Spectrometric isochronous cyclotron

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The characteristics of a spectrometric isochronous cyclotron for producing beams of protons, deuterons and other particles having a maximum energy of 80 MeV (for protons), average current 100 μA and energy spread 10^{-4} are considered. The indicated values of parameters may be obtained by using a magnet having divided sectors, external injection and introducing the third harmonic of the accelerating field. The principal requirements as regards the magnet system, injector and rf system of such a cyclotron are formulated. Preliminary results of the magnetic field calculations and ion motion during acceleration are presented and discussed.

At the P. N. Lebedev Physical Institute of the Academy of Sciences of the U.S.S.R. and the D. V. Efremov Institute of Electrophysical Apparatus the design project for an isochronous cyclotron for spectrometric investigations in the field of nuclear physics is being worked out. A programme of possible experiments on such an accelerator is described in some detail in another paper.[1] The energy range (10–80 MeV for protons), small energy spread ($\sim 10^{-4}$) and high average beam current (100 μA) of this accelerator will make it possible not only to perform all those experiments which can be conducted on electrostatic tandem accelerators at present or in the near future, but to significantly expand the scope of these investigations.

To achieve the indicated beam parameters during acceleration in an isochronous cyclotron, and maintain them after beam extraction, rather stringent requirements must be met as regards the choice of its major systems and a number of conditions necessary for stability of the accelerating regime must be fulfilled.

Some idea of the characteristics of the accelerator being developed can be gleaned from the table of basic parameters (Table 1). These parameters should be considered tentative since they may be changed somewhat during the design process. The cyclotron has an external injection system, a divided-sector magnet system[2, 3] of relatively low average field level, a large energy increment per revolution, a supplementary accelerating system based on the third harmonic, and rather strict tolerances as regards the precision and stability of the magnetic and rf accelerating fields as well as the parameters of the beam being injected.

In such a 'spectrometric' cyclotron there will be a clear separation of orbits in the region of the cyclotron deflector, which will make possible a significant decrease in the energy spread of the ion beam being extracted. It will be possible to go from values of the order of hundreds of keV (beam extraction takes place from several orbits due to betatron oscillations) to values of the order of tens of keV (the spread in a separate bunch of accelerated ions). An additional harmonic of the accelerating voltage will make it possible to eliminate the principal cause of the energy spread in the bunch—the dependence of the energy gain on the phase of the accelerating voltage. Choosing, for example, the third harmonic and keeping its amplitude at a level of 0·126 ±0·0002 of the ion energy gain one can obtain an accelerating voltage variation of less than 10^{-5}, which provides an energy spread of $10^{-5} \times 100$ MeV = 1 keV in the rather large phase interval of $-6^\circ < \varphi_s < +6^\circ$. In this case, the inaccuracy of phasing the basic and supplementary accelerating voltages must be less than ±0·1°.

In addition to the fulfilment of the orbit separation condition and obtaining a flat-top voltage vs time curve, it is necessary to keep the accelerated ions within the limits of the phase region having the 'flat' accelerating voltage. This may be achieved by injecting rather small bunches of 2-3 ns duration followed by automatic correction of the bunch phase position during acceleration. It is assumed that the tolerances on the stability of the basic accelerating voltage amplitude ($\sim 3 \times 10^{-5}$) and the accuracy and stability of the magnetic field isochronism (10^{-4} without the automatic correction system) are met.

In the design of the spectrometric cyclotron an optimum choice of all its systems and parameters should be made. At present, investigations are proceeding

Table 1. SOME PARAMETERS OF THE SPECTROMETRIC CYCLOTRON

Energy range (for proton)	10–80 MeV
Energy spread	10^{-4}
Average current of extracted beam	100 μA
Final radius	260 cm
Number of magnet sectors	4
Maximum field intensity	10 kG
Average field intensity	5 kG
Overall weight of electromagnet	600 tons
Required power	450 kW
Frequency range of rf-generator	10–15 MHz
Energy gain per revolution	350 keV/turn
Number of main accelerating devices	2
Power of rf-system	150 kW
Injection energy	1 MeV
Permissible magnitude of 1st harmonic of azimuthal asymmetry of field	1 G
Stability of magnetic field	5×10^{-6}
Frequency stability of accelerating voltage	3×10^{-6}
Amplitude stability of accelerating voltage	3×10^{-5}
Accuracy of phasing of main and supplementary accelerating voltage	±0·1°
Permissible deviation of magnetic field from isochronous (without auto-correction)	10^{-4}

along several, generally speaking, related lines: beam dynamics, magnetic system, accelerating system, injection.

One of the conditions for good orbit separation is that the free radial oscillation amplitude should be limited to a value of the order of 2 mm. To meet this stringent requirement it is necessary that the injected beam have a rather small emittance, that the initial conditions at injection be precisely maintained and all effects exciting free oscillations of particles be minimised. In particular, it appears to be necessary to take into account the effect of the accelerating rf-system on the transverse motion of particles. The influence of the accelerating system on radial oscillations is completely excluded in the design of the monoenergetic cyclotron,[4] for example, by using 90° dees protruding into the magnet sectors. On the other hand, from the construction point of view, it is natural to try to restrict the azimuthal width of an accelerating element to the dimensions of a straight section (45° for $N=4$), which would make it possible to reduce the power of the rf-system and the weight of the electromagnet. In this connection, the investigations at the Lebedev Physical Institute and the Efremov Institute of Electrophysical Apparatus are directed toward establishing the conditions which will provide the required limitation of the amplitudes of the free oscillations, without sacrificing the constructional advantages of a cyclotron having divided magnet sectors.

Reliable data to serve as a basis for the investigation of ion dynamics were obtained using a computer to numerically integrate a system of exact equations of motion, taking into account the accelerating electric field. Thus, there were determined, in particular, the dependence of betatron oscillation frequencies on radius and the envelope of the oscillations, the trajectories of ions in the process of acceleration, and the effect of various perturbing factors. In certain cases, for example when analysing the motion of ions in a field that is practically 'step-shaped', approximate methods proved advantageous. Analytic methods were also used.

Calculations have shown that for a given injection energy and a given energy gain per turn, among the possible trajectories which spiral outwards there exists one trajectory (usually called the equilibrium orbit) for which the precession due to the accelerating gap action is compensated for by betatron oscillations. One can control the precession of orbits, which is especially important in the region of beam extraction. In particular, the precession may be reduced to a minimum determined by the final dimensions of the particle bunch.

The component of the space charge electrostatic force acting along the bunch axis contributes an additional energy spread to the particles. Under certain conditions this spread may be comparable to the initial one and result in a limitation of the useful bunch length.

In view of the stringent requirements regarding accuracy and stability of configuration of the magnetic field of a spectrometric cyclotron, it is necessary to use distributed pole windings to shape the isochronous field to an accuracy of $\sim 10^{-4}$ and a system of field auto-correction based on the phase of the beam flight; this system will reduce the field deviation to $\sim 3 \times 10^{-5}$.

Although the isochronous field can be shaped to an accuracy of only several per cent solely by means of iron poles of simple geometry, the choice of pole geometry is very important since, in essence, it determines the azimuthal modulation depth of the parameters of the correcting windings and their power supplies. When analysing various magnet geometries in order to determine the optimum variant, it is convenient to use analytic representations of the field which relate the geometric and magnetic parameters of the system.[5] Use of approximate analytic calculations makes it possible to reduce the volume of work in modelling the field.

The most important problems which must be solved in designing an accelerating rf-system are stabilisation of the amplitude of the accelerating voltage, synchronisation of the main and supplementary voltages and providing a constant ratio of their amplitudes at all orbits. Preliminary consideration indicated that the above problems can be solved technically, but require additional investigation. A possible main accelerating system can consist of two vertical half-wave coaxial resonators of variable cross-section.[6] Taking into account the power of the beam and losses in the rf-system, the required power of the generator should be equal to 150 kW.

Particles may be injected, for example, along the median plane, as in the FIAN cyclotron.[7] Another method involves injection of an ion beam into the chamber at a small angle with respect to the cyclotron axis (axial injection). As an accelerating voltage source for the injector, it is proposed to use a compact 1 MV cascade generator which is being developed at the D. V. Efremov Institute of Electrophysical Apparatus. This generator should provide an average load current of 2–3 mA and a voltage stability of 10^{-3}.

The simplest way to achieve deflection and extraction of the beam involves the use of an electrostatic deflector in conjunction with an extracting magnet. The energy of the extracted beam will be variable in steps equal to the energy gain per turn. Fine variation of energy within these limits can be realised by changing the accelerating voltage amplitude or by passing the extracted beam through an additional resonator.

A more detailed description of the cyclotron under consideration as well as the programme of experiments on the cyclotron are given in reference 1.

DISCUSSION

Speaker addressed: A. A. Kolomensky (Lebedev Institute)

Question by R. S. Livingston (ORNL): The magnetic field of the Lebedev proposal differs by being larger than that of the Dubna group and smaller than the cyclotrons described in the first session. What are the factors governing the choice of field value?
Answer: We have chosen a compact design with some compromises between physical and economical arguments. But the spectrometric direction is too new, and the tendency to build large machines may be more economic in the end. Perhaps then 3 kG is the optimum.

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