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**2021 snowmass Letter of Interest: Pushing Brightness and Current limits of Normal-Conducting Radiofrequency Electron Sources**

Daniele Filippetto, Fernando Sannibale, Derun Li
Lawrence Berkeley National Laboratory, Berkeley, CA 94720 USA)
dfilippetto@lbl.gov

Following the research needs in basic energy sciences, the development of radiofrequency-based electron beam sources over the last decades have led to a constant increase in beam performance. Accelerating fields in excess of 150 MV/m are not routinely used for applications such as Coherent and incoherent X-ray production and time-resolved electron scattering, generating high density electron beams.

While most of the source development focused on achieving higher accelerating gradient, only a limited effort was devoted to the equally challenging goal of increasing source average performance such as electron flux and average brightness, limiting the spectrum of applications of this technology, especially in the high energy physics area.

High-repetition rate, high brightness electron sources could produce very stable electron beams with average currents relevant to collider applications. Few examples are described in the following.

Production of low emittance beams with large horizontal-to-vertical emittance ratio would potentially avoid the need of expensive damping rings in linear colliders. Electron beams with net angular momentum can indeed be produced by applying strong magnetic fields at the cathode plane. The resulting magnetized beam can then be transformed to a flat beam via the use of coupling electron optics downstream the injector [1].

Future Electron-Ion collider designs include hadron cooling sections, to increase luminosity and to prevent the beam heating up by intrabeam scattering. One experimentally demonstrated solution entails co-propagation of ions and colder and lighter electron beams along a straight section of the machine, forming a two-component plasma thermalizing upon Coulomb scattering, with electrons being continuously replenished and therefore acting as a thermostat whose set temperature is defined by the electron beam emittance [2]. The idea was recently demonstrated with electron beams generated from a DC gun and then accelerated by radiofrequency cavities [3]. A future optimized electron cooler system would need to produce dense beams with average currents in the tens of mA, with repetition rates in excess of 100 MHz, and emittance values as small as possible to increase the cooling efficiency.

A longer-term application of CW-high gradient electron guns to HEP applications includes injection of nanoscale electron beams into advance acceleration schemes, such as Laser-Plasma [4] or Dielelectric/Metal based structures [5]. Here, phase space matching of injected beam with the acceleration and focusing bucket of the acceleration device is of paramount importance to provide stable injection for lepton colliders. This poses severe constraints on the emittance of the injected beams, limiting the maximum charge per pulse that can be efficiently accelerated. In order to obtain high luminosity for collider applications, a different format including low charge bunches at high repetition rate has been proposed [6], and beams of the right emittance and pulse length have already been demonstrated in CW-RF normal conducting guns.

Different technologies can be used to generate bright beams, including Direct-Current (DC) and radiofrequency-based (RF) electron guns, but the use of time-varying fields, if successfully demonstrated for the set of beam parameters required, would provide higher accelerating fields and kinetic energies, ultimately leading to denser beams in phase space. Possible RF-based solutions include the use of super-conducting and normal conducting technologies.

The intent of this letter is to provide arguments as of why R&D on Normal-Conducting Continuous-Wave radiofrequency guns ((NCRF CW)) should be strongly pursued at this scope. Our arguments draw entirely from the experience in designing, fabricating and operating a CW-NCRF electron gun at LBNL, the APEX gun [8]. The idea of a new electron gun design originated from scientists in the ATAP and Engineering divisions at LBNL, in response to an urgent need in performance leap (three orders of magnitude) that would form the cornerstone for the next generation of X-ray FELs. By clever design choices, the source successful in achieving simultaneously continuous operations with mA-class average currents and exceptional vacuum performance, assuring long lifetime for sensitive semiconductor cathodes [9] and leaving the doors open for further improvements enabling production of polarized electron beams. A built-in cathode exchange system allowed testing of different photoemission materials over the years.

The price to pay in terms of peak brightness for running high repetition rates was minimized in the design by the careful choice of the operating frequency, 185.7 MHz, compared with typical choices in the multi-GHz region. Such design choice was key in the success of the experiment: a large cavity volume allowed to keep the heat density dissipation to manageable values. At the same time, the cavity accelerating field in the cathode-anode gap was maximized through reentrant-cavity shape design. As a consequence of the long RF wavelength, the electron beam phase slippage in the accelerating gap is negligible, and so particles travelling in the accelerating gap experience the full 20MV/m peak accelerating electric field at all times.

Remarkably, already the first prototype was able to demonstrate all the performance described above simultaneously. Today, a slightly revised version of the gun drives the LCLS-II, while the initial prototype is still in operation at LBNL, providing two different beamlines with high repetition rate relativistic electrons for research and development in high precision controls of low emittance/high flux beams, and for applications in ultrafast science [10].

The fast-paced development described above, if on one hand bears witness of the advantages of such technology, it also raises the question as of whether the ultimate performance of such technology have been reached yet. Can the accelerating field and the output beam kinetic energy be further increased? What is the maximum average current that can be achieved?

Although we are lacking of experimental data for RF-breakdown fields in this frequency range, based on the LBNL experience we can comfortably say the technology limits have not been reached yet. Over the 10 years of experimental runs of the VHF gun prototype we have yet to register any significant disruptive RF activity in the cavity pointing to the gun surface approaching the breakdown limit. Similarly, while the maximum average current extracted was at the mA level, experimental characterization at these regimes does not suggest any impediments in running higher currents [9][10].

Many countries in Europe (Germany, Italy) and Asia (China) are now following our design for their proposed facilities or upgrades. Our strategic temporal advantage can be used to keep the US leadership in this field, by continuing to improve the technology and to understand how to master the use of the source for applications in the frontiers of high energy physics and beyond. As a starting point, a new cavity design for achieving higher accelerating fields and output energies has already been presented [11] [12].

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