

# CO-LINEAR X-BAND ENERGY BOOSTER (XCEB) CAVITY AND RF SYSTEM DETAILS

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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) 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. This is done by simple switching of the 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.

While we have presented this concept before in other conference papers [2,3,4], we would like to reiterate the idea as well as add some additional information that has been accomplished since our last publication on the topic.

## X-BAND POWER EXTRACTION CAVITY DESIGN

Here we choose to use a  $2\pi/3$  mode TW X-band structure with parameters given in Table 1 and as computed by the design code SUPERFISH [5] (Figure 1). 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 [6]. 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.

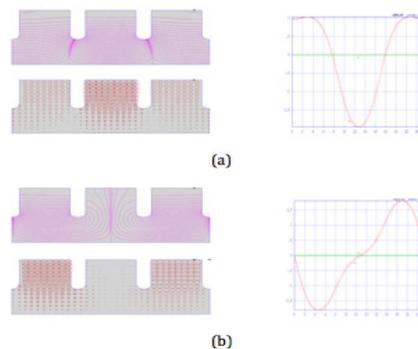


Figure 1: Electric and magnetic field patterns for  $a/\lambda = 0.2$  in (a) Neumann boundary condition at end walls for  $2\pi/3$  mode (b) Dirichlet boundary condition at end walls for  $2\pi/3$  mode

Table 1: Parameters for X-band PEC Structure

$a/\lambda$	0.2
Phase Advance per cell ( $\psi$ )	$2\pi/3$ 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

## X-BAND MAIN ACCELERATING CAVITY DESIGN

The optimization for the 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  $2\pi/3$  to a higher mode,  $5\pi/6$ . This slows the group velocity and allows us to increase the length of the structure and provide more opportunity to increase the integrated potential [7,8,9].

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 as with the PEC. 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.

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Our L-band system is also capable of generating beam for over 10  $\mu\text{s}$ , 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

$a/\lambda$	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 M $\Omega$
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.

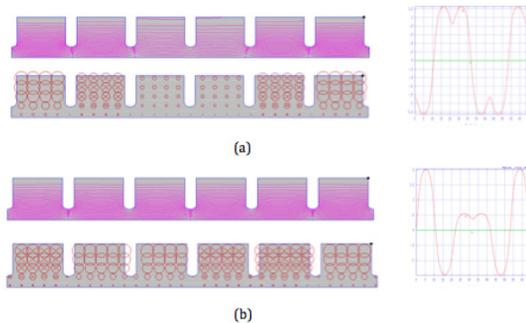


Figure 2: Electric and magnetic field patterns for  $a/\lambda = 0.1$  in (a) Neumann boundary condition for  $5\pi/6$  mode (b) Dirichlet boundary condition for  $5\pi/6$  mode.

### Power Extraction Mechanism

When a bunch passes through an unfilled RF cavity it interacts with the cavity and deposits some of its kinetic energy. This energy is converted into rf fields that can be decomposed into the resonant modes of the RF cavity. If a steady stream of bunches is passed through the cavity and the spacing of the bunches is such that they are precisely in phase with one of the cavity modes, then this mode gets reinforced and can grow to large values. As time progresses the field builds up as does the impact on the passing electron bunch until an equilibrium is reached where the power being dissipated/extracted is equal to the power delivered. In the case of power extraction this power can be delivered to another device and be used as desired.

In order for the mode excitation to be coherent and therefore constructive, the bunch spacing  $T_b/c$  needs to be a multiple of the mode period and the mode phase velocity needs to be equal to the speed of the relativistic bunches. The bunch separation time  $T_b$ , however, must be much shorter than the cavity fill time in order for several bunches to contribute to the build up of the voltage  $V_d$ .

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 3 (red plot, shows the response).

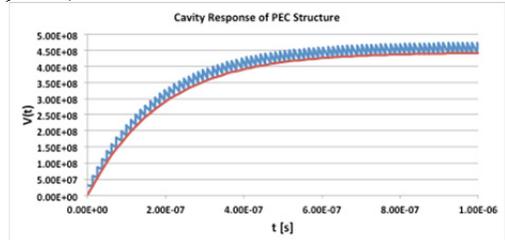


Figure 3: Cavity response of PEC structure [10].

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.

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  $\sigma$  is the bunch length,  $F^2(\sigma)$  is the power form factor [11, 12].

The results of X-band PEC for bunch spacing  $T_b = 770 \text{ ps}$  and  $13.6 \text{ ps}$  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 (M $\Omega$ /m)	57.15
Normalized velocity	13.86%
R/Q per PEC length ( $\Omega$ /m)	110
Cell length (m)	0.00854
Cell Number	18
X-band PEC Length (m)	0.15372
Field 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

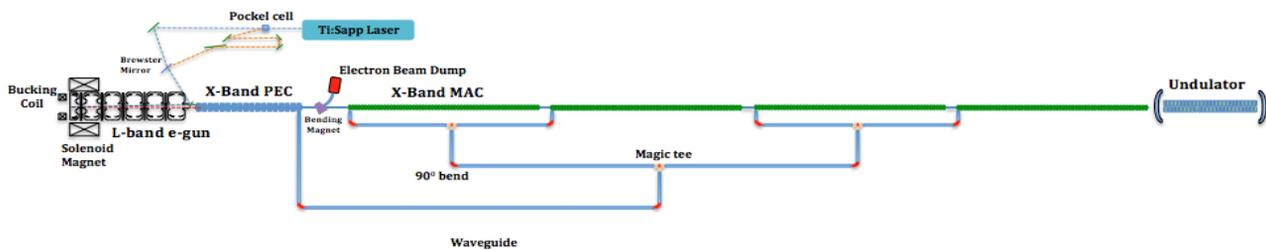


Figure 4: The case of four accelerating structures for the system under study.

### Available Potential and Maximum Energy Gain

Our primary goal of the proposed research will be to boost the energy of our existing 6-MeV system by over a factor of 4, thus proving the Co-linear X-band Energy Booster concept.

Figure 4 shows a basic overview of the concept. The primary beam is produced in the L-band gun (left). Bunches of a few  $nC$ , spaced by  $12.3 ns$ , over a duration of roughly  $10 \mu s$  are accelerated to 6 MeV by the L-band accelerator system. These bunches then pass through the X-band power extraction cavity (PEC). This cavity is tuned to 11.7 GHz, the 9<sup>th</sup> harmonic of the L-band system (1.3 GHz). The electrons drive the 11.7 GHz in the cavity and lose power to the cavity. After a number of bunches have passed through the PEC the equilibrium X-band field is reached. At this point the beam loading is such that 6 MeV bunches entering the X-band cavity are decelerated by 5 MeV and depart the PEC at 1 MeV. This beam is discarded into an electron dump. The power of the beam is converted to X-band power that is directed from the exit of the PEC to a co-linear X-band main accelerating cavity (MAC). The fill time of the structure is relatively short and the whole process from the start of beam in the L-band linac to full gradient along the entire length of the systems is achieved in a few hundred nanoseconds. This leaves many microseconds of beam to be used.

A clever trick is then employed to periodically accelerate a lower charge, very high-brightness beam. A single pulse is periodically switched out of the laser pulse train and sent on a separate path. This path length is adjusted to place the laser pulse precisely 20 degrees offset in L-band phase from the other pulses. Its energy is also adjusted downwards to the desired value. Upon striking the photocathode, the electron bunch produced by this laser pulse is in near the ideal phase for optimal emittance out of the L-band gun; it is also precisely 180 degrees offset in X-band phase from the other electron bunches that are generating the accelerating field. This 6 MeV bunch, then, enters the PEC at the maximum accelerating potential and picks up another 5 MeV bringing its total energy to 11 MeV after passage through the PEC. The dipole directing the 1 MeV bunches to the beam dump has little impact on this 11 MeV bunch and two more following dipoles brings this bunch back on line with the accelerator system with zero residual dispersion. This bunch is then ready for acceleration by the MAC. The 1+ MW of RF power from the PEC is split 4 ways and fed into the MAC, a series of 4 optimally designed X-

band accelerating structures. This power is then converted into an additional roughly 14 MV of accelerating potential and is used to bring the high-brightness bunch up to a total of 25 MeV. Because the beam loading from this single small bunch is relatively small compared to the beam loading from the drive bunches it has minimal impact on the PEC field, as such many lower charge, high-brightness bunches can be accelerated over the course of the remaining  $10 \mu s$  of X-band power generation.

### Possible Use of the Higher Energy Beam

As for an example application of this system, we expect to be able to accommodate an additional high-brightness bunch spaced by between 5 to 10 drive bunches. This will allow us to take the high-brightness bunch and pass it through an undulator cavity set up in an oscillator configuration and so have an operational, saturated FEL operating at wavelengths at least 17 times shorter in wavelength than what is possible with the 6-MeV beam, a very significant jump for a relatively small additional investment on the existing relatively large capital investment.

## 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 high brightness photons at wavelengths at least 17 times shorter in wavelength than what is possible with the 6-MeV beam.

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