High Power RF Radiation at W-band based on Wakefield Excited by Intense Electron Beam

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***Abstract*—We report the experimental design and initial experimental results on high power RF generation at W-band based on coherent wakefield from the metallic periodic structure of 91 GHz, excited by intense electron beam at the Argonne Wakefield Accelerator (AWA) facility. The recently output RF power is 0.7 MW, with 67 MeV, 1.4 nano-column (nC) single electron beam go through the 12cm structure. The RF pulse is 3.4 nano-second (ns). We measure the energy loss of electron beam in the experiment. Next run is to increase the output RF power with higher charge in the driven beam and to excite higher gradient of wakefield with electron bunch train.**

I. INTRODUCTION

High power and high frequency RF generation benefits the advanced accelerator of high energy and compact system [1]. W-band RF radiation is also important in many applications such as satellite communications, millimeter-wave radar research, and some non-military applications [2].

We report the experimental design and initial results on high power RF radiation at W-band with method of electron beam drive RF generation. That is to use the wakefield structure representing a PETS (Power Extraction and Transfer Structure) to transfer the energy of ultra-relativistic electron beam into the RF radiation [3]. We take advantage of a high impedance wakefield structure of 91 GHz. Excite the structure with the ~67 MeV intense electron beam at the Argonne Wakefield Accelerator (AWA) facility [4]. Since wakefield will be enhanced coherently when excited by electron bunch train with proper bunch interval [5], the plan for next run is to use intense electron bunch train of 1.3 GHz interval at AWA.

Two copper plates with periodic grooves make up the W-band wakefield structure, which is similar to Valery Dolgashev's 100 GHz structure [6]. As shown in Fig. 1. The gap between the two plates in x direction is 0.94 mm when work at 91 GHz. Electron beam goes through the Z direction along the grooves, the grooves make up a chain of resonant cavities. And RF will comes out from sides of the structure because of the matching cell and waveguide design. The dimensions of the periodic groove in x/y/z direction are all about 1 mm, the total length of the structure L is 12.3 cm. And the group velocity of RF energy flow is $\beta_g=v_g/c=0.1$ inside the structure, and the wakefield loss factor is k_L=13.3 MV/m/nC, which shows high impedance of this structure.

Theory on the wakefield excited by a drive bunch (or bunch train) in the traveling wave waveguide is described in Ref. [5]. The excited pulse duration is $\tau_s = L/v_g - L/c = 3.4$[ns] for our structure. And the wakefield gradients E_s excite by a single bunch with charge q_b is given by $E_s=2k_L \cdot q_b \cdot F(\sigma_z)$. Here $F(\sigma_z)$ is the form factor, for a Gaussian electron beam with rms bunch length σ_z, $F(\sigma_z)=\exp(-(k_z\sigma_z)^2/2)$, with k_z is the wave number. Once we know the gradient, we can calculate the RF power with formula: $P = E_s^2 v_g /4\, k_L/(1-\beta_g)$.

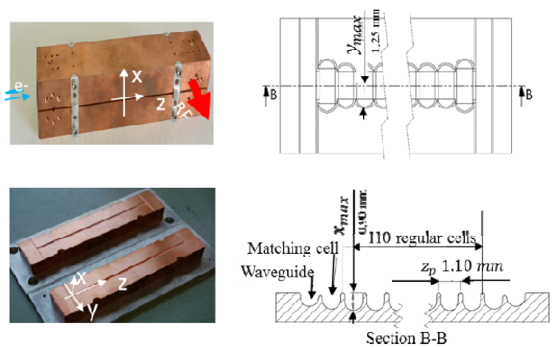

Fig. 1 Sketch of W-band wakefield structure

For the case of bunch train, the RF pulses generated by each bunch are simply superposed linearly. Because the frequency of the wakefield is chosen to be harmonic of the bunch spacing, the RF generated by the first bunch will decelerate the following *N* bunches within the structure, and the power is coherently enhanced within the RF overlapping. The power gets saturated due to the finite length of the structure. Here we introduce *N* as the least number of sub-bunches needed to reach power saturation, which is given by $N = \text{ceiling}(\tau_s/T_b)$, determined by the overlapping of the individual single-bunch RF pulses. For a long train with *n* bunches spaced by T_b, the time structure of the RF pulse consists of a rise time given by $\tau_r = (N-1)T_b$, a flattop expressed as $\tau_f = (n-1)T_b + \tau_s - 2\tau_r$, and a fall time $\tau_d = \tau_r$.

CST wakefield solver [7] is used to calculate the excited gradients E_s by a single bunch and E_t by a bunch train, respectively, simulation results agree well with the theory. The values are smaller than the analysis, because we have count the attenuation of the structure in the simulation. As shown in Fig. 2(a), we use a 5nC Gaussian electron bunch with rms. bunch length $\sigma_z = 0.53\ mm$ in the simulations, which is a typical set of beam parameters of the AWA facility. The gradient is 80 MV/m excited by a single bunch, corresponding to 4.2 MW peak power of the RF output when calculated with Eq. 2. The RF duration is 3.4 ns. For an 8-bunch train case, RF output is shown in Fig. 2(b), the field reaches saturation after 5 bunches, with a rise/fall time of 3.1 ns, a flattop time of 2.1 ns. The maximum gradient is 325 MV/m, corresponding to 69.6 MW RF output. For 8-bunch of 10nC train, we would expect to generate over 100 MW RF power with gradient over 400 MV/m.

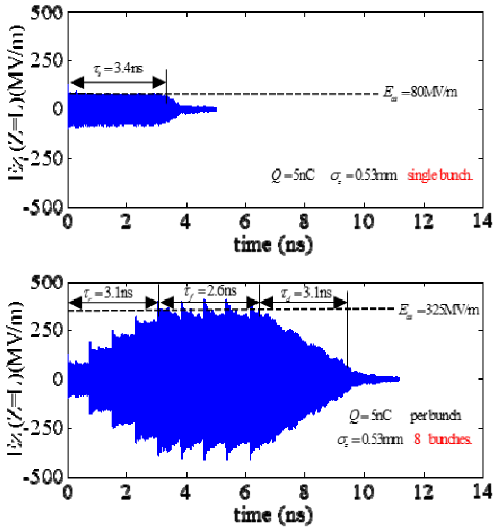

Fig. 2 RF output simulation results from CST

II. RESULTS

We have performed the preliminary experiment at the AWA drive beam line. Experimental set up is shown in Fig.4. The structure is able to pop-in and out for comparison. As we know the W-band RF radiation comes from the electron beam energy, we measured the beam energy change with and without the W-band structure on the spectrometer.

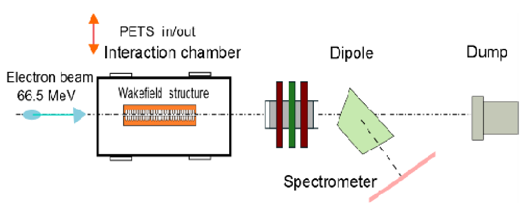

Fig. 3 Sketch of the beam line for electron beam energy measurement

Experimental results of electron beam energy distribution agree well with the beam dynamics simulation from wakefield module in ASTRA [8] as shown in Fig. 4. In the experiment, we have 2.4 nC charges without the PETS and 1.4 nC charge with the PETS because of beam loss through the structure to the spectrummeter. Mean energy loss is 1.6 MeV of the 1.4 nC, shows that at least RF power $P \approx 1.6[MeV]*1.4[nC]/3.4[ns]$ =0.66 MW at 91 GHz comes out. This also goes well with the RF output simulation in Fig. 4. The wakefield gradient E_S in the structure is 31.6 MV/m corresponding to the power.

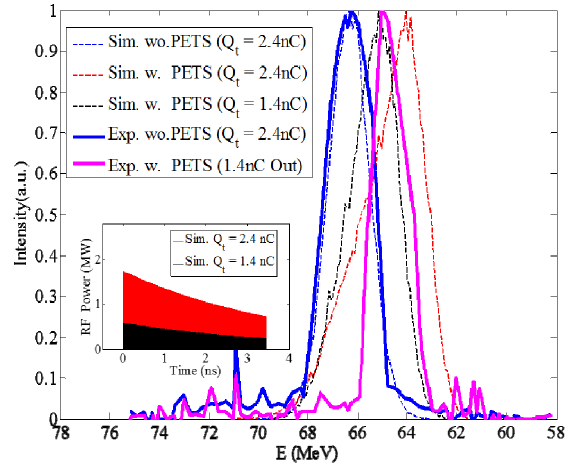

Fig. 4. Energy distribution and RF output simulation: Blue lines give the simulation (dashed line) and experimental (solid line) energy distribution without the PETS, it is of 2.4 nC beam. After the PETS, beam dynamics shown that if we only have 1.4 nC beam all go through the structure, the mean energy loss is 0.9MeV (black dashed line), while if we have 2.4 nC beam all go through, the mean energy loss is 1.7MeV (red dashed line). The experimental results go as the magenta solid line, mean energy loss is 1.6 MeV of the 1.4 nC, which means that more than 1.4nC beam has contribute to the wakefield (RF output), some particles lost after the PETS. RF output simulation give the result of 91 GHz signal when excited by 1.4 nC (black line) and 2.4 nC beam (red line), it decays because of the structure attenuation.

III. SUMMARY

We have designed the high power RF generation of W-band based on wakefield excited by intense electron bunch train at the AWA facility. We performed the preliminary experiment with low charge single electron bunch, experimental results demonstrate ~0.7 MW RF output with 1.4 nC single electron bunch, which agree with the simulation. We plan to increase the output RF power next run with higher charge in the driven beam and to excite coherent wakefield with 5~10 nC charge in a single bunch and up to 4~8 sub-bunches in total at the AWA facility. The RF power is expected to be ~100 MW level and the wakefield gradient can reach up to ~400MV/m.

REFERENCES

[1] R. B. Palmer, "Pulsed RF Sources for Linear Colliders", AIP Conf. Proc. 337, New York, Am. Inst. Phys. (1994) pp. 1-15

[2] https://en.wikipedia.org/wiki/W_band

[3] D. Wang, S. Antipov, M. Condel1, S. Doran, W. Gai , G. Ha, C. Jing, W. Liu, J. Power, J. Qiu, C.Tang, E.Wisniewski, "High Power RF Radiation at W-band based on wakefields Excited by Intense Electron Beam", Proceedings of IPAC2015, Richmond, VA, USA.

[4] J. G. Power, M. E. Conde, W. Gai, D. Mihalcea, Z. Li, J. Wang and Menlo Park, "Upgrade of the Drive LINAC for the AWA Facility Dielectric Two-Beam Accelerator", SLAC-Pub-15138, 2012.

[5] F. Gao, M. E. Conde, W. Gai, "Design and testing of a 7.8 GHz power extractor using a cylindrical dielectric-loaded waveguide", Phys. Rev. ST Accel. Beams, 11, 041301 (2008).

[6] V. A. Dolgashev and S. Tantawi, "Testing of Metallic Periodic Structures at FACET", FACET 2012 Users Meeting, SLAC National Accelerator Laboratory, Menlo Park, California, 2012 .

[7] CST Particle Studio, developed by Computer Simulation Technology.

[8] K. Flottmann, "Astra—A Space Charge Tracking Algorithm", available at http://www.desy.de/~mpyflo/.