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GENERATION OF HIGH POWER SHORT RF PULSES USING AN X-BAND METALLIC POWER EXTRACTOR DRIVEN BY HIGH CHARGE MULTI-BUNCH TRAIN

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Abstract

Short pulse two-beam acceleration (TBA) is a structure wakefield acceleration (SWFA) approach aiming to achieve gradient above 250 MV/m using rf pulses less than 20 ns. An X-band 11.7 GHz metallic power extractor has been developed as the power source to test accelerating structures in this extreme regime. The power extractor is designed to be driven by high charge bunches separated by 769.2 ps (9 times the X-band period) on an L-band 1.3 GHz beamline. In the recent experiment, ~280 MW rf pulses with 3 ns flat-top have been measured by a coaxial rf pickup when driven by 8-bunch trains with a total charge of ~500 nC. The power level is ~50% lower than the theoretical prediction and simulation. Experimental investigation suggests that the missing power was mainly caused by the multipacting issue inside the rf pickup, which could be eliminated by a newly-designed directional coupler.

INTRODUCTION

RF breakdown is one of the main limitations to achieve high gradient in normal conducting accelerating structures [1]. Despite solid progress in understanding the complicated breakdown phenomenon and much effort to solve the issue, the state-of-the-art gradient when driven by rf pulses of hundreds of nanosecond long is limited to 120 MV/m in multi-cell structures [2], 150-200 MV/m in single-cell ones [3], and 250 MV/m in single-cell cryogenic ones [4]. As suggested by the exponential dependence of rf breakdown rate on pulse length [5], a promising approach to achieve gradient above 250 MV/m is to drive structures with rf pulses shorter than 20 ns. Such short rf pulses are typically out of the scope of klystrons, even with pulse compressors [6], but align well with the wakefield approach. Currently, a short pulse TBA program is under development at the Argonne Wakefield Accelerator (AWA) facility where various types of structures are under investigation [7–12].

Several power extractors have been tested at AWA and successfully applied to two-beam acceleration [9, 13], staging acceleration [9], and THz generation [7]. These structures are designed to operate at harmonics of 1.3 GHz so as to obtain coherent wakefield superposition when driven by bunches separated by 769.2 ps on L-band beamline. Recently, a tunable X-band 11.7 GHz metallic power extractor has been developed [14], aiming to generate over 500 MW rf power with 8-bunch trains and 60 nC/bunch (maximum charge limited by rf breakdowns inside the photocathode rf gun).

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COLD TEST

The layout of the X-band metallic power extractor is illustrated in Fig. 1. The $2\pi/3$-mode structure consists of 36 normal cells, 2 matching cells, and 2 dual-feed couplers. Detailed design parameters can be found in Ref. [14].

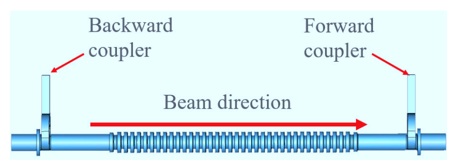

Figure 1: Layout of the X-band metallic power extractor.

The on-axis field distribution and the S-parameters of the structure after tuning are illustrated in Fig. 2 and Fig. 3, respectively. The synchronization frequency at which the phase velocity equals to the speed of light is 11.72 GHz. The drive bunches therefore need to be launched every 359.4° instead of every 360° in the 1.3 GHz cycle to compensate the slight frequency offset from 11.7 GHz so as to achieve coherent wakefield superposition. The S_{21} at 11.72 GHz is -0.9 dB with a -3 dB bandwidth above 500 MHz.

EXPERIMENT SETUP

The 248 nm UV input laser is split into a pulse train by a multi-splitter stage. The pulse separation is nominally set to be 769.2 ps and can be adjusted by the delay stages. A detailed description of the laser setup can be found in Ref. [12]. In experiment, the drive bunches were generated by the laser pulses from a high quantum efficiency Cs2Te cathode in an L-band rf gun and accelerated to ~65 MeV by six L-band standing-wave linacs. Solenoids and quadrupoles along the beamline were used to transmit the beam through the X-band metallic power extractor. Two integrating current transformers (ICTs) before and after the structure were used to measure the charge and the transmission. Two rf

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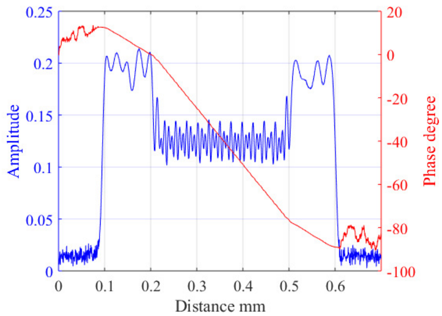

Figure 2: On-axis field distribution of the X-band metallic power extractor at 11.72 GHz. The phase velocity can be fitted from the slope of the phase distribution.

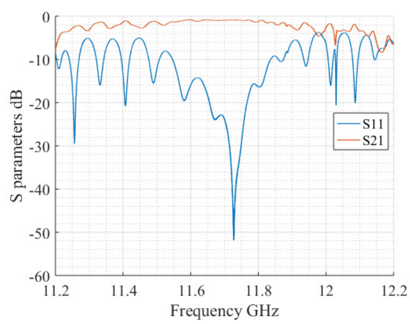

Figure 3: S-parameters of the X-band metallic power extractor. Port 1 and Port 2 are defined at the waveguide port on the backward and the forward coupler, respectively.

loads were connected to the couplers to absorb the generated and reflected rf power. The power level was measured by coaxial rf pickups installed near the loads. All signals were recorded by an oscilloscope with 20 GHz bandwidth and 50 GS/s sampling rate.

EXPERIMENTAL RESULT

In experiment, the launching phases of the drive bunches were fine tuned to obtain coherent wakefield superposition. The envelop of the rf pickup signal measured at the forward coupler agrees well with the simulation results, as illustrated in Fig. 4. The slope of the flat-top driven by 8-bunch train was caused by imperfect charge balance (~80%).

The charge level was gradually increased to condition the structure. The forward rf power measured at various charge levels is illustrated in Fig. 5. During the measurement, the charge transmission was kept to be ~100%. At each charge level, the generated rf power was maximized by adjusting the laser pulse length, the laser spot size, the rf gun gradient, and the gun solenoid strength so as to obtain a short beam bunch length and a high form factor correspondingly.

Discrepancy of the forward rf power between the measurement and the theoretical prediction/simulation can be found at the high charge end with 4 or 8 bunches. For 8-bunch trains with a total charge of ~500 nC, the measured power was ~280 MW, nearly 50% lower than the predicted

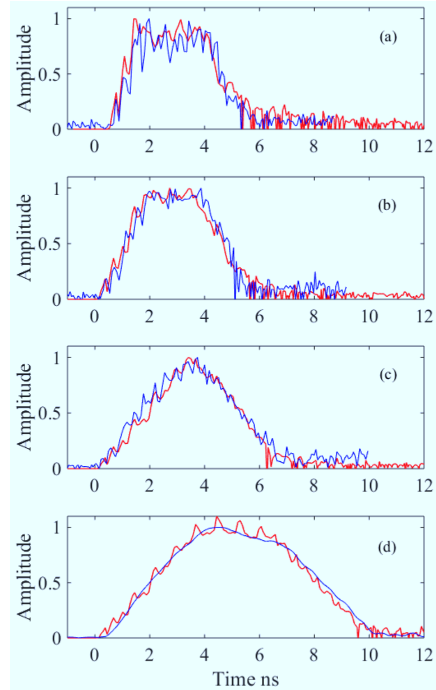

Figure 4: Comparison of the forward rf signal envelope between measurement (blue) and simulation (red) when driven by single bunch (a), 2-bunch train (b), 4-bunch train (c), and 8-bunch train (d).

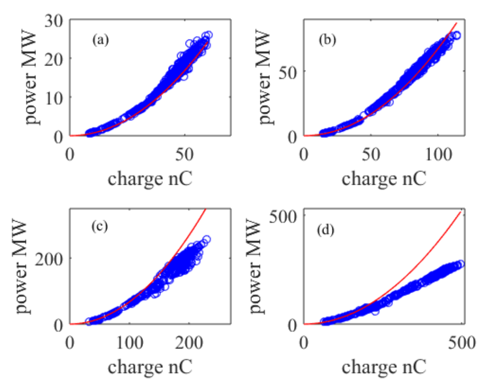

Figure 5: The measured forward rf power (blue dot) and the simulated value (red line) as a function of total transmitted charge when driven by single bunch (a), 2-bunch train (b), 4-bunch train (c), and 8-bunch train (d).

value of ~500 MW. There are several factors that could contribute to this disagreement: longer bunch length (lower form factor) at high charge due to the space-charge effect, imperfect wakefield superposition of the bunches, and multipacting inside the structure or the rf pickup [15]. According to the bunch length simulation by GPT, the form factor in the worst case could drop by 5% at high charge compared to low charge cases, which would only result in 10% difference in power. The good agreement between measurement and simulation with single bunch and 2-bunch train suggests this factor is negligible after the bunch length was

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experimentally optimized. The accuracy of the launching phase was controlled to be 1 ° in L-band or 9 ° in X-band. In the worst scenario, the imperfect wakefield superposition due to the launching phase accuracy could only lead to 12% drop in power.

rf signal at the backward coupler has been analyzed to check the possible multipacting location, as illustrated in Fig. 6. If multipacting occurred inside the structure, the reflected signal at the backward coupler would have similar behavior as the forward one, e.g. the rf signal is not linear with charge and the derived power does not quadratically depend on charge. In the measured results, however, the dependence of the signal strength and the power on the transmitted charge is linear and quadratic respectively, which confirms that multipacting was not inside the structure. Therefore, multipacting should occur inside the rf pickup.

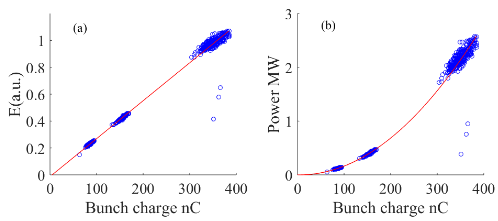

Figure 6: The measured rf signal (a) and the derived power (b) at the backward coupler as a function of the transmitted charge when driven by 8-bunch trains. The red line in (a) represents the linear fitting of the experiment data. The red line in (b) uses the same fitting results in (a) to calculate the power.

The detailed design of the pickup is illustrated in Fig. 7. Two small openings on the WR-90 waveguide are used to couple out the rf power and an rf probe installed near the openings is used to detected the signal. The short distances between the openings and between the opening and the probe could lead to multipacting in vacuum when the power is high. The pickup multipacting issue could also explain the limited measured power in several previous experiments with metallic and dielectric-loaded power extractors [9, 12].

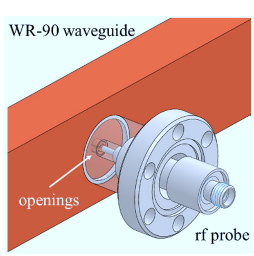

Figure 7: Design of the rf pickup. The pipe near the openings is set to be transparent to present the details.

DIRECTIONAL COUPLER

A directional coupler has been designed to eliminate the multipacting issue in the rf pickup, as illustrate in Fig. 8. Two large coupling holes on the WR-90 waveguide are far away from each other. Ceramic windows are applied to seal the vacuum at the coupling holes so that the waveguide-to-SMA adapters could be connected in air without potential multipacting issues.

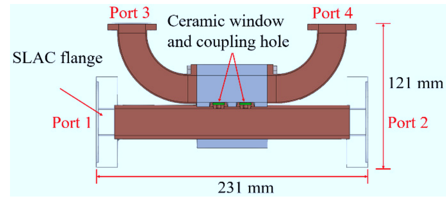

Figure 8: Layout of the directional coupler. Port 4 is used to measure the forward rf power going through Port 1 to Port 2. Port 3 is used to measure the reflected rf power coming from Port 2 to Port 1.

The directional coupler has a coupling of ~-60 dB and a forward/backward isolation of ~-52 dB, as illustrated in Fig. 9. It's currently under fabrication at Tsinghua University.

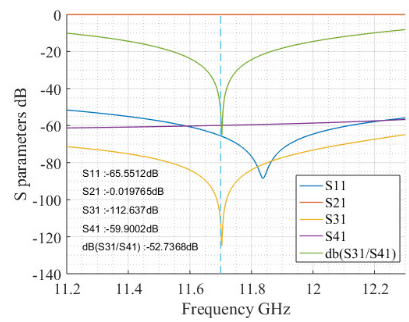

Figure 9: S-parameters of the directional coupler.

CONCLUSION

An X-band metallic power extractor has been developed as a power source for accelerating structure high power tests in the short-pulse two-beam acceleration program at the Argonne Wakefield Accelerator facility. rf pulses with ~280 MW power and 3 ns flat-top have been achieved when driven by 8-bunch trains with a total charge of ~500 nC. The highest generated power is ~50% lower than the theoretical prediction and simulation, which is experimentally confirmed to be limited by the multipacting issue inside the rf pickup. A direction coupler has been designed to replace the pickup in order to solve the problem.

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