Reduction of Ion Energies From a Multicomponent Z-Pinch Plasma

David N. Ruzic, *Member, IEEE*, Keith C. Thompson, Brian E. Jurczyk, Erik L. Antonsen, Shailendra N. Srivastava, and Josh B. Spencer

***Abstract*—This paper studies the expanding plasma dynamics of ions produced from a 5J Z-pinch xenon light source used for extreme ultraviolet (EUV) lithography. Fast ion debris produced in such plasmas cause damage to the collector mirror surface. Because of the great degree of erosion and the change in surface roughness properties, the reflectivity of EUV light at 13.5 nm drops drastically. Reducing ion energies and stopping the ion flux are a potential solution toward the success of EUV lithography. Ion energies are measured in kiloelectronvolt range using a spherical sector electrostatic energy analyzer. Preliminary computational work indicates that the observed high energies of ions are probably resulting from coulomb explosion initiated by pinch instability. Mixed fuel experiments are performed using a mixture of Xe, N_2, and H_2. The average energy of the expelled Xe ions is significantly decreased if the mobile lighter gas species are present in the main fuel. The magnitude of the Xe ion signal is reduced as well. This reduction in the quantity of heavy ions and their energy could greatly extend the lifetime of the collector optics used in EUV lithography.**

***Index Terms*—EUV lithography, ion acceleration, multicomponent plasma, Z-pinch plasma.**

I. INTRODUCTION

HIGH-ENERGY ion acceleration in expanding plasma is of considerable interest to the extreme ultraviolet (EUV) lithography community, since laser- and discharge-produced plasma (LPP and DPP) sources are being investigated for generating 13.5-nm exposure light.

Plasma expansion in vacuum has been studied since Gurevich *et al.* [1]. Once a plasma cloud is formed (from LPP or DPP source), it expands into vacuum. There are numerous processes such as ion acceleration, recombination, charge exchange, collisions, etc., which determine the plasma dynamics. Experimental studies [2]–[7] show the existence of surprisingly high energetic ions from 100 eV to several thousands of electronvolts, even though the temperature of the plasma itself is significantly less than 100 eV.

The physics of plasma dynamics has been studied mostly using the hydrodynamic model [8]. Recently, the kinetic aspects of plasma expansion have been developed concerning the ion acceleration by a strong electrostatic field where the electrons fly away quickly, creating a charge separation [9]–[12]. Progress in particle-in-cell (PIC) simulations is free from the oversimplified assumption of quasi-neutral plasma expansion and thus gives a powerful technique for a thorough investigation of ion acceleration mechanism [13]–[15]. The hybrid semi-analytical model described recently by Mora [16] is simpler, although it is able to describe physical features quantitatively about the ion acceleration process.

Bychenkov *et al.* [17] studied the ion acceleration in expanding multispecie plasma and report a more quickly accelerating electric field at the ion front compared to the case of quasi-neutral plasma expansion [10]–[12]. He showed that the charge-separation effect was responsible for the formation of an ion front moving with different velocities. Also, a significant increase of the electric field in the vicinity of heavy ion front provides additional acceleration for higher species, as reported in [13] and [18]. Bulanov *et al.* [19] studied the maximum energy of ions accelerated at the front of the electron cloud expanding into vacuum and demonstrated that the maximum energy of fast ions can substantially exceed the electron energy.

Gurevich *et al.* [1] solved the expansion problem of multicomponent plasma and also reported that the ion acceleration depends essentially on the ratio Z/M. He showed that the ions having the same Z/M values have the same acceleration, i.e., their relative densities have an identical dependence on velocity. In the case of a two-specie plasma, the ions with smaller Z/M are less accelerated by the electric field.

Although the idea of coulomb explosion is classically attributed to LPPs where energy deposition is nearly instantaneous and where charge separation comes very naturally from multiphoton ionization of the target material, the presented data appear to also point to an electrostatic potential difference as the primary cause for Z-pinch plasma expansion. A Z-pinch deposits energy to a plasma through ohmic heating over several hundred nanoseconds, therefore energy deposition is by no means instantaneous. How then is charge imbalance initiated? Several authors [20]–[23] have studied the instability properties of Z-pinch plasmas. It will be demonstrated by means of a dispersion analysis later in this paper that a sausage-mode instability could be responsible for charge imbalance that will result in the coulomblike expansion observed experimentally.

Although this phenomenon is studied by several theoretical researchers, an experimental investigation of the same is not performed in detail. In this paper, a Xe DPP EUV source is used as a plasma source. High energetic ions are produced, which are measured using spherical sector energy analyzer (ESA). Five-percent hydrogen is mixed in Xe, and the ion energy spectra are

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The authors are with the Plasma Material Interaction Group, University of Illinois, Urbana, IL 61801 USA (e-mail: druzic@uiuc.edu; sns@uiuc.edu).

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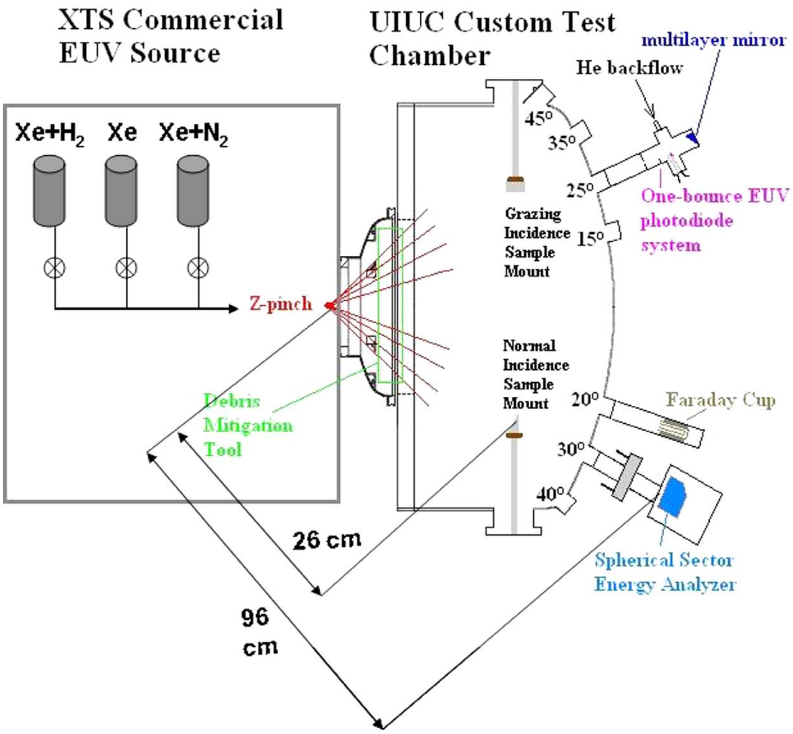


Fig. 1. Schematic diagram of experimental apparatus. Gas flow can be added directly to the Z-pinch or to the test chamber. The debris mitigation tool is a 2-D collimator.

measured to see the effect of mixing an additional fuel on ion flux and ion energy. Similar experiment is performed by mixing 5% N_2 to the main Xe fuel.

While the formation of highly energetic ions could be quite useful in sputtering in several fields of material synthesis, they are anathema to utilizing a high-density ~20–30-eV plasma as a source for EUV light (~13.5 nm) for lithography in semiconductor manufacturing. Xe is used in these plasmas to produce the EUV light from high-level transitions of Xe^{+8} to Xe^{+10}. Xe energies up to 10 keV have been reported emanating from the expanding plasma [24], and these accelerated ions damage the collector optics [25] and can significantly reduce their reflectivity [26], [27].

This paper serves the dual purpose of providing possible experimental evidence for the basic plasma dynamics responsible for the high-energy ion production in such plasmas, as well as providing a solution to the lifetime issue for EUV lithography collector optics. Adding a small percentage of a light species, such as H_2, to the dense plasma region significantly reduces both the number and energy of the Xe ions reaching the delicate downstream collector surface, thereby extending the collector's lifetime while having a negligible effect on the EUV light production.

II. EXPERIMENT AND RESULTS

Fig. 1 shows the experimental setup used in this paper. The plasma source is the XTREME technologies XTS 13–35 [27] DPP source currently used in the Excitech, Ltd., Micro Exposure Tool. This plasma source uses Xenon gas to create 35 W of EUV light (2% BW) in 2π sr with a conversion efficiency of 0.55%. The self-compression of the Xe gas column results in heating, sufficient for the generation of Xe^{8+} to Xe^{12+} ions, necessary for the emission of EUV light at 13.5 nm. First, Xe or a mixture of Xenon and another low Z gas is fed into the chamber where it encounters a stream of free electrons which via collision produce a low temperature and density plasma. Shortly after preionization, large current discharge pulse will ark over the insulator that separates the cylindrical electrodes through which the low temperature and density plasma was passing. The current pulse will heat the plasma to the necessary 30 eV required for efficient EUV production via the inherent ohmic resistance in the plasma while at the same time compressing it with an induced azimuthal magnetic field. As the current pulse passes, the internal plasma pressure will overcome the magnetic confinement and will then expand rapidly into the vacuum chamber. Fast and energetic ions are produced in this process and measured with ESA. The ion energy analyzer ESA is fitted with a set of Burle [28] dual microchannel plates (MCP) to measure the flux of ion debris emitted by the plasma source [24]. ESA consists of two spherical segments that are charged to equal and opposite voltages to guide ions of a specific energy-to-charge ratio between them toward the MCPs. Ions with too much energy extinguish against the outer wall, while ions with too little energy extinguish against the inner wall. Neutral and negatively charged particles are also unable to traverse the spherical path. The Faraday cup shown in the Fig. 1 is used to calibrate the ESA. The EUV output from the source is measured using International Radiation Detectors (IRD) SXUVHS5 Zr/Si EUV photodiodes. To ensure that changes in the ion energy spectra were not due to scattering, the same gas flow of each species was always used

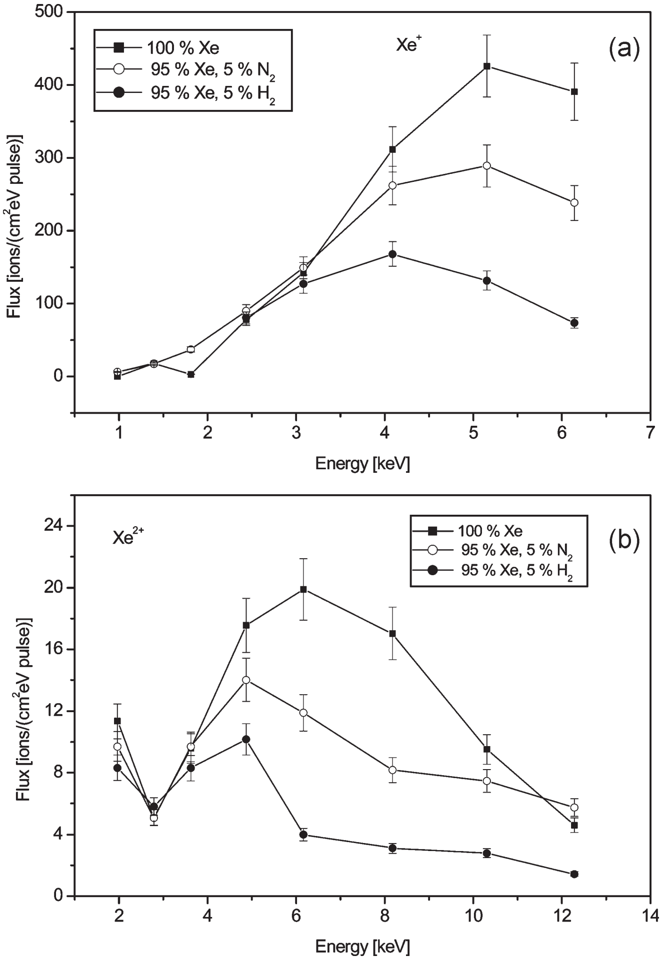


Fig. 2. Ion energy spectra under different gas fueling mixtures keeping the partial pressures of all components equal in the analysis chamber. These flux numbers are for a distance of 96 cm from the pinch.

so that the partial pressure of each gas in the diagnostic chamber remained constant. For example, during the “95% Xe, 5% H_2” experiment, both gases were added directly to the pinch. During the “100% Xe” case, only the Xe component was added to the pinch, but the same flow of H_2 as was used in the other experiment was added to the diagnostic chamber.

Fig. 2(a) and (b) shows the Xe^+ and Xe^{2+} ion spectra under 100% Xe, 95% Xe with 5% N_2, and 95% Xe with 5% H_2. It is noticed that the Xe energy spectra shift to lower energies and lower in magnitude when lighter gases are added. It appears that charge separation takes place as electrons move faster, leaving an induced electric field, which might cause ions to accelerate. Reduction of Xe ion energy by adding H_2 can be understood as a result of screening of electrostatic potential by hydrogen ions, because they move faster having lower mass than Xe. An intermediate result occurred with the addition of N_2.

Also, it is shown in Fig. 2(a) and (b) that the energy where the flux peaks for Xe^{+2} is higher than Xe^+. This also supports the idea that an electrostatic force exists which accelerates the charges with higher ionization states faster than the charges with low-ionization states, as the force is proportional to the charge states. Comparing the ion fluxes for two measured charge states of Xe, Xe^{+2} has much lower flux than Xe^+. It is also noticed that much higher charges with ionization states up to +10 have completely disappeared. Detailed experiments in this device have only seen charge states as high as +4, and their magnitude is extremely small [24]. This could be a consequence of recombination processes, where the higher charges have recombined to lower charges. This actually happens very near to the pinch location where the plasma is very dense. In Fig. 2(b), data set at 2 keV for Xe^{2+} has larger error bars. During the pinch, ~100-eV photons in the soft X-ray and EUV regimes (essentially coming from $Xe^{+8} - Xe^{+10}$, $Sn^{+6} - Sn^{+14}$), which are the intended product of the source, as well as a large amount of out-of-band radiation, are released. After the pinch, ejection of multiply charged ions can damage the collection optics used in applications, such as EUV lithography. At this stage, fast particles, both ionic and neutral, as well as a cloud of slower moving particles, including spent fuel and electrode materials, spread from the source.

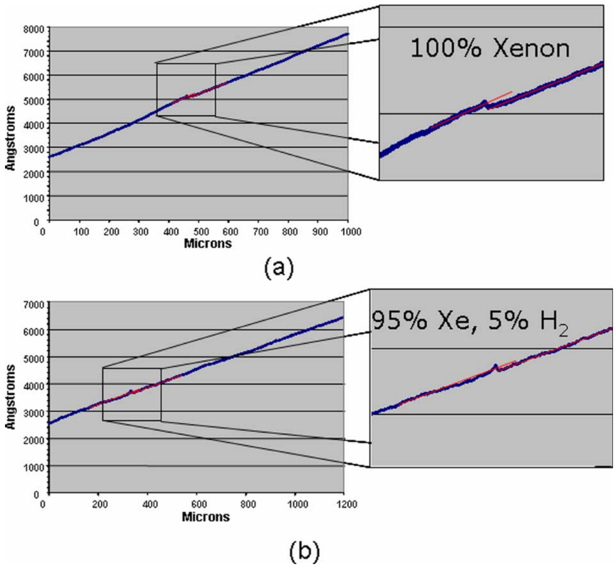


Fig. 3. (a) Step-height change seen when exposed to a pure Xe discharge. (b) Witness plate result with 5% hydrogen mixed into the fuel. No step-height change (at least less than 15 A) is seen.

The reduced ion energy and fluxes obtained in this experiment are of immense importance for a successful EUV lithography. The light is collected in this technology using reflective collector mirrors, which are placed near the plasma pinch area. Collection efficiency of these mirrors and their ability to direct EUV light to the intermediate focus depend heavily on its reflectivity, which in turn depends on the surface morphology. Fast ion bombardment on the mirror surface reduces the EUV reflectivity. Collector optics would need to be changed frequently as a result of reflectivity loss, which would increase the cost of ownership. Thus, the results obtained in this paper are of substantial importance for the EUV technology.

To further confirm the ESA results, we placed Si witness plate samples in the same position that collector optic mirrors would be placed ~26 cm from the source. A cover slip of Si was placed across the sample throughout the exposure. After exposure, the cover slip was removed, and the samples were measured with a profilometer to check for erosion. For the case of exposure to 100% Xe [Fig. 3(a)], a small 75 ± 10-Å step height was observed—the right-hand side of the plot was exposed to the energetic ion flux from the pinch; the left-hand side was under the cover slip. Note that the line in the graph goes "uphill" only due to an imprecise leveling of the profilometer.

The corresponding experiment for a 5% H_2 and 95% Xe mixture is shown in Fig. 3(b). No change in erosion is seen, i.e., less than 10 to 15 Å, in the resolution of our device. The small blip at the interface is due to sputtered material from a number of locations being redeposited at the junction between the cover slip and the sample.

The expected sputtered thickness can be calculated from the measured flux corrected for the sample position. These calculations underpredict the erosion as may be expected. Other ions come from the pinch, and scattering also occurs, decreasing the measured signal at the ESA relative to its value just after the debris mitigation tool. However, the ratio of the expected sputtering from the Xe alone case to the 5% hydrogen case (approximately 4) is in line with the measurements. A step-height change of less than 20 A would be quite difficult to see.

During all of these experiments, the EUV output was measured with an IRDs SXUVHS5 Zr/Si filtered photodiode after a single bounce on a Si/Mo multilayer mirror, as reported in our earlier paper [29]. The output of the signal stayed constant within our measurement error. For example, on one run of 100% Xe, the signal height was 961 pV. When 5% hydrogen was added, the signal actually rose to 977 pV. On the next run, the 100% Xe signal gave an EUV output of 935 pV. When 5% nitrogen was added, the signal fell slightly to 912 pV. All of these results are within the normal run-to-run variation seen within this experiment.

It would be reasonable to understand the ion energy distribution and the effect of mixed fuel if the phenomenon of ion acceleration is assumed as a result of in-build electrostatic potential. Thus, to understand the origin of charge separation, preliminary computational work is performed based on the experimental finding to verify the fact. As suggested by numerous authors, pinch stability is studied as a possible reason for charge separation, which may ultimately result into a coulomb explosion.

This paper is ultimately interested in the transport of ions and debris that emanate from the pinch, but in order to get appropriate initial conditions for that calculation, one must have an understanding of the behavior of the pinch. Given the possibility that the acceleration of the ions could come as a result of instabilities in the pinch, a magnetohydrodynamic (MHD) stability analysis has been carried out. Fig. 4 illustrates the plasma geometry that is assumed in the simulations and stability analysis that follow. In these calculations, it is assumed that there is only current in the z-direction, and that B_θ is the only nonzero component of the magnetic field affecting the pinch. Furthermore, only a linear treatment of the single fluid ideal MHD equations is carried out. Given these simplifications, the remaining terms are J_z, which is the z-component of the current density, B_θ, which is the θ-component of the magnetic field, and r_o, which is the initial radius of the plasma. This calculation follows the work of Jaworski [20], Bennett [21], Freidberg [22], and Boyd and Sanderson [23].

To get critical numbers for this stability calculation, such as peak density and pinch time, a commercial grade 1-D Lagrangian radiation MHD simulation HELIOS-CR produced by Prism Computational Sciences [30] was run for the conditions of the XTS 13–35 source, as shown in Fig. 4. The EUV power output of the pinch that was predicted from the HELIOS is shown in Fig. 5. This curve is interesting for two reasons: first, because it can be integrated to give an estimate of the conversion efficiency from electrical input power to EUV light out and, second, by evaluating the interval between the two extrema in its derivative, which is a good estimate of the pinch time determined. The ion density distribution predicted by HELIOS, which is shown in Fig. 6, is needed to find the peak density that should be expected. It should be noted that the oscillations shown in this figure are very likely numerical artifacts that are created by the symmetry boundary condition that is imposed on the axis of the pinch.

To determine the rest of the needed initial conditions, we assume Bennett pinch equilibrium, and in so doing, the magnetic induction, current density, and pressure conditions in the

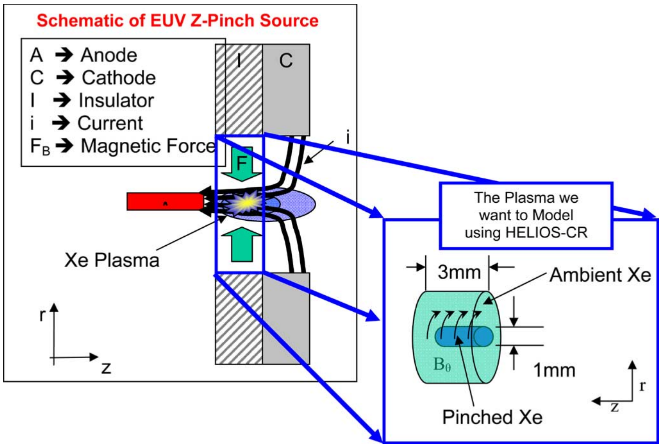


Fig. 4. Pinch geometry assumed for both the HELIOS simulation and the dispersion analysis of an $m = 0$ sausage-mode instability.

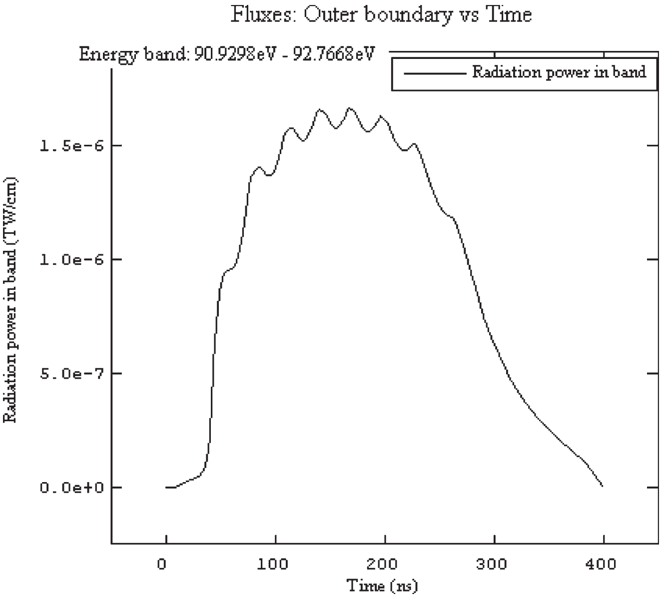


Fig. 5. Temporally resolved EUV emission power predicted by HELIOS.

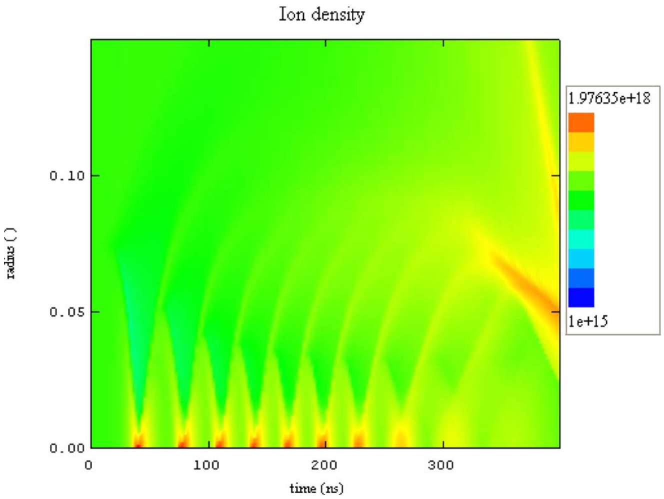


Fig. 6. Ion density distribution as predicted by HELIOS.

plasma can be expressed as formulated by Freidberg [22], as shown in the following:

$$B_\theta = \frac{\mu_o I_o}{2\pi}\frac{r}{r^2 + r_o^2}$$
$$J_z = \frac{I_o}{\pi}\frac{r_o^2}{(r^2 + r_o^2)^2}$$
$$p = \frac{\mu_o I_o^2}{2\pi^2}\frac{r_o^2}{(r^2 + r_o^2)^2}. \qquad (1)$$

Finally, to evaluate the stability of the pinch, the single-fluid Z-pinch dispersion relation (2), given by Boyd and Sanderson [23], can be evaluated, where k is the wavenumber, ω is the instability frequency, and m is the mode of instability

$$\frac{\omega^2}{k^2} = \frac{B_0^2}{\mu_o\rho} - \frac{\left(B_z + \frac{mB_\theta(r_o)}{kr_o}\right)^2}{\mu_o\rho} \times \frac{I_m'(kr_o)K_m(kr_o)}{I_m(kr_o)K_m'(kr_o)} - \frac{B_\theta^2(a)}{\mu_o\rho}\frac{I_m'(kr_o)}{kr_oI_m(kr_o)}. \qquad (2)$$

To evaluate the dispersion relation, a mode of instability must be selected. The most likely mode given the assumptions and symmetry made in this calculation is the $m = 0$ or sausage-mode instability. The name sausage mode refers to phenomena of the plasma being symmetrically pinched off like a link of sausage in a chain.

Given $m = 0$ and the recurrence relations of the modified Bessel functions of the first and second kind, as well as remembering the previously stated assumption that both B_o and B_z terms will drop out, the dispersion relation can now be reduced to

$$\frac{\omega^2}{k^2} = -\frac{\left(\frac{mB_\theta(r_o)}{kr_o}\right)^2}{\mu_o\rho}\frac{I_1(kr_o)K_0(kr_o)}{I_0(kr_o)K_1(kr_o)} - \frac{B_\theta^2(r_o)}{\mu_o\rho}\frac{I_1(kr_o)}{kr_oI_0(kr_o)}. \qquad (3)$$

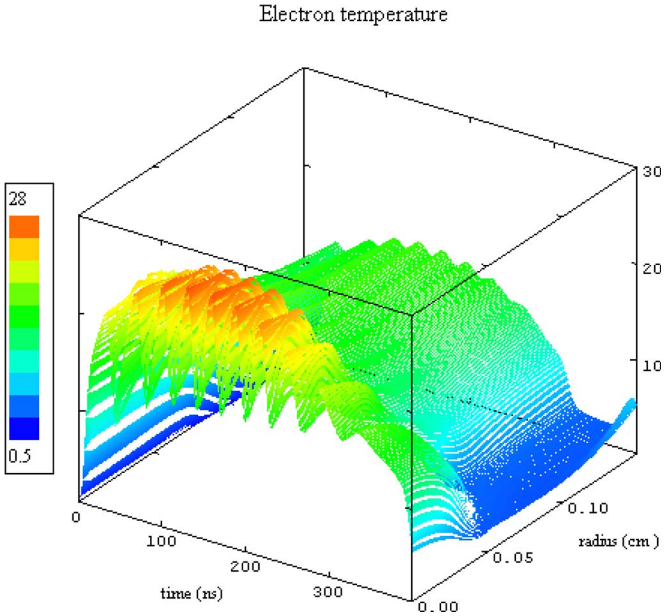


Fig. 7. Characteristic growth time of a sausage-mode pinch instability as a function of the product of the initial radius of the pinch multiplied by the wavenumber of the perturbation.

Dropping the B_o and B_z terms out leaves no positive contributing factor in the dispersion relation which means that this pinch will always be unstable. However, what is left to be determined is the characteristic growth time of the instability which is the inverse of the frequency given in the dispersion relation. Given that the dispersion relation is always negative and is nonoscillatory, it can be inverted directly.

Given the Bennett distributions as stated in (1), all of the terms in the dispersion relation in as written in (3) are known. Evaluating B_θ at r_o gives 3.2 T. If the peak number density is taken to be the maximum, as calculated with HELIOS ($n_\text{i} = 1.97 \times 10^{18}$ cm^{-3}), then the mass density would be 0.43 kg $\cdot$ m^{-3}. For an $m = 0$ instability with a growth time that is equivalent to the time of the pinch which judging from the EUV signal predicted by HELIOS shown in Fig. 5 should be roughly 150 ns. If the characteristic growth time is plotted as a function of the product of the wavenumber and the initial radius, as shown in Fig. 7, then a growth time of 150 ns yields a product of the wavenumber and the radius of the pinch of about 1.2. Since the radius of the pinch is 1/2 mm, which makes the wavenumber for this perturbation 2300 m^{-1}. The wavelength of the perturbation will be roughly 2.7-mm long which is approximately the length of the pinch seen in the XTS 13–35. Given this, it is possible that the pinch length is being limited or perhaps determined by sausage instability.

The question is, how does this revelation affect the acceleration of ions away from the pinch? As previously noted, the sausage instability is a constriction of the current-carrying plasma due to the tension force imposed by the discharge current. Following the work of Jaworski [20], the plasma may be thought of as an inductive current carrying medium. The inductance of a set of coaxial conductors is given by

$$L = \frac{\mu_o}{8\pi} + \frac{\mu_o}{2\pi}\ln\left(\frac{r_b}{r_a}\right). \qquad (4)$$

The voltage across the terminals of an inductor is given by

$$V_a - V_b = \frac{d}{dt}(LI) = L\frac{dI}{dt} + I\frac{dL}{dt}. \tag{5}$$

Combining (4) and (5), and noting that the frequency of the instability of interest is in the order of four times greater than the frequency of the current pulse, the time rate of change of the current can be neglected, yielding (6) where it is also assumed that the radius of the pinch is variable

$$E \approx \frac{V_a - V_b}{\lambda} = \frac{\mu_o I}{2\pi}\frac{d}{dt}\left(n\left(\frac{r_b}{r_a(t)}\right)\right). \tag{6}$$

If it is assumed that the variation of the pinch goes as the initial pinch radius minus a small perturbation of the form $\xi\exp(\omega t)$, thus, (6) becomes

$$E = \frac{\mu_o I\omega}{2\pi}\frac{\xi e^{\omega t}}{r_o - \xi e^{\omega t}}. \tag{7}$$

If it is assumed that the perturbation at the time of evaluation is of the same order as the original pinch radius, leading to a near break in the plasma column, (7) reduces to

$$E \approx \frac{\mu_o I\omega}{2\pi}. \tag{8}$$

Evaluating (8) for the previously stated conditions yields an electric field in excess of 21 kV $\cdot$ m^{-1} with a voltage drop of 64 V across the pinch length of 3 mm. Therefore, it is postulated that the charge separation generated by the instability will initiate the coulomb explosion that will accelerate the ions to the high energies that have been measured in the experiment. This theory is also consistent with the results shown in Fig. 2 where low-mass impurities were introduced into the pinch with the result of a massive reduction of ion energy because the acceleration of the ions will be given by

$$a = \frac{ZeE}{m_{\mathrm{i}}}. \tag{9}$$

This means that an ion with a small mass will be accelerated more rapidly than an ion with a large mass and large charge state. Therefore, for example, hydrogen will follow the instability much more quickly than xenon. Given that the hydrogen maintains its charge state, it will effectively attenuate the electric field seen by the xenon, resulting in a greatly reduced energy.

To add further evidence to the theory that coulomb explosion is the primary mechanism of fast ion acceleration, a calculation of the ion energy is done which assumes as coulomb explosion, and the results of this calculation are compared to the experimentally measured results. Following the work of Mora [16], a self-similar coulombic explosion is assumed. With this assumption, the collisionless Boltzman or Vlasov equation of motion can be reduced to

$$V_{\mathrm{f}} \approx 2{c_{\mathrm{s}}}^{*}\ln(2\tau) \tag{10}$$

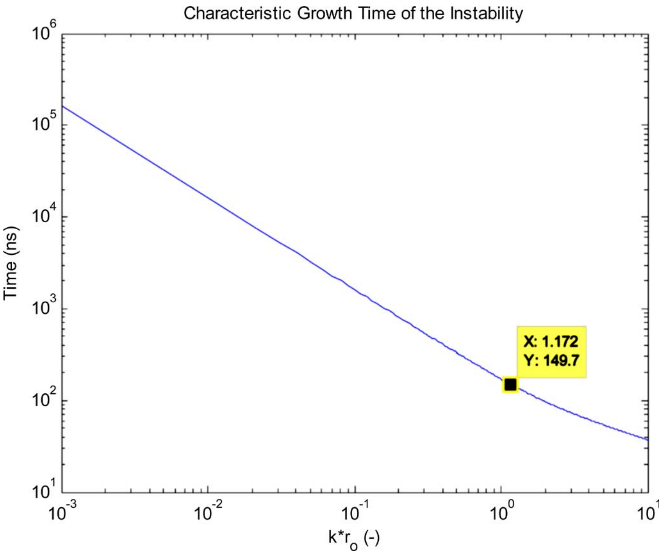


Fig. 8. Electron-temperature distribution as predicted by HELIOS.

where c_{s} is the ion acoustic speed of the expanding ions which can be expressed as

$$c_{\mathrm{s}} = \sqrt{\frac{2T_{\mathrm{e}}q}{m_{\mathrm{i}}}} \tag{11}$$

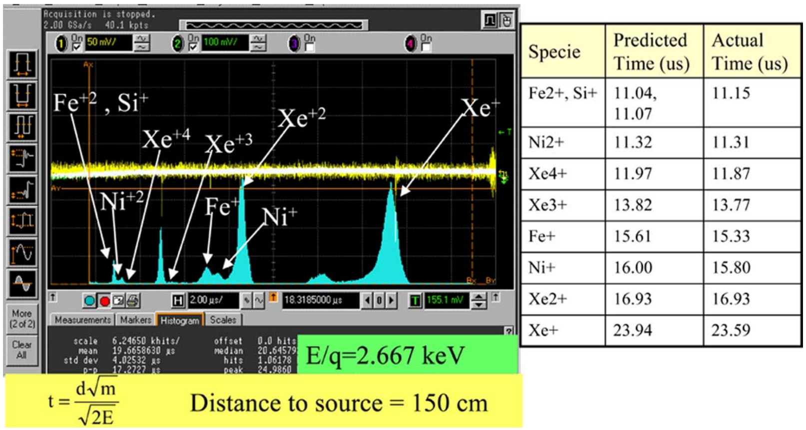
where T_{e} is the electron temperature given in electronvolts, q is the unit charge, and m_{i} is the mass of the ion in kilograms. The characteristic time length τ is given by

$$\tau = \frac{\omega_{\mathrm{pi}}t}{\sqrt{2e}}. \tag{12}$$

where t is the time of flight, e is the natural logarithm constant, $e = 2.71828, \ldots$, and ω_{pi} is the ion plasma frequency expressed by

$$\omega_{\mathrm{pi}} = \sqrt{\frac{N_{e0}Zq^2}{m_{\mathrm{i}}\varepsilon_o}} \tag{13}$$

where N_{e0} is the initial electron density in inverse meters cubed, and ε_o is the dielectric constant. To evaluate this equation, the electron temperature must be known. The electron-temperature distribution calculated by HELIOS is given in Fig. 8. The temperature, as the pinch is breaking up, appears to be 10 eV. The time of flight, as measured experimentally, from the pinch to the ESA must also be known for this calculation and is therefore shown in Fig. 9. Finally, the velocity of the ion front can be evaluated and then directly converted into a classical kinetic energy, as shown in Fig. 10. As would be expected, the energy of the ions right after the pinch approaches zero. Then, after the charge imbalance is formed by the instability, a very rapid expansion occurs. Then, finally, the acceleration slows as the plasma becomes more diffuse. This shows that this plasma was expanding due to a coulomb explosion, that an energy of 2.4 keV should be measured for a Xenon ion that has maintained a single charge for the duration of the transport from pinch to the ESA. As it turns out, this prediction is only 5% lower than the experimentally measured energy of 2.667 keV.



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  scale   6.24650 khits/      offset   0.0 hits
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std dev   4.02532 µs            hits   1.06178
    p-p   17.2727 µs            peak   24.9860
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E/q=2.667 keV

$t = \frac{d\sqrt{m}}{\sqrt{2E}}$ Distance to source = 150 cm

Specie	Predicted Time (us)	Actual Time (us)
Fe2+, Si+	11.04, 11.07	11.15
Ni2+	11.32	11.31
Xe4+	11.97	11.87
Xe3+	13.82	13.77
Fe+	15.61	15.33
Ni+	16.00	15.80
Xe2+	16.93	16.93
Xe+	23.94	23.59

Fig. 9. Spectra from the Illinois TOF-ESA, showing ion energies at an E/q of 2.667 keV.

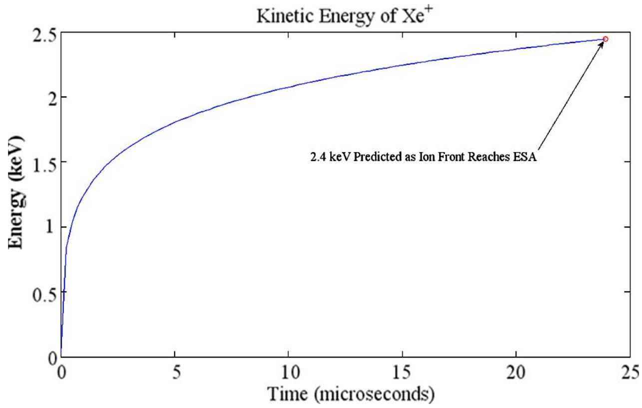

Fig. 10. Kinetic energy of Xe^{+} as predicted by a self-similar coulomb expansion model.

Given the close correlation between the predicted and measured energies, it would seem reasonable to assume that the theory that a pinch instability initiates a charge imbalance, which ultimately results in a coulomb explosion, is justified.

III. CONCLUSION

Ion energy from a Z-pinch DPP plasma source is measured, and the effect of introducing a small percentage of low Z material on the ion energy and flux is investigated. It is found out that presence of low mass such as H_2 or N_2 shows a considerable reduction in total flux and in average energy. Also, such a combination leads to a decrease in sputtering without changing the EUV output. Thus, the addition of H_2 into EUV sources is an effective way of increasing the lifetime of the collector optics and provides experimental evidence to the theories on plasma expansion.

A study of the possible mechanism supporting the experimental results is numerically calculated. It is found that pinch instability creates an electric field, which is responsible for initial charge separation. Our understanding is that the high energies of ions are then an effect of coulomb explosion initiated by instability. It is postulated that the electrons leave first, setting up an electrostatic potential which accelerates the ions. The addition of even a small amount of a lighter weight gas effectively screens the potential and causes less acceleration of the heavier species.

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David N. Ruzic (M'01) received the Ph.D. degree in physics from Princeton University, Princeton, NJ, in 1984.

He is a Professor in the Department of Nuclear, Plasma, and Radiological Engineering, University of Illinois, Urbana. He joined the faculty in 1984 after receiving the Ph.D. degree and doing postdoctoral work at the Princeton Plasma Physics Laboratory. His research centers on the interaction of plasmas with materials; applications include magnetic fusion energy, as well as microelectronic processing. He has a passion for teaching, particularly about energy sources, because he gets to blow something up in almost every class.

Keith C. Thompson was born in Chicago, IL. He is currently working toward the master's degree at the Department of Electrical Engineering and Business Administration, University of Illinois, Urbana.

His areas of interest include plasma discharges and power electronics, with a business focus in technology management. He is currently working on developing methods for debris mitigation in Z-pinch plasmas for EUVL applications at the Center for Plasma Material Interactions.

Brian E. Jurczyk is the President of Starfire Industries LLC, Champaign, IL, which is a research and development firm specializing in innovative plasma technologies. His research interests include plasma space propulsion, intense light sources for photolithography, and plasma-based systems for nuclear fusion applications.

Erik L. Antonsen was born and raised in Chicago, IL. He received the B.S., M.S., and Ph.D. degrees in aeronautical and astronautical engineering from the University of Illinois (UIUC), Urbana, in 1997, 2001, and 2004, respectively, and joined the Medical Scholars (M.D./Ph.D.) Program in 2001.

From 1997 to 2004, he was periodically with the U.S. Air Force. His research focused on plasma rockets for satellite attitude control and diagnostic testing. In May 2004, he started his first year of medical school and took up a postdoctoral research position with the Center for Plasma Material Interactions, UIUC. This research focused on extreme ultraviolet lithography, including plasma light sources and ion spectrometry. He is currently finishing his third year of medical school and works part time for the College of Medicine, as well as the Department of Nuclear, Plasma, and Radiological Engineering.

Shailendra N. Srivastava received the Ph.D. degree in experimental physics from Technische Universitaet Kaiserslautern, Kaiserslautern, Germany, where he worked extensively on laser-produced plasmas.

He is currently a Postdoctoral Fellow in the Department of Nuclear, Plasma and Radiological Engineering, University of Illinois, Urbana. His current research interests are plasma material interaction, advanced debris mitigation technique for Sn- and Xe-fueled EUV sources and contamination study from collector optics and methods to remove them.

Josh B. Spencer was born on March 19, 1981, in Bozeman, MT. He received the associate's degree in both physics and math in 2002 and the bachelor's degree in physics and math from Monmouth College, Monmouth, IL. Immediately after graduating from Monmouth, he moved to Champaign and started graduate study at the Center for Plasma Material Interactions, Department of Nuclear, Plasma and Radiological Engineering, University of Illinois, Urbana, under Prof. D. Ruzic. He will complete the master's degree in the spring of 2007 and will then work toward the Ph.D. degree, studying symmetry methods for solving differential equations for plasma physics applications under Prof. R. Axford.