OPTIMIZED LOW-COST, HIGH-EFFICIENCY CAVITY DESIGN FOR 90-500 MEV PROTON LINACS

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Abstract

Over the past four decades, the accelerator community has made substantial progress in advancing both normal-conducting and superconducting RF cavity design and fabrication technologies. As the global demand for new accelerator facilities continues to increase, the development of low-cost, high-efficiency RF cavities has become essential for ensuring the long-term sustainability of accelerator science.

In this work, we introduce a new RF cavity concept, designated ALANSA-PL, developed by the ISIS Linac R&D Group. This design provides a simpler and more efficient alternative to conventional coupled-cavity structures. Preliminary studies indicate that the ALANSA-PL cavity exhibits enhanced performance for proton accelerators in the 90–500 MeV energy range. The conceptual design and electromagnetic modelling of the cavity, operating at 972 MHz with $\beta = 0.5$, are presented and discussed in this paper.

INTRODUCTION

RF cavities for high-intensity proton accelerators must ensure power efficient, stable, and reliable operation under high beam currents while minimising losses and activation [1]. A key requirement is high accelerating efficiency, typically achieved through a high effective shunt impedance to maximise energy transfer and reduce RF power consumption [2]. Cavities must also maintain stable electromagnetic fields and control higher-order modes (HOMs) to prevent beam instabilities [3].

Beam dynamics compatibility is critical, as β increases continuously along proton linacs, requiring varying cell lengths and careful optimisation to maintain synchronism and minimise emittance growth. This contrasts with electron accelerators, where β rapidly approaches 1, allowing constant cell lengths ($\approx \beta\lambda$) and simpler designs [4].

Conventional normal-conducting structures such as side coupled cavity (CCL), annular ring cavities (ACS), and cutting-disk cavities rely on intermediate coupling cells between accelerating gaps, increasing complexity, size, and length [5-7]. In contrast, parallel-coupled cavities eliminate these coupling cells, enabling more compact structures, reduced losses, and simpler fabrication [8]. However, their application to proton accelerators is more challenging due to the continuous change in β, which disrupts periodicity and complicates field distribution, coupling, and frequency control [9].

Thermal, mechanical, and practical constraints remain essential, including efficient cooling, structural stability, manufacturability, and ease of tuning [10, 11].

If parallel-coupled structures demonstrate robust performance after prototyping, low and high-power measurements, they could enable the use of a single cavity type and design concept across a wide β range (≈0.41 to 0.758, corresponding to 90–500 MeV). While the geometry would still scale with β, the electromagnetic configuration, power feed scheme, and mechanical layout would remain consistent, reducing the need for multiple cavity families and simplifying system integration.

This unified approach improves scalability and engineering efficiency. It also supports the development of brazeless cavity technologies, as the design can reduce or eliminate brazing and electron beam welding [12, 13]. This is critical for accelerator sustainability, significantly lowering production costs, reducing manufacturing complexity, minimising failure points, and simplifying tuning and maintenance.

Although some performance variation (e.g. transit-time factor) is expected across the β range, the overall concept offers a strong balance between RF efficiency, cost-effectiveness, and operational simplicity for high-intensity proton linacs.

To address these challenges, we introduce the ALANSA-PL cavity, a novel parallel-coupled cavity concept developed by the ISIS Accelerator Physics Group. The design targets proton accelerators in the 100–500 MeV energy range. Initial simulation studies are based on operation at 972 MHz with $\beta = 0.5$. The ALANSA-PL structure aims to provide a simpler and more efficient alternative to conventional coupled-cavity systems.

500 MEV INJECTOR RF CAVITIES AND ALANSA-PL FEATURES

Two normal-conducting linac configurations are considered for the 3–500 MeV injector linac of ISIS-II. In both options, a 324 MHz drift tube linac (DTL) is used up to 90 MeV, followed by a 972 MHz annular coupled structure (ACS) from 180 to 500 MeV. The difference lies in the intermediate energy range (90–180 MeV): either a 972 MHz coupled-cavity linac (CCL) is used (Option A: 324/972/972 MHz), or a 324 MHz PIMS structure (Option B: 324/324/972 MHz). The RF frequency scheme is based on 324 MHz and its third harmonic (972 MHz), enabling simultaneous H^+ and H^- acceleration by shaping the RF waveform to create two stable phase regions within a single RF period.

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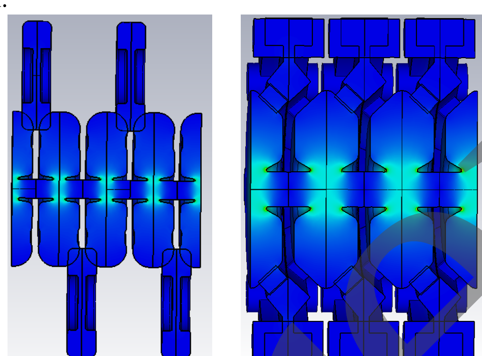
As a first step, the 324/972/972 MHz option (Option A) has been investigated. Fig. 1. presents the electromagnetic modelling of representative CCL and ACS cavities. The models correspond to β = 0.4 (≈90 MeV) for the CCL and β = 0.55 (≈180 MeV) for the ACS structure. The effective shunt impedance obtained from these models is approximately 31 MΩ/m for the CCL and 35 MΩ/m for the ACS.

As expected, the shunt impedance is lower in the low-energy (low-β) region and improves with increasing β. At higher energies, around 500 MeV, the cavity performance is projected to reach values of approximately 55 MΩ/m. The AC-CC coupling factor (fπ-f0/fπ/2) for both structures is in the range of 5.5% to 4.5% up to 180 MeV and decreases from about 4.5% to 4.2% within the ACS section at higher energies. These values indicate adequate field stability while maintaining good accelerating efficiency across the linac.

Instead of relying on these relatively complex structures, which require expensive manufacturing and tuning procedures, we investigate the possibility of replacing them with a series of cells fed in parallel using a compensated coaxial disk-loaded structure, in which each accelerating cell is powered independently along the cavity length.



(a) (b)

Figure 1: RF cavities for 90-180 MeV and 180-500 MeV (a) side coupled linac, (b) annular ring cavity.

In this concept, disks are inserted along the coaxial line to reduce the wave propagation velocity and satisfy the required synchronism condition, corresponding to a cell length of approximately βλ/2 for each module. This provides a practical way to adapt the structure to proton acceleration while preserving a simpler coupling scheme. The proposed cavity concept is illustrated in Fig. 2.

This new design offers several advantages compared to conventional side-coupled structures. Its geometry provides improved accessibility, allowing easier integration of cooling channels and brazeless stacking of the cells. In addition, due to the concentration of magnetic field around the central conductor of coaxial distributer, efficient cooling can be achieved by circulating water through the inner conductor, making the structure suitable for higher average power of 48 kW operation for each cavity of 8 cells with longer RF pulses of 1.5 ms instead of 1 ms.

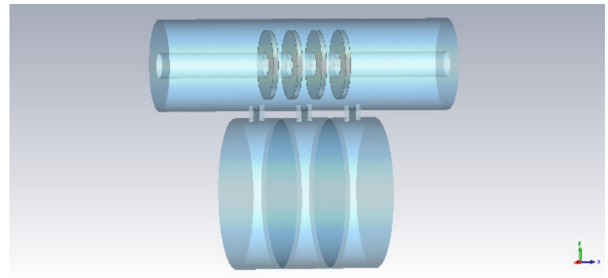
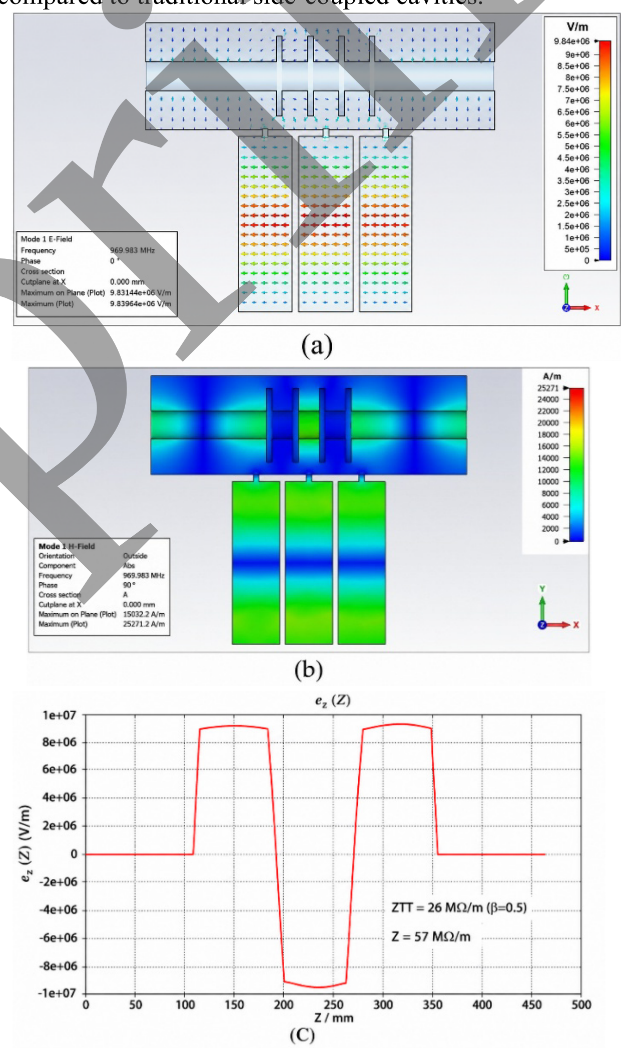


Figure 2: Topology of parallel coupled RF cavities for proton linacs.

Tuning of the disk-loaded section can be performed by controlled deformation of the internal coaxial conductor between adjacent disks, providing a relatively simple and localised tuning mechanism. As β increases, the disk radius decreases, which leads to reduced RF power losses compared to traditional side-coupled cavities.



(a)

(b)

(C)

Figure 3: Three cell parallel feed proton linac (a) electric field (b) magnetic field (c) axial electric field.

A further advantage is the independent feeding of each cell through rectangular slots. In the event of a local issue, such as a breakdown in a single cell, the impact on the overall structure is limited. The reflected power is redistributed to neighbouring cells, increasing their field amplitudes and helping to preserve the integrated accelerating field, which is critical for stable proton linac operation. The CST MWS [14] model of the structure is shown in Fig. 3. In addition to slot coupling from the distribution coaxial line to the accelerating cells, each cell can also be fed individually via coaxial couplers through the RF power manifold. The main parameters used for the design and optimisation of the distribution coaxial waveguide are presented in Fig. 4.

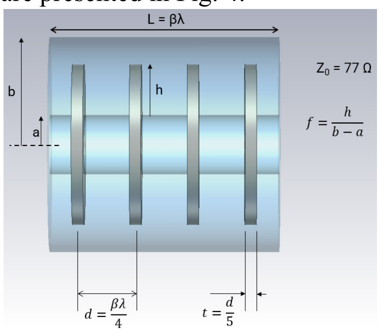


Figure 4: Parametric view of distributer coaxial waveguide.

Due to the absence of strict geometrical constraints, the cavity shape can be freely optimised to improve RF performance. This provides sufficient flexibility to adjust key geometrical parameters and enhance the effective shunt impedance. Using this approach, a 3–5% improvement in shunt impedance was achieved in the first optimisation cycle, reaching approximately 35 MΩ/m in comparison to CCL and ACS structures. The optimised cavity model after this initial step is shown in Fig. 5.

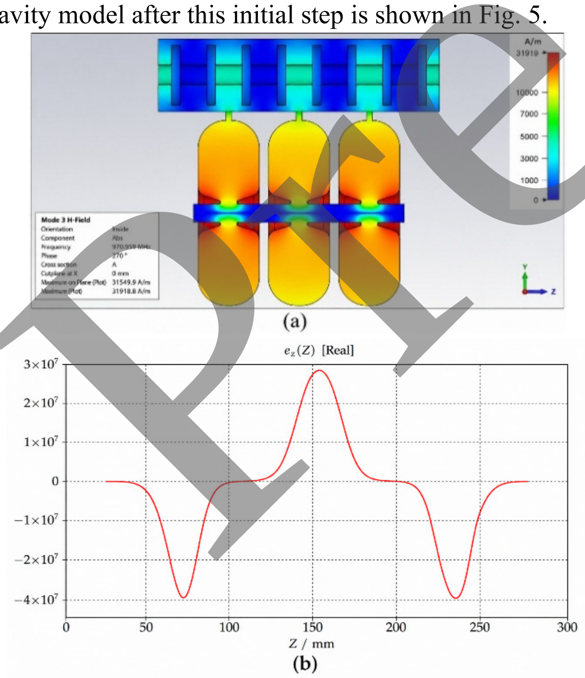


Figure 5: RF cavity with simple optimization of dimensions (a) magnetic field distribution, (b) axial electric field.

CONCLUSION

The ALANSA-PL cavity demonstrates several promising features that make it a strong candidate for application in proton linac design and manufacturing worldwide. Its simplified structure, independent cell feeding, improved cooling capability, and potential for brazeless fabrication offer clear advantages in terms of efficiency, reliability, and cost reduction compared to conventional cavity types.

Ongoing simulations and R&D efforts are focused on evaluating all relevant aspects of the design, including its advantages, limitations, and optimisation potential. These studies aim to further enhance its performance and fully assess its competitiveness with existing technologies. A more comprehensive analysis and detailed results will be presented in a future publication.

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