CALCULATIONS ON THE POSSIBILITY OF THE SIMULTANEOUS ACCELERATION OF IONS WITH DIFFERENT CHARGE STATES IN A RFQ[*]

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Direct injection into a RFQ without mass or charge separation is discussed especially in those cases, where a larger number of accelerated ions or higher beam currents are required. Assuming an electrostatic ion-source extraction system and an Einzellens e. g. for focusing the beam into the RFQ, all charge states are offered but with different input energies corresponding to their charge to mass ratio. Particle dynamics calculations show, that ions with higher charge states than the design value are accelerated to the final energy with good beam quality whereas ions with lower charge states are only partly accelerated, partly drifting or are lost. Results of calculations three different cases will be presented and discussed for different ion species.

I. INTRODUCTION

A Radio Frequency Quadrupole (RFQ) accelerator [1,2] is mainly used for the capture, focusing and preacceleration of light as well as heavy ion beams directly behind the ion source the ion energies ranging from some 10 keV at the input up to MeV at the RFQ output. The covers the critical region of very low ion velocities, where the necessary focusing especially in the case of high currents can only be provided with great difficulties in conventional structures. A RFQ is a linear accelerator structure with four quadrupole electrodes, in which an axial field is created by the geometrical modulation of these electrodes. The electrical quadrupole focusing is independent of the ion velocity, which leads to a wide range of masses and energies being stabely transported. But for an accelerator the design for a fixed velocity profile is typical, leading to fixed input and output energies per nucleon. Once the electrodes are machined, this profile is fixed and can be changed only by an exchange of the structure or by changing the resonant frequency, the latter is used in VE-RFQ accelerators [3].

In a fixed velocity profile structure all ions can be accelerated with identical particle dynamics for which the product of the charge-to-mass Z/A times the electrode voltage V can be kept constant. Limitations on the highest applicable electrode voltage V_{max} are imposed by Kilpatriks criterion for sparking. If V_{max} is fixed, the particle dynamics layout is made for the lowest charge-to-mass ratio (highest voltage required), for all higher values of Z/A the voltage is reduced correspondingly. For stable acceleration of the ions the particle velocity and phase velocity of the accelerating field component must be always adapted to each other, for a synchronous particle with a phase φ_s relatively to the rf field the energy gain per cell is proportional to Z/A*V* cos φ_s with φ_s between 0° and -90°.

When Z/A is now changed for a fixed electrode voltage, the energy gain changes correspondingly. This can be compensated by shifting the particles to another synchronous phase but is limited by the range of φ_s for stable particle motion. Higher values of Z/A are preferred, for lower ones the energy gain soon becomes to small and the fall out of the fixed velocity profile for acceleration. In the following results of calculations for different cases are presented and discussed.

II. BEAM DYNAMICS CALCULATIONS

a) Singly charged heavy ions

In Heavy Ion Inertial Fusion (HIIF) projects high currents of single charged very heavy ions are considered for acceleration in a driver linac for a pellet ignition facility [4]. The linac starts with a set of ion sources, RFQs and RF linacs, the beams are successively funneled and finally accelerated in a common main linac [5]. To overcome space charge limitations in the driver, Koshkarev [6] proposed to use ions with many isotopes for simultanous acceleration in the main linac, but being separately accelerated in the beginning. Using negative and positive ions the final merging of the beams would lead to neutralization of the final beam in the target chamber. The first concept deals with a separate acceleration of each isotope and charge state in an RFQ, which demands for a separation line between source and RFQ. Therefore calculations have been performed for the case, that all different masses are injected into the same RFQ. On ion proposed is Te (A: 130,128,126, 125,124,123,122,120), which is similar in A/Z to an existing data set for an heavy ion prototype RFQ for U^{2+} [7,8] which accelerates ions from 2.2 to 17.6 keV/u. This data set - not optimized for Te - was used for the calculations. Using mass 130 as design value, all lighter isotopes have an higher input energy per nucleon than the design value and a higher charge-to-mass ratio too. Due to this the lighter masses change the synchronous phase and the energy spread increases in comparison to the design mass. This is illustrated in Fig. 1, where the output emittances for mass 130 and mass 122 are plotted, if separately accelerated at the design voltage for mass 130. The transverse emittance growth increases from 20% for 130 to 50% for 120, the longitudial rms emittance by a factor of 6. For mass 122 the transmission is still 81%

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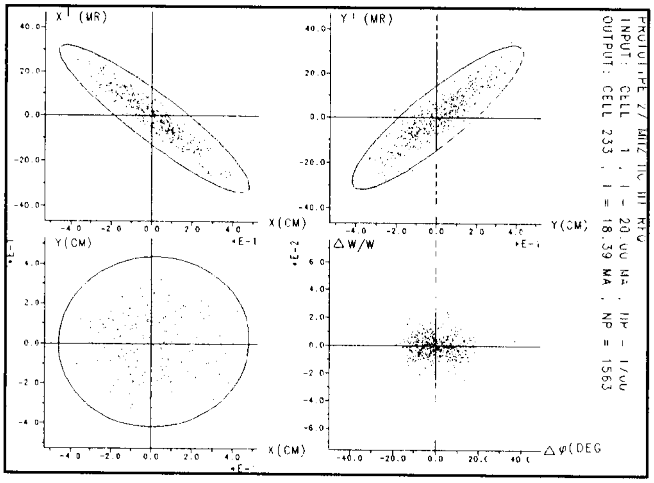

Fig. 1a) Output emittances for design mass 130

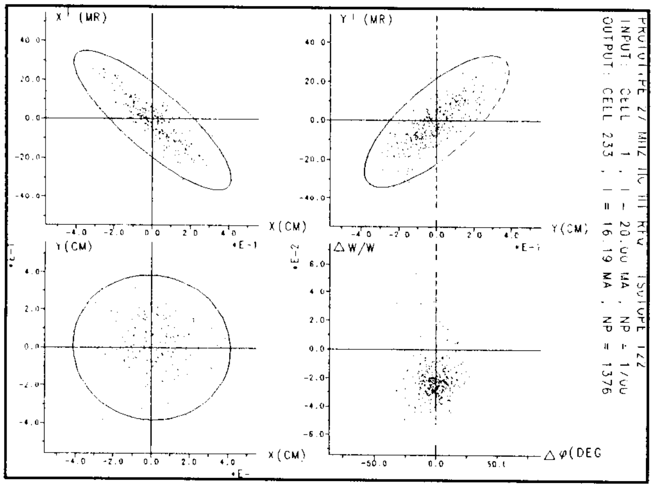

Fig. 1 b) Output emittances for isotope 122, calculated with the voltages for mass 130

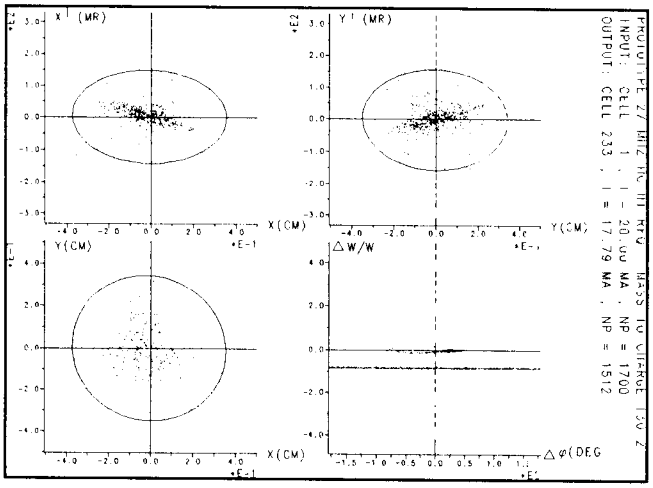

Fig. 2: Output emittances for charge state 2, mass 130 calculated for the voltages for charge state 1

compared to 92% for the design mass. When the three main isotopes 130,128 and 126 are taken - calculations could be made only for equal parts of them, which is not quite correct - the total transverse emittance growhts is 30%, the longitudinal emittance is 3 times larger than for mass 130 alone. The overall transmission is rather high with 88%. It still must be checked, if the large emittances can be tolerated for the following linac structures of the chain, especially funneling may not work in this case properly.

If the ion source also generates ions with charge state 2, which are directly injected, the output emittances will be spoiled. The ions with A/Z = 65 have a to high input energy per nucleon and are drifting through the RFQ, well focused and with good transmission. Fig. 2 shows the output emittances, the longitudinal emittances showing a hugh energy and phase spread. Drifting of ions through a RFQ is well known from measurements and can be reproduced in calculations too with good accuracy [9,10].

b) Highly charged heavy ions

The new high charge state injector of GSI [11] now in routine operation is an example, where highly charged heavy ions are extracted from an ion source, e.g. an ECR source and accelerated by an RFQ to an energy as high as 300 keV/u. The ion source generates an charge spectrum ranging over several charge states. Normally by a separation line one charge state is singled out and injected. For very high charge states it could be desirable to accelerate several charge states simultameously to increase the number of particles. Here again the RFQ is designed for a fixed charge to mass ratio, ions with higher or lower charge states than the design value must be treated separately. For a higher charge state the results of beam dynamics calculations are identical with those for the lower mass isotopes in chapter a): The input energy again is higher and the ions change to another synchronous phase to compensate the higher energy gain. The output longitudinal output emittances are shifted in phase and show a higher energy spread than for the design ion, but stable acceleration takes place with high transmission. For lower charge states the input energy is to low and the energy gain too, which leads to losses from particles out of the bunches. Finally the particles are widely spread in energy and phase. This behaviour is demonstrated in figs. 3-5. In fig. 3 output emittances and distributions are shown for the design charge 28 and mass 238, in fig. 4 for charge 29 and in fig. for charge 27. For all cases the same transverse input emittances were assumed.

c) Light ions

RFQs are also proposed for the use in high-energy high-current ion implantation for singly charged N or O ions [12]. The mass-to-charge ratio of 7 or 8 resp. is nearly the same as for the high charge state implanters. When looking to the results we can immediately see, that in an implanter RFQ for Oxygen N^+ ions can be captured and accelerated to the same final energy per nucleon. In an implanter designed for

Nitrogen O^+ ions can be captured too but are only drifting to the end. This is also true for any impurity ions which can have a rather large spectrum of charge-to-mass ratios.

III. REFERENCES

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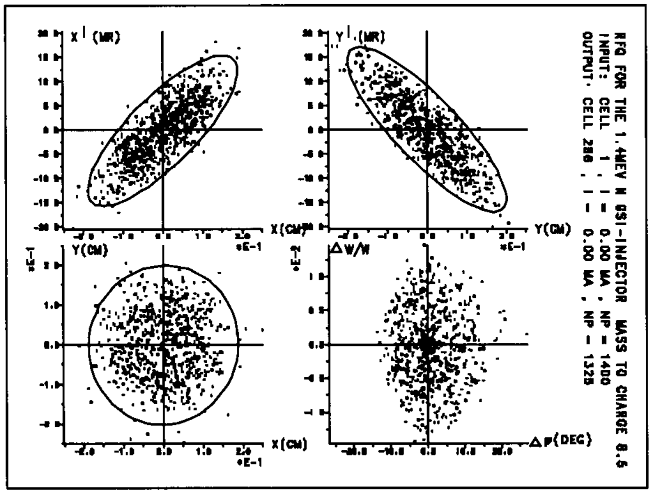

Fig. 3 a) Output emittances for design value of Z/A = 8.5

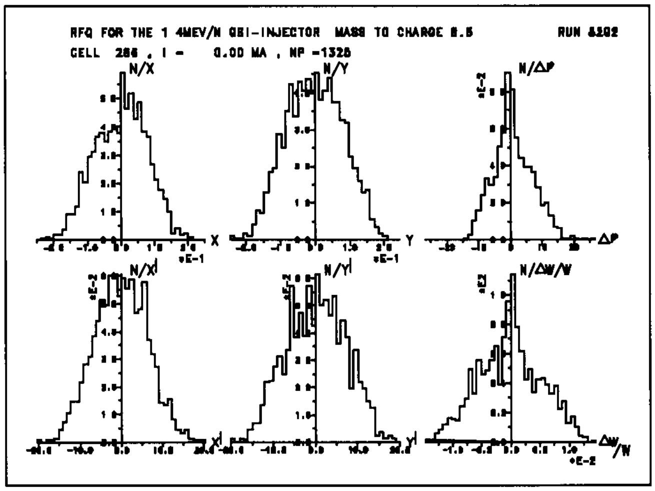

Fig.3 b) Output distributions for Z/A = 8.5

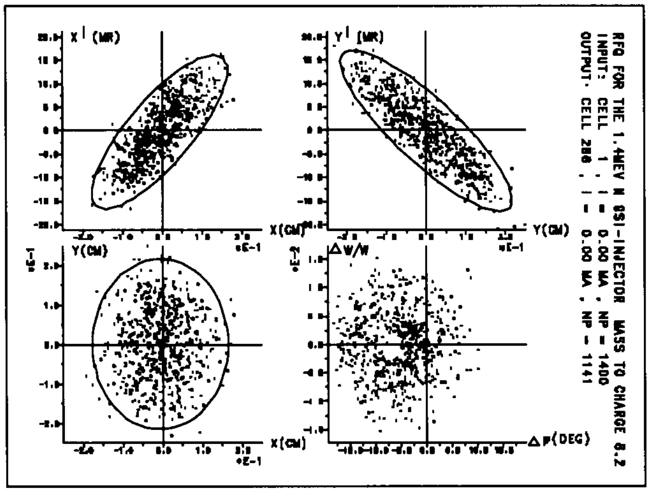

Fig. 4 Charge state 29, mass 238

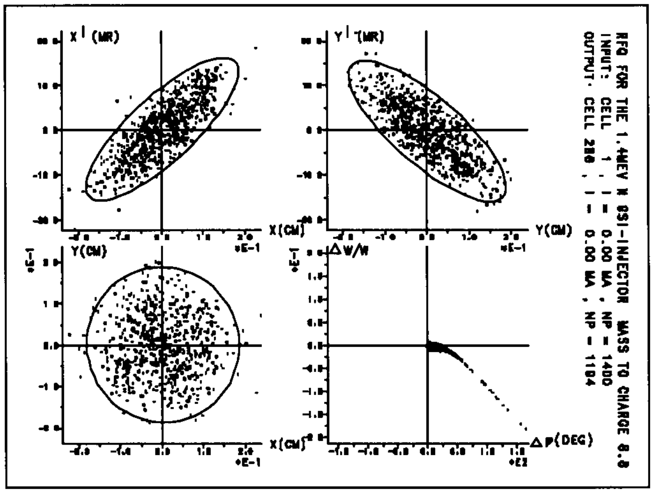

Fig. 5 Charge state 27, mass 238