

High-power radiofrequency quadrupoles: Review of recent developments, common problems, and solutions

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The RFQ accelerator, often the initial rf component in a hadron accelerator, focuses, bunches, and accelerates the beam from several keV to MeV across a several-meter quadrupole channel. Due to the significant application potential of high-power RFQs, research efforts have grown substantially in recent years. This paper reviews global advancements in high-power RFQ technology. The stable operation of these high-power RFQs faces many design challenges and technological limitations. The experiences and lessons learned from the recent design, fabrication, high-power rf conditioning, and beam commissioning processes have been summarized. Key issues related to thermal effects, multipacting, sparking, stability, and frequency detuning in the components of the RFQ system are presented, and the proposed solutions are discussed.

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I. INTRODUCTION

High-power hadron accelerators are becoming increasingly in demand as drivers for secondary beams, finding applications in various fields such as high-flux neutron sources for material science, accelerator driven systems, material irradiation facilities, and high-flux neutrino factories for high-energy physics. In recent decades, substantial increases in average beam power have posed challenges in achieving high beam power and availability with minimal activation levels. The beam power can be enhanced by increasing both the beam energy and the average beam current. However, it is more economical to focus on increasing the average beam current. The study of the high-power RFQ accelerator, which is typically the first rf component in a high-power hadron accelerator, is becoming increasingly active. High-power RFQs, including those designed for protons, deuterons, and heavy ions, exhibit extensive application prospects.

The primary application of high-power RFQs [1] is to serve as injectors for MW-level superconducting linear accelerators (linacs), capable of accelerating proton beams to energies exceeding 1 GeV. This capability facilitates the development of MW-level spallation neutron sources, which include systems designed for nuclear waste transmutation,

such as the China Accelerator Driven System (C-ADS) [2] and MYRRHA [3], as well as those intended for fundamental scientific research, like ISIS [4], SNS [5], J-PARC [6], CSNS [7], and ESS [8]. Furthermore, proton linacs operating at tens of megawatts power levels can be utilized in neutrino factories, such as PIP-II (PXIE) [9] and the High-Power Superconducting Proton Linac [10]. High-power RFQs also serve as injectors for deuteron linacs at material irradiation facilities, including the International Fusion Materials Irradiation Facility (IFMIF) [11], SARAF [12], and CMIF [13]. Additionally, high-power RFQs are employed as injectors for heavy-ion linacs in nuclear physics facilities, such as EURISOL [14], FRIB [15], ATLAS [16], RIBF [17], SPIRAL2 [18], HIAF [19], and RAON [20]. Moreover, independent high-power RFQs dedicated to compact neutron sources have been extensively researched for medical applications, particularly Boron Neutron Capture Therapy [21].

High-power RFQs, particularly those operating in continuous wave (cw) mode, face numerous design challenges and technological limitations. Based on recent operational experiences and lessons learned from high-power RFQs, most efforts and challenges focus on high-power rf conditioning and beam commissioning. The primary challenges associated with the RFQ system components are thermal management, multipacting phenomena, sparking, stability issues, and frequency detuning.

II. RECENT PROGRESS OF HIGH-POWER RFQS

The general parameters and operational states of various RFQs are summarized in Table I. Several representative examples are discussed below.

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TABLE I. Parameters and states of various RFQs.

Project	Lab	Ion	Frequency (MHz)	Voltage (kV)	Vane length (m)	Current (emA)	Duty factor (%)	Input energy (keV)	Output energy (MeV)	Type	State
SNS	ORNL	H ⁺	402.5	83	3.72	38	6.2	65	2.5	Four-vane	Operation
LINAC4	CERN	H ⁺	352.2	78	3.06	80	7.5	45	3	Four-vane	Operation
CPHS	THU	P	325	60–132	3	50	2.5	50	3	Four-vane	Operation
CSNS	IHEP	H ⁺	324	80	3.62	40	1.24	50	3	Four-vane	Operation
IPHI	CEA	P	352.2	80–120	6	100	cw	45	3	Four-vane	Commission
C-ADS inj-I	IHEP	P	325	55	4.69	10	cw	35	3.2	Four-vane	Upgrade
C-ADS inj-II	IMP	P	162.5	65	4.21	10	cw	35	2.1	Four-vane	Operation
PIP II (PXIE)	FNAL	P	162.5	65	4.21	5	cw	35	2.1	Four-vane	Commission
FRANZ	IAP	P	175	65	1.75	30	cw	60	0.7	Four-rod	Operation
SARAF	SNRC	D	176	65	3.8	5	cw	20	3	Four-rod	Commission
MYRRHA	SCK/IAP	P	176.1	44	4.0	4	cw	30	1.5	Four-rod	Operationnn
IFMIF	INFN	D	175	79–132	9.8	130	cw	50	5	Four-vane	Commission
CIMF	IMP	D	162.5	65	5.27	10	cw	20	3	Four-vane	Operation
SSC-linac	IMP	A/q = 7	53.667	70	2.51	0.5	cw	25	1	Four-rod	Operation
Spiral2	GANIL	A/q = 3	88	100–113	5	5	cw	60	2.25	Four-vane	Operation
FRIB	MSU	A/q = 7	80.5	60–112	5.04	0.45	cw	84	3.5	Four-vane	Operation
LEAF (HIAF)	IMP	A/q = 7	81.25	70	5.98	2	cw	98	3.5	Four-vane	Operation
ATLAS	ANL	A/q = 7	60.625	70	3.81	1	cw	210	2.1	Split-coaxial	Operation

A. RFQs at C-ADS

The prototype of the Chinese Accelerator Driven System (C-ADS) proton accelerator includes two injectors and a main linac that operates in continuous wave mode, delivering 1.5 GeV energy and 10 mA current with superconducting technology. The injectors were designed to operate at different resonant frequencies. The Injector I was developed at the Institute of High Energy Physics (Chinese Academy of Sciences), with the RFQ designed to operate at a frequency of 325 MHz. While a 162.5 MHz RFQ is used

in Injector II, which was developed at the Institute of Modern Physics, Chinese Academy of Sciences.

The C-ADS Injector I RFQ [22] accelerates a continuous wave (cw) proton beam to an energy of 3.2 MeV with a beam current of 15 mA. The rf conditioning of the RFQ commenced on May 15, 2014. During the rf conditioning process, a vacuum leak occurred at the coupling plate due to a welding defect when the rf power reached 257 kW with a duty factor of 80%. The inlet cooling plate pipe of the second coupler developed a leak at a cw rf

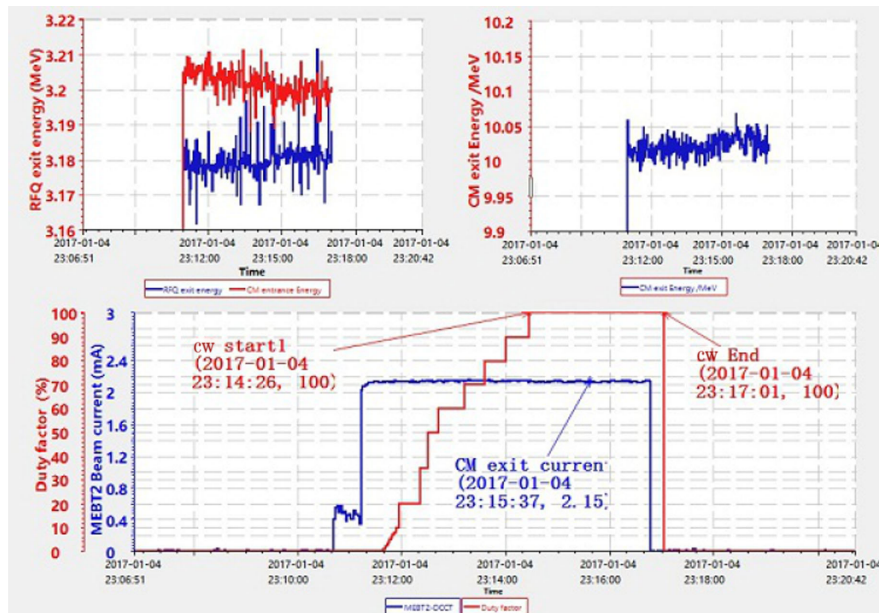


FIG. 1. 2.1 mA cw beam current was achieved in C-ADS Injector I RFQ.

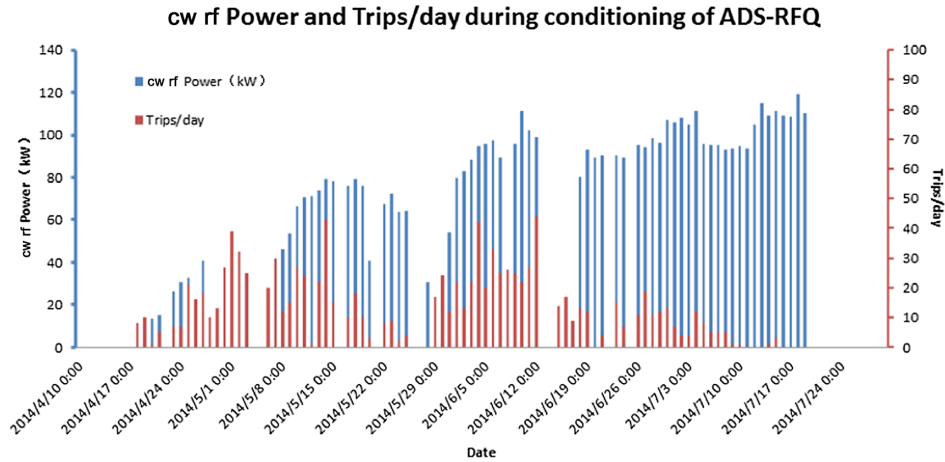


FIG. 2. Conditioning procedures of C-ADS Injector II RFQ.

power of 194 kW. Despite numerous attempts to address these issues, the cw rf power was ultimately constrained to 158 kW. Subsequently, a new RFQ was designed and fabricated. This new RFQ underwent high-power rf conditioning for 27 consecutive days without interruption. On November 8, 2016, the duty factor reached 100% at an input rf power of 260 kW, surpassing the required power level of 250 kW. Thereafter, a cw beam current of 2.1 mA was achieved on January 4, 2017, as illustrated in Fig. 1. It was subsequently determined that the RFQ could deliver beam currents up to 10 mA. However, the superconducting section of the accelerator was not designed to accommodate such high beam currents.

The RFQ of C-ADS Injector II [23] accelerates a continuous wave (cw) proton beam to an energy of 2.1 MeV with a beam current of 15 mA. This RFQ was designed by LBNL and fabricated at IMP. The rf conditioning commenced on April 10, 2014, and lasted for a period of three months. Figure 2 illustrates the evolution of cw rf power and trips per day. The first pulsed beam was achieved on June 6, 2014, with an RFQ transmission

efficiency of 97%. The record for achieving the first 10 mA cw proton beam was set on June 30, 2014, as shown in Fig. 3. Subsequently, the coupler experienced two instances of cracking, and the tetrode amplifier suffered multiple failures due to high reflected power. After replacing the old tetrode amplifier with two 80 kW solid-state power amplifiers (SSPAs) as the RFQ power source, the coupler no longer cracked, and the operational stability of the RFQ was significantly improved. In April 2018, the C-ADS Injector II RFQ was replaced with the CMIF RFQ. By the end of the online operation period, the system had operated for a total of approximately 5902 h at full power, including about 2776 h of beam time, with 104 h dedicated to cw beam operation.

B. RFQs at SNS ORNL

The primary objective of the Spallation Neutron Source (SNS) RFQ is to accelerate an H^- beam, achieving a peak current of 38 mA and delivering it to an energy level of 2.5 MeV. The original RFQ, made of Glidcop and copper, was designed and fabricated by Lawrence Berkeley National Laboratory (LBNL). Following the acquisition of the initial beam in 2002, three distinct detuning incidents occurred. Despite the field distribution was tuned, there was a noticeable degradation in the RFQ performance, resulting in a transmission decrease of over 20%. A new RFQ02 was designed and fabricated using a single block of oxygen-free copper. It is more robust, offering enhanced vacuum pumping and water cooling capabilities. The first beam from the new RFQ02 was achieved in September 2016 at the beam test facility. Subsequently, the output beam energy, transmission efficiency, and emittance of RFQ02 were measured [24]. The high-power test demonstrated that the RFQ can accelerate a pulsed beam with a maximum current of 50 mA, operating at a pulse width of 900 μ s and a repetition rate of 60 Hz. The RFQ02 was installed in spring 2018, replacing the old one, and was commissioned at the end of April. It performed well, although the rf seals

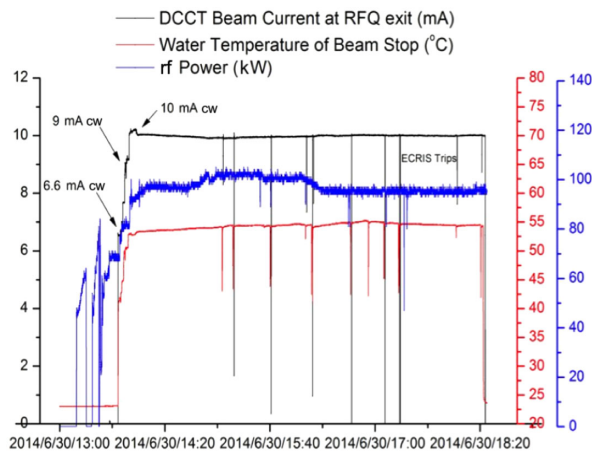


FIG. 3. Historical record of the first 10 mA cw proton beam in C-ADS Injector II RFQ.

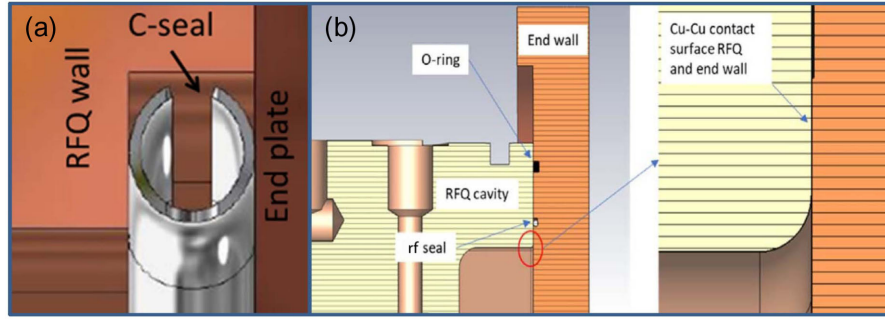


FIG. 4. RFQ03 improved design of contact interfaces between RFQ and end wall. (a) is the original design and (b) is the improved design.

on both end flanges melted. This issue was ultimately mitigated by redesigning the end flanges and rf seals. Upon investigation, damaged C-seals were discovered at both endplates in November 2018. To address the issues encountered with RFQ02, SNS decided to develop RFQ03. While maintaining the core design of RFQ02, they introduced significant modifications to the end-wall contacts specifically aimed at preventing rf seal failures [25]. To improve performance, RFQ03 was designed with copper-to-copper contacts at both ends. Additionally, the rf seals were relocated outside the rf contact surfaces, ensuring they are not directly exposed to the rf field. The detailed design is illustrated in Fig. 4. Rf power conditioning and beam commissioning conducted at the Beam Test Facility (BTF) demonstrated that the newly developed RFQ03 successfully meets all of its design specifications. The output beam current reached 42 mA when the input beam current, as measured at the chopper target, was 45 mA. The beam transmission through RFQ03 exceeded 90%. Measurements of the beam emittance and beam energy at the RFQ output were conducted, and the obtained results met all design specifications. Following testing at the Beam Test Facility (BTF), RFQ03 was installed in the SNS front end and commenced operation in June 2023.

C. SARAF RFQ at Soreq NRC

The RFQ for the Soreq Applied Research Accelerator Facility (SARAF) was installed and conditioned in 2009. The four-rod structure, featuring minivanes, offers notable cost-effectiveness advantages, making it an attractive option for specific applications. However, this design also presents technical challenges, particularly due to the extremely high-power density observed at the stem bases, which may necessitate additional cooling or structural reinforcement. Operating a 4 mA continuous wave (cw) deuteron beam requires 260 kW of power, supplied through a single coupler equipped with an antenna loop. This configuration achieves the highest recorded power density for a four-rod cavity to date. Figure 5 illustrates the rf conditioning campaigns conducted on the RFQ. Until the end of 2014, the achieved rf power was approximately 210 kW in cw mode and 250 kW at a duty factor of 50%. A SARAF study identified the coupler as the primary bottleneck limiting operations at higher rf power levels [26]. To address this limitation, the rf system was upgraded to couple power through two newly designed couplers. By the end of 2016, the objective of RFQ conditioning had not yet been fully realized. Stable operation at 250 kW with duty factors ranging from 50% to 80%, as well as

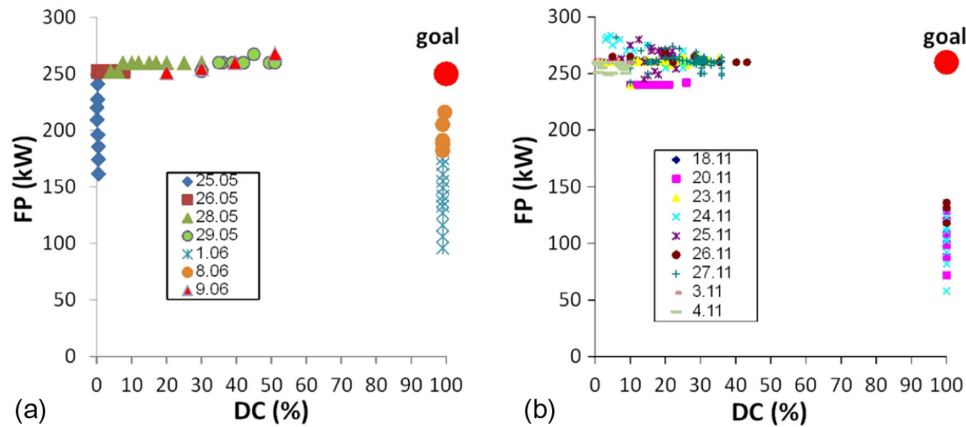


FIG. 5. Conditioning campaigns of SARAF RFQ.

cw operation at 200 kW, has been successfully demonstrated. A pulsed deuteron beam with a current of 5.5 mA was accelerated to an energy of 1.5 MeV/u. In April 2017, the RFQ forward power was successfully maintained at 240 kW for over 2 h. Nevertheless, achieving reliable cw operation at the 250 kW level remained a challenge.

Driven by the need for more stable and efficient deuteron beam operation, the redesign of the SARAF RFQ rods to reduce the integrated RFQ load has been completed. The designed accelerating voltage was reduced from 65 to 56 kV, which correspondingly decreased the output beam energy from 1.5 to 1.27 MeV/u. During the second installation campaign in June 2017, the new electrodes were installed with adapted shims. The upgraded RFQ was successfully conditioned to achieve an rf power of 200 kW for cw deuteron operation, demonstrating a sufficient power margin to ensure stable performance. As reported in Ref. [27], a 5.3 mA pulsed deuteron beam has been successfully accelerated using the RFQ operating in continuous wave (cw) mode. The primary RFQ parameters, including rf power loss, output energy, and emittances, are close to their design specifications. However, the RFQ transmission efficiency remains relatively low. During the beam commissioning of the SARAF RFQ in 2022, the achieved transmission was significantly higher than 90%. The cause of this discrepancy remains unclear but could be attributed to improvements made to the SARAF ion source during this period.

D. SPIRAL2 RFQ at GANIL

The SPIRAL2 RFQ, part of the Second Generation System for On-Line Production of Radioactive Ions, features a four-vane structure with an innovative mechanical design that eliminates the need for brazing such a large assembly. The RFQ electrodes, fabricated from solid copper, are bolted to a thick copper tube using metallic vacuum and rf joints. It was designed to accelerate a continuous wave (cw) ion beam with a charge-to-mass ratio

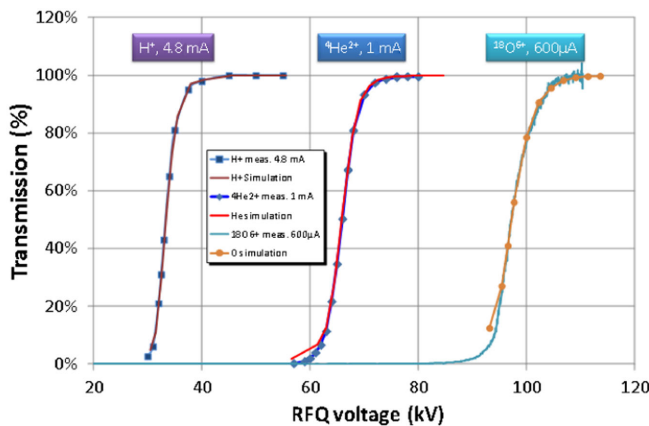


FIG. 6. Results of simulation and measurement with various beams of SPIRAL2 RFQ.

of 1/3 from 20 keV/u to 0.73 MeV/u. The RFQ transmission results from simulations and pulse mode measurements are compared in Fig. 6 [28]. Under nominal conditions, the RFQ achieves a transmission efficiency of approximately 100%. Continuous wave (cw) proton, helium, and oxygen beams were successfully accelerated up to 2018. However, in cw mode, sparking began to occur at 105 kV within the cavity. The cw $^{18}\text{O}^{6+}$ beam was successfully accelerated at a reduced voltage of 105 kV, achieving a transmission efficiency of 93%. Improvements in the low-level radio frequency (LLRF) system and cavity conditioning procedures enabled operation at voltages exceeding 114 kV with an availability above 95%, resulting in enhanced RFQ transmission. Specifically, as the vane voltage increased from 105 to 114 kV for the $A/q = 3$ beam, the transmission efficiency improved from 93% to 100% [29,30].

E. FRANZ RFQ at IAP

The Frankfurt Neutron Source at Stern-Gerlach Center (FRANZ) was originally designed to accelerate a 200 mA proton beam from 120 to 700 keV within a length of 1.6 m. The RFQ is coupled to an 8-cell Interdigital H-mode Drift Tube Linac (IH-DTL), which further accelerates the proton beam to a final energy of 2.1 MeV. Within a total length of 0.7 m, this system includes an xy-steerer followed by three gaps, a magnetic quadrupole triplet, and a gap section. The coupled RFQ-DTL cavity with one feeder line is illustrated in Fig. 7 [31]. Measurement results comparing the vane-vane voltage and gap voltages with design values are shown in Fig. 8. The RFQ power was tested up to 90 kW in continuous wave (cw) operation, approaching the nominal power. However, overheating at the exit flange necessitated maintenance. Given that the CHORDIS ion source only provides a 35 keV proton beam, an electrostatic postaccelerator was developed and commissioned at the Institute for Applied Physics (IAP) to elevate the beam energy to 60 keV. Due to the inability to reach the designated RFQ injection energy of 120 keV, the injection energy was reduced to 60 keV, and the RFQ electrodes were redesigned [32]. Beam commissioning of the post-accelerator was conducted in October 2021, successfully

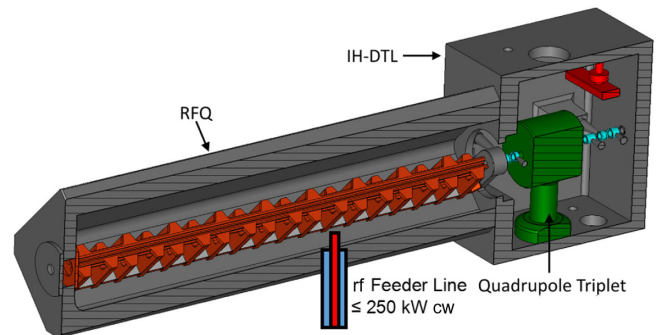


FIG. 7. FRANZ coupled RFQ-DTL cavity with one feeder line.

rf Coupling – Investigations: Vane-Vane voltage and gap voltages compared to design values

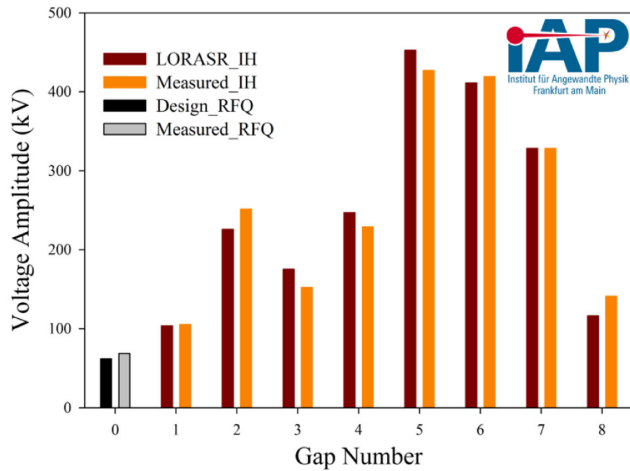


FIG. 8. FRANZ RFQ vane-vane voltage and IH-DTL gap voltages compared to design values.

achieving a 60 keV proton beam. The final design optimization and precision machining of the RFQ electrodes were completed in 2022. In 2024, the RFQ was conditioned up to 140 kW cw. Additionally, beam tests have been conducted, demonstrating a transmission efficiency exceeding 95%. The 2 MeV beam is expected in 2025.

F. IFMIF RFQ by INFN

The International Fusion Materials Irradiation Facility (IFMIF) RFQ aims to demonstrate the acceleration of a 125 mA continuous wave (cw) deuterium ion beam up to 5 MeV. At 9.8 m in length, it is the longest RFQ in the world. After the RFQ cavity underwent baking and was connected to both the cooling and rf systems, rf conditioning commenced in July 2017. The first proton beam acceleration commenced in June 2018. In the summer of 2019, the RFQ successfully accelerated its nominal 125 mA deuteron (D^+) beam current to 5 MeV, achieving a 90% transmission efficiency for pulse lengths of 1 ms at a

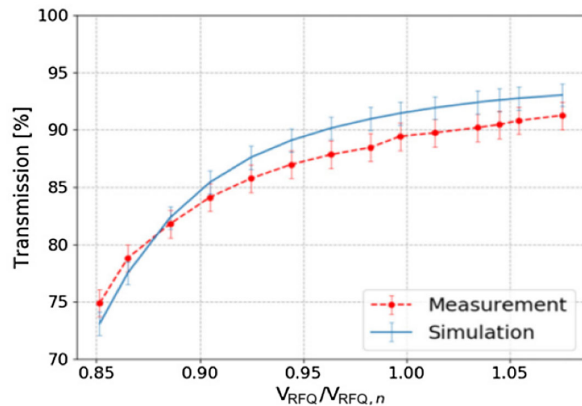


FIG. 9. IFMIF RFQ transmissions at different voltages for 125 mA deuteron beam.

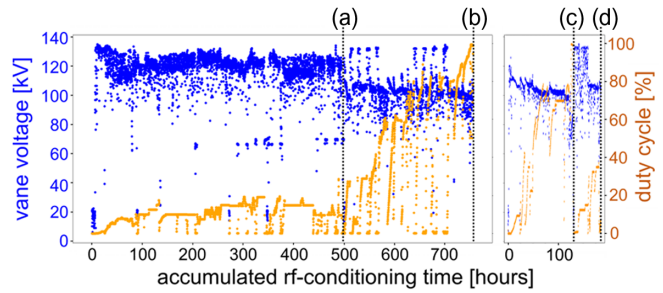


FIG. 10. IFMIF RFQ voltage and duty cycle histories during rf conditioning. (a)–(d) are the boundaries of different conditioning stage. Before (a), the duty cycle is limited at 25%, after (a) the strategy is changed to reach cw first at a reduced RFQ voltage, and at (b) 80% of the nominal RFQ voltage reached cw, at (c) a circulator in the RFPS was found damaged, at (d) a vacuum leak was detected.

repetition rate of 1 Hz, as illustrated in Fig. 9 [33]. In 2022, the RFQ successfully conducted continuous wave (cw) operation at 80% of the nominal voltage. Cw beam commissioning of the injector was performed using various aperture sizes. Figure 10 shows the RFQ voltage and duty cycle histories during rf conditioning. When rf conditioning was resumed to reach the nominal RFQ voltage in continuous wave (cw) mode, a circulator in the rf power supply (RFPS) was damaged, and a vacuum leak was detected in the remaining seven chains [34]. The damaged circulators in power link have been replaced with new units, and the ceramic window O-ring sealed couplers have been upgraded to couplers featuring brazed ceramic windows [35,36]. Based on the latest available information, the injector has successfully completed its continuous-wave (cw) operational mission [37].

III. COMMON PROBLEMS AND SOLUTIONS

With the rapid advancement in high-power RFQ technology, numerous challenges have been identified and valuable lessons learned regarding high-power rf conditioning and beam commissioning. The RFQ system is highly complex, and operational issues are frequently encountered in several key components: the resonator, amplifier, transmission line (primarily power coupler), and tuning system. Each of these components presents unique challenges that can significantly impact overall system performance. A typical system configuration is illustrated in Fig. 11. Common problems in high-power RFQ systems include thermal issues, multipacting, sparking, stability concerns, and frequency detuning. Different solutions have been proposed and implemented across various laboratories to address these challenges.

A. Thermal problems and solutions

The SARAF RFQ coupler was identified as the bottleneck preventing long-term continuous wave (cw) opera-

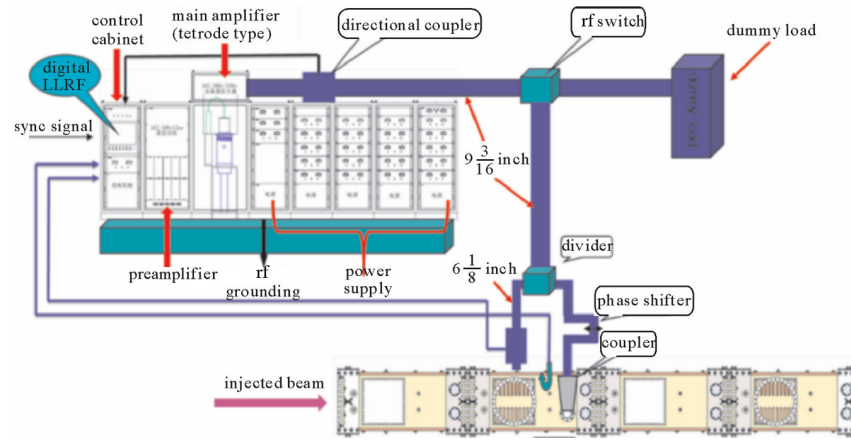


FIG. 11. Typical rf power system and cooling system of an RFQ.

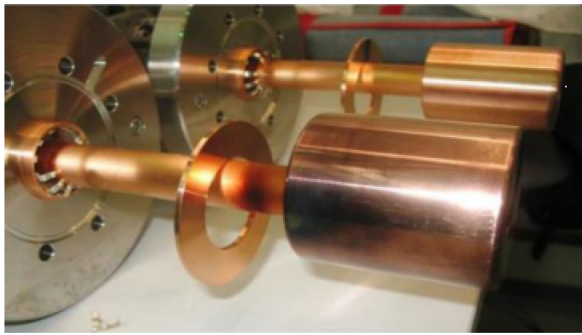


FIG. 12. Broken and deformed rf fingers of the plunger sliding contacts of SARAF RFQ.

tion at high dissipated power. Several improvements were implemented to enhance system performance. Specifically, to reduce the heat load on each coupler, the RFQ's rf feeding line was split into two couplers. Additionally, the couplers were redesigned to mitigate potential failure modes [38]. The issues preventing the RFQ from achieving cw 250 kW are complex, necessitating a comprehensive design review to address thermal problems effectively [39]. Indeed, the rf fingers of the plunger sliding contacts were found to be broken and deformed, as

illustrated in Fig. 12. To prevent cold welding and ensure uniform contact pressure, rhodium-plated, more rigid finger shafts were used to provide stable alignment for the plungers. Severe heating of the RFQ end flanges was observed, leading to discoloration as illustrated in Fig. 13. To address this issue, an efficient water cooling design was implemented, and the rf contact between the flanges and the end plates was enhanced.

The C-ADS Injector I RFQ also encountered thermal issues [40]. The conditioning of the RFQ at a duty factor of 71% and 250 kW was halted due to a vacuum leak in the entrance plate. The temperature exceeded 400 °C because the cooling water valve for the plate had been closed. An RFQ power level of 257 kW at a duty factor of 80% was achieved in June 2014. However, the conditioning process was once again interrupted due to a vacuum leak in the RFQ coupling plate. Vacuum leaks in the RFQ entrance and coupling plates are illustrated in Fig. 14. The intricate design of both the cooling channel and the dipole stabilization rod posed significant challenges for welding. To address these challenges, a new cooling channel design was developed.

In summary, the primary challenge facing cw RFQs is thermal issues. Solutions to these thermal issues include

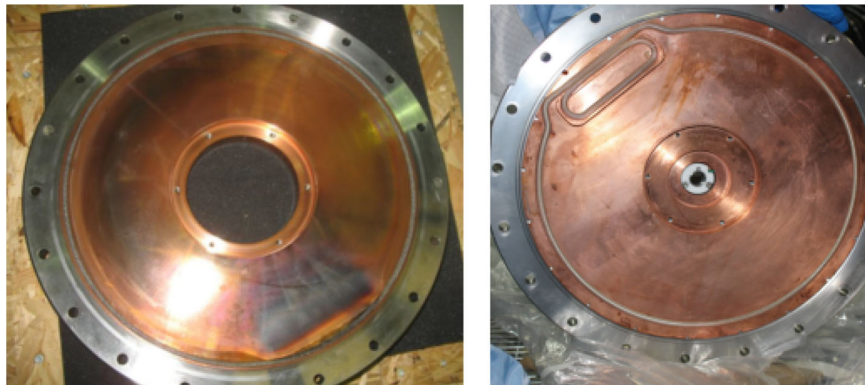


FIG. 13. Heating of RFQ end plates and the discoloration of flanges of SARAF RFQ.

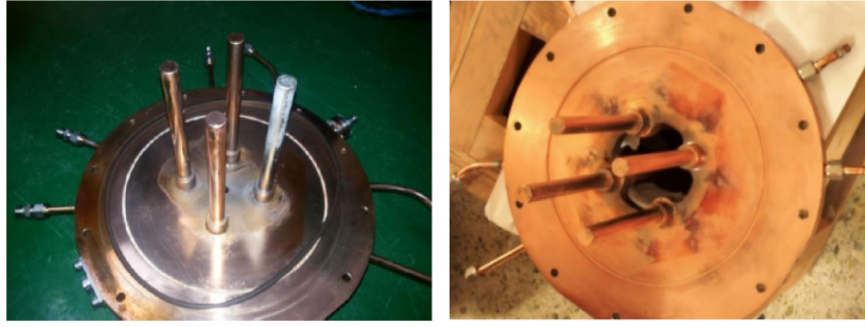


FIG. 14. Vacuum leakage in entrance plate (left) and coupling plate (right) of the C-ADS Injector I RFQ.

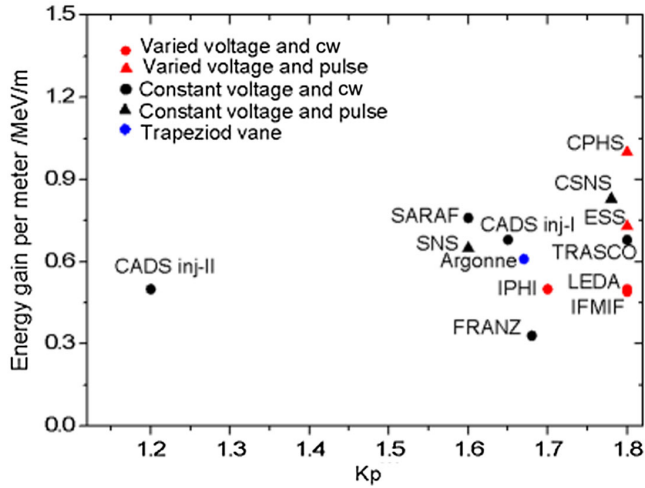


FIG. 15. Varied voltage and the trapezoid vane adopted in many projects.

optimizing the accelerating electric field E_{acc} and peak magnetic field B_{peak} . Optimizing E_{acc} results in lower power consumption for the entire cavity, thereby facilitating the achievement of rf conditioning goals. This optimization also improves accelerating efficiency and reduces the length of the RFQ. Two effective strategies have been adopted to enhance the accelerating efficiency of the acceleration section in numerous projects, as shown in Fig. 15. One strategy is to vary the voltage, a method that has been implemented in several RFQs, including IFMIF, IPHI, ESS, LEDA, and CPHS. The average peak axial accelerating fields of the varied voltage and constant voltage designs are compared in the CPHS, as illustrated in Fig. 16 [41]. Another innovative idea is the trapezoidal vane design from Argonne. Results indicate that this trapezoidal vane can increase the resonator's shunt impedance by 34% [42].

Optimizing B_{peak} contributes to a decrease in maximum power density. Among existing RFQ systems, the LEDA RFQ demonstrates the highest power loss per meter, reaching up to 185 kW/m. Despite this considerable power dissipation, the RFQ successfully operated in continuous wave (cw) mode. Subsequently, the C-ADS Injector I RFQ achieved a maximum of 58 kW/m with effective cooling,

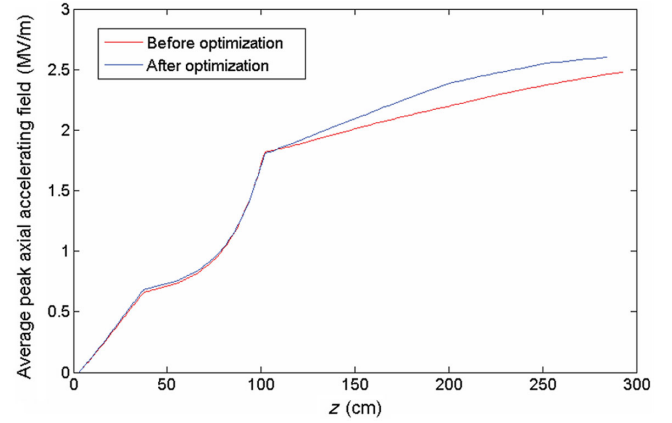


FIG. 16. Comparison of varied voltage and constant voltage in CPHS.

whereas other RFQs have either failed to meet rf conditioning goals or have functioned at lower power densities. The discrepancy between cw performance and power loss per meter remains unclear. Therefore, a comprehensive review of cw RFQ design parameters on a global scale was conducted. The study compared power loss per meter, maximum power density, average power density, and the ratio of maximum power density to power loss per meter across various projects, as illustrated in Fig. 17 [43,44]. The findings indicate that maximum local power density is more critical for cooling efficiency than power loss per meter. Although the LEDA RFQ has the world's highest power loss per meter, its maximum local power density is not correspondingly high, effectively cooled at 65 W/cm². Consequently, careful consideration and optimization of the ratio between maximum power density and power loss per meter are essential.

B. Multipacting problem and solution

Multipacting discharge represents a significant challenge in the rf conditioning of the C-ADS Injector I RFQ. During rf power ramp-up to high levels, such as 250 kW with a duty factor of 99.97%, multipacting barriers were encountered and could not be mitigated. To address this

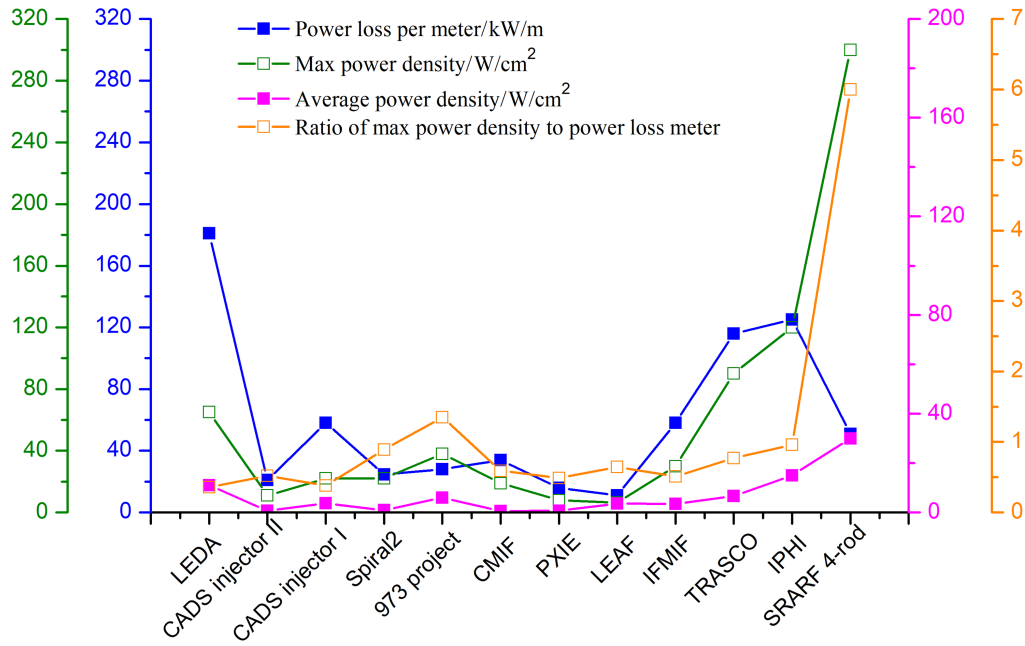


FIG. 17. Power loss per meter, max power density, average power density, and the ratio of max power density to power loss per meter were compared.



FIG. 18. Inlet cooling pipe of the second coupler of C-ADS Injector I RFQ leaked possibly resulting from strong multipacting.

issue, the conditioning mode was switched from pulse to continuous wave (cw). However, during cw operation at 194 kW, the conditioning process faced an interruption due to a leak in the inlet cooling pipe of the second coupler, which is believed to have been caused by strong multipacting effects, as illustrated in Fig. 18 [45]. A 0.6-m-long RFQ model was utilized for multipacting analysis, where the surface conductivity was artificially reduced to achieve a β value of approximately 1.5 and a power reflection coefficient of 4%. Analysis results indicated that very strong multipacting patterns were observed primarily within the narrow section of the coaxial waveguide when the power was below 60 kW. Furthermore, in the power range of 130 to 170 kW, strong multipacting effects were noted on the RFQ flat wall. Simulation studies initially focused on long-pulse full-power conditioning followed by cw conditioning exceeding 170 kW. Conditioning resumed in pulse mode after encountering limitations. When operating at high rf powers, such as 270 kW with a duty factor of 94%, the system continued to face challenges, including being limited to 158 kW cw power due to multipacting discharge. Upon disassembly of the first coupler, discharge spots were observed on the vane, as shown in Fig. 19.



FIG. 19. Vane surface of C-ADS Injector I RFQ nearby coupler and electrode surface opposite to coupler.

Despite these issues, the Q value remained within the normal range of 7000 to 7700, indicating that the cavity's Q value was not significantly affected by the discharge spots.

Multipacting phenomena were identified not only in the C-ADS Injector II but also in the SARAF RFQs. The beam current of the C-ADS Injector II RFQ achieved a continuous wave (cw) level of 10 mA and was sustained over an extended period, demonstrating stable operation. After completing rf conditioning and cw beam commissioning, the RFQ was maintained in readiness for subsequent superconducting linac commissioning. During this process, blue marks were observed on the vane tips and end plates (Fig. 20), while arc detectors continued to register light emissions despite the surface near the coupler remaining clean. In the SARAF RFQ with a four-rod structure, discharge was observed between the back sides of the rods and stems (Fig. 21 [46]). To mitigate field emission toward the opposite voltage stem, the back side was machined. Prior to machining, the electric field in this

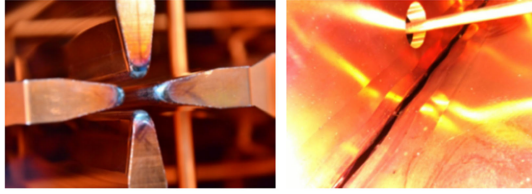


FIG. 20. Blue marks can be seen at the vane tips and end plate of C-ADS Injector II RFQ.



FIG. 21. Discharge between back of the rods and stems of the SARAF RFQ.

area reached as high as 65 kV per 5 mm, highlighting the necessity of such modifications to ensure operational stability and safety.

Several strategies aimed at suppressing multipacting discharge during rf conditioning have been proposed. These approaches include optimizing the geometry of rf components, enhancing surface treatments, and adjusting operational parameters to mitigate multipacting effects. First, an rf-vacuum feedback control logic was implemented to regulate rf power in response to vacuum pressure changes during conditioning. Second, drawing on experiences from the commissioning of the LEDA RFQ, a pulsing method involving pulses up to 10 ms in duration

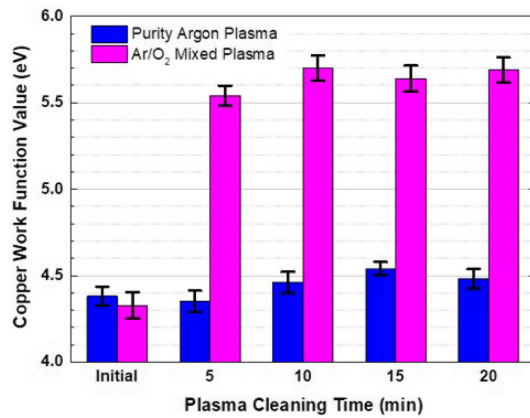


FIG. 22. Work function of copper increased by plasma processing.

at 100 Hz has been consistently applied, even during near-continuous wave (cw) operation. Third, improving the quality of oxygen-free high conductivity (OFHC) copper has been emphasized to reduce electron emission. Additionally, the successful plasma cleaning technique originally developed for superconducting cavities has been adapted for use in copper cavities. Notably, plasma processing has been shown to increase the work function of copper, effectively suppressing multipacting discharge, as illustrated in Fig. 22. This enhancement highlights the importance of advanced surface treatments in achieving stable rf system performance.

C. Power coupler problem and solution

In the context of delivering power to the RFQ resonator, the power coupler plays a crucial role. During the commissioning of ADS-Injector II, the ceramic window of the RFQ coupler experienced two significant cracking incidents, as illustrated in Fig. 23. The first incident was attributed to the rf seal spring breaking and subsequently falling onto the ceramic surface. Due to heating caused by vortex currents, the rf seal spring on the ceramic window reached temperatures exceeding 800 °C, creating a hot spot that resulted in the ceramic window cracking. After this incident, the necessity of the rf seal spring was reassessed. It was found that the boss on the outer conductor of the ceramic window ensures rf contact. Given that an improperly assembled rf seal spring can introduce instability into the system, it was determined that the rf seal spring is not indispensable. Consequently, the decision was made to eliminate the rf seal spring positioned between the outer conductor of the ceramic window and the outer conductor of the coupler. The second incident occurred during the conditioning process following the installation of a spare ceramic window. This issue arose because the flexible pipes used for cooling the inner conductor of the ceramic window were folded, leading to insufficient cooling of the inner conductor. To address this problem and prevent future

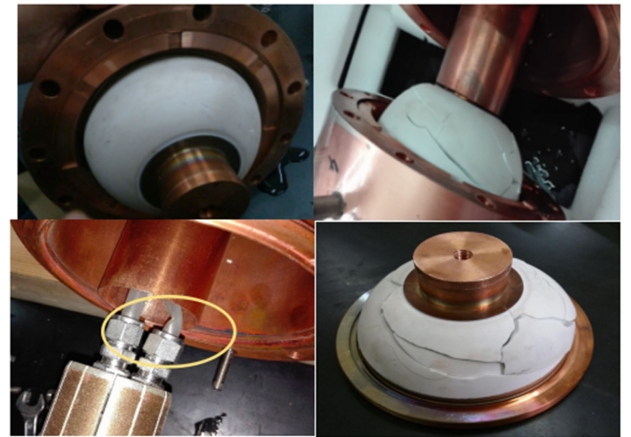


FIG. 23. Ceramic window of C-ADS Injector II RFQ broken 2 times.

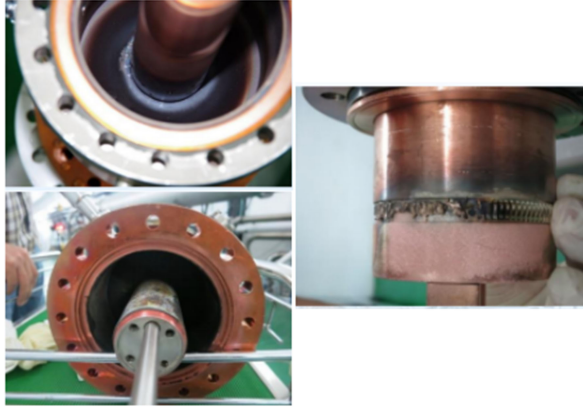


FIG. 24. Window was damaged due to the disabled interlock (higher left), the rf contact spring burning (right), the ceramic cracked due to excessive humidity of the tunnel (lower left) in C-ADS Injector I RFQ.

folding, the flexible cooling pipe was replaced with a rigid pipe to ensure adequate cooling performance.

The ceramic window of the coupler in C-ADS Injector I experienced cracking incidents on four separate occasions during high-power testing and online operation, as illustrated in Fig. 24. The first incident was attributed to a disabled interlock and human operational error. In response, a safe commissioning mode was introduced for subsequent online operations to mitigate such risks. The second incident resulted from a vacuum leak at the antenna tip, which was traced back to severe multipacting occurring in the narrow coaxial section. To address this issue, a titanium nitride coating was applied as a solution. The third incident involved the burning out of the rf contact spring. Following this event, improvements were made to the rf contact structures to enhance reliability and performance. The final incident was caused by the shorting of the inner and outer conductors due to condensate water. Measures were taken to reduce the humidity in the tunnel and increase the temperature of the coupler cooling water to prevent condensation, thereby addressing the underlying cause of this failure.

D. High-power amplifier problems and solutions

Today, numerous RFQ accelerators are operational in laboratories worldwide. Regardless of whether a four-rod

or four-vane structure is employed, the rf system provides two primary options for power sources: vacuum electronic power sources (such as tetrodes or klystrons) and SSPAs. Several high-power RFQs have considered vacuum electronic power sources due to cost considerations and the demands of high-power structures. These systems require very high-voltage dc power supplies and complex control logic. Indeed, this power source operates as a chain system where the stable operation of each device or component is critical; any failure in the rf system can lead to beam shutdown.

For the RFQ cavity of the C-ADS Injector II, a 200 kW tetrode amplifier was utilized to accomplish the conditioning and commissioning in 2014. A highly complex rf system was developed, incorporating a TH781 final-stage amplifier, a solid-state preamplifier, power supplies, modulators, and a transmission system. To accommodate two identical couplers for power feeding, a specialized high-power splitter and phase shifter were integrated into the transmission system. Additionally, a 200 kW rf switch was employed to independently evaluate the performance and identify failure points of both the couplers and the RFQ cavity. However, during the initial two years of continuous operation, several burning failures occurred within the rf system, as illustrated in Fig. 25. These failures, observed in components such as the tube socket and insulation film, are likely attributable to very high voltage conditions. Furthermore, the input/output cavity within the TH571B assembly suffered burn damage due to extremely high-power levels and a compact rf structure.

Another power source is the SSPA, which operates within a low voltage range of 30 to 100 V. The SSPA solution presents several significant advantages over vacuum tubes. These include high modularity with built-in redundancy and flexibility, elimination of the need for high-voltage supplies and high-power circulators, simplified startup procedures and operational controls, a reduced requirement for periodic replacements, and easier maintenance.

As previously discussed, solid-state amplifiers are exceptionally suitable for the construction of accelerator projects, particularly those involving large-scale linear accelerators. Their suitability is attributed to several key advantages: high reliability facilitated by modular design, the capability to operate in parallel configurations, and enhanced



FIG. 25. Input cavity, socket of tube, output cavity of a 200 kW tetrodes amplifier were burned in C-ADS Injector II.



FIG. 26. Tetrode AMP (left) and two 80 kW SSPAs (right).

maintainability. These features collectively contribute to more dependable system performance and reduced downtime, making them ideal for demanding applications. Moreover, in our design, all core components, such as power amplifier pallets and dc supply modules, are standardized to ensure interchangeability across different manufacturers. Most importantly, the new design supports “hot swapping,” allowing for the immediate replacement of any failed module without interrupting beam operation.

In pursuit of high reliability, two 80 kW SSPAs were installed for the RFQ cavity in 2016, replacing the old tetrode amplifiers, as shown in Fig. 26. Over the subsequent five years of operation, minor issues were addressed by exchanging power pallets and related components. Consequently, the failure rate of the rf system has significantly decreased, thereby providing robust support for beam commissioning.

Furthermore, the simple structure and low voltage requirements of SSPA have facilitated the introduction of innovative technologies and concepts such as hot swapping, single-stage power combining, and load-pull methodologies. Additionally, advancements in solid-state amplifiers, driven by progress in 5 G communications and defense industry, have led to significant improvements. These advancements have been particularly notable with the adoption of the latest semiconductor materials. As of 2023, civilian research institutes and companies have mastered and optimized processing technologies and performance enhancements. Specifically, third-generation semiconductor devices, such as GaN-on-SiC substrate power transistors, have been integrated into the power source for the CiADS project. This integration has significantly enhanced efficiency and power density.

In summary, several tube amplifiers in the RFQ system have been replaced with new solid-state amplifiers, akin to those deployed in systems such as ADS and SARAF, owing to their advantages in simpler operation and maintenance. Recent technological advancements continue to astonish; for example, in December 2022, the Institute of Modern Physics (IMP) completed the first prototype of

a SSPA utilizing GaN high electron mobility transistors (HEMT). This prototype showcased at least a 50% increase in power density and a 15% enhancement in efficiency compared to previous models, which was remarkable. In May 2023, the genuine hot-swap capability—based on controllable short-circuit technology—was successfully demonstrated under conditions of full reflection, wherein a single channel from a failed module was entirely isolated from the overall rf system through an adjustable short port. More recently, our developments in pulsed SSPA applications have led to measuring a high-power pulsed RFQ SSPA lasting 300 μ s. Notably, this system achieved significant milestones, including the installation of a 410 kW SSPA within a solitary 30-inch rack, thus realizing an ultrahigh-power density. This amplifier is designed around a 10 kW GaN HEMT operating at a pulse width of 10 μ s.

In the future, solid-state rf systems are poised to unlock greater potential and will concentrate on multiple facets of accelerator development. These aspects include enhancing high reliability, developing specialized combining structures, advancing rf isolation techniques, achieving high-accuracy measurements in complex electromagnetic environments, and realizing ultrahigh pulsed power capabilities. Such advancements are anticipated to significantly contribute to the progression of accelerator technology.

E. Frequency detuning of RFQ and solutions

During the beam experiment on C-ADS Injector II, a significant power reflection from the power coupler was observed when a 10 mA continuous wave (cw) beam passed through the RFQ. To minimize this reflected power and ensure stable operation, the RFQ had to be detuned. The beam commissioning process of the RFQ at a 10 mA cw beam is illustrated in Fig. 27. During the ramping process to achieve a 10 mA cw beam, the vane temperature fluctuated by up to -0.5°C . Given an experimental detuning value of -16 kHz per degree Celsius of temperature change, this indicates that the RFQ experienced

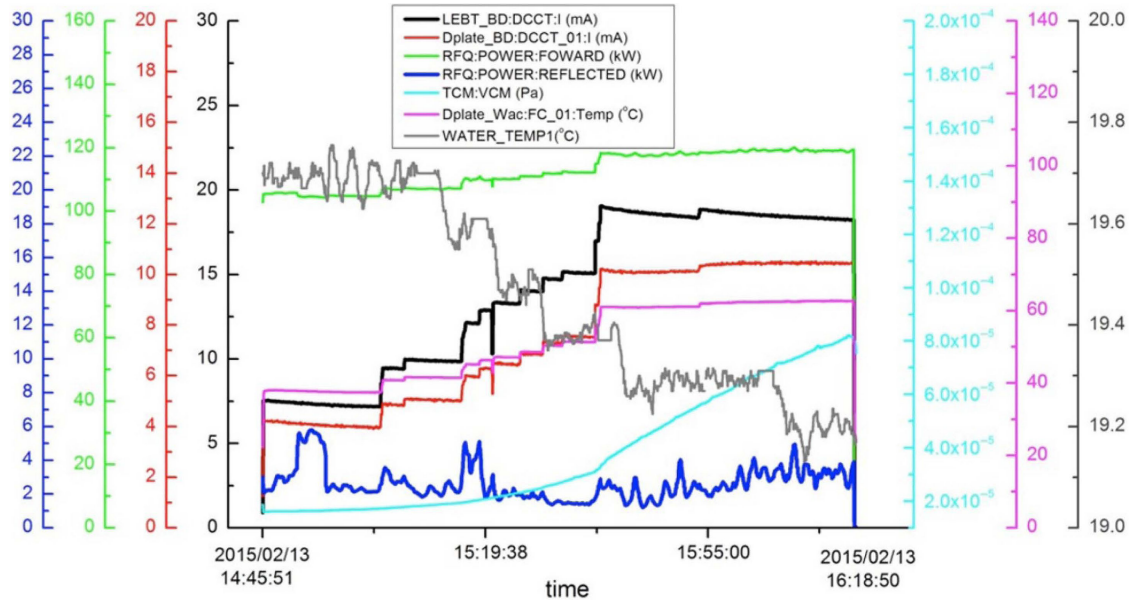


FIG. 27. 10 mA cw beam loading of C-ADS Injector II RFQ.

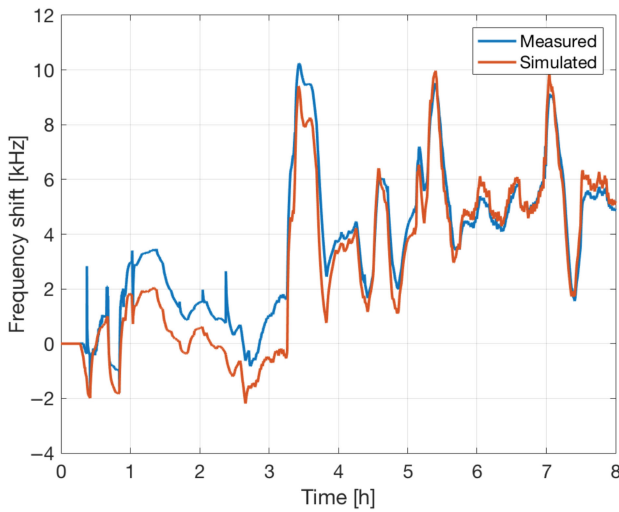


FIG. 28. Simulated and measured frequency shifts of PXIE RFQ.

a detuning of approximately 8 kHz for the observed temperature variation.

The eigenfrequency of the PXIE RFQ exhibited shifts due to perturbations in both the water cooling and rf systems [47]. As shown in Fig. 28, the frequency shift ranged from -2 to 10 kHz, with measurement results closely matching the simulation outcomes. To mitigate these frequency shifts, proportional-integral (PI) control was implemented. The comparison between measured and simulated frequency shifts under PI control during thermal testing is illustrated in Fig. 29. It was observed that the application of PI control effectively reduced the frequency shift; however, the response time remained relatively long.

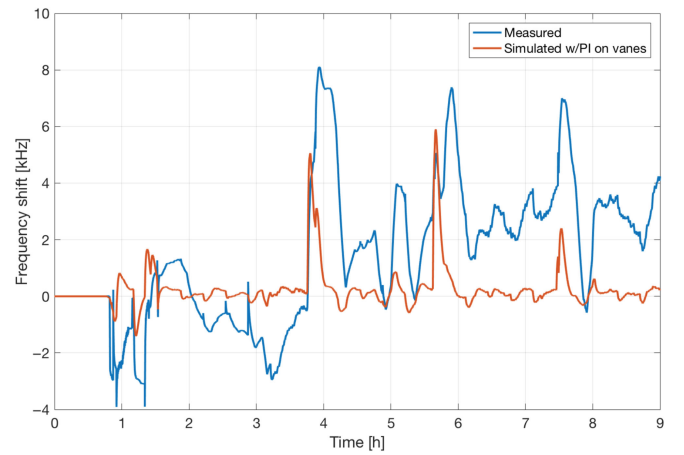


FIG. 29. Measured and simulated frequency shifts with PI control of PXIE RFQ.

A rapid and significant detuning of approximately 50 kHz was observed during the turn-on process of the C-ADS Injector II RFQ. The existing thermostatic water system was unable to compensate for this rapid detuning by temperature adjustments alone. Consequently, a water mixing system was developed at IMP to reduce the response time required for RFQ frequency tuning. The logic diagram of this water mixing system is shown in Fig. 30. This system can rapidly adjust the RFQ frequency by changing the cooling water temperature of the vane. However, additional work is still required on the low-level radio frequency (LLRF) system to ensure stable RFQ operation.

For heavy-ion RFQs, the commissioning with different kinds of beams (e.g., A/q ratios) requires different cavity

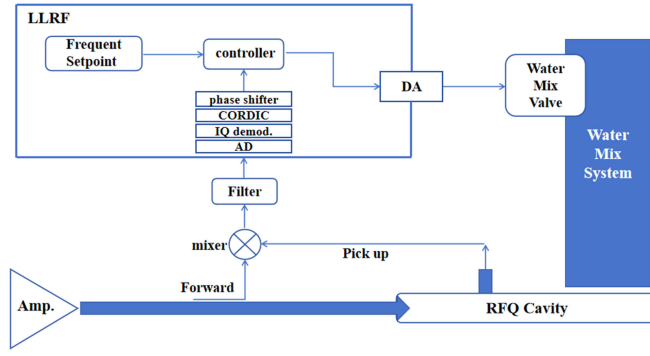


FIG. 30. rf control block diagram of water mix system of C-ADS Injector II RFQ.

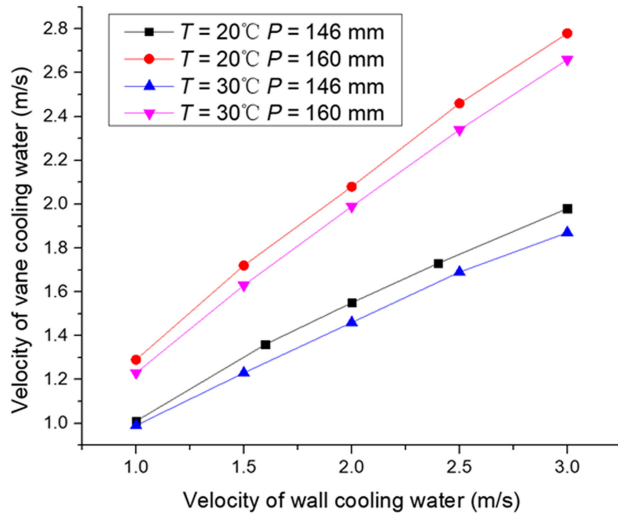


FIG. 31. Cooling water velocity groups achieving no frequency shift in C-ADS Injector II RFQ.

powers. With an appropriately designed cooling channel layout and optimized velocities for both wall and vane cooling water, frequency shifts can be avoided across various cavity power levels. The groups of cooling water velocities used in this optimization are illustrated in Fig. 31.

IV. SUMMARY

Over the past few decades, high-power RFQs have emerged as a focal area of research due to their extensive application prospects. This review examines the development of several typical high-power RFQs worldwide, summarizing the challenges and issues encountered during their development along with corresponding solutions. The most significant challenge for continuous wave (cw) high-power RFQs is thermal management, which can be mitigated by optimizing the accelerating gradient (E_{acc}) and the peak magnetic field strength (B_{peak}). Multipacting discharge poses a significant challenge during rf conditioning. Solutions include implementing rf-vacuum feedback mechanisms, adopting specific pulse modes, enhancing the

quality of oxygen-free high conductivity (OFHC) copper, and utilizing plasma cleaning techniques. Power couplers for high-power RFQs encounter numerous challenges. Achieving optimal performance from these couplers requires precise adjustment of the phase shift between them. High-power amplifiers are another critical component within high-power RFQ systems. The adoption of SSPAs has proven effective in addressing related issues. To mitigate detuning problems, both proportional-integral (PI) control and a water mixing system have been developed. These measures collectively enhance the performance and reliability of high-power RFQ systems.

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