PASSIVELY DRIVING X-BAND STRUCTURES TO ACHIEVE HIGHER BEAM ENERGIES

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Abstract

Particle accelerators at X-band frequencies have been shown to reach gradients of greater than 100 MV/m [1,2]. Such technology permits more compact accelerators. One of our aims at the Colorado State University (CSU) Accelerator Laboratory is to adapt this technology to our L-band (1.3 GHz) accelerator system to increase our overall beam energy; however, we would like to do this in a passive manner, i.e. one that does not require investment in an expensive, custom, and high-power klystron system. In this paper we explore using the beam from our L-band 6-MeV photo-injector to power an X-band structure tuned to the 9th harmonic of our 1.3 GHz L-band system, 11.7 GHz. Electron bunches will be generated at a repetition rate of 81.25 MHz and passed through a high shunt impedance X-band accelerating structure where they will resonantly excite the fundamental field. Once the peak gradient is achieved a single electron bunch can be passed through the system at a phase that places it near the crest of the X-band accelerating wave thereby increasing the electron bunch energy without need for additional external power sources.

GENERAL CONCEPT

The CSU Accelerator Facility will initially focus on the generation of long-wavelength, free-electron laser pulses, as well as the development of electron-beam components and peripherals for free-electron lasers and other light sources. It will also serve as a test bed for particle and laser beam research and development.

One of the most important parts of this accelerator is the linac that was constructed by the Los Alamos National Laboratory for the University of Twente TEU-FEL Project [3]. In addition to the capabilities of this linac we would like to further increase the electron beam energy without additional significant investments. Our idea is to utilize the electron beam from the L-Band RF gun as a drive source for a passive X-band linac structure thus allowing us to increase the beam energy by using the L-band power together with the inherent high shunt impedance of the X-band structure.

PASSIVE X-BAND LINAC STRUCTURE

Table 1 provides the basic parameters of the CSU accelerator system [4]. SLAC has had a long history of developing X-band accelerator systems [5]; unfortunately for us, their chosen frequency is at 11.424 GHz and this is not a simple multiple of 1.3 GHz. As such, we need to slightly redesign the basic X-band accelerating structure geometry to meet our need for operation at a reasonable harmonic of 1.3 GHz. For this study we have chosen the 9th harmonic, i.e. 11.7 GHz. Given there are no existing 11.7 GHz klystrons to power such a structure we consider an alternative power source. Here we propose to use the beam from the L-band system to resonantly drive the X-band structure.

We would like to achieve the highest possible energies for our given beam parameters and proposed X-band drive system and therefore we will design the X-band system to have the highest practical shunt impedance.

Table 1. Parameters of CSU Accelerator Laboratory

Laser Frequency	81.25 MHz
L-Band RF Gun Frequency	1.3 GHz
L-Band RF Gun Energy	6 MeV
L-Band Macropulse Length	10 μs
X-band Linac Frequency	11.7 GHz
Repetition Rate	10 Hz
RF gun Charge/Bunch	3.5 nC

Geometry of the X-band Linac Structure

In general, the aim is to transfer energy from the L-Band RF wave to the electron beam, consisting of bunches of charged particles, and then from the electron beam to the RF wave induced in the X-band structure, thus we need to design a proper structure that maximizes this interaction.

We start by modifying the linac structure geometry of some of the successful SLAC designs [6]. Adjustments were made to ensure that the structure was resonant at 11.7 GHz, that it had high effective shunt impedance, that it was resonant on the π mode and that the iris dimensions were sufficient to ensure clean beam transport and minimize to some degree the effect of higher-order modes. As we plan to use an electron beam to provide power to the structure, a constant impedance structure is more appropriate than constant gradient. Figure 1 and Table 2 show the output from the design program SUPERFISH [7] following our optimization of the geometry using three different values for the iris to wavelength ratio, $a/\lambda = 0.2$, 0.15, and 0.1.

The Beam – Cavity Interaction

We wish to study the beam-cavity interaction seen within an X-band linac structure driven by a beam produced in our L-band linac traversing the X-band linac. The schematic view of the beam-structure system is shown in Figure 2.

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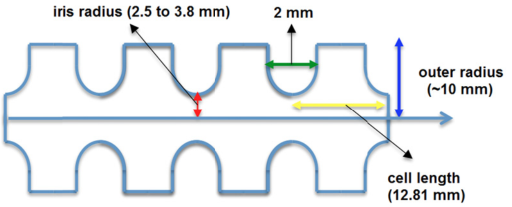

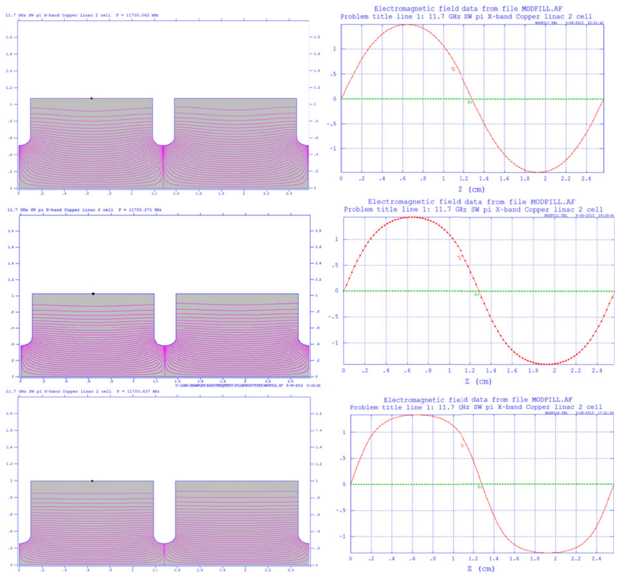

Figure 1: Two-cell models of the 11.7 GHz X-band linac performed using SUPERFISH [8,9,10] for 3 different values of the iris radius to wavelength ratio a/λ. Top 0.2, middle, 0.15, and bottom 0.1.

Table 2. Parameters of CSU X-band Linac

Parameters	**Unit**	**Values**		
Ratio of iris radius to wavelength (a/λ)		0.20	0.15	0.10
Shunt Impedance (R_{sh})	[MΩ]	62.4	83	170
Quality Factor (Q)		8958	8681	8512
Stored Energy (U)	[μJ]	29.9	21.3	15.5
Power Dissipation (P)	[W]	245.6	180.3	134.2
Ratio of Accelerating Gradient to Peak Surface **E** field (E_{max}/E_0)		2.28	1.95	1.68
Ratio of Peak Surface **B** Field to Accelerating Gradient (B_{max}/E_{max})	$\left[\frac{\text{mT}}{(\text{MV/m})}\right]$	1.56	1.60	1.62

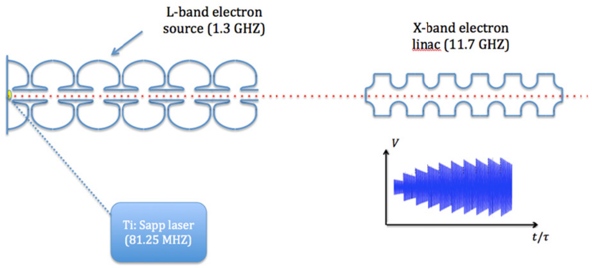

Figure 2: The schematic view of the beam structure for the system under study.

The configuration is unconventional in that the X-band linac does not require a klystron system to achieve high accelerating fields. Rather it uses the power existing in the electron beam to resonantly power the fields in the structure.

We can use two equivalent models for the interaction, one in the frequency domain and one in the time domain.

First let's consider the frequency domain. Our L-band linac and drive laser combination will deliver electron bunches at a frequency of 81.25 MHz. In the frequency domain the current will appear as a comb of frequencies with a spacing of 81.25 MHz. If our bunch length is short compared to the X-band wavelength the amplitude of these signals will equal I_o out well past 11.7 GHz. Thus, due to our choice of harmonic frequencies there will be a current drive term at 11.7 GHz. The voltage imparted to a single cell is then $I_o R_{s1}$ where R_{s1} is the single-cell shunt impedance at the resonant frequency.

We obtain an identical result in the time-domain using an equivalent circuit model. Upon each passage of a bunch of charge q through a cavity, the voltage steps up by $V_1 = q/C$ where C is the equivalent capacitance of the single cell. If the cavity fill time is τ then the voltage droops by the factor $V_t(1\text{-}e^{-t/\tau})$ for every period of time t. At equilibrium the droop equals the step. Assuming $t << \tau$

$$V_m = \frac{q/C}{t/\tau}$$

where V_m is the maximum achieved voltage. Using relations for the equivalent circuit

$$\tau = \frac{Q}{\omega},\ Q = \frac{R_{s1}}{\sqrt{L/C}},\ \omega = 1\big/\sqrt{LC},\ I_o = q/t$$

we arrive once again at a maximum voltage attained across a single cell of $I_o R_{s1}$[11].

Although this equation looks very promising, one must remember that the beam is not an infinite source of power, i.e. it has a finite starting beam energy, and so we must consider the available initial energy of the beam.

$$E_{initial} = qV_{gun}$$

where V_{gun} is the gun voltage and q is the charge in the bunch. The energy lost by the beam per cell must be accounted for and must not be larger than the total energy available. This sets a limit on the overall length of the X-band structure. Equating the energy loss to the energy gain one can solve for the number of X-band cells required to pull the L-band beam down to a chosen final beam energy. With this number one can determine the maximum net potential achieved within the X-band structure when supplied power by the beam from the L-band system.

$$V_{avail} = NV_m = V_m \frac{q\left(V_s - V_f\right)}{\Delta E}$$

where V_{avail} is the the net potential achieved, N is the number of X-band cells needed $eV_{s,f}$ are the start and final electron beam energies, and ΔE is the electron beam energy lost traversing an X-band cell. Again this can be obtained using the equivalent circuit model $E=(CV^2)/2$; therefore,

$$\Delta E=\frac{q^2}{C}\frac{\tau}{t} \quad \text{and} \quad N=\frac{\left(V_s-V_f\right)Ct}{q\tau}$$

Substituting one finally arrives at the simple solution

$$V_{avail}=\left(V_s-V_f\right)$$

i.e. the net potential achieved in the X-band system is exactly the potential lost by the beam from the L-band system.

Once the X-band structure has been powered up to the full potential a properly phased electron bunch can then be injected and accelerated and, for a properly designed and configured system can raise the beam energy to nearly twice what would have been available from the L-band system alone.

Table 3: Beam – Cavity Interaction Parameters

L-Band Bunch Charge	3.5 nC
L-Band Initial Beam Energy	6 MeV
L-Band Final Beam Energy	1 MeV
X-band Max. Gradient	30 MV/m
X-Band Shunt Impedance	191 MΩ/m
X-Band Eff. Shunt Impedance	107 MΩ/m
X-Band Q	8512
X-Band Equivalent Capacitance	8.5e-14 F
Damping Factor (t/τ)	0.1
X-Band Cell length	0.01281 m
Number of X-Band cells	13
Total length of X-Band structure	17 cm
Available X-Band Potential	5 MV

DISCUSSION AND CONCLUSION

The above result is independent of the frequency of the passive structure; however, the X-band system can be made much more compact due to its ability to handle the very high gradients. Nevertheless this basic result does represent a limitation. To achieve higher gradients one really needs to extract the X-band power and transfer it to a TW structure. This structure can be filled over a period of time thus utilizing the time-integrated power of the L-band beam.

We have shown that by proper design we can, by utilizing the beam from our L-band linac, resonantly excite an X-band accelerating structure to meaningful accelerating gradients. In our design example we can achieve up to 6-MV additional accelerating potential. Configured properly this implies that we can periodically achieve beam energies almost double our original 6 MeV and potentially reach roughly 12-MeV in occasional single pulses without the need for an additional X-band power source.

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