SRF, COMPACT ACCELERATORS FOR INDUSTRY & SOCIETY

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Abstract

Accelerators developed for science now are used broadly for industrial, medical, and security applications. Over 30,000 accelerators [1] touch over $500B/yr in products producing a major impact on our economy, health, and well being. Industrial accelerators must be cost-effective, simple, versatile, efficient, and robust. Many industrial applications require high average beam power. Exploiting recent advances in Superconducting Radio Frequency (SRF) cavities and RF power sources as well as innovative solutions for the SRF gun and cathode system we have developed a design for a compact SRF high-average power electron linac. Capable of 5-50 kW average power and continuous wave operation this accelerator will produce electron beam energies up to 10 MeV. Small and light enough to mount on mobile platforms, such accelerators will enable new in-situ environmental remediation, in-situ crosslinking of materials, and security applications. More importantly, we believe this accelerator will be the first of a new class of simple, turn-key SRF accelerators that will find broad application in industry, medicine, security, and science.

OVERVIEW

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 with average beam powers measured in 10's of kW. Such compact SRF accelerators can have high wall plug power efficiencies and will require smaller radiation enclosures reducing overall installation costs. Recent technological breakthroughs are expected to reduce capital costs such that such accelerators can be cost effective for many existing and proposed 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; radiation driven chemistry; 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 in-situ remediation methods for chemical and biological spills and may create entire new industries by enabling in-situ crosslinking of materials.

A team from Fermilab, Colorado State University, Northern Illinois University, Euclid Techlabs, and PAVAC has started an effort to design, construct, and validate a compact, 10 kW average power linac capable of operating continuous wave (CW); 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) 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 [2], cryomodule, and the required radiation shielding. Fortunately, due to several recent breakthroughs, low cryogenic loss elliptical cavities operating at 650 MHz or 1.3 GHz are now a viable and excellent choices that can be used to create more compact and efficient solutions.

BREAKTHROUGH TECHNOLOGY

There are six 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 "N-doping" [3] has been developed and demonstrated at Fermilab which dramatically reduces the cryogenic

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refrigeration requirement for 650 MHz and 1.3-GHz SRF cavities at 1.8 K. This technology also has been shown to significantly reduce losses at 4.4 K and can be further optimized for operations at this temperature.

2) Recent results from Cornell University [4] have shown that 1.3-GHz, single cell niobium cavities coated with Nb_3Sn can be operated with gradients of 10 Megavolts/m with a quality factor (Q_0) of 2 x 10^{10} at a temperature of 4.2K. A nine cell cavity with this Q_0 could be operated with Continuous Wave (CW) RF power dissipating 3.5 W, in range to be cooled by a single 5 W commercial cryocooler.

3) With reduced dynamic heating due to the advancements highlighted in 1) and 2), one can then envision conduction cooling [5] of the SRF cavity resulting in a drastically simplified cryogenic system requiring no gas or liquid Helium inventory.

4) Recent Fermilab proprietary technology [6] 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 [7] like an 1.3 GHz SRF cavity 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) An SRF gun cavity with an integrated thermionic cartridge or Field-Emission (FE) electron cathode provides the opportunity to integrate the gun cavity into the accelerating cavity creating a very short and compact accelerator design. 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 cathode can operate in a high Q_0 SRF cavity based gun without contamination of the cavity internal surface.

6) A robust and very low heat leak fundamental RF power coupler capable of handling many 10's of kW of RF power. A new proprietary FNAL design based on previous work [8] encorporates an RF shield to decrease the magnetic field at the outer wall of the coupler eliminating the need for copper plating and shunting dynamic losses out to an intermediate temperature (e.g. 60 K) vs into the SRF cavity at 4.5 K. This design dramatically reduces static heat loads and can effectively eliminate dynamic losses to 4.5 K.

When integrated into a single design, these innovations can be used to create a high-power, high-energy electron source that is compact, efficient, and simple enough for industrial applications. Initially we plan to construct a proto-type accelerator around a single, 9-cell, 1.3 GHz cavity with its first cell modified to be the gun, operated at 4.5K and powered by a CW injection-locked magnetron RF source with a thermionic cathode as the source of the electrons. The cavity will initially be pure Nb treated with a version of Fermilab's new N-doping high Q_0 surface processing optimized for 4.5 K operation. We will adjust the RF duty factor to ~5% by making long pulses to limit dynamic heating to an average of about 3.5 W. We estimate that 5 kW of average beam power is achievable in this mode.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 a similar one coated with Nb_3Sn with processing optimized for 4.5 K operation. This cavity will enable true CW operation and substantially higher average beam power ~10's of kW, limited primarily by our ability to control beam losses to cold cavity surfaces.

A schematic of the prototype accelerator is shown in Figure 1. While the implementation in Figure 1 will be a useful platform technology for many applications, it is important to understand that this is but one realization of what we believe will be an entirely new class of simple SRF accelerators. For example, one can imagine employing similar techniques to achieve higher beam powers (e.g. using a 650 MHz elliptical cavity with a larger aperature and even lower cryogenic losses) or multi-cavity system to achieve higher beam energy. In the sections that follow we describe in more detail some of the key technologies required using the compact 1.3 GHz design shown in Figure 1 as the example.

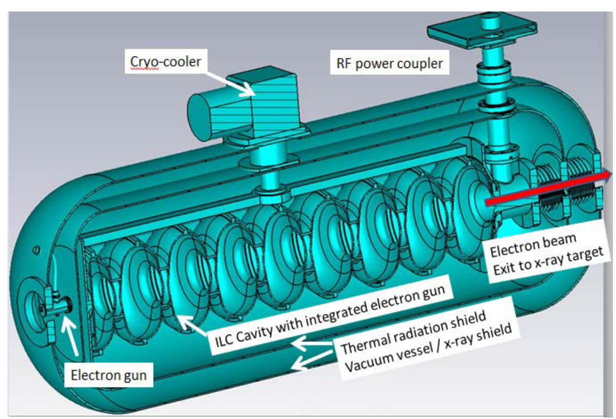


Figure 1: Overview of the proposed compact SRF accelerator. The overall length is 1.5 M with a diameter of < 0.5 M. For simplicity, no cavity magnetic shield is shown. Tuners are not needed since the RF system will be designed to lock to the cavity resonant frequency.

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. This is equivalent to increasing the cavity quality factor (Q_0) defined as $Q_0 = U/dU$, where U is the cavity stored energy and dU is the energy lost per RF cycle as heat at the desired operating temperature and accelerating field;

2) lower the cavity operating frequency since an important part of dynamic losses due to unpaired electrons 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 simple, low cost, compact, high-average power industrial accelerators. 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 can result in dynamic heat loads per cavity under 5 W at 4.5 K allowing 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 to maintain the cavity at operating temperature. Figures 2, 3 and 4 illustrate the dramatic simplifications possible if the accelerator heat load can be reduced to the range serviceable by a cryocooler.

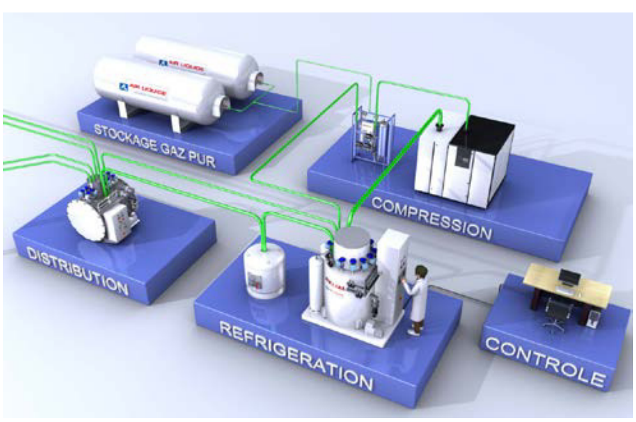
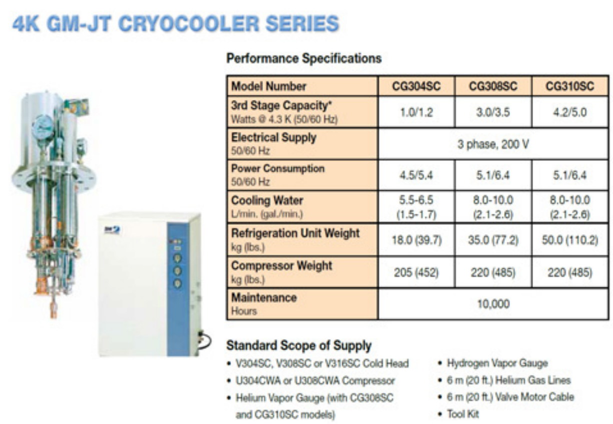


Figure 2: Typical commercial 4K refrigerators or liquifiers are elegant but complex requiring many external systems such as compressors, water cooling, electrical infrastructure, LN2 and LHe storage vessels, He gas storage and recovery systems, a He purification system, extenisve piping, etc [9]. System maintenance and reliability are always an issue.

Figure 3: Commercial 4K refrigerators like this small machine made by Linde are excellent for many applications, but have cold boxes that use pistons or turbo expanders that are sensitive to comtamination, require regular maintenance, and are physically large. They also depend on significant external infrasturcture as illustrated in Figure 2.



4K GM-JT CRYOCOOLER SERIES

Performance Specifications

Model Number	CG304SC	CG308SC	CG310SC
3rd Stage Capacity* Watts @ 4.3 K (50/60 Hz)	1.0/1.2	3.0/3.5	4.2/5.0
Electrical Supply 50/60 Hz	3 phase, 200 V		
Power Consumption 50/60 Hz	4.5/5.4	5.1/6.4	5.1/6.4
Cooling Water L/min. (gal./min.)	5.5-6.5 (1.5-1.7)	8.0-10.0 (2.1-2.6)	8.0-10.0 (2.1-2.6)
Refrigeration Unit Weight kg (lbs.)	18.0 (39.7)	35.0 (77.2)	50.0 (110.2)
Compressor Weight kg (lbs.)	205 (452)	220 (485)	220 (485)
Maintenance Hours	10,000		

Standard Scope of Supply

- V304SC, V308SC or V316SC Cold Head
- U304CWA or U308CWA Compressor
- Helium Vapor Gauge (with CG308SC and CG310SC models)
- Hydrogen Vapor Gauge
- 6 m (20 ft.) Helium Gas Lines
- 6 m (20 ft.) Valve Motor Cable
- Tool Kit

Figure 4: Advanced 4K cryo-coolers like this commercial example from Sumitomo can provide up to 5 Watts of refrigeration at 4.2 K in very compact, simple, reliable package. Note that for this unit the entire system weight is under 600 lbs for a 5 W system which enables compact mobile SRF accelerator applications. Source: http://www.shicryogenics.com//wp-content/ uploads/2012/11/Cryocooler-Product-Catalogue.pdf

N-DOPED PURE NIOBIUM CAVITIES

A new Niobium surface processing technique developed at Fermilab "N-doping" has demonstrated consistently outstanding Q_0 performance on 9-cell 1.3 GHz [10] (See Figure 5). The average Q_0 achieved at 1.8 K exceeds 3 x 10^{10}. Cavities prepared in this way and operated at 4.4 K achieve a Q_0 of ~6-7 x 10^8 at 6 MeV/m. See Figure 6. A 9-cell cavity prepared in this way and operated at 7 MV/m with CW RF leads to expected cryogenic losses of ~70 W. If such a cavity were operated in pulsed mode with 5% duty factor the refrigeration requirement would be ~3.5 W, in range for a commerical 5 W cryocooler.

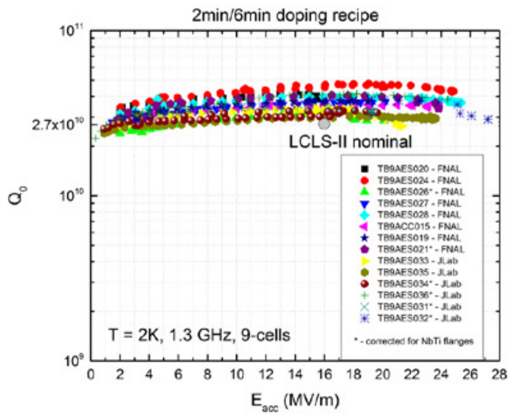


Figure 5: Q_0 vs Eacc for N-doped 1.3 GHz 9-cell cavities. The average Q_0 is > 3 x 10^{10} . Process confirmed at FNAL, Jefferson Lab, and at Cornell.

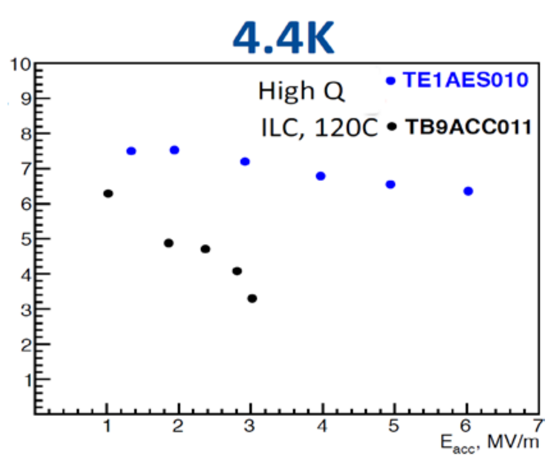


Figure 6: Q_0 vs Eacc for non-optimized N-doped 1.3 GHz cavities at 4.4 K. The Q_0 falls slowly with gradient and is ~6-7 x 10^8 at 6 MV/m (maximum gradient was limited by the coupler vs by quench.)

THE PROMISE OF Nb_3Sn

For Continuous Wave (CW) operation it would be much better to employ a cavity with and RF surface made using a superconductor with a higher transition temperature such as Nb_3Sn which has a superconducting transition temperature of 18 K. The higher transition temperature vs Tc of 9 K for pure Nb means that 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. See Figure 7.

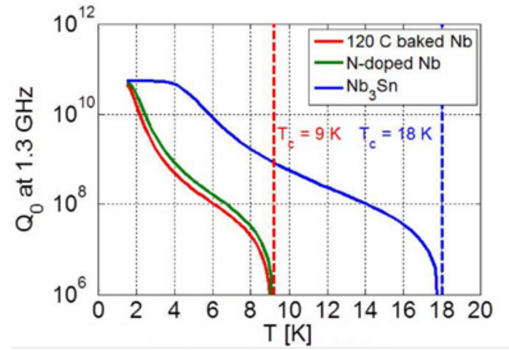


Figure 7: Calculated Q_0 comparison between a pure Nb cavity and an Nb cavity coated with Nb_3Sn at Cornell. Note Q_0 increase by a factor of ~30 at ~4.2 K. (S. Posen, private comm.)

Since the cryogenic heat load is dramatically reduced with a Nb_3Sn coated cavity, it will become possible to operate the cavity at 100% RF duty factor even at temperatures ~4.5 K allowing the accelerator to produce beam continuously.

A single cell 1.3 GHz elliptical Nb cavity coated with Nb_3Sn recently achieved a record Q_0 (~2 x $10^{10)}$ at 14 MV/m. See Figure 8. [11] A 9-cell cavity prepared in this way will dissipate only 3.5 W of dynamic losses into the cryo-system 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. Care in cavity processing can lead to negligible field emission at this gradient such that it is likely that beam losses to the cryogenic cavity become the new limiting feature for such an accelerator.

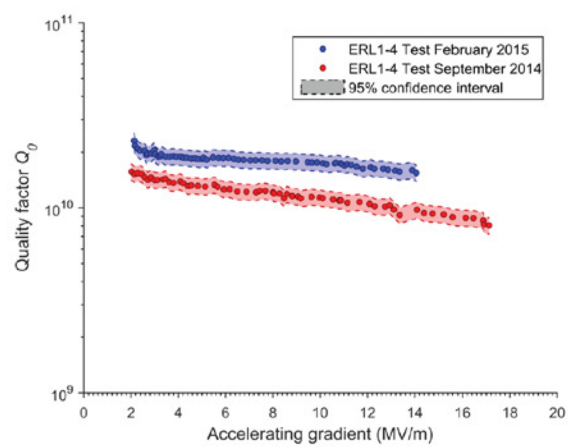


Figure 8: Q_0 vs E plot for an Nb 1.3 GHz single cell cavity coated with Nb3Sn at Cornell. The cool-down procedure was improved between the tests, which results in a higher quality factor and reduced Q-slope.

Although the Nb_3Sn coated cavities developed and tested at Cornell demonstrate outstanding performance, the number of cavities produced to date is small and the process has not yet been demonstrated on 9-cell cavities. 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, and studies of the Nb_3Sn surface (see Figure 9) indicate appropriate grain size and texture, it is expected that 9-cell (or more correctly 8.5 cell) cavities meeting program specifications will quickly be developed.

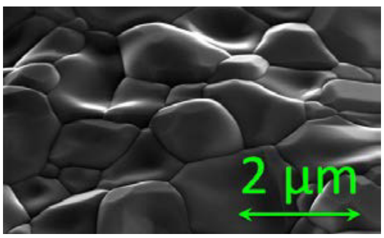


Figure 9: SEM image of Nb_3Sn surface SEM indicates appropriate grain size and texture. EDX shows desired tin content for highest Tc and confirms uniformity.

CONDUCTION COOLING

With dynamic heating estimated at < 5 W for a high Q_0 nine-cell 1300 MHz SRF cavity, one can envision conduction cooling of the SRF cavity vs locating it inside a liquid Helium filled pressure vessel. Using proprietary techniques [5] 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 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 resulting in both large cost savings and dramatic simplifications in the required safety analysis. If the electron source is also made compact and integrated into to cavity additional reductions in size, weight, and cost are possible.

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 [12,13]. However, in our design we plan to integrate the gun cavity into the first cell of a standard ILC/XFEL 9-cell 1.3 GHz cavity to form an 8.5 cell accelerating structue. This design feature is also key to a compact design. Figure 10 shows a schematic of an SRF gun that can be integrated into a 1.3 GHz 9-cell elliptical cavity. The cathode shown is a thermionic cartridge cathode but the assembly is removable allowing both optimization and exploration of various cathode technologies.

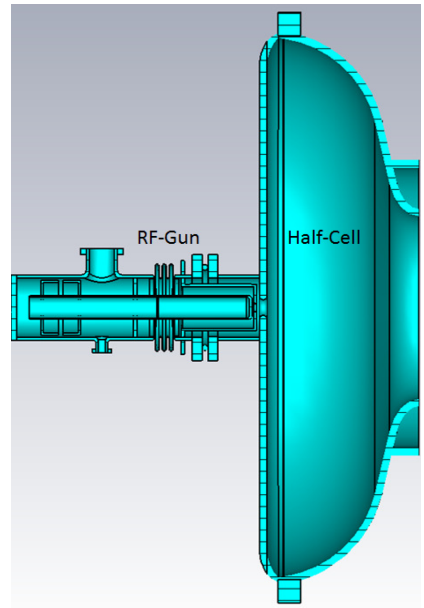


Figure 10: Schematic drawing of the electron gun with thermionic cathode that can be integrated into a multi-cell 1.3 GHz elliptical cavity. The thermionic cathode consumes 3 W leading to an estimated heat load from the cathode to the cavity cold surface at 4.5K of 0.1 W.

We can also envision further simplifications by 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. There are several promising approaches for FE cathodes including is a new technique developed at CSU [14] which allows the creation of cold Field Emission (FE) electron cathodes based on arrays of metallic nanowires (see Figure 11); a design based on robust carbon nanotubes (see Figure 12) being developed by Radiabeam Technologies and tested by Fermilab and NIU [15]; and a method using nano-diamonds (see Figure 13) being developed by a collaboration including Euclid Tech Labs [16].

Since material evaporated from the cathode may end up contaminating the interior of the SRF cavity reducing the cavity Q_0, we plan to explore cathode options using a single cell, high Q_0, SRF gun cavity and down select based on both emission characteristics and minimal contamination to SRF surfaces.

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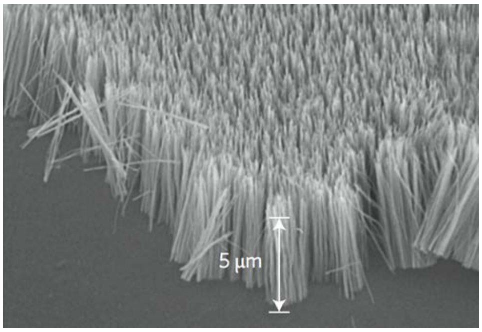

Figure 11: CSU developed conductive 15 µm long Nickel nanowires. The interior of the array is very uniform. Our intent is to attempt to use this technology to create nanowires of Nb.

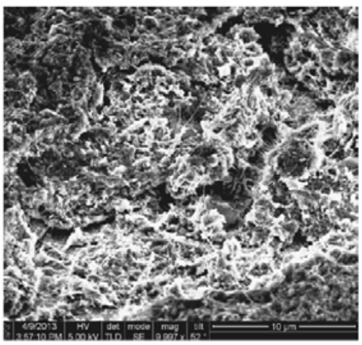

Figure 12: SEM micrograph of carbon nanotubes (CNT) used in a FE cathode built and tested by Radiabeam Technology, Fermilab and NIU [15].

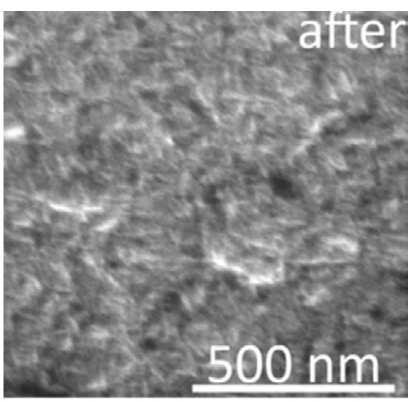

Figure 13: SEM images, typical for nitrogen-incorporated ultra-nano-crystalline diamond, (N)UNCD films, on Mo/SS after high power testing [16].

LOW HEAT LEAK FUNDAMENTAL POWER COUPLER

The coupler's function is to deliver RF power from the outside RF power source with minimal ohmic losses to the superconducting cavity. The coupler isolates cavity vacuum and must minimize heat flow from the surroundings at room temperature to the cryogenic temperature cavity. In current couplers the outer conductor is made of stainless steel coated with a thin layer of copper. Heating into the cryogenic system results from ohmic heating in this outer conductor and heat flow from surroundings thermally conducted to the cavity. The copper coatings are often problematic due to poor adhesion of copper to stainless steel, flaking and contamination the cavity.

Fermilab has developed a new design [17] that employs solid copper shields instead of plated copper arranged to produce very low electromagnetic losses in a low thermal conductivity uncoated outer stainless steel tube. See Figure 14. Since the copper shields are made of solid copper the RRR is very high and ohmic losses are smaller than plated copper. Solid copper also eliminates flaking. Slots prevent heat flow throough these copper shields into the cavity. The only unbroken path from cavity to room temperature is via low thermal conductivity stainless steel tube. The combination with appropriate radiation baffels results in very small (~ 0.5 W) dynamic and static losses to 4 K.

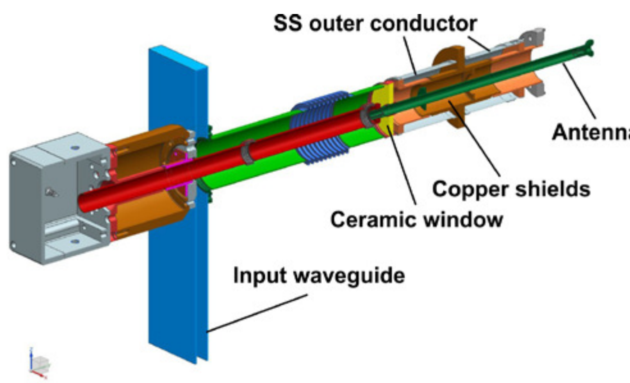

Figure 14: Cut view of low heat leak fundamental power coupler.

BEAM LOSS AND OTHER DESIGN CONSIDERATIONS

To operate successfully with a 5 W cryocooler, the accelerator shown in Figure 1 must reside in a cryostat designed to achieve a low static heat leak. From previous experience at Fermilab building small superconducting magnets cooled by cryocoolers we believe a robust design with < 0.5 W static heat leak at 4 K is achievable. To establish and maintain the required high cavity Q_0, the cavity either be must be carefully magnetically shielded or employ controlled cool down techniques to expel ambient magnetic fields [18]. The cavity must also employ surface processing techniques that prevent unwanted field emission. For CW operation we envision an injection locked magnetron RF system that dynamically locks to the cavity resonant frequency eliminating the need for either a slow or fast tuner. Controlling and minimizing beam lost to cold surfaces will be crucial and is likely to be the limiting factor in achievable beam power.

SUMMARY

While development work is still required, the goal of a very compact simple high-energy, high-power, SRF-based industrial 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 enabling mobile applications. At the expense of higher weight and cost, higher power versions of such an accelerator can employ 650 MHz elliptical cavities with twice the beam aperature and even smaller cryogenic losses.

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 injection locked magnetron control technology. Taken together these innovative technologies enable a new class of compact, simple, SRF based accelerators for industrial, scientific, non-destructive testing, and security applications. This paper reports the first steps towards realization of a new class of industrial SRF accelerators based on these principles.

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