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Publication Date
1999-07-01

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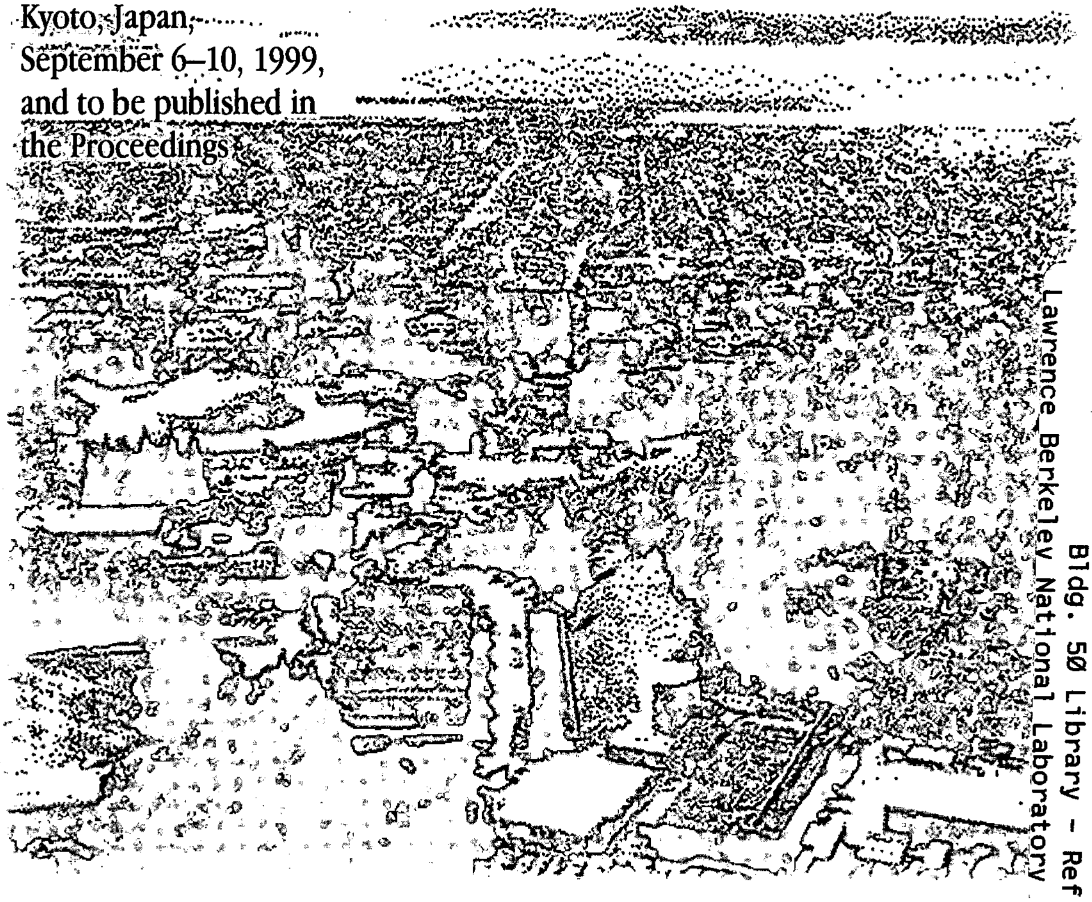
July 1999

Presented at the
8th International Conference on Ion Sources,
Kyoto, Japan,
September 6–10, 1999,
and to be published in
the Proceedings



LBNL-43112

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This work was supported by the Director, Office of Science, Office of Basic Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

On the Use of Magnetic Buckets for Ion Beam Profile Tailoring

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Abstract

Magnetic multipole plasma confinement geometries employing permanent magnet "buckets" are used extensively for a range of laboratory plasma applications. Among the several consequences for plasma confinement is the important result that the plasma can acquire a more-or-less flat density profile, which when embodied in an ion source can lead to a flat profile for the extracted ion beam also. For many applications a uniform ion beam current density profile is quite advantageous, for example for carrying out large-area ion implantation. There are, however, inherent limitations on the extent to which this approach to beam "homogenization" can be utilized, and even for a perfectly flat profile in the immediate post-extraction region, the beam will evolve toward gaussian as it propagates downstream. Here we describe the rare-earth permanent magnet bucket that we've incorporated into our broad-beam vacuum arc ion source, and its effect on the beam profile at the extractor and downstream. The experimental results are compared with a simple model for the beam profile evolution with axial distance.

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I. INTRODUCTION

The formation of high quality ion beams requires that the plasma density profile presented to the extractor (beam formation electrodes) be flat across the extractor dimension, because the ion optics of the extractor is density dependent. One important consequence of a uniform plasma density at the extractor is that the perveance match condition can then be met everywhere (in the extractor plane), and the beam emittance and divergence can be minimized. Another important consequence is that the extracted ion beam current density will also be uniform across the extractor plane. For ion beams of large cross-sectional area formed from broad-beam ion sources using multi-aperture extractors, the importance of these concerns is yet more apparent.

The confinement of plasma by magnetic walls formed from a large number of magnetic cusp-like field regions is a technique that originated in the controlled fusion program. Tuck proposed the use of a "picket fence" plasma boundary formed by an array of parallel conductors in which the current alternates in direction so as to produce a linear cusped field configuration facing the plasma [1]. The addition to a simple mirror magnetic geometry of a quadrupole cusp geometry formed by four rods carrying opposite currents in adjacent conductors ("Ioffe bars") was one of the first applications of this approach [2]. The concept was subsequently expanded to hexapole and octopole fields [3]. Stabilization of the mirror-confined hot-electron plasma in ECR ion sources by hexapole (or higher order multipole) fields is an essential ingredient to the production of high charge state ions in ECR sources, in order to increase the plasma confinement time to allow stripping to successively higher charge states to occur [4]. The important feature of these kinds of confinement schemes is that they have “minimum-B”-like magnetic structure ($d|B|/dr < 0$, or convex field curvature toward the plasma) and so are magnetohydrodynamically stable to many macroscopic plasma instabilities [5].

For typical ion source plasmas, the plasma pressure nkT is small compared to the magnetic pressure $B^2/2\mu$ for even quite modest magnetic field strengths. Then it becomes feasible to establish the multi-cusp magnetic wall using permanent magnets rather than current-carrying conductors, particularly, for example, by using rare-earth magnets (samarium-cobalt or neodymium-iron). This approach was first demonstrated by McKenzie and coworkers [6,7], and has since been developed and used extensively for basic plasma physics experiments and in ion source design. Typically a large number of magnets is used, effectively establishing a very high order multipole field.

High order magnetic multipole confinement systems using permanent magnets have the additional characteristic that the magnetic field in the plasma region distant from the magnetic walls is very low. One can think of the plasma particles as being confined in a homogeneous, isotropic space with low-loss magnetic walls – a "magnetic bucket". Then, not only is the plasma macroscopically stable, and so of low fluctuation level ("low noise"), but also it assumes a more-or-less flat density profile. Thus the use of a permanent magnet magnetic bucket can provide a low-noise, uniform plasma for ion source application, and a large area ion beam extracted from such a bucket-confined plasma can be quiescent, with a uniform current density profile, and of low divergence. This approach has been exploited well, for example, for the large ion sources developed for neutral beam injectors for fusion [8].

Here we address the question: how far downstream does the beam propagate before it loses memory of its initially-flat current profile and develops a gaussian shape? We describe a vacuum arc ion source incorporating a magnetic bucket, and summarize the measurements we've made of the beam profile near to and far from the extractor. A simple computer model is outlined and the predictions of the model summarized. Finally, we suggest a simple semi-empirical expression for the beam propagation distance for it to relax from an initially flat profile to a more-or-less gaussian profile.

II. EXPERIMENTAL SET-UP

The measurements were carried out using our broad-beam vacuum arc ion source, described in detail in a number of previous publications [9,10]. Metal ion beams of energy in the range 20 to 200 keV and peak pulse ion beam current up to about 1 A can be produced in a repetitively pulsed mode with pulse width ~250 μs and repetition rate up to several tens of pulses per second. In the work described here, we formed a Ti ion beam at an extraction voltage of 50 kV, corresponding to a mean ion beam energy of 105 keV (the mean Ti ion charge state is 2.1+ [10]). Background gas pressure was ~2 x 10^{-6} Torr. The ion source extractor diameter was 10 cm, but for these experiments we installed an aperture-limiter of 6.8 cm diameter in order to better form an ion beam with an initially ($z = 0$) flat radial profile of current density. A tapered magnetic bucket formed from a multipole array of 12 samarium cobalt magnets of dimension 1.2 cm (azimuthal direction) x 2 cm (radial direction) x 5.5 cm (axial direction), was installed in the ion source, in the 'drift space' between the arc region where the plasma is formed and the extractor grids. A schematic of the ion source with duodecapole bucket is shown in Figure 1.

Magnetically-suppressed Faraday cups with 1 cm diameter entrance aperture were positioned at axial locations $z \approx 0$ cm (immediately following the aperture-limiter) and $z = 65$ cm. The Faraday cups could be radially scanned, allowing us to measure the ion beam radial current density profiles at these two axial locations.

III. RESULTS AND DISCUSSION

Measured radial profiles of beam current are shown in Figure 2. The initially rectangular distribution has evolved into a gaussian (or, at least, bell-shaped) distribution at the downstream location. We observe this kind of behavior under all operating conditions. (We ascribe the small asymmetry in the z = 0 profiles as being due to a small asymmetry in the bucket magnet strengths; this is unimportant to the present context).

A simple computer model of the beam spatial evolution has been developed. In the model we assume the ion beam to be formed at an axial position $z = 0$ from a number N of beamlets positioned equally-spaced along the line $x < |R|$; we thus assume a simplified 1-D model for the present. Each beamlet is taken to be a point source of ions which travel in straight lines in the forward direction with a radial current density profile that is gaussian with half-angle beamlet divergence angle θ; we take, simply, $z\theta$ as the standard deviation of the gaussian. At chosen distances downstream the contributions to the total beam current are summed over all beamlets and the beam current density distribution is obtained,

$$j(x;z) \quad = \quad k\sum_{n=1}^{N}\frac{1}{z\theta}\exp -\tfrac{1}{2}\left(\frac{x-x_n}{z\theta}\right)^2 \qquad (1)$$

where k is a constant. Typical results from the model are shown in Figure 3. Here we plot the radial density distribution of beam current as a function of axial distance from the extractor. We have assumed an initially flat profile over a 10 cm wide extractor. Four different cases are shown, for beam divergence angles of 2°, 3°, 4° and 5°. The evolution of the beam from flat to gaussian is evident. From these data we can estimate the axial distance λ_r required for the beam to lose memory of its initially flat profile and to relax to a more-or-less gaussian shape as $\lambda_r \sim w/4\theta$.

We know from other experimental measurements that the divergence of the Mevva beam is typically about 3° half-angle at perveance match. Thus the experimentally observed transition of flat profile to gaussian-like in a distance of 65 cm downstream is in good agreement with our expectations.

We can take the interpretation further. The experimental data of Figure 2 indicate a "beam width growth factor" (ratio of beam half-width (FWHM) at z = 65 cm to beam half-width at z = 0) of about 1.55 ± 0.5, and we can compare this with the predictions of the model outlined above. Taking an initial beam diameter of 6.8 cm as used in the experiment, beam radial profiles have been calculated for several different beam divergence half-angles as shown in Figure 4. Here the profiles have all been normalized to the same amplitude for ease of width comparison. Comparing the measured width growth factor from Figure 2 (1.55 ± 0.5) with the calculated width growth factors obtained from Figure 4, we find that a beam divergence half-angle of 3.6° ± 0.3° is implied, again in excellent agreement with expectations and with prior results.

The experimental results and the simple model both point out that the beam profile loses memory of its initial rectangular shape rather rapidly. For the broad-beam configuration considered here, with an initial beam diameter of order 10 cm, we find that the axial distance over which the ion beam current density profile retains its flat radial distribution is only a few tens of centimeters even for a beam divergence half-angle of 2 or 3 degrees. There is thus limited advantage to be gained, with respect to beam uniformity at a distant target, by the use of a magnetic bucket as a plasma homogenizer within the ion source.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

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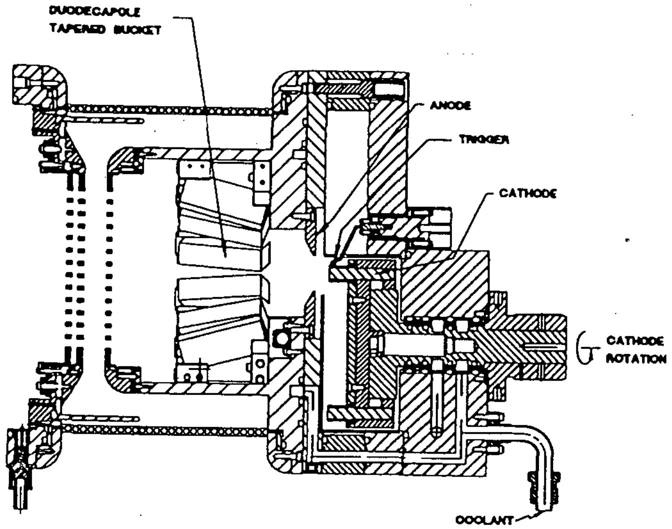
FIGURE CAPTIONS

Fig. 1 Schematic of the Mevva V broad-beam vacuum arc ion source with tapered permanent magnet multipole bucket installed.

Fig. 2 Measured radial profiles of the ion beam current density, j_i (r), for z = 0 (lower) and z = 65 cm (upper).

Fig. 3 Evolution of beam radial current density profile as predicted by the model. Top-to-bottom for the cases of beam divergence half-angles of 2°, 3°, 4° and 5°. Initial (z = 0) beam diameter is 10 cm.

Fig. 4 Normalized beam profiles at z = 65 cm calculated from the model for the conditions of the experiment, for beam divergences 2°, 3°, 4° and 5°. The initial (z = 0) rectangular profile is also shown; initial beam width is 6.8 cm.



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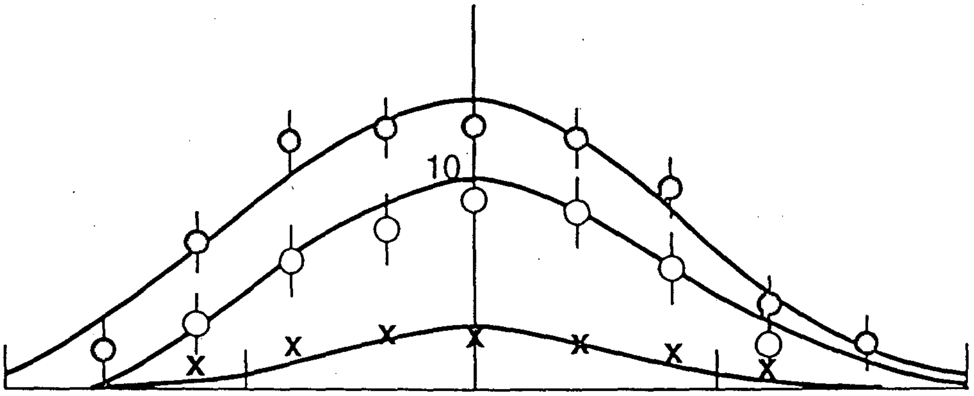

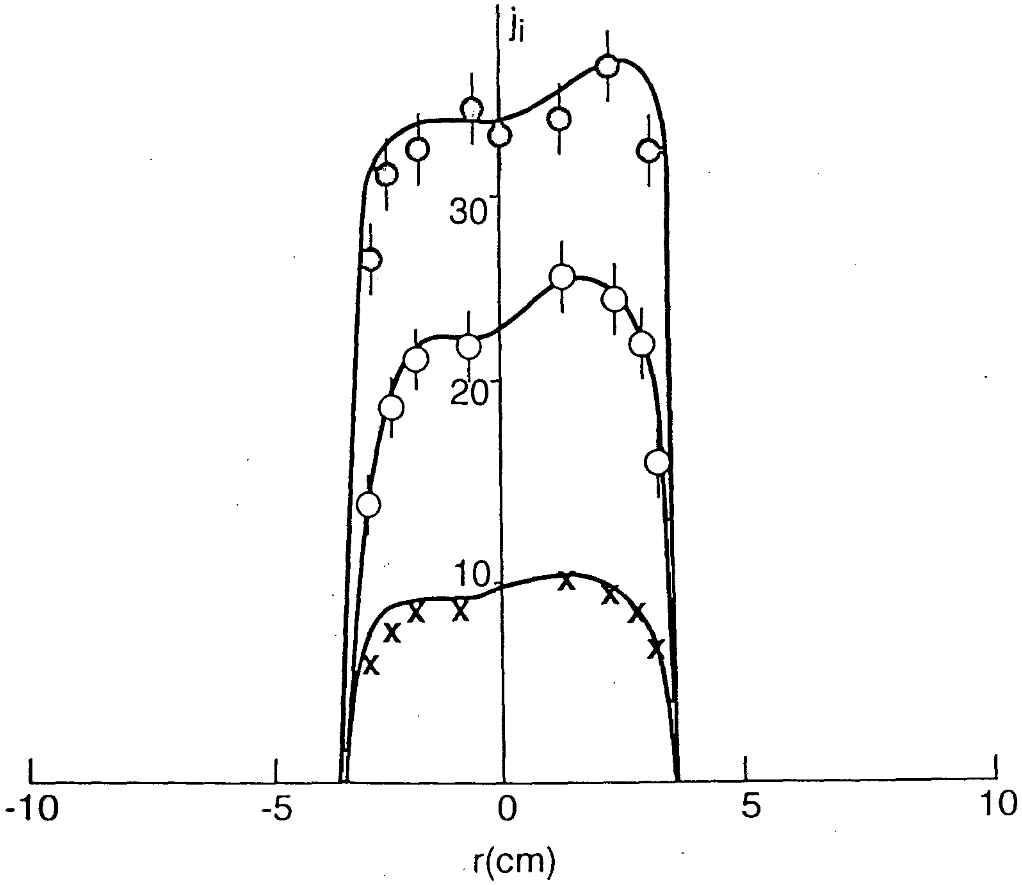

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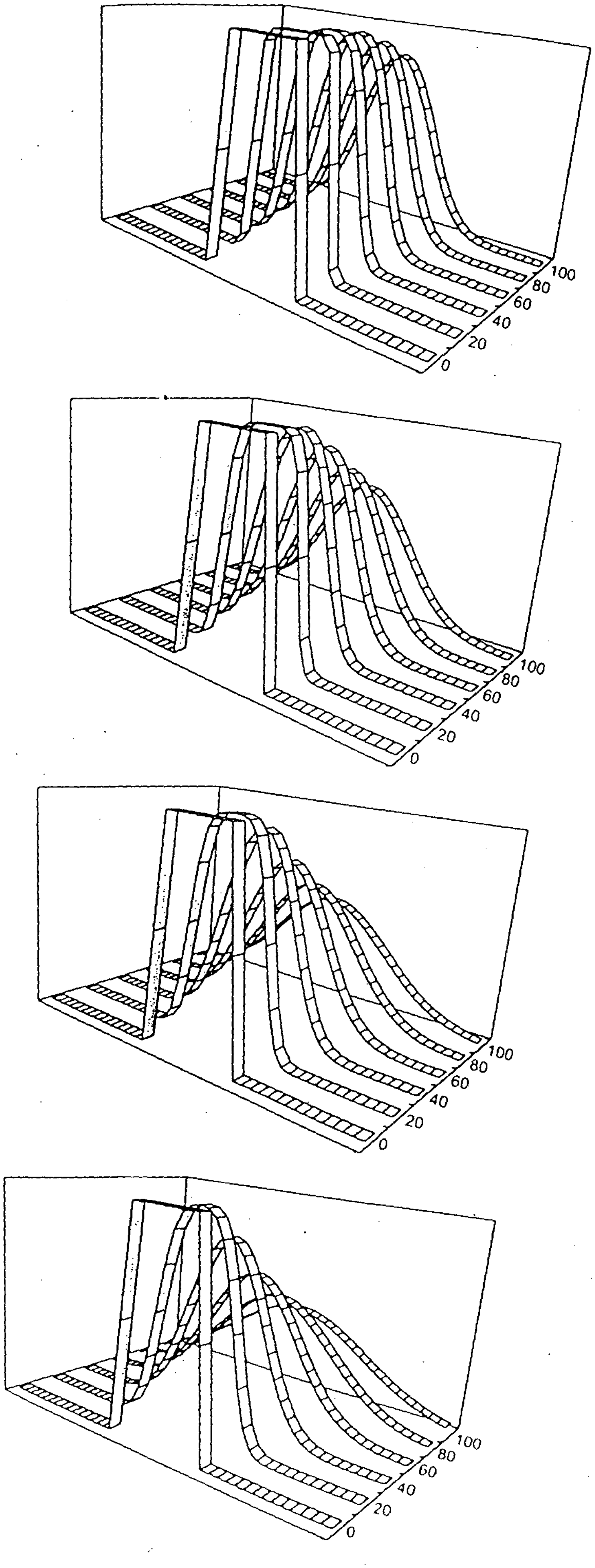

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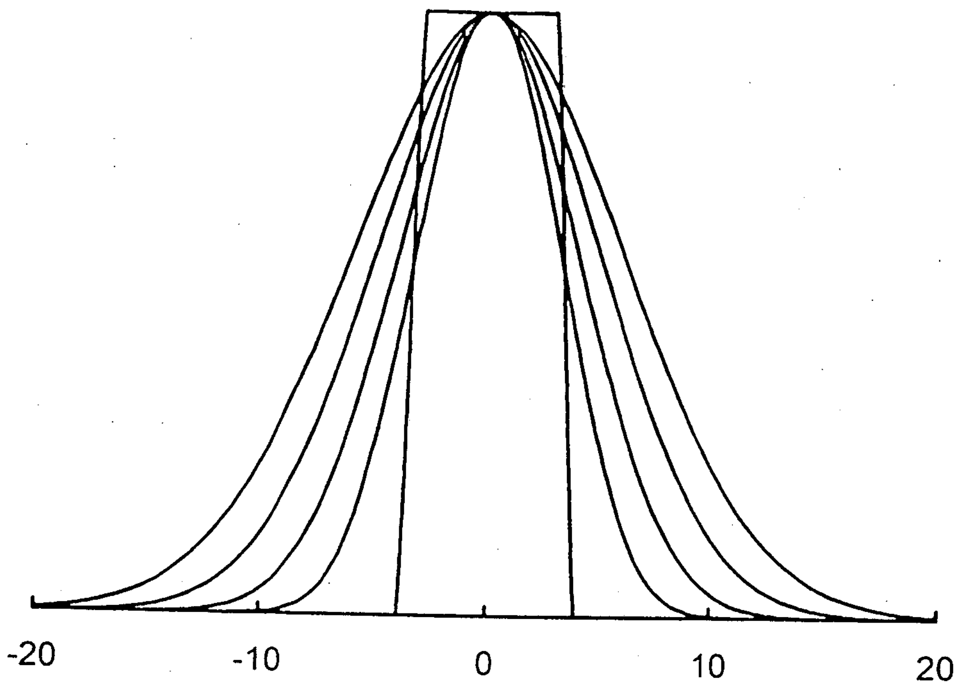

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Prepared for the U.S. Department of Energy under Contract No. DE-AC03-76SF00098