

INJECTION AND PROPAGATION OF MULTIPLE RELATIVISTIC ELECTRON BEAMS INTO PREFORMED PLASMA CHANNELS FOR HIGH-POWER X-RAY PRODUCTION

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Abstract

A program is presently underway to apply the multiple, high- v/γ relativistic electron beams from the Casino I accelerator to achieve high-power x-ray production via the bremsstrahlung process. The approach seeks to combine the $v/\gamma = 15$, 1.0 MV, 700 kA beams produced by each of the four modules using plasma-channel transport and relativistic beam overlap to maximize the power density and total energy delivered to the x-ray target. Experimental work in the areas of pinch formation, beam injection, wire plasma channel formation, background gas and pressure dependence, beam transport efficiency and repeatability is presented. Recent experiments at the Naval Surface Weapons Center have demonstrated transport of individual 700 kA beams over distances of 71 cm using wire-initiated air-plasma channels. Transport efficiencies of 85% have been achieved at reduced air pressures (75 Torr) based on x-ray measurements at the source and at 71 cm. Results are encouraging and indicate that the plasma-channel multi-beam approach is a viable one for achieving electron-beam power multiplication.

Introduction

Efficient transport of relativistic electron beams in gas-discharge plasma channels opens up a new realm of possibilities for coupling multiple intense-beam sources into a common x-ray converter. In the near term, existing multi-modular machines like Casino I can derive immediate benefit since this transport technique provides these machines with a reasonably simple method for realizing their full-power potential. In the far term, new machine designs can embrace plasma-channel transport and multi-beam coupling to overcome the impedance and power constraints imposed by single-diode machine designs. We present results of the several aspects of the ongoing work related to the problem of combining the high v/γ beams from Casino I.

Casino I

The Casino I electron beam generator (Figure 1) is a four-module system, designed to simultaneously produce four 1.0 MV, 0.8 MA, 65 nanosecond electron beams for delivery to a centrally-located bremsstrahlung converter. The generator consists of two 410 kJ, oil-submerged Marx generators, four water-dielectric pulse-forming and impedance-transforming transmission lines, and four low-inductance, high-current diodes. Each Marx generator supplies 4.2 MV in 2.0 micro seconds to two pulse-forming/diode modules (Figure 2) via 3.5 meter diameter polyurethane diaphragms which support the water coax and interface between the oil/water. Each beam module is inclined at 13.6 degrees toward the central target area thus making possible an expansion to twelve beams (in the horizontal plane). The overall length of each Casino I module from the rear of the Marx generator to the central bremsstrahlung target is 16 meters. This distance allows room surrounding the central converter for apparatus and experiments in the intense bremsstrahlung environment produced. Radiation shielding is provided by a 7.0 x 7.6 x 12.8 meter partially-demountable concrete blockhouse.

Each of the four water-dielectric modules can be energized singly or in concert, with each having its own set of diagnostics.¹ Each beam is transported from

launch at the field emission diodes 2.7 meters to the central converter. The diodes are magnetically-insulated by an externally-applied 10 kilogauss field and transport is achieved by injection into a 1.5 Torr neutral-gas which has a 10-15 kilogauss quasi-static longitudinal guide field impressed on it. The guide field solenoids are turntable-mounted and are energized by a supplementary 720 kJ capacitor bank system.

Generator Improvements

Several improvements to the generator have been made or are now in progress. Switch losses have been reduced by operating the existing water switch at nearly twice the average field (300 kV/cm) than used previously. As a result input energy delivered to each module has been increased by about 15 percent. This change in operating mode was motivated by a review of output water switch performance which culminated in the formulation of a time-dependent electrical streamer model² for the output switch-action. Also a higher-frequency trigger voltage is being tested on the water switch with hopes of achieving more rapid water-streamer onset. Gas switch development and testing is being conducted on Casino I³ and on a separate 4.0 MV pulser/test chamber which has been designed and assembled. A new gas switch column has been designed and will undergo voltage testing on the new pulser this year.

Prepulse suppression switches have been added to the transformer on the basic power module. The switches consist of 32 water-filled electrode pairs located near the output end of the transformer. The electrodes are made of stainless and rod steel respectively and are operated in an over-voltage triggered mode. Pre-pulse on the transformer has been reduced by one-half to 8 kV as a result.

An important improvement has been made to the pinch-stability of the focused-diodes on Casino I. A spiral-cage cathode shank⁴ and a surface-flashover prepulse switch were added to the focused-beam diodes. These changes have improved the pinch stability of the focused beam. In a recent shot series, fifteen stable 550 kA, 1.5 MV, 80 nanosecond beams with 24 mm pinch diameters were produced with an average beam energy for the series of 52 + 10 kJ. The spiral-slotted shank produces an additional axial component of self-magnetic field because of the circumferentially-flowing portion of the diode conduction current which assists in reducing beam-spot fluctuations.

Beam Injection and Transport

In the context of these generator improvements, single-beam injection and transport via the plasma channel from an exploding wire have been successfully achieved from two different diode configurations. Initial success was achieved using the original magnetically-insulated Casino I diode and a plasma channel initiated by a 0.0254 mm diameter exploding tungsten wire. The configuration is shown in Figure 3. The 700 kA, 1.0 MV, 80 nanosecond beam was propagated 71 cm from diode to external bremsstrahlung converter in open laboratory air at normal temperature and pressure. The anode consisted of a sandwich of titanium foil/kapton/aluminum foil with the wire being attached directly to the outer aluminum foil with a piece of mylar tape. The diode

Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE JUN 1981		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE Injection And Propagation Of Multiple Relativistic Electron Beams Into Preformed Plasma Channels For High-Power X-Ray Production				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Surface Weapons Center White Oak, Silver Spring, Maryland 20g10				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.					
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15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 5	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

insulating field was reduced to the minimum (3 kilogauss) so as to reduce irregularities in the beam spatial transition from the field lines produced by the diode solenoid to those produced by the plasma channel current. Figure 4 is transport photo.

Twenty-four successful injections/propagations have been demonstrated with the magnetically-insulated diode, out of thirty-eight attempts. A range of transport conditions were experimented with using two different wire-driving capacitor banks (16.2 μ F, 40 kV and 300 μ F, 20 kV) and two different ambient air pressures (75 and 760 Torr.) Results are summarized in Table I. Plasma channel diameters averaging 24 mm were achieved beginning from 760 Torr ambient air while 55 mm diameter channels were achieved starting from 75 Torr air. The low energy transport efficiency of 10% (first row, Table I) obtained initially is attributed to the fact that the beam diameter at injection (50 mm) was two times larger than the plasma channel diameter (25 mm)!. The fact that transport efficiency increased to 85% when the plasma channel diameter was increased (row 2, Table I) suggests that the beam may have been hollow with most of the electrons moving near the outer circumference of the plasma channel. $\text{CaF}_2\text{:Mn}$ thermoluminescent dosimeter (TLD) radiation dose measurements with the TLDs shielded all around with 0.76 mm aluminum and back-shielded with 4.72 mm aluminum (so as to eliminate electron contamination of the x-ray dose measurement) were made to establish this energy transport efficiency. Separate baseline TLD dose measurements were made near the point of injection and at the end of the wire channel but were unable to establish that the beam was hollow. The data shown in Table I (rows 1 thru 4) is believed to be the first time a magnetically-insulated diode beam has been successfully injected into a wire plasma column. Success has also been demonstrated in propagating the Casino I beam over the larger distances of 117 cm and 152 cm (rows 3 and 4, Table I).

Approximate plasma channel-front expansion velocities from the exploding wire as inferred from the experimental data are 0.8 mm per microsecond for the 760 Torr shots and 1.5 mm per microsecond for the 75 Torr shots. These expansion velocities were obtained from measurements of x-ray converter beam spot diameters and wire-current rise times. These expansion velocities compare favorable with those obtained by Miller⁵ and by Bacon⁶.

Wire transport studies have recently begun using a focused diode configuration. This diode employs the spiral-cage cathode mentioned previously and a shank-flashover prepulse switch. Excellent repeatability has been achieved in generating pinch-stable beams with this spiral-cage shank. The spiral cage is constructed from a hollow stainless steel cylinder with 12 each 6.4 mm-wide equally-spaced spiral slots cut in its shank and tipped with a 76 mm O.D., 66 mm I.D., carbon ring with a 30° taper. The diode-to-wire transition assembly (Figure 5) incorporates a beam expansion space variable from 3 to 16 mm beyond the titanium anode foil. The titanium anode foil is perforated circumferentially so the foil itself bears no pressure differential and thus avoids any curvature variations inherent in the earlier anode-cathode configuration (Figure 3). One transport attempt has been made with the above configuration with resounding success. The x-ray converter TLDs were scattered widely over the blockhouse floor from the impact blast of the smaller diameter beam (row 5, Table I).

Channel-formation studies are centering on wire strike-time and wire peak-current dependence on capacitor bank voltage. Only tungsten wires are being studied.

Wires of 120 cm, 140 cm and 150 cm lengths are being exploded. Generally peak wire current increases proportionately with bank voltage while strike time (the time from application of the bank voltage until lift-off of the plasma channel current) decreases with increasing bank voltage. Scalability conforms to the simple electrical model put forth by Miller⁷.

Dual-beam propagation tests will begin soon with the configuration shown in Figure 6. The injectors will be two spiral-cathode focused-diodes identical to those just previously described because they are expected to prove successful. Multi-wire beam overlap studies should begin soon thereafter.

Future Considerations & Summary

Future plans on Casino I are to extend the wire beam transport out to 2.7 meters into the center of the blockhouse (Figure 7). This will permit all four beams to be brought together at the common x-ray converter. The plasma channel transport technique exhibits spacial and hardware advantages over the previous neutral-gas injection scheme. If placement and handling of the fine tungsten wires proves impractical, laser designated channels⁸ with capacitor bank drivers will be considered. Sixteen channel configurations for Casino II have been studied by us and appear practical using plasma channel transport techniques.

Considerable progress has been made in adapting recent pulse-power advances to Casino I. These developments hold considerable promise of advancing the reliability and power levels achievable on Casino I. Promising future multi-beam possibilities are therefore open for Casino II.

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Table I. Beam Injection & Transport Summary.

Diode	Injected Beam	Propagation Length/No. of Shots	Ambient Gas Medium	Plasma Channel Current	Beam Diameter @ Injection	Plasma Channel Diameter	Energy Transport Efficiency
1. Magnetically-Insulated Diode(3kG)	700 kA 1.0 MV 80 ns (laminar)	71 cm 11 shots	760 Torr Air, 20 C	40 kA	50 mm	24 mm	10%
2. Magnetically-Insulated Diode(3kG)	540 kA 1.3 MV 80 ns (laminar)	61 cm/6 & 71 cm/4	75 Torr Air, 20 C	55 kA	50 mm	55 mm	85%
3. Magnetically-Insulated Diode(3kG)	630 kA 1.0 MV 80 ns (laminar)	117 cm 2 shots	760 Torr Air, 20 C	40 kA	50 mm	55 mm	~ 80%
4. Magnetically-Insulated Diode(3kG)	600 kA 1.2 MV 80 ns (laminar)	152 cm 1 shot	760 Torr Air, 20 C	25 kA	50 mm	55 mm	~ 20%
5. Focused Diode w/ Spiral-Cage Cathode	540 kA 1.5 MV 80 ns (focused)	83 cm 1 shot	75 Torr Air, 20 C	108 kA	25 mm	30 mm	~ 90%

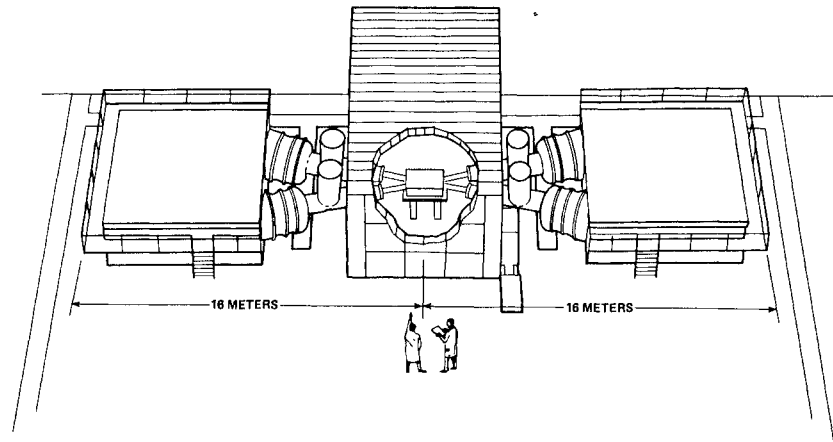


Figure 1. The Casino I electron beam generator.

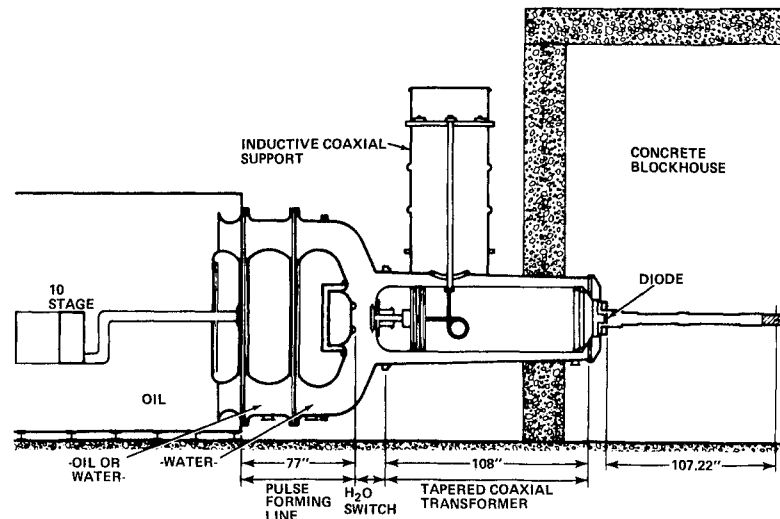


Figure 2. Casino I pulse-power module.

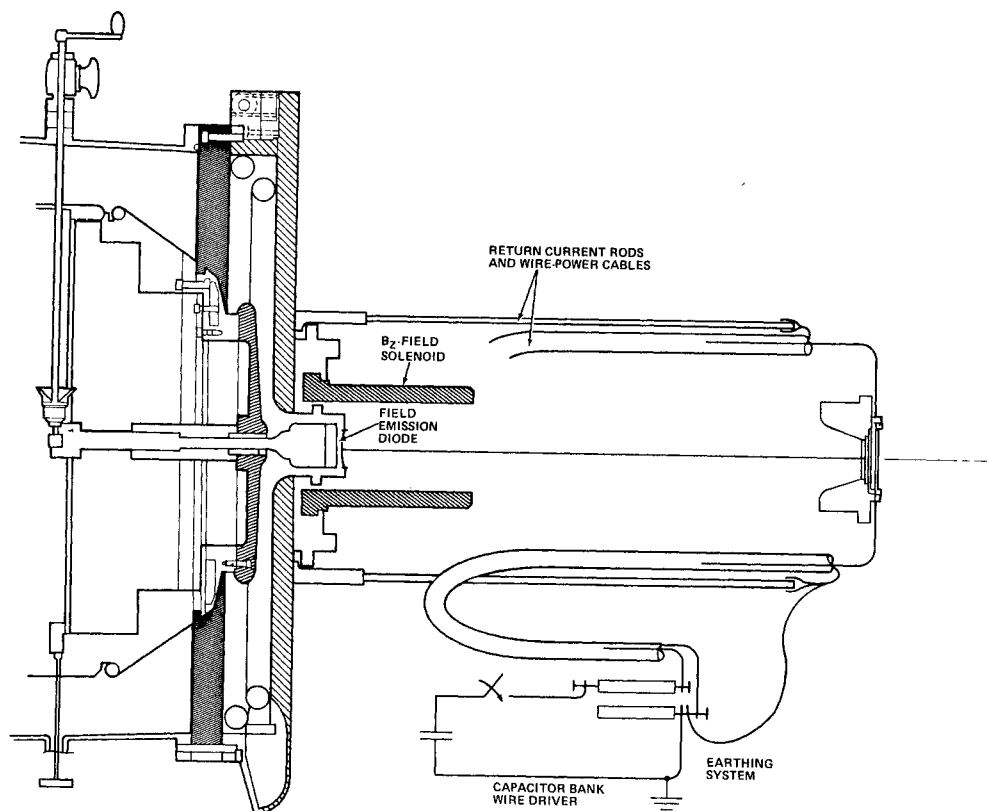


Figure 3. Single-beam wire-transport configuration using the Casino I magnetically-insulated diode.

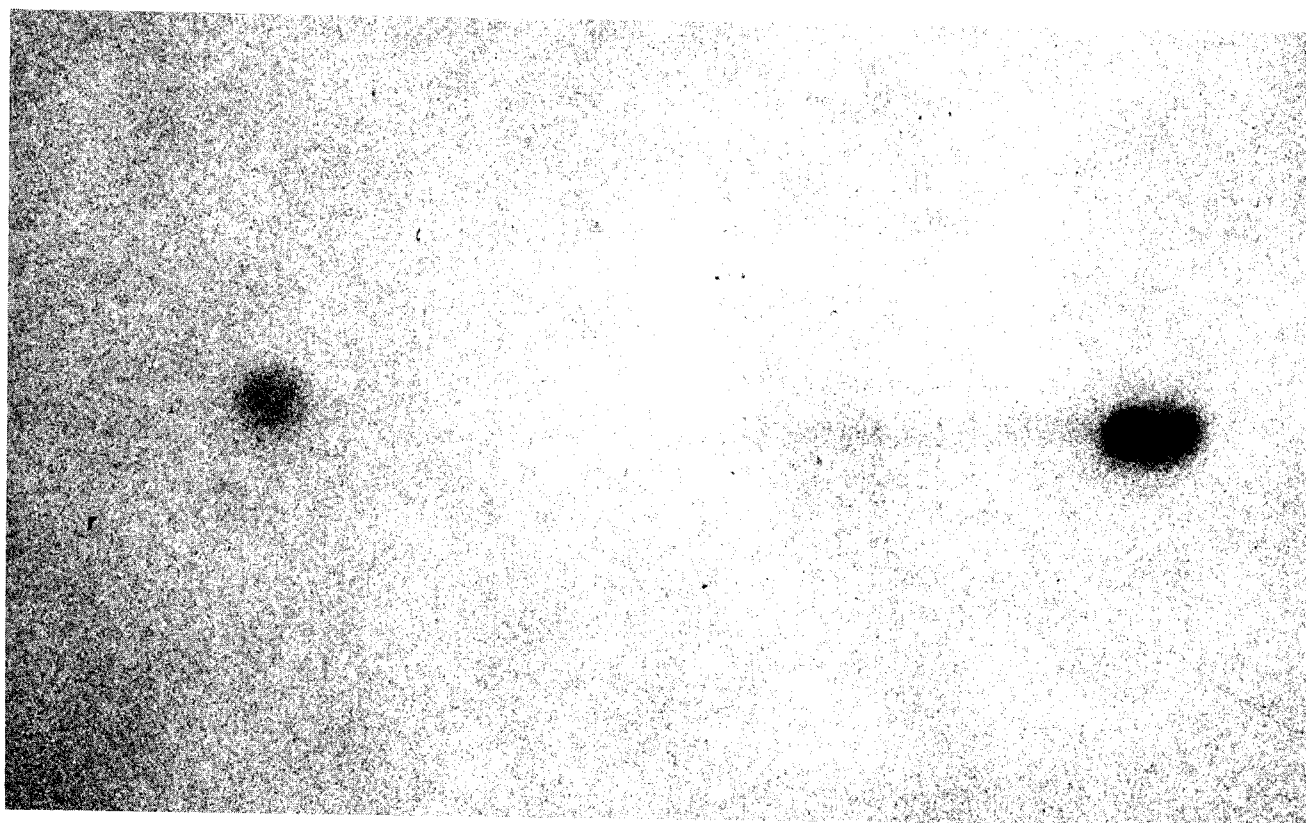


Figure 4. X-ray pinhole photo of beam transported 117 cm from left to right.

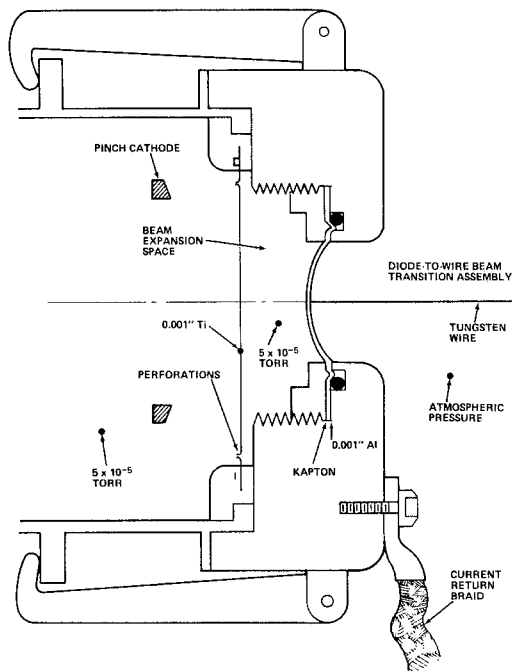


Figure 5. Diode-to-wire beam transition assembly.

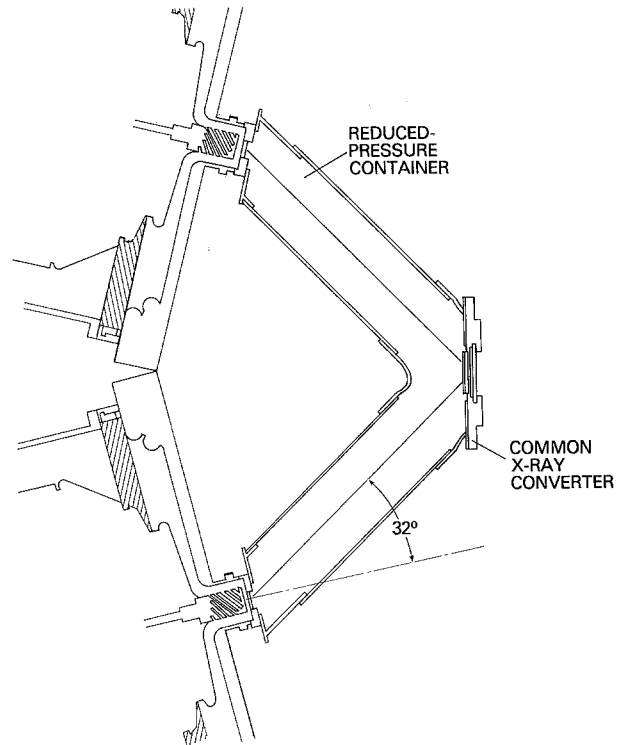


Figure 6. Dual-beam, 1.0 meter wire transport configuration.

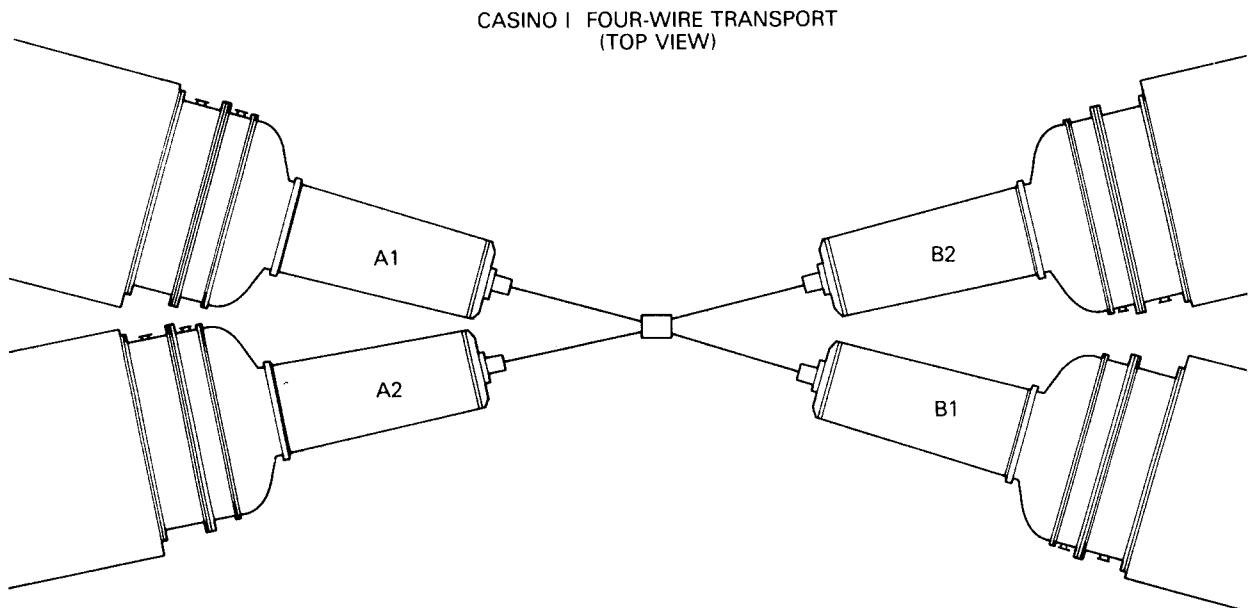


Figure 7. Casino I four-wire beam transport system (top view).