Development of high power energy recovery absorbing load for large scale accelerators

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Abstract

For large particle accelerators, the radio-frequency (RF) power source system accounts for a significant portion of total energy consumption. A considerable fraction of the RF power that is not used for particle acceleration is delivered to an absorbing load located at the output of the accelerating structure, where it is converted into heat and dissipated. Recovering this otherwise wasted energy is therefore of great interest for improving the overall energy efficiency of accelerator facilities.

RF-DC rectification technology offers a potential approach to convert the RF power into usable DC electricity. However, the practical implementation of this concept has long been limited by insufficient high-frequency and high-power handling capabilities of conventional semiconductor devices. As a result, although the concept is attractive, it has rarely been demonstrated in experimental or engineering applications at the GHz frequencies.

With the recent development of Gallium Nitride (GaN) transistors, significant improvements in high-frequency and high-power performance have been achieved, making RF energy recovery at microwave frequencies more feasible.This work investigates the feasibility of GaN-based RF rectification and its potential for improving energy efficiency in future colliders like the CEPC and BEPCII, the energy loss of the s-band power source system is shown in the Fig. 1.

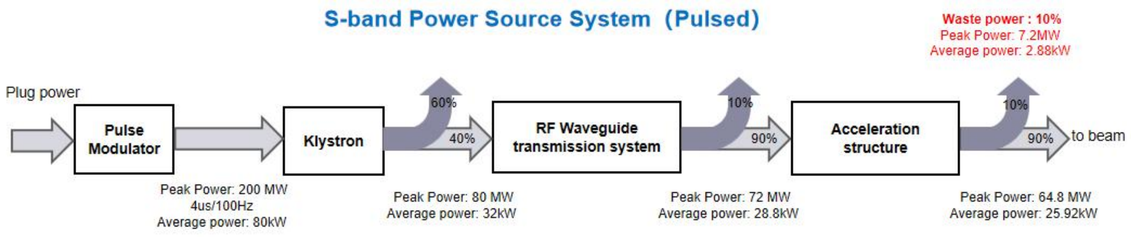


Fig. 1.Power-flow distribution in a pulsed S-band RF source system, illustrating the RF power not delivered to the beam as a potential source for energy recovery.

Energy-recovery absorbing-load architecture

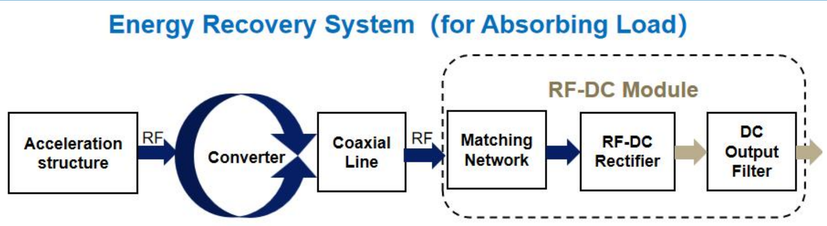


Fig. 2. Functional chain:
accelerating structure → RF extraction and transport → impedance matching → GaN RF–DC rectification → DC-output filtering.

The proposed energy-recovery absorbing load consists of two integrated subsystems: a microwave-extraction-and-transmission section and a core RF–DC rectification section.

The microwave-extraction section couples recoverable RF power from the accelerating structure and transfers it to the rectifier through a waveguide-to-coaxial transition and an impedance-matching interface. Its role is to establish an efficient RF link between the accelerator-side absorbing-load environment and the rectification circuit.

The RF–DC rectification section is the core of the system. It employs a GaN-based rectifier together with matching, bias, and DC-filtering networks to convert the extracted microwave power into usable DC power. The interface between the two subsystems must be co-designed to ensure effective power transfer while avoiding excessive reflected power toward the accelerating structure.

Microwave-extraction circuit design

Design Concept

The microwave-extraction device is designed to route unused RF energy remaining at the downstream end of the accelerating structure into a subsequent rectification circuit. Within the accelerating structure, RF energy propagates as guided electromagnetic waves and therefore cannot be fed directly into an RF rectifier. The extraction device is a specially designed waveguide-to-coaxial transition comprising a coupling plate, coupling aperture, and output port, as shown in Fig. 3a. By adjusting the insertion depth of the coupling plate, the extracted RF power can be continuously controlled, enabling the device to interface with RF rectifiers designed for different input-power levels.

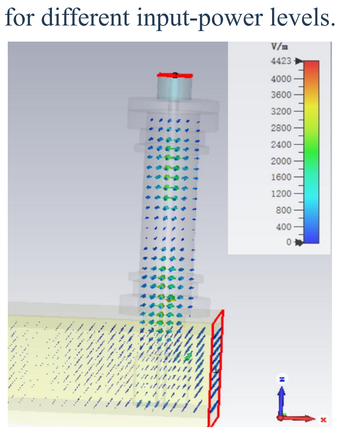


Fig. 3a. EM model used to assess extraction coupling and field distribution.



Fig. 3b. Microwave-extraction hardware used in the prior system study.

Simulation Results

CST simulation results show that the extraction structure provides controllable coupling over the investigated tuning range while maintaining low input reflection.

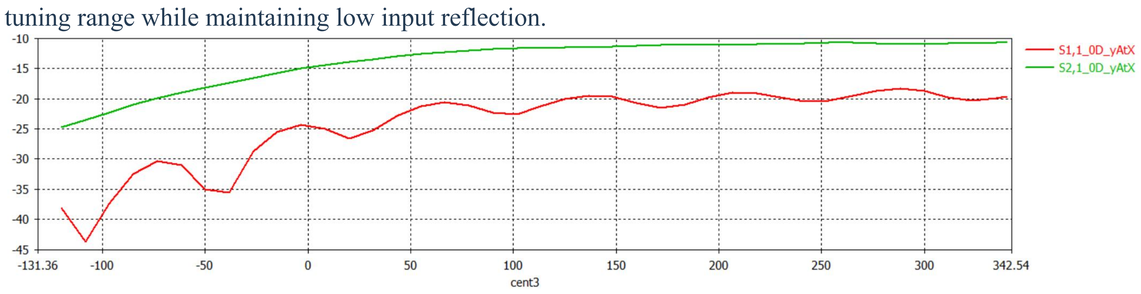


Fig. 4.CST-simulated S11 and S21 responses of the microwave-extraction structure over the investigated tuning range, demonstrating controllable RF extraction with low input reflection.

High-Power GaN RF–DC Rectifier Design

What's the difficulty?

- Owing to the limitations imposed by semiconductor material properties, high-power S-band RF rectification can currently be realized only with GaN devices; conventional SiC devices have exceeded their applicable power–frequency limits.
- The power-handling capability of GaN-based diodes remains relatively limited. Therefore, the rectifier topology must differ from that of conventional diode rectifiers.

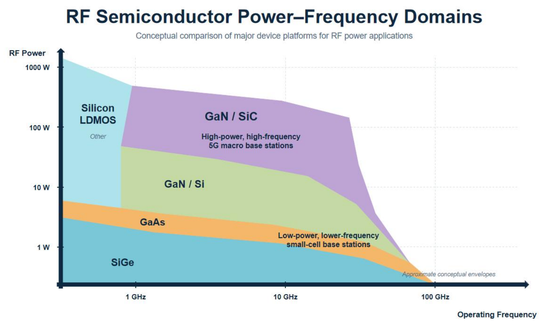


Fig. 5. Power–frequency operating domains of representative RF semiconductor technologies, highlighting the suitability of GaN devices for high-power S-band RF–DC conversion.

How to design an RF–DC module at high frequencies and high power levels

The practical circuit is implemented using dedicated input matching, gate matching and bias, drain harmonic-control, and DC-output networks. At S-band, these networks must be treated as an integrated electromagnetic system rather than as independent lumped elements. The drain-side RF port receives the extracted RF power, while a sampled and phase-adjusted signal is applied to the gate. The gate and drain networks establish the required impedance transformation and phase relationship, and the bias networks provide the DC operating conditions while isolating the RF paths. The final layout is refined through combined circuit and full-wave electromagnetic simulations.

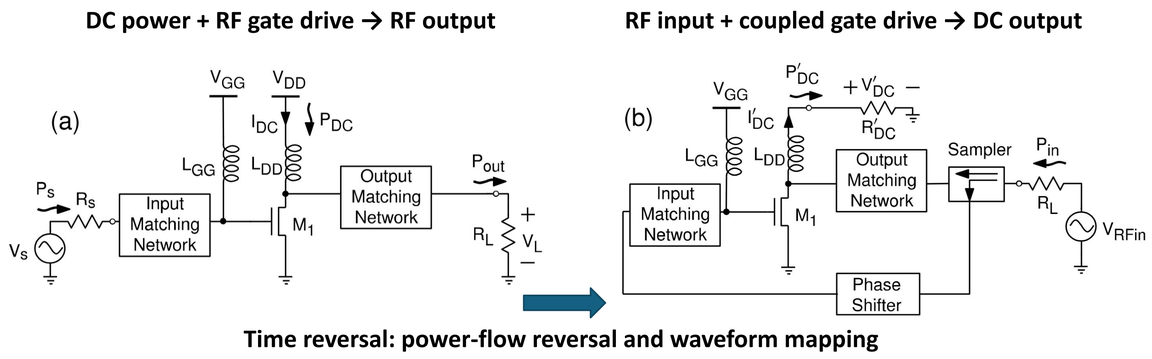


Fig. 6.Time-reversal duality between (a) a high-efficiency power amplifier and (b) the corresponding GaN HEMT RF–DC rectifier with a coupled, phase-adjusted gate drive.

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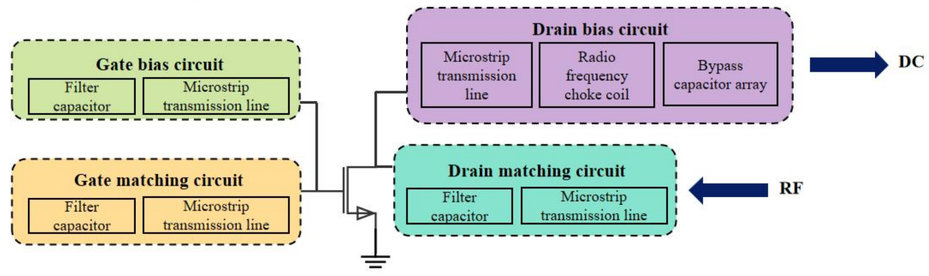
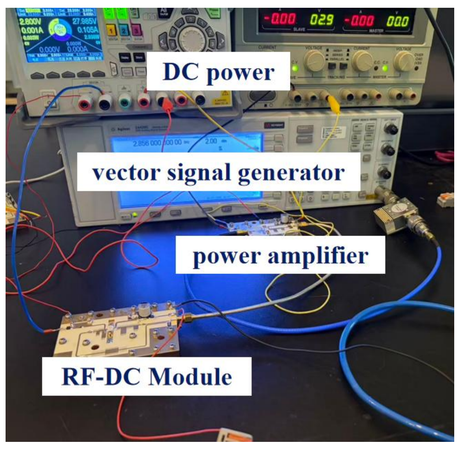


Fig. 7.Functional block diagram of the proposed RF–DC module, including the input matching, gate matching and bias, drain harmonic-control, drain-bias, and DC-output networks.

Experimental Validation

A CG2H40010F-based GaN HEMT RF–DC rectifier has been fabricated and tested. Preliminary continuous-wave measurements at 2.856 GHz demonstrate conversion of a 10 W RF input into DC power, verifying the basic operating principle of the proposed circuit.



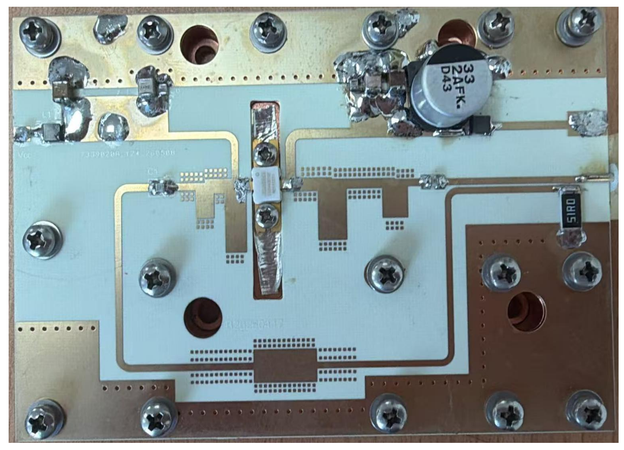


Fig. 8.Continuous-wave test setup (left) and fabricated CG2H40010F-based RF–DC rectifier prototype (right).

Conclusions

This work presents an energy-recovery RF–DC conversion approach for large-scale accelerators by combining microwave extraction and GaN HEMT rectification. A CG2H40010F-based RF–DC rectification module has been fabricated and preliminarily tested at 2.856 GHz with a 10 W RF input. Future work will investigate the mechanisms governing RF–DC conversion efficiency, refine the matching, bias, and harmonic-control networks, and conduct integrated tests of the microwave-extraction and rectification subsystems. Once the design methodology is validated, the approach will be extended to a 100-W-class RF–DC rectifier.

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