FEATURES OF ACCELERATION AND FOCUSING OF CLUSTER ION BEAM IN RESONANT LINAC STRUCTURES

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Abstract

The prospective opportunity for high-temperature plasma generation by opposing collision of accelerated to 10-20 keV/amu cluster ion beams of hydrogen isotopes within the rectilinear section of magnetic trap was considered earlier in ITEP. It showed the aggregate deuteron (or tritium) atom per charge unit in accelerated cluster ions may consider a possibility to create the thermonuclear fuel mass up to values when the mutual retardation of all the nucleons in colliding beams. In the present work some examples of earlier created RF accelerating systems for heavy ion linac may be considered as prototypes for study of features and some off-beatings of heavy cluster ions of hydrogen isotopes for plasma generation are discussed. Some features of basic possibility for creation such kind accelerator systems for ion with mass-to-charge ratio of 10^3-10^4 are considered.

INTRODUCTION

Currently NRC KI ITEP is working on the study of processes occurring under the influence of an intense accelerated heavy ion beam on a substance in various states including extreme thermodynamic ones. One of the approaches is related to the effective transformation of the energy of accelerated super-heavy (cluster) hydrogen ions into the energy of thermal motion of nuclei as a result of turbulent relaxation of plasmoids in mutual collisions of accelerated cluster ions. These studies in particular are a consequence of the fact that traditional fusion schemes based on the initiation of a thermonuclear reaction by heating and compressing the fuel-containing target with powerful beams of accelerated heavy ions lead to create very complicated bulky and expensive complexes.

An original method of high-temperature plasma generation by counter-collision of hydrogen cluster ions accelerated to the energy of 10-20 keV per deuteron inside a magnetic trap was proposed in ITEF about 30 years ago by V.V. Okorokov et al.[1]. The bottom line is that due to the large number of deuterium atoms per charge unit in clusters it is possible to bring the density of particles in accelerated beams to values that provide mutual inhibition of all deuterons of colliding clusters. Thus, clusters allow accelerating the mass of matter necessary for initiating a thermonuclear reaction due to reducing the space charge effect by 3-4 orders.

The method has no fundamental limitations for the production of thermonuclear plasma with a temperature of not only 10 keV (DT-synthesis), but also 100 keV (DD-synthesis) and even 200-500 keV (p-Li, p-B and D-He^3 – the so-called "neutron-free" fusion. To obtain a temperature of 10 keV the energy of each cluster at $N=10^3$ must be at least 20 MeV.

LINAC FOR CLUSTER IONS

The term "cluster" is used to show that the beam particles are combined into atomic clusters connected by van der Waals forces. The size of these clusters span a wide range from dimer to micro-crystals or micro-droplets containing millions of atoms.

Let us estimate the possibility of creating an accelerating-focusing system with the mass of accelerated single-charge ions of $N=10^2$-10^6 with no going into details of the physical implementation of this approach just taking into account the features of cluster ion acceleration. Note that cluster charge is usually equal to $z= +1$ since even at $z= +2$ the cluster is broken by the Coulomb field of these charges.

In Fig. 1 the example of cluster ion source is shown. Gas clusters are composed of atoms of a substance that is in a gaseous state under normal conditions. To obtain gas clusters it is necessary to use cooling. This is usually achieved by use the cooling effect of the gas expanding in the supersonic nozzle. Depending on the nozzle parameters clusters of any size can be generated.

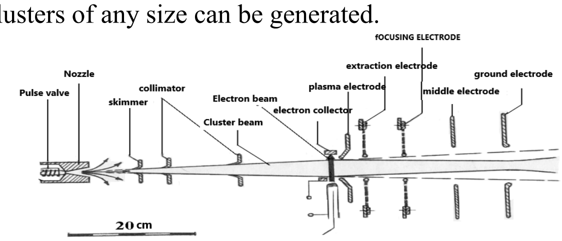

Figure 1: Scheme example of cluster ion source.

In Fig. 2 the mass spectrum coming from the cluster ion source [2] is shown. Due to wide mass spectrum it is required to capture the maximum part of this spectrum in the acceleration mode. The most natural seems to be the cluster acceleration in RFQ linac. The calculations show in the acceleration mode can be captured ~50% of the continuous mass spectrum obtained from this type source.

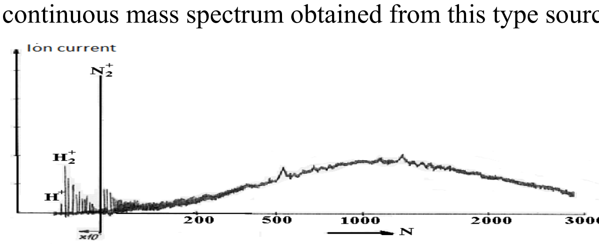

Figure 2: Typical spectrum of hydrogen cluster beam.

The 2.5 MeV 6 MHz RFQ linac designed for heavy ion acceleration with mass-to-charge ratio of ~100 was earlier created in ITEP (Fig.3) [3]. The linac structure with such a low frequency of the accelerating field required the solution of number of some technological problems. The spiral supports are made in three-rayed star form to provide acceptable mechanical stiffness. Acceleration of heavy

ISBN 978-3-95450-197-7

ions in the RFQ structure showed the principal possibility of the systems to accelerate heavy cluster ions.

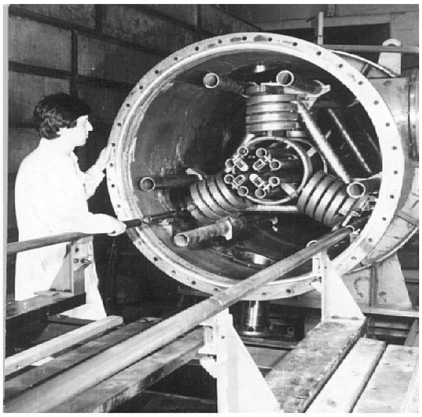

Figure 3: 6 MHz RFQ linac for ions with m*=10^2.

Besides cluster acceleration has also the specific problem of inelastic collisions of clusters with each other and their partial elimination at the acceleration. Therefore one of the most important issues requiring experimental study is the stability of charged clusters in the course of acceleration. In particular, there are problems associated with the dissociation of cluster ions in their interactions with residual gas atoms among themselves as well as with strong RF accelerating fields. The most promising way to preserve the initial intensity of the beam is the use of multiple channel accelerating-focusing systems.

Unfortunately work experience with RFQ multiple channel systems points to a number of limitations. It makes some difficulties for wide use them in practice. Firstly it is seen accelerating-focusing electrodes occupy a high percentage of the system cross-section. Secondly to reduce aperture diameter in order to increase the number of channels it should be considered with a decrease in the electrical strength due to bring nearer of the electrodes to each other. It leads to the abrupt reduction in the rate of energy gain. Therefore some other accelerating focusing systems for simultaneous acceleration of many cluster beams were considered.

Table 1: Calculated Parameters APF Linac for Various Mass-to-Charge Ratio

Mass-to-charge ratio	10^2	10^4	10^6
Injection voltage, kV	100	100	150
Linac frequency, MHz	12	2	0,33
Initial velocity β	$1{,}5\cdot10^{-3}$	$1{,}5\cdot10^{-4}$	$1{,}5\cdot10^{-5}$
Focusing period (input)	2βλ	3βλ	4βλ
Aperture radius, mm	5	3,5	3
Limit current/channel, μA	520	40	6
Number of linac channels	19	37	1
Drift tube diameter, mm	70-90	90-100	100
Acceleration rate (input) , MeV/m	2,5	1,5	1,5
Maximum current, mA	10	1,4	0,4

In the Table 1 the basic parameters of the APF channels for the variants with very different value of ion mass-to-charge ratio are shown.

The first option is associated with the acceleration of ions in the range of frequencies and velocities which have already accumulated some experience in the world of accelerating practice. In particular, for the field frequency of some tens MHz, there are a number of developments of accelerating structures based on vibratory systems.

In option 1 the limit current in a separate channel of 12 MHz 19-channel APF structure is 0.5 mA so total limit current is about 10 mA. In such kind of the system it is possible to increase the acceleration rate several times compared to other types of quadruple focusing.

The Fig. 4 shows the 18 MHz accelerating structure developed earlier in the ITEP [4].

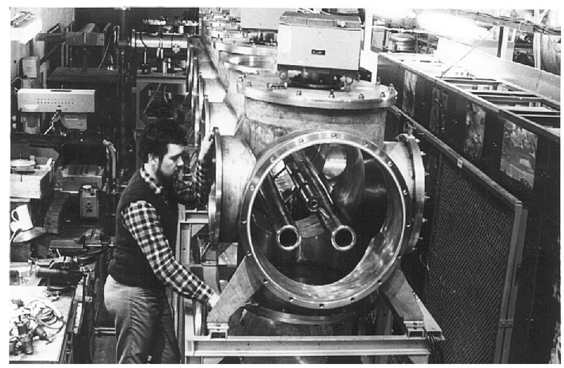

Figure 4: 18 MHz APF accelerating structure (m*=50) In the columns 2, 3 the results of calculating options of APF linac for clusters with m*=10^4 and m*=10^6.

Option 3 considers the possibility of ensuring a steady acceleration of the heaviest clusters that necessary use acceleration frequencies of hundreds kHz. It radically changes the approach to the linac resonant system. Obviously systems designed to accelerate at frequencies of units and tens of MHz are not suitable. Therefore, accelerating electrodes must be installed on dielectric insulators which reduces significantly its electrical strength. The maximum potential supplied to drift tubes installed on the insulators does not exceed 30 kV and acceleration rate at the input is only 1.5 MeV. To obtain a maximum current of about 0.4 mA the 61-channel system with drift tubes of 100 mm in diameter is required.

MAGNETIC QUADRUPOLE (MQ)

At cluster acceleration to maintain the magnetic field gradient it is necessary to increase the length of the focusing period as the ion reduced mass increases that is the wavelength of the accelerating field and the multiplicity of the focusing period. It leads to a significant reduction in the channel capacity and the maximum accelerated current. The length of the focusing period at linac input has to be chosen not less than minimum value so that the lenses can be placed in the drift tubes without significant distortion at the lens edges. It means the wavelength of the accelerating field has to be increased by

ISBN 978-3-95450-197-7

$\lambda \sim \beta^{-1} \sim (m^*)^{0.5}$. The maximum gradient of the magnetic field achievable in lenses at a given aperture of radius a is expressed by the formula: $Ha^2 = 2.25 \cdot 10^{-6} NI$, where NI is the number of ampere-turns at each pole of the lens. The limit current of the cluster beam in the channel with magnetic quadruple focusing is inversely proportional to the reduced mass of the cluster ion. Thus if the frequency of 150 MHz is selected for the proton linac and the accelerated current is 200 mA, then the corresponding values of frequency and maximum accelerated current can be expected in the range of 1.5 MHz and 20 µA for the acceleration of cluster ions with $m^*=10^4$.

ELECTROSTATIC QUADRUPOLE (ESQ)

The relationship between the gradients of the electrostatic and magnetic fields at a given velocity and equal to the length of the focusing period is as follows: E [V/cm^2] = 300βH [Oe/cm]. The electric field intensity on the surface in the center of the electrodes of a quadruple lens has the form $E = E' a$, and the magnetic field intensity in the center of the pole tip can be written as $H = h \cdot a$ at the same aperture radius for the centers on the surfaces of the electrodes have the ratio $E = 300\ \beta \cdot H$. Since the achievable value of the magnetic field intensity in the center of the pole tip usually does not exceed 10 kOe, it is necessary to ensure the ratio $3 \cdot 10^3 \beta \leq E$ [kV/cm] for the transition to electrostatic lenses. Taking into account the electric field gradient in practice usually does not exceed 75 kV/cm, the transition to electrostatic lenses may be appropriate for $\beta \leq 2.5 \cdot 10^{-2}$.

So for the ESQ the main limitation is the electrical breakdown between adjacent lens electrodes. The analysis of calculation variants of the ESQ system for clusters with $m^*=10^2$ shows this focusing can be effective in the range of $5 \cdot 10^{-3} \leq \beta \leq 2{,}5 \cdot 10^{-2}$ given that the focusing field gradient on the electrode surface is at least 60-70 kV/cm The energy growth rate of 1-1.5 MV/m achievable at the accelerating field frequency of 6 MHz.

The difficulty of making clear data on the reliability of the operation of ESQ linac for cluster ions is due to the lack of data on whether it is possible to sustain the electric field gradient between the electrodes of 60-70 kV/cm because of the lack of experimental data on the electrical strength of insulators and vacuum gaps in the presence of cluster ion beams.

RADIOFREQUENCY QUADRUPLE (RFQ)

RFQ focusing means a system of quadruple lenses are applied with high-frequency potentials. The lenses can be located inside the drift tubes, and then the accelerating voltage is applied between the drift tubes. This is associated with structural difficulties due to the need to supply high voltage inside the drift tubes supplied with high accelerating voltage.

A channel with no drift tubes was considered where the lenses and drift tubes are combined – the lens electrodes are the lateral surfaces of the drift tubes. If we assume that the length of the accelerating gaps is much less than the length of the focusing period we can again use the stability diagram for the simplest focusing period for analysis.

In contrast to the channel with ESQ where you have to choose only the synchronous phase there are additional requirements for the phase of the RF field in the lenses. Therefore in order to achieve maximum RFQ efficiency it is necessary to provide in the accelerating structure the possibility of phase shift between the RF voltage in the accelerating gaps and the RF voltage applied to the electrodes of RF lenses.

RFQ channel variant was considered under the assumption that the RF voltage to the accelerating gaps and focusing lenses are fed independently of each other and it is possible to provide the necessary phase shift between them by means of radio engineering. In this case, the structure of RFQ period coincides with the structure of the period in the ESQ. If the length of the periods and the applied voltage are the same, the focusing voltage at RFQ is less than at ESQ. However the electrical strength of vacuum gaps at high frequency is usually several times higher than the corresponding value at direct current. In addition when RFQF is used no need to provide an appropriate structural gap between the lens and the drift tube body. Therefore the focusing force in RFQ is higher than at ESQ. In addition when RFQ no need to use insulators so significantly increases the dielectric strength of the focusing system. For all this we have to pay the complication of RF power supply for the introduction of phase shift between the voltage in the accelerating gap and the voltage on the focusing lens.

CONCLUSION

The study showed the trend in accelerator technology associated with the acceleration of super-heavy particles - cluster ions forced to turn to multi-channel systems with electrostatic and alternating phase focusing at frequency of several MHz and even hundreds of kHz. If dielectric insulators necessary to use the systems with ESQ are preferable due to lower voltages compared to other systems. APF structures having in multichannel execution constructive simplicity and manufacture ability are expedient to use in cases when it is required to accelerate a lot of cluster beams. Since the achieved currents of heavy ions are tens of mA, estimates show that the mass of hydrogen clusters should be ~10^3-10^4 atoms per cluster. The acceleration of smaller cluster masses does not reach the optimal current values due to the space charge restrictions. Acceleration of large masses is impractical due to a decrease in the current of accelerated ions at given proportion of losses of accelerated clusters due to collisions of clusters with each other. Features of cluster ion generation associated with formation in low-temperature zones, small charge and large mass contribute to the extraction of ion beams with small phase volumes from sources allowing them to be accelerated in channels of small cross-section.

ISBN 978-3-95450-197-7

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ISBN 978-3-95450-197-7