DEVELOPMENT AND FABRICATION OF A CW COPPER INJECTOR FOR SRF INDUSTRIAL CRYOMODULES

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Abstract

Compact SRF industrial linacs enabled by conduction cooling provide high-power (>100 kW) electron beams within a compact footprint. However, the limited cryogenic cooling capacity imposes strict requirements on beam quality, particularly near-zero beam loss in the SRF cavity. We report on the development and fabrication of a CW normal-conducting RF injector consisting of a gridded RF gun integrated with a multi-cell copper booster cavity. Compared to previous designs, beam dynamics optimization has reduced injector beam losses from several percent to ~0.1% while maintaining full transmission through the SRF cryomodule. The design incorporates RF, thermal, multipacting, and engineering optimizations. A full injector structure has been fabricated, and initial bench RF measurements of the pre-brazed assembly are presented. These results demonstrate readiness toward integration with conduction-cooled Nb_3Sn SRF cryomodules.

INTRODUCTION

Compact SRF linacs have emerged as a promising solution for industrial applications such as irradiation, sterilization, and environmental processing, where beam energies around 10 MeV and power levels up to hundreds of kW are required. Conduction-cooled Nb_3Sn SRF technology enables standalone systems without liquid helium infrastructure, significantly reducing system complexity and footprint. However, the limited cryocooling capacity and vulnerability of Nb_3Sn layer impose stringent constraints on beam losses, requiring essentially zero beam interception on SRF cavity walls.

To meet these requirements, an external injector capable of producing well-bunched, low-loss beam is essential. In earlier work [1], a CW normal-conducting injector based on a gridded RF gun integrated with a multi-cell copper booster cavity was proposed and demonstrated in simulation. While initial designs achieved acceptable performance, injector losses remained at a few percent level, which is incompatible with long term SRF cryomodule operation.

This paper reports significant progress in injector optimization, engineering design, fabrication, and initial RF characterization. Beam dynamics improvements have reduced injector losses to near-zero levels, and a full injector structure has been fabricated and bench-tested, waiting for the final brazing.

INJECTOR RF OPTIMIZATION

The injector consists of six independently powered RF cells operating at 1.3 GHz, with the first cell integrated with a gridded RF gun. Independent solid-state amplifiers (SSA) provide flexibility in phase and amplitude control for each cell, enabling optimization of beam dynamics and RF efficiency.

Each cell was optimized to balance accelerating gradient, shunt impedance, and thermal load under CW operation. Compared to earlier designs, the updated geometry increases shunt impedance while maintaining acceptable surface fields and power dissipation (Fig. 1). Typical RF parameters include ~800 W total power per cell, with ~500–700 W wall losses and the remainder beam loading, as shown previously.

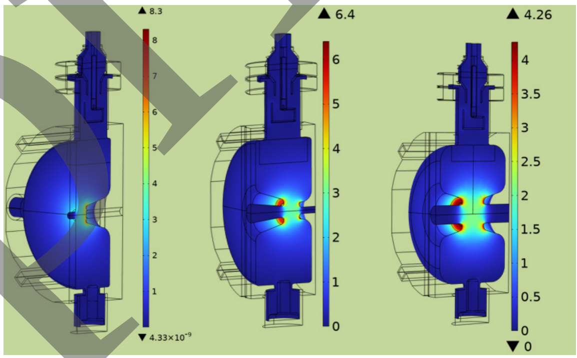

Figure 1: E-field of linac: (from left to right) Cell 0, Cell 2 and Cell2-5. Cells were optimized to provide uniform power dissipation along the injector to maximize the voltage gain and to provide optimum beam dynamics.

Table 1: Main RF Parameters of The Cavity Cells.

Parameter	C0	C1	C2-5
Gap, mm	13.5	16.2	25
V, kV	43.6	53	57
R/Q, ohm	193	254	318
Q	13850	15600	17000
Wall Losses, W	715	694	684
Beamloading, W	87	106	114
Total power, W	800	800	800
Emax_axis, MV/m	4.5	3.0	2.0

Each cell has its own tuning plunger and RF pickup. Multipacting was carefully evaluated and mitigated through geometry optimization of RF couplers and tuning plungers. As shown in the previous study [1],

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modifications to coupler loop diameter and plunger geometry effectively eliminate multipacting barriers at operating gradients.

Thermal simulations confirm that the CW operation is feasible with water cooling. The optimized cooling scheme uses multiple channels around the cavity outer diameter, maintaining acceptable temperature rise and frequency shift. Updated cooling analysis (Fig. 2) demonstrates that practical chiller systems can support required heat removal with moderate flow rates and pressure drop.

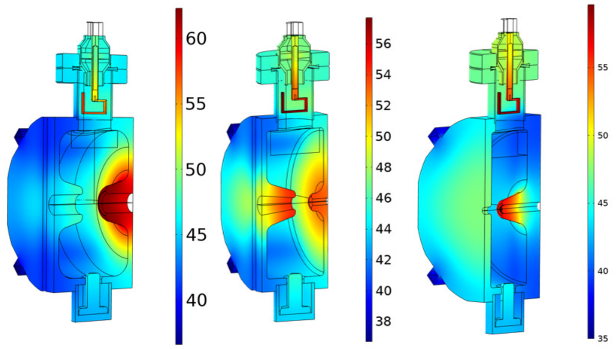

Figure 2: Temperature distribution of linac: (from right to left) Cell 0, Cell 1 and Cell2-5, assuming 35C of the cooling water temperature. Partial water flow parameters: 8 channels 0.4m long each, at 1.9m/s will require 7.12gpm providing 11,000 W/m2/K convection coefficient. Pressure drop ~4psi, water T rise 2.5C.

BEAM DYNAMICS OPTIMIZATION

Beam dynamics has been significantly improved compared to earlier work [2]. Previous injector configurations exhibited losses at the level of a few percent due to incomplete bunching and phase mismatch. Through optimization of RF phases, particularly in the first two cells following the gun, the injector performance has been substantially enhanced. Recent simulation results show that injector losses have been reduced to approximately 0.1%, while maintaining full transmission through the SRF cryomodule. The injector output energy has been increased to approximately 311 keV, providing improved matching into the SRF cavity. Downstream acceleration yields ~9.8–10 MeV beam energy with essentially 0% beam loss in the cryomodule. The key improvement comes from phase tuning of early cells, which enhances bunching efficiency and reduces longitudinal tails. Table 2 shows the phase for each cell that achieves the best performance in terms of least beam loss and sufficient energy gain. Table 3 shows performance with different phase settings. This demonstrates that independent RF control of cells is critical for achieving the stringent beam quality required for conduction-cooled SRF systems.

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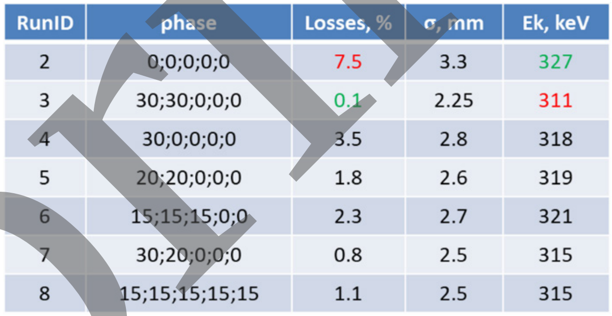
Table 2: The Parameter Set for 311keV Beam Production.

Cell #	Phase, deg	Ploss, W	Wkin_out,keV	ΔW kin, keV	Ez-max, MV/m
0	20	715	43.6	43.6	4.5
1	220.6	698	100.7	57.0	3.0
2	296.8	690	155.7	56.3	2.08
3	89.2	688	212.0	56.3	2.08
4	261.7	685	269.0	57.0	2.08
5	85.2	685	326.6	57.6	2.08

Table 3: Performance Dependence on Combination of Different Operating Phase for Cell 1-5 in Respect to Cell-0



RunID	phase	Losses, %	σ, mm	Ek, keV
2	0;0;0;0;0	7.5	3.3	327
3	30;30;0;0;0	0.1	2.25	311
4	30;0;0;0;0	3.5	2.8	318
5	20;20;0;0;0	1.8	2.6	319
6	15;15;15;0;0	2.3	2.7	321
7	30;20;0;0;0	0.8	2.5	315
8	15;15;15;15;15	1.1	2.5	315

ENGINEERING DESIGN AND FABRICATION

The injector mechanical design incorporates all necessary subsystems for CW operation, including RF couplers, pick-up probes, tuning plungers, vacuum ports, and integrated cooling channels. Each cell is individually powered and controlled, providing flexibility and redundancy.

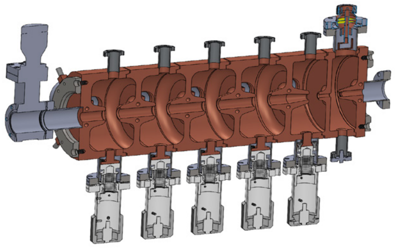


Figure 3: A cut-away view of the injector. Note, due to the narrow cell length, the RF coupler for Cell-0 is 90-degree rotated from the rest of cells.

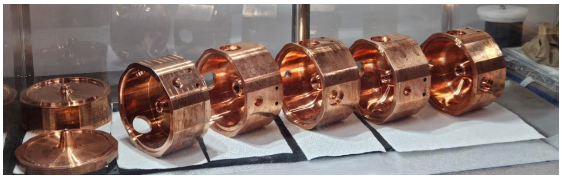


Figure 4: Fabricated cells.

A complete copper injector structure has been fabricated by Euclid Techlabs. The fabrication process includes precision machining of individual cells followed by assembly prior to brazing. The design emphasizes manufacturability and thermal robustness under CW operation.

BENCH RF MEASUREMENTS (PRE-BRAZING)

Initial RF bench measurements have been performed on the fabricated injector prior to brazing. These measurements provide early validation of the electromagnetic design and fabrication accuracy (100 kHz range). The measured resonant frequencies of individual cells are consistent with simulation within expected tolerances, confirming the validity of the machining process.

Field profiles and coupling behavior are also consistent with design expectations, demonstrating proper alignment of RF features. These results confirm that the structure is ready for final assembly and brazing, with no major design deviations observed. Figures 5-7 show the beadpull results of each cell. Excellent agreement is achieved.

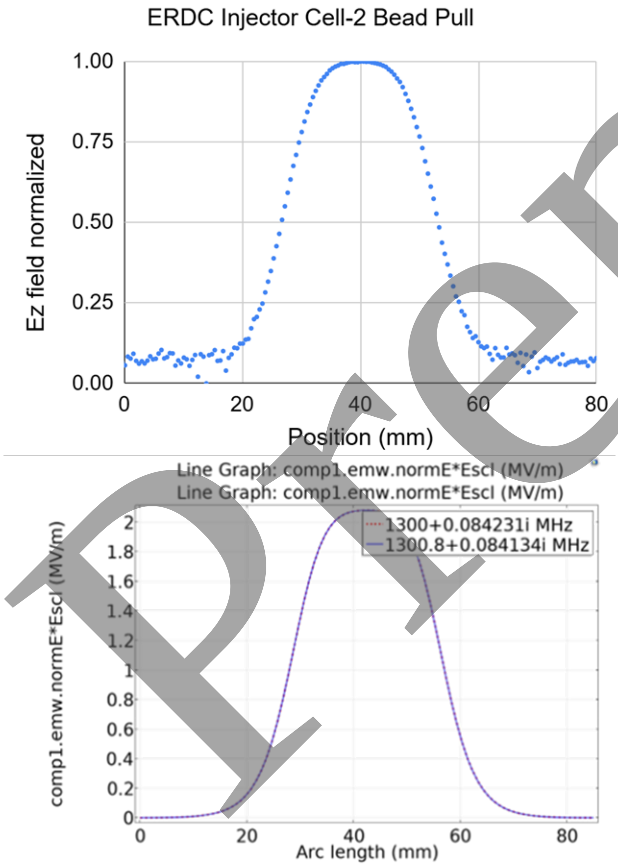


Figure 5: Beadpull result (top) of the Cell2 as an example of Cell2-5, and its comparison with the simulation (bottom).

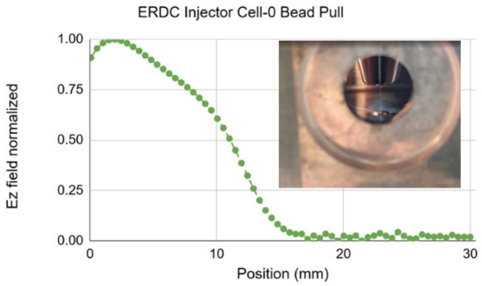


Figure 6: Beadpull result (top) of the Cell-0. Note, there is no cathode so that the field profile is slightly different from the real case.

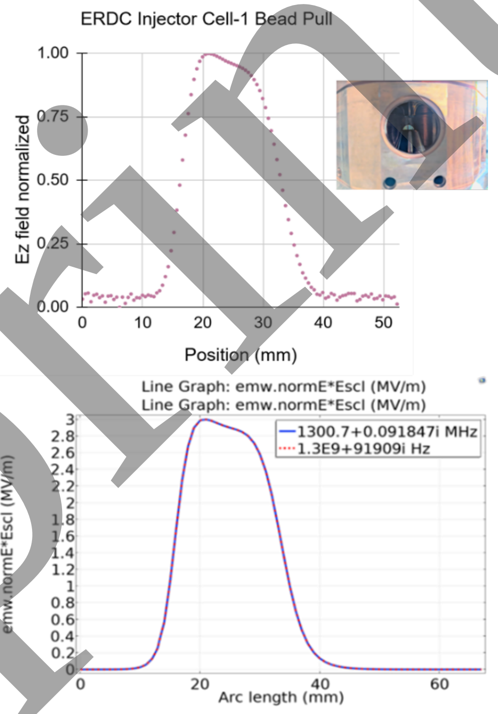


Figure 7: Beadpull result (top) of the Cell-1 and its comparison with the simulation (bottom).

ACKNOWLEDGEMENT

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