WAKEFIELD EXCITATION IN POWER EXTRACTION CAVITY (PEC) OF CO-LINEAR X-BAND ENERGY BOOSTER (CXEB) IN TIME DOMAIN WITH ACE3P

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Abstract

In our previous papers we provided the general concept and the design details of our proposed Co-linear X-band Energy Booster (CXEB) as well as more advanced 3D simulations of our system using the frequency domain solvers OMEGA3P and S3P of the ACE3P Suite. Here, using the time domain solver T3P of ACE3P, we provide the single bunch and multiple bunch wakefield excitations resulting from a Gaussian bunch. The related power extraction mechanism for our traveling wave (TW) X-band power extraction cavity (PEC) are also discussed further.

BEAM BUILD-UP AND POWER EXTRACTION MECHANISM FOR X-BAND PEC

As spelled out in our previous papers on this topic 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 equilibrium is reached where the power being dissipated 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 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 shorter than the cavity fill time of the excited RF mode in order that several bunches can contribute to the build up of the voltage V_d.

At the equilibrium condition, the induced voltage generated by the following bunch compensates the voltage drop experienced between bunches.

In our X-band Co-linear Energy Booster system, that is presented in another paper at this conference [1], the resonant frequency of the power extraction cavity (PEC) is 11.7 GHz and our Ti:Sapp laser is capable of producing pulses at a rate of 81.25 MHz, therefore the X-band RF oscillates 144 times for each passage of an electron bunch.

This is a lot of time and so the Q of the X-band structure needs to be taken into account, as there will be some decay in the field between excitations from the electron bunch.

We apply the mechanism described by the fundamental theorem of beam loading. According to this theorem [2] the induced voltage that a charge passing through the cavity experiences is equal to half the induced voltage that the particle leaves behind in the PEC.

$$V_q = \frac{V_b}{2}$$

Assume a bunch train passes through an RF structure of length L , shunt impedance per unit length of R and quality factor of Q. The total charge passing through the structure in one fill time T_d is equal to $q_b T_d$ where q_b is the charge per bunch. The voltage across the structure will reach a peak value of

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

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 wavelength and the mode phase velocity needs to be equal to the speed of the relativistic bunches. The bunch time separation T_b , however, must be much shorter than one fill time $T_d = \left(\frac{1}{\beta_g} - 1\right) L/c$, where β_g is the group velocity of the wave in the TW structure. This condition will allow several bunches to contribute to the build up of the voltage V_d. The energy deposition rate by the electron beam or the RF power generated in the PEC can be obtained by multiplying the voltage V_d by the average beam current in one fill time:

$$P = \frac{\omega}{4}\left(\frac{R}{Q}\right) L \frac{{q_d}^2}{T_d} F^2(\sigma)$$

where $F^2(\sigma)$ is the power form factor that takes into account the finite length and shape of the bunches. $F^2(\sigma) = 1$ for infinitely short bunches.

For a train of bunches lasting much longer than the structure fill time the peak power level of the equation above will not be exceeded but the average will stay constant provided that the charge per fill time remains constant. Therefore, this equation gives the steady-state power level at the structure output when neglecting the internal wall losses. It can be now written as [3]:

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

We performed our time domain beam dynamics simulations on the NERSC (National Energy Research Scientific Computing Center) [4] computers. The code used was T3P a time domain solver and part of SLAC's Advanced Computational Electromagnetics Code Suite ACE3P's (Advanced Computational Electromagnetics 3D Parallel) [5, 6] . The 3D CAD modeling and visualization were done using the Trelis [7] and Paraview [8] software, respectively. Some of the important parameters are given in Table 1.

Table 1: Parameters for TW X-band PEC

Parameter	Value
Frequency	11.7001 GHz
Phase advance per cell	$2\pi/3$ Radians
Inner radius to wavelength ratio	0.11
Quality factor	6449.36
Cell length	0.0085411
Shunt Impedance	104 MΩ/m

GAUSSIAN BEAM OPTIMIZATION FOR X-BAND PEC STRUCTURE

For an efficient and successful power extraction at the end of the X-band PEC our longer drive beam needs to be optimized. We can calculate the power using the formula for the maximum current with a very thin bunch size (almost flat that gives us the form factor 1) and shunt impedance.

$$P_{rf} = I_0^2 R_{sh}$$

$$I_0 = Q f_{laser}$$

However, a flat beam is unrealistic and would lead to zero charge delivered for a finite current density off the cathode. Furthermore, a bunch that is too long does not have the frequency components to drive the cavity efficiently so there is an optimal bunch length for some given allowed cathode current density and desired resonant frequency. Instead of using a very flat beam we need to define a more realistic Gaussian bunch distribution shown in Figure 1 for our specific frequency and drive beam parameters to achieve an efficient power extraction mechanism. Then, our current will be:

$$I_x = I_0 e^{\frac{\omega^2 \sigma_r^2}{2}}$$

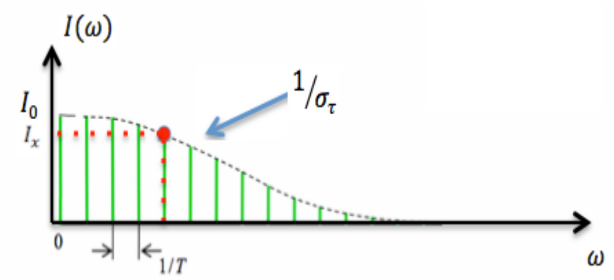

Figure 1: Current optimization for X-band PEC.

From the definition of the Gaussian beam distribution we define a Gaussian bunch in T3P for the mode excitation using a single bunch that has 5 nC bunch charge and extends out +/- 5σ. This is used to calculate the number of bunches that contributes to the power build-up process for our X-band PEC length optimization in order to achieve our desired beam power at the excitation port.

A multi bunch simulation using 20 Gaussian bunches spaced by 12.3 ns was performed. We used bunch length of 4, 2 and 1 mm this corresponds to a form factor of 0.6 for the longest bunch and 0.97 for the shortest:

$$F(\sigma) = e^{-(k\sigma)^2/2}$$

where k is the wavenumber for the excited mode in X-band PEC.

Using the field attenuation factor per unit length for a constant shunt impedance traveling wave cavity we can write the equation:

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

where

$$\alpha = \frac{w}{2Q v_g}$$

Using the equation above for the parameters in Table 1 and 2 we have the extracted beam power for our X-band PEC.

Table 2: Beam Parameters for X-band PEC

Parameter	Value
Number of X-band PEC cells	51
Bunch charge	5 nC
Bunch separation	12.3 ns
Bunch length	4 mm to 1 mm
Relative group velocity	0.0231%c
Form factor	0.6 - 0.97
Extracted power	0.55 - 1.42 MW

The simulated power build-up for these parameters is shown in Figure 2. This is consistent with our previously presented cavity voltage response in our recent studies [9].

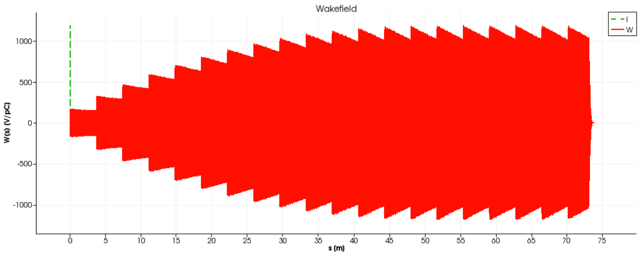

Figure 2: Power build-up for X-band PEC.

CONCLUSION

In this study we provided the time domain beam dynamics results for our design of a TW X-band PEC that will allow us to achieve higher energies in a compact way. Our calculations showed that we can achieve 1.4 MW extracted power with our X-band PEC structure. If we then direct this power to our four TW X-band main accelerating structures [10] we can achieve 23.6 MeV maximum energy at the end of CXEB. Finally, the resultant high-energy electron beam can be used with our existing hybrid undulator for achieving photons at MID-IR range.

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