Cygnus X-ray Performance Using High-Z and Low-Z Anode Rods *

J. Vargas[ξ], J. Adams, A. Augustine, S. Breckling, P. Flores, K. Hogge, I. Pohl, J. Smith, C. Spillers Jr., J. Taylor, H. Truong
Mission Support and Test Services, LLC
North Las Vegas, NV 89030 USA

D. Duke
Los Alamos National Laboratory
Los Alamos, NM 87545 USA

M. Garcia, E. Ormond, M. Parrales
Sandia National Laboratories
Albuquerque, NM 87185-1193 USA

Abstract

The Cygnus Dual Beam Radiographic Facility has been developed for support of the Subcritical Experiments (SCE) Program at the Nevada National Security Site. Some key features of the Cygnus source are; a dramatically reduced spot size (as compared to existing alternatives), layout flexibility, and reliability. Cygnus has a 2.25 MeV endpoint energy and a 50 ns radiation pulse length. The diode uses a rod pinch geometry which readily achieves a small source diameter. The majority of SCEs require an x-ray spectrum where the high energy component is maximized, and therefore use a high-Z anode rod (tungsten). Recently there has been a new requirement on the x-ray spectrum - enhancement of the low energy component. Therefore, a diode using a low-Z anode rod (titanium) has been employed. In this paper we present a comparison of Cygnus performance using both high-Z and low-Z anode rods.

I. INTRODUCTION

Pulsed Power systems play a crucial role in various scientific and technological applications, ranging from high-energy physics research to nuclear weapon testing. The development of advanced pulsed power facilities is essential for supporting these endeavors and facilitating important experimental programs. In this context, the Cygnus Dual Beam Radiographic Facility has been specifically designed to meet the requirements of the Subcritical Experiments (SCE) Program at the Nevada National Security Site.

Cygnus boast several key features that set it apart from existing alternatives. One prominent characteristic is its ability to achieve a dramatically reduced spot size, which offers significant advantages over conventional systems. Additionally, the facility offers enhance layout flexibility, enabling researchers to optimize the experimental setup according to specific requirements. Moreover, Cygnus has demonstrated remarkable reliability, ensuring consistent and accurate performance throughout its operation.

The primary objective of Cygnus is to generate high-energy x-ray radiation pulses for various subcritical experiments. To achieve this, the source utilizes a rod pinch geometry in its diode configuration, allowing for the attainment of a small source diameter. In the past, the majority of subcritical experiments have emphasized the maximization of the high-energy component in the x-ray spectrum. Consequently, a high-Z anode rod, typically composed of tungsten, has been employed to fulfill this requirement effectively.

However, recent development have introduced a new demand in the SCE program, necessitating the enhancement of the low energy component in the x-ray spectrum. To address this requirement, an alternative approach utilizing a low-Z anode rod, specifically titanium, has been incorporated into the Cygnus source design. This modification allows for a more pronounced low energy component in the x-ray spectrum, catering to the evolving experimental needs of the SCE program. The requirement for the new demand has an areal mass dynamic range of 0.001 – 0.1 g/cm^2 which was achieved.

This paper aims to present a comprehensive comparison of the Cygnus performance using both high-Z and low-Z anode rods. By evaluating the effects of these anode rod materials of the generated x-ray spectrum, we can assess the efficacy of each configuration in meeting the specific experimental objective. The obtained results will contribute to a deeper understanding of the Cygnus source capabilities and aid in optimizing its performance for future subcritical experiments.

In the subsequent section, we will delve into the experimental setup, measurement techniques, and results obtained from the comparison of the Cygnus source performance using high-Z and low-Z anode rods. By analyzing the data, we aim to provide valuable insight into the advantages and limitations associated with each configuration, ultimately guiding future improvements in the design and operation of the Cygnus Dual Beam Radiographic Facility.

---

* This work was done by Mission Support and Test Services, LLC, under Contract No. DE-NA0003624 with the U.S. Department of Energy. DOE/NV/03624--1768.

[ξ] email: Vargasjp@nv.doe.gov

II. METHODOLOGY

A. Description of the rod pinch diode

The rod-pinch diode, shown in Figure 1, comprises of a thin anode rod protruding through an annular cathode. The electron beams self-magnetic field causes it to pinch at the end of the rod, producing a bright x-ray source. The diode has been studied for radiographic applications for many years. As the voltage increases beyond a few MV, electrons in a rod-pinch diode impinge mainly in the backward direction so that the diode should be in a negative polarity to maximize the extracted dose.

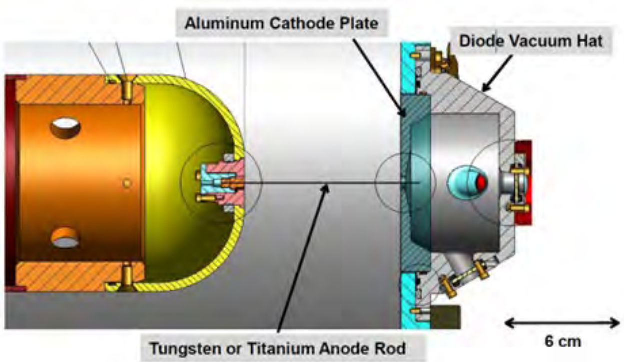

Figure 1. Compact Pinhole Camera.

The difference between a high-Z and low-Z anode rod lies in composition of the material used in the construction of the rod and its impact on the x-ray spectrum generated by the pulsed power system. Since the high-Z have a greater number of protons in their nuclei, the x-ray spectrum produced tends to be dominated by higher energy x-rays. These higher energy x-rays are more penetrating and have the capability to reach deeper into the target material. Consequently, they are well-suited for experiments that require a higher-energy x-ray components to investigate dense or thick objects. On the other hand, low-Z anode rods are made of materials with lower atomic numbers where the x-ray spectrum is characterized by a higher proportion of low-energy x-rays that are less penetrating and better suited for experiments that require enhanced contrast and resolution in imaging thin or low-density materials. Throughout these series of shots, a tapered tungsten and blunt titanium rods were used as shown in Figure 2.

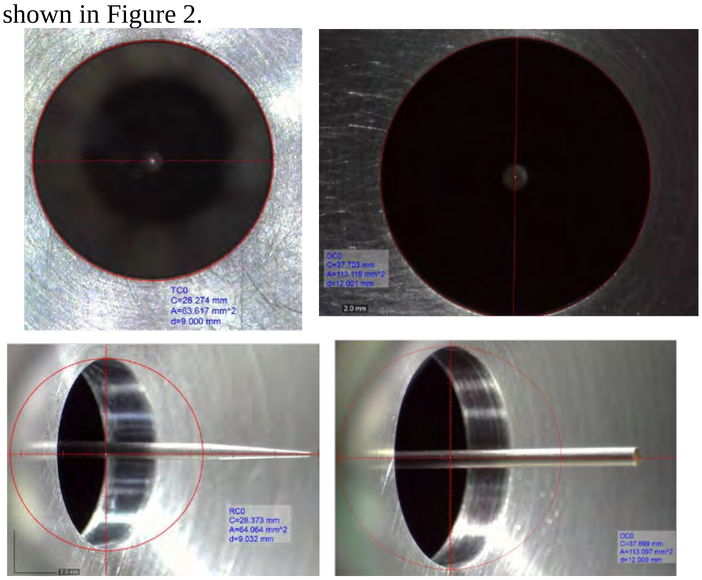

Figure 1. Tapered Tungsten vs Blunt Titanium

Key measurements were taken to evaluate the x-ray spectrum and dose characteristics. On the Cygnus dose performance, the primary diagnostic tools employed for the Cygnus dose were the LiF thermoluminescent dosimeters (TLDs) and Data Acquisition PINS, where the TLDs were given precedence in assessing Cygnus' performance. The different anode rods were also employed interchangeably to keep investigating the impact of their composition on the generated x-ray spectra. As for the radiography measurements, radiographic imaging was conducted using two imagers, each optimized for different aspect of the x-ray spectrum: Radiographic Imager 1 which was equipped with a thin CSL detector, making it highly sensitive to softer X-rays. This imager was positioned upstream from Imager 2, facilitating a comprehensive analysis of the x-ray spectrum transition. The two common fiducial targets that were employed to characterize the radiography produced by Cygnus were the basketweaves and the step wedge which can be seen in Figured 3.

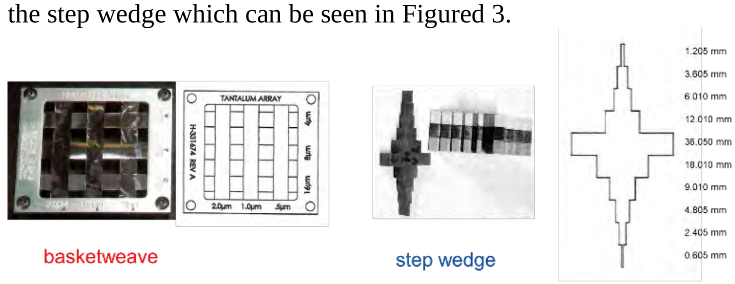

Figure 2. Basketweave and Step Wedge

The basketweave consisted of overlapping strips of very thin tantalum (on the order of microns). These targets served as an analogy for low areal density regions within dynamic experiments. The step wedges were thicker targets made of different materials, such as aluminum, iron and tantalum (on the order of almost 2 inches at the thickest point). They represented high areal density regions within dynamic experiments. The combination of the Radiographic Imager 1, Radiographic Imager 2, and the common fiducial targets allowed for a comprehensive analysis of the x-ray spectra generated by both high-Z and low-Z anode rod configuration. This set up can be seen in Figured 4.

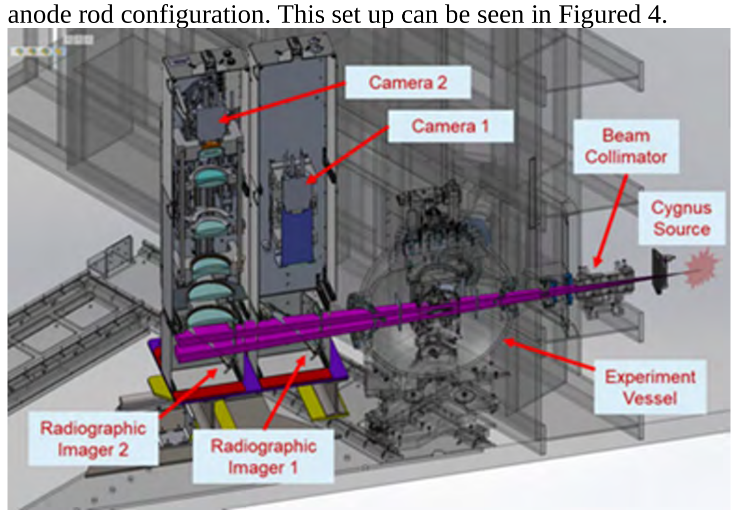

Figure 3. Radiography Imager Set-up

III. RESULTS AND ANALYSIS

The dose measurements obtained during Cygnus shots demonstrated excellent machine performance, leading to outstanding radiography data results, as illustrated in Figure 5-8. Here we compare previous tungsten results [1] to a new titanium-series of shots; Nightshade A, Nightshade B, and Nightshade C. The Cygnus source exhibited remarkable stability and consistency in delivering the required radiation doses for the experiments.

Shot	C1 Dose	C2 Dose
Armando	4.51	4.19
Bacchus	4.67	4.3
Barolo A	4.73	4.3
Barolo B	4.76	4.51
Pollux	4.35	4.34
Vega	4.26	4.15
Ediza	4.4	3.88
Design	4	4

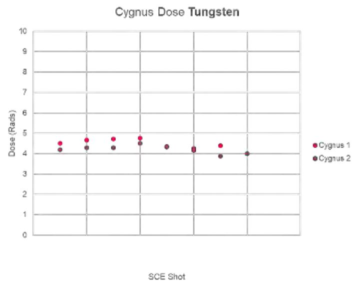

Figure 4. Tungsten Rod Dose SCE shots

NightShade A		
Shot #	C1 Dose	C2 Dose
4488	0.98	0.97
4490	0.98	0.94
4492	0.98	0.93
4494	0.99	0.94
4496	1	0.91
4499	0.98	0.92
4502	0.96	0.94
4510	0.99	0.87
4512	0.99	0.95
4514	0.98	0.96
4518	**0.94**	**0.93**

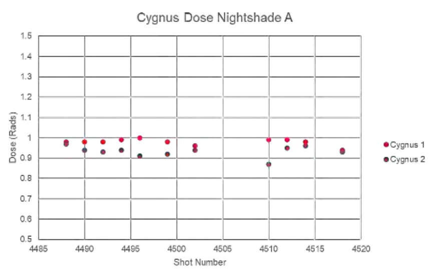

Figure 5. Cygnus Dose Nightshade A

NightShade B		
Shot #	C1 Dose	C2 Dose
4694	0.96	0.96
4698	0.99	0.94
4700	1	0.95
4702	0.97	0.99
4704	0.99	0.98
4706	1	0.99
4708	0.99	0.94
4710	0.96	0.96
4712	1	0.98
4714	0.99	0.97
4724	**1**	**0.92**

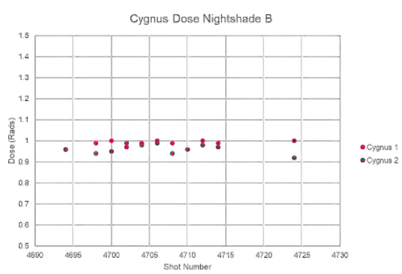

Figure 6. Cygnus Dose Nightshade B

NightShade C		
Shot #	C1 Dose	C2 Dose
4752	1.01	0.99
4753	1	0.97
4754	1	0.99
4755	0.97	0.99
4756	0.99	0.94
4757	0.97	0.99
4758	0.96	0.98
4759	0.99	0.97
4760	1.01	0.94
4761	1.02	0.97
4763	**0.98**	**0.99**

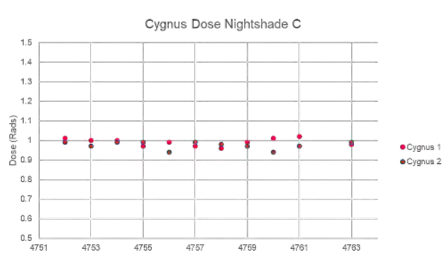

Figure 7. Cygnus Dose Nightshade C

On the radiography side, to assess the production of softer X-rays, we employed an array of tantalum (Ta) foils arranged in a grid with thicknesses ranging from 4.5 micrometers to 17 micrometers. Both images presented below were flat-field normalized for accurate comparison. Upon qualitative analysis, it may not be readily apparent which anode rod configuration possesses the preferred dynamic range. However, a more in-depth transfer curve analysis revealed noteworthy differences between the two configurations.

After conducting the transfer curve analysis, it became evident that the blunt titanium rod (low-Z) exhibited a larger dynamic range between 0 and 0.03 g/cm^2 of tantalum. This observation is marked by a steeper slope in the transfer curve, indicating superior performance in generating and capturing low-energy X-rays. The enhanced dynamic range of the titanium rod configuration demonstrates its suitability for imaging low-density or thinner materials with improved contrast and resolution.

In contrast, the tapered tungsten rod (high-Z) produced a slightly reduced dynamic range within the same range of tantalum thicknesses. This outcome can be attributed to the predominant generation of higher-energy X-rays, which are less sensitive to the low-density materials. Nonetheless, the high-Z configuration excels in imaging denser or thicker materials, as supported by previous studies [2].

To evaluate the production of harder X-rays, we employed a collection of step wedges arranged in a grid. Similar to the softer X-ray experiments, both images below were flat-field normalized for accurate comparison. Upon qualitative assessment, discerning a noticeable improvement in dynamic range between the two anode rod configurations was not immediately apparent.

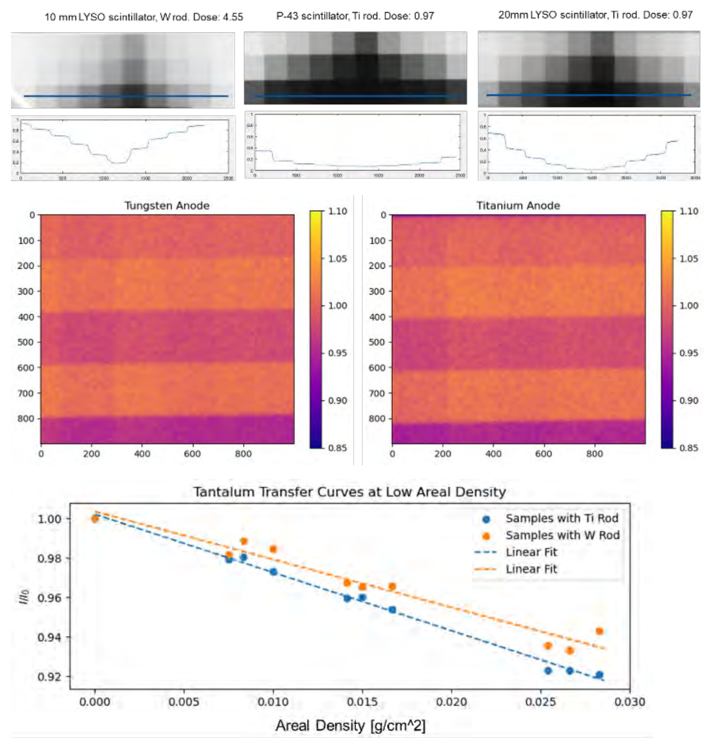

Figure 8. Dynamic Range for High Areal Density Objects

The difficulty in observing a significant difference in dynamic range can be attributed to the fact that step wedges are primarily designed to simulate higher areal density regions within dynamic experiments. Consequently, the focus of the analysis shifted towards the optimal performance of each configuration concerning softer X-ray production, which holds more significance for certain experimental objectives. This can be seen in Figure 10.

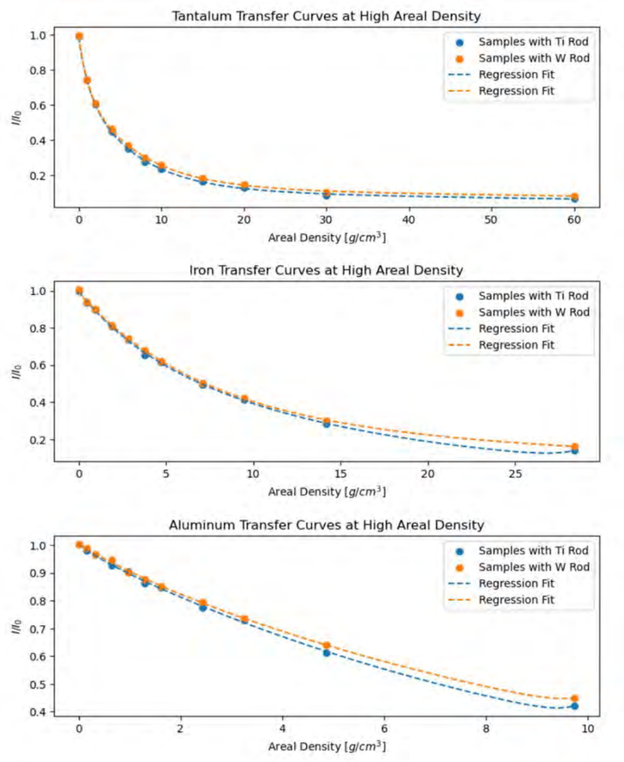

Figure 9. Transfer Curve Analysis

IV. CONCLUSION AND FUTURE WORK

Overall, the radiography results emphasize the importance of tailoring the anode rod material to the specific requirements of the experimental setup. The titanium rod showcased superior performance in generating softer X-rays, enabling enhanced imaging capabilities for low-density or thinner materials. The requirement for the new demand has an areal mass dynamic range of 0.001 – 0.1 g/cm^2 which was achieved. On the other hand, the tungsten rod excelled in generating higher-energy X-rays, making it more suitable for imaging denser or thicker materials. These insights further support the adaptability of the Cygnus Dual Beam Radiographic Facility to cater to diverse experimental needs within the Subcritical Experiments Program. Future work in the development and enhancement of the Cygnus Dual Beam Radiographic Facility will focus on exploring various configurations of Low-Z and High-Z anode rods. Additionally, the facility will experiment with coated titanium and tungsten anode rods to assess their potential for optimizing the x-ray spectrum for specific experimental needs. Data will be collected on different fabrication methods, comparing diamond ground welded rods with wire EDM rods (electrical discharge machining) to identify the most efficient and reliable manufacturing technique. Furthermore, ongoing efforts will be dedicated to investigating different combinations of fiducial targets, anode rods, and LYSO detectors to further improve the quality and versatility of radiography measurements. As part of the facility's continuous improvement, the development of uncertainty quantification (UQ) capabilities for measurements of ejecta mass will be pursued, ensuring a more comprehensive understanding of experimental outcomes, and enhancing the reliability of data interpretation.

VI. REFERENCES

J. Smith et al., “Performance of the Cygnus x-ray source” in Proceedings of the 15th IEEE Pulsed Power Conf., 13-17 June 2005.

J. Smith et al., “Cygnus dual beam radiography source,” in Proceedings of the 15th IEEE International Pulsed Power Conference, 2005.