

BEAM EXTRACTION FROM ANALOGUE II

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(Presented by J.A. Martin)

The construction and performance of the eight-sector Cyclotron Analogue at the Oak Ridge National Laboratory have been reported previously^{1,2,3)}. The Analogue was conceived and designed to duplicate, as far as possible, the orbit dynamics expected in the 810 MeV Mc^2 Cyclotron. The maximum energy, limited by loss of axial focusing, is approximately 530 keV. The integral resonance $\nu_r = 2$ is reached at an energy of 445 keV. One of the primary goals for constructing the Analogue was to evaluate beam extraction problems experimentally. The results to date, although incomplete, are gratifying.

The energy of the Mc^2 Cyclotron is well beyond that at which an electrostatic extraction system is adequate; therefore, a magnetic channel system is suggested. To obtain a sufficient decrease in magnetic field (some thousands of gauss) a channel entrance lip thickness of about 1 cm will be required. At maximum energy, the turn separation in the Mc^2 Cyclotron is only about 2 mm, and for the Analogue about 0.11 mm. Hence, some means to increase the turn separation is essential.

The system used to increase the turn separation in the Analogue is a modification of the Tuck, Teng, LeCouteur scheme wherein the basic idea is to make use of a naturally occurring resonance. An appropriate point for extraction in a high-energy cyclotron is at $\nu_r = 2$, where there are exactly two radial oscillations per revolution. In an eight-sector cyclotron this is the cubic essential $8/4$ resonance.

Gordon⁴⁾ has worked out the main details of the motion in the resonance. There are two important features. First, for motion along an asymptote in the phase plot, the change in radius per revolution is proportional to the cube of the displacement from the equilibrium orbit. Second, as a consequence of the first, the growth rate is exceedingly small for small amplitudes. The implication is that ions can be accelerated through the resonance with only a modest amplitude increase if the initial radial amplitude is small.

To use the $8/4$ resonance effectively in an extraction system, the small amplitude stability must be destroyed. This is accomplished by use of the $2/1$ resonance, an imperfection resonance in an eight-sector cyclotron. The addition of a

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$\cos 2\theta$ component to the magnetic field causes a shift in the location of the equilibrium orbit, a shift which increases rapidly as $\nu_r = 2$ is approached; the small amplitude stability is destroyed before the resonance is reached, and one or two corners are opened in the otherwise closed phase contours depending upon the orientation of the bump.

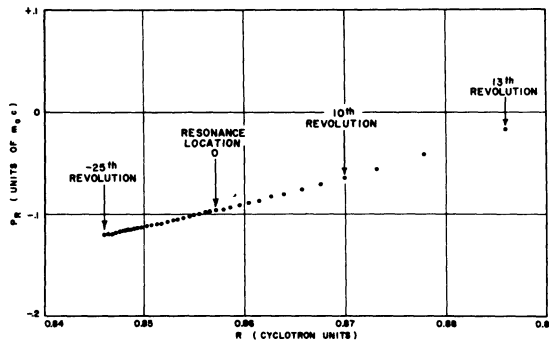


Fig. 1 Location of accelerated particle on successive revolutions in the r, p_r plane.

The computed location of an accelerating particle in the r, p_r plane on successive revolutions, Fig. 1, illustrates the rapid growth of radial amplitude that occurs in the resonance. The particle was started on the equilibrium orbit at an energy of 410 keV in the Analogue magnetic field, with an added $\cos 2\theta$ term of amplitude 0.2% of the mean field. The energy gain per turn is $0.001 m_0 c^2$. The optimum phase of the $\cos 2\theta$ component is such that its maximum is 22.5° forward of the hill on which maximum radial growth occurs. The trajectory of a particle on successive revolutions and the approximate path of the extracted beam are shown in Fig. 2.

Even though the turn separation in the accelerated beam is magnified by the combination of a properly located $\cos 2\theta$ field perturbation and the $8/4$ resonance, an additional mechanism must be provided to permit the particles to leave the cyclotron. The magnetic field must be made to decrease sharply by a magnetic channel

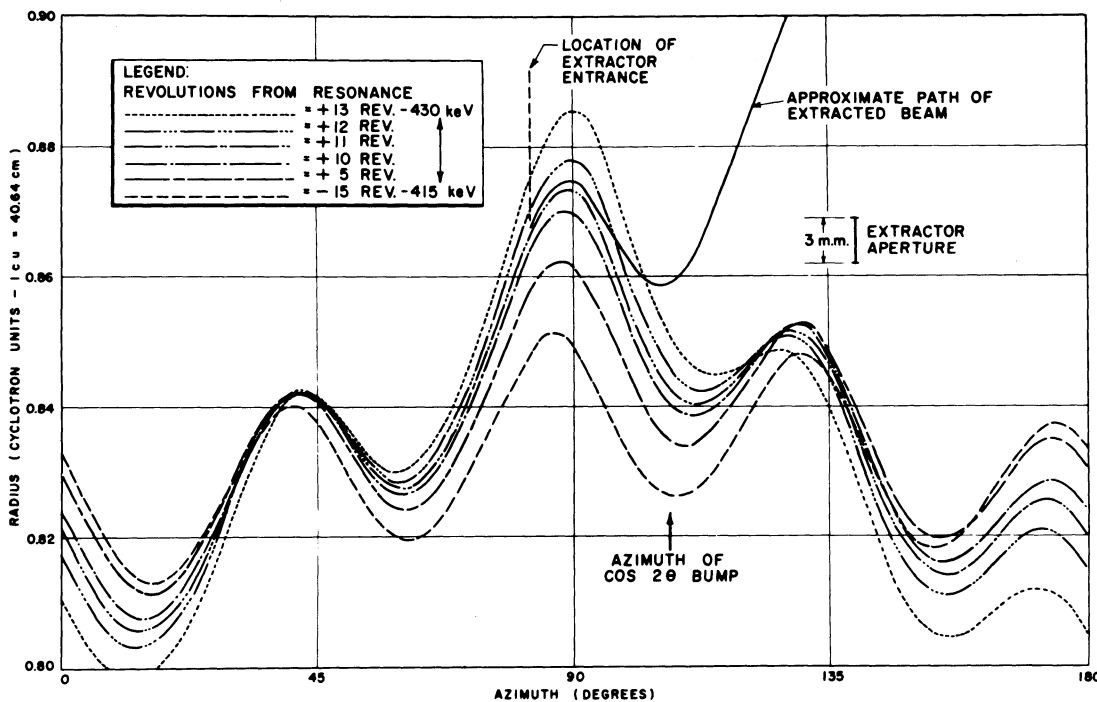


Fig. 2 Calculated trajectory of accelerated particle on successive revolutions. The approximate path of the extracted beam is shown.

along the intended path, or an electrostatic force must be provided to counteract the magnetic field, as in an electrostatic deflector. In the Analogue experiments an electrostatic channel is used, although an electrostatic system will not be applicable for the Mc^2 Cyclotron. One of the prime ingredients for a successful

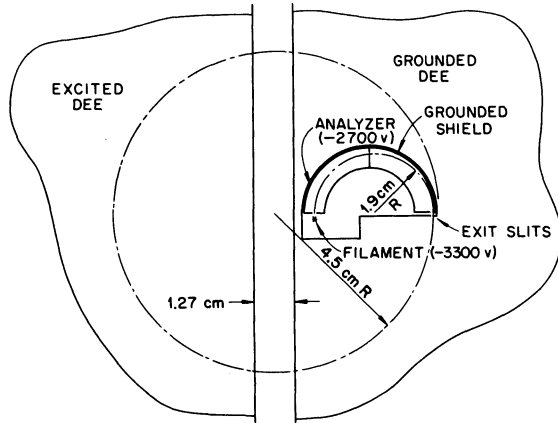


Fig. 3 Schematic of electron injector.

extraction system is a high-quality internal beam. The electron source used in previously reported analogue work was a filament mounted at the center of the gap between the dee and the dummy dee. For the beam extraction tests a d.c. injector was developed which produces a well collimated beam of electrons at 3.3 keV. This electron injector, shown schematically in Fig. 3, is a two-stage device; the first stage defines the beam, the second defines the energy. Electrons from a heated filament are accelerated by a potential of about 600 V through the first slit, which has an aperture of 4 mm axially by 1 mm radially. They then pass through a 180° spectrometer to an image slit of the same dimensions. At 90° a 1 mm slit limits the angular divergence. As the electrons emerge from the image slit they are accelerated through an additional 2700 V. Their final energy is 3300 eV, which corresponds to an orbit radius of 45 mm in the central field of the Analogue. The assembly pivots about the exit slit, so that the angle of injection can be adjusted.

The radial amplitude in the Analogue beam has been measured just inside the $\nu_r = 2$ point by shadow measurements using two probes 90° apart. Using the injector the amplitude indicated is about 0.2 mm, whereas with the filament source a value two to three times larger is obtained.

Certain features of the performance of the Analogue are much improved by the injection of the highly defined beam. It is now possible to accelerate the beam through the difference coupling resonance $\nu_r - \nu_z = 1$ without attenuation, even without the horizontal magnetic field compensated. Also, in the absence of the $\cos 2\theta$ perturbation, the beam is accelerated through $\nu_r = 2$ with only slight evidence of radial blowup.

The Analogue extraction mechanism, Fig. 4, consists of two 0.125 mm thick tantalum strips spaced by about 3 mm. The inner strip (the septum) is grounded while the outer (the deflector) is maintained at a potential of several kilovolts. The channel is supported at five equidistant points, each of which can be moved radially by means of a screw adjustment to make the shape of the channel match the path of the beam. An additional screw permits precise adjustment of the entrance angle of the

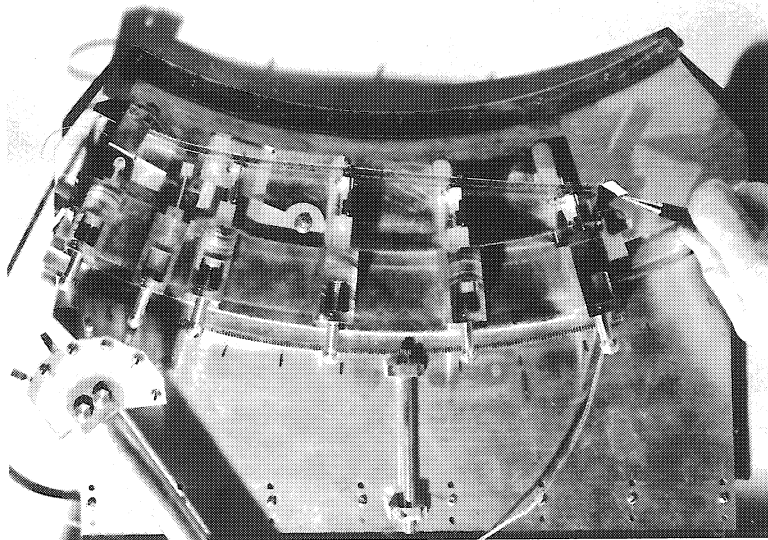


Fig. 4 Analogue II beam extraction mechanism.

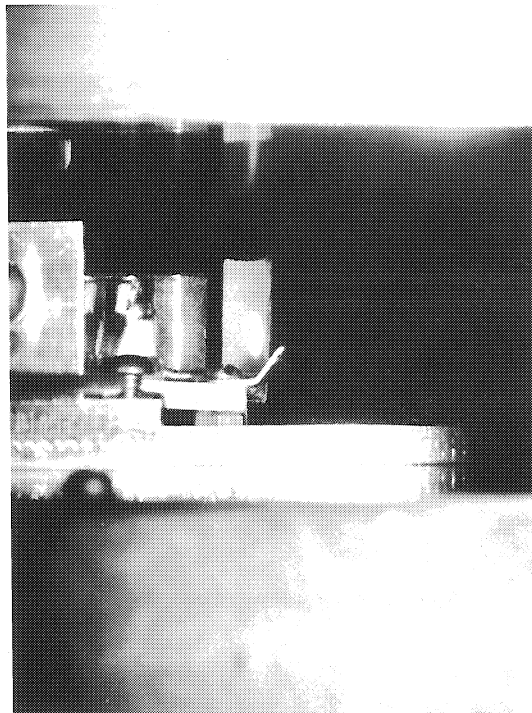


Fig. 6 Beam spot produced at extractor exit.
Dimensions of spot are 1 x 5 mm.

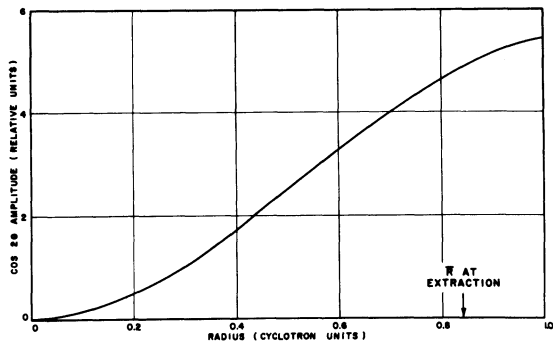


Fig. 5 Radial dependence of magnetic field perturbation.

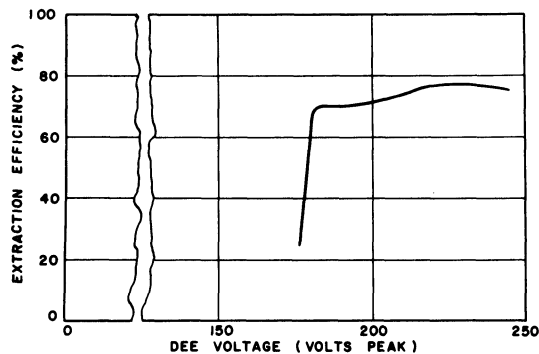


Fig. 7 Extraction efficiency versus peak dee voltage.

channel without changing the entrance position.

The electrostatic channel assembly is positioned azimuthally by means of a rack and pinion mechanism. The several adjusting screws are controlled from outside the vacuum chamber with a multiheaded screwdriver, the shaft of which moves through a ball and socket vacuum seal on the faceplate.

The $\cos 2\theta$ magnetic field perturbation is provided by coils wound symmetrically to produce two hills and two valleys in the magnetic field without any effect on the average field. The coils are attached to the top and bottom lids of the vacuum approximately 40 cm from the median plane and are movable in azimuth to optimize the phase of the field perturbation. The radial dependence of the $\cos 2\theta$ amplitude is shown in Fig. 5.

To date the best extraction efficiency obtained has been about 85% with an extractor voltage of about 2 kV. The gradient is then about 6.6 kV/cm. The 85% efficiency figure is obtained only after very careful adjustment; 75% is readily obtained. The optimum $\cos 2\theta$ amplitude is about 0.3% of the mean field. The beam impinging on a phosphor-coated target at the exit of the extraction system, Fig. 6, produces a spot approximately 1 x 5 mm. The 6.6 kV/cm electric field for the Analogue extractor is equivalent to a magnetic channel strength of 3,000 gauss for the Mc^2 Cyclotron.

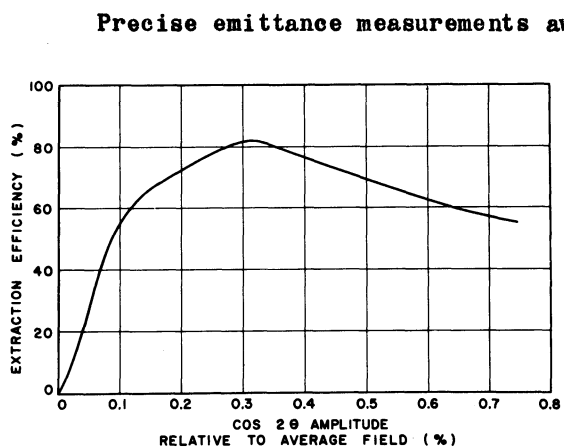


Fig. 8 Extraction efficiency versus bump amplitude.

Precise emittance measurements await bringing the beam completely out of the fringing field. The emittance of the Mc^2 Cyclotron beam, calculated from the radial amplitude measurements, is 20 mm mrad, which is the lower limit for 100% extraction assuming no distortion. For estimating the Mc^2 Cyclotron ion optics system requirements, we have used an emittance of 80 mm mrad.

To characterize the performance of the system, the extraction efficiency was

measured as a function of several parameters. Fig. 7 illustrates that the dee voltage is not a critical parameter. The abrupt drop in efficiency at about 180 V is a result of poor injection conditions. The minimum source clearing voltage has approximately this value. The internal beam current shows a similar abrupt decrease. Fig. 8 illustrates that the dependence of extraction efficiency on bump amplitude is only modestly critical, the optimum being about 0.3% of the mean field. These results indicate that the non-linear $8/4$ resonance dominates the particle motion in extraction region. The performance of the extraction system has also been tested with the simple filament source. The best efficiency obtained was then only 30%. This illustrates the great importance of minimizing radial amplitude.

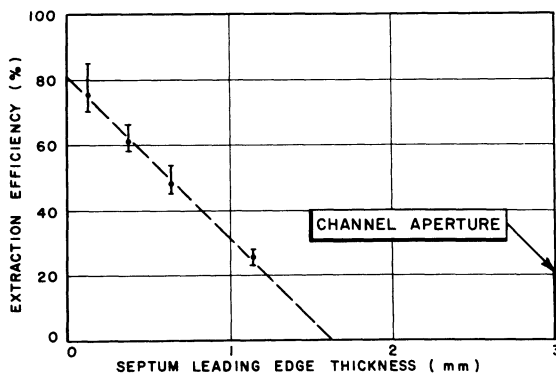


Fig. 9 Extraction efficiency versus septum thickness.

The azimuthal location of the extractor, indicated in Fig. 2, is about 8° forward of the point of maximum turn separation. This position was chosen as a compromise between outward angle and radial separation. To evaluate the dependence on extraction efficiency on septum thickness for this particular azimuthal location, the septum thickness was increased stepwise by adding thin metal strips to the septum. The results, Fig. 9, illustrates several interesting features. First, the roughly linear relationship between septum thickness and extraction efficiency shows that the radial distribution of the beam entering the channel is approximately uniform. Second, the efficiency does not extrapolate to 100% at zero septum thickness, which suggests that the septum is improperly shaped at the entrance, or that the septum is effectively thicker because of the inherent angular distribution in the beam. Third, the efficiency extrapolates to zero at about one half the channel aperture; therefore, the beam does not fill the channel at the entrance. This is in agreement with Fig. 2. If we assume that the channel is filled at the point of maximum turn separation, as a result of optimizing its shape, gradient, and the bump amplitude, then the beam width would not fill the channel at the entrance. Higher efficiencies with less dependence on septum thickness can be realized by moving the entrance of the channel nearer the point of maximum turn separation. Preliminary experimental results tend to confirm this expectation.

So far, we have shown that a resonance extraction system based on the $8/4$ resonance is indeed a practical one. Much work remains, however, to optimize the system and to convert the results of the Analogue studies to the design of a suitable magnetic channel system for the Mc^2 Cyclotron.

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DISCUSSION

HUGHES : Do you anticipate that the requirements on beam quality for efficient beam extraction will limit seriously the total beam intensity of the Mc²Cyclotron?

MARTIN : Our present thinking in this connection is that we will use an external d.c. injector; if we cannot do that we will have difficulty in achieving the required current and required injection quality. The system will also have other advantages, e.g. the easy pulsing of the beam for certain applications.

BLOSSER : What septum thickness do you consider feasible in the proton machine, and what efficiency is inferred for a septum of corresponding thickness in the model?

MARTIN : We are forced to extract between the 11th and the 12th turn, beyond that we develop axial instability. Our present aperture is 3 mm which scales to something like 5 cm, and we feel that if we can design a suitable magnetic channel with a 1 cm thickness, we possibly can achieve better than 80% extraction efficiency.

JOHO : Why did you not provide the necessary $\cos 2\theta$ term for resonance extraction by two local bumps displaced by 180° at the maximum radius, instead of using trimming coils?

MARTIN : This is the dominant term in the magnetic field. Our bump coils are mounted about 40 cm from the median plane. They produce two hills and two valleys in the magnetic field, but the higher harmonics in the bump field are negligible. However, if we did go to localized bumps the same situation would pertain; the same 2θ component would be dominant in the extraction.

REISER : You mentioned that the d.c. injection scheme improved the extraction efficiency considerably. Would you comment on this fact in more detail? What conditions did you have with the normal injection arrangement?

MARTIN : We achieve 25 to 30% extraction efficiency with a filament mounted near the center so that it can be moved in the gap, and we achieve the high extraction efficiencies with d.c. injection. However, I must point out that we do not even have an accelerating slit on the simple filament at the center. I think we could just as efficiently design an ordinary central region geometry. The difficulty is that everything is so very small, the gap only a $\frac{1}{2}$ " , and it is very hard to make small slits and move them around in the center of the machine. The maximum radius is 40 cm.

HADDOCK : Have you measured the phase width of the beam that corresponds to 85% extraction?

MARTIN : No. It is difficult to measure in the Analogue, because it operates at 117 Mc/s.

WIDEROE : How much will the bump field increase the axial amplitudes?

MARTIN : With the small radial amplitudes with which we have been working, the change in axial amplitudes is not observable. Computer studies corroborate this; they show

that the axial amplitudes increase only when the radial amplitudes become considerably greater, because of the coupling between the radial and axial motion. However, we are extracting before this sets in.

BLASER : Your magnetic channel is going to perturb the magnetic field with a first harmonic close to the edge. Did you investigate the effect on the orbit?

MARTIN : No. We have not investigated that, but we will use one of the many systems available which will produce as little leakage field as possible. If we are careful we can get it down to a fraction of a promille and we can put a similar magnetic perturbation on more than one hill so that we destroy the $\cos \vartheta$ symmetry. There is no difficulty with this symmetry, it is the $\cos 2\vartheta$ that we have to watch.

VERSTER : The field bumps of the Tuck-Teng-Le Couteur system serve two purposes; namely to obtain radial turn separation and to keep the axial amplitude limited. The second requirement has an essential influence on the design, if large radial turn separation is required. Have you tried to optimize your field bump with respect to vertical stability?

MARTIN : We have not studied the manner in which the mean field should fall off beyond the resonance so that the radial-axial coupling is minimized. This is something we must do. In the magnetic field that we are studying here we maintain isochronism well through the resonance.

BLOSSER : I wish to comment on Verster's question. We have studied the variation of the vertical instability with field shape. A field which continues to be isochronous beyond the resonance energy appears to be approximately the best configuration. Any reduction of the average field appears to always make the axial instability much worse.