DESIGN OF A 20.8/35.1 GHz HIGHER-ORDER-MODE DIELECTRIC-LOADED POWER EXTRACTOR SET*

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Abstract

We report on the design of a dual-frequency higher-order-mode dielectric-loaded power extractor set. The power extractor set consists of a dual-frequency dielectric-loaded decelerating structure (decelerator) and two changeable output couplers. In the decelerator, an ultra-relativistic electron beam synchronizes with the TM_{02} mode at 20.8GHz and the TM_{03} mode at 35.1GHz. These frequencies are both harmonics of 1.3GHz, the operating frequency of the electron gun and linac at the Argonne Wakefield Accelerator. The power generated in the unintended TM_{01} mode is effectively suppressed for bunch train operation with a novel mode suppression technique. To extract power from the decelerator to standard rectangular waveguides, a TM_{02}-TE_{10} output coupler was designed with S_{21} = -0.26dB at 20.8GHz, and a TM_{03}-TE_{10} output coupler with S21 = -0.66dB at 35.1GHz. For a drive beam with 50nC of charge per bunch, power levels of 90.4MW and 8.68MW are expected to be delivered by the device at 20.8GHz and 35.1GHz respectively.

INTRODUCTION

In the mm-wave and near-mm-wave range, megawatt-level power vacuum sources have been intensively investigated [1], such as a 17.1GHz gyroklystron [2], a 34GHz magnicon [3], a 42GHz gyrotron [4] and a 91GHz gyroklystron [5]. Other than these entirely metallic structures, recently there has been some interest in generating high power waves with dielectric-loaded (DL) waveguides in this range. Attempts include initial tests on a 21GHz DL structure [6], a proposed 26GHz DL power extractor [7] and simulation on a 220GHz DL traveling-wave amplifier [8].

A typical DL power extractor consists of two components: a DL decelerating waveguide (*decelerator*) in which the power of a drive particle beam is transferred to trailing radiofrequency (RF) wakefields, with no external power applied; and an *output coupler* which couples the generated power to an output waveguide. An example is the 7.8GHz DL power extractor operating on the TM_{01} mode demonstrated at the Argonne Wakefield Accelerator (AWA) [9]. In order to extract power in the mm-wave or near-mm-wave range, the size of the beam channel needs to be greatly reduced if the TM_{01} mode is still used as the interacting mode [7]. If higher-order-modes (HOMs) are used instead, a more manageable beam channel diameter can be used. Compared to the first option, the second one allows a much larger beam channel which leads to easier fabrication, and possibly less severe space charge effects when a high current beam is transported. However, when using HOMs the lower-order-modes (such as the TM_{01}) which usually possess much stronger coupling to the beam, will need to be suppressed in order to improve efficiency. Furthermore, design of output couplers for HOMs in a DL waveguide is technologically challenging.

In this paper we report on the design of a DL power extractor set using the TM_{02} mode at 20.8GHz and the TM_{03} mode at 35.1GHz, which consists of a dual-frequency decelerator and two changeable output couplers. The idea is that one can choose the metallic housing of an output coupler for the desired frequency (20.8 or 35.1GHz), attach it to the metallic housing of the decelerator, and then insert the dielectric tube to complete a power extractor for this frequency.

DECELERATOR DESIGN

The design of the decelerator is based on the current parameters of the AWA beamline. The beamline consists of an electron gun and a linac, both operating at 1.3GHz, leading to a bunch frequency f_b also at 1.3GHz. The electron gun is able to deliver 1-100nC charge per bunch with an r.m.s. bunch length of σ_z = 1.5-2.5mm. The beam energy is ~8MeV upon exiting the gun and is accelerated to ~15MeV by the linac. In the decelerator design the beam is assumed to have β=1 for simplicity.

The dielectric used for the decelerator is Cordierite with a relative permittivity ε_r = 4.76. The TM_{02} and TM_{03} modes were chosen as operating modes since their synchronous frequencies (f_0) are in the near-mm-wave and mm-wave range with a beam channel of a manageable size. The f_0 for the TM_{02} mode was determined to be 20.8GHz, the 16th harmonic of f_b; and f_0 for the TM_{02} mode was determined to be 35.1GHz, the 27th harmonic of f_b. Accordingly, the inner radius of the dielectric tube *a* was determined to be 7.85mm, and the outer radius *b* was determined to be 12.76mm. The loss tangent of the dielectric is assumed to be 0.0005 at both 20.8GHz and 35.1GHz. The metallic sleeve holding the dielectric is assumed to be OFE copper.

Unlike the TM_{02} and TM_{03} mode, the f_0 of the unintended TM_{01} mode is 7.53GHz, not an integer multiple of f_b. The length of the decelerator is properly chosen to be 38cm so that the TM_{01} mode is effectively suppressed. As shown in Fig. 1, with this decelerator length, a zero of the voltage spectrum magnitude

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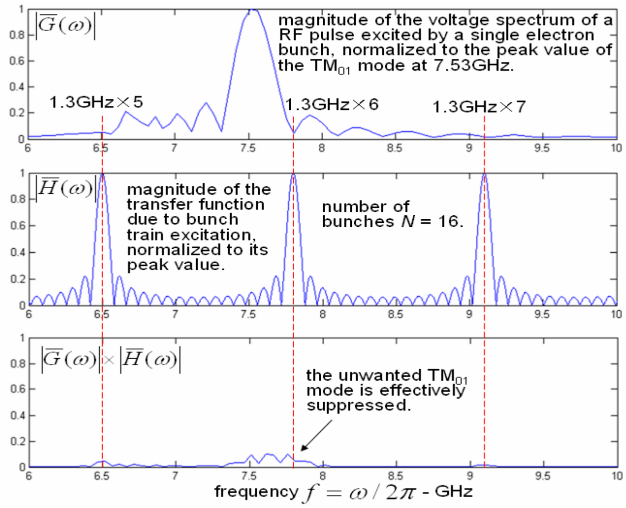

Figure 1: Properly choice of the decelerator length effectively suppresses the unintended TM_{01} mode. The train consists of 16 electron bunches in this case.

$|G(\omega)|$ of the TM_{01} signal excited by a single electron bunch coincides with a peak of the transfer function magnitude $|H(\omega)|$ of the bunch train excitation. In other words, for the TM_{01} mode the peaks of $|G(\omega)|$ and $|H(\omega)|$ are intentionally displaced so that their product $|G(\omega)|\times|H(\omega)|$, which represents the strength of the TM_{01} mode under bunch train operation, is effectively suppressed. It also needs to be mentioned that the relative strength of the TM_{01} mode (compared to the TM_{02} and TM_{03} modes) becomes smaller as the number of bunches increases.

The characteristics and resultant power levels of the TM_{02} and TM_{03} modes are listed in Table 1, where the power levels were calculated with the assumption of ultrarelativistic Gaussian bunches with a bunch length σ_z = 2mm. Results of the calculation indicate that 95.9MW and 10.1MW can be generated in the TM_{02} and TM_{03} modes respectively, by a bunch train with a bunch frequency of 1.3GHz, and with charge of 50nC per bunch.

Table 1: Characteristics of the TM_{02} and TM_{03} Modes.

modes	TM_{02}	TM_{03}
synchronous frequency f_0 – GHz	20.8	35.1
"r over Q" per meter $[r/Q]$ – kΩ/m	1.214	0.392
quality factor Q	3170	3377
shunt impedance per meter r_{sh} -MΩ/m	3.85	1.32
normalized group velocity $\beta_g = v_g/c$	0.37	0.46
generated P (MW) @50nC per bunch	95.9	10.1

CST Mafia [25] simulations were performed for both single bunch and bunch train excitations, where for simplicity the structure was assumed to be lossless. From Figs. 2(a) and (b) it can be seen the in single bunch operation the TM_{01} mode dominates the spectrum. Figure 3(a) shows the electric field excited by a train of 16 bunches, superposed from the one in Fig. 2(a). The spectrum in Fig. 3(b) shows that the TM_{01} mode is effectively suppressed, with much lower relative strength (from 3 times the height of the TM_{02} peak in single bunch excitation to only 1/3 in bunch train excitation), while the TM_{02} and TM_{03} modes are enhanced.

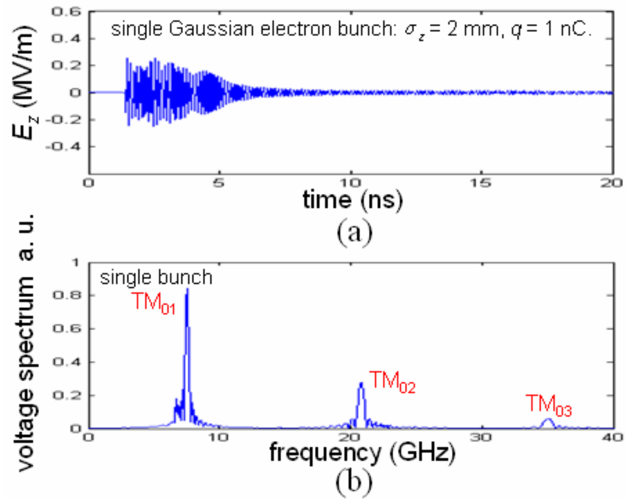

Figure 2: The longitudinal electric field E_z at the downstream end of the decelerator, excited by a single bunch. (a) E-field; (b) voltage spectrum.

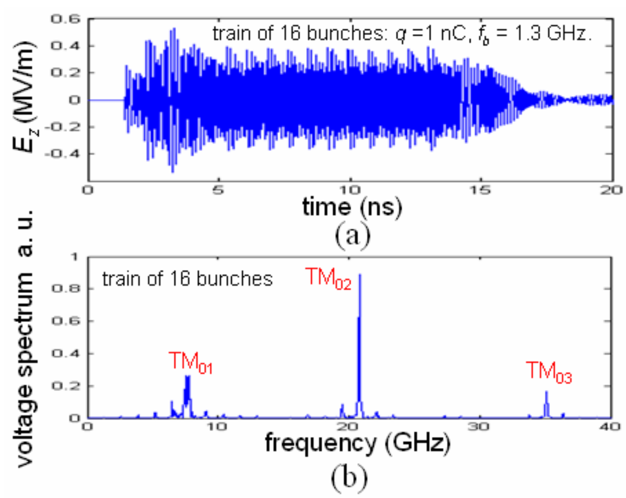

Figure 3: E_z at the downstream end of the decelerator, excited by a train of 16 bunches. (a) E-field; (b) voltage spectrum.

THE OUTPUT COUPLERS

At the downstream end of the decelerator, couplers are needed to couple the excited RF power to a WR42 waveguide at 20.8GHz and to a WR28 waveguide at 35.1GHz, respectively. In this section the design of the output couplers is shown.

Figure 4 shows the design of a TM_{02}-TE_{10} coupler at 20.8GHz. At the exit of the decelerator the beam channel is extended to form a circular waveguide, while a vacuum ring is used as a choke to convert the TM_{02} mode to the TM_{01} mode in the circular waveguide. The TM_{01} mode is then converted to the TE_{10} mode in the WR42 rectangular waveguide, where a metallic pin is used for impedance matching. The beam channel at the end of the output coupler is below cutoff for the RF signal. Figure 5 shows the design of the TM_{03}-TE_{10} coupler at 35.1GHz. The

TM_{03} mode is first converted to the TM_{02} mode by a step at the exit of the decelerator, and then converted to the TM_{01} mode by the ring choke. The reflections at the two transitions are expected to cancel for good transmission. Finally the TM_{01} mode is converted to the TE_{10} mode in the WR28 rectangular waveguide with a metallic pin for impedance matching.

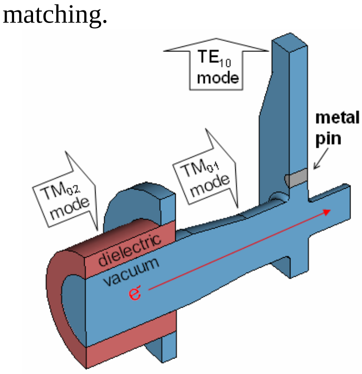

Figure 4: CST Microwave Studio model of the 20.8GHz TM_{02}-TE_{10} output coupler.

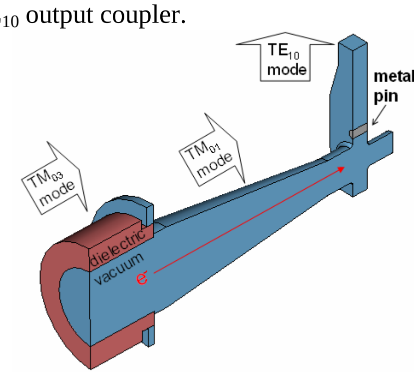

Figure 5: CST Microwave Studio model of the 35.1GHz TM_{03}-TE_{10} output coupler.

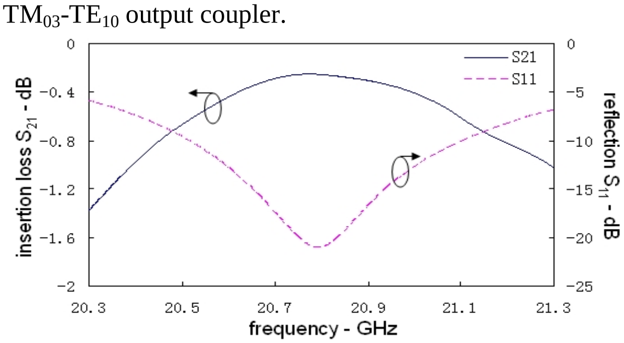

Figure 6: Simulated S-parameters of the 20.8GHz TM_{02}-TE_{10} output coupler.

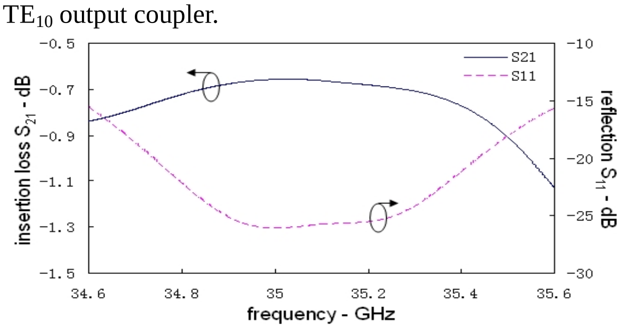

Figure 7: Simulated S-parameters of the 35.1GHz TM_{03}-TE_{10} output coupler.

Figure 6 shows the simulated S-parameters of the TM_{02}-TE_{10} output coupler. The transmission S_{21} = -0.26dB at 20.8GHz indicates power coupling efficiency of 94.3%, and better than -1dB in the range from 20.40GHz to 21.29GHz. The reflection is S_{11} = -20.98dB at 20.8GHz. Figure 7 shows the simulated S-parameters for the entire 35.1GHz TM_{03}-TE_{10} output coupler. The S_{21} = -0.66dB at 35.1GHz indicates power coupling efficiency of 85.9%, and it is better than -1dB from 34.6GHz, the lower frequency limit in simulation, up to 35.54GHz. The reflection is S_{11} = -25.77dB at 35.1GHz. It can also be observed that the sum of $|S_{21}|^2$ and $|S_{11}|^2$ is always smaller than 1, since many other unintended modes are also excited along with the TM_{02}/TM_{03} modes. From the power coupling efficiencies (calculated from S_{21}: 94.3% at 20.8GHz and 85.9% at 35.1GHz) and power levels calculated in Table 1, we can conclude that a drive bunch train with charge of 50nC per bunch, 95.9×0.943 = 90.4MW is expected to be extracted at 20.8GHz, and 10.1×0.859 = 8.68MW is expected to be extracted at 35.1GHz.

SUMMARY

In this paper we have presented the design of a dual 20.8/35.1GHz DL power extraction set that makes use of the abundant near-mm-wave and mm-wave power in the intense drive beam at AWA. The design outcome shows that 90.4MW and 8.68MW of power are expected to be extracted from a drive beam with charge of 50nC per bunch, at 20.8GHz and 35.1GHz respectively.

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