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The Q_{weak} target performance

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Summary. — The Q_{weak} Experiment at Jefferson Laboratory aims to measure the parity violating ep scattering asymmetry at low Q^2 to a statistical precision of only 5 ppb. Such precision presents many challenges for the liquid-hydrogen target used in the experiment. The 35 cm long Q_{weak} target was designed to withstand 180 μA of beam current. Although this is the highest power cryotarget ever built, the target must also provide < 50 ppm of target noise under these demanding conditions, which makes it the lowest noise target ever built at the same time. These seemingly mutually exclusive goals have both been met. The target will be described, and measurements of its performance will be presented.

PACS `24.80.+y` – Nuclear tests of fundamental interactions and symmetries.
PACS `25.30.Bf` – Elastic electron scattering.
PACS `29.25.-t` – Particle sources and targets.

1. – Introduction

At the PAVI 09 conference, the design of the as yet unbuilt Q_{weak} target was described [1]. Since then the target has been built, commissioned, characterized, and used for six months in the Q_{weak} experiment [2]. We present selected aspects of the measured performance of the target in this article.

2. – Description of the target

The length of the target along the beam direction is 35 cm. The target cell in which the beam interacts with the liquid employs a fluid flow (3–7 m/s) transverse to the electron beam axis and was carefully tailored using computational fluid dynamics (CFD) simulations, as described in [1]. CFD simulations were used to either design or check the analytical design of almost every aspect of the target. Our position is that the success of this target validates the use of CFD as a design tool for these next generation targets. The entrance window to the cell consists of 0.097 mm thick Al 7075-T6 at the downstream end of a 41.4 mm long cylinder with an inner diameter of 22.2 mm. The Al

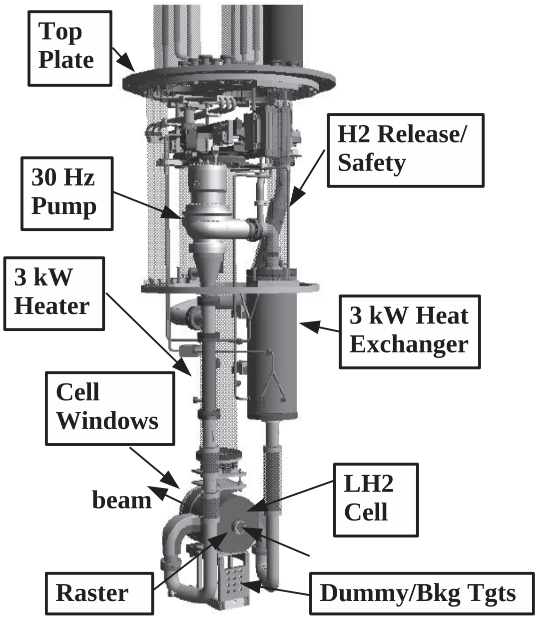

Fig. 1. – A CAD model of the target showing the basic components. Everything below the top plate is in vacuum.

7075-T6 exit window consists of a 25.4 mm thick flange 305 mm in diameter. Inside a diameter of 173 mm the thickness is 0.635 mm over a machined surface with a radius of curvature of 254 mm. At the center of the window, the thickness is only 0.125 mm over a diameter of 15 mm. The unscattered electron beam goes through this thin nipple. The scattered electrons falling into the experiment's acceptance ($6^\circ < \theta < 12^\circ$) pass through the 0.635 mm thick section of the window.

A CAD picture of the target is shown in fig. 1. The nominal diameter of the loop itself is 76 mm.

The target was designed [3] to operate at 20 ± 0.02 K at an operating pressure of 30–35 psia (207–241 kPa). The liquid volume of the target is approximately 55 liters when the H2 is fully condensed, at which point about 50000 STP liters of hydrogen gas at ~ 2 bars remains in the 23000 STP liter capacity storage tanks. The ionization energy loss of the 1.165 GeV electron beam traversing the 35 cm of LH2 is approximately 2.1 kW. Accounting for viscous heating, pump heat, conductive and radiative heat loss, as well as a reserve power of about 150 W for the feedback loop to work with, the total cooling power that must be provided to the target is near 2.8 kW. The target employs a 3 kW hybrid heat exchanger employing two sources of helium coolant in a single counterflow heat exchanger. The heat exchanger is constructed in 3 sections of 3 concentric coils each consisting of 12.7 mm ϕ finned copper tubing with 6.3 fins/cm. The coils are connected in such a way as to provide equal impedance for each circuit. One circuit employs helium coolant supplied at 12 atm and 14 K and returned at 3 atm and 20 K. The other two circuits are supplied with helium coolant at 3 atm and 4 K which is returned at 1.3 atm and 20 K. Typical helium coolant mass flows are 20 g/s (4 K source) and 40 g/s (15 K source), but this load includes considerable 4 K flow diverted to a superconducting solenoid used for polarimetry measurements in the experiment. A

3 kW capacity heater consisting of 2 parallel coils of nichrome wire with a total resistance of 3.185 Ω replaces the heat deposited by the electron beam when the beam is off, and is used to regulate the temperature of the hydrogen in the loop to within 20 mK of the 20 K goal temperature. The liquid hydrogen is contained in a closed loop and circulated by means of a 1 hp (746 W) centrifugal pump spinning at 30 Hz. The pump was designed to achieve a differential pressure (head) of 1.2 psid (8.3 kPa), and a hydrogen mass flow of 1.1 kg/s (15 liters/s). Initially, bearings employing ceramic balls and race with a teflon retainer failed. They were replaced with bearings using ceramic balls, a stainless steel race, and graphite impregnated vespel retainers. The bearings are pressed onto a shaft of diameter 15.9 mm on one side of the pump rotor, and 22.2 mm on the other.

The incident beam, which has an intrinsic diameter of approximately 200 μm, is rastered into uniform distributions typically between $3 \times 3\,\mathrm{mm}^2$ and $4 \times 4\,\mathrm{mm}^2$ using a 25 kHz triangular waveform exciting iron-free magnets wound with aluminum wire. The LH2 target employs a 2-axis motion system which allows it to be accurately positioned on the experiment's neutral axis, as well as to position one of 24 other background and diagnostic targets in the beam. Approximately 500 mm of vertical travel and 86 mm of horizontal travel are provided. Special aluminum targets with squares 2 mm on a side cut out of the center are used to center the other various targets to within ±0.25 mm, by forming x-y images of the raster magnet currents triggered by events detected at the experiment's focal plane. The pattern shows a clear shadow where the square hole is within the larger raster pattern.

Some auxiliary systems deployed in the target include a 500 W heater on the 4 K supply line, which can be used to quench the 4 K cooling power when necessary, typically during initial cooldown when there is a risk of freezing the hydrogen in the heat exchanger. Further insurance is provided by placing the 4 K coolant supply valve on a feedback loop which closes the valve if the hydrogen temperature approaches the 13.8 K freezing point. Another heater supplying typically 40 W inside the evacuated scattering chamber insures the target motion system remains at 300 K.

To limit the amount of additional experimental running time due to target noise to less than 5%, the target noise must be $\lesssim 50$ ppm in this experiment. That requirement was based on the expected rate of scattered electrons in the Q_{weak} detectors of 5.3 GHz, and the helicity reversal frequency used in the experiment. The Q_{weak} experiment reverses the helicity of the electron beam at 960 Hz, and makes use of quad patterns (*e.g.*, $+--+$). Until now JLab has typically employed 30 Hz helicity reversal.

3. – Measured performance

The target was commissioned in the fall of 2010 and after an initial failure of the pump bearings, ran smoothly and successfully for the six month duration of the first phase of the experiment. A comparison of the design goals discussed at the previous PAVI meeting [1] and what was actually achieved is presented in table I.

Beam currents from 0.1 nA up to 182 μA were employed. Raster areas varying from $3 \times 3\,\mathrm{mm}^2$ to $5 \times 5\,\mathrm{mm}^2$ were used. The pump speed was varied from 12 Hz to 30 Hz. These variations of pump speed, beam current, and raster size were used to characterize the performance of the target. Measuring the target noise with three different techniques improves confidence in the final results. Here, the results obtained by varying the raster area at a fixed beam current of 182 μA is presented in fig. 2.

The upper plot in fig. 2 shows the measured main detector asymmetry width as a function of the width x of the (square) raster pattern. The asymmetry width is determined

TABLE I. – *Comparison of design specifications for the target versus measured performance. In some cases (heater power, heat exchanger) the measured performance was limited to what was actually needed rather than what the design goal was.*

Specification	Design Goal	Measured
LH2 Mass Flow	1.1 kg/s	1.1 ± 0.1 kg/s
Pump Head	1.2 psid	1.1 psid
Heater Power	3 kW	2.4 kW
Heat Exchanger	3 kW	2.9 kW
Target Noise	50 ppm	46 ppm

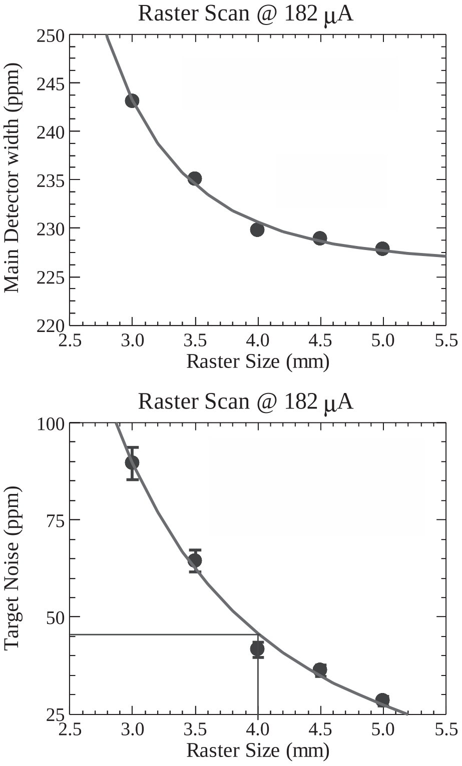

Fig. 2. – Top: the measured asymmetry width of all 8 main detectors is plotted as a function of the raster size. The raster area is the square of this size. The red curve is a fit to the measured widths. Bottom: the target noise extracted in quadrature from the variation of the measured asymmetry widths in the upper figure. At the $4 \times 4\,\mathrm{mm}^2$ raster size used for most of the measurements, the measured target noise is only 46 ppm. All these data were acquired with a beam current of 182 μA.

from a histogram of the measured asymmetry for each electron beam helicity quartet acquired at a rate of 240 Hz (960 Hz helicity reversal frequency). All eight main detectors in the experiment, arrayed symmetrically every 45° around the beam axis, are combined to produce the asymmetry measurement used here. The measured asymmetry width can be broken down into contributions arising from counting statistics (200 ppm including the 70 μs settle time associated with the helicity reversal), detector resolution (92 ppm), beam current monitor resolution (50 ppm), and target noise. These contributions contribute in quadrature to the observed asymmetry width. The 3 parameter fit to the data shown in the upper half of fig. 2 is

$$\sigma_{\text{MD}} = 226 + (5.57/x)^{4.6}\,\text{ppm},$$

where x denotes the raster width. To extract the target noise, the assumption is made that the second term (which is the term that varies with raster size) accounts for the target noise. According to the fit, the asymmetry width would be 226 ppm without target noise. The target noise extracted from the second term is plotted in the lower half of fig. 2, and the fit there is

$$\sigma_{\text{target noise}} = 1.3 + (19.4/x)^{2.4}\,\text{ppm}.$$

With the $4 \times 4\,\text{mm}^2$ raster area typically used in the experiment, the target noise is only 46 ppm.

Similar results are found from the studies in which the beam current was varied, and in which the pump speed was varied. All results are in reasonable agreement (within 5 ppm) with one another when scaled to the same conditions. An empirical formula which describes this scaling based on fits to the beam current (I_{beam}) and raster width (x_{raster}) scans is

$$\sigma_{\text{target noise}} \sim (1.3 + (19.4/(x_{\text{raster}}(\text{mm})))^{2.4}) \times (I_{\text{beam}}(\mu\text{A})/169)^3\,\text{ppm}.$$

* * *

This work is presented on behalf of the Q_{weak} Collaboration. Those collaborators working closely on the target included S. Covrig, J. Dunne, D. Meekins, A. Subedi, and the author. Notice: Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

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