ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-THPRI073

ACHIEVING HIGHER ENERGIES VIA PASSIVELY DRIVEN X-BAND STRUCTURES

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Abstract

Due to their higher intrinsic shunt impedance X-band accelerating structures offer significant gradients with relatively modest input powers. At the Colorado State University Accelerator Laboratory (CSUAL) [1] we would like to adapt this technology to our 1.3-GHz, L-band accelerator system in order to increase our overall beam energy in a manner that does not require investment in an expensive, custom, high-power X-band klystron system. Here we provide the design details of the X-band structures that will allow us to achieve our goal of reaching the maximum practical net potential across the X-band accelerating structure while driven solely by the beam from the L-band system.

GENERAL CONCEPT

The Colorado State University Accelerator and FEL Laboratory has an L-band system capable of generating 6-MeV electron bunches [1]. We would like to further increase the electron beam energy without additional significant investment. Our idea is to utilize the electron beam from our linac as a drive source for an otherwise unpowered (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.

For our proposed Co-linear X-band Energy Booster system we start with the power extraction mechanism using the beam from the L-band linac passing through the power extraction cavity (PEC). This power is then delivered to the X-band main accelerating cavity (MAC) structures. One can then periodically pass a bunch through the whole system and achieve significantly higher beam energies [2,3]. This is done by simple switching of photocathode drive laser pulses and shifting the phase onto the cathode such that it puts the bunch into the accelerating phase of all accelerator structures. Finally, we describe a possible use of this high-energy electron beam using our existing undulator at CSU.

X-BAND PEC DESIGN

Here we choose to use a *2π/3*-mode TW X-band structure with parameters given in Table 1 and as computed by the design code SUPERFISH [4]. As we found in our earlier paper even for moderate shunt impedance the structure is relatively short as we are limited by the maximum amount of energy we can remove from the drive beam [5]. Based on our previous study the length of this cavity should be 15.4 cm in order to decelerate the beam from 6 MeV down to 1 MeV. Under such conditions the net X-band rf power that can be generated is 1.42 MW. More details can be found in the earlier references.

Table 1: Parameters for X-band PEC Structure

a/λ	0.2
Phase Advance per cell (ψ)	$2\pi/3$ Radian
Iris radius (a)	0.00512466 m
Cavity Radius (R)	0.0110955 m
Disk Thickness (h= $2r_1$)	0.002 m
Quality factor	6656 .15
Length	0.154 m
Frequency	11.7 GHz
Shunt impedance	57.15 MΩ
Power Dissipation	16142.1 W

X-BAND MAC DESIGN

The optimization for X-band MAC design follows a different path. In this design we wish to maximize the energy gain in an optimum length and get the highest integrated potential through one or more cavities; therefore, we chose to design a new geometry, and change the phase advance from 2π/3 to a higher mode, 5π/6. This slows the group velocity and allows us to increase the length of the structure and provide more opportunity to increase the integrated potential [6]. All structure parameters for the TW accelerator can be deduced from those of the SW structure. In particular, the group velocity can be computed by

$$\vartheta_g = \frac{d\omega}{dk_z} = \frac{2(2.405)c}{3\pi J_1^2(2.405)}\left(\frac{a}{R}\right)^2 \sin\psi e^{-\alpha h}$$

where ψ is the phase advance per cavity and α is the attenuation per unit length of the field for the TM_{010} mode through an iris of wall thickness h.

If we wish to decrease the group velocity and we have chosen a minimum *a,* we are left only with ψ as a variable. This then argues for a large TW mode number defined as n in $2\pi/n$, and is shown in Figure 1 where the relative velocity comes from the sine term.

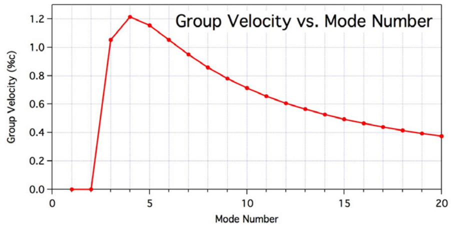

Figure 1: Relative Velocity vs. Mode Number.

This certainly would argue that that the $2\pi/3$–mode is not the best choice and that a mode number of more like 8 or 10 would be better and might still be practical;

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however, as it is seen from Figure 2, choosing a proper value such that 2<n<3 can give us the required solution. For that purpose and for an $a/\lambda = 0.1$ single cell geometry, moving the rf phase advance to $5\pi/6$ and using a longer cell length compared to that of the $2\pi/3$ mode in order to preserve synchronous acceleration of the electron bunch slows down the group velocity to 0.95% c and increases α_0 from 0.30 to 1.69 allowing more efficient deposition of the rf power in the accelerating structure [7,8].

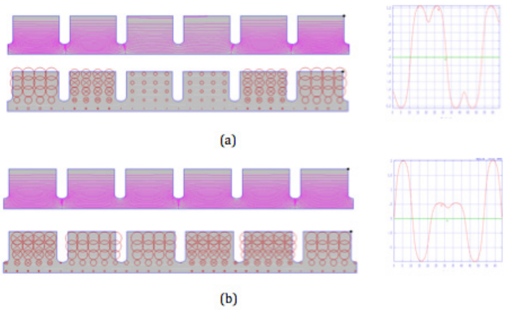
Table 2 gives the resulting geometry parameters for a $5\pi/6$ phase advance MAC structure. This cavity will see a single, relatively low charge electron bunch, so the aperture requirements are not as severe. Further, we wish to maximize the overall integrated voltage seen by the beam during its passage. This clearly argues for high shunt impedance and as long a structure as reasonable.

Our L-band system is also capable of generating beam for over 10 µs, i.e. significantly longer than the fill time of typical X-band structures. This then argues for a structure with a very slow group velocity as it will allow us to fill a longer cavity and capitalize on the long L-band rf pulses.

Table 2: Parameters for MAC Structure

a/λ	0.1
Inner radius	0.00256233 m
Phase Advance	$5\pi/6$ Radians
Cavity Radius	0.01012 m
Disk Thickness	0.002 m
Frequency	11.7 GHz
Quality factor	7598.7
Shunt impedance	153.67 MΩ
Group Velocity	0.95 %

Shown in Figure 2 are the cavity fields, both electric and magnetic, as computed by SUPERFISH for both Neumann and Dirichlet boundary conditions as specified at the end walls for MAC.


(a)

(b)

Figure 2: Electric and magnetic field patterns for $a/\lambda = 0.1$ in (a) Neumann boundary condition for $5\pi/6$ mode (b) Dirichlet boundary condition for $5\pi/6$ mode.

Increased Number of Linac Sections Configuration for Higher-Energy Gain

The basic one linac configuration, that is an L-band gun system beam powering PEC used to generate X-band power and all the power fed into a single optimized MAC, achieves an integrated potential significantly higher than our original direct attempt; however, we considered three different scenarios that allowed us to achieve a higher potential with our new proposed system. The most recent configuration is shown in Figure 3. In these configurations we divide the power into four different structures to achieve a higher integrated potential than possible with a single structure; furthermore, if the input power and shunt impedance are fixed, the maximum energy gain over a structure of given length depends on maximizing the total attenuation parameter. In this case it becomes 1.26. Then, by using the quality factor and group velocity parameters from Table 2, we can calculate the optimal MAC length. Available potential and maximum energy gain values for 0.64 m length MAC structure are given in Table 3.

Table 3: Available potential and maximum energy gain values for 0.64 m length MAC.

Number of x-band cells	60
Filling time per section	223 ns
Available potential (1section)	9.67 MV/m
Available potential (2section)	6.84 MV/m
Available potential (4section)	4.83 MV/m
Maximum energy gain (1 section)	11.6 MeV
Maximum energy gain (2 section)	16.4 MeV
Maximum energy gain (4 section)	23.2 MeV

Cavity Response of X-band PEC Structure

Using the ideas described above we want to build up an efficient power gain mechanism in our X-band PEC using the pulse train generated from our photocathode RF electron gun system. If we generate 3.5-nC bunch charge at a repetition rate of 81.25 MHz we will have 284 mA of drive beam current. At the equilibrium condition, the induced voltage generated by the following bunch compensates the voltage drop experienced between bunches. The equations, which are used to get the maximum voltage, are given in Figure 4 (red plot, shows the response).

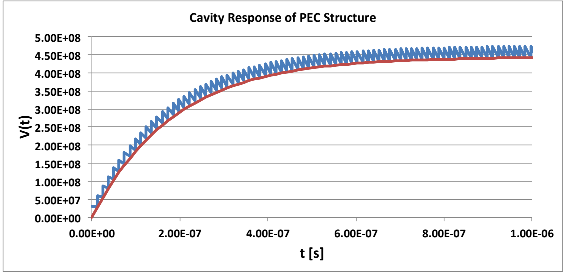


Figure 4: Cavity response of PEC structure [9].

RF Power Generation with X-band PEC

A relevant and well-optimized Gaussian bunch train structure passing through the structure of length L builds up a voltage across the structure of peak value.

$$V_d = \frac{\omega}{4}\left(\frac{R}{Q}\right) L q_d$$

where q_d is the total beam charge, L is the length of the X-band PEC structure.

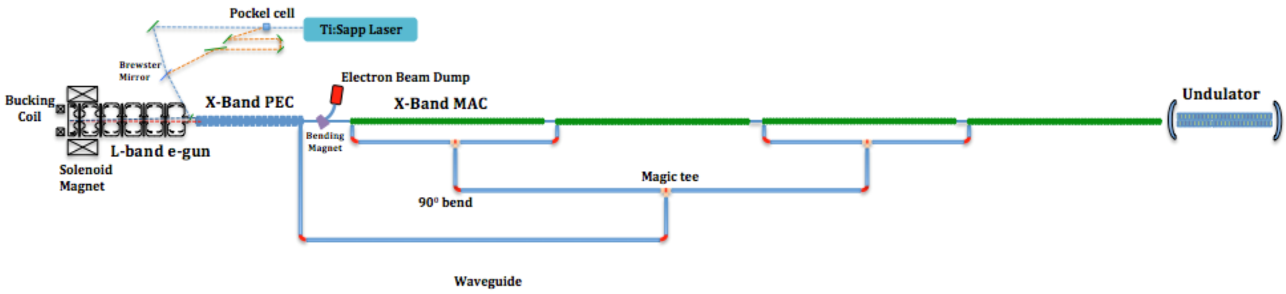


Figure 3: The case of four accelerating structures for the system under study.

The duration time can be fixed by adjusting the X-band PEC structure length and therefore the output power. The power extracted from a relativistic bunch train can be calculated as

$$P = \frac{\omega}{4c}\left(\frac{R}{Q}\right)\frac{L^2 I^2}{\beta_g}\left(\frac{1-e^{-\alpha L}}{\alpha L}\right)^2 F^2(\sigma)$$

where $\alpha = \frac{\omega}{2Qv_g}$ is the attenuation factor. $F(\sigma) = e^{-(k\sigma)^2/2}$ is the form factor for a relativistic Gaussian bunch, k is the propagation constant of the excited mode and σ is the bunch length, $F^2(\sigma)$ is the power form factor [10, 11].

The results of X-band PEC for bunch spacing $T_b = 770\, ps$ and 13.6 ps bunch length are given in Table 4 according to these parameters.

Table 4:Power Extraction Results for X-band PEC

Extracted Power (MW)	1.37
Frequency (GHz)	11.7
Shunt Impedance per meter (MΩ/m)	57.15
Normalized velocity	13.86%
R/Q per PEC length (Ω/m)	110
Cell length (m)	0.00854
Cell Number	18
X-band PEC Length (m)	0.15372
Filed attenuation factor per unit length	0.133
Form factor of the bunch	1.65
Group velocity (m/s)	6.4010^{6}
Sigma (m)	6.2810^{-4}
Propagation constant (1/m)	245.44

Possible Use of the Higher Energy Beam

A possible use of the 25.8-MeV high-energy electron beam would be to reach IR wavelengths, possibly in an FEL configuration, using our existing undulator [12].

CONCLUSION

In this study we provided designs for two different TW X-band structures that would allow us to achieve higher energies in a compact way. To achieve higher potential one really needs to extract the X-band power from the X-band decelerating cavity and transfer it to a low group velocity traveling wave structure. Optimizing the group velocity by adjusting the inner radius of the constant-impedance structure and using a more relevant mode both improves the power efficiency and overall integrated potential. We can achieve 25.8 MeV maximum energy with four TW linac structures included serially at the end. That possible high energy electron beam can be used in our hybrid undulator at CSU for achieving photons at MID-IR range instead of the racetrack microtron at TEU-FEL.

ACKNOWLEDGMENT

We wish to thank the SLAC National Accelerator Laboratory for their support of this work and in particular our fruitful discussions with Chris Adolphsen. We also wish to thank the senior management of CSU for their support of the accelerator laboratory and accelerator education.

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