PERFORMANCE REPORT ON THE KAZAKHSTAN VARIABLE ENERGY ISOCHRONOUS CYCLOTRON

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Abstract

A I50 cm pole diameter variable energy isochronous cyclotron was constructed at the Institute of Nuclear Physics near Alma-Ata to provide a nuclear physics research facility in Kazakhstan[I,2]. It was put into operation in I965 as an ordinary fixed-frequency cyclotron[3], was converted in I972 and sheduled for use in isochronous mode since the March I972.

A brief description of the main features and current operation of the converted cyclotron is given and further improvement program is presented.

The magnetic field of the cyclotron has threefold symmetry. The maximum field-radius product of the magnet is I064 kG.cm. For correcting the magnetic field shape a trimming coil system is used. The RF system is tunable over the range 8,5-I9,0 MHz. The maximum energy of 30 MeV protons, 25 MeV deuterons, 50 MeV alphas, 62 MeV helium-3 ions at the external target are available.

During first three years different improvements have been made, the principal ones being increasing the extraction efficiency at maximum energies from 60 % to 70 % by changing the electrostatic deflector, installation of the new puller with two slits and movable slit in the central region, adjustable length magnetic shield channel, a helium-3 recovery system. The operational time of the cyclotron was increased up to I65 hours per week.

In order to satisfy an increasing demand a new beam transport system is designed and its installation is planned for the end of I976. Some changes will be made in the RF amplifier. We hope that these improvements will give a better efficiency of cyclotron performance.

I. Introduction

The main goal for the Kazakhstan isochronous cyclotron installation is to provide rather intense and high quality beams of ions over the wide mass range, but the main attention has been concentrated upon production of light ion beams suitable for work of experimental groups from Kazakhstan Academy of Sciences and from other research labolatories.

A survey of parameters associated with the acceleration of various ions is given in operating diagram (fig. I). On the order of I0-30 μA and in some cases up to I00 μA current of light ion beams at the target are available. An emittance of the extracted beam for 30 MeV alphas is 20 mm.mrad in horizontal phase plane and 30 mm.mrad in vertical phase plane for the whole beam and accordingly I0 mm.mrad and I5 mm.mrad for the 70 % of the beam.

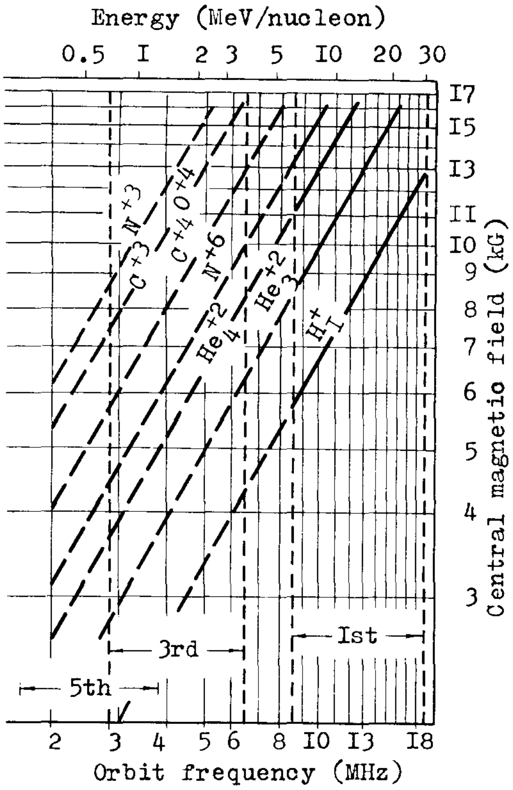

Fig. I. The cyclotron operating diagram

2. Magnetic field

2.I Magnet and field characteristics

The cyclotron magnet has a pole diameter of I50 cm, a gap in the valley of 39 cm. The azimuthally varying field is provided by three sectors. This configuration was chosen on account of its more favourable focusing properties in the central region in comparison with another number sector configuration. Much attention was paid for simplicity of machining of pole tip components in order to minimize

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the probability of a large first harmonic component of the magnetic field. The sectors have one edge straight and the other cylindrical shaped. They are flat and are mounted on a flat lid, which is fastened directly to the magnet pole by eight bolts. The sectors extend from a radius of I0,5 cm to the edge of the pole at 75 cm, and have angular width of 22° at I0,5 cm and 82° at 75 cm. There is a central cone which causes a field bump inside a I0,5 cm radius. The iron-to-iron gap is 2I,6 cm. The design of the pole tip configuration is based on I:3 scale model measurements.

The average mafnetic field induction range of the cyclotron runs from 6 to I7 kG, beam extraction radius is 66,5 cm. The maximum value of the amplitude of the main harmonic reaches 3,5 kG at large radii. The spiral angle is nearly zero at radii less than 37 cm. Over that radius the spiral angle increases approximately linearly with radius to 25° at the extraction radius. The values of the first and second harmonic amplitudes are on the order of 4 parts in $I0^4$ at all radii, that is the evidence of rather accurate machining and assembling of pole tip components. Departures from isochronism are only 7 G at all radii except central and extraction regions.

In fig. 2 radial ν_r and azimuthal ν_z frequency oscillations for proton beam at I3 kG are plotted, as determined by numerical orbit dynamics calculations.

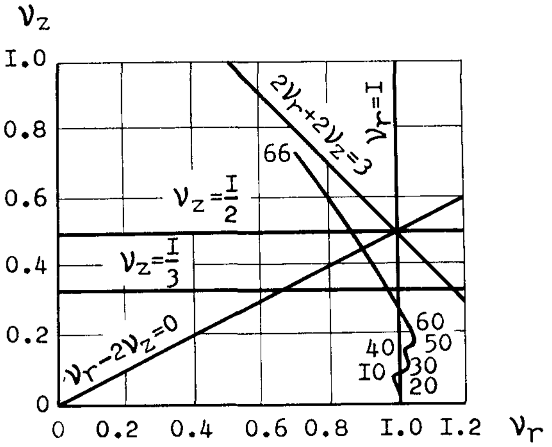

Fig. 2 The diagram of stability. Protons 30 MeV

The numbers in the diagram indicate average orbit radii. At 6I cm radius axial frequency is rapidly rising and radial frequency is rapidly decreasing as the average magnetic field begins to fall off. The beam passes ν_r=I resonances and $\nu_r=2\nu_z$ resonance.

2.2 Measurements

Orbit dynamics calculations used full scale magnetic field measurements which were performed by means of specially designed apparatures4). As a sensing device the Hall generator was chosen because of its rather good adaptability to a digital system.

The median plane magnetic field was mapped in polar grid at I cm radial step and 3° azimuthal step. Radial positioning of the probe was made manually at the desired radius at a maximum tolerance of 0,I mm. Azimuthal positioning of the probe was made automatically and was accurate to ± 8". The vertical positioning of the probe was accurate to 0,3 mm. The dimentions of the Hall element were I,5x0,8x0,2 mm^3. The magnetic field measurements were made at the speed of 3,8 sec per point.

The output Hall voltages were amplified, converted to frequency by series of successive transformations and punched on a paper tape. The recorded data were appended to a computer and wrong magnetic field records were corrected by interpolation from the adjacent points. The overall measurement accuracy was 2 G.

2.3 Trimming coils

Nine pairs of circular and six pairs of harmonic trimming coils are installed on the pole tips to adjust the magnetic field shape. Circular trimming coils are fabricated from square copper tubing and wrapped with an epoxy impregnant glass tape. They are cooled by water. Each trimming coil is epoxy cast and forms a rugged mechanical assembly. To keep a clean high vacuum all the coils are separated from main vacuum chamber and are located in a vacuum chamber at an intermediate pressure. The number of circular coil turns ranges from 4 in the outermost coil to 9 in the innermost coil. The coils which carry electric current from 600 to 750 A maximum produce average magnetic field radial gradient on the order of 30 G/cm at all radii at the medium field induction.

The circular coils power supplies consist of six phase rectified power unites and are completely solid state5). They are capable of operating from 2-5 to I00 % of rated current and provide current regulation on the order of $I0^{-3}$. Short-term drift is $I0^{-4}$, long-term drift is $3.I0^{-4}$. Ripple of the magnetic field induction in the accelerator chamber at the maximum coil currents is less than I G.

3. RF system

The voltage for accelerating the ions is provided by two I80° dees. They are parts of the quarter-wavelength resonators. The RF system is tunable over the range 8,5-I9,0 MHz by changing the position of shorting plates in the resonator tanks without breaking the main vacuum. Fine tuning is done with trimming capacitors. Resonator characteristics are the main limiting factors in the tuning range. The RF oscillator is located outside the cyclotron vault and the high-frequency power is transmitted from the final stage of a multistage amplifier by means of two 60 Ω rigid coaxial lines. The power is inductively coupled by turnable loops[2] to the resonators. The amplitude of the dee voltage is 80 kV which provides approximately 300 keV gain in energy per turn for protons. This rather high energy gain provides sufficiently rapid passage through resonance regions and improves turn separation conditions for beam extraction.

4. Central region

A conventional hooded arc hot filament ion source is inserted radially and it can be remotely adjusted from the central control desk. The associated puller electrode has two slits and is located in a fixed position at the dee edge. Although an adjustable puller is desirable for constant voltage acceleration, there are technical difficulties in such adjusting at the present dee geometry. On the other hand at constant orbit acceleration there is decrease of source output, when the accelerating voltage is lowered for low energy operation. In such a case the source is placed at a larger radius and ions are extracted by the second slit at the corresponding radius. This provides a higher electric field at the source, thus increasing the source output. Thus the cyclotron can perform at two constant orbit accelerations with reduced range of the dee voltage changing.

Particles extracted from the source with undesirable starting conditions are clipped by narrow defining slit, thus avoiding unnecessary radiation problem and increasing deflection efficiency. The water cooled defining slit can be remotely adjusted along the center line of the dee gap. The vertical focusing of ions in the central region is improved by providing a magnetic field fall-off. When accelerating the helium-3 ions a recovery system is used to recycle the gas.

5. Beams

The first internal beam of 30 MeV protons was obtained in September I97I. At the present time the cyclotron provides a variety of light ion beams at different energies. Measurements of beam current versus radius gave evidence of no appreciable loss of beam between central and extraction regions. The maximum phase excurtion was estimated as 40° and was caused by the rapid decrease of the magnetic field in the extraction region.

By optimizing the ion source and defining slit positions and the dee voltage amplitude the amplitude of coherent radial oscillations at the large radii can be decreased to 2 mm.

The dimentions of the internal beam were measured by means of multi-finger probes and radiografically in both horizontal and vertical planes. The obtained internal alpha partical beam profiles at I6,5 kG are shown in fig. 3. The exposures were made at 50 cm and 65 cm radii. The spots are nearly 6 mm horizontally and I0 mm vertically.

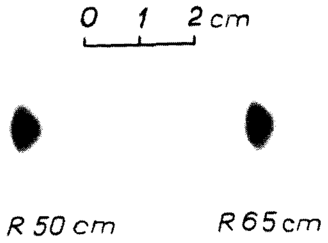

Fig. 3. The internal alpha particle beam spots at I6,5 kG

As previously was mentioned wide range of beams can be accelerated, but the most used beams since I972 are protons 6,5-30,0 MeV, deuterons I2,0-25,0 MeV, alphas 24,0-50,5 MeV, helium-3 ions I8,6-6I,8 MeV. Third harmonic operation was tested. Average internal beam currents for protons 200-300 μA, alphas 20-30 μA, helium-3 ions up to 20 μA are available at the duty cycle of I0-20 %. This would extrapolate to 2 mA of protons at I00 % duty cycle. While large internal beams can be accelerated, normal practice was to reduce the beam intensity in the central region so that only that beam useful for high efficiency extraction was accelerated.

6. Extraction

The beam extraction system consists of a I,2 meter-long or II0° in azimuth electrostatic deflector located inside the dee and a magnetic shield channel. The deflector consists of two parts: the first part is of conventional type. The gap between the electrodes of the first part enlarges parabolically from 7 mm at entrance to I8 mm at exit to allow for the increasing horizontal width of the beam. The gap between the electrodes of the second part of the deflector is constant and I8 mm wide. The electrodes of the second part are curved in the vertical plane to compensate magnetic fringing field effects 6). The thickness of the copper septum is 0,5 mm. The deflector entrance is located near the beginning of a valley. The maximum deflector voltage is 70 kV.

The magnetic field in the shielding channel is reduced to 0,I kG from 4,5 kG of the cyclotron fringing field in the same region. By making the shielding channel length variable the beam is steered into the beam transporting system.

As was mentioned above the beam is accelerated far into the fringing field up to the highest possible radius where a radial oscillation friquency differs much from unity (fig. 2). Sufficient turn spacing is generated by precession mechanism. The separation is optimized with the harmonic coils. Extraction efficiency ranging from 20 % for low energies to 70 % for high energies has been achieved. Average target beam current exceeding I0 µA for helium-3 ions, 20 µA for alphas and 30 µA for protons are available over the whole energy range at duty cycle of I0 %. Beam currents can sufficiently be increased if necessary. For example, the largest obtained alphas beam current has been on the order of I00 µA at the optimizing all the cyclotron parameters, especially the ion source parameters.

Measured emittance of the external beams varies depending on the magnetic field value. For example emittance for 30 MeV alphas is 20 mm.mrad in horizontal phase plane and 30 mm.mrad in vertical phase plane for the whole beam and decreases accordingly to I0 and I5 mm.mrad for 70 % of the extracted beam. Extracted beams have an energy spread on the order of 0,6 % full width at half maximum. There are no extraordinary features in the external beam handling system. The general view of the cyclotron is shown in fig. 4.

7. Conclusion

On conclusion we are pleased to state that the cyclotron performs quite satisfactorily. The sheduled time of cyclotron operation was increased from I38 to I65 hours per week. Many of the problems have been solved but of course, we still have a few problems to work on. Now we are planning three additional beam lines of a new beam transport system. It is anticipated that they will be installed in I976. Some changes will be made in the RF amplifier.

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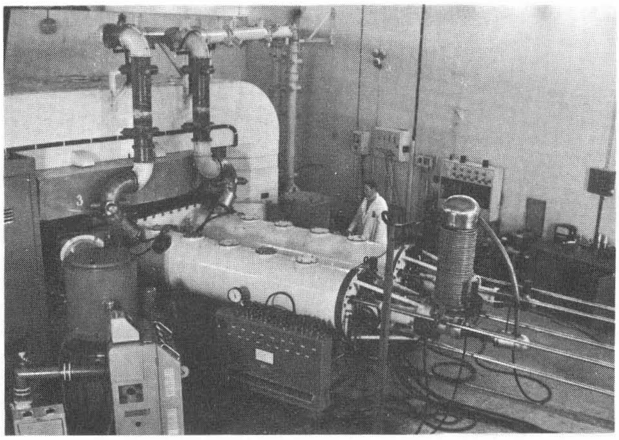

Fig. 4. Main vault of the Kazakhstan isochronous cyclotron