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TO AN X-RAY SOURCE

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THE VNIIEF MAGNETIC BUBBLE APPROACH TO AN X-RAY SOURCE

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ABSTRACT

Both analytic and cursory numerical investigations indicate that the All-Russian Scientific Institute for Experimental Physics (VNIIEF) approach to x-ray generation has potential advantages. An experimental test of this concept was conducted at VNIIEF in Sarov, Russia, in the spring of 1994. We present only the analytic and numerical investigations, which clearly demonstrate the potential advantages of the approach.

INTRODUCTION

One approach to hydrodynamics based thermal X-ray generation involves the acceleration of a thin liner to high inward radial velocity and stagnation on axis to achieve a high enough temperature to provide soft X-radiation from the liner material. An estimate based on equating the inward kinetic energy to the internal energy after stagnation occurs on axis yields $T = v^2 / 2c_v$. A more general result could be obtained by considering the details of the stagnation process were considered, but for the purpose of an estimate, this is adequate. To achieve about 300 eV, about 40 cm/ms is needed.

Several problems arise in trying to realize this approach to X-ray generation. First, to achieve the high velocities that are needed, very thin liners must be used. For very thin liners the current must achieve its maximum value very quickly to reach the high velocity desired. This requires fast switching of large currents. Second, the liner is Rayleigh-Taylor unstable, so it is very sensitive to the fabrication process and the assembly of the experiment.

Recently, personnel at the All Russian Scientific Institute for Experimental Physics (for which the transliterated acronym is VNIIEF) proposed a variation on the collapse of a cylindrical target as a means of producing a burst of X-radiation. Their proposal is to create a magnetic "bubble" which expands axially as it is driven toward an axis of convergence, so that the increasing magnetic pressure is no longer acting on a continually increasing mass per unit area (areal density).

ANALYSIS

A very simple analysis of the acceleration of a thin cylinder by an azimuthal magnetic field ($B = \mu_0 I / 2\pi r$) leads to an equation for the velocity v of the cylinder at a given radius r :

$$v^2 = KL(\ln R/r) / \pi ,$$

where $K = \mu_0 I^2 / 2\pi M$, I is the current (assumed constant here), R the initial radius, L the cylinder length, μ_0 is the permeability of free space, and M is the mass of the cylinder.

The magnetic bubble proposed by VNIIEF is not a spherical bubble. Rather, it would be roughly circular in shape in the (r, z) plane, but cylindrically symmetric. It is expanded and imploded by an azimuthal field created by the current flowing through it, so that the volume between the starting surface of rotation and the instantaneous surface is continually

Figure 1. Analytic functions comparing velocities of cylindrical liner (solid line) and magnetic bubble (dashed line).

Figure 2. RADGEN implosion of a cylindrical liner.

increasing. For the analysis that follows we assume that the mass of the bubble spreads evenly along a circular shape. While this assumption is very simple and it may not be accurate, nor may the assumption of circular shape be accurate, it serves as a convenient basis for a simple analysis. Specifically, the radius $(R-r)$ of the circle with a center at a $z=0$ and a fixed distance R from the axis increases so that part of the mass collapses on axis and part is constrained to travel along a constant R path. The part in between is shaped by the accelerating field, but to see what the maximum inwardly radial velocity is, it is only necessary to track the velocity of the radially directed part. Assuming that the bubble is thin and that it maintains a circular shape in (r, z) starting with a half circumference of the circle equal to L , i.e., $\pi(R-r_0) = L$, a simple analysis similar to that for the cylinder yields:

$$v^2 = K p \{ R \ln(r_0/r) - (r_0 - r) \}$$

along the path $z=0$. Here, r_0 is the initial and r the instantaneous distance of the circle from the axis. K is the same as defined above. R is the radial distance of the center of the circular shape of the bubble from the axis. Initially the circle radius $(R-r)=(R-r_0)$ is small, but approaches R , as the bubble expands laterally and collapses on the axis. After the bubble collapses, of course, it is no longer circular in shape, but the analysis is not meant to extend beyond collapse at $z=0$.

Both of the above equations suggest that near collapse (i.e., as r approaches zero) the velocity increases without limit. However, a finite thickness should set a different maximum velocity for each case, because the minimum r should be the thickness, and that thickness would be less for the case of the bubble because of its thinning due to expansion and also due to the greater acceleration. Setting $L = \pi(R-r_0)$ for the same mass M , the ratio of the squares of the velocities becomes:

$$(R-r_0) \ln(R/r) : [R \ln((R-r_0)/r) - (r-r_0)]$$

For $r = r_0$, the bubble velocity is zero, as is the cylinder velocity for $r = R$. For a modest decrease in r ($< r_0$), the inward velocity of the bubble exceeds that of the cylinder.

As the $z=0$ part of the bubble approaches the axis ($r \sim R/20$) the bubble velocity exceeds the cylinder velocity by more than 2.5x at the same radius. Figure 1 shows the functions $\sqrt{(R-r_0) \ln(R/r)}$ and $\sqrt{R \ln((R-r_0)/r) - (r-r_0)}$ for $R=2$ cm and $r_0 = 1.9$ cm. For the case of $R = 20$ cm, $r_0 = 19.5$ cm, $M = 5$ gm, and $I = 100$ MA, at $r = 2$ cm the bubble attains 62 cm/ms, but the liner only reaches 12 cm/ms.

CALCULATIONS WITH RADGEN

To better assess the magnetic bubble idea, a very simple explicit code RADGEN was written to follow the dynamic development of the bubble. It assumes that the magnetic pressure acts normal to the surface of the expanding bubble. So far, only initially circular 2-D bubble shapes with a small initial radius $(R-r_0)$ have been used. The actual 3-D shape is a rotation of the 2-D (r,z) shape about the axis of symmetry. For the 3-D bubble the areal density $(\rho \Delta r)$ increases due to convergence toward the axis, but decreases as the bubble expands in (r,z) . In the code a string of mass points was accelerated normal to the local surface as defined by each mass point and its two (r,z) neighbors.

The dynamic load represented by the expanding magnetic bubble is part of a circuit that provides the driving current for the bubble.

Figure 3. Implosion velocity computed by RADGEN for a cylindrical liner.

Figure 4. Shaping of the magnetic bubble starting with an initial circular shape.

For comparison the simple code has been used to treat both a cylinder and a bubble. The cylindrical case is shown in Figure 2 with an expanded z scale. The acceleration would be the same for a long cylinder with the same mass per unit length. The velocities of the implosion are shown as a function of the position r in Figure 3.

Note that the finely zoned cylindrical calculations show a very early onset of instability. This is partly numerical, as demonstrated by the fact that the growth starts at the outer edge where the boundary condition is different from the simple reflection used at the inner edge. However, it is also consistent with what one would expect for Raleigh-Taylor instability.

The expanding magnetic bubble implosion is shown in Figure 4. Here the z scale is not expanded. Figure 5 shows the velocity along $z=0$ for the magnetic bubble as a function of r . It appears that the (r,z) outflow along the expanding bubble surface may be stabilizing. However, more refined calculations show an onset of instability similar to that of the cylindrical case. The late time velocities for the bubble are generally about a factor of more than two times higher ($\sim 2.5 \times$) than for the equivalent cylinder. While the bubble appears to evolve from its initial circular shape, VINNEF's approximation of the (r,z) shape as a circle with an offset center seems to be fairly reasonable. The velocities attained by the bubble do not exceed those of the cylinder by as much as the simple analysis above would suggest, but the results from the simple code are in reasonable agreement with that analysis. Part of the deviation from the analytic results may be due to the fact that in the calculations the current is not constant (dashed curve in Figure 5).

Figure 5. Magnetic bubble implosion velocity for $z = 0$ computed with RADGEN. The current that drives the bubble expansion is shown as a dashed line.

The energy in the implosion goes as Mv^2 , and according to the earlier relation used to estimate the velocity required to achieve a given radiation temperature, the temperature goes

as v^2 . The magnetic bubble appears to sacrifice total energy for increased velocity, hence higher radiation temperature. The bubble collapse on axis is not instantaneous as is the case for an idealized cylindrical shell. Rather, the faster moving part at $z=0$ collapses first, followed by the slower parts. One would expect an initial burst of radiation at high temperature with a prolonged decay having continually decreasing radiation temperature, depending on the details of the experimental geometry (i.e., whether or not walls limit the bubble volume, hence inductance). Also, one would expect jetting along the axis. While the total radiation energy may be greater for the cylindrical case, the useful radiative energy may be greater for the bubble case, simply because the temperature is expected to be much higher, leading to better transport characteristics.

ADDITIONAL THEORETICAL AND COMPUTATIONAL WORK NEEDED

The question of bubble symmetry needs to be addressed. The analysis and simple code model are axially symmetric, but there is a possibility that the arc that would form the bubble would be initiated first at only one point in azimuth. implosion. We need to do some work that addresses the possibility of azimuthally asymmetry. Additional analysis or even a 3-D MHD code may be necessary to answer the question of whether one should expect that uniform arcing should occur and lead to an azimuthally symmetric bubble.

The simple code discussed above relies on an ability to define a normal to the local surface defined by the adjacent mass points. Two methods that have been tried are to define a center of a circle using triplets of points and to use a weighted mean of the normals to the two straight lines between the point of interest and its two neighboring points. Neither of these approaches is entirely satisfactory. Higher order methods have not been tried.

The bubble and cylindrical liner calculations are not on the same footing when considering the growth of the instability that appears in Figure 2. This is because the mass points that define the liner remain close together allowing short wavelengths to grow at their more rapid rate, while the bubble calculation having the same number of points initially supports the short wavelength growth, but soon does not as the mass points spread out along the bubble. More work is needed on this problem.