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DISTRIBUTED COUPLING LINAC FOR EFFICIENT ACCELERATION OF HIGH CHARGE ELECTRON BUNCHES

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Abstract

Future colliders will require injector linacs to accelerate large electron bunches over a wide range of energies. For example the Electron Ion Collider requires a pre-injector linac from 4 MeV up to 400 MeV over 35 m. Currently this linac is being designed with 3 m long travelling wave structures, which provide a gradient of 16 MV/m. We propose the use of a 1 m distributed coupling design as a potential alternative and future upgrade path to this design. Distributed coupling allows power to be fed into each cavity directly via a waveguide manifold, avoiding on-axis coupling. A distributed coupling structure at S-band was designed to optimize for shunt impedance and large aperture size. This design provides greater efficiency, thereby lowering the number of klystrons required to power the full linac. In addition, particle tracking analysis shows that this linac maintains lower emittance as bunch charge increases to 14 nC and wake-fields become more prevalent. We present the design of this distributed coupling structure, as well as preliminary data from cold tests on the structure's real world performance.

INTRODUCTION

Future colliders, such as the Electron Ion Collider (EIC) will require injector linacs to accelerate large electron bunches over a wide range of energies [1]. Current designs are typically based around long travelling wave structures, where power is coupled on axis between cavities. We propose the use of a distributed coupling design as an efficient means of achieving high gradient acceleration. Distributed coupling uses unique waveguide and coupler design to power each cavity individually [2]. This in turn allows the cavity geometry to be optimized for shunt impedance, resulting in more efficient structures generating an equivalent gradient. Using the known parameters and specifications of the travelling wave design planned for EIC, we present here a potential alternative that leverages distributed coupling for better efficiency and higher bunch charge handling.

LINAC DESIGN

The re-entrant style cavity has become quite common amongst standing wave structures, featuring a nose cone to improve field enhancement while preventing surface magnetic fields from getting too large. As seen in Fig. 1, these designs exhibit the highest shunt impedance and efficiency with smaller beam apertures [2]. However in order to effectively handle large bunch charges, a large beam aperture would be needed. Based on this chart S-band (2.856 GHz) structures represent the best balance between efficiency and beam aperture, and so an aperture radius of 14.12 mm in diameter was chosen, which corresponds to a ratio of $a/\lambda = 0.135$.

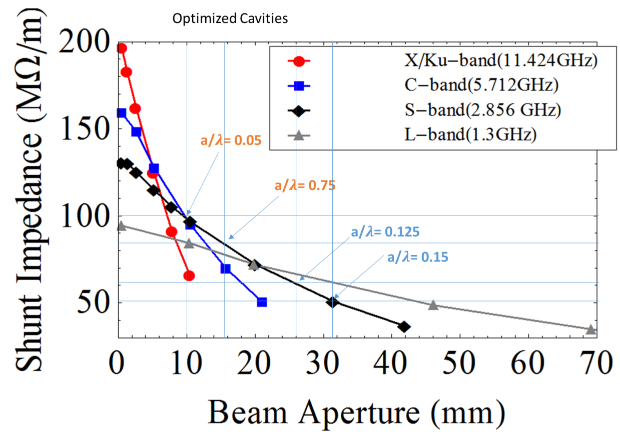

Figure 1: Plot of shunt impedance versus beam aperture for re-entrant cavities designed at various frequencies. When looking for a good balance between the two value, S-band cavities with a/λ ratios around 0.125. Reproduced from [2].

Implementing a distributed coupling manifold onto this choice of cavity results in a structure as shown in Fig. 2. The manifold incorporates a Y-coupler to split the power evenly between two halves. The lengths of the couplers to each cavity are design to provide π relative phase shift between cavities, to ensure the maximal power is coupled to the π mode. In order to reach the target gradient of 16 MV/m, this linac requires 4 MW of power. The relevant properties of interest for this mode of operation are summarized in Table 1. Further study in simulation revealed that cooling the structure down to liquid nitrogen temperatures (≅80K), would greatly improve performance within the same footprint [3].

Table 1: Distributed Coupling Linac Properties with 5 MW of Power.

Field Ratios	–	
E_{max}/E_{acc}	2.63	
E_{acc}/Z_0H_{max}	0.995	
Operation Temperature	300K	80K
Shunt Impedance	60 MΩ/m	210 MΩ/m
Acceleration Gradient	16 MV/m	30 MV/m

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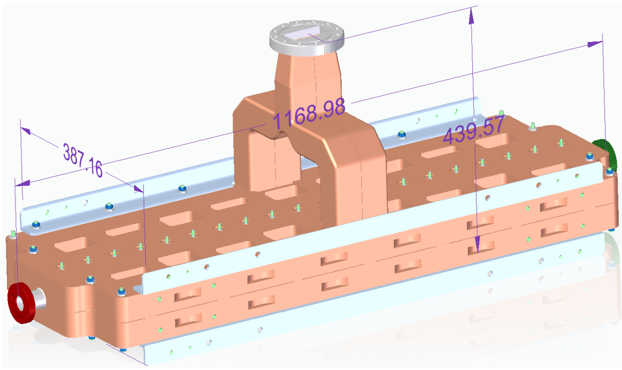


Figure 2: A CAD model of the meter-long linac mechanical design, with the distributed manifold splitting into two halves, each of which feeds 10 cavities each of the full 20-cavity structure. Rails are included to protect tuning pins along the central axis. Dimensions are in mm.

ELECTROMAGNETIC SIMULATION

In order to validate the theoretical performance properties for the linac, simulations in HFSS and ACE3P were used [4, 5]. These simulations helped verify the π phase advance between cavities, as well as the power splitting on the Y-coupler. One phenomena that became apparent through this analysis was the sensitivity of field flatness across the linac to the relative tuning of individual cavities. Since the wide aperture allows for cross coupling, cavity resonances can affect each other and in turn how well they couple to the π mode. This will be taken into consideration during tuning steps as assembly continues.

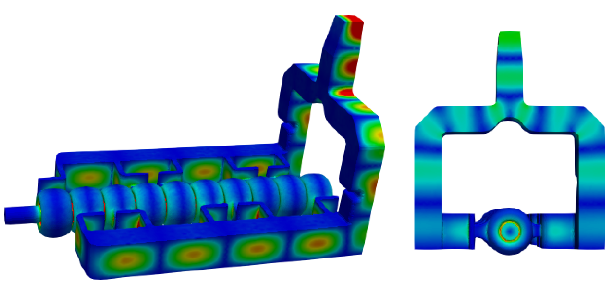
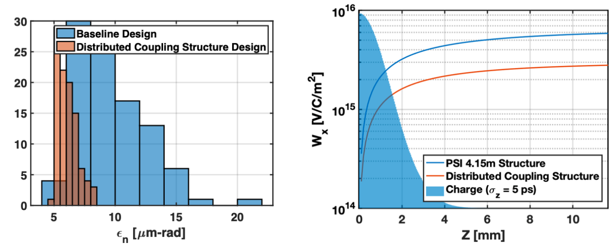


Figure 3: Cross-sectional views of the linac vacuum space as simulated within ACE3P. The left view shows how powers flows within the manifold into each cavity with π phasing. This is done equally on both sides to ensure correct phasing for every cavity to couple to the π mode.

To evaluate beam dynamics under operation, calculations were done to evaluate the output emittance and wake-field effects of the structure as compared to existing designs for EIC and other baseline travelling wave structures. When considering emittance for bunches as large as 14 nC, we find that the distributed coupling design maintains better emittance by a factor of 2, as shown in Fig. 4. Similarly looking at wake-field distributions, we find a significant improvement of wake-field handling as compared to a comparable travelling-wave structure from PSI [6].

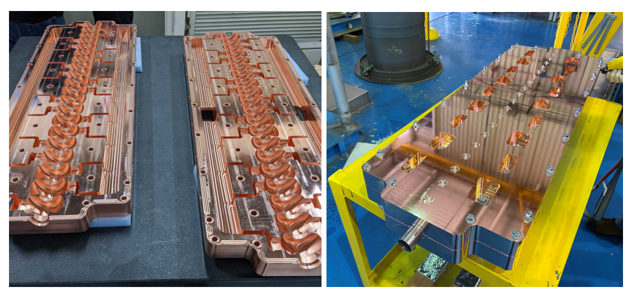


(a) Emittance Simulations (b) Wakefield Distributions

Figure 4: Simulation results for beam dynamics through the 20-cell structure. Significant improvement in emittance can be seen when compared to baseline travelling wave designs (a). The transverse wakes are also significantly better handled for a bunch charge of 14 nC when compared to an existing design from PSI (b).

FABRICATION AND ASSEMBLY

Fabrication of the components for this structure has been completed, and assembly of the first structure is underway. The bulk of the vacuum space is formed from two slabs which are brazed together (see Fig. 5) and then joined with a separate Y-coupler piece. As assembly was underway several cold tests were done to evaluate the cross coupling between cells, as well as evaluating the shifts in the π mode throughout the assembly process.



(a) Machined slabs (b) Brazed structure

Figure 5: View of the machined slabs after initial fabrication (a) and their assembly after the first round of brazing together (b). Further braze cycles will be used to braze the Y-coupler on as well.

Based on our initial cold tests, we have seen that the π mode is already very close to the target frequency before brazing, but drifts further up after brazing. More importantly, the strength of the coupling to the π mode increased dramatically, implying that most cavities are already efficiently coupling to this mode. Tuning this structure will involve adjusting each cavity to couple to this mode more strongly, and then collectively tune the structure back down to 2.856 GHz. This collectively tuning could be done through temperature or mechanical deformation. These initial results are extremely promising for how well the fabricated structure is matching simulated design.

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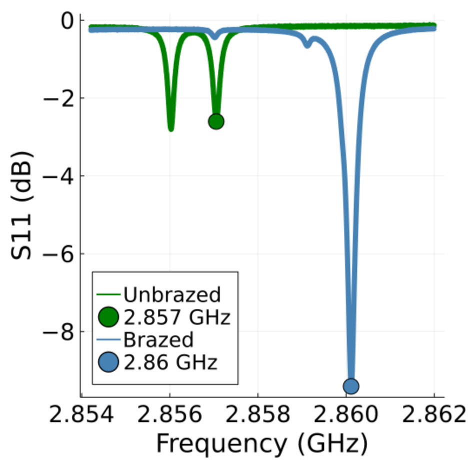

Figure 6: Comparison of the mode structure of the linac before and after brazing. The measurements before brazing were taken by aligning and placing the slabs on top of each other.

CONCLUSION

In conclusion, this distributed coupling structure presents a pathway to far more efficient structures for electron injection and other high bunch charge applications. While the power savings are certainly an advantage, this efficiency will also allow for more longer uptime for acceleration facilities, since fewer klystrons per unit length are required to provide the same acceleration gradient. As assembly of the prototype structure completes, we aim to perform final tuning of the structure before conducting high power tests and beam-line tests at SLAC. This design could act as a template for future injector designs for upcoming colliders and accelerator facilities [7].

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