

THE ACCELERATION OF DIFFERENT SPECIFIC CHARGE IONS IN THE HEAVY IONS RFQ LINAC.

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Abstract

The acceleration of ions with different specific charge in the heavy ions RFQ linac has enabled to determine both several linacs experimental characteristics and the ion beam parameters at the injector output which is undetermined by the another technique. They are: the dependence of the capture efficiency on specific charge of ion; the magnitude of the limit current for the linac and its dependence on the ion specific charge. In particular there is the possibility to find non-linear disturbance in RF field distribution. The technique is acceptable to test any RFQ accelerator in action.

Introduction.

The first section of the accelerator TIPr-1, working on frequency 6,19 MHz, has been intended for acceleration of twice charged bismuth ions under the inertial thermonuclear fusion program [1]. It has been designed for energy 36 keV/u. Its start and the first researches of a regime of ion acceleration were made with twice charged xenon ions produced by a duoplasmatron ion source. Now a vacuum arc source of metal ions (MEVVA) is used for the accelerator TIPr-1. It has enabled to produce and accelerate in TIPr-1 a set of ions of different metals, in particular, ions of copper ($\text{Cu}^+, \text{Cu}^{2+}, \text{Cu}^{3+}$), tantalum ($\text{Xe}^{2+}, \text{Xe}^{3+}, \text{Xe}^{4+}, \text{Xe}^{5+}$), tungsten ($\text{W}^{3+}, \text{W}^{4+}, \text{W}^{5+}$), lead (Pb^{3+}) and uranium ($\text{U}^{3+}, \text{U}^{4+}$) [2]. The measurements of ion charge state distribution (CSD) and the research of acceleration regimes in TIPr-1 were made by time-of-flight method. The whole length of the RFQ structure (13 m) was used as drift channel for CSD measurements. In addition to further study of the already mastered (on ions Xe^{2+}) acceleration mode of ions with specific charge about 1/60, the possibility of acceleration of ions with other specific charges was investigated. Below we consider features of acceleration of ions with various specific charges in RFQ structure and experimental results obtained on TIPr-1.

Results and Discussion.

The basic purpose of work is to obtain data about dependence of capture efficiency for transversal movement and maximum current at the output of the accelerator from magnitude of ions specific charge. At first, in order to exclude the influence of a non-resonance (non-accelerated) ions flow at the output of the accelerator to the basic

measurements results, we consider the passage of non-resonance ions through the channel with RFQ. For non-resonance ions the RFQ structure represents the channel with an RFQ focusing without acceleration. (Their average longitudinal speed does not vary, $\langle \beta c \rangle = \text{const}$). It is possible to assert that longitudinal component of the RF field keeping the average longitudinal speed of non-resonance ions can increase the spread of their longitudinal speeds in the beam. For short (about 2 μs) pulses of a beam current which are used for the time-of-flight technique, the expansion of longitudinal ions speed spread leads to the increase of the beam current pulse duration.

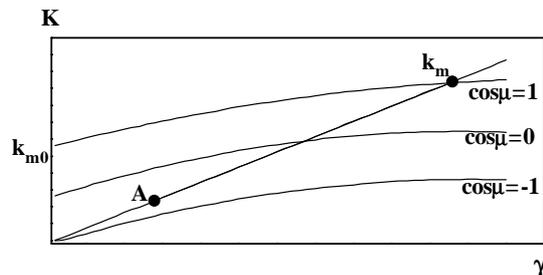


Fig.1. The diagram Smith-Gluckstern.
A - a working point for TIPr-1

On Fig.1. the Smith-Gluckstern diagram of a transversal movement stability. is shown. Where μ is a phase advance per focusing period for transversal oscillations, K - rigidity of the channel, γ - factor of defocusing.

$$\cos \mu = \cos \mu_0 + \gamma f(K),$$

where $\cos \mu_0$ characterises the focusing channel without acceleration, i.e. at $\gamma = 0$. If in the accelerator with RFQ the average value of the defocusing factor for non-resonance particles is equal to zero the non-resonance particles are kept in the channel while an amplitude of the RF field increases (i.e. the increase of the value of K on the diagram S-G, Fig.1) up to the value corresponding to $(K_m)_0$ (while $|\cos \mu| < 1$). At larger K the transversal movement becomes unstable, the focusing in the channel stops and the beam current at the output of the channel disappears.

The phenomena described above has been observed on the experiment at the accelerator TIPr-1. Experimental dependence of a beam current of non-resonance ions (single charged xenon (Xe^+) and ions $\text{W}^{2+}, \text{U}^{2+}$) from amplitude of the RF field is shown on Fig.2.

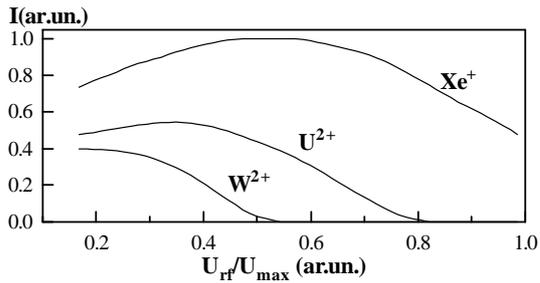


Fig.2. Dependence of a nonaccelerated ions current from amplitude of RF field

We have to note that the critical value of RF amplitude for Xe^+ ions has not achieved (beam current has not fallen down to zero), because during measurements the electrical strength of RF system has been insufficiently high. For ions W^{2+} , U^{2+} the data Fig.2 enable to determine value (K_m) for ions with reverse specific charge 90 and 119.

Measurements have shown that the beam current pulse length of the non-accelerated ions is increased from $2 \mu s$ at $U_{rf}=0$ up to $6 \mu s$ at the maximum amplitude of a RF field. It means that the spread of longitudinal speeds accordingly grows. Thus in contrary to the influence of a RF field accelerating component on the resonant particle (for which the point A representing a synchronous particle on the diagram on Fig.1 moves to the right while an RF field amplitude grows), from experimental data it follows that for non-resonance particles of beam the average value of the defocusing factor remains practically constant, $\langle \gamma \rangle = 0$. It means that the location of peak corresponding to the current of non-resonance ions in time-of-flight spectrum at the output of the accelerator remains constant in time for all levels of RF field changing its duration only. That allows easily to distinguish it from peaks corresponding to resonant, accelerated ions.

It is necessary to consider a behavior of resonant ions beam current while the amplitude of a RF field in RFQ structure increases. For resonant particles the increase of a RF field on the one hand leads to the increase of an equilibrium phase, i.e. to the increase of separatrix scope both on a phase and on a momentum, and on the other hand increases the rigidity of the focusing channel. The stability in a transversal movement and, hence, a focusing of the ion beam disappears when the RF amplitude reaches U_m ($K = K_m$, Fig.1.). On the diagram of the dependence of the ion beam current with the given relation Zm/A on amplitude of the RF field in the accelerator the beam current should at first grows (from the threshold level of a RF field) up to a maximum, and then falls practically to zero when the amplitude of a field equals to critical value U_m . Such experimental dependencies were obtained for copper (Fig. 3.) and for the ions $Ta^{3+, 4+}$, $W^{3+, 4+}$, $U^{3+, 4+}$. On Fig. 4 the dependence of relative capture efficiency for a transversal movement (divided to

capture efficiency for $Ze/M = 1/60$) on specific charge of ions is shown.

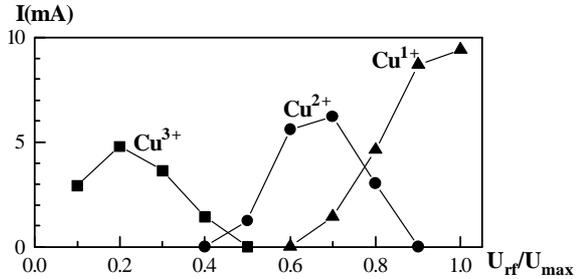


Fig.3. Acceleration of a copper ions

Data from Fig. 3. and data for ions of tantalum, tungsten and uranium were used. The question of optimum tuning of the accelerator is essential to reach the greatest possible current of the accelerated beam at the output of the accelerator, and hence for measurement of transversal capture factor. Therefore for measurement of each points for dependence Fig. 4. the special work to optimize the operation regime of the accelerator was required.

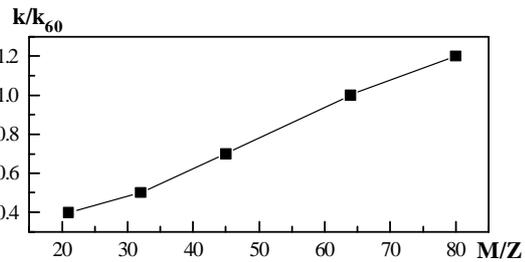


Fig.4. Dependence of capture efficiency from specific mass.

From the diagram Fig. 4. one can see, that for the greatest achieved beam current, the capture efficiency on a transversal movement in RFQ structure of the accelerator TlPr-1 decreases with the specific charge growth.

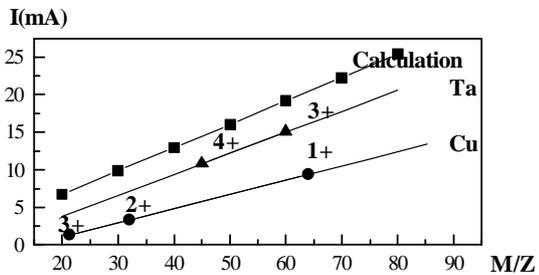


Fig.5. Dependence of a Ta and Cu ion beam current greatest achieved on experience from M/Z

The result for a beam current, which is lower than calculated value of the limiting current, is unexpected and requires an explanation, because the K and γ depend on parameter UZe/M , which for

each points on the diagram Fig.4. remains constant. Therefore, the working point on the diagram S-G does not leave the place while Ze/M changes. A number of processes can cause these results.

1) The influence of a beam space charge can cause a reduction of the capture efficiency with the specific charge growth.

A limiting current $I_l \sim I_0$ where

$$I_0 = 4\pi\epsilon_0 c^3 M_0 / Ze$$

and M_0 is a rest mass, so I_l linearly depends from M/Ze . It means the higher Ze/M , the less limit current. The experimental dependence, which is shown on Fig.5. gives linear dependence of the greatest achieved current on size M/Ze , as well as the dependence $I_l = f(M/Ze)$. It probably means that for data Fig.5. the greatest achieved beam current is close to its limit value.

2) The emittance of a beam with the given Ze/M at the output of the injector is not exactly equal to the emittance of beam with other Ze/M values. Therefore the losses of particles are probably resulted by the worse matching of the ion beam with a specific charge larger, than 1/60. The direct measurements of the matching quality for each beam components can give the answer to this question.

3) The decrease of capture efficiency can be caused by a dependence from a RF field quality. Non-linear distortions in the focusing RF field or in the its distribution along the axis of structure (and also other differences from the calculated distribution) can result the loss of particles by an excitation of a coherent oscillation of particles. If other factors of decrease of capture are excluded, the nonlinear distortions in the distribution of the RF field along the structure axis can be detected by the reduction of transversal capture factor. Distortions in the distribution of the RF field take place in TIPr-1 at a joint point of two parts of structure and have caused decrease of capture efficiency when a small beam current is accelerated, at that moment the space charge restriction of a current could not influence on a capture efficiency.

Conclusion.

The study of acceleration of ions with various specific charge in the linear accelerator with RFQ enables to determine a number of the characteristics both of the accelerator and beam of ions at the injector output, which can not be determined by other methods. Such as: dependence of capture efficiency from specific charge of ions; experimental value of limiting (maximum) current in TIPr-1 and dependence it from specific charge of ions. Also this study enables to detect presence of essential non-linear distortions in the distribution of the RF field along the axis of structure and their influence on an ion beam passage.

The results of this work allow to state the following assumptions:

The space charge limit for the accelerated beam current is defined by space charge of a total unseparated beam instead of space charge for only the resonant component of a beam as it is assumed for calculated limit current. Apparently it is the main reason of difference between the maximal achieved current in our measurements and the calculated one.

To overcome this limiting, it is useful to accelerate simultaneously beams of particles with different polarity. It eliminates space charge restriction of a beam current at the beginning of RFQ structure (where beam is bunched) and allows to obtain at the accelerator output the extreme permissible beam current.

As mentioned above the presence of ion beam components with lower specific charge than accelerated ion beam components leads to the increase of beam space charge and limits accelerated beam current. The RFQ structure focuses only this component but not accelerates it. On other hand if this nonaccelerated component would have an opposite sign (for example W^{3+} is accelerated ions and Bi^- is nonaccelerated ions), the limit current should increase. In this case the space charge compensation should take place in any point and at every moment of ion beam acceleration. Probably it is useful to inject into structure such nonaccelerated ions with opposite sign simultaneously with accelerated ions. It should result to the increase of the accelerated beam intensity.

References

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2. V.A.Batalin, Y.N.Volkov, T.V.Kulevoy, S.V.Petrenko. Rev. Sci. Instrum. 65 (10), (1994), p.3104 - 108.