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A Compact Superconducting RF Accelerator for Electron Beam and X-ray Irradiation

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Abstract

As commercial and industrial applications of electron beam and x-ray irradiation have developed, new applications have emerged that require very high beam power to create the required radiation field. These new applications require dependable, efficient, high-energy, high-power electron accelerators.

Recent developments in Superconducting Radio-Frequency (SRF) technology can now enable accelerators with lower costs and improved performance. Cryogenic heat loads are dramatically reduced through use of new materials and improved component designs. New cooling methods allow the replacement of complex systems requiring cryogenic fluids with simple robust systems with no fluids. New RF sources can greatly reduce the cost of RF power. Each of these developments has been individually proven and an effort is underway at the Illinois Accelerator Research Center at Fermilab to integrate them into the first prototype of an entirely new class of industrial SRF-based accelerators. These accelerators will enable robust, turn-key operation with very high electrical efficiency. The accelerator prototype under design will be capable of 10 MeV beam, CW operation, and 250 kW of electron beam power. These modular systems are small enough to be palletized and transported to the point of use. Their high electrical efficiency mean that portable power generation systems can be enable their use in mobile applications.

The goal is a compact, cost-effective, high-power accelerator suitable for many of the applications covered by this conference. Fermilab is actively working to build the prototype. The end-product will be a commercially available, robust, turn-key system for applications requiring reliable electron beam or X-ray irradiation.

Keywords: accelerator, applications, conduction-cooling, cryogen-free, industrial, super-conducting RF

Introduction

Industry has used accelerated beams of particles for many decades. Many of these applications have used beams of low energy (< 1 MeV) and moderate power (10s of kW) for applications such as cross-linking of polymers, electron-beam welding, and printing. Newer applications that require higher energy and higher power have emerged such as electron-beam flue-gas treatment, waste-water and sludge treatment, sterilization of medical devices and foods, and interrogation of enclosed objects for safeguards and security. However, the state-of-the-art of high-power, high-energy accelerators has not been adequate to reliably support these applications. [1] While improvements in normal-conducting accelerators continue to be made, fundamental constraints of physics limit their duty factors to a few percent at most. This places severe limitations on their efficiency.

We propose and are presently developing an accelerator using super-conducting RF (SRF) for greatly improved efficiency that allows continuous-wave (CW), or 100% duty factor, operation. Five recently demonstrated technological advances in SRF technology developed for DOE Office of High Energy Physics (OHEP) programs are combined to create an entirely new class of compact, high-power, CW electron accelerators for industrial applications. Leveraging R&D programs already supported by OHEP and the powerful accelerator design/test capability and extensive SRF infrastructure at Fermilab, our approach is to integrate these advances to create a transformational SRF-based accelerator that will allow the fulfilment of the needs of emerging accelerator applications. While the accelerator system described in this paper can deliver up to 250 kW of beam power, specific parameters described below refer to a 10 kW design.

Overview

Superconducting Radio Frequency (SRF) cavities are the most efficient accelerator technology capable of producing CW beams at the energies and intensities that are of interest for industrial applications. The underlying requirement for superconducting materials is to maintain the temperature of the accelerating structure below the critical temperature, which is the temperature where the material transitions from normal- to super-conducting. Until now, this has required liquid cryogens and a large amount of ancillary cryogenic equipment. The approach of the proposed accelerator is to keep heat production to a minimum and to efficiently remove heat using commercial 4K cryo-coolers.

The enabling advances used in the proposed accelerator are:

1. Nb_3Sn Coated SRF Cavities: A 1.3 GHz single cell niobium cavity coated with Nb_3Sn has been operated at Cornell University at gradients of 14 Megavolts/m with a quality factor (Q_0) of 2×10^{10} at 4^oK demonstrating the feasibility of such cavities. Q_0 is the ratio of the resonant RF energy stored in the cavity to the energy lost as heat in an RF cycle. From this work, it can reliably be predicted that a 650 MHz 4.5 single cell accelerator cavity operated at similar gradients will dissipate less than 2.5 W at 4^oK. The leader of the Cornell Nb_3Sn effort is now a member of the Fermilab team and recently received a DOE early career award of $ 2.5 M for continued Nb_3Sn cavity development at Fermilab.
2. Conduction Cooling and Cryo-coolers: Conduction cooling of SRF cavities is a Fermilab proprietary technology [2] that when combined with commercial cryocoolers enables operation without liquid cryogens. This novel and proprietary configuration [6] results in dramatic reductions in complexity, size, weight, and cost. Commercial 5W @4K cryo-

coolers (e.g. Sumitomo) are on the horizon, however existing 2 W@4K units (CryoMech) already exhibit sufficient reliability (>40,000 hrs MTBF) that a system using three such units can be built today that can reliably support a 4°K heat budget of ~6 W (Table 1).

3. Integrated Electron Gun: By integrating the electron gun directly onto the SRF accelerating cavity, the overall size and complexity of the accelerator is substantially reduced. Feasibility of this basic approach has already been demonstrated in a 1.5 cell design [3]. Our plan is to integrate such a gun into a larger 4.5 cell accelerating cavity to create an entire accelerator. Simulation indicates miniature commercial thermionic cathodes provide needed beam currents yet introduce very small (< 0.1 W) 4K heat loads. A 2nd harmonic RF system on the gun leads to very high beam transmission and low beam power losses to cold cavity surfaces. Computer simulation of the resultant beam energy, profiles, and particle losses were funded by an OHEP grant and demonstrate the feasibility of this approach. (Fig. 1) A key demonstration will be that the electron gun can operate in close proximity to a high Q_0 SRF cavity without degradation of the cavity internal surface.
4. Low Heat-Leak RF Power Couplers: Fermilab, working with Euclid TechLabs, has developed a proprietary [4] design for a very low heat-leak, fundamental RF power coupler that can deliver 10 kW average power to the SRF cavity with less than 0.7 W heat input at 4°K. Feasibility has been demonstrated by RF and thermal simulation. A DOE OHEP grant is funding fabrication of two 1.3 GHz prototypes that will be RF tested in 2017.
5. Low-Cost RF Power Source: Commercial inductive output tubes (IOTs) and solid-state based RF power sources are readily available at 650 MHz where extensive DOE OHEP funded development has already occurred for elliptical SRF cavities. These commercial RF sources are feasible for the proposed proof-of-concept (POC) accelerator. However, use of

magnetrons can reduce the cost/Watt of RF power by a factor of 5 while achieving efficiencies in excess of 80% leading to substantial cost, weight, and size reductions for mobile accelerator applications. Excellent RF phase and amplitude control with a single cell SRF cavity using proprietary [5] technology has been demonstrated at Fermilab based on a single injection-locked, 1-kW, 2.45-GHz magnetron.

These breakthrough technologies enable an overall approach to create a multi-cell SRF accelerator cavity with integrated electron gun and coated with Nb3Sn to achieve low losses at 4K [6]. This cavity will be conduction cooled by commercial 4 K cryo-coolers, integrated into in a low heat leak cryostat, powered via low loss RF couplers that are mated to a modern, efficient, and agile RF power source and control system.

Implementation

The proposed accelerator consists of a single 4 ½ cell 650 MHz elliptical SRF cavity fabricated from pure Niobium (Nb) and coated internally with Nb_3Sn superconductor. Use of high-frequency elliptical cavities permits a physically compact accelerator with a small footprint and low weight. Use of Nb_3Sn superconductor (T_c =18 K) allows very high Quality factors (Q_0) and thus low cryogenic losses when the cavity (resonator) is excited by CW Radio Frequency (RF) at an operating temperature of 4 K. The first ½ cell serves as the gun cavity, receiving and accelerating electrons emitted from a nearby commercial thermionic cathode. Use of higher order harmonic frequencies and bias voltage on the gun allows electron emission and acceleration over a limited phase angle (~4 degrees). Adjusting the gun RF amplitude and phase angle relative to the accelerating cavity RF allows rapid (~ 100 μs) changes of accelerator output beam power and energy. A fast FPGA-based Low Level RF (LLRF) system maintains constant accelerating gradient in the cavity as beam loading changes. These beam control techniques are well proven and are in current use in SRF science accelerators including those at Fermilab.

The resulting high-power, high-energy electron accelerator achieved by this technical approach will be lighter, more compact, more efficient and when produced in quantity, less costly than existing state-of-the-art commercial CW accelerators. Small size, light weight, and excellent energy efficiency will enable use in mobile platforms. The proposed prototype represents the first of a new class of simple, turn-key SRF accelerators that will find broad use in industry, medicine, security, and science leading to significant cost reductions for DNDO applications.

Cavities and Nb_3Sn coating: Fermilab has an extensive history of working with vendors to produce superconducting Nb cavities for large DOE, Office of Science projects. The 650 MHz elliptical cell shape is scaled from the well understood ILC shape and is similar to cavities already procured by Fermilab for its PIP-II project. A Nb_3Sn coating optimized for high quality factor (Q_0) at 4K will be applied to the inside of the cavity.

Following past 650 MHz development efforts, a 1-cell cavity of pure Niobium (Nb) will be fabricated by a vendor. It will be processed and tested bare in Fermilab's vertical test stand (VTS). After initial testing, it will be coated with Nb_3Sn. It will be tested again in the VTS to determine the Q_0 at 4K. In the VTS, the cavity is immersed in liquid helium. Following this, tests will be performed in a test dewar with the Nb_3Sn coated single cell conduction-cooled from a cryo-cooler. This test dewar will be acquired through Fermilab internal Lab-Directed R&D (LDRD) funding.

The same procedure will be followed for the 1.5 cell gun cavity followed by validation of the gun geometry with an electron source in a modified version of the LDRD test dewar that permits access for the electron source and extracted beam. Instrumentation built by Northern Illinois University (NIU) will be added to create an SRF gun test-stand to fully characterize beam from the gun. The same process will then be followed for the full 4.5 cell accelerator cavity. Additional modifications of the LDRD dewar will enable it to serve for the test of the 4.5 cell POC accelerator cavity including tests with beam.

Conduction Cooling: The elimination of cryogens depends on successful operation of SRF cavities with conduction-cooling. Conduction-cooling from a cryo-cooler has been successfully demonstrated for a superconducting magnet at Fermilab [7]. Conduction-cooling relies on the high thermal conductivity of high-purity aluminum to conduct the heat from the cavity to the cold-head of the cryo-cooler. Extension of these techniques from the magnet demonstration to SRF cavities is straight forward. Another Fermilab LDRD project is focused on optimizing these techniques by demonstrating: (a) low thermal contact resistance can be achieved between Nb and high purity Al, (b) optimizing the aluminum thermal bridge from cavity to the cryo-cooler head and c) RF operation of pure Nb cavities cooled by a commercial cryo-cooler with no liquid cryogens. Preliminary experiments are already providing encouraging results by achieving the required contact resistance (< 0.2 K/W) thus proving the method to be feasible. We anticipate further improvements in conduction cooling technology from the LDRD project.

Electron Gun and Beam Dynamics: The electron gun is directly integrated into the first half-cell of the 4.5 cell accelerator cavity. A summary of parameters, for the SRF-gun and the first cell layout including calculated the electric field distribution is shown in Fig. 1.

A preliminary feasibility study of the beam dynamics of the RF-gun – accelerator system has been done using SMASON [8] software. Gun geometry, 2nd harmonic of the RF voltage, DC bias and the operating RF phase interval has been evaluated to optimize the output beam parameters.

The beam current is changed by adjusting the gun RF voltage of the 2nd harmonic applied to the gap between the cathode and the cavity. To increase the current, the difference between the RF voltage and DC bias is increased. The energy of the beam is changed by adjusting the phase between the gun RF voltage and the accelerating cavity voltage. Because the loaded Q_0 of the RF gun is low for both harmonics, it is possible to alter both the beam current and energy in <100 μs.

Proper phase difference between the gun-cell and accelerating cavity results in an average energy of 10 MeV. For 1 mA beam current, the output-phase r.m.s. size of a bunch is less than 4°; energy spread is less than 4%; and the emittance is 7.5 mm*mrad. There are no observable power losses on cold cavity surfaces and the cathode receives less than 1W total power due to electron back bombardment. Fig. 2 shows results of SMASON simulations of the beam distribution at the exit of the accelerator. The color of the points in the left and middle plots represents the charge weight of the macroparticle (blue is minimum, red is maximum). Beam dynamics will be crosschecked and further optimized by using more sophisticated software (ASTRA[9], MICHELLE[10]).

<u>RF Power Coupler:</u> A new RF power coupler with very low heat losses was recently designed for Fermilab by Euclid Techlabs. Normally couplers include stainless steel parts plated with copper to satisfy the contradictory requirements of low thermal conductivity and high electrical conductivity. The copper plating often fails. The new coupler design does not include any parts coated with copper but instead it includes "floating" electromagnetic shields made of solid copper. The result is a coupler with dramatically lower thermal conductivity and improved reliability. The structure of the new 650 MHz coupler is presented at Fig. 3.

Low Heat Leak Cryostat: Following preliminary 4.5 cell cavity tests in the LDRD test cryostat, the accelerating cavity will be integrated into a low static-heat-leak dewar equipped with 6 W @ 4K of commercial cryo-coolers, a low loss RF coupler, 60 K thermal shields, and a magnetic shield that maintains the high Q_0 of the Nb_3Sn coated cavity. Table 1 contains a summary of the estimated 4K heat load for the entire accelerator.

RF Power: Some applications may require fast changes to the electron beam energy. This can be accomplished by changing the phase between the gun and the cavity RF. The accelerator cavity voltage remains constant (and therefore constant RF stored energy in the cavity) but the phase of the injected electrons from the electron gun relative to the phase of main RF accelerating cavity is adjusted. Large amounts of RF power are not needed to quickly change the stored energy in the accelerating cavity. (e.g. changing the beam energy in 100 microseconds by changing the cavity stored energy this would normally require an RF source with a peak power of ~500 kW). Instead, shifting the SRF gun phase compensates for the reactance introduced by the beam at low beam-energy caused by accelerating far off crest. (~10 kW). This provides an RF source capable of 20 kW peak power and 10 kW average power. Initially, the POC accelerator may use a commercially produced IOT or solid state 650 MHz RF power source. In our scheme, the RF power source will lock to the resonant frequency of the accelerating cavity to actively compensate for microphonic noise

Future cost savings can be realized by developing a 650 MHz CW injection-locked magnetron based RF source. The RF sources feeding superconducting cavities in CW accelerators require phase control to compensate the parasitic modulations (microphonics) inherent in superconducting cavity operation. This is especially important for low beam-loading, when the bandwidth is narrow. For this application, the bandwidth is about 30-40 Hz. However, because we use a single-cavity accelerator, we do not need to preserve the same phase of the bunches, and thus will be able to operate in closed-loop mode, where the frequency of the RF source will follow the frequency of the SRF cavity.

The cost of a unit of power for the traditional RF sources (klystrons, IOTs or solid-state amplifiers) is quite high, ~ $10-15 per Watt. In contrast, the cost of a unit of power of a commercial, L-band, CW, high-power magnetron RF source is ~$1 per Watt. Since the magnetron has a higher efficiency compared to traditional RF sources, magnetron transmitters are preferable for application to industrial superconducting accelerators.

The method of phase control in magnetrons is realized by a wideband phase modulation of the driving resonant (injection-locking) signal. Multiple methods have been suggested on how the power of the magnetron-based transmitter can be changed with rates required for powering SRF cavities. The most recently developed method provides a significantly higher average efficiency (more than 80%) via a single magnetron with a range of power control up to 10 dB and wideband phase control. The power control in this technique is realized by the variation of the magnetron current over an extended range, when the magnetron is driven by a sufficient (in magnitude) injection-locking signal, it may work at a voltage less than the threshold of self-excitation. The bandwidth of the power control in this technique is determined by the bandwidth of the current feedback loop in the magnetron-switching high-voltage (HV) power supply operating as a current source. Presently the bandwidth may be up to 10 kHz without compromising the efficiency of the power supply, which allows changing the output power in ~100 microseconds. In order to decrease the cost of the magnetron-based RF source, a cascade scheme is suggested as shown in Figure 4. In this scheme, the first, low-power magnetron provides phase modulation (control) of the signal frequency-locking the second, high-power magnetron. Power control in the required range (up to

10 dB) is realized by modulation (control) of the current in the high-power magnetron which at the low current operates at a voltage less than the critical voltage in free-run mode.

Control System: The major functions of the controls system are: a) to control the phase difference and amplitudes of the two RF harmonics and the RF ramp in the presence of beam loading, b) govern the thermionic cathode heater setting to control the output current, and c) incorporate feedback from the cryo-cooler system and other relevant variables for both monitoring and machine protection. The drive frequency of the cavity will track the cavity resonant frequency via a self-excited loop. The control execution will be primarily in firmware (e.g. FPGAs). The machine protection system will monitor the cryo-cooler (e.g. temperatures, pressures), beam current monitor(s), cathode temperature readings, and the RF field readings. A model of the relationship between the cathode field, cathode temperature, and the resultant beam current will be created using simulation and then refined with measurements Predictive modeling will allow testing the control system to identify unforeseen diagnostic requirements or problematic system design settings. Predictive control will be used for the RF ramp during the turn-on process, power and current variations.

Summary

The result of integrating all these components into a complete system is shown in figures 5 and 6. The accelerator itself is approximately 0.7 m in diameter and 1.5 meters long (Fig. 5). When the ancillary systems, power supplies, external cryo-cooler components, etc. are included the system will have a volume of approximately 2m x 2m x 5m (Fig. 6). In addition to minimizing site costs at a permanent installation, this form factor opens the possibility of mobile applications. This will allow moving the accelerator from application site to application site such as in-situ environmental remediation or upgrading of hydrocarbons at the well-head. The compact size also allows truly mobile uses such as cross-linking of pavements after they have been laid [11][12]. The relative simplicity of the system will enable accelerated beams to fulfil their promise in high-energy, high-power applications such as various environmental remediations. Finally, new applications in radiation-driven or radiolytic chemistry may be achievable that have not yet been envisioned.

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Figure 1: Accelerator parameters (left), RF-gun layout (upper-right), and electric field distribution of the 4.5 cell (lower-right).

	Value
Electron energy	9 MeV±5%
Current modulation range	0.1 μA - 1 mA
Beam loss at 4K	<0.5 W
Cathode backward bombardment	<1 W
Cathode blackbody radiation	< 200 mW

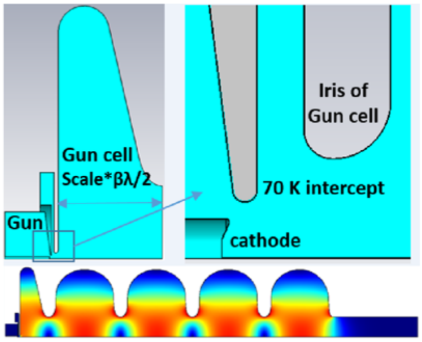

Figure 2: angular distribution (left), longitudinal beam profile (middle), radial charge distribution (right)

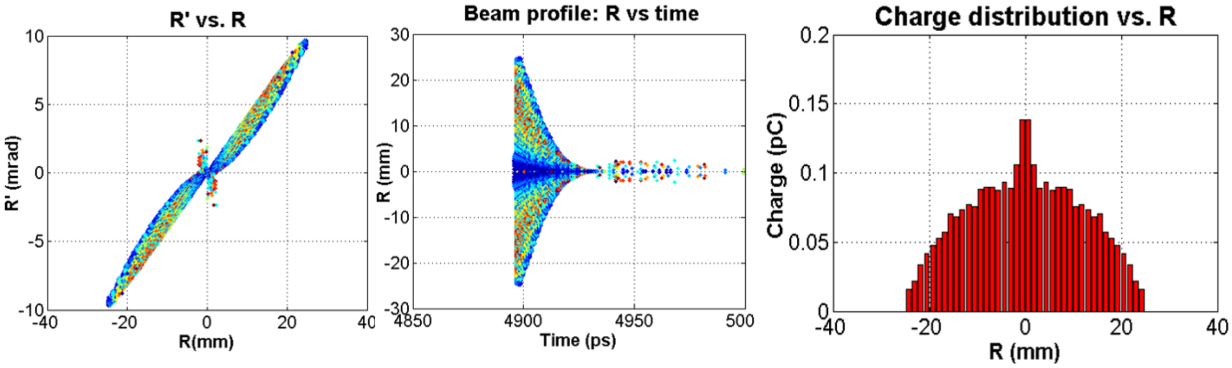

Figure 3: Structure of 650 MHz low loss coupler.

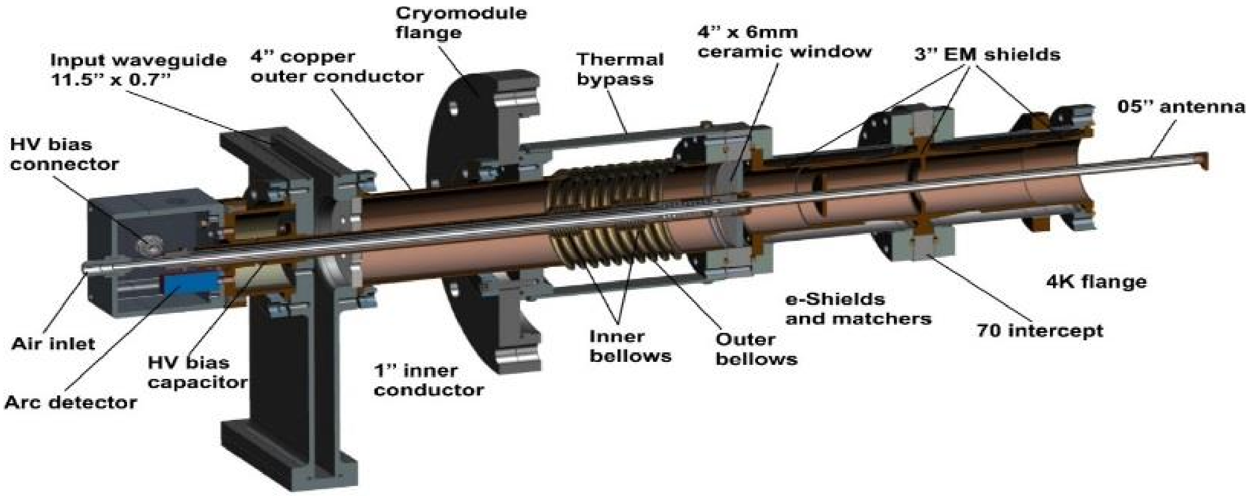

Figure 4. Conceptual scheme of a single 2-cascade magnetron transmitter allowing dynamic phase and power control.

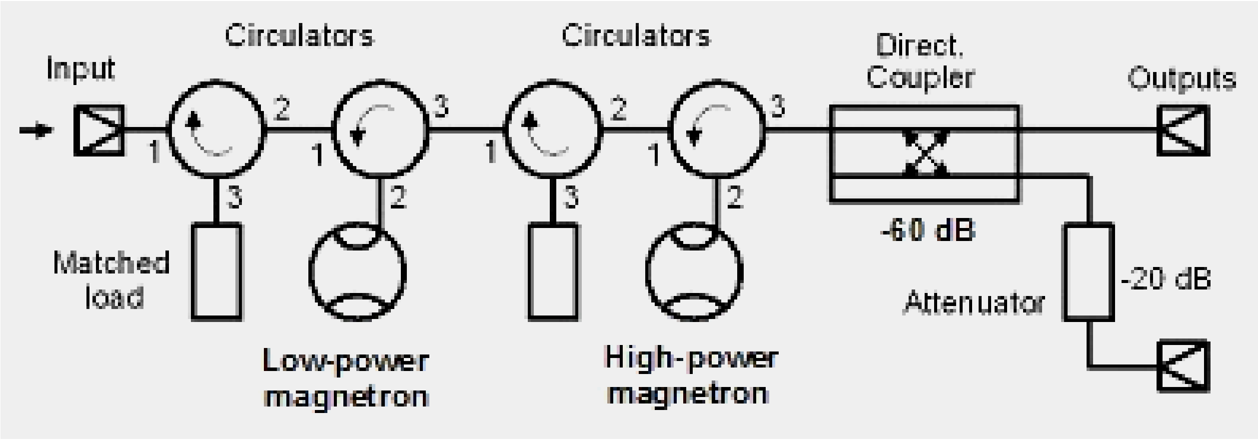

Figure 5 Internal view of Compact SRF Accelerator.

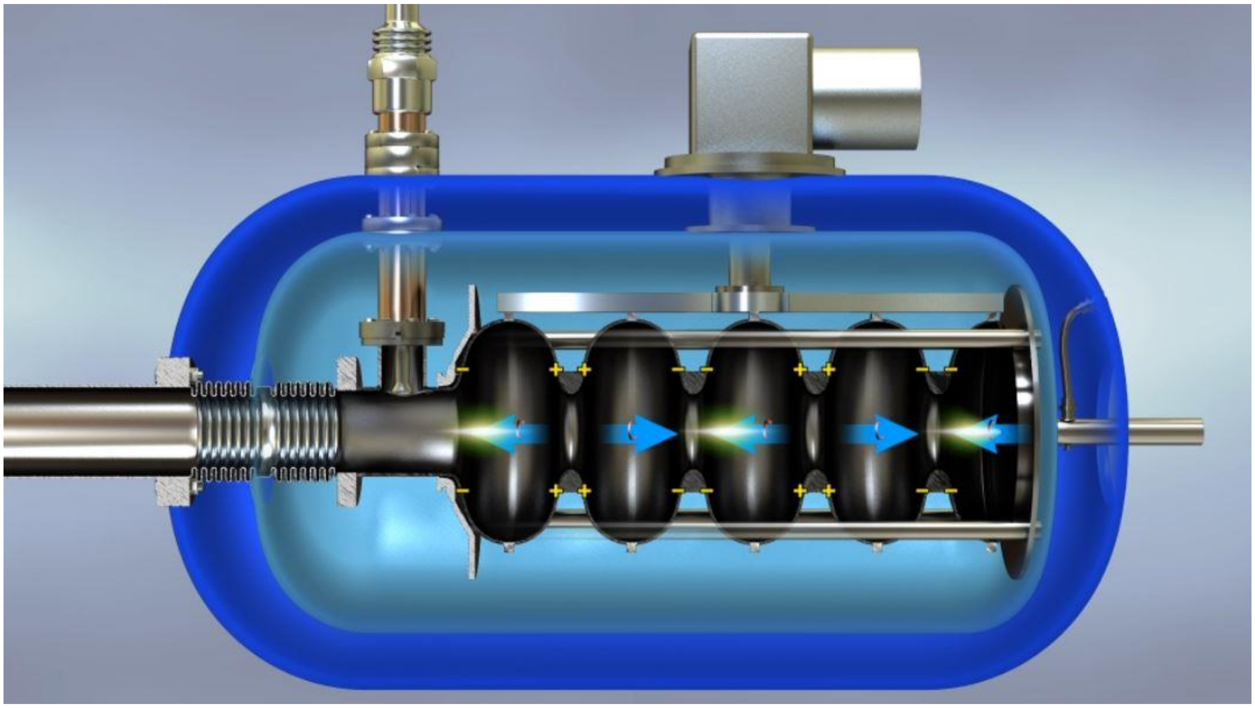

Figure 6 The complete Compact SRF Accelerator system.

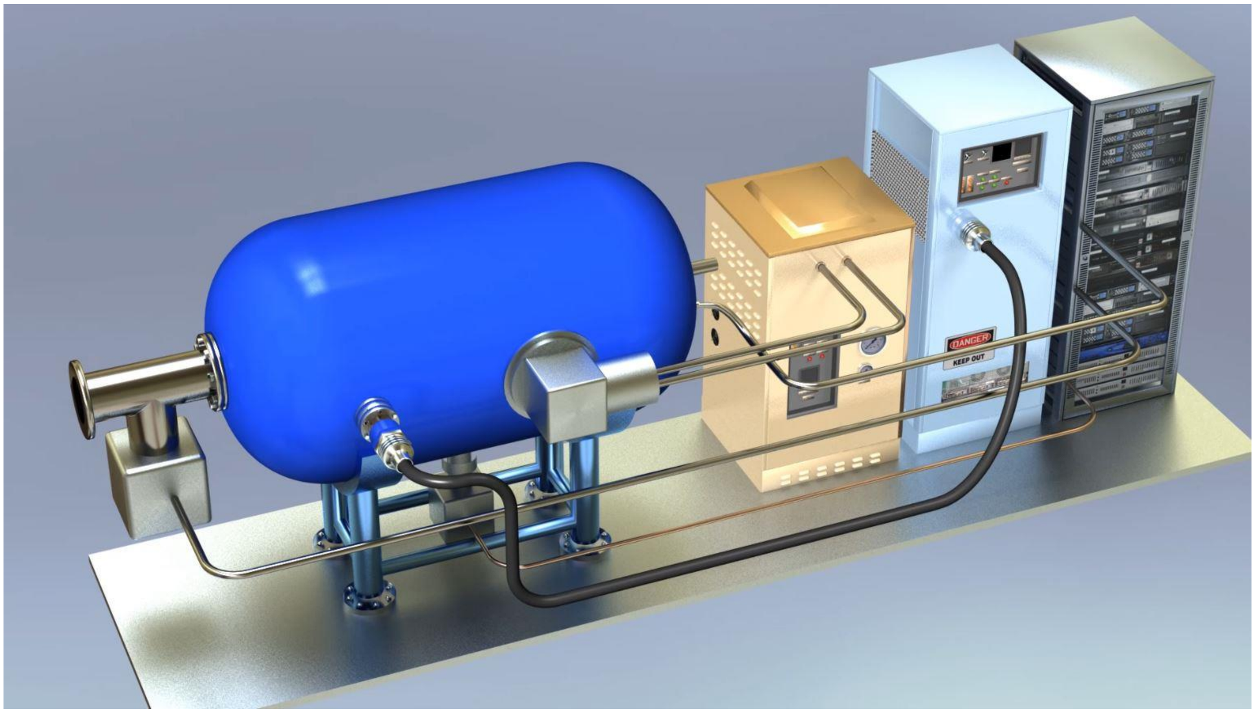

Table 1. Heat budget at 4k for 4.5 cell 650 MHz cavity.

Source of losses at 4K	Value
Losses in cavity walls (BCS)	2.5 W
Losses in coupler	0.7 W
Beam losses	0 W
Cathode blackbody radiation	0.2 W
External radiation & through support structure	0.5 W
Total	3.9 W
Reserve (6W capacity)	2.1 W