Final technical report

1. Introduction

Due to its very high RF-to-beam efficiency, superconducting radiofrequency (SRF) cavities have become the technology of choice for the construction of large linear accelerators (linacs) for basic science applications (examples, ESS [1] and PIP-II [2]]. The technology is also attractive for high-volume industrial applications such as electron irradiation processing of wastewater and flue gas. However, SRF's current reliance on liquid helium for cryogenic cooling introduces infrastructural and safety challenges [3-5] for use in industrial settings. Cryocooler conduction-cooling is a recently developed novel technique [6-12] for operating SRF cavities without requiring liquid helium. This project aims for technical design and economic assessment of a medium energy, high average power e-beam linac based on the conduction-cooled SRF technique for high volume irradiation treatment of wastewater.

The goals of this project are (1) to design a medium energy (10 MeV), high average power (1 MW) electron beam accelerator around the cryocooler conduction-cooled SRF cavity technology, (2) demonstrate the required accelerating voltage on a prototype cavity, and (3) build a cost-model to evaluate capital and operating expense of the accelerator.

2. Research activities and key results

(a) Accelerator design

For the design activity, the accelerator was divided into three sections: pre-accelerator, main accelerator, and beam delivery system. Figure 1 shows the accelerator layout. The pre-accelerator and beam delivery system designs were largely taken from the authors' previous work reported in [13] and so will only be briefly described here. The pre-accelerator uses a gridded thermionic cathode to generate low very electrons of 100 mA average current, which are subsequently accelerated to 300 keV using a room temperature injector cavity. A room temperature solenoid then focuses the 300 keV, 100 mA electron to match transverse acceptance of the main accelerator

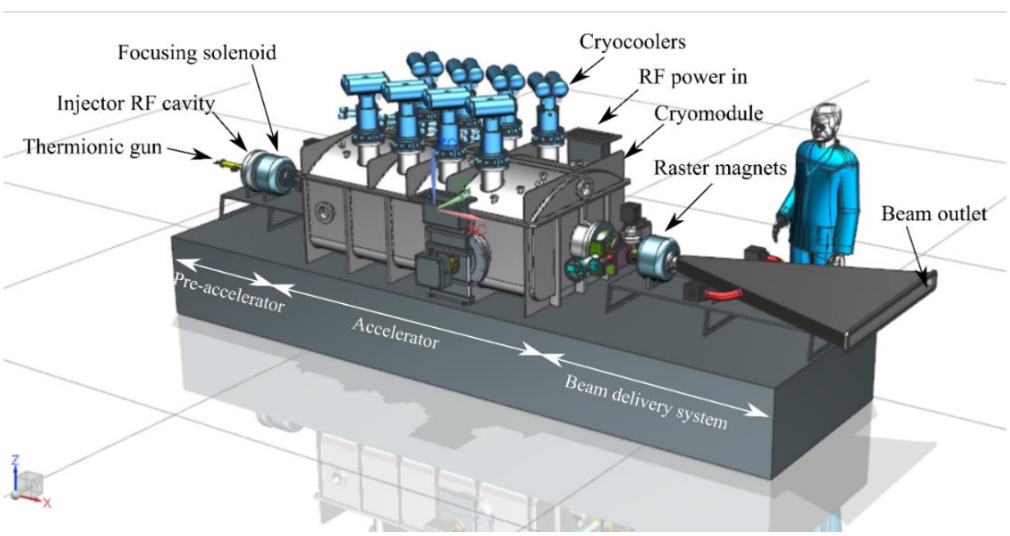

Figure 1: SRF e-beam accelerator components and layout.

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cavity. The main accelerator section accelerates the electrons to their final energy of 10 MeV and outlets them into the beam delivery section. This section has a set of raster magnets and a beam horn to shape the beam for irradiating wastewater.

The main accelerator section comprises an elliptical 5-cell Nb_3Sn SRF cavity conduction cooled using a 4 K stages of a bank of cryocoolers. The conduction link between the cryocoolers and the cavity is made of high purity (>99.999%) aluminum. The cavity is enclosed in a superinsulation-wrapped aluminum thermal shield (alloy Al1100) to reduce thermal radiation heat load on the cavity. The thermal shield is conduction-cooled to the 50 K stages of the cryocoolers. The cavity and thermal shield assemblies is enclosed in a mu-metal magnetic shield that provides low magnetic field background to the SRF cavity. Finally, a vacuum vessel is provided to around the magnetic shield to cut down convection heat transfer from the ambient to the cavity. Two fundamental power couplers pierce the vacuum vessel through two ports at 180 degrees to each other, to feed RF power into the SRF cavity. Figure 2 depicts the 5-cell cavity with thermal conduction links and a cross section of the main accelerator section (hereafter called as *cryomodule*).

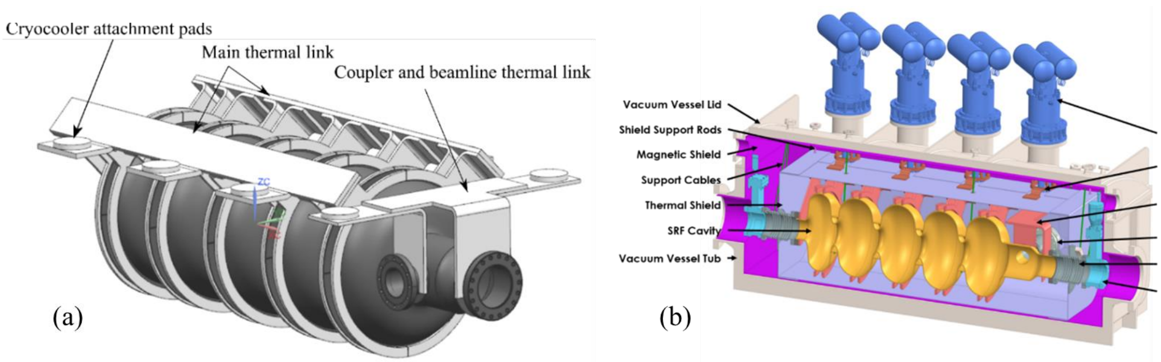
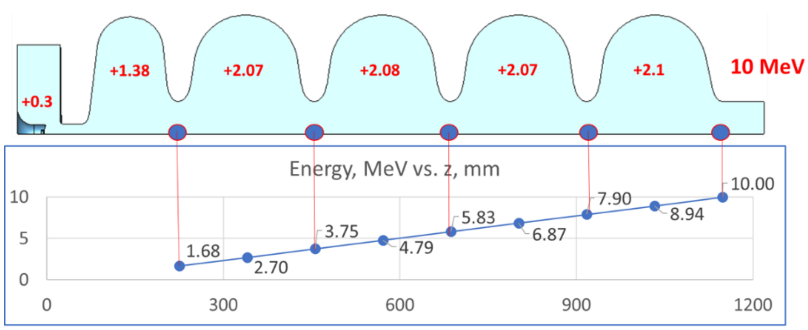


Figure 2: 3D rendering of (a) SRF cavity with conduction links and (b) SRF cryomodule.

The design of individual cryomodule components is done *via* simulations. RF simulations using CST Microwave Studio determined the cavity cell shape that optimizes peak field ratios and field flatness while generating a total voltage gain of 10 MV. Beam transport simulations were performed using MICHELLE to obtain cell-by-cell energy gain of the 100 mA electron beam as it travels through the 5-cell cavity. Figure 3 shows that the 5-cell cavity produces uniform cell-by-



Frequency	650	MHz
Energy	10	MeV
Current	100	mA
phase shift gun-injector	90	o
phase shift injector-cavity	-15	o
σ Energy	2.4	%
Beam phase duration rms	7.5	o
Losses on the cavity walls	0	W

Figure 3: Energy gain profile and beam properties during beam transport simulation through the 5-cell SRF cavity.

cell energy gain with 10 MeV as the final output beam energy. The calculated beam parameters are also given in Figure 3. Higher Order Modes (HOMs) calculation indicated that both monopole and dipole modes are non-detrimental to beam transport through the cavity. Further results on this topic are presented in [14].

Figure 4 presents results of COMSOL Multiphysics simulation of (a) thermal performance of the cavity, thermal link, and cryocooler during steady beam transport at full average current of 100 mA, (b) thermal performance of the thermal shield, (c) shielding performance of the magnetic shield, and (d) stability of the vacuum vessel under external loading of 1 atm pressure. The results

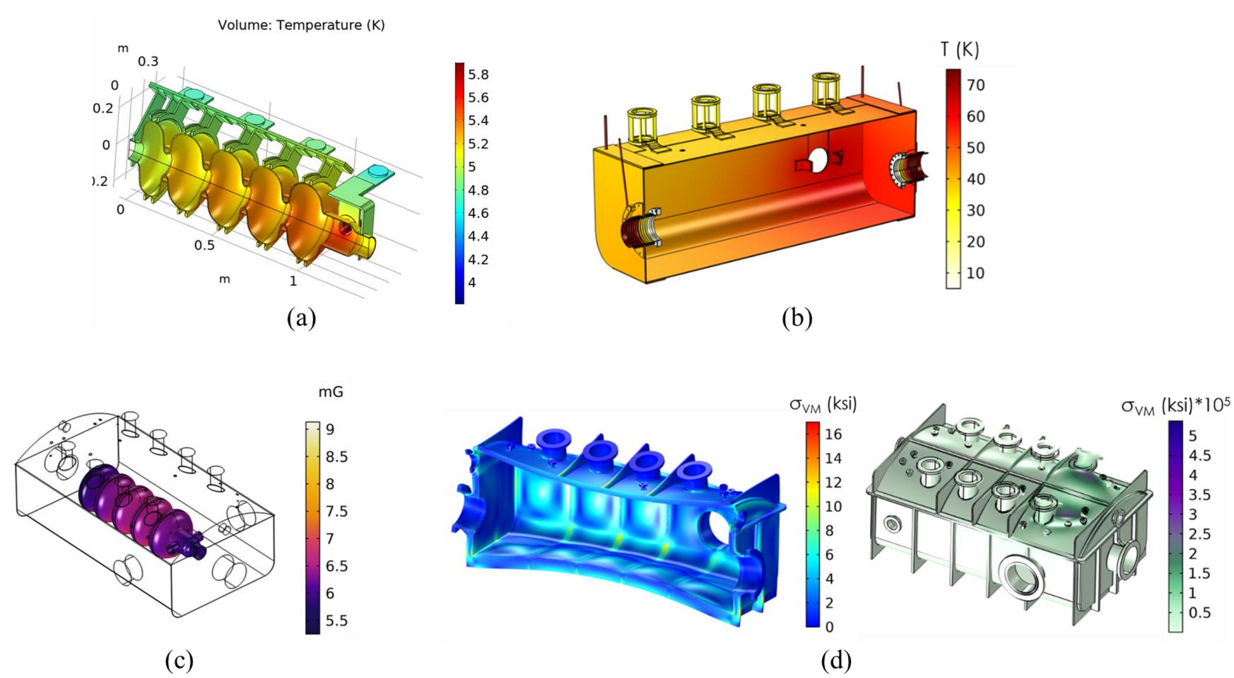


Figure 4: FEM results for (a) SRF cavity (b) thermal shield (c) magnetic shield and (d) vacuum vessel (left - elastic/plastic stability and right - buckling stability).

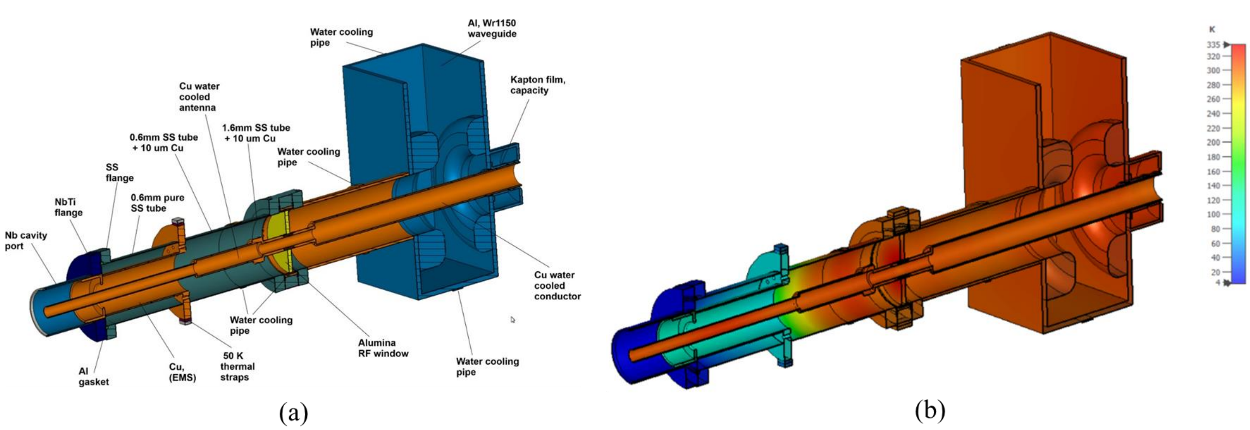


Figure 5: Fundamental power coupler (a) main components and (b) thermal profile at 500 kW cw operation.

indicate that (a) the cavity operates stably around 5 K, (b) the thermal shield holds steady between 50-60 K, (c) the magnetic shield is sufficient to generate <10 mG total background field at the location of the cavity, and (d) the vacuum vessel is structurally stable to prevent elastic/plastic collapse as well as buckling under 1 atm external pressure. All these findings confirm that the individual cryomodule components function as expected. The present accelerator design uses a PIP-II HB650 type fundamental power coupler [15] for feeding RF power to the SRF cavity. Figure 5 shows cross sectional view of this power coupler along with its thermal profile while transporting 500 kW cw power at 650 MHz. Due to the novel multi-electromagnetic shield design of the coupler, the coupler is expected to leak <1 W of heat to the SRF cavity at ~4 K. Reference [13] gives more details of each component's simulation model, including structural and thermal simulations of the fundamental power coupler.

(b) Experimental demonstration of full voltage gain on a prototype SRF cavity

For this goal, we demonstrated ~10 MV/m cw gradient on an elliptical single-cell 650 MHz β~1 Nb_3Sn cavity conductively coupled to a 2 W @ 4.2 K Cryomech Pulse Tube cryocooler [15]. The equivalent voltage gain over this 0.23 m long cavity is 2.3 MV. The 10 MV/m cw gradient when generated on the 5-cell cavity designed in this work will be equivalent to >10 MV voltage gain.

The single-cell 650 MHz cavity preparation for conduction cooling, design of thermal conduction link, the design and construction of a test setup, and the first demonstration of cw gradients on this cavity have all been described in our prior publications [6-10]. Our prior experiments produced ~6.5 MV/m cw gradient on the single-cell cavity, limited by the magnetic hygiene of our test setup and the intrinsic quality of the Nb_3Sn coating. In the phase of this project, we significantly improved the magnetic hygiene of our setup, developed a new improved Nb_3Sn coating recipe, and installed the capability of controlling the cooldown rate of the cavity across the Nb_3Sn superconducting transition temperature. The latter helps to reduce thermocurrent induced flex trapping in the Nb_3Sn layer and preserves the cavity quality factor, Q_0. All these efforts led to the generation of 10 MV/m on the single cell cavity, whose results are summarized in Figure 6.

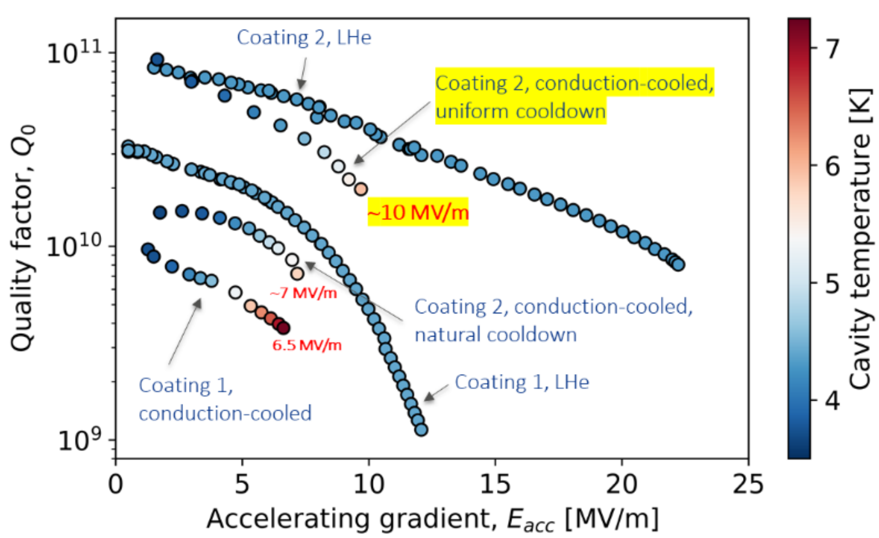


Figure 6: Summary of Q_0 - E_{acc} measurements on the single-cell 650 MHz Nb_3Sn cavity.

In Figure 6, 'Coating 1' represents the prior Nb_3Sn coating while 'Coating 2' is the new coating developed under this project phase. The improved Coating-2 with a controlled cooldown rate of the cavity led to the generation of 10 MV/m cw gradient on the cavity. Further details of cavity development, experimental work, data analysis, and results are covered in [17].

(c) Cost estimate of the 10 MeV, 1 MW SRF e-beam linac

The final task of this project is to develop a cost model for the construction and operation of the SRF e-beam accelerator. In this project, we principally focused on costing the SRF cryomodule. The cost estimates for pre-accelerator, beam delivery system, and infrastructure that houses the accelerator are derived from the cost model built by Ciovati *et al.* [18].

Table 1 lists the estimated capital cost of the e-beam accelerator, separated into the sections of pre-accelerator, cryomodule, RF power supply, and beam delivery and controls. The item-wise cost of cryomodule components is based on their 3D models developed in this work. The cost estimates are obtained via direct consultation vendors and manufacturers of these items. The material and fabrication cost of the cryomodule is ~$1.56M (or $1.5/watt of e-beam) and that of the complete SRF accelerator is ~$5.1M.

Table 1: Estimated capital cost of the 10 MeV, 1 MW e-beam accelerator.

Total	**5,134**
1 MW RF Power Source [18]	**3,200**
Cryomodule	**1,554**
Cryocoolers w/ He Compressors	492
650MHz Nb_3Sn Cavity	402
RF Couplers	282
Vacuum Vessel	100
Beamline (Bellows, Valves)	104
Auxiliary Hardware (Chillers, Pumps)	93
Magnetic Shield	65
Thermal Shield	16
Pre-accelerator [18]	**217**
Beam Delivery System [18]	**125**
Beam Diagnostics & Controls [18]	**38**

The estimated capital cost of the e-beam accelerator facility including radiation shielding infrastructure is presented in Table 2. The infrastructure cost is determined by scaling up Ciovati *et al.*'s [18] estimate of radiation shielding requirement for 1 MeV to the 10 MeV beam energy used in the present work. Overall, the total capital expenditure for the e-beam irradiation facility is estimated to be ~$8.1M (or ~$8.1/watt of e-beam). Table 2 also gives the operating cost of the e-beam SRF accelerator. Using unit electricity cost of 7 ¢/kWhr and annual maintenance cost of $163k, the total operating cost is estimated to be ~$278/hr. This is equivalent of 13.5 ¢/ton/kGy in material processing cost. For wastewater treatment where dosage of 1-to-4 kGy may be required, the present system could offer a processing capacity of 3-to-12 MGD for a cost of \$500-to-\$2,000 per mega-gallon of water.

Further details of the costing model are presented in reference [14].

Table 2: Estimated capital and operating cost of the e-beam water treatment facility.

Capital Investment	
SRF Accelerator	\$5.13M
Infrastructure	\$3.00M
Investment (20%)	\$1.63M
Amortization (15 yrs @ 8%)	\$760k
Operating Cost	
Power (\$/W)	\$162 /hr
Maintenance	\$163k /yr
Total operating cost	**\$278 /hr**
Processing Cost (¢/ton/kGy)	**13.5**

3. Summary

In this project, we developed detailed beam dynamics, RF, thermal, and engineering design of a 10 MeV, 1 MW average power e-beam accelerator driven by a room temperature pre-accelerator and a conduction-cooled SRF accelerator cryomodule. The technical design is supplemented by a detailed analysis of capital/construction and operation cost of the e-beam accelerator. The analysis determined that the capital cost is around \$8/watt of beam power while ~13.5 ¢/ton/kGy is required for irradiation processing. While one accelerator unit can treat up to 12 MGD of wastewater, the installation can be easily scaled up for higher volumes by deploying multiple accelerator units.

Acknowledgment

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