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I. INTRODUCTION

Oosik was the name given to a barium release experiment carried out jointly by the University of Alaska and the Los Alamos Scientific Laboratory on March 7, 1972, with the intention of tracing an L $\sim$ 6.75 field line from the northern conjugate to the magnetic equator.[1]

In the Oosik experiment, an explosion of a conically shaped charge was used to inject barium vapor upwards along the geomagnetic field from a high magnetic latitude. The shaped charge assembly with a barium liner was lofted by rocket from the Poker Flats Range to an altitude of 544 km and detonated at $6^h58^m59^s$ UT. The fast component of the barium vapor produced in the explosion ionized and formed a jet that was observed to move upwards along the burst-point field line with speeds 12-14 km/sec. This jet apparently maintained integrity for at least 5 min after release. At release plus 8 min, the fast ion streak began to show evidence of separating into smaller streaks, each lying in different tubes of magnetic flux. By T + 17^m, at least eight well separated streaks could be distinguished. Shortly after this time, a sudden-commencement magnetic perturbation with accompanying auroral displays occurred and optical contact with the streaks was terminated. The sequence of phenomena just described is shown in Fig. 1, a set of image orthicon frames taken by the University of Alaska group at Barter Island. The line of sight from Barter Island to the streak is nearly parallel to the geomagnetic field lines, and the fast ion streaks (s) are well resolved even though the ion density is small.

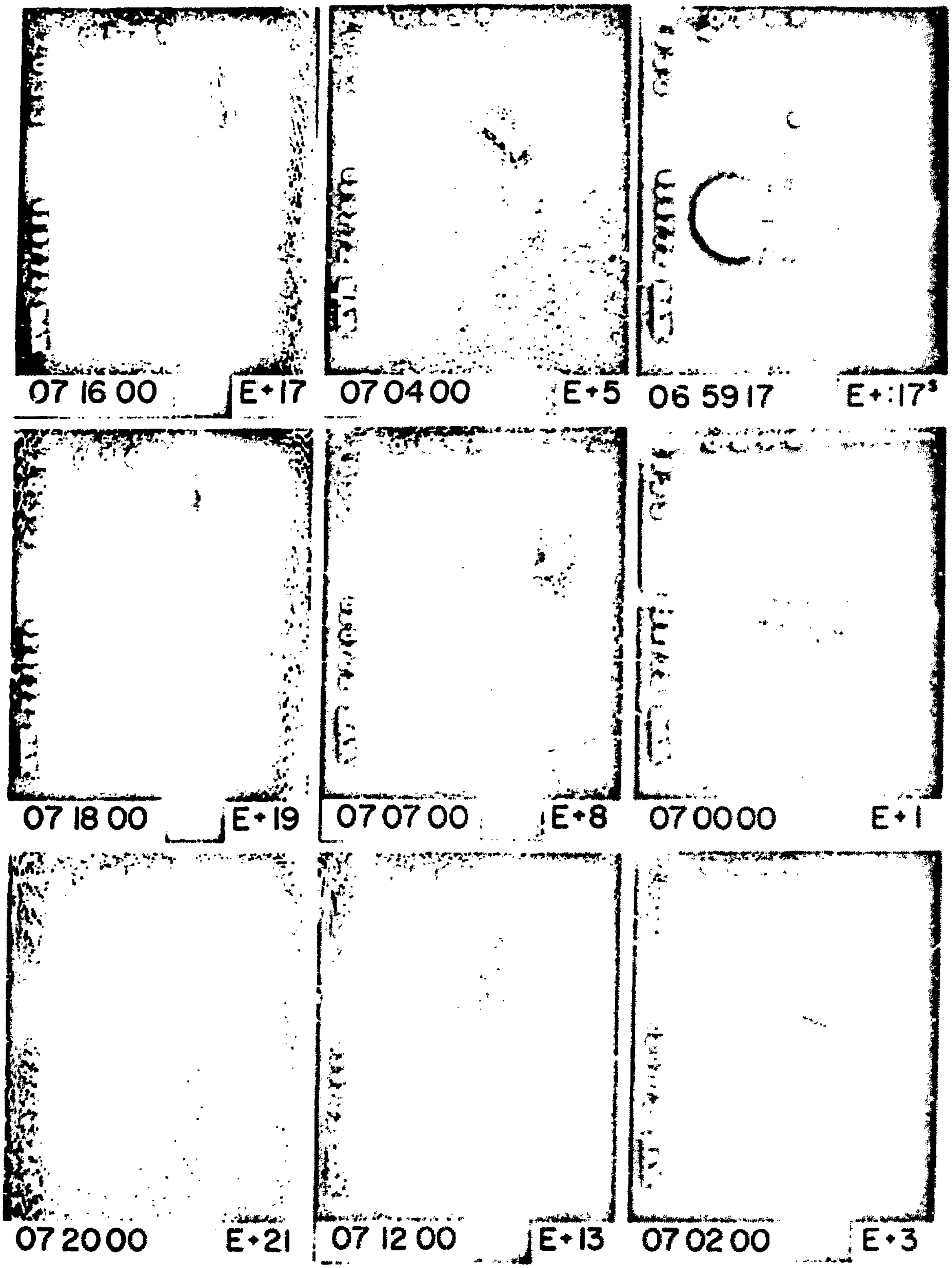

Fig. 1. Selected image orthicon frames of the Oosik event taken from Barter Island, Alaska. Up is to the right in each frame.

It is the purpose of this note to examine several possible mechanisms that could cause the "striation" of the Oosik fast ion jet. We will suggest that the observed separations of the ion cloud were the consequence of steady, small-scale, field-aligned irregularities in a general, large-scale electrostatic field existing in the high ionosphere (> 500 km altitude) at the time of the release. The other likely mechanisms for ion cloud deformation seem to operate on too long of a time scale in the presence of certain "short-circuiting" currents to have the observed effect under Oosik conditions.

II. ESTIMATES OF OOSIK ION CLOUD PARAMETERS

A preliminary study[2] of photographs of the event taken from Fort Yukon and Ester Dome observatories during the first minute after release indicates that the fast component of the ion jet was born with about 2×10^{23} ions (5% of the total barium payload) moving with velocities 12 to 14 km/sec parallel to the burst point field line, and contained within a magnetic flux tube of about 2.5 km initial diameter.

Later, at $T + 3^m$, triangulation data[3] show that the head of the streak lay at an altitude of 2841 km, while the apparent tail lay at 1037 km. From these values, the estimated initial conditions, and the known divergence of field lines in a simple geomagnetic field, we can estimate the parameters of the fast ion jet at this time.

$T + 3^m$:

Effective diameter of streak = 6 km,
mean Ba ion density = 3.7×10^3 cm^{-3},
length of streak = 1900 km.

Barium ion thermal energies are of the order of 150 eV for these release conditions; the plasma has a very low β and the plasma motion is largely guided by the magnetic field (curvature and gravitational drift speeds for the Ba ions are both of the order of 3 m/sec, which is negligible).

Evidence for motion of the fast ion streak in a direction perpendicular to the field during the first 4 min after release is shown in Fig. 2, which is a plot of the 100 km altitude intersection of the feet of the magnetic field lines along which lay the main and subsequently formed streaks. The points are labelled with the time in minutes after release. During the first 4 min, the main streak apparently drifts to the southeast at 400 m/sec, suggesting the presence of a large-scale E-field, largely perpendicular to the geomagnetic field and of strength $\sim$ 7.5 mV/m. Between $T + 4^m$ and $T + 8^m$, the direction of drift of the main streak changes radically for unknown reasons, though it is interesting to note that the "striations" first appear in the time interval during which the drift direction changes.

As mentioned previously, a sudden-commencement magnetic perturbation occurred approximately 17 min after Oosik release, and interrupted a phase of slow recovery in the geomagnetic field following a moderate positive excursion that began roughly 40 min prior to launch. Carpenter[4] provides the best record of magnetic and ionospheric conditions prior to, and during the Oosik experiment. The point to be made is that the magnetic conditions were not radically disturbed during the first 10 min after the release.

III. DEFORMATION AND STRIATION MECHANISMS

The most obvious candidate for the mechanism producing the observed splitting of the Oosik fast ion jet at $T + 8^m$ is the gradient drift instability, which is believed to be the major cause of striation formation in larger, isotropic releases of barium in the E region.[5] The maximum growth rate of the gradient drift instability is V_o/ℓ, where V_o is the drift speed relative to the neutral background and $\ell = |\nabla \ln n_i|^{-1}$ is the ion density scale length. Applied to

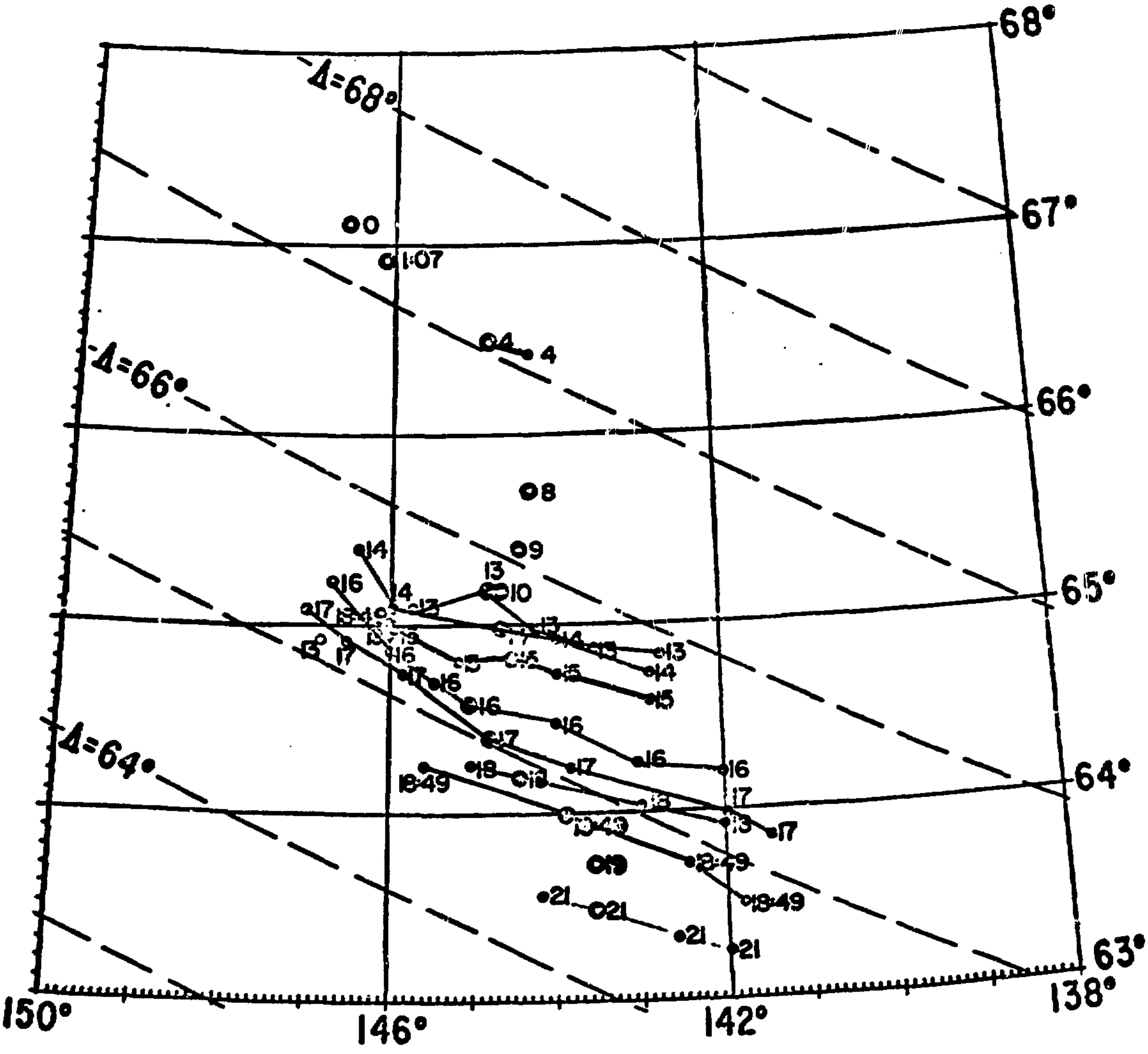

Fig. 2. Plot of the 100 km altitude intersection of field lines carrying primary and subsequently formed streaks in the Oosik event. Dashed lines are magnetic latitude. Solid lines connect points corresponding to a single, identifiable feature.

the fast Oosik jet at, say, T + 48^s, this prescription gives a growth time of about 3 sec which is obviously too fast. Even by T + 5^m, there is no evidence of the development of well defined striations (although the barely apparent division in the tail of the streak shown in the T + 5^m frame of Fig. 1 could be so interpreted).

The absence of striation development in the Oosik fast ion jet by means of the gradient drift instability is understandable in the light of the work of Völk and Haerendel,[6] and of Zabusky, Perkins, and Doles.[7] The first-mentioned authors have shown that the growth rate of a striation can be substantially decreased by short-circuiting currents flowing in the background ionosphere, and for a weak striation having a sufficiently large dimension across the magnetic field, Linson and Workman's analysis[5] must be modified to read

$$\gamma \simeq \frac{V_o}{\ell} \frac{\Sigma_p^c}{\Sigma_p^c + \Sigma_p^i} , \tag{1}$$

where γ is the growth rate, V_o is again the drift velocity, and ℓ is now an averaged characteristic dimension of the cloud. Σ_p^c is the Pederson conductivity integrated through the cloud along the magnetic field direction, and Σ_p^i is the integrated Pederson conductivity of the ionosphere, taken along the field lines threading the artificial ion cloud. By viewing the Oosik fast ion jet as a single, large striation at very high altitudes (> 600 km), we find that Eq. (1) predicts a growth time, γ^{-1}, of about 10^5 sec. This is because the integrated ionospheric conductivity overwhelmingly dominates the integrated cloud conductivity. Zabusky et al.[7] also show that the short-circuiting effect can be circumvented if the electric field driving the striation exceeds $\sim 10^2$ mV/m. Oosik conditions seem to exclude such strong fields.

There are several other instabilities of low-β ion clouds that are similar to the gradient drift instability insofar as they require an ion density gradient and a charge-dependent drift velocity to drive them. Among these are the field line curvature instability and the Rayleigh-Taylor instability under gravity. Erick Lindman[8] has also suggested that overstable drift waves may have been the source of deformation in the Oosik cloud. We have estimated the nominal growth rates for these last three instabilities with Oosik parameters, and find growth times of 4 to 8 sec in the absence of short-circuiting effects. However, the short-circuiting or "line-tying" effects of the conducting lower ionosphere should play the same, stabilizing role for the last three instabilities mentioned as for the gradient drift instability. Although no analysis is presented as proof of this assertion, we will cite the evidence from another shaped charge, barium injection experiment[9] (code-named Bubia), conducted on an L = 1.26 magnetic flux tube over Kauai, Hawaii. In Bubia, the barium ions travelled along the entire length of the field line from one conjugate to the other in roughly 7 min, but the barium streak exhibited no evidence of striation near apogee when, in particular, conditions for growth of the field line curvature instability were favorable.

Large amplitude, transverse Alfvén waves propagating in the vicinity of the Oosik streak are another possible cause of the observed breakup. This alternative seems to be an unlikely one since, as stated earlier, the magnetograms shows no radical disturbance in the interval 30 min prior to, and up to 15 min after the event time.

It is therefore plausible that the Oosik fast ion streak was an efficient probe of the lower magnetosphere in the sense that the observed deformation was caused by steady, pre-existing conditions in the magnetosphere.

IV. ION CLOUD DEFORMATION IN THE PRESENCE OF STEADY, ELECTROSTATIC IRREGULARITIES

Reid[10] has suggested that the appearance of striations in low-density ion clouds might give a visual indication of the process of small-scale electric field transfer along the geomagnetic field. The effect of suitably small electrostatic inhomogeneities upon the motion and shape of a field-aligned ion cloud is best seen by reviewing Reid's theory.

If the ratio of the ion-neutral collision frequency to the ion gyrofrequency is very small (as it must be at Oosik altitudes), then the ion drift velocity is

$$\vec{V} = c\,\frac{\vec{E} \times \vec{B}}{B^2} + \vec{V}_{||}$$

where $\vec{V}_{||}$ is the ion drift velocity parallel to the $\vec{B}$ field and $\vec{E}$ is the steady, ambient electric field which is taken to be the sum of a large-scale, uniform field $\vec{E}_0$ and a small-scale, spatially varying component $\vec{\mathcal{E}}$. Provided that $\vec{E} \cdot \vec{B} = 0$ (i.e., the field lines are equipotentials), the large-scale field causes the ion cloud as a whole to drift with a velocity

$$\vec{V}_0 = c\,\frac{\vec{E}_0 \times \vec{B}}{B^2}$$

while the small-scale field will cause differential drifts within the cloud and consequently lead to deformation of the cloud. Under steady conditions, $\nabla \times \vec{E} = 0$, and if a small term arising from the magnetic field curvature drift is neglected (i.e., assume $\nabla \times (\vec{B}/B^2) \underline{\sim} 0$), then $\nabla \cdot \vec{V} = 0$. In other words, the ions behave as though they were an incompressible fluid. The equation of continuity for the ions is then

$$\frac{\partial N}{\partial t} = -\frac{c\vec{B}\cdot}{B^2}\,(\nabla N \times \vec{\mathcal{E}}) \quad , \qquad (2)$$

in a frame of reference moving with the uniform velocity

$V_o + V_{||}$. For a field-aligned ion cloud, the N appearing in Eq. (2) can be interpreted as the ion density integrated along the B field direction over the length of the cloud, and the ∇-operation as a gradient operator in directions perpendicular to B. However, note that

$$\vec{\mathcal{E}} = \vec{\mathcal{E}}\,(\vec{r} + [\vec{V}_o + \vec{V}_{||}]t)$$

in the moving reference frame, so that in this frame, the inhomogeneities in $\vec{E}$ appear to approach and pass through the stationary ion cloud. If $\vec{\mathcal{E}} = -\nabla\Phi$, where Φ is the electrostatic potential generating the inhomogeneities in E, then the steady-state solution of Eq. (2) is

$$\nabla\Phi \times \nabla N = 0 \quad .$$

In other words, after a long time the curves of constant ion columnar density coincide with the equipotentials of the field inhomogeneities. As each inhomogeneity passes through the ion cloud (viewed in the moving reference frame), a fraction of the ions are trapped and carried away.

From Eq. (2), the time τ required for a fractional change, $\Delta N/N$, in the columnar ion density can be estimated:[10] ,

$$\tau \simeq \frac{B\ell}{c\mathcal{E}}\left(\frac{\Delta N}{N}\right) \quad , \tag{3}$$

where ℓ is the ion gradient scale length in the direction perpendicular to $\vec{B}$. If the scale size of $\vec{\mathcal{E}}$ is smaller than or comparable to ℓ, then substantial changes in N occur only after several passages. The following rough model may be convincing.

Suppose for simplicity that the inhomogeneities specified by $\vec{\mathcal{E}}$ are periodic step functions of one sign and of length δ. Then, as each inhomogeneity passes through the ion cloud, the field is applied for a time $\tau \simeq \delta/V_o$ to a fixed point in the cloud. From Eq. (3), the fractional change in columnar density is

$$\frac{\Delta N}{N} = \frac{c\mathcal{E}}{B\ell}\,\frac{\delta}{V_o} = \frac{\delta}{\ell}\,\frac{\mathcal{E}}{E_0} \quad .$$

Presuming that ℓ remains constant, the total fractional change after n passages of inhomogeneities is

$$\frac{(\Delta N)_n}{N_0} = \frac{\delta}{\ell}\,\frac{\mathcal{E}}{E_0}\left(1 + \frac{\delta}{\ell}\,\frac{\mathcal{E}}{E_0}\right)^n \qquad (4)$$

If we take $(\Delta N)_n/N_0 = 1$, $\delta \simeq 1$ km, $\ell = 2.5$ km, and $\mathcal{E}/E_0 \simeq 0.1$ (a 10% rms fluctuation in the large-scale field), then Eq. (4) indicates that $n \simeq 61$. Now, if the large-scale field drives the cloud at 400 m/sec for $\sim 480^s$ (see frame E + 8^m in Fig. 1), an average spacing of the irregularities of about 3 km is indicated. Such a scale size, amplitude, and spacing for the electrostatic fluctuations of the mean field appear to compare reasonably well with the measured variations of electric fields from polar orbiting satellites.[11] An analysis that is more convincing than the one just given would require numerical simulation of the phenomena associated with Eq. (2) in at least two dimensions.

The point to be emphasized here is that small-scale inhomogeneities in the large-scale polar electric field, having reasonable amplitudes and spacing, seem to be capable of explaining the breakup of the Oosik cloud.

V. RELEVANCE OF OOSIK TO STRIATION FORMATION IN THE STARFISH EVENT

Field-aligned striations appearing at late times and at altitudes of up to 1500 km were observed during the Starfish event of the Dominic test series in 1962. Hodges and Chesnut[12] have analyzed photographs of these phenomena taken from Canton Island and Christmas Island. They conclude that the luminous streaks observed as late as 350 sec after event time resulted from ionized and excited air travelling up magnetic field lines from the burst region and the southern conjugate at velocities of 4.5 to 5 km/sec. These striations were of sufficient densities to return radar echoes in the VHF band, and actual electron concentrations in the disturbances may have been as high as 10^7 cm^{-3}.

Though we initially believed otherwise, Oosik has no relevance to the study of the weapon-induced striations in Starfish. The Starfish "aurora" observed at the highest altitudes and at late times showed well developed field-aligned structure when they first appeared in the Canton Island photographs as early as 60 sec after event time.[12] Such rapidly developing structure can be easily explained by calling upon any one of the several instabilities mentioned in Section III of this paper. The nominal growth rates are consistent with the observed structure in the Starfish striations; the short-circuiting effects postulated for the weak Oosik jet are negligible in an ionosphere that is massively disturbed by a nuclear explosion at high altitudes.

VI. CONCLUSIONS

The major conclusion to be drawn from our first and somewhat qualitative analysis of the Oosik phenomena is that:

> The Oosik fast ion streak was an efficient probe of the lower magnetosphere in the sense that the deformation of the streak was caused by nearly steady, pre-existing conditions in the magnetosphere and not by the growth of instabilities within the ion cloud itself.

A corollary to the conclusion is worth mentioning. Field-line tracing experiments, or shaped charge injections of barium into the magnetosphere as a probe of natural magnetospheric conditions, could conceivably fail their intended scientific objectives if the ion densities in the fast streak became too large ($\gtrsim 10^6$). Given the present (and anticipated) capabilities of the technique of shaped charge injection, the achievement of such a large ion density in a directed jet of barium vapor seems unlikely. Some caution should nevertheless be observed.

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