HIGH AVERAGE POWER DEUTERON BEAM DYNAMICS *

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Abstract

Lawrence Livermore National Laboratory (LLNL) is developing an intense, high-brightness fast neutron source to create sub-millimeter-scale resolution neutron radiographs and images. A pulsed 7 MeV, 300 μA average-current commercial deuteron accelerator will produce an intense source (10^{11} n/s/sr at 0°) of fast neutrons (10 MeV) using a novel neutron target with a small (1.5 mm diameter) beam spot size to achieve high resolution. A highly flexible multi-accelerator beamline has been developed allowing for the use of both 4 MeV and 7 MeV RFQ/DTL deuteron accelerators. TRACE3D has been used to model the beam transport and design the quadrupole lattice and results will be presented including iterated design within beamline mechanical constraints, sensitivities, and multiple use of the magnets. Because of the high power density of such a tightly focused, modest-energy ion beam, intercepting beam diagnostics are extremely challenging, motivating novel concepts and extensions of current techniques to higher average power densities. Full duty factor beamline diagnostics will be discussed including charge, position, emittance via beam-induced fluorescence, and a full power beam dump and Faraday cup.

INTRODUCTION

Fast neutrons are highly effective for producing radiographic images with sub-millimeter-scale resolution in objects with areal densities greater than ~100 g/cm^2 [1]. LLNL is developing fast neutron imaging (NI) as an advanced, compact non-destructive evaluation (NDE) technique for dense objects [2]. Typical fast neutron sources are inconveniently large (nuclear reactor or linac-driven spallation); the LLNL NI system will be a much more compact lab-scale instrument. A significant effort is underway at LLNL to complete the construction and installation of the accelerators, beamline, target, and imaging systems needed to demonstrate a lab-scale intense fast neutron source suitable for advancing fast neutron imaging of dense, thick objects that are inaccessible to X-rays for non-destructive evaluation [3], and recent progress is reported elsewhere in these proceedings [4].

The deuteron accelerators that will be used to produce this compact fast neutron imaging platform are custom built by industry, and will couple to a flexible beamline so that research and development can be completed on the neutron target, controls, and imaging systems. Future research on making the system more robust, compact, and easy to operate are also being planned and accommodated as part of the initial machine design. The high average power of the moderate energy deuteron beam raises the impact of beam interception, and requires non-intercepting diagnostics and careful engineering of beam dumps to survive the kW average power deposition. The neutron imaging machine is shown in Figure 1, and the accelerator parameters are shown in Table 1.

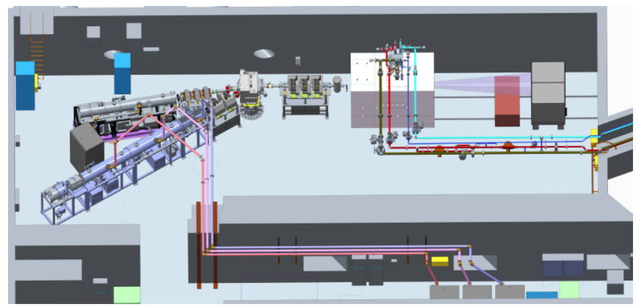

Figure 1: CAD rendering of machine showing the DL4 accelerator (top left), DL7 accelerator (bottom left), beamline, differential pump line, and gas target.

Table 1: Neutron Imaging Accelerator Parameters

D$^+$ energy	7	[MeV]
D$^+$ average current	300	[microamps]
Accelerator duty factor	2	[%]
Neutron intensity	10^{11}	[n/s/sr @ 0 deg]
Source spot diameter	1.5	[mm]
Source spot length	40	[mm]

The starting point for the beamline model is the predicted output beam from ACCSYS, which is responsible for the refurbishment of the DL4 accelerator and the fabrication of the new DL7 accelerator. The un-normalized 5x RMS emittance ϵ, α, β, and γ for the x, y, and z dimensions are given in Table 2 for both accelerators. A quadrupole triplet will be used to focus the beam through a bending dipole into a final focus triplet which will deliver the mm spot size for the neutron target. The long focal length is necessary for diagnostics and differential pumping between the target and accelerator vacuum systems. Detailed CAD designs have been iterated with beam dynamics modeling to arrive at the current configuration so that a small enough beam can be delivered and there is sufficient space for the associated hardware. In order to preserve the emittance, the first focus minimizes the x (horizontal) extent of the beam going into the bend dipole, allowing the beam to blow up in the y (vertical) direction constrained by the dipole vacuum chamber. The final focus strives to deliver a 1.5 mm round

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beam over 40 mm for the neutron target. The quadrupole and dipole magnets have been specified and delivered, and their effective lengths are used for modeling so that only the field strength or gradient is adjusted (with their physical location already constrained by iteration with the facility layout design).

Table 2: DL4 and DL7 Initial Emittance Parameters

Parameter	DL4	DL7	Units
ϵ_x	4.75	4.43	mm mrad
α_x	1.51	-1.68	
β_x	0.095	10.1	mm/mrad
γ_x	34.527	0.378	mrad/mm
ϵ_y	4.55	4.47	mm mrad
α_y	-1.12	-1.44	
β_y	0.068	1.49	mm/mrad
γ_y	33.153	2.063	mrad/mm
ϵ_z	600	630	deg keV
α_z	0.04	3.45	
β_z	0.626	1.03	deg/keV
γ_z	1.600	12.527	keV/deg

BEAM DYNAMICS

The PBOLAB interface for TRACE3D was used to calculate the beam envelope and tune the magnets for minimal spot size while limiting emittance growth [5]. The input parameters in Table 2 were matched to ACCSYS simulations rather than using actual output distributions. A small round final beam was sought using the built in matching algorithm for the final spot. The first set of quadrupoles was tuned for the DL4 accelerator and similar results were achievable using a doublet rather than triplet. In order to shorten the overall accelerator layout a doublet was optimized and will be used for the DL7 accelerator line. Code output is shown in Figure 2 for the final DL4 and DL7 matches, with parameters summarized in Table 3. Results are stable to 10% growth in β for variations of order 1% change in a single quadrupole strength from its design value, 0.5° variation in bend angle, or a change of up to 8 cm in a given beamline component. The sensitivity to known fabrication errors is smaller, allowing for looser tolerances on bend angle or length if the beam physics can be remodeled and retuned to compensate, i.e., 1.0° variance in bend angle or 15 cm length change. The current regulation on the magnet power supplies will directly affect the achievable focus as well as the long term stability of neutron production based on maintaining the design tune over time. The supplies have a listed 0.15% specification for current stability, which will make for a reasonably robust final focus.

DIAGNOSTICS

Charge in the accelerators will be measured using in flange AC current transformers on the individual DL4 and DL7 lines, and on the final focus line just before the neutron target. Position will be measured using log-ratio beam position monitors on capacitive pickups positioned after the bend dipole and after the final focus triplet. Measuring the deuteron beam emittance out of the accelerators and delivered on target at full duty factor is the goal for a non destructive tomographic imaging diagnostic based on residual gas fluorescence, similar to [6]. For the gas-based neutron targets, residual gas pressures may be sufficient to produce visible fluorescence signals, and would be background signal for any intentional gas release. Calculations using SRIM [7] and direct fluorescence yield measurements will enable a

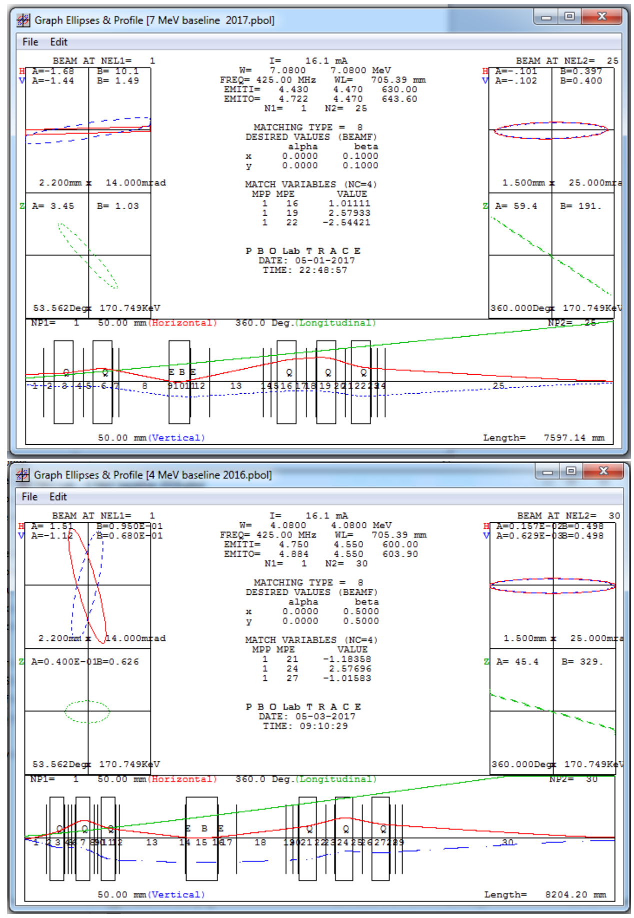

Figure 2: TRACE3D output for final focus beamline layout for DL7 and DL4.

Table 3: DL4 and DL7 Final Focus Parameters

Parameter	DL4	DL7	Units
ϵ_x	4.884	4.72	mm mrad
α_x	0.00157	-0.156	
β_x	0.498	0.396	mm/mrad
ϵ_y	4.55	4.47	mm mrad
α_y	0.000629	-0.0524	
β_y	0.498	0.403	mm/mrad
ϵ_z	604	644	deg keV
α_z	45.38	59.39	
β_z	329.3	191.4	deg/keV

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full calibration of the system. A custom chamber will house this diagnostic and a combination beam dump and Faraday cup capable of handling the full beam power, as shown in Figure 3. The beam dump features a reverse ogive profiled beam stop to intercept as much of the focused deuteron beam at as grazing an incidence as possible. The full power beam dump will be fabricated out of a high Z material and water cooled, and will be mounted on a stage so that it can be retracted vertically out of the beam path.

Computational thermal analysis of the full power beam dump was performed using ANSYS to determine the best design to safely cool and minimize melting of material intercepting the focused deuteron beam. The Faraday cup intercepting the beam is electrically isolated by ceramic rings and a vacuum gap between the cup and water cooling jacket. In the analysis TZM alloy (Ti-0.5%, Zr-0.08%, Mo-balance) was used as the cup material due to its high melting temperature, thermal conductivity, electrical conductivity, and models showing TZM's superior resistance to damage under a heat load compared to other beam target materials [8]. The cup is designed with high volume and surface area to absorb heat from the beam intercepting walls and radiatively transfer it to the water cooling jacket. A groove in the cup restricts unwanted heat conduction to the front of the beam stop. Both steady-state and transient thermal analyses were performed, and a typical steady-state temperature profile is shown in the bottom of Figure 3. Typical simulations parameters used an on-axis 120 kW beam with a Gaussian power density profile, beam radius of 2.5–10.0 mm, repetition rate of 140 Hz, and 2% duty cycle. The power density of the deuterium beam on the intercepting walls is approximated as a surface heat flux distribution with radial symmetry.

CONCLUSION

The beam physics design is complete and both robust and flexible. Using Twiss parameters from the ACCSYS design for the DL7, TRACE3D was used to design a transport lattice for both a 6 quadrupole 10 degree bend angle 4 MeV deuteron accelerator and a 5 quadrupole 33 degree bend angle 7 MeV deuteron accelerator. Both systems deliver small focus beams at the position of the gas cell target, are flexible to several cm level variations in the position of components, mm alignment tolerances, 0.15% current stability, and can be used to diagnose the emittance of the beams with adequate range via quadrupole scan techniques. Beam physics has been used to confirm and inform the beamline design so that the CAD model is consistent with the expected performance of the deuteron beam. Major components including the refurbished DL4 accelerator and all magnets have been delivered and are being installed, with the current status of the project summarized in [4].

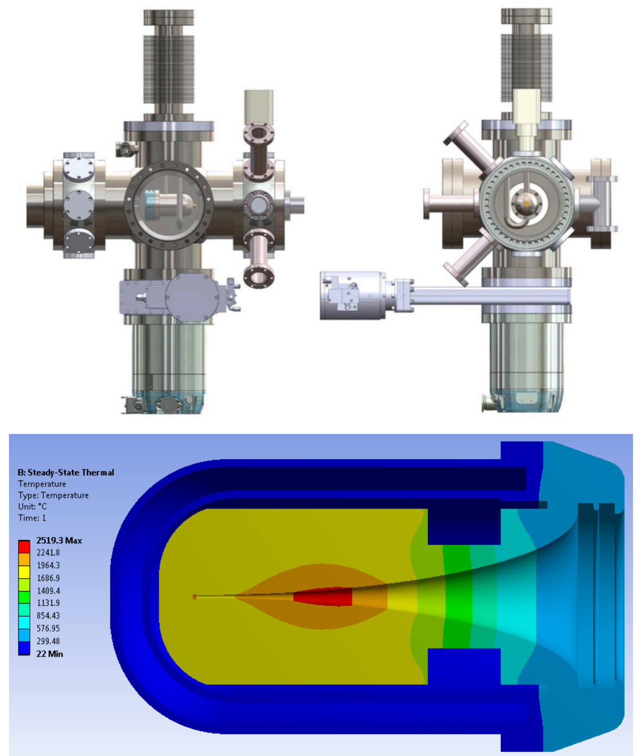

Figure 3: CAD rendering of side view and beam view of full power beam dump and beam fluorescence imaging diagnostic chamber, and detail of modeled thermal profile from full power beam dumped at final focus.

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