DESIGN AND BEAM TESTS OF AN RFQ TO ACCELERATE A LEAD ION BEAM FROM A LASER ION SOURCE

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Abstract

A Radio Frequency Quadrupole (RFQ) for acceleration of a 10 mA lead 18+ ion beam from 6.9 keV/u to 100 keV/u has been designed, built and tested in the framework of the CERN Laser Ion Source (LIS) study. The challenge of the RFQ design was to deal with a lead ion beam that includes about 10 charge states with an overall current of some 100 mA. A new RFQ design, intermediate between the two standard high-intensity and low-intensity designs, has been applied in order to have a compact structure giving small longitudinal emittance and high transmission.

The transport and matching line from the source to the RFQ is made of two solenoids. The unwanted charge states are not filtered and will enter the RFQ mis-matched. In order to test the RFQ performance proper it was decided to operate it with an equivalent mono-species proton beam during the first stage of the commissioning.

The design criteria for this intermediate current RFQ, the problems involved in dealing with a mixture of different charge states, as well as the results of the first test with an equivalent proton beam are presented in this paper.

RFQ Design

The general criteria for designing the RFQ were a high transmission (>90%) and good output beam quality: in particular the r.m.s. longitudinal emittance should not exceed the value of 18 deg keV/u at 100 MHz. Other limitations were given by the length (fixed to 250 cm) and the output energy, which had to be in the range of 100 keV/u to match the downstream analysing magnet.

The beam coming from the laser ion source is composed of a mixture of about ten charge states [1] of varying energies. The overall current was estimated to be 100 mA, of which 10 mA represent the design particle. The unwanted charge states are not filtered out prior to entering the RFQ and will contribute considerably to the degradation of the beam quality, even considering that the beam will eventually be partially filtered by the RFQ itself. The challenge, then, was to design a machine which could stand a rather high beam current and preserve the beam quality but without reaching prohibitive lengths. For RFQ design, two standard “recipes” are normally used: the “high current” design [2] and the “low current” design [3]. However, neither of these approaches could be successfully applied to the current problem: the first would result in an excessively long structure and the latter would give poor beam quality and low transmission rates. The solution which proved to be successful was to treat the beam as low-current when it is continuous and as high-current as soon as the longitudinal current density starts to increase. This strategy gave the rough design for the intermediate current RFQ; subsequent modifications were made on the low energy section to meet the requirement of an output r.m.s. longitudinal emittance inferior to 18 deg keV/u at 100 MHz. Three techniques have been tried in our case for limiting the longitudinal emittance from the start: 1) to have a very long shaper; 2) to prebunch the beam with an independent RF cavity before injection in the RFQ; and 3) to keep the synchronous phase at -90 deg. while increasing the accelerating component for about 20 cm at the low energy end. This last method is equivalent to having a series of about 30 bunchers with a voltage adiabatically increasing. This was also the selected approach as it provided a resulting longitudinal emittance remarkably small with respect to the others. In Table 1 the RFQ characteristics are summarised and in Fig.1 the main RFQ parameters are represented as a function of length. In Fig. 2 the evolution of the beam emittance for a nominal matched beam is reported.

Table 1

RFQ Characteristics

Design Ion : Charge 18+, Mass 208 a.m.u
Frequency : 101.28 MHz
Vane voltage : 71 kV (1.8 Kilp)
Power losses (at 90 kΩ-m) : 70 kW
Maximum electric field : 27 MV/m
Vane Length : 253.18 cm
Number of cells : 287
Minimum bore radius : 0.2 cm
Modulation factor (max) : 2.1
Transmission : 94 %
Current : 10 mA
Input energy : 6.9 keV/u (extrac. volt. 80 kV)
Output energy : 100 keV/u
Input acceptance : 300 π mm mrad (tot,unnorm)
Transv. emittance growth : 0
Output long. emittance : 12 π deg keV/u

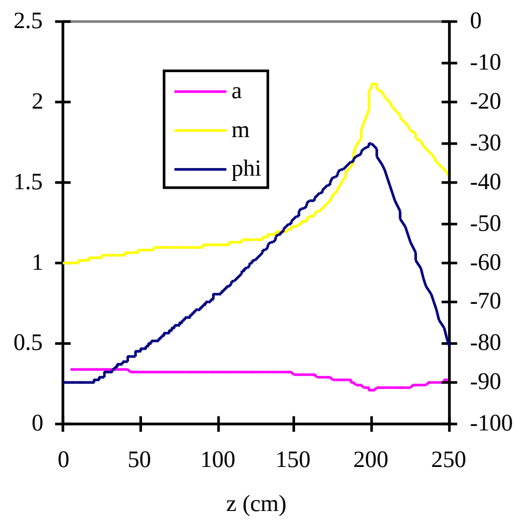

Fig. 1. Variation of RFQ aperture, modulation and phase vs. length. Phase and modulation are tapered down in the last section in order to limit the output energy to 100 keV/u for the first phase of the experiment.

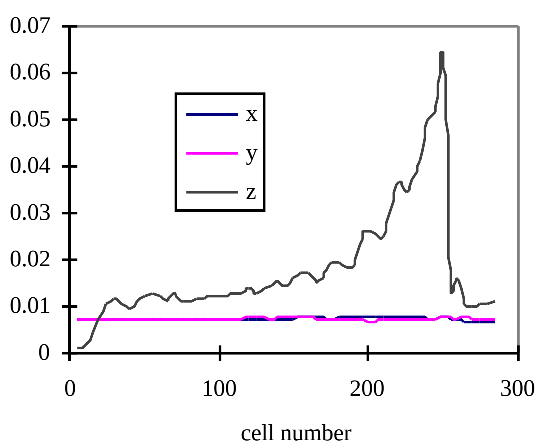

Fig. 2 Transverse and longitudinal emittance evolution for a mono-species beam.

Owing to the 4-rod structure the RF field pattern is different in the horizontal and vertical plane [4]. Longitudinally the beam undergoes a voltage difference on axis equal to half the operating voltage. The input region has been modelled with MAFIA and the beam trajectories have been integrated in the MAFIA calculated field in order to estimate the effect on the beam dynamics. The effect on the transverse plane (asymmetry between the x and y focusing field component in the RMS) turns out to be negligible in our case, and the 1-2% energy spread resulting from the non-zero longitudinal field does not have any effect on the final beam quality.

Due to the complexity and the uncertainties of the beam parameters at the output of the LIS, it was decided to test the performance of the RFQ itself with an equivalent proton beam. The equivalent proton beam has an energy equal to the energy per nucleon of the lead ion beam and a current scaled like the ratio of charge to mass (11.56 in our case). The RFQ is run at a voltage equally scaled like the ratio charge to mass.

Measurements on the Pb Equivalent Proton Beam

The source used for the equivalent proton beam test is a duoplasmatron source designed to produce a 90 keV 250 mA proton beam [5]. As the beam required for the test is a 6.9 keV 20 mA proton beam the source was operated in a regime very far from that of standard operations, giving rise to some instabilities as well as a reduced proton yield. More specifically in normal operation protons represent 70% of the total current, composed also of H_2^+ and H_3^+; in the low energy regime the protons are only 45%. Operating the source with Helium 1+ provided a cleaner beam with only few percent of unwanted particles.

Before testing the performance of the RFQ in the experimental set-up as in Fig. 3, various beam parameters were measured at the position corresponding to the RFQ input plane and the solenoid settings giving the match to the RFQ were found.

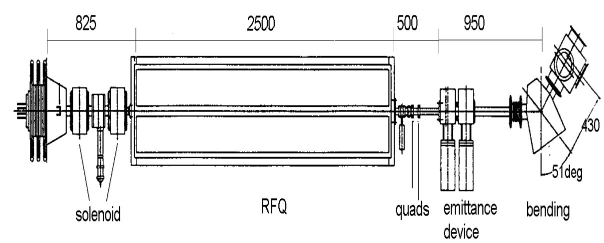

Fig. 3 The experimental set-up consisting of a proton source, two solenoids, the RFQ, and a measurement line. Dimensions are in mm.

As there was margin to increase the RFQ power from the nominal level, several tests in different equivalent "rescaled" conditions were performed. These provided insight to the RFQ dynamics in areas that could not be explored before. The configurations tested are reported in Table 2; the values underlined are the "nominal" values for that configuration (i.e. the value that corresponds to the design operation for lead 18+).

Table 2

Configurations tested

	charge /mass	extraction voltage (kV)	RFQ voltage (kV)
proton	1/1	<u>7</u>,14,21	<u>6.2</u> to 19
H_2^+	1/2	7,<u>14</u>,21	6.2 to 19, <u>12.4</u>
H_3^+	1/3	7,14,<u>21</u>	6.2 to <u>19</u>
Helium	1/4	<u>28</u>	<u>25</u>

What is expected is that each configuration when operated with the nominal settings gives the same output beam.
The measuring line shown in Fig. 3 - two quads, a beam transformer, an emittance measurement device and a spectrometer - allows the measurement of the RFQ transmission, of the output transverse emittances and of the output energy spread. The measured performances of the RFQ for the nominal settings are summarised and compared to the calculated ones in Table 3, Fig. 4 and Fig. 5.

Table 3

RFQ performance, nominal setting

	calculated	measured
transmission	94%	88%
energy (keV/u)	97	97
rms, un, x-emitt (mm mrad)	7.9	7.6
rms, un, y-emitt (mm mrad)	7.9	8.0
total energy spread (keV/u)	5.6	5.1

The difference between the calculated and measured transmission can be explained by a non-perfect matching due to the solenoid field limit.

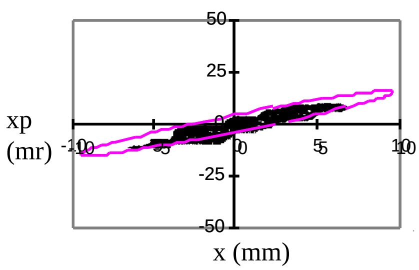

Fig. 4 Measured horizontal emittance , the solid line represents the calculated ellipse.

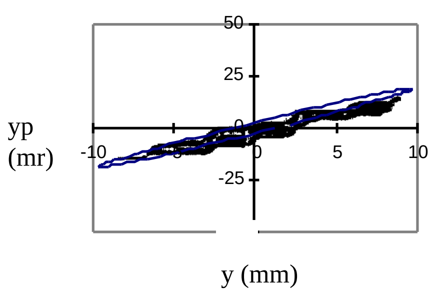

Fig. 5 Measured vertical emittance , the solid line represents the calculated ellipse.

After completion of the measurements for the equivalent beam other measurements were performed. The goal here was to study and verify the calculated performance when the RFQ is operated in other-than-design conditions. In particular we will report here the most interesting results:

- transmission and energy spread vs. rf voltage: the output current grows with rf voltage till the nominal level is reached, then it stays constant till the rf voltage is about 3 times the nominal voltage. Above this value the transmission drops very rapidly to zero as the transverse focusing becomes excessively high and causes cross-over. The output energy spread is at a minimum for the nominal voltage and grows for higher-than-nominal voltage due to longitudinal mis-match.

- transmission versus input energy: when the extraction voltage was set for protons (7 kV) for any RF level the other species (H_2^+ and H_3^+) were not accelerated through the RFQ. However, when the extraction voltage was set to the nominal values for H_2^+ or H_3^+, protons were always transmitted with a rate depending on the rf level. This result shows that, as calculated, the energy acceptance of the RFQ is quite large due to the very adiabatic design in the first part of the machine. In fact, particles which enter the RFQ outside the longitudinal stability region can be reabsorbed in the stable bucket after the bunching process is completed.

Conclusion

An RFQ for acceleration of a 300pi mm mrad, 18+ lead ion beam from 6.9 keV/u to 100 keV/u with high transmission and excellent output beam quality has been designed and constructed at CERN in the framework of the LIS study. The first beam test with an equivalent proton beam confirmed the theoretical prediction of transmission and output beam quality.

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