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Status report of the VINCY Cyclotron

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Abstract The VINCY Cyclotron is the main part of the TESLA Accelerator Installation. The diameter of the pole of this machine is 2000 mm. Its bending constant is 145 MeV while its focusing constant is 75 MeV. The radiofrequency system of the machine consists of two λ/4-resonators with the eigenfrequency in the range from 17 to 31 MHz. Ions coming from a heavy ion source or a light ion source will be injected into the machine axially. They will be introduced into its median plane by a spiral inflector. Heavy ions accelerated in the machine will be extracted from it by a foil stripping system or by an electrostatic deflection system. Light ions will be extracted from it by the foil stripping system. The first programs of use of the VINCY Cyclotron are related to routine and experimental production of radioisotopes and radiopharmaceuticals, and to biomedical research with ion beams. The first beam extracted from the machine will be the proton beam of the energy of 22 MeV obtained from the H_2^+ beam extracted from the light ion source. This beam will be used first for production of radioisotope ^{18}F and radiopharmaceutical ^{18}FDG, to be employed for positron emission tomography.

Key words accelerators • cyclotrons • ion sources • radioisotopes • radiation research

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Introduction

The TESLA Accelerator Installation, in the Vinča Institute of Nuclear Sciences, includes the VINCY Cyclotron – a compact isochronous cyclotron, the mVINIS Ion Source – an electron cyclotron resonance heavy ion source, the pVINIS Ion Source – a volume positive or negative light ion source, and a number of low energy and high energy experimental channels [10, 11]. In the low energy experimental channels one will be able to use ion beams from the mVINIS Ion Source and in the high energy experimental channels ion beams from the VINCY Cyclotron. Programs of use of this facility comprise basic and applied research in physics, chemistry and biology, development of materials and nuclear technologies, production of radioisotopes and radiopharmaceuticals, and proton therapy.

So far, we have commissioned the pVINIS Ion Source (in July 1997) [4], the mVINIS Ion Source (in May 1998) [8], and the (low energy) channel for modification of materials (also in May 1998) [9]. In June 1998 construction of the facility was stopped, due to the severe economic crisis in the country. It was resumed in September 2002.

Magnetic structure and radiofrequency system

The magnetic structure of the cyclotron consists of the ferromagnetic elements – the yoke, poles, sectors and plugs, the main coils, and the correction coils – the trim coils and harmonic coils [1, 2]. The diameter of the pole is 2000 mm. The distance between the poles, i.e., between the magnet's valleys, is 190 mm. The spiral angle of the sectors is 0°, their angular span is 42°, their height is 66 mm and there are four of them per pole. All the radial, azimuthal and axial sides of the sectors are shimmed. The minimal distance between the sectors, i.e., between the magnet's hills, is 31 mm. The plug is made of three pieces.

The machine has two main coils. Each of them consists of eight segments. The main coils are wound with a rectangular hollow copper conductor. Their segments are powered in series, their maximal current is 1000 A and they are cooled by demineralized water.

The machine has 10 circular trim coils per pole and they are placed between the poles and sectors. It has eight quasi-trapezoidal harmonic coils per pole – four of them in the central region of the machine and four of them in its extraction region. The trim coils and harmonic coils are wound with a square hollow copper conductor with the magnesium oxide insulation in the copper sheath. They are powered independently, their maximal currents are 200 A and they are cooled by demineralized water.

The ferromagnetic elements, the main coils and the correction coils have been fabricated, assembled and partly tested; testing of the correction coils has not been finished. The shimming of the sectors and plugs has not been completed yet.

The main chamber of the machine consists of an octagonal skeleton, two horizontal sides and eight vertical sides. The skeleton is made of stainless steel and the sides of duralumin. The main chamber is evacuated by two cryogenic vacuum pumps of the pumping speed of 10,000 l/s each and two turbomolecular vacuum pumps of the pumping speed of 1500 l/s each. The main chamber has been fabricated, assembled and tested.

The radiofrequency system (RF) of the machine consists of two $\lambda/4$-resonators with the eigenfrequency in the range from 17 to 31 MHz, two coupling lines with coupling loops, two amplifier chains, the safety subsystem, and the control subsystem [5, 6]. Each resonator consists of a part that is out of the main chamber and a part penetrating it and lying between the valleys. The inner electrode of the resonator consists of a cylindrical part, being partly out and partly in the main chamber, terminated by a triangularly shaped dee. Its outer electrode consists of a cylindrical part, a transition part, both of which are out of the main chamber, and a box, that is in the main chamber, terminated by the anti-dee with the shape following the shapes of the valleys. The average angular span of the dee is 34°, while that of the anti-dee is 48°. The vertical dimension of the ion beam aperture of the dee is 22 mm. The course changes of the eigenfrequency of the resonator are performed by a sliding short, while its fine changes are performed by a trim loop attached to the sliding short. The amplitude of the dee voltage varies from 35 to 100 kV. The phase difference between the dee voltages is either 0 or 180°, depending on the harmonic number of the dee voltage. The resonators are cooled by demineralized water flowing through a system of tubes.

The amplifier chains begin with a frequency synthesizer and each of them include a predriver amplifier, a driver amplifier and a power amplifier. The predriver amplifier is a 2 kW broad-band amplifier. The main element of the driver amplifier is a 20 kW tetrode in the grounded cathode configuration while the main element of the power amplifier is a 50 kW tetrode in the grounded grid configuration. The tetrodes operate in class B or C. They are cooled by demineralized water. The maximal amplitude of the anode voltage of the power amplifier is 10 kV.

The coupling lines with coupling loops provide the direct coupling of the power amplifiers to the resonators. The coupling loop is fixed and the matching of the impedances of the primary and secondary circuits is achieved by varying the eigenfrequency of the power amplifier, with a variable condenser [6]. With this novel method we avoid the need to move the coupling loop and, thus, minimize the probablity of electrical dicharges in the coupling line.

The control subsystem is made of three feedback loops. It makes possible the control of the amplitude of the dee voltages, the phases of the dee voltages and the eigenfrequencies of the resonators.

The resonators, the amplifier chains, the safety subsystem and the control subsystem have been fabricated. Fabrication of the coupling lines with the coupling loops has not been finished yet.

The maximal value of the magnetic induction at the center of the machine is 2.016 T and its extraction radius is 860 mm. Its bending constant is 145 MeV, while its focusing constant is 75 MeV. This means that for the ion specific charge below 0.52 the ion energy is limited by the bending ability of the machine, and that for this parameter above 0.52 it is limited by its focusing ability. The former range includes heavy ions, H_2^+ ions and D^- ions, and the latter range H^- ions. Heavy ions will be accelerated with the harmonic number of the dee voltage equal to 2, 3 or 4, H_2^+ and D^- ions with this parameter equal to 2, and H^- ions with this parameter equal to 1.

Injection, acceleration and extraction

The injection system of the cyclotron includes a spiral inflector and the electrodes in the central region – three electrodes at the dee potential and one electrode at the anti-dee potential [3]. The inflector is placed at the end of the lower axial channel of the machine.

The machine has two extraction systems – a foil stripping system and an electrostatic deflection system [14]. Low charge state heavy ions and light ions accelerated in the machine will be extracted from it by the foil stripping system, which is placed between the free valleys on the front side of the machine. The foil can be moved radially and azimuthally. The extracted ion beam passes first through a combined magnet and then through a bending magnet. The combined magnet has the focusing function as well as the bending function. High charge state heavy ions accelerated in the machine will be extracted from it by the electrostatic deflection system, which includes an electrostatic deflector and a passive magnetic channel. The deflector is placed between the free valleys on the back side of the machine and the magnetic channel between the free valleys on the front side of the machine.

Here, we shall present the results of the calculations of the H_2^+ ion beam transport through the machine for the final ion energy of 30 MeV per nucleon, at the extraction radius of 860 mm. The corresponding values of the magnetic induction at the center and of the eigenfrequency of the resonators are 1.791 T and 13.75 MHz, respectively. The isochronous magnetic field map in the median plane

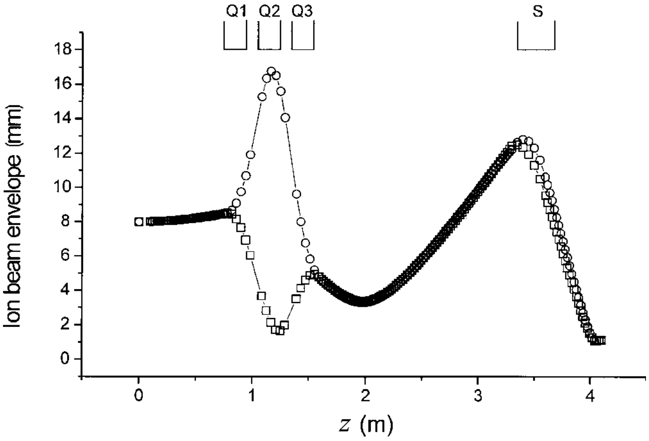

Fig. 1. The x (squares) and y (circles) H_2^+ ion beam envelopes from the pVINIS Ion Source to the entrance of the inflector. The quadrupole magnet triplet is designated by Q1–Q3 and the solenoid by S. The initial and final values of the beam parameters are given in the text.

was calculated on the basis of the measured magnetic field maps for the values of the main coil current of 250, 600 and 1000 A using the Gordon's procedure. The corresponding magnetic field dependence in the lower axial channel was calculated using a simplified model of the magnetic structure and a three-dimensional computer code.

Figure 1 shows the transversal H_2^+ ion beam envelopes from the pVINIS Ion Source to the entrance of the inflector. The initial values of the energy, the transversal emittances, the maximal transversal half-widths and the maximal transversal half-angles of the beam, having a double waist, were: $E = 26.4$ keV, $\varepsilon_x = \varepsilon_y = 30\pi$ mm·mrad, $x_m = y_m = 8$ mm and $x_m' = y_m' = 3.75$ mrad, respectively. The transport line includes a quadrupole magnet triplet and a solenoid. The final values of the parameters of the beam, having a double waist again, were: $\varepsilon_x = 30.21\pi$ mm·mrad, $\varepsilon_y = 30.21\pi$ mm·mrad, $x_m = 1.126$ mm, $y_m = 1.123$ mm, $x_m' = 26.82$ mrad and $y_m' = 26.91$ mrad.

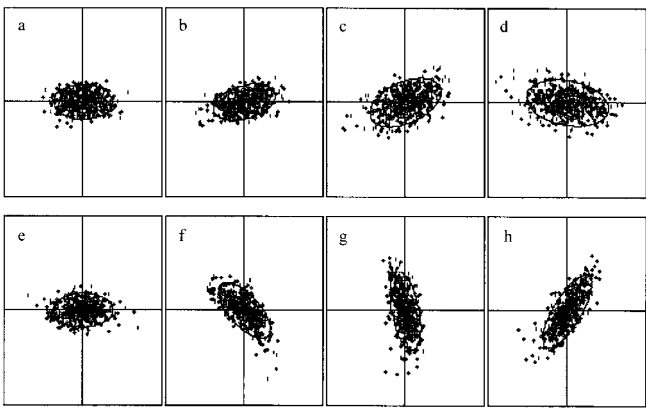

Fig. 2. The evolution of the transversal H_2^+ ion beam emittances through the inflector. The upper four graphs (a–d) give the radial (x or r) beam emittances and the lower four graphs (e–h) the axial (y or z) beam emittances at the entrance of the inflector, for the beam inflection angle of 30°, for the beam inflection angle of 60° and at the exit of the inflector, respectively. The ranges of the parameters on the abscissas and ordinates of the eight graphs are ±3 mm and ±160 mrad, respectively. The initial and final values of the beam parameters are given in the text.

Figure 2 gives the evolution of the transversal H_2^+ ion beam emittances through the inflector. At the entrance of the inflector they are the x and y beam emittances while at its exit they can be considered as the r and z beam emittances. The initial values of the beam parameters were taken to be equal to their final values in the calculation of the beam transport from the pVINIS Ion Source to the entrance of the inflector. The electric radius, the electric gap, the magnetic radius, the tilt parameter and the voltage of the inflector were: 25 mm, 7 mm, 18.32 mm, –0.44 and ±7.28 kV, respectively. The final values of the radial and axial emittances and the corresponding Twiss parameters of the beam were: $\varepsilon_r = 55.22\pi$ mm·mrad, $\varepsilon_z = 34.72\pi$ mm·mrad, $\alpha_r = 0.2487$, $\beta_r = 0.04422$ mm/mrad, $\gamma_r = 24.01$ mrad/mm, $\alpha_z = -1.155$, $\beta_z = 0.02483$ mm/mrad and $\gamma_z = 95.02$ mrad/mm.

Figure 3 shows the projections of the H_2^+ ion trajectories onto the median plane for the radii up to about 90 mm. The initial values of the ion beam parameters were taken to be close to their final values in the calculation of the beam transport through the inflector. The dee voltage was 80 kV and the RF phase range from –50 to –20°.

Figure 4 shows the envelopes of the proton beams generated in the foil exposed to the H_2^+ ion beams of the energies of 30 and 22 MeV per nucleon. The initial values of the transversal emittances, the maximal transversal half-widths, the maximal transversal half-angles and the energy spread of the beams, having a double waist, were: $\varepsilon_r = 12\pi$ mm·mrad, $\varepsilon_z = 5\pi$ mm·mrad, $r_m = 2$ mm, $z_m = 5$ mm, $r_m' = 6$ mrad, $z_m' = 1$ mrad and $\Delta E = \pm 1\%$. The Figure also shows the envelopes of the proton beams generated in the foil exposed to the H^- beams of the energies of 65 and 55 MeV, and the envelopes of the Ne^{9+} beams generated in the foil exposed to the Ne^{3+} beams of the energies of 3.1 and 2.7 MeV per nucleon. The initial

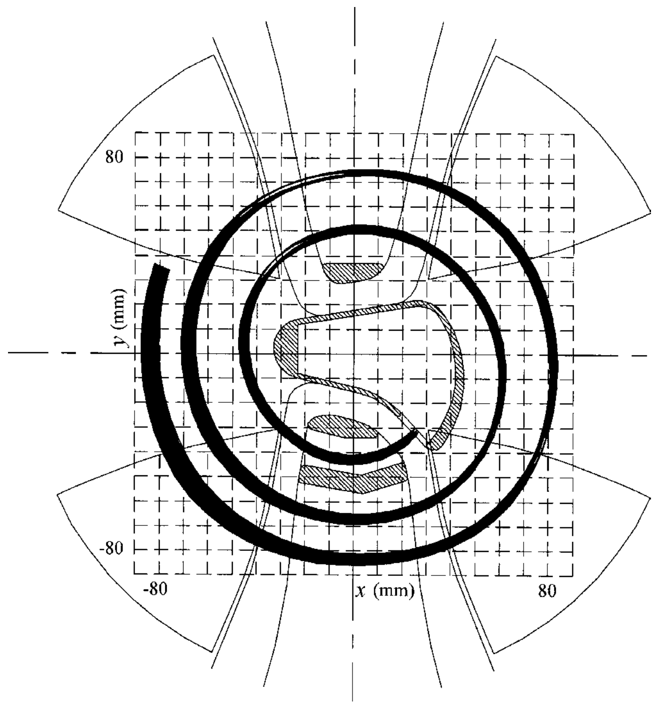

Fig. 3. The projections of the H_2^+ ion trajectories onto the median plane for the radii up to about 90 mm. The initial values of the beam parameters are given in the text.

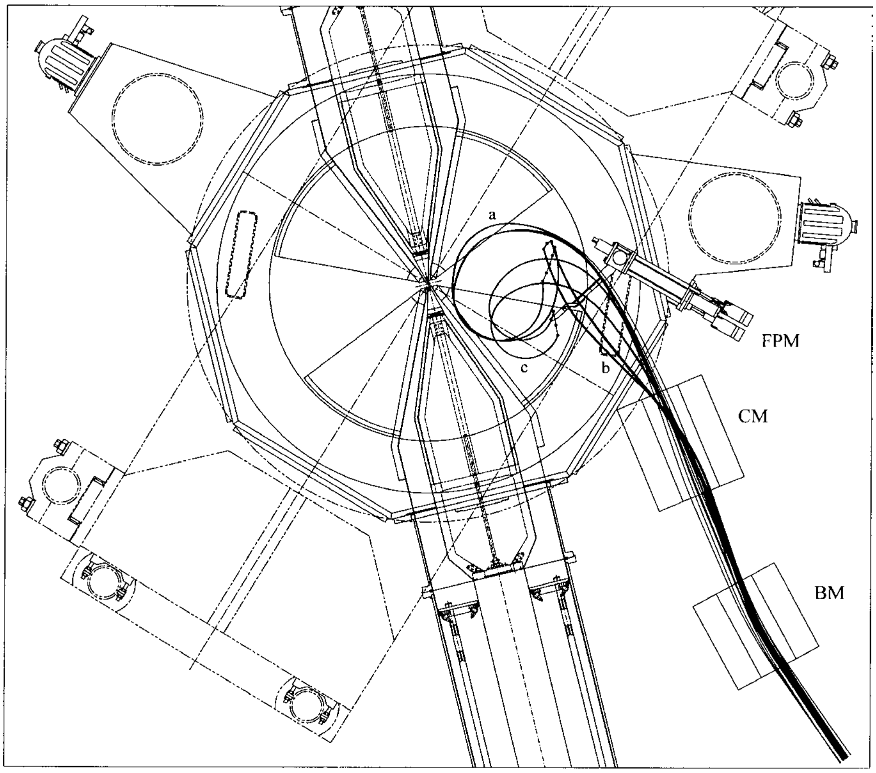

Fig. 4. The envelopes of the proton beams generated in the foil exposed to the 30 and 22 MeV per nucleon H_2^+ ion beams (a), of the proton beams generated in the foil exposed to the 65 and 55 MeV H^- beams (b), and of the Ne^{9+} ion beams generated in the foil exposed to the 3.1 and 2.7 MeV per nucleon Ne^{3+} beams (c). The foil positioning mechanism is designated by FPM, the combined magnet by CM and the bending magnet by BM. The initial values of the beam parameters are given in the text.

values of the beam parameters in the case of H^- ions were: $\varepsilon_r = 5\pi$ mm·mrad, $\varepsilon_z = 5\pi$ mm·mrad, $r_m = 1$ mm, $z_m = 5$ mm, $r_m' = 5$ mrad, $z_m' = 1$ mrad and $\Delta E = \pm 1\%$. The initial values of the beam parameters in the case of Ne^{3+} ions were the same as in the case of H_2^+ ions. In the cases of H_2^+ and Ne^{3+} ions, in which they make a loop before leaving the machine, the combined magnet acts predominantly as a focusing element. In the cases of H^- ions, in which they leave the machine immediately upon the interaction with the foil, this magnet acts as a bending element.

First programs of use

The realization of the program of use of the channel for modification of materials, with ion beams from the mVINIS Ion Source, has been going on since May 1998 [9]. The first programs of use of the VINCY Cyclotron are related (i) to routine production of radioisotopes, (ii) to research, development of technologies and experimental production of radioisotopes [7, 15, 16], and (iii) to biomedical research with ion beams [12, 13]. They will be realized at the (high energy) channels for production of radioisotopes and for radiation research. The first beam extracted from the machine will be the proton beam of the energy of 22 MeV obtained from the H_2^+ beam extracted from the pVINIS Ion Source. It will be used for routine production of radioisotope ^{18}F and radiopharmaceutical ^{18}FDG, to be employed for positron emission tomography. In the beginning, the production will be going on in the machine's vault.

The program of experimental production of radioisotopes will be focused on medium half-life positron emitters such as ^{64}Cu, ^{86}Y, ^{94}Tc and ^{124}I, to be employed for positron emission tomography, and on α-emitters such as ^{149}Tb and ^{211}At, to be employed for endoradiotherapy. The program of biomedical research with ion beams will be focused on insufficiently known effects of ionizing radiation on the structural and functional integrity of normal and malignantly transformed cells, and it will be connected directly to various diagnostic and therapeutic procedures.

Conclusions

We have described here the VINCY Cyclotron, the status of its construction and the first programs of its use. So far, the ferromagnetic elements, the main coils, the correction coils, the main chamber, the resonators, and the amplifier chains with the safety subsystem and the control subsystem have been fabricated. Construction of the machine had began in September 1992, it had been stopped in June 1998 and it was resumed in September 2002. The first beam extracted from the machine will be the proton beam of the energy of 22 MeV, and it will be used for routine production of the radioisotope ^{18}F. The production should commence in the first half of 2005.

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