A DECADE OF PROGRESS IN CYCLOTRONS -- FREQUENCY-MODULATED AND ISOCHRONOUS

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Summary

The advent of the isochronous cyclotron, capable of accelerating a wide selection of particles with energies variable up to limits previously inaccessible, has spurred the development of techniques leading to increased knowledge of orbit behavior and hence to external beams of greatly bettered quality. Among these activities are improved methods of magnet design, of field control and of beam diagnostics, novel means of launching the projectiles and more effective extraction schemes. Increased versatility has engendered new obstacles; e.g., space charge and charge exchange problems in the use of heavy ions.

Advances in synchrocyclotrons, though still largely in the planning stage, reflect the present state of the art of spiral orbit machines. Increased current is the major goal. A variety of schemes for better axial focusing and higher repetition rate are under consideration. Beam stretching and improved focusing by grids or by einzel-type lenses have already been achieved.

Cyclotrons

Early Variable Energy Machines

The hey-day of the fixed-frequency cyclotron lasted until about 1954; by then about four dozen had been built. The words "fixed frequency" are well chosen, for once the circuit had been coaxed into decent resonance, it was left strictly alone. The users were very docile; they took what they got and were grateful.

A sudden burst of activity in obtaining some variability in energy occurred in 1954 and '55. The 20 year old, 26-inch Rochester machine acquired remote positioning of the dee-stem shorting spider. The 90-inch Livermore cyclotron came into action with variable frequency and with some pole-face windings, used primarily to steer the beam into the deflector. At Los Alamos, the 42-inch device which had been borrowed from Harvard during the war was rebuilt once again, this time with adjustable frequency and with trimming and harmonic coils. And most importantly, it was given a mild amount of three-pole Thomas focusing; not enough for isochronism, but sufficient to improve the axial focusing.

Isochronous Machines

You will recall that although Thomas' paper on azimuthally varying fields came out in 1938, it was way ahead of its time. Few people paid attention to it, perhaps because a clear picture of orbit behavior, due to Kerst and Serber, did not appear until three years later. Two small electron cyclotrons following Thomas' idea were built under security wraps in 1950 at Berkeley, but their description was not published until 1956. Since the renovation of the Los Alamos machine was accomplished before Thomas' ideas were re-discovered by Symon and by the Russians, we may surmise that there was an information leak between Berkeley and Los Alamos.

The first fully-fledged isochronous proton cyclotron was completed in early 1958 by Heyn and Khoe at Delft. It ran at 12 MeV. So rapidly did enthusiasm spread that one year later the first conference on sector-focused, isochronous machines took place at Sea Island, with reports of 13 under construction or being planned. Today there are about 30 in use for protons under 100 MeV; 15 are being built and 15 more are under study with energies ranging upwards to 500 and even 1000 MeV.

In general, provision is made for variability of energy and for ions of different charge-to-mass ratio. This flexibility requires a multiplicity of field contours in the same magnet. In most cases this is achieved with a fixed iron structure plus circular pole-face windings, hill coils and valley coils, in various combinations. The number of these correcting coils has been reduced, in some cases, by ingenious substitutes: interchangeable iron hills at the Naval Research Defense Laboratory; the use of materials of different permeability at Orsay. At Manitoba there are no auxiliary coils at all, the field shape being controlled by temperature variation of the permeability, plus the motion of a central plug.

The complexity and required accuracy of the field is such that model magnet studies are necessary for any new machine, so that intuitive or theoretical design may be supplemented by empiricism. Measurements on the model, and finally on the full scale magnet, are accomplished with great precision by automated equipment. It is most fortunate that the high speed digital computer has come into being, for without its aid the reduction of several hundred thousand data points, including Fourier analysis, would be hopelessly impractical.

The computer also plays a role in the completed magnet, for it calculates the proper currents in the auxiliary coils- perhaps 3 dozen- at each desired energy for each particle. Usually this information is stored in the log book, but at several institutes servo mechanisms directed by punched cards are planned to replace the setting-by-hand of a large number of knobs. Complete control by a computer, with beam maximizing, is just around the corner, if indeed it has not already been accomplished.

The central region of the field has received much attention. No longer does one rely on a shot gun technique in launching ions, with the hope that some of them will find their way down the deflector. Accurate positioning of the hooded arc, the extracting electrodes and the beam stops, acts to define a group of particles which will reach the outside world with negligible loss en route and with good emittance characteristics. To accomplish all this, it is very important that during most of the acceleration the orbits should rotate around the center of the magnet with no coherent radial oscillation (unless this is deliberately induced as an aid in extraction at ν_r greater than one, as is done at Oak Ridge). Off-setting the source and pullers, so that the first so-called half turn exceeds 180 degrees, makes subsequent gap crossings occur while the dee voltage is falling, thus producing an axial focusing force. This is often augmented by a central bump in the magnetic field, since sector focusing does not extend to the middle. With high dee voltage, the subsequent crossing of the $\nu_r = 1$ resonance has no ill effect, nor does the small phase slip that is induced because the field is not isochronous all the way to the center.

Tune-up, when the machine first gets into operation, is now greatly aided by beam-diagnostic techniques. Multi-fingered probes measure the axial height; total current- and differential current- probes reveal the radial orbit pattern and its concentricity with the center; phase probes indicate departure from isochronism. Information of this nature has led to better understanding of orbit behavior and hence to better initial design.

The expressions "programmed orbits" or "single geometry systems" are nowadays heard more and more. They indicate that a single spiral path is used, no matter what the projectile or its energy, since then the source, the pullers, the beam stops and the deflector may remain fixed in position. To accomplish this, the dee voltage must be reduced as the energy per nucleon is lowered or as the charge-to-mass ratio is increased. There are disadvantages to this, however, for although the path length remains constant, the reduced early velocity increases the loss of ions by charge exchange with atoms of the residual gas. Some designers have taken the opposite approach, building movable source and pullers, so that the full dee voltage is always used. There is then a multitude of possible orbits. A middle-of-the-road method involves moving only the source so that it may be positioned between two of three fixed pullers. This gives two programmed orbit patterns, and the reduction in dee voltage need not be so great.

These efforts at pre-trimming the beam plus those devoted to reducing radial and axial divergence, and in stabilizing the magnetic fields, the dee voltage and its frequency, have brought about external beams which approach the quality of that paragon of precision accelerators, the Van de Graaff, and at considerably higher energy.

With well-defined and well-separated early orbits which traverse a rapidly pulsed axial deflector, the Karlsruhe group has accelerated single pulses, at desirable intervals, to produce short neutron bursts, about 1 nanosecond long. The NRDL cyclotron will carry this technique even further, through the application of the klystron bunching principle to shorten the proton bunch by a factor two before it strikes the neutron-producing target.

Axial Injection

All cyclotron ion sources were located in the central region until 1962, when the Birmingham group initiated axial injection down a channel along the pole's axis, from an external source. The ions were then turned through 90 degrees by an electric mirror to launch them into their first orbit. Transport efficiency from the source to the dee was 23 percent. This was a major advance with great possibilities, since the source needs no longer be confined to a volume no larger than your finger. Large external sources, consuming as much power as needed, can be used in this manner to produce negative ions, polarized ions, or multi-charged heavy ions. With an initial energy, on entering the dee system, of 10 to 40 keV, in addition to what is gained from the dee potential, ions can be accepted over a larger fraction of the cycle- up to about 90 degrees- so that the duty factor rises. Furthermore, the continuous output from very weak sources may be bunched, prior to injection, into the phase range acceptable by the cyclotron. As an alternative to the electric mirror, an electric deflector has been investigated at Grenoble. It must be realized that space charge can be troublesome if axial injection of intense currents is contemplated; because of limited voltage-holding clearances at the mirror or deflector, the ions must be moving slowly, when repulsive forces are most powerful. Nevertheless, axial injection is being pursued with vigor at over a dozen institutes and interesting results may be anticipated.

Mid-Plane Injection

Test bench experiments have been carried out at Saclay to assess the feasibility of injection along the median plane by the use of crossed magnetic and electric fields. The latter field must be perpendicular to the radius, and this can be attained by an array of radial plates that have a gap in the neighborhood of the median plane to permit passage of the ions during acceleration. Since the injection path covers almost the radius of the magnet's pole, the crossed fields should supply azimuthal and axial focusing forces. Progress in fulfilling this need has been made. When complete success is attained, this method of injection will offer competition to axial injection of heavy ions and polarized particles.

Thought has also been given to the practicality of injecting neutral atoms along the mid-plane with stripping to occur at the radius appropriate to the injection energy and the ionic charge and mass.

Initial experiments on mid-plane injection by cycloidal motion at the straight-line boundary between a hill and a valley have been carried out at the Lebedeff Institute. The ions make several loops on their passage towards the central region, where an electrostatic deflector gudies them into their first orbit. It is perhaps not surprising that focusing exists along the cycloid for a reasonably wide span of injection positions.

Heavy Ions

Interest in the acceleration of heavy ions has been growing rapidly. At present, the Dubna group appears to lead the field, employing those ions that can be obtained from modifications of a standard hooded source in the central region.

Injection of heavy ions along the median plane is also being pursued, notably at Orsay, following the 1952 suggestion of Tobias. A heavy ion of comparatively low charge is accelerated by a Van de Graaff or a linac and is injected along the mid-plane with a large radius of curvature that takes it to an appropriate position near the cyclotron's center. At this point the ion is further stripped by passage through a foil and then starts to be accelerated. Since the final energy is proportional to the square of the charge, heavy ions of high energy can be obtained in a cyclotron of modest dimensions.

Extraction

The simple electrostatic deflector of the classical cyclotron is generally not suitable for an isochronous machine; because of the latter's higher energy, the final orbit separations are too small to straddle the septum. Resonance methods must be applied to increase the distance between turns. Two methods are in use.

In the precessional scheme, a first harmonic field distortion, of as small a radial extent as possible, is introduced at the radius where $\nu_r = 1$. This induces a coherent radial oscillation whose amplitude is approximately constant, being proportional to that of the first harmonic distortion, and whose wavelength subsequently increases since ν_r becomes less as energy is gained. Hence the separation of successive orbits varies with azimuth and will be a maximum at the position of the septum provided the orientation of the field disturbance has been properly chosen. The axial betatron motion is not altered.

In the regenerative method, a second harmonic field gradient is introduced at the extraction radius which is near a half-integral resonance. The effect of this gradient is to bring the radial betatron frequency to this resonance. The envelope of the amplitude of the oscillation increases exponentially, until finally the septum fits between two successive turns. The growth in axial motion can be kept tolerable if the induced field gradient is not excessive.

The precessional method appears to be superior, since there is no increase in axial motion and the radial amplitudes are smaller, so that the external beam is of better quality.

A charge-exchange method of extraction for heavy ions has been developed at Dubna and at Orsay. Incompletely stripped ions are accelerated and then pass through a foil placed in the neighborhood of a hill. The charge is increased by several units, so that a portion of a turn of small radius is executed in the hill region, followed by a somewhat larger part turn in the valley, with the result that the ion leaves the cyclotron. Some energy variation is possible by radial motion of the foil. The stripping process can lead to ions of several charge states, though all of the same energy, so that several beams may emerge. This can be both an advantage and a disadvantage.

Negative Ions

The acceleration of negative hydrogen ions, first carried out by Rickey at Boulder, is a most fruitful development. Within limits, particles of various energies may be extracted from the cyclotron with no further adjustment than the repositioning of the stripping foil. The use of negative ions also has increased the resolution capability of energy-analyzing magnets. Contamination of the beam by particles degraded in energy by slit-scattering need no longer set a lower limit to the slit width or to the permissible demagnification. The slit jaws may be made of foil; negative ions that strike them change the sign of their charge and are deflected out of the beam by a downstream switch magnet. The user may have just about any resolution he wants, if he will pay the price of reduced intensity.

The marriage of a cyclotron and a Van de Graaff is in the offing, in a variable energy combination called a "Cyclo-Graaff" soon to be installed at Duke University. Negative ions from an external source will be injected axially into the cyclotron which brings them to 15 MeV. After electrostatic extraction they will be introduced into a tandem Van de Graaff with a stripper in the high voltage terminal. Ideally, such a system can produce a final energy anywhere in the range of the cyclotron energy plus or minus twice the terminal voltage. Because of space charge difficulties at low velocities, not quite this span will be reached, It is expected that a variation between 3 and 30 MeV will be obtained.

Beam Transport

Although beam transport and energy analyzing systems are not cyclotrons, they have become a most important adjunct. On-target time is so precious that all installations built in the past decade and a half have at least two separate shielded target vaults, each serving several targets. Quadrupoles, switch magnets, momentum analyzers and their power supplies, controls and vacuum pumps now constitute an appreciable fraction of the total cost of a complete cyclotron installation. The tax-payer may rejoice over two items of expense which have practically disappeared: the user's data book and his stubby pencil. They have been replaced by the multi-channel analyzer and the on-line computer.

Superconductivity

Superconductivity is already playing a role in the magnets of bubble chambers used with multi- BeV synchrotrons. As yet, the ice-box boys have not invaded the cyclotron laboratory, but it won't be long. We foresee little prospect for table-top cyclotrons at 100 kilogauss, for the orbits would be too closely spaced for extraction. But there are other possibilities: cyclotrons at conventional field levels with negligible magnet power; very high field switch magnets introducing little dispersion; second stage extraction by magnetic channels that use the shielding properties of superconducting plates.

Synchrocyclotrons

Let us now turn to synchrocyclotrons. As you will recall, the principle of phase stability was announced almost simultaneously by Veksler and by McMillan just at the end of the war. There was an immediate flurry in building synchrocyclotrons; 8 were completed by 1950, and 8 more by 1955. I believe there are now 19, the last one done in '58. Only 6 have energies under 100 MeV; the others range up to 740 MeV.

Let me remind you of certain aspects of their behavior, so you can see the rationale behind the present plans to upgrade their output. During the first part of the frequency modulation program, a so-called micro-pulse of ions starts being accelerated at every oscillator cycle. But after about 10,000 cycles the initial energy of ions leaving the source is so small compared to that then appropriate to the existing oscillator frequency, that capture into a phase-stable orbit is no longer possible. From then on, the already-captured ions continue to be accelerated as a macro-pulse, but no new ones can join the procession. With a frequency modulation rate of, say, 60 cycles per second, the output is 600,000 micro-pulses per second.

A fixed frequency cyclotron, however, starts ions off at every cycle continuously, so for a frequency of, say, 20 MHz, there are 20 million micro-pulses per second-- about 30 times as great as from the synchrocyclotron. Since the cyclotron has an internal beam of about 1 milliampere, one might expect the synchrocyclotron to have a beam of one thirtieth of this, or about 30 microamperes. Alas, this is far from the case; one machine has 20, another has 8, but for the most part, the yield is about 1 microampere.

The success of sector-focused cyclotrons in overcoming the relativity problem, and the various proposals to extend their energy up into the band previously dominated by the synchrocyclotron, has caused some hard thinking to discover why the frequency modulated machines do not give as much current as might be expected, and to see what can be done about it.

What should be done (when you know the answer) and what can be done, are not necessarily the same. There is always the problem of money. Renovators are well advised to retain as much existing equipment as is possible. Another problem, and a nasty one, is the very great radioactivity that has built up in these high energy machines in 10 to 20 years. It is not easy to find a large crew of skilled mechanics to spread the exposure among, nor is it convenient to work behind and around a wall of lead bricks. Consequently, the plans for improvements are of varying degrees of complexity.

There are three general categories in the problem of increasing the output. First, the number of ions in a bunch. Second, the number of bunches per second. Third, the quality of the ions in a bunch. Since some of the palliative measures to be mentioned often have an influence on more than one category, it is not possible to nicely compartmentalize the various schemes that are being considered, but one can keep them in mind.

Most frequency modulated machines have a dee potential of only 5 to 20 kV, since a comparable voltage occurs at the tuning capacitor, which has small clearance. Hence the early orbits are too tiny to clear the chimney of a hooded arc, so an open "volcano" type source must be used. This must be fairly far away from the dee to avoid serious axially defocusing components of the electric field, so the initial orbits do not get inside the dee. As a result they gain energy very slowly.

The rate of change of frequency, df/dt, of the synchronous ion (and hence of the dee voltage) is proportional to the energy gain per turn, ΔE. With an open arc, the early value of ΔE cannot be described exactly in general terms, since the ions do not penetrate the dee, but one can say with certainty that ΔE is small. Consequently df/dt is small and the capture time is large, which is all to the good. Later on, when the orbits do enter the dee, ΔE may be expressed precisely as $\Delta E = qV \cos \phi$, where the phase angle is measured from the voltage peak. The capture process is now complete, and it is profitable to raise df/dt and the dee voltage, in order to more rapidly finish the existing accelerative cycle and to start on the next one.

Space Charge

With the open source and the necessarily wide gap between the dee and the dummy, a cloud of low velocity ions rotates for a long time in the central region where axial focusing forces are lacking. The importance of space charge in blowing this cloud vertically apart has been emphasized by MacKenzie and by Lawson. They have derived expressions for the current as a function of the dee voltage raised to a power ranging from 5/3 to 3, depending on what assumptions are made as to the onset of axial focusing as a function of radius. Rainwater has extended these calculations to include the dependence of capture time on dee voltage. Since these investigations assume an energy gain in the form qV cos ϕ , they would seem to be more applicable to the narrow gap geometry associated with a hooded arc, rather than to the wide gap and open arc of conventional machines. We have investigated the situation for the latter case, assuming a uniform electric field, and find that the space charge limited current varies as the electric field to the 5/2 power.

But even though the exact functional relation between dee potential and beam current may still be in doubt, there is ample evidence that the current does rise with voltage, at least up to limits which strain the capability of most existing machines. The data, however, do not disentangle the various effects that the voltage can have. It is noteworthy that the machine at Orsay, with the largest starting voltage (25 kV) and the largest dee height (20 cm), also has the largest number of ions per macro-pulse: 2.8×10^{11}.

Various methods have been used in attempts to counteract space charge. It has long been the practice to obtain some early magnetic focusing by a central field bump, even though the force is small because of the low velocity. Electric focusing has been applied by the Dubna people through what amounts to an einzel lens; a constant negative voltage is applied to a small dee beyond the dummy. Somewhat the same scheme has been used at CERN. The Berkeley group, experimenting with a 28-inch model, has had some success by mounting grid wires on the entrance faces of the dee and dummy, following the lead of the Birmingham sector-focused cyclotron. Magnetic focusing in the central region by the use of local hill and valley shims has been studied. If the radius is small compared to the hill-to-hill gap, as when the shims are attached to the poles in the usual manner, very little flutter is produced. It could be increased by bringing the ridges very close together, but this might result in a large central field bump which would reduce the capture interval. Flutter without a bump could be obtained if the gap were reduced by separating the ridges from the poles by non-magnetic spacers. But this scheme, as well as the one just mentioned, would bring the ridges so close to the dees as to prohibit high voltage. A courageous solution is the suggestion of mounting the ridges inside the dees, with the aid of ceramic columns to ground. Such a possibility is being studied at Uppsala, Columbia and Berkeley.

Sector-Focusing at All Radii

Magnetic focusing in the central region has its difficulties, nevertheless. If sectors are used throughout and if the average field rises gradually with radius, then the radial betatron oscillation frequency ν_r will rise only slowly from unity, and it will remain in this neighborhood for a relatively long time because of the slow energy gain (compared with an isochronous cyclotron with very much higher dee voltage). Since the FM machine is not isochronous, it will exhibit phase stability, so that synchrotron oscillations may cause the ions to travel in and out of the $\nu_r = 1$ resonance band several times. One may attempt to avoid this hazard by tailoring the field to rise rapidly, because ν_r^2 rises with dB/dr. But this must not be overdone, else vertical stability will be destroyed, since ν_z^2 decreases with dB/dr. Extremely careful field shaping will be required.

If a central field bump is used in conjunction with sectors, ν_r starts off by dropping below unity, but further out, where the field starts rising on a partly isochronous schedule, the $\nu_r = 1$ resonance must be crossed, and possibly recrossed several times, because of phase stability.

By adding sector focusing at all radii (not enough to make the machine isochronous, but sufficient to reduce the frequency span that the oscillator must cover) the duration of the acceleration process is reduced, so the repetition rate will rise. Carnegie Tech, Columbia and Uppsala are planning changes of this nature. (For the high energies involved, it is generally not possible to obtain enough flutter in the existing magnets for completely isochronous operation.)

New RF Schemes

The proposal for reconstruction of the 160 MeV machine at Harwell embraces a new dee of much reduced capacitance. This will be obtained by cutting it back to 90 degrees, yet leaving a 180 degree portion in the central region where maximum energy gain is wanted. The voltage will be increased from the present 8 kV up to 30 kV, and a new rotating capacitor will raise the repetition rate from 200 up to 1600 cycles per second. A hooded arc and puller are planned, and it is believed that 10 to 20 microamperes will be obtained.

The Chicago group is planning to leave its 450 MeV magnet alone and to quadruple the average beam current by a novel accelerating system. The first half of the RF program will be applied to a 180 degree dee and the second half to a 180 degree cee. These two electrodes will be on opposite sides of a diameter and will slightly overlap each other, radially. The amplifier driving the dee is turned off before the amplifier connected to the cee is turned on, but both units are driven through the entire frequency spectrum (11 MHz wide) by a low level, electronically tuned oscillator, in order to maintain phase relations. Because there is no mechanically moving capacitor, the fly-back time to the starting frequency ideally can be zero. In practice it must be finite, so that the ions can move somewhat into the cee before the dee voltage is turned on, in order to avoid the fringing field of the dee. By the use of two low-level amplifiers, a second batch of ions will be moving through the dee while the first batch is gaining energy in the cee. Peak voltage will be about 28 kV, which is double the present figure.

Very much the same scheme is planned for the 185 MeV Uppsala machine, but with the addition of sector focusing without isochronism. This will reduce the frequency swing from the present 7 MHz band width to 1.6 MHz. The 180 degree dee will be opposite to a 90 degree cee, both so oriented that a large fraction of their areas lie over valley regions, thus reducing their capacitance to ground. A hooded arc, a puller and beam defining slits will be included.

Use of Hooded Arc

With a dee voltage considerably higher than is customary, it is possible to employ a hooded arc. This can be close enough to the dee and its pullers so that axially defocusing forces are minimized. The ions penetrate into the dee from the very start, so they acquire enough energy to miss the hood on the next half turn. Since energy is gained more rapidly than with an open source, the frequency modulation must be faster and therefore, most unfortunately, the acceptance time into phase-stable orbits is reduced, by a factor which in one case is as large as 10.

From this standpoint, a hooded arc looks like a bad bargain. But there are compensations. The higher electric field at its orifice increases the number of ions extracted per micropulse, and by off-setting the source so that the first "half turn" exceeds 180 degrees, subsequent gap crossings occur when the electric field is falling, thus introducing substantial axial focusing. There is also the advantage that the particles are brought close to the synchronous phase, which tends to increase slightly the acceptance interval and more completely fill the bucket. If beam-defining slits are added, the quality is much improved, so that extraction efficiency rises. In fact, constant orbit geometry has been considered at Uppsala, with acceleration on either the first or third harmonic.

Finally, the dee bias customarily used to prevent multipacting causes a drift of the cloud of ions emitted from an open source; but with the hooded arc, the initial energy gained is very large compared to the bias voltage, so that the effective location of the source is not smeared out.

Beam-Stretching

Improvement in duty factor (i.e., beam stretching) of the external ions is customarily accomplished by turning off the RF voltage so that the particles are stacked and debunched at a radius which lies within a peripheral cee electrode. This, driven by noise or some high frequency modulation program, gives a final acceleration into the extraction elements. At Berkeley, the yield of particles from an internal target is stretched by gradually raising the target into the stacked and coasting beam. At Dubna, a time-dependent field bump near the pole edge directs the projectiles, while still being accelerated, onto the internal target; this procedure lasts for one quarter of the repetition period.

In conclusion, we believe that some of the schemes being contemplated are straight-forward and of assured success; others will require much thought in design and skill in execution. The efforts are decidedly worthwhile, and will keep the FM machines on the active list for a long time to come.