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X-BAND HIGH GRADIENT ACCELERATING STRUCTURE FOR VIGAS PROJECT AT TSINGHUA UNIVERSITY *

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Abstract

A light source project named **V**ery Compact **I**nverse Compton **GA**mma-ray **S**ource (VIGAS) is under development at Tsinghua University. VIGAS aims to generate monochromatic high-energy gamma rays by colliding a 350 MeV electron beam with a 400-nm laser. To produce a high-energy electron beam in a compact accelerator with a length shorter than 12 meters, the system consists of an S-band high-brightness injector and six X-band high-gradient accelerating structures. The X-band structure's frequency is 11.424 GHz, and it adopts a constant gradient traveling wave approach; thus, the iris from the first cell to the end cell is tapered. The total cell number is 72, so we named it XT72. In the last two years, we conducted the design, fabrication, and tuning of the first prototype of XT72. Recently, we finished the high-power test, and the result demonstrates that it has the ability to work at an 80 MV/m gradient. In this paper, we present the latest update on this structure.

INTRODUCTION

Inverse Compton scattering is one of the promising methods to generate X-ray source with tunable energy, high brightness and monochromaticity. Recently, Tsinghua University has proposed a program to develop a **V**ery compact **I**nverse compton scattering **GA**mma-ray **S**ource (**VIGAS**), the goal of VIGAS is to generate a high flux gamma rays of 10^8 ph/s with continuously adjustable energy in the range of 0.2 MeV ~ 4.8 MeV by colliding an electron bunch with a 400-nm or 800-nm laser, the electron's energy can be tuned from 50 MeV to 350 MeV and the emittance is less than 0.6 μm [1–3]. Currently the beamline is under construction and we expect to achieve the first light by the end of 2025.

The beamline of VIGAS consists of 6 X-band high gradient structures, and energy gain of each should not be less than 50 MeV, requiring a gradient not less than 80 MV/m. In 2021, we developed a prototype of a CI X-band travelling wave structure with 72 cells, which we named XC72 (**X**-band **C**onstant impedance structure with **72** cells) [4]. XC72 underwent conditioning for nearly 20 million pulses. Although XC72 has reached almost 80 MV/m, the BDR is about 10^{-3}/pulse·m, slightly higher than we required, mostly because the field in the first cell is too high. Therefore, we decided to switch to the constant gradient (CG) approach. The CG structure has the same number of cells as XC72, but the apertures are tapered from head to tail, thus we name it XT72 (**X**-band **T**apered structure with **72** cells).

In this paper, we present the fully detailed design of XT72, along with the fabrication, RF tuning and high-power test results of the first XT72 structure. The results demonstrate its ability to operate at a gradient of 80 MV/m with a lower BDR.

DESIGN

We choose $2\pi/3$ phase advance per cell as the working mode for a better trade off between shunt impedance and filling time. The aperture of the cell is a crucial variable; the smaller it is, the higher the shunt impedance and longer the filling time, but the wakefield is more intense. The apertures of the CG structure are selected to be in the range of 3.12 mm to 3.92 mm, resulting in an average aperture of 3.52 mm. The shunt impedance of XT72 is similar to that of XC72. The RF properties of first, middle and end cell are shown in Tab. 1, the other cells' properties can be interpolated from these values. The v_g/c denotes the group velocity relative to the speed of light, r/Q represents the shunt impedance over quality factor, E_s denotes the surface electric field, E_a represents the accelerating gradient of the cell, H_s denotes the surface magnetic field, and S_c is the modified Poynting factor [5].

Table 1: RF Properties of the First, Middle and End Cell

Properties	first cell	middle cell	end cell
Aperture radius [mm]	3.92	3.52	3.12
Frequency [GHz]	11.424	11.424	11.424
Quality factor	7056	7024	6996
v_g/c [%]	3.20	2.23	1.44
r/Q [Ω/m]	13261	14404	15650
E_s/E_a	2.06	1.99	1.96
H_s/E_a [mA/V]	2.85	2.75	2.66
S_c/Ea^2 [mA/V]	0.52	0.44	0.35

Using the data in Tab. 1, we can calculate the power required output from the pulse compressor for XT72 to achieve 80 MV/m by the method in Ref. [6], as shown in Fig 1. The blue line is the power incident into the power compressor, the total pulse length is 1.2 μs, with a phase reverse at 1.1 μs. The quality of the PC is 90000 with coupling ratio of 3.5, thus the output power from PC is a factor of 5 to the incident power, but only 100 ns pulse length, as indicating with the red line. The gradient in time domain of XT72 can

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be numerically calculated using the following equation,

$$G(t) = \int_0^L \sqrt{\frac{\omega r(z) P[t-\tau(z)]}{v_g(z) Q(z)}} e^{-\alpha(z)} H[t-\tau(z)] dz \quad (1)$$

where $P(t)$ is the structure incident power, $\alpha(z) = \frac{1}{2}\int_0^z \frac{\omega}{v_g(z')Q(z')}dz'$ denotes the power attenuation factor along the structure, $\tau(z) = \int_0^z \frac{dz'}{v_g(z')}$ represents the signal time delay, and $H(t-\tau)$ is the heavyside function. Substituting the input power (red line in Fig. 1) and RF properties of each cell in Tab. 1 into Eq. 1, the gradient in time domain can be derived as shown by the black line in Fig. 1.

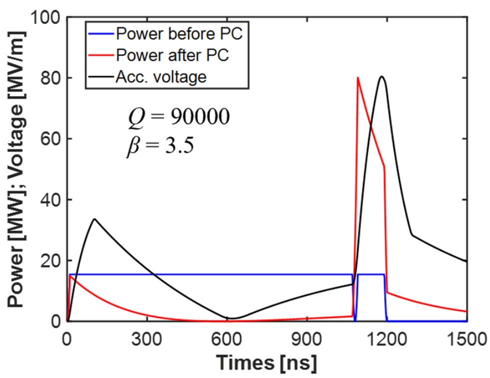

Figure 1: Numerical calculation results of required power and gradient in time domain

From this calculation, the required peak power out of the PC is 80 MW in order to achieve gradient of 80 MV/m. It should be noted that for the CG structure, the optimal pulse shape is square, rather than the exponentially decaying shape from a pulse compressor. Therefore, if a pulse with a longer flat-top is used, the required power should be less than 80 MW.

We adopted racetrack coupler to suppress the emittance growth due to multipole field in the coupler, and also analysed the transverse and longitudinal wakefield effect. The details are presented in the poster and oral presentation.

TUNING AND HIGH-POWER TEST

The bowl-shape regular cells are machined and the couplers are milled. All the dimensions tolerance are within 5 μm and the surface roughness is less than 0.1 μm. The pictures of cells of XT72#1 before and after brazing is shown in Fig. 2. The structure was tuned using a 4-port VNA after brazing by the local reflection method in Ref. [7], and the results are depicted in Fig. 3. Before tuning, there is a strong standing wave inside the structure and the phase advance per cell is far from 120 °. As illustrated in Fig. 3(c-d), the field balance and phase after tuning are improved and meet the requirements of the $2\pi/3$ constant gradient structure. The phase advance per cell is 120$\pm$1.4 ° from Fig. 3(e).

When tuning was finished, the structure was exhausted and then installed on the **T**singhua high **PO**wer **T**est stand for **X**-band (TPOT-X) [8]. The power source is a CPI VKX8311B

Figure 2: Cells of XT72#1 before brazing (up) and structure after brazing (down).

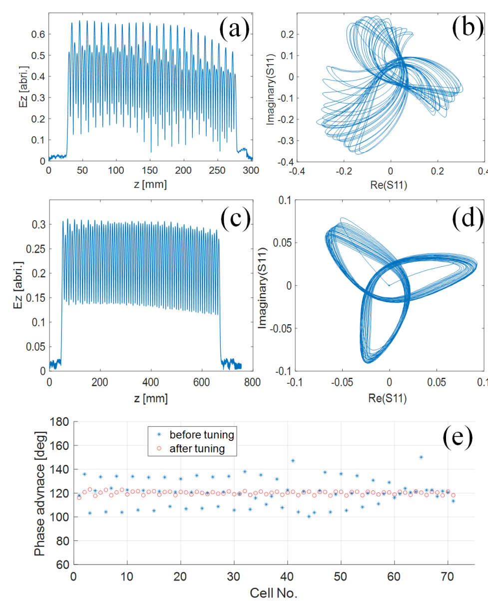

Figure 3: Tuning results. (a-b) Amplitude and phase of field before tuning. (c-d) Amplitude and phase of field after tuning. (e) Comparison of phase advance per cell between before tuning and after tuning.

Klystron capable of emitting 50-MW power with a pulse width of 1.5 μs and a repetition rate of 40 Hz, operating at a frequency around 11.4 GHz. Fig. 4 depicts the setup of high-power test stand.

The amplitude power emitting from the Klystron is boosted by the pulse compressor by a factor of 4, and the pulse width is compressed by a factor of 10. Therefore, the maximum peak power injected into the test stand can reach 200 MW with a 150-ns pulse width. The power transmitting outside through the device under test is absorbed by an X-band high-power RF load, which is scaled from S-band

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version. Directional couplers (DC6 and DC7) located at the entrance and exit monitor the transmission and reflection RF power, used to analyze the test structure's conditioning status. Other directional couplers (DC1-DC4) are used to monitor the output power of SSA, Klystron and pulse compressor. A Faraday cup is installed at the exist of the device under test for dark current recording. A high-power RF window separates the test structure from the upstream, thus there is no need to break the upstream vacuum when switching the device under test.

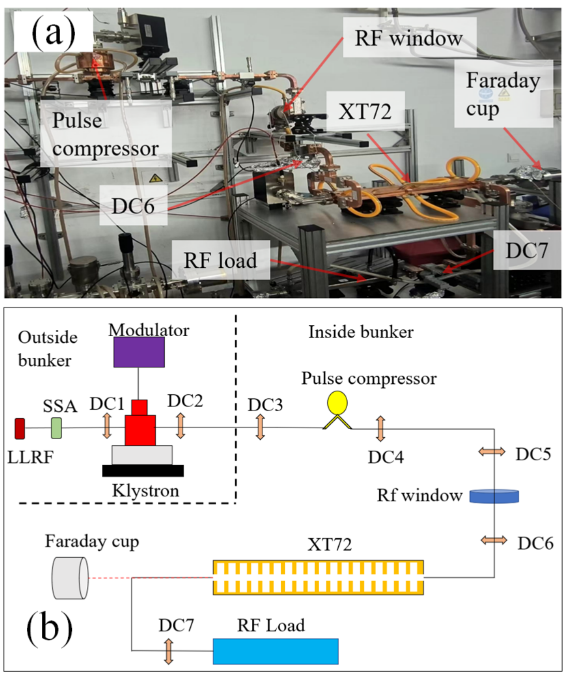

Figure 4: Picture and schematic of high power test stand.

During the RF conditioning, the transmission and reflection power waveforms from DC6 and DC7 are recorded every 5 seconds. The vacuum level and dark current signals are also monitored by the system. The conditioning strategy is described as follows: the power level increasing period is set to 60 seconds with a rest time of 30 seconds. During the 60-second conditioning period, if no breakdown occurs, the power level is increased by 0.1 MW. However, in the event of a breakdown, the RF is turned off for 30 seconds to evacuate the structure, and the power level is decreased by 0.1 MW. There are thresholds for the reflection signal from DC6 at the entrance of the device under test, the vacuum level, and the dark current. If any of them exceeds the set thresholds, the interlock is triggered, and an event of breakdown is recognized and recorded.

The high power test results of first XT72 are shown in Fig. 5, The total conditioning pulses number is about 17 million. The waveforms in Fig. 5 (i) were captured at BDR level of 10^{-4} /pulse/m, the peak power and gradient of XT72#1 were measured as 76.1 MW and calculated as 81.0 MV/m. The maximum surface electric field is 182 MV/m, which is lower than the empirical thresholds of 210 MV/m from CERN's

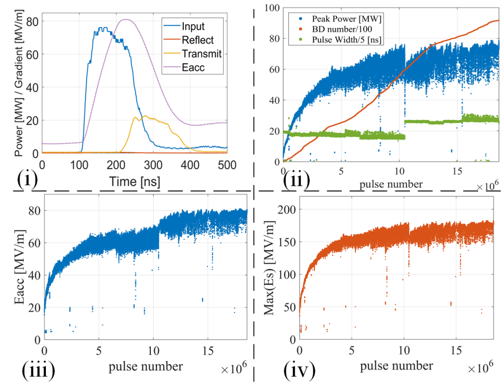

Figure 5: High power test results of XT72#1. (i) Input power (blue line), reflection power(red line), transmission power(yellow line) and gradient(Eacc, dotted purple line). (ii-iv) Conditioning history of peak power, breakdown (BD) numbers, pulse width, gradient(Eacc), maximum surface electric field(Max(Es)).

experience [9]. The reason that the peak power of XT72#1 needed for 80 MV/m in Fig. 5 (i) is lower than that of in Fig. 1 is because of the different pulse shapes. The ideal pulse shape output from a pulse compressor is exponentially decaying, however, in the experiment, we increased the phase reverse time and applied the amplitude modulation for the input pulse, thus a relative flat pulse was generated compared to the ideal case.

CONCLUSION

We present the design, fabrication, and testing of an X-band constant gradient structure for the VIGAS project at Tsinghua University. The high-power test results of the first XT72 structure demonstrate that it reached 81 MV/m at BDR of 10^{-4} /pulse/m within 17 million pules conditioning. The repetition rate of VIGAS is 10 Hz, which means the break down rate (BDR) should not exceed 2×10^{-5} /pulse in order to avoid break down during one hour of continuous operation. We believe that by conditioning more pulses the BDR will decrease to the level of 10^{-5} /pulse/m. Since the VIGAS project requires six X-band high-gradient structures by the end of this year and we currently have only one X-band test stand, we have decided to proceed with the high-power testing of the second XT72. Each structure will be conditioned with no more than 20 million pulses. Once the beamline construction is completed, we will be able to condition all six structures online simultaneously. This approach will help save time and achieve a lower breakdown rate more quickly. More details can be found in our oral talk and poster.

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