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उच्च शक्ति वाले आर. एफ. युग्मकों का डिजाइन और विकास और प्रोटॉन त्वरकों के लिए परीक्षण व्यवस्था

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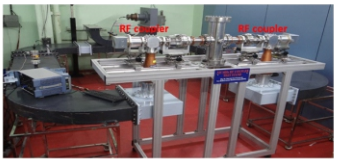

उच्च-शक्ति 325 MHZ अनुनाद वलय परीक्षण स्टैंड जिसमें से दो एकीकृत प्रोटोटाइप युग्मक परीक्षण के दौर से गुजर रहे हैं

सारांश

उच्च-शक्ति वाले रेडियो-आवृत्ति (आरएफ) युग्मक रैखिक त्वरक (लिनॉक) में महत्वपूर्ण इंटरफेस घटकों के रूप में कार्य करते हैं, जो निर्वात विलगन और तापीय भार का प्रबंधन करते हुए बाह्य आरएफ स्रोतों से विद्युत चुम्बकीय ऊर्जा को गति देने वाली गुहिकाओं में स्थानांतरित करते हैं। यह पांडुलिपि भापअ केंद्र में लेहिपा और मेहिपा कार्यक्रमों के सामान्य प्रचालन और अति-चालकता संरचनाओं हेतु विकसित विभिन्न आरएफ युग्मकों के अभिकल्पन, अनुकरण और उच्च शक्ति अभिलक्षणन को प्रस्तुत करती है। रेडियो आवृत्ति चतुर्ध्रुवी (आरएफक्यू) और अपवाह नलिका लिनॉक (डीटीएल) गुहिकाओं के लिए सुयोजित वेवगाइड-आधारित युग्मक 325 MHz पर 300 kW निरंतर-तरंग (सीडब्ल्यू) शक्ति के प्रहस्तन हेतु सुयोजित किए गए हैं, जबकि समाक्षीय लूप युग्मक का उपयोग एमईबीटी/एचईबीटी गुच्छक गुहिकाओं के लिए किया जाता है। अति-चालक संरचनाओं के लिए, भारतीय संस्थान एवं फर्मीलैब सहयोग (आईआईएफसी) तथा स्वदेशी कार्यक्रमों दोनों के तहत 325 MHz और 650 MHz समाक्षीय युग्मक विकसित किए गए हैं। इन युग्मकों का लागत प्रभावी ढंग से परीक्षण एवं सत्यापन हेतु, समर्पित उच्च-शक्ति परीक्षण स्टैंड स्थापित किए गए हैं, जिनमें 325 MHz अनुनाद वलय सुविधा शामिल है जो >12 dB शक्ति लाभ प्रदान करती है और 650 MHz स्थायी तरंग परीक्षण सुविधा हेतु सफलतापूर्वक प्रचालित की गई है।

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Design and Development of High Power RF Couplers and Test Setup for Proton Accelerators

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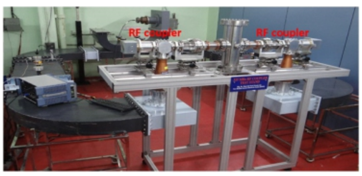

The high-power 325 MHz resonant ring test stand with two integrated prototype couplers undergoing testing

ABSTRACT

High-power radio-frequency (RF) couplers serve as critical interface components in linear accelerators (linacs), transferring electromagnetic energy from external RF sources into accelerating cavities while managing vacuum isolation and thermal loads. This manuscript presents the design, simulation, and high-power characterization of various RF couplers developed for the normal conducting and superconducting structures of the LEHIPA and MEHIPA programs at BARC. Waveguide-based couplers designed for Radio Frequency Quadrupole (RFQ) and Drift Tube Linac (DTL) cavities are engineered to handle up to 300 kW continuous-wave (CW) power at 325 MHz, while coaxial loop couplers are utilized for MEBT/HEBT buncher cavities. For superconducting structures, 325 MHz and 650 MHz coaxial couplers have been developed under both the Indian Institute and Fermilab Collaboration (IIFC) and domestic programs. To test and validate these couplers cost-effectively, dedicated high-power test stands, including a 325 MHz resonant ring facility providing a power gain of >12 dB and a 650 MHz standing wave test facility, have been established and successfully operated.

KEYWORDS: *LEHIPA, MEHIPA, Radio Frequency Quadrupole (RFQ), Proton accelerators, Drift Tube Linac (DTL), Radio-frequency (RF).*

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Introduction

In a linear accelerator (linac), high-power radio-frequency (RF) couplers serve as critical interface components that transfer electromagnetic energy from an external source, such as a klystron or solid-state amplifier, into accelerating cavities. These couplers perform several essential functions simultaneously, including efficient power transfer, vacuum isolation, and thermal management across different regions of the system [1, 2]. The primary role of an RF coupler is to ensure efficient delivery of power from the generator to the load, which consists of the accelerating cavity and the beam. From this standpoint, a coupler can be viewed as a carefully engineered transition within an otherwise perfectly matched transmission line, enabling the precise amount of power required for beam acceleration to be delivered with minimal reflection and loss.

Typically, a linear accelerator consists of an initial section of normal conducting accelerating cavities followed by superconducting accelerating cavities. Since normal conducting cavities require significantly higher RF power compared to superconducting cavities, the design and operational requirements of RF couplers differ for these two sections. This article presents the detailed design and development of various high-power RF couplers, along with their associated test setups [1,3,4], for the linear accelerators LEHIPA and MEHIPA of BARC.

Design Methodology

RF Couplers for Warm Accelerating Structures of LEHIPA and MEHIPA

The RF couplers for the Radio Frequency Quadrupole (RFQ) and Drift Tube Linac (DTL) cavities of LEHIPA and MEHIPA are waveguide-based [2, 5, 6]. The RFQ features two input ports requiring two couplers. For the LEHIPA DTL1 and DTL2, four ports are configured each, requiring a total of eight waveguide RF couplers. In contrast, the MEHIPA DTL up to 10 MeV requires only four waveguide couplers. Each DTL waveguide coupler is engineered to handle 250 kW to 300 kW of continuous-wave (CW) power.

Because the dimensions of the input waveguide transmission lines (WR2300 Half-Height) are significantly larger than the cavity dimensions, a narrow cross-section transition with an iris of suitable dimensions is required at the coupler interface to establish sufficient coupling with minimal frequency perturbation. A separate waveguide window provides the necessary vacuum barrier separating the air-filled waveguide from the vacuum-driven cavity structure. The electromagnetic design progresses through three stages: a waveguide transition at 325 MHz matching the WR2300HH interface to a smaller ridge waveguide, an optimized iris configuration, and mechanical interfaces facilitating ease of manufacture, vacuum sealing, and thermal management, as illustrated in the schematic layout in Fig.1.

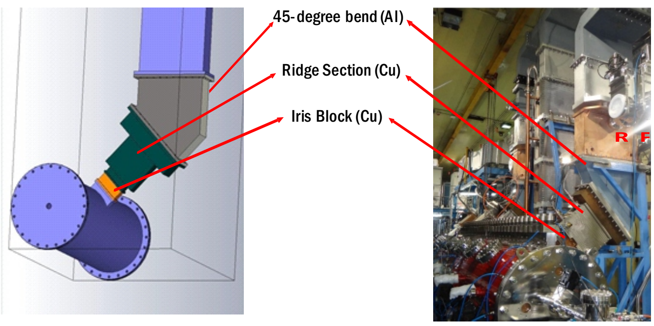

Fig.1: Schematic of the waveguide couplers designed for DTL cavities, highlighting the RF window, ridge section, and iris block.

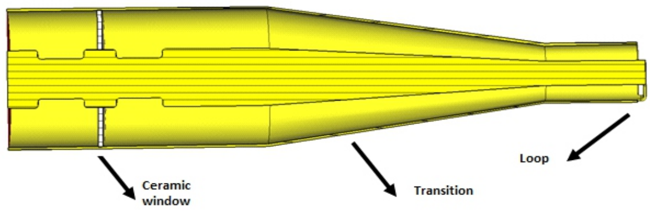

Fig.2: Cross-sectional design model of the 50 kW CW coaxial loop coupler optimized for MEBT and HEBT buncher cavities.

For the Medium Energy Beam Transport (MEBT) and High Energy Beam Transport (HEBT) buncher cavities of MEHIPA, coaxial couplers are employed [7]. Five coaxial couplers are planned in total: two for the MEBT bunchers and three for the HEBT bunchers. This coaxial design incorporates an RF window, a coaxial transition from a 6-inch line to a 70 mm outer diameter coaxial line, and a rotatable loop coupler that allows tunability of the coupling coefficient (as shown in Fig.2). The loop is water-cooled through its inner conductor to fulfill a 50 kW CW power rating while the structure is optimized to suppress multipacting probabilities.

RF Couplers for Superconducting Cavities

Under the Indian Institute and Fermilab Collaboration (IIFC), BARC has developed coaxial RF couplers to deliver high RF power to Single Spoke Resonators (SSR, 325 MHz) and elliptical (650 MHz) superconducting cavities [8]. Prototype units—consisting of two 650 MHz and three 325 MHz couplers—have been successfully built (Fig.3), with an additional 19 production-phase couplers under development for Fermilab.

For the superconducting spoke resonator cavities (SSR-B) of MEHIPA-1, 18 coaxial couplers operating at 325 MHz are being developed [9]. Waveguide structures at 325 MHz would be prohibitively bulky and impose unsustainable thermal loads on the cryogenic system, making coaxial lines the ideal choice. The domestic design builds upon the Fermilab configuration but implements geometric changes to accommodate a significantly higher power requirement of 50 kW CW, which is 2.5 times greater than Fermilab's 20 kW rating.

The coupler utilizes a 105 Ω coaxial geometry featuring a single 7 mm thick alumina ceramic disk acting as a room-temperature vacuum RF window between the warm and cold

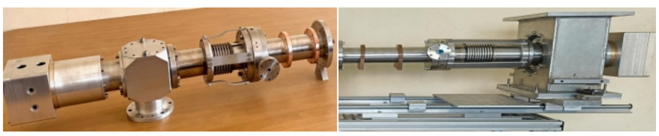

Fig.3: Fabricated prototype IIFC coaxial RF couplers operating at 325 MHz and 650 MHz for superconducting cavities.

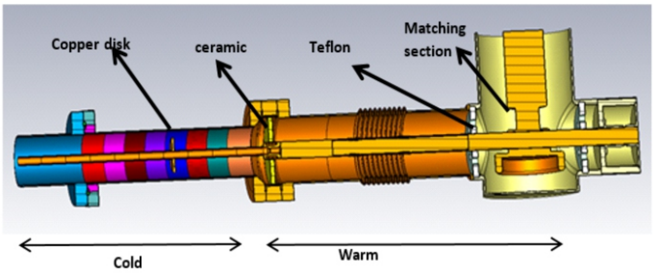

Fig.4: Structural (cutaway) view of the 325 MHz SSR-B coaxial coupler, detailing the warm and cold parts, ceramic RF window, and matching section.

regions. It employs an air-cooled inner antenna for capacitive coupling to the SSR-B cavity, converting from a 6-1/8" rigid coaxial line on the air side to a 4" coaxial line at the cavity interface. The structural arrangement and detailed cutaway view of this assembly are depicted in Fig.4. It has an integrated provision to apply a high-voltage (HV) DC bias to suppress multipacting, and specialized mechanical bellows to accommodate thermal contraction.

Result & Discussion

RF, Thermal, and Stress Simulation Performance

Electromagnetic and multi-physics simulations for the MEHIPA superconducting couplers were conducted using CST Microwave Studio and COMSOL [10]. RF simulation results demonstrate excellent impedance matching, achieving a return loss better than 34 dB at the input port. Evaluation of the electric field monitors indicates a maximum RF field strength of 27 kV/cm on the vacuum side, which remains well below critical breakdown thresholds, as shown in the electric field distribution profile in Fig.5.

Thermal simulations were directly coupled with the RF field profiles to calculate temperature distribution and heat loads. Managing the thermal gradient of the cold section is essential to minimize the cryogenic load, as the temperature transitions from 293 K on the warm side to 2 K at the cavity interface. Two thermal intercepts, positioned at 5 K and 50 K respectively, are integrated to actively cool the outer conductor. Under the worst-case operating envelope of 50 kW full reflection, the maximum antenna temperature reaches 341 K, while the residual heat leakage into the 2 K cryogenic environment is tightly restricted to 0.68 W (Fig.6). Structural stress analyses under atmospheric pressure combined with thermal expansion (50 kW, 20% reflection case) indicate a maximum stress of less than 70 MPa at the critical outer

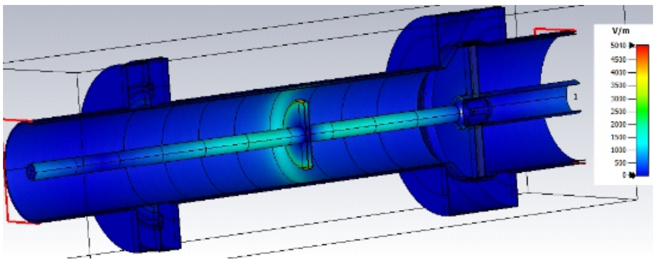

Fig.5: Electromagnetic simulation identifying the maximum electric field distribution (27 kV/cm) within the vacuum side of the SSR-B coupler.

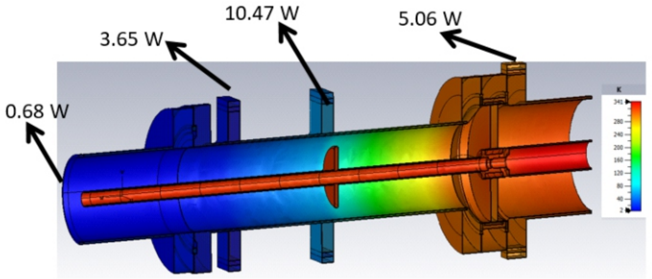

Fig.6: Multi-physics thermal profile of the coupler's cold section during the worst-case scenario (50 kW, full reflection), showing a maximum heat flow of 0.68 W towards the cavity.

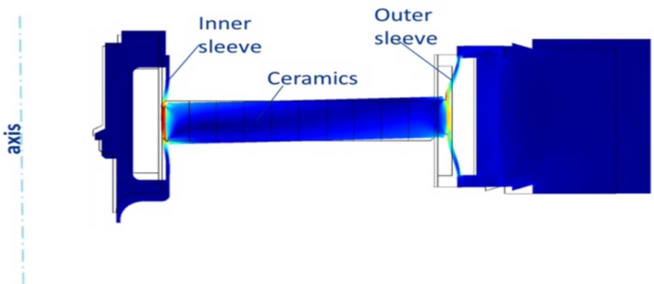

Fig.7: 2D analysis displaying mechanical deformation and stress distribution at the alumina ceramic joint due to atmospheric pressure and thermal expansion.

sleeve-to-alumina ceramic brazed joint, ensuring a highly reliable mechanical safety margin, as shown in the deformation analysis in Fig.7.

High-Power Characterization and Test Setups

To validate and qualify the engineered couplers before accelerator integration, cost-effective high-power test stands have been developed [1, 3,4]. Two primary test facilities have been established:

325 MHz Test Facility: A high-power resonant ring-based test stand was developed where two couplers can be tested simultaneously under either traveling wave (TW) or standing wave (SW) regimes [1,3]. When the electrical length of the ring is tuned to an integral multiple of the guided wavelength, resonance is established, leading to an optimal power multiplication gain. Initial bare-ring testing reached up to 130 kW CW power with a 4.5 kW input, achieving a power gain of 14.4 dB. Recently, two fabricated 325 MHz couplers were integrated into the ring assembly, pre-tuned with the help of Vector Network Analyzer (VNA) measurements. The couplers were tested upto 25 kW in pulsed traveling wave mode, yielding a measured gain of 12.4 to 12.83 dB with respect to the input RF Amplifier output. The fully assembled physical setup is shown in Fig.8. The critical experimental parameters from this evaluation run are outlined in table 1, and the corresponding transient high-power data is illustrated in Fig.9.

650 MHz Test Facility: Based on a Fermilab layout, a high-power test stand configured around a central tuning cavity positioned between two prototype 650 MHz couplers has been established, as shown in Fig.10. Low-power tuning and S-parameter optimization were verified using a VNA, showing an achieved power multiplication gain of approximately 6 dB

Table 1: High-power testing parameters of 325 MHz couplers in the resonant ring facility.

Sr. No.	Parameter	Measured Value
1	Input Power	1.3 kW
2	Output Power (Circulating / Ring)	25 kW
3	Frequency of Operation	325.37 MHz
4	Measured Ring Gain	12.83 dB
5	Pulse Width	500 µs
6	Pulse Repetition Rate (PRR)	1 Hz

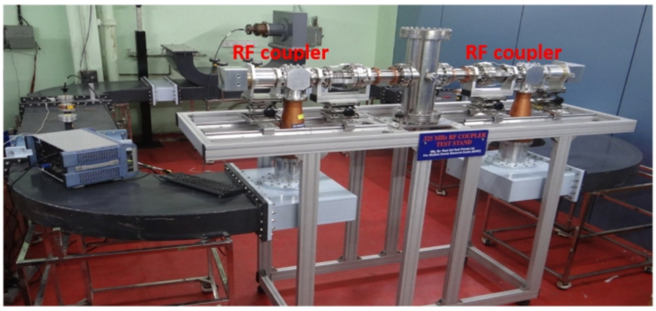

Fig.8: The high-power 325 MHz resonant ring test stand with two integrated prototype couplers undergoing testing.

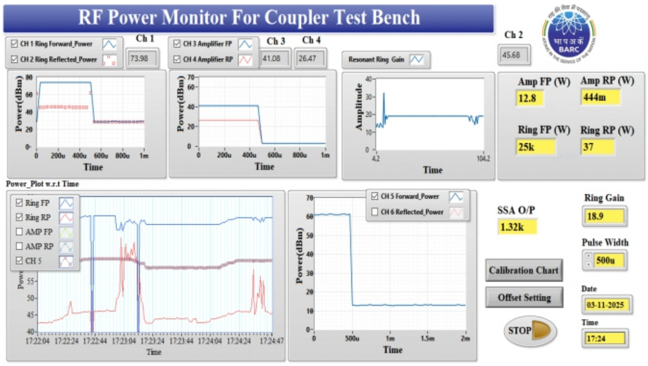

Fig.9: High power test results of the 325 MHz couplers characterized in the resonant ring facility.

[4]. This setup allows high-power testing exclusively in the standing wave (SW) mode when the electrical length is configured to match an integral multiple of the operating wavelength.

Conclusions

A comprehensive suite of high-power waveguide and coaxial RF couplers has been engineered, fabricated, and simulated to support the normal conducting and superconducting linac infrastructure of BARC's LEHIPA and MEHIPA programs. Multi-physics analyses validate that the specialized 325 MHz 50 kW coaxial couplers operate within safe breakdown (27 kV/cm) and structural stress (< 70 MPa) bounds while minimizing cryogenic heat leakage down to 0.68 W. Furthermore, operational implementation of the 325 MHz resonant ring and 650 MHz test stands demonstrates reliable power gains (>12 dB and 6 dB respectively), establishing an efficient methodology for full-scale high-power verification of accelerator-grade RF window and coupler systems.

Fig.10: The 650 MHz high-power test facility setup, featuring a central cavity positioned between two prototype couplers for standing wave mode evaluation.

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