The control system of the Dubna monoenergy cyclotron

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Presented by Yu. N. Denisov.

The characteristics of a monoenergy cyclotron and the method of particle extraction accepted in our design[1] impose specific requirements on the control system of the whole machine, consisting of the electrostatic accelerator-injector, the ring cyclotron and all the parts of the beam transport channels. In order to produce particles of the proper energy at the channel exit it is necessary to control the regime of operation of the electrostatic accelerator and the channel for shaping nanosecond bunches of injected particles, the mode of the injection channel, the cyclotron average magnetic field, the frequency of the accelerating voltage, the radial position of the entrance plate of the electrostatic deflector and the bending magnet, the electrical field intensity in the deflector, the field in the deflecting magnet, the magnetic field in the focusing lenses in the channel employed, the fields in the bending magnets, the magnetic field in and the gap width at the foci of analysing magnets and the positions of beam stops at collimator exits in the experimental rooms, etc. All these adjustments should be performed in the shortest possible time.

It is natural that the need to monitor so many parts simultaneously excludes manual control of the accelerator process. The control of all the parts of the accelerating system and the beam transport channel is to be achieved by an automatic control system consisting of a digital programmer for modes and analogue correcting devices. The schematic view of the control system is shown in Fig. 1.

The control computer serves as a programmer and proper modes of operation are calculated using functional dependences pre-recorded on computer tape. These modes are then implemented by means of stabilised power units with digital control, nuclear resonance magnetic field stabilisers with digital frequency control of the autodyne and electromechanical activating devices with co-ordinate encoders.

The accurate correction of regimes and co-ordinates of separate parts of the accelerating system and channels is performed, if necessary, by local analogue

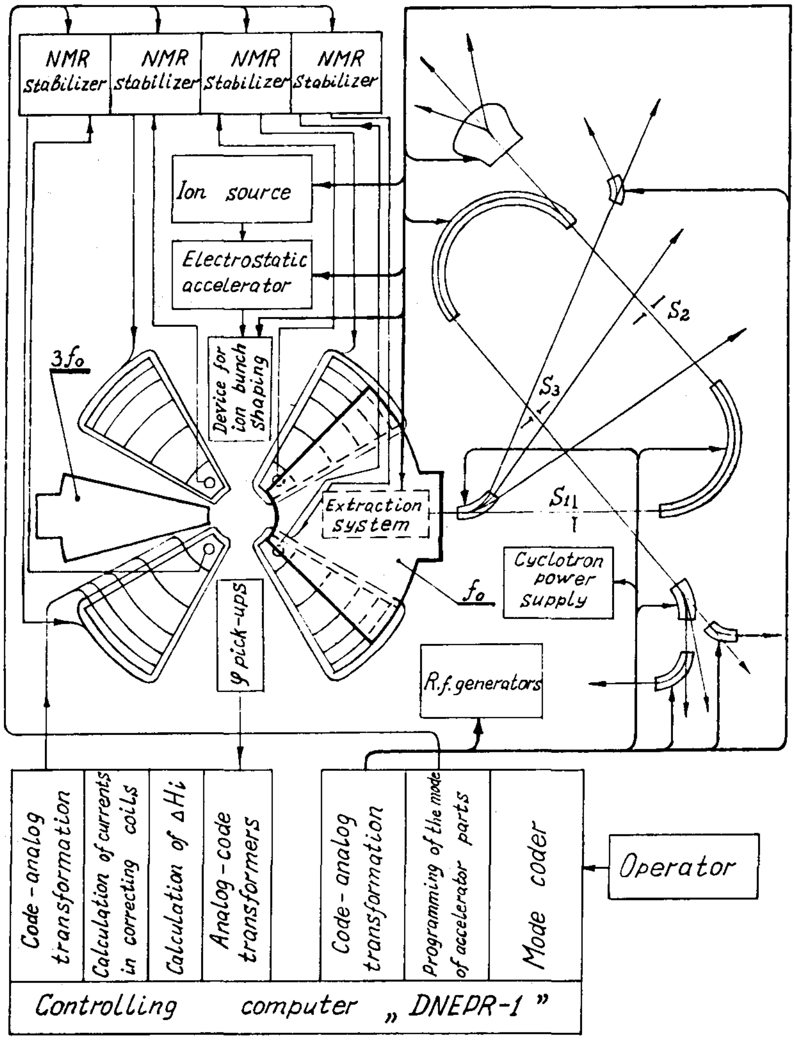

Fig. 1. Schematic view of the cyclotron control system

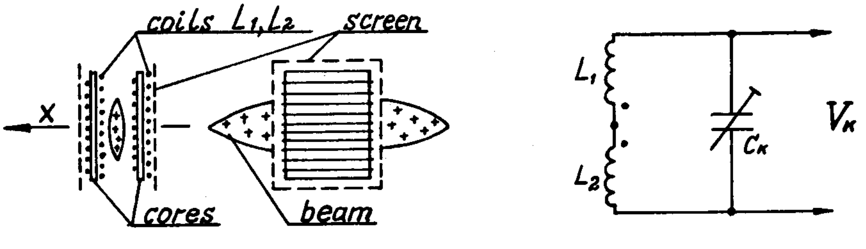

Fig. 2. Schematic view of the induction pick-up of the beam radial co-ordinates

correcting systems having induction pick-ups for beam position[3] located at specific points of the particle trajectory.

In particular, our method of particle extraction ensures a sufficiently monoenergetic beam only if particles which have performed equal numbers of rotations enter the deflector. Since the monoenergy cyclotron ensures orbit separation at all energies up to the maximum, this condition can hold but the radial position of the electrostatic deflector entrance must be accurately matched with the position of the last orbit.

The radial positions of the parts of the extraction system are determined initially by the programmer of the accelerator control system. Their positions are precisely corrected by signals from the induction pick-ups of the radial co-ordinates of the last orbit. Fig. 2 shows a schematic view of a pick-up.

The operation of the beam position pick-up under consideration when compared with analogous devices used either with external beams[4] or linear accelerators[5] is characterized by much higher noise at frequencies which are a multiple of the bunch repetition rate. This requires one to take special measures for selecting the beam signal. Putting the coils L_1 and L_2 into a circuit tuned to the second or third harmonic of the bunch repetition rate would be the most effective method for increasing the signal-to-noise ratio in these conditions. For an azimuthal width of 12° for the bunch which is accepted in our cyclotron[1] the amplitude of the second and third harmonics of the signal is smaller than the first harmonic by only 0·8% and 1·4%, respectively, whereas the noise level is reduced ten times.

Under resonance conditions the voltage over the loop L_1, L_2, C_k is as follows:

$$V_k = \left(\frac{2I_m\,\mu_{\text{eff}}\,S_k n Q\omega}{\pi a^2}\cdot\sin h\pi\tau/T\right)\,\Delta r\,\sin h\omega t \tag{1}$$

where I_m is the amplitude of the pulse current, μ_{eff} is the effective magnetic permeability of the coil core, S_k is the coil cross section, n is the number of turns, Q is the quality-factor of the circuit L_1, L_2, C_k, $\omega = 2\pi/T$ is the current pulse rate, a is the distance between the centres of the coils L_1 and L_2, τ/T is the current pulse on-off ratio and h is the number of the harmonic used. A preliminary test of the pick-up model when the beam was simulated by current pulses along a wire between L_1 and L_2 has shown that its sensitivity with a mean beam current of about 10 μA makes it possible to detect an orbit shift of about 0·1 mm. Such sensitivity is quite sufficient to correct the radial position of a part of the particle extraction system.

Beam position pick-ups of similar design can be used for detecting the orbit vertical shift from the median plane of the cyclotron magnet in the process of acceleration, and for determining the position of particle trajectories in the beam lines to experimental rooms.

The pick-up system allows the performance of one more very important operation for the monoenergy cyclotron, i.e. the control of the stability of external particle energy, which is defined by beam deviation at the output end of the analysing magnet.

The output signal from the detection circuit can be used for correcting the accelerating voltage in the cyclotron and hence, to stabilise the energy of ions entering the extraction system. The pass band of the feed-back in this stabilisation system can amount to some tens of kHz. Such fast operation allows one to control not only slow energy drift but also fast fluctuations due to voltage pulsations of the power sources of the rf generator as well as those due to vibrations of parts of the rf resonator of the accelerating system. Strict requirements imposed on the monoenergy quality of accelerated particles result in rigid tolerances for the phase deviation of particle flight through the accelerating gaps. An accelerating voltage with a flat top about 20° wide and an azimuthal bunch width of about 12° used in our cyclotron allow a shift of the beam flight phase from the optimum of not more than 2°. The tolerance for magnetic field deviation of the accelerator field from the given law for the cyclotron[1] related to this phase shift is $\Delta\bar{H}/H\,|_p = 1{\cdot}4 \times 10^{-3}\%$ (harmonic number, $h = 2$, energy gain per turn $eV_0 = 0{\cdot}2$ MeV, the maximum energy of accelerated protons $E_{pk} = 80$ MeV). It is difficult to maintain the cyclotron magnetic field topography with such tolerances by using programmes. The tolerances for $\Delta\phi$ can be maintained only by automatic control of the cyclotron magnetic field using the measurements of beam flight phase at several positions.

If the flight phase is controlled systematically through intervals of radius which correspond to an energy gain ΔE, then the tolerances for the field inside each interval are given by the formula,

$$\frac{\Delta\bar{H}}{H} = \frac{\Delta\phi \; eV_0}{2\pi h \, \Delta E} \tag{2}$$

The magnetic field control at intervals between the measurement points of the beam flight phase is performed using concentric coils equal in number to the number of phase pick-ups. For the acceptance aperture of the accelerator magnet system[1] of about 16 cm the number of phase pick-ups and correcting coils should be about 25. The tolerance for the magnetic field deviation in the intervals between coils can then be increased to about $1{\cdot}7 \times 10^{-2}\%$, which appears to be possible.

The most important problem to be solved in developing a system of magnetic field stabilisation for our cyclotron was to find a method of detecting the phase of beam flight through the accelerating gaps without affecting the process of acceleration, i.e. without beam interception. Usually, electrostatic pick-ups are used for this purpose, but their application in the cyclotron is impeded by heavy noise on the pick-up plates at harmonics of the rotation frequency of the accelerated ions. The signal-to-noise ratio necessary for measuring flight phase to one degree accuracy is extremely difficult to achieve with a mean beam current

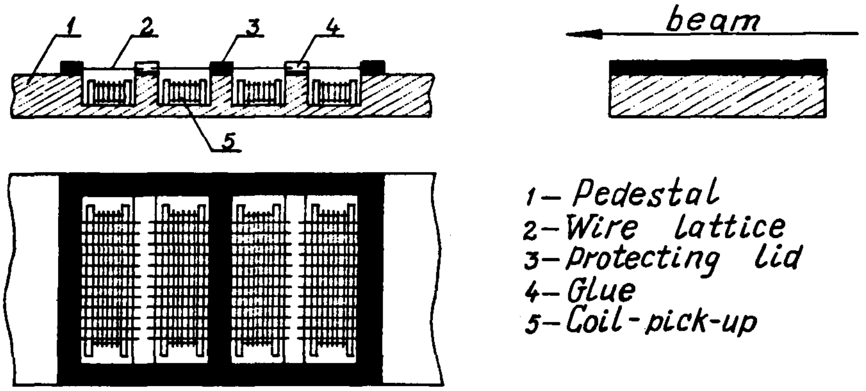

Fig. 3. The screened induction pick-up for phase measurements

of one micro-ampere (the ordinary adjustment mode of the accelerator) even when working on harmonics of the ion rotation frequency.

Much better results can be obtained by employing induction electrodes. This is due to the fact that induction electrodes can be screened from the electrical field of the accelerating plates. Thus, the signal-to-noise ratios obtained in the cyclotron can be considerably increased. A schematic view of the screened induction electrode is shown in Fig. 3.

In order to study the properties of such plates in real conditions and to perform comparison tests, a system of electrostatic and screened induction electrodes has been made and put in the electron model of the isochronous ring cyclotron.^{6} The results of measurements carried out at the second harmonic of the rotation rate of accelerated electrons are summarised in Table 1.

Table 1

Pick-up	*Induction*								*Capacitance*			
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
Sensitivity (mV/μA)	0·6	0·4	0·4	0·5	0·4	0·5	0·6	1·0	1·5	1·9	0·4	0·4
Signal-to-noise ratio (adjustment mode $\bar{I} \simeq 1\ \mu$A)	47	134	125	42	103	88	35	199	0·6	0·7	0·3	0·4

The comparison of signal-to-noise ratios obtained for electrostatic and induction electrodes vividly shows the advantages of the latter. These results confirm at the same time the possibility of measuring the phase to about 1° accuracy since the signal-to-noise ratio, necessary for this, calculated by using the formula

$$\tan \phi_{\text{meas}} - \tan \phi_S = \frac{1}{m \cos \phi_S} \tag{3}$$

is about 60. In the above formula ϕ_{meas} is the measured phase of the signal from the flight phase pick-up, ϕ_S is the real phase of beam flight, and m is the signal-to-noise ratio.

The block diagram of one of the tracks for measuring the beam flight phase is shown in Fig. 4.

An output signal from the phase detector is proportional to beam flight phase

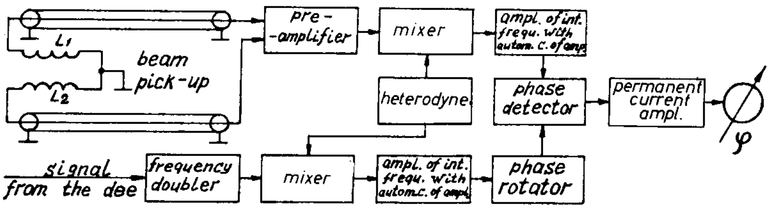

Fig. 4. Block-diagram of the track for measuring the beam flight-phase

with respect to the given phase ϕ_s at the orbit corresponding to the radial position of the induction pick-up. A schematic view of the whole system for stabilising the cyclotron magnetic field or, in fact, the flight phase of the beam through accelerating gaps is shown in Fig. 1.

The whole process of pick-up read out, the treatment of control signals and magnetic field correction using the computer, model 'DNEPR-1' can be accomplished in some minutes. The required correction frequency can be determined by considering all parts of the stabilisation system, and this speed of operation of the system for treatment of the input information seems to be sufficient.

DISCUSSION

Speaker addressed: Yu. N. Denisov (Dubna)

Question by K. V. Ettinger (Birmingham): 'What is the sensitivity of the positioning beam probe expressed in terms of mm displacement and μA of current?
Answer: One millimetre per microamp.

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