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DESIGN STUDY OF NOVEL DEUTERON CYCLOTRON AUTO-RESONANCE ACCELERATOR

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Abstract

A novel deuteron cyclotron auto-resonance accelerator (dCARA) is described here. It is predicted to produce a 40-MeV, 125 mA CW deuteron beam, with notable features including continuous acceleration without bunching for good beam stability, high efficiency, wide beam aperture, and an exceptionally short length of 1.6 meters. Such an accelerated beam can be used to produce the intense neutron flux via breakup of deuterons on a low-Z target. It is estimated that 5-10 small dCARA-based modules could provide the same level of transmutation as one acceleration driven system (ADS) employing a GeV-level 25-MW linac. Other applications of dCARA include medical isotope production system, or fusion prototypic neutron source for testing inner-wall materials for a future fusion power reactor.

INTRODUCTION

The scientific concept that underlies a deuteron Cyclotron Auto-Resonance Accelerator (dCARA) has its origins in the phenomenon of Cyclotron Auto-Resonance Accelerator (CARA), which was introduced decades ago [1]: there exists a regime of motion of a charged particle in a static uniform magnetic field, in which the particle interacts and preserves an initial condition of cyclotron resonance with a transverse electromagnetic wave, even when the Lorentz factor increases. The CARA mechanism has been demonstrated in the 1990's via its electron accelerator manifestation [2].

The dCARA can continuously accelerate deuterons at arbitrary injection phases, and the final beam energy is independent of the injection phase. Yet the direction of the exit beam depends on the injection phase, as the charged beam goes along a gyrating trajectory along a longitudinal magnetic field, where the initial transverse kick depends on the polarization angle of the transverse electromagnetic field. With continuous injection of a beam during a full RF cycle, the output beam follows a circular path. The sweeping beam intersection on a planar target perpendicular to the cavity axis constitutes self-scanning. Here the "self" is to emphasize the differences to the scanning method used in the conventional industrial linacs where alternative current electromagnets deflect the charged particles off-axis to create a zigzag path on a beam window. CARA self-scanning completes a full scanning path at a time scale of tens of nano-seconds (as RF period) instead of a few milliseconds, without using additional alternative current electromagnets.

Hence, the CARA differs fundamentally from conventional accelerators, such as linear accelerators (linacs), conventional cyclotrons, or multiple-pass machines (microtrons, Rhodotrons), all of which involve bunched beams. Particularly, the readers shall not confuse CARA with conventional cyclotrons. In cyclotrons, charged particles are accelerated outwards from the center of a flat cylindrical vacuum chamber along a spiral path in a plane; while in CARA, the particles are propagating with a significant longitudinal velocity along a conical spiral path.

The novel breakthrough of dCARA is to utilize a single compact TEM mode cavity as its accelerating structure [3], because the TEM cavity diameter can be significantly smaller than for other resonant modes otherwise it would be impractical due to the excessively large diameter waveguides and magnet bore radii required for ion acceleration.

BEAM DYNAMIC STUDY OF dCARA

The conceptual beam dynamics design was carried out using CST Studio Particle Tracking solver and preliminarily tested using Particle-In-Cell (PIC) simulation. The deuterons move on helical orbits around a strong magnetic field, acquiring energy continuously and without bunching during many revolutions within the cavity, in synchronism with the rotating radio-frequency fields. The main magnet for dCARA is a superconducting solenoid with a bore diameter < 1m and magnetic field strength < 7 T. The dimension of the main magnet is considered conventional since it is similar to those for commercial magnets now used in nuclear magnetic resonance (NMR) medical diagnostic systems.

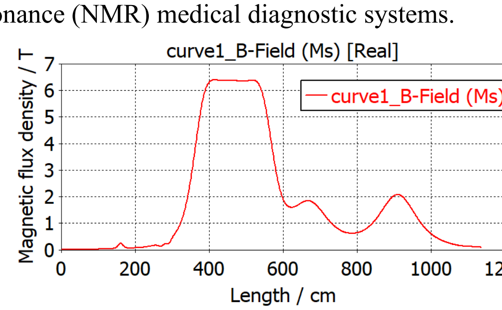

Figure 1: Magnetic field along the z-axis of the dCARA.

The beam transport system is composed of a low energy beam transport (LEBT) and a high energy beam transport (HEBT) section to guide the deuteron beam (CW or

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pulsed) from ion source and to the breakup target. A two-solenoid magnetic lens LEBT system is designed to transport and focus a 40 keV D+ beam from the ion source and match the beam into the dCARA. The total length of the LEBT is about 1.3 m. The HEBT magnets allow the diameter of the area swept by the deuteron beam to be adjusted to match the area of the breakup target as well as the incident angle to the target, which in turn can match the area for parts arrayed for UNF transmutation. For the preliminary design, the magnetic field profile used in the simulation shown in Fig. 1. The flat-top region of the magnetic field profile is where the acceleration occurs.

The simulated accelerated particle traces in Fig. 2 portray dCARA performance. Design parameters for this example are given in Table 1. The Twiss parameters of the 30 mA 40 keV deuteron input beam are α=-12.986, β=7.012 meter. Further design studies are underway to scan the acceptable range of the input beam emittance and improve the beam matching. It is worth emphasizing that as the CST Particle Tracking simulations only depict the history of individual particle trajectories, there are actually no tightly adjacent simultaneous orbits as seemingly implied in Figs. 2a and 2b. The PIC simulation result reflects the instantaneous spatial distribution of the continuous beam as shown in Fig. 2c, where prolonged gyrating orbits make dCARA much more resilient to the beam halo effect and inter-orbit instability.

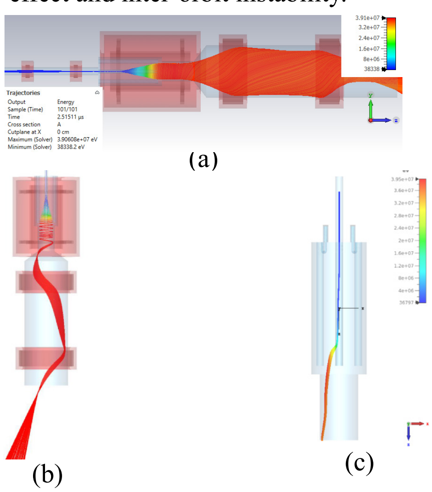

Figure 2: (a) Superposition of deuteron orbits in dCARA with deuteron injected at all RF phases, indicating beam envelope; (b) deuteron orbit injected at one given RF phase using CST Tracking solver; and (c) instantaneous spatial distribution of deuteron beam in dCARA using CST PIC solver. The main magnet, LEBT and HEBT magnets are shown as red shells.

APPLICATION STUDY OF dCARA

A dCARA-based high-intensity neutron source may offer a disruptive approach for transmuting long-lived, highly toxic isotopes in used nuclear fuel (UNF). Currently nearly all of the UNF is stored on the sites of operating nuclear plants [4]. If unattended, species with lifetimes of more than thousands of years in UNF would pose a constant threat to health and security and pollute our planet far beyond the time when any present plan for storage and safe management can realistically be expected to apply. Moreover, the present lack of any means to confront this issue for existing UNF is one factor that can inhibit the construction of any new power plants based on nuclear fission, as this would compound the problem by increasing UNF.

Table 1: Parameters for Simulation Shown in Fig. 1

Cavity Diameter	0.72 m
Cavity Length	1.58 m
Cavity Resonance Frequency	48.68 MHz
Cavity Quality Factor *Q*	8,069
Max RF *E*-field on Cavity Axis	2.36 MV/m
Stored Energy in Cavity	49.66 J
Magnetic Field Across Cavity	6.4 T
Deuteron Injection Energy	40 keV
Deuteron Current	25 - 125 mA
Deuteron Final Energy	40 MeV
Final Deuteron Beam Power	1.0 - 5.0 MW
Cavity Ohmic Wall Loss	1.88 MW
RF-to-Beam Efficiency	72.6%
Peak Local Value of Surface Loss	581.5 W/cm^2

Accelerator Driven Systems (ADS) have been proposed [4] for addressing nuclear missions related to nuclear waste transmutation and energy production, which use high-power particle accelerators with spallation targets coupled to the reactor core to produce intensive neutron flux and drive subcritical nuclear reactors. ADS can process the UNF and reduce their long-lived toxicity, potentially recycle some into reusable fuel, and offer new avenues for energy production through efficient utilization of UNF. Key advantages of ADS over traditional critical reactors include greater flexibility in fuel composition and enhanced safety.

But there are still significant challenges in ADS technical implementation, economic viability, scalability, and regulatory issues. It requires a specialized accelerator system capable of generating high-power high-intensity particle beams. For existing accelerator technologies — including cyclotrons, normal conducting linacs, and superconducting radiofrequency linac (SRF) systems — each provides distinct advantages but also faces unique challenges. For example, SRF linacs have demonstrated exceptional performance, as seen at facilities like SNS, FRIB, and MYRRHA [4]. A typical ADS specification would be for a 1-2 GeV proton beam, comprising multi-MW-level power load on a spallation target. Yet the high upfront costs of hundreds of millions of dollars must be justified by significant reductions in actinide waste or

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energy production. The industrial ADS application has much more stringent trip rate requirements than any high-power proton accelerator built for science discovery. Further, a beam-delivery system needs to transport the beam to the spallation target, and shape the beam to the required size, profile, and uniformity, which is crucial for minimizing peak deposited power density and maximizing the target's lifetime. Conventional techniques are high-frequency beam rastering and magnification by beamline magnets. Addressing these challenges involves advancing research in accelerator and target technologies, improving component reliability, integrating complex systems effectively, and ensuring maintenance strategies that support continuous and efficient operations.

As an alternative to an RFQ/Linac or cyclotron deuteron accelerator for the ADS application, dCARA introduced here as a compact room-temperature single-cavity accelerator is predicted to produce a multi-MW 40 MeV deuteron beam, with high wall-plug efficiency, and generate high intensity neutrons via breakup of 40-MeV deuterons on a low-Z target. After impinging on the target of materials such as lithium, carbon or beryllium, neutrons of the accelerated deuterium nuclei are stripped off and continue forward with a peak energy at about 40% of incident deuteron energy. The energy and intensity of the outgoing neutron distribution are roughly proportional to the energy and intensity of the incident deuteron beam. If one assumes a stripping efficiency of 10% [5], 80 mA of deuterons would correspond to a neutron production rate of 5×10^{16} sec-1. The relevant neutronics analysis of low/medium energy deuteron beams on target systems [6] and the numerical study of nuclear transmutation possibility by 14 MeV neutrons [7] are reported. These parameters appear to be favorably competitive with those of either a linac or cyclotron for the same application. High current deuteron ion source up to 125 mA [8] and high-power liquid lithium target [9] for IFMIF project have been reported, which are applicable to the dCARA settings. Reliability is expected to be higher in the approach described here, in that the use of several smaller neutron sources with a total capacity equal to one or more huge units, as in the mainline approaches, avoids the serious consequences that a large unit's shutdown would engender. Further, the use of a normal conducting accelerator cavity, as in dCARA, with its large beam aperture, should avoid trips due to beam interception and concurrent quenches that are possible with superconducting materials that are used in high energy SRF linacs.

The case made here is that dCARA shows promise to be a novel ADS choice for nuclear waste transmutation application. Further, other potential applications of dCARA include, tritium breeding, production of radioisotopic species that are in demand for medical diagnostics and therapy, and in National Security.

CONCLUSION

Prominent innovative features of dCARA are (a) its remarkably compact size of a single novel resonant cavity; (b) deuterons acquire energy continuously and without bunching within a single cavity, rather than through individual short boosts at narrow gaps as in cyclotrons or at multiple cavities in linear accelerators; (c) self-rastering on the breakup target can minimize peak deposited power density. A dCARA-based high-intensity neutron source may offer a disruptive approach for transmuting long-lived, highly toxic isotopes in used nuclear fuel. Introduction of smaller, more reliable, less costly dCARA modular units allows for the customary pathway to industrialization for the UNF transmutation.

ACKNOWLEDGEMENTS

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