Beam Dynamics Studies for the CERN Lead-Ion RFQ

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Abstract

The RFQ for the new CERN lead ion injector will accelerate Pb^{25+} ions from an energy of 2.5 keV/u to 250 keV/u. This paper describes the studies concerning the delicate beam dynamics in the RFQ :The limited current from the ions source demands a high transmission and a good beam quality for the following accelerator. As already pointed out by other authors, in an RFQ for heavy ions the low current allows a quicker change of parameters , like the accelerating field strength and the synchronous phase along the structure. By optimizing the bunching part of the accelerator it is possible to design a 2.5 m long RFQ, that fulfills all the specified characteristics, both for beam parameters and peak surface field.

1. INTRODUCTION

Kapchinskij's original proposal for an RFQ accelerator [1] dealt with a high intensity machine, where the compensation of space charge forces was central in the design . An approach for low intensity RFQ was put forward by Yamada [2], where a fast bunching, not maintaining a constant bunch length, is applied, resulting in a shorter RFQ. RFQs with fast bunching are built in several places (e.g. University of Frankfurt) and used, in particular, for low intensity ion beams with charge to mass ratio Q/A <<1 .

For the CERN lead ion RFQ a design procedure has been developed [3] based essentially on Kapchinskij's and Yamada's approaches and on algorithms established by LANL. With this procedure one could control the beam dynamics in the RFQ in such a way as to find a design satisfying all the requirements.

The subject of this paper includes an explanation of the essential points of our design procedure and, as a result, the description of the lead ion RFQ, analyzed from the beam optics point of view.

2. DESIGN PROCEDURE FOR LOW INTENSITY RFQS

The conditions imposed on high intensity RFQs, such as constancy of beam dimensions and of betatron and synchrotron oscillation frequencies, are no longer necessary when dealing with low intensities. Here, other conditions can be established, resulting essentially in shorter accelerators.

It has been found convenient to divide the RFQ structure into six sections, as Yamada did . These sections are :

the radial matching section (we follow the design procedure proposed by Crandall [4]);

the shaper (short section of ten to twenty cells; creation of the bucket);

the prebuncher (fast phase compression of the beam with the bucket area kept constant);

the adiabatic buncher (completion of the bunching process and start of a more efficient acceleration by maintaining the maximum allowable surface field; slight increase of the bucket area);

the booster (fast rise of the acceleration by increasing the modulation factor, as allowed by acceptance considerations; synchrotron frequency is kept constant);

the accelerating section (acceleration up to the final energy).

The design of all the sections, except the adiabatic buncher, essentially follows Yamada's procedure. The adiabatic buncher is based on a more recent proposal by Kapchinskij [5] to maintain the maximum surface field in the whole section in order to have a more efficient acceleration.

We have treated the adiabatic buncher in the following way . The surface field is given by

$$E_s = \frac{\chi V}{R_0} ,$$

where V is the vane voltage, R_0 the average radius and χ a factor depending on the form of the vane tips. In principle :

$$\chi = \chi(m,kR_0) ,$$

with m being the modulation factor and $k=\frac{2\pi}{\beta\lambda}$.

The factor χ cannot be expressed analytically and is given in tables [6]. However , the condition

$$\chi = \text{const}$$

is well approximated by the relation between m and kR_0 of the form:

$$m=b+\frac{c}{(kR_0)^2} ,$$

where b and c are determined by the least square fit of values in the above mentioned tables. Another condition applied in this section is :

$$\Phi\beta^{\alpha} = \text{const} ,$$

with Φ being the bucket length, β the relativistic factor and α an exponent. It has been found that values of α slightly smaller than one were the most satisfactory

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3. DESIGN OF THE RFQ FOR THE CERN LEAD ION PROJECT

The design procedure, outlined in the previous chapter, has been included in a computer code called RFQADB and used for the design of the lead ion RFQ. We recall in table 1 the main design specifications, relevant to beam optics:

table 1

Specification for lead ion RFQ

particle	Pb^{25+}
input energy [kev/u]	2.5
output energy [kev/u]	250
RF frequency [MHz]	101.28
Max surface field [MV/m] $\leq 2 E_K$	23.
Length of cavity, inside [m]	2.5
Radial norm acceptance [mm mrad]	$\geq 0.8\pi$
Radial norm. output emittance [mm mrad]	$< 0.8\pi$
Longitudinal rms output emittance [kev/u deg]	$\leq 10\pi$
Output energy spread [± %]	< 2
Output phase spread [± deg]	< 12
Transmission efficiency [%]	≥ 90

Complementary to the program RFQADB are various considerations, physical and practical, which help in the choice of initial RFQ parameters. As usual, the classical program PARMTEQ, with its beam simulation, shows the final validity of the design. It has been found necessary to include also a test concerning parametric resonances, which occur in systems obeying Mathieu's differential equation. The first unstable region is particularly dangerous, as it has a short time constant for the exponential build-up of oscillation amplitudes. In Figure 1a we present the beam envelopes in the adiabatic buncher, which show a characteristic resonance behavior; a test confirmed that one was in the first unstable region during ten consecutive cells, corresponding to about half of the synchrotron oscillation period. By reducing progressively the maximum surface field in the adiabatic buncher (total field reduction of about 1%), one could avoid this instability, as shown in Figure 1b.

In table 2 are listed some of the important lead ion RFQ parameters :

table 2

Some parameters of lead ion RFQ

Vane voltage [kV]	70
Vane length [cm]	250
Average aperture radius [mm]	4.5
Transverse vane tip curvature radius [mm]	4.5
Trapping efficiency [%]	93
Transverse emittance increase [%]	----
Longitudinal rms output emittance [kev/u deg]	6.5π

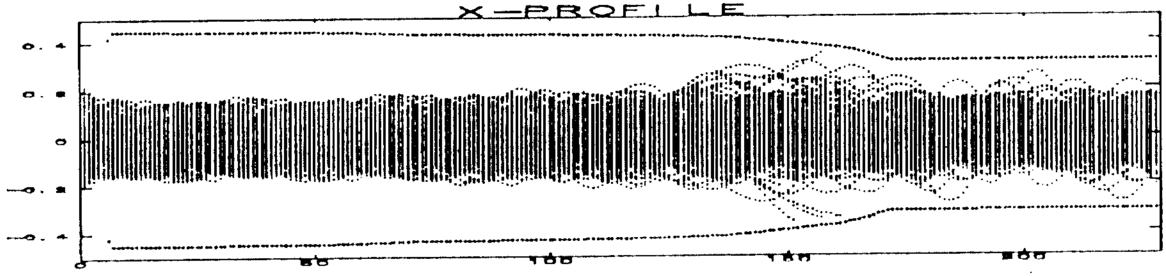

Figure 1a . x[cm] vs. cell number

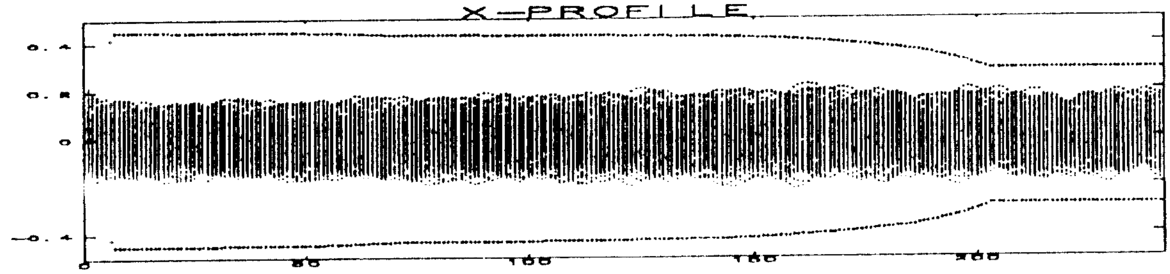

Figure 1b. x[cm] vs. cell number

Figure 1 . Beam envelope with (1a) and without (1b) parametric resonance

Figure 2, shows how the parameters, relevant to beam optics, vary along the RFQ. In Figure 3 the phase profile, which corresponds to transverse envelope of Figure 1b is represented .

4. CONCLUSIONS

A method for the design of low intensity RFQs has been developed and satisfactorily applied to the lead ion RFQ. The method is in many aspects based on earlier works in other laboratories but shows several new features . Parametric resonances have been encountered during the design phase and a method to avoid them has been found.

5. ACKNOWLEDGMENTS

During our study of low intensity RFQs, we had interesting and fruitful discussions with P. Lapostolle and I.M. Kapchinskij. We thank them for their precious help

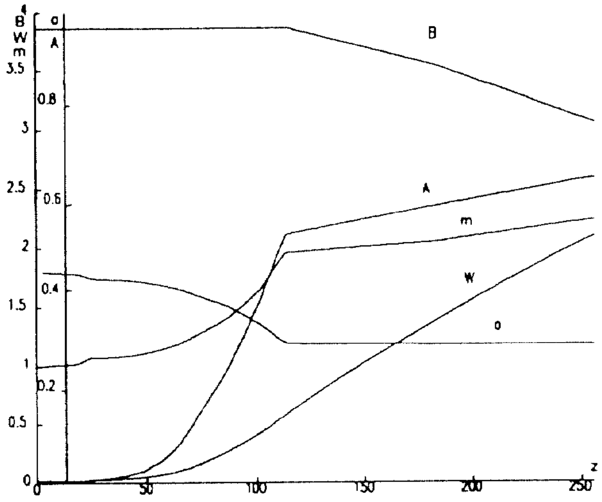

Figure 2. Variation of parameters along the Pb RFQ vs z[cm] B=focusing factor, A=accelerating factor, m=modulation factor, W=energy per unit charge [MeV], a=bore radius [cm]

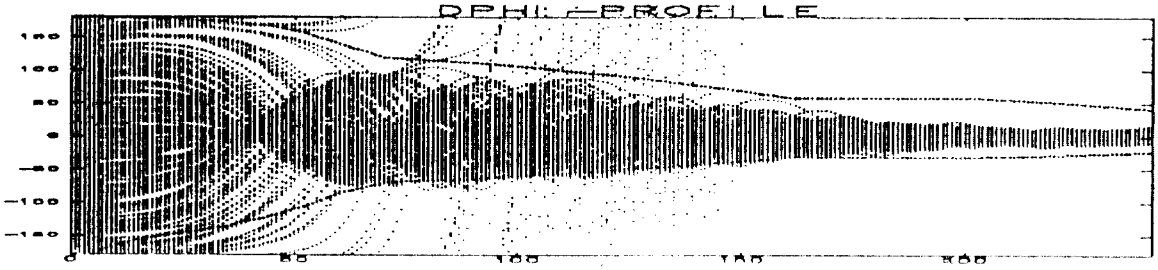

Figure 3 . Phase profile along the Pb RFQ.
dphi [deg] vs. cell number

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