BEAM EXTRACTION FROM SECTOR-FOCUSED CYCLOTRONS

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Beam extraction systems have come a long way since the invention of the cyclotron by E.O. Lawrence in 1930. In the earliest machines there was no provision for beam extraction. In 1936 Cooksey and Lawrence1) and later Alvarez, McMillan, and Snell2) reported extraction of the 6 MeV deuteron beam from the $27\frac{1}{2}$-inch cyclotron. The beam had a radial extent of 10 cm at a distance of 40 cm from the tank wall, but the addition of an inhomogeneous field provided by pieces of iron bolted to the magnet poles, focused the beam to a 3 x 3 cm spot at the end of a 6 ft pipe. Most systems designed in the ensuing fifteen years differed in detail but not in principle. For classical cyclotrons limited to energies of the order of 10 to 20 MeV per nucleon, purely electrostatic systems are entirely adequate. Magnetic deflectors or channels were seldom used and then only following electrostatic deflectors to bring the beam through the fringing field. During this fifteen year period the performance of the extraction systems improved considerably, not only as a result of better deflector design but also because of the development of better ion sources, the addition of accelerating electrodes, and allied improvements in the central region.

Beam extraction for the new generation of cyclotrons, the isochronous AVF machines, is in general a much more difficult problem, not only design-wise but also mechanically. Speaking now of the medium-energy machines, most are being designed for variable energy multi-particle acceleration. Orbit shapes at full radius vary by a small but significant amount. Extra flexibility in extractor adjustment is needed to meet demands of the various operating conditions. With few exceptions, the new AVF cyclotrons are designed for higher energies than the largest classical machines, yet operate with comparable energy gain per turn. An electrostatic system with a thin septum can generally be used without magnification of the turn separation by special means. Most machines now in operation or construction use, or plan to use, this classical approach. The highest energy machine with a purely electrostatic system is the Berkeley 88 inch Cyclotron (50 MeV protons, 60 MeV deutrons). An excellent guide for the design of such systems is the work of Garren, Judd, Smith, and Willax3). The excellent performance of the 88-inch beam extractor has been reported by Grunder4). At higher energies it may be necessary to incorporate magnetic elements to bring

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the beam through the fringing field. An example is the Oak Ridge Isochronous Cyclotron (75 MeV protons) wherein a relatively short electrostatic deflector followed by two magnetic deflectors of different strength are used[5].

The possibility of magnifying the turn separation at extraction radius has intrigued many designers. The first system was the regerative deflector described by Tuck and Teng[6)] in 1950 and 1951, and LeCouteur[7)] in 1951 and 1953 for the extraction of synchrocyclotron beams. This method, now universal in synchro-cyclotrons is being used in the University of Birmingham Cyclotrons[8)]. In the linear regenerative system, the driving forces produced by peeler and regenerator are arranged to have linear gradients so that the change in radial amplitude on successive revolutions is proportional to the amplitude, resulting in exponential amplitude growth. It is important to note that this system does not require a non-linear resonance for its operation, but depends solely on the peeler and regenerator fields. Operation near a resonance, for example $\nu_r = 1$, is required so that the phase change per revolution of the radial betatron oscillations is quite small, otherwise excessive peeler-regenerator strengths may be required.

The 1950 and 1951 work at LRL with a 75 keV three-sector electron model[9)] suggested that it was possible to extract a large fraction of the beam from a single hill. This effect occured at the $\nu_r = 3/2$ resonance and suggested that inherent radial instabilities in sector-focused cyclotrons could be successfully employed as the beam extraction agency.

In 1957-59 Welton and Gordon[10)] demonstrated theoretically that beam extraction could be obtained at the 8/4 resonance in an eight-sector cyclotron and the 3/3 or 4/4 resonances could be successfully used in three and four sector machines. For these non-linear system a bump of periodicity appropriate to the ν value is used to destroy the small amplitude stability.

The design of resonant extraction systems for medium-energy cyclotrons requires great care. Extraction must be delayed until $\nu_r = 1$ is reached which for the highest energy machines may cause excessive departure from isochronism. The strong non-linearity of the fields at the magnet edge can lead to frequency shifting and formation of super-stable orbits. Another complication is the nearness of the difference coupling resonance $\nu_r - 2\,\nu_z = 0$. With careful design these problems can be practically eliminated. Distortion can be minimized by proper choice of bump amplitude and azimuth, and careful attention to the shape of the field at the magnet edge. Detailed computer studies seem to be essential for the optimization of these systems. Excellent guides for the design of non-linear resonance extractors for medium-energy cyclotrons are the work of Bassel, Bender and Innes[11)] and Blosser, Gordon, and Arnette[12)].

A resonance extraction system is planned for the Michigan State University Cyclotron 40 MeV protons), the details of which will be reported at this Conference[13)].

Beam extraction from the machines in meson factory class -- from 450 MeV upwards --

is in a sense more difficult and in another sense, easier. Electrostatic system are ineffective; therefore, greater turn spacing is required to clear the entrance to a to a magnetic deflector. The regenerative or non-linear resonance systems seem to offer the only solutions. For the non-linear resonances one is restricted to certain energies. The radial-focusing frequency is determined chiefly by the mean field gradient, which for isochronous machines will have suitable values only at specific energies. In six or eight-sector cyclotrons, suitable choices are $\nu_r = 3/2$ (400 - 450 MeV) and $\nu_r = 2$ (700 - 800 MeV). The 3/2 resonance can be excited by a three-sector field gradient perturbation and the $\nu_r = 2$ by a two-sector field perturbation. An advantage in these cases is that the resonance is reached naturally; it is not necessary to await field turnover as in the case of the medium energy $\nu_r = 1$ systems. For this reason the distortion may not be so severe, and there need be no loss of isochronism. An additional simplification results because these machines are being designed for single particle, single energy operation.

Presently, Richardson and Hopp$^{14)}$ at UCLA are making studies relative to use of the 6/3 resonance in a six-sector cyclotron. At ETH, Zurich, Willax$^{15)}$ has studied 3/2 resonance extraction with favorable preliminary results. At ORNL, 8/4 resonance extraction has been demonstrated experimentally in a 430 keV electron cyclotron.

The secret to high-extraction efficiency in any of the systems discussed, for either medium or high-energy machines, is the achievement of small radial amplitudes at the center of the cyclotron. The considerable efforts expended in design of the central region geometry and in the injection system will ultimately pay great dividends. Our experiences with the electron analogue at ORNL emphasizes this - a decrease in extraction efficiency by a factor of three results from an approximate doubling of the radial amplitude of the beam.

Any report on extraction systems would be incomplete without mention of negative ion acceleration which has been accomplished successfully at at least three laboratories. H^- ions have been accelerated to about 50 MeV at UCLA and to 18 MeV at the University of Colorado. Most recently D^- ions have been accelerated to 11 MeV at the University of Birmingham. The usual extraction system can be replaced by a thin foil of suitable material with only modest precautions to prevent optical distortions in the fringing field. A further advantage is that the external beam energy can be rather easily varied.

We note that for the negative ion cyclotrons the desirability of low radial oscillation amplitudes is still important, the radial amplitude influences directly the energy spread and emittance of the external beam and, therefore, in a rather direct way determines the design of the beam transport and analysis systems.

In summary it is observed that there is no unanimity on the choice of the extractor system for medium-energy cyclotrons. In a few years there will have been enough operating experience to make a judgment. For those planning new machines, the choice of method is not an easy one. For most machines, the classical extractor is adequate but it is suggested that with careful design, the resonant systems will ultimately provide much higher extraction efficiency with excellent beam emittance. Most new machines in the planning stage are of relatively high energy; the induced radioactivity and radiation damage problems are not negligible. It seems a better choice to achieve as high an extraction efficiency as possible, and if required, collimate the beam outside the cyclotron where the radioactivity problem is more tractable. The cyclotrons of the meson factory class are forced to that approach.

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