# OPTIMIZATION OF THE X-BAND STRUCTURE FOR THE JLC/NLC*

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*Abstract*

In this paper, we present design considerations to address the high gradient, wakefields, and RF efficiency issues for the JLC/NLC structures. We will present the rationale for the choices of phase advance, structure length, structure aperture, and other design aspects in the optimization of the structure. We will study the impact of parameter choices for the JLC/NLC beam environment and discuss approaches being taken for an optimal JLC/NLC structure design.

## 1 INTRODUCTION

The NLC [1] accelerator structures must have high gradient and high RF efficiency to minimize the linac cost. High power tests of NLC test structures [2] have shown correlations between the breakdown and input power, group velocity, and RF pulse heating. Though not fully understood, it is necessary that these issues be addressed in the future structure design. It has been found that to operate at high gradients, the X-band structures must limit the group velocity to about 3% of *c* and must be designed to have high efficiency and low pulsed heating. However, it is also essential for the structure design to minimize the long and short-range dipole wakefields to prevent emittance degradation and the beam breakup instability (BBU). To prevent single bunch BBU, the structure aperture cannot be smaller than certain limit since the short-range wakefield is proportional to $a^{-3.8}$. Finally, to be effective at wakefield suppression, the accelerator structure is required to have a prescribed detuned dipole spectrum and satisfy certain dipole dispersion requirements.

All of these requirements put stringent constraints on the choice of structure parameters. In addition, beam loading compensation and BNS damping are required to ensure high quality beams at the interaction point. The parameters that maximize the single structure efficiency may require a large overhead for loading compensation and BNS phase offsets and, therefore, result in lower effective efficiency. As part of the optimization process, various structure parameters such as the phase advance, the average aperture, and structure length have been explored. In this paper, we present the parameter studies for the X-band structure and discuss issues need to be addressed for an optimal JLC/NLC structure design.

## 1 STRUCTURE LENGTH

Structures running at a higher input power levels have shown significantly more damaging breakdown events [2]. One acceptable explanation of which is that more RF energy is deposited into a breakdown event, which could potentially cause damage to the surface and trigger subsequent events. For a given average gradient, the power per structure is roughly proportional to the length. This motivates the choice of a shorter length for the structure to maintain the power level below some "threshold". However, using shorter structures requires more high power couplers for the linac, which increases the linac cost. So the length needs to be chosen properly to balance these two issues. The 90-*cm* design, with an average group velocity of 3% of *c*, requires about 100-*MW* input power to reach a 70-*MV/m* gradient, and, in tests, is marginal in breakdown rate. Presently, we have chosen a length of 60-*cm* for the baseline design. Simply by scaling the length, the 60-*cm* structure requires about 30% lower peak power per structure than the 90-*cm*. The actual design varies slightly depending on the optimal shunt impedance obtainable under the restriction of large $a/\lambda$. The average group velocity of the 60-*cm* structure is about 2% of *c* since the optimal filling time at X-band is about 100-*ns*. The dipole detuning results in a group velocity variation from 3% to 1% of *c* along the structure.

## 2 PHASE ADVANCE AND $a/\lambda$

Designing structures with high RF efficiency not only reduces RF power requirement but also reduces the RF pulse heating. With the constraint of large $a/\lambda$ needed to minimize the BBU and emittance dilutions, it is hard to design a structure with 2%*c* average group velocity using the standard $2\pi/3$ phase advance without losing substantial RF efficiency. While magnetic coupling can reduce the group velocity, it is potentially bad due to pulse heating around the slots. Using a higher phase advance can effectively lower the group velocity and maintain good RF efficiency. In Fig.1 the *R* and *R/Q* are plotted versus the phase advance and $a/\lambda$. Notice the drop in R for lower phase advance, which is due to the thick disks needed to reach the 2%*c* group velocity. Consider the gradient in a traveling wave structure is given by

$$G(z)=\sqrt{(\omega R(z)/Q(z)v_g(z))P_{in}e^{-\omega t(z)/Q(z)}}$$

The power needed per structure to reach a required unloaded gradient is inversely proportional to $R/Q(1+0.5\Delta Q/Q_{150})$ (as compared to $150^0$ design). The $0.5\Delta Q/Q_{150}$ factor is due to the higher attenuation in a low *Q* structure that needs more power to compensate. The figure clearly shows efficiency gain at higher phase advances. On the other hand, bandwidth and surface fields become significant issues at phase advance higher than

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$150^0$. In the present design, we have adopted the $150^0$, or 5π/6 phase advance.

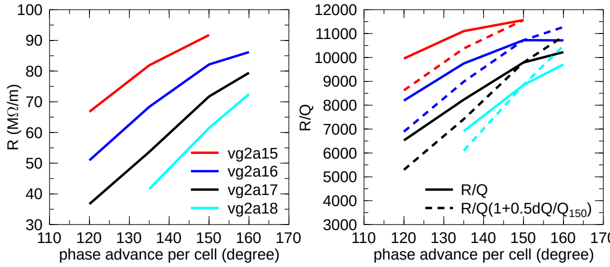


Figure 1 Shunt impedance $R$ and $R/Q$ versus phase advance and $a/\lambda$ for structures with $v_{g,ave}$=2%$c$.

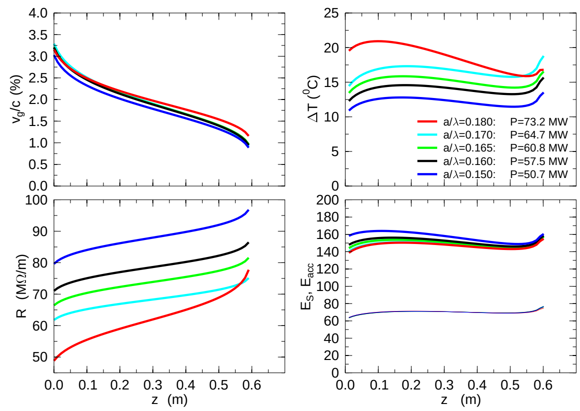


Figure 2 60-*cm* structure parameters for different $a/\lambda$.

Clearly, smaller $a/\lambda$ improves the RF efficiency as expected. A comparison of RF parameters at different $a/\lambda$'s, with 5π/6 phase advance, is shown in Fig. 2. The improved RF efficiency reduces the RF pulse heating which is desirable for high power. However, the impacts of higher wakefield and beam loading are the major concerns that will set a lower limit on $a/\lambda$ and these are discussed in the following section. Finally, dispersive effects from a narrow bandwidth ($\propto v_g * sin(\phi)$) may result in energy variation along the bunch train. Simulation studies [3] have shown that the NLC requirements can be met with minimal effort by shaping the pulse profile.

## 3 OPTIMIZE FOR HEAVILY LOADED JLC/NLC LINACS

In the heavily loaded linacs, emittance preservation and suppression of single/multi-band BBU are important requirements for the linac to deliver quality beams and produce high luminosity. These requirements are tightly coupled to the structure design and in turn set limits on the parameter choices. The overall efficiency of the structures and linac needs to be evaluated with the beam loading and BNS damping overhead included.

### *1 Beam loading*

The multi-bunch beam loading ($\propto R$) is more sensitive to $a/\lambda$ than the RF gradient ($\propto R^{1/2}$). One expects a larger loading ratio at smaller $a/\lambda$ that would reduce the gain in efficiency. The single-bunch loading causes an energy loss and produces head-tail energy spread, which also needs to be compensated by accelerating the beam slightly off crest. Both effects should be included when evaluating the structure efficiency. The $a/\lambda$ dependence of the beam loading is shown in Tab. 1. The $\phi_0$ column is the phase offset needed to cancel the head-tail effect.

Table 1 Single and multi-bunch beam loading versus $a/\lambda$

| $a/\lambda$ | Multi bunch (MV/A/m) | Single bunch | |
|---|---|---|---|
| | | MV/A/m | $\phi_0$,degrees |
| 0.18 | 14.17 | 0.83 | -10.5 |
| 0.17 | 15.78 | 0.85 | -10.7 |
| 0.16 | 17.67 | 0.95 | -12.6 |
| 0.15 | 19.23 | 1.05 | -15.0 |

### *2 Long-range dipole wakefield*

The long-range dipole wakefield is suppressed in the structure design by detuning the dipole mode frequencies and damping the fields with dipole coupling channels. For the manifold damping scheme adopted in the present design, it is required that the bandwidth at zero phase advance be larger than and overlap the π-phase advance bandwidth [4], which can only be satisfied with a proper combination of phase advance and average group velocity. With the 5π/6 phase advance and an average group velocity of 2%$c$, this condition can be met for a wide range of $a/\lambda$'s. Stronger damping is needed in a short structure since there are fewer cells available for detuning and damping. Analysis has shown that an acceptable wakefield can be achieved for the 60-*cm* structure with manifold damping. Further improvement on the wakefield can be achieved by 2, 3, or 4 fold interleaving, depending on the girder configuration. Detailed analysis of such schemes is presented in [5]. A compact HOM coupler is needed to reduce the number of "uncoupled" cells. A design with a broadband matching is realized using simple steps as shown in Fig.3. The new design reduces the number of uncoupled cells to one and the wakefield studies show satisfactory reflection and bandwidth. Other damping schemes, e.g. choke mode damping, are also being studied. However we will not address them here because of space limitations.

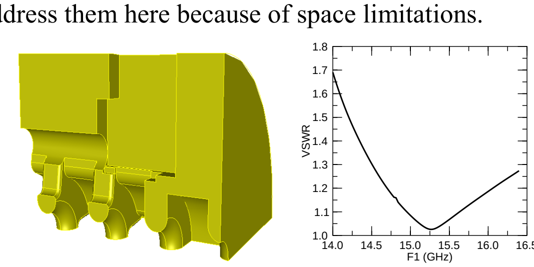


Figure 3 Compact HOM coupler reduces number of unslotted cells to one.

### *3 BNS damping - Single-bunch dipole wakefield*

The single-bunch dipole wakefield, scales as $a^{-3.8}$. To mitigate the associated single-bunch BBU, BNS damping, which introduces a head-tail energy spread, is necessary. The BNS damping energy spread is generated by accelerating the beam off crest and then must be removed at the end of the linac. Strong wakefield with smaller *a/λ* may subject the linac to large overheads for BNS damping as well as large emittance dilutions and tighter tolerance on the quad alignment. Here, we study the *a/λ* dependence of these effects for the JLC/NLC linac. The linac, in this model, is divided into three BNS [6,7] sections. The BNS phase configurations required for the linacs with different *a/λ* are shown in Table 2. A loaded gradient of 50-*MV/m* is assumed for all cases.

Table 2 BNS phases versus *a/λ*.

| *a/λ* | $\phi_1$, *degrees* | $E_1$, *GeV* | $\phi_2$, *degrees* | $E_2$, *GeV* | $\phi_3$, *degrees* |
|---|---|---|---|---|---|
| 0.18 | 12 | 30 | 0 | 165 | -30 |
| 0.17 | 14 | 30 | 0 | 162 | -30 |
| 0.16 | 16 | 30 | 1 | 142 | -30 |
| 0.15 | 19 | 30 | 4 | 113 | -30 |

The emittance along the linac due to an initial one $\sigma_y$ betatron oscillation and the emittance dilution at the end of the linac due to a misaligned quad as a function of the quad's position in the linac are shown in Fig. 4. For the betatron oscillation studies, the initial energy spread was set to zero. For the quad tolerance studies, the quad was misaligned such as to introduce a 1-$\sigma_y$ oscillation, and the nominal initial uncorrelated energy spread of 1.4% is included. Notice that it was not possible to achieve an acceptable emittance for *a/λ*=0.15, despite the significant BNS phase offsets utilized.

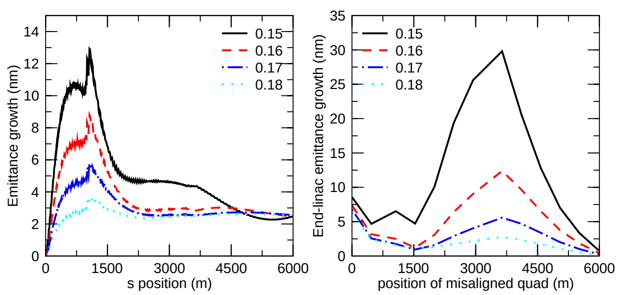


Figure 4 Left: Emittance growth along the linac due to an initial one $\sigma_y$ betatron oscillation; right) Emittance growth in end-linac emittance from a misaligned quad as a function quad position in the linac.

Table 3 RF requirement for 500-*GeV* machine, $G_L$=50*MV/m*.

| *a/λ* | *P*/struct (*MW*) | *N* struct | Total RF Power (*MW*) |
|---|---|---|---|
| 0.18 | 58.6 | 8434 | 494232 |
| 0.17 | 55.5 | 8454 | 469197 |
| 0.16 | 51.1 | 8564 | 437620 |
| 0.15 | 48.1 | 8731 | 419961 |

The RF power requirements for a 500-*GeV* center-of-mass (CM) energy machine are shown in Table 3 for comparison. Though requiring larger BNS overhead and beam loading, the gains in RF efficiency with smaller *a/λ* is still significant. Considering all the RF efficiency and beam dynamics issues for the JLC/NLC linacs, we believe an *a/λ* of 0.17 is a reasonable choice for the JLC/NLC baseline design. This will allow improved high power handling capability as compared with the design of *a/λ* =0.18 while maintaining high quality beams.

## 4 SURFACE FIELD AND PULSE HEATING

Measures to reduce the surface fields have been incorporated into the new structure design. Using elliptical irises, the surface fields can be reduced to about 2 times the average accelerating gradient. Sharp edges around the coupling iris in the high power coupler [8,9] and the dipole damping slot/manifold in the Damped Detuned Structure (DDS) cell have been rounded to reduce the enhancement of E and B fields and thus minimize potential multi-pactoring and high pulse heating related material fatigue, out gassing and breakdown. Using pie-shaped slots for the DDS cell, as shown in Fig.5, further reduces the enhancement of RF pulse heating around the slots. With these approaches, the pulse heating temperature rise is below $50^0C$ at a gradient of 70-*MV/m*, which is thought acceptable.

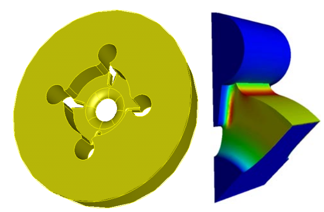

Figure 5 DDS cell with pie-shaped slots and rounded edges. Minimizes field enhancement and pulse heating.

## SUMMARY

In this paper, we have presented the design considerations needed to address the RF efficiency, high power breakdown, and beam dynamics issues. These measures are being incorporated in the future structure design to improve the high gradient performance of the JLC/NLC structures.

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