BEAM DYNAMIC SIMULATION IN THE ISOCHRONOUS CYCLOTRON U-120M

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Abstract

Conversion of the isochronous cyclotron U-120M into H^-, D^- accelerator has extended significantly its utilization. A prompt and reliable setup of cyclotron regimes and tuning of the beam parameters according to a wide range of specific requirements is desirable. For this purpose, a new software has been developed and continually upgraded in last few years. A set of computer codes simulates a detailed numerical analysis of the accelerated beam parameters and trajectories for both positive and negative regimes. The software package is also used for optimization of the beam parameters for extraction by the stripping method. Our experience shows that only the setup of the main coil current and stripping foil position suggested by the code is to be slightly corrected in order to extract the beam to the target position. Several examples demonstrate a good agreement of calculated and monitored beam parameters and its behaviour.

INTRODUCTION

So far, WMODEL4 mathematical matrix model [1] of the U-120M cyclotron has been exploited to compute the RF and magnetic system parameters as a basic tool for acquirement of an arbitrarily entered isochronous accelerating regime. The results of the calculation, verified by the cyclotron operation, have been saved in files that are constantly ready for a repetitive tuning of the cyclotron. During many years of the use of the program, a database of the files facilitating a very quick and reliable setup of any regime in a wide range of energies for any of basic particles (p, d/alpha, $^3He^{2+}$) has been created. However, the matrix model calculates only average values of the cyclotron parameters (i.e. magnetic fields, index, energy, RF phase, frequencies of free radial and axial oscilation etc.).

In order to obtain a good knowledge of a beam properties for a particular configuration of the central region a new means of dynamic simulation have been developed. The system enables to use harmonic coils for the beam centring, to find the stripping foil position ensuring proper extraction to the selected target, to optimize the accelerating process, and to analyse the beam properties during its acceleration and extraction.

Due to a wide range of accelerating regimes, no adaptations of the central region limiting the emittance of the injected beam, as it was suggested i.e. in [2], have been introduced. That is why, already the low radii show a continuous mixture of trajectories of a miscelaneous origin. Therefore, as an ion beam we regard a cluster of particles, impinging either non-transparent probe or stripping foil at a given radius and azimuth. The original codes were written in Borland Pascal, the later ones in Borland Delphi.

BEAM TRAJECTORY SIMULATION

Acceleration

DURYCNM4 program calculates 3D trajectories of ions accelerated in an arbitrarily chosen accelerating regime with a large variety of initial conditions and required final parameters. The relativistic equations of motion in the orthogonal coordinates are solved in 3 dimensional phase space *(x, x', y, y', z, z')* with the time as an independent variable by the Runge-Kutta method. The integration step is the time that corresponds to the RF angular step 0.1° in the injection region and 0.5° in the further course. Actual values of magnetic field components B_x, B_y, B_z and electric field components E_x, E_y, E_z are calculated [3] at each step. The program continuously calculates the position and velocity components, RF ion phases at the moment of the ion pass through the acceleration gap, centres of the orbits of particular ions or of the whole beam, their energies and, if required, also their radial and axial emittance, beam profiles, energy dissipation, space distribution and radial density of the ions in the beam at a given radius. The bellow shown examples concern 36 MeV of an H^- ion acceleration regime.

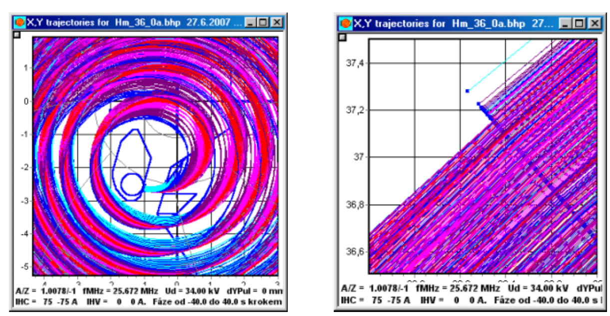

Figure 1: Beam structure in the central and extraction region of the cyclotron.

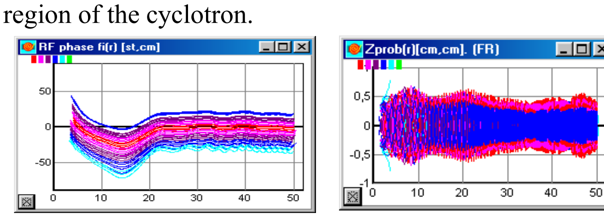

Figure 2: Radial histories of the beam RF phase and the beam axial size.

As a rule, the beam phase radial history calculated by the program is very well matched up with the phase calculated by the matrix model by the means of the analytic formula. A good conformity of the beam axial size and axial free oscillation frequency Q_z has been observed, too.

Centring of the beam

The layout of the U-120M cyclotron central region allows only small operational corrections of its geometrical configuration. Therefore a bad beam centring can deteriorate the beam quality, when the acceleration regimes are changed. A pair of harmonic coils positioned at inner radii can solve this problem. The coils are also included in the mathematical description of the cyclotron.

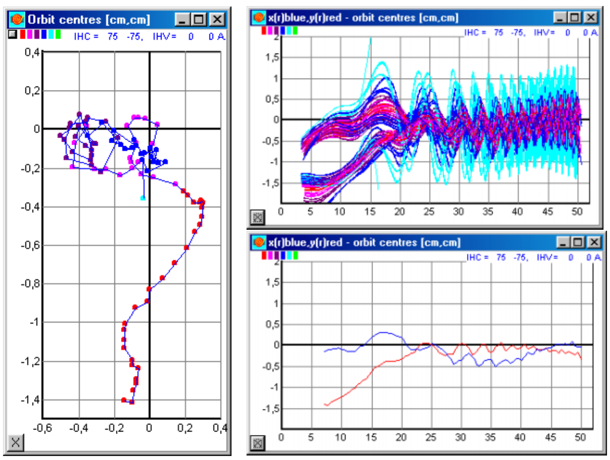

Figure 3: Simulated centres of the centred beam at the radii stepping from 6 to 50 cm. *Left:* Beam centres at an *X-Y* plane, *Upper right:* Radial dependence of the *X* and *Y* coordinates for each ion, *Lower right:* equals to upper right, but for the whole beam.

The beam centring considerably affects the radial beam size and the ion density distribution in the beam. However, in some cases, a worse centring is chosen in order to get a higher beam density, for example in the region of an electrostatic deflector septum etc.

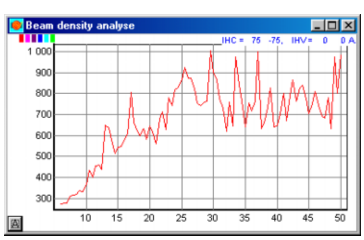

Figure 4: Radial dependence of the relative beam density for the centring shown at Fig. 3.

Extraction

In case of the negative ion acceleration, DURYCNM4 calculates the trajectories from the stripping foil to the entry of the quadrupole triplet. The formerly measured stray magnetic field of the cyclotron and the magnetic field of the correction magnet are considered. A semi-automated algorithm of the extraction of the particles with the requested energy finds the stripping foil position, enabling the transport of the beam to the selected target. Attainment of more precise trajectory course and the final beam angle and position is possible by the fine manual adjustment of the foil position and by the current of the correction magnet. The calculated properties of the beam extracted to the quadrupole triplet entry are shown below.

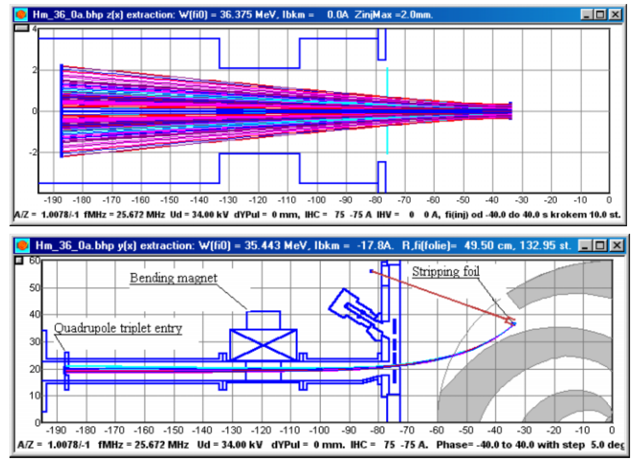

Figure 5: Vertical and horizontal view of the extracted beam trajectories. (*X* and *Z* scales are not equal).

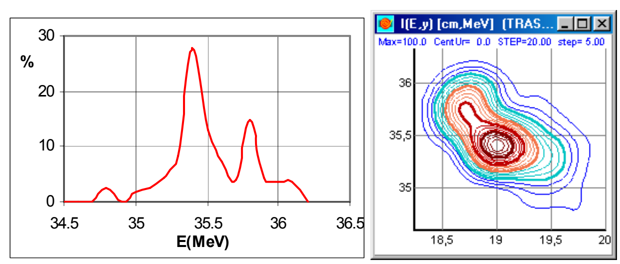

Figure 6: Percentage beam energy distribution and horizontal beam energy distribution.

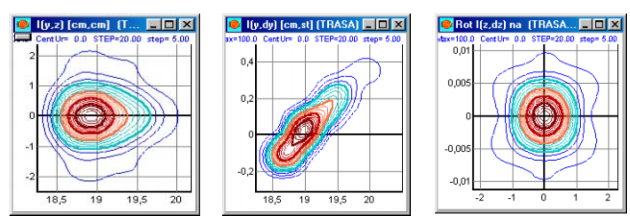

Figure 7: *X,Y* beam density distribution, horizontal Y, Y' and vertical Z,Z' emittance*
(*the ellipse axes are rotated to the coordinate ones.)

In fact, it is not possible to attain a perfect beam centring in a whole range of radii. Due to this fact, the shape of the beam percentage energy and density distributions depends on the radius which sometimes results in occurrence of two or more density peaks. A bifurcation of the extracted beam has been also sometimes observed in a real extracted beam. This effect can be easily avoided by a slight adjustment of the harmonic coil currents.

Analogous outputs, shown for extracted beam, have also been obtained at any radius during acceleration. All parameters crucial for the optimal acceleration and extraction regime, as well as the data, describing the average energy, the position and sizes of the beam, the values of the emittances and other beam properties are also provided in a numeral form.

COMPARISON OF THE CALCULATED AND MEASURED RESULTS

The cyclotron is set up for each course according to pre-calculated parameters and consequently the real parameters are measured. This system provides a pool of data available for identification of the difference between the simulation and the reality.

The observed differences lie typically in order of a few mm for the stripping foil position or up to 10–15 mm at a final plane of the extracted beam. However, some cases need no corrections at all.

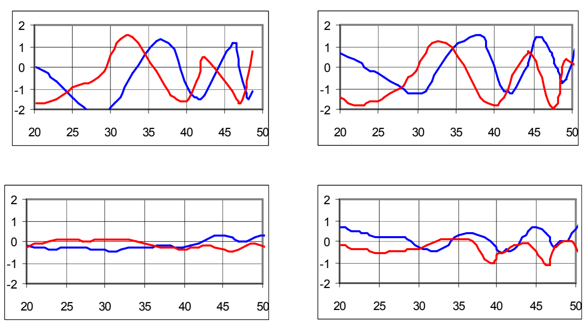

Figure 8: Comparison of the calculated *(left)* and measured *(right)* radial dependences of orbit centres for 16 MeV of D^- ions. Horizontal axis—orbit radii, vertical axis—coordinates of the orbit centres, Xc (blue line) and Yc (red line) [cm]. *Left and right upper:* results for an un-centred beam, *Left and right bellow:* orbit centres optimized by a simulation with the help of the harmonic coils at a central part of the cyclotron.

The real beam centring does not always exactly correspond to the simulated one, because the mathematical description of the cyclotron does not enable inclusion of all circumstances affecting the beam centring. That is why, the average beam energy obtained from the dynamic simulation can differ from the real one in the range of a few hundreds keV. More accurate determination of the extracted beam energy has been accomplished by measuring the extracted beam orbit radius and calculating the energy by the means of the matrix model.

In order to estimate the accuracy of method, beam parameters were monitored with the help of parallel monitoring reactions $^{nat}Cu(p,x)^{62}Zn$, ^{63}Zn, ^{65}Zn on thin copper foils (10.6 µm). Ratio of the EOB activities of any two monitor reaction products for a given beam energy is then dependent only on the products half-life, irradiation time and well-known cross sections of both monitoring reactions. This enables to avoid any inaccuracy in the beam intensity and foil thickness [4, 5]. A comparison of both methods is displayed in Fig. 9. The results show good correlation between both methods (R > 0.999). The statistical average energy deviation was only 175 keV with dispersion 143 keV.

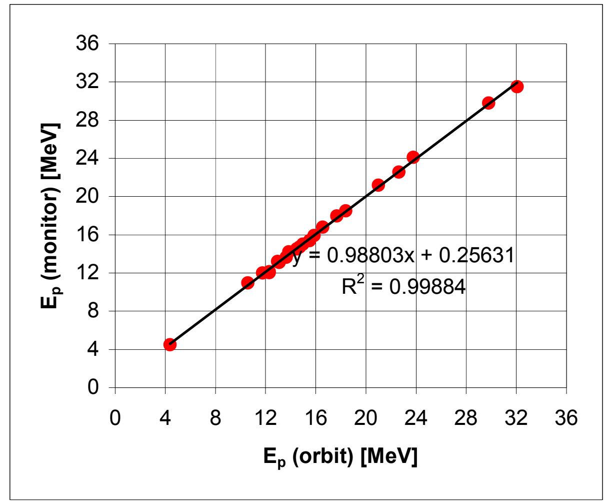

Figure 9: Correlation between beam energy calculated from the beam orbit and from the beam monitor.

CONCLUSION

For a reliable tuning of the cyclotron according to calculated data it was necessary to complete detailed magnetic measurements. Developed processing of the measured data allowed interpolation of the magnetic field map at any given level with sufficient accuracy. A 3D electric field description of an actual geometrical lay-out was calculated by means of the relax method. The code for the equilibrium orbit analysis for any investigated regime was developed as well. Everyday use of this software for cyclotron tuning and operation resulted in much better beam quality and saved a great deal of tuning time. On one hand implementation of the stripping extraction method worsen extracted beam energy dispersion but on the other hand considerably increased extracted beam intensities. Regardless slightly impaired beam quality most of applications especially radioisotope production could be introduced due to higher beam intensities. If it is required, beams of better quality are extracted by means of the classical electrostatic deflection system and analyzed by the magnet monochromator which is much more time consuming. Then the beam intensities are few µA and energy spread dE/E is about 5.10^{-4}.

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