Письма в ЭЧАЯ. 2010. Т. 7, № 7(163). С. 803–808

ФИЗИКА И ТЕХНИКА УСКОРИТЕЛЕЙ

AXIAL INJECTION BEAM LINES OF THE CYCLOTRONS

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The overview of possible arrangement of optical elements of axial injection beam line is fulfilled. The methods of calculation of focusing system are discussed. The space charge effects are considered.

Проводится обзор возможных компоновок оптических элементов канала аксиальной инжекции. Обсуждаются методы расчета фокусирующей системы канала. Рассматриваются эффекты пространственного заряда.

PACS: 29.20.dg; 29.90.+r

INTRODUCTION

The axial injection beam lines provide transportation of ions from external sources to the median plane of the cyclotron for its subsequent acceleration. At the final stage of transportation, ions are moving along the vertical axis within the holes in the magnet yoke.

The ratio of the number of particles at external target to the injected one (acceleration efficiency) usually does not exceed 10–20 %. Therefore, the intensity of the beam in the channel of the axial injection often exceeds the intensity of the beam captured in the acceleration mode by more than an order of magnitude, and ion beam currents in the channel can reach several mA. Multicharged ion beams of the required intensity are produced in ECR ion sources operating at frequencies ranging from 2.5 to 18 GHz.

The transfer of beam from the axial channel to the median plane of the cyclotron is produced by means of a mirror or a spiral inflector.

In this paper, using as an example the axial injection beam lines of the cyclotrons of JINR's FLNR (U400, U400R, U400M, IC100, U200) [1–4], DC72 (Slovak Republic) [5], DC60, DC350 (Republic of Kazakhstan) [6–7], VINCY (Serbia) [8], K500 NSCL MSU (USA) [9–10], C400 IBA (Belgium) [11], the overview of possible arrangement of optical elements is fulfilled. The methods of calculation of focusing system taking into account the influence of the cyclotron magnetic field are discussed. The invariants of the set of equations of motion, matching conditions and possible particle distribution at the spiral inflector entrance are given. The space charge effects and the ways of its mitigation are considered.

1. BEAM LINE ARRANGEMENT

The axial injection beam line has two main parts. In the first part the beam charge distribution analysis and separation of the required beam are carried out. The ECR ion source and analysis magnet are placed in this part. The focusing solenoid is installed usually between the ion source and the magnet for decreasing the beam divergence. The beam focusing in this part of the channel is provided by solenoidal and edge magnet fields. In the case of $90°$ bending magnet with pole face angles of $26.5°$, the beam has approximately equal transverse dimensions after the magnet. The distance between the extraction hole of the ion source and the magnet must be equal to double bending radius.

When using simultaneously two or more ion sources the combination magnet — with two entrances and one exit — is often used. In this case the exit pole angle equals zero and vertical beam focusing is provided by the quadrupole lens installed just after the magnet. The equality of beam dimensions may be given by fitting the quad gradient. The pole angles at entrances must be approximately equal to $42°$.

The analysis of the beam charge spectrum is carried out by means of the movable Faraday cup placed at the focal plane of the magnet in the special diagnostic box.

In the second part of the beam line, the matching of the beam parameters with acceptance of the cyclotron is performed. In accordance with results of simulation, it is sufficient to form the axial-symmetric beam at the entrance of the inflector. The beam radius must be fitted in such a way as to exclude the envelope oscillation during motion in homogeneous magnetic field with value of induction equal to one in the center of the cyclotron (beam matched with longitudinal magnetic field).

In most of the previously mentioned axial injection beam lines, the separation of required beam and analysis of the charge spectrum is performed by means of $90°$ magnet in which the axial-symmetric beam from ECR ion source is rotated onto the vertical axis. The symmetry of the beam may be preserved by correct choice of edge angles of the magnet.

If working frequency of ECR ion source is greater than 2.5 GHz, the magnetic field of the source has significant influence on particle motion and leads to rotation around the longitudinal axis. Thereby the mean angular momentum of the beam is not equal to zero. In the case of big magnetic field (big working frequencies), the beam angular momentum defines the value of the beam emittance. In this case for conservation of axial symmetry of the beam it is needed to use three quadrupole lenses placed in the separation part of beam line as, for example, in the DC72 cyclotron.

The matching conditions of axially symmetric beam require at least two solenoids in the vertical part of the channel. For the cyclotron with big induction of magnetic field, of about 2 T, when the level of yoke and poles saturation is very high, the value of magnetic field in axial hole inside the magnet may be about 2–4 kG and may worsen conditions of beam transport. For compensation of cyclotron magnetic field, additional solenoids may be installed in the axial hole of the magnet as in the U400M cyclotron, where three solenoids are used for this purpose.

The losses of particles in the inflector will be absent if the matched beam diameter is less than gap between electrodes. The beam size inside the focusing solenoid near the inflector is in inverse proportion to the one at the inflector entrance. Therefore, to avoid losses of particles in the solenoid it is needed to place it as close as possible to the inflector, in practice closely to the magnetic plug of the axial injection channel. This is true for room temperature (RT) cyclotrons with the level of magnetic field $\leqslant 1.8$ T.

In the superconducting (SC) cyclotrons the beam focusing inside the axial hole is provided by cyclotron magnetic field and matching solenoids may be installed outside the magnet [11]. At design of axial injection beam line in SC cyclotron it is necessary to take into account the high level of stray magnetic fields. To reduce its influence on beam dynamics, the distance between the separation part of the channel and the median plane of the cyclotron should be increased up to 6–8 m. Otherwise the shielding of the optical elements of the beam line, such as analysis magnet and quadrupole lenses, must be provided by special magnetic screens [12].

2. METHODS OF CALCULATION

For the numerical simulation of beam dynamics in the transport lines with various magnetic and electrostatic elements and for fitting of the optical elements parameters, the program library MultiComponent Ion Beam code MCIB04 [13] is used at FLNR, JINR. The space charge fields are taken into account in these calculations. The library has 2D and 3D versions of the programs.

The library is based on two methods that give a good agreement of results of calculations:

• PIC (Particle-In-Cell) method using the fast Fourier transformation method for the solution of Poisson equation in 2D Cartesian coordinates;

• the momentum method for particle distribution function.

The PIC method is successfully used for detailed investigation of beam distribution function. This method is also helpful to consider the nonlinearity of ion space charge fields. The program may be used for numerical simulation of dynamics of multicomponent beams with a realistic charged state distribution. The external electromagnetic fields may be considered both in the analytic form and with the help of the field map.

The analysis and study of the averaged beam characteristics, such as root-mean-square (RMS) dimensions and angular spread, is attained by the momentum method. In this method the external and the beam self-fields are assumed to be linearized. The advantage of this method is a fast calculation, which allows one to carry out the fitting of the parameters of the channel elements.

In considering the motion of particle in the longitudinal magnetic field it is convenient to use the system of coordinates rotating with Larmor's frequency around the longitudinal axis [14]. The equations of motion in this coordinate system in the linear approximation for the two transverse degrees of freedom are not coupled. Therefore, beam RMS emittances are constant for each of the transverse phase planes.

Besides beam RMS emittancies in this coordinate system, the average angular momentum of particles is also constant (in the lab frame this is equivalent to the conservation of canonical angular momentum). This is also true in the presence of self-field of the beam with elliptical cross section. In the absence of coupling between the different degrees of freedom, the average angular momentum of the beam is conserved in a focusing system (not necessarily axial-symmetrical) if it conserves the axial symmetry of the beam [15].

To preserve the axial symmetry of the beam, it is sufficient that the transfer matrices of the focusing system for the two transverse degrees of freedom coincide with each other. In general case this requires equality of three corresponding elements of the transfer matrices and, hence, the three varying parameters of the optical elements. If the average angular momentum is equal to zero, the sufficient condition of conservation of axial symmetry of the beam consists of the equalities of values of Twiss's functions for two degrees of freedom. In this case one can use only two varying parameters.

These matching conditions were applied in calculations of the separation part of the channel. Besides, the conditions for axial-symmetric beam matched with longitudinal magnetic field are used in calculation of the beam line. These matching conditions lead to equality of the beam β function at the median plane of the cyclotron and the double magnetic radius of the inflector and equality of α function to zero. In this case two varying parameters are also needed.

3. SPACE CHARGE EFFECTS

The beam self-field leads to an increase in size of the beam, both transverse and longitudinal, during the bunching, and, often, to a substantial increase of the magnetic field of lenses. An increase of the transverse dimension of the beam demands an increasing of the optical elements apertures. An increase of the longitudinal dimension of the beam leads to a decreasing of accelerated beam intensity. Influence of self-fields can be reduced through increasing the kinetic energy of injected beam, which, however, leads to increased electrical power of the channel power supply.

In addition to these effects, the self-field of the beam leads to the excitation of difference coupling resonance [15] in the longitudinal magnetic field in the vertical part of the channel, as well as to the formation of hollow beam in the separation part [16].

The influence of the coupling resonance results in significant asymmetry of the transverse beam emittances. This effect may be corrected by means of the normal quadrupole lens installed in the vertical part of the beam line just after the analysis magnet.

One explanation of the hole formation in the required (injected) beam is «short focusing» by the solenoid placed between the ion source and the analysis magnet. The focusing length of the solenoid for the lighter ions (that is the ion with the smaller mass-to-charge ratio) is less than for the one injected into the cyclotron. For this reason in the region between the solenoid and the analysis magnet the lighter ion beams have significantly smaller transverse dimensions compared to the injected beam ones. In the region out of the lighter ion beam boundary, the defocusing field decreases as inverse distance of the ions from the axis of the beam. For big magnitude of the lighter ion beam space charge, this leads to the formation of the hollow beam of injected ions just after the analyzing magnet and increases the emittance of the injected ions beam.

To mitigate this effect, the following scheme of the separation part of the channel can be used [9]. The ion beam produced with an ECR ion source with an extraction voltage of about 30 kV may be additionally accelerated using a negative voltage of about -30 kV applied to the third electrode of the accel–decel extraction system, connected to the vacuum pipe of the beam line biased to the same -30 kV potential. In this way the kinetic energy of the beam is increased to 60 keV per unit charge. The influence of the space charge on the ion beam is decreased two times, and it is possible to remove the focusing elements between the ECR and the analyzing magnet. Shortening the distance between the ECRIS and the analyzing magnet further reduces the negative effect of the space charge on the ion beam emittance. The voltage on the vacuum pipe of the beam line must be kept constant from the ECR till the image focal plane of the analyzing magnet where the full separation of the beam charge states is achieved. A vacuum pipe insulator break separates the biased beam line from the downstream section, which is at zero potential. Passing through this section of the beam line, the ion beam is decelerated to 30 keV per unit charge, the energy necessary for the injection in the cyclotron.

This scheme was successfully realized in the NSCL MSU (USA) [10]. The separated ion beam of $^{132}Xe^{22+}$ with current of about 400 μA was obtained in 2009 [17].

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