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Resolving microstructures in Z pinches with intensity interferometry

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Nearly 60 years ago, Hanbury Brown and Twiss [R. Hanbury Brown and R. Q. Twiss, Nature **178**, 1046 (1956)] succeeded in measuring the 30 nrad angular diameter of Sirius using a new type of interferometry that exploited the interference of photons independently emitted from different regions of the stellar disk. Its basis was the measurement of intensity correlations as a function of detector spacing, with no beam splitting or preservation of phase information needed. Applied to Z pinches, X pinches, or laser-produced plasmas, this method could potentially provide spatial resolution under one micron. A quantitative analysis based on the work of Purcell [E. M. Purcell, Nature **178**, 1449 (1956)] reveals that obtaining adequate statistics from x-ray interferometry of a Z-pinch microstructure would require using the highest-current generators available. However, using visible light interferometry would reduce the needed photon count and could enable its use on sub-MA machines. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4864336]

I. INTRODUCTION

Despite the enormous progress that has been made during the last three decades in understanding the physics of Z pinches and in improving their radiative properties, significant open questions remain. One such issue concerns the nature of localized (microns to hundreds of microns in extent), intense radiating regions, frequently referred to as "bright spots," "hot spots," or "micropinches." These structures have been observed in both time-integrated and time-resolved x-ray pinhole images at least as far back as the 1970s.[1] The diameters of these structures in Z pinches typically range from tens to hundreds of microns. They also appear in X pinches, where the term "micropinch" is more commonly applied to this phenomenon, and their dimensions (sometimes just a few microns) are often smaller.[2,3] Small intensely radiating spots within X pinches have been applied to produce high-resolution radiography.[4] For a detailed exposition and summary of these features applied to X pinches, see, e.g., Ref. 5. Images of bright spots within Z pinches driven by currents ranging up to 19 MA on the Z generator at Sandia National Laboratories are presented in Fig. 3 of Ref. 6 and in Fig. 1 of Ref. 7.

No theory yet proposed to explain this phenomenon has been widely accepted as definitive. Radiatively driven compression or condensation, enhancing MHD instabilities, has often been invoked. An early analysis of this physical process appears in the work of Field[8] on astrophysical objects such as planetary nebulae. In 1991, Koshelev and Pereira[9] reviewed the status of work on what they termed "plasma points" (intense, small x-ray emitting regions) in high-current discharges, and found that a radiative collapse model would account for their properties. Mosher and Colombant[10] observed and modeled the formation of intense radiating spots in high-atomic-number Z pinches. Their two-dimensional "gasbag" model employed a radiative emissivity expressed as a fraction of blackbody flux that depends on an estimated optical depth. The rapid compression calculated in their model inhibits potentially important axial outflow and compression proceeds until "resistive loading limits the discharge current." During compression, according to their model, the density increase is large, but the enhancement of temperature is slight. Interest in this topic remains substantial, as evidenced by recent work. Ivanov *et al.*[11,12] used both laser shadowgraphy and x-ray spectroscopy to analyze the temperature-density structure of a stagnated Al pinch driven by the University of Nevada's 1 MA Zebra generator. They found that the dense micropinches revealed by the laser diagnostics correlated with bright spots on the x-ray images. Typical sizes of the micropinches were 60-100 μm. Al K-shell spectra showed that bright spots were also correlated with regions of higher temperature. The analysis of Apruzese *et al.*,[7] considered a total of 74 axial zones from 4 Z pinches using loads of 3 different atomic numbers driven by Sandia's Z generator. Correlations of K-shell power from each zone with various possible properties of the plasma were examined. For Al, the spectroscopic and imaging data showed that the principal correlation was with density. For Cu loads, correlations with both temperature and density were found. For a Ti pinch, the principal correlation was with the opacities of the various zones.

If radiative collapse turns out to be part or most of the physics that drives the "bright spot" phenomenon, the opacity of the collapsing region of the load would be of prime importance. An optically thin "volume" radiator would accelerate local compression by cooling at a greater rate as the density increases during compression. But, this increasing density would eventually result in the condensing region becoming optically thick, transforming it into a "surface" radiator, which would be stable against further collapse. Consider a Z pinch containing bright spots that radiate mostly in the K-shell. The radiation physics and atomic number scaling of such sources have been reviewed in Refs. 13 and 14. The strongest K-shell radiating line is often the principal resonance line of the He-like stage, $1s^2$-$1s2p\,^1P_1$, known as He-α. For an effective ion temperature of 20 keV, Doppler broadening (whether thermal or motional) will exceed that due to the Stark effect, for this line, even at an electron density as high as $10^{24}\,cm^{-3}$ (see Table III of Ref. 15). The Al He-α Doppler line center absorption cross section (at an effective ion temperature of 20 keV) is $2.3 \times 10^{-17}\,cm^2$. For an ion density of $10^{22}\,cm^{-3}$, with half of the ions in the He-like stage, the mean free path at line center would be $[(0.5)(2.3 \times 10^{-17})(10^{22})]^{-1} = 8.7 \times 10^{-6}$ cm, less than 0.1 μm. Our assumed ion density of $10^{22}\,cm^{-3}$ is consistent with the electron densities of $\sim 10^{23}\,cm^{-3}$ quoted in the review by Koshelev and Pereira.[9] Therefore, it is possible that collapse to submicron radii could occur prior to stabilization by opacity effects. Thus, it is of interest to ascertain experimentally whether submicron structures exist in Z pinches.

Unlike imaging with geometries that are not severely constrained, which could provide sub-micron resolution, imaging of Z pinches or high-energy-density (HED) plasmas, in general, suffers from limitations that may significantly degrade spatial resolution. One such limitation is the lens-object distance. It is constrained by experimental parameters such as the vacuum chamber size and optics damage threshold. Also, for filtered pinholes for x-ray imaging under vacuum, the damage threshold plays a significant role, and photon counting determines the minimum pinhole size. Moreover, achieving temporal resolution generally requires the use of a microchannel plate detector coupled to a CCD camera, which can limit the resolution to a few tens of microns at the detector. The spatial resolution at the target plasma is a convolution of the detector spatial resolution, the image resolution, and the system magnification. Some of the limitations of conventional pinhole imaging have been overcome by collecting x-ray slit images[16] or through translucent meshes[17] and fitting the data to wave optics calculations. These techniques have resolved micron-sized sources within X-pinches.

Standard interferometric methods, in which fringe shifts from a probing laser are used to unfold electron density and its gradients, have been of great value in the diagnosis of Z pinches. Measurements have been made of the density of coronal wire plasmas,[18] bubbles within plasma streams,[19] and the development of both $m = 0$ and $m = 1$ instabilities within the dense, stagnated pinch.[11,12] However, laser interferometry, as employed in a Z-pinch environment, is also subject to some limitations. The beam cannot penetrate regions whose electron density exceeds critical, which is $4 \times 10^{21}\,cm^{-3}$ for the commonly used laser wavelength of 532 nm. Recently, Ivanov *et al.*[11,12] have extended this method to the use of UV lasers of wavelength 266 nm, whose critical density is $1.6 \times 10^{22}\,cm^{-3}$. While this is a noteworthy advance, such a beam would still be unable to penetrate and thus resolve a condensation, whose electron density could be as high as $10^{23}\,cm^{-3}$ or even greater.[9] In addition to the constraints imposed by the existence of a critical electron density, laser interferometry is also limited in its spatial resolution by refraction of the rays. Shelkovenko *et al.*[20] found that the apparent diameters of some dense regions in Z pinches were determined more by refraction of the beam out of the collection optics than by the intrinsic size of the region, and also that dense wire cores were much smaller than the region that is not transparent to their (532 nm) laser.

However, interferometry that uses emission from the source can often employ baselines which are larger than conventional apertures. Therefore, it can in principle and often has in practice, provided superior spatial resolution. In Secs. II–IV, we consider the advantages and challenges of intensity interferometry as a possible Z-pinch diagnostic.

II. BASICS OF INTENSITY INTERFEROMETRY

To our knowledge, intensity interferometry has not been employed to date in measurements of laboratory plasmas. This section is a brief review of its principles and development, including some of its known and proposed applications.

Intensity interferometry was demonstrated and initially applied to astronomical measurements in the 1950s by Hanbury Brown and Twiss. At first, it was employed to measure the diameters of astrophysical radio sources.[21] Within a few years, they extended the method to the visible spectrum, where a laboratory mercury-arc source of known dimensions was used to further validate the technique.[22] The angular diameter of Sirius was then measured[23] and its value (30 nrad) was found to be consistent with existing astrophysical theories of stellar structure and atmospheres.

In its initial and simplest form, intensity interferometry functions as follow. Light (wavelength λ) from a source, whose angular size (θ) is to be measured is directed onto two time-resolving sensors separated by a distance d, which is the interferometric baseline. The light can be, and often is, incoherent and/or thermal. The signals from the sensors collected during each resolving time are multiplied together and integrated over a total count time (which can be, but usually isn't, as small as one resolving time). Sometimes, the deviations of the signals from the random (uncorrelated) coincidence rate are used rather than the signals themselves. Either method gives a quantitative correlation coefficient for the intensities at the sites of the sensors. As the baseline d is increased, the correlation coefficient decreases. The observed functional form of the decrease with increasing sensor separation is fitted to theoretically calculated values for various source sizes. The best fit gives the statistically most probable angular diameter of the object (see, e.g., Fig. 2 of Ref. 23). The mathematical theory underlying the decrease of the correlation coefficient was presented in Ref. 21. The source need not be monochromatic. A large bandwidth reduces the strength of the correlation, but does not eliminate it. It can be taken into account by numerical integration and fitting as was done for the original Sirius measurements.[23]

That this type of interferometry is viable, especially given an incoherent, thermal source, is far from obvious. However, good, intuitive, physical explanations have been given by Purcell,[24] Paul,[25] and Kleppner.[26] Hanbury Brown and Twiss's initial report of their Sirius measurements sparked an intense debate (for instance, see Ref. 27 for an account of Feynman's initial skepticism). As reported in

Ref. 26, it appeared to "defy quantum physics, at least at first." Also, the success of the experiments contradicted Dirac's well-known statement[28] that "interference between two different photons never occurs" (see Ref. 25 for a discussion of this point). However, further experiments as well as a quantum treatment of the phenomenon by Fano[29] soon settled the issue, now universally accepted and known as the HBT effect. Diverse applications have emerged, including the study of correlations in ultracold quantum gases.[30] Recently, HBT correlations have been proposed[31] as a method to study the expansion dynamics of quark-gluon plasmas.

The main issue responsible for most of the difficulty in understanding the HBT effect is: why should there be intensity correlations from a randomly excited thermal source? As pointed out in Ref. 25, no visible, persistent interference pattern can arise from such a source. However, the transient superposition of wavetrains produces fleeting interference which, in principle, can be detected as intensity modulations by time-resolving sensors. These short-lived interference patterns produce correlations, which are evidenced in the mean value of the product of the intensities in the two channels. As stated by Paul in Ref. 25, "intensity correlations exhibit interference effects even in situations, where no conventional interference pattern is visible." The correlations diminish when the phase difference between photons emitted from opposite sides of the source changes significantly. This happens when the distance d between the detectors approaches the transverse coherence length $\lambda/2\theta$. For visible light of wavelength 500 nm, and Sirius' angular diameter of 30 nrad, $\lambda/2\theta \approx 8$ m, consistent with Fig. 2 of Ref. 23. We now consider intensity interferometry as a possible diagnostic of the structure of Z pinches.

III. EVALUATION OF INTENSITY INTERFEROMETRY FOR Z-PINCH MEASUREMENTS

HBT correlations are present in the radiation fields of incoherent sources such as Z pinches, but their detectability depends on the specific properties of the source as well as the arrangement, sensitivity, and resolution of the detectors. In supporting the soundness of the original HBT experiments, Purcell[24] developed a formula that demonstrated why HBT succeeded and an independent attempt[32] to demonstrate the correlations did not. In assessing the viability of applying HBT intensity interferometry to Z-pinch measurements, we follow Purcell's approach.

Suppose that radiative energy equivalent to $2n$ photons is traveling toward 2 detectors within one resolving time T. The number of different pairs of the total of $2n$ photons is $\sim 2n^2$. Only a fraction of these $2n^2$ pairs will interact and produce interference. If the spectral bandwidth of the source is $\Delta\nu$, the coherence time τ_0 is $\sim 1/\Delta\nu$. For a pair of photons to interfere, they must coincide within τ_0, which will usually be a much smaller time interval than T. The $2n^2$ photon pairs are detected over the full time interval T, but the probability that any one pair coincides within τ_0 is just τ_0/T. Therefore, we expect that interaction of the $2n^2$ photon pairs might produce as many as $2n^2(\tau_0/T)$ extra coincidence counts. In fact, when polarization and other effects were taken into account, Purcell found that the enhancement was lower by a factor of 4, $n^2(\tau_0/2T)$ (see Eq. (6) of Ref. 24). Since the product of the counts in the two channels will be about n^2, the fractional enhancement is $\tau_0/2T$.

To measure the size of a feature within a Z pinch, the rate of decrease in the product of the photon counts as the distance between detectors (within a deployed array) increases must be determined. This rate of decrease needs to be statistically significant. If the product due to random coincidences (not from HBT correlations) is n^2, its fractional standard deviation, assuming Poisson statistics, is $\sqrt{2/n}$. If we require that the fractional product enhancement due to HBT correlations must exceed the variation in random coincidences by 3 standard deviations, then

$$\frac{\tau_0}{2T} \geq 3\sqrt{\frac{2}{n}}, or \tag{1}$$

$$n \geq 72\left(\frac{T}{\tau_0}\right)^2 \tag{2}$$

for the number of photons that need to be counted by each channel to obtain 3σ statistically significant HBT correlations.

As a basis for evaluating the applicability of HBT intensity interferometry to Z-pinch measurements, we consider the diagnostic setup pictured in Fig. 1. It is representative of, but not unique to, gas-puff experiments performed at the Weizmann Institute.[33,34] If the load is Ne, the K-shell x-radiation can under some conditions be dominated by the He-α line at 922 eV. To obtain the needed photon count from Eq. (2), we need to know the resolution time T (10^{-10} s from Fig. 1) and also the coherence time $\tau_0 = 1/\Delta\nu$. If the broadening of the 922 eV line is mostly Doppler, due to an effective ion temperature of 1 keV (see Fig. 2 of Ref. 34), $\Delta\nu = 10^{14}$ Hz, $\tau_0 = 10^{-14}$ s, and n from Eq. (2) is 7.2×10^9. Our chosen representative effective ion temperature has no special significance: Stark broadening can produce similar bandwidths in nearby x-ray lines. In Fig. 1, the detector depicted is a microchannel plate with a spatial resolution of 50 μm and whose resolution time of 100 ps occupies a strip 1 cm long. Therefore, the effective area for photon detection is ~ 0.005 cm^2. For the 6 m pinch-to-detector distance,

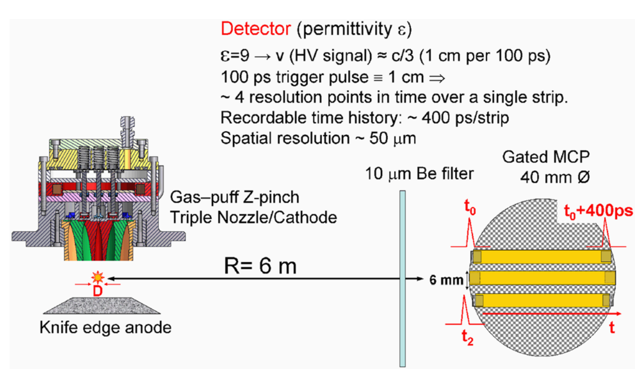

FIG. 1. Representative experimental setup used as a basis for evaluating the application of intensity interferometry to Z-pinch measurements.

assuming isotropic emission and detector quantum efficiency of unity, a fluence of 7.2×10^9 photons over that area (within a sub-nsec counting time) requires 1 kJ to be emitted by a structure within the pinch at 922 eV, to 4π. This is probably not achievable for generators of peak currents ≤ 1 MA. However, it might be feasible at the high-current machines Saturn and Z at Sandia National Laboratories. Employing Ar gas-puff loads, Saturn has achieved[35] a total K-shell yield of 72 kJ at a peak current of 6.5 MA, and Z has produced nearly 300 kJ of Ar K-shell radiation[36] at 15 MA. Ar requires 8 times as much energy per atom as Ne to heat and strip to its K-shell ionization stages.[37] Therefore, with proper load design, it is likely that Ne gas-puffs on Saturn and/or Z could produce K-shell yields significantly exceeding the above-quoted experimental Ar K-shell yields.

An alternative approach to enabling HBT measurements on Z pinches driven by lower-current machines would be to use UV or visible lines. This would reduce the bandwidth, and increase the coherence time τ_0 of the radiation, especially if combinations of filters were used to exclude other radiation from the detectors. According to Eq. (2), this would be highly advantageous in reducing the needed photon count. A suitable line could be emitted by the primary load material, or by a dopant gas. Consider, for example, the prominent 3s-3p line of O VI at 381 nm (3.25 eV). This line has been detected and used as a Z-pinch diagnostic at Weizmann.[38–40] If its broadening is also dominated by the Doppler effect at an effective ion temperature of 1 keV, its bandwidth $\Delta\nu$ and coherence time τ_0 would be 4.8×10^{11} Hz and 2.1×10^{-12} s, respectively. Keeping the resolution time T at 100 ps, Eq. (2) gives for the required per-channel photon count $n = 1.6 \times 10^5$, a reduction of more than 4 orders of magnitude from that required for the 922 eV soft x-ray line. Moreover, the lower energy of each photon results in a reduction of the required line yield from 1 kJ to just 7.8×10^{-5} J. The O VI line was chosen for illustrative purposes and it is not necessarily the best option, depending on the generator and available diagnostics.

IV. SUMMARY AND DISCUSSION

The phenomenon of intense radiating localized "bright spots" within Z pinches has been noted and observed for at least three decades. There is as yet no generally accepted theory explaining their development and the dynamics that produces the elevated emission. There may not be any single valid explanation. Various analyses have linked the elevated radiation intensity to higher density, higher temperature, or increased opacity (product of density and path length). Often, some type of radiative collapse has been proposed as a key feature of their dynamics. Conventional imaging techniques using pinholes or x-ray backlighting have shown that their sizes in Z pinches range from tens to hundreds of microns. If radiative collapse is present, it can be terminated when the increased density transforms the spot from a volume to a surface radiator. As shown in Sec. I, this may not occur until the spot has reached sub-micron dimensions, smaller than any currently reported resolution. Therefore, it would be valuable to experimentally determine a lower limit to their size, if it exists.

Due to its long baselines, interferometry is often superior to direct imaging in obtaining spatial resolution of radiating objects under study. This was dramatically demonstrated in the 1950s, when the invention of intensity interferometry by Hanbury Brown and Twiss enabled the measurement of the diameter of Sirius, which cannot be done by direct imaging with telescopes. In Secs. I–III, we have examined the possibility of applying intensity interferometry to resolving the spatial structure of Z pinches. The basic measurement involves measuring the photon fluence in an array of detectors, examining the intensity products from pairs of those detectors (serving as a correlation coefficient), and determining the distance at which the correlations cease. This distance is the transverse coherence length $\lambda/2\theta$. Since the wavelength λ of the radiation used is obviously known, determining the transverse coherence length measures the angular diameter θ of the source. Within a Z pinch, it is not likely that the "bright spot" source will be as cleanly isolated as the nearly circular disk of a star surrounded by dark sky. However, the hybrid X-pinch[17] has been demonstrated to produce single, stable hot spots. In any event, the technique can be generalized by numerical methods to resolve irregular sources. This was done as long ago as 1954 by Hanbury Brown and Twiss in radio astronomy (see p. 671 of Ref. 21).

Our evaluation of the viability of intensity interferometry for Z-pinch measurements has been based on Purcell's analysis,[24] applied to a possible experimental setup illustrated in Fig. 1. For a pinch-to-detector distance of 6 m, and a source size of 1 μm, the transverse coherence length would be 0.4 cm, if the 922 eV (1.345 nm) He-α line of Ne were employed for the measurement. If the O VI line at 3.25 eV (381 nm) were chosen instead, the coherence length would increase to 114 cm. These coherence lengths are reasonable, but good photon count statistics are also needed for a viable measurement. Purcell's analysis shows that the coherence time of the photons being detected is a key element: the longer the time, the fewer the photons needed, reducing the requirements for source brightness. If the measurements are focused on a single bright line, and its width is dominated by Doppler broadening, the coherence time is approximately inversely proportional to the line energy. Quantitatively, this scaling implies that x-ray measurements on Z pinches using intensity interferometry can only be carried out on the highest-current generators (Saturn and Z at Sandia National Laboratories), but the use of visible light could enable its use on MA-current university-scale facilities.

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