CONCEPTUAL DESIGN OF A NOVEL DEUTERON ACCELERATOR DRIVEN NEUTRON SOURCE FOR NUCLEAR WASTE TRANSMUTATION

Y. Jiang[†] and J.L. Hirshfield, Omega-P R&D, Inc., New Haven, USA
M. Gai, University of Connecticut, Groton, CT, USA

Abstract

A novel deuteron cyclotron auto-resonance accelerator (dCARA) is under development to produce neutrons via breakup of high current 40-MeV deuterons on a low-Z target. Compared to the proton-based Accelerator-Driven Subcritical systems (ADS), a dCARA system can be much more compact and cost effective, with notable features including continuous acceleration without bunching for good beam stability, high efficiency, wide beam aperture, and an exceptionally short length of few meters. The applications of dCARA include transmutation of used nuclear fuel, medical isotope production system, or material test for a future fusion power reactor. The R&D progress and the conceptual design of dCARA are reported here.

INTRODUCTION

Accelerator-Driven Subcritical systems (ADS) technologies have been widely studied as a means to reduce the lifetime and toxicity of nuclear waste through neutron-induced transmutation [1, 2]. In conventional ADS designs, high-energy (GeV scale) proton beams generate neutrons via spallation reactions in targets of high-Z materials. While technically feasible, such systems require a rf quadrupole structure (RFQ) and long superconducting radio-frequency (SRF) linacs, leading to high capital costs, complex operation, and stringent reliability requirements. Another approach is to use a conventional proton cyclotron, but increasing beam current and beam power is quite challenging.

This work explores an alternative ADS architecture [3-5] based on accelerating moderate-energy deuteron beams (~ 40 MeV) to produce neutrons through deuteron breakup reactions [6]. In this approach, a novel compact deuteron cyclotron auto-resonance accelerator (dCARA) supports high-current operation with simplified structure and potentially lower cost, enabling the possibility of using multiple small-scale neutron sources collectively to achieve transmutation performance comparable to a single large facility while improving reliability and scalability.

DESCRIPTION OF dCARA

The dCARA concept builds upon the mechanism of cyclotron auto-resonance acceleration (CARA) [7], in which charged particles maintain phase synchronism with transverse electromagnetic fields while gyrating in a uniform static magnetic field. Unlike conventional accelerators where bunched particles gain energy in discrete gaps or cavities during a narrow rf phase, dCARA allows continuous energy gain without bunching throughout the acceleration. The absence of bunching mitigates space charge instability and allows accelerating beams of high currents.

A key innovation in dCARA is the use of a transverse electromagnetic mode (TEM) cavity which has a much smaller transverse dimension to allow accelerator cavities at tens of MHz frequency range fit inside a strong superconducting magnet similar to a whole-body MRI magnet. This configuration opens up a new parameter space suitable for ion acceleration, bringing a paradigm shift in the application of CARA from limited electron acceleration [7] into ion acceleration [3-5].

Fig. 1 shows the schematics of a compact dCARA-driven neutron source. A low-energy deuteron beam at tens of keV is transported from an ion source by a low energy beam transport (LEBT) to a dCARA cavity. A high current deuteron ion source and LEBT similar to the IFMIF-DONES deuteron source with the maximum deuteron current > 100 mA [8] is suitable for the dCARA system. The cavity is submerged within a strong axial magnetic field (~5–10 T) generated by a superconducting solenoid which is similar to a full-body high-field MRI superconducting magnet [9]. The cavity is driven by external rf sources at different rf phases through multiple ports, to support a rotating dipole mode at tens of MHz frequency range [3-5]. The large cavity aperture enhances tolerance to misalignment and beam losses, contributing to improved operational reliability. With continuous acceleration through phase synchronization governed by the CARA mechanism, the deuteron beam is accelerated to tens of MeV energy, transported by a high energy beam transport (HEBT) and injected into a neutron production target, where a high flux of neutrons is generated via deuteron breakup.

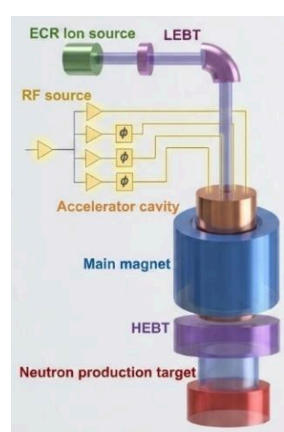

Figure 1: Schematics of a compact dCARA-driven neutron source.

† email: yong.jinag@aya.yale.edu

As shown in Fig. 2, inside a dCARA cavity, deuterons follow helical trajectories. Because particles can be injected at arbitrary rf phases (with different rf field polarization), the output beam produces a circular sweeping pattern on the target surface, effectively achieving beam rastering without external scanning magnets. The rapid sweeping at the rf timescale reduces peak power density and enhances target lifetime. The rf-to-beam efficiency is estimated to exceed 70%, with manageable wall losses for a normal-conducting structure [5].

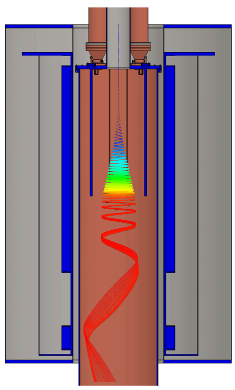

Figure 2: Deuteron beam trajectory injected at one given rf phase, with a dCARA cavity submerged inside a superconducting magnet which includes both the main and HEBT solenoids.

A typical configuration of a 40-MeV dCARA includes:

- Beam current: 25–125 mA (pulsed, up to CW)
- Beam power: 1–5 MW (peak)
- Acceleration length: ~1–2 m
- Cavity diameter: ~0.7 m
- RF frequency: ~36–75 MHz
- Static Magnetic field: ~5–10 T

When a 40 MeV deuteron beam strikes a low-Z target (e.g., lithium, beryllium, or carbon), neutrons are produced through breakup reactions mainly. The resulting neutron spectrum peaks near ~40% of the incident deuteron energy, with a conversion efficiency on the order of 10% [6]. So, a beam current of ~100 mA can yield neutron fluxes approaching 10^{16}–10^{17} neutrons per second. Although the neutron yield per incident particle is lower than in GeV-scale proton spallation, this is compensated by significantly higher beam currents and simpler accelerator infrastructure.

CONCEPTUAL LAYOUT OF dCARA SYSTEM

A conceptual layout of one unit of dCARA-driven neutron source is shown in Fig. 3. Instead of relying on a single large proton accelerator, the proposed approach employs multiple dCARA-based neutron production modules. A cluster of tens of units could collectively match the transmutation capability of a proton linac while still remaining cost competitive. The advantages of modularity are

- **Reliability:** Failure of one module has limited full-system impact
- **Scalability:** Capacity can be expanded incrementally
- **Cost:** Lower upfront investment per unit
- **Deployment:** Smaller footprint enables siting near existing facilities

This distributed scalable deployment aligns with standard industrialization strategies, where redundancy and modularity improve overall system resilience.

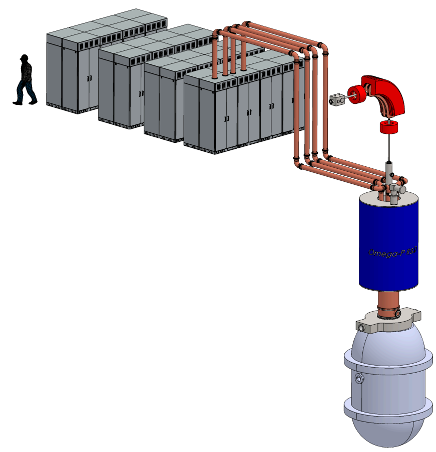

Figure 3: Conceptual layout of a dCARA-driven neutron source, from left to right and top to bottom, including rf source, waveguide, ion source, LEBT, dCARA cavity, superconducting magnet, neutron production target and reactor. Thermal management, vacuum system, power supply, radiation shielding and mechanical supports are not shown.

R&D ROADMAP OF dCARA

The R&D roadmap of our dCARA program is shown in Fig. 4. Currently, the dCARA-driven neutron source is under conceptual and engineering design, preparing for the Proof of Concept (PoC) stage. During the PoC test, experimental demonstration of accelerated beam with beam current ≥ 25 mA at a low duty cycle of 0.01% (low heat load) will be carried out to validate the acceleration mechanism and beam dynamics by measuring beam quality and rf-to-beam efficiency. Because of the compactness of a dCARA accelerator, the test facility to carry out the PoC test only requires a small footprint, as shown in Fig. 5. It is envisioned that such an accelerator can be even fit inside the shaft of an industrial elevator, with rf sources located on the nearby floor.

Further during the High Duty Pilot (HDP) stage, the duty cycle and rf power will scale up gradually towards 1 MW long pulse to continuous-wave (CW) operation. It will introduce additional challenges, including heavy-load thermal management and radiation shielding. Collaboration with industrial partners is expected to play a critical role in this phase and beyond. And the industrialized version of the dCARA-driven neutron source is aiming towards 125 mA 5 MW CW operation.

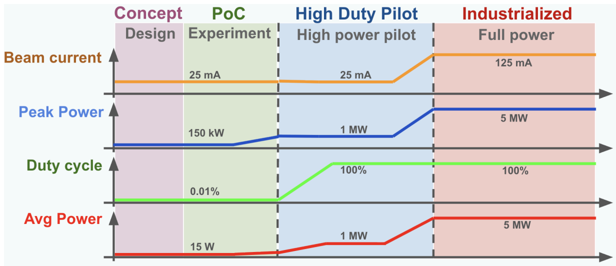

Figure 4: R&D roadmap of dCARA, from conceptual design, proof-of-concept, high-duty pilot to industrialized application, based on stages of incremental beam current, duty cycle and beam power.

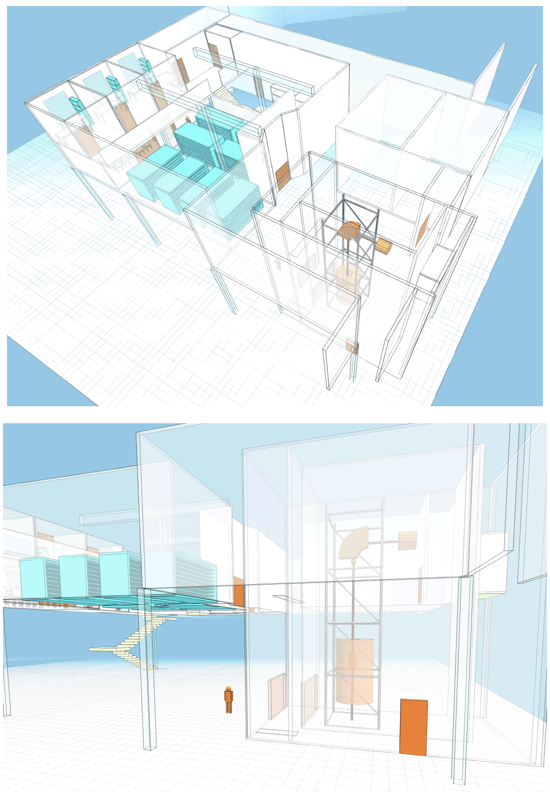

Figure 5: Top and side views of a test facility for the dCARA Proof-of-Concept experiment.

Besides applications in nuclear waste transmutation, dCARA-based neutron sources have other potential applications including medical isotope production, fusion materials testing (e.g., neutron irradiation of structural components), tritium breeding, scientific research and national security. Some of these applications can be enabled even in early stages along this R&D roadmap.

CONCLUSION

The dCARA concept represents a promising alternative to conventional accelerator technologies for nuclear waste transmutation. Its compact size, high efficiency, and continuous-beam operation distinguish it from existing approaches. By enabling a modular architecture of distributed neutron sources, dCARA may reduce both the economic and technical barriers associated with a single large-scale transmutation system. Further R&D are required to validate the concept experimentally and address engineering challenges associated with high-power operation. If successful, this approach could significantly advance the feasibility of nuclear waste transmutation, support the long-term sustainability of nuclear energy, and improve public acceptance of nuclear energy as a crucial component for energy security.

ACKNOWLEDGMENT

The first two authors acknowledge support for this work from Particle Accelerator Research Foundation.

REFERENCES

[1] H. Abderrahim et al., “Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production,” Office of Scientific and Technical Information (OSTI), Sep. 2010. doi: 10.2172/1847382

[2] Y. Gohar, Y. Cao, and A. R. Kraus, “ADS design concept for disposing of the U.S. spent nuclear fuel inventory,” *Ann. Nucl. Energy*, vol. 160, p. 108385, Sep. 2021. doi: 10.1016/j.anucene.2021.108385

[3] Y. Jiang, X. Chang, J. Hirshfield, and M. Palmer, “High-current deuteron accelerator for neutron production”, in *Proc. IPAC'24*, Nashville, TN, USA, May 2024, pp. 1071-1073. doi:10.18429/JACoW-IPAC2024-TUPC32

[4] Y. Jiang, M. Gai, J. Hirshfield, M. Palmer, and S. Shchelkunov, “Novel deuteron accelerator for nuclear waste transmutation”, in *Proc. IPAC'25*, Taipei, Taiwan, Jun. 2025, pp. 1564-1566. doi:10.18429/JACoW-IPAC2025-TUPS059

[5] Y. Jiang, X. Chang, J. Hirshfield, M. Gai, S. Shchelkunov, and M. Palmer, “Design study of novel deuteron cyclotron auto-resonance accelerator”, in *Proc. NAPAC'25*, Sacramento, California, USA, Aug. 2025, pp. 741-744. doi:10.18429/JACoW-NAPAC2025-WEP024

[6] J. T. Morrell, A. S. Voyles, J. C. Batchelder, J. A. Brown, and L. A. Bernstein, “Secondary neutron production from thick target deuteron breakup,” *Phys. Rev. C*, vol. 108, no. 2, Aug. 2023. doi: 10.1103/physrevc.108.024616

[7] V. P. Milant’ev, “Cyclotron autoresonance — 50 years since discovery,” V P Milant'ev, *Phys. Usp.*, vol. 183, no. 8, pp. 875–884, 2013. doi: 10.3367/ufne.0183.201308f.0875

[8] I. Podadera, et al, “Overview and current status of the IFMIF-DONES accelerator systems”, Nucl. Fusion 65 122011, 2025. doi: 10.1088/1741-4326/ade267

[9] M.E. Ladd, H.H. Quick, O. Speck, et al. “Germany’s journey toward 14 Tesla human magnetic resonance”, *Magn. Reson. Mater. Phy.*, 36, 191–210, 2023. doi: 10.1007/s10334-023-01085-z

[10] B. Yee-Rendón, “Overview of ADS Projects in the World”, in Proc. LINAC'22, Liverpool, UK, Aug.-Sep. 2022, pp. 310-313.. doi:10.18429/JACoW-LINAC2022-TU2AA01