A NOVEL APPROACH TO RF POWER COUPLING IN RADIO-FREQUENCY QUADRUPOLE (RFQ) STRUCTURES: BUILT-IN COAXIAL DOUBLE-LOOP COUPLING PORT*

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Abstract

Efficient and reliable RF power coupling in accelerating cavities requires precise impedance matching and mechanical stability to ensure optimal beam energy transfer. In radio-frequency quadrupole (RFQ) accelerators, RF power is commonly delivered using waveguide iris couplers or coaxial loop couplers. Iris couplers can handle high RF power but present challenges in tuning, while coaxial loop couplers offer tuning flexibility but are limited in power handling and thermal performance. This paper proposes a novel RFQ power coupling concept: a single-input coaxial center-fed double-loop antenna built directly into the vane structure of an RFQ. The design integrates back-to-back loops into the RFQ vanes, fed by a TEM coaxial transmission line with a standard 50-Ω characteristic impedance. The configuration enables straightforward ceramic window replacement without retuning, and coupling strength can be adjusted with protruding tuning rods. Numerical simulations using a simplified RFQ model have demonstrated that the coaxial double-loop coupler is a practical alternative for high-power RFQ coupling.

INTRODUCTION

The SNS front end accelerates H^- ions to 2.5 MeV using a 402.5 MHz RFQ fed with two balanced coaxial couplers up to 700 kW peak RF power at 8% duty cycle. RF couplers must transfer power into the RFQ resonant structure with minimal reflection and thermal stress while maintaining vacuum integrity and field symmetry. Waveguide iris couplers accommodate high average power but have fixed geometry that limits retuning. Coaxial loop couplers provide tunability but require a tapered coaxial transition when the port area is small, constraining power handling and thermal performance. Loop coupler replacement is labor-intensive, requiring rotational realignment, vacuum reassembly, and rebalancing when multiple couplers are used in parallel [1].

Operational and maintenance experience with SNS RFQ couplers has motivated a study of coupling alternatives, with improvements sought in thermal management, RF tuning flexibility, multipacting mitigation, and window maintenance [2]. This paper proposes the coaxial double-loop coupler built-in to the cavity structure to address these issues. The design integrates the coupler directly into the RFQ vane body, enabling a larger coaxial conductor cross-section, direct thermal coupling to the RFQ cooling infrastructure, and improved mechanical stability delivering simplified window maintenance. The larger port geometry also opens the possibility of a single-coupler configuration, which would eliminate the magic-tee power splitter and associated balancing requirements. The concept is evaluated through electromagnetic simulations on a short benchmark RFQ model.

* ORNL/SNS is managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract DE-AC05-00OR22725
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RF COUPLING PHYSICS IN THE RFQ

The RFQ operates in the quadrupole transverse-electric (TE_{210}) mode, in which the magnetic field runs longitudinally along the vane faces with the H-field in adjacent quadrants oriented in antiparallel directions. For efficient coupling, the driven magnetic flux must align longitudinally along the vane faces and alternate in sign between adjacent quadrants. Both conventional coaxial loop couplers and iris couplers achieve this by penetrating the quadrant wall, but introduce local cavity field perturbations that shift the resonant frequency and can excite dipole modes (TE_{110}-family), which distort the transverse focusing fields and degrade beam quality (Fig. 1). The proposed coupling scheme may also introduce some field perturbations in the cavity. Its effect and compensations are considered later in this paper.

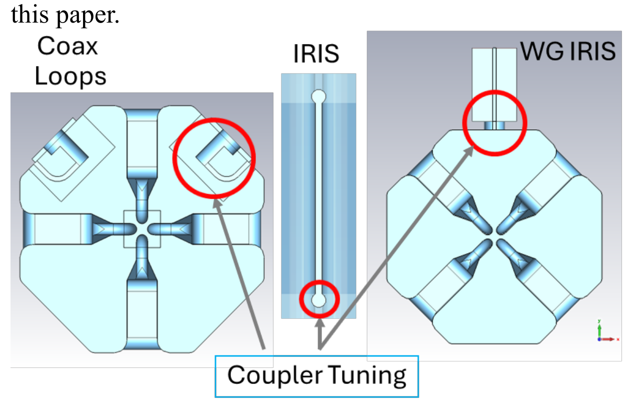

Figure 1: Conventional RFQ power coupling methods: coaxial loop coupler (left) and waveguide iris coupler (right) shown in cross-section. Red circles indicate the coupling loop and iris aperture locations. Both configurations penetrate may introduce geometric perturbations that can affect the cavity fields.

PROPOSED CONCEPT: BUILT-IN COAXIAL DOUBLE-LOOP COUPLER

As shown in Fig. 2, a single coaxial feed enters the RFQ through the top vane. The center conductor is electrically connected to the vane while the outer conductor is referenced to the RFQ wall, forming two back-to-back coupling loops on each face of the vane. This symmetric configuration drives adjacent quadrants simultaneously with the correct field orientation, establishing opposite longitudinal H-field vectors consistent with the TE_{210} mode and eliminating the phase imbalances associated with external feed networks. The coaxial feed operates with a 50-Ω TEM transmission line, and the magnetic flux wraps longitudinally around the vane cutback region, aligning naturally with the quadrupole accelerating eigenmode of the structure.

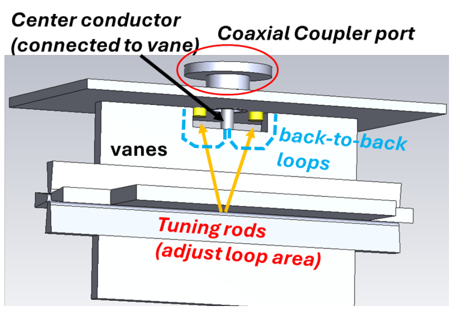

Figure 2: Simplified RFQ vane assembly with built-in coaxial double-loop coupler. The coaxial feed (circled) connects to the top vane forming back-to-back coupling loops (blue dashed region). Tuning rods allow coupling adjustment. Side, bottom, and end walls are not shown.

Coupling Coefficient Adjustment. Coarse coupling strength is set by the vane cut geometry — wider and deeper cuts increase the effective loop area and strengthen coupling. Fine adjustment is provided by one or two tuning rods inserted into the coupling apertures, trimming the RF coupling β continuously without modifying the vane geometry.

Window Maintenance. The ceramic vacuum window is positioned on the external coaxial feedline, mechanically separate from the coupling loops by a straight 50-Ω transmission section. The window can be replaced without accessing the RFQ interior or disturbing the coupling geometry, eliminating the loop realignment and β rebalancing required by the current SNS coaxial coupling design. Windows can also be pre-conditioned in a dedicated coaxial test fixture more easily, reducing commissioning time and the risk of window failure during initial high-power operation.

Thermal Management. Since the coupling loops are formed within the vane body, the existing RFQ cooling channel network can be extended into the coupler section, placing the coupling region under the same thermal regime as the main vane structure and reducing the thermal discontinuity present in external loop assemblies.

Potential Multipacting Suppression Design. In the current design the center conductor is connected to the vane, precluding DC bias. A design modification to isolate the center conductor would enable DC biasing for multipacting suppression and is noted as a potential development path [2].

NUMERICAL SIMULATIONS

Electromagnetic simulations were performed using CST Studio Suite [3] on a simplified reconfigurable aluminium RFQ model — 25 inches in length, 5 inches in width, with a vane gap of 0.4 inches — enabling rapid parametric studies at reduced computational cost. The same model was fabricated as a reconfigurable cold model with interchangeable coupler sections for future experimental verification (Fig. 3).

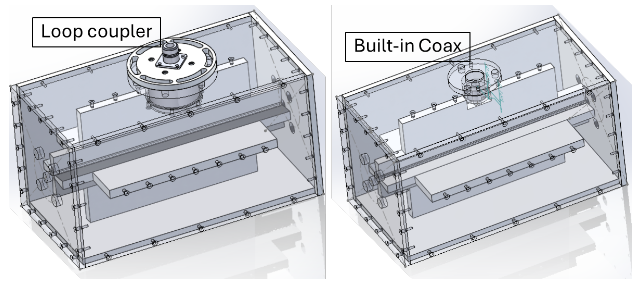

Figure 3: Reconfigurable Benchmark RFQ Model.

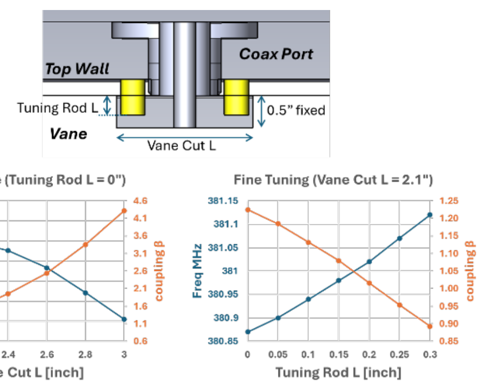

Figure 4: Built-in coaxial double-loop coupler parameter study: (top) cross-sectional schematic defining the vane cut length and tuning rod insertion depth; (bottom left) resonant frequency and coupling coefficient β versus vane cut length with tuning rods retracted; (bottom right) resonant frequency and coupling coefficient β versus tuning rod insertion depth at a fixed vane cut length of 2.1 inches.

Coupling Coefficient. The coupling coefficient β was evaluated as a function of vane cut length and tuning rod insertion depth (Fig. 4) with the model. Vane cut length provides coarse adjustment alongside the RFQ vane geometry design: increasing the cut from 2.0 to 3.0 inches raises β approximately to 4.5 from 1.1, while decreasing the accelerating quadrupole mode resonant frequency by ~2.6 MHz. This frequency shift, driven by the enlarged vane cut volume, is directly related to the adoption of magnetic coupling windows discussed in the following subsection. Tuning rods provide fine correction during commissioning and operation: 0.3 inches of rod insertion at a fixed vane cut length of 2.1 inches reduces β from 1.23 to 0.88, with a modest accompanying frequency rise. Since the Q factor of the benchmark model differs from that of the full SNS RFQ copper structures, the absolute β values are not directly transferable. This study demonstrates the feasibility of the design process and two-stage tuning

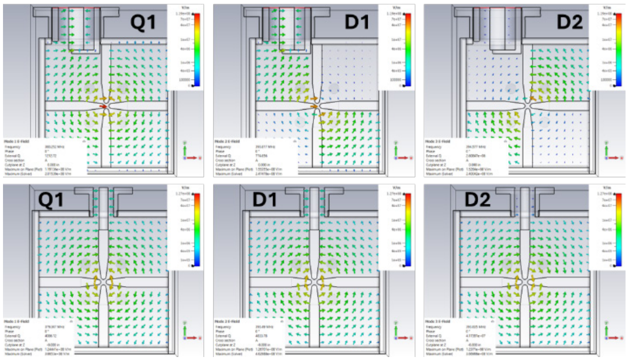

Figure 5: Comparison of electric field distributions for conventional coaxial loop coupler (top) and built-in coaxial double-loop coupler (bottom) in a simplified single-coupler RFQ model. Q1: quadrupole mode; D1, D2: dipole modes.

methodology, to be applied to the full RFQ geometry in subsequent work.

Mode Spectrum Comparison. Figure 5 compares the electric field distributions for the conventional coaxial loop coupler and the built-in double-loop coupler. Table 1 summarises the mode frequencies and dipole mode separations. The built-in coupler yields dipole mode separations of 3.72% (D1−Q1) and 3.76% (D2−Q1), comparable to the conventional coupler values of 3.59% and 3.73% respectively, confirming that the built-in design does not compromise the electromagnetic integrity of the RFQ cavity.

Table 1: Benchmark RFQ Mode Characteristics

Coupler Type	Q1 (MHz)	D1 (MHz)	D2 (MHz)	D1-Q1 (%)	D2-Q1 (%)
Conv. Coax Loop	380.37	394.01	394.58	**3.59**	**3.73**
Built-in Double Loop	379.37	393.48	393.63	**3.72**	**3.76**

Dipole Mode Suppression. Four progressive vane modifications were investigated to assess dipole mode suppression, adopting magnetic coupling windows [4] and pi-mode stabilizing loops (PISLs): no vane cut, bottom vane cut only, all vane cut, and all vane cut with PISLs (Fig. 6). Field asymmetry was quantified as $\Delta E = |E\_QA - E\_QB| / E\_QA$. The no-cut baseline exhibits a field imbalance of 14.88%. A bottom vane cut reduces this to 0.03%, while the all-cut configuration yields 0.31% with a dipole mode separation of 5.37%. Adding PISLs further increases separation to 6.68% at a modest imbalance of 0.44%, the best result achieved in this study (Table 2).

Table 2: Maximum Quadrupole E-Field Imbalances and Dipole Mode Separation for Progressive Vane Modifications

Configuration	Max. Quad. E(z) Imbalance (ΔE) (%)	Quad. Freq. (MHz)	Dipole Freq. (MHz)	Dipole Separation (%)
No cut	14.882	381.03	395.13	3.700
Bottom cut	0.030	377.73	392.03	3.786
All cut	0.307	371.23	391.18	5.374
All cut + PISL	0.440	371.28	396.08	6.680

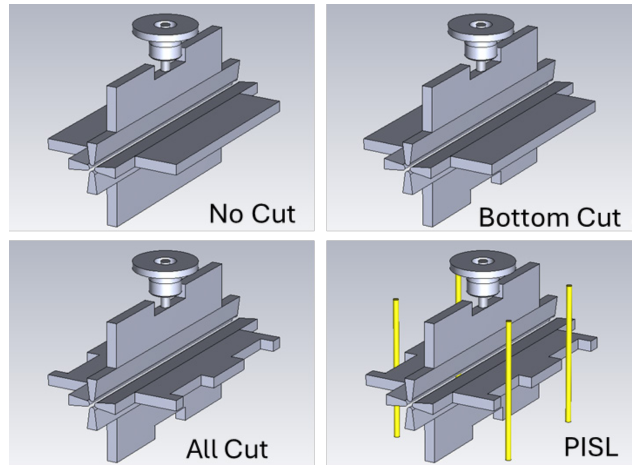

Figure 6: Progressive vane modifications on the benchmark RFQ: no vane cut (top left), bottom vane cut (top right), all vane cut (bottom left), and all vane cut with PISLs (bottom right). Walls are not shown.

DISCUSSION AND CONCLUSIONS

Simulations confirm that the built-in coaxial double-loop coupler is electromagnetically viable, maintaining dipole mode separation and field symmetry comparable to the conventional coaxial loop coupler while offering operational advantages in window maintenance, thermal management, and a pathway for multipacting suppression. A reconfigurable aluminium cold model with interchangeable coupler sections is in fabrication for experimental verification. Low-power VNA measurements will benchmark the CST simulations, with high-power prototype testing planned for subsequent work.

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