

A LOW-CHARGE-STATE CW RFQ

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Abstract

A two-meter long, 12 MHz RFQ has operated cw at an intervane voltage above 100 kV, the voltage required to accelerate singly-charged ions of mass 132. The prototype unit is the first of three that will be required to provide for efficient injection of exotic beams into the existing ATLAS heavy-ion linac, while maintaining the high beam quality characteristic of ATLAS beams. The room-temperature, normal conducting RFQ utilizes indium gasketed joints, originally developed for the superconducting resonators of ATLAS, to maintain good vacuum, thermal, and rf properties while permitting a highly modular design. Another unusual feature of the design was the use of aluminum for the main structure, which was electroplated with 100 microns of silver to minimize rf losses in critical areas. Preparations are currently underway for beam tests to be performed later this year.

1 INTRODUCTION

The superconducting heavy-ion accelerator ATLAS can provide ion beams of any mass, including uranium, with state-of-the-art beam quality, particularly with respect to longitudinal emittance [1]. A related characteristic of ATLAS is very large transverse acceptance. Because of these characteristics, ATLAS is highly suitable for the task of accelerating radioactive ion beams [2,3]. ATLAS is presently injected by an electron cyclotron resonant (ECR) ion source capable of producing high charge-state ions, for example uranium 26+ [1]. For hard-to-produce exotic species, however, we require the use of more efficient ion sources, which produce singly-charged ions. For such charge states obtaining sufficient transverse focussing to maintain good beam quality becomes problematic, particularly for the heavier ions.

Table 1: RFQ Design Parameters

Parameter	Value
Frequency	12.125 MHz
Structure	Split-coaxial
Voltage (vane-vane)	100 kV
Peak Electric Field	12.8 MV/m
Minimum Aperture	8 mm radius
Modulation Factor	1.5
Benchmark Beam	$^{132}\text{Sn}^{1+}$
Entrance Energy	378 keV
Exit Energy	1508 keV
Number of cells	44
Length	222 cm
Synchronous phase	-30 degrees

Adapting ATLAS to radioactive beams requires development of a low-charge-state injector capable of maintaining the good features of ATLAS. The design of the entire injector system has been discussed elsewhere [2,3]. This paper discusses the design and development of the entrance section [4].

For heavy ions of charge state 1+ and energies of a few hundred keV, an electric quadrupole provides the strongest possible transverse focusing, and thus the greatest possible transverse acceptance. This consideration dictates the choice of an RFQ structure for the entrance section. The primary technical challenge arises from the requirement of maintaining substantially smaller longitudinal emittance than is typical for an RFQ.

2 DESIGN FEATURES AND PARAMETERS

The RFQ design parameters are shown in Table 1. These parameters provide for our initial development goal of producing high-quality beams of singly-charged ions as heavy as mass 132. Ions of less mass can then be accommodated by turning down the RFQ operating voltage.

The split-coaxial geometry was chosen since it has already been shown to be suitable for very low frequencies [5], and to maximize the aperture of the device, we want the RFQ to operate at as low a frequency as practicable. In this way we both maximize the transverse acceptance and also minimize longitudinal emittance growth.

The primary reason we chose to inject the RFQ with a pre-bunched beam was to maintain a smaller longitudinal emittance than results from bunching within the RFQ

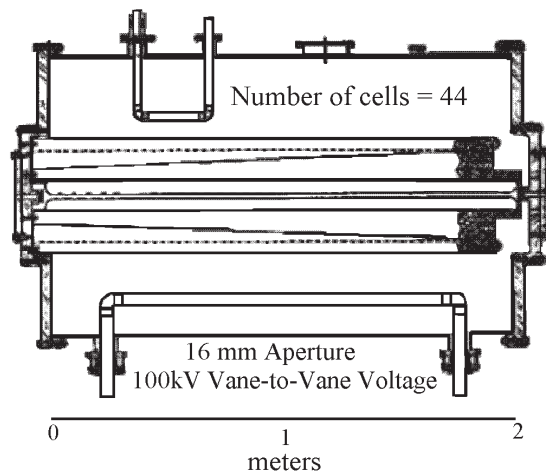


Figure 1: Section of 12 MHz split-coaxial RFQ

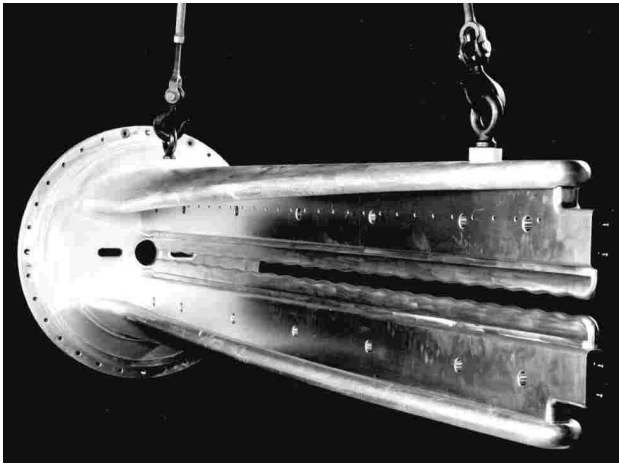


Figure 2: Two-meter long vertical vane pair.

structure [6]. There are several additional benefits from pre-bunching. By separating out the bunching function, the entire length of the RFQ can be used for acceleration, providing more voltage gain. A less obvious benefit results from the fact that the split-coaxial structure is characterized by a voltage offset at entrance and exit of half the vane-vane voltage. With a pre-bunched beam, we are able to make use of the voltage offset by attaching a drift tube to the high-voltage vane pair at both the entrance and the exit of the RFQ. The two drift tubes provide appreciable accelerating field, and increase the voltage gain through the structure by more than 20%.

3 MECHANICAL CONSTRUCTION

Figure 1 shows a section of the cavity. The structure is fabricated as several elements which are demountably joined using an indium-gasket seal described in more detail below. All elements are of 6061 aluminum, except for the RFQ vane tips which are formed of copper. Assembling the cavity from several elements greatly simplifies the machining and forming of the structure. Mechanical tolerances are effectively relaxed, since the structure can be assembled and examined, then disassembled and critical surfaces re-machined to correct mechanical misalignments or errors in rf tuning or field distribution.

A major sub-assembly, the vertical vane pair, is shown in Figure 2. The two-meter long vanes are cantilevered from the end flange which mounts at one end of the cylindrical outer housing. The low density of aluminum permits massive, monolithic structural elements providing good thermal and mechanical stability, while keeping mechanical resonant modes at high frequency. This helps minimize the effects of ambient vibration on the rf eigenfrequency.

Using a demountable joint to attach the vane tips provides several advantages. It is relatively inexpensive to completely replace the vane tips, and by so doing modify virtually any RFQ beam parameter. Also, we can then use copper in the high electric field region of the cavity,

where the use of aluminum would possibly increase sparking and reduce the maximum attainable voltage.

Aluminum is appreciably inferior to copper or silver as an rf conductor. To reduce rf losses, those areas of the RFQ supporting high rf currents were electroplated with a 100 micron thick layer of silver.

3.1 Demountable Indium Gasket Joint

The demountable joint used was developed more than two decades ago: several thousand such seals have been used in the superconducting cavities and cryogenic plumbing of the ATLAS accelerator. The design has been found to provide a highly reliable seal with good vacuum and thermal properties. The rf losses in metal to metal joints formed in this way are known to be small from direct measurement in superconducting cavities.

A section of a typical gasketed joint is shown in Figure 3. The gasket is 1.6 mm diameter, high-purity indium wire. One surface of the joint is planar. The opposing surface is grooved to hold the indium wire, the groove having a cross-sectional area typically 65% of the wire cross-section. A key feature of the seal design is that the region to either side of the indium groove is relieved. The relief provides that when the mating surfaces are clamped together, excess indium is extruded into the relief volume. In this way, the compressed area is well-defined and limited in size. The loading on the seal is uniform, and the flow of indium when the seal is made up proceeds rapidly, with a short relaxation time.

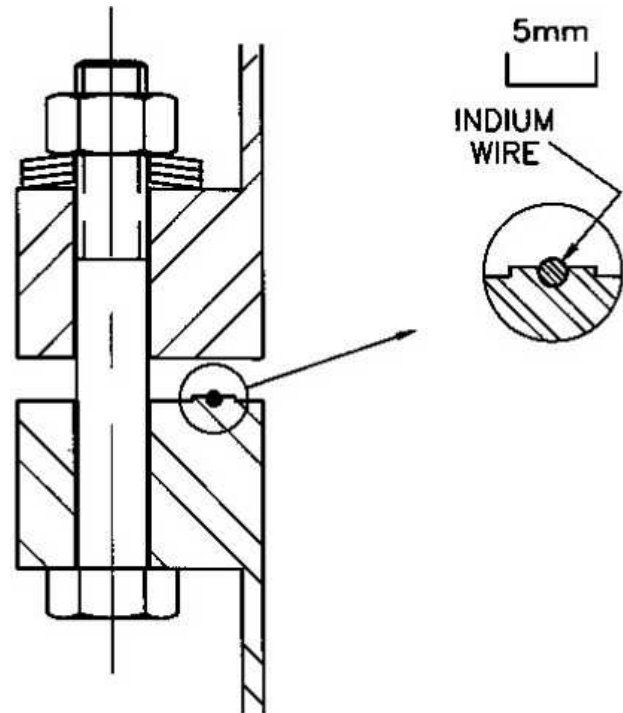


Figure 3: Details of the indium gasket seal used to make a joint with good RF, thermal, and vacuum characteristics.

4 EXPERIMENTAL RESULTS AND DISCUSSION

Optical measurements following initial assembly indicate that the errors in transverse position of the vane tips are everywhere less than 0.8 mm and the rms error is 0.5 mm. Note that the mean aperture is 20 mm, as is the vane thickness. The observed level of error is expected to be tolerable both for tuning and for the beam interaction. The definitive test, however, will be the planned measurements with beam.

When assembled, the rf eigenfrequency was found to be 11.6 MHz. The loop-coupled tuner can bring the frequency up to 11.9 MHz, still slightly below the design value of 12.125 MHz. For initial testing, and even testing with beam, this discrepancy is of no consequence. For eventual use with the ATLAS linac, a slight change in the vane tips will be required to tune to the design frequency.

The measured intrinsic Q of the RFQ resonant cavity is 8863, a result that indicates the rf losses to be appreciably less than were expected from earlier tests of a (nominally) half-scale model [4]. This result implies that the rf loss properties of the silver plating are excellent, as is discussed further below. To operate at a vane to vane voltage of 100 kV, the RFQ requires 16.6 kW of rf input.

Because of the high Q, the 3 dB bandwidth is slightly more than 1 kHz. In designing the RFQ, there was some concern that the effects of ambient acoustic noise might induce troublesome fluctuations in the rf eigenfrequency. Measured microphonic frequency jitter was less than 100 Hz peak to peak, a small fraction of the intrinsic bandwidth and too small to present any operational problems.

Water cooling to the cavity was configured in nine separate loops to enable calorimetric measurement of the detailed distribution of rf power. The distribution, shown in Table 2, was determined by measuring the flow rate and temperature rise (typically 2 C) in each loop separately. The summed total of calorimetric power agrees quite well with the measured rf input power of 17.4 kW. Of particular interest is the fact that one vane exhibits 40% higher rf loss than the other three. This result indicates the critical nature of the plating process in obtaining good rf performance.

Table 2: Calorimetrically measured RF heating

RFQ Element	Calorimetric Power
Top Vane	2.75 kW
Right Vane	2.72 kW
Bottom Vane	2.86 kW
Left Vane	3.90 kW
Entrance End Flange	1.40 kW
Exit End Flange	1.61 kW
Housing	2.19 kW
Drive Loop	0.07 kW
Tuner Loop	0.87 kW
TOTAL	18.37 kW

The cavity vacuum is maintained by two 500 l/sec turbopumps. With no baking, the vacuum in the cavity reached $6.4 \cdot 10^{-7}$ torr in 72 hours. On initial application

of rf power, sparking was first encountered at a vane-vane voltage of approximately 60 kV and the input power was limited by outgassing. The cavity quickly conditioned up in voltage. After a few hours of conditioning the vacuum outgassing diminished and the RFQ could be operated above 100 kV. During initial tests, the RFQ was operated continuously for some 90 minutes with the vane voltage between 100 and 108 kV and vacuum in the low 10^{-6} torr range. Thermal stability of the RFQ during these tests was excellent.

In the design phase, the performance of the RFQ was projected using the Kilpatrick model. Figure 4 shows the frequency and gap dependent voltage limit (parallel-plate) as originally put forward by Kilpatrick [7]. It should be noted that the often quoted value for the Kilpatrick limit is the asymptotic limit for large gaps from the model shown in Figure 4. For most RFQ implementations, the frequency is sufficiently high that typical vane spacing is in the asymptotic region, where the gap dependence of the voltage limit can be ignored. As we have shown both in the earlier in the half-scale model pulsed rf tests [4] and also in the present 12 MHz cw result, the gap dependence is important in establishing the voltage limits for very low frequency RFQ's.

5 CONCLUSIONS AND FUTURE PLANS

The basic design concepts, i.e., indium rf joints, silver-plated aluminum rf surfaces, demountable copper tips, etc. have proven feasible as evidenced by the voltages achieved in initial tests of the low-charge-state RFQ.

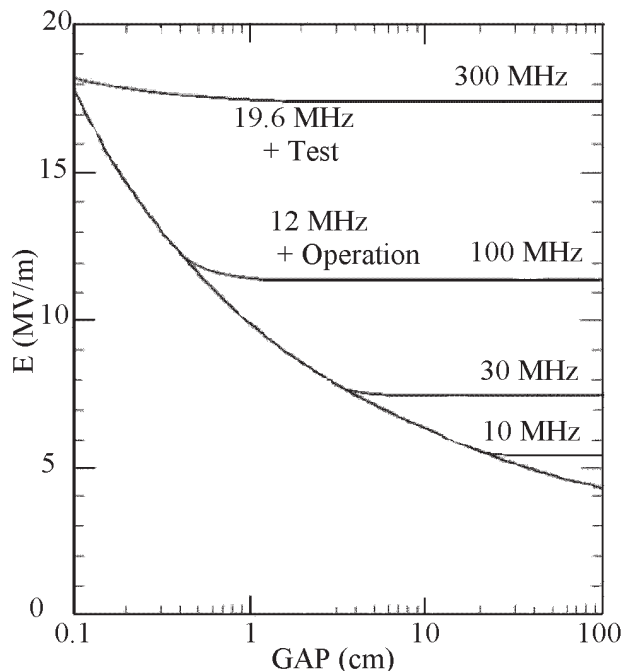


Figure 4: Sparking electric field limits in the Kilpatrick model, including electrode gap dependence.

The vane voltages achieved are sufficient to permit high-quality beams as heavy as uranium to be injected into ATLAS. Although our initial design was for Sn¹³² beam with a transverse acceptance of 0.25 π -mm-mrad, numerical simulation indicates that acceleration of uranium with a transverse acceptance of 0.16 π -mm-mrad while maintaining longitudinal emittance of a few keV-nsec is possible with the voltages achieved.

A remaining development task is demonstration of the expected transverse acceptance and longitudinal beam quality by beam tests. Preparation for such tests are currently underway.

6 ACKNOWLEDGEMENTS

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