The Rf system of the monoenergetic cyclotron

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The accelerating system of the Dubna monoenergetic cyclotron (MC) is to provide 200 keV energy gain per revolution per charge for all accelerated particles: p, d, α, ^3He, ^6Li. Particles are to be accelerated at the maximum of the rf voltage, and the vector of the accelerating electrical field strength is directed along the closed particle orbit at all radii. To increase the working phase region a non-sinusoidal rf accelerating field must be applied (sinusoid with a flat top); this is achieved by using additional dees operating at three times the basic frequency.[1]

Before considering a possible scheme for the rf system, let us analyse the effect of various factors related to it. The equivalent accelerating voltage is determined by the expression

$$U_e = U_o\,(\cos\varphi - 1/9\cos 3\varphi) \tag{1}$$

If the tolerances for various systems are taken into account, then to keep the energy stability within 10^{-4}, the time stability of the equivalent accelerating voltage should be 10^{-5}. Tolerance of voltage stability of the third harmonic is an order of magnitude smaller than that of the first one. Apart from the instability of the rf voltage amplitude a required phase relation between U_1 and U_3 and the ratio U_3/U_1 can be violated. The effect of these parameters on the shape of the accelerating voltage is shown in Figs 1 and 2. It is clear that a phase shift in the main harmonic is very dangerous. Fortunately this effect can be cancelled out by proper connection of the frequency tripler.

The scheme and configuration of the accelerating cavities of the rf system are determined, first, by the requirement to provide optimum conditions for acceleration and, second, by the general accelerator arrangements. Consideration of the above requirements with the four-sector magnet design resulted in the following scheme for the accelerating systems of the monoenergy cyclotron.

The main accelerating electrodes have an angular width of 90° and are placed in opposite quadrants. Their accelerating edges are directed along the radius in the centre of sectors perpendicular to the velocity vector. The working frequency corresponds to the second harmonic of the rotation frequency so that the effective angular width of the electrodes is 180°. The electrodes are fed in phase. In the centres of the remaining free sectors there are additional electrodes with

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an angular width of 30°, working on the six-fold rotation frequency or the third harmonic of the main frequency (Fig. 3).

The main accelerating electrodes are $\lambda/4$ resonance-tuned by means of the shorted plane line 1·2 m long, 2 m wide. Its internal electrode is a continued dee. Frequency is tuned by movable panels which change the characteristic impedance of the line. Since the central part of the dee and the whole resonance line are between the magnet sectors, their axial dimensions may be large, and it is possible to place the extraction system together with the driving system inside the dee and the resonance line. The resonance line stub is used to control the

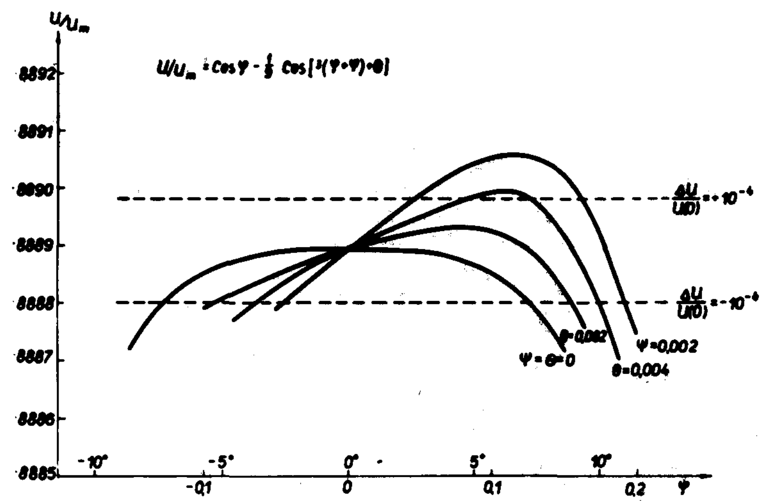

Fig. 1. The values of the equivalent voltage for various phase relations between U_1 *and* U_3

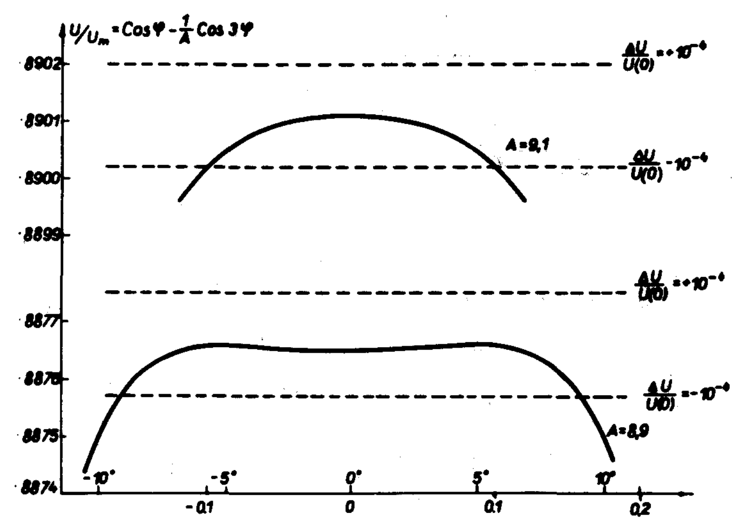

Fig. 2. The values of the equivalent accelerating voltage for various ratios U_1/U_3

displacement of the channel and the withdrawal of the channel from the chamber.

Calculations and a 1:4 scale model of this resonance system were made. The approximate expression for estimating the resonance frequency is as follows:

$$\frac{\pi}{2}\frac{d_1}{d_2}\frac{R}{\pi + 2d_1}\frac{1 + d_3/d_2}{d_3/d_2}\tan \beta l = \frac{J_0(\beta R)}{J_1(\beta R)} - 0{\cdot}404\beta R(0{\cdot}2 - d_3/d_2) \qquad (2)$$

where R is the external radius of the dee, π is the perimeter of the resonance line cross section, d_1 is the axial gap in the resonance line, d_2 is the axial gap between the dee and the chamber outside the magnetic blocks, d_3 is the axial gap between the dee and the chamber inside the magnetic blocks, and l is the feeder length. Calculation according to formula (2) gave good agreement with experiment. The maximum difference in the working frequency range did not exceed 7·5%.

The frequency range (9·3–5·9 MHz) is covered by changing the gap in the line from 12 to 64 cm. Voltage over the accelerating edge is practically constant at the lower frequency and is decreased by 4% from the centre to the edge at the higher one. Power losses are about 70 kW per dee.

The harmonic accelerating electrode is an isosceles triangle with a top angle of 30°, and is the developed central part of the internal electrode of the shorted halfwave resonance line. Each of the two vertical resonance lines is 2 m long and its axis is perpendicular to the median plane. Movable shorting plates are used to retune the frequency.

The system of rf power generation and parameter stabilisation should ensure the production and maintenance of voltage on the accelerating electrodes with the above mentioned amplitude and phase stability. A block-diagram for the rf supply to the electrodes is shown in Fig. 3. It consists of two channels of power amplifiers (first and third harmonics) with AAC systems (automatic amplitude control) and two channels for stabilising the fundamental frequency (AFC) of

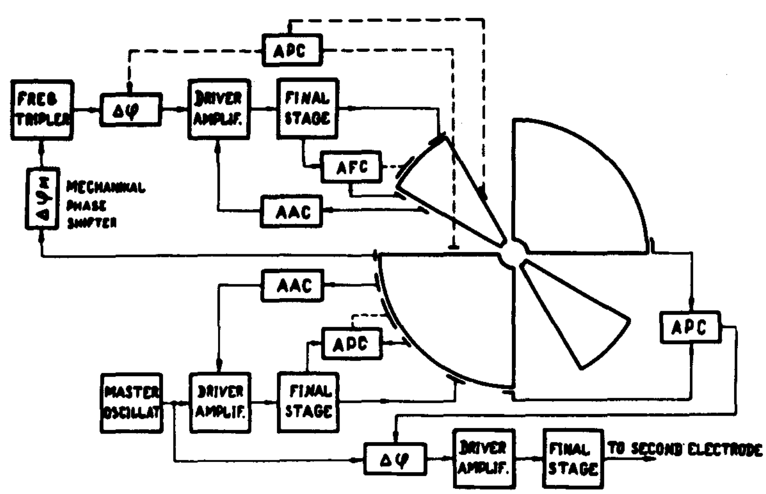

Fig. 3. Block-diagram of the rf supply

the accelerating cavities operating according to the phase principle. Both channels are fed from the common master oscillator. The frequency tripler is driven by the signal coming directly from the main accelerating electrode. This makes it possible to eliminate a very dangerous parasitic phase shift in the main harmonic, U_e, and to avoid phase shifts in the main power amplifier cascades.

In order to produce an accelerating voltage with about 10^{-5} stability the main power amplifier elements should, of course, satisfy special requirements. However, if one proceeds from the assumption that the coefficient of the closed AAC system stabilisation may be about 100 for slow voltage deviations and is five times smaller for the fast one, these requirements will not be strong, and they can be satisfied easily by simple means (supply from ordinary but high power stabilisers, with thermostabilisation within 1°C, phasing within a few degrees). Thermostatic control within 0·1°C will be needed only in the AAC system pick-up. The requirement for the accelerated particle current stability is a specific one. For beam powers of about 10% of the power losses, slow current deviations should not exceed 1–2% while fast deviations should not exceed a few parts of 1%.

In our design of the rf system, input voltage is supplied to the frequency tripler by the non-resonant feeder from the main accelerating electrode directly. Uncontrolled phase shift is most dangerous in this circuit since it becomes three times larger after the frequency tripler. If a phase shift per cascade of 2×10^{-4} (0·0115°) is considered to be tolerable, then the feeder length (l_m) and its temperature are related as follows:

$$l_m \, \Delta t^\circ < 20$$

Phase losses due to the variation of supply voltage in the cascade power amplifiers have been studied at the Radiotechnical Institute of the USSR Academy of Sciences.[2] From the results obtained it follows that in order to ensure that the phase shift is not greater than 2×10^{-4} it is necessary to have

$$\Delta E_a/E_a < 3{\cdot}8 \times 10^{-4}; \qquad \Delta U_f/U_f < 2{\cdot}3 \times 10^{-5}$$

The third harmonic accelerating cavity has a peculiarity that due to a necessity to artificially increase the power loss ten-fold (so that $P_{\text{loss}} > P_{\text{beam}}$) its Q will be $\sim 10^2$. With $\Delta t \cong 0{\cdot}1^\circ$ this will provide $\Delta\varphi \cong (2 \text{ to } 6) \times 10^{-4}$.

The calculations show that the necessary phase dependence between the voltage of the first and the third harmonics can be maintained even without the (AFC) cavity and the (APC) system, and so, the rf system considered above satisfies the conditions required to produce a monoenergetic beam of accelerated particles.

The analysis of requirements imposed on the various components of this system shows that although unusual for present accelerator and rf facilities they are nevertheless within modern technical possibilities.

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