High Efficiency, Low Cost, RF Sources for Accelerators and Colliders

R. Lawrence Ives[1], Michael Read[1], Thuc Bui[1], David Marsden[1], George Collins[1], Brian Chase[4], John Reid[4], Chris Walker[3], Jeff Conant[3], Ricky Ho[2], Jams M. Potter[5], Leroy Higgins[2], Aaron Jensen[6], Henry Freund[1], and Walter Sessions[7]

[1]Calabazas Creek Research, Inc., 690 Port Drive, San Mateo, CA 94404
[2]Communications & Power Industries, LLC, 811 Hansen Way, Palo Alto, CA 94304
[3]Communications & Power Industries, LLC, Beverley Microwave Division, Beverley, MA
[4]Fermi National Laboratory, Batavia, IL, 60510
[5]JP Accelerator Works, Inc., 2245 47th Street, Los Alamos, NM 87544
[6]Leidos, Inc., 11951 Freedom Drive, Reston, VA 20190
[7]Georgia Tech Research Institute, 7220 Richardson Road, Smyrna, GA 30080

Introduction

Numerous U.S. Department of Energy (DOE) workshops and studies describe the aspirations of the high energy physics community in addressing the technical requirements and applications for accelerators and colliders [1-4]. These range from advancing our understanding of the universe to purifying water. While the energy required for these applications spans orders of magnitude, a common requirement is to reduce the cost and improve efficiency of RF sources. This is most apparent for large systems requiring hundreds or thousands of sources where acquisition costs can be prohibitive, or CW systems where efficiency is of paramount importance. For many applications, including medical and defense, size, weight, and input power can be critical. Once the electrons are emitted at the input to an accelerator, it is the RF source(s) that determines the final energy at the ultimate destination.

Calabazas Creek Research, Inc. (CCR) and its partners and collaborators are developing high efficiency, low cost RF sources operating at frequencies from a few hundred MHz to X-Band and power levels from tens to hundreds of kilowatts with the goal of providing MW-relevant sources. The efficiency of these sources exceeds 80% with projected costs as low as $0.50/Watt. Successful development of these sources will significantly alter the cost/performance landscape for RF power generation.

Phase and Amplitude Controlled Magnetrons

CCR, Fermilab, and Communications & Power Industries, LLC (CPI) recently completed development of a 100 kW, 1.3 GHz magnetron system with amplitude and phase control [5,6]. The system operated at more than 80% efficiency and demonstrated rapid control of amplitude and phase. The systems was based on Fermilab research demonstrating that rapid amplitude control could be obtained by phase modulating a locking RF signal [7]. The modulation shifts power to sidebands outside the acceptance range of high Q, superconducting, accelerator cavities, effectively reducing the cavity input power. Tests by CCR and Fermilab staff at Fermilab demonstrated 22 dB of amplitude control with a drive power 25 dB below the output power. In all cases, the efficiency exceeded 80%. The projected cost is less than $1.00/Watt.

Multiple Beam Triodes

Triodes were invented in 1902 and still provide low levels of RF power for low level RF amplifiers and transmitters and high-end audio [8]. CCR began investigating high RF power production using multiple beams in 2016. Many triodes use flat, barium oxide cathodes with grids cut from commercial tungsten screen. In RF sources, they operate in Class C, producing power at efficiencies approaching or exceeding 90%. The extremely simple geometry allows power generation in extremely small packages at surprisingly low cost.

CCR, in collaboration with CPI and JP Accelerator Works, Inc., is developing 200 kW, pulsed and CW RF sources from 350 to 700 MHz with projected efficiencies exceeding 80% and cost of $0.50/Watt [9]. The 200 kW, 350 MHz, multiple beam triode-based, RF source is 24 inches long, 10 inches in diameter, and weighs approximately 150 pounds. This is dramatically smaller than alternative, high power sources in this frequency range. The only issue is the low gain, typically 14 dB. Consequently, the program is developing single-beam, triode-based sources to drive the multiple beam device. The 80% efficiency and

$0.50/Watt cost represents the combined values for the single and multiple beam devices. Prototype tubes are scheduled for tests in fall 2020.

High Efficiency Klystrons

Recent development of the "core oscillation method" (COM) and the "Bunch, Align, and Collect" (BAC) design approaches offer the opportunity to increase klystron efficiencies to 80% or more. CCR, CPI, and Leidos, Inc. are collaborating to design, build and test a 1.3 GHz, 100 kW klystron operating at 80% efficiency. While simulations indicated both the COM and BAC methods could achieve the goal efficiency, the COM method required fewer cavities at the expense of a longer tube. The tube under construction includes seven cavities and is nine feet, nine inches long. Simulations from three codes, AJDISK, TESLA and MAGIC, predict efficiencies of 80% or higher. While the power and efficiency are similar to the magnetron system described above, the klystron offers higher gain and a path to higher peak and average powers. Fabrication is in progress with high power testing scheduled for fall 2020.

Multiple Beam IOTs

In 2014, developers of the European Spallation Source (ESS) funded L3 Electron Devices and a consortium including CPI and Thales Electron Devices to develop 1.2 MW, 704 MHz multiple beam IOTs [10]. Both tubes achieved the goal power with efficiency exceeding 70%. These designs provided separate coaxial drive lines for each electron gun, representing a relatively expensive and complex configuration. In 2019, CCR, in collaboration with Georgia Tech Research Institute (GTRI), began research to simplify the input coupling and increase efficiency by adding 3rd harmonic power to the drive signal [11]. GTRI's input coupler design drives each electron gun from a single coaxial line, representing a significant simplification. Simulations indicate that 3rd harmonic power added to the input drive at the appropriate power and phase can increase electron bunching and the efficiency 8-10 %. The program is designing a prototype tube to produce 200 kW peak, 100 kW average power at 704 MHz. The emphasis of this program is development of high average power RF sources.

Summary

RF source development programs are pursuing research to improve the performance and lower the cost of accelerator systems. Results indicate that efficiencies exceeding 80% are achievable at costs significantly lower than previously available.

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