Proceedings of the International Conference on Isochronous Cyclotrons, Gatlinburg, Tennessee, 1966

SYNCHROCYCLOTRON CONVERSION *

Invited Paper

K. R. MacKenzie
University of California
Los Angeles, Calif.

Abstract

The possibility of increasing the output of fm cyclotrons is being explored simultaneously in many laboratories. Space charge seems to be the limiting factor. Practically every laboratory is investigating a form of hooded source known as the Livingston, calutron or Oak Ridge source. The ions must clear such a source so higher dee voltages are needed. The higher dee voltage is desirable in any case since the beam usually increases as some power of this voltage (if the repetition rate is increased correspondingly). The theoretical picture indicates a variation between V and V^2. Some fm cyclotrons will try to increase performance by this method alone. Others will include all the possible improvements including a complete sector field near isochronism which will provide strong vertical focusing and reduce the frequency swing. The largest machines will probably try to achieve their goal by small sectors near the source and somewhat larger limited radii sectors on the poles (with an unchanged radial profile). The status of these efforts is reviewed and some data on the Berkeley model program is given. It appears that most fm cyclotrons will eventually be partially or wholly converted to sector focused synchrocyclotrons.

Introduction

A paper on synchrocyclotron conversion at a conference on isochronous cyclotrons makes one think that a movement is afoot to convert such machines to isochronous machines. This impression would not be far wrong. For several years many laboratories have seriously considered such a move, but at present the thinking seems to be in terms of a partial conversion to a sector focused synchrocyclotron, which appears less expensive and makes little or no sacrifice in energy. As far as I know, UCLA has the only synchrocyclotron which has been fully converted to an isochronous machine (although before completion). In this special case, due to a rather radical design, there was no loss in final energy.

Recently I emphasized the role of space charge in limiting the output of synchrocyclotrons[1]. Lawson[2] and Rainwater[3], in papers which modified and refined the analysis, have at the same time strengthened the conclusion that space charge is indeed a major factor which must be considered if synchrocyclotron outputs are to go up. At the present time most of the synchrocyclotrons above 300 MeV (and some below) are seriously considering making changes which will raise the space charge limit, hopefully improve the beam in quantity and quality, and in some cases raise the energy. One of the most interesting changes is a "conversion" to a non-isochronous sector focused synchrocyclotron which will limit the space charge blow up through increased vertical focusing. The various laboratories hope for an increase ranging from 10 to 100 in intensity and a significant improvement in the quality of the beam. However, it usually turns out that intensity must be sacrified for quality and vice versa. Beam quality is intimately connected with deflection problems, but in this paper the discussion will be confined to the source and internal beam.

A sector field conversion is only one of the many improvements that have been suggested. A more complete list is given below:

1. Raise the dee voltage and corresponding fm rate by designing a new capacitor or other fm system which will cycle faster and stand more voltage.
2. Increase vertical focusing by adding sector shims to the poles faces (with very little or no change in radial profile).
3. Add shims as above, but at the same time change the radial profile in the direction of isochronism.
4. Add sector or electrostatic focusing locally very near the source and median plane.
5. Use a hooded source of the type that is often called a calutron source, Livingston source, or Oak Ridge source.
6. Modify the initial conditions to maximize the capture efficiency.

Raising the dee voltage and correspinding fm rate as suggested in item 1 seems to be a sure way to increase the output. The beam is expected to vary as the first power of V or higher.[3] At large radii a linear dependence on V is predicted.[1,3,4] Rainwater[3] and Clark[5] have shown that the Columbia and Berkeley synchrocyclotrons are operating very close to the space charge limit as soon as the radius is about equal to one magnet gap. This is considered to be a large radius, and therefore the beam would be expected to vary linearly with V as the voltage is raised above the present level in these machines.

Unfortunately the voltage cannot be raised appreciably, but it can be lowered. Henrich, Sewell and Vale found a V^3 dependence when this experiment was done,[6] and since this agreed with a calculation based on the assumption of an abrupt onset of magnetic focusing, I decided the region in the immediate vicinity of the source was important. Since the published information,

Reprinted from IEEE Transactions on Nuclear Science NS-13 (4), Aug 1966

Proceedings of the International Conference on Isochronous Cyclotrons, Gatlinburg, Tennessee, 1966

I have found, indicates that the beam varies more rapidly than the first power of V, it now appears that both regions are limiting the beam at about the same time. The data of Henrich et al., is shown in Fig. 1. Uppsala has performed the same experiment and their data,[7] extracted from Fig. 5 of their report, is shown in Fig. 2. Fig. 3 shows the beam dependence taken from a table reported by the Orsay group with a hooded source.[8] The variation is linear but the intercept does not go through zero, so the curve might be part of curve that is concave upward. Fig. 4 shows data reported by Rochester at the Williamsberg Conference on High Energy Cyclotrom Improvement.[9] More published data of this type would be helpful.

For the center region, Lawson[2] has shown that if the abrupt onset of focusing is replaced by focusing in the field usually encountered, the beam varies as $V^{5/3}$. His theory is in good agreement with the data of Ruby et al.,[10] who used such a field in a conventional cyclotron model study. (Ruby's data is shown in Fig. 5). His theory is also in approximate agreement with the data in Figs. 2 and 3. However, a more rapid variation with V should occur if the focusing enters more abruptly, as would happen in a sector field. The Uppsala group has considered such a case[7] and calculate a beam variation as V^2.

The program of raising the dee voltage and fm rate as outlined in item 1 requires a new rf system. In some cases a new rf system is badly needed anyway. This program, with no other major changes is therefore particularly attractive for the smaller synchrocyclotrons where the frequency swing is not excessive. In fact one can already point to examples where large beams are being produced under these conditions by the smaller machines. The 160 MeV synchrocyclotron at Orsay has reported currents around 20 μA with repetition rates of 450 per sec and dee voltages around 25 kV.[11] In 1965 Orsay reported some model studies with a hooded source and some improved performance figures when installed in their synchrocyclotron.[8] Recently the information has been relayed by CERN that the calutron source has increased the deflection efficiency at Orsay from 8 to 20% and has decreased the energy spread from 2% to 0.4%.[12] At the Williamsburg Conference on High Energy Cyclotron Improvement,[9] Barnes reported that the internal beam of the 240 MeV Rochester machine was increased from 1 to 5 μA by increasing the dee voltage and the internal dee height. (it has been noted that the space charge limit is proportional to the internal dee height).[1]

The Harwell Plan

Harwell has elected to take the route in item 1. At the Williamsberg Conference, Huxtable[9] outlined the plans for increased output. The program today is essentially unchanged except in detail. The present internal beam of about 1 μA is expected to be in the range between 10 and 30 μA at 147 MeV after installation of a new rf system. The dee will be cut back to 90 degrees to lower the capacity and a new rotating capacitor is being designed to give a nominal repetition rate of 1000 cycles per sec and 30 kV on the dee. At the same time, the system is being designed to accelerate protons, dueterons and helium 3. A calutron or hooded source is also to be tested. For a more complete story, the reader is referred to a paper, "Modifications of the Harwell 279 cm Synchrocyclotron" by J. P. Scanlon, which is to be included in the proceedings of this conference.

This is probably the place to comment on the effect of varying the initial fm rate (or df/dt) without changing the dee voltage, because Harwell has just confirmed an unpublished measurement at Berkeley. The first version of the 184" cyclotron at Berkeley accelerated deuterons to 100 MeV, and the capacitor had some 25% extra range at the upper frequency end. The initial value of df/dt was high, in accordance with the theory of Bohm and Foldy.[13]

When conversion to a 340 MeV proton machine was undertaken, the importance of the value of df/dt was examined in order to determine how much extra range to build into the capacitor. Extra capacity was connected into the circuit to lower the upper frequency limit. No effect on the beam could be detected even when the initial value of df/dt was zero.[14] Needless to say, this fact simplified the capacitor design.

These identical experiments have recently been repeated at Harwell[15] with exactly the same result. A logical explanation is that space charge is the limiting factor and is masking any variation due to df/dt.

Advantages of Sectors

As the size of the machine increases, this approach alone becomes progressively difficult. The capacitor max/min ratio increases faster than the square of f_{max}/f_{min} which makes the capacitor design quite a problem, especially if high voltages and large spacings are wanted. These difficulties prompted the development of vibrating blades, which have the property, when used in a "3/4 wave system," [16] that the voltage across the gap is proportional to the gap, so that high voltages can be used. Unfortunately, little is gained because the fm repetition rate is fixed.

Several advantages are realized at once if sectors are installed such that the field increases with radius, but not enough to achieve isochronism.[1] The flutter and spiral angle need not be severe, and it turns out that with a given magnet a higher average B can be maintained at the final radius than if the field is isochronous.[3] The frequency swing is of course reduced, so that the rf system design is made much easier. Of equal importance is the fact that the reduction in frequency range is achieved at the expense of the high frequency limit, which means that the capacitor can be located farther from the center of the machine. Higher voltage and repetition rates can certainly be achieved with present technology. And the last advantage, but not the least, is the large increase in vertical focusing that can be obtained with ridges.

The Columbia, Carnegie and Uppsala Proposals

This general approach is proposed by Columbia, Carnegie and Uppsala. An increase in beam is predicted on the basis of increased dee voltage and repetition rate. Added to this is the strong focusing supplied by the ridges. Calutron sources are being considered (which may result primarily in a quality improvement). Columbia and Carnegie hope to also increase the beam energy. Columbia is planning and building a 1/5 scale model complete with frequency modulation. In view of the demonstrated increase in beam that follows an increase in dee voltage and repetition rate, it seems almost a certainty that if these proposals are funded they will yield an increase by an order of magnitude. The main difficulties are money, time and radiation hazards. The proposal by the Uppsala group[7] is very interesting. The frequency range is reduced to the point where electronic broad-band frequency modulation is possible without excessive power. The papers to follow will elaborate on these comments.

The Chicago Program

In contrast with Uppsala, the Chicago group is working on the very difficult problem of trying to raise the voltage and repetition rate by electronic modulation without reducing the original frequency range.[9] This attitude is very understandable. A complete overhaul is very expensive and time consuming. An increase by a factor of 5 or 10 is sufficient for a lot of new experiments, especially if the quality is improved. An increase by more than a factor of 10 might constitute a problem with excess radiation and require a lot more shielding, money and time.

Radiation Hazards

The comments in the previous paragraph emphasize one of the worst problems in modernizing these large machines. The iron poles and tank are so radioactive that installation of sectors and a prolonged shimming program constitute a serious health hazard. The Chicago group hopes to leave the poles alone and put in a new rf system with no dead time and a higher voltage and repetition rate. A new source might be installed. If their plans can be carried out, it seems reasonable to count on the desired factor of about 10.

Center Region Models

The cyclotrons at Berkeley and CERN are searching for a simpler and cheaper solution. They both use vibrating blades. These fm devices are extremely reliable and there is a natural reluctance to abandon them. Consequently, a lot of thought has been given to ways of attaining the desired increase (again about a factor of 10) without disturbing either the field or the rf system. Both laboratories have decided that the hope lies in the center region and have constructed center region models which in effect are small fm cyclotrons capable of reaching about 10 and 20 MeV respectively. At this radius, capture should be complete and there is some confidence that space charge forces in this region can be calculated with reasonable accuracy. The Columbia model has already been noted and will be used for similar studies. Orsay has already studied the Livingston source in an rf model prior to the tests in their synchrocyclotron.

The CERN Program

As previously mentioned the hooded arc source has apparently given good results at Orsay. The CERN people have studied the source problem,[17] constructed a test facility, and may use such a source to increase the intensity and obtain better quality.[12] A higher dee voltage is needed in order to clear the source with a correspondingly greater fm rate or df/dt. A rotating capacitor has been investigated.[17] Another interesting study is a new vibrating capacitor with a higher initial df/dt to go along with the increased voltage.[18]

The Berkeley Program

The incentive to find a simple solution in the ion source region is particularly strong at Berkeley. The machine has been in operation since 1947 and is probably the most radioactive cyclotron in the world. Removal of the dee (which sounds like a simple task) will be a very lengthy and costly operation due to the high level of activity. While this move may be necessary, it is hoped that studies on the model will lead to something which can be easily added to the center region with the dee in place.

Some initial tests have been completed on this model and will be reported in more detail in a following paper. Some results will be mentioned here. One of the most interesting is the magnitude of the current that can be extracted from a calutron or hooded source with low rf accelerating voltages. The maximum current in a 100 μ sec pulse was 40 ma on the first turn with 20 kV on one dee in a field of 15 kG. Separate turns were observed on a probe. The vertical spreading of the beam was very evident, and in 2 to 3 turns the current had decreased to the order of 1 ma. The loss was attributed to space charge since the effect was very dependent on beam intensity. Some field measurements with sector wedges were made, but not intensively as yet, since it was obvious that no magnetic focusing could be effective in the first turn at a radius of about a cm. Vertical grid wires of 2 mil tungsten were installed to provide electrostatic focusing to a radius of 8 cm and were found to be quite

Proceedings of the International Conference on Isochronous Cyclotrons, Gatlinburg, Tennessee, 1966

effective. As much as 4 ma was accelerated to a radius of 8 cm where the wires stopped. Most of this beam disappeared vertically when the radius was increased beyond this point. About 1/3 of the beam was lost on the wires. The initial wires were cold, but the final wire glowed white hot. It was evident that if such a focusing system were used, the wires would have to terminate at a very small radius and magnetic focusing would then be required.

If ridges are used to obtain such focusing at a radius of 8 cm, the vertical separation must also be about 8 cm (preferably less). In this region the dee must therefore have a very small vertical aperture and the dee to ground spacing must also be small. Such a reduction in dee height cannot be realized in the Berkeley machine without rebuilding the dee. As mentioned earlier this is a major step and very unattractive. Hopefully, some other solution can be found.

Iron Sectors Inside the Dees

Columbia[2] and Uppsala[7] are seriously considering putting iron sectors inside the dee at dee potential. They would extend only over a limited radius until the effect of sectors on the pole faces could be felt. This is a bold step because the forces can be large, but it is also true that modern ceramics are very strong. The advantage of this arrangement is so great that it seems almost certain that in the near future some iron will be found inside the dees of synchrocyclotrons.

Capture Problems

The large number of ions that can be drawn from a calutron source serve little purpose if only a small fraction can be caught in stable orbits. Such appears to be the situation when it is used in conjuction with the focusing wires. If the fm rate is low, the high voltage accelerates the ions rapidly to a large radius where they get out of phase and return to the source. Those that survive execute large amplitude phase oscillations and most of them are lost on the wires. If the initial fm rate is increased, the number of ions that return can be greatly reduced, but then the acceptance time is shortened. A typical time is about 10 μ sec. This is to be compared with the acceptance time in the present Berkeley machine which is about 100 μ sec. The calutron source must therefore supply 10 times as many ions as the present source just to break even. This is about the order of magnitude observed. The payoff might not be in quantity, but in beam quality.

The reason for the order of magnitude difference in acceptance times seems to lie in the phase focusing properties of the uniform electric field that is impressed on the open source. The ions are forced into phase with the rf even though the frequency is not synchronous, so ions accumulate around the source for quite some time. Presumably they build up until space charge limited, but they also drift sideways in the dc dee bias field, which spreads the charge cloud. Ions are probably caught in a stable phase over a range of radii.

It would be very desirable to capture ions from the calutron source for at least a comparable time interval. Two possibilities are being considered. The ions can be accelerated with essentially zero frequency change. Normally they would return to the center as they slip in phase. In principle, the radial field profile can be tailored in a sector field so that the ions slip in phase toward the phase stable point. They gain less and less energy as this happens. Therefore they accumulate and move slowly at some radius which must be large enough so that the vertical focusing can be made very strong. When this has gone on for as long as possible, the fm program is turned on. A computer study is underway to find out if this is possible. The other approach is successive acceleration of ions in 10 μ sec intervals out to some storage radius where again the vertical focusing is strong. This could occur about 10 times, and then the fm cycle, when started, would hopefully catch most of the ions and accelerate them to full radius. This is the acceleration scheme that has been tested by the MURA group in their electron model.[19]

However, all these possible improvements mean nothing if the beam is limited by space charge later on. Clark[5] has calculated that the focusing on the Berkeley machine must be increased in the neighborhood of 10 in. radius. This can be done by sectors on the poles with a surrounding trim coil to maintain the original average field.

References

* Supported in part by the U.S. Atomic Energy Commission.

1. K. R. MacKenzie, Nucl. Instr. and Meth. 31, 139 (1964).
2. J. D. Lawson, Nucl. Instr. and Meth. 34, 173 (1965).
3. James Rainwater, Rev. Sci. Instr. 37, 262 (1966).
4. H. G. Blosser and M. M. Gordon, Nucl. Instr. and Meth. 13, 101 (1961).
5. D. J. Clark, (private communication).
6. L. R. Henrich, D. C. Sewell and J. Vale, Rev. Sci. Instr. 20, 887 (1949).
7. Synchrocyclotron Development Report, Univ. of Uppsala, Apr. 1 - Dec. 15, (1965).
8. La nouvelle source d'ions du synchrocyclotron d'Orsay, European Colloquium on A.V.F. Cyclotrons, Eindhoven, Holland, Apr. 21-23, (1965).
9. Conference on High Energy Cyclotron Improvement, Williamsberg, Md., Feb. 6, (1964).
10. L. Ruby et al., Rev. Sci. Instr. 27, 490 (1956)

Proceedings of the International Conference on Isochronous Cyclotrons, Gatlinburg, Tennessee, 1966

11. G. T. Kruiff and N. F. Verster, Philips Tech. Rev. 23, 381 (1961).

12. G. Brianti and E. G. Michaelis, MSC/M-1a/13 (1966) (CERN).

13. D. Bohm and L. L. Foldy, Phys. Rev. 72, 649 (1947).

14. J. Vale and K. R. MacKenzie (unpublished).

15. G. Huxtable (private communication).

16. K. R. MacKenzie, Rev. Sci. Instr. 22, 302 (1951).

17. R. Hecken, MSC Internal Report 65-3, Nov. 24, (1965).

18. H. Beger, M 51, Dec. 16, (1965) (CERN).

19. K. R. Symon et al., Rev. Sci. Instr. 35, 1459 (1964).

Addendum

The performance of the 30-MeV deuteron synchrocyclotrons at Buenos Aires, Lyon, and Göttingen strikingly demonstrates the effect of increasing the dee voltage. In particular, the machine at Lyon has achieved 56 μA of protons and 16 μA of alpha particles with 30 kV at 2000 pulses per sec.

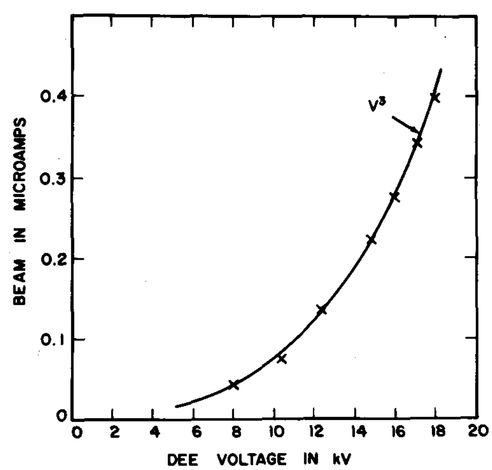

Fig. 1. Beam vs dee voltage as measured by Henrich, Sewell, and Vale on the 184 in. deuteron fm cyclotron. The beam is probably not intense enough to be limited at large radius.

Proceedings of the International Conference on Isochronous Cyclotrons, Gatlinburg, Tennessee, 1966

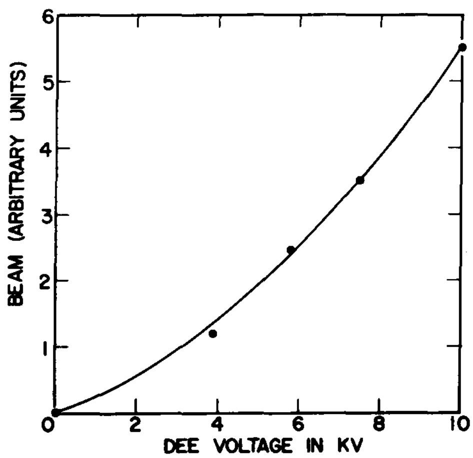

Fig. 2. Beam vs dee voltage as measured on the Uppsala fm cyclotron.

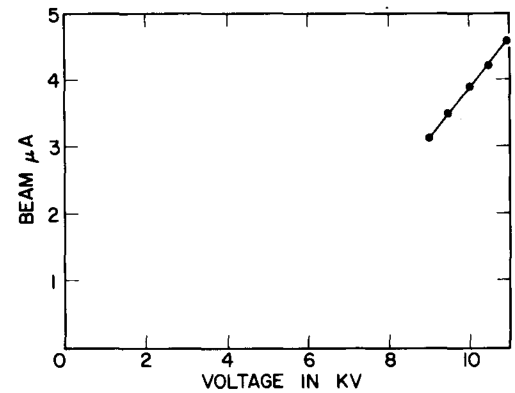

Fig. 3. Beam vs power supply voltage (proportional to dee voltage) as measured on the Orsay fm cyclotron with an Oak Ridge type ion source. There is a lower cut-off where the ions no longer clear the source. The 20 μA reported earlier (Reference 11) was obtained with C Cl_4 added to the gas. The reason for this performance seems to be not understood. The source failed in less than one hour due to corrosion and the test has not been repeated. The beam intensity before installation of the Oak Ridge source was normally about 3 μA.

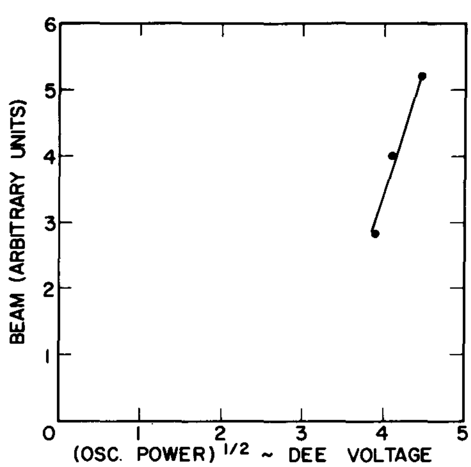

Fig. 4. Beam vs the square root of oscillator power (which should be proportional to dee voltage) as measured on the Rochester synchrolcyclotron.

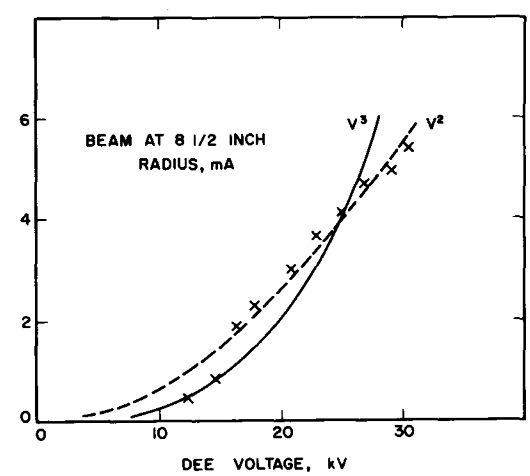

Fig. 5. Beam vs dee voltage for a conventional cyclotron. Data from the model studies of Ruby et al.[10]

DISCUSSION

RICHARDSON: About eight years ago, Ken had this idea about putting iron inside the gap; fortunately, our cyclotron survived that experiment!

HOPP: Dr. MacKenzie mentioned ion sources, and the strange things that happened. It was noticed that after leak-hunting with Freon in the Amsterdam machine, the internal beam went up appreciably; the same as with carbon tetrachloride. Evidently the chlorine and flourine both affect the ion source and increase the internal current. Both the machine at CERN and its copy at SREL use a mixture of argon and hydrogen. I don't know why, or if anyone does, but it doesn't work if argon isn't mixed with the hydrogen.

Also, a cross-coupling mode bothers both CERN and SREL, a beam-destroying mode that decreases the accelerating voltage. It is very beam-dependent, and, of course, must be eliminated before we can really make any progress.

Both the CERN and the SREL ion sources are very primitive, cold cathodes, just a little box down below the median plane, with a hole in the top. I think we will be starting an ion source improvement program in the very near future. We already have 50 nA extracted at 600 MeV.

MACKENZIE: Dave Hopp's comment about the ion source, I must say, is one of the things that prompted me to take up the occupation of plasma physics!

The cross-coupling mode is unique to the CERN and Chicago machines, but not Berkeley! The latter has two vibrating blades with what is called the upper and lower cross mode; they are so tailored that the correct mode stays in between them, all the way.

FOSS: Our space-charge limit has been increased by getting rid of the crossed mode on the dee with a trap on one side of the dee. We now get about two or three times the beam. Now, we have some other cause of blowup; we are still not limited by the ion source. I can only guess how much current we are getting; possible 5 μA, half on the target.

MACKENZIE: That's very encouraging to hear. I believe you have a higher repetition rate than some of the other machines. Something like 300 cycles a second; is this right?

FOSS: Right. 250.

ZUCKSCHWERDT: I would like to comment on the plateau in the ion source output as you increase the dee voltage. We realized at Heidelberg that the cyclotron with one-dee geometry and the hooded arc type ion source in the middle destroys the symmetry of the electric field. Having a large opening in the ion source creates a vertical component of the electrical field. This can disturb the electrons in the plasma so that no ionizing takes place at all. So, for a certain dee voltage range you get a flattening, then a decrease in the output of the ion source. With a single-dee system, and the ion source with a large opening, you will always have a flattening, or even a decrease in output.

MACKENZIE: I am aware of this. Lots of people have blown out the ion source with the dee voltage. I have ignored all such data on these plots.

BEGER: Concerning acceptance and df/dt, we have made five measurements showing that there is a clear dependence between the df/dt value and the accelerated beam as long as you extract relatively low current from the ion source. When the gas flow is increased in such a way that a tremendous amount of current is available, however, you don't see any increase. So I agree completely with your conclusion that there is, at high current, a complete space-charge limitation, and this may explain the experience of the Harwell people.

LIVINGSTON: Is there any new data on the matter of the rather large radial amplitudes associated with beams from synchrocyclotrons, which have been recorded in many prior meetings, and which apparently are a major drawback to designing efficient extraction systems?

MACKENZIE: Yes. I don't know whether anyone has ever pinpointed the exact reasons, but presumably the ions drift off center, maybe in the dc-bias field, or some other reason. This is assuming they start off center. Because, Orsay has shown that use of the Oak Ridge type ion source definitely cuts down the energy spread, and probably the radial oscillation.

REISER: I just want to comment that if you increase the voltage, the electrical focusing and defocusing effects become increasingly important, and also that one has to look into these effects, in any case, because they are highly space sensitive and they are defocusing as well as focusing for different phases. This is very important, and might be even stronger than ridge focusing, with iron. Of course, right at the ion source the only practical focusing is by electrical means, because of the low velocity.

MACKENZIE: Yes. I neglected to mention that Orsay has achieved some success in electrical focusing with shaped electrodes.

