DEVELOPMENT OF A 500 MHz HIGH POWER SOLID STATE POWER AMPLIFIER BASED ON GAN TRANSISTORS

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Abstract

The adoption of Solid State Power Amplifier (SSPA) is rapidly increasing in major accelerators worldwide, replacing tube amplifiers such as Klystron and IoT. This study aimed to develop a High-Power RF system for Multipurpose Synchrotron Radiation Accelerators and to design and implement a GaN (Gallium Nitride) transistor-based SSPA. Through this research, we verified control performance equivalent to that of a 150 kW SSPA and successfully developed a prototype of a 5 kW RF module. Experimental results confirmed that the GaN transistor-based SSPA provides high efficiency and stable performance in the 500 MHz band, and based on this, we established a performance assurance plan for the 150 kW SSPA. This study demonstrates that GaN devices can effectively replace LDMOS (Lateral Double diffused MOS) devices with similar performance and competitiveness in the RF applications operating in the 500 MHz frequency range, which has traditionally been dominated by LDMOS. These results have significant implications for enhancing the performance and efficiency of High-Power RF systems and are expected to greatly expand the potential applications of GaN-based SSPA in various scientific and industrial research fields.

CONFIGURATION

In modern storage rings serving as synchrotron radiation sources, the RF system represents the primary cost driver for both construction and operational expenses. Its performance critically influences key parameters such as beam stability, operational capacity, system uptime, and radiation quality—all essential metrics for contemporary synchrotron facilities. The storage ring design for the 4GSR incorporates ten RF cavities installed across straight sections 13, 14, and 15 (Fig. 1). To optimize infrastructure efficiency, the RF building has been strategically positioned adjacent to utility and electrical service areas, significantly reducing the required lengths of cooling water pipes and power distribution cabling. [1]

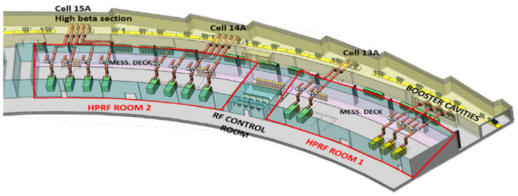

Figure 1: Layout of RF building.

RF System for 4GSR

Table 1: RF System Parameter

Parameter	Value	Unit
Beam current	400	mA
Revolution frequency	0.375	MHz
Harmonic number	1332	-
RF frequency	499.593	MHz
Energy loss /turn by Bending magnet	1097.65	keV
Energy loss /turn by ID	351	keV
Energy loss /turn by Others	60	keV
Total beam energy loss /turn	1877.65	keV
Total accelerating voltage	3.52	MV
Number of cavity	10	-
Wall loss power per cavity	18.22	kW/unit
Beam loading power per cavity	84	kW/unit
Power loss at HOM absorber	5	kW/unit
Required power to coupler per cavity	108.15	kW/unit
Transmission line loss per cavity	10	kW/unit
Output power of HPRF	118.15	kW/unit
Rated power of HPRF	150	kW/unit

Table 1 summarizes the key operational parameters of the storage ring RF system. The design specifies a maximum beam current of 400 mA and a resonant frequency of 499.5934 MHz, intentionally aligned with the booster's operating frequency to ensure synchronization. Cumulative energy dissipation across bending magnets, insertion devices, and ancillary components totals 1.51 MeV, necessitating a beam acceleration voltage of 3.52 MV. [2]

To achieve this voltage, a normal-conducting RF cavity architecture was prioritized over superconducting alternatives. This decision balances performance with operational reliability, mitigating risks of prolonged downtime associated with superconducting system maintenance. The EU-HOM damped cavity design, validated for effective higher-order mode (HOM) [3] suppression in comparable facilities, is under consideration to enhance spectral purity and long-term stability.

High Power RF System

The RF station serves as a core component of synchrotron radiation facilities and consists of Low-Level RF

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(LLRF) control systems, High-Power RF (HPRF) amplifiers, RF transmission lines, cavities, and instrumentation (Fig. 2). To supply the beam loading power of 83.63 kW, the HPRF amplifier is designed for a rated output of 150 kW. This specification accounts for transmission efficiency, ease of amplitude control via the LLRF system, and system lifespan, securing an operational margin of approximately 138% compared to the estimated 108 kW power throughput via the cavity coupler. The cavity assembly integrates a normal-conducting cavity with vacuum systems, temperature sensors, and cooling systems. Additionally, critical components such as HOM dampers (for higher-order mode suppression), power couplers (for energy transfer), and mechanical tuners (for frequency stabilization) are installed to optimize system reliability and performance. [4]

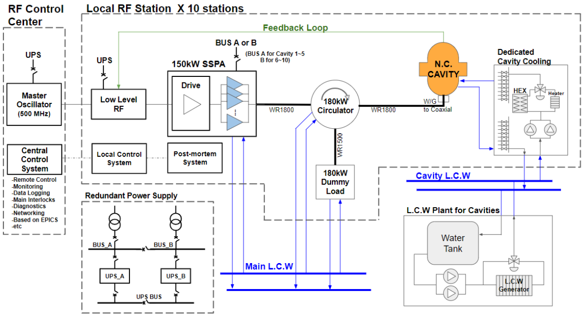

Figure 2: 4GSR HPRF single line diagram.

Solid State Power Amplifier

The SSPA system architecture depicted in Fig. 3 outlines critical components, interconnections, and operational specifications.

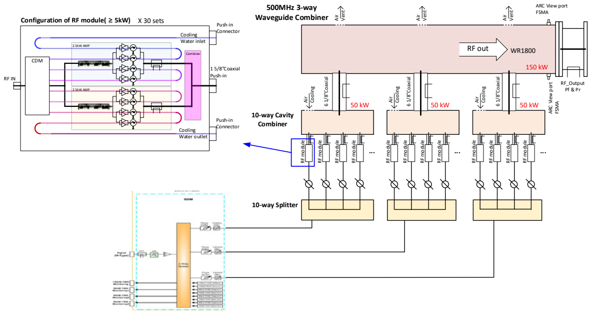

Figure 3: SSPA single line diagram.

Key monitoring points are strategically positioned across amplification stages to enable real-time diagnostics and streamline maintenance workflows. To mitigate risks associated with RF reflections during accelerator operation, each RF module incorporates circulators and dummy loads, ensuring robust protection against anomalous signal feedback. The design emphasizes modularity and serviceability: Cooling systems and RF connectors utilize modular plug-in interfaces for rapid replacement, minimizing downtime. For spatial efficiency and scalability, a waveguide-based combiner architecture is employed at the final stage, balancing compact footprint requirements with future output expansion capabilities.

The SSPA's core performance parameters, including power handling thresholds and efficiency metrics, are comprehensively tabulated in Table 2.

Table 2: SSPA System Parameter

Parameter	Value
Frequency	499.594 MHz
Bandwidth	≥ ±1 MHz
Operating mode	CW and pulsed (100 us / 10 Hz)
Ramping mode	Zero to Rated kW within 200 ms
RF Input Power	0 dBm_max
RF Output Power	≥ 150 kW
Efficiency	≥ 50%
Gain Flatness	0.5 dB within BW (0.5 dB within 50 kW ~ 110 kW)
Output Power Stability	0.5% $Vp-p$
Phase Stability	3° / dB
Acceptable VSWR at RF output	≤ 1.58
Harmonics 2nd	≤ -36 dBc
Harmonics 3rd	≤ -50 dBc
Spurious	≤ -60 dBc

DEVELOPMENT PROGRESS

The SSPA System architecture integrates four critical subsystems high-frequency combiners, signal dividers, amplifier modules, and control systems. Development efforts initially focused on the high-power RF combiner, a component demanding significant design time due to its pivotal role in power handling and system stability. After iterative design refinement, this combiner was successfully fabricated. Subsequent validation phases included the development of a 5 kW RF amplifier unit module, which served as a foundational building block for assessing the SSPA's RF performance metrics, including gain linearity and harmonic suppression.

To finalize the verification process, a reduced-scale SSPA prototype was constructed. This prototype retains the full-scale system's mechanical and control architecture but operates at 1/100th of the target output power, allowing thorough evaluation of mechanical stability, control algorithm robustness, and subsystem interoperability under controlled conditions.

TEST RESULTS

The fabricated RF Module was tested as a unit module for the final target output of 150 kW to verify the performance characteristics of the GaN transistor.

The unit RF module was developed to meet the final specifications required for the above parameters. The design specifications and measured values are summarized in Table 3.

Table 3: 5kW RF Module Test Results

Parameter	Value	Measure
Frequency	500 MHz	500 MHz
Bandwidth	≥ +/-1 MHz	≥ +/-1 MHz
Operating mode	≥ 5 kW	5.2 kW
Efficiency	≥ 50%	69.68% @ 42 V 67.26% @ 46 V 61.99% @ 50 V
Gain Flatness	0.5 dB within BW 0.5 dB within 50 kW ~ 110 kW	0.5 dB within BW
Output Power Stability	0.5% Vp-p	0.5% Vp-p
Phase Stability	3° / dB	2.4° / dB
Harmonics 2nd	0.5°	0.5°
Harmonics 3rd	≤ -36 dBc 2nd	-47.28 dBc 2nd
Spurious	≤ -50 dBc 3rd	-79.95 dBc 3rd

The transistor's bias voltage was varied to measure efficiency and gain (Fig. 4). By adjusting the bias voltage, we expect to identify the optimal operating point for SSPA output under various initial operating conditions.

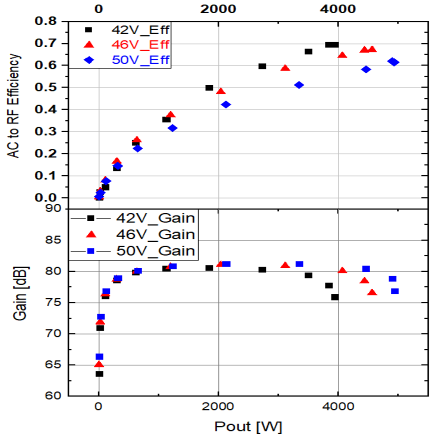

Figure 4: Efficiency & gain by Pout.

A heat dissipation strategy is essential for GaN transistor-based SSPA designs, which is a key factor in maintaining consistent output characteristics and long-term reliability during long-term operation. [5] To quantify thermal-induced performance drift, thermal stability was systematically evaluated by monitoring output power displacement and phase coherence after thermal equilibrium was achieved (Fig. 5). Thermal sensors embedded in the amplifier pallet confirmed temperature stabilization at 53°C, and excellent thermal regulation was observed during continuous operation for the following 12 hours. Temperature fluctuations were limited to ±1°C. During this period, output power deviation was measured to be 0.4% and phase shift was measured to be 0.5°, verifying the reliability of the amplifier. [6]

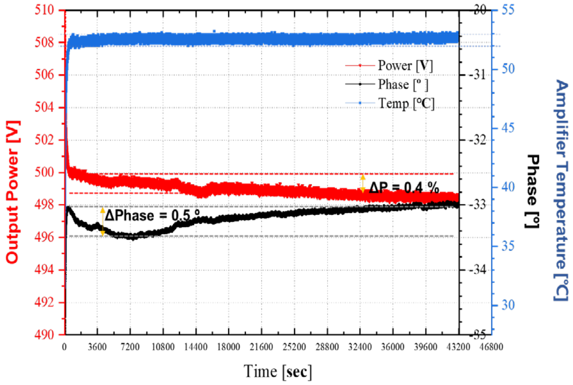

Figure 5: 5kW RF module long-term test.

CONCLUSION

In this study, we have successfully overcome key technological challenges associated with GaN transistors, such as thermal management, high manufacturing costs, and junction reliability, leading to the development of a high-efficiency and high-power SSPA. A high-power combiner was designed and fabricated, and its reliability was verified through 150 kW power testing. The performance of a 5 kW RF amplifier was also confirmed as a unit module. In addition, we developed a system capable of integrated control of 30 modules, verifying control performance, interlock and interface functions. Through stepwise performance verification, we have established a technical foundation for the future commercialization of 150 kW-class SSPA systems. This research is expected to contribute to the domestic production of high-power SSPAs by enhancing cost competitiveness, reducing lead times, and improving maintenance efficiency.

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