The CLICopti RF structure parameter estimator", CERN, Geneva, Switzerland, Rep. CERN-OPEN-2014-036, Jun. 2014.

[5] PulseCompressor, Octave optimization scripts, CERN, https://gitlab.cern.ch/clic-software/pulsecompressor

[6] Z. D. Farkas, H. A. Hoag, G. A. Loew and P. B Wilson, "SLED: A Method of Doubling SLAC's Energy.", in *Proc. HEACC 1974*, pp 576–583.

[7] David M. Beazley, "SWIG: an easy to use tool for integrating scripting languages with C and C++", TCLTK'96 Proceedings of the 4th conference on USENIX Tcl/Tk Workshop, 1996 - Volume 4.

[8] CLICopti Library, CERN, https://gitlab.cern.ch/clic-software/clicopti

[9] D. Schulte, "Multi-Bunch Calculations in the CLIC Main Linac", in *Proc. 23rd Particle Accelerator Conf. (PAC'09)*, Vancouver, Canada, May 2009, paper FR5RFP055, pp. 4664–4666.