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CHARGE COLLECTORS FOR THE OMEGA UPGRADE

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I. INTRODUCTION

Charge collectors placed at several distances from the target measure the current of ions resulting from target disassembly and expansion, as a function of arrival time at the detector. Since the expanding plasma is neutral, comprising both electrons and ions moving together, the role of the charge collector is to separate out the electrons, so that the net ion current can be measured. The time-integrated current, or the total charge, can yield the total mass ablated from the target, provided the ionic charge Z is known. From the total ablated mass, the mass ablation rate during the target implosion can be estimated. This quantity provides a useful gauge of the combined effects of absorption, heat conduction, and hydrodynamic efficiency in target interactions.

In principle, one charge collector can yield useful results because we assume spherical symmetry of the expansion (this question is addressed directly by the plasma calorimeters of which there are many around the target). In practice there will be four charge collectors, two at the tank wall (distance R from the target) and two in an extension tube, at a distance of about $2R$ from the target. The reason for the two different distances is to check that complete charge separation within the detector has been achieved. A signature of such separation will be to verify that the current falls off as $1/R^2$ with distance from the target. Since the separation can be inadequate due to space charges within the detector, the farther detector, having smaller charge density, will be more

reliable. The two pairs will be oriented at about 90° with respect to each other (say, east and north) to give a rough idea on the isotropy.

II. DEDUCTION OF MASS ABLATION RATE

Here we describe how the charge collectors are used to derive the ablated mass for the case of a polymer (CH) target; for other targets (such as glass) the analysis is similar.

The total mass ablated is given by

$$\Delta M = \langle m \rangle \int [I(t)/e\langle Z \rangle] dt , \quad (1)$$

where $\langle m \rangle$ is the average mass of C and H, $I(t)$ the measured current (into the 4π solid angle), and $\langle Z \rangle$ the average charge of carbon and hydrogen ions:

$$\langle Z \rangle = 1/2 \left[1 + \sum_z z (N_z / N_C) \right] , \quad (2)$$

where N_z is the density of charge-Z carbon ions, and N_C is the total density of carbon ions. The quantity $\langle Z \rangle$ has to be assumed from the code (otherwise we would have to measure it with a magnetic mass spectrometer). We further address this question in the subsequent section.

In using Eq. (1) we need to know both the current in absolute units the solid angle subtended by the charge collector, but instead we can make use of the absorbed energy, measured by the plasma calorimeters. This energy is about equal to the total energy in the ablated mass (more accurately, we need to subtract from the absorbed energy the energy going into x-rays, whose relative contribution is a few percents). Using the absorbed energy E , the ablated mass is given by

$$\Delta M = 2E / \langle V^2 \rangle , \quad (3)$$

where transforming from velocity to the time space yields

$$\langle V^2 \rangle = L^2 \int [I(t)/\langle Z \rangle] (dt/t^2) / \int [I(t)/\langle Z \rangle] dt , \quad (4)$$

and L is the distance from the target to the charge collector. Here only the shape of the current curve needs to be known since it appears both in the denominator and the numerator. However, this method has some disadvantages over the first method. Here, more weight is given to the rising part of the current, where the signal to noise is worse, rather than to the peak of the curve, as is the case in the first method. Also, because of the $1/t^2$ factor in Eq. (4), an accurate zero time must be known. We achieve this by providing a straight path for x-ray photons through the charge collector to the plate collecting the ions. Photons cause the ejection of some photo-electrons, which register as a positive current to the plate. On the charge trace, which lasts for a few microseconds, a fiducial of a few nanoseconds appears, and accurately marks the zero time (i.e., the time of the laser pulse).

Using the measured total ablated mass, we can then estimate the mass ablation rate (during the laser interaction). The simplest assumption will be to write the peak mass ablation rate as

$$(dm/dt)_{peak} \sim \Delta M / \Delta t_{laser} , \quad (5)$$

where m is the mass areal density (g/cm^2) and Δt_{laser} the laser pulse width. There is here an assumption that dm/dt is proportional to the instantaneous laser intensity P . Normally it is assumed that $dm/dt \sim P^\alpha$, where $\alpha < 1$. We can find α by comparing the measured $(dm/dt)_{peak}$ for different shots where the peak laser power P_{max} has been varied. We then assume that the same dependence exists between dm/dt and P within a single shot, as between $(dm/dt)_{peak}$ and P_{max} . As an example, for Gaussian pulses

$$(dm/dt)_{peak} \sim \Delta M \alpha^{1/2} / \Delta t_{laser} . \quad (6)$$

For the shaped pulses of the Upgrade, Eq. (6) has to be generalized to

$$dm(t)/dt = \Delta M \left[I(t)^\alpha / \int I(t)^\alpha dt \right] . \quad (7)$$

The instantaneous mass ablation rate within the target (which needs careful definition) will clearly vary during the pulse and, depending on the target hydrodynamics, can have different values early and late in the pulse for the same instantaneous absorbed intensity. Nevertheless, this quantity provides a useful gauge of the combined effects of absorption, heat conduction, and hydrodynamic efficiency in target interactions.

III. CODE CALCULATION OF THE CHARGE-COLLECTOR SIGNAL

We consider a typical polymer (CH) shell target for the OMEGA Upgrade and calculate the expected charge-collector signal; in particular, we examine the question of the average charge state $\langle Z \rangle$ of the expanding plasma.

The assumed target is a CH shell of 440- μm inner radius and 30- μm thickness, filled with an 80-atm pressure of DT. The laser pulse is trapezoidal: it rises linearly over 100 ps to a power of 13.5 TW, remains there for 2.2 ns, then falls linearly over 100 ps. In Fig. 1 we show the electron density and velocity profiles at 14.8 ns after the peak of the pulse. From these results the charge-collector current $I(t)$ at a distance L from the target can be calculated as

$$I(t) = 4\pi e R^2 N_e V^2 / [L(dV/dR)] . \quad (8)$$

The result is shown in Fig. 2. As seen, the signal duration at a distance of 1 m is $\sim 1 \mu\text{s}$. Because of the linearly rising velocity curve, the values of $\langle Z \rangle$ calculated by the code for the various target layers simply translate to values of $\langle Z \rangle$ as a function of arrival time at the charge collector. As seen in Fig. 2, the plasma contributing significantly to the charge-collector current can be assumed to be completely ionized; for complete ionization $\langle Z \rangle = (6 + 1)/2 = 3.5$. We can calculate the ablated mass using Eqs. (3) and (4) with either the $\langle Z \rangle$ curve of Fig. 2, or assuming that $\langle Z \rangle = 3.5$ uniformly. The difference

1(a)

1(b)

Fig. 1 (a) Code-calculated electron-density profile of the expanding plasma from a typical OMEGA Upgrade CH target. (b) Code-calculated velocity profile of the expanding plasma from a typical OMEGA Upgrade CH target. These N_e and V profiles were used to calculate the resulting charge-collector signal (Fig. 2). The target layer [shown by an arrow in (a)] gives rise to the peak in the charge-collector current.

in the two results amounts to only 0.6%. Therefore, we can assume complete ionization without using a Thompson-parabola mass spectrometer. In the case of glass targets the deviation between complete ionization ($\langle Z \rangle = 10$) and the actual $\langle Z \rangle$ at the later times of the signal will be larger. However, even a much larger error than the 0.6% found here can be tolerated. Also, one can use the code-predicted $\langle Z \rangle$ since we need to know the correct $\langle Z \rangle$ only as a small correction.

Fig. 2 Code-calculated charge-collector signal from a typical OMEGA Upgrade CH target at a nominal target-to-charge-collector distance of 100 cm. The average charge state of the expanding plasma is also shown.

IV. DESCRIPTION OF THE INSTRUMENT

We describe here the principles on which the charge collector is based. A schematic of the charge collector employed on OMEGA is shown in Fig. 3. The charge collector consists of two compartments. The front compartment achieves the charge separation by two ways: First, there is a magnetic field generated by a pair of permanent magnets attached to the wall of the charge collector. The direction of the field is

transverse to the direction of plasma flow into the collector (i.e., the radial direction). The ions and electrons entering the field will rotate around field lines with the gyromagnetic radius given by

$$R_B = mvc / ZeB , \quad (9)$$

where m and Ze are the mass and charge of the particle, c the velocity of light, and B the magnetic field. For the existing charge collectors, $B = 500$ G (ferrite material). The velocity of plasma expansion has a distribution with a maximum velocity of about $1-2 \times 10^8$ cm/s. Using Eq. (9) we find that for C^{+6} ions R_B is <80 cm; for hydrogen ions $R_B < 40$ cm, whereas for electrons $R_B < 0.2$ mm. We see then that the ions will be hardly affected by the magnetic field, whereas the electrons will be stopped by the field and prevented from entering the charge collector. In order to facilitate the routing of the electrons to ground, a honeycomb structure is provided. However, the charge separation by the magnetic field may not be complete because space charge generated within the collector may accelerate electrons into the collector. For that, an electric field between that honeycomb and the mesh provides additional separation. Since charge neutrality causes the electrons and ions to expand together, their energies are very different. For $v < 2 \times 10^8$ cm/s, the energy of carbon ions is $E < 240$ keV, for hydrogen $E < 20$ keV, whereas for electrons $E < 12$ eV. Therefore, an applied negative voltage of 100–200 eV will have a negligible (accelerating) effect on the ions, but will stop most electrons and drive them into the honeycomb structure and, hence, to ground.

The opening size of the mesh is determined by the charge density due to the flowing plasma. To minimize loss of signal due to the mesh, that opening should be relatively large, but to assure sufficient charge separation the opening should be smaller than a certain critical size, which we determine here. When placing a metal plate of a certain voltage V in a plasma, the plasma forms a sheath of charge along the metal surface, beyond which charge neutrality and wall potential exist. If the sheath thickness is

d , the voltage drop V corresponds to a field $F = V/d$. On the other hand the field near a plate of areal charge density σ is σ/ϵ , ϵ being the permittivity of empty space. Since $\sigma = \rho d$, where ρ is the volume density of charge in the charge collector, we find

$$d = (\epsilon V / \rho)^{1/2} . \quad (10)$$

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Fig. 3 Schematic drawing of the charge-collector design currently employed on OMEGA.

We now roughly estimate d for the Upgrade target described above (Fig. 2). The total ablated mass is about $20 \mu\text{g}$, which, when completely stripped, corresponds to a charge of $\sim 1 \text{ C}$. This charge over $\sim 1 \mu\text{s}$ yields a current of $\sim 10^6 \text{ A}$ into 4π solid angle, or about 1 A into a charge collector at a distance of 2 m . The total charge entering the charge collector is then $\sim 1 \mu\text{C}$. Since it takes the ions $\sim 10^{-8} \text{ s}$ to cross the charge collector, which is about 100 times shorter than the current signal length, the charge density with the charge collector during the peak of the pulse will be of the order of $10^{-2} \mu\text{C}/\text{cm}^3 = 10^{-8} \text{ C}/\text{cm}^3$. Using Eq. (10) we find a sheath thickness of $d \sim 3 \text{ mm}$; therefore, the mesh opening must

be much smaller than 3 mm in order that the plane containing the mesh will have a well-defined potential given by the applied voltage. Otherwise, the spaces in between the mesh wires will have potentials approaching the wall potential, and the electrons will freely flow through these openings without being separated out.

The second compartment of the charge collector has the role of reabsorbing the secondary electrons emitted by the plate when the very energetic ions hit it. These electrons, if going to ground, constitute positive current into the plate and will artificially increase the measured current. The second honeycomb structure makes sure that most secondary electrons will be reabsorbed by the plate to which it is connected. Also, a capacitor (~ 1 pF or somewhat smaller) should be provided between the mesh and ground to smooth fluctuations in the applied voltage. Figure 4 shows actual drawings of the OMEGA charge collectors.

Fig. 4 Side (a) and front (b) views of a charge collector.

V. PAST AND FUTURE MASS ABLATION MEASUREMENTS

We show in Fig. 5 some examples of past measurements of mass ablation rates derived from charge collectors. Also shown are mass ablation rates derived from

burnthrough spectroscopic measurements, as well as code predictions of mass ablation rates. As seen, charge collectors consistently measured values that agreed, both in value and in scaling, with the code. Burnthrough measurements often yield unrealistically large rates, which are attributed to shinethrough and Rayleigh-Taylor hydrodynamic instability of the ablation region. It is not completely clear why such behavior would not leave an imprint on the charge-collector signals. In other words, these two measurements taken together could be said to indicate material that is heated but not ablated. A possible explanation is that the spectroscopic measurements are very sensitive to even a small penetration into the target signature layer or to a nonuniform penetration in only some locations. This would be particularly true for strong resonance lines that saturate due to opacity effects. Using weaker lines may remove this sensitivity and yield results that agree more closely with charge-collector data. The charge-collector data, occurring so late after the implosion, depend only on the gross features of the ablation, not on the finer details of uniformity and stability.

Fig. 5 Examples of past results showing that mass ablation rates as measured by charge collectors generally agree better with code predictions than those derived from spectroscopic ("burnthrough") measurements.

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