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FIRST RESULTS FROM A DOUBLE VLASOV MODEL FOR NEGATIVE ION EXTRACTION FROM VOLUME SOURCES
The Possibility of an Enhanced Transverse Space Charge Limit

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FIRST RESULTS FROM A DOUBLE VLASOV MODEL FOR NEGATIVE ION EXRACTION FROM VOLUME SOURCES — The Possibility of an Enhanced Transverse Space Charge Limit

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Abstract. *A new negative ion source extraction model has been formulated and implemented which explicitly considers the motion of positive ions and the volume generation of negative ions. It is found that (1) for high-beam currents, the beam current is limited by a transverse space charge limit, meaning that an increase in negative ion density at the extraction sheath will result in a lower beam current (this result is universally observed at high beam currents); (2) there is a saddle point with a potential barrier preventing most volume produced negative ions from being extracted (the combination of 1 and 2 indicates that most of the negative ions being created do not find their way into the beam); (3) introduction of cesium may cause, most importantly, an increase in the transverse space charge limit (there is an abundance of experimental data supporting this effect); (4) cesium may also result in an increase in the fraction of volume produced negative ions which are extracted; (5) cesium may also result in a reduction of extracted electrons by dint of a less negative bias on the plasma electrode with respect to the adjacent plasma, thus allowing the transverse space charge limit budget to be taken up wholly by the ions. (The combination of 3–5 represents the way an actual increase in the beam current can be achieved); (6) a strong ion time scale sheath instability due to violation of Bohm criteria produces an anomalous ion temperature that increases with beam current routinely seen in experiments; and (7) introduction of cesium may result in a reduction in this instability. These insights may lead to improvements in volume negative ion sources, and the most important finding of an increased*

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space charge limit has apparently been verified experimentally by reinterpretation of the findings of Bacal, Allison and Leung.

Differences between Negative Ion and Positive Ion Extraction

Several phenomena surrounding the production of extractable negative ions have apparently not yet been explained in a self-consistent manner. For example, why does cesium addition add to the negative ion output and avoid the negative current saturation as a function of plasma density that is observed so often without cesium? If the extracted negative ion and electron current is transverse space charge limited, as supported by a multitude of experimental evidence, then why should an increase in negative ion production, as cesium injection is expected to produce, increase the extracted beam current above and beyond merely replacing the space charge of the reduced extracted electron flux? Why does the RMS emittance of the extracted beam not appear to increase when cesium is added? These questions form an apparent contradiction. We approach these problems by considering a more accurate physics model for negative ion extraction, which is cognizant of most of the five major asymmetries between positive ion extraction that the analysis is well developed, and negative ion extraction, where it has been less so [1].

$$\nabla^2\phi\left(\vec{r},t\right) = \int f\left(\vec{r},\vec{v},t\right)d\vec{v} - \exp\left[-\phi\left(\vec{r},t\right)\right] \tag{1}$$

$$\frac{\partial f\left(\vec{r},\vec{v},t\right)}{\partial t} + \vec{v}\bullet\nabla f\left(\vec{r},\vec{v},t\right) + \left\{\vec{v}\times\vec{B}-\nabla\phi\right\}\bullet\nabla_{\vec{v}} f\left(\vec{r},\vec{v},t\right) = 0 \tag{2}$$

The first asymmetry is that the electrons cancel charge imbalance excursions in positive ion sources much better than positive ions do in negative ion sources. This is explicitly addressed in the present model by considering the positive ions as a coupled Vlasov equation added to the conventional system of Poisson-Vlasov equations for a self-consistent treatment of the negative ions and the electromagnetic fields.

$$\frac{\partial f_+}{\partial t} + \vec{v} \bullet \nabla f_+ + \left\{ \vec{v} \times \vec{B} - \nabla\phi \right\} \bullet \nabla_v f_+ = \delta\left(S_1\right) \tag{3}$$

$$\frac{\partial f_-}{\partial t} + \vec{v} \bullet \nabla f_- - \left\{ \vec{v} \times \vec{B} - \nabla\phi \right\} \bullet \nabla_v f_- = G\left(\vec{r}\right) \tag{4}$$

$$\frac{\partial f_e}{\partial t} + \vec{v}_e \bullet \nabla f_e - \frac{M}{m_e} \left\{ \vec{v} \times \vec{B} - \nabla\phi \right\} \bullet \nabla_v f_e = \delta\left(S_2\right) \tag{5}$$

$$\nabla^2 \phi = \int \left\{ f_+(v) - f_-(v) - f_e(v) \right\} dv - e^{-\phi} \tag{6}$$

The second asymmetry is the observation that the plasma electrode is biased negative to the local plasma potential for negative ion sources just like in positive ion sources and for the same reason—to contain the plasma electrons electrostatically. Therefore, in a positive ion source, there is a continuous monotonic downhill run for the positive ions generated deep in the plasma from formation to extraction. For negative ions, there is a saddle point formed within the plasma since the plasma potential lies intermediate between that of the plasma electrode and the acceleration electrode. This observation was made ten years ago [1, 2] but has attracted scant attention. Negative ions formed from one side of the ridge, formed from the saddle point to the plasma electrode, go toward the source plasma instead of the extraction aperture. In these cases, the location and control of such ridges could be important.

The third asymmetry is that negative ions, due to their short mean free extinction path, must be born in a volume close to the extraction aperture in order to be extracted. For positive ions, it is conventional to assume that they are transported from deep within the plasma. A fourth asymmetry is that electrons are extracted along with the negative ions, unlike the case for positive ion sources. This effect will not be considered in this paper. A fifth asymmetry is that the Bohm sheath stability criteria could be violated more extensively in certain regions for negative ion sources than in the case for positive ion sources, at least in the absence of cesium. This is because any process that increases the negative space charge in the pre-extraction region causes the curvature of the potential to become positive (as evidenced from the structure of the Poisson Equation), which is precisely the condition for the Bohm instability. Analysis capable of considering sheath produced ion-acoustic waves from the Bohm instability has been considered for positive ions [2] and will be a necessary future step in the modeling of negative ion sources.

Experimental evidence for the existence of unstable sheaths in negative ion sources takes the form of extracted beam temperatures (as interpreted from emittance measurements), which are as much as an order of magnitude higher than the temperature of negative ions in the plasma. We will average over these instabilities as a temporary expedient, which will deny us the possibility of explaining some features of the ion beam emittance, while making other features more apparent.

A standard positive ion extraction result is shown in Fig. 1a, showing a monotonic downhill run from center of plasma to extraction, with an attraction toward the plasma electrode greeting the ions not extracted. In order to elucidate the phenomena of negative ion extraction, we will consider separately a low- and high-density regime. At low densities positive ions falling downhill from the center of the plasma as shown in Fig. 2a., being accelerated until they reach the saddle ridge. Then the positive ions are repelled by the accelerator fields and are attracted into the plasma electrode as shown. This is in contrast to positive ions shown in Fig. 1. For volume produced negative ions, the trajectories are shown in Fig. 2b. Here we see that only a small fraction of the negative ions produced are extracted, and the rest are attracted to the center of the plasma since they are repulsed by the plasma electrode. The densities and sheath properties are not unlike the case considered in [3] (shown in Fig. 3a); however, in [3] a trivial variation of a positive ion extraction model was used with an ad hoc representation of only the first asymmetric property as mentioned above.

The situation becomes more interesting at higher densities. For illustration purposes, Fig. 4 shows a higher plasma density. In many cases, such as those shown in [3] (see Fig.3b herein), the beam (negative ions and electrons) is transverse space charge limited. The very nature of a transverse space charge limit means, if the generation rate is increased (beyond any decrease in electron space charge), the beam current actually decreases. This is because the excess generation not only gets intercepted by the electrodes but causes some of the formerly transmitted ions to be intercepted by the accelerator structure. Therefore, the question of how the cesium addition could increase the beam current beyond the decrease in electron space charge assumes greater importance. It has been found that a cesium surface coating very near the extraction apertures is especially beneficial, sometimes adding substantially to beam current beyond the decrease in extracted electron space charge [3, 4]. Since a cesium surface coating is known to produce negative ions when bombarded by positive ions, this would seem, at first sight, to be a possible explanation for the beneficial effects of cesium. However, since the beam current is usually transverse space charge limited, an increase in production current will not result in an increase in beam current (beyond the decrease in electron space charge). In fact, it may make it lower. The explanation of the effect of cesium must be from another source. In those cases where the transverse space charge limit appears to be increased with the presence of cesium, the extraction sheath somehow must become more concave since all other things are the same. This would not usually happen, i.e., compare Fig. 3a with Fig. 3b, which shows the result of increasing density. However, this extra concavity could be obtained if there were an additional source of positive space charge due to the cesium. Since surface sputtering of neutral cesium by the impinging positive ion flux is inevitable, the ionization (Cs^+) mean free path is short, and the cesium ions are heavy and slow, the opportunity for an excess of positive charge is present. An example of the effect of positive charge is shown in Fig. 5 which, except for an abundance of positive charge, is the same as Fig. 4. Not only can the sheath be seen to be further toward the plasma in Fig. 5 than that of Fig. 4 (thus allowing in some cases a higher transverse space charge limit), but the fraction of negative ions that get extracted in a specific case increases from 21 percent to 37 percent, almost doubling. This by itself does not result in an increased beam but means that less arc power is required. The fraction of volume produced negative ions being extracted as a function of plasma density is shown in Fig. 7 for a case where the initial velocity is low.

Another feature of negative ion extraction from volume sources is the presence of ion acoustic instabilities in the sheath due to violation of the Bohm sheath criteria [1]. This violation occurs whenever the negative space charge in the presheath region exceeds the positive space charge (see the simulation of Fig. 1b for positive ion extraction). This will generally occur in some presheath regions in volume negative ion sources. The instability will take the form shown in Fig. 6, with a relatively stable region slightly dominated by positive ions followed by an unstable region (on ion time scales). Negative ions born in the unstable region will have an enhanced "temperature" due to their bouncing on the electric potential waves. In the instance of a potential barrier near the extraction sheath, these instabilities may actually increase negative ion extraction, although we do not so far have much evidence for this. Injection of positive space charge as may be possible with cesium will tend the presheath toward stability, thus lowering the ion temperature (Fig. 4 vs Fig. 5).

As a natural consequence of negative ions and electrons being ejected from the plasma electrode, and returning Cs^+ ions intercepting it (those that escape the sheath adjacent to the plasma electrodes are sputtered off as neutrals), an isolated plasma electrode will be biased less negative with respect to the plasma than would otherwise be expected. Therefore, more plasma electrons will intercept the plasma electrode than would otherwise be the case, and fewer electrons will make it to the extraction region. This is an explanation for the dearth of extraction of electrons from the plasma when cesium is injected.

In summary, a new model has been described that takes into account four differences between positive- and negative-ion extraction. The new model appears to explain such important observations as reduced electron extraction and increased beam current when cesium is added to negative ion volume sources.

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7. A. Holmes (86 BNL/305)

Figure Legends

Figure 1a. Plot of ion trajectories (solid lines) and equipotentials (dotted lines) in the extraction region bounded by an electrode (solid) with an aperture for ions to get out. On the left-hand side is the source plasma modelled by the ions kinetically and equilibrium Boltzmann electrons. On the right-hand side is the applied extraction/-acceleration fields. On the bottom half, the ion orbits are left out so that the electric field structure is more clearly shown . A typical positive ion sheath and plasma electrode structure near optimum perveance is shown with a downhill run of the positive ions from the source plasma to extraction—no saddle point, no potential barriers.

Figure 1b. Same as Fig. 1a, except that an ion time scale solution to the Vlasov-Poisson equations is shown for positive ion extraction (electrons are still Boltzmann) in a region where the Bohm sheath stability criteria is not satisfied resulting in ion-acoustic waves in the presheath and concomitant RMS emittance growth.

Figure 2a. Plot of ion trajectories (solid lines) in real 2-D space and equipotentials (dotted lines) in the extraction region bounded by an electrode (solid) with an aperture for ions to get out. On the left-hand side is the source plasma modeled kinetically by the positive and negative ions and Boltzmann electrons. On the right-hand side is the applied extraction/-acceleration fields. On the bottom half, the ion orbits are left out so that the electric field structure is more clearly shown Positive ion trajectories are arriving toward the extraction sheath (low density) and being repelled by the accelerator fields. A saddle point in the electrostatic potential is formed as shown by the dashed contours; electrons are represented by a modified Boltzmann distribution.

Figure 2b. Same as 2a, except that the volume produced negative ions are shown; those formed on the extraction side of the saddle point ridge will be included to be extracted; negative ions formed on the plasma side will tend to not get extracted. The plasma electrode with coller shown is typical of volume negative ion sources.

Figure 3a. Plot of ion trajectories (solid lines) in real 2-D space and equipotentials (dotted lines) in the extraction region bounded by an electrode (solid) with an aperture for ions to get out. On the left-hand side is the source plasma modeled by the ions and Boltzmann electrons. On the right hand side is the applied extraction/-accleration fields. On the bottom half, the ion orbits are left out so that the electric field structure is more clearly shown. Shown here are the results of a heuristically modified positive ion model for very low perveance indicating amplification of the ion beam current due to the accelerator electric field penetration. This result is especially significant because of the apparent agreement with experiment.

Figure 3b. Results of heuristic modified positive ion model for very high perveance, beyond the transverse space charge limit, indicating suppression of the ion beam current due to accelerator electrode interception. This result also is apparently in agreement with experiment.

Figure 4a. Same as Fig. 2a, except the plasma density is higher. Instabilities have been suppressed by space charge under-relaxation.

Figure 4b. Same as Fig. 2b, except the plasma density is higher.

Figure 5a. Same as Fig. 4a, but positive space charge added in the presheath region.

Figure 5b. Same as Fig 4b, but positive space charge added in the presheath region.

Figure 6. Fraction of volume produced negative ions extracted as a function of negative ion density— the potential barrier prevents the rest from getting out. One of the effects of the introduction of Cs^+ (simulated by addition of positive charge in the presheath) is that the extracted fraction remains at a relatively high value as compared to the case labeled no Cs^+ where no positive charge was added to the presheath. The error bars refer to the fluctuations of the results due to physical instabilities.

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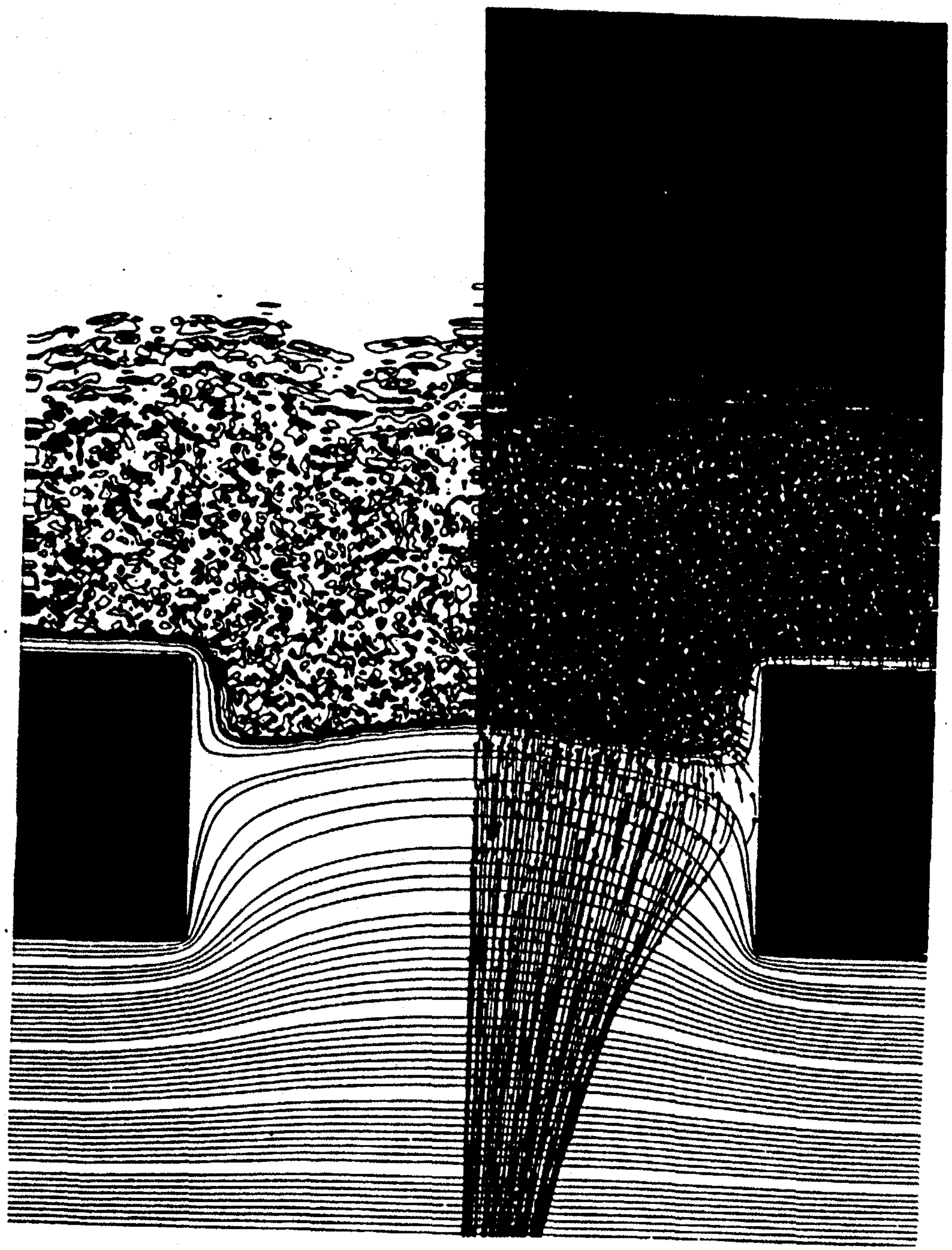

Fig. 1a

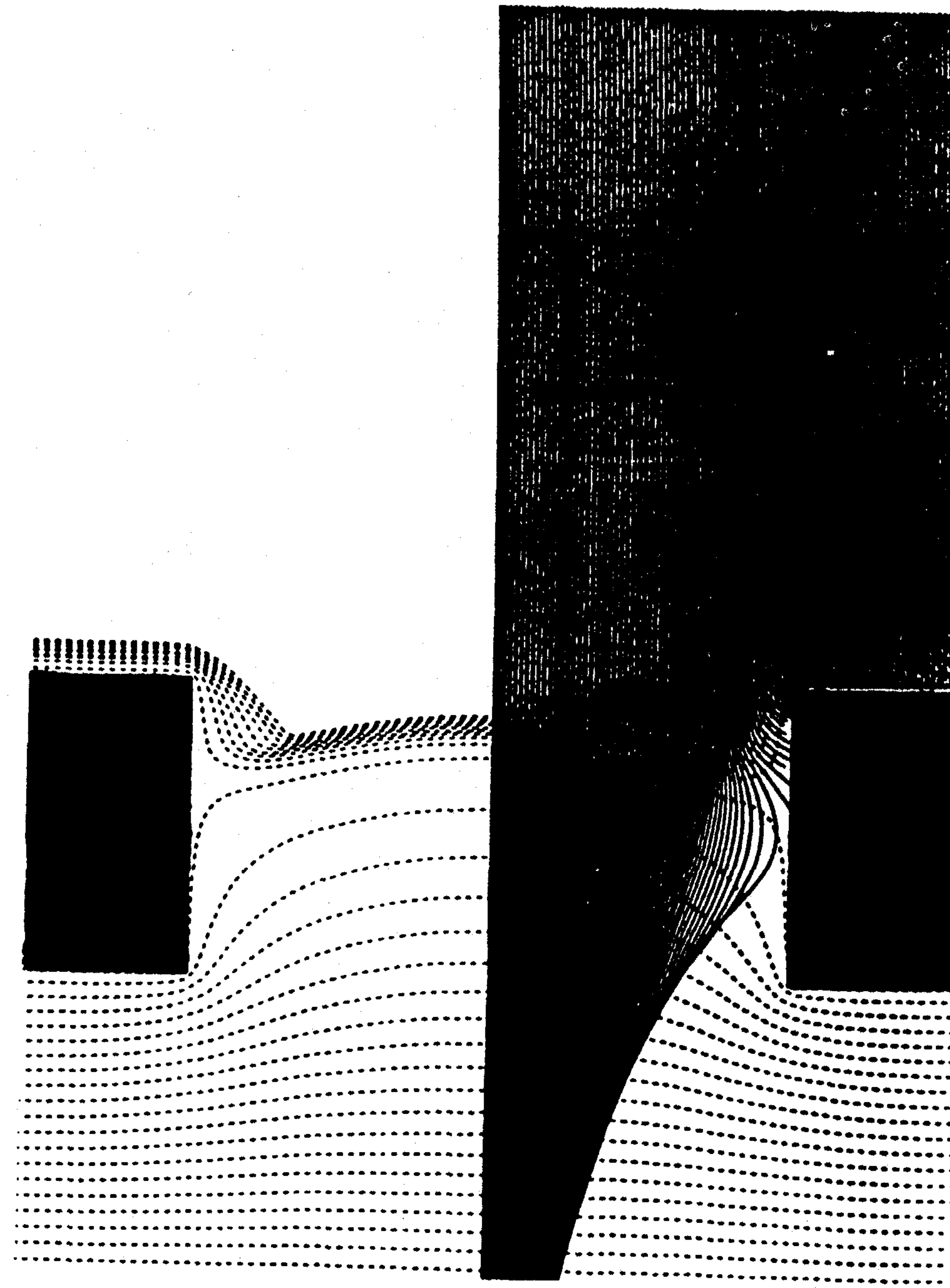

Fig. 1b

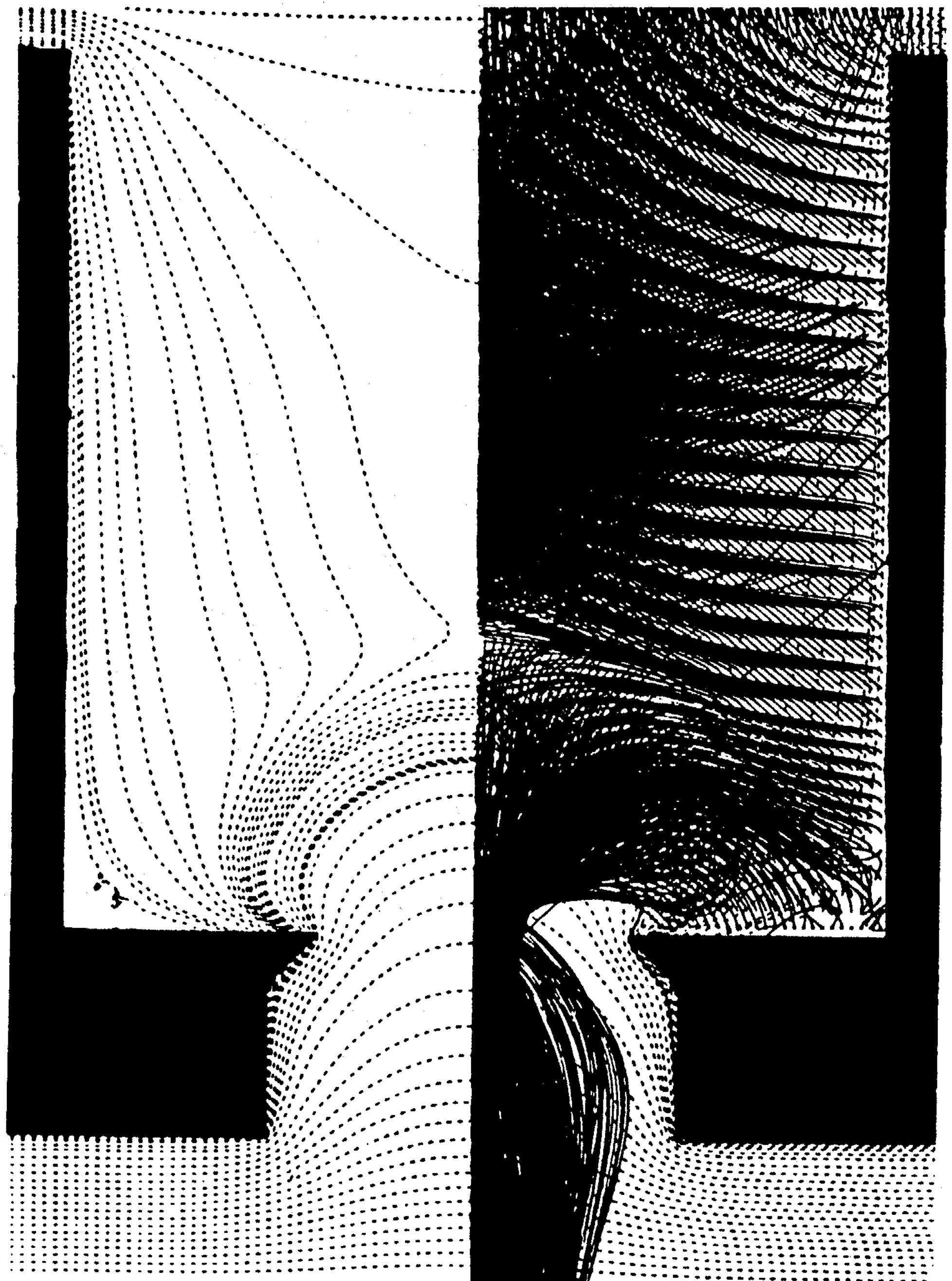

Fig. 2a

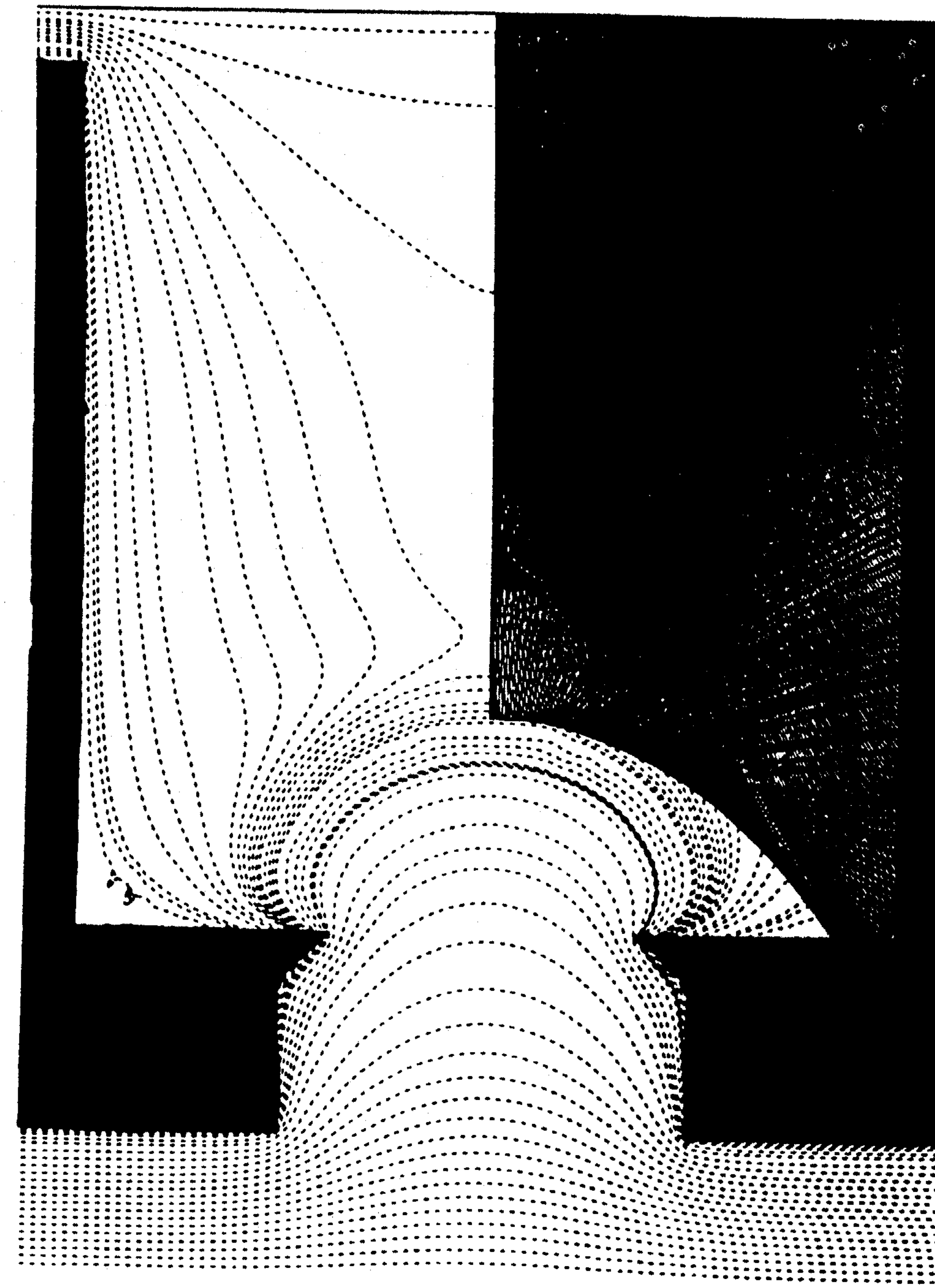

Fig. 2b

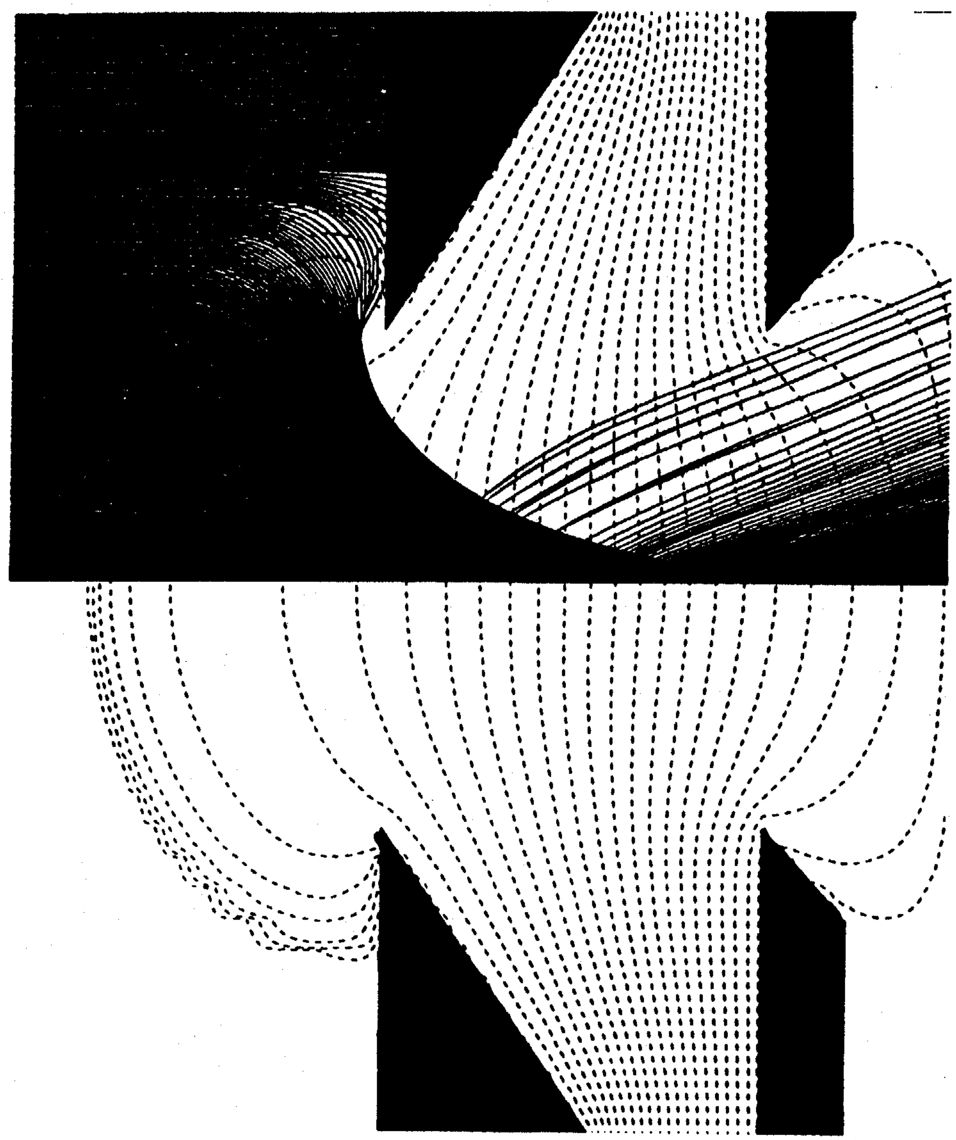

Fig. 3a

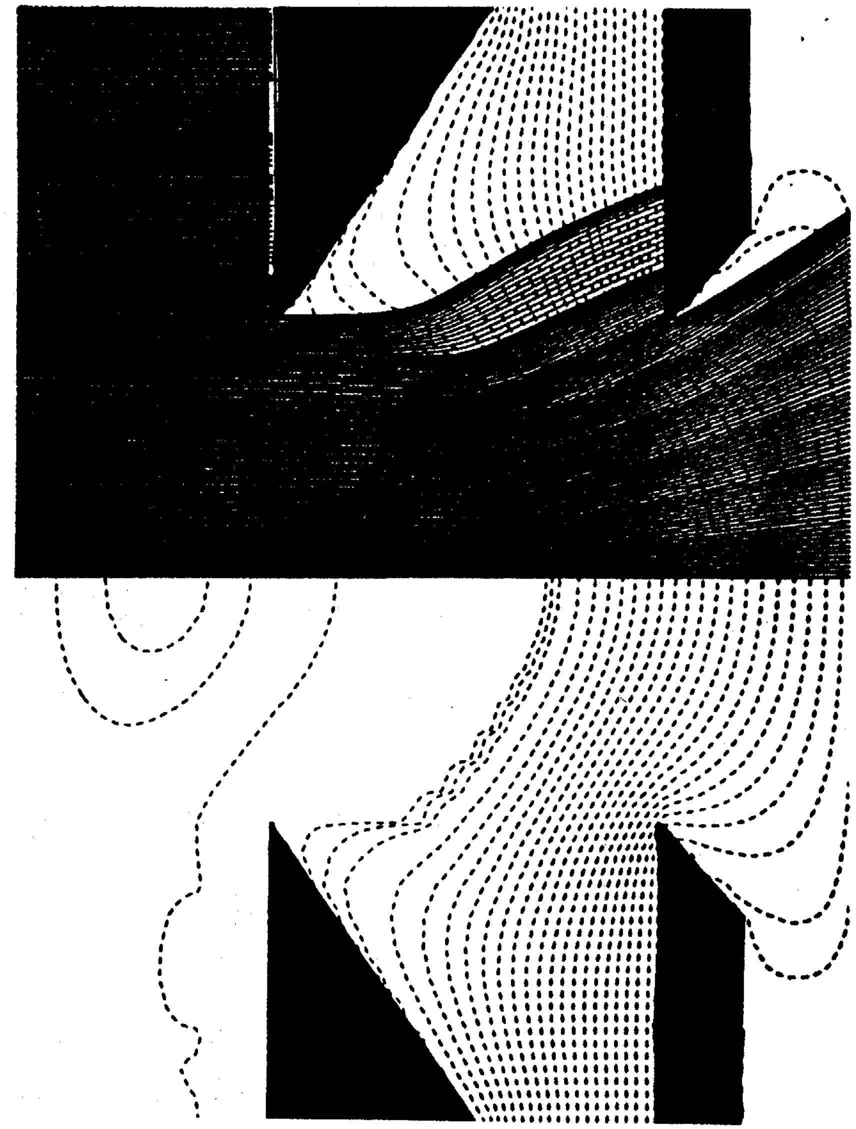

Fig. 3b

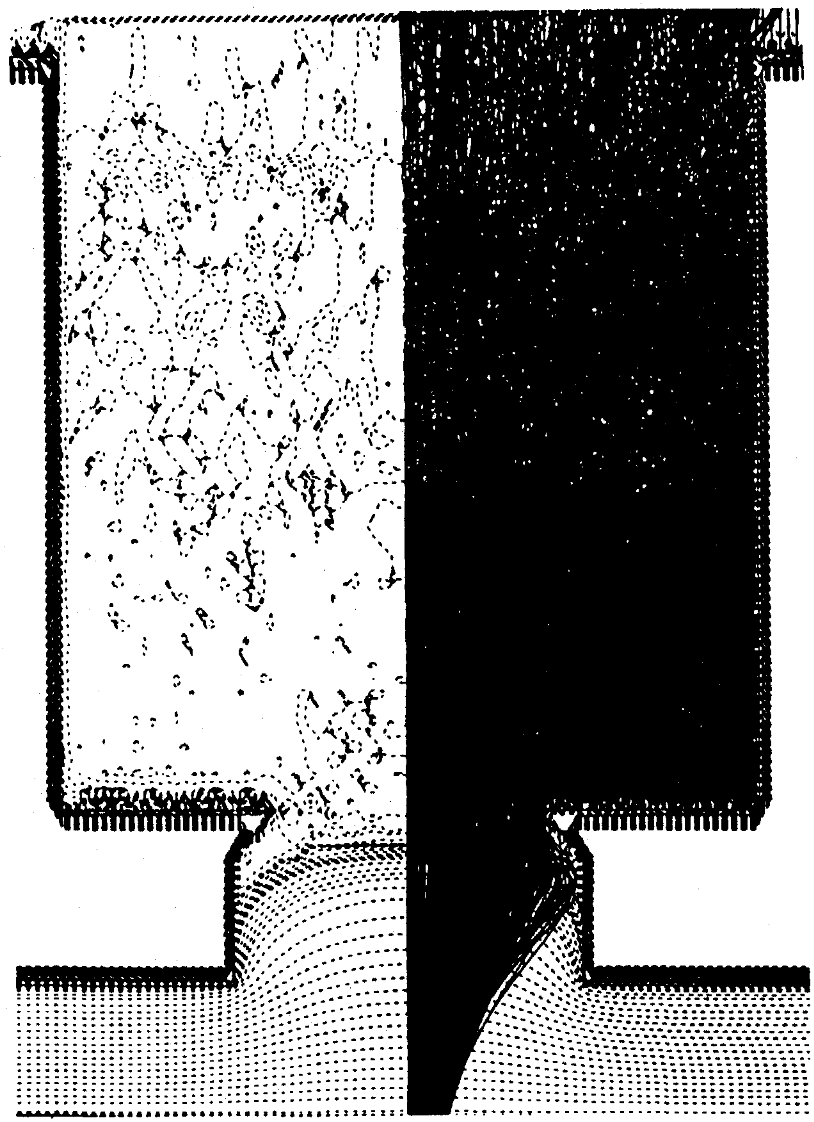
Fig. 4a

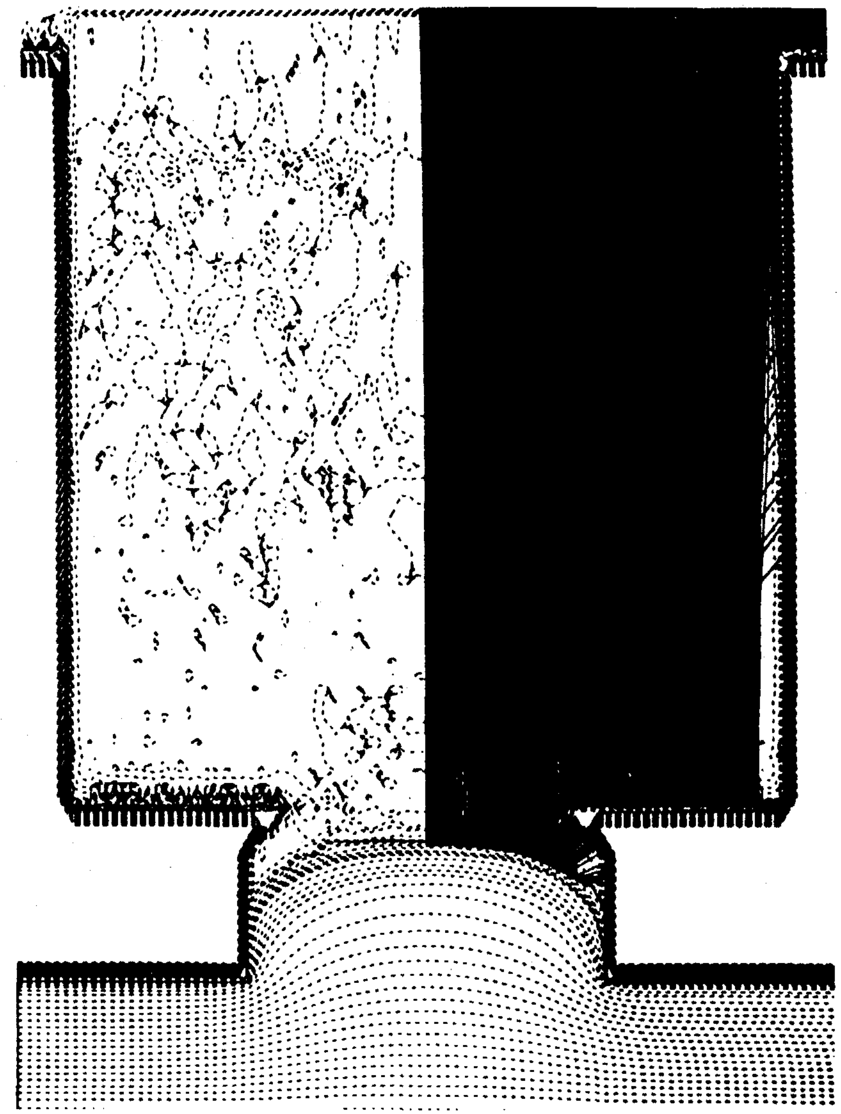
Fig. 4b

FIG 5

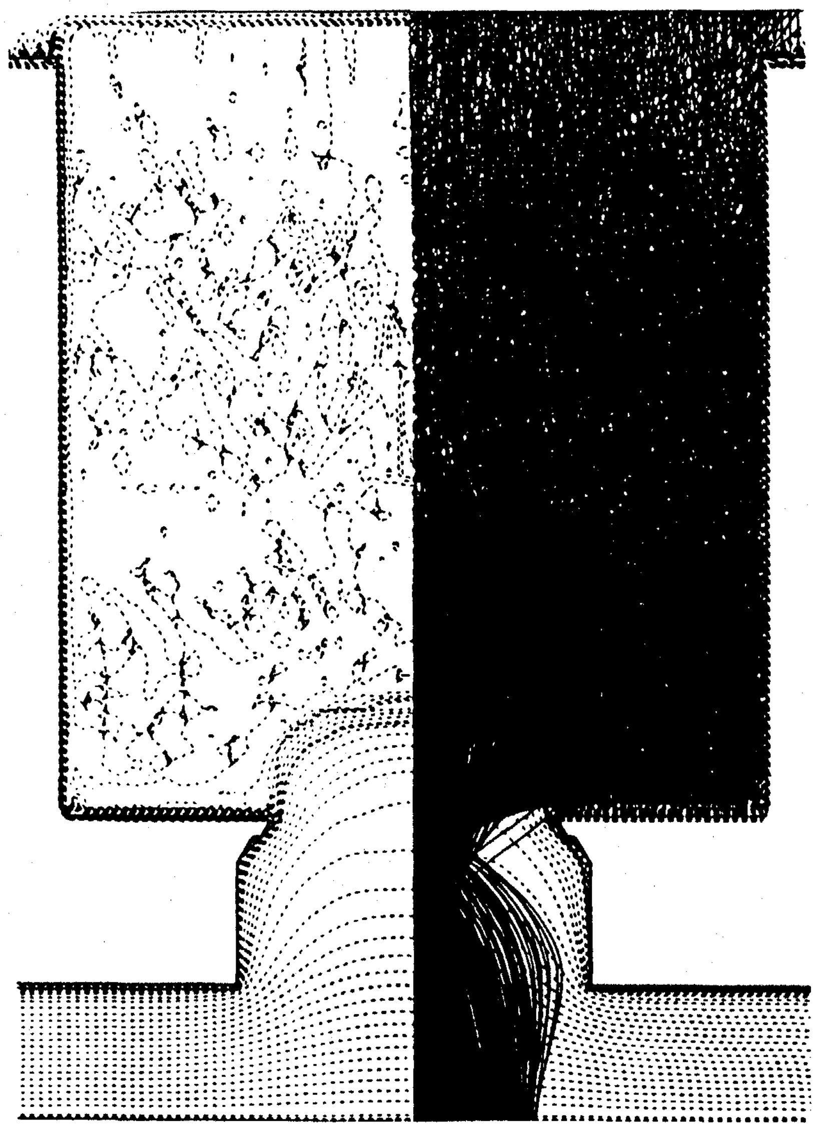

Fig. 5a

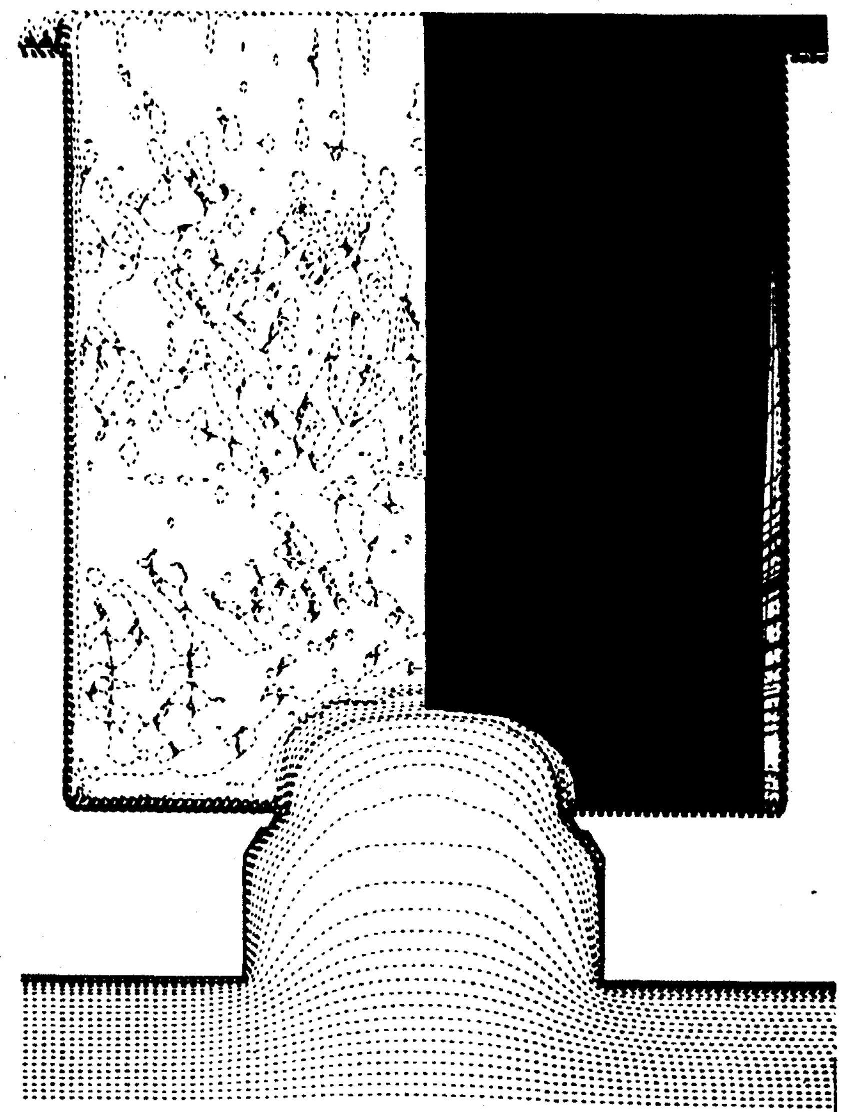

Fig. 5b

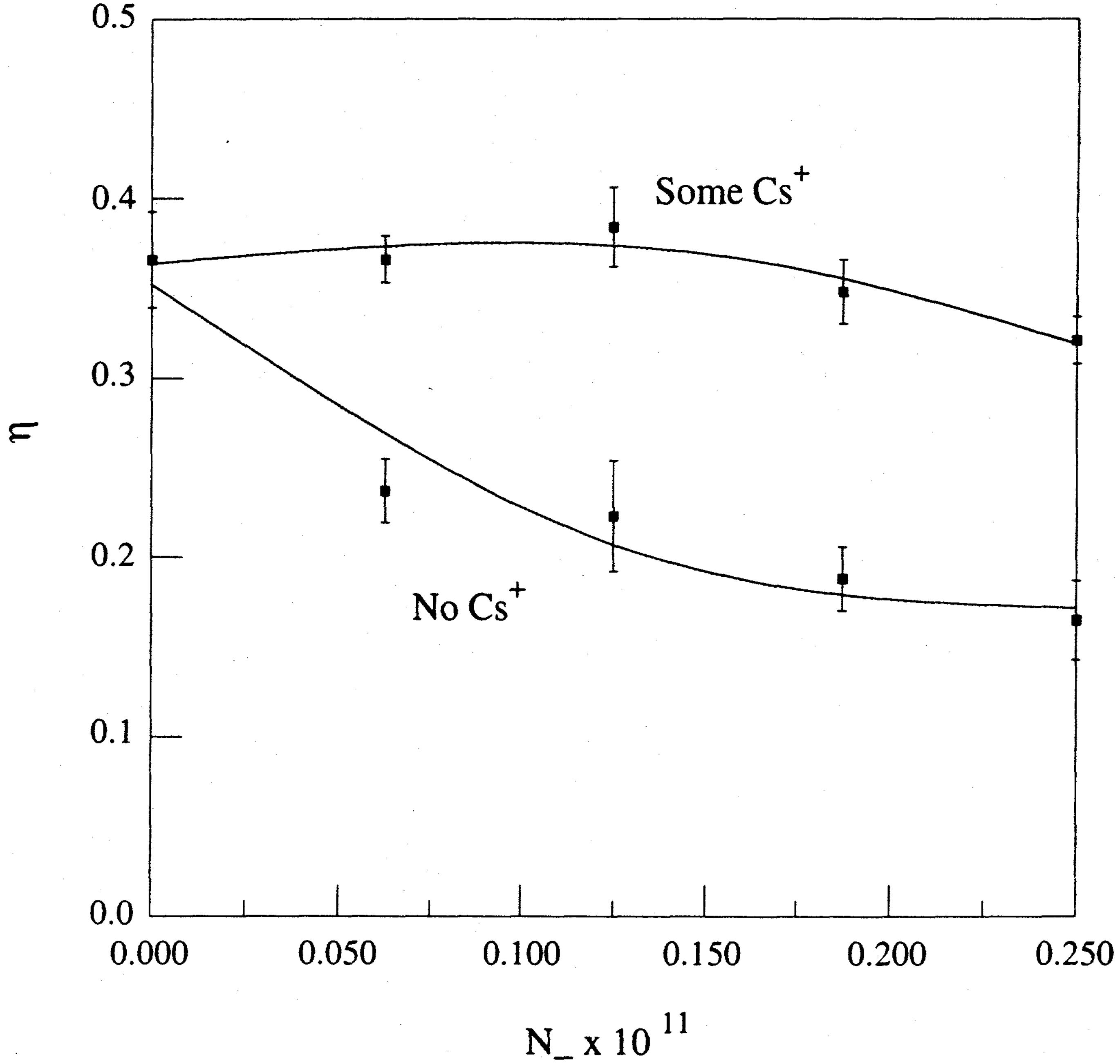

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Fig. 6