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DEE VOLTAGE REGULATOR FOR THE 88-INCH CYCLOTRON*

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Abstract

A new broadband Dee voltage regulator was designed and built for the 88-Inch Cyclotron at Lawrence Berkeley National Laboratory. The previous regulator was obsolete, consequently, it was difficult to troubleshoot and repair. Additionally, during operation, it displayed problems of distortion and stability at certain frequencies. The new regulator uses off-the-shelf components that can detect and disable the RF during sparking events, protecting the RF driver system. Furthermore, it improves the tuning of the cyclotron and allows consistency in operation.

INTRODUCTION

The 88-inch Cyclotron at Lawrence Berkeley National Laboratory is a sector-focused Cyclotron that has three ion sources with escalating intensities and charge states [1, 2]. These sources can produce mixtures of ions that contain nearly identical charge-to-mass ratios, known as "cocktails" [3].

The cyclotron accelerates protons through uranium to maximum energies of 55 MeV/u. In addition, it supports the ongoing research programs in nuclear structure, astrophysics, heavy element studies, and technology R&D by Lawrence Berkeley National Laboratory (Berkeley Lab) and UC Berkeley. Moreover, it is also home to the Berkeley Accelerator Space Effects Facility that uses these beams to understand the effect of radiation on microelectronics, optics, materials, and cells [4].

The cyclotron has a broadband RF system that operates between the frequency range of 5.5 to 16.5 MHz, Fig. 1. As shown, the 1 Vpp RF signal, generated by the frequency synthesizer, goes through the redundant chain, RF drive, and RF clamp circuits. If malfunctions were to occur, compromising the safety of personnel or damaging equipment, these circuits turn off RF signals, stopping the beam and radiation production. Then the RF signal passes into the RF modulator that samples and regulates the Dee voltage amplitude. The modulator also protects the RF system during a sparking event by shutting off the RF, avoiding momentarily overdrive of the RF system, similar to other cyclotron regulators [5, 6].

The signal from the RF modulator is increased by a 10 Watt wideband amplifier. This amplifier is followed by an attenuator switch, which is used to normalize different system attenuations at different frequencies, mainly due to losses on the coaxial cables. Finally, the signal is increased via the 1200A225 amplifier that drives the 150 KW Final Power Amplifier before being applied to the RF tank that has adjustable RF panels to drive the Dee electrode.

DEE VOLTAGE FEEDBACK

The capacitive Dee probe is displayed on the top right side of Fig. 1. The probe consists of an isolated flush plate that faces the Dee electrode and has a 1 pF capacitance to the Dee electrode. A 1000 pF capacitor is connected to the plate to sample the RF, working as a 1000 divider. The RF feedback voltage is sent to the Dee voltage regulator.

DEE VOLTAGE REGULATOR

Figure 1 displays the new Dee voltage regulator interfaced with the RF system. The feedback voltage is attenuated 3 dB before it is processed by two broadband voltage-controlled attenuators GC2001C are connected in series with the RF system and controlled by the regulator board. These attenuators provide up to 50 dB of attenuation to control and stabilize the Dee voltage. The control board is divided into sections to understand its functionality.

The LM7171 was chosen for the design of the circuit board because it is a high-speed voltage feedback amplifier that has the slewing characteristic of a current feedback amplifier [7]. It can do all of this while being used in all traditional voltage feedback amplifier configurations. The LM7171 is intrinsically stable for gains as low as +2 or -1. This is further shown by its high slew rate of 4100V/µs and a wide unity-gain bandwidth of 200 MHz while only consuming 6.5mA of the supply current.

Usage of ±15 V power supplies allows large signal swings and provides greater dynamic range and signal-to-noise ratio. One necessary aspect to maintain low power supply impedance across frequency is to bypass the power supply [7]. Both positive and negative power supplies should be bypassed individually by placing 0.1 µF ceramic capacitors in parallel with a 10 µF tantalum capacitor directly to the power supply pins of the LM7171. The 51 Ω isolation resistor located at the output of the amplifier increases the stability by reducing the reflections.

Peak-to-Peak Detector

The dashed green section of the Fig. 1 shows a passive peak-to-peak detector. The 50 Ω termination resistor matches the source impedance of the Dee electrode voltage feedback. The detector is a combination of two cascaded parts: the first is the clamp circuit formed by a capacitor and diode at the left, and the second is the peak rectifier circuit formed by a diode and capacitor at the right. It converts the RF signal of peak amplitude Vpeak into a DC signal. The capacitor of 1nF at the end of the circuit is charged

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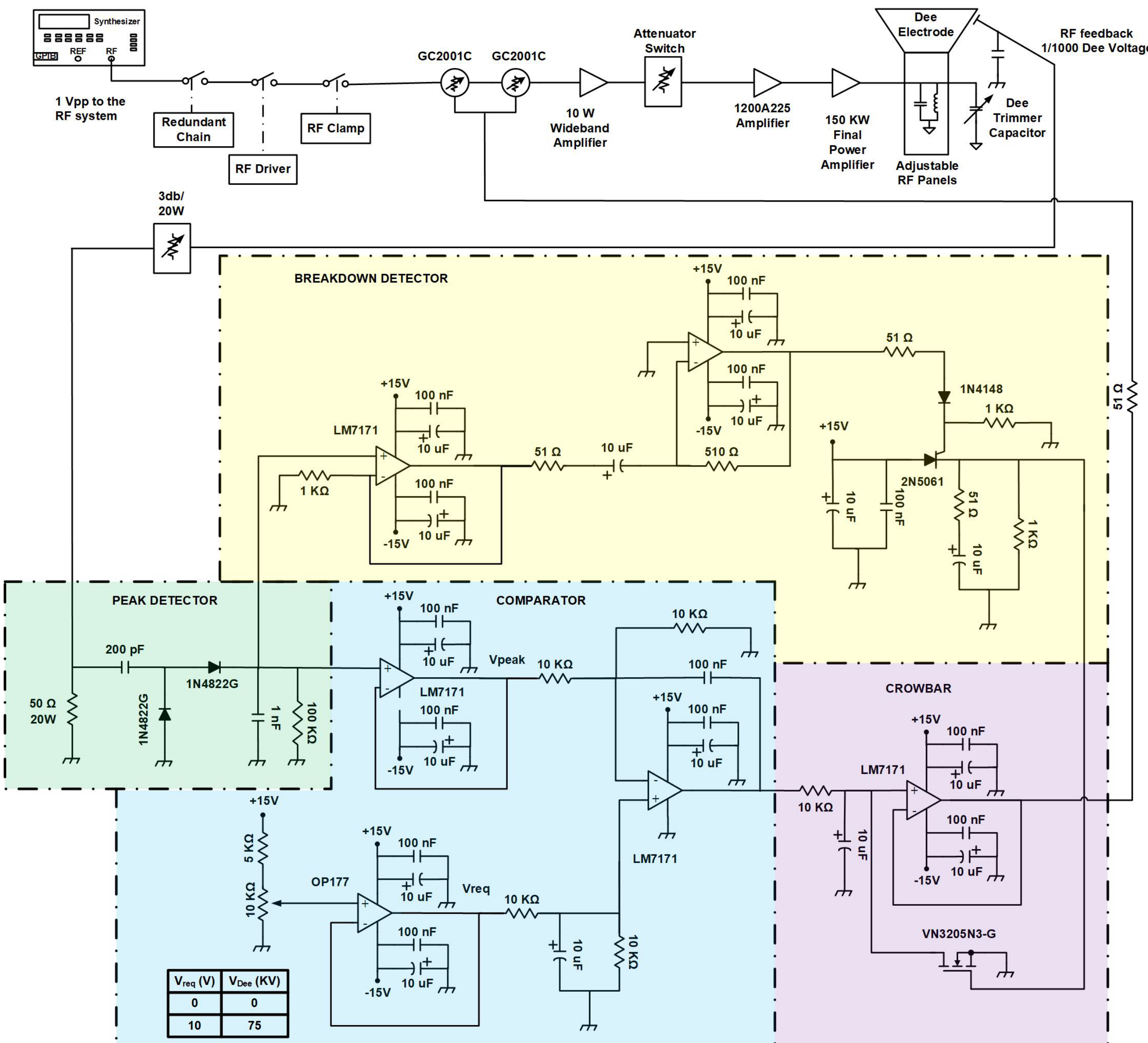

Figure 1: Dee voltage regulator interfaced with the RF system.

up to the maximum voltage which corresponds to the peak-to-peak voltage, 2Vpeak. A resistor of 100 KΩ discharges the capacitor with a time constant of 100 µs, proportional to several periods of the RF signal.

Comparator

The lower left side dashed section of Fig. 1 represented in blue shows the comparator. A 10 KΩ potentiometer produces the requested voltage that is buffered by a OP177 Ultraprecision Operational Amplifier, which is configured as a voltage follower. The OP177 contains one of the highest precision performances of any operational amplifier [8].

The buffered signal is applied to the positive input of the LM7171 and the peak-to-peak voltage is buffered and applied to the negative input of the LM7171. The LM7171 is configured as a differential amplifier to produce an error signal that will drive the GC2001C. If the signal from the peak detector is above the requested voltage, the output voltage will decrease and the GC2001C attenuation will increase, or vice-versa. If the reference voltage is set to 10 V, the Dee voltage will correspond to 75 KV.

Breakdown Detector

The dashed section of Fig. 1 represented in yellow shows the non-inverter amplifier that was used to enhance the variations of the peak-to-peak detector. The input impedance of the circuit is very high and it doesn't load the previous stages. The voltage gain of the amplifier of 1.5 is obtained from the equation:

$$Av = 1 + \frac{R2}{R1}$$

where:

Av is the voltage gain

R2 is the feedback resistor (500 Ω)

R1 is the resistance of resistor to ground (1000 Ω)

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The signal is then applied to a differentiator amplifier that has a voltage output, Vout, given by:

$$Vout = -RC\frac{d(Vin)}{dt}$$

where:
R is the feedback resistor (510 Ω)
C is the input capacitor (10 μF)
d(Vin)/dt is the rate of change of the input voltage with respect to time

This means that the faster the change in the input voltage signal, the greater is the output voltage. The differentiator is used to detect a sparking event that produces a sudden drop of input voltage. It disables the RF before the regulator overdrives the RF system.

The 1N4148 allows only the positive cycle of the differentiator to trigger the gate of the 2N5061, which is a Silicon Controlled Rectifier (SCR). The 1 KΩ resistor gives a reference to ground for the signal. The 2N5061 works as a bistable switch. After the SCR is triggered, it turns on and starts to charge the 10 μF capacitor through the 51 Ω resistor that limits the current inrush. The SCR will remain on until the 10 μF capacitor is charged, i.e. until the anode-to-cathode current drops below the holding current value. The 1 KΩ resistor in parallel with the 10 μF capacitor works as a bleeder resistor, giving a time constant of 10 ms to the pulse applied to the crowbar that is enough time to dissipate the plasma that would sustain the breakdown.

Crowbar

The lower right side dashed section of Fig. 1 represented in violet shows the crowbar circuit. The VN3205N3-G metal-oxide-semiconductor field-effect transistor (MOSFET) is chosen because it contains very high drain resistance when the gate is off. Additionally, it has a high speed of commutation, allowing to quickly discharge the 10 μF capacitor at the left bottom side of the Fig. 1. Discharging the capacitor brings the voltage of the output of the LM7171 to zero applying maximum attenuation at the GC2001C voltage-controlled attenuator, consequently driving off the RF and protecting the RF system during a sparking event in the cyclotron. After the gate of the MOSFET recovers, the 10 μF capacitor starts to charge back though a 10 KΩ resistor with a time constant of 100 ms, avoiding to hammer the amplifiers and giving enough time to the plasma generated by the breakdown to dissipate.

MEASUREMENTS

The Dee voltage regulator was tested on the bench. A synthesizer was adjusted to 1 Vpp at 10 MHz and sent to the two GC2001C voltage-controlled attenuators. The RF output voltage after the attenuators was attenuated with 6 dB and amplified by an 320LA amplifier to provide 26 Vpp when the GC2001C did not provide attenuation. The RF output from the 320LA was applied to the regulator board through an RF switch, that could simulate a RF sparking event.

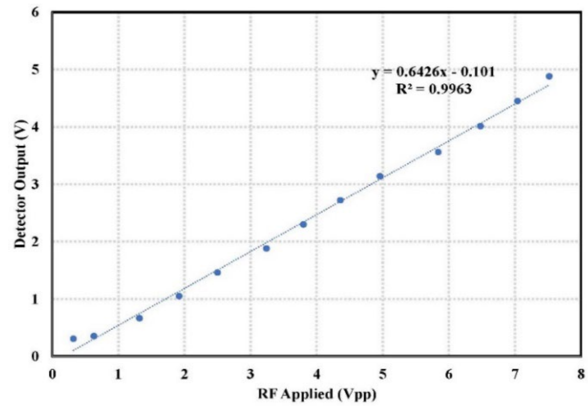

Figure 2: Linear fit of the peak-to-peak detector.

Figure 2 shows the DC voltage measured at the output of the peak-to-peak detector. The amplitude keeps a R-squared value of 1, which shows an excellent linear fit approximation.

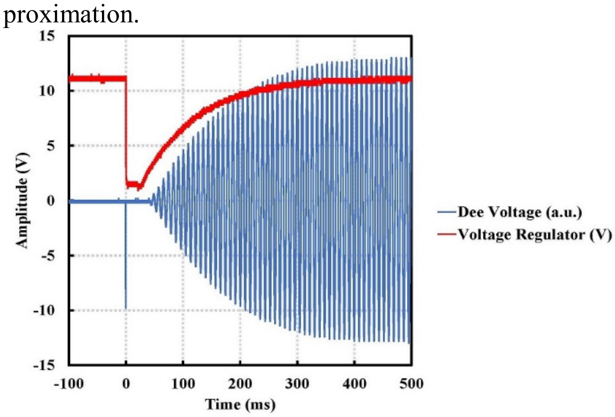

Figure 3: Recovery time of the Dee voltage after a RF sparking event is detected.

Figure 3 shows the Dee voltage recovery time after a sparking event of 200 ms. The recovery time was set to hundreds of ms to allow the plasma produced during the sparking event to vanish before the RF is reapplied, avoiding the plasma to sustain the sparking event. The structure produced in the Dee voltage represented in blue is caused by aliasing of the oscilloscope.

CONCLUSION

A new Dee voltage regulator was designed and a prototype was built and tested on a bench to substitute an obsolete regulator that had problems of distortion and stability.

The new regulator can detect and disable the RF during sparking events, allowing the plasma produced during these events to dissipate, protecting the RF driver system. The new regulator will reduce the RF distortions and improve the stability, improving the tune of the cyclotron. The hardware is currently being tested and commissioned in the cyclotron.

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