A PATHWAY TO ACCELERATE ION BEAMS TO 3 GeV WITH A K140 CYCLOTRON*

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Abstract

The capabilities of the K140, 88-Inch Cyclotron at Lawrence Berkeley National Laboratory (LBNL) have been significantly enhanced through the addition of three successive generations of electron cyclotron resonance ion sources (ECRISs). These ion sources have helped the 88-Inch Cyclotron to evolve from a light-ion accelerator to one that has accelerated over half of the naturally-occurring elements in the periodic table, and in particular has accelerated ultra-high charge state heavy ions, such as xenon and uranium. Recently, with ^{124}Xe^{49+} ions injected from the superconducting ECRIS VENUS, the 88-Inch Cyclotron reached a new peak extracted kinetic energy of ~2.6 GeV. This is approximately a fifteen-fold energy increase over what this K140 cyclotron could achieve when it started operation almost six decades ago. A next-generation ECRIS, MARS-D, is under development and will further raise the extracted beam energy from the cyclotron. It is anticipated that the higher charge state ions produced by MARS-D will result in the 88-Inch Cyclotron accelerating ions in excess of 3 GeV for use by the radiation effects testing community. This paper will present and discuss the development of the MARS-D ECRIS and the 88-Inch Cyclotron's recent and possible future achievements.

INTRODUCTION

The K140, 88-Inch Cyclotron at Lawrence Berkeley National Laboratory (LBNL) has, in its nearly six decades of service, evolved from a light ion accelerator to one that has successfully accelerated ions ranging in mass from protons to the heaviest naturally-occurring element, uranium [1, 2]. The enhancement of this cyclotron's capabilities has continued through the addition of three successive generations of Electron Cyclotron Resonance Ion Sources (ECRISs). To date the 88-Inch Cyclotron has accelerated the 49 elements indicated in Fig. 1, which represents more than half of the naturally occurring elements including quite a number of their isotopes.

The wide range of ions capable of being accelerated by the 88-Inch Cyclotron has led to its use for a diverse range of applications, such as nuclear chemistry, syntheses of super heavy isotopes, nuclear structure, neutron beams for isotope breeding, space effects testing, etc. The very first single event effects (SEE) tests in the world were conducted using beams from LBNL's 88-Inch Cyclotron by the Aerospace Corporation in 1979 [3]. The combined versatility of the ECRIS, coupled with flexibilities in both the 88-Inch Cyclotron's magnetic field and accelerating frequency, allowed for the development of a number of "cocktail beams" in the mid-1980s where a collection of ions with very similar mass-to-charge ratios are injected into the cyclotron simultaneously and by employing small accelerating frequency changes, single ion species are fully accelerated and extracted [1, 4]. This capability led to the establishment of the Berkeley Accelerator Space Effects (BASE) Facility operating in conjunction with the 88-Inch Cyclotron to provide beams of heavy ions, protons, and neutrons for radiation effects testing. The continued advancement of different generations of ECRIS has led to great enhancement of both ion energy and variety enabling the BASE Facility continue to be at the forefront of radiation effects testing.

Though older, 88-Inch Cyclotron has not yet reached its full potential and the proposed ion source discussed below could push this accelerator to new heights. A brief introduction to ECRISs is given, followed by a description of how advancements in ECR technology at LBNL have enhanced the capabilities of the 88-Inch Cyclotron. Finally, a case is made the novel design of a next-generation ECRIS at LBNL may present the easiest path to the 88-Inch Cyclotron producing 3 GeV ion beams.

ECR ION SOURCE BASICS

The production of multiply-charged ions via ECR ion source was first reported by Geller at GANIL in 1972. This ion source uses a superposition of axial solenoids and a radial multipole (typically a sextupole) to confine a plasma in a magnetic field where that increases in all directions from the source center, i.e., a minimum-B field. Microwaves are injected into the source chamber at frequencies that allow for resonant electron heating on closed shells of constant magnetic field. These energetic electrons ionize neutrals and ions in a step-wise fashion.

The ionizing electrons are more energetic and are more likely to ionize if their source lifetime is long, therefore better plasma confinement leads to both higher currents and higher charge states. Geller developed semi-empirical scaling laws [5] predicting that extracted ion currents will increase as the square of both the injected microwave frequency and the confining magnetic field ($I_q \propto f^2 \propto B^2$). These scaling laws have continued to hold for three generations of ECRIS development, and it is expected that source performance will continue to improve with increased confining magnetic field.

ECRIS development since its invention has shown that

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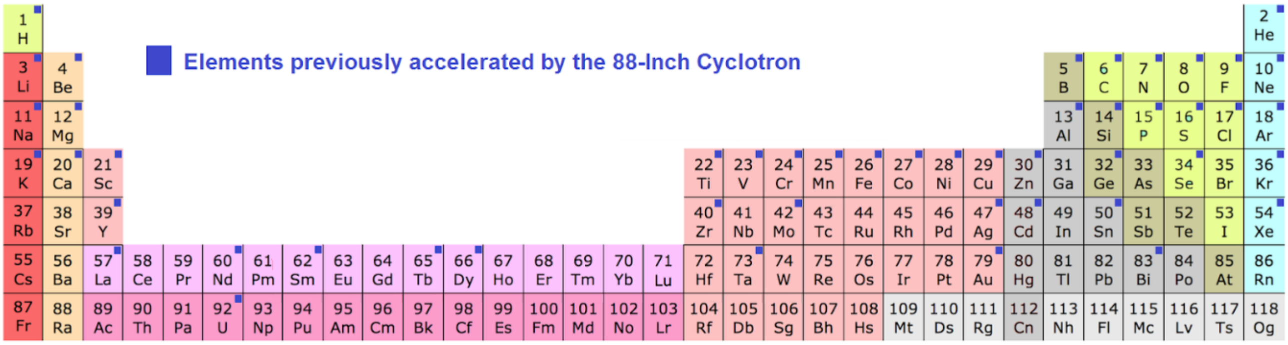


Figure 1: Since its commencement in 1962, so far the 88-Inch Cyclotron at Lawrence Berkeley National Laboratory has accelerated 49 elements (indicated with blue color squares), which is more than one half of the natural elements, and a great number of isotopes.

the source plasma is insensitive to the specific magnetic geometry of the source and all that is required is a high-strength minimum-B field [6]. Further, recent studies at LBNL have demonstrated that a cylindrical plasma chamber is not necessary for a high charge state ECRIS as the centimeter-or-smaller microwave wavelengths can easily travel into and resonate in a large complex-shaped plasma chamber [7]. This insensitivity to both magnet geometry and chamber geometry allows considerable flexibility when designing a high charge state ECRIS.

ECR ION SOURCES AT LBNL

Motivated by Geller's new ion sources, a 1st generation ECRIS named the LBL ECR replaced the 88-Inch Cyclotron's PIG sources in 1984 [1]. The increased versatility this ion source provided the cyclotron led to the construction and implementation of a 2nd and a 3rd generation ECR ion sources, AECR-U and VENUS, that were installed in 1996 and 2002, respectively [2, 8]. Each successive generation of added ion source had higher confining magnetic field and microwave frequencies, culminating with VENUS, the first 3rd generation ECR ion source built with a superconducting magnet. VENUS is capable of producing maximum axial and radial fields at the plasma chamber walls of 4 and 2.2 T, respectively and utilizing 18 and 28 GHz microwave heating.

Figure 2 clearly shows the greatly enhanced capability of the 88-Inch Cyclotron with each successive generation of ECR ion source. With the introduction of each new ECRIS, the 88-Inch Cyclotron's ability to accelerate heavier ions at higher currents followed. As can be seen in Fig. 2, before the introduction of AECR-U (the 2nd generation ECRIS) only ions with mass numbers up to 40 could be accelerated by the cyclotron to energies that reach the coulomb barrier for nuclear reactions (~5 MeV/nucleon). The AECR-U increased the mass of ion species reaching this energy threshold up to uranium, while the addition of the 3rd generation source VENUS increased beam intensities, as indicated in Fig. 2 by "Present with AECR-U" and "Present with VENUS," respectively. In particular, going from a 2nd to a 3rd generation ECRIS increased the intensity of cyclotron-extracted uranium from 10s of epA to 1 enA.

Listed in Table 1 are a few of the ultra-high charge state ion beams that have been accelerated through the cyclotron in recent years with maximum total energies in the 2.4-2.7 GeV range. This represents an energy increase of about fifteen-fold over what the 88-Inch Cyclotron could achieve almost six decades ago, and has been greeted enthusiastically by BASE Facility users desiring higher energy beams. Two of these high-energy beams, Xe^{49+} and Au^{63+}, are believed to represent the highest charge states of these species that the cyclotron can accelerate using VENUS as an injector source. Any further energy advancement will require the development of a more advanced ion source operating at higher confining fields and microwave frequencies in order to produce higher charge state ions with higher currents. Drawing on over 35 years of ECR ion source development at LBNL, we believe the development of a 4th generation ECRIS is the best path forward for this facility to acceleration ions in excess of 3 GeV in the near future.

Table 1: Ultra-High Charge State Ions Produced with VENUS and Accelerated by the 88-Inch Cyclotron

Ion	**Ip**# (keV)	**E** (MeV/n)	$\mathbf{E_{total}}$ (GeV)	$\mathbf{I_{ex}}^{\alpha}$ (epA)
$^{124}Xe^{47+}$	7.76	19.2	2.38	62
$^{124}Xe^{48+}$	8.02	20.0	2.48	10.5
$^{124}Xe^{49+}$	8.62	20.8	2.58	2.1
$^{179}Au^{63+}$	6.64	13.5	2.66	~1

#: Ip the ionization potential.
α: I_{ex} the current extracted from the 88-Inch Cyclotron.

CHALLENGES OF DEVELOPING A 4TH GENERATION ECRIS

All existing 3rd generation ECRISs, including LBNL's VENUS, have been built using NbTi superconducting coils. These advanced sources have two different, successful magnet geometries to produce the source magnetic fields: the radially-confining racetrack sextupole coils are either inside or outside of the axially-confining solenoids. For either coil configuration, however, existing 3rd generation sources are operating very near the NbTi conductor limits for safe operation in their high field environments. A

4th generation ECR ion source using one of these geometries would therefore need to employ a superconducting material capable of safe operation at even higher magnetic fields. The present leading candidate for a higher field material is Nb_3Sn. However, this material has never been successfully used in the construction of the very complex ECRIS magnet. To use Nb_3Sn many issues and challenges need to be addressed and overcome, such as conductor brittleness, increased coil fabrication complexity due to the heat-and-react processes, substantially poorer Nb_3Sn quench propagation requiring very demanding quench protection, etc.

Although there has been conceptual exploration into the design of a Nb_3Sn magnet for a future ECRIS [9], the ion source group at the Institute of Modern Physics in Lanzhou, China, is the only group currently working on the fabrication of an ECRIS utilizing Nb_3Sn coils (attempting sextupole-inside-solenoids geometry. This Nb_3Sn magnet is being designed to generate magnetic fields on axis and radially at the chamber walls of 6.5 and 3.3 tesla, respectively, which will allow for operation at 45 GHz [10]. Unfortunately, the progress of the magnet fabrication has been exceedingly slow as they attempt to address the expected challenges and complexities.

The difficulties faced in utilizing a new superconducting material to increase ECRIS magnetic fields motivates one to ask whether source geometry changes could be used to reach these higher fields while still employing NbTi coils. Reaching these higher fields using a coil material with nearly two decades of successful ECR ion source application could offer an easier route to a 4th generation, 45 GHz ECRIS.

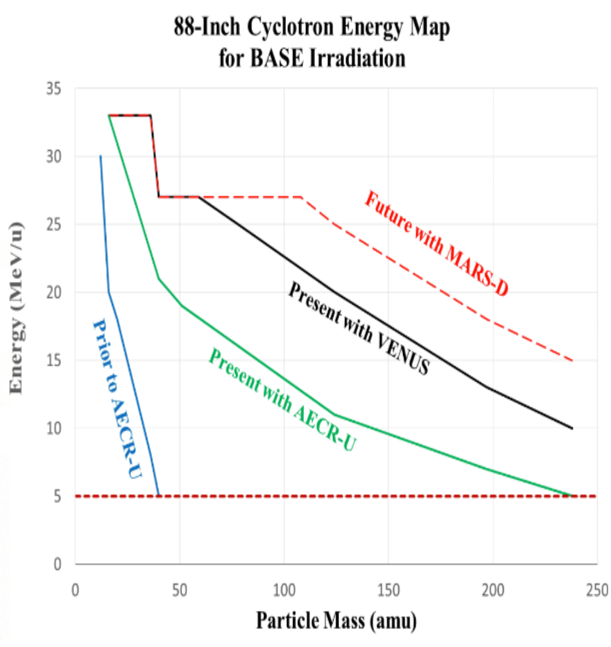


Figure 2: This plot shows the energy-mass curves achieved by the 88-Inch Cyclotron with the existing ECRISs and extrapolation with a future ECRIS for the BASE Facility.

MARS-D: A 4TH GENERATION ECRIS

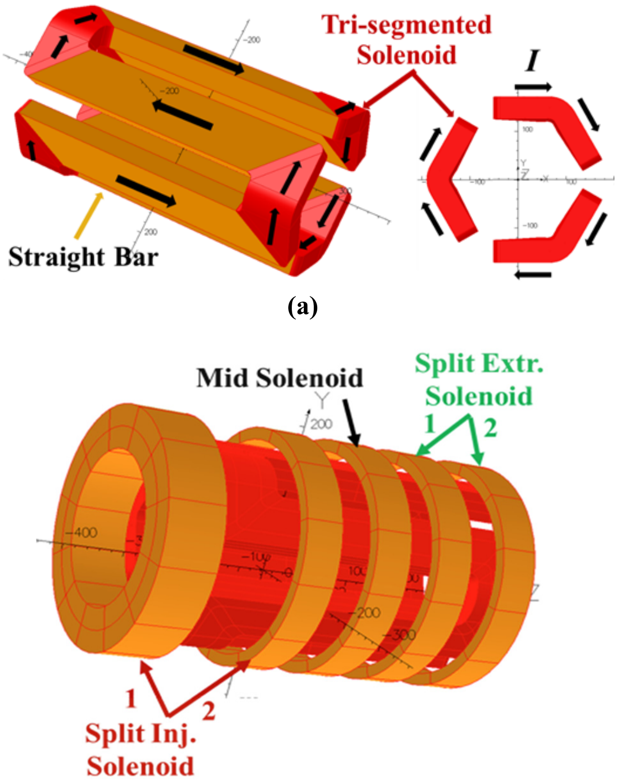
A 4th generation ECRIS, MARS-D, capable of operation at 45 GHz is under continuing development at LBNL. This advanced source is expected to serve many roles, but it will be a key element in the quest for using the 88-Inch Cyclotron to accelerate ions in excess of 3 GeV total energy.

MARS-D employs a new magnet geometry: a Mixed Axial and Radial field System (MARS), that will allow NbTi-magnet-based ECR ion sources to achieve higher confining fields [11]. The critical component of MARS is a closed-loop-coil with a hexagonally-shaped cross section, as shown schematically in Fig. 3 (a). The major difference between the MARS geometry and a conventional racetrack design comes in the connections between the long sextupole sections. The closed-loop-coil is one continuous winding, and as a result the currents in the ends of the sextupole structure all rotate in the same sense about the long axis of the sextupole. This is not true for the six racetrack coils that make up a more typical electromagnetic sextupole, where neighboring racetrack coils have end currents with opposite rotations about the long axis. This difference presents two major advantages for the closed-loop-coil over a set of racetrack coils: there is a net solenoidal field at each end of the closed-loop-coil so that this structure alone generates a minimum-B structure, and the forces on each end of the structure are always in the same direction (outward) which makes for much easier coil clamping. By generating its own axial magnetic field, smaller additional solenoid coils can be used, which keeps the internal coil fields for the superposed structure further from critical operation points. A design using relatively small solenoids combined with a closed-loop-coil to construct a NbTi magnet for MARS-D is shown in Fig. 3 (b). Generally, ECRIS design requires that the maximum axial fields within the source, B_{inj} and B_{ext} (injection and extraction), along with the radial field at the chamber wall, B_{rad}, be related to the magnetic field for ECR heating via injected microwave, B_{ECR} in the following manner: $B_{inj} \sim 3.5 - 4\ B_{ECR}$ and $B_{ext} \approx B_{rad} \geq 2\ B_{ECR}$. Based on these requirements, MARS-D has been designed to produce maximum fields of 5.7 T on axis and 3.2 T radially at the plasma chamber walls: sufficient for supporting operations at 45 GHz.

The two main advantages of the MARS magnet come at the cost of a more complex winding for the closed-loop-coil. Specific tooling and a new winding technique have allowed for the successful construction of a closed-loop-coil using copper wires. Field mapping of this coil agrees very well with the computations demonstrating the feasibility of fabricating a NbTi closed-loop-coil [12]. The MARS-D plasma chamber and the warm bore of the cryostat are to have a hexagonal cross-section to match the shape of the closed-loop-coil and more efficiently use its confining radial field.

Full construction of MARS-D is anticipated to begin soon with scheduled completion in approximately four to five years. Initial commissioning is planned by using multiple-frequency heating, such as a combination of commercially available microwave generators of 22, 28, 35 and

45 GHz with a total power of ~4-5 kW. This power level is estimated to be sufficient for the production of ultra-high charge state ion beams for use by the BASE facility. A full power solution for MARS-D would be 15-20 kW and that will be treated as a power upgrade for the production of intense highly-charge ion beams for other applications.



(a)

(b)

Figure 3: (a). Schematic layout of a closed-loop-coil, the MARS critical component. It combines six rectangular straight bars (yellow color) and two three-segmented solenoids (red color) into a closed-loop-coil. (b). The solenoids superimposed magnet system for producing the minimum-B field with high mirror ratios for MARS-D ECRIS.

Table 2: Possible Ultra-High Charge State Ions Produced with MARS-D and Accelerated by the 88-Inch Cyclotron

Ion	**Ip**[#] (keV)	**E** (MeV/n)	$\mathbf{E_{total}}$ (GeV)
^{124}Xe^{52+}	9.57	23.4	2.90
^{124}Xe^{54+}	40.3	25.2	3.12
^{179}Au^{69+}	8.26	16.2	3.19
^{179}Au^{70+}	17.1	16.6	3.27
^{179}Au^{73+}	18.3	18.0	3.55

[#]: Ip the ionization potential.

With a higher density of hotter electrons and a longer plasma confinement time compared to VENUS, MARS-D is anticipated to enhance the production of higher charge states heavy ions, such as xenon, gold, and uranium. Listed in Table 2 are a few ultra-high charge state ion beams with ionization potentials in the 10-40 keV range that are anticipated to be produced with MARS-D. The 88-Inch Cyclotron should be capable of accelerating these ions to a total energy in excess of 3 GeV, thus furthering the achievements of this nearly 60-year-old machine and benefitting the radiation testing community.

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