Challenges in Advanced RF Sources R&D

Brandon Weatherford, Emilio Nanni, and Sami Tantawi
SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025

The RF power system – consisting of high voltage modulator and RF amplifier – is a substantial driver of capital and operating costs for any new large-scale accelerator facility. Budgeting models suggest that for a TeV-scale collider, the construction cost of the RF power system likely exceeds the combined cost of the tunnel construction and the beam line including accelerator structures; likely more than $10B. The impact of RF power on facility costs was clearly articulated in the 2017 DOE Radiofrequency Accelerator R&D Strategy Report:

> "When pushing high gradient or intensity limits, RF sources become the leading cost driver for normal conducting accelerators and a significant cost driver for superconducting accelerators. Only with innovative concepts for designing and building RF sources will dramatic reduction in cost and increased efficiency be achieved."

That same report suggests a cost/capability target of $2/kW for the complete RF power chain – at least ten times less expensive than what is commercially available today. There may be a perception that RF amplifiers are a "known quantity," because klystrons are well established and can be purchased directly from industry. However, the cost of these conventional sources is unacceptable, and industrial partners have little incentive to solve this cost problem, on their own funds, for any proposed project that will take decades to complete. Support for revolutionary research in RF sources, led by government labs and academia, is desperately needed if we are to realize the order of magnitude improvement in cost-capability that is required.

The solution will likely arise from novel RF source and modulator topologies that deviate substantially from existing high voltage, high power klystrons. Part of the answer involves optimizing the complete RF power chain, which naturally leads to using low-voltage modulators made from mass-produced commercially available components. Then, high efficiency RF sources must be developed which ideally operate at low voltage and high current, while breaking the tradeoff between efficiency and perveance that is inherent in conventional linear-beam devices. Reconsidering RF sources in this way raises several interesting fundamental physics and engineering challenges.

One approach involves using multi-dimensional electron beams, allowing for higher current densities at a given voltage, and minimizing the impact of space charge on RF efficiency. Another new topology leverages the deflection of a monoenergetic beam as a modulation scheme; this is promising for high efficiency devices or for frequency multiplication. Finally, massively parallel arrays of mass-produced compact RF sources, taken as a whole, can function as an extremely high perveance amplifier; but individually these compact sources can also be utilized in compact accelerators for commercial applications, presenting a real incentive cost-effective mass production.

Complementing these system-level R&D efforts, there are many opportunities to improve upon RF source subcomponents and study their underlying physics. For example, thermionic cathode-based electron guns can by themselves consume the entire $2/kW budget in conventional klystrons. Instead, novel low-cost electron sources are needed that are optimized for low-voltage operation and massively parallel systems. Plasma cathode electron sources can deliver up to hundreds of Amperes of electron current at hundreds of Volts, and can operate at substantial pressures, mitigating the need for ultra high vacuum environments. Beam focusing in RF sources is another major challenge – with magnets for a single klystron costing tens of $k themselves, alternative focusing approaches for low voltage beams should be investigated. Potential areas of interest include electrostatic, ion, and self-focusing of high current beams. These efforts would require significant computational and experimental work but raise many interesting basic physics questions, and in some cases, would be synergistic with R&D efforts in the plasma wakefield accelerator community. Finally, the assembly process for conventional RF sources is extremely expensive, and additive manufacturing is a promising technique for mitigating this issue. Additive processes are constantly evolving, and many could be suitable for RF source fabrication, but have not been fully characterized in the context of high vacuum, high voltage, etc. When existing additive processes are not suitable, fundamental research in novel additive manufacturing processes should be supported as well.

In summary, the high cost of RF power can be a major budgetary constraint for any new high energy physics facility. Although it is often assumed that RF sources are "established," the truth is the current state of the art is nowhere near what the HEP community needs regarding cost/capability. Solving this enormous challenge will require significant support for both computational and experimental R&D efforts in RF sources. A real solution demands that we fundamentally reimagine RF source topologies and rigorously attack the many exciting basic physics questions that arise from this challenge.