BEAM STABILIZATION AND AUTOMATIC ENERGY VARIATION AT THE BONN ISOCHRONOUS CYCLOTRON

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Abstract

Control systems have been developed for the stabilization of the external cyclotron beam with respect to the horizontal and vertical alignment, the beam energy and the beam intensity. The operating characteristics of the feedback circuits are presented and the joint operation is discussed. The incorporation of the control systems into a microcomputer controlled energy variation program makes it possible to obtain a reliable and convenient system for the automatic measurement of excitation functions with an isochronous cyclotron.

Introduction

During the last years various control systems have been developed for the stabilization of the external beam at the Bonn isochronous cyclotron[1-3]. The design of the control systems followed mainly from the experimental requirements of a high beam position and beam direction stability as well as of a high energy resolution and beam current constancy. Beam position and direction stability follow from the energy resolution requirement because of the narrow entrance slit and the second-order effects of the analysing system (and, for light targets, from kinematic broadening due to beam position and angle fluctuations on the target). Apart from the energy resolution certain experiments, like the precise measurement of angular distributions with sharp diffraction structures, channeling and blocking experiments as well as microbeam investigations, require an especially high stability of beam position and beam direction.

Since beam position and direction fluctuations of a cyclotron beam are strongly correlated with beam energy fluctuations, a cascade control had to be developed to stabilize both. The purpose of the energy stabilization is to keep the hot spot of the beam permanently fixed in the aperture of the analysing slit. Finally, an intensity stabilization has been developed in order to obtain extremely constant beam currents on the target.

From the operator's viewpoint, there also was a strong impetus to obtain an improved beam handling and eased adjustment of the extracted beam using closed-loop controls. As a consequence, a faster setting-up and greater flexibility was achieved resulting in more useful beam time.

The progress made in stabilizing the beam axis and beam energy enabled the development of an automatic energy variation control using a microcomputer control for the analysing magnet and the cyclotron. Using this system it was possible to measure automatically the $\alpha+\alpha \rightarrow {}^8Be$ excitation function in 300 steps in the energy range 32.5 - 35.5 MeV within 24 h.

Automatic Beam Alignment

After emerging from the cyclotron, the beam is matched onto the entrance slits of the beam preparation system (see. fig. 1). The matching system consists of two quadrupole lenses Q1 and Q2, two horizontal steering magnets SH1 and SH2 and two vertical steering units SV1 and SV2. The horizontal steering unit SH2 is identical with the switching magnet A0. The following beam transport elements are highly stabilized. They consist of the beam analysing system and the beam transport onto the target. Therefore stabilizing the inherent position and direction instabilities of the cyclotron beam immediately after the extraction (and in front of the monochromator system) results in an appropriate stability of the beam axis at the target.

The extracted beam is, horizontally, nearly parallel with a divergence of about 1 mrad and vertically divergent with a 2.5 mm waist 1.7 m before the quadrupole Q1. In the normal mode of operation the quadrupole Q1 is horizontally defocusing and Q2 horizontally focusing in order to produce a sharp horizontal waist of less than 1 mm at the horizontal entrance slit SX1 of the monochromator system. As a result the quadrupole doublet Q1 and Q2 yields horizontally a parallel-to-point transformation: that means the horizontal focus of the lens pair is located at the entrance slit SX1. The horizontal slit SX2 is used for a limitation of the divergence. Vertically the beam is transformed in such a manner that a waist of about 2 mm occurs between the vertical slit units SY1 and SY2.

The slit units are mechanically aligned to the optical axis of the monochromator system. The slit jaws are mounted on a watercooled copper block. The electrical isolation is achieved with the aid of mica foils. The precise adjustment of the slit position and slit width is performed by remote control using precision linear potentiometers.

For the diagnostics and the automatic centering of the beam the peripheral beam currents impinging on the slit jaws are amplified and displayed in analogue form. A difference signal is formed by electronic hardware. Each slit unit is connected with a certain steering unit using standard electronic control units. The difference error signal of the slit jaws then adjusts the steering strength until the opposite slit jaw currents are equal. The basic feedback principle for use with automatic beam-centering control has been proposed and used in various forms by different laboratories. However in most cases, only the beam position at a certain narrow collimator slit is regulated and the beam direction can vary with the inherent instabilities of the accelerator. In the present system the horizontal position x and direction x' as well as the vertical position y and direction y' are stabilized using the following slit-steerer combinations: SX1-SH1, SX2-SH2, SY1-SV1 and SY2-SV2.

As vertical steerers SV1 and SV2 we use additional coils mounted at the quadrupoles Q1 and Q2. This was necessary to conform to a very compact design of the beam matching systems. The resulting magnetic field of those vertical steering coils exhibits distorting multipole components besides its main dipole component. However, since the required vertical steering strengths are very low, the resulting distortion of the beam quality can be neglected. It should be noted that the close distance

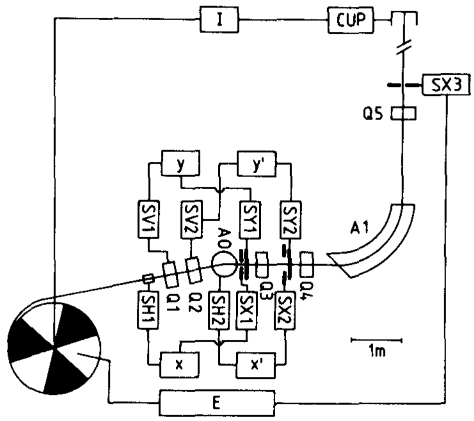

Fig. 1. The closed-loop control systems for the stabilization of the external cyclotron beam. x-horizontal position, x'-horizontal direction, E-energy, y-vertical position, y'-vertical direction, I-intensity

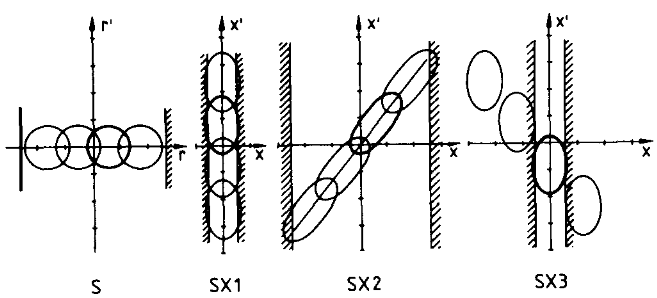

Fig. 2. Schematic diagram of the horizontal (=radial) phase space distribution at the septum S, monochromator entrance slit SX1, divergence limiting slit SX2, and energy analysing slit SX3. The dispersion is indicated by 4 incoherent phase ellipses at slightly different energies. The "hot spot" is marked by a heavy line. Scale divisions are in 1 mm and 1 mrad respectively.

between SV1 and SV2 is not ideal with respect to the location of the vertical slit units SY1 and SY2. As a consequence there is a strong coupling between the control loops SY1-SV1 and SY2-SV2. Fortunately instabilities of the beam position and direction in the vertical (=axial) plane are much smaller than in the horizontal (=radial) plane.

An ideal steerer configuration conforming to our horizontal focusing situation is as follows. The steering unit SH2 is precisely located at the position of slit unit SX1. Thus a deflection with SH2 yields only a displacement at slit SX2 and no displacement at slit SX1. Similarly the steering unit SH1 and slit unit SX2 are located in such a way that a point-to-point imaging results. Therefore a change of the SH1 strength leaves the beam position at SX2 unchanged, i.e. there is no coupling between the control loops SX1-SH1 and SX2-SH2.

In reality steering unit SH2 is very near to the slit SX1 and steering unit SH1 and slit SX2 are not precisely at a point-to-point imaging distance. Therefore the coupling coefficients, i.e. the off-diagonal elements of the variation matrix, are not precisely zero but very small. Thus a very fast and uncritical stabilization of the horizontal beam position and direction can be achieved. In the case that quadrupole Q3 is used, the relations between SX2 and SH1 as well as SH2 are changed. However, the main properties of the control system are unchanged and the analogue devices automatically compensate position and angle deviations according to the modified variation matrix.

Instabilities of the cyclotron parameters resulting in deviations of the beam position and direction occur with different time constants. Fluctuations of the magnetic field parameters are relatively slow. However, distorting RF frequency instabilities occur at mechanical resonances of the Dee's in the 10-50 Hz frequency range. Thus an automatic beam steering control loop should exhibit time constants of the order of 20 msec. In principle it should be possible to obtain such time constants with the present control loops. However it will be shown in the next section that small RF frequency instabilities of the order of $2\cdot10^{-5}$ are well compensated by our fast Dee-voltage control loop between the analysing slit SX3 and the Dee-voltage. Therefore a time constant of 0.2 sec is sufficient for our purposes.

Before discussing the resulting position and direction stability, it is necessary to define the term "beam axis." The beam axis is the center of gravity of all individual rays going through the target of the experimenter. Without an automatic beam centering control, any fluctuation of the position and direction of the cyclotron beam will result in an equivalent fluctuation of the beam position and direction at the target.

Since the beam axis as defined by the condition of symmetrical slit jaw currents depends on the beam intensity distribution in the X-X' and Y-Y' subspaces, the beam axis can only be stabilized if this intensity distribution can be kept appropriately constant. The most critical point is the horizontal X-X' distribution which strongly depends on the beam energy distribution because of the dispersion effects

0018-9499/79/0400-2352$00.75

of the cyclotron magnet. The development of the X-X' distribution with an indication of the energy-dependent effects is sketched in fig. 2. As shown by Blosser[4], a cyclotron beam is inherently well collimated to a very narrow radial phase space distribution (the incoherent radial phase ellipse for particles with the same energy, i.e. $\Delta E = 0$). However, the radial emittance as measured at the exit of the cyclotron is broadened according to the energy spread because of the dispersion effects of the cyclotron magnet. This energy spread is due to the inherent finite phase width and instabilities of the RF amplitude and frequency. It will be shown in the next section that an appropriate stabilization of the beam energy distribution is possible with a special Dee-voltage closed loop control between the energy-analysing slit SX3 and the Dee voltage.

Thus for a typical slit width configuration of 1 mm for SX1 and 2 mm for SX2 we estimate a position stability of 0.01 mm and a direction stability of 0.03 mrad in the horizontal (=radial) plane. In the vertical (=axial) plane the achievable stabilities are in the same order of magnitude for a typical slit width configuration of 2.5 mm at SY1 and 2.5 mm at SY2, though the vertical steering units SV1 and SV2 are not ideally located. This is due to the fact that instabilities of the primary cyclotron beam are much weaker in the vertical plane.

Energy Stabilization

For a detailed discussion of the closed-loop energy stabilization at the Bonn isochronous cyclotron we refer to ref.[5]. As reference signal the slit current left-right asymmetry at the first analysing slit SX3 (or SX4) of the double monochromator system[3] is used for driving a fast fine regulation circuit acting on the Dee voltage, see figs. 1 and 2. Using this fine regulation the "hot spot" of the beam is precisely fixed between the jaws of the analysing slit. Thus the stability of the cyclotron beam energy is directly controlled by the monochromator system. The field of the monochromator magnet is stabilized via an NMR probe to an accuracy of $1.5 \cdot 10^{-7}$ using a recently developed magnet field control [6]. The final energy resolution of the analysed beam depends on the experimental requirements. Most experiments require a standard energy resolution of 2000, but there are high precision experiments requiring an energy resolution of up to 15000. For a given operational mode of the cyclotron, i.e. for well adjusted trim coil currents, main coil current, and RF frequency, the optimum Dee voltage is characterized by a beam energy distribution with a characteristic asymmetrical shape (This left-right asymmetry is indicated in the horizontal phase space distribution at the analysing slit SX3 in fig. 2.) As a consequence, the signature of optimum Dee voltage is a characteristic left-right asymmetry of the beam intensities impinging on the slit jaws of the analysing slit. Thus the Dee voltage can be kept on its optimum value by a closed-loop control where the difference between the measured left-right asymmetry and the optimum left-right-asymmetry is taken as error signal to drive the Dee voltage fine regulation.

However, variations of the mean beam energy are not only caused by a Dee voltage ripple but also by instabilities of the magnetic field and/or the RF frequency. These instabilities produce a phase shift of the beam relative to the RF and hence a change in acceleration. The necessary magnetic field stability of better than 1 part in 100 000 can readily be achieved with the existing stabilized power supplies. However short-term instabilities of the RF frequency of the order of $1\text{-}2 \cdot 10^{-5}$ cannot be avoided with our present RF frequency regulation systems though the system has an excellent long-term stability.

Theoretical considerations as well as practical experience show that such "phase shift" instabilities lead primarily to a variation of the mean energy whereas the energy distribution with its asymmetric shape is only weakly affected. Therefore those instabilities can also be well compensated by the Dee voltage fine regulation as long as the RF frequency and/or magnetic field instabilities are less than $5 \cdot 10^{-5}$.

Intensity Stabilization

Using the automatic beam centering and energy stabilization control, very stable beam currents are achieved. The observed intensity ripple of the currents at the target, i.e. behind the beam preparation system are less than 5 %. It should be noted, that only variations with a time duration of more than 0.1 sec are observed because of the slow response of the current amplifier in use.

However, certain experiments require an especially high beam current constancy. An example is the measurement of excitation functions where extremely weak resonance anomalies are to be found. This is especially true if gas targets are used because of the unavoidable changes of the target gas density in the reaction volume if beam current fluctuations are present. Another type of experiment where the beam current constancy plays an important role is the measurement of extremely weak effects such as, for instance, parity violating effects in the scattering of polarized particles.

In order to avoid residual intensity fluctuations as far as possible, we developed a very simple but efficient intensity stabilization. From the observation that the output of a properly adjusted ion source depends on the arc current, we smooth the residual beam intensity ripple through the arc current. Using the modulation input of a current stabilized 1kV-2A power supply, the beam current at the target can be stabilized to a constancy of $1{:}10^3$. Though the time constant of the current amplifier is 0.1 sec, we estimate that there are no stronger fluctuations than 0.5 % in the 10 msec range (because of the fast Dee voltage fine regulation and the slowness of most cyclotron parameters). The arc-current regulation was achieved with our internal ion source, which is a conventional Livingston type ion source. However, the same regulation may also be applied to other ion sources such as external PIG sources.

Operating Characteristics of the Complete System

The complete system of closed-loop controls for the stabilization of the external beam is shown in fig. 1. Since the system consists of six single parameter feedback circuits, the coupling between the individual control loops has to be considered in order to avoid regulation instabilities in a joint operation.

The coupling of the vertical with the horizontal beam alignment and the energy stabilization is negligibly small. Since the instabilities of the essential cyclotron parameters result primarily in fluctuations of the horizontal phase space distribution, the control of the vertical beam position and direction is rather a convenient tool for an eased beam handling.

The coupling problems arising in the stabilization of the horizontal beam position and direction, as well as the beam energy are solved ved by an appropriate hierarchy of the control loops, i.e. by different time constants. The fastest control loop is the Dee voltage fine regulation for the energy stabilization (time constant 10 msec). The horizontal position and direction control loops act as cascade controls. Their function is a pre-requisite for the energy stabilization. In stationary operation the main cyclotron instabilities are smoothed by the fast energy stabilization. The horizontal position and direction control loops add only fine and long-term corrections.

The intensity stabilization of the target cup current is practically uncoupled from the stabilization of beam energy and beam axis. This control loop yields a very high stability of the ion source output. It has also the convenient ability to smooth residual intensity fluctuations due to other cyclotron instabilities (if present).

Automatic Energy Variation

For the measurement of excitation functions an automatic energy variation is highly desired because the optimum speed of adjustment is achieved and the operation is free from subjective human control and maladjustment. Extensive investigations of weak and narrow resonances are feasible. First trials with respect to an automatic energy variation started in an experiment where the analyzing magnet was changed in small steps and the cyclotron beam energy followed via the Dee voltage fine regulation. Though the variation range was strongly limited to about $3\cdot10^{-3}$, the experiment showed us that it should be possible to achieve a greater energy variation range by a synchronous change of the cyclotron magnetic field and RF frequency with the cyclotron beam energy permanently kept on the optimum value.

Details of the automatic energy variation will be published in a forthcoming article[7]. A PDP-8 equivalent microcomputer, IM 6100, is used to calculate the nominal values for the cyclotron magnet current, RF frequency and the NMR control of the analyzing magnet. Having received a program interrupt from the data acquisition control unit, the microcomputer adjusts the nominal analyzing magnet field and the main coil current of the cyclotron instantaneously, whereas the cyclotron frequency is changed stepwise with a predetermined time pattern according to the time constant of the cyclotron magnet (15 sec). Such a matched increase of the cyclotron frequency is necessary for $\Delta E/E > 5\cdot10^{-5}$ steps in order to maintain approximate isochronism and beam geometry inside the cyclotron. Dee voltage fine regulation and the automatic beam alignment ensure a smooth transition and continous operation.

The system enables an energy variation range of 10 %. It has been successfully used to measure the $\alpha+\alpha \rightarrow {}^8Be$ excitation function[8] in 300 steps in the energy range 32.5-35.5 MeV within 24 h. An energy shift was accomplished within 20 sec. It should be noted that two manual readjustments of critical parameters of the extraction elements and the RF generator have been performed in the course of the experiment. The energy variation range can be expanded by including the trim coil currents and the parameters of the extraction system and the RF generator, as well as the quadrupole lenses, in the automatic control.

Acknowledgement

The authors wish to thank Prof. T. Mayer-Kuckuk for his support and interest in this work. The work has been supported by the Bundesmin. Forschung und Technologie.

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