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First high-energy hydrogen cluster beams. A new facility at IPN Lyon, France

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Abstract.

I

The hydrogen cluster accelerator existing at Institut de Physique Nucléaire de Lyon (IPN Lyon) has been upgraded by adding a Variable Energy Post-accelerator of RFQ type (VE-RFQ). This operation has been performed in the frame of a collaboration between KfK Karlsruhe, IAP Frankfurt and IPN Lyon. The facility has been designed to deliver beams of mass selected Hn^+ clusters, n chosen between 3 and 49, in the energy range 65-100 keV/u. For the first time, hydrogen clusters have been accelerated at energies as high as 2 MeV. This facility opens new fields for experiments which will greatly benefit from a velocity range never available until now for such exotic projectiles.

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The IPN Lyon hydrogen cluster accelerator was initiated 18 years ago within a collaboration between the Institut de Physique Nucléaire de Lyon with CERN contribution towards the high gradient accelerator tube, and Kernforschungszentrum Karlsruhe (KfK). The collaboration was conducted by KfK and aimed at the development of intense hydrogen cluster ion beams produced by a cryogenic source [1] for nuclear fusion. At the end of the fusion oriented work, physicists had at their disposal a very original and unique tool for fundamental and applied research with or on hydrogen clusters. This tool, equipped with a cryogenic cluster ion source, is able to accelerate cluster ions, preferably of hydrogen (Hn^+, where n is the number of protons bound by n-1 electrons). The high voltage (<650 kV) is delivered by an open air rectifier cascade (Cockroft Walton type). The high gradient accelerator tube is inclosed in a larger insulating tube filled with SF6 gas at atmospheric pressure.

Hydrogen clusters are of special interest from both an experimental and theoretical point of view because of their relative simplicity. All the light clusters that have been produced and observed up to now are mainly singly charged species of odd mass numbers and their stability, according to theoretical predictions (ab initio calculations performed up to n=15 [2]), is due to the clustering of H2 molecules around an $H3^+$ positive core.

Light and medium mass clusters (n<100) have been used for a variety of experiments which mainly deal with their interaction with matter as shown in some examples. First experiments [3] were devoted to measurements of secondary electron emission from thick targets under bombardment of Hn^+. In order to obtain crude information on their structure, the dissociation cross sections of hydrogen clusters in a variable thickness gas target were measured at various velocities for different sizes of clusters [4]. Then a large series of experiments was developed concerning the study of neutral H^0 atoms emerging from thin foils (measurements of the neutral fraction and of the angular distributions of atoms at emergence [5]). For very light incident clusters collective effects have been observed. They are increasing with the mass but saturation of these effects occurs for n=5 or 7. In connection with these experiments the atomic excitation of atoms after the break up of hydrogen clusters in thin foils was measured by conventional beam foil spectroscopy techniques [6]. The desorption of ions following the interaction of clusters with insulating materials has been studied extensively in an attempt to correlate the emission yield to the stopping power of the material for clusters [7]. Furthermore, the slowing down of hydrogen clusters in thin foils has also been studied [8]. Measurements of the secondary electron emission (from thin foil targets) induced by hydrogen clusters have revealed a strong inhibition effect which has been qualitatively explained [9]. Mass and velocity of clusters were always variable parameters in these experiments.

A Monte Carlo simulation program has been developed [10] to describe the penetration of clusters in matter. It calculates distributions of separations and of relative velocities at the exit surface of thin foils as well as angular distributions of fragments at emergence, energy loss by fragments in foils, etc. Comparison of calculated angular distributions with experimental results shows that effects observed are of the same magnitude as the effects which would be obtained with molecular beams of $H3^+$ and H2 in their fundamental states. So such comparisons involving three dimensional structure of clusters give information about their vibrational state. Other physical quantities like the stopping power of the material, the Coulomb repulsion between constituents of the cluster inside the solid, the distances between fragments and their directions at the exit of the foil can be predicted. That can be a step leading to the possibility of building a model of charge exchange processes.

The velocity is a critical parameter of particle or cluster interaction with matter. A maximum total energy of 650 keV was a severe limitation, the maximum velocity depending on the cluster mass. For n=49 the maximum energy per proton is about 13 keV which corresponds to a velocity of about $0.7v_0$, v_0 being the Bohr velocity. Moreover, this is too low an energy to be measured by a barrier surface detector. Then it was evident that it would be necessary to have clusters at higher energies and at velocities up to $2v_0$. That would allow investigations in another range of velocities and new experiments leading to a better understanding of particle-matter interaction as well as new possibilities for investigating more deeply the structure of these clusters.

The upgrading of the hydrogen cluster facility was really started 4 years ago after it was decided to add to the first machine an RFQ type post-accelerator as proposed by two of us [11]. The upgrading program has been performed within a collaboration between three laboratories, KfK Karlsruhe, IAP Frankfurt and IPN Lyon. The advantages of such accelerating structures are the possibilities of having strong electrical focusing at high operating frequencies and therefore compact and low cost cavities, and of keeping the ion source, here the rather huge cluster accelerator, on ground potential. The post-accelerator developed in Frankfurt is a 4-rod Radio Frequency Quadrupole, the first one allowing a Variable Energy (VE-RFQ) at entrance and therefore at its exit, the energy amplification factor being 10. The final energy range for selected mass hydrogen clusters Hn^+, (49 is the maximum value for n) is 65-100 keV/u, the maximum total energy being at the present time limited to 3 MeV. The VHF-band was usable (range of 80-110 MHz) because of the relative high entrance energy, 6.5-10 keV/u, and of the maximum mass (n=49 in a first step). For a given mass, the frequency to be applied is directly dependent on the chosen energy, the RF power depending on the mass only. For each entrance energy the resonance frequency of the cavity has to be adjusted by means of a mechanical tuning device. This prototype of VE-RFQ is a very compact one (length is about 2m), for reasons explained above. The VE-RFQ parameters are described in references [12].

A layout of the new high energy hydrogen cluster facility is shown on Fig.1. Charged clusters of different masses result from the break up by an electron gun of pulsed mode produced hydrogen droplets. All of them are accelerated vertically to the same energy, then bent towards the horizontal direction by a cylindrical electrostatic deflector succeeded by a bending magnet which provides the mass selection. The beam transportation and matching to the severe RFQ entrance conditions are done by sets of electrostatic quadrupole triplets and deflecting plates. Four wire-chambers installed at judicious places allow the x-y profiles of the cluster beam to be visualized for comparison with the results of transport calculations. This instrumentation will be used to measure when necessary the emittance of the beam when it enters the post accelerator and will provide the main data needed to control the beam transportation by on line computers.

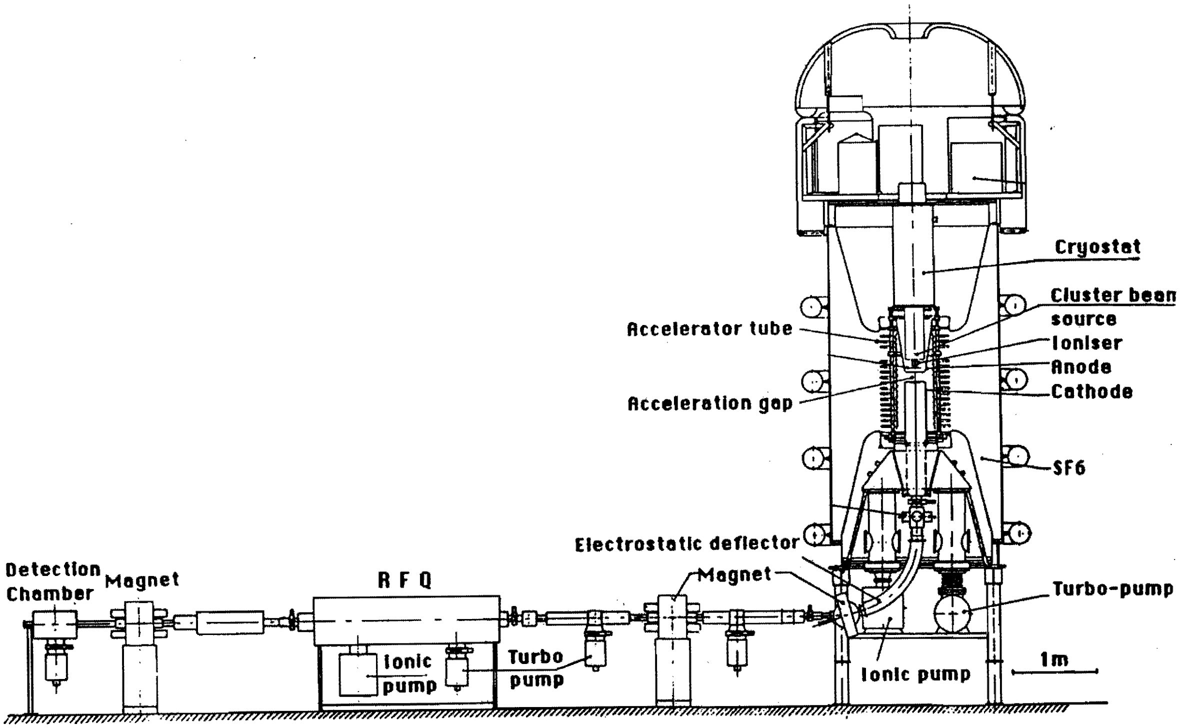

Fig. 1. Layout of the high energy hydrogen cluster facility

$N2^+$ molecular ion beams accelerated at 1.83 MeV were used to verify the design of the beam transportation, the ability to match the RFQ entrance conditions and to measure the energy amplification (factor 10). The energy calibration of the surface barrier detector used for these tests had been made with $N2^+$ beams of well known energy delivered by a 2.5 MeV Van de Graaff accelerator.

High energy hydrogen clusters of randomly chosen mass have been delivered for the first time by the upgraded facility in January 1992, $H21^+$ at 1.4 MeV, $H31^+$ at 2.07 MeV. Post accelerated cluster beams have been studied by physicists in the high energy beam line which includes an electrostatic quadrupole downstream from the RFQ to focus the beam in the experiment chamber, deflecting plates in the horizontal plane and a magnet. This third magnet "cleans up" the beam and will offer the possibility to have more than one experimental high energy beam line. In addition, a magnet located before the RFQ offers the possibility to perform experiments with low energy beams (< 650keV) of heavier hydrogen clusters, heavy Dn^+ clusters [13] or other clusters like $(CH4)n^+$ (for masses higher than 100 u, the first magnet which performs the mass selection has to be replaced by an electrostatic deflector). Preliminary tests indicate that the intensity of the beam during each burst of RFQ acceleration corresponds to about 10^5 clusters per second. For the post-accelerator, a duty-cycle close to 25% is expected after 4 rods cooling improvements.

This new and unique facility, at IPN Lyon, opens an experimental activity which will greatly benefit from a velocity range never available until now for such exotic projectiles. First planned investigations will focus on the interaction of these projectiles with solid and gas-jet targets to study, in connection with various theoretical approaches, the structure of these projectiles as well as the interaction processes. Preliminary experiments with high energy clusters impinging on a gas-jet target have been performed with success in June.

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