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Efficient focusing, bunching, and acceleration of high current heavy ion beams at low energy

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ABSTRACT

The efficient focusing, bunching and acceleration of high current, low energy heavy ion beams in an RFQ accelerator have been investigated. The considerations on the choice of the working frequency for increasing the beam current are introduced. Designed using an unconventional procedure, this 20 emA RFQ will be able to work with $A/q \leq 60$ ion beams in the β range of 0.002–0.016. The beam dynamics simulation shows that the design fulfills all requirements with good beam quality and a compact structure.

1. Introduction

There is worldwide an increasing interest to acquire more and more intense ion beams from particle accelerators for modern research and applications. For light ions e.g. hydrogen ions, the beam current requirement up to 200 emA is still well within the capability of modern accelerators [1,2]. For heavy ions, however, to increase the beam current could become a very challenging issue, especially at low energy, due to the space charge effects.

This study has been performed to investigate how to efficiently focus, bunch, and then accelerate continuous heavy ion beams from particle sources in the range of β <0.02 which is corresponding to the beam energy up to 200 keV/u. As the standard first-stage accelerating structure for today's ion beam facilities, the RFQ (Radio Frequency Quadrupole) accelerator can well cover this energy range, but it is often a bottle-neck for increasing the beam current.

This paper presents the conceptual design of a heavy ion RFQ accelerator which is able to work with low energy, high current heavy ions up to the ratio of mass to charge $A/q = 60$. The design beam current has been chosen as 20 emA.

2. Choice of the frequency

To choose a suitable working frequency is usually the first step for designing an RF (Radio Frequency) accelerator. In order to accelerate high current beams, naturally the choice of the frequency should lead to an as big as possible value of the current limit I_{lim}. From the formulae given by T. P. Wangler [3], one can deduce the following relationship between the current limit and some other RFQ parameters as:

$$I_{\text{lim}} \propto \frac{q}{A} \cdot E_s^2 \cdot \frac{\beta}{f^2} \tag{1}$$

where q is the charge state of the ion, A is the mass number, E_s is the maximum surface electric field, β is the beam velocity, and f is the frequency. The maximum surface electric field is limited by RF breakdown. For a convenient comparison of the current limits at various frequencies, therefore, a same Kilpatrick factor (the bravery factor for RF breakdown) is assumed for E_s and one can rewrite (1) as:

$$I_{\text{lim}} \propto \frac{q}{A} E_k^2 \cdot \frac{\beta}{f^2} \tag{2}$$

where E_k is the so-called Kilpatrick limit, and its relationship to f can be given as [4]:

$$f = 1.64 \cdot E_k^2 \cdot e^{\frac{-8.5}{E_k}}. \tag{3}$$

with E_k in MV/m and f in MHz. At low frequencies, the E_k value calculated by Eq. (3) is usually pessimistic, so the current limit values given by (2) can be even higher.

In term of (2) and (3), one can plot the relative current limit as a function of β at the five candidate frequencies for this study (see Fig. 1). For obtaining a higher current limit, obviously, a lower frequency should be used, especially at the low energy end.

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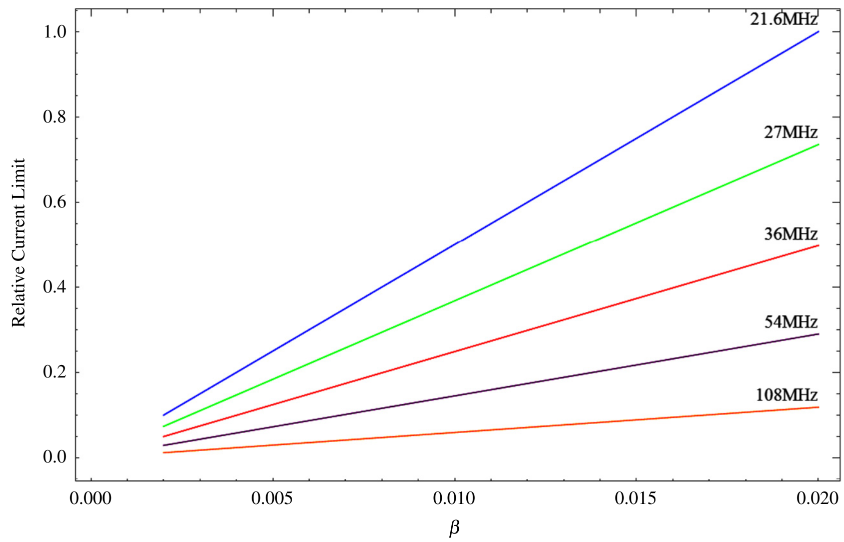

Fig. 1. Current limit as a function of the beam velocity.

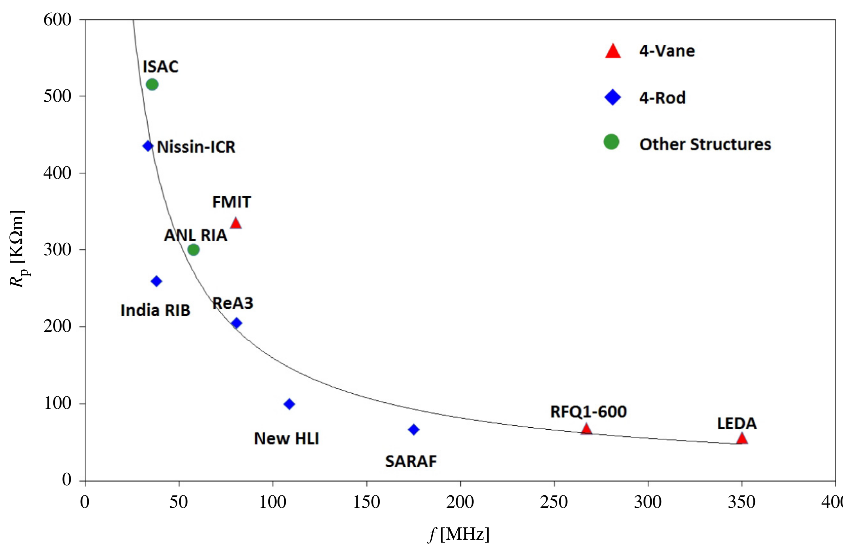

Fig. 2. Shunt impedance of some built RFQs in the world.

Another consideration for choosing the frequency is based on the RF efficiency. Fig. 2 shows the shunt impedance R_p of ten built RFQ accelerators as a function of f.

Generally speaking, the R_p value is inversely proportional to the frequency. A formula can be developed here for expressing this relationship conveniently as:

$$R_p = 16/f. \tag{4}$$

with R_p in MΩm and f in MHz. It is clear that a lower frequency is also favorable for a higher R_p namely higher RF efficiency.

However, a lower frequency will of course result in a longer cell length, as shown in Fig. 3. One goal of this RFQ design is to keep the whole structure length ≤ 10 m which is still practical in reality. To fulfill it as well as to reach high current limit and high shunt impedance, 27 MHz could be an ideal choice among the candidates, if the acceleration stops at β = 0.016. Therefore, the RF frequency and the design output beam velocity of this RFQ have been chosen as f = 27 MHz and β = 0.016, respectively.

3. Design procedure

After a continuous beam is injected, the RFQ accelerator should on one side focus the beam transversely and on the other side bunch and then accelerate it to the design energy longitudinally. The RFQ is a kind of special accelerator for which bunching is actually a more important function than acceleration.

During the bunching process, the space charge force is increasing with the decreasing bunch size and behaves most significantly when the beam is maximally bunched. The more intense the beam is, the more serious the space charge effects will be. Afterwards, the transverse defocusing force will be naturally weakened by the acceleration. So the most difficult task for designing an intense RFQ accelerator is how to form the required beam bunch while remaining good beam quality and a compact structure.

For this study, the beam dynamics of this 20 emA RFQ accelerator has been optimized for the reference particle with A/q = 60. An efficient design has been realized using a so-called BABBLE (Balanced and Accelerated Beam Bunching at Low Energy) procedure [5]. Trying to keep the whole beam development under a transverse–longitudinal balance, this method varies the transverse focusing strength by changing