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STATUS OF HIGH-CURRENT ELECTROSTATIC ACCELERATOR - TANDEM FOR THE NEUTRON THERAPY FACILITY

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Abstract

Original 2.5 MeV, 40 mA proton tandem accelerator for the neutron therapy facility is described. The results of computer simulations of high current hydrogen negative ions beam transmission through the special geometry of potential electrodes with vacuum insulation are presented. The results of experiments with prototype vacuum insulation tandem accelerator are given also. Various charge-exchange targets are considered. Namely, targets are gas target with outward pumping, gas target with pumping inside of high-voltage electrode.

1 INTRODUCTION

The development of a neutrons source for boron neutron capture therapy based on the compact and inexpensive accelerator is possible [1]. Neutron generation is proposed to be carried out by dropping an intensive proton beam onto lithium target using ^{7}Li(p,n)^{7}Be threshold reaction. In the case of boron neutron capture therapy the proton energy stability is expected to be provided with accuracy of 0.1 %. Creation of accelerator with proton beam intensity of tens milliamperes will decrease exposure time for necessary therapeutic dose to tens minutes.

Characteristic feature of the neutrons source is use of tandem accelerator with vacuum insulation instead of accelerating columns. In the conventional scheme of the tandem, two accelerating columns, based on ceramic tubes, are connected by the high voltage parts with the charge-exchange target in between. The prospect of high current (a few tens milliamperes) accelerator design according to this scheme is limited by its two basic disadvantages — the necessity of pumping the gas of charge-exchange target through accelerating columns and an inevitable current emission of secondary electrons and ions from the high current beam passage region to the inner surfaces of high voltage electrodes and ceramic insulators. The tandem accelerator with vacuum insulation provides the higher reliability compared to tandem based on accelerating columns with ceramic insulation and high intensity of beam.

2 RESULTS AND DISCUSSION

Fig. 1 shows the construction of vacuum insulation tandem accelerator developed at BINP, as a base of neutrons source, using the sectionalized rectifier 1 from industrial ELV-type electron accelerator, as a powerful source of high voltage. Negative hydrogen ion beam 3 is injected into electrostatic tandem accelerator with vacuum insulation. After charge-exchange of negative hydrogen ion in proton inside charge-exchange tube 7 in the center of high-voltage electrode 5, a proton beam is formed at the outlet of the tandem, which is accelerated to double voltage of high-voltage electrode.

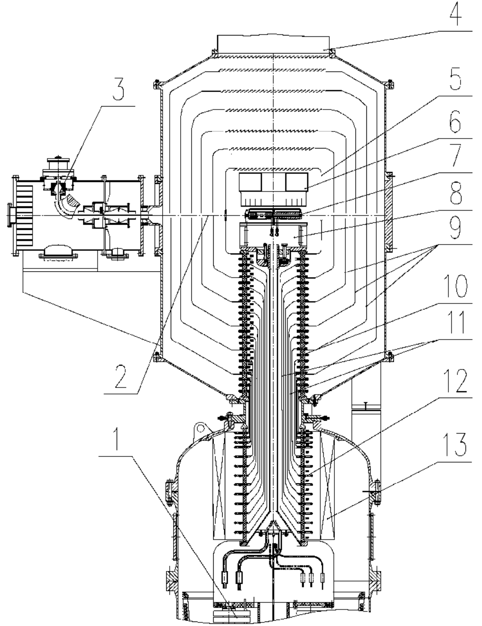

Figure 1: Vacuum insulation tandem accelerator.

The high voltage electrode is surrounded by system of different potential shields 9 providing the homogeneous distribution of the potential and preventing the full voltage effect.

The most important component of the accelerator is the high-voltage through-pass insulator, which transfers the high-voltage powerful source potential into the vacuum tank from the tank filled with SF_6 gas. Insulator can be arbitrarily remote from the accelerated beam passage region 2. The high-voltage electrode is placed on the vacuum part end 10 of the through-pass insulator on the metal flange which is vacuum tightened by the tightening pipe passing along its axis connected to the another metal flange placed on the gas part end 12 of insulator. This metal flange contacts with high-voltage source. The gas part of the through-pass insulator (placed in SF_6) manufactured of ceramic rings separated by metal rings for the potential distribution. The vacuum part of the insulator manufactured of glass rings, also separated by metal rings. Inside the insulator (under SF_6 gas pressure lower, than outside gas part insulator pressure) around the tightening pipe thin wall pipes of various lengths 11 are concentrically located to connect the respective metal rings of different potential on the gas part of the insulator and its vacuum part. The voltage is applied to these rings from the resistive divider 13 providing the homogeneous distribution of the potential along the insulator length. Vacuum pumping is carried out through mouth 4.

Coaxial round holes for the beam passage are in the walls of vacuum tank, high-voltage electrode and in the shields. Since the thin-wall shields placed along the equipotential surfaces of the electrostatic field hardly contribute into focusing. In general the low energy beam focusing in this system is provided by two axisymmetric lenses: electrostatic (input hole of the first accelerating gap) and magnet one, placed before input hole. The defocusing lens in the high-voltage electrode input hole is weak since here the beam has already high energy.

Computer simulation of transport of a dense beam from the source to the charge-exchange target in electric and magnetic fields taking account of space charge and emittance of the beam is carried out. Focusing optic system is to be optimized for transporting negative hydrogen ion beam without significant increase of the beam emittance. Minimization of effect of spatial charge compensation is desirable. It was determined that transporting may be provided by both electrostatic and magnetic lenses in variant of the "hard" beam introduction into tandem.

Fig.2 shows computer simulation envelope results for 40 mA, 10 mA and 1 mA H^- beams with 1 eV initial ions cross energy.

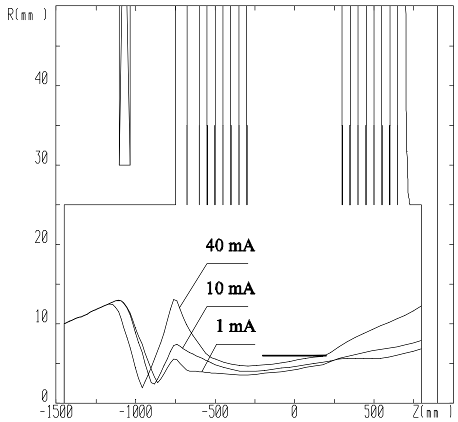

Figure 2: Example of computer simulation envelope results for some H^- beams.

A "soft" beam introduction into tandem, which is realized by more fluent increase of electric field for Pierce geometry of electrodes, was discussed also. Accelerating voltage must be in good accordance with ion beam density in "soft" beam introduction.

At the test desk available, dc H^- 5 mA, 25 keV ion beam was obtained at the model of negative ion source. Preliminary measurements of dc H^- ion beam emittance were carried out [2]. The value obtained for the normalized emittance $0.3 \cdot \pi$ mm·mrad meets the requirements.

An analysis of application of different charge-exchange targets has been made [3]. A gas target was chosen for use. The charge-exchange target is a pipe with an inner hole of 6 - 15 mm diameter and ~ 400 mm length. In the center of the pipe, gas leaks at a rate providing the efficient density of the target 3×10^{16} mol·cm^{-2} required for the 99 % charge-exchange. The next gas charge-exchange targets were assigned to be used: i) argon gas target with outer pumping through the heads of potential shields;
ii) argon gas target with recycling turbo-molecular pumping inside the high-voltage electrode; iii) gas target with gas freezing on the nitrogen trap inside the high-voltage electrode. Fig.1 shows the nitrogen trap variant.

The pump 6 is a toroidal volume of ~ 12 liters placed in the upper part of the high-voltage electrode above the tube of the charge-exchange target. It can be filled with liquid nitrogen. The lower part of the toroidal volume is the surface of pumping out. It is constructed as copper rings that are in close heat contact with the pump body manufactured of stainless steel. A number of copper plates increasing the surface of pumping out to ~ 1 m^2 is soldered to the rings.

Some coaxial dielectric tubes are placed in the center of the rectifier to provide liquid nitrogen supply into the pump, which is under high voltage potential. The outer ceramic tube separates the rectifier volume filled with SF_6 and the inner high voltage electrode volume of the tube filled with nitrogen. Liquid nitrogen is supplied to toroidal volume through the inner tubes thermoinsulated in this way. In this case some gases, as CO_2 is supposed to be used as charge-exchange gas. CO_2 condenses at –56 °C and is highly heat-conducting in solid state.

In volume 8 are placed charge-exchange target control systems.

There are exist energy evolving on account of ion beam interacts both residual gas of vacuum tank and charge-exchange target gas. It was determined that heat up to 5 kW can be taken from high-voltage electrode region using transformer oil.

In general, there are two kind of consequences of vacuum breakdowns in dependence on vacuum gap storage energy: with increasing and decreasing of electrical strength of high-voltage vacuum gap. For tandem accelerator with vacuum insulation the separate vacuum gap storage energy is depended on number of accelerating (vacuum) gaps. Maximum separate vacuum gap storage energy is 44 J for 4-gaps system, 30 J for 6-gaps system and 15 J for 12-gaps system.

There are 2 types of breakdowns in accelerator - tandem: breakdowns at full voltage and breakdowns of any separate vacuum gap. Fig. 3 shows vacuum gaps overvoltages E_N/E_0 under breakdowns at full voltage. E_N and E_0 are vacuum gap electric field intensities after and before breakdown, accordingly. The vacuum gap number increases from high-voltage electrode to “ground” one.

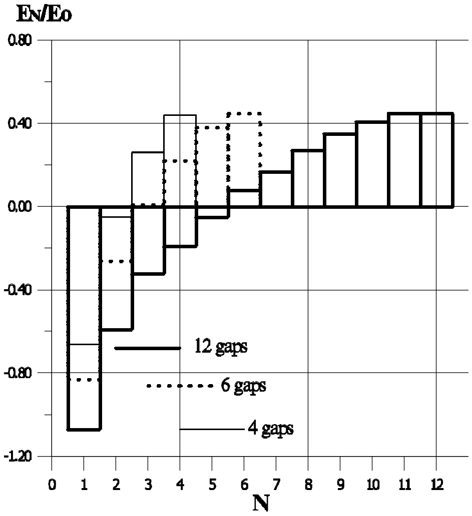

Figure 3: Vacuum gaps overvoltages under breakdown at full voltage.

Maximum near by vacuum gaps overvoltages E_N/E_0 under breakdowns of any vacuum gap are 0.08, 0.14, 0.17 for 12, 6 and 4 gaps accordingly.

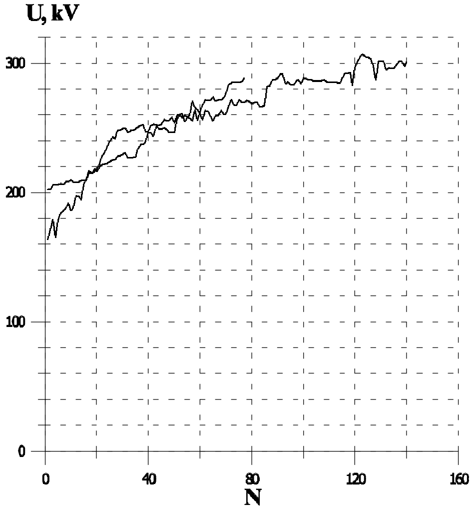

Figure 4: Example of two training curves of 45 mm vacuum gap.

The prototype of such tandem with vacuum insulation was used successfully as an injector of the proton synchrotron. Now it is used for providing necessary experiments for final design of the high-current electrostatic accelerator-tandem.

A set of experiments on study of high voltage strength of vacuum gap with large square electrodes is carried out at prototype tandem-accelerator with electrodes square ≈ 0.7 m^2 and 45 mm high voltage vacuum gap. Fig.4 shows the breakdown voltage U opposite number of regular breakdown N in previous high-voltage experiments. First breakdowns of vacuum gap took place at intensity of electrostatic field higher, than vacuum gaps accelerator tandem one: ≈ 33 kV/cm and storage energy up to 10 J released at breakdowns did not result in detraining of vacuum gap.

High-voltage experiments with storage energy up to 20 J, H$^-$ ion pulse beam injection experiments, and charge-exchange target experiments, are planned.

3 CONCLUSION

Accelerator based neutron source for boron neutron capture therapy for cancer is under realization now. The vacuum tank diameter was determined to be 1400 mm, high-voltage electrode diameter — 600 mm. Electrostatic intensity at accelerating gaps is 33 kV/cm. Energy storage in every high-voltage vacuum gap is lower then 20 J. High-voltage through-pass insulator is under construction. Electrodes and glass insulators were manufactured for vacuum part of insulator. It is determined that overvoltages on the high-voltage vacuum gaps and insulators are permissible at ELV breakdowns at full voltage or breakdowns of any vacuum gap. Therefore, there is no need to mount a compensating capacity divider. Development of tandem surface plasma source of H$^-$ ions was continued to obtain dc 40 mA H$^-$ ion beam with small emittance, high gas efficiency and low attendant electron current. Design drawings were finished for plasma generator, the first stage of the source.

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