HIGH FREQUENCY HIGH POWER RF GENERATION USING A RELATIVISTIC ELECTRON BEAM

C. Jing#, S. Antipov, P. Schoessow, and A. Kanareykin, Euclid Techlabs LLC, Solon, OH-44139
J.G. Power, M. Conde, and W. Gai, Argonne National Laboratory, Argonne, IL-60439
Y. Yang and H. Chen, Tsinghua University, Beijing, China

Abstract

High frequency, high power rf sources are required for many applications. Benefiting from the ~10 GW beam power provided by the high current linac at the Argonne Wakefield Accelerator (AWA) facility, we propose to develop a series of high power rf sources based on the extraction of coherent Cherenkov radiation from the relativistic electron beam. The frequencies cover from C-band up to W-band with different structures. Simulations show that ~1 GW 20 ns rf pulse can be generated for an 11.7 GHz structure, ~400 MW for a 26 GHz structure, and ~14 MW for a 91 GHz structure.

INTRODUCTION

Wakefield effects are very important considerations for accelerator design because they are the major source of beam instabilities such as bunch lengthening, head-tail turbulence and emittance growth. However, the wakefield energy generated by a charged particle beam also can be used to accelerate an appropriately phased trailing beam or extracted by a high efficiency RF coupler working as a high power RF source. Generally, the RF packet generated by a single particle bunch lasts a few nanoseconds. A properly spaced bunch train can stack the RF pulses from each bunch so that both the pulse length and amplitude are increased [1]. Due to the ease with which the RF power characteristics can be changed by manipulating the decelerator and its drive bunches, this method may overcome some of the limitations of other conventional high-power RF systems at frequencies above X-band and power levels beyond a few hundred megawatts. A successful example is the CLIC PETS (Power Extraction and Transfer Structure) which can provide ~240 ns, 135 MW RF power using ~100 A drive beam current [2].

PETS uses a metallic corrugated waveguide working as a decelerator, where the electron drive beam loses kinetic energy and generates the wakefields. Another option is to use a dielectric loaded waveguide. The applications of dielectric loaded waveguides as accelerating structures have been under extensive study for the past two decades. The basic RF structure is very simple - a cylindrical, dielectric tube with an axial vacuum channel is inserted into a conductive sleeve. The dielectric constant and the inner and outer radii of the dielectric tube are chosen to adjust the fundamental monopole mode frequency generated by passing beam (here the TM_{01} mode). The phase velocity of the mode will equal the beam velocity ~ c. Such a simple geometry makes dielectric-lined waveguides attractive candidates for high frequency band accelerating structures, where it is expensive and difficult to precisely fabricate conventional iris-loaded copper structures. Some other advantages of using dielectric based structure include a potentially higher breakdown threshold, easy parasitic mode damping, and very low values of the ratio of the electric field on the dielectric surface to that on axis.

TIME STRUCTURE AND POWER

Relativistic beam based wakefield power generators usually consist of two parts: the decelerator section to transfer beam kinetic energy to the EM wave, and the coupling section to efficiently extract the EM wave. The decelerator is in general a constant impedance, high group velocity structure. When a high current bunch train passes through it, a high power rf packet moving in the same direction of beam will be generated. Figure 1 shows the formation of rf packet in this process. We assume a drive bunch travelling in the $+z$ direction enters the decelerator of length L at the moment $t=0$ and location $z=0$ (Fig. 1a). At time t when the bunch is still inside the decelerator (Fig. 1b), the head of the rf pulse (moving at c) is located at $z=ct$, while the tail of the rf pulse (moving at v_g) is located at $z=v_g t$. When the bunch (and the head of the rf pulse) reaches the downstream end ($z=L$) of the decelerator (Fig. 1c) the time is $t=L/c$ and the tail of the rf pulse has reached the position $z=v_g L/c$. At this moment, the generated rf pulse would begin to be extracted by an rf coupler (not shown) at $z=L$, but in this heuristic description we imagine the rf packet propagating out of the end of the decelerator at $z=L$. The tail of the rf pulse exits the decelerator (Fig. 1d) at time $t=L/v_g$. The duration of the rf pulse is the difference between the moment the bunch reaches the exit ($t=L/c$) and the moment the tail of the rf pulse reaches the exit ($t=v_g L/c$). Therefore, the rf pulse duration for a single-bunch excitation is given by $\tau_s=L(1-\beta_g)/v_g$, where $\beta_g=v_g/c$.

Now let us consider the field build-up process due to bunch-train excitation. If a second bunch reaches the exit after the first bunch but before the tail of the first rf pulse, then there will be a region where the rf pulses of the two bunches overlap. To create constructive interference (in-phase superposition) of the excited rf fields, the frequency of the excited rf mode (f_0) is chosen to be a harmonic of the bunch frequency, $1/T_b$, for a train of n bunches evenly spaced in time by T_b. The build-up in time of the amplitude of the longitudinal electrical field due to a

#jingchg@anl.gov

bunch train (E_{at}) at the exit of the decelerator ($z=L$) is shown in Fig. 2. (Note: This is the field that would be

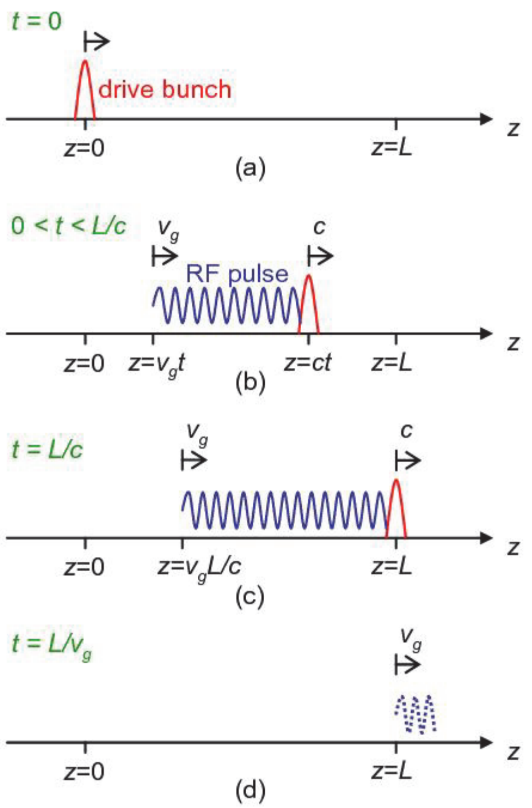

Figure 1. The rf pulse generated in the decelerator by a single drive bunch. Snapshots of a single bunch and the excited rf pulse inside the decelerator region $0\leq z \leq L$. (a) the bunch enters the decelerator ($t=0$); (b) the bunch and the rf pulse are fully inside the decelerator and the head and the tail of the rf pulse travel at different speeds ($0<t<L/c$); (c) the bunch reaches the exit of the decelerator ($t=L/c$); (d) the tail of the rf pulse exits the decelerator ($t=v_gL/c$).

observed by an antenna located at $z=L$ and we have now redefined the time origin so that $t=0$ corresponds to arrival of the first bunch at $z=L$.) The rf pulses excited by individual bunches are labeled in color and the increasing amplitude of the net field (E_{at}) is due to their superposition. The time structure of the bunch train rf pulse (at $z=L$) consists of a rise-time, a flat-top, and a fall-time; all of which are determined by the overlap of the individual single-bunch rf pulses. The rise-time is determined by the number of bunches whose rf pulses overlap with the first rf pulse and is equal to $ceiling(\tau_s/T_b)-1$. For example, if the single-bunch pulse length is $\tau_s=2.4ns$ and the bunches are spaced at $T_b=0.769ns$, then there will be $ceiling(\tau_s/T_b)-1=3$ trailing bunches whose rf pulses overlap with the first rf pulse. In general, the number of rf pulses that overlap at the exit of the decelerator is $N=ceiling(\tau_s/T_b)$. From Fig. 2, it can be seen for a long bunch train with $n\geq N$, the rise-time t_r can be written as $t_r=(N-1)\times T_b$. Similarly the fall-time is $t_f=t_r$. The steady-state (flat-top) duration of the rf pulse is simply the total length duration minus the rise-time and the fall-time, i.e. $\tau_t=(n-1)\times T_b+\tau_s-2_{tr}$. Note that for a very long train ($n>>N$) the pulse length is simply $\tau_t\approx nT_b$.

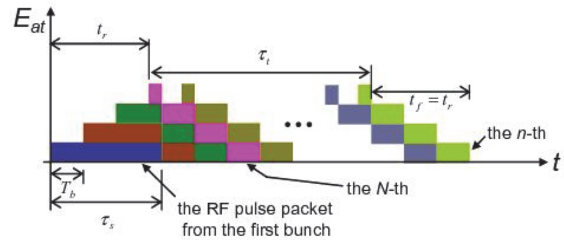

Figure 2. The rf pulse due to a drive bunch train. The longitudinal electric field amplitude experienced by a probe at the exit of the decelerator with a bunch train excitation (pulses excited by different bunches are labeled with different colors).

The generated RF power by an ultra-relativistic bunch train in such a decelerator is given by [1]:

$$P=\frac{1}{4}\frac{\omega}{v_g}\frac{r}{Q}L^2I^2F^2\left(\frac{1-e^{-\alpha L}}{\alpha L}\right)^2, \qquad (1)$$

where I is the beam current (the charge per bunch over the bunch spacing), L is the active length of the decelerator, ω is the angular frequency of the RF mode, v_g is the group velocity, [r/Q] is the shunt impedance per unit length divided by the quality factor, α is the attenuation per unit length, and F is the single bunch form factor. For a Gaussian bunch with an r.m.s. bunch length σ_z, the bunch form factor can be calculated as :

$$F=\exp\left[-\left(\frac{\omega}{c}\sigma_z\right)^2\Big/2\right]. \qquad (2)$$

BEAM SOURCES AT AWA

The new 75 MeV drive beamline (under construction; scheduled to be online in 2013) at AWA facility [3] provides an ideal platform to generate high power rf using its high current beam. It aims to produce a variety of bunch trains of up to 32 electron bunches and up to 100 nC per bunch, although not simultaneously. The AWA beamline operates at 1.3 GHz so that the bunch spacing is 0.77 ns, which leads to 10 GW beam power available to be extracted. In addition, the frequency content of the AWA beam can cover up to W-band with significant power output. Table 1 shows parameter designs of some selected dielectric based wakefield power generators with frequency ranges from C-band to W-band. The bunch length of the AWA beam varies with the charge. In order to cover the W-band, a bunch compressor may be required. As stated earlier, the operating frequency of the device has to be chosen the harmonic of the bunch repetition rate in a train. The length of all structures

ISBN 978-3-95450-115-1

shown in Table 1 is assumed to be 30 cm. We assume the structure has a transverse damping feature to ensure the transmission of the entire bunch train. The detailed dielectric device design can be found in [4].

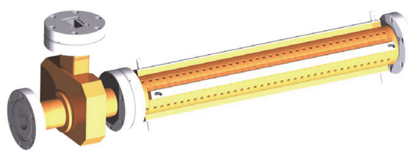

Figure 3. 3D CAD view of an 11.7 GHz metallic ultra high power short pulse wakefield power generator.

Certainly, the wakefield power generator is not limited to dielectric based devices. In fact, due to the short rf pulse generated by the AWA beam, a metallic structure may be operated at the GW level as well. The metallic decelerator is in general more like a corrugated waveguide (or a disk loaded waveguide with a large aperture). For a corrugated waveguide, the modes by an electron bunch are discrete but extend to infinity (high pass system) while the frequency spectrum (i.e. form factor) of a beam is continuous and bandwidth limited (low pass signal). The bandwidth of a beam is determined by the temporal shape of the bunch, for example, the shorter a Gaussian bunch, the broader its bandwidth. Although part of the beam energy is radiated in the unwanted high order modes, it is in general not a concern in the application of wakefield power extraction where a bunch train is used to drive the power extractor. The microbunch frequency (repetition rate) is chosen to be the same as harmonic of the fundamental mode of the wakefield power extractor so that only this mode can be coherently enhanced. In addition, the output coupler of the wakefield power extractor is also designed to favor only the fundamental mode.

Table 1: Examples of dielectric wakefield power generation using AWA beam parameters.

Freq. (GHz)	Aperture (mm)	Q (nC)	σz (mm)	Power (MW)
7.8	12	100	2.5	1107
11.7	10	80	2.5	1012
15.6	8	60	2.3	766
26	6	30	1.7	276
91	2	10	1	14

AN X-BAND METALLIC WAKEFIELD POWER GENERATOR

An 11.7 GHz metallic wakefield power generator was recently designed (Fig. 3). It is a standard $2\pi/3$ mode structure with aperture of 8.7 mm and group velocity of 22% of the speed of light. The decelerator section is 30 cm long so that the generated rf pulse will reach the flat top after the fourth bunch. With assumption of a bunch train of 60 nC per bunch and *r.m.s.* bunch length of 2.3 mm (equiv. to a form factor of 0.85), this device can generate 440 MW rf power. The gradient on axis is around 90 MV/m which is well within the breakdown limits for a <30 ns pulse.

REMARKS

The new 75 MeV drive beam at the AWA Facility will provide exceptional capabilities for the study of RF power generation. The development and testing of high gradient structures can greatly benefit from the availability of this new drive beam and RF power source.

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