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Performance Estimate for a 200 Mev Sector Cyclotron

A performance estimate such as indicated by the title is difficult to make with accuracy since (a) what could be classed as a precision cyclotron has yet to be built (the group at MSU hopes to build such a machine but is presently held up by lack of funds) and (b) for a 200 Mev machine, a detailed design study has not been made as yet. To estimate performance of such a machine a two step process has been used, the first step consists of estimating the performance of the proposed 40 Mev MSU cyclotron from the collected results of the design studies for that machine and the second consisting of an extrapolation from 40 Mev to 200 Mev. In such a procedure a number of somewhat involved arguments and approximations are required which have been presented in more detail in MURA report no. 593 by Blosser and Gordon. The present summary will briefly outline the various steps involved, with particular emphasis directed to the degree of validity of the produres employed.

Basic to any accelerator performance estimate are the properties of the source. For this purpose data obtained by Smith with the Canberra cyclotron are used. These data indicate a luminosity of 40 amps/cm^2 sterradian at 250 Kev and dc. This figure is not markedly different from normal Cockcroft-Walton rf ion source performance. It would seem moderately safe to assume that any substantial improvements in source technology could be successfully adopted to the cyclotron since there is nothing in the cyclotron environment which inhibits the use of dense plasmas and intense extraction fields, the essential factors in any source.

Consideration of the performance of the cyclotron (as distinct from the source) is simplified if one considers first a group of particles leaving the source at fixed time and with fixed energy - call this the instantaneous beam - and then subsequently generalize to include spreads in starting time and energy.

For the instantaneous beam there are three distinct problem areas where dynamical non-linearities can dilute the beam phase space density, namely the central region, the intermediate radius region, and the extraction region.

The central region problem arises from the unfortunate tune values at the magnetic center of the cyclotron i.e. $\nu_r = 1$ and $\nu_z = 0$, both of which are bad. A field configuration is needed which shifts the tune away from these values as rapidly as possible. An initial radial fall-off in the zero order azimuthal harmonic of the magnetic field (the "average" field) accomplishes this quite effectively. For reasonable accelerating voltages, fields can be found which give ν_z values of 0.15 and higher from the source extractor slit on. This has the double advantage of giving both a large axial phase-space acceptance and a large space charge limit; the implications of each of these advantages will be discussed later. The region of field fall-off must of course be limited in order to maintain the rotational motion of the beam in the accelerating rf phase; at the transition from decreasing to increasing average field, the $\nu_r = 1$ resonance is traversed. Effects of this resonance have been investigated and shown to be inconsequential for reasonable traversal conditions.

In the intermediate radius region, the finite number of accelerating gaps produces a coherent radial amplitude due to an effect similar to rf knockout. If non-linearities are substantial, this coherent amplitude can diffuse into an incoherent amplitude thereby diluting the phase space density of the beam. This effect has also been investigated numerically and magnetic fields have been designed in which this effect is absent.

To accomplish extraction, the small turn separation in a high energy cyclotron dictates the use of resonant techniques. For the 40 Mev MSU study, a magnetic field arrangement has been worked out which successfully employs the $\nu_r = 3/3$ resonance to sort out the overlapping turns of the instantaneous beam into spatially well separated groups. Distortions in this process are relatively minor. At 200 Mev a different resonance would have to be employed but intuitively it appears probable that comparable results can be achieved.

Summarizing the instantaneous beam performance, it is expected that all of the beam will be transmitted through the cyclotron and that distortions will be small. The predictions are based on numerical integration of exact equations of motion using experimental magnetic field information and should, therefore, be quite accurate.

The instantaneous result must be generalized to include the effect of variation in starting time and energy. The time dependance of the cyclotron performance arises from the rf voltage, which is, ideally, completely cyclic. Consideration of time variation is, therefore, equivalent to consideration of the effect of variations in starting phase of the particles. In turn, since starting phase is preserved in an isochronous cyclotron, the effect reduces to consideration of effedts of variation in the energy gain per turn. The extraction process is energy selective. Detailed numerical analysis indicates that particles are transmitted only if they experience an average energy gain per turn which is the same as that of the design particle to one part in (10•n) where n is the total number of revolutions made by the particle in the cyclotron. For a certain fraction of each cycle the sine wave accelerating voltage will be constant to this specified tolerance. For this period the extractor will transmit the beam, for the remainder of the cycle the beam is lost. For a 200 Mev cyclotron the usable fraction of a sine wave cycle is approximately 1 per cent.

The fractional on time can be increased by partial flat-topping of the rf wave. If an optimum amplitude of third harmonic acceleration is included, the usable cycle fraction for a 200 Mev cyclotron is extended to approximately 9 per cent.

The computation of the usable fraction of a cycle is based on essentially the same principles as the computations of the instantaneous beam, with one exception, near the center of the cyclotron the spatial distribution of the electric field will have a perceptible effect, giving rise presumably to a slight phase bunching of the particles. This effect has not been studied in detail or included in the calculations.. The influence seems to be favorable.

Finally, in the performance estimates, space charge effects must be included; their influence, however, is more difficult to evaluate. The principle effect is on axial tune. This has been calculated in first approximation by considering the cyclotron beam to be equivalent to an infinite layer of rotating charge of the same density per unit area, i.e., edge effects and turn structure are neglected. Using now the formula thus derived, the accelerated beam is assumed to have one-half the space charge limited current and the axial phase space acceptance is recomputed taking into account the reduction in ν_z due to the space charge force. With this result and using the source luminosity value mentioned previously, the radial phase acceptance necessary to obtain the desired current is computed. Output beam characteristics are then obtained, assuming the input characteristics to be adiabatically damped in the usual way and with a factor of two enlargement in the radial area included to allow for wandering of the beam spot due to the slight variation of the energy gain per turn within the allowed limits.

The specific numbers obtained from this design study for a 200 Mev cyclotron are given in the following table.

ESTIMATED PERFORMANCE CHARACTERISTICS OF A 200 MEV INJECTOR CYCLOTRON FOR TWO CHOICES OF AXIAL APERTURE.

Axial Aperture	25 mm	50 mm
Volts/turn	5×10^5	5×10^5
Number of turns	400	400
Central Magnetic Field (kilogauss)	14	14
Duty cycle:		
$\sin\omega t$	1 %	1 %
$\sin\omega t + a \sin 3\omega t$ voltage	8.5 %	8.5 %
Repetition Rate (pulse/sec)	21×10^6	21×10^6
Source Extraction Energy	125 Kev	125 Kev
Phase Space Acceptance from Source (full width-full angle):		
Radial (milli-radian cm)	60	30
Axial (milli-radian cm)	350	1400
Output Beam Current (time average):		
$\sin\omega t$ voltage	3 ma	6 ma
$\sin\omega t + a \sin 3\omega t$ voltage	25 ma	50 ma
Output Beam Spot Size-Divergence (full width angle):		
Radial (milli-radian cm)	3	1.5
Axial (milli-radian cm)	9	35
Output Beam Energy Spread	±50 Kev	±50 Kev