Advanced Klystron Development for High Peak Power and Variable Pulse Structure

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Development of novel klystron concepts have been identified as a core technology needed for next generation accelerator applications in a recent Department of Energy (DOE) High Energy Physics (HEP) report [1].

As one example, we look toward intense X-ray pulses with variable separation from 100 ps to 100 µs are required for Dynamic Mesoscale Materials Science Capability (DMMSC) facilities [2]. The DMMSC requires a method for imaging dense, high Z materials of varying thickness over a wide range of time scales. Moreover, it requires extraordinary flexibility in terms of X-ray pulse delivery timing, as will any accelerator-based instrument (such as UED/UEM, compact backscatter light source, etc.) intended to study phenomena with similar timescales of interest. To meet this challenge, LANL is developing technologies to enable construction of several analytical instruments, including world's highest photon energy free electron laser (FEL) to provide intense X-ray pulses with variable separation.

Currently available particle accelerator technologies, particularly the klystrons, cannot provide the required pulse structure needed by this example and other systems. Improved accelerator structures are under development; however, corresponding advances in high-peak-power RF generators, such as klystrons, are required to power those structures. Concurrent, transformational improvements are required in three key areas of multiple beam klystron design: the electron beam source (order-of-magnitude cathode current density increase); the operating frequency (more than quadrupled, from 1.3 GHz to 5.7 GHz); and non-intercepting beam gating techniques (to reduce switching losses by two orders of magnitude).

High gradient accelerators require very high peak RF power; existing linacs use dozens of 50 MW klystrons [3]. These tubes are, however, not capable of generating the high "burst rate" sequences of sub-microsecond pulses required by future facilities, such as an FEL for DMMSC. A fast-gateable electron gun using high current density cathodes, and a complementary circuit design, are needed to enable an RF source for these new accelerator imaging applications.

Two technologies need to be developed to enable a high gradient option for the DMMSC-like FEL. The first is to demonstrate that (cryogenically cooled) copper cavities can reliably operate at gradients >50 MV/m. The second is the capability to rapidly modulate klystron output power to enable the required pulse structure. The Canon E37212 50 MW C-band klystron used at SACLA (Japan), SwissFEL and CERF (the new C-band Engineering Research Facility at the Los Alamos Neutron Science Center (LANSCE)) operates at 370 kV and 325 A. The nominal pulse repetition rate is 100 Hz; switching losses, proportional to $CV^2/2$, preclude pulse burst operation. Therefore, a new method for rapidly switching very high peak power klystrons is required.

An electron gun design incorporating an isolated focus electrode (F.E.) provides a means to rapidly gate the klystron beam current, and therefore the RF output. The F.E. is non-intercepting,

LA-UR-20-26592

i.e., no current flows to it, and is controlled at a fraction of the anode voltage, significantly reducing switching losses. However, because the F.E. is located at the outside edge of the cathode, the voltage required to gate the beam exponentially increases with cathode diameter. Consequently this technique cannot be directly adapted to the Canon E37212; the cathode is much too large.

As an alternative, combining the beams of several smaller "mini" cathodes has been proposed [4, 5]. This concept, shown in Figure 1, uses an electrode forward of the cathode with a corresponding number of apertures for beam gating. The example shown is for a relatively low current electron gun; a 50 MW class klystron requires hundreds of amperes. M-type cathodes, the standard for the microwave tube industry, have a sustainable emission limit of 5 A/cm^2; on the order of eighty 1 cm mini-cathodes would be required to produce 325 A. Fabricating an electron gun with that number of cathodes is not practical. The solution, rather, is to use fewer cathodes, of similar size but with much higher emission density. Nanocomposite Scandate Tungsten (NST) cathodes are the leading choice for this application; small samples have demonstrated 40 A/cm^2 in experiment [6]. Research is needed, however, to determine if larger cathodes can be consistently fabricated with similar performance, and lifetimes, when run in high power tubes. A related research question is whether higher emission density can be sustainably achieved through the use of specialized coatings on thermionic mini-cathodes that allow for higher temperature operation without the loss of low work function material at the surface required for emission. A separate LOI from members of the LANL electron source team focuses specifically on developing advanced cathodes for next generation HEP applications.

Minimizing the control electrode (F.E.) switching voltage is the key to fast modulation. As detailed above, small cathode size is critical. Further improvements can be realized by decreasing the anode voltage to the extent possible. The surest method to achieve this is to use more than one beam. A multiple beam klystron (MBK) incorporates several individual beamlets in parallel, and has higher total current than a single beam tube [7]. The higher current enables MBKs to produce the output power of a single beam tube at half the anode voltage, allowing a similar reduction in F.E. gate voltage, further decreasing switching losses. Smaller cathodes are also needed to provide sufficient higher-order mode (HOM) separation for a C-Band (5.7 GHz) MBK; there are presently no high power MBKs operating above L-band (1.3 GHz) due to HOM limitations caused by the size of the drive beam and corresponding cavity.

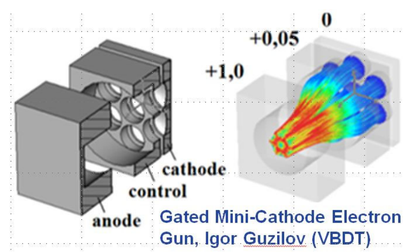

Figure 1: Gated mini-cathode gun concept.

DMMSC requires extraordinary flexibility in terms of X-ray pulse delivery timing. This, in turn, demands similar flexibility from the RF systems used to power the DMMSC accelerator. Present RF power sources, simply, cannot meet the demand. We propose to address this problem by driving innovation and development in three areas that provide a pathway to meeting the demands of DMMSC-type FEL RF power systems.

First, an approximate order-of-magnitude increase in cathode current density is required, without lifetime or other performance sacrifice. The high-current-density cathodes, combined with novel RF cavity/circuit design, allows the klystron operating frequency to be more than quadrupled, to that required by DMMSC-suitable accelerator structures. Finally, a high-performance beam gating system is necessary to enable burst-mode delivery and 50-fold reduction of switching losses.

Above all, accelerator klystrons must be reliable; cathode lifetimes in excess of 50,000 hours are expected. Success is thus predicated upon optimizing the NST cathode fabrication process to achieve consistent performance. The initial target is to enable production of 1.26 cm diameter cathodes with an emission density of 40 A/cm^2. Eight such cathodes would each provide, in aggregate, the anticipated 400 A needed for a 60 MW C-band MBK operating at 200 kV. Accomplishing this goal will require a concerted materials science effort, including diagnostic work at a synchrotron user facility. A comprehensive analysis of the relationship between emission density, cathode temperature and wear-out mechanisms should be accomplished by coordinated theoretical and experimental approaches. Tools such as X-ray absorption spectroscopy and X-ray photoemission spectroscopy [8] will inform emission modeling. Ab-initio modeling of how scandium affects cathode work function, and on Ba diffusion, should help illuminate experimental results.

The three major thrust areas described above are interdependent, requiring a multi-disciplinary approach that is uniquely enabled by experimental, theoretical, and simulation capabilities available at LANL and at collaborating research institutions (UNM and PSI).

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LA-UR-20-26592