Compact Superconducting Radio-frequency Accelerators and Innovative RF Systems

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ABSTRACT

Use of Superconducting Radio-Frequency (SRF) cavities allow linear accelerators (linacs) less than 1.5 M in length to create electron beams beyond 10 MeV and with average beam powers measured in 10's of KW. Such compact accelerators will be cost effective for many existing and new industrial applications. Examples include radiation crosslinking of plastics and rubbers; creation of pure materials with surface properties radically altered from the bulk; modification of bulk or surface optical properties of materials; food preservation; sterilization of medical instruments; sterilization of animal solid or liquid waste, and destruction of organic compounds in industrial waste water effluents. Small and light enough to be located on a mobile platform, such accelerators will enable new remediation methods for chemical and biological spills and enable in-situ crosslinking of materials.

Keywords: accelerators, environment, cross-link, materials, security

OVERVIEW

Our team has designed and plans to construct and validate a compact, 10-kW average power linac capable of delivering beam energies up to 10 MeV, weighing less than 3,000 pounds, and that can be palletized and made portable for a variety of industrial applications. This will be done by exploiting recent, robust, technological advancements in Superconducting Radio Frequency (SRF) cavities and RF power source technologies as well as innovative solutions for the SRF gun and cathode system.

A major design choice for high-average power, compact SRF accelerators is the choice of RF frequency. As the frequency goes up, the size and weight of an SRF accelerator decreases. However, as the frequency goes up, the SRF cryogenic cooling requirements grow with the square of the frequency leading to the need for large cryogenic systems that without additional technological advances outpace the gains in going to higher frequencies. Until recently the mitigation approach was to adopt low frequencies (~350 MHz) that in turn lead to large physical size and weight for the cavities [1], cryomodule, and the required radiation shielding. Fortunately, due to several recent breakthroughs at Fermilab, low cryogenic loss elliptical cavities operating at 1.3 GHz are now a viable and excellent choice that can be used to create a much more compact and efficient solution.

BREAKTHROUGH TECHNOLOGIES

There are five transformational, technological advances in SRF and peripheral equipment that pave the way for our ability to create a viable, compact, robust, high-power, high-energy, electron-beam or x-ray source. When these advances are integrated into a single design they enable an entire new class of compact, mobile, high-power electron accelerators. These technologies are:

1) A new Niobium surface processing technique [2] has been developed and demonstrated at Fermilab which dramatically reduce the cryogenic refrigeration requirement for 1.3-GHz SRF cavities at 1.8 K. This technology can be further optimized for 4 K operations. For a pulsed machine (e.g. a 5% duty factor) this technology allows cooling of a small (few KW) SRF linac with a simple, commercial, 5-W cryocooler.

2) Recent results from Cornell University [3] have shown that 1.3-GHz, 9-cell Niobium cavities coated with Nb_3Sn can be operated with gradients of ~ 10 Megavolts/M with a quality factor at a temperature of 4.2K of 2×10^{10}. Such a cavity could be operated with Continuous Wave (CW) RF power while cooled by a single 5 W commercial cryocooler.

3) With reduced dynamic heating due to the advancements highlighted in bullets 1 and 2, one can then envision conduction cooling [4] of the SRF cavity resulting in a drastically simplified cryogenic system requiring no gas or liquid Helium inventory. In such a design the vacuum vessel may be able to serve as the radiation shield leading to additional reductions in size, weight, and overall system cost.

4) Recent Fermilab proprietary technology [5] utilizing a single, injection-locked, 1-kW, magnetron has demonstrated excellent phase and amplitude control at 2.45-GHz on a single-cell SRF cavity. Such a method can be scaled to other frequencies such as 1.3-GHz. Using magnetrons to drive a narrow-band load like an 1.3 GHz SRF cavity [6] can dramatically lower the cost and

improve the efficiency of the RF system. We estimate that this technology can reduce the cost of RF power for compact SRF accelerators by a factor of 5 while at the same time achieving efficiencies in excess of 80%. This will also result in substantial size, weight, and cost reductions in both power and cooling systems compared to current solid-state or klystron solutions.

5) Cold, Field-Emission (FE) electron cathodes provide the opportunity to integrate the SRF injection cavity and gun to the SRF accelerating cavity creating a very short and compact accelerator. Small physical size is a key feature to limit the weight of radiation shielding for mobile applications. One key to success will be demonstrating that the FE gun can operate in a high Q_0 SRF cavity without contamination of the cavity internal surface. One promising approach is a new technique developed at CSU which allows the creation of cold Field Emission (FE) electron cathodes based on Nb nano-pillars. An alternative design based on robust carbon nanotubes is being developed at NIU.

When integrated into a single design, these innovations can be used to create high-power, high-energy electron source that is both compact and efficient. Initially we will construct an accelerator built around a single, 9-cell, 1.3- GHz cavity, operated at 4 K with a ~5 % duty factor and delivering ~ 3 kW average beam power over a range of electron energies up to 10 MeV.

This accelerator would be powered by an injection-locked, pulsed magnetron RF source and use a Field Emission cathode as the source of the electrons. The cavity will initially be pure Nb treated with a version of Fermilab's new high Q_0 surface processing optimized for 4 K operation. The cavity will be housed in a low heat leak cryostat and conduction cooled via one or more 5 W commercial cryocoolers such that the system requires no gas or liquid Helium inventory. When ready we will replace this cavity with one coated with Nb3Sn optimized for 4 K operation that would enable CW operation and substantially higher average beam power.

A schematic of the planned accelerator is shown in Figure 1. In the sections that follow we describe in more detail some of the key technologies required.

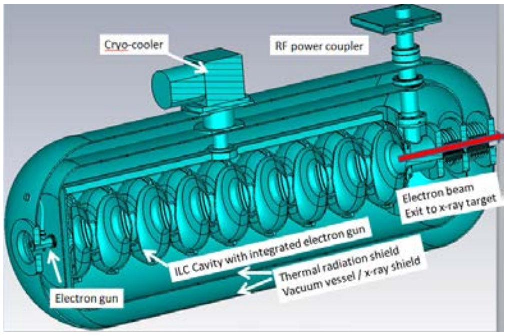

Figure 1: Overview of the proposed compact 10 KW SRF accelerator. The overall length of the accelerator is 1.5 M with a diameter of ~ 0.5 M.

LOW LOSS SRF CAVITIES

Heating in a SRF cavity is the result of non-zero resistance due to scattering of unpaired electrons excited by the radio frequency alternating fields. These so called "dynamic losses" can be reduced by one of several methods:

(1) improved cavity surface processing to decrease surface impedance (frequency dependent resistance). This is equivalent to increasing the cavity quality factor (Q_0) defined as $Q_0 = U/\Delta U$, where U is the cavity stored energy and ΔU is the energy lost per RF cycle as heat at the desired operating temperature and accelerating field;

(2) lower the cavity operating frequency since dynamic losses due to unpaired electron scale as the frequency squared;

(3) lower the operating temperature resulting in fewer unpaired electrons (e.g. 1.8 K for Nb), but with increasingly complex refrigeration requirements; or

(4) use a superconductor with a higher transition temperature (Tc) such as Nb_3Sn.

Methods (2) and (3) above are counter to the goal of a compact, simple, high-average power accelerator. Therefore our solution leverages recently proven methods that improve the Q_0 for smaller higher frequency SRF cavities as well as utilize materials with higher transition temperatures. The very high Q_0 anticipated allows for the first time use of pulse tube refrigerators (cryocoolers) eliminating the need for large 4K refrigerators, pressure vessels, complex gas or liquid Helium inventory management systems. Figure 2 illustrates the dramatic simplifications possible with this method.

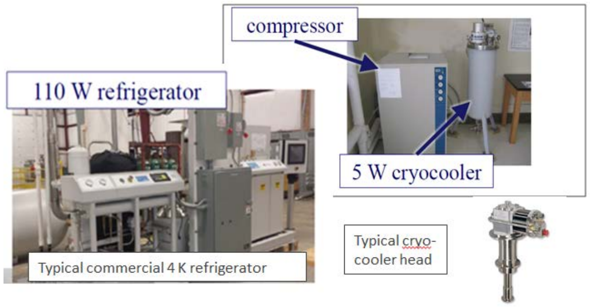

Figure 2: Commercial 4K refrigerators vs cryocoolers

The Promise of Nb_3Sn

Although a compact SRF based accelerator can be built today using cavities fabricated of pure Niobium, processed with the best surface processing available today, and operated with RF power that is pulsed (e.g. 5% duty factor) to limit cryogenic losses, it would be much better to employ a cavity employing an RF surface made using a superconductor with a higher transition temperature. Nb_3Sn has a superconducting transition temperature of 18 K. Because it has a much higher transition temperature than the Tc of 9 K for pure Nb, at temperatures near the helium boiling point at atmospheric pressure (4.2 K), an SRF cavity surface coated with Nb_3Sn will have a much lower number of unpaired electrons. This leads to measured Q_0 values higher by a factor of >30 at a temperature ~ 4.2 K. See Figure 3.

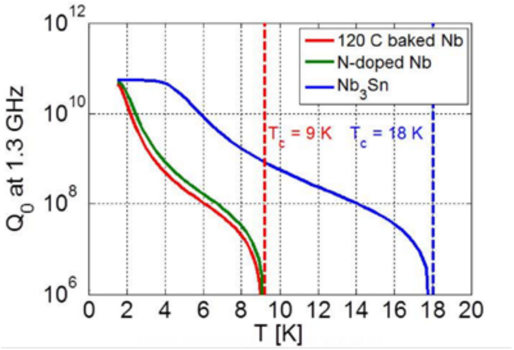

Figure 3: Q_0 comparison between a pure Nb cavity and a Nb cavity coated with Nb3Sn at Cornell. Note Q_0 increase by a factor of ~ 30 at ~4.2 K. (S. Posen, private comm.)

Since the cryogenic heat load is dramatically reduced with a Nb_3Sn coated cavity, it now becomes possible to operate the cavity at 100% RF duty factor even at temperatures ~ 4-5K allowing the accelerator to produce beam continuously. Moreover, for a cavity Q0 ~ 2 x 10^{10} a 5 W commercial cryocooler would have sufficient capacity to cool a 9-cell Nb_3Sn cavity in CW operation at 10 MV/M accelerating gradient. If operated with 1 mA of average beam current this means ~10 kW of beam power. If the current could be increased to 5 mA, then 50 KW of beam power would be produced. It is likely that beam losses to the cryogenic system become the new limiting feature for such a machine.

Although the Nb_3Sn coated cavities developed and tested at Cornell demonstrate outstanding performance, the number of cavities produced to date is small. New facilities are currently being designed at Fermilab to take the next steps in Nb_3Sn coated cavity development. Since, single cell 1300 MHz Nb_3Sn coated cavities consistently show results excellent results, it is expected that 9-cells meeting program specifications will quickly be developed. Figure 4 shows a Scanning Electron Microscope image of a Nb_3Sn surface indicating well controlled grain structure and surface smoothness. Figure 5 shows the dependence of Q_0 with the accelerating gradient. Note especially, the Q_0 value and accelerating gradient for the point corresponding to cavity 2, coating 1 produced at Cornell.

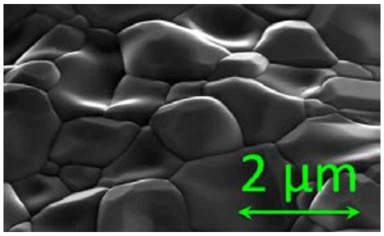

Figure 4: SEM image of Nb_3Sn surface SEM indicates appropriate grain size and texture. EDX shows desired tin content for highest Tc and confirms uniformity

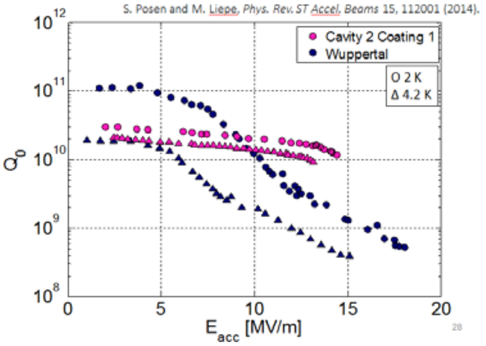
S. Posen and M. Liepe, *Phys. Rev. ST Accel. Beams* 15, 112001 (2014).

Figure 5: Q_0 dependence on the accelerating gradient for Nb3Sn coated cavities. Note especially, the Q_0 at 4.2 K for Cavity 2, coating 1 produced at Cornell.

Conduction Cooling

With dynamic heating estimated at < 5 W for high Q_0 nine-cell 1300 MHz SRF cavities, (operated in pulse mode if fabricated from pure Niobium or continuously if fabricated with Nb_3Sn coatings) one can envision conduction cooling of the SRF cavity vs locating it inside a Liquid Helium filled pressure vessel. Using proprietary techniques [4] and materials, we estimate that the temperature increase from the cryocooler cold tip to the cavity in Figure 1 will be less than 0.5 degrees K. Conduction cooling results in further simplification of the SRF accelerator cryomodule. It is important to realize that the accelerator cryomodule illustrated in Figure 1 contains no liquid Helium pressure vessels, piping, or inventory. In such a design, if the electron source can also be made compact, then the vacuum vessel may be able to serve also as the radiation shield leading to additional reductions in size, weight, and cost.

Electron Gun and Cathode

The electron gun and the cathode system are critical components for stable intensity and high-average powers. Our team has experience in high-average power electron gun design and fabrication. The basic gun design envisioned provides short bunches and thus small current interception. It also employs features of other successful RF and SRF guns

[7,8]. However, in our design we have integrated the gun cavity into the single 9 cell cavity that forms the entire accelerating structure. This design feature is also key to a compact design. Figure 6 a schematic of an SRF gun integrated into a single 9 cell ILC-like cavity. The cathode assembly is removable allowing both optimization and exploration of the various cathode technologies.

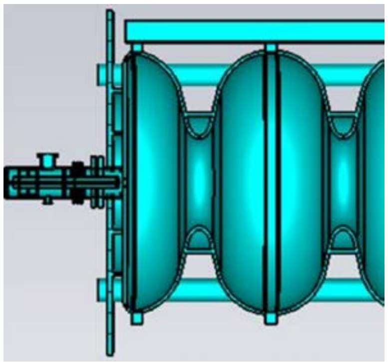

Figure 6: Schematic drawing of the electron gun integrated into a single 9 cell ILC-like cavity

We envision employing a cathode fabricated from an array of field emitters (FE). This allows the cathode to operate near the temperature of the SRF cavity minimizing heat sources into the cryogenic system. FE cathodes have been demonstrated using variety of materials including diamond tips, carbon nanotubes, and arrays of nanowires. Since material evaporated from the cathode may end up contaminating the interior of the SRF cavity, we intend to explore a novel approach bases on nanowires fabricated from pure Niobium. Figure 7 is a photo of an array of Nickel nanowires produced at Colorado State University. It is expected that the same technique can be used to produce Niobium nanowire FE cathodes.

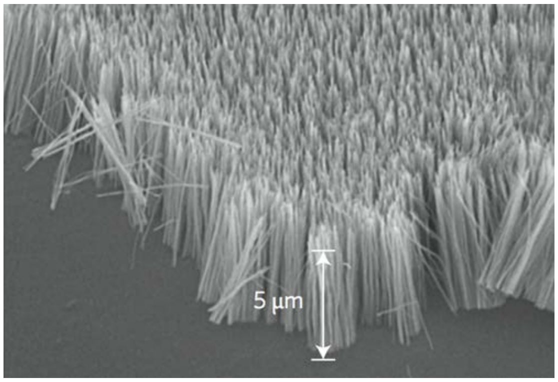

Figure 7: CSU developed conductive 15 µm long Nickel nanowires. The interior of the array is very uniform.

SUMMARY

The goal of a very compact mobile, high-energy, high-power, SRF-based electron linac appears to be feasible. The use of high frequency (1.3 GHz) SRF cavities with very low cryogenic losses permits the accelerator to be more compact, cheaper, and achieve better performance including continuous wave operation compared to copper pulsed linacs or lower frequency SRF accelerators based on spoke resonators. Very low cryogenic losses permit the elimination of cryogens from the accelerator drastically simplifying the system and reducing size and weight.

Further innovations enabling this approach are the use of a compact nanostructure field emission electron sources and a novel, efficient, low cost RF power system based on a proprietary Fermilab magnetron and control technology. Taken together these innovative technologies enable a new class of compact, simple, SRF based accelerators for industrial and security applications. This paper reports the first steps towards realization of such a machine.

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