REDUCTION OF EFFECTIVE EMITTANCE BY STACKING BEAMLETS IN PHASE SPACE

M.R. Shubaly

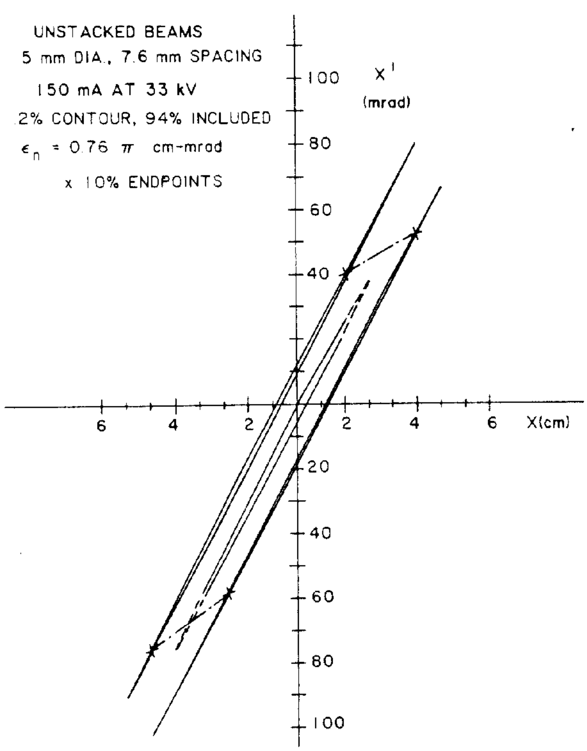
Atomic Energy of Canada Limited, Research Company
Chalk River Nuclear Laboratories
Chalk River, Ontario, Canada K0J 1J0

Summary

Multiple aperture extraction systems are commonly used to produce high current ion beams. One disadvantage of such systems is the dilution of the beam brightness by the grids. Typically, for the seven beamlets from a hexagonal array with a central aperture, the beamlets occupy only one-quarter of the area of the ellipse enclosing them. Beamlet steering by aperture displacement is commonly used in neutral beam injectors to reduce the size of the beam. For realistic beams, typical of high current-density extraction systems, beamlets can be stacked in phase space to reduce the effective emittance of the beam. This paper presents the concept of the technique and the experimental verification. In initial tests, the emittance of a 150 mA hydrogen beam from three in-line apertures was halved using the technique. The reduction was not from reduction in the source size as this decreased less than eight percent.

Introduction

Multiple aperture extraction systems are often used to achieve very high current ion beams. These systems have one major problem for accelerator application - the brightness is diluted by the grids. Although the individual beamlets have a very small emittance, the effective emittance of the total beam depends to a large extent on the physical dimension of the array. Measurements at Chalk River and at GSI[1] made on seven aperture arrays (six apertures in a hexagon plus a central aperture) show that the beam fills less than one-quarter of the phase space area of an ellipse enclosing the beamlets. This disparity increases as the beamlet emittance improves. Beamlet steering is commonly used in neutral beam injectors to superimpose beamlets in real space. Beamlet steering can also be used to "stack" beamlets in phase space to reduce the effective emittance of the total beam. The next section of this paper describes the concept of beamlet stacking. Results of some preliminary measurements are given in the subsequent section.



Description of the Concept

Figure 1 shows a measured emittance plot typical of an ion source with three in-line plasma apertures. The normalized effective emittance of the pattern is 7.6 π mm-mrad, however the sum of the emittances of the individual beamlets is only 1.0 π mm-mrad. Even with seven beamlets in a hexagonal array plus a central aperture, 75-85% of the enclosing emittance ellipse (depending on the orientation of the array relative to the emittance scan) is devoid of beam. Inspection of Figure 1 suggests that, if the positions of the individual beamlets could be displaced judiciously, the effective emittance could be reduced.

Figure 2 shows the geometry considered, and representative emittance diagrams. For simplicity, we consider two beamlets of radius r_1, convergence angle β_1 spaced a distance "d" apart emanating from a source. The beams drift a distance $\ell(\ell >> d)$ to an observation plane, where the centre-to-centre spacing remains at d, and each beamlet has a radius r_2, and divergence β_2. In this treatment, space charge is neglected (therefore $\beta_1 = \beta_2 = \beta_3$) and the emittance of each beamlet is small but non-zero. The beamlets at the observation plane appear to emanate from a point source or waist a distance "m" back from the observation plane, where

$$m = \frac{r_2}{\beta_2} \qquad (1)$$

To achieve beamlet stacking, the beamlets at the source plane are deflected so that their axes intersect at the plane a distance "m" back from the observation plane (the "crossover" plane). The required deflection angle is

$$\alpha = \frac{d}{2(\ell - m)}, \qquad (2)$$

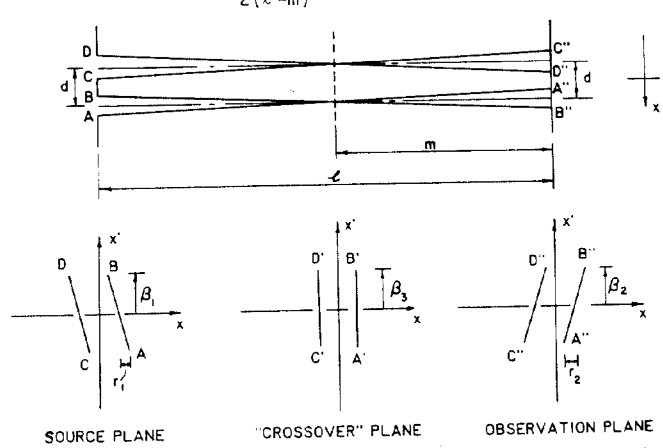


Fig. 2 Geometry and phase space plots of two beamlet system.

0018-9499/83/0800-2621$01.00© 1983 IEEE

and the displacement of the beamlet centres at the observation plane is

$$p = \alpha \ell = \frac{d\ell}{2(\ell - m)} \qquad (3)$$

Figure 3 shows the beamlet trajectories and phase space plots with the correct convergence for stacking. To estimate the emittance of the system, we can take the "emittance ellipse" for each beamlet to be a parallelogram with a full width (in the x direction) of $\delta(\delta < d)$, and a vertical extent of 2β. For the unstacked case, the area of the parallelogram enclosing the phase space area of the two beamlets is

$$\begin{aligned} \varepsilon_0 &= 2\beta(\delta + d) \\ &= 2\beta\delta + 2\beta d. \end{aligned} \qquad (4)$$

For the stacked beamlets, the area of the emittance parallelogram is

$$\begin{aligned} \varepsilon_s &= 2\delta(\beta + \alpha) \\ &= 2\beta\delta + 2\alpha\delta \end{aligned} \qquad (5)$$

To minimize the effective emittance of the stacked beamlets, α must be kept small. Thus the beamlets should be kept close together at the exit of the extraction column (to keep "d" small), and the beamlet waist should be far from the extraction plane (to keep $(\ell-m)$ large). In practice, the minimum value of "d" will be set by the space required for shaping of the area around the plasma grid aperture (to give good beamlet optics) and for the aperture displacement required for steering.

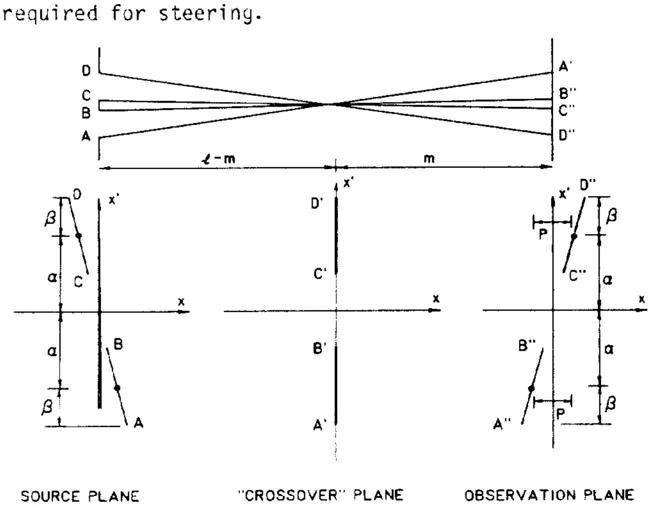


Fig. 3 Geometry and phase space plots of stacked beamlets.

The divergence at the edge of the stacked beam has increased from the original value of β to $(\beta + \alpha)$. The beamlet A''B''has been shifted in the negative "x" direction a distance "p" from its original position of + d/2. Thus, the radius of the stacked beam has changed from its initial value of $(d/2 + r_2)$ to $(p - d/2 + r_2)$. Depending on the values of ℓ and m (which is derived from the beamlet parameters r_2 and β_2), the radius of the stacked beam can be larger or smaller than the radius of the unstacked beam. However, the orientation in phase space has greatly reduced the effective emittance.

The above discussion has considered beamlets that are initially convergent - however the same arguments apply to the case of beams that are initially divergent In this case, the beamlets are angled away from each other as the virtual waist of each beamlet is behind the source. This arrangement always gives a larger beam at the observation plane. The one case that will not stack is when the beamlets have a waist at the source plane.

Experimental Measurements and Discussion

The preliminary measurements reported here used an extraction system with three 5 mm dia apertures in-line spaced 7.6 mm centre to centre (for the undeflected case). Figure 1 shows the phase space plot for the 2% contour of the beam which includes 94% of the total beam. Normalized emittance for the entire beam was 7.6 π mm-mrad and the emittance of an individual beamlet was 0.34 π mm-mrad for a 2% contour enclosing 93% of the beam.

Considering the two outer beamlets and following the analysis of the previous section, the apparent waist was a distance of 53 cm back from the plane of the emittance measuring unit. The distance from the exit of the extraction column to the plane of the emittance unit is only 57 cm. Thus a deflection angle of 190 mrad would be required to stack the beamlets properly. This calculation does not take into account the effect of space charge which is significant even for the well space-charge neutralized beams considered here. As this deflection is far in excess of what is possible with the extraction array used, a lesser deflection angle was used to demonstrate the concept. If the full deflection could be used, a four-fold reduction in the normalized emittance of the beam should be achieved.

Figure 4 shows the phase space plot measured with the outer apertures in the plasma grid displaced inwards to a spacing of 14.0 mm (from the undisplaced 15.2 mm). To reduce the effect of small changes in the beam on calculations of the deflection angle, the

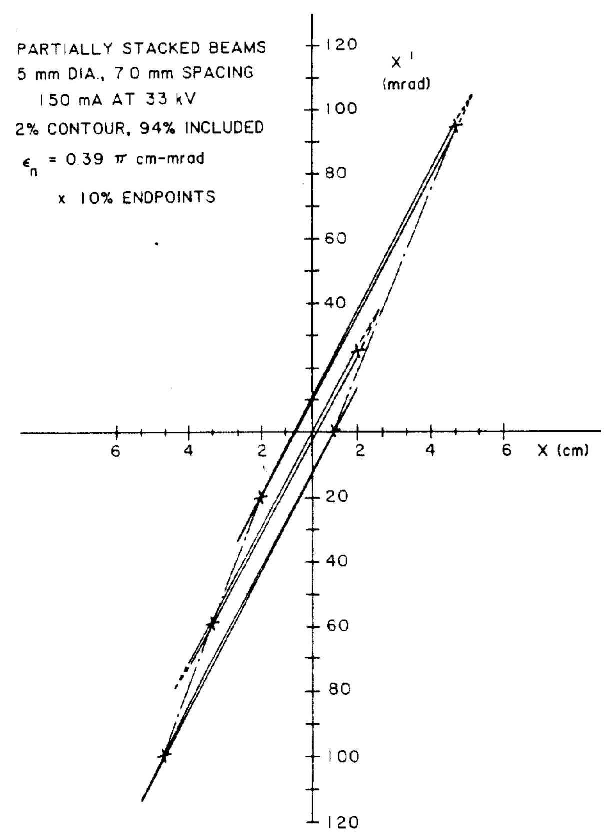


Fig. 4 Measured phase space plot of partially stacked beams.

analysis was based on the 10% contour, rather than the 2% contour normally used. The "x"s on Figs. 1 and 4 show the extent of this contour. From an analysis of the change in divergence of these end points, the steering angle is 51 mrad; the change in position of these points gives a steering angle of 54 mrad. This is fairly good agreement considering the stepwise nature of the emittance measurements.

The emittance of the beam enclosed by the 2% contour decreased to 52% of its original value after stacking. If we consider the beam enclosed by the 10% contour, the emittance enclosed by the four-sided figure defined by the end points decreased to 70% of the unstacked value. The effect is not from the decrease in effective source dimension as this decreased only 8%.

These preliminary measurements indicate that beamlet stacking by beamlet steering can reduce the effective emittance of beams from multi-aperture ion sources. The extraction column geometry is being redesigned to move the beamlet waist further from the base of the extraction column to permit full stacking of the beamlets. Also the effect of space charge, neglected in the treatment above but certainly of importance in lowemittance, high-current beamlets, is being considered.

Acknowledgements

The author received much stimulation from discussions with W. Joho (SIN), B. Piosczyk (KfK), R. Keller (GSI) and J.H. Ormrod and G. Lee-Whiting at Chalk River. He would also like to acknowledge the assistance of A.E. Weeden who carried out the measurements for this work.

References

1. R. Keller, GSI, private communication, 1981.