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

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Abstract

We provide the general concept and the design details of our proposed Co-linear X-band Energy Booster (CXEB). Here, using the time domain solver T3P of the ACE3P Suite we provide the single bunch and multiple bunch wakefield excitation mechanism for the power build up when using a symmetric Gaussian bunch distribution in our traveling wave (TW) X-band power extraction cavity (PEC). Finally, we determine the achievable X-band power at the end of the PEC structure.

POWER EXTRACTION FOR X-BAND PEC

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 passage 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, presented in our previous studies [1,2,3], the resonant frequency of the power extraction cavity (PEC) is 11.7 GHz. Our Ti:Sapp laser is capable of producing 81.25 MHz pulses, therefore the X-band RF osclates 144 times for each passage of an electron bunch.

Equation 1 gives the steady-state power level at the structure output when neglecting the internal wall losses [4]:

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

or in terms of the field attenuation factor per unit length (α) for a constant shunt impedance traveling wave cavity we can write the Equation 1 as [5]:

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

where

$$\alpha = \frac{w}{2Qv_g} \tag{3}$$

ω is the frequency, Q is the quality factor of the cavity, v_g is the cavity group velocity, L is the length of the cavity, R is the cavity resonant mode shunt impedance, and $F(\sigma)$ is the form factor for a bunch of length σ. This equation is used as an initial estimate for performance and as a check of the simulation.

We performed our time domain beam dynamics simulations using the NERSC (National Energy Research Scientific Computing Center [6]) parallel computing sources and SLAC's Advanced Computational Electromagnetics Code Suite ACE3P's (Advanced Computational Electromagnetics 3D Parallel) [7] time domain solver T3P [8]. The 3D CAD modeling and visualization were done using the Trelis [9] and Paraview [10] software, respectively. Some of the important X-band PEC structure parameters that are presented in another paper of this conference were simulated using OMEGA3P are given in Table 1 [11].

Table 1: Parameters for TW X-Band PEC

Parameter	Value
Frequency [GHz]	11.7001
Phase advance per cell [Radians]	$2\pi/3$
Inner radius to wavelength ratio	0.10
Quality factor	6458
Cell length [mm]	8.5411
Shunt Impedance $\text{M}\Omega/\text{m}$	110

GAUSSIAN BEAM OPTIMIZATION FOR CONSTRUCTIVE WAKEFIELD EXCITATION IN 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.

$$P_{rf} = I_0^2 R_{sh} \tag{4}$$

$$I_0 = Nef_{laser} \tag{5}$$

Instead of using a very flat beam that gives the form factor 1, 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:

$$I_x = I_0 e^{\frac{\omega^2 \sigma_T^2}{2}} \tag{6}$$

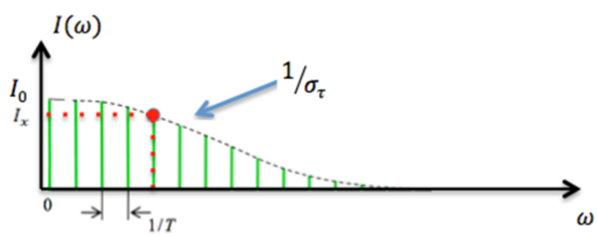

Figure 1: Current optimization for X-band PEC.

From the definition of the Gaussian beam distribution we define a symmetric Gaussian bunch in T3P [10] for the mode excitation using a single bunch that has 3 nC bunch charge with $\pm 5\sigma$ to calculate the number of bunches that contributes the beam build-up process in our X-band PEC length optimization to achieve our desired beam power at the excitation port using Equation 7.

$$\tau_s = L(1 - \beta_g)/v_g \tag{7}$$

where, $\beta_g = v_g/c$.

Figures 2 and 3, respectively, shows the wakefield excitation and impedance spectrum, of a single bunch that has 3 nC bunch charge and 1 mm bunch length in a 66-cell X-band PEC structure.

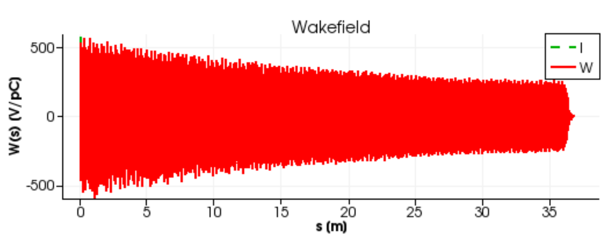

Figure 2: Wakefield excitation of a single bunch for the length optimization of the X-band PEC.

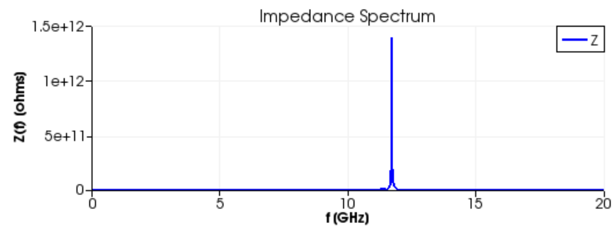

Figure 3: Impedance spectrum of X-band PEC using a single bunch.

If a second bunch reaches the end of PEC after the first bunch but before the power from the RF pulse dissipates, then there will be a region where the RF pulses of the two bunches overlap. To create an in-phase superposition of the excited RF fields, the frequency of the excited RF mode f_{X-band} is chosen to be a harmonic of the bunch frequency, that is $1/T_{laser}$ for our case, for a train of n bunches evenly spaced in time by $1/T_{laser}$. Then the filling time of the X-band PEC can be calculated by the number of bunches whose RF pulses overlap with the first RF pulse using τ_s/T_{laser}.

We adjusted our X-band PEC length using Equation 1 for our desired power loss, i.e. a loss 5-MeV per particle. After that we performed simulations using the description above for a bunch train that has 20 symmetric Gaussian shaped bunches with 12.3 ns bunch separation between each other. Theses bunches have 3 nC bunch charges each. We used bunch lengths 4, 2 and 1 mm. In that case we had the form factor 0.62 for the longest bunch length (4 mm) and 0.97 for the shortest one (1mm) using the equation:

$$F(\sigma) = e^{-(k\sigma)^2/2} \tag{8}$$

where, k is the propagation constant for the excited mode 11.7 GHz in X-band PEC.

Using either Equation 1 or 2 with the parameters in Tables 1 and 2 we have the extracted X-band beam power for our X-band PEC. Compared with our most recent study [12] we reduced the bunch charge and increased the X-band PEC length. The 66-cell structure, wakefield excitation for the beam build-up in it and the impedance spectrum of the X-band PEC are shown in Figures 4, 5 and 6, respectively.

Table 2: Beam Parameters for X-Band PEC

Parameter	Value
Number of X-band PEC cells	66
Bunch charge	3 nC
Bunch separation	12.3 ns
Bunch length	1 mm
Relative group velocity	% 0.0163
Form factor	0.97
Extracted power	1.14 MW

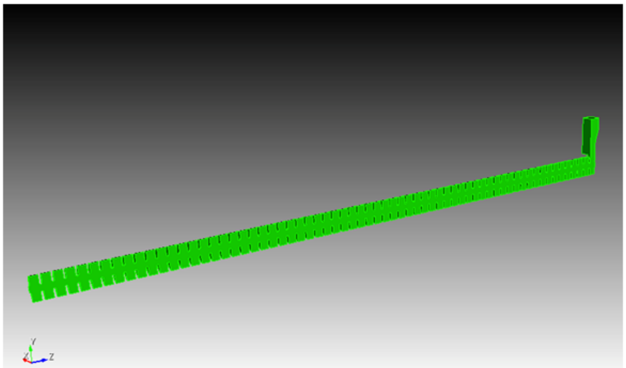

Figure 4: 66-cell X-band PEC with the half symmetry.

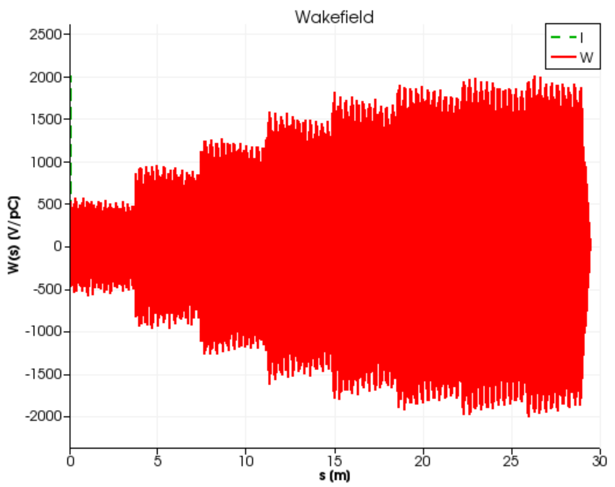

Figure 5: Wakefield excitation of multiple bunches for the beam build-up in X-band PEC.

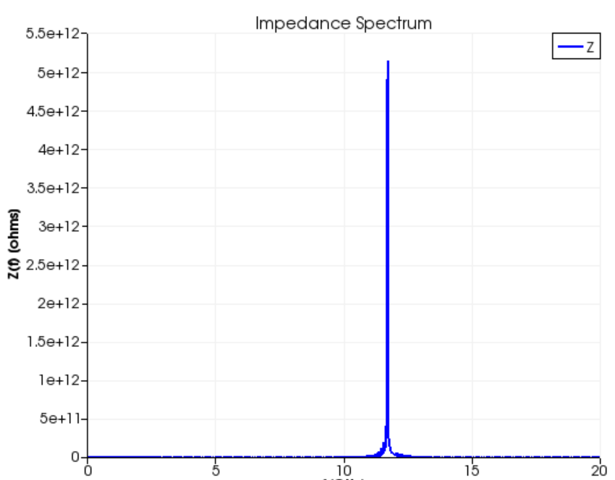

Figure 6: Impedance spectrum of X-band PEC using multiple bunches.

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 1.14 MW extracted power with our X-band PEC structure. Then using that power to feed our 4 TW MAC structures [13] we can achieve 21.2 MeV maximum energy at the end of CXEB. Finally, the resultant high-energy electron beam can be used in an FEL system for achieving photons at MID-IR range.

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