EXTRACTION EFFICIENCY IMPROVEMENT THROUGH CENTRAL REGION STUDIES

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Abstract

To enhance Crocker Nuclear Laboratory's ability to supply large beam currents to experiments in MFE, medical, and basic nuclear physics, it is necessary to increase the extraction efficiency of its cyclotron. Adding axial slits to the central region (as done at SIN) has increased deuteron extraction efficiency from 55% to 75%. Another improvement planned will decrease the large radial phase space presented to the extractor. A radial slit system is being designed to limit the radial momentum and displacement from early equilibrium orbits. To optimize this, studies were made with a 3-dimensional electrolytic tank system in which realistic central electric fields can be simulated. Central orbits were calculated using an adaptation of the Michigan State University code PINWHEEL, which allows placement of radial slits. Using a general orbit code the ions are then accelerated to the extractor where radial phase space and extraction efficiency are determined.

Beam Intensity Goals

At the present time the Davis 76" isochronous cyclotron provides beams for a wide variety of experiments, including studies of basic nuclear interactions, trace element analysis, radioisotope production for medical use, and neutron production in the MFE program. The Crocker Nuclear Laboratory's ability to reliably supply large beam currents over long periods has been well established. It is now desirable to increase the beam intensity available, and studies have been undertaken to see how this might best be accomplished.

Of particular interest to the MFE program is the maximum deuteron beam intensity. Prior to the work discussed here the limits were 25μA on external target at 40 MeV and 40μA at 14 MeV. Our interest is to increase the deuteron beam intensity five-fold to provide at least 125μA external beam at 40 MeV, 150μA at 30 MeV, and 200μA at 14 MeV. This will produce a five-fold increase in the neutron flux from deuterons on a beryllium target.

As Figure 1 shows, an increase in external beam by a factor of 5 requires an improvement in extraction efficiency of about a factor of 2. Thus the deuteron extraction efficiency of the cyclotron must be increased from its original value of 45% (at 40 MeV) to about 80%. The amount of external beam is limited by the power, P, the extractor elements can accept. The limit at present time is 1.0 kW, which therefore limits beam losses on the extractor to 25μA using 40 MeV deuterons. Defining the extraction efficiency, ε, to be $\frac{\text{extracted beam}}{\text{circulating beam}}$ and using the requirement that

extracted beam + extractor beam loss = circulating beam

we have

$$P = I\left(\frac{1-\varepsilon}{\varepsilon}\right) E = 1000. \qquad (1)$$

I is plotted vs. E in Figure 1. As can be seen in the figure, if we wish I = 125μA at E = 40 MeV, then an ε = 0.806 is required. At 14 MeV the desired final current of 200μA is achieved with ε = 0.70.

Table 1

Observed Beam Intensity Improvement with Axial Collimation

		No Axial Slit				7/16" Axial Slit			
Particle	Energy	Circ. Beam (μA)	Defl. Beam (μA)	ε	I_{max} (μA)	Circ. Beam (μA)	Defl. Beam (μA)	ε	I_{max} (μA)
Alpha	18.0	14	7.7	0.55	68	20	12.5	0.63	94
Deuteron	27.5	52	32	0.62	59	84	71	0.84	191
Deuteron	30.0	71	39	0.55	41	50	39	0.78	118
Proton	20.0	80	44	0.55	61	40	28	0.70	116
Proton	30.0	48	17	0.35	18	5	3.6	0.72	86
Proton	34.8	38	24	0.63	49	45	31	0.69	64
Proton	47.0	12	6	0.50	21	16	11	0.69	47
Proton	61.8	24	12	0.50	16	30	25	0.83	79

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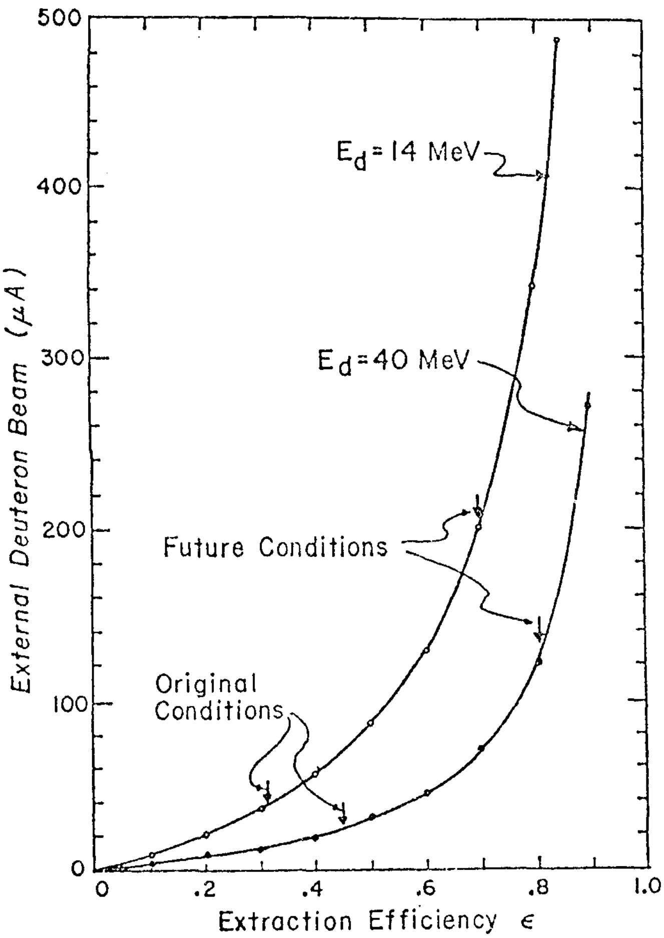

Figure 1. External beam current vs. extraction efficiency.

Beam is lost in the extractor elements because of radial oscillations and a limited radial gain per turn. Any energy dispersion during acceleration contributes to a radial displacement at the extractor by the equation

$$\frac{\Delta r}{r} = \frac{1}{2}\frac{\Delta E}{E} . \qquad (2)$$

The thrust of the current work is to limit the axial and radial oscillations and energy spread of the internal beam of the cyclotron so that the extractor elements will not be subjected to more than the present (1000 watt) power dissipation even though a beam of five times the present one will be passing through these elements.

Original Internal Geometry

The Davis isochronous cyclotron consists of the ORIC flutter field and a central region similar to the 88" cyclotron at UCLRL Berkeley. Our present central region geometry is approximately as described by Willax and Garren[1]. During the design and construction of the Davis cyclotron, model magnet studies were made to give an appropriate radial profile to the magnetic field in the central region, since we had removed an eight inch diameter from the center of the ORIC magnet for insertion of the Berkeley axial ion source[2]. This source can be much more precisely located than the ORIC source, which is inserted in the median plane. The design of the central region of the Davis cyclotron was reported at the Gatlinburg Conference[3].

The extraction system of the 76 inch cyclotron is a duplicate of that used in the Oak Ridge Isochronous Cyclotron, which has been described elsewhere by R.J. Jones et al.[4]. It will suffice to only briefly describe the system here. Figure 2 illustrates the elements of the system, which consists of an electrostatic channel of about 1/2 inch radial entrance width with a thin carbon septum, a co-axial channel, and finally an iron channel.

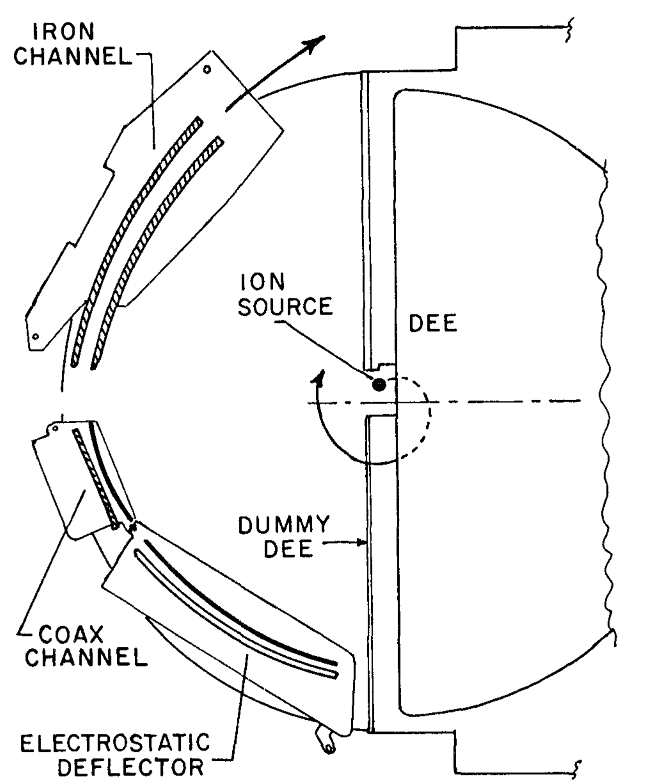

Figure 2. Extractor elements of the Davis 76" cyclotron.

Beam Summary

Table I lists several of the beams currently available and some of their important characteristics. The first columns refer to conditions prior to any central region changes.

Prior to the beginning of the modifications discussed here, the carbon septum would be replaced every 3 or 4 months due to erosion by the beam lost upon it. The septum installed just prior to the introduction of the axial slit discussed below had a greater lifetime.

Axial Defining Slit

In the 1976 annual report from the Swiss Nuclear Research Institute there was some information on improvement of extraction efficiency in their 70 MeV injector cyclotron by use of an axial slit[5]. Following this suggestion, during the past several months we have installed and tested a similar slit in the central region of the Davis isochronous cyclotron. This slit, which limits the beam to 7/16" axially, also limits the axial phase space in a manner similar to that discussed below for the radial phase space. The slit has the additional advantage that its action is independent of particle type or particle energy. Figure 3 shows a face view of the axial slit. Table I shows the performance of the cyclotron with/without an axial defining slit in the central region of the accelerator. In each case the extraction efficiency was measured, namely the ratio of the deflected beam to the circulating beam. Equation I then can be used to calculate the maximum current that can be extracted subject ot the limitation of one kilowatt dissipated on the extractor elements.

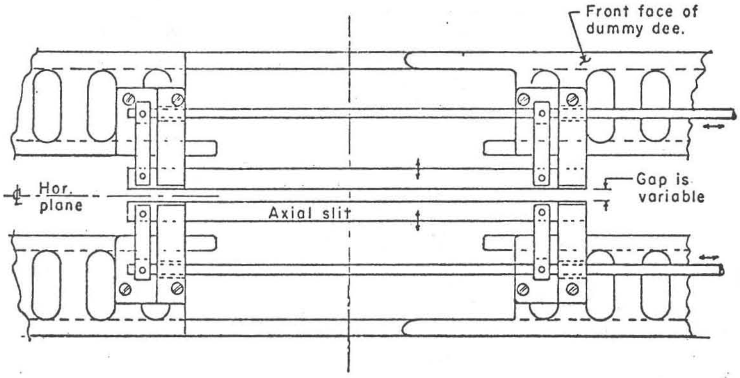

Figure 3. Face view of axial slit.

As can be seen from Table I in the case of deuterons of 27½ and 30 MeV that have been tested, the maximum beam current accelerable has been increased by a factor of 2 to 3 with an axial slit installed alone. However, subsequent phase measurements of the beam show a much sharper beam pulse being emitted now from the cyclotron. For example, for protons of 50 MeV the duty cycle of the machine is now about ½ nanosecond out of 50 nanoseconds between beam bursts—this implies a phase acceptance of the cyclotron of about 4 degrees; the previous phase acceptance was the order of 10 to 15 degrees. Although this is a very desirable feature from the point of view of time of flight measurements of neutrons, it may turn out to be a limitation in terms of maximum possible current that can be accelerated because of possible space charge limitations in this narrow azimuthal range. For this reason it seems prudent to increase the beam current not only by axial phase space limitation but also by radial phase space limitation so that the optimum maximum current can be obtained.

Radial Defining Slits

The radial phase space in the extracted beam as measured at ORIC[6] and confirmed for the Davis cyclotron is 55 mm - mrad. A considerable part of this area is probably due to the energy spread in the extracted beam (due in part to r.f. voltage ripple) as has been pointed out by Blosser[7]. This is typically 0.4% in the Davis cyclotron. If the ions forming the internal beam are unrestricted as to radial phase space, they can in principle fill such phase space available within the radial stability limits of the magnetic field. From the data presented by Bassel et. al.[8] this area is about 2000 mm - mrad for the ORIC magnetic field. In practice not all the available phase space is used for the internal beam, but it is clear that it is possible to considerably exceed the radial phase space that the deflecting system will accept to form an external beam. The beam that is not accepted by the extractor is lost upon it, resulting in power dissipation (max. 1000 watts in the Davis cyclotron) and build up of radioactivity.

We propose to limit the radial momentum and displacement from equilibrium orbits by an adjustable slit placed at approximately 150° from the ion source. This will reject, along with the axial slit discussed above, most of the ions that would have eventually fallen upon the extractor. This will permit some empirical adjustment from the computer predicted position as described below.

The radial slit consists of two carbon bars with adjustable spacing between the bars. The slit can also be adjusted empirically as to radial position and radial spacing. Figures 4 and 5 show section and plan views of the radial slit (and axial slit). Figure 6 shows a demonstration calculation of central orbits using an adaptation of the Michigan State code PINWHEEL to CNL's PDP 15-40 computer. The figure shows the trajectories of ions of various phases as they encounter the radial slit. To do these calculations the electric field (potential) due to ion source, puller, dee, dummy dee, and axial slit was measured. This was done with a 3-dimensional electrolytic tank system in which a realistic central region electric field geometry can be simulated. The electrostatic potential is then measured in the median plane[9]. Figure 7 shows an isometric plot of the potential used for the calculation. The puller-ion source geometry is similar to the one now in actual use. This permits a phase lag to produce electric axial focusing in the central region as described by Smith[10]. The magnetic cone in the central region then gives additional axial focusing until focusing from the flutter begins[3].

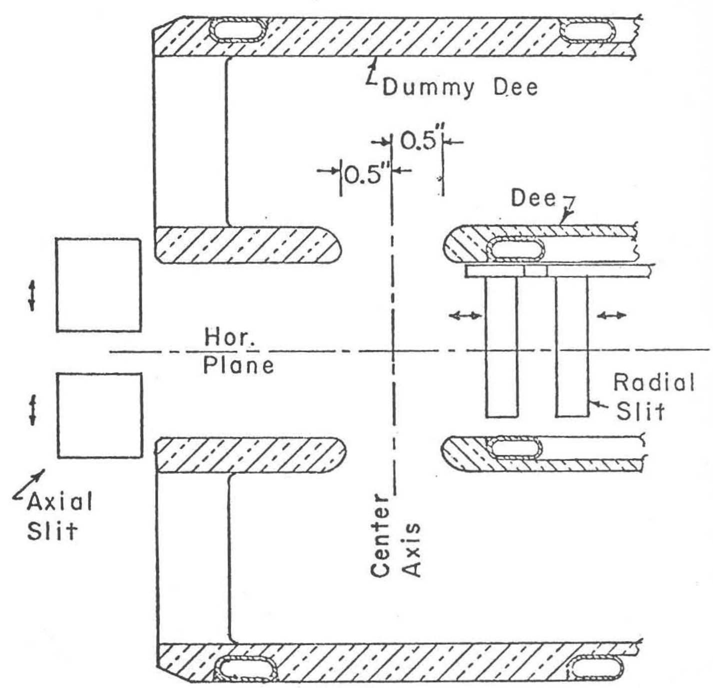

Figure 4. Section at center showing radial and axial slits.

After the ions have been accelerated (by computer simulation) through the central region, they are then accelerated to the extractor using a general orbit code. This is done by utilizing the measured magnetic field configuration of the Davis cyclotron. Some 10^5 magnetic field data points are available for this purpose. The general orbit code was developed at Davis by Prof. F.P. Brady and Dr. L.W. Baumhoff and has been used in previous design studies[11]. By following ions to the extractor in this way it is possible to limit in the central region those ions for acceleration that will have the radial oscillation amplitude and phase that the beam deflecting system will accept.

Figure 8 shows the radial phase space acceptable to the extraction system. Because the phase space accelerable is larger than that acceptable, some beam is lost (approximately 50%) on the extractor. Most of the loss occurs on the carbon septum (.062" thick) that separates the internal and external beam. For efficient extraction there must be enough energy gain per turn at the extraction radius for the beam to jump into the extraction channel. For 30 MeV deuterons and 56 kilovolts on the dee, this gain is 0.056". However orbital precession verified by GOCODE calculation approximately doubles this figure to 0.130". This is the distance given in the figure between the internal and deflected beam. The location of the deflecting electrode is indicated.

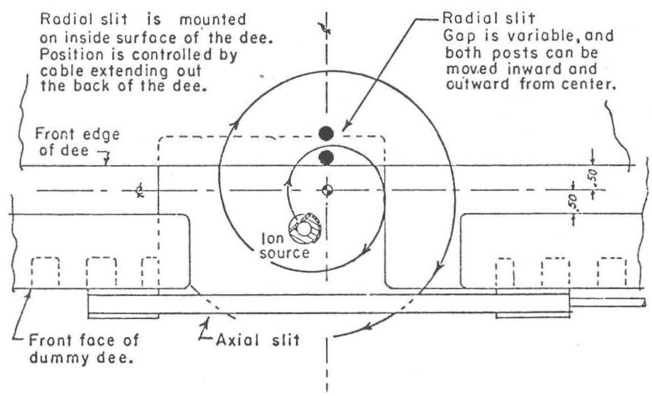

Figure 5. View of radial slit in plane of acceleration.

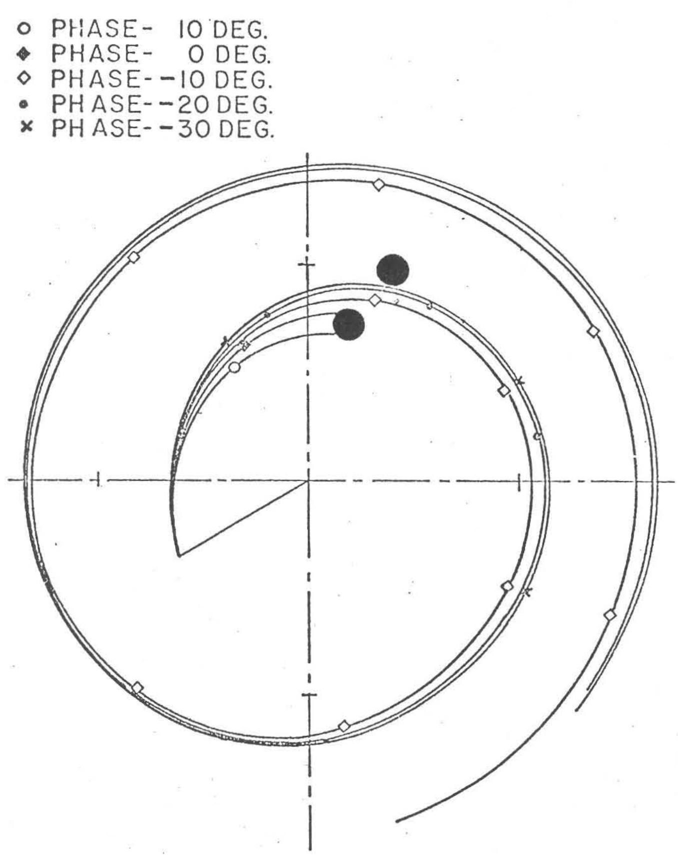

Figure 6. Demonstration computer calculation of central region showing selecting action of radial slit.

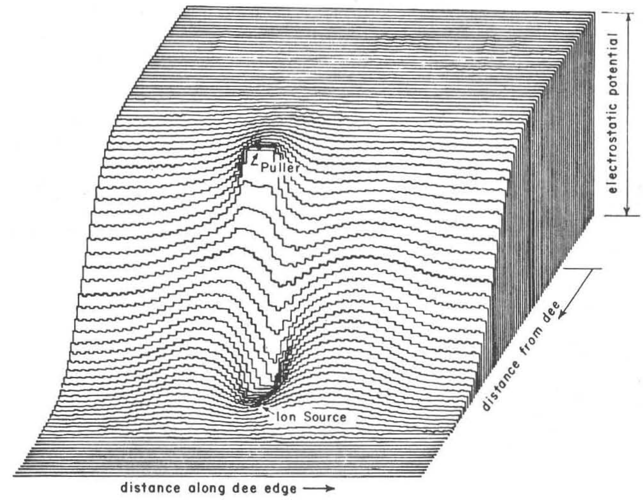

Figure 7. Measured electrostatic field for starting orbits (with axial slit present).

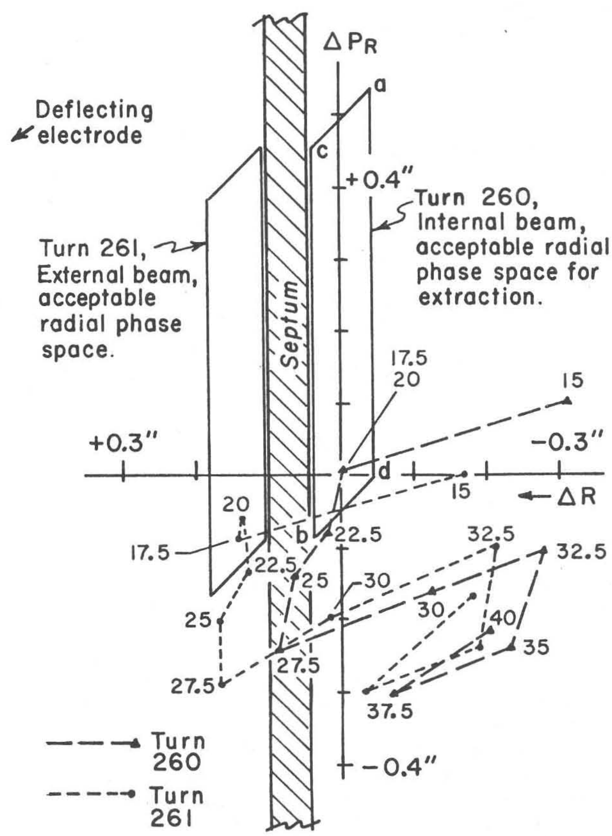

Figure 8. Radial phase space at extraction.

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If the particle has radial momentum either greater or less than that for the equilibrium orbit, it may strike the septum or deflecting electrode before exiting from the deflection channel. A simple estimate is that the radial momentum permitted is just enough so that a particle grazing the septum on entrance will just graze the deflecting electrode upon exit from the electrostatic deflector, i.e., $(p_r)\ max = \frac{2\pi g\ m\ r\ f}{l}$,

where g is the deflector gap at exit (9/16"), m is the mass of the ion, r the extraction radius, f the cyclotron frequency, and l the deflector length. This point is shown as point a in Figure 8. Similarly a particle having a maximum negative radial momentum with respect to the equilibrium orbit will just graze the deflecting electrode at entrance and emerge just grazing the septum at exit (point b in Figure 8).

Particles that have radial momenta (a,b) or radial positions (c,d) at the extractor greater than given by points a, b, c and d will be lost on the extractor. Points are plotted in Figure 8 representing complete calculations of orbits beginning in the cyclotron center via PINWHEEL and continued by computer simulation using GOCODE to the extractor. The points are labeled with initial phase lags. Only particles in the 5° - wide phase region between $\sim 17.5^{\circ}$ and $\gtrsim 22.5^{\circ}$ are deflected, agreeing with the expected phase acceptance discussed earlier.

From the above it can be concluded that particles with unfavorable initial phases for extraction can be rejected by a radial slit at the 150° position, as shown in Figure 5. PINWHEEL results indicate the posts should be 0.2" in diameter, and centered at 0.05" and 0.45". At present with an axial slit only, the extraction efficiency is 78%. To give the additional factor of 1.27 needed to achieve the design goal, an 82% extraction efficiency is required by using both radial and axial slits.

There is indication from several sources that central region selection is successful in improving extraction efficiency. A 135° long carbon slit was at one time installed in ORIC in the central region and it was noted that "the highest extraction efficiencies have been observed when the beam is defined with the electrode". These efficiencies were measured to be about 50% at that time[6]. Recently a 0.5 mm radial slit was used in the new medical cyclotron in Japan to achieve an extraction efficiency of 70% for 30 μA of 30 MeV deuterons[12]. E.J. Jones et al.[13] report that 70% extraction efficiency is routinely obtainable with a single slit near the cyclotron center (deuterons from 30 to 40 MeV).

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