

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 ITEP 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-He³ – 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.

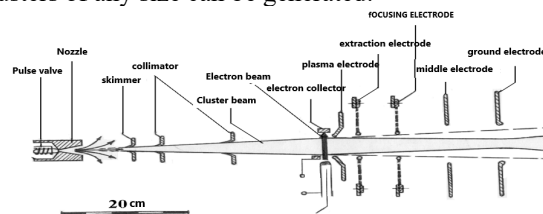


Figure 1: Scheme example of cluster ion source.

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.

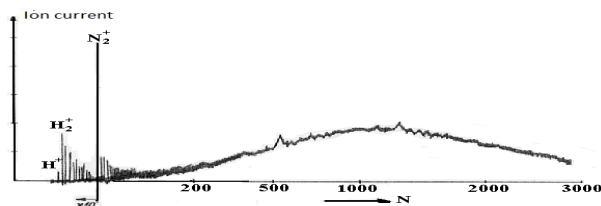


Figure 2: Typical spectrum of hydrogen cluster beam.

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

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

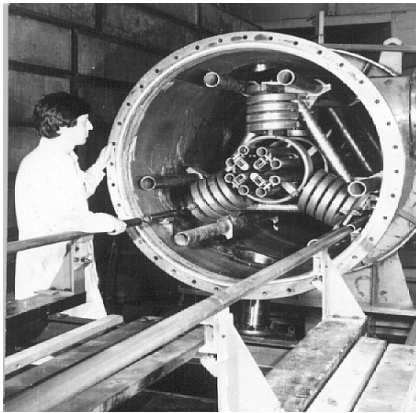


Figure 3: 6 MHz RFQ linac for ions with $m^*=10^2$.

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	$1,5 \cdot 10^{-3}$	$1,5 \cdot 10^{-4}$	$1,5 \cdot 10^{-5}$
Focusing period (input)	$2\beta\lambda$	$3\beta\lambda$	$4\beta\lambda$
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].

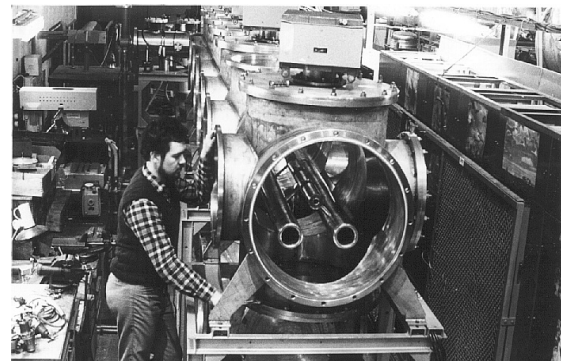


Figure 4: 18 MHz APF accelerating structure ($m^*=50$)
In the columns 2, 3 the results of calculating options of APF linac for clusters with $m^*=10^4$ and $m^*=10^6$.

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

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