Czech Technical University in Prague
Faculty of Nuclear Sciences and Physical Engineering

Dissertation thesis

Positive ion extraction system design for the U-120M cyclotron

Prague 2023

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Nazev prace	Navrh soustavy pro vyvod kladnych iontu z cyklotronu U-120M
Studijní program	Aplikace prírodních ved
Studijní obor	Jaderne inzenyrství
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Akademicky rok	2022/2023
Pocet stran	131
Klícova slova	cyklotron, extrakcní soustava, deflektor, magneticky kanal magneticke merení, simulace dynamiky urychlenych castic

Bibliografic entry

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Title of Dissertation	Positive ion extraction system design for the U-120M cyclotron
Degree Programme	Applications of Natural Sciences
Field of Study	Nuclear Engineering
Supervisor	**Prof. Ing. Ladislav Musílek, CSc.** Czech Technical University in Prague, Faculty of Nuclear Sciences and Physical Engineering, Department of Dosimetry and Application of Ionizing Radiation
Supervisor specialist	**Ing. Jan Štursa** Nuclear Physics Institute of the CAS, Accelerators department
Academic Year	2022/2023
Number of Pages	131
Keywords	cyclotron, extraction system, deflector, magnetic channel magnetic field measurement, beam dynamics simulation

Abstrakt

Cílem teto disertacní prace je navrh nove extrakcní soustavy pro vyvod kladnych iontu z cyklotronu U-120M. Za tímto ucelem byla provedena presna merení rozlození intenzity magnetickeho pole cyklotronu pomocí zrekonstruovaneho aparatu, pro ktery autor teto prace navrhl novou merící cast a napsal ovladací software. Autor dale provedl magneticka merení, na jejichz zaklade byla minimalizovana porucha v magnetickem poli cyklotronu. Pro analyzu fungovaní puvodního extrakcního systemu byl autorem vytvoren CAD model originalních extrakcních prvku a byla provedena simulace, ktera potvrdila nízkou ucinnost teto konfigurace. Pro novou extrakcní soustavu autor navrhl nove vnejsí harmonicke cívky, ktere byly v ramci odstavky urychlovace v roce 2022 nainstalovany do magnetickeho systemu cyklotronu. Tyto cívky do znacne míry kompenzují negativní vliv poruchove první harmonicke slozky magnetickeho pole a umoznují navysení vystupní energie cyklotronu v rezimu zapornych iontu. Tyto cívky hrají take dulezitou roli i v nove navrzene extrakcní soustave pro kladne ionty, ktera nyní sestava ze dvou deflektoru a dvou magnetickych kanalu. Tento system vyzaduje nizsí provozní napetí deflektoru oproti puvodnímu systemu a umoznuje tak jejich dlouhodoby provoz i v protonovem rezimu 36.7 MeV, kde puvodní extrakcní soustava není pouzitelna. Prace take ukazuje moznost, jak zvysit extrakcní ucinnost pro castice nizsích energií vhodnou upravou geometrie extrakcních elektrod, ktera muze byt s vyhodou vyuzita i v prípade stavajícího extrakcního systemu.

Abstract

The goal of this dissertation is the design of a new extraction system for the extraction of positive ions from the U-120M cyclotron. For this purpose, precise measurements of the distribution of the cyclotron's magnetic field were made using a reconstructed apparatus, for which the author of this work designed a new measuring part and wrote the control software. The author also performed magnetic measurements, based on which the disturbance amplitude in the magnetic field of the cyclotron was minimized. To analyze the operation of the original extraction system, the author created a CAD model of the original extraction elements and performed simulations that confirmed the low efficiency of this configuration. For the new extraction system, the author designed new external harmonic coils, which were installed in the magnetic system of the cyclotron during the accelerator shutdown in 2022. These coils largely compensate for the negative influence of the disturbed first harmonic component of the magnetic field and enable an increase in the output energy of the cyclotron in the negative ion mode. These coils also play an important role in the newly designed extraction system for positive ions, which now consists of two deflectors and two magnetic channels. This system requires a lower operating voltage of the deflectors compared to the original system and thus enables their long-term operation even in the proton mode of 36.7 MeV, where the original extraction system is not applicable. The work also shows the possibility of increasing the extraction efficiency for particles of lower energies by appropriate modification of the geometry of the extraction electrodes, which can be advantageously used even in the case of the existing extraction system.

Acknowledgment

I would like to express my deepest gratitude to my colleague Ing. Milan Cihak CSc. for invaluable discussions and moral support, without which this work would not have been possible.

Words cannot express my gratitude to my supervisor Prof. Ing. Ladislav Musílek, CSc. for his patience and academic guidance during the work.

I could not have undertaken this journey without the support of my supervisor specialist Ing. Jan Stursa, who created the conditions enabling the realization of this work.

I am extremely grateful to RNDr. Filip Krízek, Ph.D. for his stimulating comments and careful proofreading.

Many thanks belongs to all the colleagues from the accelerator department, whose continuous and diligent work enables the operation of the cyclotron.

This work is dedicated to my family
for their immense support

Contents

1 Introduction

This work aims to increase the efficiency of the extraction of positive ions from the isochronous cyclotron U-120M at the Nuclear Physics Institute in Řež near Prague. The efficiency of the currently used system depends on the specific operating mode of the cyclotron and varies in the range of 5–15% only. The prospect of future use of the accelerator for the production of positive ion beams is conditioned by the construction of a new system with significantly higher efficiency. The efficiency of the extraction largely depends on the design of the deflection system, which ensures the separation of the particle orbits at the final acceleration radii and the extraction of the beam from the accelerator space with a minimum of losses.

Although the primary consequence of the successful design of the new deflection system will be an increase in the maximum available flux of charged particles at the exit of the cyclotron, the side effect of reducing the transport losses of the accelerated beam is no less important. Losses of the positively charged particle beam occur mainly in the deflection system and then result in radioactive activation of the material. Thus another important side effect of the successful design will also be significant reduction in the radiation load of the operating personnel.

At the beginning of the work, it was known about the existence of a disturbance in the magnetic field of the U-120M cyclotron, which prevented acceleration to radii higher than 50 cm and significantly complicated the extraction of positive ions. Since the extraction of protons was only possible up to an energy of approximately 25 MeV, the goals of the thesis can be summarized as follows:

- confirm the presence of a cyclotron magnetic field disturbance by detailed magnetic field measurements,
- identify the cause of this disturbance and minimize its magnitude to an acceptable level,
- design such an extraction system that will be able to efficiently extract protons of the highest energies.

In the following paragraphs, the basic principles of cyclotron operation will be briefly described and an overview of phenomena that affect the properties of an accelerated beam of charged particles will be discussed. Chapter 2 deals with theory of beam extraction and overviews for recommended procedures for successful extraction of ions from the cyclotron magnetic field. In chapter 3, the individual technological blocks of the accelerator and the likely cause of a significant disturbance in the magnetic field will be briefly described together with the method of its minimization using detailed measurement of the magnetic field of the cyclotron. Chapter 4 presents software tools which were used to find the optimal design and analysis of the extraction system. The steps in preparing the configuration of the electromagnetic fields for simulations of the extraction process will be summarized in chapter 5. For a specific acceleration mode, losses in the central area of the accelerator and during the extraction will be estimated. In the final chapter, the achieved results will be summarized, the limitation of their validity will be discussed and outlook for future work will be provided.

2 Theory of cyclotron operation

Over the course of more than ninety years of history, a cyclotron has evolved from a wax-sealed brass box [43], through high-end, large-scale scientific equipment [31, 12], to a regular part of every major hospital or research center [63]. Thousands of cyclotrons around the world are used every day to produce a number of different radionuclides for preparation of radio-pharmaceuticals [57], to irradiate patients as part of proton therapy, or for scientific experiments of various focuses. The cyclotron thus became a workhorse in the field of nuclear medicine and in fields using accelerated beams of charged particles.

A detailed overview of the characteristics and theoretical analysis of the cyclotron function can be found in the literature of the last century [42], from the latest publications it should be mentioned, for example [64], which solve practical tasks associated with the design of a cyclotron and the use of modern computer procedures.

2.1 Acceleration process

The cyclotron is a circular particle accelerator with a constant acceleration frequency and a stationary, spatially variable magnetic field. Acceleration occurs between the pole extensions of the electromagnet and the accelerated particles move along a trajectory similar to a spiral.

This work will be dealing with an isochronous cyclotron. This type of cyclotron, unlike the classical Lawrence-type cyclotron, compensates for the relativistic increase in the mass of the accelerated particle and thus enables significantly higher energies to be achieved. Although classical cyclotrons of the Lawrence type are used today rather exceptionally, in recent years there have been attempts to use them as cheap substitutes for isochronous cyclotrons for the production of radio-pharmaceuticals, e.g. for PET tomography, where low output energy is not a problem [25].

A particle with charge q and mass m, moving at a constant speed v in a homogeneous magnetic field with induction B, moves in this magnetic field along a circle with radius r. The centrifugal force mv^2/r acting on the particle is mediated by the Lorentz force qvB

$$\frac{mv^2}{r} = qvB. \tag{2.1}$$

Hence, the angular frequency of the particle ω will be equal to

$$\omega = \frac{v}{r} = \frac{qB}{m} \tag{2.2}$$

and will be independent of the radius and velocity of the particle. The angular frequency and therefore also the period of rotation depends only on the ratio of charge and mass of the particle q/m and on the magnitude of the magnetic field.

The function of the classical cyclotron, constructed by Lawrence and Livingston in 1932 at the University of Berkeley [40], is based on the above-mentioned principle. The acceleration takes place in a homogeneous circularly symmetrical magnetic field between