# The Berkeley synchrocyclotron improvement programme*

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ABSTRACT

Studies to improve the 184-in Berkeley Synchrocyclotron have led to a design for a new rf system providing higher dee voltage and repetition rate. The one-half scale model is described along with a brief description of a model high power broadband beam stretching cee.

## 1. INTRODUCTION

### 1.1. *The central region model studies*

Most of the results obtained have already been reported at Gatlinberg in 1966.[1] In summary the initial results were very promising in that the use of a hooded (or calutron) source and puller electrodes on the dee gave milliampere beams (which were immediately lost due to space charge). The addition of focusing grids on the dee and flutter focusing with iron ridges close to the median plane retained most of this large increase. Several milliamperes at 15 kV were obtained.

However, when a frequency modulation programme was added to the model, the beam acceptance time was found to be some two orders of magnitude lower than for the diffuse open source in use at present. The net gain, if any, was small. A computer study shows that one might possibly gain, at most, a factor of 10 by very careful tailoring of the flutter field in the central region. However, efficiently trapping the beam in the existing accelerating electrode presents many unsolved problems. Such a programme would certainly be pursued vigorously in any new machine, but the situation in the case of the 184-in

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machine is quite different. It is the most radioactive machine in the world. The prospect of assembling critical parts and then carefully tailoring the field shape in the centre of the machine is most discouraging. No solution has appeared within the present radiation tolerance limits. In view of this fact, the central region programme is now semi-dormant and emphasis has been on a more certain method of increasing the beam intensity by changing the rf system.

### 1.2. *Beam extraction*

Computer studies of regenerative beam extraction[2] are being carried on. The results will be reported at a later time.

### 1.3. *Carbon tetrachloride*

It was noted at Orsay[3] that the addition of $CCl_4$ to the ion source gas increased the proton beam considerably (and destroyed the source). In general a factor of 1·5 is realised this way at Berkeley with no obvious source deterioration. A modest programme to investigate this effect is continuing.

## 2. THE HIGH VOLTAGE, HIGH REPETITION RATE MODEL RF SYSTEM

From the very beginning it was recognised that raising the dee voltage and repetition rate was the most certain way of overcoming the space charge limit.[4] An increase somewhere between the first and second power of the voltage is expected.[5] A figure of 40 kV on the dee was chosen as a design goal.

Raising the dee voltage is not a very appealing solution, since it means that the extremely reliable vibrating blades will have to be replaced by a rotating capacitor. (A separate study showed that electronic systems were completely impractical.[6] At 40 kV the voltage bandwidth product for the 184-in cyclotron exceeded by far the theoretical limit set by the emission capacity ratio of modern high power tubes.)

The main problem to be answered was whether or not the frequency range could be covered with rotating devices, since it was in fact this difficulty that led in part to the development of the vibrating blades. Several half-scale models were built with rotating capacitors in various orientations with respect to the dee.[7] Finally, after incorporating the design developed by the CERN group,[8] the problem was solved by using two capacitors in parallel.

### 2.1. *The dee*

The arrangement using two capacitors is shown in Fig. 1. The dee consists of two 90° dees in parallel, each with half the capacity of a single large dee. This approach, also, stretches the dee electrically in that each 90° dee tapers to a point at the centre of the machine making it an effective tapered transmission line of non-uniform impedance in approximately the right way to make it possible to cover the range. However, the tapering effect is not quite sufficient, and a further decrease in characteristic impedance is needed near the edge of the poles. This is shown in Fig. 2 where the liner approaches to within 2 cm (full scale) of the dee structure just over the edge of the magnet pole. This point is approximately a voltage node at the high frequency end of the range and rather close to maximum dee voltage at the low end of the range. As a rule the requirements of the magnet designers are diametrically out of phase with the desires of the rf engineers in that high magnetic fields dictate small gaps while high voltages dictate large gaps. It is, therefore, pleasant to note that the restricted gap over the shims and magnet coils is (for once) in line with the rf requirements.

The use of two separate structures virtually eliminates the cross mode problem which consumed a considerable amount of time in the vibrating blade

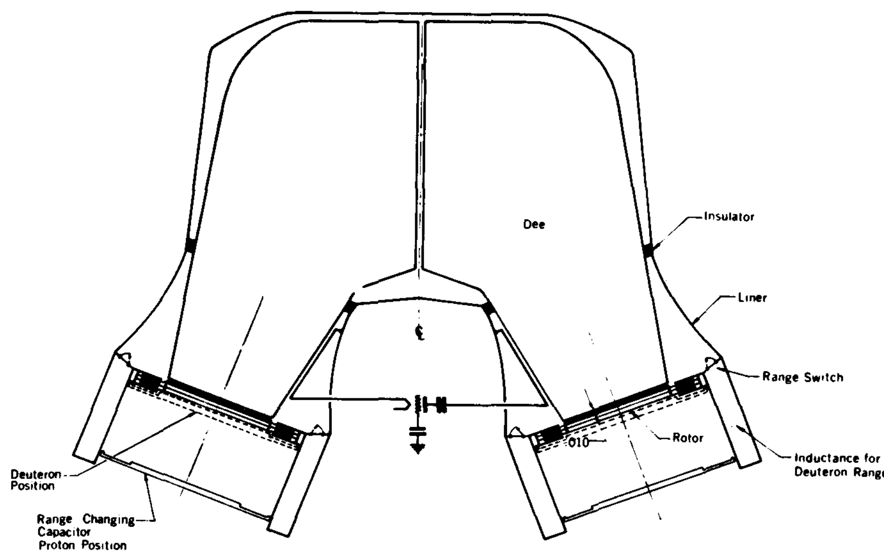


*Fig. 1. 184-in synchrocyclotron model rf system. Plan view*

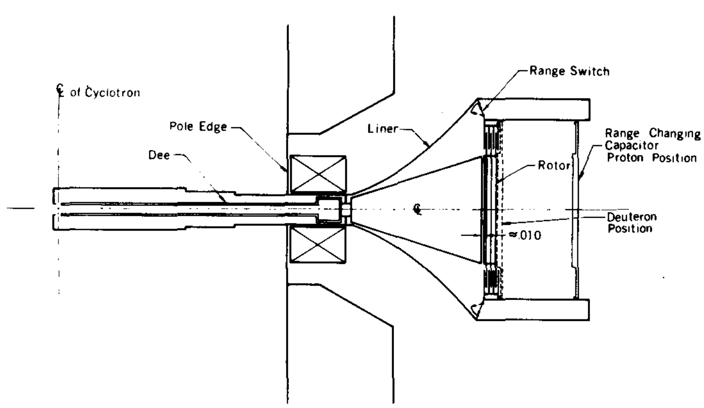


*Fig. 2. 184-in synchrocyclotron model rf system. Profile view*

model programme before a solution was found. It, also, seems that the mechanical design of the 90° dees will be simpler than the present large dee. At present, a half dee is envisaged which is cantilevered from a vacuum insulator of quite radical shape. As shown in Table 1, it is large and rectangular. Fabrication of this insulator is a problem in itself, since no supplier has ever attempted anything this large. But they agree that it can be done.

**Table 1.** ONE-HALF SCALE MODEL DEE DIMENSIONS

| | |
|---|---|
| Dee width | 224 cm |
| Lip to vacuum barrier | 153 cm |
| Lip to rotary capacitor | 216 cm |
| Dee height | 8·25 cm |
| Maximum dee to liner spacing | 5·1 cm |
| Minimum dee to liner spacing (at vac. bar.) | 1·0 cm |
| Vacuum barrier insulator | 72·5 cm × 30 cm × 2·5 cm |
| Capacity of dee inside vac. barrier | 1900 pF |
| Hole through vac. barrier insulator | 51 cm × 17·8 cm |

### 2.2. *The rotating capacitors*

The basic concept behind each capacitor is described in detail in a CERN report.[8] In the Berkeley version changes have been made since the magnet design allows considerably more room. The overall features are listed in Table 2.

**Table 2.** ONE-HALF SCALE INCLUDING CAPACITOR DIMENSIONS

| | |
|---|---|
| Overall rotor diam. | 76 cm |
| Rotor hub diam. | 51 cm |
| Sets of teeth | 10 |
| Rotor teeth in each set | 3 |
| Stator teeth in each set | 4 |
| Speed | 1800 rpm |
| Repetition rate | 300 pps |
| Maximum capacity | 1300 pF |
| Minimum capacity | 130 pF |
| Padder capacity for deuteron range | 300 pF |

The guidelines one uses in designing a capacitor at the end of an electrical half wave line are quite simple, but rather ill defined. The tooth to tooth gap at the highest frequency must be sufficient to stand the design voltage; the capacity ratio must be large enough to cover the range; and the number of teeth and rotation speed must be consistent with the desired repetition rate.

All these factors dictate the use of a large capacitor. There is a limit, however, when the size becomes an appreciable fraction of a wavelength. At this point one runs into cross mode effects which can be very troublesome. By cut and try the size was varied until the cross modes, with the edges of the stator teeth strapped together, remained above the proper mode throughout the frequency range.

This size is shown in Table 2. Such a capacitor turned out to have a capacity about equal to the dee capacity which means that at the upper frequency limit it must hold off a voltage equal to dee voltage, namely 40 kV. A tooth to tooth gap of 0·64 cm (full scale) was judged adequate to stand this voltage provided that the vacuum was reasonably good.

To ensure a better vacuum than found in the main cyclotron chamber a separate system is planned for the capacitor. The vacuum barrier is the large rectangular insulator described earlier. The main contaminant is expected to be a slight amount of oil vapour from the bearing lubricating system. It seems that the bearings themselves can be either ball bearings or sleeve bearings. In either case some sort of oil seal is needed if a really clean vacuum system is to be realised. This seal is still one of the question marks in the programme.

One of the chief sources of failure in the old rotating capacitor was breakdown of the brushes which bypassed the rf current past the bearings, followed by failure of the bearings. One of the causes of bearing failure has been traced to metal ball retainers, which spark due to poor rubbing contact. A big improvement follows when they are replaced by insulating spacers. In addition to this advance, a bridge balancing network has been conceptually designed which reduces the current through the bearings to practically zero.[7] Brushes are, therefore, unnecessary. The oil seal remains as the critical problem. However, it must be noted that if oil cannot be kept from the capacitor vacuum system a gap of 0·64 cm will still permit much higher voltages than are possible on present machines with much smaller gaps.

### 2.3. *Capacitor voltage throughout the range*

It turns out that the low impedance section near the magnet pole stores a considerable amount of energy as soon as the frequency decreases some 20% below the upper limit. This in turn causes a voltage rise at the rotary capacitor. This rise is quite sensitive to the detailed non-uniformity in the dee stem transmission line. In designing this region it was, therefore, necessary to effect a compromise between capacitor voltage and the non-uniformity needed to produce the necessary frequency range. This was done by means of a mechanical computer which displays the trend continually during the computation.[9] For the optimum arrangement the computed capacitor voltage and measured capacitor voltage are compared with each other in Fig. 3. The dee voltage (scaled for the full size version) is held at 40 kV. Voltages in other parts of the system, at several frequencies, are shown in Fig. 4.

### 2.4. *The oscillator*

The choice of two capacitors and two dee stems has the slight disadvantage that the two capacitors must be synchronised within 0·04°. This problem has not really been faced, but it is not considered too serious since a similar problem existed with the vibrating blades which had to be held in phase within 1°. It is, also, evident that the Columbia group under Rainwater[10] with a very similar arrangement using two capacitors will have solved this problem by the time it is needed at Lawrence Radiation Laboratory. From the viewpoint of the oscillator, however, having the stems resonate in phase makes it very easy to couple a grounded grid tube into the system.

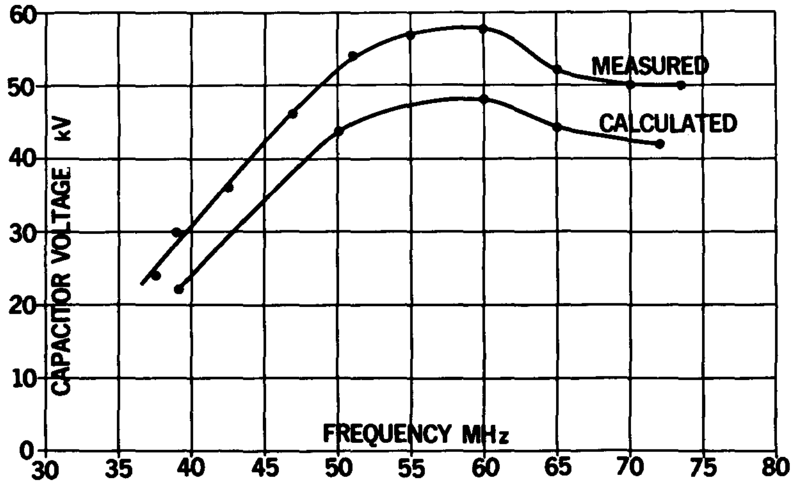


*Fig. 3. Computed and measured capacitor voltage vs frequency. Scaled for 40 kV on the dee lip*

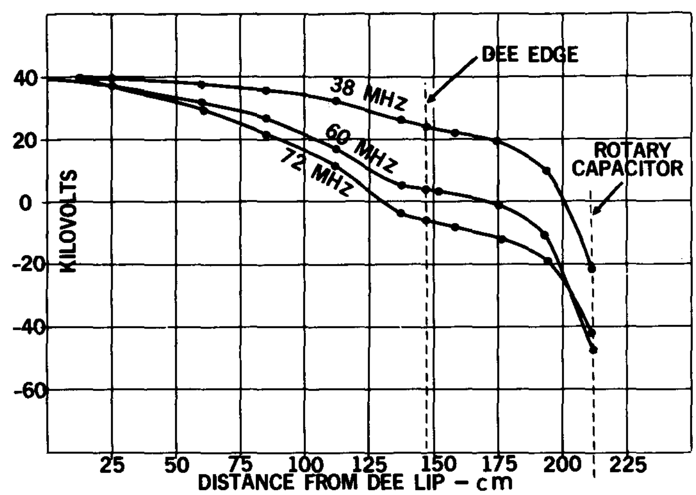


*Fig. 4. One-half scale rf model. Voltage vs distance from the dee lip*

Fig. 1 shows a schematic diagram of the oscillator located between the two dee stems. The anode of the oscillator tube feeds power via a transmission line to one dee which in turn drives the other dee through the dee to dee capacity. The inter-dee coupling is tight enough to reduce phase shifts to negligible proportions. A much more serious effect is the voltage unbalance caused by the two capacitors falling out of synchronism (the problem mentioned above). The cathode of the tube is driven in similar manner via a transmission line of shorter length which is loaded by capacity at the cathode to reduce phase shifts. Both lines operate with one voltage node and are non-uniform in impedance in order to provide an approximate voltage match over the range. This match which is only approximate gives a relatively flat dee voltage for constant oscillator voltage (shown in Fig. 5).

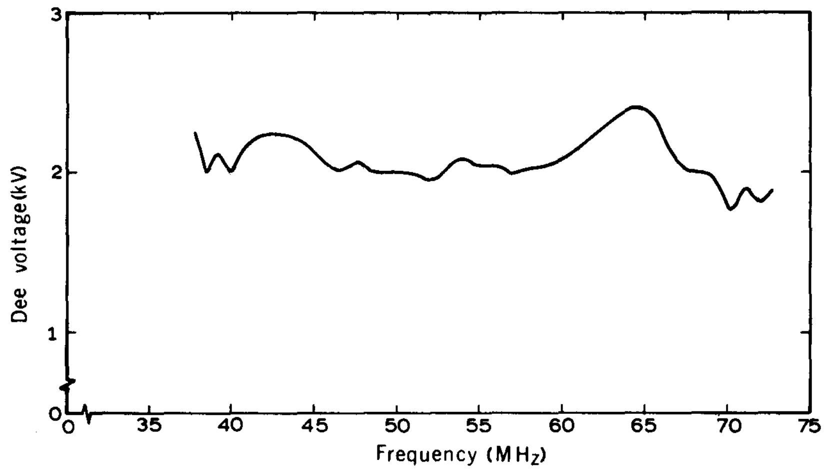


*Fig. 5. One-half scale rf model. Measured dee voltage vs frequency*

The almost complete separation between input and output virtually eliminates the parasitic problem. The only one encountered so far on the model involves the grid inductance of the Eimac 3CW 30 000 tube. This parasitic, which occurs in a tuned plate tuned grid mode with the relatively fixed frequency mode (in which the anode line stores most of the energy) acting as a plate load, is easily damped by a wave trap. The model oscillator performs very well, exciting the system to several kV over the range, limited only by breakdown in air.

### 2.5. *Power*

Although one 3CW 30 000 tube simulates the voltage current ratio of the larger tube rather well, two of these small tubes should really be used on the model since the skin depth losses are 1·4 times the full scale losses. The fact that the model oscillator oscillates very satisfactorily over the range is a good sign; since it always turns out that the full scale version is easier to excite by reason of its higher $Q$. The oscillator input figures obtained from the model, but scaled to full size at a measured 65% efficiency are shown in Table 3.

**Table 3.** FULL SCALE OSCILLATOR INPUT

| | | | | |
|---|---|---|---|---|
| Frequency MHz | 36·5 | 35 | 28 | 19 |
| Power kW | 240 | 300 | 370 | 200 |

Maximum power is required at intermediate frequencies where the teeth are partially meshed and most of the current is concentrated on the edges of the teeth where the radius of curvature is small. An Eimac 250 kW triode is proposed for the full scale system.

### 2.6. *The deuteron range*

The 184-in machine was first built as a 200 MeV deuteron machine. When rf techniques were developed for higher frequencies it was converted to a proton and deuteron machine at 350 MeV proton energy using a rotary capacitor, and then to a proton and deuteron machine at 730 MeV proton energy with vibrating blades. The deuteron range has thus become an integral part of the experimental programme at Berkeley, and has to be retained in a future conversion.

The deuteron range is covered on the half scale model by adding capacity to the rotor in the form of a large disc which is pushed forward to within 3 mm of the rotor. This simple addition of capacity is insufficient, so inductance is added also, in the form of a concentric volume outside the capacitor. Both these additions can be seen in Figs 1 and 2. For operation on the proton range the disc is withdrawn and the extra volume is shorted out by a circular row of knife switches.

As can be seen in Fig. 1, the oscillator circuit is extremely simple. The only change needed in going from protons to deuterons is a simple change of line length. The lines are made from flat sheet (with folded over edges so that no sharp edges are exposed). Much of the line is folded within a large rectangular box. Switching lengths in and out is therefore a simple procedure.

## 3. SECOND DEE (BEAM STRETCHING CEE)

A second item in the model programme (not related to the main rf conversion) is the study of a higher voltage cee which will cover the range from 20·2 to 18·9 MHz at 20 kV compared to 4 kV for the present system. The full scale model studies show that 115 pF is about the lowest cee capacity that can be expected. The FM system being tested is based on a theory for wide band electronic modulation using the overcoupled transformer, in which the dee and its stem form one circuit and the tube and its connections form the other.[6] The simple looking circuit is shown in Fig. 6. An Eimac 4CW 100 000E is being considered for the tube, and it will operate at 17 kV. This is 0·85 times the cee voltage so capacity must be added to the tube to bring its capacity up to 1·4 times cee capacity. If one were striving for maximum bandwidth, this capacity

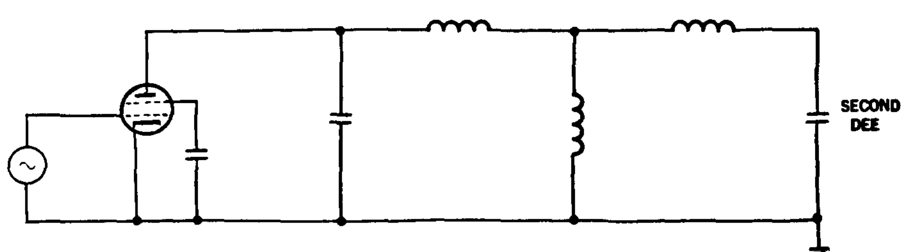


*Fig. 6. Schematic diagram of broadband cee system*

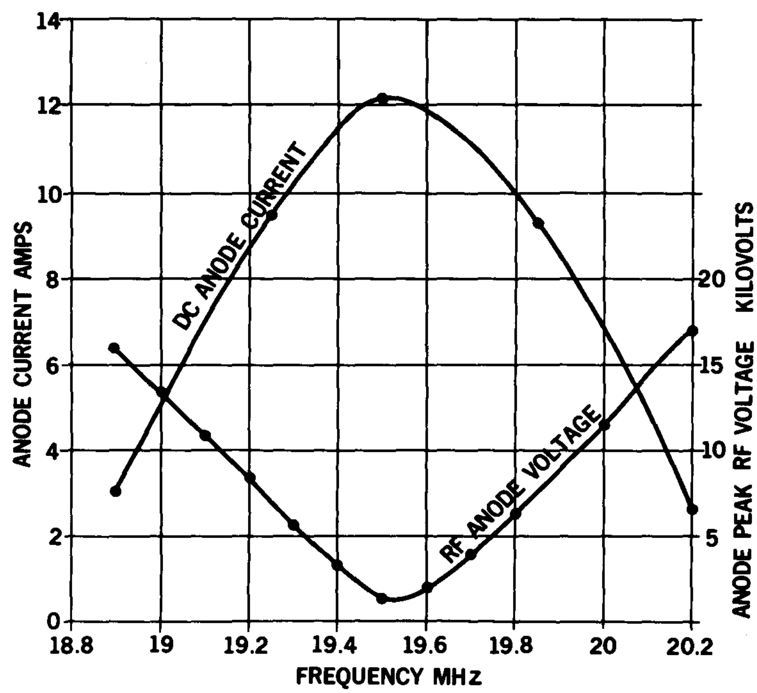


*Fig. 7. Broadband cee system. D.C. anode current and rf anode voltage vs frequency. Scaled for 20 kV cee voltage*

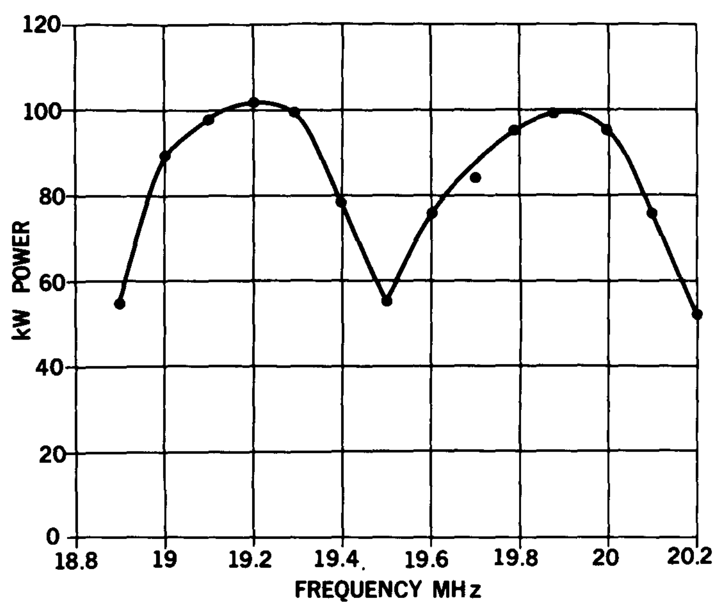


*Fig. 8. Broadband cee system. Input power vs frequency. Scaled for 20 kV cee voltage*

would be added in the form of more tubes so that more emission would be available. However, the voltage bandwidth product is not great and is well within the 'g' factor for a single Eimac tube, so a simple addition of capacity suffices. The remaining problem is then simply a matter of conserving power.

Fig. 7 shows the d.c. anode current, and also shows how the anode rf voltage varies throughout the range for 20 kV on the cee. There is no need for the d.c. anode voltage to exceed the peak rf anode voltage by more than a kilovolt or so. Any extra voltage simply means power down the drain. Hence, the tube will be fed from a programmed d.c. power supply which serves the dual purpose of conserving power and maintaining an approximately constant cee voltage.
The input to the amplifier tube is a more or less conventional wide band, low power driving system. Fig. 8 shows the input power as obtained on the model using point by point control of the power supply voltage. The data was obtained on the full scale model in air using a 4CX250B tube at 1·0 kV maximum and then scaled to 20 kV.

## DISCUSSION

Speaker addressed: K. MacKenzie (UCLA)

*Comment by W. van Genderen* (Amsterdam): In our synchrocyclotron we also use carbon tetrachloride. Normally one applies it to the ion-source. We have applied it directly to the accelerating chamber through a hole in the wall. It was surprising that very small amounts already had a marked effect. For all particles improvement with a factor 3 has been found (except for protons, where the effect has been smaller and more irregular). The maximum currents were: deuterons 45 $\mu$A, protons 20 $\mu$A, $^4$He 6 $\mu$A, and $^3$He 10 $\mu$A. The method has been in continuous use now for more than a year with full satisfaction.

*Question by W. B. Powell* (Birmingham University) (referring to a suggestion made by MacKenzie for a possible mode of action of $CCl_4$ in increasing beam intensities): Professor MacKenzie, you mentioned the negative ion neutralisation of high intensity positive beams. Should we picture a uniform distribution of negative ions over the machine? And, if so, can you suggest the method by which longitudinal space charge is neutralised? I can't see how a uniform negative charge would neutralise space charge (as Gordon suggested in an earlier paper).
*Answer:* I'm not sure. I was just trying to excite interest in $Cl^-$ ions. Possibly it is a second order effect (like strong focusing) due to the fact that the negative ion cloud is not azimuthally uniform. The ion cloud will be wiped out in the region of the accelerating gaps.

*Comment by W. van Genderen* (Amsterdam): We did the following experiment. We measured the current lost on the dee. When the space charge becomes smaller you could expect more beam at full radius, for the same current extracted from the source (and mostly lost on the dee). We could not measure this effect, so we are in doubt if compensation of space charge is the explanation.

*Comment by E. G. Michaelis* (CERN): The view that heavy gas addition increases the internal beam by a process of space charge neutralisation is not supported by the experience with CERN synchrocyclotron. There a gain of a factor 2 is obtained by the addition of argon, which does not readily form negative ions by capturing electrons. It is thought that the addition of argon facilitates the formation of an arc in the source.

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