10th Int. Particle Accelerator Conf. IPAC2019, Melbourne, Australia JACoW Publishing
ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-TUPMP033

DESIGN OF THE NEUTRON IMAGING DIFFERENTIAL PUMPING LINE AT LLNL*

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Abstract

The neutron imaging system at LLNL is a radiographic capability for imaging objects with fast, quasi-monoenergetic neutrons at ≤1mm spatial resolution. The neutron production source is a deuteron beam (4 or 7 MeV) incident upon a rotating, high-pressure, windowless, pure-deuterium gas target. The windowless nature of the target combined with the high pressure leads to significant gas leakage upstream of the neutron production target. This leakage degrades the imaging quality by (1) increasing the depth-of-field blurring and (2) increasing the beam diameter and divergence in the transverse direction via angular straggling in the residual gas. To mitigate these effects, and guided by bench tests and simulations, we designed a differential pumping line (DPL) to ensure the highest quality imaging system. The system consists of three primary stages (chambers), each separated by carefully shaped apertures. These apertures can be long and thin with low-angle tapers due to the high quality of the beam optics (convergence at the target < 5mrad) and low emittance of the beam (~5 pi mm-mrad). The primary cascaded roots pumps are sized to remove >99% of the incoming mass flow in each stage, ensuring that by the third stage furthest from the target, turbomolecular pumps are able to operate in a nominal ~mTorr range. We anticipate full system testing with helium in mid 2019.

MOTIVATION

X-ray radiography has a long history of high-resolution imaging, but is less effective for very radiographically-thick objects. Further, it is challenging to see features in low-z, low-density objects behind high-density, high-z objects. Fast neutron imaging is able of overcoming these limitations in some circumstances because of the penetrability of the fast neutrons in those specific situations. Fast neutron imaging can be thought of as complementary to high-energy x-ray imaging since neutrons and x-rays penetrate different materials in different ways, allowing for a differential diagnosis of sorts [1].

DESIGN

Neutron Imaging System

The Neutron Imaging (NI) accelerators accelerate d+ ions to 4 or 7 MeV and strike the windowless gas target to produce quasi-monenergetic 7 or 10 MeV neutrons, respectively. The NI system relies on beam pulses that are coincident with the opening of a shutter in a rotary valving system [2,3,4]. The beam pulses are incident upon a high pressure, windowless target; the rotating shutter opens for approximately 1 millisecond, and closes for approximately 16 milliseconds. This coincidence makes a burst of fast neutrons, but the resulting pulse of gas upstream to the beamline must be managed effectively to minimize various image-degrading effects, such as beam angular straggling, beam spot blooming, and depth-of-field blurring.

Differential Pumping Line

The design of the DPL is essentially a combination of three main design features: (1) lots of massive pumps, (2) long, thin, low-conductance apertures and (3) directional flow (see Figure 1).

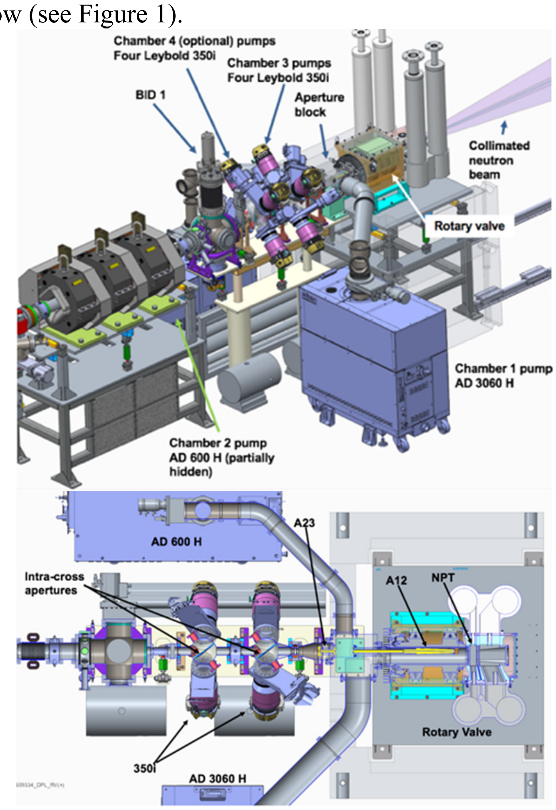

Figure 1: The final beamline components of the NI system at LLNL. (top) rendering of the concept, target shield removed. (bottom) horizontal cross section of the DPL, including notional target shielding.

* This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.
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ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-TUPMP033

These features appear in other systems such as DRAGON at TRIUMF-ISAC [5] and JENSA [6].

The DPL consists of 3 chambers, each differentially pumped and separated by shaped apertures to limit flow up the beamline and between chambers. Chamber 1 receives the outlet flow from the neutron production target (NPT) up the beamline and is therefore attached to the largest pump, the Pfeiffer AD 3060 H, multi-stage cascaded roots pump. It is essentially an AD 600 H pump with a 3600 m^3/h roots blower on top. This pump is expected to remove approximately 99% of the ejected gas from the beamline and recirculate it to the main compressor. There is a 50° angled aperture (6mm diameter, beam passing) on the upstream side of the inlet aperture from the NPT into chamber 1 that directs the flow away from the inlet of the upstream aperture and toward the large pump, increasing pumping efficiency and further reducing upstream gas flow. Computational Fluid Dynamics (CFD) simulations indicate that this design feature significantly reduces the pressure (flow) up the beamline (see Figure 2).

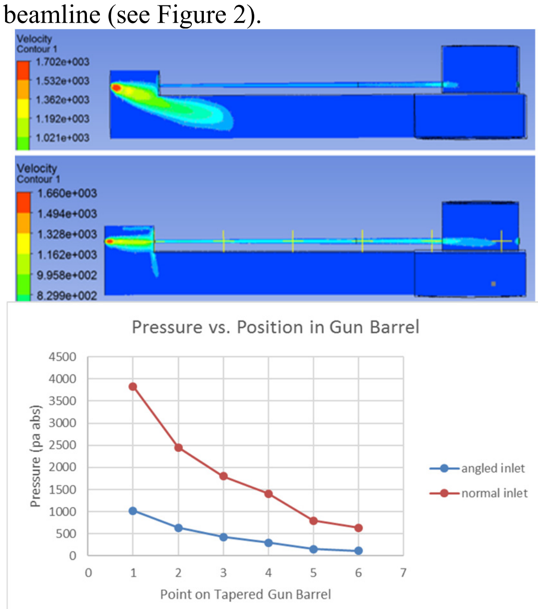

Figure 2: CFD simulations of directed flow using angled inlet aperture. (top) Angled vs straight aperture flow profiles in the simulated chambers 1,2, and aperture (bottom) a 4-fold pressure improvement is realized with angled aperture vs straight aperture by eliminating most of the jetting effect.

The flow to Chambers 1 and 2 is split by an aperture block. Chambers 1 and 2 are separated by the first conductance limiting aperture A12 (aka "gun barrel"). It is a conically shaped aperture with 4mm and 8mm diameter holes at each end. The conical shape reduces the conductance by ~50 % over a straight 8mm diameter aperture that passes the beam. The 6.4mrad angle of the aperture is chosen to be approximately twice that of the horizontal beam convergence (3mrad) and the vertical beam convergence (4mrad) (see Figure 3). This angle passes the expected 5x-RMS beam envelope. The aperture body is made of tungsten or W/Cu/Ni Hevimet and is conically shaped to produce a upstream neutron shadow to assist in shielding electronics located upstream. The neutron-producing cross section of the tungsten also limits neutron production from deuteron beam scraping.

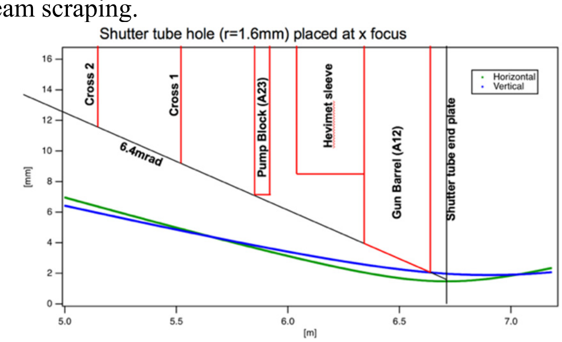

Figure 3: Aperture dimensions and angle overlaid on the 5-RMS horizontal and vertical beam envelopes in the DPL. The horizontal waist occurs at the shutter opening.

Chamber 2 is pumped by an AD 600H 5-stage cascaded roots pump designed to receive most of the remaining 1% of the gas coming up the beamline. It is also designed to back the DPL turbo pumps. Chamber 2 and 3 are separated by a roughly 4" by 18mm diameter hole aperture.

Chamber 3 is essentially a beampipe and a cross that houses 4 Leybold 350i 350 l/s turbomolecular pumps. These turbos are designed to be mounted in any orientation and can handle high backing pressure. The downside is that the electronics must be mounted locally and require more shielding. An optional chamber 4 is essentially the same as chamber 3.

The baseline design incorporates only three chambers: Chamber 1, 2, and 3, where chamber 3 has 4 turbos and chamber 4 is simply a lightly-instrumented vacuum cross. Optional inter-chamber apertures may be deployed for additional differential pumping. This option splits chambers 3 and 4 into three chambers: chamber 3 pumped by two turbos, chamber 4 pumped by 4 turbos, and chamber 5 pumped by two additional turbos. We don't expect this option to be necessary based on the performance anticipated below.

EXPECTED PERFORMANCE

The solution to the flow performance equations in the transitional flow regime [7,8] is essentially a transcendental set that must be solved iteratively because the pumping speed, conductance, and pressure are all interdependent. However, these are not hard to solve, and can be done so in a simple spreadsheet. Because the operation is pulsed, the static limiting cases for each chamber must be first calculated, then the time component is added, similar to the equations for charging and discharging a capacitor via an RC circuit. Pumping speed curves obtained from the manufacturers were used as inputs into the equations. It should be noted that pumping speed curves for helium with the Pfeiffer roots pumps have been measured and match or exceed those supplied by Pfeiffer. The nominal mass flow into the DPL is approximately 0.7g/s of deuterium gas. Note that we have sized the pumps to handle a 50% increase in gas flow (1.05 g/s).

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Based on the nominal mass flow, apertures, and pumps, the temporal performance for our baseline case is presented in Figure 4.

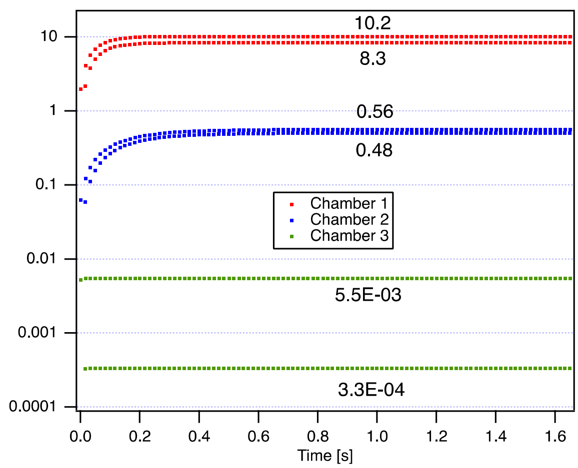

Figure 4: Expected temporal performance of the NI DPL. Red is chamber 1 (AD 3060H pump), blue is chamber 2 (AD600H pump), and green is chamber 3 (4 350-l/s turbos). The upper and lower dots of each trace represent the max/min pressures during shutter open/closed, respectively.

These calculations account for volume of the pipes/chambers, which is why the temporal behavior of the three chambers is different. The relevant time constant is equal to the volume of the chamber divided by the pumping speed of the pumps attached to the chamber. The high pumping speed of 4 turbos combined with the low volume of the vacuum cross in chamber 3 translates into a time constant for chamber 3 of order 5ms. Increasing the volume of chamber 3 allows us take advantage of this behavior, combined with the short shutter-open cycle, to reduce the maximum pressure achieved, a feature we intend to exploit by adding 6-12” spool pieces to the inlet of each turbo pump.

Given this temporal performance, and assuming 5atm of deuterium gas flowing into the NPT, the pressure profile along the beamline is expected to look like Figure 5:

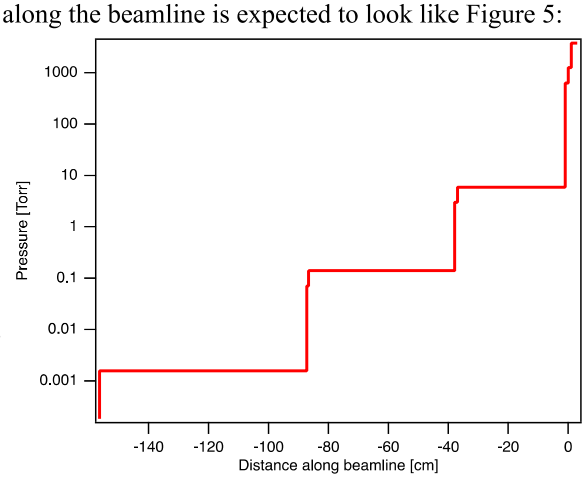

Figure 5: Expected pressure profile of the NI DPL up to and including the NPT at 5atm. Note the logarithmic pressure scale.

Where aperture pressure gradients are modeled as averages of inlet and outlet pressure, and no intra-chamber pressure gradients are modeled. Given this pressure profile, the additional gas length of the target is approximately 3%, well below our chosen 10% requirement, keeping the off-axis depth-of-field blurring to a minimum.

Angular straggling and Rutherford scattering of the d+ beam is expected to be at the level of 1mrad or less for this pressure profile. This small spread also keeps the beam spot small, further maintaining the performance of the imaging system.

CONCLUSION

A differential pumping line has been designed that preserves the imaging requirements of the neutron imaging system at LLNL. The system is partially complete; the two large pumps, one turbomolecular pump, and the aperture block are in hand and being tested. We plan to empirically verify and validate the expected performance in mid-2019, so that we can make any adjustments prior to putting beam on target. We are bench testing further improvements, such as replacing the primary tapered aperture with a series of shorter chambers connected by angled holes to further impede gas flow upstream, and reducing gaps in the rotary valve to limit gas leakage into the DPL while the shutter is closed.

REFERENCES

[1] R.C. Runkle *et al.,* “Photon and neutron interrogation techniques for chemical explosives in air cargo: a critical review”, Nucl. Instrum. Meth. A603, pp. 510-528 (2009), `https://doi.org/10.1016/j.nima.2009.02.015`

[2] B. Rusnak *et al.,* “Advancement of an accelerator-driven high-brightness source for fast neutron imaging”, in *Proc. 8th Int. Particle Accelerator Conf. (IPAC’17),* Copenhagen, Denmark, April-May 2017, `https://doi.org/10.18429/JACoW-IPAC2017-MOPIK112`

[3] B. Rusnak *et al*., “A high-intensity neutron production source based on rotary valving”, in *Proc. North American Particle Accelerator Conf. (NAPAC2013),* Pasadena, CA, USA, Sept.-Oct. 2013, `https://doi.org/10.18429/JACoW-NAPAC2013-THPMA14`

[4] B. Rusnak *et al.*, “Development of a high-brightness source for fast neutron imaging”, in *Proc. North American Particle Accelerator Conf. (NAPAC2016),* Chicago, IL, USA, Oct 9-14, 2016, `https://doi.org/10.18429/JACoW-NAPAC2016-THB3IO01`.

[5] D.A. Hutcheon *et al.*, “The DRAGON facility for nuclear astrophysics at TRIUMF-ISAC: design, construction, and operation”, Nucl. Instrum. Meth. A498, 190-210 (2003), `https://doi.org/10.1016/S0168-9002(02)01990-3`

[6] K.A. Chipps *et al.*, “The Jet Experiments in Nuclear Structure and Astrophysics (JENSA) gas jet target”, Nucl. Instrum. Meth. A763, pp. 553-564 (2014), `https://doi.org/10.1016/j.nima.2014.06.042`

[7] S. Dushman and J.M. Lafferty, “Scientific Foundations of Vacuum Technique, 2nd ed.”, *Wiley*, 1962.

[8] R.W. Carlson, in Methods of Experimental Physics, vol. 14, “Vacuum Physics and Technology”, L. Marton and C. Marton, eds. in chief, *Academic Press*, 1979.