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ACCELERATION OF CLUSTER IONS TO ENERGIES UP TO 0,1 MeV/u

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Résumé - Au cours des dernières années, le nombre d'expériences utilisant des ions d’agrégats, en particulier, d’hydrogène, a augmenté rapidement. Ces investigations traitent les aspects différents de l’interaction des ions d’agrégats accélérés à des énergies de quelques centaines de keV avec des cibles gazeuses ou solides afin de mesurer des rendements de production de particules secondaires et des sections efficaces de désintégration des agrégats, et pour obtenir des renseignements sur la structure des agrégats. On peut prévoir facilement que la demande concernant les gammes accessibles de masses et d’énergie des agrégats augmentera afin d’étendre ces recherches à d’autres matériaux que l’hydrogène, d’être plus flexible dans les expériences, et d’améliorer la detection des signaux. Dans la contribution présente, nous discutons les futures possibilités d’accélération des ions d’agrégats en supposant, pour première approximation, que l’accélérateur est essentiellement indépendant de la source d’agrégats. Après une courte revue des propriétés générales de la postaccélération d’agrégats nous décrivons le projet d’un accélérateur d’agrégats basé sur le premier accélérateur RFQ (Radiofrequency Quadrupole) à énergie variable qui est au cours de sa réalisation à l’IPN de Lyon. L’utilisation de structures RFQ est analysée pour des gammes de masse typiques, notamment de 1 à 50 u, et, pour conclure, nous faisons quelques remarques concernant l’influence éventuelle d’autres techniques d’accélération de particules.

Abstract – During the last few years, the number of experiments with accelerated clusters, mainly of hydrogen, has been rapidly growing. These investigations deal with various aspects of the interaction of cluster ions accelerated to several hundreds of keV with gaseous or solid targets to obtain yields of secondary particle production, disintegration cross-sections, or structural information on the clusters. It is easily foreseeable that the demands concerning the accessible ranges of cluster mass and energy will become higher in order to extend investigations to other cluster materials than hydrogen, to have more flexibility in the experiments, and to improve the signal detection. In this contribution, we discuss future possibilities of cluster ion acceleration assuming, to a first approximation, that the accelerator is essentially independent of the cluster source. After a brief review of general features of cluster postacceleration we describe the project of the first variable energy cluster-ion Radiofrequency Quadrupole accelerator currently under realization at IPN Lyon. The use of RFQ structures is analyzed for typical mass ranges, namely 1 to 50 u and finally, an outlook is given on the possible impact of other particle acceleration techniques.

1 - INTRODUCTION

The Lyon cluster ion accelerator was initiated 16 years ago within the frame of a collaboration between the Institut de Physique Nucleaire de Lyon and KfK as part of a project conducted by KfK and aimed at the development of intense hydrogen cluster ion beams for nuclear fusion. After completion of the fusion-oriented work in 1978, and in particular during the past few years, this accelerator has seen a growing experimental activity (for references see /1/). In order to widen the available range of beam parameters, and to improve the performance, an upgrading program was started, which includes, as the most important part, an RFQ as a postaccelerator and a new beam line to transport the beam from the exit of the acceleration gap to the target or the entrance of the postaccelerator /2,3/.
The upgrading of the Cluster Facility is being performed in a collaboration between IPN Lyon, KfK Karlsruhe and IAP Frankfurt. The RFQ for postacceleration of clusters is designed for 500 keV (10 keV/u) injection energy and 5 MeV (100 keV/u) final energy. This is a unique possibility for cluster acceleration, because such a combination can use typical advantages of an RFQ /4,5,6/. At first, the ion source, in this case the rather huge cluster preaccelerator, will be on ground potential. Higher energy by means of dc acceleration is hardly possible. RF acceleration offers in principle unlimited energy gain at rather low peak potentials. The second advantage of the RFQ is the use of strong radiofrequency electrical quadrupole focussing, which solves the focussing problems. Alternatively, a very low frequency and a very bulky postacceleration with a classical structure e.g. of the Wideroe type, would be required. Because the specific energy per nucleon is rather low, the limited focussing strength is the main problem of rf postacceleration at these energies (per mass unit u).

The third feature of the RFQ is not used in the Lyon RFQ project: the input velocity incoming acceptance is restricted to approximately ± 5 % for the beam. The RFQ postaccelerator would select a narrow band out of the broad energy and mass spectrum of the incoming cluster beam, which will open new experimental possibilities.

A new feature, the possibility to vary the final energy has been included. Up to now, RFQs have been fixed energy accelerators and energy variation could only be done by adding an additional rf cavity /7/. The resonance frequency of the 4Rod RFQ structure /8,9/ which has been developed in Frankfurt and will be used in the Lyon project can be appreciably tuned so that it seems possible to scan the FM range from about 80 MHz to 110 MHz corresponding to an energy change by a factor of approximately two.

2 - RFQ DESIGN CONSIDERATIONS

The postaccelerator will be placed in the horizontal beam line of the existing 0.5 MeV DC accelerator. A schematic of the cluster accelerator is displayed in fig.1. The beam is accelerated vertically, then bent into the horizontal direction by a cylindrical electrostatic deflector and a bending magnet which provides mass selection. For the beam transport and matching into the RFQ electrostatic quadrupole triplets , which are very effective at the low cluster velocities, have been added to the beam line /3/.

RFQs are accelerator structures, which use electrical RF quadrupole fields for focusing and acceleration of low energy ion beams. A typical application is the replacement of Cockroft-Walton-preaccelerators for synchrotron injectors (short pulses, high currents). Work on heavy ion RFQ accelerators is done typically using an ion source of EBIS or ECR type delivering highly charged ions, which are postaccelerated by the RFQ. Beam space charge is neglected for these beams, which are typically also pulsed.

At GSI a high current heavy ion accelerator (U²⁺, 25 mA, pulses 1 msec, 2 Hz) is planned /10/, using a very low frequency of 27 MHz and a rather big accelerator, which finally will be approximately 40 m long at a diameter of 1.2 m. A postaccelerator for clusters has to be compared with a low current heavy ion RFQ for ions with a low specific charge of the particles and no internal beam space charge forces. So in the design of the RFQ the space charge problems will be replaced by rf defocussing, which is dominating the design. RF defocussing is proportional to the accelerating Field E_z, to the rf frequency ω and inversal proportional to the velocity v_C of the clusters:

E_f ∝ E_z \frac{ω}{v_C}, \quad E_f ∝ \frac{U_Q}{a^2},

while the focussing field E_f is proportional to the electrode voltage U_Q and to the square of the effective aperture a and the focusing strength is independent of the particle velocity. The electrode design of the RFQ must keep the balance between these defocusing forces and the focusing forces during the acceleration.

This leads to typical RFQ design, a small electrical field E_z at the low energies, which is smooth an increasing modulation m of the electrodes and the cell lengths L_C along the structure as indicated in fig. 2.

The velocity of the clusters is given by the cluster energy in the preaccelerator and the masses of the clusters. The frequency will be chosen as high as possible to have a compact accelerator because of the most important boundary conditions of structure size and costs of the postaccelerator. For the Lyon postaccelerator a frequency of 108 MHz could be used because of the relatively high preaccelerator voltage of 500 kV and the restriction to cluster masses of 25u resp. 50u in pulsed mode.
Fig. 1 - Scheme of the cluster accelerator at the IPN Lyon

Fig. 2 - RFQ electrode arrangement
The design of the RFQ can be divided into two parts: The first and most important is the electrode design, which determines the beam properties and gives starting values for the rf design, like the frequency and the electrode voltage, the clear aperture and the kind of modulation being used. The second part, the rf design, uses this input to choose a cavity, which delivers a homogeneous quadrupole voltage along the electrodes as used in the particle design calculations. The cavity should have a high efficiency that means the conversion from rf power to electrode voltage should be very efficient and the cavity should have good operational stability.

The 4 Rod structure developed in Frankfurt \cite{8,9} will be applied in the cluster postaccelerator project. It is a compact and a relatively simple rf structure very well suited for heavy ion and cluster acceleration and for cw operation, too. It has been successfully applied in proton preaccelerators and is presently being built as injector for the heavy ion storage ring of the CRYRING project in Stockholm \cite{11}. The structure consists of four rods as electrodes, which are part of a resonator, which can be described as a linear array of $\lambda/4$ resonant lines as shown in fig. 3.

![Fig.3 - Scheme of the 4Rod RFQ](image1)

![Fig.4 - View of the 4Rod Proton accelerator](image2)

Figure 4 shows a view of a 18-750 keV proton RFQ which has been successfully operated with a 36 mA H$^+$ beam. Prototypes have also been operated at high average power, which is one essential feature of the Lyon project. While the average power of normal RFQs is approximately in the 100 W to 1 kW range, for the cluster accelerator an average RF power of 20 kW is planned, which matches the output power of a standard FM transmitter (20 kW cw, 80 kW on 25 % duty cycle). The voltage $U_Q$ between the electrodes will be 50 kV, which is a relatively low value but gives a good power efficiency of the accelerator. With this electrode voltage the energy gain in cw operation can be as high as 2.5 MeV for light cluster masses up to $m = 25u$ at 110 MHz.

It should be pointed out that the rf design and the particle dynamics design have to be made for the heaviest particle and the highest frequency. Lighter clusters can be easily accelerated to the same velocity $v_C$ (energy per nucleon) by reducing the electrode voltage. A unique feature of the Lyon Cluster RFQ is the energy variation possibility, that means that low energies can be achieved by tuning the resonator to lower frequencies, which in case of the Lyon RFQ will be done with inductive tuners along the RFQ which are shown in fig. 5. The frequency range of 80 to 110 MHz gives the energy variation of a factor of about 2, which is thought to be a good compromise for a first resonator of this type.

3 - PARTICLE DYNAMICS DESIGN

The particle dynamics design is a choice of the electrode modulation $m$, the cell length $L_c$ along the RFQ, which for the beam dynamics means the stable phase $\varphi_s$ of the cluster bunch and the energy gain $\Delta E$ along the structure. In addition, radial focussing has to be matched to transport the beam stably. This choice of modulation and cell length along the electrodes determines beam properties like energy spread and radial emittance at the RFQ exit.
The recipe for electrode design has been established by Kapchinskij /4/ and the work in Los Alamos /5/. So a radial matching section, a shaper, a gentle buncher and an accelerator section are used to bunch the beam and accelerate it simultaneously.

These particle design procedures have been changed to give a significantly shorter RFQ or higher beam currents with the same electrode voltage /11/. Fig. 6 shows the layout of the Lyon RFQ for $U_Q$ 50 kV and $f=110$ MHz. Fig. 7 shows the beam dynamics parameters along the RFQ, the radial focusing frequencies $\sigma_r$, the current transport limits $I_r$ and $I_1$, and the particle energy $W$. The RFQ will be 2.5 m long, and the beam current, which could be accelerated in this RFQ is 3 mA, which is a high current for these low charged particles and not available for cluster beams at present. The low value of the radial focusing frequency $\sigma_r$ is only 6.0°, indicates that the focusing strength is the design limit.

The fact that radial velocities are small is advantageous concerning intra-beam scattering. A lower rf frequency and a higher electrode voltage would facilitate the design, but this would scale the size and the costs of the RFQ structure proportionally. Figure 8 shows the velocity acceptance of the RFQ, which is designed for an input energy of 10 keV/u. Table 1 summarizes the parameters of the RFQ.

Table 1 – Cluster RFQ parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial kinetic energy per mass unit (keV/u)</td>
<td>10</td>
</tr>
<tr>
<td>Final kinetic energy per u (keV/u)</td>
<td>100</td>
</tr>
<tr>
<td>Maximum total kinetic energy (MeV)</td>
<td>2.5 (5)</td>
</tr>
<tr>
<td>Maximum ion mass (u*mp)</td>
<td>25 (50)</td>
</tr>
<tr>
<td>Length of structure (m)</td>
<td>2.54</td>
</tr>
<tr>
<td>Clear aperture radius between electrodes (mm)</td>
<td>2.2</td>
</tr>
<tr>
<td>Number of cells</td>
<td>214</td>
</tr>
<tr>
<td>Maximum modulation of electrodes</td>
<td>2.0</td>
</tr>
<tr>
<td>Diameter of vacuum chamber (m)</td>
<td>0.5</td>
</tr>
<tr>
<td>Frequency (MHz)</td>
<td>80-110</td>
</tr>
<tr>
<td>Peak voltage (kV)</td>
<td>50 (100)</td>
</tr>
<tr>
<td>Power (kW)</td>
<td>20 (80)</td>
</tr>
<tr>
<td>Maximum field strength (MV/m)</td>
<td>4.1 (8.2)</td>
</tr>
<tr>
<td>Final longitudinal phase</td>
<td>28°</td>
</tr>
<tr>
<td>Final longitudinal phase spread</td>
<td>20°</td>
</tr>
<tr>
<td>Final relative energy spread (%)</td>
<td>1.2</td>
</tr>
<tr>
<td>Transmission (%)</td>
<td>54</td>
</tr>
<tr>
<td>Normalized acceptance (mrad-mm)</td>
<td>2.2</td>
</tr>
</tbody>
</table>

(Values in parentheses are valid for pulsed operation)
Fig. 6 RFQ electrode parameters

Fig. 7 Beam dynamic parameters along the RFQ

Fig. 8 Energy acceptance of the Cluster RFQ
The 4 Rod structure is an efficient RF structure for the application as RFQ electrode drive at a frequency of 110 MHz. It can be operated in cw, and the frequency tuning in the range planned for the cluster accelerator is possible. Fig. 3 shows the scheme of the structure, which uses a chain of radial stems supporting the electrodes, in which the electrode and the stems are part of $\lambda/2$-resp. $\lambda/4$-resonators.

Fig. 9 shows calculations for the shuntimpedance $R$ (electrode voltage $U_Q$ squared/rf power $N$ per cavity length $L_{cav}$: $R = U_Q^2 / (N/L_{cav})$), as function of the cell number $N_c$ or the number of stems per length of the RFQ. The frequency of the RFQ is used as parameter. Fig. 10 shows the efficiency $R$ as function of the width of the stems for different cell numbers $N_c$. Shuntimpedance values well over 200 kOhm can be achieved with the 4Rod RFQ, which are necessary to get the necessary electrode voltage $U_Q$ for the rf power available. Fig. 11 shows drawings of the actual electrodes for the entrance, the middle and the end of the RFQ, (diameters are enlarged by a factor of 1.5) indicating the change of modulation and cell length along the RFQ.
5 - FURTHER PERSPECTIVES

The RFQ is designed for 1 - 50 u and 100 keV/u final energy and used with a frequency between 80 MHz and 110 MHz. Heavier cluster ions can be accelerated by choosing smaller values for the frequency and by this a smaller final energy per mass unit. The scaling laws connecting the mass number N with the frequency f and final energy $E_{uf}$ are $N'f^2 = \text{const}$ and $N'E_{uf} = \text{const}$, respectively. A rather cheap way to obtain the mass range of 1 to $10^3$ with an initial energy and a final energy of 0.5 keV/u and 5 keV/u, respectively, would be to modify the transmitter and the structure such that they work between 17.9 and 24.6 MHz. The option for this modification is included in the rf transmitter design.

This mass range comprises cluster ions with e.g. 1000 hydrogen atoms, 62 oxygen atoms, 17 nickel atoms or 9 silver atoms. For an analysis of the mass range 1 to $10^6$ u see ref. /2/.

Since the total energy of 5 MeV is about the limit for this RFQ, higher energies would require RFQ's with higher operation frequency, like for light ions or application of other accelerating schemes. In this context, low-velocity superconducting linear accelerating structures, which appear to be useful and available from $\beta = 1\%$ to higher values /13/ might be of help. Even further acceleration by circular accelerators is conceivable.

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