NUCLEAR PHYSICS INSTITUTE OF THE CAS, v. v. i.
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DISSERTATION ASSESSMENT

Author of the dissertation: Ing. Tomáš Matlocha

Dissertation theme: Design of a new extraction system of positive ions from the cyclotron U-120M

The isochronous cyclotron U-120M of the Nuclear Physics Institute of the CAS, v.v.i. is widely used by domestic and foreign teams for basic and applied research experiments. It is the only accelerator in the Czech Republic that provides accelerated ions p^+, D^+, $^3He^{2+}$, $^4He^{2+}$. It is unique not only in the spectrum of ions offered (e.g. accelerated 3He ions are rarely available even in laboratories throughout Europe), but also in the range and maximum energies achieved (p^+: 8 - 37MeV, D^+: 10 - 20 MeV, $^3He^{2+}$: 17 - 54 MeV, $^4He^{2+}$: 20 - 40MeV.

The positive ion extraction system was designed by Ing. Zdenek Trejbal, CSc. at the Joint Institute for Nuclear Research in Dubna, where it was also manufactured and implemented. The system required high potentials at the deflector electrodes, which led to frequent discharges, subsequent plating of insulators and decommissioning. Even after its modification in the 1990s, the efficiency of accelerated particle extraction did not reach more than about 15%, besides proton beams could not be extracted at all. In addition, the low efficiency of the accelerated beams leads to considerable activation of the materials, especially of the Deflector I, and thus to an increase in the operator's radiation doses during servicing and adjusting the extraction system.

This fact led us to assign a dissertation work which aim is to design a new more efficient system of positive ion extraction. This work was undertaken by our employee Ing. Tomáš Matlocha.

The isochronous magnetic field of the cyclotron U-120M for a given particle and energy is formed by the current of the main coil, the magnetic contribution of 18 trimming coils and the magnetic structure (4 spiral shims). The working harmonics of the magnetic field are multiples of 4. The magnitude of the 1st harmonic of the magnetic field has a significant effect on the particle extraction. Its identification and subsequent elimination were one of the tasks specified in the assignment.

It should be said that practically the whole year 2022 was devoted to a very complex repair of the U-120M cyclotron (short-circuiting of two correction coils, repair of the burnt central region, etc.). One of the other objectives of this repair was also to design and implement modifications that would lead to and enable more efficient positive ion discharge. Of course, Ing. Tomáš Matlocha played a key role in it.

In the first chapters of his thesis he deals in detail with the theory of cyclotron type accelerators (acceleration process, beam stability conditions, resonances of horizontal and vertical betatron oscillations, description of parameters of accelerated beams and formation of 1. harmonics of the magnetic field), then describes in detail the methods of extraction of both positive and negative ions (acceleration method, resonance method, stripping method), and describes specific subsystems of the U-120M cyclotron (RF system, ion source, vacuum system).

For the ion source, it should be emphasized that for some applications, experiments for testing the

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radiation hardness of electronic components, very small current of the accelerated and extracted particles are needed (e.g. CERN - Alice detector, ADVACAM, irradiation of biological samples, detector testing, etc.). This issue was also successfully studied and successfully solved by the author.

The author paid great attention to the description of the magnetic system (main magnet, spiral sectors, correction and harmonic coils).
The measurement of the magnetic field maps was a necessary condition not only for the correct reassembly of the magnet of the cyclotron after the repair, but especially for the determination of the magnitude of the 1st harmonic of the magnetic field, i.e. an important quantity for the extraction of positive particles.
For this purpose, the author upgraded the magnetic field mapper (originally designed in SÚJV Dubna), selected and chose a suitable Hall probe, found its thermal dependence and the resulting measurement errors, debugged the control software and designed and debugged the software for readout the magnetic induction values including their graphical display (LabView). Without this measurement, the work could not have been carried out. It must be said that this part of Ing. Matlocha solved and implemented this part very well and was a key person in this work.

Thanks to the repair of the cyclotron, it was possible to measure the parameters of the disassembled magnetic system of the cyclotron (errors in the assembly of the magnetic circuit components, inaccuracies in the manufacturing, deformation of the vacuum chamber, the influence of the burnt centre, the influence of the ferromagnetic screws of the vacuum chamber, etc.).

At this stage, much attention was paid to measuring the magnitude and phase of the 1st harmonic. Subsequently, its amplitude was eliminated by subtle horizontal movement of the vacuum chamber, not by insertion of ferromagnetic inserts at appropriately chosen azimuths and radii, which was the procedure chosen in the magnetic measurements performed by our colleagues in 1988. From the original value of 15 Gauss, the first harmonic was reduced to 2 Gauss, which is an excellent result. Without a good magnetic field measurement and its prompt evaluation, it would have been impossible to complete this procedure in such a short time.

In order to simulate the parameters of the accelerated beam, the author used programs developed in the accelerator department by Ing. Milan Čihák, CSc (now retired). These are the matrix mathematical program Wmodel, which calculates the average values of the beam parameters, and the program Durycnm4, which calculates the dynamics of the beam during acceleration, i.e. 3D trajectories including a wide range of initial conditions. Actually, the benefit for Department of Accelerators is adoption and active use of this programs by the author.
In addition, the author acquired the SNOP program during his internship at SÚJV Dubna. It is a comprehensive well-established program for simulation of accelerated cyclotron beam dynamics widely used for design of small cyclotrons and for analysis of accelerated beam properties. Detailed description of the programs, comparison of simulation results is given in the following chapters. A positive finding is the very good agreement between the results of SNOP and our programs.

Magnetic measurements have monitored in detail the magnetic field of the cyclotron in the range of radii up to 600 mm. The beam extraction, however, takes place in radii up to 800 mm. It was therefore necessary to calculate the fringe magnetic field up to these radii.
The author created a model of the magnetic circuit of the cyclotron and with the inclusion of all necessary parameters (i.e. the magnetic properties of the magnet material) simulated the magnetic

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field using Opera software up to a radius of 800 mm. By comparing it with a small section of the magnetic field previously measured up to 1000 mm in the negative ion discharge regions, he found some differences which were explained by a simplified model of the magnetic circuit. Anyway, this calculated fringe magnetic field is sufficient for the simulations of extraction.
Using Opera, the author simulated the electric fields of the accelerator parts (puller vers. Dee) and the deflectors. The input mechanical dimensions of all necessary parts to Opera were made in AutoCAD Inventor.

For the simulations of accelerating process, it was necessary to know the parameters of the beam extracted from the cold-cathode PIG ion source. Here the author used the capabilities of CST Studio and simulated possible variations of the plasma boundary. The most probable shape of the plasma boundary (also according to the known beam properties from cyclotron operation) is a slightly concave boundary resulted in beam focusing between the puller and the ion source slit.

In the next chapter, the author discusses the original fully electrostatic extraction system (Deflector I, II, III, electrostatic exciter and compensator) and the reasons for the transition to an extraction system with electrostatic deflectors (Defl. I, II, III) and a magnetic exciter. It describes this system in detail, including detailed simulations of the electric fields of the deflectors and the magnetic field of the exciter.

In the following chapters, the author simulated the extraction of a single particle with the existing extraction system using both Durycnm4 and SNOP and compared the results. Furthermore, he simulated the extraction of a bunch of particles with analysis of their losses on the individual parts of the extraction system. Based on the results, he proposed modifications especially to the shape of Deflector I to improve the extraction efficiency of the existing extraction system.

For the design of the new extraction system, it was necessary to determine the basic parameters, which are presented, including discussion, in the next chapter. These are the radius at which the extraction system will be placed. The most difficult regime in terms of the extraction, the proton regime with maximum energy was chosen for the design.

The new harmonic coils centred on the extraction radius of 500 mm played a significant role in the design of the new extraction system. These coils allow radial lifting of the orbits at the extraction radii before entering the extraction system (Deflector I). The design of these harmonic coils was very challenging and time consuming due to the very limited space. Finding suitable windings (5 x 5 mm and 4 x 4 mm Cu tubes respectively) and arranging for their manufacture including insulation moulds was also challenging. This whole anabasis can be followed in the chapter on harmonic coils. The author of this thesis also played an important role here.

The new extraction system was designed by the author of the thesis in the following configuration: a short Deflector 0, properly replacing the magnetic exciter, an extended Deflector I and two passive magnetic channels. For both deflectors he designed the shape of the electrodes, simulated the electric field and the beam passage including the losses at the deflector electrodes. The results of the simulations are clearly presented in tables (beam energy, scattering, deflector input and output emittance, output beam shape, etc.).
The proposed passive magnetic channels, including their dimensions and shape, are designed to ensure radial focusing of the beam and its direction to the input of the correction magnet and then to the input of the ion-optical path. The calculation and design of the magnetic channels including

simulation of the passage through these channels is also very illustrative and valuable. Here the positive focusing effect of the magnetic channels on the outgoing beam is evident. It should be said that we have no experience with the design of magnetic channels and their properties, including the effect on the magnetic field of the cyclotron outside the extraction region. The question is their shape and size for lower energies and other particles.

Conclusion:

The dissertation thesis of Ing. Tomas Matlocha is clearly written, well structured, with a number of graphical illustrations, tables and simulations including photo documentation. The author has mastered a number of new programs and used them effectively in his dissertation work. He devoted himself intensively to it both in the Accelerator Department of the Nuclear Physics Institute and also in respected world cyclotron laboratories.
The design of the new extraction system is a valuable basis for future detailed design and implementation of a new extraction system.
The only criticism, in my opinion, is the unnecessarily long and detailed description of the theory of cyclotron-type accelerators and extraction methods.

The author has fulfilled the assignment of the thesis. I recommend a positive evaluation of this work.

The report was prepared by Specialist Supervisor:

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