October 23, 1963

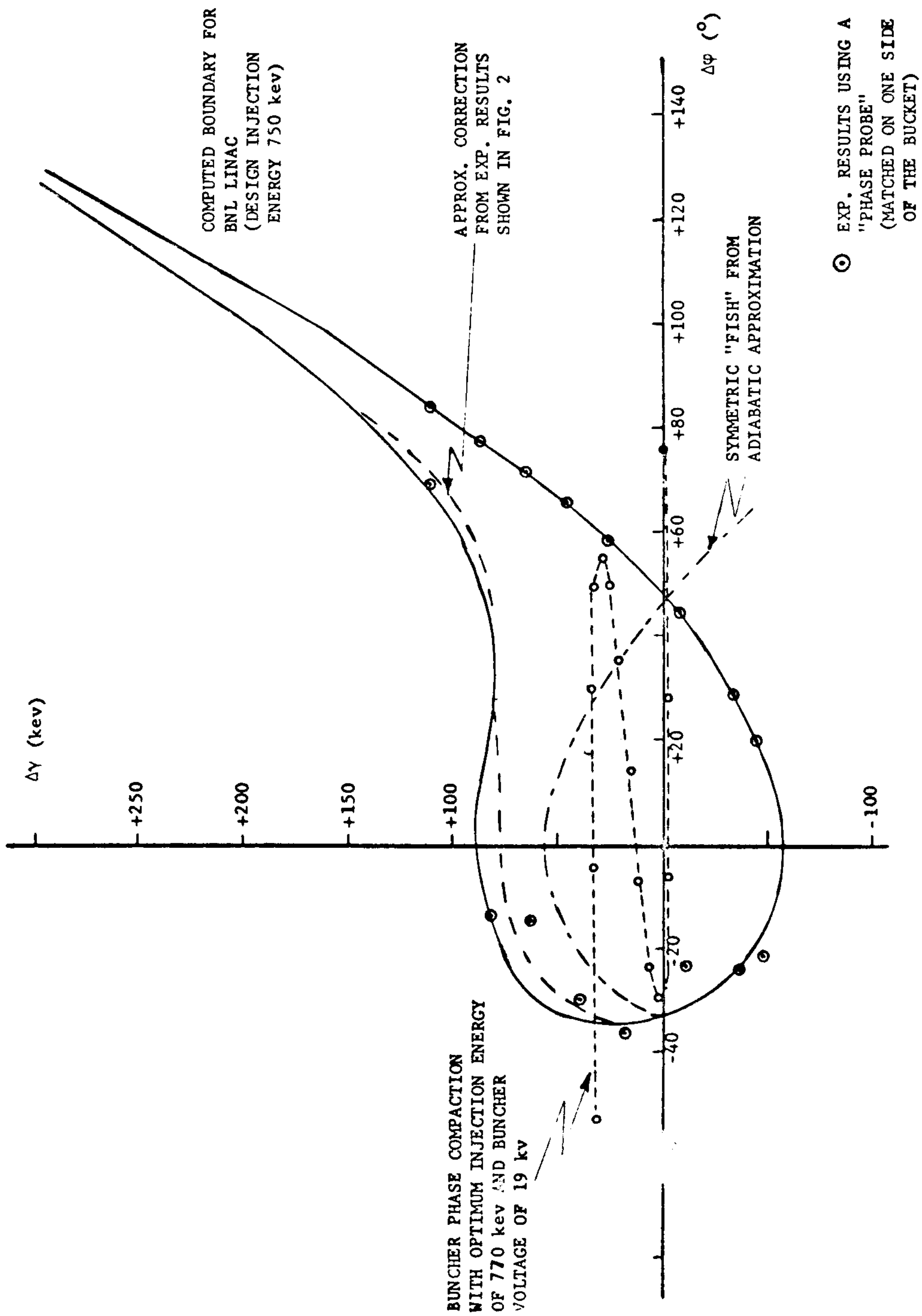
AGS INJECTOR AND PREINJECTOR BEAM STUDIES

A. van Steenbergen
Brookhaven National Laboratory

Before reporting on the results of the linac experimental studies, I should like to make a few comments on present linac operational plans. At the moment, concentrated efforts are being made to increase the linac beam intensity to values of the order of 50 mA of protons. Presently (October 1963) the linac usually runs around 15 to 20 mA at 50 MeV. Work is being carried out on a higher gradient structure for the preinjector. An operational duoplasmatron ion source is being constructed and will be life-tested shortly. New beam transport elements between preinjector and linac are being designed with apertures of up to 2 1/2 inches instead of the present 1 inch diameter. This is in order to reduce beam losses while running with larger beam intensities. New drift tubes with larger apertures together with focussing quadrupoles are being constructed to replace the first eight drift tubes in the linac. This is done to increase the transverse phase space acceptance of the linac which has been found to be limiting the linac output beam intensity while running with the duoplasmatron source.

Part of the rf system is being redesigned in order eventually to provide up to 8 MW of pulsed rf power for driving the linac cavity and adequately compensate for beam loading. Improvements in instrumentation are being carried out. A pulsed momentum analyzer will be made operational in the course of next year in order to measure the absolute energy, energy spread and emittance of the 50 MeV beam, simultaneous with AGS operation. In the past year, AGS study periods have been used regularly to investigate linac behavior and some of the results obtained will be reported here.

The longitudinal phase acceptance has been calculated by J. P. Blewett for the BNL linac and by R. Taylor for the 15 MeV Nimrod injector. The results indicated a high energy acceptance tail attached to the usual and expected symmetric "fish" diagram. This is shown in Fig. 1. It was interesting to try to verify this experimentally and this was done with a "phase probe" provided by the buncher. The usual phase compaction of the buncher at the time of linac capture is shown in Fig. 2a. This is a calculated shape for a buncher voltage of 19 kV. The phase width ("S" width) of this compacted bunch is approximately 90^{o} ($3\varphi_s$). Also the energy spread of this bunch is relatively high. Consequently this bunch would cover a rather large area of the longitudinal phase acceptance diagram and the resolving power of the

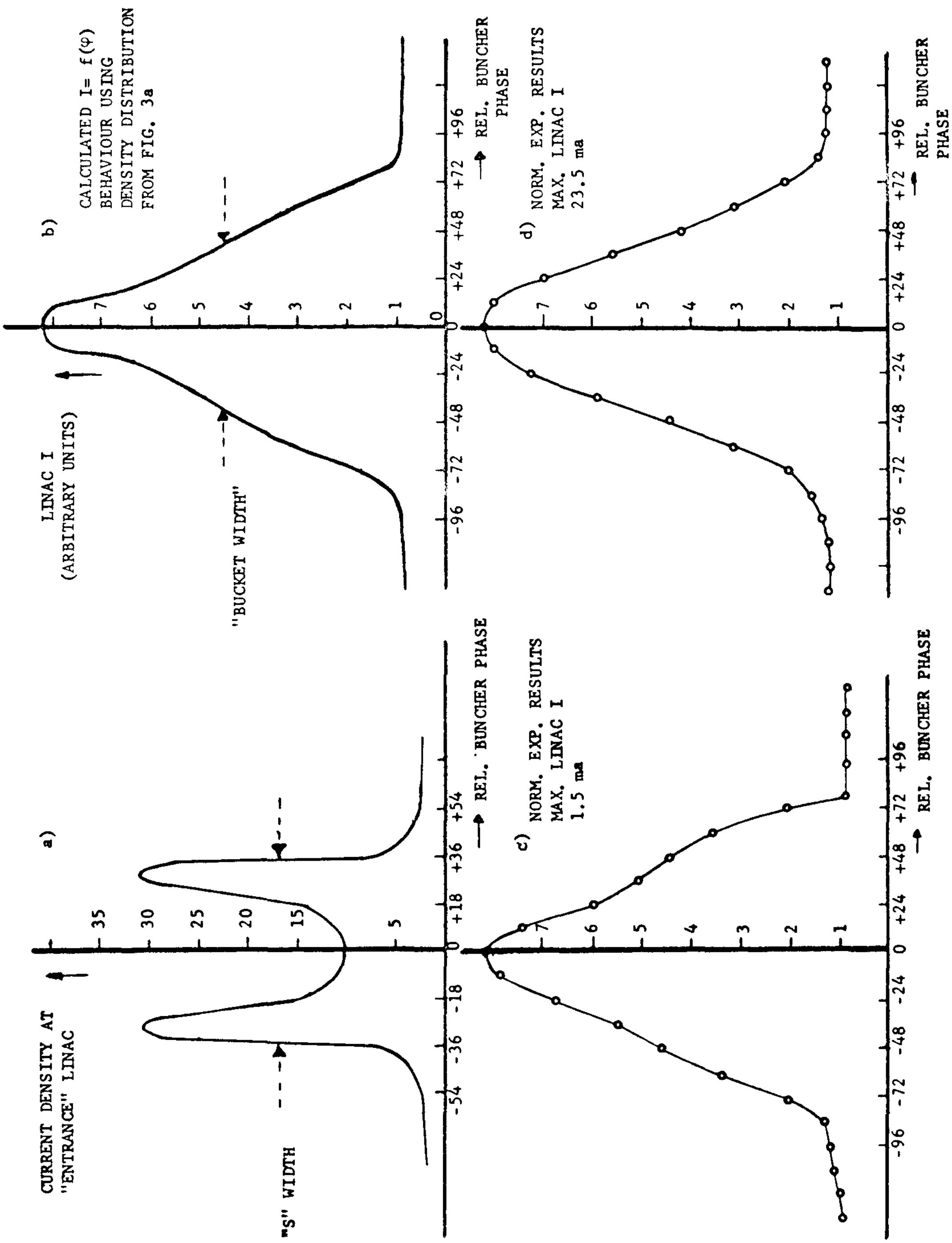


$\Delta\gamma$ - $\Delta\varphi$ STABILITY BOUNDARY

Figure 1

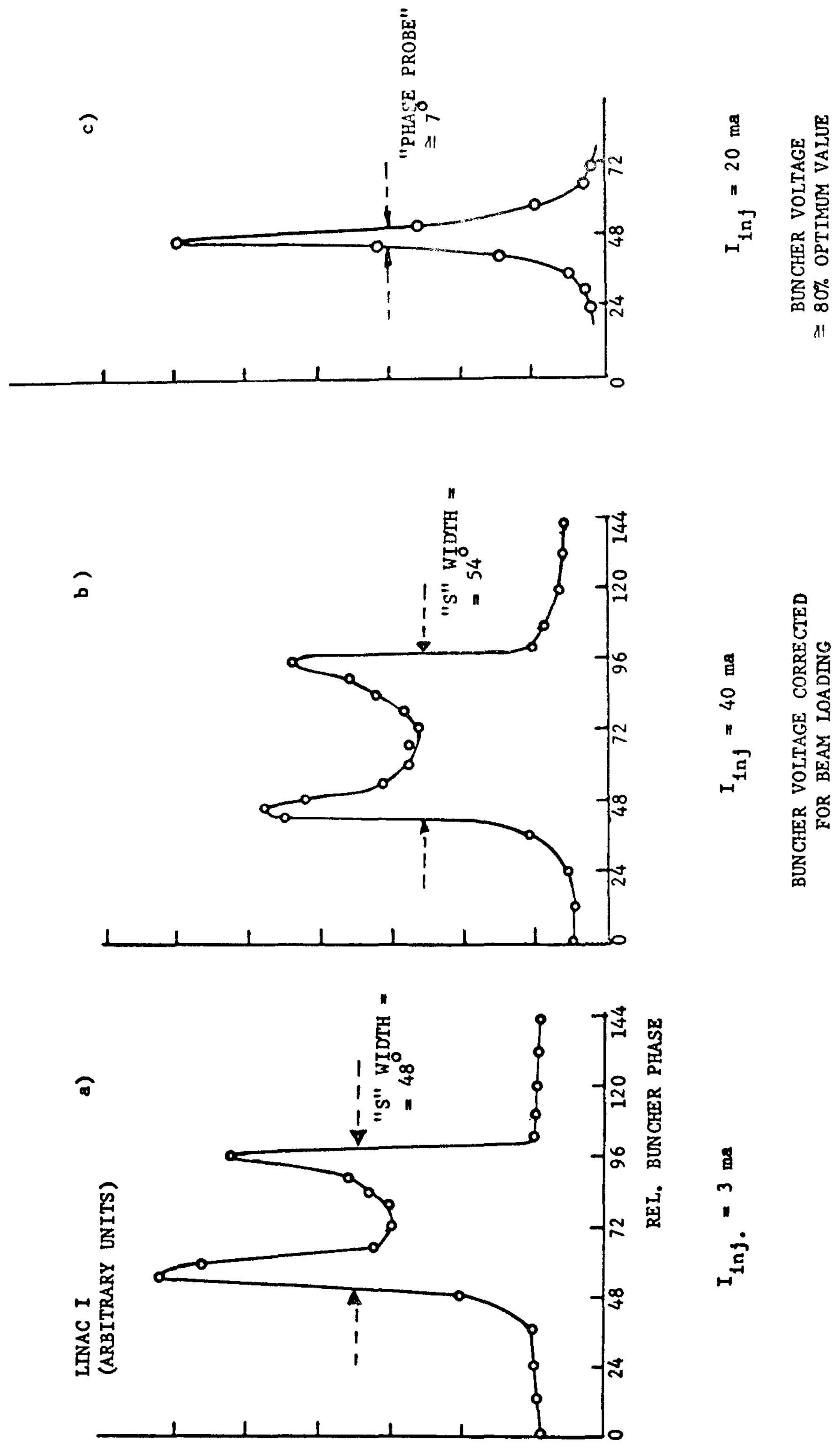
method for phase acceptance determination would not be very good. Decreasing the buncher voltage, however, provides a much more satisfactory "phase probe." This is because the folding of the sinusoidal shape into the optimum capture "S" shape (see Fig. 1) is not completed then at the time of linac capture and a single intensity peak as a function of time is obtained.

To adjust the buncher voltage properly it was necessary to study the "phase probe" shape and this could be done by using the linac as a detector. Increasing the injection energy from the operational value of 770 keV to about 850 keV and reducing the longitudinal acceptance by reducing φ_s results in a very narrow acceptance window at 850 keV of the order of 10° or less. Adjusting the buncher phase now relative to the linac rf phase resulted in a scanning of this narrow phase window over the time compacted bunch. A plot of the linac output intensity as a function of relative (linac-buncher) phase for a typical case is shown in Fig. 3c. Having obtained an ideal buncher voltage setting for minimum width "phase probe," scanning over the linac acceptance at various input energies can be done to determine the acceptance diagram. Some results are shown in Fig. 1, verifying computer results. Some results of beam compaction using the above mentioned method of detection with optimum buncher voltage settings are shown in Fig. 3a and Fig. 3b. Here, qualitatively,



BUCKET WIDTH DETERMINATION

Figure 2



BUNCHER PHASE COMPACTION

Figure 3

some effects can be seen of longitudinal space charge blow up. Especially for high relative buncher phase values in Fig. 3, the cutoff is extremely sharp for low injected current and somewhat smoothed out for higher injected current values.

BLEWETT: Swenson spoke Monday morning about the effects of radial motion on the phase acceptance and showed some results that indicated that it should shrink this acceptance area. In this case, radial motion is not taken into account in the computation, and yet you seem to have had fair agreement with the theoretical predictions.

COURANT: I might add that I recently modified the same program in order to get the radial matrices but while I have not as yet obtained many results, the few I have indicate that the radial stability for this kind of capture is quite good up in the tail also.

VAN STEENBERGEN: The only thing that I can say in this respect is that we have not actually looked, at this particular stage, for any radial-longitudinal interaction effects. The results were obtained with a normal diameter beam. Ideally, of course, a pencil beam should be used to study longitudinal phenomena. This might be done in the future when more sophisticated beam defining devices are introduced between the pre-injector and linac.

Experimental verification of proper transverse phase space matching of the preinjector beam to the linac radial acceptance can be obtained by measurement of the linac emittance with a preinjector beam of known (measured) emittance. Computed results for radial phase space properties of the linac obtained by L. Smith of Berkeley and D. Cohen of Argonne indicated that because of rf phase dependence, the effective emittance value (the boundary enclosing all instantaneous emittance values for all stable phase values) to be expected experimentally is approximately 1.5 times the instantaneous value for theoretically "good" matching. Consequently, the expected correlation of emittances for the BNL linac is

$$0.2 \text{ Area } F\ (x,\ \alpha_x)_{750\ \text{keV}} = \text{Area } F\ (x,\ \alpha_x)_{50\ \text{MeV}}$$

Any deviation from this relationship will be taken up in a "mismatch factor." Some typical results are given in Table I.

TABLE I

Area:* $F(x,\alpha_x)_{750\text{keV}}$ (cm-mrad)	I_{ej} (mA)	Area:* $F(x,\alpha_x)_{50\text{MeV}}$ (cm-mrad)	Expected Area: $F(x,\alpha_x)_{50\ \text{MeV}}$ (cm-mrad)	Mismatch Factor
13.0	23	5.0 (x,α_x)	3.6	$\cong$ 1.5**
		5.9 (y,α_y)		

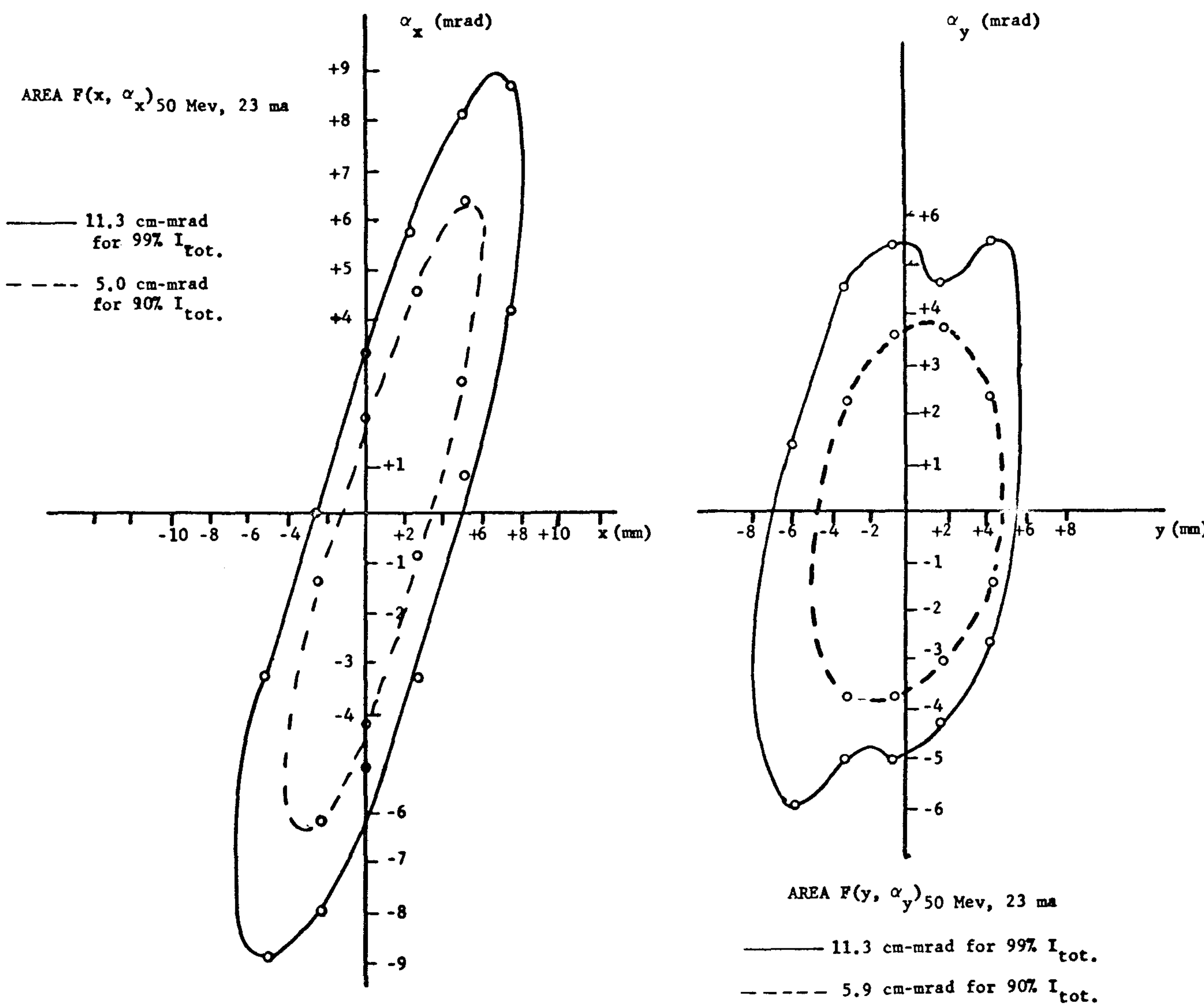
* 90% of I_{tot}

** With buncher excitation

The above figures were obtained with the use of the buncher preceding the linac. The mismatch factor in this case is about 1.5. Some typical linac beam emittance diagrams are shown in Fig. 4. Similar results obtained with identical preinjector conditions but without buncher excitation showed a smaller linac emittance. The mismatch factor in this case was approximately 1.1. These results qualitatively verify the coupling between longitudinal and transverse motion in the linac.

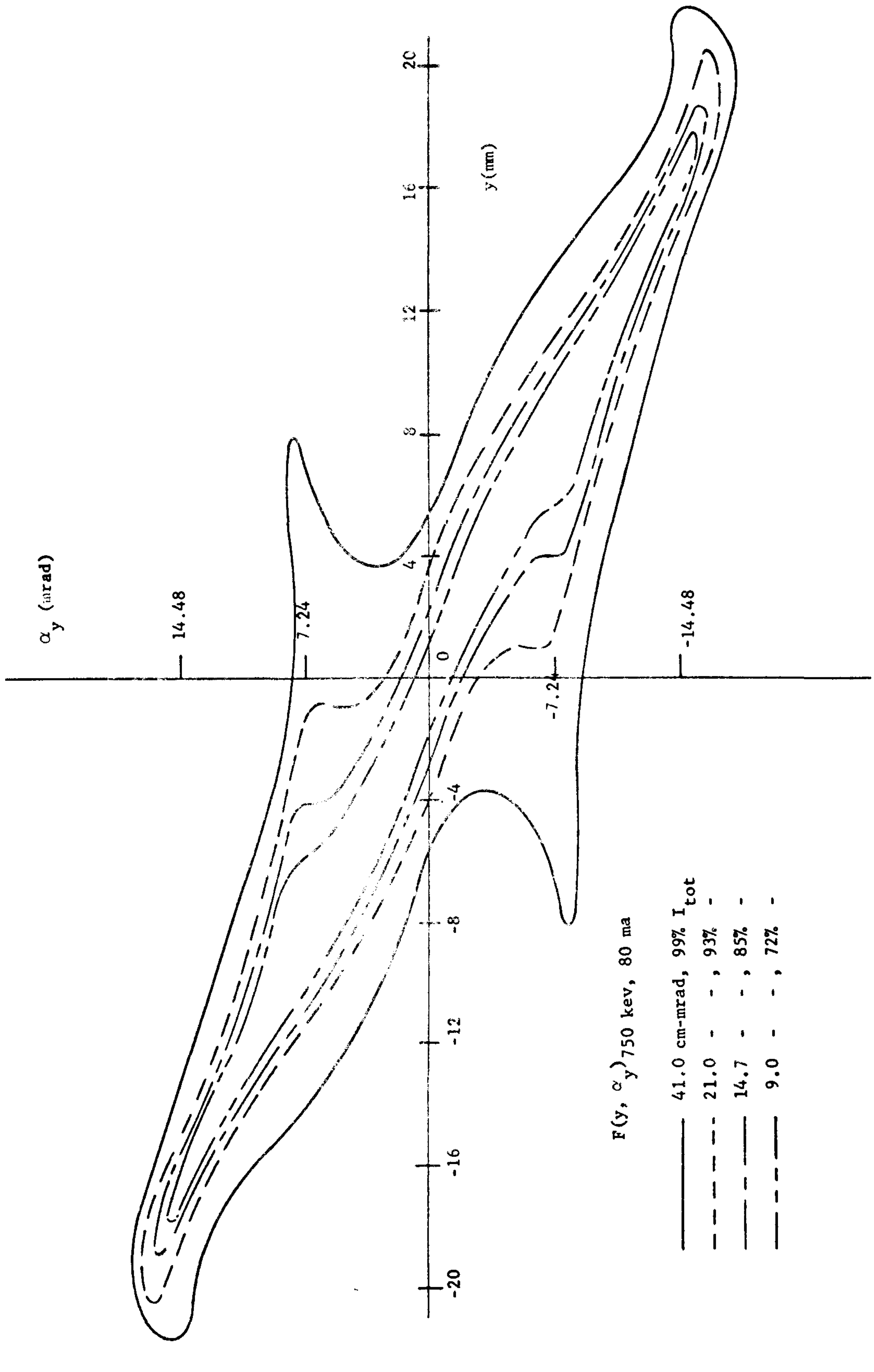
Some typical results on preinjector emittances are given in Fig. 5 and Fig. 6. These results indicate clearly the inhomogeneous density distribution in phase space and distorted boundaries. It is worth while to bring out this point because when comparing performances of various ion sources the simplified approach is to use an assumed homogeneous density distribution within a certain emittance boundary.

Collected results of preinjector emittances with the duoplasmatron source were compared with similar results obtained at CERN by T. Sluyters and U. Talgren with the rf ion source. The CERN group has reported currents of the order of 150 mA at 500 keV and has done even better than this. At BNL, the highest current obtained at 750 keV with the duoplasmatron was approximately 100 mA, this being limited by the preinjector optical system rather than by the duoplasmatron source. These results are given in Fig. 7 and indicate that the 2-dimensional phase space "density" for both sources is comparable in magnitude. Actually, a better figure



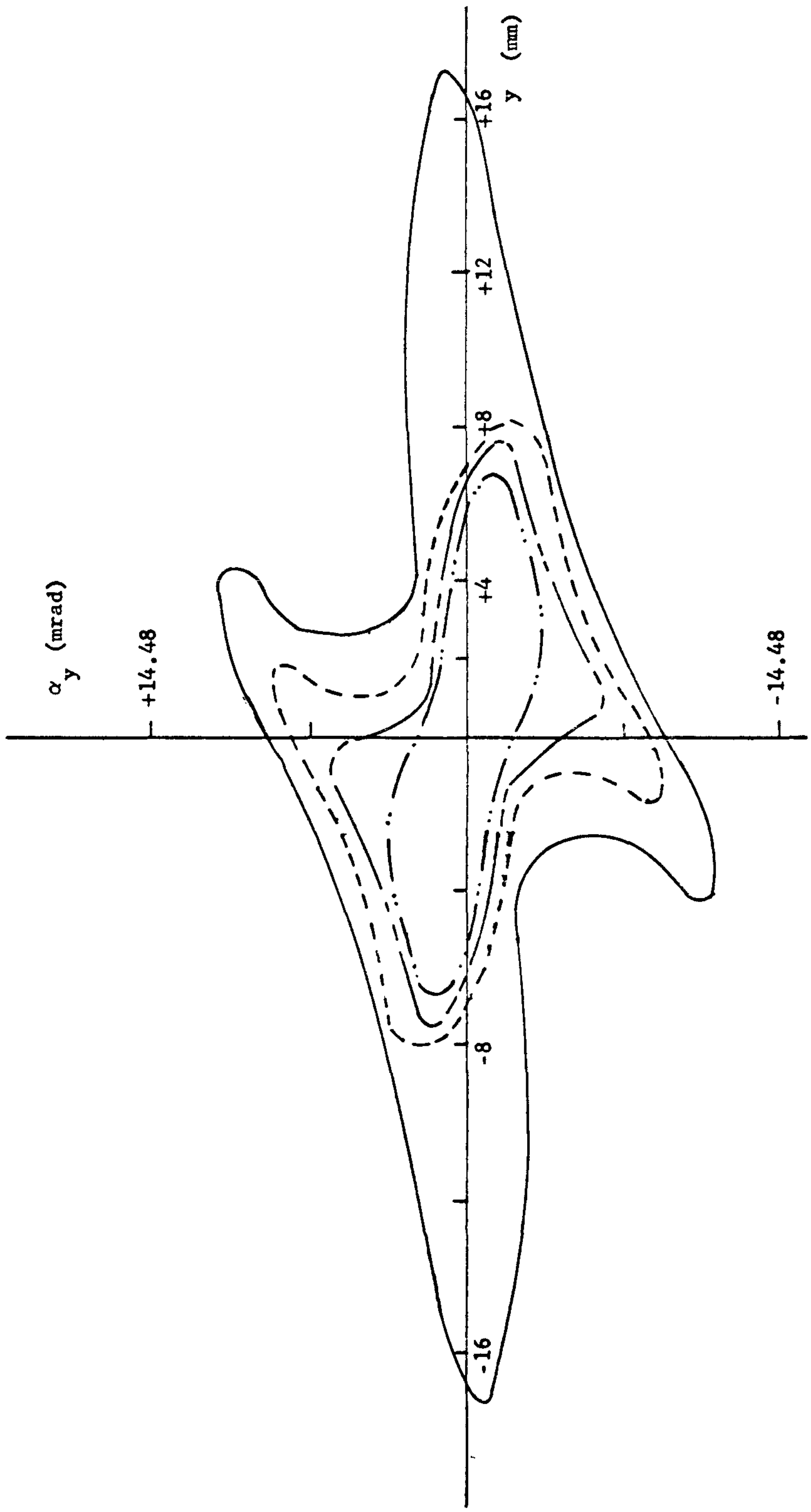
LINAC EMITTANCE

Figure 4



DUOPLASMATRON SOURCE EMITTANCE

Figure 5

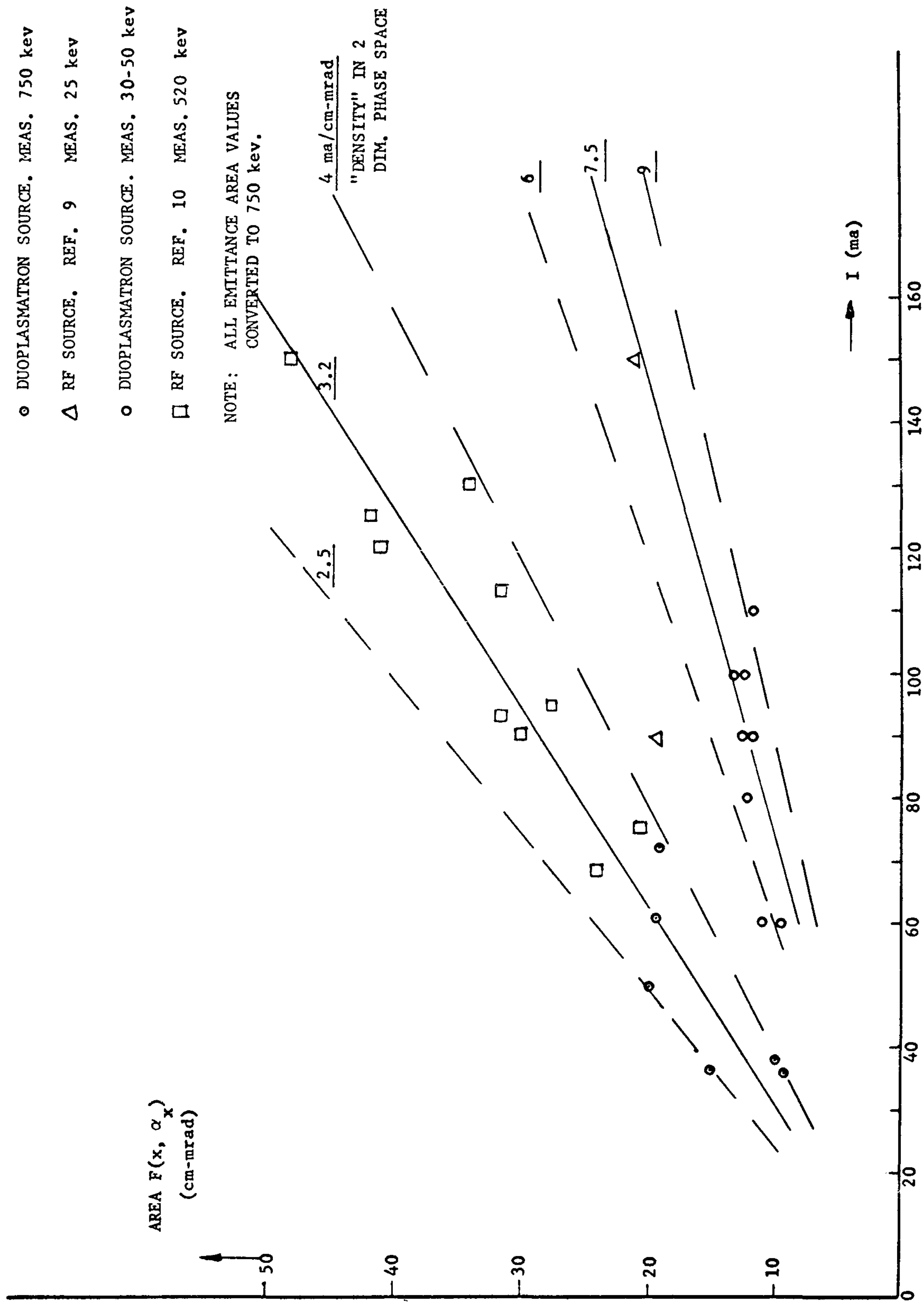


AREA F(y, α_y)750 kev, 40 ma

26.0 cm-mrad, 99% $I_{tot.}$
12.3 " " , 91% "
8.0 " " , 79% "
5.0 " " , 65% "

P.I.G. ION SOURCE EMITTANCE

Figure 6



COMPARISON DUOPLASMATRON AND RF SOURCE

Figure 7

of merit for comparison is the particle density in six dimensional phase space, which for the case at hand can be simplified to particles per unit time density in the 4-dimensional phase space projection. Therefore, the "brightness" of the ion source or pre-accelerator beam is defined here as

$$B = \frac{I}{\pi^2 v_x y_x} \qquad \frac{mA}{cm^2\text{-}sr}$$

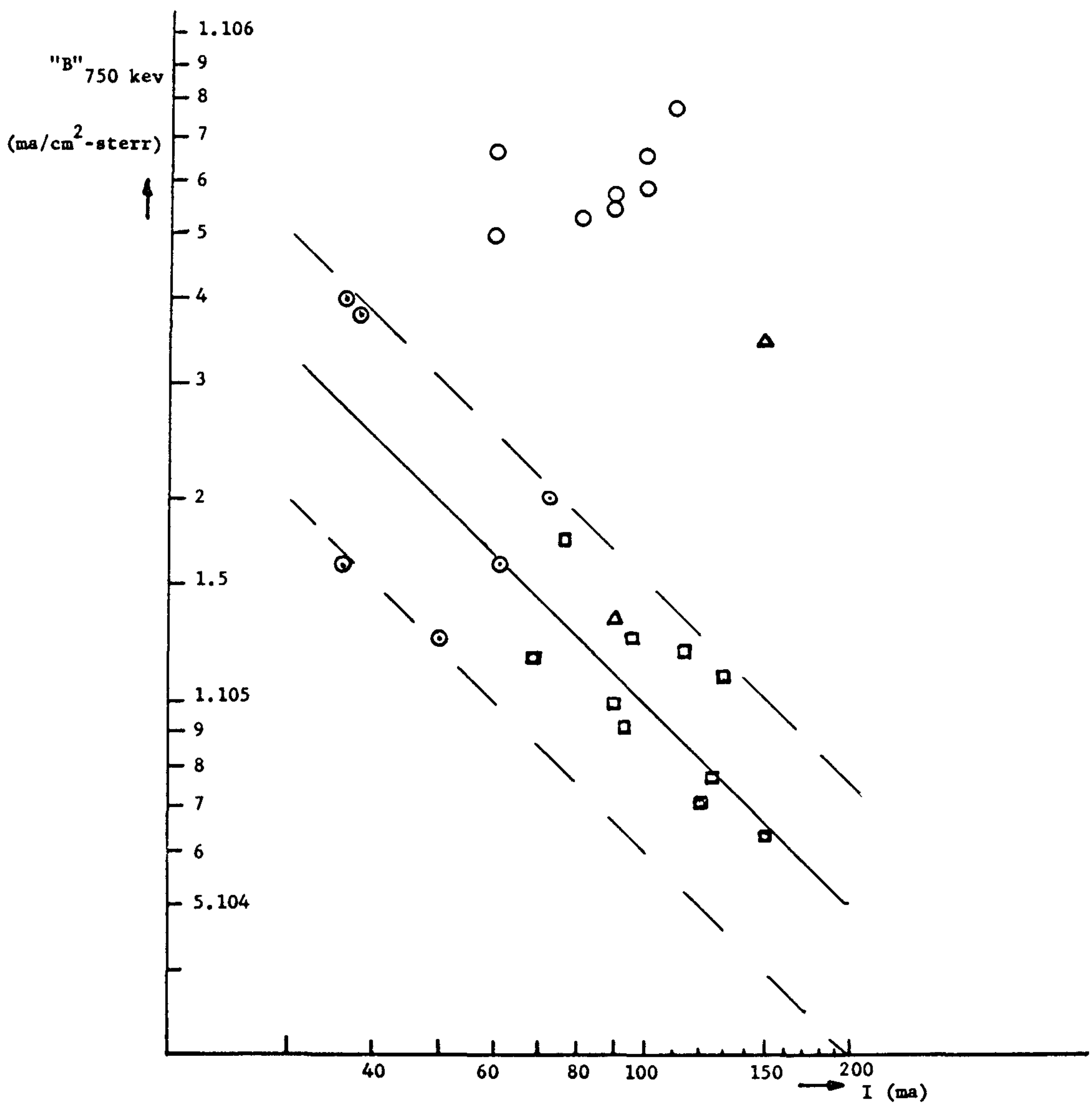
where v_x (or v_y) is defined as:

$$v_x = \text{Emittance} \quad (p_z) \quad \frac{\beta}{(1 - \beta^2)^{1/2}}$$

$$= \frac{\text{Area } F(x, \alpha_x)}{\pi} \quad \frac{\beta}{(1 - \beta^2)^{1/2}} \text{ (cm-rad}$$

In Fig. 5, the values of $B\beta^2/(1 - \beta^2)$ for 750 keV beams are plotted as a function of beam current showing the rather unpleasant behavior to the effect that the "brightness" for both ion sources is inversely proportional to beam output.

A significant observation from the results shown in Fig. 8 is that there is a loss of "brightness" in the present preinjector of the order of a factor of 10. In other words, an effective dilution in phase space takes place during transport and acceleration



"BRIGHTNESS"750 kev

DUOPLASMATRON, RF SOURCE

⊙ DUOPLASMATRON SOURCE, MEAS. 750 kev

△ RF SOURCE, FROM FIG. 10, MEAS. 25 kev

○ DUOPLASMATRON SOURCE, MEAS. 30-50 kev

□ RF SOURCE, FROM FIG. 10, MEAS. 520 kev

NOTE: ALL VALUES CONVERTED TO 750 kev.

Figure 8

from the ion source to the 750 keV level.

A similar comparison of "brightness" values at input and output of the linac can be made using the emittance values mentioned above. However, here the time structure of the proton beam in the linac has to be taken into account. The results indicate that during linac acceleration there is no observable loss of brightness over what is calculable and predictable in a simple approach.

The approach at present is to try to eliminate the effective phase space dilution in the preinjector in order to increase AGS beam intensity.

Regarding the above results, it is worthwhile to mention here the encouraging results obtained by A. I. Solnyshkov at the Leningrad Research Institute of Electrophysical Equipment. At 700 keV a beam current of 400 mA was obtained with a modified duoplasmatron as ion source. Preliminary measurements seem to indicate emittance values substantially better than mentioned above. Two interesting modifications from conventional preaccelerator systems and duoplasmatron sources have been made.

(a) Both the ground plane and the ion source are located inside an accelerator column with a normal voltage gradient on the air side (approx. 4 kV/cm), such that a mean gradient of up to 12 kV/cm can be provided in the accelerator region. Essentially the only lens action provided for near the ion source is that obtained from the transition of low to high field at the entrance of the accelerator region.

(b) Instead of a small plasma expansion cup used up until now in a conventional duoplasmatron source, a rather large cup has been used (up to 10 cm diameter and 20 cm length) providing the possibility of maintaining a relatively large beam diameter even in the near zero energy region close to the plasma boundary. Also a large diameter extraction electrode with grid is used opposite the plasma boundary.

As stated, currents of up to 450 mA have been observed at 700 keV. The observed beam diameter at the waist in this case was 15 mm. No detailed emittance measurements had been done yet (Sept. 1963) but from the recorded beam profiles at 700 keV it is possible to obtain approximately an upper limit of the phase space area. The results are given in Table II where they are compared with BNL (duoplasmatron) and CERN (rf source) preinjector performance:

TABLE II

Preaccelerator	Ion Source	I (mA)	v (cm-mrad)	B mA/cm^2-sr
Leningrad	Modified Duo-plasmatron	400	0.1	4.3×10^9
BNL	Duoplas-matron	100*	0.5	5.3×10^7
CERN	rf source	150-200	0.6	4.6×10^7

* The present BNL preinjector limits the maximum output current rather than the duoplasmatron source performance.

It is suggested from these figures that the "brightness" of the Leningrad preinjector is two orders of magnitude better than either the present BNL or the CERN preinjector. As indicated before, there is evidence with the BNL preinjector which indicates a loss of brightness of a factor of approximately 10 between the extraction region, the 50 keV level, and the 750 keV level.

Studies have been started at BNL to evaluate in more detail the beam quality with a duoplasmatron source with large plasma expansion cup.

LEISS: What is the quadrupole configuration in your linac?

VAN STEENBERGEN: We use the (+,+,-,-) configuration.

LEISS: Then you still have the original quadrupole arrangement?

VAN STEENBERGEN: Yes. We have not changed this because we need about 2 1/2 times the current in each quadrupole in the (+,-,+,-) arrangement. Aside from the availability of the electronics to drive the quadrupoles we would like to check some quadrupoles on the bench and find out if we get essentially the same percentage of higher harmonics because of saturation effects in the steel.

LEISS: Can the quadrupoles be individually adjusted?

VAN STEENBERGEN: Yes. All quadrupoles run at design current values except the first quadrupole, which is normally adjusted somewhat around the design value for maximum beam output. But if the rf level is increased in the tank by about 5% to 10% then it is found that the whole distribution of quadrupoles must have a current increase of about 10% in order to get a maximum beam current. The gain in total beam intensity is, however, negligible and therefore we run normally with design current values.