fore also assumed to be due to a difference in collisional vacancy production, in analogy to the I L-shell excitation. The promotion of Se $2p$ electrons to an unoccupied I M level is possible, e.g., via $4f\sigma$ (Fig. 2). In agreement with the observations, the gas-solid effect on the Se and Kr L excitation yield is expected to be smaller than in I, since, at somewhat smaller internuclear separations, the Se as well as the Kr $2p$ electrons can be excited by rotational coupling of $4f\sigma$ to ionized outer shells in the I projectile.

In contrast to the L radiation, the I M radiation yield is less in solid than in gas targets. A difference in collisional excitation probability is not expected since I $3d$ electrons may readily be promoted to a large number of unoccupied levels in upper shells. There is, however, a qualitative difference in M and L vacancy relaxation in the two media in terms of the structure of the adjacent shells. For both solid and gas, the O shell is completely stripped. In a gas target 4 to 5 N-shell vacancies are expected,[6] while in a solid it is probable that all electrons outside the M shell are in excited states. Moreover, in the solid the ion is always moving through regions of high electron density. This milieu may tend to enhance decay via less selective nonradiative transitions and, thus, cause an effective suppression of the fluorescence yield. This effect was also observed for I ions in targets of Xe and Te; at 22.5 MeV, the collisional M x-ray yield was found to be about a factor of 6 larger in the system I-Xe than in the system I-Te. At 48 MeV, this factor was 4. It thus appears that these effects may provide considerable information on the state of an ion moving through dense and dilute targets.

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Combination of Intense Relativistic Electron Beams in a Z Pinch*

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Two intense relativistic electron beams have been combined while propagating within the collapsing current sheet of a Z pinch. Appropriate choice of the time of injection of the beams into the pinch gave high transport efficiency as well as beam mixing.

The present state of technology for intense-electron-beam generators limits the current of single beams of usable diameter to ~1 MA.[1] One way around this limitation is the combination of separately generated beams into a single beam. Beam combination has been studied using neutral gas in conducting pipes,[2-4] but this method seems incompatable with high transport efficiency, at least for intense (≥ 1 kJ) beams. Previous experiments have shown that intense relativistic elec-

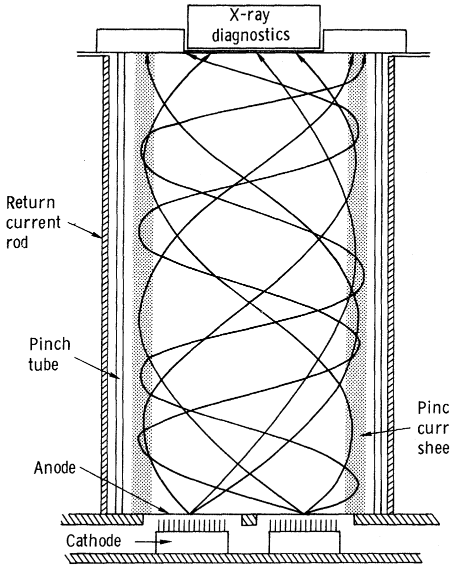

FIG. 1. Schematic showing mixing of electron beams inside the current sheet of a Z pinch.

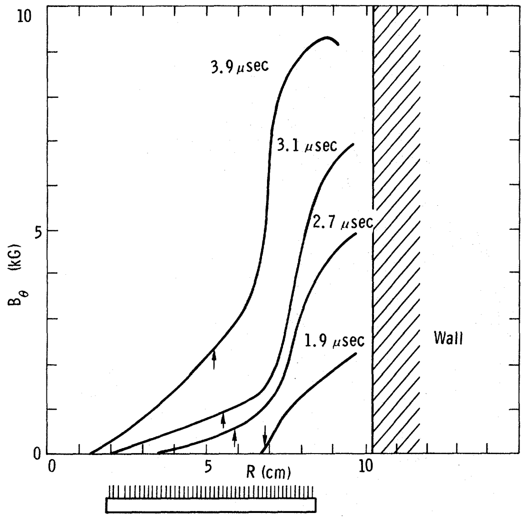

FIG. 2. Magnetic field profiles for beam injection times. The location and size of one cathode is shown. Arrows indicate radial outer limit of target damage (± 1 cm).

tron beams can propagate within a Z pinch with little loss.[5-7] The model developed to explain this finding[6] offers a simple means to combine beams while transporting them.

When a beam is injected into a Z pinch (which is essentially static on the 10^{-7}-sec beam time scale), the beam current is neutralized by the induced counterstreaming of plasma electrons.[8-10] The beam electrons follow single-particle trajectories in the magnetic field of the pinch, and the beam expands to fill the cylindrical volume inside of the current sheet. A second beam, injected inside the current sheet at the same time, will do the same (Fig. 1). There is no interaction between the beams because their fields are suppressed by the conducting plasma.[11] Since each beam is injected off-axis into the Z pinch and since intense beams have substantial velocity components transverse to the beam axis, θ components of velocity (with respect to the pinch axis) result. These velocity components provide azimuthal mixing, and this beam mixture becomes azimuthally symmetric as it propagates down the pinch. The advantage of this scheme is that the beams are truly mixed, not merely brought into proximity, and behave as one beam. This Letter reports an experiment which confirms this extension of the transport model.

The Snark generator[1] was used to produce the two beams which were extracted from cathodes separated by 10 cm and magnetically isolated to prevent their interaction prior to injection into the pinch chamber. The two 700-keV beams injected into the pinch differed in peak current by ~20% on each shot. Their sum varied from 365 to 375 kA. Total injected energy (both beams) was 16 kJ.

The pinch was 20.3 cm in diameter, 45 cm long, and was energized by a 27-kJ capacitor bank at 15 kV. The primary indicator of beam combination was the obvious damage produced in the pinch anode, an aluminum disk 0.635 cm thick. Bremsstrahlung produced by the beam in the pinch anode was time resolved by a scintillator-photodiode combination and time integrated by LiF thermoluminescent detectors. Transport efficiency was determined by comparing these measurements with those taken when the target plate was placed at the entrance plane. New electrodes and Pyrex pinch tube were installed for each discharge/injection event, and on successive shots the pair of beams was injected at different times during the collapse of the pinch. Current-sheet profiles corresponding to the times of beam injection are shown in Fig. 2 along with the radial location of one of the two cathodes. The current-sheet velocity was low at early times (because of low dI/dt), but increased after 0.8 μsec; maximum compression occurred at 6.5 μsec.

Figure 3 shows damage to four anode plates produced by transported beams. For comparison, a witness plate placed behind the anode demonstrates the distinct separation of the two beams at the injection plane. The damage patterns for

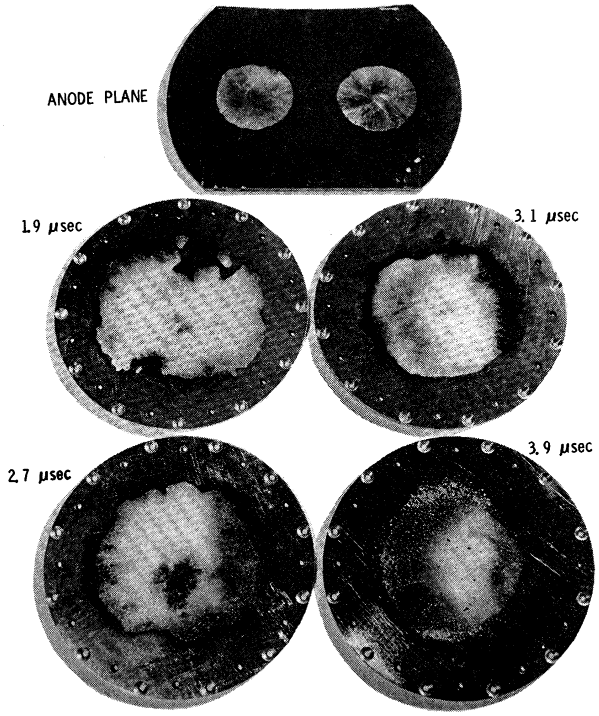

FIG. 3. Damage patterns in Z-pinch anodes and anode plane witness plate.

beam injection at 2.7, 3.1, and 3.9 μsec show no sign that they were caused by two separate beams, and the latter two shots clearly show thorough azimuthal mixing. Damage at 1.9 and 2.7 μsec was composed of irregular areas. The damage pattern for the earliest injection time, 1.9 μsec, has something of a figure-eight appearance, as if the beams were only partially merged. This can be understood as the results of less complete beam-current neutralization due to a relatively low plasma conductivity interior to the current sheet at 1.9 μsec; self magnetic fields were incompletely quenched and partially preserved the identity of each beam. Also, the field profile for 1.9 μsec shows that there was little Z-pinch magnetic field at radii inside the damage pattern region (inside a 7-cm radius), so that the beams must have been contained by self-fields.

The measured transport efficiency appeared to decrease with increasing injection time. The 1.9- and 2.7-μsec shots were efficiently transported, $(95\pm5)\%$ and $(87\pm15)\%$, respectively. No efficiency measurement was obtained for the 3.1-μsec shot, and the 3.9-μsec shot gave transport of only $(60\pm20)\%$ of the injected energy. This seeming decrease in efficiency does not imply a new loss mechanism. Rather, it is a symptom of the less-than-optimal design of the apparatus: It is apparent that at 3.9 μsec the current sheet had swept inward past the outer portions of the cathodes, and that not all of each beam was injected sufficiently inside the current sheet. Presumably, electrons injected into the high–field-gradient region (5 to 8 cm radius for the 3.9-μsec case) underwent ∇B drift back into the diode and were lost.[4] Supporting this interpretation is the decline of the damage radius as injection time increased. This situation could be easily remedied by increasing the diameter of the pinch tube so that more time would elapse before the sheet reaches the cathode radial position. This extra time would result in both a higher magnetic field in the sheet and increased photoionization of the gas inside the sheet, aiding current neutralization and the mixing process.

The experiment reported above is a demonstration that limitations on single-beam generation can be circumvented by beam combination. For example, a configuration that might produce a single multimegampere beam with current density 10^5 A/cm^2 consists of three stages. The first stage is an array of individual transport tubes (neutral gas[1] or Z pinch) to bring beams from an array of separate diodes to the entrance to the mixer stage, a large-diameter Z pinch. Leaving the mixer, the beam mixture enters the third stage, a gradually tapered Z pinch that compresses the composite beam into its final, high–current-density form.

The limitations or scaling of this transport-combination-compression scheme involve two main factors. First, the single-particle model of beam transport in a Z pinch depends, presumably, on a substantial pressure imbalance between the pinch pressure (both magnetic and plasma pressure) and the transverse kinetic pressure of the beam. In a recent model of the beam-pinch interaction, Putnam[12] has examined the role of pressure imbalance between the beam and the pinch. Z pinches used for beam control must meet the pressure-balance requirements; this means more energetic pinches for higher-intensity beams. Second, the large spread in transverse and axial electron-velocity components with which intense beam pulses are generated (because of self-magnetic interaction in the diode) represents the most serious barrier to strong radial compression even when a sufficient pressure imbalance is attained. Our initial results with a tapered pinch, which illustrate both of these problem areas, will be reported shortly.

We wish to thank Dr. Sidney Putnam for pointing out the relevancy of the pressure balance viewpoint in interpreting our findings and Dr. Gerold Yonas for helpful conversations.

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Nonstationary Behavior of Collisionless Shocks*

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Laboratory measurements indicate that a collisionless shock wave formed in a plasma-wind-tunnel device is nonstationary on the time scale of the ion gyroperiod. This behavior suggests a possible interpretation of recent data on magnetic field structure in the vicinity of Earth's bow shock. Comparison is made between the laboratory measurements and earlier computer simulations in which ion gyromotion was included.

We wish to report what we believe to be the first observation in the laboratory of nonstationary collisionless shocks in magnetized plasma. Our experiments were conducted in a plasma wind tunnel designed to produce steady-state shock profiles. Details of this device and results of earlier measurements may be found elsewhere.[1] Recent refinements in our measurements, as described below, reveal that the interaction of an essentially steady plasma stream in the magnetosonic Mach-number range 4 to 8 with a fixed magnetic obstacle leads to a standoff shock which is not stationary. Rather, the plane containing the shock interface oscillates back and forth in the direction of the upstream plasma flow with a frequency comparable to the upstream ion gyrofrequency.

A large number of workers have reported observations of collisionless shocks in magnetized plasmas.[2-5] These observations were made on radially imploding pinch devices, and to the best of our knowledge the fact that these shocks may be nonstationary has not been reported earlier. It may be argued that under conditions where the shock is produced by radial implosion, physical limitations in the available space preclude the observation of fluctuations within the shock interface on the time scale of the ion gyroperiod.

Recent observations[6] made by satellite-based sensors of Earth's bow shock may also be interpreted in terms of a nonstationary shock. Precursor compressions and rotations of the magnetic field on the upstream side of the shock, and fluctuations behind the shock of amplitude approximately 10 gammas are frequently observed. The origin of the precursor structure was concluded to be large-amplitude wave trains, which are frequently destroyed by changes in conditions at the shock. In light of our experiments, however, we feel that the possibility that

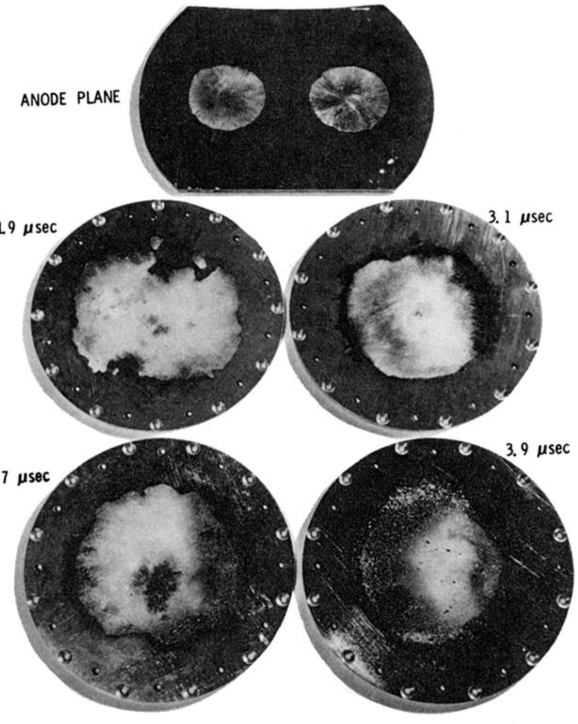

FIG. 3. Damage patterns in Z-pinch anodes and anode plane witness plate.