ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-THPRI075

S-BAND STRUCTURE STUDY FOR THE MaRIE PROJECT*

Zenghai Li[1], Liling Xiao, Chris Adolphsen, Sami Tantawei, Michael Fazio
SLAC, Menlo Park, CA 94025, USA

Abstract

The Matter-Radiation Interactions in Extremes (MaRIE) XFEL concept at LANL utilizes a 20-GeV electron linac to drive a 50-keV XFEL. Experimental requirements drive a need for multiple photon bunches over time durations of about 10 microsecond produced by a bunch train of interleaving 0.1 nC very low-emittance bunches with 2-nC electron bunches. The linac is required not only to provide high gradient and high efficient acceleration, but also a controlled wakefield profile to maintain the beam quality. In this paper, we explore the feasibility of using the S-Band technology to meet such acceleration requirements. We will present the design optimization and comparison of S-Band structures based on different design considerations.

INTRODUCTION

The MaRIE [1] XFEL 12 GeV drive linac conceptual design uses normal conducting, S-band structures operating at 25 MV/m, accelerating up to 30 100 pC bunches in 10-µs-long RF pulses, with a minimum bunch spacing of 50 ns and a pulse repetition frequency of 60 Hz. In choosing a specific accelerator design, considerations need to be given to the low beam loading, the tradeoff of efficiency with wakefield strength and the fact the bunch train length is long compared to the ~ 1 µs S-band copper cavity time constant. Given these and other factors, both traveling wave (TW) and standing wave (SW) designs are being explored for this application. The goal is not only to maximize the RF-to-beam energy transfer efficiency, but also to suppress the long range wakefields generated by the bunches so that significant coupling of the bunch motion does not occur. We present these design considerations and RF parameter comparisons for both types of structures as possible options for the MaRIE XFEL accelerator.

TRAVELING WAVE STRUCTURE

A traveling wave (TW) structure is composed of a series of metallic cylinders and washers to form the so called disk-loaded waveguide (DLWG) [2]. In a TW structure, the RF power injected from one end of the structure travels along the structure with a group velocity much smaller than in the power waveguide thus the RF power is compressed in the structure to achieve a high acceleration field while the RF phase maintains synchronous with the beam being accelerated. The basic parameters of a TW structures are the phase advance per cell, the average iris radius (a) and the RF field attenuation constant (tau). A 120 degrees phase advance per cell is chosen for this comparison to maximize the structure shunt impedance. The iris opening is tapered to achieve a constant accelerating gradient along the structure. An average iris radius of 10 mm is chosen for RF efficiency and short-range wakefield considerations.

Cell Shape

A typical TW cell has a rectangular cylinder and a flat disk with a fully rounded iris opening (DLWG). A 10% increase in shunt impedance could be achieved by simply rounding the top of the DLWG cell (RTOP). A re-entrant iris (RDS) cell could further improve the shunt impedance by about 5% depending on the iris aperture. The typical geometry of these three variations in cell shape is shown in Figure 1. Given that the re-entrant RDS shape is harder to machine and clean, the RTOP cell is chosen in this study as it is relatively simple in shape and good in RF efficiency. Figure 2 shows the impedance improvement with the RTOP cell as compared with the DLWG cell in the range of iris opening interested for the MaRIE linac.

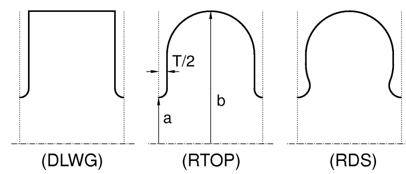


Figure 1: Traveling wave structure cell shapes.

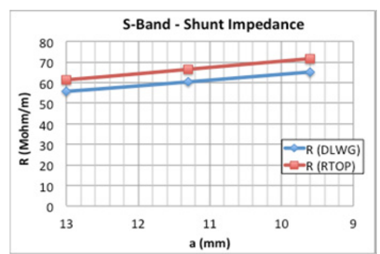


Figure 2: RF parameter comparison between DLWG and RTOP cell shapes.

The peak surface electric field appears at the surface of the rounded iris. An elliptical rounding profile at the iris can reduce the peak surface field by 10-15%, as sown in Fig. 3, which is desirable in high gradient applications such as the MaRIE linac.

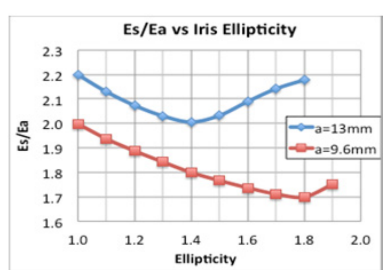


Figure 3: Peak surface electric field v.s. ellipticity of the iris rounding for iris openings of 9.6mm and 13mm. A 10-15% reduction is achievable with an optimal ellipticity.

*Work was supported by the US Department of Energy through Los Alamos National Laboratory, and used resources of NERSC at LBNL under US DOE Contract No. DE-AC03-76SF00098.
[1] lizh@slac.stanford.edu

ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-THPRI075

Structure Detuning

There are two main reasons that the iris diameter in a TW structure is tapered. One is to produce a constant acceleration gradient profile along the structure, which improves RF efficiency and reduces the peak surface field to average accelerating field (Es/Ea) gradient ratio. The second reason is to detune the dipole modes so the long-range wakefield decoheres. Such detuning occurs naturally in order to achieve a constant gradient, but can be further optimized in what is called a "detuned structure". That is, the dipole mode frequency of each cell is specified differently so a bunch excitation of all cells produces a net wakefield where the mode contributions cancel (decohere) to a large extent following the bunch. In some applications, additional damping is needed to suppress the "re-coherence" of the wakefield at a later time. About 100 cells are needed to achieve a good suppression in a single structure. This can be done effectively in a S-band structure about 4 m and longer. We chose a 6 m detuned TW design for the purpose of comparison. The design incorporated a Gaussian dipole mode detuning, which cause a de-coherence reduction of the wakefield following a Gaussian profile within a distance inversely proportional to the total frequency detuning. Figure 4 shows the detuned dipole mode spectrum of the structure. Figure 5 shows a few typical coupled dipole modes in the tapered structure.

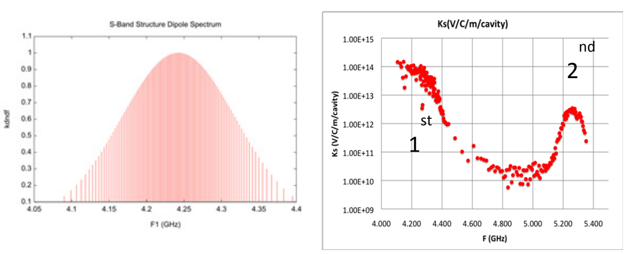


Figure 4 Dipole mode spectrum of the detuned structure: left: frequencies of "un-coupled" cells; right: frequencies of "coupled" modes of the tapered structure up to 2nd band.

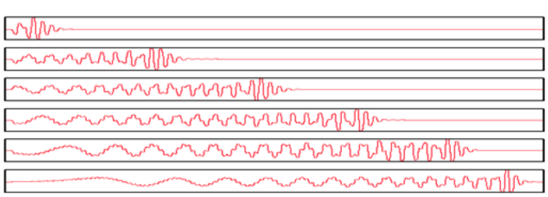


Figure 5: Typical dipole modes in a tapered structure. A large fraction of modes reside only in a portion of the structure due to the change of bandwidth by tapering.

Gradient and Wakefield in the Detuned Structure

The left figure in Fig. 6 are the gradient profiles in the structure for two detuning cases of 8% and 11% total detuning respectively. Both cases produced the typical "over constant" gradient profile, with the larger detuning producing a larger gradient variation. The long-range wakefield in the detuned structure is shown in the right figure in Fig. 6 and is compared with the "un-coupled" mode approximation. Notice that the wakefield drops significantly in the first 2 meters due to the detuning (11%).

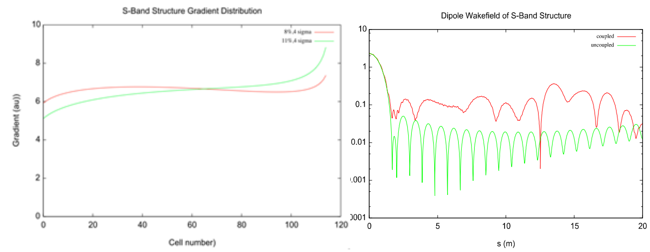


Figure 6: Gradient and dipole wakefield profile of the detuned TW structure.

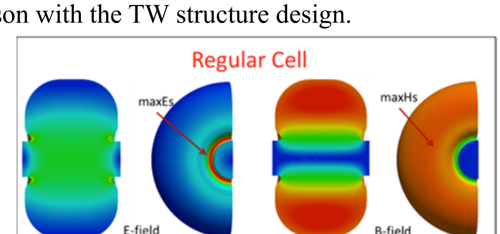
STANDING WAVE STRUCTURE

Standing wave (SW) accelerator structures have been suggested in the past to reduce the demand for peak power from the source. By appropriately shaping structure cavities, SW accelerator structures can achieve a higher shunt impedance. Feeding RF power to an appreciable length of a pi-mode SW structure is challenging because the group velocity of such a structure is "zero" [3]. For this reason, a pi-mode SW structure normally has only a few number of cells. The RF power is fed into the structure via a coupling slot on one of the cells by "diffusion". Recently the RF feeding difficulty of a long SW structure was resolved by using an RF distribution feed system which utilizes a distribution waveguide with feed arms each feeds a section of a few SW cells. We propose to use such a feed scheme for the MaRIE accelerator.

Cell Shape

The aperture is chosen to be similar to the average aperture of the TW structure. Because the cells will be fed by a distribution system, the cell-to-cell coupling is not considered a design constraint, so the iris region can incorporate special shaping in the cell optimization.

The SW cavity shape and the basic RF parameters are shown in Fig. 7. The rounding and re-entrant features of the cavity are essential for obtaining the high shunt impedance. The shape shown here is by no means absolute optimal but it is good enough for the purpose of this comparison with the TW structure design.



Mesh Element (K)	F (GHz)	R/Q (Ω/cell)	Q0	Rs(MΩ/m)	Es/Eacc	Hs/Eacc (kA/m/MV/m)
124	2.855864	189.142	20035	72.18	3.80	2.41
347	2.855863	189.147	20035	72.18	3.80	2.40

Rs=R/Q*Q0/cell_length, cell_length=52.4846mm

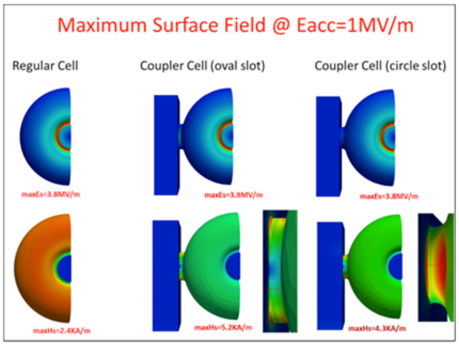
Figure 7: SW cell profile with improved shun impedance

RF Power Coupling

RF power to the SW structure is fed at the outer radius of the cell via coupling slots. Different slot shapes were

ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-THPRI075

examined for both field enhancement and reduction in shunt impedance. A circular coupling slot was chosen as it has minimal effect on the reduction in shunt impedance. The edges of slot are rounded to minimize magnetic field enhancement.



Coupling slot	F (GHz)	Q0	Qext	R/Q (Ω/cavity)	Field Balance	βin	Rs(MΩ/m)	Ep/Eacc	Hp/Eacc (KA/m/ MV/m)
Oval	2.8557	19844	19206	738	1:0.96	1.03	70	3.8	5.2
Circular	2.8557	19911	20645	739	0.97:1	0.96	70	3.8	4.3

Figure 8: RF coupling slot for the SW cell. A pair of symmetric slots on a coupler cell feed a section of 4 SW cells.

Distributed RF Feed System

A distributed coupling scheme (SLAC patent pending) [4] was proposed to feed a chain of many SW cavities. A single RF distribution waveguide delivers power equally to 16 accelerator sections consisting of 4 cavities each, a total of 64 cavities as shown in Fig. 9. The length of a SW unit of 64 cells is around 3.4 meters.

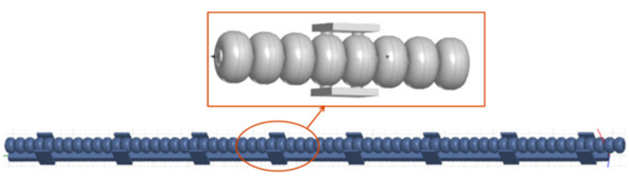


Figure 9: Distributed RF coupling system.

A detuned dipole mode spectrum to suppress dipole wakefield could in principal be incorporated into a 64 cell SW unit design similar to that of a travelling wave structure. Unlike in a TW structure where tapering comes by naturally in order to produce an efficient constant gradient structure, the constant iris SW unit by itself is a constant gradient structure. The tapering in a SW unit would induce a non-uniform gradient distribution. So the power coupling may need to be tailored to maintain the SW unit with a reasonable field profile. The wakefield suppression using detuning in a SW unit is not as well understood as in the TW structure, which requires further investigation.

COMPARISON AND SUMMARY

Aside of some specific design details as mentioned above, the TW and SW structures are shown to have quite comparable RF efficiencies as shown in Table 1. For the SW option, there is about 7% reduction in the peak power/unit length, but with a cost of 3% more RF energy per pulse than using the TW design. With the distributed feed scheme, the number of SW sections in a RF feed system is flexible, which can reduce the peak power per feed making it possible to use lower power klystrons. However this comes at the expense of having a larger number of klystrons. The length of a TW structure on the other hand is determined by the optimal filling time or attenuation (and effective detuning for wakefield). The detuning of a TW structure is well suited for wakefield suppression, while the wakefield suppression for the SW structure need to be evaluated.

One other important concern in a normal conducting structure at high gradient is the RF breakdown. The SW structure design has a higher surface electric field enhancement though it is not clear that this enhancement will affect the performance of the structure. Recent studies [5, 6] showed advantages for SW structure in terms of high gradient operation. These studies were conducted with pulse lengths much shorter than the MaRIE RF pulse length of 13μs. The long pulse length effect needs to be studied experimentally for both TW and SW designs.

Table 1: RF Parameter Comparison Cetween TW and SW

	6-m TW (rounded)		SW (rounded)
	Struct-1	Struct-2	
Peak Power per Meter for a 25MV/m Gradient	11.1	10.3	9.6
Relative RF Energy Required	1.041	1	1.027
Number of cells	172	172	(feed 4 cells per RF coupler, 19 cells/m)
Average a/lambda	0.104	0.098	0.09
a_max (mm)	14.416	14.08	9.447 (not tapered)
a_min (mm)	7.617	6.937	9.447 (not tapered)
vg/c (%)	3.00 – 0.32	2.73-0.20	NA
DeltaF/F1 (%)	10	10	
N_sigma_DeltaF	3	3	
Q0	15562	15548	20035
Qext			20035
R (average) (Mohm/m)	65.1	66.7	72.18
Tf (micro-sec)	1.711	2.117	1.117
Es/Ea	2.27-1.89	2.25-1.85	3.8
Hs/Ea (kA/(MV/m))	2.51-2.19	2.49-2.16	2.41
Tau	0.988	1.224	
Beam pulse length (micro-sec)	10	10	10
RF Pulse length (micro-sec)	11.71	12.12	13.35 (3Tf)

REFERENCES

[1] http://marie.lanl.gov
[2] G.A. Loew, R.B. Neal, "Electron Linacs: Theory, Accelerating Structures," from Lapostolle and Septier, Linear Accelerators, North Holland Publ. Co. 1970, p. 97.
[3] R.H Miller "Comparison Of Standing-wave and Traveling-wave Structures." *Linear Accelerator Conference, Stanford, CA, USA, 2 Jun 1986.*
[4] S. Tantawi, J. Neilson, "Distributed Coupling High Efficiency Linear Accelerator," US Patent Application 13/947043, filed 7/20/2013.
[5] V. Dolgashev, S.Tantawi, Y. Higashi, B. Spataro, "Geometric dependence of radio-frequency breakdown in normal conducting accelerating structures," Appl. Phys. Lett. 97, 171501 (2010).
[6] A. Grudiev, S. Calatroni, W. Wuensch, "New local field quantity describing the high gradient limit of accelerating structures," Phys. Rev. ST Accel. Beams 12, 102001 (2009).