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HIGH POWER RF RADIATION AT W-BAND BASED ON WAKEFIELDS EXCITED BY INTENSE ELECTRON BEAM

D. Wang[1, 2], S. Antipov[1, 3], M. Conde[1], S. Doran[1], W. Gai[1], G. Ha[1], C. Jing[1, 3]
W. Liu[1] J. Power[1], J. Qiu[1, 3], C.Tang[2], E.Wisniewski[1]
[1] Argonne National Laboratory, IL, 60439, USA
[2] Tsinghua University, Beijing, 100084, China
[3] Euclid Tech. labs LLC, IL, 60439, USA

Abstract

We report the experiment design and preliminary results on high power RF generation at W-band based on coherent wakefields from the metallic periodic structure of 91 GHz PETS (power extraction and transfer structure), 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 nC single electron beam going through the structure. The RF pulse length is 3.4 ns. We measure the energy loss of electron beam as reference to the RF generation, which agrees well with the simulation results. Next run is to increase the output RF power with higher charge and to excite coherent wakefields with electron bunch train. The output RF peak power is expected to be ~100 MW and the electrical field gradient can reach up to 400 MV/m, with RF pulse duration adjustable from few ns to 30 ns when excited with 5~10 nC charge in a single bunch and up to 32 sub bunches in total.

INTRODUCTION

High power and high frequency RF generation benefits high energy and compact accelerator, and is also important for high gradient and breakdown study [1].

We use a copper periodic structure with wakefields frequency of 91 GHz as a PETS (power extraction and transfer structure) to transfer energy of ultra-relativistic electron beam into the RF radiation. Preliminary experiment has been conducted at the Argonne Wakefield Accelerator (AWA) drive beam line. Experimental results demonstrate the mean energy loss is 1.6 MeV of the 1.4 nC electron single bunch, corresponding to RF power generation of 0.66 MW.

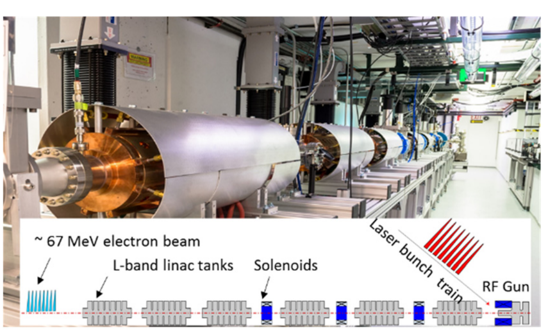

Figure 1: Layout of AWA drive beam line.

Since wakefields will be enhanced coherently when excited by bunch train with proper bunch spacing. We design the experiment aimed at 100 MW level RF generation at 91 GHz for the next run based on intense 1.3 GHz electron bunch train at AWA, with 5~10 nC charge in single bunch and up to 32 sub bunches in total.

The upgraded AWA drive beam line consists of a 1.3 GHz RF photocathode gun and 6 RF cavities [2], which has the capability to generate intense charged electron beam of 67 MeV, with picosecond RMS bunch length. AWA is designed to work at two modes of operation. In single-bunch mode, a high charge (up to 100 nC) bunch is generated. While in bunch-train mode, a laser bunch train illuminates the high current photocathode to generate an electron beam distributed up to 32 sub-bunches, with 1.3 GHz (769 ps) spacing. The electron bunch train will deliver up to ~ 1000 nC total charge. The layout of AWA is shown in Fig. 1.

ANALYSIS OF WAKEFIELD EXCITED BY BUNCH TRAIN

Two copper plates with periodic grooves make up the W-band structure, which is similar to Valery Dolgashev's 100 GHz structure [3]. We design two couplers on both end of the structure for bench test purpose and getting RF band pass. As shown in Fig. 2. We can choose the frequency by adjusting the gap between the two plates, when the gap 2a = 0.94 mm, the phase velocity is matched to the particle velocity at 91 GHz, thus wakefields interacts strongly with the on-axis bunch. 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. The relative group velocity $\beta_g = \frac{v_g}{c} = 0.1$ and the loss factor is $\kappa_L = 13.3 MV/m/nC$.

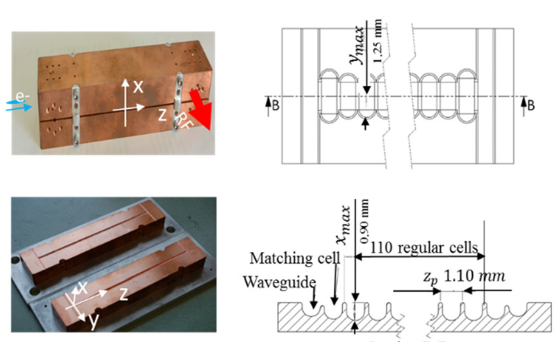

Figure 2: Sketch of W-band wakefield structure.

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Theory on the wakefields excited by a drive bunch (or bunch train) in the traveling wave structure is described in Ref. [4]. When a single bunch entering a structure of length L, wakefield is excited. The head of the RF pulse travels at speed of light following the drive beam, while the tail of the RF pulse travels at the group velocity. So the duration of the RF pulse excited by a single bunch τ_s is the difference between the traveling time of the head and tail of RF, $\tau_s = \frac{L}{v_g} - \frac{L}{c} = 3.4[ns]$ for our structure.

The excited gradient E_s as shown in Eq. 1, is determined by the loss factor κ_L, the relative group velocity β_g, and the charge of the drive beam q_b, as well as a form factor $F(k, \rho_z)$, which is decided by the radiation wave number k and mainly the longitudinal beam distribution ρ_z.

$$E_s = 2\kappa_L q_b F(k, \rho_z) \qquad (1)$$

For a Gaussian distribution beam with rms bunch length σ_z, form factor is given as $F(k, \sigma_z) = \exp(-(k\sigma_z)^2/2)$.

Once we know the gradient, we can calculate the RF power with Eq. 2.

$$P_s = \frac{E_s^2 v_g}{4k_L(1-\beta_g)} \qquad (2)$$

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 wakefields solver [5] 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. 3(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. 3(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.

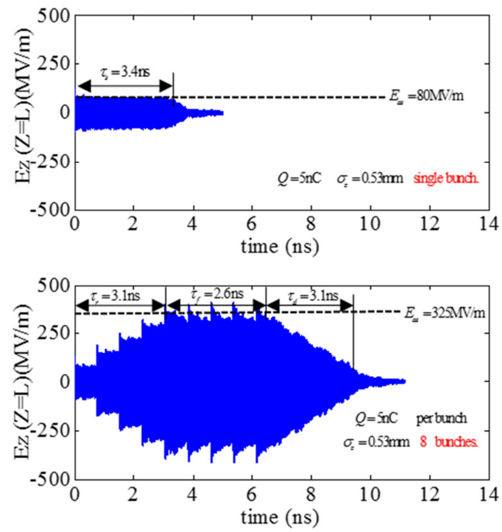

Figure 3: RF output simulation results from CST.

EXPERIMENT

We have performed the preliminary experiment at the AWA drive beam line as shown in Fig. 1. 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. Experimental results agree well with the beam dynamics simulation from wakefields module in ASTRA.

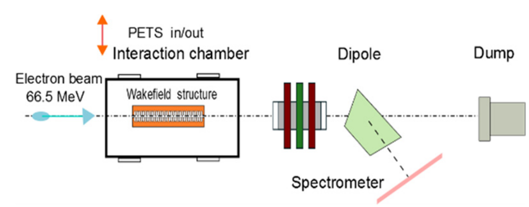

Figure 4: Schematic diagram of the beam line for electron beam energy measurement.

In the experiment, we have 2.4 nC charge single bunch without the PETS and 1.4 nC charge with the PETS to the spectrometer due to beam loss. Energy distribution is shown in Fig. 5, blue lines give the simulation (dashed line) and experimental (solid line) energy distribution without the PETS, it is of 2.4 nC single bunch. After the PETS, beam dynamics simulations show that if we only have 1.4 nC beam 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 is shown with the magenta solid line, mean energy loss is 1.6 MeV of 1.4 nC beam which comes to the spectrometer, which means that more than 1.4nC beam has contribute to the wakefield (RF output), implies that some particles are lost after the PETS. RF output simulation gives the result of 91 GHz RF signal when

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excited by 1.4 nC (black line) and 2.4 nC beam (red line), it decays due to the structure attenuation.

From the preliminary experimental results, we have get mean energy loss 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. The wakefield gradient E_S in the structure is 31.6 MV/m corresponding to this RF power.

We were limited by the beam transmission and frequency measurement in the first run. It is still promising that the experimental results of low charge single drive bunch agree with the simulation results. As beam stability improved a lot at AWA. We proposed the next run to increase the W-band radiation power with high charge electron bunch train. And we are developing the interferometer to measure the RF frequency signal for next run.

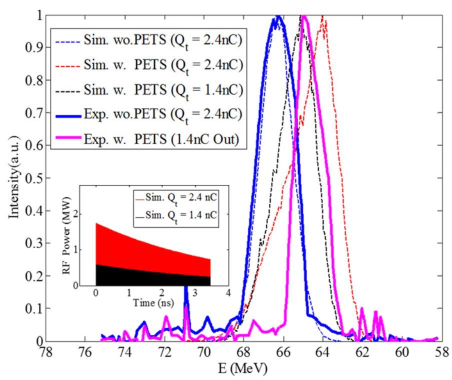

Figure 5: Energy distribution comparison and RF output pulse of simulation.

SUMMARY AND FUTURE PLAN

We have designed the high power RF generation of W-band at the AWA facility. The power is expected to be ~100 MW level and the wakefield gradient can reach up to ~400MV/m with high charge electron bunch train. We performed the preliminary experiment with low charge single electron bunch, experimental results demonstrate ~0.7 MW RF output with 1.6MeV energy loss of 1.4 nC beam, 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 wakefields with 5~10 nC charge in a single bunch and up to 32 sub-bunches in total at the AWA facility with more stable electron beam.

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