Novel Ion Accelerator for Nuclear Physics Research

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INTRODUCTION

Forefront research in physics demands forefront technology and instrumentation, and drives the innovation in the design and engineering of accelerators. The concept and design of a novel high intensity ion Cyclotron Auto-Resonance Accelerator (iCARA), and the feasibility and scientific opportunity of next generation nuclear physics facility supported by iCARA are discussed here.

By operating in continuous-wave (CW) mode and full phase acceptance of injecting charged particles at 100% duty factor, this compact ion accelerator iCARA can mitigate space-charge effect which can otherwise limit the ion intensity. The artistic illustration of an iCARA system is shown in Fig. 1. The operating parameters of the iCARA will be centered on the region with ion beam current 5~120 mA DC, particle energy 1~10 MeV, and beam power < 250 kW, covering a relatively vacant parameter space as compared to the global efforts in developing high intensity proton/deuteron accelerators [1].

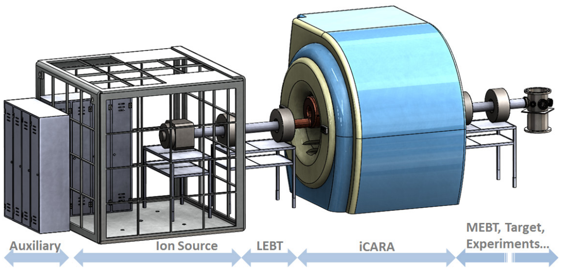


Fig. 1. Simplified cartoon of iCARA layout.

One of the applications of the iCARA is to support future precision experiments in nuclear physics including nuclear astrophysics and neutron physics, as shown in Fig. 2. The potential also exists to impact experimental research at neutrino physics and fusion energy, as well as applications in medical isotope production.

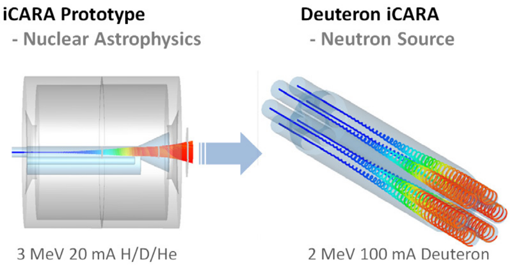


Fig. 2. R&D direction and applications of iCARA.

The breakthrough nature of our new accelerator design concept can bring compact high intensity ion accelerators into reality to support small-to-mid-scale projects and initiatives that enable forefront research at universities and laboratories.

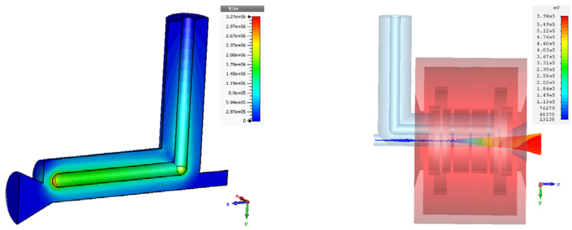
NOVEL ION ACCELERATOR ICARA

The iCARA concept described here is based on extensions of the scientifically-proven Cyclotron Auto-Resonance Accelerator, which we dub as CARA [2-6]. CARA is distinguished by its continuous particle acceleration without bunching prior to the injection, by its exceptionally-high RF-to-beam efficiency (measured at >97% for electron CARA [2]), and by its production of a self-scanning beam. Considerable theoretical analysis and experimental confirmation of the CARA mechanism, for electron acceleration acceleration, was reported in the past [2-6]. In CARA, the power from an RF source is coupled into a waveguide or resonant cavity and a charged particle source injects a continuous (un-bunched) DC beam with the structure permeated in a profiled DC axial magnetic field. At resonance [4], continuous acceleration of the gyrating beam occurs. The accelerated beam then spreads adiabatically in the diverging magnetic field and self-scans on a circle as it exits the magnet. As examples, for 10 keV deuteron injection, the theoretical limit of the energy gain is 3 MeV; and for 54 keV deuteron injection, the limit is increased to 10 MeV. By adjusting the injection voltage of ion beam, the energy of the output beam can be adjusted to meet the requirement of experimental demands. The acceleration mechanism is rather robust, as shown in Ref. [4], up to 5% amplitude perturbation in magnetic field space distribution was introduced yet the output energy was only reduced by a small factor of 0.06% in the simulation, compared to the exact resonant field.

But the CARA extension into ion acceleration has not been realized, hampered by the enormous requirement of microwave power and magnet system in the previous configuration. In iCARA concept, this acceleration mechanism can be implemented with a much practical parameter range to allow the accelerator fit within a high field magnet similar to medical full-body MRI magnets. Such choice of parameters is enabled by introducing Transverse Electromagnetic Mode (TEM) coaxial cavity as the accelerating structure.

In an ideal TEM mode coaxial cavity with cylindrical conductor along its center, the cavity frequency is only determined by the length of the cavity, not by its transverse radius as in TE/TM mode cavities. Hence the transverse dimension can be significantly reduced compared to TE/TM cavity, which allows it to be fit inside the bore of the conventional MRI-type magnet. Similar strategy to reduce dimensions has been applied in superconducting quarter wave resonator (QWR) or half wave resonator (HWR) in low beta ion linear accelerator [7]. Yet significant differences between this particular TEM mode cavity and QWR/HWR cavities are (1) transverse electromagnetic field is utilized for ion acceleration hence the beam is propagating along the direction of inserted conductor, not perpendicular to it as in QWR/HWR; (2) the CARA acceleration does not require charge particle to be well bunched so no radio frequency quadrupole (RFQ) is necessary and DC ion beam with very low injection energy can be accelerated directly. The RFQ-based accelerator technology has been demonstrated at LEDA [8] and LIPAc [9]. But the RFQ is a sophisticated combined-function component that accelerates, bunches and focuses ion beam, which imposes severe challenges on the mechanical and RF design. The cost of high intensity RFQ-based accelerators such as LEDA and LIPAc is daunting. The iCARA concept described here is an alternative cost-effective approach to accelerate high intensity ion beams.

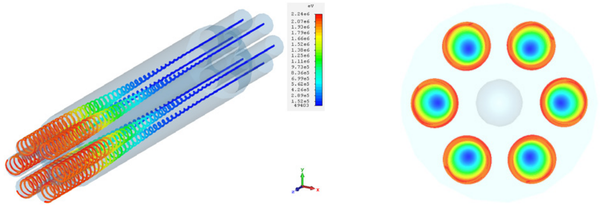
The preliminary design of the iCARA demonstration prototype is shown in Fig. 4, with CST Studio simulation [10]. It is composed of a 6 mA 15kV proton source, a 1.5Tesla MRI scanner as the magnet, and 10 kW 26 MHz solid state RF amplifier as the rf source. The output beam energy is 0.6 MeV and total beam power is 4 kW with 5 kW wall-loss in the room-temperature copper cavity. The TEM cavity diameter is 1.2 meter, compared to 6.7 meters of a TE_{11} mode cavity at the same frequency. To reduce the effective cavity length and the required magnet length, a bent L-shaped QWR coaxial cavity is used as shown in Fig. 4a. Beaming match is not applied here so the beam scalloping could induce significant beam energy spread. Suitable beam optics will be developed. Other ion species, such as ^{4}He, can be accelerated in this system as well. In this prototype, the energy of output beam falls within the interested energy region for nuclear astrophysics research.



(a) (b)

Fig. 4. (a) RF Electric field distribution in bent coaxial cavity; and (b) beam trajectory of accelerated proton.

Another example is shown in Fig. 5 to demonstrate the multi-beam acceleration possibility within a single accelerator structure with 50 keV 20 mA/beamlet CW deuteron injection. The ion beam will be injected off axis, such that a multi-beam injection can be arranged with all beam-lets located along a circle, with up to 120 mA deuteron beam as shown. Wall loss is 18 kW in the copper cavity and each beamlet absorbs 44 kW RF power to be accelerated to the final output deuteron energy about 2.2 MeV. The TEM cavity which operates at 30 MHz with diameter 0.7 m, length 2.5 m as a QWR is used in this preliminary model. In this simulation, an ideal 4T uniform magnetic field is used without field strength ramping, and space charge effect is included. The deuteron beams clear the apertures without interception. Higher output energy or beam power is achievable with higher injection energy and/or higher available RF power. For example, with about 250 kW RF power and five-beamlet injection, total current of 100 mA, 2 MeV deuteron can be delivered for neutron source application.



(a) (b)

Fig. 5. (a) and (b) trajectories of accelerated deuteron beams (six beams with 20 mA each shown) in deuteron iCARA accelerator based on TEM coaxial cavity.

TECHNOLOGY READINESS OF ICARA

Preliminary research indicates that there is no showstopper for the iCARA implementation on technology readiness. The desired beam injection configuration is within the capability of the commercial ion sources. 5 mA D- turnkey ion source is commercially available (e.g. F.D-5.30-SYS from D-Pace) and 140 mA D+ ion source has been experimentally demonstrated [11]. New full-body MRI magnet up to 7-Tesla can be purchased at the cost of $0.7 M/T approximately. The iCARA only requires a mild magnetic field homogeneity (1% estimated) not as PPM level in MRI magnet, so that the cost of the magnet can be reduced significantly. RF power requirement is 20~100 MHz, 20~100 kW CW, within the range of commercially available RF source Tetrodes, Triodes, or solid state RF amplifiers [12]. The TEM coaxial cavity has a very simple geometry for manufacturing and can be tuned easily by modifying the cavity length. High power targets are the critical components for accelerator-driven nuclear physics research. A windowless gas target supplies pure contents of the target element and offers stability over the long running times, a solid target allows more compact experimental setups and close installation of the detectors, while liquid target offers great heat dissipation capacities. At current phase, various target configurations [13-18] are under consideration as candidates for nuclear astrophysical reactions and neutron production simulation. Further performance and cost optimization of iCARA will be carried out in the future.

APPLICATIONS IN NUCLEAR PHYSICS

The compact high intensity iCARA can deliver various types of ion beam, including proton and helium, with current up to 120 mA DC, energy up to 10 MeV, which can find applications in nuclear physics, including astrophysics and precision neutron physics, as well as in neutrino physics and fusion energy research.

Nuclear astrophysics, at the interface of nuclear physics and astrophysics, is crucial in explaining the nuclear processes on the evolution of the universe and the origin of the elements. The nuclear reaction rates which determine the fuel consumption, chemical composition, energy production and lifetime of stellar evolutions phases still carry large uncertainties. These reactions in the astrophysically-important energy region have extremely low cross sections, ranging from pico to femto-barn and even below, which require the extreme experimental condition and stability to achieve a successful measurement, The signal to background ratio at the Earth's surface is usually too small mainly due to the cosmic ray interactions. To circumvent this issue, one should resort to either improve the signal strength with high beam intensities as pursued in the Facility for Rare Isotope Beams (FRIB) [19], or reduce the noise by pursuing in deep underground laboratories that provide shielding from cosmic radiation background. A high-intensity underground accelerator would be essential for addressing the broad range of experimental questions associated with the nucleosynthesis in stars.

Due to the bulky size of the conventional high intensity ion accelerators, there are severe limitations in the ion beam current intensity, beam energy, beam type, and detection versatility for measuring the key reactions for underground accelerators. The R&D of this compact high intensity iCARA concept is motivated in response to such scientific need for a next-generation high intensity underground accelerator facility. By running at CW steady mode instead of pulsed mode, the performance of accelerator system can be well stabilized to ensure the long-term operation required by precision measurement of ultra-low cross section of those nuclear reactions. The operating parameters of iCARA, even in prototype configuration, cover a broader dynamics range interested in nuclear astrophysics research than conventional electrostatic accelerators can provide.

The high intensity iCARA in principle can exploit deuteron-induced reactions to provide high intensity deuteron source to generate steady neutron intensity around 10^{12}~10^{14} n/s with 100% duty factor continuously. This capability can complement current efforts in pulsed neutron source with comparable average neutron intensity without resorting to nuclear reactors.

By the bombardment of high intensity energetic deuteron, some elements can become radioactive. For example, in the deuteron-induced nuclear reaction ${}^{2}D + {}^{A}_{Z}X \rightarrow n + {}^{A+1}_{Z+1}Y$, the energetic deuteron fuses with a target nucleus, transmuting the target to a heavier isotope while ejecting a neutron. Due to the low deuteron binding energy, deuteron stripping process may just need to overcome the nuclear Coulomb barrier. Much lower incident energy as well as the RF power to accelerate the ions is required compared to proton-induced nuclear reaction. Hence a low-energy deuteron accelerator can be used to generate intensive neutron flux without depending upon nuclear reactors or high energy accelerators. An accelerator-based neutron source allows well-controlled modulation of neutron flux to help suppress background-related systematic errors. Furthermore, it does not require tritium, while high intensity D-T reactors probably need recharge tritium fuel semi-annually.

For example, a low-energy deuteron beam of 2 MeV driven by iCARA can produce neutrons with good efficacy through the reaction ^{2}D + ^{7}Li → ^{8}Be + n. The total neutron production rate is about 10^{9} n/μA with the bombarding deuteron energy at 2 MeV [20]. Hence the neutron intensity can be as high as 10^{14} n/s for 100 mA 2 MeV CW deuteron beam. Similar neutron intensity can be scaled from the experimental data of the nuclear reaction of ^{9}Be (d, n) ^{10}B [21]. The exact neutron production rate in iCARA system requires further studies and simulation using GEANT4 [22] or MCNPX [23] software to confirm.

Neutrino physics is an active field of research with great impacts on broad scope of physical science including particle physics, nuclear physics, astrophysics and cosmology. In several short-baseline neutrino oscillation experiments, a phenomenon called the reactor anti-neutrino anomaly (RAA) may indicate a possibility of one or even two additional light sterile neutrinos. But the recent discovery that the flux deficit may result from the inadequate fission isotope flux prediction seems to disfavor such hypothesis. By providing a clean neutrino flux with better understanding of spectrum, beta decay of light isotope at rest produced by accelerators has been proposed to test the sterile neutrino hypothesis directly, including cyclotron-driven scheme IsoDAR [24]. In IsoDAR, at least 5 mA H_2^+ beam (equivalent to 10 mA proton) with energy 60 MeV is required. Such high-current cyclotrons present significant technical challenges and cost issues, as beam loss during the cyclotron injection and acceleration may limit the maximum achievable ion current to few mA or less [25].

Beta decay isotope ^{8}Li can be produced using 2 MeV deuterons through the deuteron-induced reaction ^{2}D + ^{7}Li → ^{8}Li + p, while the surrounding ^{7}Li target material can capture the thermal neutrons produced in ^{2}D + ^{7}Li → ^{8}Be + n to improve ^{8}Li production by going through ^{7}Li + n → ^{8}Li. The ^{8}Li isotope production rate driven by a CW 100 mA 2 MeV deuteron iCARA is estimated to be comparable to that of the IsoDAR experiment; hence the similar parameter space of neutrino physics as IsoDAR is expected.

Further, high intensity deuteron iCARA can be used in beam-driven fusion/fission hybrid reactor system or medical isotope production.

SUMMARY

In iCARA, CW high-current charged ion beam can be transversely accelerated by microwaves continuously, when the interaction between particle beam and electromagnetic field satisfies the so-called cyclotron auto-resonance condition. In a conventional CARA, the resonance condition implies acceleration cavities with large diameter (~meters) to support the desired electromagnetic mode at a certain frequency (<200 MHz). A remedy to this limitation is to introduce coaxial cavity as acceleration structure and operate at a different so-called TEM mode, which has no restriction on the dimension of cavity diameter. Hence the reduced diameter (~ 1 meter) allows the structure to fit inside a practical-size magnet such as medical MRI magnet.

Despite all the needed R&D refinements, but in view of the novel ideas presented, we believe that coaxial iCARA accelerators can be developed to an excellent candidate for high intensity underground accelerator for nuclear astrophysics research or high intensity neutron source for precision neutron physics. Unique features of this invention include: (a) one-stage structure to accelerate continuously, without bunching, all ion injected from a moderate-voltage tens-milliampere conventional ion source; (b) high intensity accelerated ion beam without severe space-charge issues that can arise with bunched beams; (c) inherent high microwave-to-beam efficiency; and (d) inherent self-scanning of the accelerated beam and possible reduction in power loading on the target—a crucial factor for robust long-term continuous operation. Preliminary study on technology readiness has been carried out and there is no showstopper for the realization of the iCARA.

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