Cryocooler Technology for Electron Particle Accelerators

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ABSTRACT

Particle accelerator technology is ubiquitous in modern discovery science. Accelerators are no longer limited to the more well-known high energy physics applications. They are of vital importance to many diverse fields as far reaching as biology, chemistry, condensed matter physics, medicine, and industrial manufacturing procedures. It has then of the utmost importance to develop better understanding of the physics and engineering principles necessary for advanced particle accelerator design.

The Particle Beam Physics Laboratory (PBPL) at the University of California, Los Angeles (UCLA) is at the forefront of this research. One major thrust in accelerator physics in general and PBPL in particular is the application of cryogenic technology to accelerators. The presentation will focus on the use of cryogenic technology in general accelerator R&D research as well as particular developments taking place at UCLA. Discussions will introduce general improvements of figures of merit such as beam brightness expected to come from cryogenic operations. In particular, three experiments utilizing cryocoolers will be presented: two radiofrequency (RF) resonant cavity tests of normal conducting copper at cryogenic temperatures, at low and high RF power, and one integrated test bed for studies of photoemission at cryogenic temperatures.

INTRODUCTION

Motivations for continued advancement of the field of particle accelerator physics often canonically make note of the essential role they have played in discovery science over the past century. Notable highlights include the successes in elementary particle physics at the Fermilab and CERN accelerator complexes, nuclear physics studies at Brookhaven National Laboratory and CERN, and high brilliance photon sources at synchrotron storage rings and free electron lasers such the Advanced Photon Source at Argonne National Lab and the Linac Coherent Light Source (LCLS) at SLAC [1-4]. In many respects light sources are the most compelling as they benefit fields beyond basic physics. These machines, often electron accelerators, offer extensive capabilities for scientific users, making available large numbers of high energy photons allowing breakthroughs in material science, chemistry, biology and others. Medical and various industrial applications are also at the forefront of development motivation. Many if not all of these facilities are enormous in scale, with kilometers of space needed and costs in the billions of dollars for construction and maintenance. We thus find enormous incentive to reduce the size and cost of these devices.

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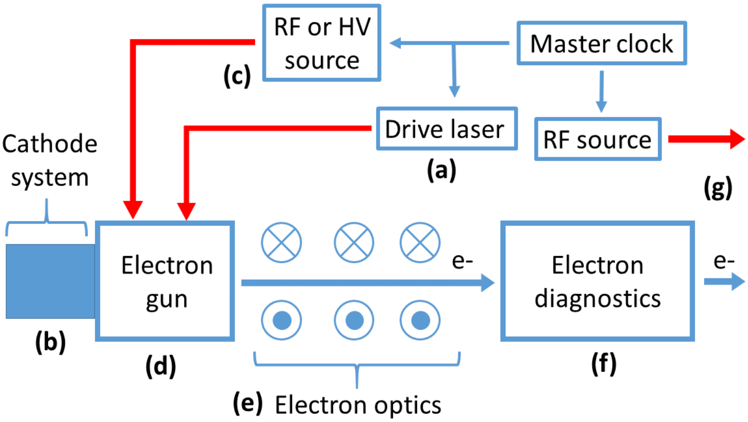

Figure 1. Schematic overview of the necessary components for a generalized electron photoinjector. **(a)** The device in general can be thought of as beginning with the drive laser, a pulsed laser source used to illuminate a photocathode and emit electrons in pulsed bunches. **(b)** The cathode system encompasses a robust removable modular portion which can be used to replace damaged cathodes and in the case of certain high brightness photocathodes be used as a growth chamber. **(c-d)** An RF source is then used to support an eigenmode in the initial high accelerating gradient cavity resonator known here as an electron gun. **(e)** Electromagnetic optics used for manipulating the electron bunches (for example) focusing following by the **(f)** diagnostic suite. **(g)** The beam bunches born then continue on to additional accelerating sections. A master clock coordinates the RF phases and the drive laser as necessary.

BEAM BRIGHTNESS & PHOTOINJECTORS

The main figure of merit we talk about and judge is termed the beam brightness. We can talk about the density of the electrons in the momentum-position phase space as beam brightness [5]. Viewed in this light, a brighter electron bunch would be one of small transverse and longitudinal spatial dimension and very small energy spread. Many electron accelerator applications especially benefit from this increased brightness. For example, it can be shown that an important figure of merit characterizing the performance of a free electron laser called the Pierce parameter is directly proportional to the so-called 6D brightness (i.e. the particle density in the abstract phase space of all three position and momenta coordinates) [5]. It can then be shown that the brightness at the start of the accelerator is the maximum brightness that can be achieved in a linear accelerator [6-7].

Since we are concerned with high brightness applications for electron accelerators it is useful to consider the temperature dependent advantages for the radiofrequency (RF) photoinjector, the most successful and brightest source developed for electron linacs. Photoinjectors are also interesting as a general system to study since they involve on an individual level, most of the components that further accelerating sections would require. A generalized schematic can be found in Figure 1. It can be shown that the brightness of an electron bunch grows as the square of the launch field (i.e. the electric field at the cathode surface) [8]. Thus increasing the launch field is one of the best options for increasing the source brightness.

CRYOGENIC ADVANTAGES

Given the explicit figure of merit of beam brightness and the implicit figures of merit of reduced cost and size we can begin discussing the general cryogenic advantages. For example, we can talk about individual physical processing like power dissipation and electron emission, general magnetic and electric effects, or static and dynamic effects. Most, if not all of these, benefit from cryogenic operation.

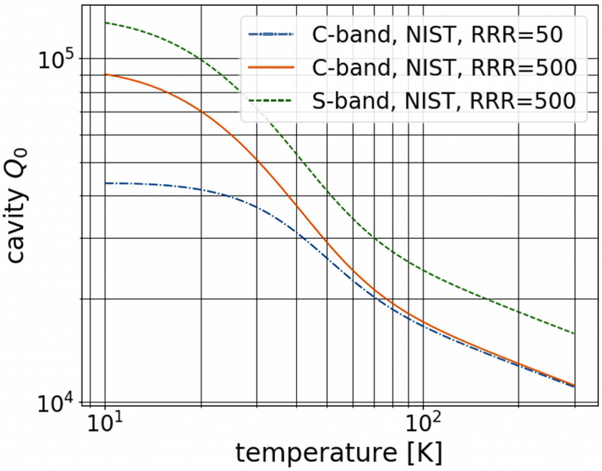

Figure 2. Temperature dependence of the quality factor for resonant cavity designed for two operational frequencies in S-band and C-band (2.856 and 5.712 GHz respectively) and with two different residual resistivity ratio (RRR) values.

RF ADVANTAGES

In the superconducting regime, the main advantage is essentially efficiency. Superconductivity here refers to the behavior associated with specific materials that when dropping below a critical temperature see their bulk resistance vanish. For superconducting RF (SRF) structures one finds that the RF losses in very low, that is the power deposited into the surface of the cavity is dramatically reduced. The case is ideal for high average current or high repetition rate machines. SRF cavities are most often designed for these high repetition cases, in excess of 1 MHz [10]. Many groups are examining the usage of superconducting RF cavities [11-13]. There are limits on the maximum accelerating gradient (around 30 MV/m) and the effectiveness of SRF cavities in the presence of high magnetic fields [10,14]. Still there is great promise in this field and SRF cavities are of increasing importance for many large accelerator projects.

In the normal conducting regime, cryogenic operation reduces bulk resistance of copper and other conductors significantly but not to zero. As a result, there is still significant advantage in terms of power dissipation reduction as in the SRF case albeit to a lesser extent. We then need only limit our use cases to lower rep rate accelerators in order to offset this additional power dissipation. The primary theory of the reduction in surface resistivity as a function of bulk resistance comes from the theory of the anomalous skin effect (ASE) which is mature and comprehensively formulated [15]. However, there remain many open questions including the precise effects of the ASE on pulse heating. The quality factor is a useful dimensionless figure of merit that informs one of the amount of power dissipation normalized to the stored energy in a cavity. For SRF cavities Q values are on the order of 10^8 while cryogenically improved NC cavities are around 10^5 (Figure 2).

Another compelling advantage is the empirical observation of the reduction of the rate of RF breakdown rates (BDR), an electrical breakdown phenomenon that occurs in high gradient and high frequency normal conducting RF cavities. The physical phenomena that causes RF breakdown is a complicated phenomenon which is difficult to model due in no small part to the necessity of interactions between different scaling of effects present in the dynamics. However, we can introduce here a general qualitative picture that informs the usefulness of cryogenic operation. We can introduce the idea of dislocations in an otherwise uniform crystal copper lattice. Higher concentrations of these crystal lattice dislocations have been observed to be proportional to the breakdown rates and so we attribute microstructures undergoing tunneling field emission which leads to Joule heating and subsequent vaporization of the microstructure, released additional material creating a crater and additional imperfections as well as coupling out energy from the RF field lowering the field gradient.

For higher residual resistivity ratio (RRR) values, the ratio of resistivity at room temperature to that at a temperature approaching 0K, we expect the copper to have fewer imperfections and so smaller breakdown rates in addition to the improved Q-values (Figure 2).

We can conclude that the smaller the breakdown rate the higher the accelerating gradient can be supported in the cavity with sufficient stability to accelerate a bright electron beam. Cryogenic operation effectively freezes these dislocations in place so prevents the development of concentrations that would lead to breakdown. Based on studies performed by SLAC and UCLA we conclude that peak surface fields in excess of 500 MV/m can be supported [16].

Cathode Emission Advantages

In both the superconducting and normal conducting case there also is an open question concerning the behavior of advanced photocathodes at cryogenic temperatures. Theory in addition to a number of experiments show that we can expect to reduced transverse energy spread for near-threshold photoemission at cryogenic temperatures which would improve brightness [17]. The quantity is often called the mean transverse energy (MTE) and it is one of the most useful figure of merit when talking about brightness improvements at the cathode [7]. However, we also expect reduced quantum efficiency, the ratio of electron emitted to photons absorbed, at these temperatures. The competing influences must be measured in order to determine the realizable brightness improvements.

CRYOCOOLER ADVANTAGES

It is worth noting that all the direct cryogenic advantages listed in the previous section are equivalently valid for a liquid cryogen based cooling system. However, this is only true at large scale of a national lab. Cost overruns would make these sorts of experiments untenable at the smaller university scale. Our intention, at UCLA especially, is to democratize the large scale accelerator research that can be performed as well as create a reduced cost and scale light source that could be accessible on the scale of tens of millions of dollars to be operated for user experiments. The primary use case can be found in the recently published ultra compact xray free electron (UC-XFEL) concept [5]. We arrive at an estimate on the order of tens of million dollars for a 40 m long concept design in a large part enabled by cost effective crycooler systems for normal conducting RF structures.

As further evidence of the more cost effective working point, we present three smaller scale test beds under development at UCLA. We are able to design small lab setups at a scale that allows basic material testing for the many low temperature studies required for full utilization of cryogenics in making the UC-XFEL concept a reality.

Lower RF Power and Material Test Cryostat

A simple cryostat for material testing and so-called low power tests for resonant cavity designs has been designed and is being manufactured. Comprehensive study of the temperature dependent properties of various materials is essential since precise cryogenic measurements of the exact alloys and technologies required for the UC-XFEL are few and far between. We plan to utilize a repurposed Cryomech AL-125 that was previously used for cryogenic undulator magnet experiments [18]. Various incidental technologies such as thermal conductance of press fits and vibration reducing straps will be tested.

The effects of cryogenic temperatures for low RF power, i.e. quality factor and surface resistivity tests are necessary at the unique RF frequencies we intend to operate. Quality factor here is the cavity figure of merit associated with dissipation in a resonator. In Figure 2 we plot the quality factor in a simple cylindrically symmetric cavity resonator (the type intended to be used in these low power tests) as a function of temperature. This quantity is simple to measure with standard low power RF probes and network analyzers. Since it is a function of the surface resistivity of the resonator material this is a necessary measurement to measure the anomalous skin effect and other thermophysical properties at the specific frequencies and temperatures to be tested in a high power breakdown test. We also have the ability to test simple cavities in differing alloys to search, in search for those that may have lower BDR. The geometry of this simple cavity geometry is shown in Figure 3. The cylindrical geometry is

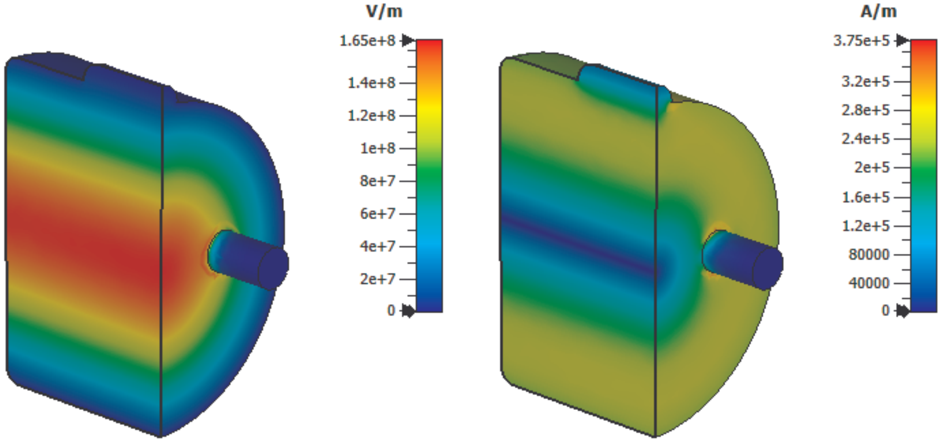

Figure 3. Cavity designed to support a standing wave of frequency 5.712 GHz. The fields plotted are the magnitudes of the electric (left) and magnetic fields (right) in the longitudinal direction. The fields are calculated as eigenmodes with 1 Joule of stored RF energy so the absolute scale of the fields are artificial. The additional asymmetry on the outer radius is placed as an intentionally placed to prevent the formation of degenerate higher modes. The smaller cylinder at the face is the placement for the lower power RF antenna.

often called a pillbox. The cavity is designed to support a standing wave of frequency 5.712 GHz. The fields plotted are the magnitudes of the electric and magnetic fields calculated storing 1 Joule of RF energy in the cavities so the absolute scales of the fields are artificial.

High RF Power Breakdown Test

We also use cryocoolers for higher powered RF tests. At these high powers we can start to create RF breakdown and study its strong temperature dependence, making estimates of the accelerating gradient supported. Past experiments have studied this at specific frequencies in X-band and S-band so there is incentive to fill in the knowledge gaps at untested frequencies [19]. For these higher power tests, we can create cavity structures that have at least three resonant cavities to symmetrize the field and focus breakdown in the middle cavity. The two outer cavities are designed such that the center cavity has an on axis field component twice that of the two flanking cells. A cross section of this geometry with the electric fields on axis plotted are shown in Figure 4. In the tests with this structure we expect to exceed 250 MV/m surface fields at 5.712 GHz. These tests will also help with the understanding of instantaneous pulse heating.

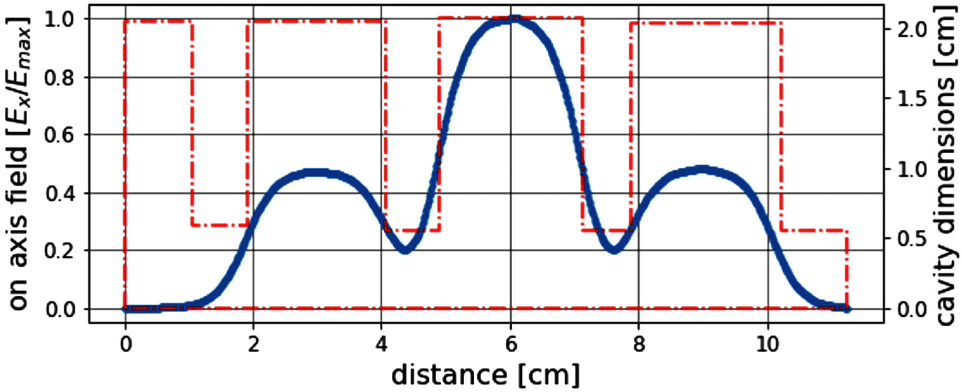

Figure 4. Basic concept for three cell cavity resonator designed for a high power RF breakdown study. Plotting the longitudinal electric field on the axis (solid line) and an outline of the cavity resonators (dotted line).

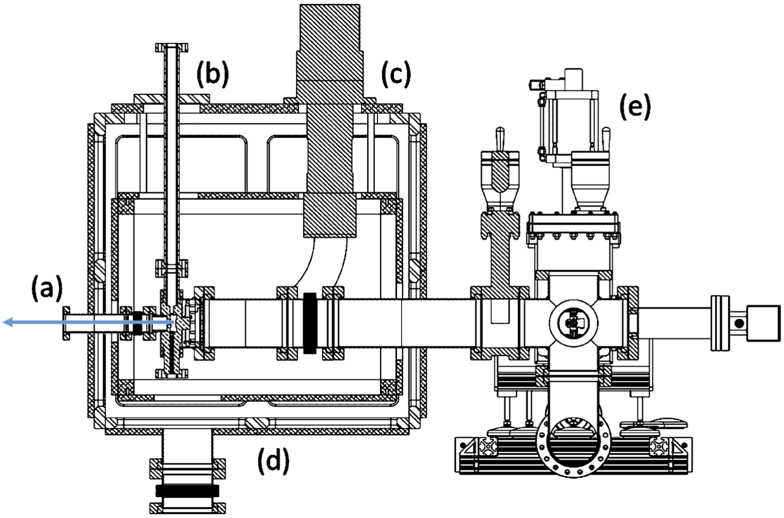

Figure 5. Simplified schematic of cathode test bed for cryogenic operation. Shown is a cutaway along the so-called beam axis which in this case is travelling to the left (**a**) arrow shows beam direction). **(b)** The waveguide to feed the accelerating structure. **(c)** Cryooler placement. **(d)** Cube shaped modular cryostat**. (e)** Cathode preparation and transport chambers.

Cryogenic Cathode Testbed

In order also to consider the cryogenic effects at the cathode we are currently working on a design for an integrated testbed for cryogenic cathode studies using a cavity structure which employs high gradient cryogenic effects. The cavity designed here takes into account the necessary power dissipation and thermal contraction requirements in order to preserve the eigenmode frequency range of a higher power klystron. The operating temperature is 40 K with an intended cathode surface field of 120 MV/m.

The primary measurement for the test bed will be the MTE of various cathodes at cryogenic temperatures. Candidates include the standard metallic photocathode materials such as high purity copper as well as more high brightness semiconductor materials such as CsTe and GaAs. Ideas for single-shot MTE measurements and other electron diagnostics for higher brightness but lower charge electron beams are mature and will be the primary method of measurement [20].

In addition to the cathode measurements, this test bed also will serve as a proof-of-principle for the necessary cryogenic infrastructure for future linacs. The operating temperature of the test bed will be a more modest 45 K with an accelerating gradient of 120 MV/m. Using a cryocooler with cooling capacity at 45 K of at least 100 W should be more than sufficient for a low rep rate (1-10 Hz) operation. Using a simplified room temperature RF pulse heating model we can estimate our heat load as on the order of 10 W [21]. Additional thermal, leaks from mounting structures and waveguide feedthroughs can be kept to a maximum of 10 W as well using sufficiently long thermal breaks made from a combination of bellows to increase effective length and stainless steel sections. A simplified cross-section of the cryostat and cathode storage and preparations chambers are shown in Figure 5.

SUMMARY

We have presented here an introduction to the goals of particle accelerator physics and the notion of general advantages of cryogenic operation on the performance of electron linear accelerators. In doing so, we have introduced the valuable impact cryocoolers are having on electron accelerator research and development. Specifically, we have presented three important tests planned for the UCLA PBPL concerning the study of normal conducting RF structures and cathode emission at cryogenic temperatures. Future work will continue to heavily rely on affordable crycooler technology and will enable the future of normal conducting RF and photocathode emission work.

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