# Beam Quality Measurements and Focusing Grid Studies

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I will review some measurements which were made 18 months or two years ago at Oak Ridge; we were trying to get our feet on the ground in the business of beam quality and to find out where we stood. We did just the experiment that Bob Livingston mentioned when he opened the session; we took deflected beams from a Cockcroft-Walton and from the 86-in. cyclotron and let them go through a small hole. We measured the current coming through the hole and its divergence. In this way one gets a measurement of the time-averaged phase-space density of the beam, provided corrections are made for the momentum difference of the two beams and for adiabatic damping. We repeated the experiment with varying ion source conditions. With optimum adjustment of the 86-in. cyclotron we obtained 0.18 amp per square centimeter per steradian; for the Cockcroft-Walton the best value obtained was 45 amp/cm$^2$-ster, so that there is a factor of about 250 in the raw data.

In addition you need to bring in adiabatic damping. The Cockcroft-Walton data is at 250 kv, the 86-in. cyclotron data at 23 Mev. The damping factor is the ratio of the momentum squared counting both coordinates so that with this factor included, if you accelerate the Cockcroft-Walton beam up to 23 Mev, it would in principle be 20,000 times brighter or more dense. This actually is not too surprising.

First of all the duty cycle of the cyclotron will reduce the time average of the brightness, which is what we measured. This accounts for a factor of between 10 and 100. In addition there are a great many poorly filtered voltages in the 86-in. cyclotron. It was built as an internal beam machine and for internal beam operation these ripples cause no bad effects. In the external beam, however, these voltages give an effect similar to the sweeping back and forth of an oscilloscope beam, which clearly further reduces the time-averaged brightness. Fortunately, most of the sources of ripple could be fairly easily removed if one started out to improve the machine, or to build a new one; the picture on cyclotron beam quality is not as black as would be assumed from taking these measurements at face value. The measurements clearly show, however, that if the concept of beam quality is disregarded, as is done in the design of an internal beam cyclotron, then results can get very bad.

At Oak Ridge we also made a study of the use of electric focusing grids at the center of the cyclotron. There are a lot of similarities with the experiments at ANU discussed by Dr. Smith.

Figure 197 is a sketch showing conceptual features of the system. The grid structure is placed on the entrant side of the dee on each half-turn so that the defocusing half of the electric field is eliminated as shown in Section A-A'. The grids are placed so that as the beam spirals out it passes through slits in the grids as it enters the respective dees and receives an axial focusing impulse. With the dimensions which we are considering, turns are well separated so that you do not have to intercept much beam if a relatively narrow slit is used on the first half-turn to skim off out-of-phase particles. If this is not done, the beam spreads out in radius due to differences in energy gain and the turn separation is soon lost. With the sort of geometry used for these grids, there is essentially no phase grouping.

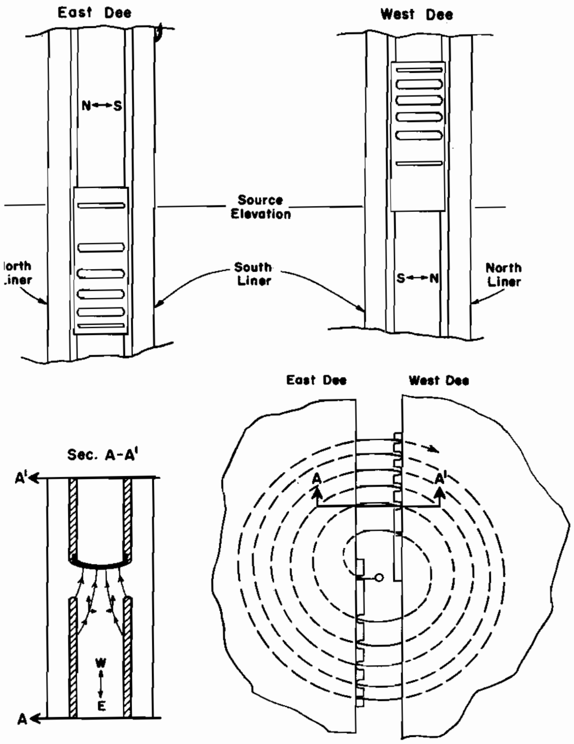

Fig. 197. Schematic of focusing grid arrangement.

The actual graphite structures used in these experiments are shown in Figure 198. The source is not shown in the photo, but would sit in between the two grids. The narrow slit in the upper grid is the extractor slit; the narrow slit in the lower grid is the phase-trimming slit. With this arrangement we threaded the beam through five turns. With a 1-in. axial aperture and with the phase slit set to transmit a 40° interval, we obtained a total proton current of 3 to 4 ma at the end of the 5 turns. The spread in orbit centers along the line of dees (principally caused by the spread in r-f phase) is held to ± 0.1 inch. These numbers compare with a current of 2 to 2.5 ma which is obtained under the same conditions without grids and with a spread of centers along the line of dees of ± 0.4 inch.

The axial focusing frequency was measured for this arrangement by blanking off part of the source and

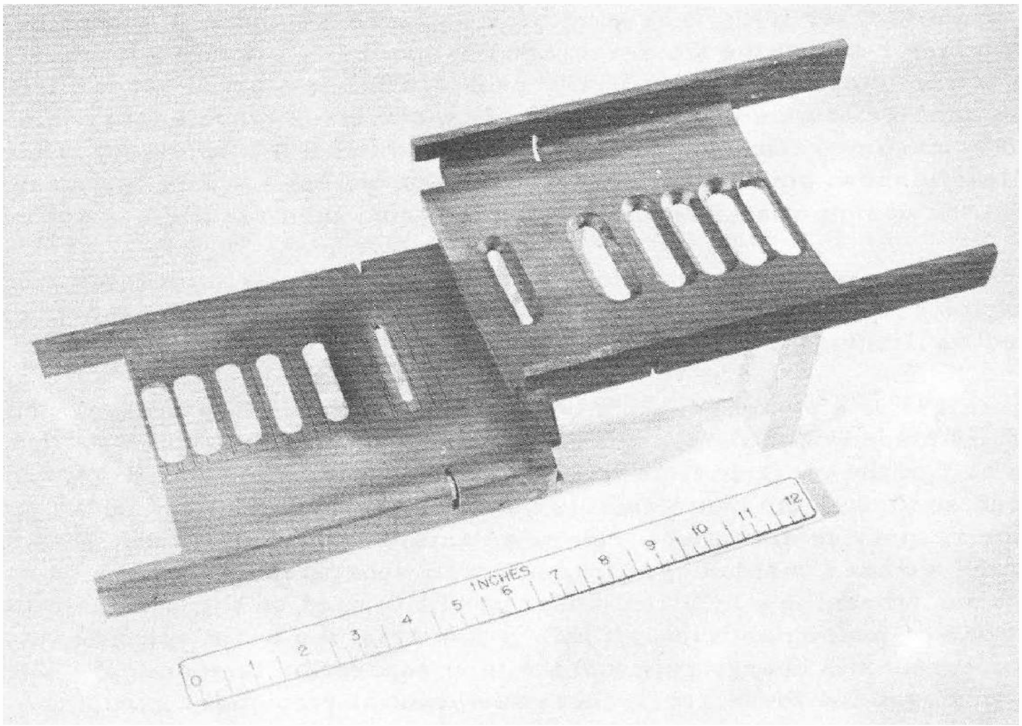

Fig. 198. Graphite grid structures.

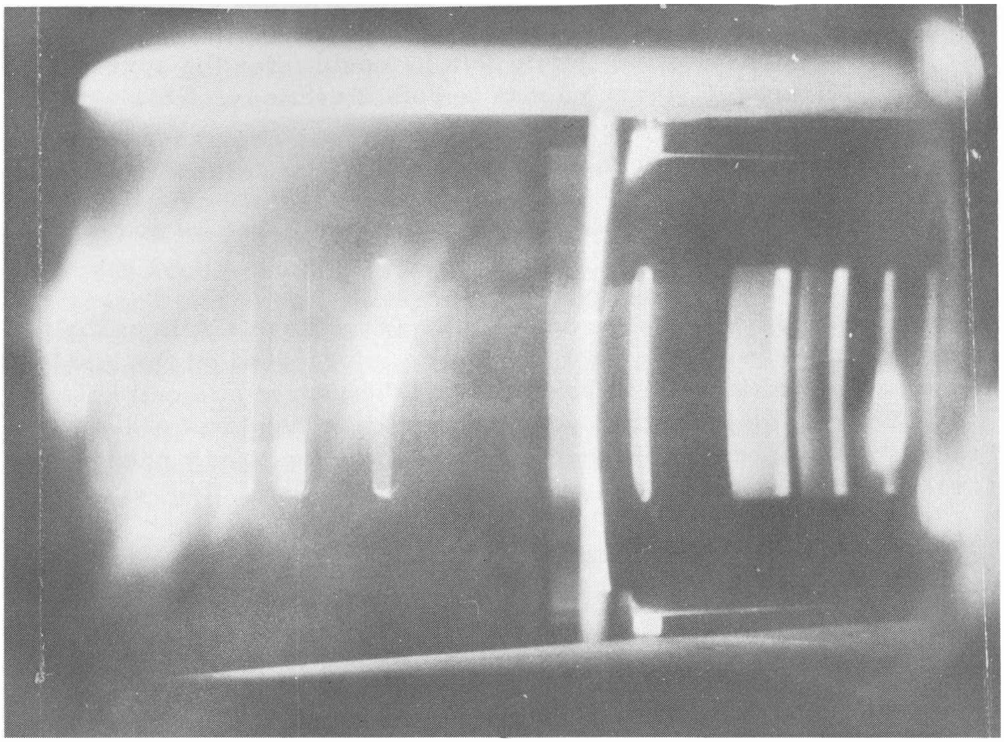

Fig. 199. Graphite grids in operation in ORNL 44-inch cyclotron.

observing the weaving back and forth of the remaining beam. From this we get the value $\nu = 0.2$, to about 25% accuracy. We got similar $\nu_z$ value from a computation based on data obtained with an electrolytic tray.

Figure 190 shows a set of grids actually in operation in the cyclotron. This is an earlier set of grids and we did not yet have the spacing worked out quite right; considerable beam is being intercepted. There is a bright spot at each point where beam is lost. The grid would become white hot at some of these spots. These graphite grids are very durable. We were never able to detect any damage to the grid structures, even after we had been dumping about two kilowatts on the grid.

We obtained also some information from these experiments relative to the distribution of orbit centers at right angles to the line of dees, which relates to the initial phase-space density of the cyclotron beam. Referring back to Figure 68, we used our phase-selecting slit near point C to trim off $P_4$, $P_5$, $P_6$ and similar orbits. We then obtained a measure of beam spread by letting the beam melt a hole in a thin foil suspended at point D. We did this a number of times; with a 1/8-in. slit at point C we got typically a 3/8 in. radial-width hole at point D. The wider beam at point D indicates that the beam is fanning out from somewhere in the neighborhood of C; there is a distribution of centers at right angles to the line of dees of about ± 1/8 inch. The effect can't be obtained from simply a spread in phase.

The calculations which Lind and Smith (W.I.B.) have presented assume that the distribution of centers at right angles to the line of dees is extremely small, essentially just a point, and that the main effect one gets is a motion of the center along the line of dees as the phase of the particles varies. Our data indicate that the distribution at right angles is also substantial and should be included in the calculations.

There is also a nice experiment which Paul Hough* did several years ago in which he measured the distribution of directions of the beam at the outside of the University of Michigan cyclotron. From this he could infer the spread of centers; he obtained a distribution of about ± 3 mm in both directions. This agrees quite well with the result which we get.

POWELL: Can you be sure that the 3/8-in. hole that you got in your foil wasn't the result of some sort of switching on, tuning-up spray, before you were running steadily?

BLOSSER: We think we are sure of this. The phase slit is at the maximum radius that the beam can reach; a lot of beam is intercepted on the inside of this slit but none on the outside. The phase slit and the source are quite closely 180° apart. If you try out the geometry, you find it is quite hard to make the beam go through the slits and then have it wiggle up and down due to any phenomenon other than a spread from the source.

POWELL: Do you not think that these effects may vary quite critically on your ion source fadeout position? What in particular was the setup just at the ion source and beyond that?

BLOSSER: The source has a circular chimney about 1 in. in diameter with a flat about 1/4 in. wide milled on the side facing the puller. The beam slit in the chimney is about 1/16 by 2 inches. The puller is a broad flat surface with a 1/4 in. wide slit in it (Fig. 198). Royce Jones should be contacted for further details of the source. These experiments were run at 21 kv dee-to-ground. The voltage was set at this value to give turn spacings equivalent to those in the new Oak Ridge cyclotron.

SCHMIDT: I might comment on the rugged character of your graphite by saying that for two and one-half years we have had the same graphite exit strip in our cyclotron.

W.I.B. SMITH: Were you very careful to get the front of the source parallel to the puller, so that the force between the ion source and the puller is perpendicular to the dee? And also do you have any measurement of the ripple on the dee?

BLOSSER: We didn't make a measurement of either of these effects.

MARTIN: This antular distribution that Blosser observed is just about what one would expect from this geometry. Unless considerable attention is paid to the shaping of the electric field, keeping it parallel, for example, Smith's suggestion, one will get a broad angle of distribution from sources of this general type.

BLOSSER: If the beam is parallel, the centers are all on a line which means infinite phase-space density. I think its reasonable to assume the Cockcroft-Walton phase-space density as an upper limit; from this you deduce that the distribution of centers cannot be much smaller than we measure.

LIND: The plasma interface on the r-f cycle is going to change. I would imagine that it would become concave and give a strong crossing effect as the ions are pulled out of the plasma. Does anyone know how much effect there is?

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*P.V.C. Hough, Rev. Sci. Instr. 24, 42 (1953).

BLOSSER: I would expect an effect, although I don't know any numbers.

MARTIN: This is dependent on the condition at which you run the arc. For example, with a low intensity arc there is a very considerable effect just near the ion source. This has been observed by looking at the edges of the arc through a hole in the pole piece in a calutron. What happens depends very strongly on the geometry of the current density. Ordinarily it takes a very high arc density to make the emitting surface bulge outward so that the beam really "blows up" at the source. At the second half of the accelerating gap, even though the beam focuses down coming out, it will defocus beyond that point unless the geometry is arranged to give good focusing throughout the whole acceleration region. This is for d-c acceleration, and I suspect that the same condition with additional complications applies for r-f acceleration.

VERSTER: Just a point. It is, of course, well known in r-f acceleration that there is always a focusing of the beam where the concaved boundary and the position of focusing depend critically on the density and on the deflection voltage.

BLOSSER: That is fine just as long as there is a good crossover rather than a parallel beam coming out.

W.I.B. SMITH: Our graphite ion source rises rather rapidly backwards, that is, right inside of the ion source, and we don't get a thin line of all the centers, as I had in my diagram; we do get a definite spread certainly of the order of a millimeter, or possibly more.

BLOSSER: This is then getting to be the same order of magnitude as we measure.

SCHMIDT: I should comment that our ion source is also that way.