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AN OVERVIEW OF THE RADIO-FREQUENCY SYSTEM FOR AN INVERSE COMPTON X-RAY SOURCE BASED ON CLIC TECHNOLOGY

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Abstract

Compact inverse Compton scattering X-ray sources are gaining in popularity as the future of lab-based x-ray sources. Smart*Light is one such facility, under commissioning at Eindhoven University of Technology (TU/e), which is based on high gradient X-band technology originally designed for the Compact Linear Collider (CLIC) and its test stands located at CERN. Critical to the beam quality is the RF system which aims to deliver 10-24 MW RF pulses at repetition rates up to 1 kHz with a high amplitude and phase stability of $< 0.5\%$ and $< 0.65^\circ$ allowing it to adhere to strict synchronicity conditions at the interaction point. This work overviews the design of the high power and low level RF systems for Smart*Light.

INTRODUCTION

Inverse Compton x-ray sources are gaining in popularity and are aiming to become the new lab x-ray source, replacing X-ray tubes and complementing synchrotrons and FELs. Smart*Light is a compact inverse Compton scattering (ICS) X-ray source based on high gradient linear accelerator technology designed for the Compact Linear Collider (CLIC) project. Central to the Smart*Light project is a European X-band (11.9942 GHz) linear accelerator whose design has been optimised for the capture of low energy electrons [1]. Producing X-rays consistently with each pulse means the ability to produce high power RF pulses which adheres to strict amplitude and phase criteria. In this paper, we will overview the low-level and high power RF systems of Smart*Light illustrating their designs and how each contributes to the required stability.

REQUIREMENTS OF RF SYSTEM

The linear accelerator (linac), which is designed for the capture of 100 keV electrons, is able to operate between 10 and 24 MW which results in a gradient of 50 to 78 MV/m [1]. Being able to produce RF peak powers up to 24 MW and for approximately 135 ns, which is the fill time of the structure, is a fundamental requirement of the high power RF system. Additionally, it is favourable that the HPRF can operate at RF pulse repetition rate up to 1 kHz which is the limit of the interaction/photocathode laser system. For the RF system, this RF pulse repetition rate is limited by the klystron and modulator available.

For the stability requirements, start-to-end beam dynamics calculations were performed using General Particle Tracer (GPT) [2]. Such simulations were optimised using genetic optimisation algorithms to find the operating conditions most suitable to the required beam characteristics at the interaction point with the laser. With these optimised values, the amplitude and phase of the RF inside the linear accelerator were varied and the beam quality at the interaction point was measured. The most sensitive parameter was found to be the arrival time at the interaction point. Setting the condition that the electron bunch must arrive within $\pm$200 fs of the mean arrival time, gives a phase and amplitude stability of $<0.65^\circ$ and $<0.5\%$, respectively. These stability requirements are a combination of all components of the RF system and below will be a discussion of the performance of some contributing components.

LOW-LEVEL RF SYSTEM

Generating the RF pulses to drive the pre-amplifier of the klystron is the low-level RF (LLRF) System. The LLRF primarily consists of three 19” crates designed and built in-house, and a National Instrumental PXI crate used as a controls and data acquisition unit. The three crates’ functionalities, as well as that of the PXI, are as follows:

- **RF control and mixing crate:** This crate is responsible for the 11.9942 GHz RF pulse generation, the phase-locked 1.499 GHz RF signal formation for the laser and bunch compressor (BC), and the IQ demodulation of the RF signals sampled from the waveguide (WG) network.
- **RF logarithmic detectors crate:** This crate is a hardware interlock crate used for the safety of the RF system. It also produces rectified 11.9942 GHz RF pulses as well as providing a digital output signal when the level exceeds a preset threshold.
- **Splitter and Multiplexing crate:** This crate distributes the RF signals sampled from the WG network. These signals are measured with the two crates discussed above or through an RF power meter attached to the output of an in-house built multiplexer.
- **PXI control system:** The PXI is the main control module of the setup. Its tasks are many but a few notable tasks, relevant to this paper, are: the control of the amplitude and phase of the 11.9942 GHz RF pulse; the digitisation of the IQ demodulated 11.9942 GHz signals; and the creation of the pulses for the triggering system.

A diagram of the LLRF system is illustrated in Fig. 1 and the following description will repeatedly refer to this

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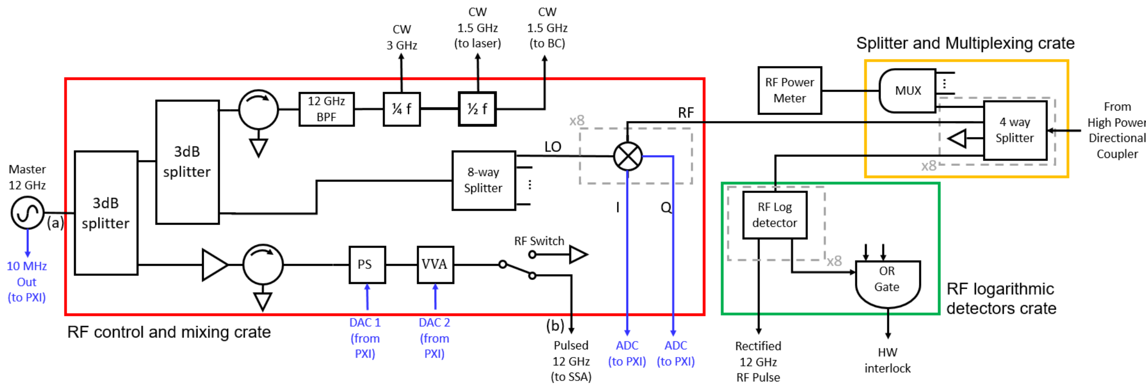

Figure 1: Simplified diagram of the Low Level RF System layout. The three coloured boxes define the three crates. Blue arrows define signals which are sent to the PXI control system.

figure. The red box encloses the components within the RF control and mixing (RFCM) crate. Half of the signal from the Master oscillator set to 11.9942 GHz, which we'll refer to as 12 GHz from here onwards, is used to create the RF pulse for the pre-amplifier. The amplitude and phase modulation are performed using an Analog devices HMC712ALP3CE Voltage Variable Attenuator (VVA) and a Qotana DBVCPS08001800A Phase shifter (PS). An additional RF switch brings the adds an addition 50 dB of attenuation outside of the pulse and means that the VVA is not required to generate the pulse's rising and falling edge. The VVA has a dynamic range of 27 dB. The 12 GHz RF pulse, this is transmitted to the pre-amplifier of the klystron through a high phase stability RF cable (Times Microwave Phase Track II) which were measured to have a phase stability of 0.124 degs/m/K for temperatures between 30 °C and 46 °C. This means that the temperature stability of this RF cables, which is 8 metres in length, is ± 0.66 K. Consequently all RF cables will be wrapped in insulation to minimise temperature drift. The phase noise from the 12 GHz RF pulse produced from the LLRF was measured using a spectrum analyser and is illustrated in Fig. 2. The figure illustrates the single side-band noise directly from the 12 GHz Master oscillator (the measurement position is shown as (a) in Fig. 1) and from the 12 GHz LLRF output (shown as (b) in Fig. 1). Integrating this curve and converting to timing jitter, from phase jitter, gives a value of 230 fs between 1 kHz and 10 MHz.

The other half of the signal from the Master 12 GHz is split for a second time which provides the local oscillator (LO) for the hardware IQ mixers and also provides the 12 GHz source for the frequency dividers which generate of a 3 GHz and two 1.5 GHz CW signals which are locked to the 12 GHz. One of the 1.5 GHz CW signals is used to feed the photo-cathode/interaction laser synchronisation system. The synchronisation is able to synchronise the phase noise of laser and RF to less than 100 fs between 1 Hz and 1 MHz. The second 1.5 GHz feeds a solid-state amplifier whose output will be fed into the 400 W bunching cavity (BC). The 3 GHz signal is generated beam quality testing allowing a streaking cavity operating at 3 GHz to be temporarily placed

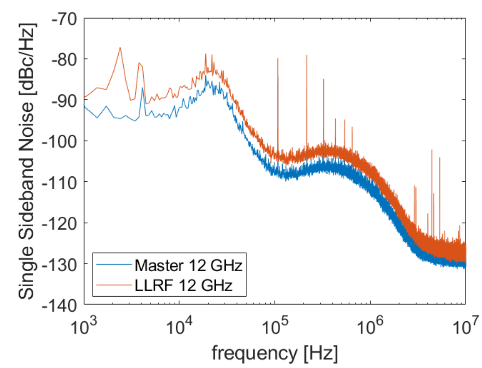

Figure 2: Phase noise measurement of the Master 12 GHz ((a) in Fig. 1) and the output of the LLRF ((b) in Fig. 1).

after the bunching cavity to measure the longitudinal profile of the bunches.

In Fig. 1, the yellow and green boxes encapsulates the splitter and multiplexing (splitter) crate, and the RF logarithmic detector (log detector) crate, respectively. The splitter crate is responsible for the distribution of RF signals sampled from the RF network using the high power directional couplers. The signals from the directional couplers are sent to the temperature stabilised rack using the same phase stable cables mentioned above. The signals arrive with approximately 33 dBm of power, when the HPRF is operating at it peak power, which is attenuated appropriately to ensure the power does not exceed the allowable limit of the splitters. The first signal from the splitter remains inside the crate and is sent to the multiplexer which is connected directly to an RF power meter. This allows for switching between each signal to check the power level from all signal sampled from the WG network with a well-calibrated measuring device. The second RF signal is sent to the log detector crate. The log detector crate rectifies the 12 GHz pulsed signals and allows the amplitude of the RF to be measured over a large dynamic range of >40 dB. The third RF signal from the splitter is sent to the RF input of the IQ mixers in the RF control and mixing crate. This signal is further attenuated if required before the RF input of the mixer and then mixed with the local oscillator (LO) to provide the I and Q component of the

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12 GHz RF pulsed sampled from the network. The I and Q components are sampled with a 250 MSPS ADC within the PXI crate which calculates the amplitude and phase using the calibrated look up table of the IQ mixers which account for imperfections in the IQ demodulation.

Preliminary measurements of the pulse creation measurement using the LLRF system have produced and measured a 5 µs pulse within an amplitude stability of 0.5% and 0.17° using an arbitrary waveform generator for the switch, lab power source for the VVA and PS, and a 10-bit oscilloscope to measure the I and Q components. These measurements are expected to be improved using the PXI system which includes two 16-bit 500 MHz DACs and several 250 MHz 14-bit ADCs. A direct measurement of pulse-to-pulse stability is to be measured soon and this will determine the final performance of the LLRF.

HIGH POWER RF SYSTEM

Central to the high power RF system is the klystron and modulator. For the ability to generate X-band pulses at high repetition rates, a Scandinova K200 modulator and the 6 MW, 5 µs Canon E37113 klystron was used. Together these have been shown to operate at repetition rates of 400 Hz for their full pulse width [3, 4]. For our RF system, this has been increased to 500 Hz for a 4 µs RF pulse which is important as the laser must operate at repetition rates of 1 kHz/N where N is an integer. In future tests, this system will be tested up to 1 kHz for a 2 µs RF pulse, keeping the average power below the allowable limit. The pulse-to-pulse amplitude stability of the modulator was measured during the factory acceptance test to be 27 ppm for 500 Hz operation which is much better than the required stability. The pre-amplifier to the klystron is a Microwave Amps Ltd AM61-12S-60-56PR 400 W solid state amplifier. The amplitude and phase stability of these amplifiers was previously measured by CERN, for their Xbox 3 X-band test stand, to be 0.02% and 0.03° [5]. The high amplitude and phase stability of these systems, and their ability to pulse at high repetition rates made them ideal candidates for this system. The combined amplitude and phase stability of the klystron and modulator powered by the pre-amplifier and the LLRF will be determined in the coming months.

To achieve the final RF peak power required for the linac, a SLED-I pulse compressor is incorporated into the RF network after the klystron (Fig. 3). The pulse compressor's design was that from the Xbox 3 X-band test stand at CERN which was optimised for this klystron/modulator [4]. The pulse compressor was fabricated completely in the Netherlands and was measured to have a coupling factor of 2.96 and a loaded Quality Factor of 51,600. The S-parameters measured from the assembled pulse compressor were used to simulate the peak power possible. With an RF input pulse with a peak power of 6 MW and pulse length of 4 µs, this can produce a peak RF power of 29 MW for 135 ns pulse. When reduced to 2 µs, the achievable peak power is reduced to 24 MW. Taking into account losses in the waveguide network which are for 11.994 GHz RF are 0.1 dB/m, the power arriving at the accelerating structure is expected to be up to 25.8 MW for 500 Hz operation while 21.39 MW for 1 kHz operation. Consequently, the accelerating gradient will be restricted during the highest repetition rate operation.

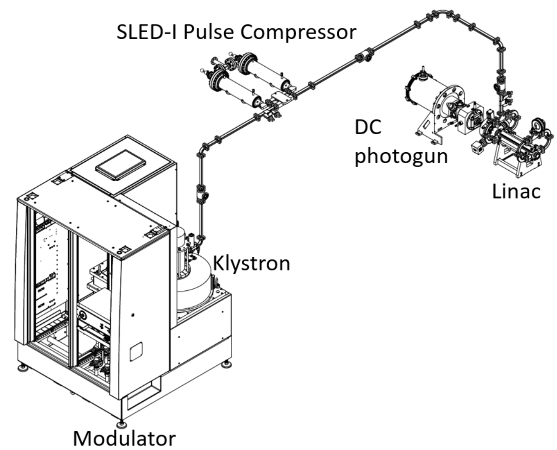

Figure 3: High Power RF Network.

CONCLUSIONS

An overview of the high power and low-level RF system for the Smart*Light Inverse Compton Scattering X-ray source has been demonstrated. The LLRF system was described in detail illustrating its ability to produce all the RF signals required for the Smart*Light beamline. An overview of the HPRF system was given which is able to produce RF pulses up to 24 MW for a 135 ns at a repetition rate of 500 Hz.

FUNDING

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