THE DESIGN OF RFQ ACCELERATORS WITH HIGH DUTY FACTORS *

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Abstract

For applications with high average beam currents or radioactive beams RFQ-accelerators have to work with high duty factors. Whereas the use of light ions typically requires high frequencies (200 MHz to 400 MHz), lower frequencies (10 MHz to 30 MHz) are chosen for the acceleration of low charged heavy ions. A low frequency resonator (36 MHz) and a high power RFQ-resonator with a high frequency of 216 MHz have been built and tested. The design of the RFQ structures, results of optimizations with respect to impedance and field quality and the status of the work on RFQ-accelerators will be discussed.

1 LOW FREQUENCY HIGH CURRENT STRUCTURES

A 27 MHz Spiral-RFQ has been built as a prototype for the GSI High Current Injector (HCI) and operated successfully [1]. For higher charge states (U^{4+}) an RFQ with an operation frequency of 36 MHz. has been designed and will be built [2]. For this High Current Injector the duty factor is approximately 1 %. For other applications of these low frequency structures a higher duty factor is necessary. Examples are the projects of ‘Tandem replacements’, e. g. at MPI-Heidelberg [3], HMI Berlin [4], and Univ. Erlangen [5]. While at HMI the cyclotron injector requires c. w. operation (80 MHz to 110 MHz), at MPI-Heidelberg (108 MHz) 25 % duty factor and at Erlangen (low frequency, singly charged ions) 20 % to 100 % duty factor are envisaged. For radioactive beam acceleration, low frequencies and high duty factor operation are required, too.

2 VERY LOW FREQUENCY APPLICATIONS

For designing RFQ structures with very low frequencies on the basis of the GSI-HLI-structure [6] with straight stems, the use of very long stems would be necessary, which leads to the compact design with spiral shaped stems at 27 MHz.

Even lower frequencies can be reached e. g. by the use of a very long folded twin-line-waveguide instead of the stems (then the electrodes have to be fixed with additional insulated supports) as e. g. the Very Heavy Cluster-RFQ, operating between 7 MHz and 10 MHz at the DPM Lyon [7].

Another possibility of building a very low frequency resonator is using a folded coaxial waveguide, with electrodes as capacitive load. The waveguide can be folded several times. A model with a resonance frequency of 9.1 MHz and a Q-value of 3500 has been built. As a four folded coaxial resonator its length and its diameter are only 75 cm each. This resonator is now being developed for high voltage tests [8].

This principle can be useful e. g. for radioactive beams like at ANL, where a 12.5 MHz RFQ is planned (c. w. operation).

Another possible application for low frequency RFQs is a cyclotron injector. A proton accelerator with a resonance frequency of 50 MHz is designed and investigated for c. w. operation (figure 1). A current of 10 mA should be no problem, while the longitudinal matching for the cyclotron is the bottleneck.

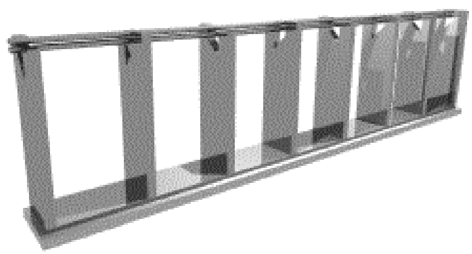

Figure 1: A 50 MHz resonator with 8 stems.

3 THE C. W. RFQ RESONATOR

For testing cooling concepts a high frequency continuous wave resonator has been built at the Institut Für Angewandte Physik in Frankfurt (IAP). It consists of a 4-rod resonator with small vane shaped electrodes and four straight stems. The cooling pipes are integrated in the stems and in the electrodes. The numerous vacuum sealings suffered no problems during high power operation with 20 kW c. w., but for operational structures less complex arrangements will be chosen: Another resonator with a different cooling principle (without vacuum-water-connection) is built now for comparison.

* Work supported by the BMBF

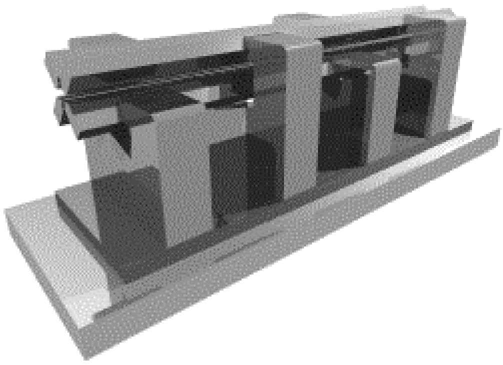

Figure 2: The 216 MHz c. w. resonator.

The prototype had a resonance frequency of 211.123 MHz, a Q-value of 2200 and a shunt impedance of Rp = 129 kΩ, so an electrode voltage of 45 kV could be reached with an rf-power consumption of 20 kW.

This is a first step towards c. w. operation. The new injector for the Rutherford Laboratories (RAL) is an ESS-type application, where light ions (H^-) are accelerated with high frequencies and rf powers of approximately 100 kW/m, duty factors up to 10 % are required.

The RAL-RFQ will work at a frequency of 200 MHz, it will be 1.20 m long and have a maximum rf-power consumption of 200 kW. The duty factor will be up to 10 %. H^--ions will be accelerated from 50 keV (extraction from the ion source) to 665 keV. The design current is 50 mA. Operational reliability and cooling of the resonator are main items within construction.

4 MULTIPOLE CONSIDERATIONS

Beside the main resonator properties like output energies, electrode voltages and power consumption, the field distribution within the electrode array is an important issue. It is responsible for beam quality and transmission.

Dipole contributions and higher order multipoles have been studied by calculating the electric field with the code MAFIA (Solution of **Ma**xwell´s equation by the use of a **fi**nite element **a**lgorithm)[9],[10].

It is well known that not all multipole numbers can occur as long as the quadrupole-symmetry of the array is not violated. The electrode shapes are shown in figure 3, as circular, hyperbolic and slim hyperbolic shapes. In figure 5 it is shown that only the 4-pole, 12-pole, 20-pole components (and very small higher components) have an influence. The columns represent the 4-pole, 12-pole and 20-poles for electrode geometries with hyperbolic, slim hyperbolic, vane shaped and circular electrodes.

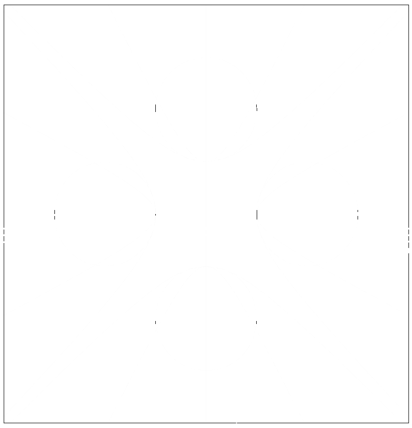

Figure 3: Electrode shapes.

The calculations have been done for an analysis radius of 2 mm (distance from the beam axis), while the aperture radius is 2.5 mm, so this is very close to the electrodes and the multipole components are distinctly high.

In figure 4 the electric field strength within the RFQ array with circular electrodes is shown at a distance of 2 mm from the axis. The total field strength is marked as an x, the 4-pole component as a rhombus, the 12-pole as a square and the 20-pole as a triangle. One can see that, depending on the ratio of aperture to electrode radius, with slimmer electrodes the total field strength and the high 20-pole do not vary significantly, but the disturbing 12-pole increases in the same amount as the 4-pole decreases. Nevertheless the percentage of the 12-pole is very low (5 %), when an RFQ geometry with circular electrodes is used and no asymmetry is produced.

Regarding the field strength as a function of the radius, one can see the 12- and 20-poles being large near the electrodes but nearly zero at beam axis. So influence on beam dynamics is small as long as the aperture is not completely filled with beam.

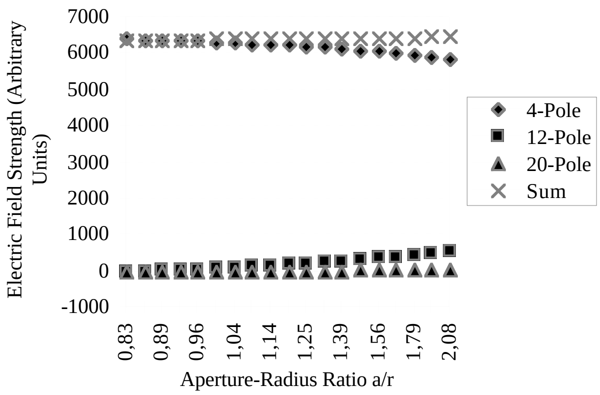

Figure 4: Multipole components of circular rods .

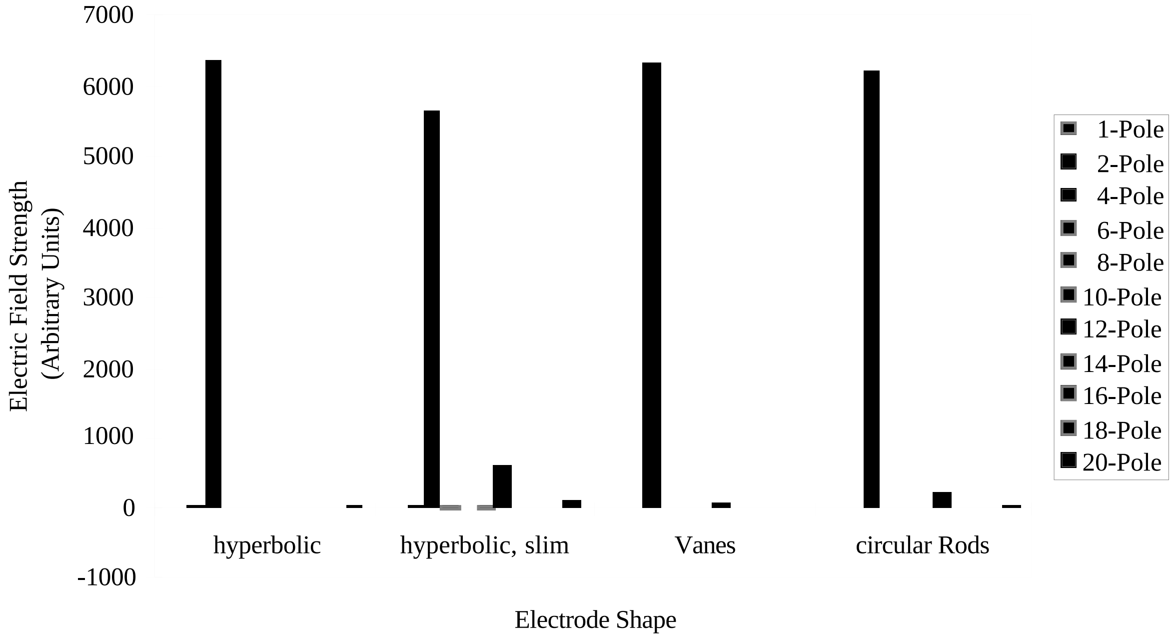

Figure 5: Multipole components of differently shaped electrodes.

5 COMPARISON OF DIFFERENT STRUCTURES

In table 1 the main properties of different RFQs with different operating frequencies are shown.

Table 1: Comparison of different RFQ-structures.

	Frequency / MHz	Q-Value	Shuntimpedance / kΩm
experimental			
Spiral-RFQ	27	5400	520
Stem-RFQ	108	4200	200
Stem-RFQ	211	2200	45
calculated			
Spiral-RFQ	27	6600	600
Stem-RFQ	27	9000	850
Stem-RFQ	36	10500	950
Stem-RFQ	50	10800	550
Stem-RFQ	108	10000	330
Stem-RFQ	214	7500	140

It is well known that RFQ-structures are less efficient with higher frequencies, but size, cost and matching to following accelerators require high frequencies for light ions.

The table shows that there are differences between calculation with the code MAFIA and experimental results. Due to the immanent computer limits, a limited matrix size of the resonator geometry has to be used; with a finer grid the results fit better. Anyway, the code MAFIA has not been designed for such inhomogeneous structures as RFQs, but it is very helpful for structure optimization.

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