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# STUDY OF POLARIZED ARGON LINES IN PLASMA-FOCUS DEVICE

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Polarization is important for analyzing line emission in the infrared, visible, and ultraviolet "Vacuum spectroscopy and its application" by A.N.Zaidel and E.Ya.Shreider [1], and also for X-rays. This paper presents experimental results for X-rays from helium-like argon in a plasma focus discharge, and discusses how polarized X-rays might be created by directional electrons or electric/magnetic fields.

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Polarized He-like X-rays have been observed in solar flares [2], laser produced plasmas [3] and vacuum sparks [4]. A fruitful collaboration between Polish and Russian scientists provided similar preliminary measurements on a plasma focus machine [5]. A complete interpretation of these spectra is not yet possible because the measurements average over space and time, and other variables are uncontrolled or incompletely known (e.g., angular distribution, or calibration as function of polarization and wavelength). Moreover, how the plasma's parameters affect the polarization of the X-rays is not yet understood in sufficient detail. This paper presents recent experimental results on evidence for polarization of He-like lines from a plasma focus device, and discusses two effects that might be responsible for the polarization. One is a preferred direction of the electrons that excite the X-rays, the other is the orientation of the excited ions in the pinch's electro-magnetic fields.

Time integrated spectra of ArXVII X-ray lines are taken on a single shot using a 500 kA plasma focus machine [5]. The instrumentation consists of two focusing Johann spectrographs, each with cylindrical dispersive element a quartz crystal ($2d = 0.8512$ nm and $2d = 0.667$ nm) on a 500 mm radius. The spectral resolution is about $d\lambda/\lambda \sim$ $\sim 8 \cdot 10^{-5}$. The crystals are calibrated in second and third orders with 8.05 keV X-rays from an X-ray tube with copper anode. The plasma and the crystals are about 700 mm apart. Direction of observation was chosen perpendicular to discharge axis. A four sheets 6 $\mu$m mylar filter, covered by 0.1 $\mu$m Al protects the spectrometers from visible light. To compare the similarity of spectrometers, spectra were measured when dispersive planes of both devices were oriented parallel to discharge axis. Fig.1 shows the results of these measurements.

All the spectra clearly show the ArXVII $1s2p(^1P_1) - 1s^2(^1S_0)$-resonance line (marked with Gabriel's notation, $w$), which is well resolved in all cases. The $1s2p(^3P_1) - 1s^2(^1S_0)$ intercombination line (marked $y$) is also easily resolved. It merges with two additional lines to the right, the $1s2p(^3P_2) - 1s^2(^1S_0)$ magneto-quadrupole transition and the $1s2s(^3S_1) - 1s^2(^1S_0)$ forbidden line. These are $x$ and $z$ in Gabriel's notation. In all

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the shots spectra from both devices show the same shapes of He-like lines, when $w$ line is more intensive, than $y$-line and relative intensities are almost the same.

To investigate polarization we rotated spectrograph with $2d = 0.667$ nm on 90 degrees. Dispersive planes of two spectrographs became mutually perpendicular. Devices were optically aligned to observe the same plasma region. Fig.2 shows the results of that measurements.

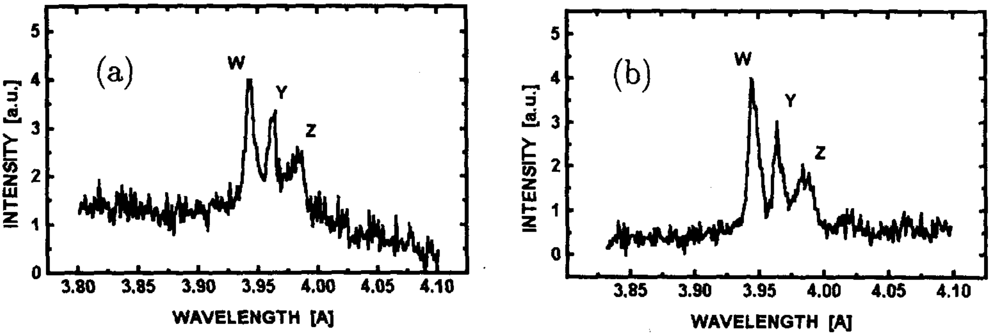

Fig.1. Ar lines profile measured with the crystal ($2d = 0.851$ nm) (a) and the crystal ($2d = 0.667$ nm) (b), both with the crystal's dispersive planes parallel to the discharge axis, obtained in the same shot

The two spectra in this figure are substantially different even though they are taken on the same shot experiment. On Fig.2a, ($2d = 0.815$ nm) the $y$-line is lower than the $w$-line, but when the same lines are taken with another crystal ($2d = 0.667$ nm) in Figure 2b, the $y$-line is higher than the $w$-line. The spatially averaging done by the instrumentation should suppress temperature and density gradients in and around the bright spots, and should not give different spectra. The same is true for different azimuthal locations for the orthogonal spectrographs: two spectrographs oriented in parallel measure identical spectra. All this evidence suggests that the differences between the two spectra on Fig.2 might reflect polarization of the X-rays. The relative intensity of the $w$ and $y$ lines can be used to estimate the plasma density. However, using the $w/y$ line ratio on spectra from Fig.2 gives substantially different density estimates, even though the spectra come from the same plasma. This problem might be resolved by taking X-ray polarization into account explicitly, and correcting for the polarization in measuring the line intensities. Finding line ratios that are consistent in the two spectra gives the degree of polarization of the X-rays. The degree of polarization would be interpretable terms of interesting plasma parameters if it were known how the plasma affects X-ray polarization.

Radiation from a plasma can be polarized if the excited ion has some given direction, if the directed excitation is not randomized before the ion emits a polarized photon, and if the polarized photon leaves the plasma with its original polarization intact. Intensity and polarization of X-rays has been calculated with quantum mechanics since 1927 [6]: reference [7] focuses on the helium-like ions and the helium-like lines used here. These lines are favored for diagnosing plasmas because they are abundant over a large temperature range, and usually well resolved by modern spectrometers. In hot dense plasmas the ions are usually excited by electrons with an anisotropic velocity distribution function, and sometimes even by a directional electron beam. Classical plasma diagnostics usually assumes maxwellian electrons, and ignores suprathermal electrons or electron beams [8].

However, recent theoretical studies [9] have shown that even a few percent hot electrons in a maxwellian tail may affect the line intensities enough to change density and temperature estimates. Moreover, energetic anisotropic electrons and electron beams polarize the X-ray lines, and polarization measurements might give information about these electrons. According to theoretical predictions [7] the degree and direction of polarization of the $w$, $x$, and y lines are different and can be equal to 10 – 60% while the forbidden line $z$ is unpolarized.

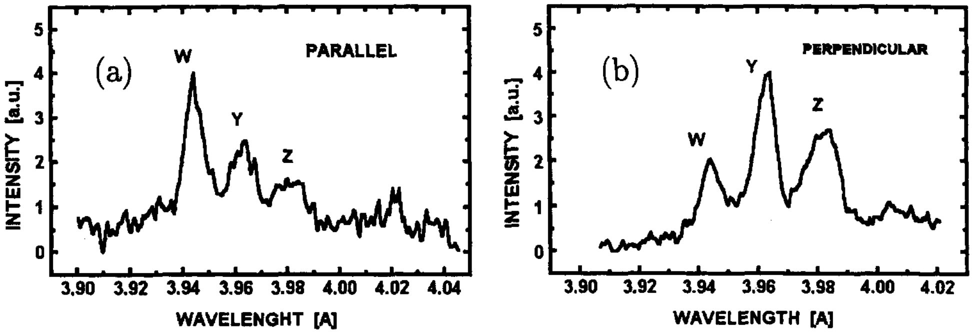

Fig.2. Ar lines profile measured with the crystal's ($2d$ = 0.851 nm) dispersive plane parallel to the discharge axis (a) and with the crystal's ($2d$ = 0.667 nm) dispersive plane perpendicular to the discharge axis (b), both obtained in one shot

Our spectra show that $w$-line is polarized in direction, perpendicular to discharge axis. This is consistent with an electron velocity distribution having a non-thermal tail of moderately energetic electrons($\sim$ 5 keV) peaked in the radial direction. Electrons with a few keV energy have quite complicated orbits that are determined by the configuration of electromagnetic fields inside the plasma.

The fine spatial structure of any type of $z$-pinch plasmas (hot spots and micropinches) is well known. In these experiments the X-rays come from hot spots in each shots, but the plasma size, the spatial extent of the electron beam, its duration, and the probable interaction of spatially anisotropic hot electrons with multicharged ions are not known in detail. Certain simplified models suggest that highly ionized ions coexist with fast electrons in the same plasma volume during some time [10].

Interpreting the polarization measurement in terms of an anisotropic electron distribution assumes that the electron's electric field dominates the orientation of the ion during the time needed to radiate the polarized X-ray. An alternate possibility is that the plasma's electric field dominates the orientation of the $2p$-electron orbit in the excited ion, as first suggested by Sholin [11]. Then the polarization measures not anisotropic electrons, but the electromagnetic fields in the plasma. Whether this is the case depends on the plasma parameters. In Sholin's model [11] the orientation of the $2p$ orbital in the excited ion is determined by the magnitude of the impact parameter, $\rho$, relative to the Weisskopf radius, $\rho_w$ [12]. The orientation is along the electric field of the outgoing electron if $\rho < \rho_w$ and along the magnetic field if $\rho > \rho_w$. In either case, if the ion decays while the electron's influence dominates the ion's orientation, the polarization is dominated by anisotropic electrons. If the electron is gone by the time the ion decays it is the electric/magnetic fields determine the polarization.

The important quantity is the radiation time compared to the collision time. The collision time is $t_c = a_0/ZV$, where $a_0$ is the Bohr radius, $V$ is the electron velocity, and $Z$ is the atomic number. The radiative decay time $t_r$ is roughly $t_0/a^3Z^4$, where $t_0 = a_0h/2pe^2 = 200$ ns is a typical atomic decay time and $a_0$ is the fine structure constant. For iron $t_r$ is maybe 0.01 fs, and for typical electron energies $t_r/t_c$ is about 10. Therefore, the polarization should primarily be interpreted in terms of the plasma electromagnetic fields. Quantitative calculations on how large the electric field must be to give essential polarization of the $w$-line are still underway. However, a preliminary number is about $10^8 - 10^9$ V/cm. Such high fields might exist in a bright spot. One might guess an axial electric field of 100 kV over a 0.1 mm length, or $E = 10$ MV/cm. However, the radial electric field is a factor of $\omega \cdot \tau$ larger, where $\omega$ is the cyclotron frequency and $\tau$ is the electron collision time. In a hot spot this factor might be up to 100, so that fields up to 1 GV/cm might exist. It is gratifying that the fields estimated from the polarization are about of this order. However, further work must be done to verify that all the relevant influences have been taken into account properly.

Spectra of He-like Ar-lines in a plasma focus clear evidence of polarization for the resonance line ($w$). Polarization affects the relative intensity of the various lines that are commonly used for diagnostics purposes. Using line ratios might be misleading unless X-ray polarization is explicitly accounted for. Two effect give rise to polarized X-rays. The first is anisotropy of the electron velocity distribution, the second is the existence of macroscopic electric/magnetic fields. A quantitative interpretation of the observed polarization in its preliminary form is in encouraging agreement with what might be expected in and around a hot spot in a $Z$-pinch. However, both the measurements and the theoretical modeling need much additional work before polarization can be used as an plasma unambiguous diagnostics technique by itself.

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