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HIGH POWER AND HIGH REPETITION RATE X-BAND POWER SOURCE USING MULTIPLE KLYSTRONS

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Abstract

In July 2016, the first X-band test facility operating with two interwoven RF pulses produced from 6 MW klystron was commissioned at CERN. Outputting up to 49 MW after pulse compression [1], the new test stand allows testing of two structures concurrently with a combined repetition rate of up to 400 Hz. Commissioning of two of the four lines has been completed and testing of high gradient accelerating structures for the Compact Linear Collider has commenced. Operations have been ongoing for more than a year, where dedicated control algorithms have been developed to conditioning the structure and to keep the pulse compressors tuned. Significant progress has been made in understanding the conditioning of two structures that are sharing an interlock and vacuum system. The higher pulse repetition rate has demonstrated a significantly reduction in the time required to condition accelerating structures.

INTRODUCTION

The Compact Linear Collider (CLIC) [2] project at CERN has led to the development of numerous high-gradient X-band accelerator technologies. Such advancements are attracting great interest from the light source and medical communities where linear accelerators are foreseen as the next generation of accelerators. Critical to CLIC's development of high-gradient X-band technology has been an investment in test stands, which allowed investigations of the complex, multi-physics effects that affect high-power behavior in operational structures.

Increasing the number of available testing slots is important because within the CLIC project there is an extensive program aiming to test 40 structures by 2019. CERN has built three test facilities called Xbox 1, Xbox 2, and the newest and subject of this report, Xbox 3 [3].

Xbox 1 and Xbox 2 use similar technologies to the original klystron-based test facilities in Japan and the US. These use costly, high peak power, 50 MW klystrons which require modulators capable of producing up to 450 kV. However, Xbox 3 uses twin low peak power, 6 MW klystrons. High peak powers are achieved by combining the output power of these klystrons and using pulse compression. This process allows the production of 47 MW for a 200 ns pulses at much higher repetition rates than would be possible with the single, 50 MW klystrons used in previous Xboxes.

CLIC prototype structures require 40–50 MW of RF power to reach a unloaded gradient of 100 MV/m. High-gradient accelerating structures take several hundred millions pulses to condition to nominal operating conditions [4]. It is therefore advantageous to make testing facilities that can pulse at high repetition rates, in order to reduce the time needed to condition structures.

In this paper, we will describe the combination scheme used in Xbox 3 and the experience of commissioning [5–7] the facility under high power.

XBOX 3 LAYOUT

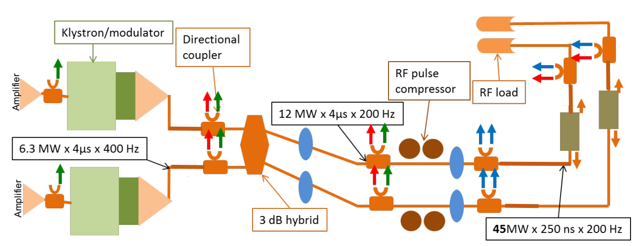

Figure 1: Schematic of the high power RF network of half the Xbox 3 facility.

Depicted in Figure 1 is the layout of one half of the Xbox 3 waveguide network. To achieve the peak power necessary, two klystrons are combined through a hybrid and subsequently compressed using a SLED-I pulse compressor (PC). The pulse repetition rate of each klystron can be increased up to 400 Hz. The whole system counts two symmetric layouts with a total of four test stands, consequently each test stand can operate up to 200 Hz.

The Low Level RF and control system is based on a National Instruments PXI crate. Each pair of klystrons shares

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one PXI crate and controller. The RF drive signals are produced using NI 5793 IQ generators. Due to inherent nonlinearities in the klystrons, they are run in saturation and the power controlled by changing the drive signal.

After the hybrid combination each line has a PC, test slot for the device under test and an RF stainless steel load to terminate the waveguide network. Directional couplers are placed at critical locations in the network for monitoring purposes. Vacuum pumping ports complete the network. There are several control loops controlling the stability of the RF power distributed to the waveguide network. Pulse-by-pulse changes can be made to the drive signal which allows the two test slots to operate independently. Sharing an interlock system, for safety reasons, an interlock in one line arrests the RF pulsing in both lines.

Breakdown rate (BDR [8]) of the structure has been demonstrated that is not affected by the previous history like power pulse ramping after a BD. That means in the next future we can still pulsing in one line if the BD/interlock happen in the other line [4].

COMMISSIONING

Initial pulsing was performed at a low repetition rate to check the performance of the subsystems, after that the repetition rate was increased to 200 Hz in each line.

An algorithm [9] was developed to flatten the pulse compressor's output pulse. Changes to the slope of the pulses flat-top can be performed through the cavities' temperature controller or by manipulating the input pulse's phase profile. By changing the input phase profile the response will be immediate. The algorithm uses a simple feedback loop and fitting the flat-top with a 5th order polynomial (Fig. 2 [9]).

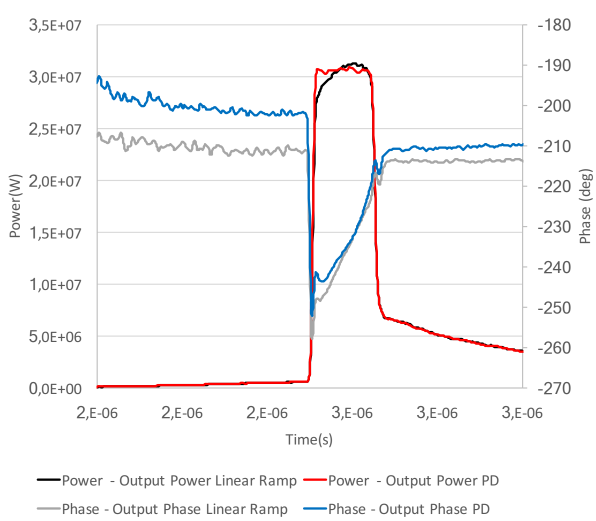

Figure 2: Power and phase of the incident and compressed pulses when tuned using the pulse flattening algorithm.

A frequency shift due the phase ramp (line blue of Fig. 2) have been observed that provoke an increase of the the dark current [10]. Thanks to the phase algorithm, Xbox 2 is running with a flat phase (Fig. 3). Flat phase is mandatory for injected bunches and it also decrease the radiation level on the structure. No correlation between BDR and flat phase have been observed.

Figure 3: Flat top pulse compressor with flat phase.

Xbox 3 uses Toshiba E37113 klystrons and ScandiNova K1 modulators which can each produce up to 5 µs pulses with 6 MW of peak power. At high repetition rate, greater than 200 Hz, the waveguide temperature increases up to the interlock limit (55°C). A dedicated cooling system based on clamps was design and installed to allow pulsing below the interlock limit. Any change in the average RF power (such as pulsing interruption due to an RF breakdown) caused the PC to cool and, as a result, detune. A frequency shift algorithm was added to the RF control GUI to tune the PCs after an RF interlock. The algorithm uses transmitted phase to choose the frequency shift as shown in Fig. 4. When the PC is perfectly tuned, the phase is exactly 180° at the minimum point of the transmitted power is zero. This occurs when the RF power leaking from the cavities begins to exceed the input power. Over tuned cavities mean that the filling phase shift is negative so that the phase flip is smaller than the desired value of about 180°, while under tuned means that the filling phase shift is positive so that the phase flip is larger than the desired value of 180°. A shift of drive frequency up to ±1 MHz can be applied to tune the PC instantaneously without waiting for temperature stabilisation. Within this range the klystrons are still stable, 1 MHz corresponds to about 5°C. The frequency shift algorithm is activated until the temperature of the cavities reach the working temperature stabilized with high power chillers.

Calibration of the entire RF system from waveguide to detector is very important, in order to reduce uncertainty in the RF measurements. There are several stages needed in order to fully calibrate the RF network. RF signal cables are split and sent to the low level RF diagnostic crate for down-mixing/log detection and simultaneously to a calibration system. Due to the temperature difference between summer and winter two sets of attenuation constants have been measured, where positive shift of 0.15 dBm is observed in summer.

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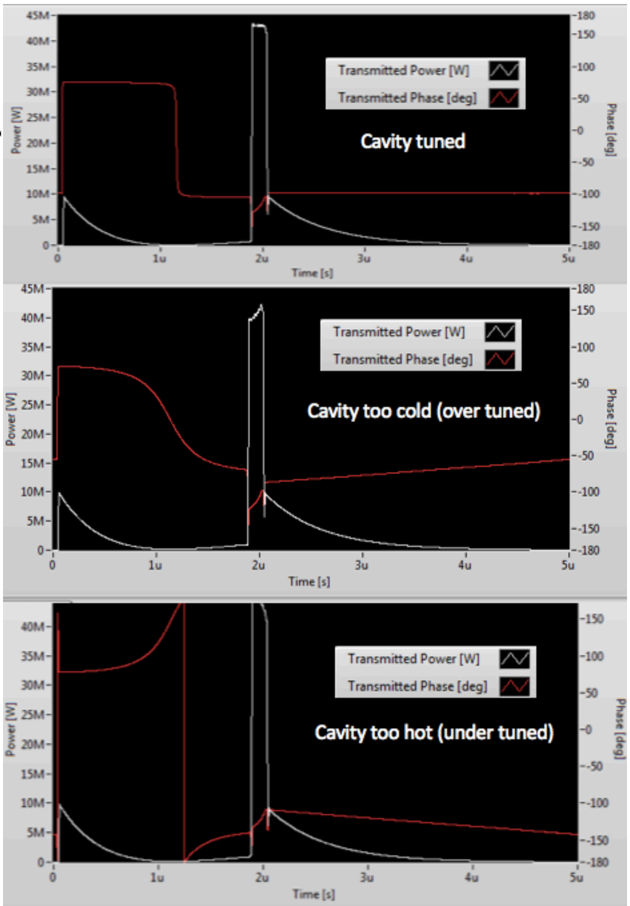

Figure 4: Simulation of tune/detuned cavity.

REFLECTION INTERFERENCE

In Xbox 2, it was observed that an interference from breakdown reflection resulted in up to a 40% increase in the input power (Fig. 5).

Xbox 2 and Xbox 3 have approximately 10 metres of waveguide that gives around 150 ns of delay minimum. If a BD occurs at the start of the structure and at the start of the pulse, the reflected signal from the structure can be interact in constructive way with itself. If the high power RF pulse is longer more than 150 ns the pulse can reenter the klystron and constructive interfere with the end of the same pulse (Figure 6).

This same effect is also observed as a small amplitude blip in the incident RF pulse flat-top. A correction in the phase program allows flattening of the pulse though this brings further challenges through a discontinuity in the incident phase. A more permanent solution to this is to have long waveguides. At least 15 meters in the CLIC design. This will of course lead to greater power loss compared to a shorter waveguide. No impact on the BDR is observed despite the structure seeing more power.

CONCLUSION AND ONGOING WORK

The commissioning of the most recent X-band test facility at CERN has been completed. The combination of two low

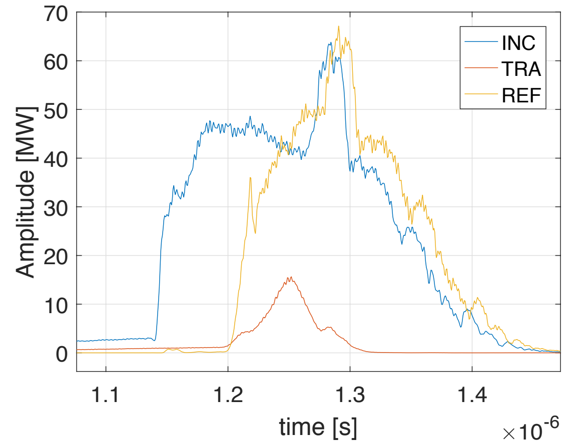

Figure 5: BD reflection interference.

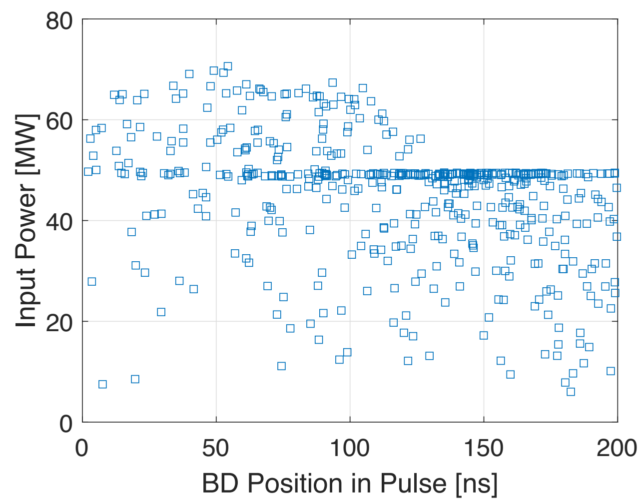

Figure 6: Power peak BD position in pulse.

power RF sources into two separate high power testing slots has been successfully demonstrated. New algorithms and new effects due to the peculiarities of this system have been observed and studied. Four CLIC prototype structures have already been tested in line 3 and 4 of Xbox 3.

In March of 2018, we installed a new klystrons in line 1 and 2. These lines are currently used to test RF components [11] such as 3D printed loads, a high power phase shifter, and variable power splitter. After testing the RF components the lines will be commissioned in the same way of line 3 and 4 with CLIC prototype structures. The high repetition rate of Xbox 3 is already showing the significantly reduced time needed to condition accelerating structures as shown in [4, 12].

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