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A POWER AMPLIFIER BASED ON RAD-HARD GALLIUM NITRIDE FETS FOR THE 10 MHz CAVITIES OF THE CERN PROTON SYNCHROTRON

G. Gnemmi*, M. Paoluzzi, S. Energico, V. Desquiens, C. Rossi
CERN, Geneva, Switzerland

Abstract

The upcoming High-Luminosity Large Hadron Collider (HL-LHC) program requires a beam performance in the CERN Proton Synchrotron (PS) that is at the limits of the current Radio-frequency (RF) systems. Following the discontinuation of the RF tube production of the driver amplifiers a new solid-state design has been developed using radiation-hard amplifier technology. In view that the current system architecture has reached its maximum achievable gain, the goal was to reduce the cavity impedance encountered by high-intensity circulating beams. This reduction is achieved by increasing the fast feedback gain around the 10 MHz cavities. A 400 W modular driver amplifier based on Gallium-Nitride Field-Effect Transistor (GaN FET) and its control system have been prototyped and are currently in the testing phase. The FETs have been qualified for radiation in J-PARC and they will undergo additional irradiation time in the PS tunnel at CERN to additionally qualify the amplifier in its entirety. The paper details the prototyping stage and the tests conducted to ensure the device meets the necessary standards.

THE 10 MHz SYSTEM OF THE PS

The 10 MHz cavities of the PS are the main RF acceleration system of the PS, consisting of 11 cavities, of which 10 are used during operations and one is kept as a spare in case one of the 10 breaks. Besides accelerating the beam, the RF systems are also necessary for RF manipulations, such as splitting and rotation, at various RF harmonics. A cavity consists of two $\lambda/4$ resonators loaded with ferrite rings, with capacitive gaps at their input ends. They cover the frequency range of 2.8–10 MHz through a longitudinal polarization magnetic field that partially saturates the ferrite.

The amplification chain consists of two main stages: a driving stage and a final stage. Four tetrodes are used: three YL1056 for the first stage and one RS1084CJ in the final stage. In the past, tetrode technology was compatible with harsh radiation environments. The final stage powers the two cavities in parallel and provides the necessary voltage to accelerate the beam. Up to 10 kVp per gap can be achieved.

The bare cavity's resistance is around 10 kΩ at 10 MHz, mainly due to ferrite losses, and it is in parallel with the anodic resistance of the power amplifier (6 kΩ) [1]. The high-intensity proton beam passing through the gaps induces a strong voltage proportional to the cavity impedance, causing distortion of the RF voltage, leading to a significant modification of the particle motion dynamics. To control the induced voltage, the cavities are equipped with a wideband direct feedback system that mitigates the effects of beam loading.

During the Long Shutdown 2 (LS2), an updated prototype of the amplifier for the 10 MHz cavities was built, tested, and installed. The amplifier brought a significant reduction in the amplifier output impedance, crucial for enabling higher beam intensities [2]. However, with this upgrade, the amplification chain reached operational limits. Moreover, in 2022, the YL1056 tetrode used in the driver stage went out of production without a suitable replacement. To address the issue of the discontinued tetrode while simultaneously increasing margins for beam performance, it was necessary to seek alternatives.

REQUIREMENTS FROM A NEW RF DRIVER AMPLIFIER

The new driving stage should power the final stage, which continues to rely on the RS1084CJ tetrode and remains in place within the cavities. Once integrated into the preexisting amplification chain and cavity, the new amplifier must meet the following requirements:

- To drive the grid of the final tube, the new amplifier requires a 200 V_{peak} output.
- The operating band of the PS 10 MHz RF system spans approximately 2.8–10 MHz. The new system should possess a bandwidth greater than this range.
- To mitigate the impact of beam loading, it's crucial to design a wideband fast RF feedback loop around the cavity. This feedback loop's effectiveness hinges on the cavity's quality factor (Q), the open loop gain (A_d) of the driver stage and the group delay (τ_L) of the amplification chain. Therefore, the amplifier must be situated close to the beam line as for the current YL1056 tetrode setup. Ionizing radiation up to 500 Gy must be considered. The device should endure at least 10 years under these conditions.

With RF tetrode technology being phased out in industry, CERN needs to find solid state alternatives. Notably, Metal Oxide Semiconductor Field-Effect Transistors (MOSFETs) are already operational within low-radiation areas at CERN, ensuring extended device lifetimes through radiation mitigation techniques [3].

However, the higher radiation levels in the 10 MHz cavity locations within the PS ring require new solutions [4]. Gallium-Nitride (GaN) Field-Effect Transistors

* giulia.gnemmi@cern.ch

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(FETs) emerge as a promising alternative. Gallium nitride (GaN) has emerged as one of the most attractive materials for RF applications that require high-power and high-frequency devices. This is due to the superior material properties of GaN including the wide bandgap, high saturation velocity, good electron mobility, large critical electric field , and good thermal conductivity additionally to their inherent immunity to Total Ionizing Dose (TID) compared to MOSFETs.

Collaborating with J-PARC in Japan, two GaN devices from Qorvo underwent extensive testing in previous years, surpassing a TID of 18 kGy without encountering any Single Event Effects (SEEs) with a neutron fluence of $1.2{\cdot}10^{14}$ n$\cdot$cm^{-2} (1 MeVeq). They have therefore been chosen for the first prototype of a GaN-based RF Driver.

THE GaN-BASED RF DRIVER

The GaN-based RF Driver prototype is composed of 3 stages:

- The input buffer and capacitive summing point utilize one QPD1013 operating in Class A. It features two RF input ports: the first for the amplifier's driving signal and the second to feed back a portion of the cavity gap RF signal via a capacitive path, facilitating the implementation of a fast, wideband RF feedback loop. Additionally, the stage is outfitted with two diodes at the input to prevent stage overdrive.
- The driver stage utilizes two QPD1016 devices connected in a push-pull configuration and biased in Class A. These devices are supplied with voltage lower than their nominal value to limit the maximum saturated output power.
- The final stage utilizes two QPD1016 devices connected in a push-pull configuration and biased in Class AB. The output power reaches saturation just above 400 W (equivalent to 200 V_{peak} over 50 Ω). Despite the QPD1016's power capabilities, the power level is limited to mitigate the charge trap effect exhibited by the device, ensuring a constant power output in continuous wave (CW) operation.

Table 1 summarizes the bias points and gains for the various stages of the GaN-based RF Driver.

Table 1: Bias Points and Gains for The 3 Stages of The RF Driver Amplifier

Parameters	Input	Driver	Final
Gain [dB]	0	27	29
DC supply [V]	15	24	55
DC current per GaN[A]	0.5	1	0.5

Several tests and measurements were conducted to qualify the prototype and assess its adherence to the specifications required for its integration into the 10 MHz RF system. Presented below are some of the most pertinent results obtained, including both frequency and time domain measurements.

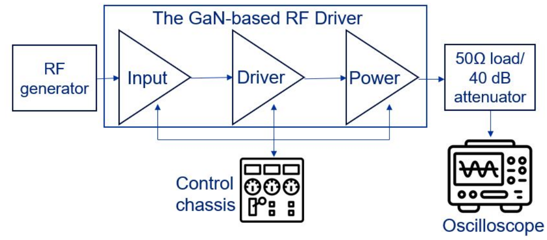

Figure 1: Test set-up of the RF Driver.

Due to space constraints, the graphs display measurements conducted solely at 10 MHz. However, it is worth noting that measurements at different frequencies within the range of 1–20 MHz were performed during the qualification process. These tests were conducted in a laboratory setting, and the device setup can be observed in Fig. 1. The amplifier is fed with an external RF signal and is situated on a 50 Ω load. To verify the correct power-on and power-off sequence, as well as to facilitate shutdown in the event of any failure, a control chassis has been designed. This chassis encompasses the power supplies and a microcontroller tasked with supervising the power amplifier.

Frequency Domain Measurements

As depicted in Fig. 2, within the frequency range pertinent to the RF system application at CERN's PS, the response remains notably flat. The total gain measures 56 dB, with a group delay of 18.5 ns.

Harmonic Distortion

Harmonic distortion has been assessed across various frequencies ranging from 1 to 20 MHz. Overall, across all frequencies tested, the harmonic components consistently remain below –20 dBc. Figure 3 exclusively displays the harmonic contribution measured at 10 MHz.

RF Gain vs Output Power

To evaluate the linearity of gain with respect to output power, the entire amplifier was driven with a 1 ms RF burst.

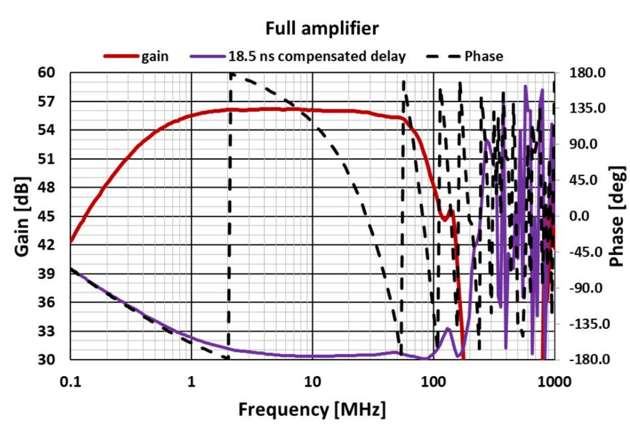

Figure 2: S21 magnitude and phase measurement of the RF Driver.

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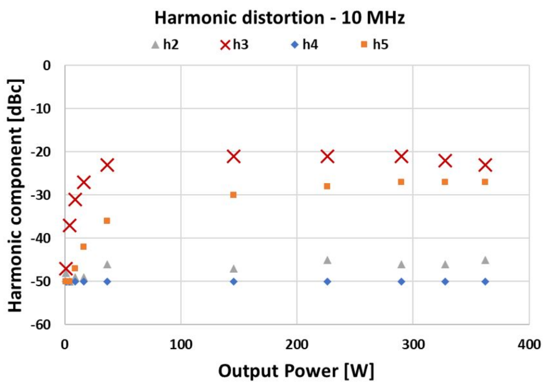

Figure 3: Harmonic content measured at 10 MHz.

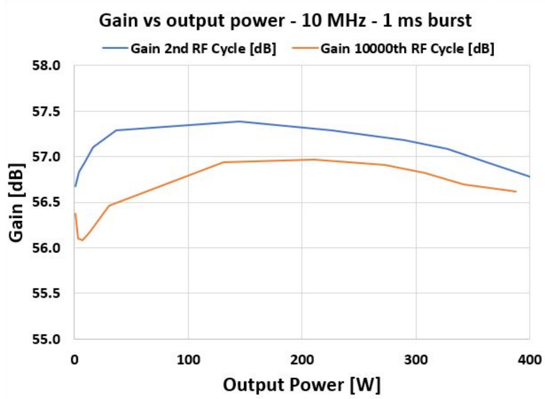

Figure 4: Gain vs output power at 10 MHz.

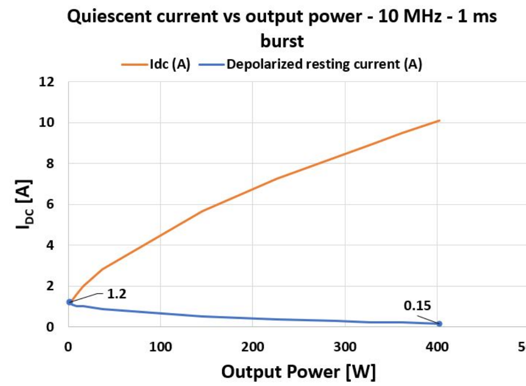

Figure 5: Quiescent current vs output power at 10 MHz.

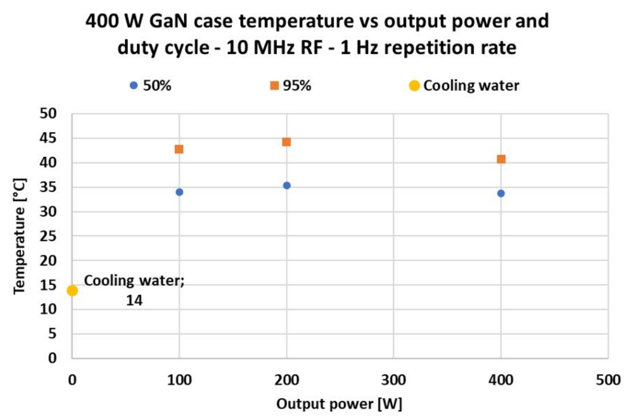

Figure 6: Operating temperature vs output power at 10 MHz.

Values were computed for the 2nd and the last RF burst cycle. Across all frequencies tested, the gain linearity consistently remains better than 1 dB. Figure 4 illustrates the results measured at 10 MHz.

Depolarisation Effect

During the tests, it was observed that the QPD1016 experiences depolarization effects, leading to changes in the bias point and altering the behavior of the system. As RF power increases, the quiescent current decreases, shifting the amplifier's operating point towards class B from the normal class AB setting, as depicted in Fig. 5. At this reduced quiescent current, the GaN transconductance decreases, resulting in a reduction in total gain. This phenomenon is dynamic and dependent on various factors such as burst length, duty cycle, repetition rate, and power amplitude. The RF frequency, up to several tens of MHz, has only a minor impact. Typically, the initial bias conditions are restored within tens or hundreds of milliseconds.

Operating Temperature Assessment

Finally, the operating temperature of the power stage was evaluated by measuring the temperatures of the two QPD1016 cases across various frequencies ranging from 1 to 20 MHz and at different duty cycles. The maximum temperature was found to be slightly below 50 °C at 1 MHz with the cooling water at 14 °C. Assuming a maximum cooling water temperature of 30 °C during the summer, the cooling appears to be compatible with reliable operation. Interestingly, the maximum temperatures were observed in all measurements when the amplifier provided 200 W output power, rather than 400 W, as depicted in Fig. 6, which displays the measurements at 10 MHz. This discrepancy is attributed to non-linearity effects, which reduce the resting current and shift the operation from class AB towards class B, thereby increasing efficiency.

CONCLUSION

A complete GaN-based RF Driver and its control chassis have been prototyped and extensively tested, demonstrating compliance with the predetermined design requirements as outlined in the paper. Furthermore, the qualification tests have aided in validating the simulation model of the amplifier developed in Advanced Design System (ADS). Additionally, a simulation of the 10 MHz cavity in its entirety has been conducted, with the new amplifier seamlessly integrated into it. Preliminary results suggest that a reduction in the output impedance by a factor of two is achievable. In 2024, the amplifier is scheduled for integration into the 10 MHz RF system and will undergo testing without beam. Subsequently, in 2025, comprehensive tests of the entire system within the PS ring under operational conditions are foreseen.

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